To act or not to act: Warning communication and decision-making in response to weather-related hazards

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To act or not to act:
Warning communication and decision-making in response to weather-related hazards

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Note

This thesis is a cumulative dissertation comprising four scientific research contributions published or under review in peer-reviewed journals. In Chapter 1, I present the context of this thesis and address the different research questions. Chapters 2 to 5 contain the four individual contributions in manuscript (i.e., pre-print) form, with supplementary information included as appendices. In Chapter 6, I briefly discuss the different results and implications in the overall context and present a broader outlook for further research. In the following, I use the personal pronoun “I” when describing the research. In fact, it was conducted by a team of researchers (mentioned in the acknowledgements), which I was the leader of.

Summary

Many severe hydro-meteorological events cause unnecessary losses of life and property despite being well forecasted with accurate and timely disseminated warning information. Apparently, warnings have no inherent value, but only become valuable once they influence people's decisions. A good warning message (i.e. in terms of accuracy and timeliness) that is not conveyed to the end-user in a way that leads to desired behaviour is useless. In future, the expected losses of bad weather are projected to further increase: climate change causes more intense, frequent and long-lasting extremes, and social vulnerability grows with population growth and spatial expansion into areas impacted by hazards. Thus, there is an urgent need to better understand why some people do not respond to warning messages and to identify effective communication strategies, which provide practical insights for policy- and decision-makers, and help people at risk take better informed decisions. The four contributions that comprise this thesis identify and answer open research questions, which aim at advancing the effectiveness of warning communication and decision-making by increasing the understanding of how message content influence people's response to warnings.

Contribution I shows how better targeted communication strategies can increase individual preparedness levels. With natural hazard management shifting towards more integrated approaches that address the role of private households in reducing risks, there is a need to investigate the readiness of people in adopting risk reduction behaviours. I build on protection motivation theory that I combine with decision-stage theory to develop a dynamic protection motivation framework, which helps to understand the motivations of different individuals to undertake risk reduction measures. Based on a household survey conducted in an Italian community that was recently affected by flash floods, I show that not all people are motivated by the same threat or coping appraisals, but that these differ depending on people's risk reduction stage, i.e. the type of measures already undertaken. Findings contribute on better targeting long-term communication strategies to individuals at risk, which ought to motivate them to undertake risk reduction measures.

Contribution II analyses the effects of inconsistent warning messages on the general public's response. This inconsistency is the result of the duplication of public weather warnings, which are disseminated by different public and private providers. Therefore, I developed a simple matrix to categorize the level of inconsistency across multiple warnings, addressing both visual and textual inconsistencies. Following a severe rainfall event in Switzerland, I conducted an online experiment with different warning pairs that provided participants with more or less consistent information. Results highlight that inconsistent messages were perceived of lower quality and negatively impacted warning response. People were less likely to engage in self-protective behaviours for different types of inconsistent warnings compared

to consistent warnings; the higher the level of inconsistency the poorer was the behavioural response.

Contribution III examines how changes in hazard description can help people at risk to translate the warning information into an appraisal of risk. With increasing interests of National Meteorological and Hydrological Services to provide impact-based warnings that focus on the impacts that result from the weather, there is a need to better understand whether these warnings would result in greater self-protective behaviours. I also investigate the individual effect of behavioural recommendations in the warning messages. I conducted the research in Switzerland using an online survey experiment that included a hypothetical decision-scenario. Results show that participants who received impact-based warnings - with and without behavioural recommendations - were more likely to engage in self-protective behaviours than people who received the standard warnings. Messages with impact text and recommendations were also reported to be clearer, easier to understand, and more credible, and people reported to be more concerned for their safety, and better understood the threats and behaviours to engage in.

Contribution IV draws on insights from Contribution III, but the research was conducted with a different method. Theory from cognitive science suggest that people can use a fast decision pathway that is largely driven by feelings and/or a slower pathway that is based on rational deliberation to process risk information. While rational deliberation must be the dominant pathway in an imagined situation, the presence of fear that emerges in a real-crisis situation could influence the effectiveness of impact-based warnings and people's actual decisions. I conduced a field experiment, in which wind warnings were disseminated through an existing smartphone application of a Swiss weather provider (*Wetter-Alarm*), and real-time data was collected on people's responses. Results show a domination of the affective model of decision-making when people are under an imminent threat of life. The influence of fear resulted in no effect of impact-based warnings. However, stronger event severity and shorter lead times generated a greater behavioural response.

The thesis makes four important contributions to the literature. First, it makes a theoretical contribution as it applies a novel protection motivation framework to identify individual motivations for risk preparedness. Second, the thesis performs the first empirical analysis of the influence of inconsistent weather warnings on people's behaviours. Third, it adds to the growing literature on impact-based warnings by investigating the individual effects of impact text and behavioural recommendations. Fourth, for the first time the dissertation investigates behaviours in real-world crisis in response to actual weather warnings.

Altogether, the findings from the four contributions have implications for practitioners, policy-makers and researchers. First, the protection motivation framework ought to help practitioners to develop more effective strategies that link patterns of perception or capacity

to effective patterns of communication and avoid to target large communities at risk with a single communication strategy. Second, public and private weather providers should enhance cooperation and deliver more consistent warning information. If cooperation fails, then policy-makers may perform modifications in the warning process and clarify the stakeholder's roles and responsibilities. Third, decision-makers should develop and use impact-based warnings with behavioural recommendations only in the case of very severe weather. At the same time, when communicating messages, they should be aware of the importance of affect in making decisions when people are under an imminent threat. Fourth, researchers that investigate responses to threats should use research designs that capture real-world conditions.

Zusammenfassung

Extremes Wetter verursachte in den letzten Jahren unnötige Verluste. Es gab Sachschäden und Menschen starben, obwohl die Extremereignisse gut vorhergesagt und Warninformationen rechtzeitig verbreitet wurden. Dies zeigt, dass genaue und rechtzeitige Warnungen nicht zwangsläufig von Nutzen sein müssen, wenn die Informationen nicht verständlich an den Endverbraucher übermittelt werden. Warnungen haben keinen eigenen Wert an sich, sondern werden erst dann wertvoll, wenn sie die Entscheidungen der Menschen positiv beeinflussen. In Zukunft werden die zu erwartenden Schäden weiter zunehmen. Einerseits verursacht der Klimawandel bereits intensivere, häufigere und länger anhaltende Extreme. Andererseits wird die soziale Verwundbarkeit durch den Bevölkerungswachstum und die räumliche Ausdehnung in gefährdete Gebiete weiter zunehmen. Daher ist es dringend erforderlich, besser zu verstehen, warum einige Menschen nicht auf Warnungen reagieren. Auch müssen wirksame Kommunikationsstrategien erarbeitet werden, welche praktische Erkenntnisse für Politik und Entscheidungsträger liefern und gefährdeten Menschen dabei helfen, besser informierte Entscheidungen zu treffen. Die vier Beiträge, welche diese Arbeit umfassen, identifizieren und beantworten offene Forschungsfragen, die darauf abzielen, die Kommunikation von Warnungen und die darauffolgende Entscheidungsfindung zu verbessern.

Im ersten Beitrag untersuche ich wie gezielte Kommunikationsstrategien die individuelle Katastrophenvorsorge erhöhen können. Da sich das Management von Naturgefahren auf stärker integrierte Ansätze verlagert, welche sich mit der Rolle der privaten Haushalte bei der Risikominderung befassen, muss die Bereitschaft der Menschen zur Übernahme von Risikominderungsverhalten untersucht werden. Ich kombiniere die *Protection Motivation Theory* mit dem *Trans-Theoretical Model*, um ein dynamisches Konstrukt der Schutzbereitschaft zu entwickeln, welches dabei hilft, die Motivationen verschiedener Personen zu verstehen und Maßnahmen zur Risikominderung durchzuführen. In einer italienischen Gemeinde, die kürzlich von Sturzfluten betroffen war, wurde eine Haushaltsumfrage durchgeführt. Die Ergebnisse zeigen, dass nicht alle Menschen von den gleichen Faktoren motiviert sind und sich diese nach Phase der Risikominderung, d.h. der Art der bereits ergriffenen Maßnahmen, unterscheiden. Die Ergebnisse tragen dazu bei, langfristige Kommunikationsstrategien zu entwickeln, welche gefährdete Personen dazu motivieren sollten, Maßnahmen zur Risikominderung zu ergreifen.

Im zweiten Beitrag werden die Auswirkungen inkonsistenter Wetterwarnungen auf die Entscheidungsfindung analysiert. Diese Inkonsistenz ist das Ergebnis der Doppelung von öffentlichen Wetterwarnungen, die von verschiedenen öffentlichen und privaten Anbietern verbreitet werden. Daher habe ich eine einfache Matrix entwickelt, um den Grad der Inkonsistenz über mehrere Warnungen hinweg zu kategorisieren, und sowohl visuelle als auch textuelle Inkonsistenzen zu berücksichtigen. Nach einem Starkregenereignis in der

Schweiz habe ich ein Online-Experiment mit verschiedenen, mehr oder weniger konsistenten, Warnpaaren durchgeführt. Die Ergebnisse zeigen, dass inkonsistente Warnungen schlechter als konsistente Warnpaare wahrgenommen werden und sich negativ auf die Reaktionen auswirkten: Je stärker die Inkonsistenz, desto gefährlicher war das Verhalten.

Im dritten Beitrag wurde untersucht, wie wirkungsbasierte Warnungen gefährdeten Personen helfen können, diese zu verstehen. Angesichts des zunehmenden Interesses der nationalen meteorologischen und hydrologischen Dienste an wirkungsbasierten Warnungen, die sich auf die wetterbedingten Auswirkungen konzentrieren, muss besser verstanden werden, ob diese Warnungen tatsächlich zu einem besseren Schutzverhalten führen. Darüber hinaus habe ich die individuelle Wirkung von Verhaltensempfehlungen in Warnungen untersucht. Die Forschung wurde mithilfe eines Online-Umfrageexperiments in der Schweiz durchgeführt, welches ein hypothetisches Entscheidungsszenario beinhaltete. Die Ergebnisse zeigen, dass Teilnehmer, die wirkungsbezogene Warnungen - mit und ohne Verhaltensempfehlungen - erhielten, sich eher schützten als Personen, die konventionelle Warnungen erhielten. Es wurde auch berichtet, dass Warnungen mit Wirkungstext und Empfehlungen klarer, verständlicher und glaubwürdiger, und dass die Bedrohungen bzw. welche Verhaltensweisen verfolgt werden sollten, ebenfalls besser verständlich waren.

Der vierte Beitrag stützt sich auf die Erkenntnisse aus dem dritten Beitrag, wobei eine andere Methode angewandt wurde. Erkenntnisse aus den Kognitionswissenschaften deuten darauf hin, dass Menschen einen schnellen Entscheidungspfad nutzen können, der weitgehend von Gefühlen getrieben wird, und/oder einen langsamen Pfad, der Risikoinformationen rational verarbeitet. In einem hypothetisches Entscheidungsszenario sollten Menschen rationale Entscheidungen treffen, da Emotionen (bezüglich des Wetters) kaum vorhanden sein können. In einer realen Krisensituation hingegen, können Angst und andere Gefühle auftreten, welche den Effekt von wirkungsbezogenen Warnungen und die Entscheidungen der Menschen beeinflussen. Daher habe ich ein Feldexperiment durchgeführt, bei welchem Windwarnungen über die Smartphone-Anwendung des Schweizer Anbieters «Wetter-Alarm» verbreitet und Daten über die Reaktionen der Personen in Echtzeit gesammelt wurden. Die Ergebnisse deuten auf eine Dominanz des gefühlsbasierten Modells bei der Entscheidungsfindung hin. Der Einfluss der Angst führte zu keinem signifikanten Effekt von wirkungsbasierten Warnungen auf das Verhalten. Allerdings beeinflussten stärkere Windereignisse und kürzere Vorlaufzeiten das Verhalten positiv, was mit dem emotionalen Entscheidungspfad einhergeht.

Die Doktorarbeit macht vier wichtige Beiträge zur Literatur. Erstens leistet die Arbeit einen theoretischen Beitrag, da ein neuartiges Konstrukt anwendet wurde, um individuelle Motivationen für die Katastrophenvorsorge besser zu identifizieren. Zweitens wurde die erste empirische Analyse des Einflusses von inkonsistenten Wetterwarnungen auf das Verhalten der Menschen durchgeführt. Drittens ergänzt die Dissertation die wachsende Literatur über

wirkungsbasierte Warnungen, indem die individuellen Auswirkungen von Wirkungstexten und Verhaltensempfehlungen untersucht werden. Viertens wird in der Arbeit erstmals das Verhalten von Menschen in Bezug auf reale Wetterextreme breitflächig untersucht.

Die vier Beiträge liefern Erkenntnisse für die Praxis, politische Entscheidungsträger und Forscher. Erstens sollte das Konstrukt der Schutzbereitschaft den Fachleuten dabei helfen, effektivere Risikostrategien zu entwickeln, welche Wahrnehmungs- oder Kapazitätsmuster mit effektiven Kommunikationsmustern verbindet. Zweitens sollten öffentliche und private Wetterdienste die Zusammenarbeit verstärken und konsistente Warnungen verbreiten. Sollte diese Zusammenarbeit scheitern, müssten die politischen Entscheidungsträger Änderungen im Warnprozess vornehmen, um die Rollen und Verantwortlichkeiten der jeweiligen Interessensvertreter besser zu definieren. Drittens sollten Entscheidungsträger wirkungsbasierte Warnungen mit Verhaltensempfehlungen nur für sehr schlechtes Wetter entwickeln. Gleichzeitig sollten sie sich bei der Kommunikation von Warnungen der Bedeutung von Gefühlen bei der Entscheidungsfindung bewusst sein. Viertens sollten Forscher, die Reaktionen auf Bedrohungen untersuchen, Forschungsdesigns anwenden, welche die realen Bedingungen bestmöglich erfassen.

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1) Introduction

1.1) Problem statement and motivation

Today, extreme weather and climatic events, as well as other natural hazards, impact every sector of society. Environmental-related risks and, especially, extreme weather events are ranked among the top global risks by likelihood and impact (World Economic Forum 2018). These risks are expected to increase with climate change causing more frequent, intense and long-lasting weather extremes (IPCC 2012). At the same time, we face an increasing social vulnerability to environmental and meteorological hazards. Population growth and spatial expansion into areas where natural hazards occur, have increased vulnerability (Gall et al. 2009; Mitchell 2003). For instance, in the USA, the growing concentration of people and properties in coastal locations, which can be impacted by hurricanes, resulted in a strong increase in reported damage as more and wealthier people have moved to these areas more and more often (Pielke et al. 2008). This trend is also documented for other hazards (Munich RE 2017). Thus, the potential human and economic losses from weather-related risks are huge.

Early warning systems (EWS) can reduce these risks and vulnerability. The United Nations International Strategy for Disaster Reduction defines early warnings as "the provision of timely and effective information through identified institutions, that allows individuals exposed to a hazard to take actions to avoid or reduce their risk and prepare for effective response" (UNISDR 2006, p. 2). An effective EWS comprises four inter-related elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability. A failure in any part could result in the failure of the whole system (UNISDR 2006). Unfortunately, improvements in risk assessment, monitoring and forecasting did not always advance in parallel with improvements in warning-related communication, so that warnings are misunderstood as they are incomplete or unclear, and fail to address the needs and concerns of the targeted groups. Sometimes warnings are also not considered or even completely ignored by the people at risk as the plurality of (often contradictory) information – easily accessible though communication technologies (i.e., mobile devices) – can confuse people or undermine the official public voice.

For example, in April 1974, the Midwest of the USA was hit by severe tornado outbreaks. Weather forecasts and warning systems did not exist back then. People were only given the night before some basic information that tornados could strike the region in the coming days. 316 people were killed by the tornadoes (Uccellini 2018). Over the last decades, our ability to observe and predict tornados has significantly improved: more and better climate data, coupled with enhanced technology, such as capabilities for modelling and dissemination of information, have given rise to warning systems that are becoming more and more sophisticated (Aitsi-Selmi et al. 2016; WMO 2015a). In 2011, an almost identical tornado outbreak hit the same region in the Midwest again: the number and strength of tornados

were very similar, including the track length and timing (Uccellini 2018). However, compared to 1974, detailed outbreak forecasts were provided already 4-6 days prior to the event. Moreover, warnings were disseminated on time, with an average lead time of 24 minutes, which should allow people to take appropriate protective measures. Unfortunately, the number of fatalities has not changed; 314 people lost their life in April 2011 (Uccellini 2018). Thus, accurate and widespread warnings, that were disseminated on time, did not necessarily trigger protective behaviours that experts recommended and were hoping to see.

We observe similar examples to this in the entire world. For instance, in February 2000, floods in Mozambique caused the loss of more than 700 lives with over half a million people homeless and 4.5 million affected (Christie and Hanlon 2001; IPCC 2012). Above-average rainfall, exacerbated by a series of cyclones bringing torrential rains, caused a flood wave that followed its way down the valley, arriving suddenly and burying low-lying farmlands under 4-8 meters of water (Patt and Schröter 2008). As Christie and Hanlon (2001) reported many of the warnings went unheeded; people did not understand the messages, as they were used to slow-onset flooding, and thus did not consider to evacuate their family and livestock when they got the warning. Earlier this year, Mozambique was hit by the cyclones Idai and Kenneth, and a similar situation was observed than 19 years ago. The cyclones were followed by heavy rainfalls (30 % of annual rainfall in 5 days), which caused severe flash floods. Many people died, were homeless or lost their livelihoods (Mustafa 2019). In both cases, the warnings from 2000 and 2019 were accurate, but inadequate; they failed to reach people or to communicate the underlying risk and impacts by being too technical (i.e., focussing on wind speed and amount of rainfall). As a result, they did not trigger protective actions of those at risk. Thus, for hazard warnings to be effective, they not only need to convey basic information about the hazard itself, but also about the impacts, so that lay people understand the underlying risks. Moreover, people did not undertake any risk reduction measures over the past years, which could have attenuated the impacts of flooding. Thus, there is a need to better understand the motivations of people at risk to appropriately prepare for natural hazards in advance, which should be addressed in long-term risk communication strategies.

In this thesis, I work on the assumption that despite significant advances in the provision and delivery of warnings, disasters continue to kill people, destroy property and impoverish communities. There is an urgency to better understand why some people do not respond to warning messages and to identify effective risk communication strategies that work with, rather than against, preparedness levels, risk perceptions and individual decisions. I want to improve warning-related communication in response to weather hazards and help people at risk take better informed decisions. I conducted my research in Switzerland and Italy, as well as in close collaboration with public and private weather providers, and international organisations engaged in the weather warning chain (i.e., MeteoSwiss, *Wetter-Alarm*, High Impact Weather Project of the WMO) in order to include stakeholder´s actual needs and problems, such as providing consistent weather information to different groups of users, in

the research design. My research aims at improving the warning communication process by strengthening the link between communication and decision-making patterns in response to warning messages. By examining how different message content and format affect peoples' decisions to respond to warnings, this research can help identify, why improvements in risk assessment and forecasting capability may not necessarily lead to better outcomes. Thereby, I will identify some key factors that must be addressed to improve the flow of information and decision-making. In addition, I make suggestions and give practical recommendations for communication practices. Better communicating risks in warning messages can strengthen community preparedness and resilience, and, ultimately, reduce disaster risk and vulnerability of our society.

1.2) Warning-related communication and decision-making

1.2.1) Warning communication

Warning-related communication is a fundamental component of a holistic risk management approach (Höppner et al. 2012). It relates to the communication that is used when a potentially severe event occurs; i.e. the warning messages that are disseminated and used for self-protective decision-making. Thus, referring to the immediate affected area and population, this short-term communication should prepare monitoring information into actionable messages understood by those that need them (UNISDR 2006). Figure 1 shows the warning chain (in *blue*), which starts with the observation of the weather, moves on with the production of different products and services, and ends with the decision-making of the end-users, such as the general public, public agencies or private businesses. These elements of the chain are performed by different stakeholders or institutions/organisations and the information is being communicated, translated and interpreted from one area of expertise to the other. For example, the weather forecast that indicates severe weather must be translated into a warning message.

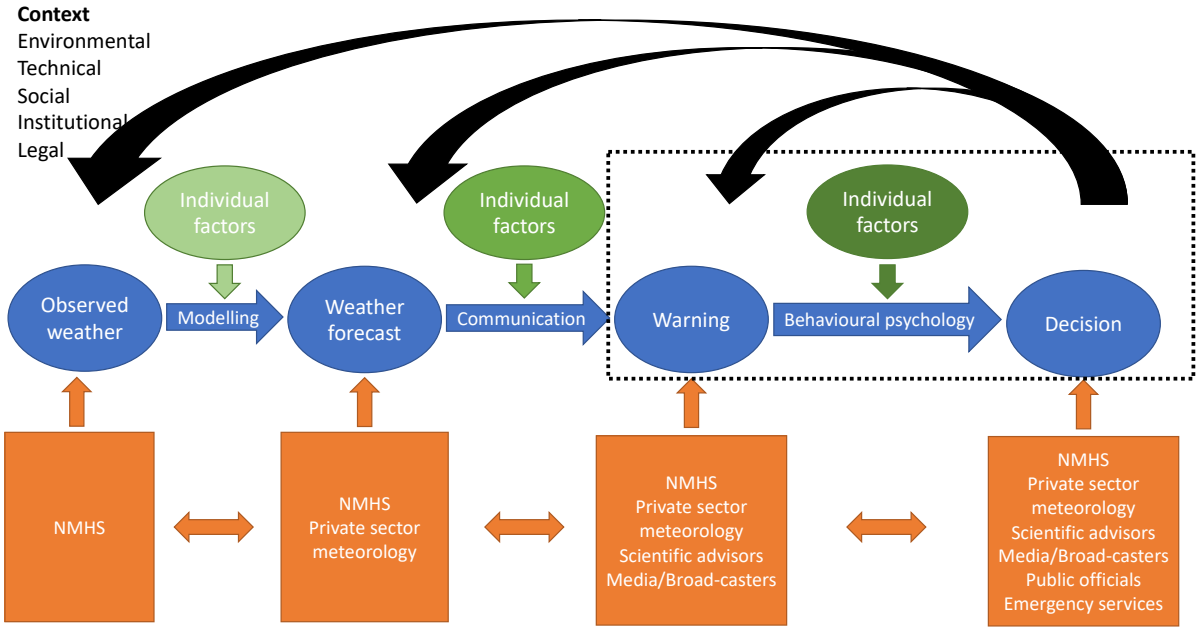

Figure 1. The warning process: From weather observation to individual decision-making.

Warning communication takes place in a complex dynamic environment, with different stakeholders under constantly changing socio-technical, environmental and political conditions. First, different institutions or groups of stakeholders are involved in the warning process. Figure 1 shows that with increasing information, the number and diversity of actors involved also increases (in *orange*). At the beginning of the chain, National Meteorological and Hydrological Services (NMHS) provide the forecast models and collect most of the meteorological data. This information is then being used by themselves and the private sector meteorology to produce forecasts and warnings (Thorpe 2016; Pettifer 2015). However, these different – public and private – weather services do not always provide warning information that is consistent across different messages, as they use different map colour-coding, warning thresholds and interpret model outputs differently, which increases the risk of apparent or actual inconsistencies in the warning information disseminated to the public. National weather services and emergency managers have suspected that these conflicting cues exist and negatively influence public behaviour (Lindell and Brooks 2013).

In the next step, these organizations disseminate warning messages to the public through their own channels, as well as through the media. The broadcasters may also give behavioural recommendations, which, again, may be in conflict with the actions recommended by the emergency services or other public officials. Scientific advisors may even provide additional information in the process. Thus, bad communication, coordination or collaboration between these stakeholders can impact the effective passing of information in the warning chain. Other sources that depend on the social context may be friends or family than can also provide information about protective actions.

Next, people use different technologies or channels to access the information. The different types of channels – print, mechanic, electronic, face-to-face – have very different characteristics too, for instance with respect to the dissemination rate or precision (Lindell and Perry 2012). For example, a siren can make people instantly aware of the threat, but has a limited reach and provides no further information. Moreover, the environmental conditions can influence decision-making of end-users. Sights and sounds that indicate hazard onset are important for people's emergency response (Lindell and Perry 2012). For example, the presence of thunders and lightnings during storms could influence response as they provide evidence of an imminent threat. At the same time, a warning message could also conflict with the environmental cue, when the weather is not as bad as described in the message (BNHCRC 2019).

The legal, institutional and political context can also influence the warning chain. For instance, we are witnessing an increase in legal conflicts related to the dissemination, use and interpretation of warning information (Altamura et al. 2011). This could result in more defensive, self-protective behaviours of public officials that issue warnings and alerts to avoid personal blame and liability. For example, the number of false alarms was observed to increase in Italy (Altamura et al. 2011), which could, again, influence weather-related decision-making. Research found that very high alarm rates let to inferior decision-making, the so-called cry wolf effect (Joslyn and LeClerc 2012). The institutional framework can also weaken the warning process, for instance in the absence of defining stakeholders' distinct roles and responsibilities (Thorpe 2016). This can impede collaboration and cooperation between the actors. Finally, politics can influence the effectiveness of the warning chain too, for instance by instructing the administration to foster two-way communication processes.

It's important to note that this whole warning process is neither solely linear nor one-way, but rather circular and two-way as it depends very much on the environmental, social, technical, and legal context, as well as the degree of partnership among the involved stakeholders. Finally, individual factors (in *green*), such as knowledge, experience, or trust influence the passing of information (Parker et al. 2009). These factors can change depending on the area of expertise or the stakeholder (therefore different shades of *green*). For instance, a weather forecaster may have a good experience with a specific weather model and has greater trust in its output than in the forecast of another model. However, I am particularly interested in how these individual factors shape the extent to which people at risk engage in self-protective behaviour.

In the following I focus on the last part of the warning chain, namely the communication of warning messages and the behavioural decision-making of the general public. This is part of the chain, which is of the biggest concern for most stakeholders. Weather providers and emergency managers have realized that despite significant improvements in forecasting, the vast majority of people do not take any action as a result of a severe weather warning (UK

Met Office 2018). Thus, to help people take better informed decisions, they have started to focus on different communication alternatives, for instance using warning messages that describe the impacts of the weather rather than the phenomenon itself.

1.2.2) The warning message

As Figure 1 suggests, the warning message directly influences people's warning response. Research has suggested that message content and style are important factors in determining whether people take self-protective behaviour or not. In order to be effective at inducing such behaviour, a message should contain five information elements: hazard (nature and magnitude), location (area affected by the hazard), time (occurring time and hazard development), guidance (action recommendations) and source (Mileti and Sorensen 1990). In addition, each of the five content elements should be addressed by the five stylistic dimensions of a warning message which are specificity, consistency, accuracy, certainty, and clarity (Mileti and Sorensen 1990).

However, weather forecasts and warnings are inherently uncertain. Research shows that people understand that there is uncertainty inherent in weather forecasts, as well as that different scientific factors shape this uncertainty (Joslyn and Savelli 2010). With respect to communication, some researchers argue that communicating scientific uncertainty (e.g., in probabilistic forecasts) leads to better outcomes (Fischhoff and Davis 2014), as it will increase understanding (Stirling 2010). LeClerc and Joslyn (2012) found that providing weather forecasts (of high consequences but low probability) with uncertainty information enhances the chances that users take precautionary action. However, conclusions about how uncertainties should be communicated (quantitative vs. qualitative, graphs/maps vs. text, etc.) are not clear yet and depend on the users, the context and the type of information (Orr et al. 2009). Nevertheless, technological improvements have continually reduced the level of uncertainty in weather forecasts and warnings.

Over the last decades, messages have been improved as warnings are being made with greater accuracy, geographic precision and lead time. However, the information is not always clear, specific, or consistent. For example, many people do not understand the standard phenomenon-based warnings and have difficulties to translate a 'heavy' rainfall warning, indicating 100 mm of rain, into effective impacts. In this case communicating specific impacts, for instance on road and rail transport, and possibilities of delays, could improve warning effectiveness. Moreover, it is important that a warning message is consistent within itself and across different messages (Mileti and Fitzpatrick 1992). This means that not only sequential messages from the same weather provider shall be consistent, but also messages from different providers at a given point in time. However, it is common that inconsistent warning information is being disseminated to the public as private weather companies can also publish and disseminate their own weather warnings.

1.2.3) Individual decision-making

Beside the warning message itself, other factors can also influence protective behaviours. Numerous studies that have been conducted in the warning context identified varying influencing factors. First, hazard and warning experiences were associated with differences in protective responses (Knocke and Kolivras 2007; Sharma and Patt 2012; Siegrist and Gutscher 2006). For example, Sharma and Patt (2012) found that prior experience with the comfort and quality of cyclone shelters, as well as with loss of property due to crime in the villages being evacuated, were major determinants of self-protective behaviour. Other research has also shown that greater knowledge of the hazard increases the likelihood that an individual will take protective action in response to a warning (Ripberger et al. 2014b; Sorensen 2000). Moreover, perceived risk was found to be a primary factor in taking self-protective behaviour in the case of storms (Lazo et al. 2015; Morss and Hayden 2010), but the relationship is not always clear, such as for floods (Bubeck et al. 2012). Other variables, for example trust in warnings (Losee and Joslyn 2018) or governments (Taylor et al. 2019; Wachinger et al. 2013), coping appraisals (Bubeck et al. 2012; Grothmann and Patt 2005a), and self-efficacy (Bubeck et al. 2013; Grothmann and Reusswig 2006) can also influence warning response. Finally, socio-demographic characteristics, including gender, age, education, residence area and ownership can affect response in dangerous situations (Mileti and Sorensen 1990; Bateman and Edwards 2002).

Over the past, different models have been developed to explain the processes that people go through when making decisions in response to warning messages. I briefly introduce three models that specifically relate to warning communication and decision-making. The Risk Information and Processing (RISP) model focusses on how information is being processed and shaped to influence decision-making. In specific, it deals with information seeking and information processing tendencies (Griffin et al. 1999). Other theories have focussed more on the social, environmental and personal factors that can influence decision-making in warning situations. For instance, Protection Motivation Theory (PMT) states that different threat and coping factors motivate people to engage in desirable behaviours to avoid risks (Floyd et al. 2000). A more recent, multistage, model is the Protective Action Decision Model (PADM) that identifies three core perceptions – threat, protective action and stakeholder – (shaped by various social, environmental, personal and contextual factors) which influence how people respond to an imminent or long-term risk (Lindell and Perry 2012). Compared to PMT, PADM has a stronger focus on response efficacy and distinguishes between three efficacy attributes: perceived efficacy of hazard adjustments to protect people, to protect property, and their utility for other situations (Kellens et al. 2013; Lindell and Prater 2002). These factors are addressed each by resource requirements that are monetary costs, effort and social cooperation.

These theories share a common element; they underline that when people receive warning information, they go through a sequential process with different stages, which shapes their

perceptions and beliefs, and ultimately triggers response. In the initial stage, people at risk must get the warning message, be it through their mobile phones (e.g., SMS, APP, social media), websites, radio, TV or sirens. Therefore, dissemination and telecommunication mechanisms must be operational, robust, available 24/7 and tailored to the needs of different threats and end users (UNISDR 2006). In the second stage, the information is then being processed by the individual, which means that it has to be understood, believed and personalized (Mileti and Peek 2000). Therefore, the information needs to be clear and easy to understand (Gibson et al. 2013). People also need to believe that the information is accurate and trust its source (Bruine de Bruin et al. 2013). The information must be viewed as personally relevant, which means that the perceived implications of the danger are being communicated on the users themselves (Mileti and Peek 2000). In other words, people have to feel concerned for their safety (Gibson et al. 2013). In the final stage, people decide how they intend to respond to the risk in the first phase and then whether to perform the intended behaviour or not (Fishbein and Ajzen 1975). Thus, the final response whether to act or not to act upon a warning message follows from a series of (rational) decisions.

1.2.4) Affective or rational decisions?

Moreover, these decision-making theories more or less assume that people use rational deliberation to make decisions, and process the information based on formal logic, risk assessment and statistical probabilities, for example the desirability and likelihood of possible outcomes. This rational model of decision-making is rather slow as it requires justification via logic and evidence (Slovic et al. 2004). However, research on affect heuristics, which explain how people make decisions based on their previous experience and their analysis of the current situation (Slovic et al. 2007), has identified that people can also process information about risk by using a different qualitative system, that is affective (Loewenstein et al. 2001; Kahneman 2011). Such a model relates to the importance of emotions and feelings in making decisions. It operates automatically and fast, with neither effort nor sense of voluntary control, although it is often influenced by beliefs, or mental models, about how the world works (Loewenstein et al. 2001; Slovic et al. 2004). Research on the affect heuristics found that people rather use intuitive thinking when making decisions about risk (Slovic et al. 2004; Finucane et al. 2000). However, the two modes of thinking – rational and affective – should not be seen as independent systems, they can interact and influence each other (Kahneman 2011). For instance, the deliberate rational process can modify, to some extent, the way we make intuitive decisions by changing the normally automatic functions of attention and memory (Kahneman 2011).

Nonetheless, people's judgments can be faulty and the decisions they make wrong as these are subject to inherent cognitive and affective biases (Slovic et al. 2004). Meyer and Kunreuther (2017) list 6 core biases that ought to explain why people underprepare for disasters: myopia, amnesia, optimism, inertia, simplification, and herding. In a nutshell, people tend to systematically focus on short time-scales, forget learned lessons,

underestimate losses, maintain status quo, consider only some factors, and follow other people's choices (Meyer and Kunreuther 2017). These biases are also reflected in related, concepts, such as the Black Swan Theory (Taleb 2007) or Cognitive Dissonance (Festinger 1962). Taleb argues that rare, high impact events could have been expected in hindsight as the relevant data were available, but unaccounted for in personal risk perceptions. The Theory of Cognitive Dissonance states that people have incompatible cognitions (Festinger 1962). These cognitions, that can be perceptions, beliefs or intentions, are rated and prioritized by people. When a person holds two or more contradictory perceptions or intentions, dissonance arises, which is perceived as unpleasant. To overcome the mental discomfort, people can either gain more information or avoid contradictory information (Festinger 1962). Some psychologists argument that people, which are trapped in their daily routine and its context-specific demands, make intuitive decisions all the time and do not think deliberatively (Welzer 2018). They tend to simplify decisions and try to maintain the status quo. One example would be changing individual behaviour to act upon climate change; people know that they should engage in mitigation, but this is not (necessarily) consistent with our growth-economic consumer society (Welzer 2018). They overcome the cognitive dissonance by devaluating or denying some of the information, and go on with their daily life (as the others do); 'I know, but …'.

Making decisions in response to extreme weather events is, however, no daily business. Extreme weather events are rare and people are generally not familiar with these phenomena and their impacts. Some researchers argue that affective thinking is rather difficult for these events due to the absence of any experience (Weber 2011). This suggests that people would rely more on rational deliberation in the case of extreme events. However, in an unfamiliar and, to some extent, unexpected situation, people may experience very strong fear and other emotions that could also trigger intuitive decisions. In fact, Slovic (1987) identified dread and the unknown as the two psychological risk dimensions that influence people's intuitive decision-making. Thus, a real-world situation of high stress, where the fast decision-making pathway could especially come into play, is the response to warnings of potentially life-threatening weather events, such as severe storms.

1.3) Research design

The overarching goal of this thesis is to better understand how we can improve warning and risk communication to help people at risk take better informed decisions. Therefore, the overall research question is: *What makes warning communication effective?* Four different contributions that are listed in Table 1 should help answering this question. Figure 2 presents the logic of the contributions that are conducted with different methodological approaches. Contribution I contributes on better targeting long-term communication strategies to individuals at risk, which ought to motivate them to undertake risk reduction measures. I build on more traditional decision-making theory, which I combine with decision-stage theory from the health domain to develop a dynamic protection motivation framework that helps to

understand the motivations of individuals (classified in three stages) to undertake risk reduction measures. The method here was a survey that was conducted face-to-face in an Italian community affected by flash floods. In Contribution II, I analyse the effect of inconsistent warning messages, disseminated by different public and private providers, on warning response. Therefore, I developed a simple matrix to categorize the level of inconsistency across multiple warnings and conducted the research using online survey experiments. In Contribution III, I examine how including information about the impact of the hazard and providing behavioural recommendations in the warning messages, could help people to translate the warning information into an appraisal of risk. I conducted the research using intended responses to hypothetical scenarios, leaving rational deliberation as the dominant factor for decision-making. Drawing on insights from Contribution III, I use a different research method in Contribution IV to show how decision-making can be influenced by feelings that emerge in real-crisis situations. Therefore, I conducted a field experiment in real-world crises and collected the data through a smartphone application for which I collaborated with a private weather provider. The research of Contribution II, III, and IV was conducted in Switzerland.

Table 1. Overview of authors and status of each contribution.

Contribution	Title	Authors	Status
I	A flood risk oriented dynamic protection motivation framework to explain risk reduction behaviours	Philippe Weyrich, Elena Mondino, Marco Borga, Giuliano di Baldassarre, Anthony Patt, Anna Scolobig	Accepted in *Natural hazards and Earth System Sciences*. Discussion paper, 10.5194/nhess-2019-120.
II	Dealing with inconsistent weather warnings: effects on warning quality and intended actions	Philippe Weyrich, Anna Scolobig, Anthony Patt	Published in *Meteorological Applications*, Volume 10, 10.1002/met.1785.
III	Effects of Impact-Based Warnings and Behavioural Recommendations for Extreme Weather Events	Philippe Weyrich, Anna Scolobig, David Bresch, Anthony Patt	Published in *Weather, Climate and Society*, Volume 10, July 2018, Pages 781-796, 10.1175/WCAS-D-18-0038.1.
IV	Responses to severe weather warnings are consistent with an affective decision-making model rather than rational deliberation	Philippe Weyrich, Anna Scolobig, Florian Walther, Anthony Patt	In review in *PLOS ONE.*

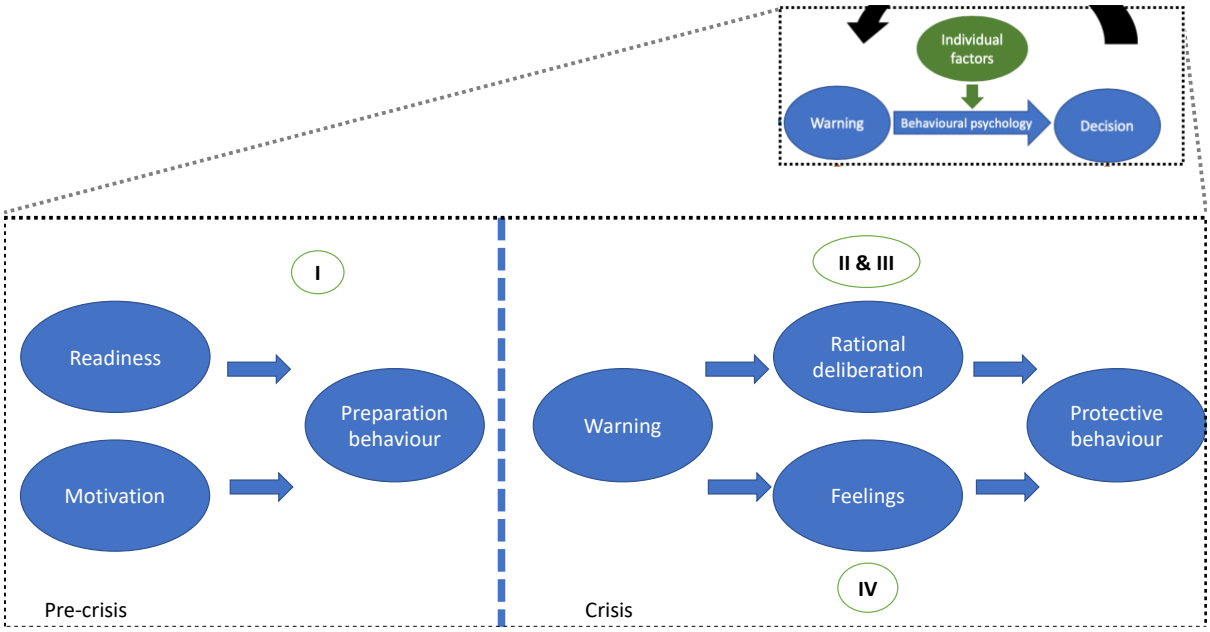

Figure 2. Logic of Contributions.

In the following section, I introduce the four research questions. Thereby, I provide additional background information and highlight research gaps. Then, for each contribution, I summarize the key findings.

1.4) Research questions and background of contributions

1.4.1) The dynamic protection motivation framework

Prior to a crisis situation and before warning communication comes into play, communication of weather-related risks can also be used to increase preparedness levels among people at risk, and is not limited to warning systems (Höppner et al. 2012; Renn and Graham 2005). For instance, before a crisis, communication could be used to create a public understanding of risk, to promote activities to build crisis response capabilities, or to motivate people to engage in risk reduction behaviours (Reynolds and Seeger 2005). These efforts could, then, be beneficial for warning-related decision-making at a later stage.

However, the development of effective risk communication is no trivial process and cannot be reduced to the dissemination of facts that some experts think are worth knowing. For instance, misconceptions will get unchecked if communication products are focused solely on the expert knowledge (Bostrom et al. 1992). Moreover, for effective risk management and communication, it is important that communication strategies are informed by and address the stakeholders' risk perceptions and preparedness levels (Lave and Lave 1991; Wood et al. 2012). Thus, in order to improve communication of natural hazard risks, it is important that emergency managers or public officials learn more about how these various stakeholders think about the hazard, how much they know and are prepared to face the risk. Communication that builds on these insights to address incomplete understandings about

risks, or build response capabilities, can equip people with the ability to interpret incoming information, make informed decisions and invest in risk preparedness.

As management of natural hazard risks, and especially floods, has shifted from a primarily top-down to more integrated approaches that increasingly address the role of private households in implementing (flood) damage mitigation measures (Kellens et al. 2013; Scolobig et al. 2015; Terpstra and Gutteling 2008), private risk reduction behaviours became even more critical than in the past to the success of any protection system. In face of this change, it is important to examine the current readiness of individuals to undertake risk reduction behaviours and to identify the triggers that influence individuals to act upon the risk. In the case of floods, such risk reduction behaviours include structural measures (e.g., special installation of heating and electric system, anti-backflow valves), avoidance measures (e.g., keeping valuables and expensive appliances above flood-prone areas of the house) and emergency preparedness (e.g., own sandbags available, emergency plan at hand). These behaviours can significantly improve preparedness levels and lower the effects of flooding (Grothmann and Reusswig 2006).

Various socio-cognitive models exist that try to explain why some people engage in risk reduction behaviours, while others do not. For example, Protection Motivation Theory (PMT) consists of two sequential underlying cognitive mediating processes; the threat- and coping-appraisals. Assessments of threat (perceived risk severity, vulnerability, and benefits) and coping factors (self-efficacy, response efficacy, and costs) should motivate people to adopt protective behaviours (Floyd et al. 2000). Studies that applied PMT to flood risk have found that different factors of threat and coping appraisals can determine people's adaptation behaviours (Grothmann and Reusswig 2006; Poussin et al. 2014; Zaalberg et al. 2009). Unfortunately, PMT and other models give only limited insights into the effectiveness of communication strategies to support risk reduction behaviours. However, it's difficult to imagine that a single communication strategy could be applied successfully across a diverse population.

Decision-stage theories acknowledge that the public is no homogeneous group. These theories, such as of the Trans-Theoretical Model (TTM), classify people into an ordered set of categories depending on their behaviour (Horwath 1999; Prochaska et al. 1995). The baseline premise of TTM is that people can be distinguished in different decision-stages based on whether they have already changed their behaviour, are about to change or have not yet decided to change (Prochaska and DiClemente 1983). Based on TTM, one could assume that variables, such as the threat and coping factors, will influence people in different ways depending on their stage readiness. The combined PMT-TTM model was introduced by (Block and Keller 1998) in the health-related context and more recently applied in the natural hazard context by (Martin et al. 2007). These researchers grouped respondents in different decision stages based on the amount of suggested protective measures that have already been

undertaken by homeowners living in areas exposed to high wildfire risks in the US. However, one could also think of a slightly different nature of stages, such as risk reduction stages, where people are not classified based on the amount of protective measures undertaken, but the quality of their behaviour (i.e. differing between emergency, avoidance and structural measures/preparedness). For instance, people who have an emergency plan for the household in case of floods may be motivated by different factors than people who keep expensive appliances above the expected flood levels. The motivation may be again different for people who installed anti-backflow valves in their houses.

Therefore, I applied a combined PMT-TTM framework to identify the factors that trigger individuals in different risk reduction stages to protect themselves from a hazard. Combining PMT with TTM helps to address the non-homogeneity of the population, who is not equally ready to adopt protective actions, and to better understand the respective motivations in order to reduce some of the uncertainty in predicting flood risk behaviour. I operationalize the dynamic framework by classifying people in three different groups based on the quality of risk reduction measures undertaken (structural, avoidance, emergency) and analyse how the PMT variables (vulnerability, severity, benefits, self-efficacy, response efficacy, costs) affect the respective behaviours. Individual household interviews were conducted in an Italian municipality that experienced severe flash flooding in September 2018 (N=124).

Question 1: *Do different protection motivation variables affect people's behaviour to undertake risk reduction measures and if so, is it depending on their risk reduction stage?*

The results show that people are motivated by different factors in prompting risk reduction behaviour based on their stage readiness. For example, people that undertook structural or avoidance measures are more likely to be motivated to protect themselves by increased perceptions of vulnerability and response efficacy, and are less worried about expected flood losses compared to people that undertook only basic emergency measures. These new insights will improve communication strategies by linking particular patterns of perception or capacity in the communities exposed to flood risks to effective patterns of communication. Thus, the results also point at why improvements in communication may not necessarily lead to improved outcomes. Practitioners should target flood risk communication strategies to groups of individuals characterized by different readiness stages and motivations to protect themselves.

1.4.2) Effects of inconsistent warnings

Consistency is an important stylistic dimension of a warning message that influences its effectiveness. Risk communication literature (Mileti and Sorensen 1990) and best practices (NOAA 2016) underline that an effective warning message is consistent within itself and across different messages. For instance, some research provides evidence that consistent messages need to be delivered through multiple channels emanating from multiple sources in order to be effective (Hovland and Weiss 1951; Mileti and Fitzpatrick 1992). The rationale

is that a consistent message is clear and credible, because it is invariant. Generally, one can distinguish between two different types of inconsistency: inconsistency of sequential same-source forecasts (i.e., from one weather provider) and inconsistency of different-source forecasts (i.e., from different weather providers).

The first type of inconsistency can result out of more recent model predictions that contradict previous forecasts or warnings, and which forces meteorologists to decide whether or not to update the information that they provide to the public. Sometimes, they are reluctant to do so out of fear that inconsistency in subsequent forecasts will be confusing and negatively impact end user trust or behaviour. In fact, research shows that inconsistency reduces trust, but also suggests that it is not advisable for decision-makers to sacrifice accuracy in warnings in favour of consistency. For instance, Losee and Joslyn (2018) manipulated the level of consistency in different thunderstorm and snow warning messages and found that increased forecast consistency led to greater trust in the forecasts. Burgeno and Joslyn (in review) confirmed these findings, but also showed that reductions in trust levels due to inaccurate forecasts were greater compared to inconsistent forecasts. Inconsistent evacuation orders for hurricanes were also found to lower perceived severity and the likelihood to evacuate among some communities (Elder et al. 2007).

Over the last decades, a private sector meteorology industry has developed next to the National Meteorological and Hydrological Services (NMHS) (Pettifer 2015). These developments have led to improvements, such as the quantity and quality of weather data and forecast, as well as to a deterioration in the warning system due to the duplication of public weather warnings (Thorpe 2016). Thus, different services can provide the public with inconsistent information. For instance, I monitored the dissemination of warning messages issued by the four Swiss weather services that provide public warnings (the national meteorological service MeteoSwiss; the national broadcasting service SRF Meteo; and the two commercial providers MeteoNews and Meteocentrale) from August to November 2017. For 13 out of 19 events, at least one of the four providers disseminated a warning message whilst at least another one did not. Several reasons exist for this observed inconsistency. When producing the warnings, providers may use different weather models or input data, and interpret the model outputs differently due to different experience levels among and/or different responsibilities between public and private forecasters. The providers may also use a different number of warning severity levels and, associated, map colour-coding. Thus, messages roughly differ in text (based on data, weather models and interpretation) and visualization (based on number and colour of warning levels). Currently, it is not possible in most warning or crisis situations to speak with one voice, respectively spread consistent messages as suggested by Mileti and Sorensen (1990). Some researchers also question whether spreading consistent messages is the optimal communication as it does not accept uncertainty and disagreement among experts and assumes that people can't handle this (Sandman 2006). So far, no experimental studies have analysed the effects of inconsistent

weather information from different sources (i.e., providers) on warning evaluation and response. To avoid negative outcomes and justify modifications in the warning process, public officials need to understand how people are affected by differing, sometimes conflicting, information coming from various weather providers at a given point in time.

Therefore, I developed a simple matrix to categorize the level of inconsistency across multiple warnings, considering both visual and textual information. Following a severe rainfall episode that happened on the 5th November 2017, a survey experiment (N=1,335) was conducted to examine the influence of different types of inconsistency on behavioural decision-making and perceived warning quality. Four combinations with warning pairs were investigated: consistent warnings; inconsistent visual warnings; inconsistent textual warnings; and inconsistent visual and textual warnings.

Question 2: *Does inconsistency in different-source forecasts affect evaluation of warning quality and does it influence intended behavioural response?*

The results show that most people regularly consult weather information and do so from several weather providers. Half of the people who have received warnings from different providers for an event indicated that these were also inconsistent. The evaluation of warning quality and intended response actions in the decision scenario characterized by the warning pairs showed a negative impact of inconsistency. Not surprisingly, consistent warnings were least confusing and fully inconsistent warnings were considered most confusing. Moreover, perceived warning quality and the likelihood to engage in risk minimizing behaviours were significantly higher for consistent warnings than for inconsistent warnings. I observed no major differences in the impacts of inconsistent textual information compared to inconsistent visual information on warning quality and intended actions. The findings implicate that enhanced cooperation between multiple weather providers is clearly warranted, in particular to agree on consistent delivery of information to incentivize risk mitigating behaviour by the public.

1.4.3) Effectiveness of IBW in imagined situations

The standard weather warning message provided by most NMHS includes information about the hazard, location, time and source. However, it does not provide behavioural recommendations or other guidance, which past research has found to positively influence decision-making (Mileti and Darlington 1997). This has several reasons, such as differences in mandates, roles, and responsibilities between the meteorological services and responding agencies (e.g., the Office of Civil Protection) or the risk of giving specific information that is inappropriate for some of the end-users. However, as Mileti and Peek (2000, p. 185) note, one cannot assume that “the public will know what would constitute an appropriate protective action”. Providing behavioural recommendations can increase warning

personalization, make the information more accurate or trustworthy and help people making the extra step from intended to actual behavioural response.

Second, the World Meteorological Organization (WMO) has speculated that people do not respond to warnings because of their inadequate understanding; they lack background knowledge that would be needed to fully understand the standard warnings (SW) that NMHS are communicating (WMO 2015b). For instance, some people cannot interpret 'heavy' snowfall warnings into effective impacts. The information that 10 cm of fresh snow is expected, does not help to personalize the risk neither. Therefore, NMHS have started to put a greater emphasis on so-called impact-based warnings (IBW). Compared to SW that solely focus on the weather phenomenon itself, IBW are designed to provide people with additional information about the expected impacts as a result of the expected weather (WMO 2015b). Providing more specific and detailed information about the hazard that is predicted, i.e. about the consequences of the hazard, could improve warning effectiveness, as the message becomes more personally relevant and more understandable. For instance, the 'heavy' snowfall could be translated into clear impacts on road and rail transportation. In analogy to (Mileti and Peek 2000)'s comment on guidance, one can neither take for granted that the public will know what impacts severe weather can have. Altogether, the additional use of impact text and behavioural recommendations in warnings ought to improve warning effectiveness.

Interviews with forecasters, emergency managers and broadcast meteorologists (Losego et al. 2013; Harrison et al. 2014) reveal a widespread belief within the expert community that providing impact information creates an added value in the specific case of high impact weather warnings. Recent studies offer empirical support for this belief, although the results are somewhat mixed (Taylor et al. 2018). Five studies investigated the benefits of including impact text in weather warnings, but they all have their shortcomings. First, Morss et al. (2018) and Casteel (2016) found that IBW increased the willingness to undertake protective actions, whereas Potter et al. (2018) and Perreault et al. (2014) found no effect of IBW on intended behavioural response compared to SW. The fifth study identified a threshold beyond which increasing the projected impact of a storm no longer significantly increased the probability of taking protective action (Ripberger et al. 2014b). None of the studies investigated the individual effect of behavioural recommendations (BR) as the investigated messages either included BR in all or none of the message variations. Ultimately, it is also important to assess how these warnings are perceived in terms of clarity, understandability, credibility, and whether they evoke feelings of concern and threat, because these attributes influence protective decision-making. Only Morss et al. (2018) and Potter et al. (2018) assessed how IBW are perceived compared to SW. They found a positive effect of IBW, but leave open the effect of BR.

Therefore, I conducted a survey with a decision scenario (N=1,219) for which I randomly assigned one of four thunderstorm warning messages (SW, SW+BR, IBW, IBW+BR) per

participant. The participants had to imagine that they would be hiking in the Swiss mountains when they received a thunderstorm warning message on their smartphone. I analysed the individual and additive effects of IBW and BR on self-protective behaviour and perceptions.

Question 3: *Are warning messages that provide impact information and/or give guidance more effective than warnings that only describe the weather phenomenon?*

Results show that IBW and BR both increase warning perception and understanding, and improve behavioural response. However, the effects have a different ordering. IBW alone have a greater effect than BR on behaviour. BR alone have a greater effect than IBW on perception. The warning messages that considered IBW and BR together had the greatest effect on perception and behaviour. I draw several implications from the research. First, practitioners should develop and use IBW with BR for high impact weather events. Second, as IBW and BR are clear and understandable regardless of the target audiences' characteristics, targeting warning messages on the basis of these characteristics may not be as important as providing IBW with BR. Third, warnings should address perceptions of credibility, concern and threat as these perceptions were found to positively influence behavioural response irrespective of the warning received. However, the major shortcoming of this and previous studies on IBW, is to make use of self-reported responses to a hypothetical and imagined situation, rather than a field observation of actual behaviour in response to actual danger. For instance, other researchers have noted that an imagined situation suffers from a lack of real consequences for decisions and people might seek fewer risks in real-life decisions (Kox and Thieken 2017).

1.4.4) Effectiveness of IBW in real-life situations

The research findings on the effectiveness of IBW have a common element that lies in their research design: they used hypothetical scenarios, and relied on people's anticipated and intended reactions to study the effects of IBW. For example, Casteel (2016) focused on tornado warnings with respondents in the hypothetical role of a factory operator having to decide whether to order workers to take shelter in response to two different warning types (SW and IBW). In Contribution III, participants had to imagine that they would be hiking in the Swiss mountains when receiving one of four different thunderstorm warnings (variations of SW and IBW), and then had to decide upon several intended actions (Weyrich et al. 2018). Potter et al. (2018) and Morss et al. (2018) used similar hypothetical situations, in which respondents received either SW or IBW. In fact, many social scientists measure behavioural intentions as a proxy for actual behaviours (Ripberger et al. 2014a). This is also supported by research in psychology, which showed that the conscious intention to take action is the principal determinant of actual behaviour (Fishbein and Ajzen 1975; Ajzen 1991). Thus, researchers studying the effectiveness of IBW have used imagined decision-scenarios assuming that people make rational decisions based on the information they receive.

However, theory from cognitive science suggests that people do not always make rational decisions, but can also use a fast decision pathway that is largely emotion-driven to make decisions about risks (Slovic et al. 2004). If feelings influence behaviour in real-life situations, then it may be that these studies on the effectiveness of IBW have generated results that are poor predictors of actual behaviour, as it is unlikely that the respondents experienced real feelings of fear, since they were not actually at risk. This could be important for the results, if in fact the presence or absence of fear is relevant for decision-making. At the same time, the cognitive theory has been hard to test in the field, because of the ethical challenge of submitting people to actually dangerous conditions. Research that has investigated whether feelings, rational deliberation or both influence people's behaviours related to risks has primarily relied on laboratory studies. For example, Finucane et al. (2000) have used different messages to manipulate affect by increasing or decreasing perceived benefits and risks of different technologies. In two experiments, these researchers demonstrated that affect influenced judgments directly and was not simply a response to a prior deliberate evaluation. In only two studies have researchers evaluated actual self-protective behaviour during a crisis. Researchers in Indonesia investigated evacuation behaviours and intentions during tsunamis, and observed that feelings, and not deliberate evaluation, drive decision-making (McCaughey et al. submitted). Their findings suggest that under an imminent threat of life, deliberative evaluation may be absent or far less influential than feelings. Scholars from the Netherlands analysed the behavioural effects to mobile fire warning messages (Gutteling et al. 2017). They found that emotions and the social environment were the main predictors for adaptive behaviour. Even though one cognitive factor, perceived message quality, was significant, other factors, such as perceived threat, were insignificant. These results point at the relevance of affective reactions as a driver for behaviour.

Compared to a rational decision-making model, where it would seem right to provide people with more (impact) information as it would help them to adjust their behaviour, in an affective model, changes in message content or style may not necessarily result in a greater response. If affective decision-making is more influential than rational deliberation in real-world crises, then SW may provide all the information that is needed to trigger the feelings of fear, with IBW adding no additional trigger. Hazard severity and warning lead time could also influence the response to weather warnings in different ways depending on the model of decision-making. In a rational model, more severe events and greater lead times should, rationally, generate a greater behavioural response: longer lead times would translate into greater ease of preparing for and actually taking self-protective behaviour. In an affective model, however, more severe events and shorter lead times should increase response, since the fear should be heightened at the time of the information reception.

Therefore, I conducted a randomized control trial in which I disseminated wind warnings through an existing smartphone application of a Swiss weather provider (*Wetter-Alarm*), and collected real-time data on people's responses. The information that people (N=2,615)

received varied randomly in terms of being SW or IBW, and given that there were a number of events for which the warnings were issued, in terms of the warning lead time, and the events' anticipated severity.

Question 4: *Does the presence of fear influence the effectiveness of impact-based warnings in real-world crises?*

My findings are important at three levels. First, they show that providing impact information for warnings of low and medium severity has no effect. Second, findings are consistent with the affective decision-making model. Feelings of fear are already triggered with the information in SW, resulting in no effect of IBW. Moreover, longer lead times generate less response than shorter, whereas stronger events generate greater response, but primarily in the case of short lead times. With long lead times, during which the fear may dissipate, stronger events generate little more response than weaker events. Third, these results point to the importance of using research methods that capture real-world conditions when investigating responses to threats. Thus, they have implications both for the design of warning systems, and also more generally for our model of self-protective behaviour. Ultimately, the research shows that smartphone applications open an enormous window of opportunity to collect data and information in real time and for relatively low cost.

2) The dynamic protection motivation framework

A flood risk oriented dynamic protection motivation framework to explain risk reduction behaviours

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Abstract
Private risk reduction behaviours can significantly reduce the negative impacts of flooding and flash floods. Over the past decades, researchers have used various socio-cognitive models or threat/coping mechanisms to explain individual protective behaviours. However, these models ignore that people are not equally ready to act upon a danger and they give limited insights into the effectiveness of communication strategies to foster risk reduction behaviours. Therefore, we explored the current state of homeowner's readiness to undertake risk reduction behaviours in flood risk areas by applying a dynamic protection motivation framework. We conducted a survey in an Italian municipality that experienced severe flash flooding in September 2018. The results show that people are motivated by different factors in prompting risk reduction behaviour based on their type of protective measures. For example, people that undertook structural or avoidance measures are more likely to be motivated to protect themselves by increased perceptions of vulnerability and response efficacy, and are less worried about expected flood losses compared to people that undertook only basic emergency measures. In this paper, we argue how these new insights contribute to target flood risk communication strategies to groups of individuals characterized by different readiness stages and motivations to protect themselves.

2.1) Introduction

Flooding and flash floods are one of the major causes of natural hazards related deaths, they affect the life and safety of millions of people worldwide (Guha-Sapir et al. 2017; Kellens et al. 2013). In 2017 alone, 345 flood events killed 6500 people and caused economic losses of US$ 42.5 billion (Munich RE 2017). With climate change influencing extreme weather events, more people will likely be exposed to higher flood risk in the near future than they are at present (IPCC 2012, 2014). For example, most cities worldwide are projected to experience an increase of precipitation rates in the form of heavy rainfall (IPCC 2012). The high proportion of sealed surfaces further increases flood risk (Carter 2011), and the concentration of people, assets, critical infrastructure, as well as political and economic activities exacerbates the impacts of extreme events (European Environment Agency 2017a). Hence, the protection of livelihoods from flood events as an adaptation strategy to climate change will be of high priority in the coming years. Different types of adaptation to flood risk exist. For social systems one can differentiate between administrative and private adaptation, as well as between reactive adaptation during a flood and precautionary adaptation before a

flood (Grothmann and Reusswig 2006). Given similar exposure and sensitivity to floods (that, along with adaptation, determine flood damage and vulnerability), private protective action can have significant effects on flood outcomes as it was documented, for instance in Grothmann and Reusswig (2006). Risk reduction behaviours include structural measures (e.g. special installation of heating and electric system, anti-backflow valves), avoidance measures (e.g. keeping valuables and expensive appliances above flood-prone areas of the house) and emergency preparedness (e.g. own sandbags available, emergency plan at hand).

The adoption of risk reduction measures plays a critical role in the transition from top-down to people-centred approaches for disaster risk management (Scolobig et al. 2015). Authorities and public officials highlight the importance of people protecting themselves and see sharing responsibility as an appropriate form of response (Bostrom et al. 2015; Box et al. 2013; Morss et al. 2015; Scolobig et al. 2015). However, it remains unclear whether this actually matches the capacity of individuals to increase their level of protection (Scolobig et al. 2015). For instance, in the case of floods, citizens often transfer the responsibility for their own safety and protection to the agencies in charge (Adger et al. 2013; Bichard and Kazmierczak 2012). This may be related to fact that people perceive flooding as a man-made phenomenon rather than a natural one, for example in the Mediterranean region (Diakakis et al. 2018; Lara et al. 2010). This clearly reveals that one of the key challenges in the transition of people-centred approaches is the responsibility shift from the authorities to the public, demanding that the latter take precautionary actions (Scolobig et al. 2015). In face of this change, it is important to investigate the current readiness of individuals to undertake risk reduction behaviours and to identify the triggers that influence individuals to act.

So far, researchers have used socio-cognitive models to explain risk reduction behaviours (Grothmann and Patt 2005b; Grothmann and Reusswig 2006). The most important factors used in these models are risk perception, hazard experience, risk aversion and socio-demographics. The influence of coping mechanisms was highlighted in studies that followed the Protection Motivation Theory (PMT) (Kellens et al. 2013; Poussin et al. 2014). More recently, the role of insurance and public assistance on private risk reduction behaviour have been investigated (Hanger et al. 2018). All these models have in common that they assume that people are equally ready to act upon danger and they give limited insights into the effectiveness of communication strategies to foster risk-reduction behaviour. However, the public is no homogeneous group (Martens et al. 2009). Some people might be ready to take responsibility and act to reduce their flood risk exposure, while others adopt different behaviours. Thus, there are different stages or degrees of readiness which can influence individual motivation and intention to protect themselves from a risk (Horwath 1999; Prochaska et al. 1995). In the Trans-Theoretical Model (TTM), people are assigned to one of several stages based on their behaviours and intentions to undertake risk reduction actions (Prochaska et al. 1995). For example, Horwath (1999) addressed the question whether eating behavioural change follows a stage process, that could be used to help nutritionists to identify

the predominant stages in a population. Enhanced knowledge about these stages allows to focus resources on the issues that will most likely move people to the next stage. In medical research, Block and Keller (1998) showed that people are at different stages of readiness to undergo medical testing, which can be affected by cognitive processes.

In this study, we focus on the drivers of risk reduction behaviours, employing a dynamic framework that combines the Protection Motivation Theory (PMT) and the Trans-Theoretical Model (TTM). The aim of this study is two-fold. First, we aim to determine the usefulness of this dynamic protection motivation framework to understand people's perception of flood risk and their readiness to undertake risk reduction behaviours. Second, we aim to identify the most important factors in prompting behaviours in different risk reduction stages. This categorization allows us to identify the key issues to improve communication with people in each stage. Thus, we contribute to target flood risk communication strategies to groups of individuals characterized by different readiness stages and motivations to protect themselves.

2.2) Background

Flood management has shifted from a primarily top-down, command and control, approach to an integrated approach that increasingly addresses the role of private households in implementing flood damage mitigation measures (Terpstra and Gutteling 2008; Kellens et al. 2013). To foster this transition, there is a need to integrate the analysis of resident´s risk perception and preparedness into local flood risk management practices (Figueiredo et al. 2009). The majority of studies have focussed on flood risk perceptions, for instance via the effect of past experience and affect (Keller et al. 2006; Siegrist and Gutscher 2006, 2008), or as a mean to explain and promote private protective behaviours (Kellens et al. 2013). However, this is not always supported on theoretical or empirical grounds as Kellens et al. (2013) document: higher risk perceptions alone do not necessarily lead to a positive change in protective behaviour. For example, Scolobig et al. (2012) found no link between resident´s level of risk awareness and preparedness. Wachinger et al. (2013) found that high risk perceptions (predominantly shaped by personal experience and trust) do not lead to risk reduction behaviours if people accept the risk (i.e. benefits that outweigh costs), if they do not feel responsible or if they have little resources. Other recent studies highlight instead that protective behaviours are not only influenced by high risk perceptions, but also by high coping appraisal (a person's perceived ability to cope with and avoid being harmed by a threat in an effective way) (Bubeck et al. 2012; Kellens et al. 2013; Parker et al. 2009). These results, in part contradictory, show that it is important to not only focus on flood risk perception as the main driver of risk reduction behaviour, but also to understand other factors that might trigger individuals to protect themselves from a hazard.

Protection motivation theory (PMT) has quite often been applied to the natural hazards and public health sectors (Floyd et al. 2000; Maddux and Rogers 1983). According to PMT, people

can be motivated to engage in desirable behaviours to avoid risks (Floyd et al. 2000). The theory consists of two sequential underlying cognitive mediating processes, the threat-appraisal process and the coping-appraisal process, whereas assessments of threats (perceived risk severity, vulnerability, and benefits) and coping factors (self-efficacy, response efficacy, and costs) combine to form a motivation in individuals to adopt protective behaviours. Several studies have applied the PMT to flood risk and analysed its influence on people's risk reduction behaviour. Grothmann and Reusswig (2006) identified that both threat and coping appraisal determined people's adaptation behaviours to increased flood risk in the past (e.g., construction of structural measures, acquisition of protection devices). They conclude that practitioners should communicate not only the flood risk and its impacts, but also the possibility, effectiveness and cost of risk reduction behaviours. Zaalberg et al. (2009) found a significant effect of response efficacy (defined as the degree to which risk reduction behaviours are perceived to be effective at reducing a particular risk) on behavioural intention, but no effect of self-efficacy (defined as the belief that one is capable or not in undertaking risk reduction measures) on behaviour. Finally, Poussin et al. (2014) found that while threat appraisals had only a small effect on people's intentions to implement flood risk mitigation measures, coping appraisal had a more important influence.

However, PMT does not consider that the public is heterogeneous and may be differently affected by variables of vulnerability, severity and ability to reduce the risk (Martin et al. 2007). A parallel stream of research in decision stage theories has been used to examine behaviour change based on the assumption that a set of variables, such as from PMT, will influence different people in different ways (Horwath 1999). The Trans-Theoretical Model (TTM) specifies an ordered set of categories into which people are classified (Martin et al. 2007). Based on this categorization, one can identify the factors (e.g. response efficacy) that can explain how to effectively communicate with each sub-group (i.e. in a specific decision-stage) (Weinstein 1998). The three decision stages which are frequently used in empirical studies are pre-contemplation, contemplation, and action. The baseline premise is that people can be distinguished based on those who have not yet decided to change their behaviour (pre-contemplation), those who have (contemplation) and those already performing the new behaviour (action) (Martin et al. 2007). Thus, TTM stages are sequential and can change through time.

In consequence, an integrated PMT-TTM model offers the possibility to investigate risk information and perception dimensions, and stage readiness for action, thus allowing to predict individuals' motivation to act upon the hazard. The PMT-TTM model was introduced by Block and Keller (1998) in the health related context and more recently applied by researchers (Bočkarjova et al. 2009; Gebrehiwot and Veen 2015; Martin et al. 2007) in the natural hazard context. In these three studies, respondents were grouped in different decision stages based on the amount of suggested protective measures that have already been undertaken. Martin et al. (2007) investigated the role of motivation, decision stages of risk readiness, and subjective knowledge on the number of risk-mitigating actions undertaken

by homeowners living in areas exposed to high wildfire risks in the US. Independent of knowledge and decision stage, they found that all PMT variables were negatively correlated with taking risk reduction behaviours. The authors did ignore the two PMT variables costs and benefits, as well as other control variables. Bočkarjova et al. (2009) analysed the cognitive perception of flood risk and the readiness of people to undertake protective actions in the Netherlands. Overall, they showed a significant influence of response-efficacy and costs on risk reduction measures. The authors used an extended model which also considered other variables and found an influence of subjective knowledge, trust in government, and experience on behaviours. Gebrehiwot and Veen (2015) applied the PMT-TTM framework to areas of drought risk in the developing countries cultural context (i.e. small-holder farmers in Ethiopia). For the whole sample, they found that vulnerability, severity, self- and response-efficacy are positively and costs negatively correlated with action-taking.

However, it cannot be ignored that there is ambiguity in their findings. The studies do not agree with respect to which PMT variable(s) (vulnerability, severity, benefits, response efficacy, self-efficacy, and costs) influence behavioural intention in the different decision stages. Moreover, differences also exist in their methodological set-up, and their models differ (e.g. including costs and benefits as PMT variables or not). These differences could have an important effect as, for example, Wachinger et al. (2013) highlighted that perceived benefits and costs can influence individuals' decisions to act upon a risk or not. In addition, Bubeck et al. (2012) argument that a possible feedback from previously adopted protective measures could change risk perceptions. This is in line with findings highlighting that individual expectations of government responses shape the public's actions in response to floods and longer-term adaptation (Adger et al. 2013; Chamlee-Wright and Storr 2010). Public adaptation and damage compensation can lead to reduced private protective behaviour, either because citizens view flood mitigation as a government responsibility (Bichard and Kazmierczak 2012; Botzen et al. 2009; Box et al. 2013; Grothmann and Reusswig 2006) or because the public adaptation reduced their perception of risk and costs (Raschky and Weck-Hannemann 2007). Finally, other variables that have been added to the PMT framework in past studies and which appear to be influential in households' risk-reduction decisions are knowledge (Martin et al. 2007), flood experience (Poussin et al. 2014; Siegrist and Gutscher 2006, 2008), public assistance (Hanger et al. 2018), and socio-demographic characteristics (e.g., Poussin et al., 2014).

In the research presented in this paper we consider the critics to the PMT-TTM framework and include some variables that previous studies did not consider. We start from the assumption that the designated shift of responsibility on flood protection from the public to the private sector implies the need to explore the current state of readiness of the public to undertake protective action. Moreover there is a need to identify good practices to inform about the adoption of risk reduction behaviours. We use a framework that combines PMT with a model inspired by TTM to identify the factors that trigger individuals to protect themselves from a hazard, while acknowledging different motivations among a

heterogeneous public (see Sect. 3 and Fig. 3). Thus, the main research question is the following: Do different PMT variables (vulnerability, severity, benefits, self-efficacy, response efficacy, costs) affect people's behaviour to undertake risk reduction measures and if so, is it depending on their risk reduction stage?

2.3) Case study and research design

The selected case study is the municipality of Negrar in the Veneto region, north of Verona, on the foothills of the Italian Alps (Fig. 1). The municipality ranges from 70 to 860 m a.s.l. and is drained by the Progno di Negrar and Progno di Novare river systems, both draining to the Adige river, which is the main river basin in the Eastern Italian Alps. Whereas the northern part of the municipality is rather hilly-mountainous, the southern part is characterized by a valley that gets wider and actually turns into a floodplain. The structure of the municipality is further characterized by several small urban conglomerates (called *frazioni*). The total population of Negrar has steadily increased over the last decades to reach a total of 17,093 inhabitants in 2018. As the city is located in a well-known wine area in Italy, the valley is intensively cultivated. The data for this research has been collected in the *frazione* Arbizzano-Santa Maria (Fig. 2, ca. 4000 inhabitants). Arbizzano is located in the floodplain area in the southern part of the municipality and was especially affected by the floods. In the last 80 years, only one major flood event occurred in the summer of 1935 and generated significant damages. The flood risk maps that are used to do the flood risk assessment in the area (called *Piano di Assetto Idrogeologico dell'Adige*) do not indicate any hydrological risk. This is due to the coarse resolution of these maps that are not fine enough to capture flood hazards and risks generated by small river basins such as the Novare basin (2 km^2). These risks will be considered by novel maps, which are still in the making. Thus, flood risk communication is poor and flood risk awareness is mainly based on historical evidences corresponding to floods which occurred in the last 80 years.

Figure 1. Map of Italy with a zoom into the Veneto region. The three major cities Venice, Verona and Padua, as well as the study area, the municipality of Negrar, are shown on the topographic map of Veneto.

On September 1, 2018, the people living in the area experienced a severe flash flood, which impacted the upper part of Progno di Novare river basin, with a drainage area of 2 km^2 (outflow at the wine farm known as *Case* Bertani, see Fig. 2). With a cumulated rain of more than 180 mm in less than three hours, the event caused a very quick flood response, with a flood peak around 20 m^3/s. Accumulated rain and flood peak are characterised by a return period far larger than 100 year. Hydrological data (rain and flood peak estimates) were collected and examined during a post flood survey organised on October 5, 2018, by using the methods described by Amponsah et al. (2018). The collected data include fine resolution weather radar data, which permitted to run a flood simulation to cross-check the internal consistency of rain and peak flood estimates. The event caused inundations and extensive material damage, with around 10 million € and 3000 affected people, mostly in the *frazione* of Arbizzano. Short lead times hindered the deployment of preventive measures. After the event, the Veneto Region funded recovery measures with the implementation of a flood diversion system which aims to divert flood volumes from Progno di Novare to Progno di Negrar. Household protection measures were not publicly funded with this initiative; private insurance schemes are used in a very limited way in the area.

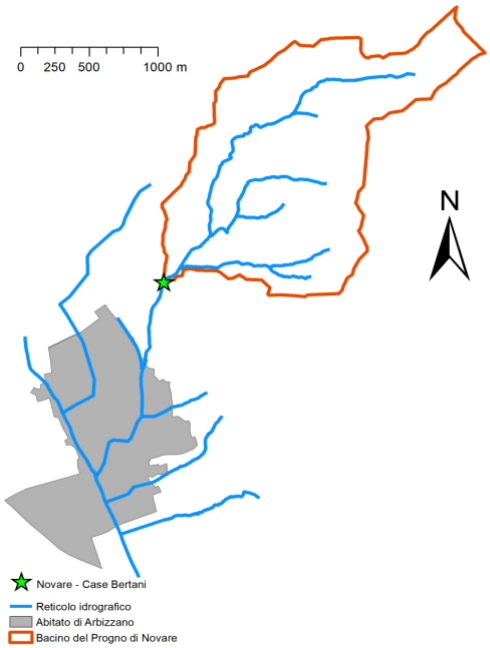

Figure 2. Map of the Progno di Novare (catchment in orange) with its outflow at *Case* Bertani and of Arbizzano (in grey), where most of the flash flood damages were reported.

Techniques of data collection included: exploration of data from existing sources, such as census data and provincial archives; interviews with local authorities to better understand the resident´s risk reduction behaviours; a questionnaire survey carried out interviewing face-to-face a total of 146 residents in Arbizzano-Santa Maria. With regard to our sampling procedure, a context-specific methodology was required to select the respondents, due to the spatial characteristics of flood hazard in the study site. The sample was drawn as to include quotas of respondents selected according to the variables age and gender, so that it reflects the demographic structure of the local population. Data on the demographics was provided by the municipal administration. The municipality also provided contact persons that were affected by the flood in Arbizzano. Using snowball sampling, these people then provided us with further contacts. However, we also randomly selected households in the most affected areas in Arbizzano. This procedure was necessary to avoid the exclusion or under-representation of precisely those residents we were particularly interested in, i.e. those living in the riskiest areas. The unit of analysis was the individual and interviewees were instructed to contact only one person per household. The interviewers read out the 28 questions included in the survey and noted the answers of the participants, which were only given a table with different risk reduction behaviours to facilitate answering some questions (see Table 1).

The data collection lasted 2 weeks from 18th of February to 1st of March 2019. The survey was approved by the local authorities and the data was evaluated anonymously. Participants received no incentive to complete the survey, which took them on average about 30 minutes. Of the 146 residents, 17 people did not own the place they lived in and thus were excluded

from data analysis. Additional 5 people were excluded during the data analysis as they did not answer some questions, leaving 124 people. Respondents ranged in age from 20 to 89 years (M = 53.38, SD = 17.99), and n = 77 (52.7 %) were female. The majority of respondents completed high school (44.5 %, n = 65), followed by college or university education (29.5 %, n = 43), with 5.5 % indicating at least some compulsory education. Compared to the average population in Negrar, the sample was slightly older than the average (M = 44.7 years), similar for the gender ratio of female (50.4 %) and male (49.6 %). Concerning education, people in the sample had similar levels compared to the population in the whole Veneto region.

The questionnaire was prepared on the basis of a review of the existing literature and the results of the documentary analysis, focus groups, semi-structured interviews and existing surveys (Bočkarjova et al. 2009; Hanger et al. 2018; Martin et al. 2007; Poussin et al. 2014). The responses to most of the questions were constructed as 5-point Likert scales, where 1 represented the minimum value and 5 the maximum one. The dependent variable was a composite behavioural measure. It was combined based on an average of eight most common measures that homeowners have undertaken or will undertake to protect their property from floods. Table 1 provides an overview of the risk reduction behaviours. These behaviours were identified by Poussin et al. (2015) and refined based on the preliminary interviews with authorities and local experts. These interviews also influenced how we operationalized the TTM. Instead of focussing on the decision stages 'pre-contemplative', 'contemplative' and 'action' and the total amount of behaviours undertaken (Bočkarjova et al. 2009; Hanger et al. 2018; Martin et al. 2007; Poussin et al. 2014), we developed different risk reduction stages that focussed on the quality of behaviours planned or undertaken. We distinguished between three types of protective measures: structural, avoidance and emergency (see Table 1 and Fig. 3). Structural measures include anti-backflow valves, special installation of electric and heating systems. Avoidance measures include keeping personal valuables/documents/ expensive appliances above expected flood levels. Emergency preparedness include the use of mobile barriers and the presence of an emergency plan. Each risk reduction behaviour was measured using a 5-point scale: 1=will never adopt the measure, 2=will maybe adopt in the long run, 3= will adopt in the near future 4= already done after the flood, 5= already done before the flood, 0=don't know. Based on their highest on average scores, the respondents were divided into one of three risk reduction stages. Even though this different operalization limited the comparability of the studies, we believed that a categorization based on the quality of measures ensures a more effective targeting of communication strategies.

Table 1. Overview of risk reduction behaviours.

Type of behaviour	**Risk reduction behaviour**	**Abbreviation (referring to Fig. 4)**
Structural measures	Anti-backflow valves	S1
	Ground floor and walls made of water-resistant materials	S2
	Special installation (e.g. higher up) of heating and electric system	S3
Avoidance measures	Keeping personal valuables and documents out of flood-prone areas of the house	A1
	Keeping expensive appliances (washing machine, boiler etc.) above expected flood levels	A2
	Adapted use of basement and ground floor	A3
Emergency preparedness	Mobile barriers (e.g. metal/wood shields) available	E1
	Emergency plan for household in case of floods (e.g. where to go, what to take with me)	E2

The independent variables drew on PMT focusing on threat appraisal (vulnerability, severity, benefits) and coping appraisal (self-efficacy, response efficacy, costs) (see Fig. 3). These 6 variables were computed based on different measures using 5-point-Likert-scales. We measured vulnerability by asking how much people considered floods as a threat for their house and themselves, and severity by asking what damages they would expect from a future flood of similar severity than the event in September 2018. Self-efficacy was measured by asking how well-prepared people felt to face a future flood, similar to the one experienced in 2018. Response efficacy was measured based on the average score of three items – structural, avoidance and emergency: people had to indicate how effective they thought the three items to be at helping to reduce the risk of floods. Costs were measured based on the time spend to implement structural, avoidance and emergency measures (three items) and the related financial costs for each of the three types of measures. Finally, benefits were measured based on the average of two items; an extrinsic reward 'I would like to take extra precautions against flooding if I am rewarded or assisted by the government' and an intrinsic reward 'Taking extra risk reduction measures against flooding is a priority'. In addition, we also measured subjective knowledge, trust in government, flood experience, public assistance, having a flood insurance and socio-demographic variables (age, gender, income, ownership and education). We performed the data analysis using IBM SPSS software, version 23, used for statistical analysis in social science. Several regression analyses were conducted to study the effect of PMT variables in each group and overall. Other covariables were also included in more extended models. Moreover, one-way analyses of variances were conducted to study the effect of socio-demographics on the PMT variables.

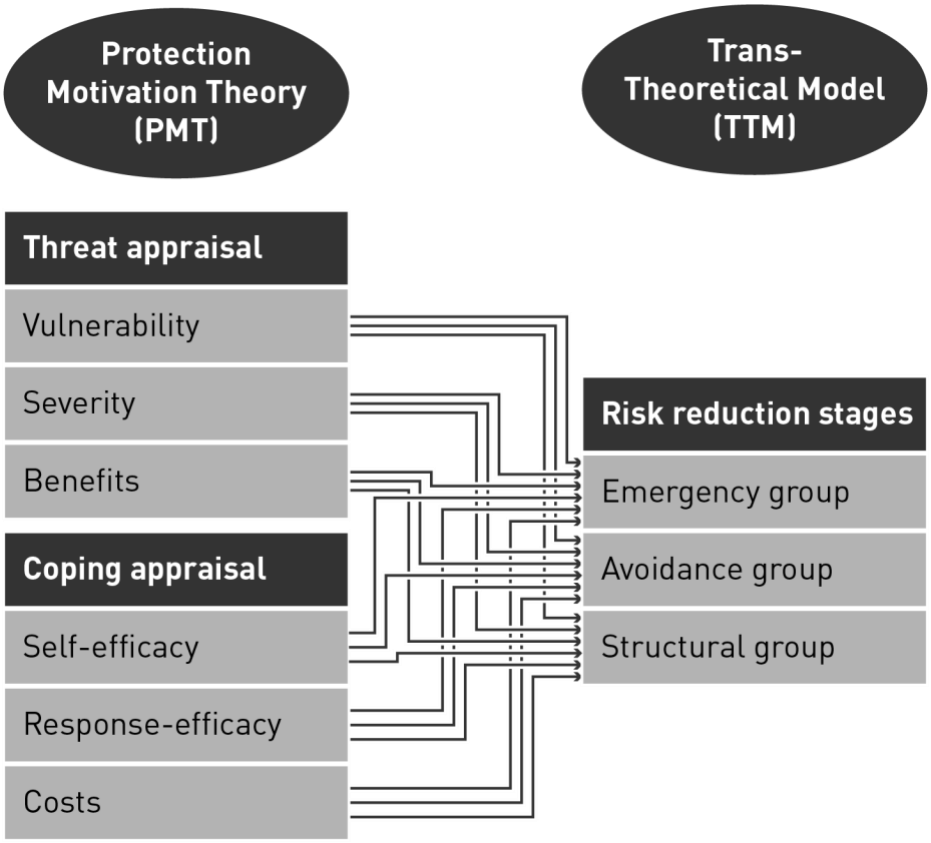

Figure 3. Dynamic protection motivation framework that builds on the Protection Motivation Theory (PMT) and the Trans-Theoretical Model (TTM). The darts highlight that in each group, people are influenced by different PMT variables to engage in risk reduction behaviours.

2.4) Results

We first analysed respondents' answers concerning risk reduction measures. As expected, the adoption of these behaviours is quite low. Figure 4 shows the results revealing that respondents generally indicated higher likelihoods of undertaking avoidance actions (A1-A3, M=2.06) than structural measures (S1-S3, M=1.41) and emergency preparedness measures (E1-E2, M=1.56). Avoidance actions include storing valuables, documents or expensive appliances above expected flood levels. 24 % of all homeowners had already stored valuables above flood levels before the flood in the year 2018 (and since then an additional 19.2 %), 34.9 % store valuable appliances above flood zones and 15.7 % have an adaptive use of basement (e.g. no sleeping rooms). A minority of people have installed special heating or electricity installations (19.8 %), anti-backflow valves (17,1 %) or use water resistant materials (7.6 %). Likewise, for the emergency measures, less than 20 % have had mobile barriers (such as sandbags) available at home and only 11 % have had an emergency plan. Overall, it is important to highlight that the majority of people indicated to have implemented just a few measures.

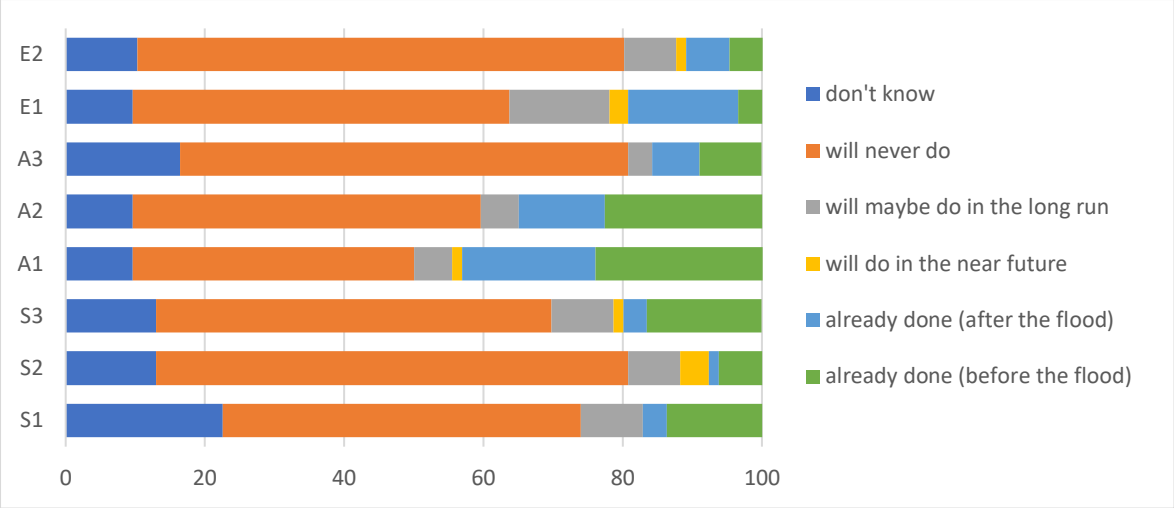

Figure 4. Results indicating the percentage of responses in each category of the Likert-scale for each risk reduction measure.

Based on the eight risk reduction measures, we computed the composite behavioural measure from 1 (will never do) to 4 (already done, before or after the flood). Thus, the higher the score, the higher the stated behaviour to undertake protective action. Following the respondents' highest on average scores on each type of behaviour (structural, avoidance and emergency), we further divided the respondents in our sample into three risk reduction stages: structural, avoidance, and emergency. Thus, those who have already undertaken more structural measures (or are most likely to do so), compared to the avoidance and emergency measures, were put into the structural group. Those who have adopted most, or were most likely to adopt avoidance measures, were grouped in the avoidance group and participants with highest scores on emergency preparedness measures were integrated into the emergency group. Thus, the 124 participants were divided into the three groups as follows: 26 in the emergency preparedness group, 53 in the avoidance group and 45 in the structural group.

We continue by analysing the influence of different PMT variables on undertaking risk reduction measures in each risk reduction stage. Table 2 shows the effects of the variables vulnerability, severity, self-efficacy, response-efficacy, benefits and costs on the composite risk reduction behaviour measure for each stage. The associated descriptive statistics are provided in Table 3. The results for the first regression for the emergency group show that the only significant predictors of risk reduction behaviour are perceived severity of damage and costs. The higher the perceived damage, respectively the lower the perceived costs, the more likely it is that people will undertake emergency measures. In the avoidance stage, vulnerability and self-efficacy are the most important predictors. The more people considered floods to be a threat and the more they believe to be well prepared to face a flood, the more likely they are to adopt avoidance behaviours. The third regression highlights that the significant predictors for people in the structural group are vulnerability, severity, response-efficacy and costs. People at this stage are more likely to be motivated to engage in structural

risk reduction behaviours by various factors: high perceived vulnerability, response-efficacy, and weak perceptions of hazard severity and costs. The overall model indicates that, independent of risk reduction stage, coping factors (self and response efficacy) are more important than the assessment of threats in motivating people to engage in risk reduction behaviours. At the same time higher costs, both in terms of time to implement a measure and money to finance it, demotivate people to engage in risk-reduction behaviours. Moreover, costs seem to be more important than benefits/rewards (i.e. taking extra precautions against flooding because it is a priority for the household or only if rewarded by government). These findings have important implications for flood risk communication, which are discussed in Section 5.

Table 2. Beta coefficients and p-values for risk reduction behaviours regressed on vulnerability, severity, self-efficacy, response-efficacy, benefits and costs.

	Risk Reduction Stage Readiness			
	Emergency	Avoidance	Structural	Overall
Vulnerability	-.477	.609*	.664*	.195
Severity	.702*	-.362	-.672*	-.023
Self-efficacy	-.223	.922**	.181	.325*
Response-efficacy	-.241	.253	.456*	.280*
Benefits	.021	-.187	-.008	-.147
Costs	-1.067*	-.154	-.741**	-.541**
F-ratio	4.331*	6.701**	5.194**	6.228**
R^2	0.79	0.73	0.66	0.42

Note: R^2 represents the amount of variance in the outcome explained by the model relative to the total variance. $*p < 0.05$ and $**p < 0.001$. To highlight trends in the three risk reduction stages, green colours indicate significant positive correlations and orange colours indicate significant negative correlations.

Table 3. Descriptive statistics of variables used in the dynamic protection motivation framework.

	Emergency		Avoidance		Structural		Overall	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Composite behavioural measure	1.57	0.48	1.68	0.49	1.65	0.66	1.64	0.55
Vulnerability	3.46	1.37	3.53	1.46	2.84	1.31	3.3	1.44
Severity	2.42	1.42	3.43	1.23	2.71	1.12	3.16	1.29
Self-efficacy	2.42	1.21	2.33	1.16	2.28	1.16	2.31	1.15
Response-efficacy	3.57	1.14	3.56	1.11	3.63	1.10	3.59	1.10
Benefits	4.38	0.95	4.02	1.15	3.86	1.05	4.03	1.10
Costs	3.23	0.71	3.24	0.47	3.45	0.69	3.31	0.60

Interestingly, the additional variables (trust, experience, knowledge, public assistance and socio-demographics) do not influence people's behaviours to act upon the risk in the extended model. Even though we find some differences with respect to PMT variables, this does not translate into a significant difference on the composite risk reduction behavioural measure. Some interesting results in this respect are that women scored significantly higher than men on the threat factors (vulnerability ($F=3.98$, $p=.048$) and severity ($F=9.43$, $p=.003$)) and on response-efficacy ($F=6.44$, $p=0.013$), as well as lower on self-efficacy ($F=7.0$, $p=0.01$).

Furthermore, we also identify specific trends that can be found for each PMT variable across the three risk reductions stages. The colours in Table 2 shall help to visually summarize the key trends. For severity of expected damages, we can observe a linear trend. Severity is positively correlated with taking protective action in the group relying on emergency measures and negatively correlated in the group relying on structural measures. Vulnerability shows the exact opposite pattern. Negative (but insignificant) in the group relying on emergency measures, it becomes positive and is a significant motivator for people to undertake avoidance or structural measures. Response efficacy shows a similar trend and becomes positively correlated with risk reduction behaviour in the groups relying on structural measures. Self-efficacy plays a critical role in the avoidance group and is less important in the other groups. Overall, costs have a negative impact, but are of special importance for people relying on structural measures.

2.5) Discussion

In order to better understand what motivates people to protect against flood risk we developed a dynamic protection motivation framework. We tested it in a municipality in Northern Italy that experienced severe flash flooding in 2018, shortly before the survey was conducted. The framework proved to be useful for assessing people's perception of flood risk and their readiness to undertake risk reduction behaviours. Our findings add to the other studies in the natural hazard field (Bočkarjova et al. 2009; Gebrehiwot and Veen 2015; Martin et al. 2007), in which people were grouped based on their risk reduction behaviours. Concerning the overall results (i.e. independent of group membership), we confirm most of the prior findings. We support Bočkarjova et al. (2009) and Gebrehiwot and Veen (2015) who also found a negative effect of costs on risk reduction behaviours. Alike both studies, we also show that people with strong perceptions of response-efficacy have a higher likelihood in taking risk reduction actions. Furthermore, we support Gebrehiwot and Veen, (2015), who showed a positive effect of self-efficacy. However, we do not find a significant overall effect of vulnerability as the other two aforementioned studies did, which could be due to the different operalization of the variable.

Our results suggest that people are motivated by different factors in prompting risk reduction behaviours based on their risk reduction stage. We show that PMT variables influence different groups of people in different ways. Structural and avoidance groups are more likely

to be motivated by increased perceptions of vulnerability and response efficacy and are less worried by expected flood damages compared to emergency group. Self-efficacy also plays an important role in the avoidance group, whereas perceived severity of a hazard is an important factor in the emergency group. Through all the groups, costs have a significant negative impact on risk reduction behaviours, whereas benefits do not matter at all. Independent of group membership, we confirm Poussin et al. (2014) and find that coping appraisal had a more important influence than threat appraisal. High perceptions of self-efficacy and response-efficacy significantly increase the likelihood to engage in risk reduction behaviour. We also support Wachinger et al. (2013) and show that costs are the biggest impediment towards action-taking. Beside costs, other reasons may also explain the low adoption of the risk reduction behaviours. The majority of people indicated that they did not think that a flood similar to 2018 could have happened and many also believed that it will not happen again anytime soon. Thus, we speculate that the non-existing flood history (e.g. low perceived risk exposure) could explain the low adoption of risk reduction behaviours before and also the limited willingness to implement measures in the aftermath of the disaster. Similarly, other research observed that people do not protect themselves even though the protective behaviour would be very easy to adopt. Gissing et al. (2016) observed that motorists ignored warnings and drove into flood waters despite an obvious risk of death. The authors list numerous motivations such as underestimating or not understanding the risk, feeling invincible and not taking the warning seriously. Hence, we have to acknowledge that each person sees and responds slightly differently to flood risk, and try to reduce the uncertainty of predicting behaviour as much as possible.

Beside the identification of factors prompting risk reduction behaviours, we also identify specific trends which help to explain the current readiness of individuals to undertake protective actions. The data shows that severity plays an important role in motivating people to act upon emergency behaviours, but as people adopt more significant protections (such as anti-backflow valves or special installations of heating/electric system), severity acts more as an inhibitor. It seems that these people feel more protected and thus do less bother about the severity of a hazard and its expected damages. For response-efficacy the opposite is true. This indicates that, as the measures become more sophisticated, they are also perceived to be more effective in reducing or even preventing flooding. For self-efficacy, there is no trend as it is only significant in the avoidance group. This highlights that people feel ready in undertaking avoidance measures on their own, but less so for the structural measures, and in consequence they are not motivated by self-efficacy to engage in structural risk reduction behaviours. In this respect, it is surprising to see that self-efficacy is not significant in the emergency group, as these measures (e.g. storing sandbags, having an emergency plan) could be more easily performed (like the avoidance measures). As the measures in the structural group are the most cost intensely, costs act as an important barrier here. This could also explain why costs are no such significant barrier in the avoidance group. These measures (e.g. store valuables or boiler above the expected flood level) do not require much effort to be

implemented, both in terms of financing and time. Intrinsic or extrinsic rewards (i.e. taking extra precautions against flooding because it is a priority for the household or only if rewarded by government) do not seem to be of any relevance in our sample. For instance, concerning the extrinsic reward, this could be explained by the non-existing public support after the flood and the, in general, low trust levels in the government.

We also explored a number of possible covariates, which could explain different levels of behaviour to act upon the risk. We do not find any significant influence of these variables on the composite risk reduction behavioural measure, but show an effect of gender on all PMT variables. Generally, women are more likely to engage in protective behaviour compared to men (e.g., Lazo et al., 2015; Morss et al., 2016). We find that women are more threatened by the hazard and its expected damages, and think measures to be more efficient than male, while they feel less prepared to face a hazard. As this does not translate into differences in risk reduction behaviours, it could indicate that even though women prefer to be more protected, they do not have the decision power in the household to implement the measures.

2.6) Conclusions

Our findings also draw implications for influencing individuals in performing desirable adaptive behaviours. We examined the motivations of people to undertake risk reduction behaviours, but did not analyse the influences of significant flood protection measures (such as the flood diversion system) separately. Property owners in flood risk areas should not be considered as a same homogeneous community that can be targeted with a single communication strategy. Thus, communication strategies should not be applied homogenously across large areas, but instead should be tailored to the individual motivations to act upon a risk or not in order to be effective. For people that are most likely to undertake emergency measures, increasing the perceptions of severity rather than focusing on perceptions of vulnerability will lead to greater risk reduction behaviours. The communication strategy should further try to decrease perceptions of costs and to describe benefits of the risk reduction measures. This can be done by providing extra information about flood risk and especially its consequences to these people. Moreover, storytelling can be also used as a powerful communication tool: positive and negative experiences of fellow residents that respectively adopted and didn´t adopt the measures can help to drive behavioural change. For the people in the avoidance group, the communication strategy should focus on the information concerning flood likelihood in the residence area and on the self-efficacy of a number of proposed flood risk reducing measures. Folders, web platforms or information events could help to raise awareness and increase flood preparedness. In the structural group, the perceptions of costs associated with taking protective action (such as time, effort and money) should be decreased. Thus, communication should stress the efficacy of structural measures, in relation to the costs and give clear explanation of the effectiveness of the proposed measures. In addition, the communication should focus on information concerning flood likelihood in the area of residence and not emphasize hazard severity as it

only seems to decrease the likelihood to act upon the risk. Finally, public assistance from the government, be it financial aid for financing flood protection (e.g. subsidies, loans, tax reliefs, etc.) or material support (e.g. distribution of sandbags), could help overcome costs, which are the biggest impediment, and outweigh the balance in favour of acting. Ultimately, these new insights should help to develop better targeted flood risk communication strategies to individuals that emphasize different motivating aspects and foci for each risk reduction stage. An enabling condition to do so will be the integration of risk perception and preparedness surveys in local flood risk management practices. These surveys should be included in longitudinal studies, which may also help to better understand the driving factors of risk reduction behaviours through time. Especially in the areas at highest risk, short surveys could be a valuable (cost and time efficient) instrument to find out at what risk reduction stage people are. If survey information is not available, practitioners may decide a-priori the desired or most likely risk reduction measure (emergency, avoidance or structural) for a community or an area and target their communication accordingly.

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3) Effects of inconsistent warnings

Dealing with inconsistent weather warnings: Effects on message quality and intended actions

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Abstract

In the past four decades, the private weather forecast sector has been developing next to the National Meteorological and Hydrological Service, resulting in additional weather providers. This plurality has led to a critical duplication of public weather warnings: For a specific event, different providers disseminate warnings that are more or less severe, or that are visualized differently, leading to inconsistent information that could impact perceived warning quality and response. So far, past research has not studied the influence of inconsistent information from multiple providers. This knowledge gap is addressed here. An inconsistency matrix was developed and employed to categorize the level of inconsistency across multiple warnings. The matrix provides warning pairs inconsistent in visualisation, message content or both. A survey experiment was conducted in Switzerland (N=1335). The results show that half of the people who have already received warnings from different providers for a same event, indicated that these were inconsistent. The evaluation of warning quality and intended actions in a decision scenario characterised by two severe rainfall warnings shows the negative impacts of inconsistency. For example, consistent warnings are least confusing and inconsistent warnings in message and visualization are most confusing. However, there are no significant differences in the effects of message inconsistency compared to visualisation inconsistency alone on warning quality and intended actions. These findings offer empirical justification to enhance cooperation between public and private weather providers. To improve warnings, the providers should find an agreement to be consistent either in the message content or in the visualization.

3.1) Introduction

3.1.1) Inconsistent weather warnings

On a rainy day in November 2017, several different weather information providers issued to the general public a variety of extreme weather warnings for the most southern part of Switzerland around Lake Lugano (a region known as Sottoceneri). The National Meteorological Sevice, MeteoSwiss (MCH), released a yellow coloured rainfall warning, which means that up to 70 mm) of rain could fall in the next 24 hours. The private weather company Meteonews disseminated a rainfall warning in orange colour, which refers to the lowest of three warning categories, indicating a light weather warning (60-90 mm in 48 hours). Another private provider, Meteocentrale, released the most severe warnings: a purple coloured warning indicating that more than 100 mm would fall in 24 hours. Finally, the Swiss Broadcasting Corporation (SRG SSR), which also runs its own weather service, SRF Meteo,

disseminated a public warning in yellow colour referring to 60-100 mm within 24 hours. What actually fell that day was 50 mm, meaning that only the MCH forecast turns out to have been correct. But the question that this research examines here is whether the inconsistency of the warnings could have made people doubt the whole information package -nowadays easily available on mobile/smartphone technologies-, choosing not to respond to any of them. If indeed the rainfall had been higher, and a flooding event following, this could have had serious negative consequences.

Over the last decades, a private sector meteorology industry has developed next to the National Meteorological and Hydrological Services (NMHS's) (Pettifer 2015). Nowadays, the private weather sector is becoming much more involved in nearly all elements of the weather value chain that goes from observations to tailored weather products (Pettifer 2015; Thorpe 2016). Even though these recent developments have led to improvements in forecast quality and weather services (Pettifer 2015), they have also resulted in more negative outcomes. Especially with respect to public weather warnings, a critical duplication exists among public and private weather providers (Thorpe 2016). In Europe, all NMHS's are obliged to issue official and authoritative weather warnings on behalf of their governments in order to warn public safety authorities, as well as the public at large, from hazardous weather. In addition to these official warnings of the NMHS's, private weather companies can also publish and disseminate their own weather warnings to the public. They do so by using different colour-coded maps, by employing different warning thresholds for their danger levels or by applying different weather models. Thus, the warning information disseminated by different weather providers for a specific point in time can be very inconsistent.

In contrast to the often inconsistent information disseminated by the weather providers, the literature suggests that for communication during an event to be effective, it should be characterised by consistent messages delivered through multiple channels emanating from multiple sources (Drabek and Boggs 1968; Hovland and Weiss 1951; Mileti and Beck 1975; Mileti and Fitzpatrick 1992). Mileti & Peek (2000) highlight that effective warning messages include information that is not only clear, specific, accurate, and certain, but also consistent. Also, the current warning landscape looks very different from what best practices in risk and crisis communication suggest. For example, the NOAA Social Science Committee highlights that those disseminating the messages shall work together to create and share consistent information, to speak with one voice, acknowledging that multiple messengers are critical to providing a consistent message that will be clear and credible, because it is invariant (NOAA 2016). In Southern Africa, the belief in counter productiveness of sometimes contradictory national forecasts led to the development of the first regional Climate Outlook Forum (COF) in Zimbabwe as Patt et al. (2007) document. The COF addressed the issue of trustworthiness by negotiating a single, multinational, consensus forecast for the region of Southern Africa. Even though Patt et al. (2007) did not provide empirical evidence, they showed that the COF organizers implemented consistent weather information that is believed to be more effective

than inconsistent information. To date, there has been little empirical evidence examining the influence of inconsistent information on warning evaluation and response, and research addressing the impact of warning information from multiple providers is completely missing. This void provided the impetus for the research reported here.

In this paper, the research focuses on the effects of inconsistent warning information on the evaluation of warning quality and intended actions. It is hypothesized that inconsistent information is worse evaluated and could decrease consistently the likelihood with which people take adaptive action compared to consistent information. To test the hypotheses, a randomized control survey with 1335 participants was conducted in Switzerland. Important empirical gaps in the literature are filled and the research demonstrates a large potential for improvements in warning design and process to lead to greater understanding and appreciation of danger.

3.1.2) Background

Generally, the risk communication literature suggests that the information provided must be consistent and spread through multiple channels in order to lead to effective decision-making. For example, Mileti & Fitzpatrick (1992) found that risk communication during an event was effective, because it was a process of multiple messages (that were consistent) delivered through multiple channels emanating from multiple sources, which confirmed findings of prior studies (Drabek and Boggs 1968; Hovland and Weiss 1951; Mileti and Beck 1975). However, these studies focussed on identical messages that were communicated differently, such as through a trustworthy or untrustworthy communicator (Hovland and Weiss 1951), or through different channels (written, electronic etc.) and sources (friends, officials, etc.) (Mileti and Fitzpatrick 1992). Mileti & Peek (2000), who reviewed the process of public response to warnings of a nuclear power plant accident, highlighted that warning messages must be consistent within messages, as well as across different messages. They summarize previous research which found that warning messages promote the formation of accurate perceptions only if it is consistent with other publicly announced advisements (Drabek 1999; Perry and Green 1982; Quarantelli 1984).

However, the effect of inconsistent information has largely been understudied. Even though Lindell & Perry (2012) acknowledge that multiple sources often deliver conflicting messages that require searching for additional information to clarify the confusion, they do not study how people are affected by inconsistent information, for instance, when there is no time to consult more information to resolve the ambiguity. In the context of climate forecasts, inconsistency in forecasts has been identified as a cause for concern in terms of farmer's decision-making related to climate change adaptation (Garrett et al. 2013; Bhatta and Aggarwal 2016). So far, only Losee & Joslyn (2018) reported direct evidence of the impact of weather forecast inconsistency on public response. They addressed the influence of inconsistency in sequential forecasts on trust (when the source is not mentioned) directly and

found that inconsistency leads to lower trust in the forecast, but also that inconsistency leads to a higher likelihood of taking risk mitigation action (Losee and Joslyn 2018). Moreover, they found that increased forecast severity was positively correlated with increased levels of trust and action-taking. To be clear, the research reported here does not focus on inconsistency in sequential warnings (so over a period of time), but on inconsistency in different warning information from different weather providers at a given point in time. However -to the authors' knowledge- there is no research on this type of inconsistency.

Not surprisingly, best practices in risk and crisis communication, also underline the need to spread consistent messages. For example, the NOAA guidelines highlight to disseminate consistent information by all messengers that will be clear and credible, because it is invariant (NOAA 2016). Other policy documents use similar language (econcept AG 2011). However, as it was depicted in the introduction, in a real warning situation, it is not consistent but inconsistent information that is spread through multiple sources. Some scholars, like Sandman (2006) question whether to speak with one voice is optimal risk communication. First, 'speak with one voice' disagrees with other best practice, for instance, that one should 'accept uncertainty and ambiguity' (Sandman 2006). Second, the impulse to speak with one voice is grounded in the conviction that lay people cannot handle expert disagreement (Sandman 2006) or uncertainty. It hides the disagreement among experts and the resulting inconsistency instead of acknowledging it. Third, Sandman (2006) argues that there is a risk that some private providers who do not agree with the single harmonized message, will stop disseminating the warnings and in consequence less people would be reached. However, Sandman provides no empirical research. Losee & Joslyn (2018) show that when confronted with inconsistent information, people tend to be more precautious and are more likely to take risk mitigation actions.

Even though research on communication of forecast uncertainty is different from research on inconsistency in information, there might be some similarities. The studies on uncertainty communication focus on the analysis of information processes and decision shortcuts (such as biases and heuristics) that often lead forecast users within the general public to interpret information or behave incorrectly (Wernstedt et al. 2018). The studies also show that the use of forecast information appears to depend critically on risk communication: inconsistency in communication, which is a consequence of scientific (weather models) and non-scientific (interpretation of model outcomes) uncertainty (at least when messages are inconsistent in content), plays a critical role but its effects have been understudied. Recent research suggests that end users of weather forecasts had well-defined uncertainty expectations highlighting that they should be able to understand explicit uncertainty forecasts (Joslyn and Savelli 2010) or that providing forecasts with uncertainty information enhances the chances that users take precautionary action when threatened with an extreme weather event with a low probability (LeClerc and Joslyn 2012). Morss et al. (2008) used empirical data from a nationwide survey of the U.S. public to investigate beliefs commonly held among meteorologists and found that

a significant majority of respondents liked weather forecasts that expressed uncertainty, and many preferred such forecasts to single-valued forecasts.

Furthermore, there has also been some research on graphical or visual salience and some findings did address the advantage or disadvantage that graphics provide in a warning. Considering the advancing of weather applications in the era of big data, this is a research topic that may deserve greater attention in the future. Graphical salience refers to the importance of visual components in a map or other visual representation that intuitively draw people's attention, indicating the most relevant and important features for cognitive processing (Fabrikant et al. 2010; Severtson 2013). Variations of colour in terms of hue, number or value, as well as size of the map are some of the most commonly studied visual features (Garlandini and Fabrikant 2009). If used properly, features can facilitate comprehension and salience (Severtson 2013; Wogalter et al. 2002). For example, Pravossoudovitch et al. (2014) document an implicit association between red and danger, and suggest using red to communicate danger in systematic signal systems. Different colour combinations and types of images have also been tested in the context of severe weather. For example, the effectiveness of different graphical communication forms (different colour palettes, legends and text descriptions) was tested for hurricane storm risk threat and it showed that shades of blue have been most difficult to interpret (Sherman-Morris 2013). The same author has also tested the impact of two different types of radar images on warning recipients and reported that respondents who viewed a reflectivity display had higher perceptions of risk and higher likelihoods of taking protective action than those who viewed a velocity display (Sherman-Morris and Lea 2016). However, interestingly, the researchers concluded that other aspects of the data suggested that these differences were due to the weathercasters' accompanying commentary (i.e. differences in spoken message) rather than the images themselves (Sherman-Morris and Lea 2016).

More specifically, findings from research that focused on improving warning messages through the inclusion of graphics or maps are ambiguous. Casteel and Downing (2015) summarize the research analysing the effects of weather graphics on warning understanding. On the one hand, there are studies which indicate, at least to some extent, positive outcomes of including graphics. Canham and Hegarty (2010) report that, in a first experiment, participants could apply newly acquired knowledge about pressure and wind direction to make appropriate choices about wind direction. However, in a second experiment, in which participants were given task irrelevant information, performance decreased. Thus, it seems that graphics should not include more information than is required for the task at hand (Canham and Hegarty 2010). Bean et al. (2016) found that indicating the user's location on a map leads to more personalization of risk and improved participants' perception of personal risk. On the other hand, other research findings do suggest that there is no such effect. Broad et al. (2007) reported that hurricane forecast graphics are misunderstood by many members of the public. Similarly, Joslyn and Savelli (2011) found that for predictive temperature

forecasts, text messages produced less errors compared to if a visualization was included. Finally, Casteel and Downing (2015) found no effect of graphics (or text) on the perceived risk, perceived severity, and likelihood to contact a loved one for each message. They used a scenario in which participants were told they were driving through an unknown region of the US to investigate wireless emergency alert weather warning message effectiveness across one of four conditions (text, text + polygon, text + radar image, text + radar image + polygon). As Casteel and Downing (2015) point out, their findings, but also those of Canham and Hegarty (2010) and Sherman-Morris and Lea (2016) highlight the equivocal influence of weather graphics on comprehension.

Based on ambiguous research results on the influence of inconsistency on adaptive/risk minimising action, there is a need to better understand how people are affected by differing, sometimes conflicting information coming from weather providers, as highlighted also by the National Academies of Sciences (2017). More precisely, to justify possible adjustments of the warning process or even the legislation, there is a need to find out whether consistent information is actually more effective than inconsistent information. In order to address this research gap, the following questions were analysed: Does inconsistency have effects on evaluation of warning quality and does it influence intended behavioural response? The research on graphical or visual salience described above provides the background for this study (see section 2 on Methods). To structure the analysis, the research reported here also analyses the possible effects of different types of inconsistency. It adds to the literature by analysing the effects of some warning characteristics (such as visual graphics) on evaluation of warning quality.

3.2) Methods and data

The issue of inconsistent weather warnings was studied in Switzerland, which is typical of having a single NMHS and many additional weather information providers. This Section describes the state of warnings in Switzerland, as well as the indicators developed to categorize the level of inconsistency across multiple forecasts, and the data gathering and analysis that was applied.

3.2.1) Inconsistent weather warnings

As alluded to in the introduction, Switzerland has a single NMHS (MeteoSwiss, MCH), the national broadcasting service (SRG SSR) with its own independent weather information service (SRF Meteo), and multiple private companies of which Meteonews and Meteocentrale issue public warnings. The inconsistency in warnings is caused by several factors. In the first place, the different weather providers use a variety of different weather forecast models (e.g. COSMO, GFS, ECMWF). Using the same data (that is, e.g., provided by the SwissMetNet), these models all calculate future atmospheric conditions but show different outcomes due to different parameterisation of processes, assimilations, and resolutions among others (Bassill 2014; MeteoSwiss 2018a). Moreover, as warnings can also be based on observations, now-

casting systems (a technique for very short-range forecasting) also differ from one provider to the other.

Second, forecasters can interpret the outputs of these models in different ways. For instance, a more experienced forecaster may understand the data differently than a less experienced colleague. Or one forecaster may have a personal preference for a specific weather model based on long-term or short-term experience. A possible reason could be that the model underestimates wind for several weeks in a row. Also, public forecasters bear a higher responsibility compared to their private colleagues. They have the legal duty to warn the regional authorities, as well as the general public, from severe weather. In contrast to the private sector meteorology, which can warn without obligation or consequences, warnings from the public agency lead to expensive deployments of police, fire brigade, military and civil defence. Thus, MeteoSwiss has the internal policy to stay below a certain false alarm ratio (FAR). Private providers have more freedom in that sense and can target a higher probability of detection (POD), but consequently have also higher FARs. Stakeholders involved in the warning chain suspect that these different responsibilities and agendas between the public and the private weather providers can lead to different warning practices, so that private providers deliver and disseminate more severe warnings on a more frequent basis than the public weather agency (Kaufmann et al. 2008). While confirming or rejecting such suspicions is beyond the framework of this paper, the monitoring of the warning messages from the four Swiss weather providers (MeteoSwiss, Meteonews, Meteocentrale, SRF Meteo) that disseminate public warnings between August and November 2017, revealed that the weather warnings differed often very much from each other and in most cases at least one private provider was disseminating more severe warnings then the public agency.

Third, the different weather providers use different threshold values that define the warning categories as is documented in Table 1. Even though the climate data, on which these thresholds are mainly based, are the same, the interpretation of these data sets change from one climatologist/forecaster to the other. Also, only some providers take into account the current climatological and topographical situation (e.g. differences in runoff on the northern and southern side of the Alps or different threshold values for the lowlands and the mountains), and/or the needs of specific groups of stakeholders (e.g. the cantonal agencies) when developing the threshold values. All this contributes to different threshold values, and to different number of warning (and pre-warning) categories. Among the four Swiss providers, warning categories differ from three to five warning, and zero to two pre-warning categories, which again go hand in hand with the choice of colours that represent the (pre-)warning categories. Also, pre-warning categories are based on lead time and probabilities (e.g. MeteoSchweiz) or based on impact thresholds (e.g. Meteonews). For example, SRF Meteo uses three warning categories (coloured in light orange, dark orange, and dark red) and issues no pre-warnings, whereas MeteoSwiss uses five warning categories (coloured in green, yellow, orange, red and dark red) for most hazards (e.g. only two categories for

thunderstorms) and, as well, has a pre-warning category (called warning outlook). Even though Meteocentrale and Meteonews use the same number of warning categories and associated colours (orange, red and violet), these categories are defined again by different threshold levels for a given hazard. Last but not least, the amount of warning regions also varies from one provider to another. As the regions are based on a very small scale (e.g. 159 warning regions for MeteoSchweiz, 172 for SRF Meteo, 140 for Meteonews and individual regions for Meteocentrale), there are only minor differences in geographical coverage.

Table 1. Warning thresholds for the weather phenomenon wind (in km h^{-1}), number of (pre-) warning categories and colours (*in italics*) used by the different weather providers.

Attribute	Level	MeteoSchweiz	SRF Meteo	MeteoNews	Meteocentrale
	Pre-warning	Probability ≥ 40 % max. lead time 24-120 h (*orange stripes*)		50 (*yellow*)	Probability (individual for each event) max. lead time 48 h before event (*yellow*)
Lowlands (< 1800 maS)	1	(*green*)			
	2	70 (*yellow*)	60 (*light orange*)		
	3	90 (*orange*)	75 (*orange*)	65 (*orange*)	75 (*orange*)
	4	110 (*red*)	100 (*dark red*)	90 (*red*)	100 (*red*)
	5	140 (*dark red*)		120 (*violet*)	130 (*violet*)
	Pre-warning	Probability ≥ 40 % max. lead time 24-120 h (*orange stripes*)		50 (*yellow*)	Probability (individual for each event) max. lead time 24-48 h (*yellow*)
Föhn	1	(*green*)			
	2	70 (*yellow*)	75 (*light orange*)		
	3	90 (*orange*)	90 (*orange*)	65 (*orange*)	75 (*orange*)
	4	110 (*red*)	120 (*dark red*)	90 (*red*)	100 (*red*)
	5	140		120 (*violet*)	130 (*violet*)
Mountains (> 1800 maS)	3	130 (*orange*)			100 (*orange*)
	4	160 (*red*)			120 (*red*)
	5	200 (*dark red*)			150 (*violet*)

3.2.2) Indicator design

In response to the challenge of dealing with warning inconsistency, an 'inconsistency matrix' was deployed to help structure analysis. It is important to highlight that the matrix focuses on inconsistency in warning information from different weather providers at a given point in time, and not on inconsistency in sequential warnings from one provider. Table 2 presents

the matrix based on two axes: the horizontal axis distinguishes between same and different visualization; the vertical axis distinguishes between same and different messages /text (with a focus on degree of warning severity) in the warnings. As a result, the four types - each one characterized by two different warnings- are described by consistent warnings (type AA); inconsistent warnings in visualization (type AB); inconsistent warnings in message content (type AC); inconsistent warnings in visualization and message content (type AD). As Table 2 shows, the four types differ on a number of characteristics such as number of categories, colours, warning thresholds, interpretation of data and used weather model. For example, in type AB the warnings appear differently as providers use different categories, thresholds and colours (considering that these three elements are interlinked) even though the message content (i.e. the forecasted hazard severity) is the same. In contrast, in type AC the forecasted weather in the warning message is different, even if the providers would use identical categories, thresholds, and colours. The typology has been used to conduct a large sample randomized control survey. In the following Section, a description of the research methods and the operationalisation of the typology is provided. Examples of the types are also reproduced in the supplemental material (Figures S1-S8).

Table 2. The inconsistency matrix

		Visualization	
		Same	Different
Message/text (severity of weather phenomenon)	Same	Type AA **Consistent warnings** Categories: same Colours: same Thresholds: same Interpretation of data: same Model used: same	Type AB **Visualization inconsistent warnings** Categories: diff Colours: diff Thresholds: diff Interpretation of data: same Model used: same
	Different	Type AC **Message inconsistent warnings** Categories: same Colours: same Thresholds: same Interpretation of data: diff Model used: diff	Type AD **Visualization and message inconsistent warnings** Categories: diff Colours: diff Thresholds: diff Interpretation of data: diff Model used: diff

Note that the number and shape of warning regions is kept constant through all types.

3.2.3) Hypotheses, data and analytic methods

The method used here was a large sample randomized control survey, that tested for effects of warning inconsistency on evaluation of warning quality and intended response. A survey containing 31 questions was conducted based on a decision scenario. The scenario was placed at the beginning of the survey. Respondents were asked to imagine that it is 19 o'clock in the evening on a Friday and that, almost simultaneously, they saw two severe rainfall warnings,

valid for the weekend. They were also told that they would be celebrating their birthday that they have planned for months on that weekend. In more detail, they were told to imagine that they would be having a picnic and barbecue with friends on the shores of Lake Lugano (on the Swiss territory). Other scenarios were considered and pre-tested as well, but the 'birthday scenario' was chosen as it (a) was simple, straightforward, and realistic, (b) forced people to face a threat taking them out of their comfort zone, and (c) required people to make the decisions on their own.

In total, 1335 respondents that were recruited through the access panel provider *Respondi* completed the online survey from 8th to 22nd May 2018. Prior to the survey, participants were informed about the ongoing research, that the data would be evaluated anonymously (names were not collected) and that their participation was voluntary. Participants received a financial incentive to complete the survey, which took them on average about 12 minutes. Because of unrealistically short answering times, as well as misunderstandings of the scenario (people imagined to be at home and not at Lake Lugano), answers of 140 respondents were excluded from analysis leading to 1,195 respondents. The survey (in German) was conducted with a large sample of the Swiss population in the German-speaking cantons (see Figure 1). Respondents ranged in age from 18 to 86 years (M = 47.85, SD = 16.44), and n = 607 (50.8 %) were female. The majority of respondents completed vocational school (45.5 %, n = 542), followed by college or university education (18.5 %, n = 221), with 7.5 % indicating at least some compulsory education. Compared to the average Swiss population, the sample was slightly older than the average (M = 43.14 years), similar for the gender ratio of female (50.5 %) and male (49.5 %) (FSO 2017a) and slightly more educated than the Swiss population (more respondents with higher vocational training or university degree and fewer respondents with only completed compulsory school) (FSO 2017b). However, as the survey was conducted online based on the people registered in the data base of the online panel, it did not reach people that do not have internet access or that are not in the data pool. Therefore, the results of the research should not be taken as being representative of the Swiss German population. Nevertheless, they can be an indication of the opinions of the users of online weather warnings.

Figure 1. Map of Switzerland with the different language regions.

Respondents were randomly assigned to one of four warning conditions described in Table 2: (1) consistent warnings, (2) visualization inconsistent warnings, (3) message inconsistent warnings, (4) visualization and message inconsistent warnings. Roughly even subgroups were achieved out of the total sample size of 1,195. Each subgroup received two warnings (respectively AA, AB, AC, and AD), that each consisted of a warning map of Switzerland and a warning text. Warning A, a very severe rainfall warning with 3 Categories, was identical across all subgroups. For type AA the two warning messages were almost identical in description/visualization and content (therefore named type 'AA'). For type AB, warning B was visualized differently (i.e. 5 Categories instead of 3 with different thresholds and associated colour scheme), but had identical content (i.e. identical text with numbers) compared to warning A. For type AC, the visualization was identical for warning A and C (3 Categories with identical thresholds and colours), but warning C was less severe than warning A. For type AD, warning D was less severe and was visualized differently (i.e. 5 Categories) compared to warning A. The number and size of warning regions were kept constant. For each subgroup, the different warning messages are provided in the supporting information (Figures S1-S8). All the warnings reflect actual inconsistencies in actual warnings. The warning messages were developed based on real warnings that weather providers disseminated in November 2017 during the event described in the introduction. Finally, experts (forecasters and other staff of MeteoSwiss) had reviewed the warning messages for plausibility.

With respect to the survey content, questions on two sets of dependent variables were asked: evaluation of warning quality and intended actions. First, participants had to evaluate the two warning messages they received separately. They rated each warning on a five-point Likert scale from 'not at all' to 'very' with respect to comprehension, credibility and meaningfulness. Differences in response were calculated between the items to rate each warning and, then, used to compute the three items to (a) one 'confusion' variable. High numbers mean large differences in evaluation between both warnings, and thus are an indicator for confusion. Second, participants also assessed the warnings together. They had to indicate whether the warnings overall are (b) 'in agreement' and (c) 'easy to understand'. Thus, three different variables (a, b, and c) were used to assess participants' evaluation of warning quality. Data was collected on intended action based on warning inconsistency through two variables linked to the decision scenario described at the beginning of this Section: a risk minimizing behaviour (i.e. 'I would cancel the party and barbecue') and searching for more information (i.e. 'I would look for more information'). Participants had to indicate how strongly they agreed or disagreed with each statement. A five-point Likert scale from 'totally disagree' to 'totally agree' was used, so those which totally agreed with the statement were most likely to engage in risk minimizing behaviour, respectively to search for additional information. Finally, after having made the decision to engage in a risk minimizing behaviour or not, participants were also asked whether they relied on the warning A or the warning A, B, C, D (depending on the experimental condition) or whether they relied on both warnings together for their decision-making. Beside the experimental condition, data on weather information sources, attitudes towards weather providers, as well as personal factors including risk perception, experience and knowledge with severe weather and warnings, and other social and demographic factors, was also gathered. The full questionnaire is available as supplemental material.

Based on the literature review in Section 1.2 and the 'inconsistency matrix' in Section 2.2, the following hypotheses were elaborated.

Table 3. Research hypotheses

H1a	Warning quality will be evaluated to be highest for type AA (most consistent warning pair) and lowest for type AD (least consistent warning pair).
H1b	Warning quality will be evaluated higher for type AC compared to type AB. Thus the (negative) effect of visualization inconsistency will be more important than the effect of message content inconsistency alone on evaluation of warning quality.
H2a	People are more likely to engage in a risk minimizing behaviour for type AA and AC, and less likely to do so for type AB and AD. Thus, message content inconsistency is expected to have a less important negative impact than visualization inconsistency on intended action.
H2b	People are less likely to search for more information for type AA and AC, and more likely to do so for type AB and AD. Again, a more important positive impact of message content inconsistency is assumed.
H3	For type AA, on average, people rely more often on both warnings together when making the decision to act or not.
H4a	With respect to single warnings, on average, people rely more often on the more severe warning, which is also better evaluated than the less severe warning.
H4b	With respect to single warnings, on average, people rely more often on the warning using a flash light system with 3 Categories, which is also better evaluated than the warning using 5 Categories.

The data analysis was performed using IBM SPSS 23 used for statistical analysis in social science. One-way analyses of variances (ANOVAs) were conducted to study the effect of warning inconsistency on evaluation of warning quality and intended actions. An average sample of n=300 respondents *per* experimental condition satisfied requirements for ANOVA. Moreover, one-way ANCOVAs were conducted to include risk perception, knowledge and experience with warning and severe weather, as well as relevant demographic variables (age, gender, education, urban/rural) as a covariant. In a further step, a series of two-way ANOVAs was performed to study possible interaction effects of warning inconsistency and participants' characteristics (knowledge, experience, and other socio-demographic variables) on the dependent variables mentioned above. In addition, a multinomial logistic regression was done to analyse if people relied more or less on one warning when they had to make the decision to take action or not.

3.3) Results

In a first step, the results about participants' weather information sources and attitudes towards weather providers are provided. Most people (79.5 %) regularly consult weather information. In a multiple response set, these people reported to consult information via the use of smartphone weather Apps (78.8 %), TV (74.9 %), own observations (71.5 %), online websites (71.3 %), radio (66 %), family and friends (45.8 %), newspapers (45.3 %), newsletters/SMS (18.8 %), and social media (9.4 %). Of those people who regularly look for

weather information, more than half do so on a daily basis (53.9 %) or at least several times a week (33.3 %). Only 11.5 % of people consult information very unregularly, such as only when they are planning an activity for which weather is important. Almost two thirds of people who look for information (64.7%) consult weather information from several providers. They compare the available weather information especially before doing outdoor activities (89.4 %) and also depending on the severity of the hazard (70 %), as well as its nature (62.5 %) (multiple response question). With respect to warning information, almost two thirds of people who regularly consult information (63.2 %) have already received warnings. Half of these people (49.7 %) have already received warning messages from different weather providers for a same event, which were inconsistent in most cases (52.9 %). The relative majority of respondents (43.8 %) also indicated that they would like to receive for a same weather event (independent of its severity) only one harmonized warning from the national authorities, whereas the remaining people would like to receive several warnings that could be visualized differently (19.1 %) or could differ in message content (12 %). 25.2 % had no preference.

In a second step, the relationship between warning inconsistency and the evaluation of warning quality is analysed. First, as expected, there is an inverse proportional relation between warning inconsistency and 'ease to understand' (light dashed line in Figure 2): an increase in warning inconsistency corresponds to a decrease in the warning understanding. There was a significant effect of warning inconsistency on understandability of the information received, $F (3, 1187) = 6.33$, $p<.001$, $r=.13$, which was supplemented by a significant linear trend, $F (1, 1187) = 16.76$, $p<.001$, $r=.12$, indicating that as the warning became more inconsistent, the understandability decreased proportionately. People found the information they received most understandable for type AA ($M=4.21$, $SD=0.8$) and least understandable for type AD ($M=3.97$, $SD=0.89$) ($p=.002$). The difference in understanding between type AB ($M=3.76$, $SD=0.69$) and type AC ($M=3.63$, $SD=0.71$) was, however, non-significant ($p=.263$).

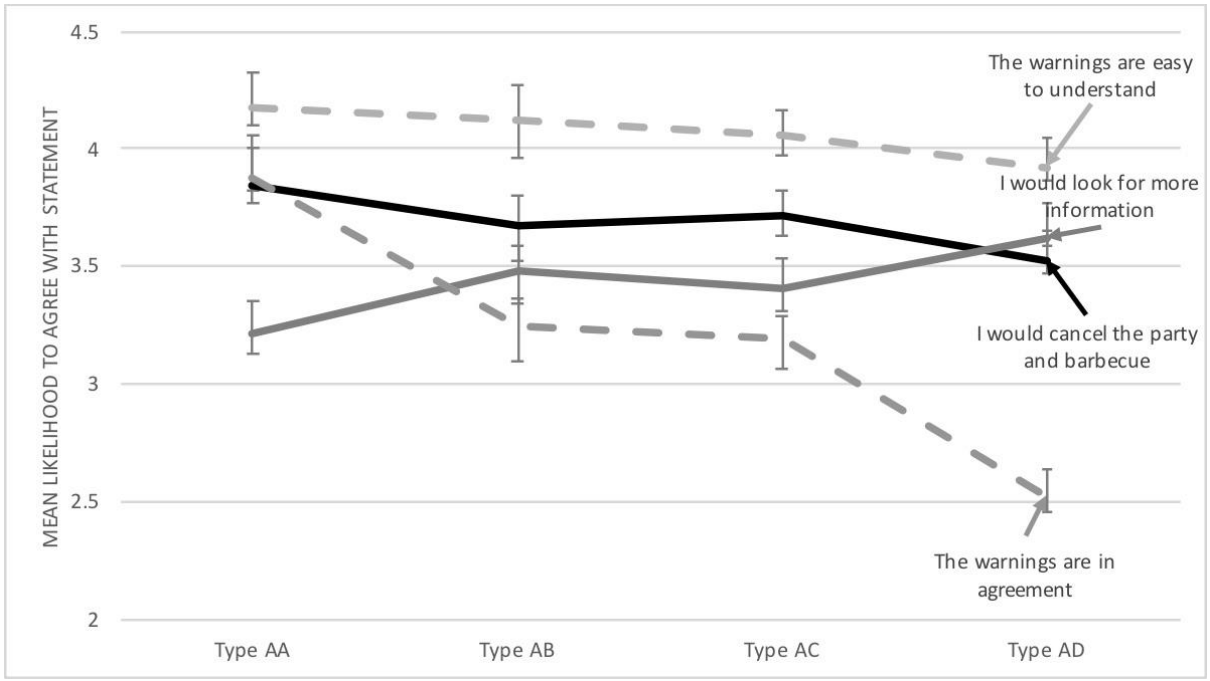

Figure 2. Intended actions and evaluation of warning quality.
Note: Error bars: 95 % confidence intervals (CI). Intended actions are represented by solid lines. Warning quality are represented by dashed lines.

Second, respondents evaluated the warning quality of consistent information more positively than of inconsistent information. When participants assessed the two warnings separately, results show a large difference in evaluation between warning A and D (M=0.49, SD=0.98) and, as expected, no difference at all for type AA, because messages were almost identical in visualization and content (M<0.01, SD=0.71). There was a significant effect of warning inconsistency on confusion F (3, 1178) = 15.8, p<.001, r= .2. As it can be seen in Figure 3 below, there was also a significant linear trend, F (1, 1178) = 44.19, p<.001, r=.19, indicating that as the warning became more inconsistent, the confusion increased proportionately. As Figure 3 shows, there are no significant differences in evaluation of warning quality between type AB (M=0.26, SD=0.83) and type AC (M=0.3, SD=0.85), thus between types characterised by visualisation and message content inconsistency. However, there are significant differences among all other types; highly significant between type AA and each of the other three types (p≤.001), significant between type AD and AB (p=.01), respectively type AD and AC (p=.05) as shown by Bonferroni post-hoc tests.

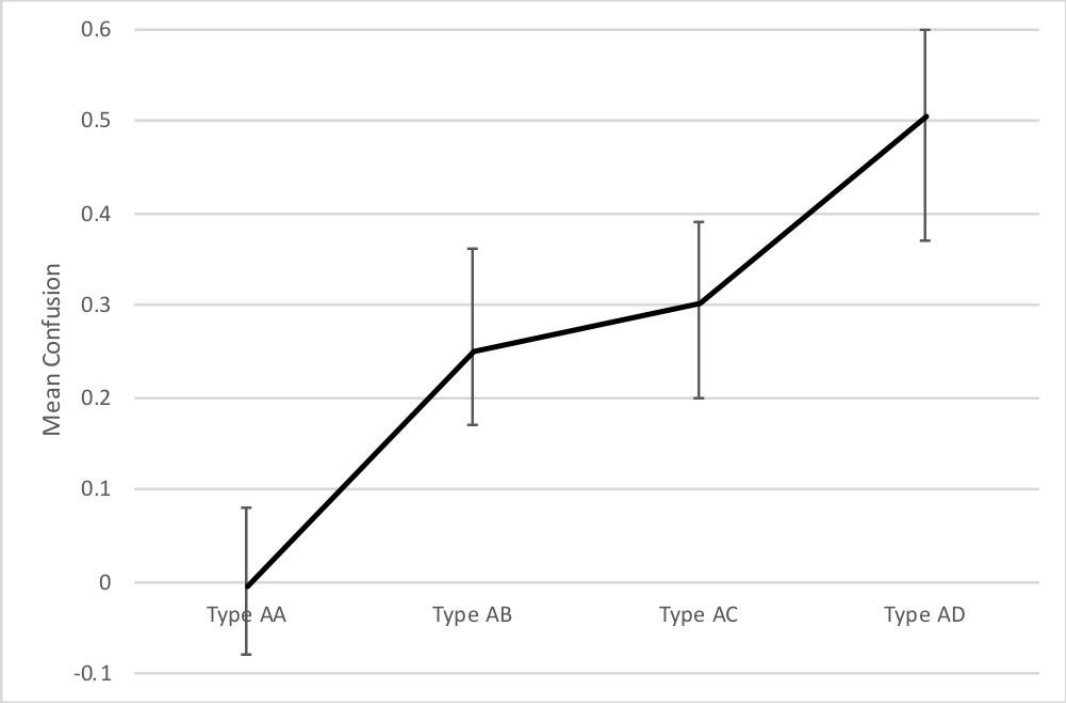

Figure 3. Confusion in the four warning conditions.
Note: Error bars: 95 % CI. Confusion was computed based on differences in evaluating the warning quality (in terms of comprehension, credibility and meaningfulness) of the two warnings separately.

Third, as the warning became more inconsistent, people evaluated that they were 'less in agreement' (dark dashed line in Figure 2). People that received type AA information perceived warnings to be more in agreement (M=3.89, SD=0.89) than people that received type AD information (M=2.51, SD=1.105). The overall effect was significant, F (3,1187) = 95.34, p=.000, r=.44, as well as the linear trend F (1, 1187) = 177.61, p<.001, r=.36. All group differences were highly significant (p<.001), but the difference between visualization (M=3.30, SD=0.96) and message inconsistency (M=3.18, SD=0.98) as shown by Bonferroni post hoc testing.

In a third step, the set of relationship between warning inconsistency and intended actions is examined. First, when faced with increasingly inconsistent information, respondents search for more information but are less likely to change behaviour (solid lines in Figure 2). There was a significant effect of warning inconsistency on engaging in the risk minimizing behaviour F (3, 1194) =5.28, p=.001, r=0.11, and on searching for more information F (3, 1194) = 7.07, p<.001, r=0.13. As expected for both variables, receiving type AA -consistency- information resulted in a significantly higher likelihood to change behaviour and in a lower likelihood to search for additional information compared to receiving type AB -visualization inconsistency-, respectively type AD -visualization and message inconsistency. However, as hypothesized, there were no significant differences between type AA and type AC -message inconsistency- on intended actions. The means and Dunett post-hoc testing are provided in the Tables 4 and 5.

Table 4. Reported means of statistical results.

Dependent variable	Type AA (*M, SD*)	Type AB (*M, SD*)	Type AC (*M, SD*)	Type AD (*M, SD*)
Take protective behaviour	3.88, 0.98	3.7, 0.1	3.78, 0.99	3.56, 1.04
Search for information	3.2, 1.22	3.46, 1.12	3.39, 1.14	3.63, 1.17

Note: M = Mean and SD = Standard Deviation.

Table 5. Results of Dunett post-hoc testing.

Dependent variable	Consistent information	Inconsistent information	Mean Difference	Standard Error	p-value
Take protective behavior	Type AA[a]	Type AB	-.19	.08	.031
	Type AA[a]	Type AC	-.11	.08	.217
	Type AA[a]	Type AD	-.32	.08	.000
Search for information	Type AA[b]	Type AB	.27	.1	.007
	Type AA[b]	Type AC	.19	.1	.06
	Type AA[b]	Type AD	.44	.1	.000

Note: Dunett t-tests with group 1 as a control group, compared against all other groups. a = Dunnett t < control. b = Dunnett t > control.

Second, people receiving type AA and AC information (consistent in visualization) are more likely to take intended action and less likely to look for more information, than people receiving type AB and AD information (inconsistent in visualization). In Figure 2, this trend can be identified. Additional testing showed significant differences in engaging in risk minimizing behaviour ($t(1193) = 3.39$, $p = .001$) and looking for more information ($t(1193) = -3.36$, $p < .001$) between warnings with and without consistent visualization. Even though not significant, the findings show that for type AC, the likelihood increases to change behaviour and decreases to look for more information compared to type AB.

In a fourth step, the set of relationship between reliance on warning and message inconsistency is analysed. First, for type AA, people tend to rely on both messages when making the decision to act or not. As documented in Table 6, almost 80 % of people relied on both warnings for type AA, whereas only 50 % of people relied on both warnings for type AD. There was a significant effect of warning inconsistency on participants' choice to rely more on one warning or the other, $F(3,1176) = 22.21$, $p < .001$, $r = .23$. The results of a subsequent multinomial logistic regression are presented in Table 7. It shows that for type AA, compared to type AD, people are significantly more likely to rely on both messages together than to rely only on the first warning message. The same pattern can be observed when comparing type AC to type AD.

Table 6. Frequencies with which people relied on the first, second or both warning *per* warning condition.

	Consistency (type AA)	Visualization inconsistency (type AB)	Message content inconsistency (type AC)	Visualization and message content inconsistency (type AD)
Rely on first warning	13 %	33.4 %	29.7 %	41.8 %
Rely on second warning	7.7 %	10.4 %	8.3 %	7.7 %
Rely on both warnings	79.2 %	56.2 %	62 %	50.5 %

Table 7. Results of multinomial regression analyses

	B (SE)	95 % CI for Odds Ratio		
		Lower	Odds Ratio	Upper
Rely on first warning vs. rely on both warnings				
Intercept	-.191 (0.12)			
Consistency	-1.61 (0.22)***	0.13	0.2	0.3
Visualization inconsistency	-0.33 (0.18)	0.51	0.72	1.02
Message content inconsistency	-0.55 (0.18)**	0.41	0.58	0.82

Note: R^2= .06 (Cox & Snell), .07 (Nagelkerke). Model χ^2 (6) = 69.77 p<.001. **p<.01, ***p<.001.

Note: B = unstandardized Beta, SE = Standard Error and CI = Confidence Interval.

Second, for type AB, AC or AD, people relied, on average, less on the second warning. As documented in Table 6, roughly one third of people in type AB (33.4 %), AC (29.7 %) and AD (41.8 %) relied on warning A compared to about the 10 % or less who relied on warning B, C or D. This pattern is confirmed by people's evaluations of warning quality. As shown in Table 8, all people who received type AB, AC, or AD information, significantly evaluated warning A more positively then warning B, C or D respectively.

Table 8. Evaluation of individual warnings

	Evaluation message A	Evaluation message A, B, C, D respectively				
Warning condition	(*M, SD*)	(*M, SD*)	t-statistic	Degrees of freedom	p-value	Effect size (r)
Type AA	4.10, 0.74	4.10, 0.73	-0.3	288	.979	.02
Type AB	4.11, 0.71	3.84, 0.75	5.44	309	<.001	.30
Type AC	4.14, 0.67	3.83, 0.75	6.16	299	<.001	.34
Type AD	4.10, 0.81	3.55, 0.93	8.39	295	<.001	.44

Note: M = Mean and SD = Standard Deviation.

Finally, this paragraph focuses on the influence of participants' individual characteristics on warning evaluation and response. Including knowledge (and also other characteristics) as a covariant did not change any of the documented results. Also, for the evaluation of warning quality, there was no significant effect of knowledge, experience or socio-demographic characteristics. However, the data show that for people with no experience with warning messages, the effect of inconsistency in visualization is more important than the effect of inconsistency in message content on evaluation of warning quality. A series of two-way ANOVAs showed significant interaction effects between warning inconsistency and whether people have adapted their behaviour in response to warnings they received in the past $F(3, 1178) = 3.61$, $p=.013$, $r=.09$, as well as warning experience $F(6, 1178) = 3.02$, $p=.006$, $r=.12$. This means that people with no general warning experience are more likely to be confused by type AB compared to type AC. For the intended actions, risk perception significantly influenced taking the risk minimizing behaviour: people with higher risk perceptions were more likely to take action compared to people with lower risk perceptions, $t(973) = 4.70$, $p<.001$, $r=.15$. Warning experience, risk perception, age and whether people consult more than one weather provider significantly influenced looking for more information. People with positive warning experience, with higher risk perceptions, who consult more than one weather provider and younger people were more likely to take action compared to people with negative experience ($t(973)=1.99$, $p=.047$, $r=.06$), lower risk perceptions ($t(973)= 2.52$, $p=.012$, $r=.08$), who consult only information from one provider ($t(973)=2.03$, $p=.042$, $r=.07$) and older people ($t(973)=3.63$, $p<.001$, $r=.12$). A series of two-way ANOVAs showed no significant interaction effects between warning inconsistency and participants' characteristics on taking intended actions. Including participants' individual characteristics into the models used did not change significant results for taking intended action, nor for warning reliance.

3.4) Discussion

The results show that, overall, inconsistency negatively impacts the evaluation of warning quality (see H1a in Table 3): evaluated warning quality was significantly higher for consistent warnings and lower for inconsistent warnings - either in visualization, message content or both. These results support earlier findings, for instance, that official warning messages promote the formation of accurate perceptions only if it is consistent with other publicly announced advisements (Drabek 1999; Perry and Green 1982; Quarantelli 1984). The research also affirms Mileti & Peek (2000), who highlighted that effective warning messages must include consistent information. The results also confirm Losee & Joslyn (2018), who addressed the issue of inconsistency in sequential forecasts on trust directly and found that consistency leads to greater trust in the forecast. Moreover, results show that for people with no experience with warning messages, the effect of inconsistency in visualization is more important than the effect of inconsistency in message content. This indicates that people who are less familiar with warnings may have more difficulty to understand warnings inconsistent in visualization compared to those with warning experience. As Parker et al. (2007)

highlighted that people's response to a (flood) warning is likely to be influenced by whether they possess previous hazard warning or hazard experience, it can be speculated that less experienced people have more difficulty to understand warnings that provide identical numbers and text but which are visualized differently.

Moreover, neither visualization inconsistency (type AB) nor message inconsistency (type AC) had a more or less important effect on evaluation of warning quality. In the following, it can be speculated about the reasons why this research could not find a more negative effect of visualization (than message content) inconsistency on evaluation of warning quality, as it was expected (see H1b in Table 3). First, the warnings were composed of a map and a text. As described in the methods in more detail, beside different maps for both types -AB and AC-, the text was very similar for type AB, but different for type AC. Thus, for type AB it could be that the similar warning text compensated for the inconsistently displayed information in the map and made the warnings more understandable. This also suggests that what makes the difference is the consistent information (i.e. text with numbers) and not the inconsistent information (i.e. figures). These speculations are supported by participants' comments (at the end of the survey people had the opportunity to leave some remarks). For instance, some people noted for type AB that the numbers in both texts were identical, resulting in a clear message to them. Thus, it could be that warning quality of type AB was evaluated that high due to similar warning texts, which (over-)compensated for the confusion arising from the different maps (and ultimately resulted in no difference compared to type AC). This highlights the importance to include a warning text with hard numbers which help people to compare warnings that have the same content but may be visualized differently. This speculation is supported by findings of Sherman-Morris & Lea (2016) who concluded in their research that it were not the differences in the graphics but rather the weathercasters' accompanying commentary that resulted in higher likelihoods of taking action. Second, the results could depend on the choice of the selected natural hazard. Several comments at the end of the survey pointed in that direction saying that rainfall is not dangerous, that irrelevant of being severe or non-severe rainfall makes the barbecue unpleasant or that also a non-severe warning remains a warning. This makes us believe that for a different hazard, which people perceive to be more threatening to their safety, there could be a negative effect of inconsistency in visualization alone, compared to message content, on evaluation of warning quality. Third, with respect to the ambiguous findings of research examining the effects of weather graphics on warning understanding and response (Casteel and Downing 2015), it may also be that there is simply no difference in effect between inconsistency in visualization and inconsistency in message content. Even though the research context is slightly different, the findings more or less support past studies (Broad et al. 2007; Casteel and Downing 2015; Joslyn and Savelli 2011) who found no effect of graphics, thus highlighting the equivocal influence of weather graphics on warning comprehension.

Moving beyond assessed quality, the research reported here also shows that inconsistency impacts decision-making. On the one hand, receiving consistent information resulted in a higher likelihood to engage in a risk minimizing behaviour (see H2a in Table 3). These findings reinforce earlier research that involved workshops with practitioners who underlined the need to agree on a single harmonized message (econcept AG 2011). In general, they support best practices in risk communication, which highlight the need to spread consistent messages and speak with one voice in order to lead to effective decision-making (e.g., NOAA, 2016) and they contradict Sandman (2006) who argues that consistency leads to worse decision-making. The findings documented here are also in line with findings in the context of climate forecasts, where inconsistency in forecasts has been identified as a cause for concern in terms of farmer's decision-making in response to climate change (Garrett et al. 2013; Bhatta and Aggarwal 2016). However, the results do not support other findings of Losee & Joslyn (2018), who showed that forecast inconsistency leads to a higher likelihood of taking risk mitigation action. This may be explained by the fact that this research did not focus on inconsistency in sequential warnings from one provider (and also not on risk mitigation actions), but on inconsistency in information from different weather providers at a given point in time. On the other hand, receiving consistent information resulted in a lower likelihood to search for more information compared to information inconsistent in visualization and/or message content (see H2b in Table 3). These findings reinforce Lindell & Perry (2012), who highlighted that conflicting messages delivered by multiple sources require searching for additional information to resolve the confusion.

Moreover, based on Sandman's (2006) argumentation, the hypothesis was made that the effect of visualization inconsistency will be more important than the effect of message content inconsistency alone on intended actions (see H2a and H2b in Table 3). Unlike for the evaluation of warning quality, the data confirm this trend and people with inconsistent information in message content were more likely to adopt a risk minimizing behaviour and less likely to resolve the ambiguity through searching more information than those with inconsistent information in visualization. This implies that visualisation inconsistency leads to less adaptive intended actions than message inconsistency. As it was explained earlier, inconsistency in message content may be a consequence of uncertainty in forecasting (weather model used and interpretation of data). So, it may be that Sandman is at least partially right and that subconsciously people understand the uncertainty in the provided information, pushing them to adopt their behaviour more often when warnings are inconsistent in message content compared to when they are not. This argumentation is also supported by other research suggesting that people prefer weather forecasts that expressed uncertainty to single-valued forecasts (Morss et al. 2008) or that forecasts with uncertainty can enhance the preparation of mitigation measures (LeClerc and Joslyn 2012). However, these conclusions have to be treated with caution, as the findings show no such pattern in participants' evaluation of warning quality.

Finally, these findings are relevant also in relation to the evaluation of single warnings. On the one hand, they indicate that when messages are consistent in visualization, people are more likely to rely on both messages together compared to messages that are inconsistent in visualization (see H3 in Table 3). This indicates an implicit association between graphics and reliance, and highlights the importance of visual salience (Severtson 2013; Wogalter et al. 2002). On the other hand, on average, in the inconsistent warning pairs, people relied less on warning B, C or D and evaluated them more negatively, compared to warning A (see H4a and H4b in Table 3). This indicates that people prefer (a) a 'flash-light' warning with 3 Categories over a warning with 5 Categories (in type AB) and (b) to be safe and stay with the worst-case scenario' (in type AC). Type AD confirms this speculation as again more people relied on warning A, 3 Categories and more severe on the category scale, compared to warning D, 5 Categories and less severe on the category scale. Although the contexts are somewhat different, part of the findings are confirmed by the research done by Losee et al. (2017) who found that participants were significantly more likely to take protective action when they saw a Category 5 hurricane warning compared to a Category 1 warning or by Losee & Joslyn (2018) who showed that greater forecast severity leads to greater trust in the forecast, because people "need them to be trustworthy" (Losee and Joslyn 2018) or because they just 'want to be on the safe side'. Moreover, the research documented here suggest that people prefer warnings with 3 Categories. Also, in other fields, e.g. road transportation or food labelling, traffic light systems have established themselves as they improved circulation flow, respectively the dietary intakes of consumers (Emrich et al. 2017). Thus, decision-makers should maybe consider the adoption of warning messages with 3 categories (such as yellow, orange, and red) as the population could be used to and intuitively understand such simple systems.

3.5) Conclusion

Several recommendations can be drawn from these results. First, at least in Switzerland, most people regularly consult weather information, primarily using smartphone applications. Almost two thirds of respondents, who regularly look for weather information, consult information from several providers, which indicates that they are aware of their existence and actively compare the available information. However, half of the people who have received warning information from different providers, indicate that these warnings were inconsistent. This highlights the importance of the problem addressed in this paper, which needs to be taken seriously into account by the public and private weather providers. Second, inconsistency in both – message content and visualization – has to be avoided as it shows to be the worst case. Thus, public and private weather providers should find at least an agreement to be consistent either in the message content or in the visualization. They need to work closer together and start a process of harmonization of warning messages. As Thorpe (2016) highlights, public-private partnerships could enable the whole weather enterprise to grow and produce more accurate and reliable weather forecasts. Therefore, the existing misunderstanding and mistrust about the respective roles of the public and private sector

(Thorpe 2016) (see, e.g., the recent successful lawsuit of private providers against the public provider DWD in Germany (ZEIT ONLINE 2017)) needs to be overcome and indeed things are slowly changing. At a European level, the '2016–2025 Strategy of the European NMHSs' highlights that "In response to the anticipated growth of the private meteorology sector, the distinct roles of the European NMHSs with respect to data collection, model development, research, warnings and alerts need to be established, while at the same time collaboration with the private sector is stimulated" (Thorpe 2016, p. 19). In Switzerland for instance, public and private weather providers are in a regular contact to improve the warning process and there are ongoing discussions on how warning information could become more consistent, especially with regards to visualization. Even though the breakthrough has not been reached yet, this study highlights the need to disseminate more consistent warning information than it is currently the case. To do so, agreeing on a similar visualization of warning messages (i.e. identical number of categories, thresholds and associated colours) seems to be doable, and could work for the private and public sector: MeteoSwiss would remain the official warning authority, while the private providers would continue to disseminate their own warnings based on their data, models and interpretations. As this paper shows that being consistent in either message content or visualization would significantly improve outcomes compared to inconsistent warnings in both (as it is currently the case), such an agreement would improve the warning process and, ultimately, the general public would strongly benefit from warning messages that are always consistent in visualization but could show some variety in message content.

The major shortcoming of this study (and also previous studies), is that the research relies on self-reported intended responses to a hypothetical situation, rather than a field observation of actual behaviour in response to an actual warning situation, even though some scholars argue that behavioural intentions are a good proxy for actual behavioural response (Ripberger et al. 2014a). In addition, an imagined situation suffers from a lack of real consequences for decisions and people might seek less risks in real-life decisions, as was pointed out also by Kox and Thieken (2017). Furthermore, the sampling technique may limit the generalizability of the findings reported in this paper. Moreover, evaluating different warning messages is somewhat subjective. As Casteel (2016) highlighted, a legitimate question to ask is what actually constitutes an effective response to warnings. Thus, it is important to remember that given the inherent uncertainty in severe weather events as well as the local conditions that can influence the weather, the most effective response may not always be the same action. Finally, as Losee & Joslyn (2018), the research reported here focussed on evaluation of quality of information when the sources are not mentioned and thus did not include the effect of source. However, source attribution was found to be an important determinant of perceived informational quality (Frewer and Shepherd 1994) and thus public reaction to warning messages may be determined by an interaction between source and inconsistency of information.

Future research is needed to address some of the limitations of this study. First, it would be interesting to investigate reactions to real inconsistent, and consistent, weather warnings, rather than using a simulated event. Recent research has shown that in a real-word crisis, feelings, and/or deliberative evaluation influence evacuation behaviours and intentions (McCaughey et al. submitted; Gutteling et al. 2017). Even though, results of such a study would be off high validity, it would also pose complicated methodological and potential ethical challenges, such as requiring public or private weather forecasters and providers to disseminate different messages during a dangerous situation. This message duplication may have the unintended side effect of reducing credibility and respondents' trust in the weather provider. Second, participants' evaluation of warning quality for type AB and AC does not necessarily translate into likelihoods to take intended action (as the effects are opposite, but not significant). Thus, future research should address the link between warning evaluation and response. Third, as the results also seem to undermine the power of visuals, more research is needed to resolve the ambiguity. Subsequent research could focus on different styles of warning messages (e.g. text-based versus image-based) and on different (more or less threatening) hazards to better depict the distinct effects of inconsistency in visualization and message content on warning evaluation and decision-making.

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4) Effectiveness of IBW in imagined situations

Effects of impact-based warnings and behavioural recommendations for extreme weather events

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Abstract
Bad weather continues to not only inflict damage on property, but kill and injure people, despite significant advances in the predictive power of meteorological warnings. There is evidence that people tend to under-react to weather warning information, to a large extent because of insufficient understanding of the impacts that severe weather events can have, as well as the appropriate response behaviour. A growing number of experts are suggesting that standard warning information should be augmented with additional information about these factors, but this has so far largely failed to take place. Past research studies have shown possible advantages of including impact-based warning (IBW's) and behavioural recommendations (BR's) into the warning information, but the results are in part ambiguous, due to a failure to have tested for effects of the two kinds of information separately and in combination. Based on quantitative results from a survey experiment in Switzerland, this knowledge gap is addressed. Results of the research reported here indicate significant benefits from providing both sets of information together, in terms of improving both perception of the threat and behavioural responses. When only one piece of information is given, BR's have a significant effect on both perception and response, whereas IBW's have a significant effect only on response. These findings offer empirical justification for the added expense and time associated with the more detailed hazard warnings.

4.1) Introduction

Bad weather and its downstream effects kill people, destroy property, and impoverish communities. This happens despite the best efforts of responsible National Meteorological and Hydrological Services (NMHS's) to provide accurate and timely disseminated warning information (WMO 2015b). In 2016, the number of people who reported to be affected by natural disasters worldwide (564.4 million) was the highest since 2006 – amounting to 1.5 times the 2006-15 annual average (224 million) – and almost 70,000 die each year (Guha-Sapir et al. 2017). In Europe, reported economic losses from extreme weather and climate related events over the 1980–2016 period amounted to € 436 billion (European Environment Agency 2017b). Losses may be even greater under future climate change, as nearly all extreme weather and climate related events are projected to change in their frequency, intensity, spatial extent, duration, and timing (IPCC 2012). Along with climate change, socio-economic developments such as growing population and economic wealth, developments in hazard-prone areas, and degradation of natural ecosystems will influence the exposure and

vulnerability of many regions, across the world and in Europe (European Environment Agency 2017a).

In response, NMHS's have improved their capacity to forecast high impact weather events, with growing precision in terms of both the hazard and the impacts. The second half of the twentieth century witnessed improvement in the quality, quantity and availability of weather and climate information, including forecasts, warning and advisory services (WMO 2015a). Enhanced technology, making use of real time data collection and capability of modelling and dissemination of information have given rise to warning systems that are becoming increasingly sophisticated (Aitsi-Selmi et al. 2016). Thus, forecasts are being made with greater accuracy, geographic precision, and lead time, which allows people at risk to take appropriate protective action. Simultaneously, advances in computer simulation and modelling have it made possible to also include information about the underlying hazards, as well as about the exposure of the population, so that warning information could truly inform response (Aitsi-Selmi et al. 2016).

However, there is a growing list of documented cases where people do not respond to these warnings. For example in 2013, Tropical Cyclone Haiyan struck the Philippines as a category 5 storm, causing many causalities on top of severe damage to infrastructures and agriculture. A post-typhoon expert mission report by the World Meteorological Organization (WMO) highlighted that accurate warnings were issued on time by the meteorological agency for heavy rains and wind, and the government deployed preparedness plans (WMO 2015b). However, in the communities at risk, the low level of knowledge, especially about the storm surge, hindered or delayed evacuations from areas hit by the cyclone. In developed countries as well, there are documented cases of people failing to take appropriate protective behaviour, with severe consequences. In 2012, Superstorm Sandy was preceded by accurate forecasts and timely disseminated warnings, but many people failed to take appropriate behaviours that experts were hoping to see (National Academies of Sciences 2017). During deadly tornado outbreaks in Oklahoma in 2013, thousands of people fled their homes in cars despite years of messaging about the dangers of encountering storms in a vehicle (National Academies of Sciences 2017). Thus, an area for improving outcomes is in terms of improving responses.

Some research has examined how responses could be improved by making it easier or more desirable for people to take self-protective behaviour. For example, Sharma and Patt (2012) examined in coastal India the decision to evacuate to cyclone shelters in response to warnings; they found that prior experience with the comfort and quality of the shelter, as well as with loss of property due to crime in the villages being evacuated, were major determinants of self-protective behaviour. Other research has focused on the psychological factors that determine whether people are motivated to protect themselves at all, and hence how warnings could address these factors (e.g., Lindell and Perry 2012; Slovic et al. 2007). In

studies of Germans' decisions to protect themselves from river flooding events, researchers found people's subjective self-confidence in their ability to protect themselves to make a larger difference than objective indicators – such as wealth or access to information (Grothmann and Patt 2005b; Grothmann and Reusswig 2006). As individual characteristics of the population receiving the warning affect warning response, targeting warning messages on the basis of these social or knowledge characteristics is another possibility (Mileti and Sorensen 1990). But perhaps the simplest change would be to alter the content of the warnings themselves, providing different information about the hazard that is predicted, the effects of that hazard, and ways for people to protect themselves. Mileti and Sorensen (1990) proposed that warning messages ought to contain five information elements – hazard, location, guidance, time, and source – in order to be more helpful. Mileti and Peek (2000) reiterated that effective warning messages should include clear, specific, accurate, certain, and consistent information. At the same time, however, there has been little empirical study examining the relative importance of these different factors, particularly in the case of short-term forecasts of high-impact weather events.

In this paper we focus on the separate and combined effects of including behavioural recommendations (BR's) and impact-based warnings (IBW's) in the information reaching the general public. BR's tell people what actions they should take (or avoid) to maximize their health and safety (Bean et al. 2015). IBW's are designed to express the expected impacts as a result of the expected weather and provide people with more information about the hazard and particularly its impacts (WMO 2015b; Casteel 2016). Including this information comes at some potential cost, both to the agency issuing the warning (which needs to analyse these factors) and to the audience (which needs to take the time to listen to them); neither is currently common practice. To justify the added costs of either or both measures, there is a need to empirically test whether BR's and IBW's, both separately and in combination, affect the perception of and behavioural response to warning information. We hypothesize that both IBW's and BR's, separately or in combination, could increase the likelihood with which people take action. We fill important empirical gaps in the literature and show a large potential for improvements in warning design to lead to greater appreciation of danger and taking of protective actions.

4.2) Background

The standard practice in high impact weather warnings is to describe only the hazard. Current standard warnings (SW's) focus on the weather phenomenon itself, rather than the potential effects of the event. Even though some NMHS's (and also the WMO) have started to put greater emphasis on the so-called IBW's, there are many reasons accounting for the continued dominant position of SW's in weather communication. First, SW's require less effort and resources to prepare, for instance in the coordination between meteorological offices and agencies that are entrusted with protecting public safety, such as police and fire departments, which have greater knowledge of local circumstances, such as specific vulnerabilities (e.g. to flash floods) or evacuation routes. Second, by only focussing on

describing the hazard itself (i.e., type of hazard, severity, timing, and location), NMHS's avoid information overload. Third, SW's guarantee less risk of giving specific information that is wrong to the user. Finally, without giving clear impact information and BR's, NMHS's avoid criticism of being paternalistic.

At the same time, however, there is an extensive literature documenting the dangers of NMHS's assuming users to have the ability to translate hazard forecasts into appropriate actions, and suggesting that it is important to have a "fit" between the information and users' actual knowledge (Orlove and Tosteson 1999). Based on the growing list of documented cases where people do not respond to the standard phenomenon-based warnings, the WMO has speculated that some of the human losses are due to people's inadequate understanding of the warnings; their background knowledge is less than what would be needed to fully understand the SW's that NMHS's are communicating (WMO 2015b). Thus, people lack knowledge that is needed to translate the information on the weather phenomenon into an appraisal of risk. As Mileti and Peek (2000) have noted, "It cannot be assumed that the public will know what would constitute an appropriate protective action." In a study on public response to an earthquake warning, Mileti and Darlington (1997) found that the more informative the guidance a person received in a warning message, the more likely they were to respond to it. Likewise, it cannot be assumed that the public will know the impacts severe weather can have as they may not be familiar with some types of hazards or its respective severities. Previous research underlines that in order to be effective, warnings should underline the exact nature of the threat (Mileti and Sorensen 1990), provide a source of confirmation (Lindell and Perry 2012), and be personally relevant (Mileti 1999). IBW's take all this into account.

There has been a growing suspicion within the expert community that providing more specific information would be beneficial in the specific case of high impact weather warnings, but very little empirical testing of this. Based on qualitative interviews with forecasters, emergency managers and broadcast meteorologists, Losego et al. (2013) and Harrison et al. (2014) identified a belief in the value of IBW's coming on top of standard warning information. There are four studies that provide quantitative evidence that this is the case, but all have their shortcoming.

The first study was by Perreault et al. (2014). They primarily investigated the effects of using fear-inducing language to describe tornados, although that language also included a brief mention of impacts and BR's. Thus, they investigated the additive effect of IBW's. In more detail, they tested the effectiveness by showing participants four different experimental stimuli: regular TV warning messages, new scary TV warning messages, regular radio warning messages, and new scary radio warning messages, and observed that behavioural intentions were not affected by any of the experimental stimuli. Moreover, they found that regular warning messages were perceived as more credible than the impact-based messages. In sum, they found no effect of IBW's on credibility and no effects on behavioural response. However,

they left open the effects of IBW's on other perception attributes, as well as the effects of BR's on behavioural response.

The second study was by Ripberger et al. (2014). They used a randomized controlled survey design (administered twice in 2012 and 2013), considering hypothetical tornado warnings. They assessed the influence of IBW's, with different levels of tornado severity, on warning response. They found that for the weaker tornado categories (i.e. the first three categories out of six), IBW's improved behavioural response. Moreover, they showed that heightened knowledge of the hazard increases the probability that an individual will take protective action when a warning is being disseminated. However, they left unresolved the effects of BR's, and also of IBW's on perception.

The third study was by Casteel (2016). He used a randomized control survey design, focusing on tornado warnings as a case, with respondents in the hypothetical role of a factory operator having to decide whether to order workers to take shelter, in response to two types of warnings, IBW's and SW's. He included the BR's to seek shelter in all warnings and investigated the additive effect of IBW's. He found that decisions did not significantly differ between the IBW's and the SW's at decision point 1 (occurring when the two versions of the warning presented the same information). However, at points 2 (when hazard, source and impact information was presented in the IBW's, but absent in the SW's) and 3 (at the end of the warnings), IBW's produced higher likelihoods of sheltering in place compared to SW's. Thus, he found the additive effect of IBW's and BR's to have an influence on the behavioural response. He also tried to account for knowledge differences but found that the pattern of response did not differ between the two groups that were studied – undergraduate students in psychology or communication and graduate students in emergency management – suggesting that the enhanced text used in the IBW's is clear and understandable to a large audience. His study left open the effects of BR's, and also of IBW's on perception. As participants were only students, the generalization of results is also questionable.

The fourth study has been by Potter et al. (2018). They conducted an online survey in New Zealand to investigate the publics' perceptions and intended protective actions in a hypothetical severe weather event involving strong winds. They examined the effects of adding impact information to warnings lacking BR's and examined the effects on both perception and behavioural response. They found an effect of IBW's on perception. The authors reported that IBW's make it easier to understand possible effects of the weather event, make the event more threatening, and make recipients more concerned about the event, in comparison to those who received SW's. However, they reported that there was no significant difference in perceptions of credibility of the message. Regarding behavioural response, they found an effect of IBW's on information seeking behaviour. Interestingly, participants who received the IBW's were significantly more likely to state that they would check other information sources for confirmation or advice, than those who received SW's. They also found an effect of decreasing the rate of taking non-protective behaviour. People

who received SW's were more likely to "do nothing differently" (i.e. to engage in a dangerous behaviour) than those people who received IBW's. However, they did not find an effect of IBW's on increasing actual protective behaviour. They leave open the effects of BR's. Moreover, the positive protective actions they investigated, for which they found no significant effect of IBW's, were primarily geared towards mitigating damage to property (such as drive more carefully or secure loose items), and also avoid possible high-risk activities (such as avoid outdoor work or activities), rather than actively seeking safety for oneself. This leaves open the question whether such behaviour would also not be affected by IBW's.

Following these studies, then, two questions remain ambiguous or unexamined. First, do both BR's and IBW's have effects, and what are their relative magnitudes? Second, are effects to be found on both perception and behavioural response? As we describe in the next section, we answer these questions with a multi-method study in Switzerland, focusing on people's responses to warnings of severe thunderstorms.

4.3) Methods

Our primary method was a large sample randomized control survey, where we tested for the separate and combined effects of IBW's and BR's on perception and behavioural response. We also supplemented this with qualitative interviews with experts in the same country, to verify that there is a perception in that expert community of the importance of IBW's and/or BR's, and also to see if our survey results in any way contradicted expert belief.

We conducted the survey in our home country of Switzerland, and focused it on thunderstorms, an important high impact event in Switzerland (BABS 2015). These storms develop rapidly and can be destructive and deadly. In Switzerland, each year people get harmed or killed by lightning strikes (e.g., Schweiz am Wochenende 2014; Blick 2005). Thunderstorms also often evolve with substantial variability and uncertainty in impacts. Beside hail and lightning strikes, flash flooding can be a significant source of danger, especially in small mountain creeks or heavily urbanized and sealed surfaces, and cause significant damage (e.g., Tagesanzeiger 2017). In spite of the most up-to-date tools and methods, it is currently not possible to issue several hours' warnings of the strength, timing and location of severe thunderstorms (MeteoSwiss 2018b). Thus, timely warning and protective decision-making are critical in case of a thunderstorm threat and, in particular, effective communication of actionable information about the hazard.

For the qualitative piece, we conducted 16 several semi-structured interviews with stakeholders involved in the natural hazard warning chain in Switzerland. We focussed on the interviewees' expertise and perspectives on the hydro-meteorological information process, the economic framework for information processing and the evaluation of information. We selected the interviewees on the basis of their experience and knowledge of the warning system. They included officials in MeteoSwiss and in other organizations dealing with risk and

emergency management at cantonal and federal level, together with university professors, research institute leaders, insurance companies, and private sector meteorology.

For the quantitative element, we conducted a survey containing 22 questions based on a decision scenario. The thunderstorm scenario was placed at the beginning of the survey. Respondents were asked to imagine that it is 2pm on a Sunday and that they would be walking in the countryside in the foothills of the Jura Mountains, when they get a thunderstorm warning message on their smartphone. While we considered and pre-tested many options for the hypothetical scenario (moving an outdoor picnic indoors, taking a bicycle to work, going for a walk in the woods, etc.), we used the "hiking" scenario because it (a) was simple, straightforward, and realistic, (b) forced people to face a real threat taking them out of their comfort zone, and (c) required people to make the decisions on their own (unlike in a scenario at work, where the employer could interfere).

We randomly assigned respondents to one of four warnings types described in Table 1 (SW; SW with BR; IBW; IBW with BR), achieving roughly even subgroups out of the total sample size of 1,219. Table 2 describes the specific messages for the separate groups. These were based on current warning information of MeteoSwiss (element A in Table 2) and adapted with publicly available information (elements B and C), that is provided on the MeteoSwiss website (http://www.meteoswiss.admin.ch) and the Natural Hazards Portal (http://www.natural-hazards.ch), which is run by a consortium of federal agencies. Experts (forecasters and other staff of MeteoSwiss) had reviewed the warning messages for plausibility. Thus, the messages reflect reality and could be disseminated in a similar form and content (given the same hazard severity) in the near future.

Table 1. Four warning types

		Behavioural recommendations	
		No	Yes
Impact information	No	SW (standard warning)	SW + B (standard warning plus behavioural recommendations)
	Yes	IBW (impact-based warning)	IBW + B (impact-based warning plus behavioural recommendations)

Table 2. Four different thunderstorm warning messages.

SW	**SW+B**	**IBW**	**IBW+B**
A	A, and C	A, and B	A, B, and C

A

Thunderstorm; Severity; Category 4
Validity: 24.08.2017, 2.30pm – 24.08.2017, 6pm

- Type of thunderstorm: Thunderstorm line
- Movement: pulling from Southwest
- Particularly affected areas: Pre-Alps
- Accompanying factors: wind gusts >120km/h, hail 2-4cm, heavy rain >50mm/h

B

Thunderstorm: In the case of rapidly developing thunderstorms, you have to expect strong wind gusts, as well as hail. Heavy wind often occurs before lightning activity and heavy rain showers.
Source: Radar images
Possible Impacts:

- Flash flooding of streams
- Toppling of trees
- Possibility of landslides on steep slopes
- Damage from hail and lightning strikes
- Failure of drainage and sewer systems. Flooding of underpasses, underground garages and cellars
- Disruption to road, rail and traffic
- Danger to vessels on lakes from very strong gusts of wind arising rapidly without warning

C

General recommendations during a thunderstorm:

- Avoid mountain ridges, exposed trees, groups of trees, masts and towers, all of which are at risk of lightning strikes
- Seek shelter – in a building or car (acts as a Faraday cage)
- If there is no shelter in sight, assume a crouched position
- Do not go hiking in the mountains and renounce to all outdoor activities
- Stay away from metal objects and water
- If a thunderstorm takes you by surprise when swimming, get out of the water immediately
- Drive slowly on flooded stretches of road, or avoid these altogether
- Avoid stream beds and steeply inclined slopes

Note: As described in the text, SW's indicate standard warnings', IBW's indicate impact-based warnings' and BR's indicate behavioural recommendations.

We asked questions on two sets of dependent variables: perception and behavioural response. Perception included five attributes: "The warning is clear and easy to understand"; "I believe the message to be credible"; "The warning makes me concerned for my safety"; "Based on the warning I understand the threats to my safety"; "Based on the warning it is clear to me how I should modify my behaviour, if necessary". The five behavioural responses included one protective action "I immediately interrupt the hike and take care of my safety", two non-protective actions "I would not alter my plans because of the information" and "I continue with the hike, but avoid potential dangers and make sure that a suitable shelter can

always be reached quickly", as well as two information seeking behaviours "I check out other information sources via my smartphone for confirmation or advice" and "I pay close attention to the sky, wind, and sounds of possible thunder". Participants indicated how much they agreed or disagreed on a five-point Likert scale from 'totally disagree' to 'totally agree' with each of these positively framed statements. We also gathered data on personal factors including risk perception, experience, knowledge, and other social and demographic factors. The full questionnaire is available as supplemental material.

The 1,219 respondents completed the survey from 23rd November to 2nd December 2017. Because of unrealistically short answering times, we excluded answers of 98 respondents from analysis leading to 1,121 respondents. We conducted the survey (in German) with a representative sample of the Swiss population in the German-speaking cantons. Respondents ranged in age from 15 to 86 years (M = 48.54, SD = 16.40), and n = 591 (52.7%) were female. The majority of respondents completed vocational school (44.4%, n = 498), followed by college or university education (17.8%, n = 200), with 7% indicating at least some compulsory education. Compared to the average Swiss population, the sample was slightly older than the average (M = 43.14 years), representative for the gender ratio of female (50.5%) and male (49.5%) (FSO 2017a) and slightly more educated than the Swiss population (more respondents with higher vocational training or university degree and fewer respondents with only completed compulsory school) (FSO 2017b).

We performed the data analysis using standard software used for statistical analysis in social science. We conducted one-way analyses of variances (ANOVAs) to study the effects of IBW's and BR's on behavioural response and respondents' perception of warning information. An average sample of n=280 respondents per experimental condition satisfied requirements for ANOVA. Moreover, we conducted one-way ANCOVAs to include risk perception, knowledge, experience with warnings, and with thunderstorms, as well as relevant demographic variables (age, gender, education, urban/rural) as a covariant. In a further step, we realized a series of two-way ANOVAs to study possible interaction effects of warning type and knowledge, respectively experience (as well as the socio-demographic variables) on the dependent variables mentioned above. In addition, we conducted a series of Multiple Regression Analyses to investigate the effects of perceptions regarding the warning information, along with other variables depicted below, on taking immediate protective action.

4.4) Results

Qualitative interviews with experts involved in the natural hazard warning chain underlined the suspicion within the expert community that providing more specific information would be beneficial in the specific case of high impact weather warnings. The majority of the stakeholders thought that IBW's and BR's may be especially helpful for the public and increase the overall understanding and right interpretation of warnings. They thought that in order to be helpful in taking appropriate actions, warnings should focus on "impacts and

recommendations, instead of warning categories". In addition, they highlighted the need for IBW's and BR's in order to help people understand the difference between different warning levels. Many experts also depicted the problems with current warnings and the potential benefits of IBW's and BR's in describing a frequent wrong behaviour during thunderstorms: most people do not know that thunderstorms are often accompanied by hail and if so, they believe that one has to protect the window from the hail and therefore let the shutter down, although the opposite reaction would be the right one (metal shutters, which can dent, are more often damaged by hail than are glass windows). Thus, information should focus on IBW's and BR's, instead of on the weather phenomenon itself and the respective warning category. However, the experts also raised two main concerns. First, a message that presents too general information regarding impacts and behavioural recommendations ridicules the warning and thus could lead recipients to ignore it. Second, too much information might overwhelm the recipients and people may not understand it.

Moving to the quantitative results from the survey instrument, we start by examining the relationship between warning type and the perception variables. Figure 1 shows effects IBW's and BR's on all five perception attributes, and these are very similar: warning perception is lowest among those who received SW's and highest among those who received IBW's with BR's, whereas SW's with BR's perform better in terms of perception than IBW's without BR's. In general, the effect of warning type was highly significant on all five variables: clarity of information, $F(3, 1105) = 7.32$, $p<.001$, $r=0.14$; credibility of information, $F(3, 1103) = 3.96$, $p=.008$, $r=0.1$; level of concern, $F(3, 1117) = 7.65$, $p<.001$, $r=0.14$; understanding of threats to participants' safety, $F(3, 1112) = 15.41$, $p<.001$, $r=0.2$; understanding how to respond to the information, $F(3, 1109) = 19.16$, $p<.001$, $r=0.22$ (using the Holm-Bonferroni method to control for the familywise error rate for multiple hypothesis tests). Likewise, we also observed highly significant linear trends.

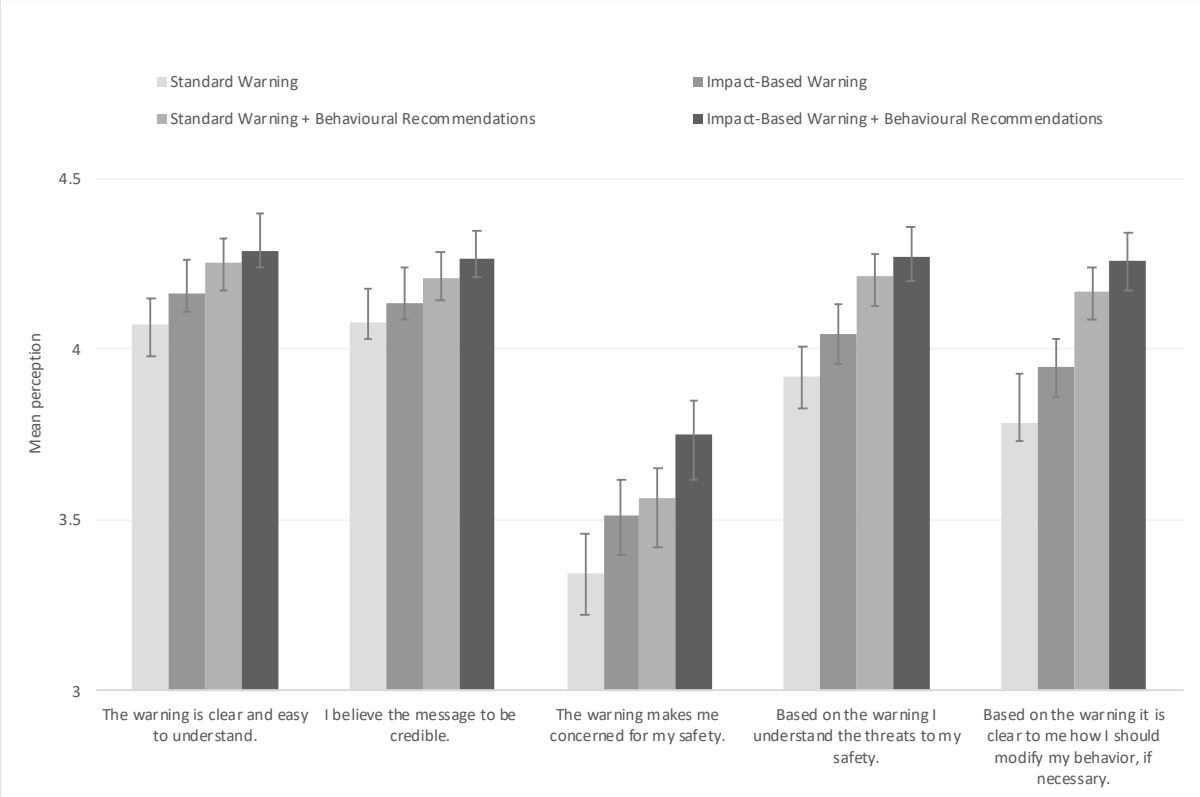

Figure 1. Mean perception of warning information for all four warning types. Bars indicate how much participants agreed or disagreed on a five-point Likert scale from 'totally disagree' to 'totally agree' with each of the five perception attributes. Error bars indicate the 95% confidence interval.

As we document in more detail in Table 3, for all the five variables, planned contrasts revealed that those participants who received SW's reported the information less clear and easy to understand, less credible, as well as recipients were less concerned about their safety, less understood the threats to their safety, and how to respond to the information compared to those who received a warning with information about behavioural recommendations or impacts or both. As an additional test, Bonferroni post-hoc testing showed that respondents who received the SW's reported finding the warning less clear (M=4.07, SD=0.73), and understood the threats to their safety (M=3.92, SD=0.76) and how to respond to the warning (M=3.83, SD=0.84) compared to those who received the SW's + BR's (M=4.25, SD=0.61), p=0.01, respectively (M=4.21, SD=0.63), p<0.001, and M=4.17, SD=0.66), p<0.001. Thus, there is an individual effect of BR's on these 3 perception attributes. We also found an additive effect of BR's and IBW's on improving perception across all five attributes as shown in Table 4.

Table 3. Effects of IBW's and BR's on perception of warning information.

Measure	Contrast 1				Contrast 2			
	SW's	Average SW's +BR's, IBW's, IBW's +BR's	t (df)	Cohen's d	IBW's	Average SW's +BR's, IBW's +BR's	t (df)	Cohen's d
	M (SD)	M (SD)			M (SD)	M (SD)		
Understand perception	4.07 (0.73)	4.26 (0.64)	3.96*** (1105)	0.28	4.19 (0.63)	4.29 (0.64)	2.14* (1105)	0.15
Credibility perception	4.1 (0.62)	4.22 (0.61)	2.7** (1103)	0.18	4.17 (0.63)	4.25 (0.61)	1.68 (1103)	0.13
Concern perception	3.34 (1.02)	3.6 (0.96)	3.76*** (1117)	0.26	3.5 (0.95)	3.63 (0.97)	1.77 (1117)	0.14
Threat perception	3.92 (0.76)	4.18 (0.67)	5.41*** (1112)	0.36	4.05 (0.73)	4.25 (0.64)	3.98*** (1112)	0.29
Behavioural response perception	3.83 (0.84)	4.12 (0.7)	5.65*** (1109)	0.38	3.95 (0.74)	4.22 (0.69)	4.9*** (1109)	0.38

Note: *p<.05, **p<.01, ***p<.001. M indicates the mean and SD the standard deviation. As described in the text, SW's indicate standard warnings', IBW's indicate impact-based warnings' and BR's indicate behavioural recommendations.

Table 4: Additive effect of BR's and IBW's on perception of warning information.

Measure	SW's (*M, SD*)	IBW's + BR's (*M, SD*)	p-value
Understand perception	M=4.07, SD=0.73	M=4.33, SD=0.66	p<.001
Credibility perception	M=4.11, SD=0.62	M=4.28, SD=0.61	p<.001
Concern perception	M=3.34, SD=1.02	M=3.74, SD=0.96	p<.001
Threat perception	M=3.92, SD=0.76	M=4.29, SD=0.64	p<.001
Behavioural response perception	M=3.83, SD=0.84	M=4.26, SD=0.71	p<.001

Note: M indicates the mean and SD the standard deviation. As described in the text, SW's indicate standard warnings', IBW's indicate impact-based warnings' and BR's indicate behavioural recommendations.

Similarly, for the second contrast in Table 3, participants who received IBW's reported the information less clear, less easy to understand, they less understood the threats to their safety and how to respond to the information, compared to those who received a warning with information about behavioural recommendations. As an additional test, Bonferroni post-hoc testing showed that respondents who received the IBW's were less concerned ***(***M=3.5, SD=0.95)**,** less understood the threats to their safety (M=4.05, SD=0.73) and how to respond

to the warning (M=3.95, SD=0.74) compared to those who received the IBW's + BR's, p=.037, respectively, p<0.001, and p<0.001 (M and SD in Table 4). These findings confirm that there is an effect of BR's on 3 perception attributes. Moreover, we find that those who received the SW's + BR's better understood the threats to their safety (M=4.21, SD=0.63) and how to respond than those who received IBW's (M=4.05, SD=0.73), p=.03, respectively (M=3.95, SD=0.74), p=.003.

The third planned contrast, comparing SW's + BR's to IBW's + BR's, was non-significant for four of the five variables, but the concern perception (SW's + BR's (M=3.54, SD=0.98) versus IBW's + BR's (M=3.74, SD=0.96), p=.014). Thus, this indicates that there is an effect of IBW's on feelings of concern evoked by the warnings. Including thunderstorm knowledge, warning and thunderstorm experiences, as well as socio-demographic variables as a covariant did not alter the significance of the differences in warning type.

Table 5: Multiple linear regression with the protective behaviour "interrupt the hike" as the pendent variable.

	B	SE B	β
Constant	1.419	.273	
Gender (male=0; female=1)	.056	.034	.057
Age (yr)	.002	.002	.035
Education level	-.045	.020	-.078
Living area (rural=0; urban=1)	-.027	.033	-.028
Risk perception (1-5 scale)	**.058**	**.016**	**.128*** **
Thunderstorm experience (no, don't know=0; yes=1)	-.023	.021	-.039
Warning experience (scale from only bad=0 to only good=1)	.088	.059	.054
Warning reaction (no=0; yes=1)	**.298**	**.073**	**.149*** **
Thunderstorm knowledge (scale from none=0 to full=1)	-.220	.179	-.043
Understand perception (1-5 scale)	-.028	.061	-.021
Credibility perception (1-5 scale)	**.166**	**.061**	**.119** **
Concern perception (1-5 scale)	**.334**	**.038**	**.343*** **
Threat perception (1-5 scale)	**.193**	**.063**	**.146** **
Behavioural response perception (1-5 scale)	-.083	.055	-.069

Note: R^2=0.33 (p<.001). **p<.01, ***p<.001. We controlled for the familywise error rate for multiple hypothesis tests by using the Holm-Bonferroni method. Significant results are in bold. B indicates the unstandardized coefficients, SE the standard error and β the standardized coefficients.

The next set of relationships we examined was between perception and action. Three of the perception attributes correlate with taking protective action. Table 5 shows that irrespective of warning type received, perceptions of credibility, threat and concern influence taking protective action, as do risk perception and whether people have already taken action in response to warnings in the past. First, the higher the risk perception, the higher the

likelihood to interrupt the hike (a unit increase in thunderstorm perception, meaning that they are perceived more severe, predicted a 0.058 unit increase in interrupting the hike). Second, when people already reacted to warnings in the past, they are more likely to interrupt the hike (by 0.298 compared to people who have not reacted). Moreover, three of the five perception variables of information showed significant effects: believing the message to be credible (β=0.119), being concerned about one's safety (β=0.343) and understanding the threats (β=0.146).

Finally, we examined the relationships between warning type and action. The upper line in Figure 2 represents the immediate protective behaviour "interrupt the hike" and shows a linear trend, F (1, 1117) = 18.94, p<.001, r=0.13, indicating that as the warnings provide more information, the likelihood to stop the hike increased proportionately, whereas IBW's alone have a greater effect than BR's alone on taking immediate protective action. The effect of warning type was significant, F (3, 1108) = 6.8, p<.001, r=0.13. Planned contrasts revealed that those participants who received a SW's (M=3.86 SD=1.05) reported being less likely to interrupt the hike than those who received a warning with information about behavioural recommendations or impacts or both (M=4.06, SD=0.93), t (1108) = 2.93, p=0.004, Cohen's d= 1.31. As an additional test, Bonferroni post-hoc testing showed that respondents who received the SW's (M=3.86 SD=1.05) had a significantly lower likelihood to interrupt the hike compared to those receiving IBW's + BR's (M=4.22, SD=0.85), p<.001. Thus, there is an additive effect of BR's and IBW's on taking protective action. The second planned contrast showed that those people who received the SW's + BR's (M=3.95, SD=1) were less likely to interrupt the hike than those who received either one of the IBW's (M=4.11, SD=0.88), t (1108) = 2.39, p=0.017, Cohen's d=0.18. According to Bonferroni post-hoc testing, respondents who received the SW's + BR's (M=4.06, SD=0.93) had a significantly lower likelihood to interrupt the hike compared to those received the IBW's + BR's (M=4.22, SD=0.85), p=.005. Thus, there is an individual effect of IBW's on taking protective action. Finally, in the last contrast, we observed IBW's with BR's (M=4.22, SD=0.85) to result in an even higher likelihood to interrupt the hike compared to IBW's without BR's (M=4.01, SD=0.91), t (1108) = 2.53, p=0.012, Cohen's d=0.23. Thus, there is an effect of BR's on taking protective action.

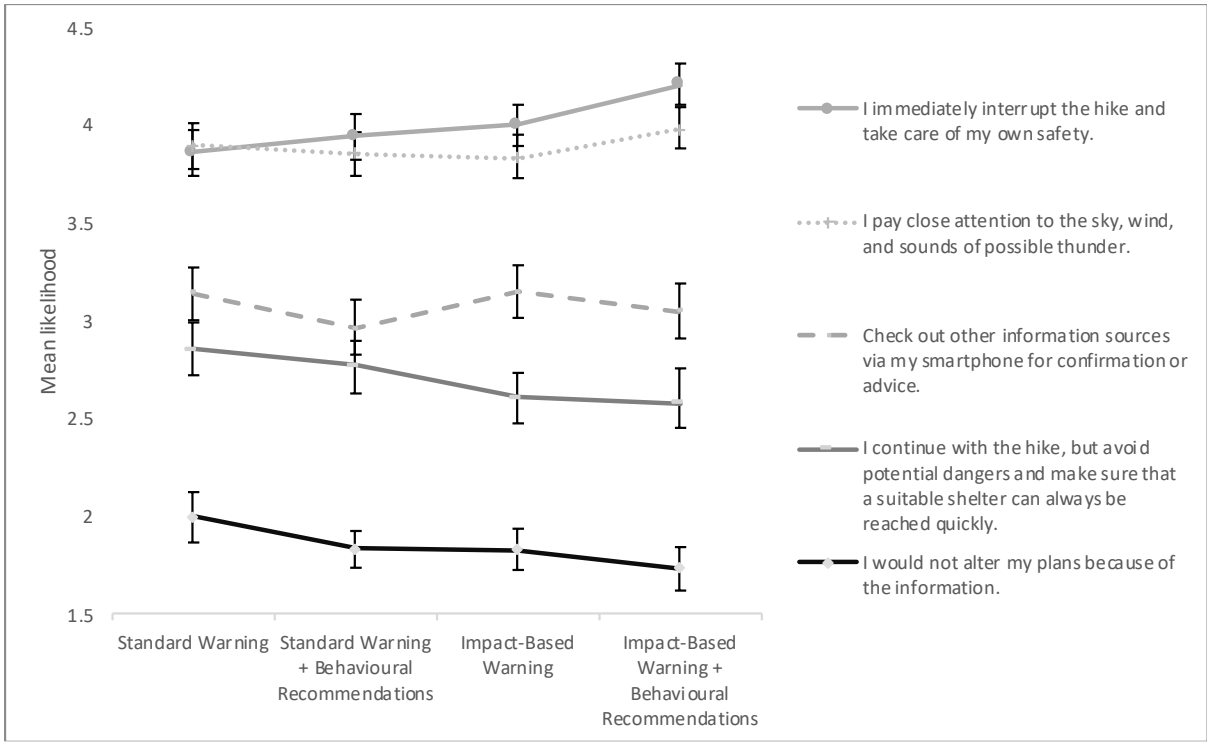

Figure 2. Mean likelihood to engage in different behaviours for all four warning types. Lines indicate how much participants agreed or disagreed on a five-point Likert scale from 'totally disagree' to 'totally agree' with each of the five behavioural responses. Solid lines represent (non-)protective actions, dashed lines represent information seeking actions. Error bars indicate the 95% confidence interval.

The non-protective behaviours "not alter plans" and "continue the hike but avoid potential dangers" (i.e. to engage in dangerous behaviours) are represented by the two bottom lines in Figure 2. Results show that the people who received SW's are more likely to engage in a dangerous behaviour than those people receiving SW's + BR's, IBW's or IBW's + BR's, and that those who receive IBW's + BR's are least likely to not change plans. While the effect of warning type was significant for the non-protective behaviour "do not alter plans", $F(3, 1093) = 3.95$, $p=.032$, $r=0.1$ (with a significant linear trend, $F(1, 1093) = 10.38$, $p=.001$, $r=0.1$), planned contrasts showed that compared to SW's ($M=2$, $SD=1.04$) having any extra information in the warnings (so either BR's or IBW's or both) ($M=1.8$, $SD=0.87$) significantly decreased the likelihood to not alter plans, $t(1093) = -3.11$, $p=0.002$, Cohen's $d=0.21$. As an additional test, Bonferroni post-hoc testing revealed that respondents who received the SW's ($M = 2$, $SD = 1.04$) had a significantly higher likelihood to not alter plans compared to those who received IBW's + BR's ($M = 1.74$, $SD = 0.9$), $p=.004$. Thus, there is an additive effect of BR's and IBW's on avoiding non-protective behaviour. When controlling for the familywise error rate using the Holm-Bonferroni method, the effect of warning type on the other non-protective behaviour "continue the hike but avoid potential dangers" became insignificant, $F(3, 1117) = 2.87$, $p=.105$, $r=0.09$.

Third, the dashed lines in Figure 2 show the changes in the two information seeking behaviours "check out other information sources" and "pay close attention to the environment". IBW's and BR's had no effect on whether participants were more or less likely to seek information, $F(3, 1117) = 1.49$, $p=.215$, respectively $F(3, 1117) = 1.27$, $p=.283$.

Including thunderstorm knowledge, warning and thunderstorm experiences, as well as socio-demographic variables as a covariant did not alter the significance of the differences in warning type. Moreover, two-way ANOVAs showed no significant interaction effects between warning type and these individual characteristics of participants.

4.5) Discussion

Impact-based warning and behavioural recommendations both increase warning perception and improve behavioural response, with effects that are additive. The ordering between IBW's and BR's differed according to perception or behavioural response. BR's alone have a greater effect than IBW's alone in increasing perception, whereas IBW's alone have a greater effect than BR's in promoting behavioural response.

Our study of warning perception included five attributes (understanding, credibility, concern, threat, and response), three of which correlate with taking protective action. Irrespective of warning type received, perceptions of credibility, threat and concern influence taking protective action, as do risk perception and whether people have already taken action in response to warnings in the past. These findings more or less confirm the results of Potter et al. (2018). Recommendations for practitioners that can be derived from these findings are that they have to make sure that people believe in the warning message, and that these warnings evoke feelings of concern and make people understand the threats to their safety, which can be stimulated by including additional impact and/or behavioural information into the warnings.

The combined effects of IBW's and BR's are on all five perception attributes. When only one piece of information is given, BR's have a significant effect, but IBW's do not. First, we found an individual, but overall non-significant effect of IBW's (except for perceptions of concern). This finding does not support the findings of Potter et al. (2018), as they identified a significant effect of IBW's alone on perception. Second, and moving beyond Potter et al. (2018), we found an individual, significant effect of BR's. Recipients of warnings that included information about BR's reported finding the warning clearer and easier to understand, than recipients of warnings without these recommendations. They were also more concerned about their safety, and better understood the threats to their safety and behaviours to engage in. Finally, IBW's and BR's together had the greatest effect on improving perception (on all five attributes).

Behavioural responses included taking immediate protective action, continuing with non-protective actions, and also seeking information actions. There were individual and additive effects of both IBW's and BR's on the positive action, a combined effect of IBW's and BR's on negative actions, and no effect on seeking information actions. First, we observed IBW's – with or without BR's – to result in a higher likelihood of taking immediate protective action compared to SW's both with and without BR's. These findings complement the results of Ripberger et al. (2014) and of Casteel (2016), but contradict with findings of Perreault et al. (2014) and Potter et al. (2018), who found no significant difference in taking protective actions. In this way, we resolve an ambiguity in the literature, given the issues we have identified about the validity of the latter two studies' findings, our results suggest them to be invalid for the reasons identified earlier. At the same time, we also observed IBW's with BR's to result in an even higher likelihood of taking positive action compared to IBW's without BR's. Second, we found that recipients of SW's were more likely to not alter plans compared to the other three warnings with enhanced information and especially those with IBW's + BR's, which confirms earlier findings of Potter et al. (2018). Third, unlike Potter et al. (2018), we found no significant effect of IBW's or BR's on seeking more (or less) information. This may be due to the fact that BR's, which add more information, were absent in the warning messages used in the study of Potter et al. (2018). In sum, if practitioners expect recipients of warning information to take immediate protective actions (i.e. to evacuate an area), then they should focus on disseminating information that contains both, IBW's and BR's (e.g. in very severe weather warnings).

Differences between individuals (risk perception, personal experience with weather hazards, level of knowledge about weather hazards, age, education, gender, urban/rural) had no significant interaction effects on either perception or behavioural response. This complements the results of Casteel (2016) who found that knowledge had no effect on decision-making in response to warnings. It suggests that a general finding in the risk communication literature (e.g., Mileti and Sorensen 1990) – that these social, knowledge and psychological characteristics of the population receiving the warning affect warning response – may not apply in the case of high impact weather events.

The consequences of our results for practitioners are twofold. First, they are an encouraging sign as they suggest that IBW's and BR's are clear and understandable, as well as evoke feelings of threat and concern regardless of the target audiences' socio-demographical characteristics or their knowledge and experience with weather and warnings. Second, it may well be that targeting warning messages on the basis of some individual characteristics of the recipients, as literature and best practices suggest (e.g., NOAA 2016; Lindell and Perry 2012), is not as important as providing clear IBW's and BR's. Whereas experts were concerned about information overload, it appears that in all cases, providing more information only helps. First, people understood the warnings: those warnings with most information (namely IBW's + BR's) were perceived as the clearest and easiest to understand among the four warning

messages and also people better understood the threats to their safety and how to respond to the warning. Second, there is no evidence that the quite general information ridicules the warnings as IBW's + BR's were believed to be most credible and people were most concerned about their safety.

Our results extend our knowledge compared to previous studies in terms of removing ambiguity about whether it is IBW's or BR's that matter, and whether the effects are on perception or behavioural response: we show benefits in all cases. We show a large potential for improvements in warning design to lead to greater appreciation of danger and taking of protective actions. The research provides important validation and support for a wider implementation of IBW's and BR's, especially when considered in combination, into future warnings in order to improve individual decision-making and, ultimately save lives.

The one shortcoming of our study, which we share with previous studies, is to make use of self-reported responses to a hypothetical and imagined situation, rather than a field observation of actual behaviour in response to actual danger, even though some argue that intentions are a good proxy for actual behaviours (Ripberger et al. 2014b). In addition, an imagined situation suffers from a lack of real consequences for decisions and people might be less risk-seeking in real-life decisions, as was pointed out also by Kox and Thieken (2016). Finally, evaluating different warning messages with impact and/or BR's is somewhat subjective. As Casteel (2016) highlighted, a legitimate question to ask is what constitutes an effective response to warnings. Thus, it is important to remember that given the inherent uncertainty in severe weather events as well as the local context and conditions that can influence the weather, the most effective response may not always be the same action. Also, given the predictive nature of the entire warning process, any suggested impacts or actions is only the forecaster's best guess at one specific point in time (Casteel 2016).

A future research direction could be to test the effectiveness of different warning types during a real event, rather than using a simulated event (McCaughey et al. 2017). While such a study would offer results of high validity, it would also pose complicated methodological and potential ethical challenges. As additional information in the warnings influences how the warning information is perceived but does not necessarily translate into a lower likelihood to engage in a dangerous behaviour or any change in seeking more information, future research should also address the link between perceptions and non-protective actions.

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5) Effectiveness of IBW in real-life situations

Responses to severe weather warnings are consistent with an affective decision-making model rather than rational deliberation

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Abstract

Informing people of an impending hazard can lead them to adopt behaviour to mitigate the harm. In this study we examine whether giving more information, and giving it earlier, leads to a greater behavioural response. Our results, which are contextually dependent, show that providing more information has no effect on behaviour, and that longer lead times lead to less behavioural change. These results conflict with those from previous studies. These previous studies differed from ours in terms of the research methods: while past studies examined people's anticipated responses to hypothetical warnings, we conducted a field experiment to observe people's responses to actual warnings of real hazards. Theory from cognitive science suggests that this difference matters. In situations of high stress people may make decisions using a "fast" decision pathway that is largely emotion-driven, while in less stressful situations they are more likely to utilize rational deliberation. The difference between actual and hypothetical warnings would capture this mismatch in stress levels, and account for the divergent findings. At the same time, the cognitive theory has been hard to test in the field, because of the ethical challenge of submitting people to actually dangerous conditions. Therefore, our results are not only relevant for the design of warning information, but also provide important empirical support for the theory of different decision-making pathways.

Significance statement

This research investigates the effectiveness of additional impact information, as well as its timing, used in warning people about an imminent threat in real time. Our results show that certain kinds of additional information results in no greater behavioural response, whereas decreasing lead times and increasing severity level positively influence response. This is consistent with an affective model of decision-making, rather than rational deliberation. We conclude that in situations of high stress, people make fast decisions that are largely driven by affect. The findings also highlight the importance of investigating responses to risks using research designs that capture real-world conditions.

5.1) Introduction

To the extent that people's decisions are based on rational deliberation, it would seem right that the more information they receive about a situation demanding potential action, and the earlier they receive it, the better they can adjust their behaviour. However, there is evidence that people often make decisions based on their emotional response to information (Slovic

et al. 2004, 2007). In such cases, more information is not necessarily better. Moreover, which decision-making pathway people utilize may depend on the context. Here, we investigate the effectiveness of different kinds of information, as well as its timing, used in warning people about impending high impact weather events. Our primary focus is on the difference between standard warnings (SW), which describe the weather event itself, compared to impact-based warnings (IBW), which, in addition, describe the impacts that result from the weather.

Research in social sciences has broadly accepted two ideas about human nature. The analytical or cognitive model suggests that people make rational decisions based on formal logic, risk assessment and statistical probabilities, for instance on the impacts and likelihood of a hazard (Loewenstein et al. 2001; Slovic et al. 2004). This system is rather slow as it requires mental work, which is effortful and orderly (Kahneman 2011; Slovic et al. 2004). The affective model relates to the importance of emotions and feelings in making decisions (Slovic et al. 2004). It operates automatically and fast, with neither effort nor sense of voluntary control, although it is often influenced by beliefs, or mental models, about how the world works (Morgan et al. 2002; Slovic et al. 2004).

Research that has investigated whether feelings, rational deliberation or both influence people's behaviours related to risks has primarily relied on laboratory studies. For example, scholars have used different messages to manipulate affect by increasing or decreasing perceived benefits and risks of different technologies (Finucane et al. 2000). In two experiments, these researchers demonstrated that affect influenced judgments directly and was not simply a response to a prior deliberate evaluation. In only two studies, which we describe below, have researchers evaluated behaviour under varying conditions of actual fear, something that cannot be simulated in a laboratory.

A real-world situation where the fast decision-making pathway could especially come into play is the response to warnings of potentially life-threatening weather events, such as tornados or severe storms. Research that is based on a rational model of decision-making has suggested that message content and style are important factors in determining whether people take self-protective behaviour to an extent that rational analysis would deem appropriate (Mileti and Sorensen 1990). In order to be effective at inducing such behaviour, a message should contain five information elements – hazard, location, time, guidance and source – which should be addressed each by five stylistic dimensions – specificity, consistency, accuracy, certainty, and clarity (Mileti and Sorensen 1990). A warning with these characteristics is easy to understand, to believe and to personalize for the recipient, identified as prerequisites for triggering behavioural change (Mileti and Peek 2000). Thus IBW, which does provide more specific and clear information on the impacts of the hazard, should help people to better understand the message compared to SW. IBW should also increase the personalization of risk and make people feel more concerned for their safety, resulting in stronger behavioural response compared to SW. For example, some people have difficulties

to interpret a “heavy” rainfall warning, indicating 100 mm of rain, into effective impacts. In this case communicating specific impacts, for instance on road and rail transport, and possibilities of delays, ought to improve warning effectiveness, according to the deliberative decision-making model. Interviews with forecasters, emergency managers and broadcast meteorologists (Losego et al. 2013; Harrison et al. 2014), as well as with officials from the public and private sector (Weyrich et al. 2018) all reveal a widespread belief within the expert community that providing impact information creates an added value in the specific case of high impact weather warnings.

Recent studies offer empirical support for this belief, although the results are somewhat mixed (Kox et al. 2018). For example, scholars showed that IBW, compared to SW, positively influenced the recipient's sense of threat and concern associated with a hypothetical event, as well as their understanding of the potential impacts (Potter et al. 2018; Morss et al. 2018; Weyrich et al. 2018). More importantly, the IBW of the hypothetical event resulted in a greater likelihood of people planning to take self-protective action, should such an event occur (Morss et al. 2018; Weyrich et al. 2018; Casteel 2016). There have also been contradictory findings. One study detected no effect of IBW on perception of warning credibility or on intended behavioural response (Perreault et al. 2014), while another study identified a threshold beyond which increasing the projected impact of a storm no longer significantly increased the probability of taking protective action (Ripberger et al. 2014b). All of these empirical studies, however, share a common research design: they used hypothetical scenarios, and relied on people’s anticipated and intended reactions to study the effects of IBW. For example, in one study of tornado warnings, the effectiveness of IBW was examined with respondents in the hypothetical role of a factory operator having to decide whether to order workers to take shelter in response to SW and IBW (Casteel 2016). In another study, participants had to imagine that they would be hiking in the Swiss mountains when receiving a thunderstorm warning, and then had to decide upon several intended actions; those receiving an IBW were more likely to modify their plans than those receiving an SW (Weyrich et al. 2018).

If indeed it is feelings, rather than deliberation, that influence behaviour in real-life situations, then it may be that these studies on the effectiveness of IBW are poor predictors of actual behaviour, as it is unlikely that the respondents experienced real feelings of fear, since they were not actually at risk. Two studies exist that have looked at actual self-protective behaviour during a crisis suggest this to be the case. Researchers in Indonesia investigated evacuation behaviours and intentions during tsunamis, and observed that feelings, and not deliberate evaluation, drive decision-making (McCaughey et al. submitted). Their findings suggest that under an imminent threat of life, deliberative evaluation may be absent or far less influential than feelings. Scholars from the Netherlands analysed the behavioural effects to mobile fire warning messages (Gutteling et al. 2017). They found that emotions and the social environment were the main predictors for adaptive behaviour. Even though one

cognitive factor, perceived message quality, was significant, other factors, such as perceived threat, were insignificant. These results confirm the importance of affective reactions as a driver for behaviour.

If affective decision-making is more influential than rational deliberation in real-world crises, then SW may provide all the information that is needed to trigger the feelings of fear, with IBW adding no additional trigger. Hazard severity and warning lead time could also influence the response to weather warnings in different ways depending on the model of decision-making. In a rational model, more severe events and greater lead times should, rationally, generate a greater behavioural response: longer lead times would translate into greater ease of preparing for and actually taking self-protective behaviour. In an affective model, however, more severe events and shorter lead times should increase response, since the fear should be heightened at the time of the information reception.

There have been two studies examining the effect of warning lead time, and one related to event magnitude. One of these examined tornado response, and showed that an increase in lead time up to about 15 minutes reduce fatalities, while lead times longer than 15 minutes increase fatalities compared with no warning (Simmons and Sutter 2008). The second study showed more generally that people have lead time preferences that do not always match with what the warning system offers, and that they engage in different protective behaviours depending on the lead time (Hoekstra et al. 2011). The one study examining event magnitude, using a hypothetical survey design, showed that the greater the severity the more likely people are to take protective action (Kox and Thieken 2017). Perceived severity of the hazard is also used in many decision-making theories. For instance in Protection Motivation Theory, it is one of four core perceptions that form the basis for decisions about how to respond to a threat (Maddux and Rogers 1983).

In this paper we report on results from a randomized control trial in which we disseminated wind warnings through an existing smartphone application of a Swiss weather provider (*Wetter-Alarm*), and collected real-time data on people's responses. The information that people received varied randomly in terms of being SW or IBW, and given that there were a number of events for which the warnings were issued, in terms of both the warning lead time and the events' anticipated severity. A detailed description of the methods and how we analysed the data of 2,615 participants is provided in *Materials and Methods*.

5.2) Results

We first evaluate the effects of warning type, lead time, and event magnitude on participants' perception and understanding, affective reaction and whether they immediately looked for more information (their "information behaviour"). We summarize the statistics in Table 1. IBW were not significantly better perceived and understood compared to SW, and did not significantly influence participant's information behaviour. They only evoked slightly stronger

feelings among respondents, but significance and effects are very low/small. Concerning the different lead times, people did not indicate any specific differences in warning perception or understanding. However, with decreasing lead times, people reported increased feelings, and they were also more likely to search for additional information. For different severity levels, people indicated a difference in perception, due to higher perceived concern levels for severe compared to moderate warnings. Participants were also more emotionally affected and more likely to look for extra information when receiving stronger severity warnings. Overall, the greatest effects of warning type, lead time and severity level were found on affective reaction.

Table 1. Statistical testing. M=Mean, SD= Standard deviation, t= t-test, F= F-test, X^2=Chi-square test, r= Pearson's r. N=2600-2615.

Dependent variable	**Independent variable**			**Test (degrees of freedom)**	**p-value**	**Effect size**
Warning type						
	SW	IBW				
Warning perception and understanding (1-5 scale)	(M=3.68, SD=0.47)	(M=3.72, SD=0.44)		n. s.		
Affective reaction (1-5 scale)	(M=2.09, SD=0.62)	(M=2.14, SD=0.63)		t (2608) =1.99	.047	r=0.04
Information behaviour (Yes/No)	Yes= 41.3%	Yes= 40.6%		n. s.		
Lead time						
	No	Short	Long			
Warning perception and understanding	(M=3.69, SD=0.50)	(M=3.68, SD=0.48)	(M=3.68, SD=0.6349)	n. s.		
Affective reaction	(M=2.19, SD=0.65)	(M=2.13, SD=0.64	(M=2.06, SD=0.63)	F (2, 2598) =11.54	<.001	r=0.09
Information behaviour	Yes= 45.8%	Yes=45.0 %	Yes= 35.8%	*X^2 (1) = 25.49*	*<.001*	*odds ratio (no/long)=1.55*
Severity level						
	Moderate	Severe				
Warning perception and understanding	(M=3.65, SD=0.49)	(M=3.70, SD=0.49)		t (2609) =2.81	.005	r=0.06

Affective reaction	(M=1.97, SD=0.60)	(M=2.20, SD=0.63)	t (2611) =8.91	<.001	r=0.17
Information behaviour	Yes= 35.3%	Yes= 44.1%	*χ^2 (1) = 19.49*	*<.001*	*odds ratio= 1.45*

To analyse the effects of warning type, severity level and lead time on behaviour, we focus on those people who indicated the warning to be relevant and analysed their behaviour. Fifty-four percent of people (n=1426) reported that the warning message affected their personal safety, impacted their daily routine or both. The majority of those people already changed their behaviour, either by adapting their activities (35.2 %) or by cancelling them (25.7 %). Fewer people indicated that they still planned to adapt (22.7 %) or to cancel (6.9 %) their activities. Nine percent of people reported not changing their behaviour, even though the message was found to be relevant. Figure 1 shows that IBW did not result in greater behavioural response compared to SW. The observed differences between IBW and SW were insignificant (p>.05) for the different lead times and severity levels. However, as Figure 2 highlights, lead time and warning severity significantly influenced people's decisions to change behaviour: decreasing lead times and increasing severity level resulted in a greater response. We also observe that the differences in behavioural response between moderate and severe warnings are quite low for long lead times. This difference becomes more important for shorter lead times. However, the interaction is not significant (p>.05). Table 2 summarizes these results in the form of a linear regression analysis that was conducted on the behaviour variable. Unlike warning type, lead time (p<.001) and warning severity (p<.01) significantly influenced the public's behaviour. With decreasing lead times, people are more likely to take protective action (a unit increase in lead time predicted a 0.154 unit decrease in changing behaviour). For severe warnings, people were also more likely to change their behaviour (by 0.073 unit) compared to people who received moderate severity warnings. We found no interaction effects between any of the three variables (type, severity and time) on behaviour. Moreover, age (increase of 0.086 unit to change behaviour with each year) and the three covariates related to the understanding and perception of information (β=0.213), the feelings (β=0.122), and the information behaviour (β=0.103) showed significant positive effects. Thus, the older the people, the better they understood the message, the more they felt in danger and the more they looked for information, the more likely they were to undertake strong risk minimizing behaviours.

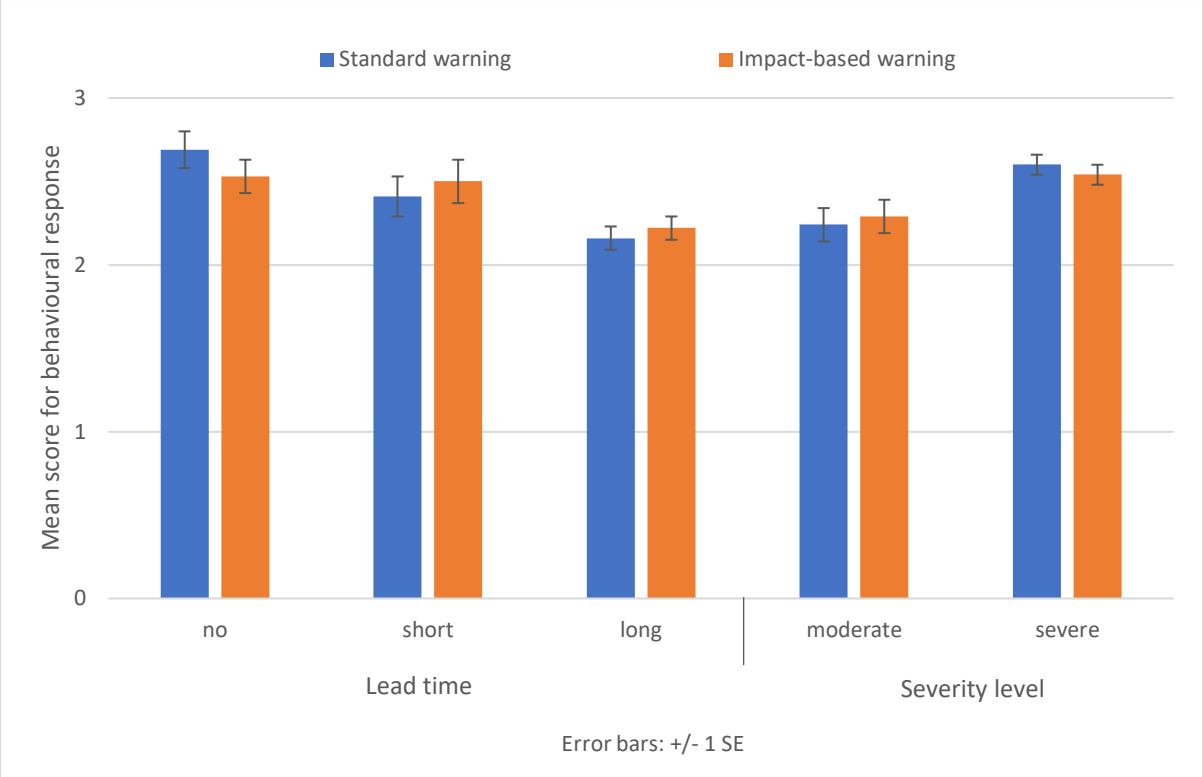

Figure 1. Mean likelihood to change behaviour for the two warning types (SW and IBW) and the three lead times (no, short and long), respectively the two severity levels (moderate and severe). Behavioural response was measured on a five-point scale from no response to strongest risk minimizing behaviour. For lead times, "no" indicates that respondents considered the warning during the event, "short" refers to 0-6 hours prior to the event and "long" to more than 6 hours. Error bars indicate +/- 1 the standard error. N=1426.

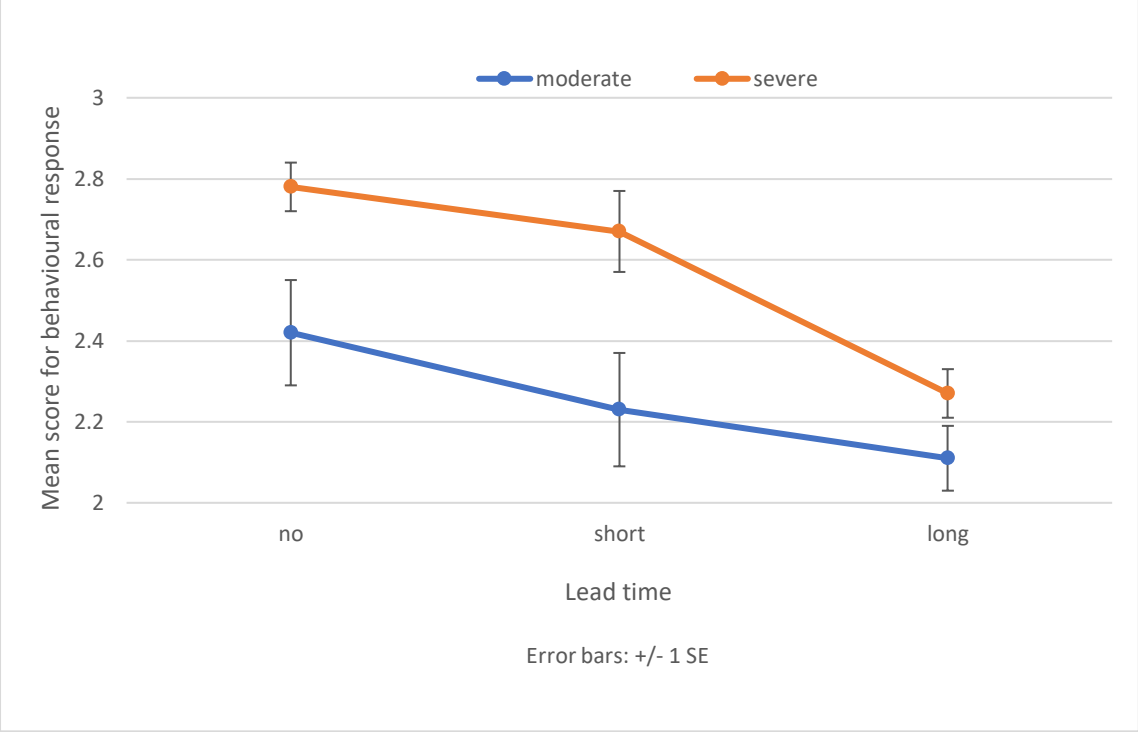

Figure 2. Mean likelihood to change behaviour for all three lead times (no, short and long) and two severity levels (moderate and severe). Behavioural response was measured on a five-point scale from no response to strongest risk minimizing behaviour. For lead times, "no" indicates that respondents considered the warning during the event, "short" refers to 0-6 hours prior to the event and "long" to more than 6 hours. Error bars indicate +/- 1 the standard error. N=1426.

Table 2. Multiple linear regression with the behavioural change as dependent variable. R^2=0.36 (p<.001), N=1426. Note: **p<.01, ***p<.001. Significant results are in bold. B indicates the unstandardized coefficients, SE the standard error and β the standardized coefficients.

	B	SE B	β
Constant	-.600	.399	
Gender (female=0; male=1)	-.111	.073	-.040
Age (year scale)	**.008**	**.002**	**.086*** **
Education level (scale 1-6)	.026	.019	.034
Warning understanding and perception (1-5 scale)	**.591**	**.071**	**.213*** **
Feelings (1-5 scale)	**.250**	**.054**	**.122*** **
Information behavior (no=0, yes=1)	**.717**	**.178**	**.103*** **
Warning type (SW=0, IBW=1)	-.041	.068	-.015
Lead time (none=0, short=1, long=2)	**-.225**	**.038**	**-.154*** **
Warning severity level (moderate=0, severe =1)	**.215**	**.077**	**.073** **

5.3) Discussion

This research investigates the effectiveness of impact information, as well as its timing, used in warning people about an imminent threat. Our results show that while IBW result in no greater behavioural response, decreasing lead times and stronger severity level do increase response. Taken together, these results suggest that affective decision-making appears to be the dominant mode of decision-making in real-world situations, rather than rational deliberation.

IBW do not significantly impact warning perception and understanding, nor do they result in greater behavioural response compared to SW. This result contradicts the majority of previous studies that used hypothetical situations to collect their data (Casteel 2016; Weyrich et al. 2018; Morss et al. 2018). We speculate that this difference in research findings can be explained by the different levels of fear experienced in a hypothetical and a real crisis. Unlike in an imagined situation, where rational deliberation acts as the dominant factor, our findings suggest that in a crisis situation, real feelings of fear arise and dominate decision-making. We assume that SW provide all the information that is needed to trigger the feeling of fear. Indeed, IBW may leave less to the imagination of the recipient, which could – in some cases – dampen the fear response.

Our results on the effects of lead time and hazard severity are also consistent with the affective model of decision-making. We observe lead time and self-protective behaviour to be inversely correlated and find that increasing lead times, decrease the likelihood to engage in greater behavioural response and observe the greatest response when the event has already unfolded. These results complement other research on different lead times for tornado warnings (Hoekstra et al. 2011). We also show that stronger events generate a greater response than weaker events, which is in line with previous research (Kox and Thieken 2017). Moreover, the two models of decision-making could lead to different responses contingent on the interaction of event severity and warning lead time. In the case of rational deliberation, longer lead time may enhance the ability to take the greater steps necessary to respond to the stronger severity event. Thus, longer lead times should generate a greater additional response to stronger rather than weaker events. However, we observe the interaction to be the opposite (even though not significant), which is in line with an affective decision-making model: with long lead times, the additional fear associated with the stronger event may dissipate, meaning that the stronger events would generate little more response than weaker events.

These findings support scholars who reached a similar conclusion when investigating evacuation behaviours following a strong earthquake (McCaughey et al. submitted). Nonetheless, cognitive factors, such as warning understanding, seem to be obvious prerequisites for behaviour (Gutteling et al. 2017). Therefore, further empirical studies of real-world crises are needed to understand if, and how feelings and deliberative evaluation interact to influence people's behaviours to risks. We conclude that practitioners cannot assume that additional impact-based information necessarily results in greater behavioural response in real-world crises. Appropriate lead times and a communication that addresses the decision-makers' feelings (e.g., by relying on images) may be more beneficial and result in a stronger behavioural response. Ultimately, the results show that people may respond differently in a field than in a scenario-based experiment, based on an affective, respectively a rational decision-making model. This has serious implications for future research emphasizing that we should examine responses to risks using research designs that capture realistic conditions and be cautious in interpreting results from hypothetical research designs as these could be a poor predictor of actual behaviour.

The research has some limitations. One shortcoming of this study is the absence of a very severe wind event in the winter season 2018/19 in Switzerland, and additional data should be collected for these events too. Indeed, most of the research on IBW used hypothetical warning messages of the most severe category, as people are least familiar with these messages and, thus, the added information could help them in decision-making. In consequence, the difference in the results on the effectiveness of IBW in our and previous studies could also be due - to some extent - to the differences in event severity level. Another limitation is that, even though we collect data on actual behaviours in response to real-life

warnings, these were still self-reported. Thus, additional research could analyse whether these results are valid for other natural hazards as well.

5.4) Materials and Methods

The method used here was a large field experiment conducted in Switzerland, which tested for effects of warning type, severity level and lead time on warning response. SW and IBW for wind were disseminated to users via the smartphone weather application (app) 'Wetter-Alarm'. More information on the app and the warning messages is provided in the appendix. A link was provided at the end of the warning message, which directed participants to a short questionnaire. The questionnaire was available from the moment on when the warning message was disseminated until the end of the event. We focused on severe wind due to its frequency, the time of the year (winter season) and the possibility to investigate different lead times. We collected data for two wind severity levels: moderate and severe. As this research involves research on humans, appropriate ethical procedures were followed[1].

A total of 3,223 participants completed the online survey from 1.12.2018 to 10.02.2019. We excluded 611 people from the analysis as they believed to have responded to a warning message with a different severity level than it was actually the case. This can be explained by the fact that the warning message they received initially, was updated in the meantime (e.g., from a moderate to a severe level) or that the participants received multiple warning messages for different locations and got confused. Thus, to avoid any possible misinterpretation of data, the analysis was conducted with data from 2,615 participants that indicated the correct severity level. As respondents were randomly assigned to either a SW or IBW, the subgroups are roughly even (1,364 and 1,247). However, more people responded to severe warning messages (n=1,667) than to moderate messages (n=948). No very severe wind was observed. Warning lead times also differed and people were grouped into three groups depending on when they looked at the warning message (i.e., participated in the survey); during the wind event itself (n=932, 35.6 %), in the 6 hours preceding the wind event (17.1 %, n=448) and prior to 6 hours, 47.2 % (n=1,235). On average, people responded to the survey 5.14 hours in advance of the wind event.

Information about the basic socio-demographic characteristics of the sample is provided in the appendix (Table S1). The sample matches the profile of the general Wetter-Alarm app user which is older (48.8 years) than the Swiss average (43.14 years), is more often male (63.1 %) than female (Swiss average 49.5 % vs. 50.5 %) (FSO, 2017b) and slightly more educated

[1] The potential risks of conducting the research were carefully considered and the research design was submitted to the Ethics Commission of ETH Zürich prior to the collection of data. Participants voluntarily participated once they had been informed about the research project and signed a declaration of consent. Prior to the survey, they were also informed that the data would be evaluated anonymously (names were not collected) and securely stored on local hard drives at ETH, as well as on the backup server at ETH. Participants received no incentive to complete the survey.

than the Swiss population (FSO, 2017a). As the survey was conducted online based on actively users of the app Wetter-Alarm, it did not reach people who did not download the application, who do not actively use the app or who do not have internet access.

In the survey, we asked questions on warning perception and understanding. Perceptions that we measured using a five-point Likert scale from 'totally disagree' to 'totally agree' were credibility, and concern. We measured three types of understanding: the warning, the threats to safety, and how to respond. Then, we asked participants whether the weather described in the warning would pose a risk to them and whether it would affect them in carrying out their usual activities (e.g., commuting, working, shopping etc.). If they answered yes, they continued with the survey. In the following questions, participants had to indicate whether they already reacted to the warning message or only planned to do so as well as how they reacted, i.e., adapting activities or cancelling activities, respectively taking other measures to protect themselves. Thus, we computed the variable behavioural response on a five-point scale (1= no action planned, 2= plan to adapt, 3=plan to protect, 4= did adapt, 5=did protect). Similar to other research (Gutteling et al. 2017), we used a battery to ask what kind of feelings the warning did trigger: relaxed, anxious, concerned, reassured and angry (five-point Likert-scale from 'not at all' to 'very much'). We also gathered data on whether people consulted other information for advice or confirmation. Finally, we collected information on the most important personal factors: gender, age, and education. The full questionnaire is available in the appendix.

For the data analysis we use standard statistical software (IBM SPSS 25) to conduct independent t-tests, one-way analyses of variances, and Chi-square tests to study the effects of warning type, severity level and lead time on warning perception and understanding, affective reaction, information behaviour and behavioural response. In addition, we did a multiple regression analyses to investigate the effects of warning type, severity level and lead time, but also other covariables on behavioural change.

Acknowledgments
We thank the chief editor from SRF Meteo Thomas Bucheli for making contacts with Wetter-Alarm. We also thank the entire Wetter-Alarm Team for their help in the implementation of our research design. Conducting the field experiment would not have been possible without their permission to use the Wetter-Alarm mobile application to. Within the Wetter-Alarm Team, we would like to especially thank Marlène Käsermann for her valuable inputs.

6) Discussion

6.1) Research questions and key findings

The research presented in this thesis should be a useful addition towards more effective warning systems. In specific, it identifies how warning communication can be improved to help affected people take better informed decisions. Through the four contributions, my co-authors and I answered the following questions:

Do different protection motivation variables affect people's behaviour to undertake risk reduction measures and if so, is it depending on their risk reduction stage?
Yes, people are motivated by different factors to engage in risk reduction behaviours. Not all people are motivated by the same threat or coping appraisals, but these differ depending on people's risk reduction stage, i.e. the type of measures already undertaken.

Does inconsistency in different-source forecasts affect evaluation of warning quality and does it influence intended behavioural response?
Yes, inconsistent messages were perceived of lower quality and negatively impacted warning response. People were less likely to engage in self-protective behaviours for different types of inconsistent warnings compared to consistent warnings; the higher the level of inconsistency the poorer was the behavioural response.

Are warning messages that provide impact information and/or give guidance more effective than warnings that only describe the weather phenomenon?
Yes, participants that received impact-based warnings - with and without behavioural recommendations - were more likely to engage in protective behaviours than people who received the standard warnings. Messages with impact text and recommendations were also reported to be clearer, easier to understand, and more credible, and people indicated to be more concerned for their safety, and better understood the threats and behaviours to engage in.

Does the presence of fear influence the effectiveness of impact-based warnings in real-world crises?
Yes, fear influences the effectiveness of impact-based warnings. These warnings did not increase behavioural response in real cries, which contradicts with findings using a hypothetical research design. However, stronger event severity and shorter lead times generated greater behavioural response. These findings are consistent with the affective model of decision-making: when people are under an imminent threat of life, fear and other feelings are more influential than deliberate evaluation.

6.2) Theoretical, empirical and methodological contributions to the literature

In Contribution I, I apply a novel protection motivation framework, which is a combination of Protection Motivation Theory (PMT) and the Trans-Theoretical Model (TTM), to explain risk

reduction behaviours that people may undertake prior to a crisis. The framework combines the strengths of both theories that complement each other: while PMT focusses on people's motivations to make decisions (Floyd et al. 2000), TTM acknowledges that the public is no homogenous group that is ready to act upon a hazard (Horwath 1999). The successful application of the dynamic protection motivation framework underlines its usefulness for researchers and practitioners that aim to better understand the interdependency between people's motivations and their readiness to undertake risk reduction behaviours.

Contribution II is the first study to perform an empirical analysis of how people respond to inconsistent warning messages disseminated by different public and private weather providers. It focusses on previously overlooked consequences due to the duplication of public weather warnings. The contribution highlights that some current gaps in the warning system must be addressed to avoid possible negative implications of contradicting warning information, which could otherwise be exacerbated with the rise of social media and individualised communications, as well as the entry of global players in the weather market. For instance, the Google Maps application will now warn people about disasters (Google Maps 2019) and IBM just launched the GRAF model, that combines the power of supercomputing with big data to provide more accurate forecasts for the entire world (IBM 2019). Thus, the dissemination of consistent information within a given institutionalized part of the warning chain is essential. In the next chapter, I provide a compromise solution involving national and private weather providers.

Contributions III and IV add to the existing literature on impact-based warnings (IBW), which has been growing in recent years (Taylor et al. 2018). In specific, I contribute to the empirical research by disentangling effects of IBW and behavioural recommendations in Contribution III. However, research is still limited and findings on the effects of IBW are mixed, which emphasizes the need to further explore the effectiveness of (impact-based) weather warnings. Drawing on the results of Contribution III, I conducted a field experiment, in which people randomly received SW or IBW. Thus, for the first time I collected data based on actual warnings disseminated in real time (Contribution IV). However, results from the field experiment contradicted those of scenario-based experiments. This has implications for our model of self-protective behaviour as my research suggests that people respond differently in a field than in a scenario-based experiment. Affective decisions may dominate in the real-world crisis, whereas in the absence of fear, rational decision-making is left as the dominant model. Thus, future research should examine responses to risks using research methods that capture realistic conditions.

Finally, I also demonstrate the use of smartphone applications to collect data in real time and for relatively low cost. Such data has not been used yet in the context of warning communication, but scholars have highlighted its potential (Knüsel et al. 2019). In medical research, mobile applications are already used, for example, to detect and monitor the symptoms of Parkinson's disease (Arora et al. 2015). Likewise, one could think of smartphone

applications that collect longitudinal data over time, to track trends and changes in attitudes and responses. Moreover, based on GPS data from phones, these applications could provide targeted semi-automated behavioural recommendations to people on how to save their lives. At the same time, smartphone technology could also help evaluating warning messages, for instance by using experience sampling methodologies. This methodology was developed to conduct research in the field and has been used in applied psychological research to observe changes in attitudes, feelings and behaviours (Dimotakis et al. 2013). The huge potential that offer mobile applications has not been explored yet, partly because it also raises ethical questions whether and how one would use the data. The main ethical dilemmas are linked to the surveillance of people by tracking their behaviours via smartphones. Once these questions have been thoroughly discussed, using smartphone applications as a research tool or method could open an enormous window of opportunity.

6.3) Policy implications

First, helping people to better cope with natural hazards and to make more informed decisions does not start with onset of an event. Decision-making can also benefit from communication efforts that are being made in the long-term, i.e. before the event strikes (Reynolds and Seeger 2005). Especially in Contribution I, I provide information and analysis for local decision-makers or practitioners, which should help them to develop better targeted flood risk communication strategies to individuals that emphasize different motivating aspects and foci for different groups of people. However, these strategies only fully develop their potential if they are informed by the readiness of homeowners at risk to engage in risk reduction behaviours. Thus, before designing these strategies, practitioners would need to conduct surveys to evaluate public preparedness. Such surveys are cost and time efficient, and would be extremely valuable in identifying the risk reduction measures already undertaken or planned by homeowners. Therefore, I recommend that policy-makers implement the standardized use of surveys in flood risk management practices.

Second, findings of Contribution II suggest that policy changes need to be made; public and private weather providers need to cooperate, rather than work against each other and find an agreement to provide consistent warnings for the benefit of society. In Switzerland, MeteoSwiss is currently discussing with the private providers to find such an agreement. However, the negotiations are difficult as the different stakeholders have their own agendas and responsibilities. For instance, the public agency wants to keep five warning severity levels in order to be consistent with other agencies that warn for different hazards, such as avalanches or floods, whereas the private providers agree on three severity levels. Moreover, the private sector claims to have a right to use their own input data and interpret weather model outputs the way they think it is correct. In interviews that I conducted with the private and the public sector prior to the study, some stakeholders also reported that the inconsistency in warnings may not negatively influence decision-making, as it would help the general public to better assess a given weather situation and to make appropriate decisions.

However, my findings clearly demonstrate that this is not true. Even though the situation seems somehow unsolvable, the fact that public and private providers are talking to each other, shows that they are - at least partly - aware of the issue and the need to improve the warning system by providing consistent information. In the paper, I present a compromise solution that could work for both sectors, public and private. The providers could agree on the same number of warning severity and, associated, threshold levels and colours, i.e. to identically visualize the warnings. At the same time, MeteoSwiss would remain the official warning authority and the private provider could continue to disseminate their own public warnings based on their input data, weather models and interpretations. If the ongoing negotiations fail to find a compromise solution, then policy-makers may perform modifications in the warning process and clarify the stakeholder's roles and responsibilities.

Third, my research has implication for the design of warning messages. Practitioners should provide IBW and give guidance, especially in the case of severest weather. Results of Contribution III are consistent with the majority of studies that used hypothetical warnings of the most severe category. At the same time, policy-makers should be aware that for lower severity warnings, additional impact-based information does not necessarily result in greater behavioural response. In a model where feelings guide decision-making during crises, information provided in SW may be enough to elicit affective reactions that ought to result in a stronger behavioural response.

Fourth, a direct implication of Contribution III and IV is that *Wetter-Alarm* considers to include impact-based information in the warning messages for all the hazards that they warn for. As I still expect IBW to result in greater behavioural change for very severe weather, this would also justify the related additional costs. Thus, my research would have a (potential) direct impact on the 1.2 million people in Switzerland that have downloaded the application and help them to better understand the warning messages and make more informed decisions. In addition, different stakeholders in the warning chain that are involved in the High Impact Weather research project of the WMO demonstrated high interests in the findings of Contribution II, III and IV. Especially forecasters and public officials are interested in how conflicting warning information or impact-based warnings influence self-protective behaviour. Based on my and other findings generated within the WMO project, some of these practitioners have initiated processes to renew some elements of the warning system (HIW 2018). This need is also being recognized by the World Bank, which published a summary of Contribution II in one of their recent reports (World Bank 2019).

Finally, including information about the weather impacts in warning messages would, however, only be a first step to changing the warning system. The warning product and its trigger would remain the same. For instance, the MeteoSwiss forecaster issues a warning when she or he has 70 % or more confidence that there would be severe weather in the next 36 hours. This is complicated and can be complex too. A more important step that would profoundly change (and simplify) the system, would be to use a risk-based approach to

generate warnings. In such a system, weather warnings should only be issued if severe weather is expected to have an impact. In such a case, the forecaster provides an expected level of impact and a likelihood of this impact to occur. A simple matrix that the UK Met Office is already applying and that can be understood intuitively is presented in Figure 3.

Likelihood	High				
	Medium				
	Low				
	Very low				
		Very low	Low	Medium	High
		Impact			

Figure 3. Warning impact matrix (adapted from the UK Met Office).

Thresholds (e.g., 100 mm of rain in 24 hours) would not be used anymore to trigger warnings, but be part of the decision process. Weather impact on different sectors could be assessed, from disruption to daily routines, transportation and property damages, to danger of life (Bevan 2017). For example, a low impact (*yellow*) warning could be defined by short lived disruption to daily routines, sometimes longer travel times, but no damage to buildings or danger to life, whereas high impact (*red*) warnings would mean prolonged disruption to daily routines, long travel delays with people stranded for long periods, extensive damage to buildings and danger to life. A third and final step would be an impact-warning system that is informed by hazard, vulnerability and exposure (WMO 2015b). In such a system, the decision-maker could provide very specific warnings targeted to the individuals at risk such as; tomorrow evening the expected travel times on a given road will be taking 30 minutes longer than usual, because of significant traffic disruptions, caused by local flooding which is expected to follow a heavy rainfall event.

6.4) Limitations

This thesis fills some of the research gaps that exist in communicating hazard warning information. However, it also has several limitations that could be addressed in future research.

One major shortcoming of this research is the absence of a very severe wind event in the winter season 2018/19 in Switzerland. Compared to lower severity events, which happen several times per season, very severe events are rare, which implies that the public is not familiar with them and their impacts. However, the studies that found IBW to be more effective than SW, were based on hypothetical decision-scenarios describing very severe events. Thus, I speculate that IBW may only be effective in the case of very severe weather, for which people lack experience and may have difficulties in judging its impacts. In consequence, the difference in the results on the effectiveness of IBW in Contributions III and IV could also be due - to some extent - to the differences in event severity level, respectively

people's levels of experience (Weber 2011). Therefore, future research should investigate the effectiveness of very severe IBW in real-world crises to resolve the current ambiguity.

At the same time, research shows that people are more or less familiar with different hazards, and perceive some hazards to be more dangerous than others (Slovic 1987). For instance, irrespective of the research context in this thesis, participants that received severe rainfall warnings indicated that they would not take any action, because they did not consider rainfall to be dangerous (Contribution II), which was not the case for thunderstorms and wind (Contribution III and IV). Thus, the different results presented in this thesis could depend on the choice of hazard, i.e. how threatening people perceive the hazard to be for their safety. Future work could therefore investigate whether the results are also valid for other meteorological and environmental hazards, including both slower-onset, spatially diffuse and rapid-onset, spatially localised natural risks.

We show that additional lead time does not necessarily result in increased behavioural response. Pace and timing of warnings have significant behavioural implications, but research is extremely limited (Lindell and Brooks 2013). Thus, additional studies on the timing of warning production and dissemination are needed. We need to better understand the consequences of current, increased and decreased lead times, and its independency with hazard progress.

Finally, it's important to highlight that this research was conducted in developed countries, where forecasting and warning systems are in place. However, these systems are not always implemented in other countries and thus people may not even receive warning information. Therefore, one should be careful in generalizing the results across countries with large economic or cultural differences (Douglas and Wildavsky 1983). Even though progress has been made in the development and implementation of early warning systems in the last years (Cools et al. 2016), many developing countries, especially in Africa, face severe challenges along the entire warning chain. For instance, NMHS lack meteorological data due to a limited number of observing stations (Venäläinen et al. 2016), the infrastructure to disseminate warning information is poor (Thiemig et al. 2011) and people who need early warnings the most, do not always receive them (Ajibade and McBean 2014). In general, research on warning communication and decision-making should also be conducted in these countries, which are, in addition, highly vulnerable to extreme weather in a changing climate.

6.5) Research outlook

I conclude with four ideas about warning-related communication and decision-making, which go beyond the individual contributions.

Weather and emergency services are working hard to advance warning systems with the aim to reduce the number of deaths or damage to its minima. Therefore, they constantly improve

their tools for predicting weather hazards and impacts (e.g., numerical and probabilistic models, impact models relating vulnerability to hazard), which ultimately results in more accurate, precise and timely warnings. However, these improvements do not necessarily lead to improved outcomes (e.g., UK Met Office 2018). Research from social and behavioural sciences have shown that various factors, such as knowledge, experience, perceptions and attitudes can influence how people prepare for, observe, predict, understand, respond to, and are impacted by (weather) hazards (National Academies of Sciences and Medicine 2018). Thus, weather and emergency services may better integrate findings from these sciences in their work. On the one hand, social sciences should help to inform how the general public's experiences, perceptions and attitudes influence their responses to warnings. On the other hand, social sciences can also assist in understanding how human cognition and social dynamics affect the warning process itself. I will outline future research ideas in more detail below.

First, people often act emotionally (and sometimes irrationally too) (Welzer 2018). This could be especially true in real-world crisis, where affective decision-making seems to be more important than rational deliberation. However, studies that have been conducted in the real world are rare – compared to laboratory experiments – and thus evidence is limited (Gutteling et al. 2017; McCaughey et al. submitted). Also, cognitive factors seem to be obvious prerequisites for behaviour (Gutteling et al. 2017). We know from theory of cognitive science that the two modes of thinking – affective and rational – can interact and influence each other (Kahneman 2011). Slovic and collaborators have observed this interaction for perceived risk and benefit judgements, but have primarily relied on laboratory research designs (Slovic et al. 2004; Finucane et al. 2000). Studies that investigate how feelings and deliberative evaluation interact to influence people's behaviours to actual (i.e. real-time) natural hazards are missing. Therefore, further empirical research that is conducted in real-world crises is needed. In order to do so, mobile applications could be used to collect the necessary data on people's attitudes and behaviours (as well as on the weather) in real time. For instance, mobile phone data could be used to analyse mobility and communication during crisis.

Second, these new technologies could also facilitate the observation of trends and changes in attitudes and behaviours over time. In fact, an individual could experience different, more or less severe hazards, which would very likely influence his or her perceptions and behaviours. Currently, there is a lack of longitudinal studies that could reveal dynamic processes, such as changes in risk perceptions and protective behaviours, which cannot be fully addressed by the conventional cross-sectional studies. Furthermore, mobile applications could serve to better integrate the needs and perceptions of people into the warning process, and, ultimately, to provide individualized warning messages.

Third, instead of asking the question what forecasters or others can do to produce better warnings, one could also examine how the existing infrastructure could be adapted to the

needs of each citizen to take informed decisions, and thus personalise warnings to an individual level. For instance, warnings for an elderly person with osteoporosis could indicate to not leave the house when it is snowing, while the warning would be a different one for a logistic operator who may need specific information on expected traffic disruptions. Thus, "personalized impact-based warnings" (PIBW), which are truly informed by the hazard, as well as the individual's vulnerability and exposure, could significantly improve warning effectiveness. Therefore, the (involvement of) citizens themselves should be part of transdisciplinary collaborative research teams to co-produce knowledge that could help develop impact-warning systems. Thus, citizens would play an active and decisive role by providing recommendations on how to shape content of weather warnings (and apps). Researchers could apply such transdisciplinary approaches that focus on a collaborative effort to design useful and trusted PIBW. Combined with improvements in modelling and forecasting, such PIBW could provide large benefits to society.

Fourth, decision-making occurs at various stages in the warning chain and not just at its end. For instance, weather forecasters and others, who produce and disseminate warnings, are in many ways also recipients of information prone to the same perception and judgement issues. Knowing the needs and perspectives of all these experts involved in the entire warning chain could help understand how changes in forecast or emergency operations would affect the quality of warning information. In this way, experts may gain new knowledge about different perspectives that they would otherwise not consider. These new insights could increase warning communication literacy (e.g., increased understanding about communication in the warning chain and its challenges) and enhance collaborative capacity (e.g., increased perceived importance of engaging diverse stakeholders in warning decision-making; increased understanding of and empathy for diverse perspectives). At the same time, increased collaboration would reduce the risk of conflicts (see for example the recent successful lawsuit of private providers against the German Weather Service (DWD)) and guarantee a constant two-way exchange of knowledge and views throughout the warning chain. Future research could apply a mental model approach to analyse the stakeholders' attitudes and perceptions (Morgan et al. 2002). For instance, public and private weather forecasters, media representatives, and emergency managers play important roles in the communication and management of bad weather, but in-depth knowledge about their conceptions, how they communicate among each other and make decisions is lacking (Morss et al. 2015). This leads to other questions, such as how forecasters actually interact with other meteorologists and public officials, and how this influences the warning process? Studying their mental models could therefore help to develop a more integrated understanding of multiple stakeholders' needs and perceptions in warning production and communication.

The end.

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Appendix A

Supplementary Information for the paper "A flood risk oriented dynamic protection motivation framework to explain risk reduction behaviours".

A.1) Questionnaire

LENGTH OF RESIDENCE & SAFETY

1. How long have you been living in Negrar?

   1. Since I was born *(skip to question nr. 3)*
   2. Since _____ (yyyy)

2. If you haven't always lived in Negrar, where did you live before?

   1. In another municipality within the same region (please specify _____)
   2. Elsewhere in Italy (please specify _____)
   3. Elsewhere (please specify _____)
   4. In another *frazione* of the same municipality

3. [On a scale from 1 (min) to 5 (max)] Does "living here" make you feel safe?

Very unsafe				Very safe	I don't know
1	2	3	4	5	0

4. [On a scale from 1 (min) to 5 (max)] In the following list, could you indicate to which extent you think each of these events represents a danger for you personally or for your house?

	Not at all				Serious danger	I don't know
1. Earthquake	1	2	3	4	5	0
2. Terror attack	1	2	3	4	5	0
3. Robbery	1	2	3	4	5	0
4. Drought	1	2	3	4	5	0
5. Fire	1	2	3	4	5	0

5. Are you or anyone in your family a member of the Civil Protection?

   1. Yes, I am a member
   2. Yes, someone of my kin is a member (specify _____)
   3. Yes, both I and a /some kin are members (specify_____)
   4. No

THREAT APPRAISAL

6. [On a scale from 1 (min) to 5 (max)] Considering floods, do you think they are a threat for

	Not at all				Serious threat	I don't know
1. Your house	1	2	3	4	5	0
2. Yourself	1	2	3	4	5	0
3. Your town	1	2	3	4	5	0

7. [On a scale from 1 (min) to 5 (max)] What damages would you expect from a future flood?

No damage				Very serious damage	I don't know
1	2	3	4	5	0

EXPERIENCE / 2018 EVENT

8. In September 2018 in Negrar it happened that _____ (short description of the event). Were you here at that time?

   1. Yes
   2. No (why _____ _____)

9. Please rate the seriousness of the damage suffered (by you or your property) after the event of September 2018, if any. [on a scale from 1 (min) to 5 (max)]

No damage				Very serious damage	I don't know
1	2	3	4	5	0

10. Have you ever been involved in similar events in the past, here or elsewhere?

    1. Yes, in the year |__|__|__|__| in _____
    2. No

11. Before the _____ (yyyy) event, would you think something like this might happen here?

    1. Yes
    2. No
    3. I don't know

INDIVIDUAL PREPAREDNESS

12. [On a scale from 1 (min) to 5 (max)] Presently, how well prepared do you feel to face a flood, in case it happens again?

Not prepared at all				Very well prepared	I don't know
1	2	3	4	5	0

13. Please indicate if and when you intend to adopt the following risk reduction measures. If you already adopted one or more of them, please state whether you did so before or after the September 2018 event.

		Non la adotterò	Magari la adotterò in futuro	La adotterò a breve	Già adottata (post-evento)	Già adottata (pre-evento)	Non so	NR
Structural measures I	Elevated ground floor above the most likely flood level	1	2	3	4	5	0	NA
	Reinforced foundations against water pressures	1	2	3	4	5	0	NA
Structural measures II	Backflow valves	1	2	3	4	5	0	NA
	Ground floor and walls made of water-resistant materials	1	2	3	4	5	0	NA
	pecial installation (e.g. higher up) of heating and electric system	1	2	3	4	5	0	NA
Avoidance measures	Keeping personal valuables and documents out of flood-prone areas of the house	1	2	3	4	5	0	NA
	Keeping expensive appliances (washing machine, boiler etc.) above expected flood levels	1	2	3	4	5	0	NA
	Adapted use of basement and ground floor	1	2	3	4	5	0	NA
Emergency measures	Mobile barriers (e.g. metal/wood shields) available	1	2	3	4	5	0	NA
	Emergency plan for household in case of	1	2	3	4	5	0	NA

floods (e.g. where to go, what to take with me)

14. [On a scale from 1 (min) to 5 (max)] How effective are the risk reduction measures overall at helping to reduce the risk of floods impacting your property and life? (show table)

	Not effective at all				Very effective	Don't know
Structural measures I	1	2	3	4	5	0
Structural measures II	1	2	3	4	5	0
Avoidance measures	1	2	3	4	5	0
Emergency measures	1	2	3	4	5	0

COSTS

15. [On a scale from 1 (min) to 5 (max)] How long will it take you to implement risk reduction measures? (show table)

	Very short time				Very long time	Don't know
Structural measures I	1	2	3	4	5	0
Structural measures II	1	2	3	4	5	0
Avoidance measures	1	2	3	4	5	0
Emergency measures	1	2	3	4	5	0

16. [On a scale from 1 (min) to 5 (max)] How expensive do you think it will be to take risk reduction measures? (show table)

	Very low cost				Very expensive	Don't know
Structural measures I	1	2	3	4	5	0
Structural measures II	1	2	3	4	5	0
Avoidance measures	1	2	3	4	5	0
Emergency measures	1	2	3	4	5	0

REWARDS

17. [On a scale from 1 (min) to 5 (max)] Please indicate how much you agree with the following statements.

	Completely disagree				Completely agree	I don't know
1. I would feel encouraged to take risk reduction	1	2	3	4	5	0

measures myself if some of my neighbors, friends or family does the same.						
2. I would like to take extra precautions against flooding if I am rewarded or assisted by the government (with subsidies, exemptions, etc.)	1	2	3	4	5	0
3. Taking extra risk reduction measures against flooding is a priority for my household	1	2	3	4	5	0
4. Taking extra precautions against flooding contributes to a safer future for my family and fellow citizens	1	2	3	4	5	0

PROTECTION WORKS

18. Are you aware of any works (infrastructures) built in this area as protection from possible damage from floods?

    1. Yes (specify _____ _____)
    2. No *(skip to question nr. 20)*

19. (If you answered yes to the previous question, answer n.1 to question 18) How much do you agree with the following statements? [On a scale from 1 (min) to 5 (max)]

	Completely disagree				Completely agree	I don't know
1. The protection works eliminate the possibility of serious damages	1	2	3	4	5	0
2. The protection works are too expensive compared to the expected benefit	1	2	3	4	5	0
3. The protection works give a sensation of security to people living here in Negrar	1	2	3	4	5	0
4. The protection works promote/help the economic development of our community	1	2	3	4	5	0

KNOWLEDGE

20. There are many ways to learn about hydrological phenomena. Please evaluate how the following have contributed to your personal knowledge about hydro-geological phenomena? [On a scale from 1 (min) to 5 (max)]

	No contribution				Maximum contribution	I don't know
1. Personal experience	1	2	3	4	5	0
2. Local knowledge (e.g. from elderly people experience)	1	2	3	4	5	0
3. Official training and information initiatives	1	2	3	4	5	0
4. Own's initiative	1	2	3	4	5	0
5. Other (specify_____)	1	2	3	4	5	0

TRUST IN GOVERNMENT

21. [On a scale from 1 (min) to 5 (max)] Please indicate how much you agree with the following statements:

	Completely disagree				Completely agree	I don't know
1. The government will inform me if the flood risks in my home area changes significantly	1	2	3	4	5	0
2. I trust the government with regard to protection against flooding	1	2	3	4	5	0
3. The government has always done well in terms of protection against flooding in Italy	1	2	3	4	5	0

PUBLIC ASSISTANCE

22. Sometimes, public bodies offer help with flood protection to private households. What kind of public support from local, regional or national bodies have you received?

	Minimum support				Maximum support	Don't know
1. Financial aid for financing flood protection (subsidies, loans, etc.)	1	2	3	4	5	0
2. Material support, such as distribution of sandbags and other mobile barriers)	1	2	3	4	5	0
3. Information and awareness raising (folders, web-platforms, early warning)	1	2	3	4	5	0

23. Is your home ensured against flooding?

1. Yes
2. No
3. I don't know

GENERAL INFORMATION

24. When were you born? (year) |__|__|__|__|

25. Gender

1. Male
2. Female
3. Other

26. The house you are living in is:

1. Yours/your family property
2. Rented
3. Other (specify _____)

27. Educational qualification (specify the last school/college year attended)

1. Primary school
2. Middle school
3. Professional high school (usually 3 years)
4. High school (5 years)
5. University degree or higher

28. [On a scale from 1 (min) to 5 (max)] To satisfy the needs of your family, your income is:

Not sufficient				Largely sufficient	I don't know
1	2	3	4	5	0

_____
_____

Would you be willing to take part in this survey again in the future?

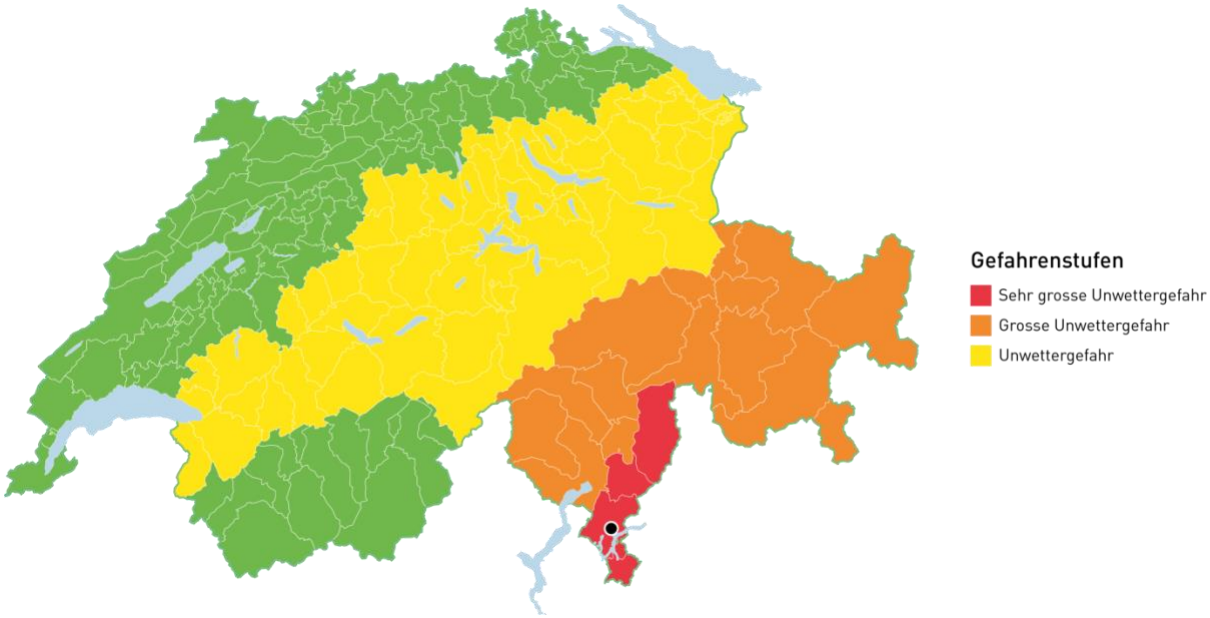
If Yes (contact – phone/email: _____)

Appendix B

Supplementary Information for the paper “Dealing with inconsistent weather warnings: effects on warning quality and intended actions”.

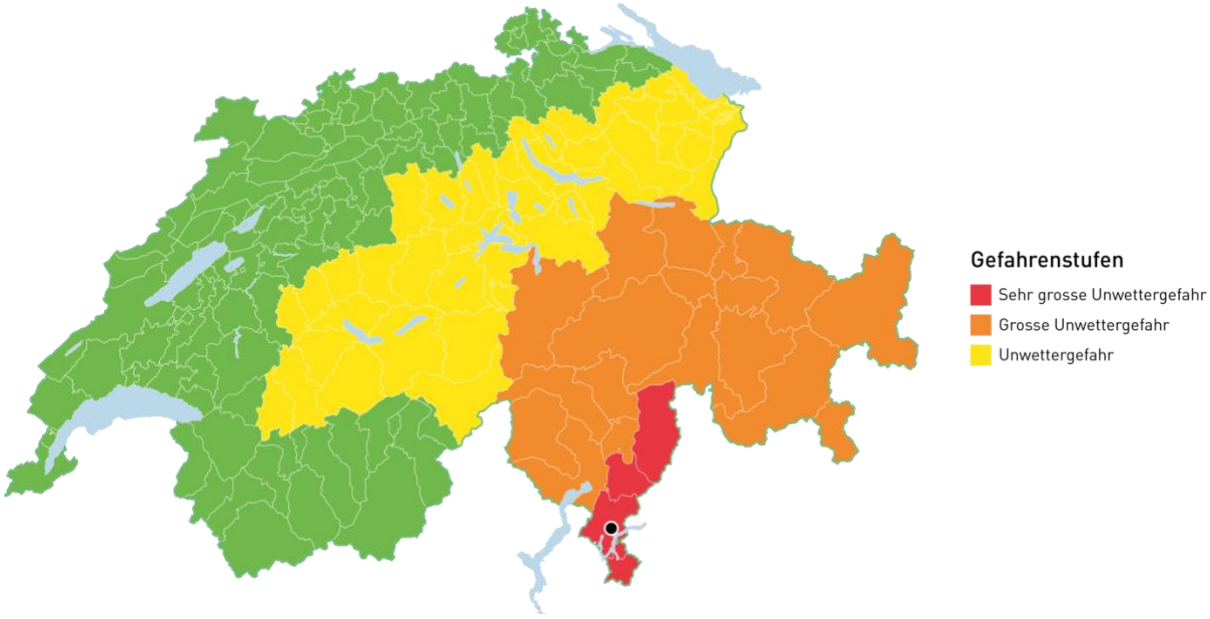
B.1) Figures

Figure S1: Type AA - Consistent warnings - Rainfall warning from provider A



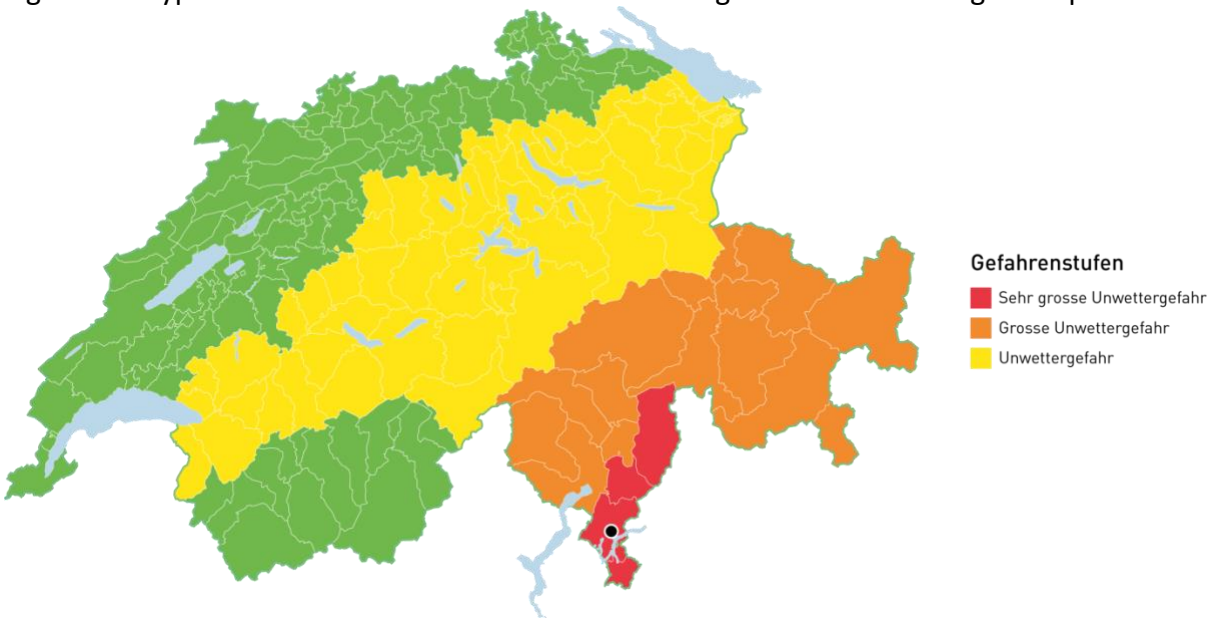
At the weekend, there will be intense rainfall in Ticino. Precipitation of up to 100 l/m^2 in 24 hours must be expected in the entire region, whereas levels of rainfall of up to 120 l/m^2 can occur in the southern part (Sottoceneri). In the night to Sunday, the rain decreases significantly.

Figure S2: Type AA - Consistent warnings - Rainfall warning from provider B



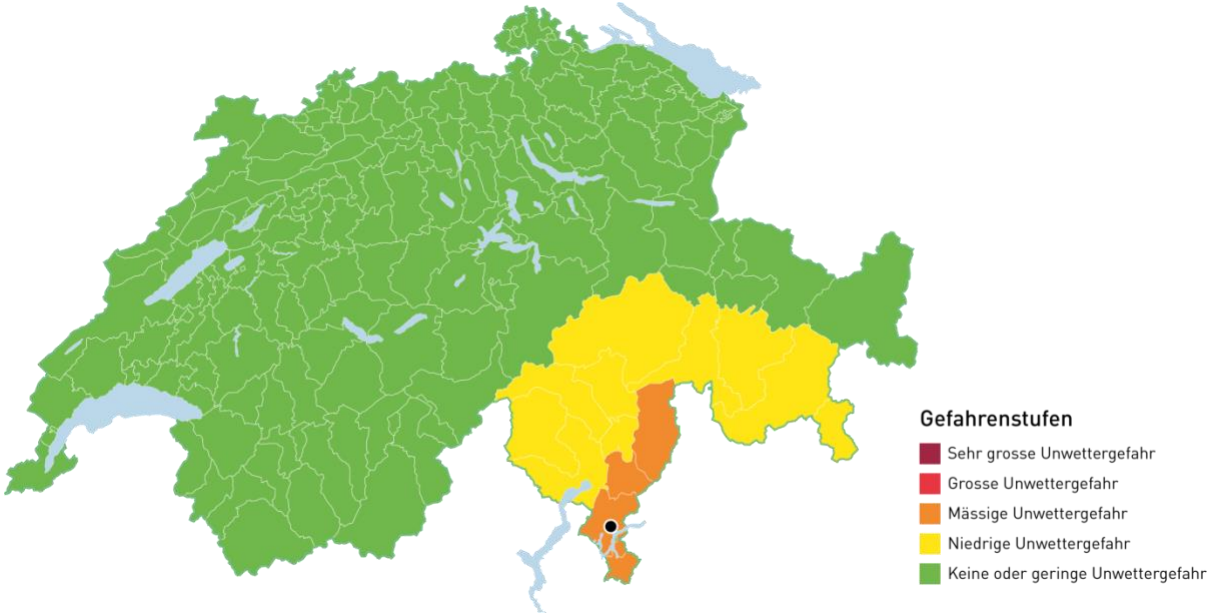
Intense rainfall is expected in Ticino on Saturday and Sunday. Rainfall in Ticino will vary between 90 and 120 l/m^2 in 24 hours, whereas the highest precipitation rates are expected in the southern part of the canton (Sottoceneri). At Sunday night, the rain decreases significantly.

Figure S3: Type AB - Visualization inconsistent warnings - Rainfall warning from provider A



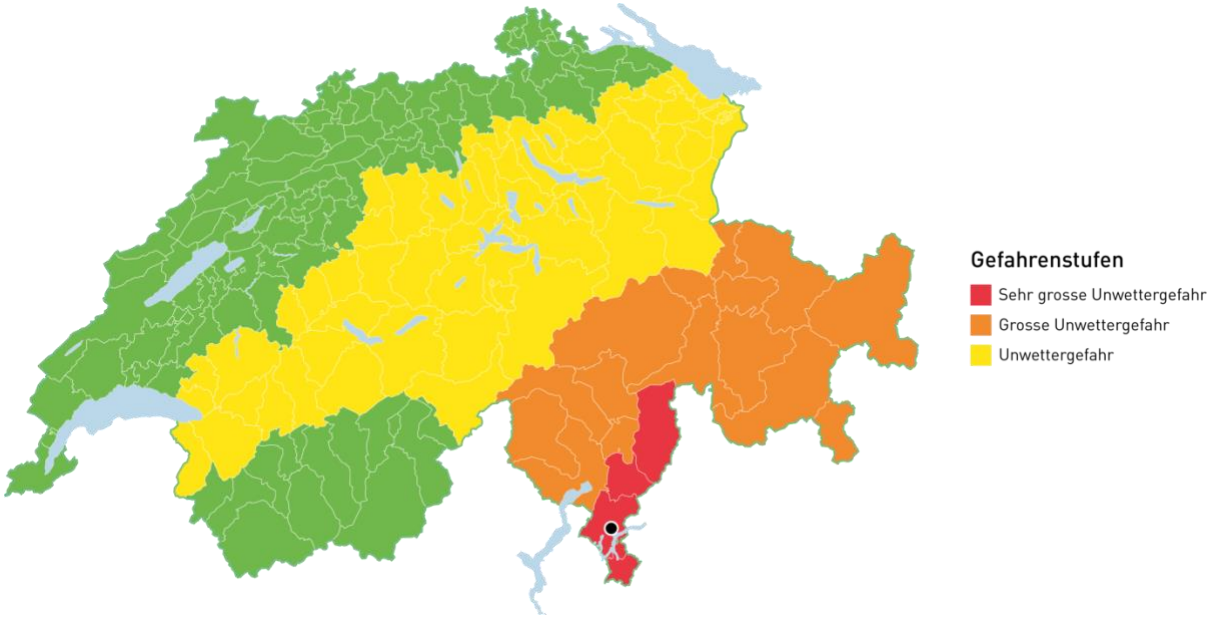
At the weekend, there will be intense rainfall in Ticino. Precipitation of up to 100 l/m^2 in 24 hours must be expected in the entire region, whereas levels of rainfall of up to 120 l/m^2 can occur in the southern part (Sottoceneri). In the night to Sunday, the rain decreases significantly.

Figure S4: Type AB - Visualization inconsistent warnings - Rainfall warning from provider B



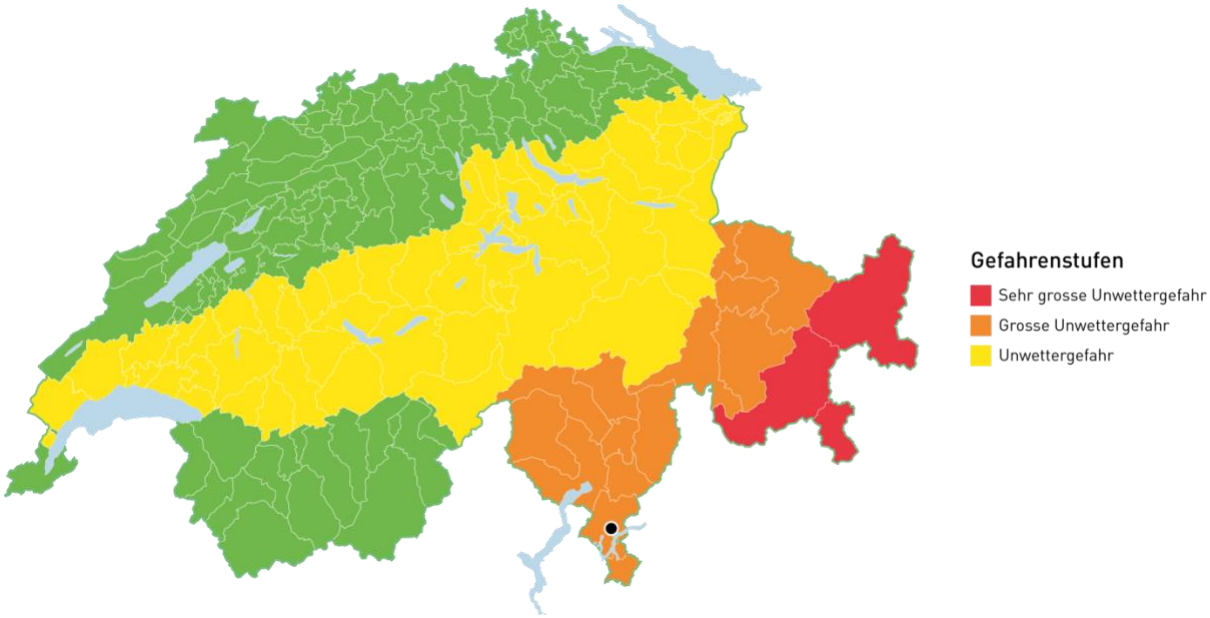
Intense rainfall is expected in Ticino on Saturday and Sunday. Rainfall in Ticino will vary between 90 and 120 l/m^2 in 24 hours, whereas the highest precipitation rates are expected in the southern part of the canton (Sottoceneri). At Sunday night, the rain decreases significantly.

Figure S5: Type AC - Message inconsistent warnings - Rainfall warning from provider A



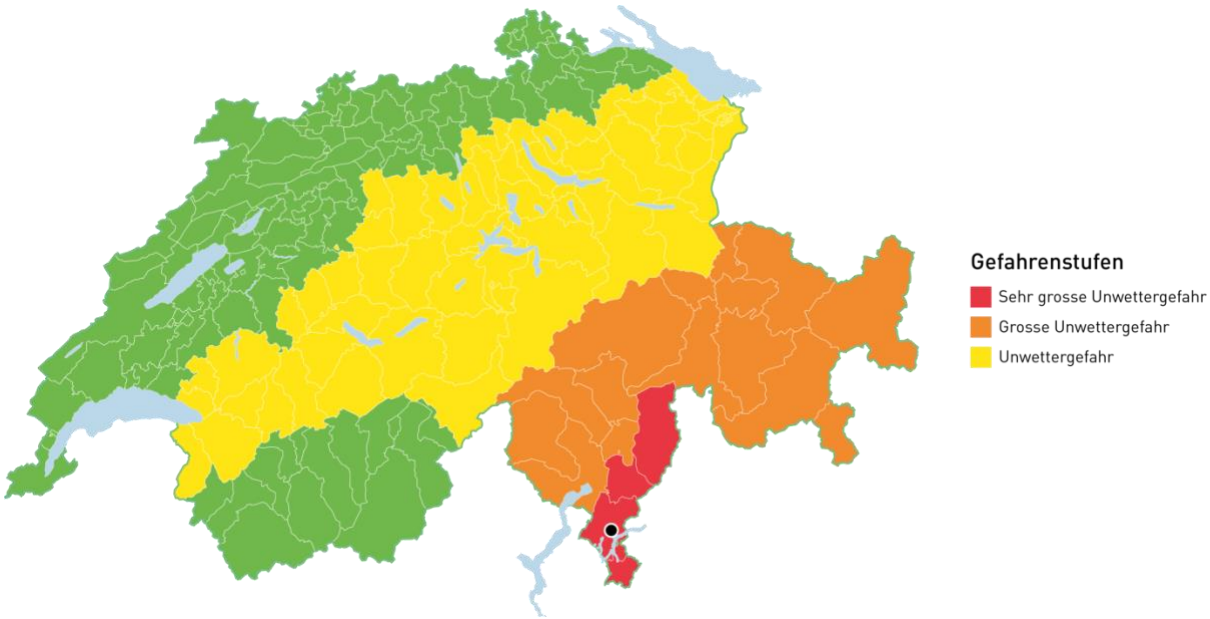
At the weekend, there will be intense rainfall in Ticino. Precipitation of up to 100 l/m^2 in 24 hours must be expected in the entire region, whereas levels of rainfall of up to 120 l/m^2 can occur in the southern part (Sottoceneri). In the night to Sunday, the rain decreases significantly.

Figure S6: Type AC - Message inconsistent warnings - Rainfall warning from provider B



Heavy rainfall is expected in Ticino on Saturday and Sunday. Rainfall are expected to vary between 50 and 100 l/m^2 in 24 hours. At Sunday night, the rain decreases significantly.

Figure S7: Type AD – Visualization and message inconsistent warnings - Rainfall warning from provider A



At the weekend, there will be intense rainfall in Ticino. Precipitation of up to 100 l/m^2 in 24 hours must be expected in the entire region, whereas levels of rainfall of up to 120 l/m^2 can occur in the southern part (Sottoceneri). In the night to Sunday, the rain decreases significantly.

Figure S8: Type AD – Visualization and message inconsistent warnings - Rainfall warning from provider B

Heavy rainfall is expected in Ticino on Saturday and Sunday. 70 l of rain per m^2 are expected in 24 hours. At Sunday night, the rain decreases significantly.

B.2) Questionnaire

Note that all questionnaires were identical, but the warning information provided (see Figures S1-S8). Here we provide the type AA warning. The original questionnaire was in German language. Instructions are in *italic*.

1) Greeting

Dear Sir or Madam,

Thank you for taking the time to complete the online survey on the communication of weather warnings. With the technical support of the Federal Office for Meteorology and Climatology MeteoSwiss, we investigate possibilities for improvement in the communication of severe weather warnings. The interview takes about 10 minutes. Your participation is voluntary and all information is evaluated anonymously and treated in accordance with the provisions of data protection.

If you have any questions, please feel free to contact the Climate Policy Group lead by Prof. Anthony Patt, Department of Environmental Systems Science at ETH Zurich ((+41) 44 632 28 39; philippe.weyrich@usys.ethz.ch).

Thank you very much for your participation,

Philippe Weyrich

2) Introduction

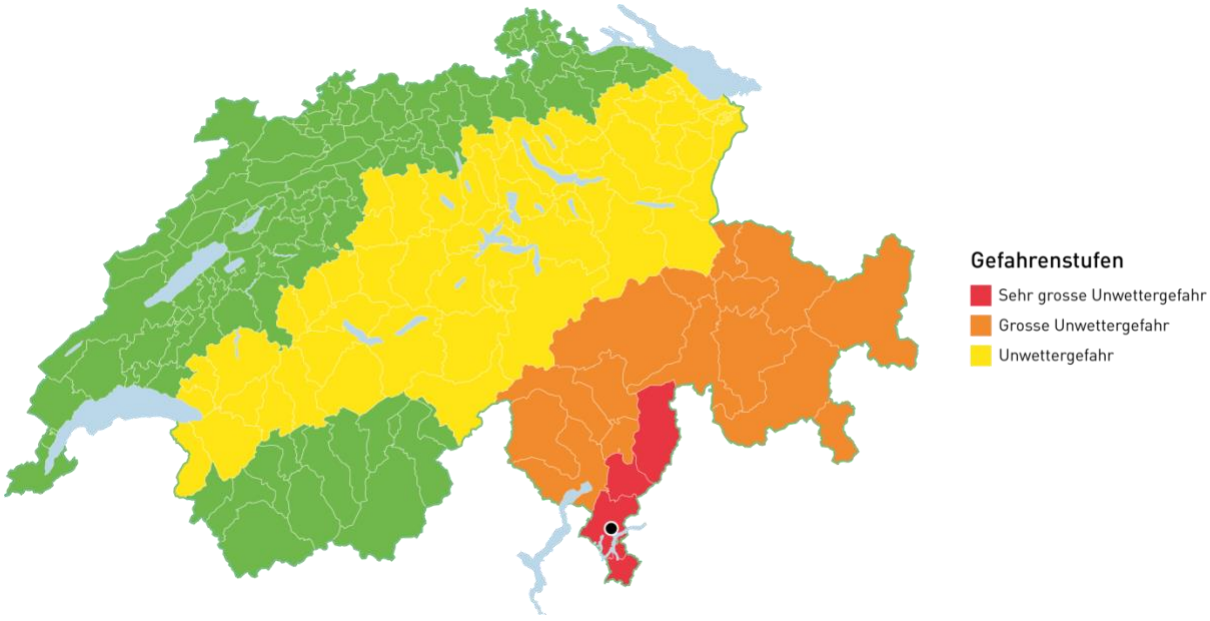
In this study, you will have to answer general questions about weather and warnings. However, you will not only have to answer "conventional" questions, but you are also introduced into a scenario. In this scenario, you will receive simultaneously two different warnings for a same weather event and will have to evaluate them. We start with the scenario. After answering a question or a question block, you can no longer navigate back.

3) Warning messages and questionnaire

In the following, you will be introduced into a scenario in which you will receive either two very similar warnings or two different warnings from different weather providers. These warnings may differ on the one hand in their categorization and visualization, and on the other hand in the message content (i.e., the severity of the weather phenomenon). Each warning includes a warning map of Switzerland and a warning text that describes the weather in Ticino in more detail. It is important that you accurately study the warning map and text. After studying the warnings, you will have to evaluate them and answer more general questions.

It is 19 o'clock in the evening on a Friday. Almost simultaneously you see the following two severe weather warnings, which are valid for the next day. However, for your birthday tomorrow, you have planned a big birthday party with barbecue with all your friends on Lake Lugano. How do you react?

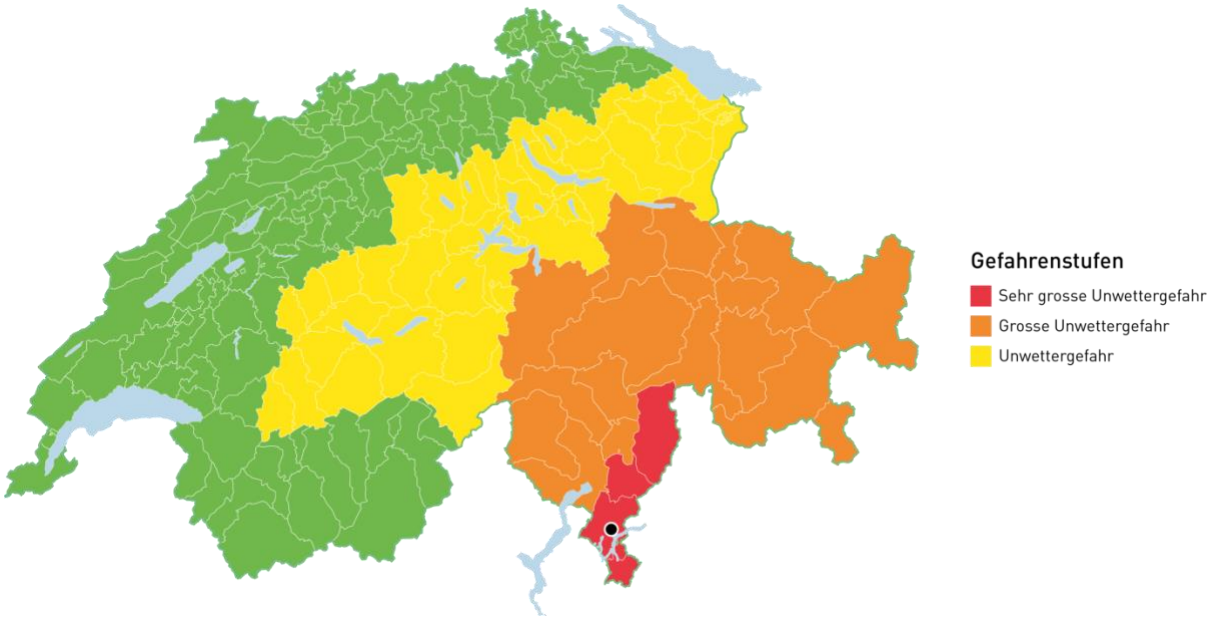
Rainfall warning from provider A



At the weekend, there will be intense rainfall in Ticino. Precipitation of up to 100 l/m^2 in 24 hours must be expected in the entire region, whereas levels of rainfall of up to 120 l/m^2 can

occur in the southern part (Sottoceneri). In the night to Sunday, the rain decreases significantly.

Rainfall warning from provider B



Intense rainfall is expected in Ticino on Saturday and Sunday. Rainfall in Ticino will vary between 90 and 120 l/m^2 in 24 hours, whereas the highest precipitation rates are expected in the southern part of the canton (Sottoceneri). At Sunday night, the rain decreases significantly.

Thinking about the warning message from provider A you have just received; how would you rate the warning?

	Not at all	*Rather not*	*Neither*	*Rather*	*Very*
The warning is comprehensible.	☐	☐	☐	☐	☐
The warning is credible.	☐	☐	☐	☐	☐
I find the warning meaningful.	☐	☐	☐	☐	☐

Thinking about the warning message from provider B you have just received; how would you rate the warning?

	Not at all	*Rather not*	*Neither*	*Rather*	*Very*
The warning is comprehensible.	☐	☐	☐	☐	☐

The warning is credible.	□	□	□	□	□
I find the warning meaningful.	□	□	□	□	□

Thinking about the two warnings you have received almost simultaneously; how would you rate the warnings overall?

	Not at all	*Rather not*	*Neither*	*Rather*	*Very*
The warnings are in agreement.	□	□	□	□	□
The warnings are easy to understand.	□	□	□	□	□

What do you do? Thinking about the warnings, how strongly do you agree or disagree with the following statements?

	Totally disagree	*Disagree*	*Neither*	*Agree*	*Totally agree*
I would cancel the party and barbecue.	□	□	□	□	□
I would look for more weather information.	□	□	□	□	□

Regarding the decision, you have just made, whether to cancel the event or not, have you relied more on one warning to make a decision? *Please select one statement.*

I relied on warning A.	I relied on both taken together.	I relied on warning B.
□	□	□

What was the reason?

	Yes	*No*	*Not applicable*
I relied on the most severe warning to be on the safe side.	□	□	□
I relied on the warning based on the visualization (e.g. number of colours and categories).	□	□	□
Other reason? (please specify)			

Please answer the following questions regarding the warning information you've received.

	Yes	*No*	*Don't know*

Is the visualization of information different among the two warnings?	☐	☐	☐
Is the degree of severity of weather in warning message different among the two warnings?	☐	☐	☐

The scenario above was imaginary. Here, we are interested in your beliefs about actual weather forecasts in Switzerland.

Please indicate whether you believe that the following statements are right or wrong.

	True	*False*	*Don't know*
MeteoSwiss is the only provider of weather information in Switzerland.	☐	☐	☐
MeteoSwiss has a legal mandate to warn the authorities and the general public from severe meteorological hazards in Switzerland.			
In Switzerland some private weather providers offer weather warnings in addition to general weather information (e.g. forecasts).	☐	☐	☐
Swiss weather providers use the same number of warning categories.	☐	☐	☐

Next, we are interested in your general weather and warning information behaviour. There are 5 questions.

Do you inform yourself about the weather?

Yes	*No*
☐	☐

If yes, which sources do you use?

	Yes	*No*
TV	☐	☐
Radio	☐	☐
Newspapers	☐	☐
Websites (e.g. met providers, press)	☐	☐
Social media (e.g. Facebook, Twitter)	☐	☐
Own observations	☐	☐
Smartphone weather apps	☐	☐

SMS/FAX-/E-mail-information service (incl. newsletters)	□	□
Information by family or friends	□	□

How often do you usually receive information from the sources mentioned above?

Daily	*Several times a week*	*In preparation for outdoor activities*	*Occasionally if the weather seems unusual*	*Rarely or never*
□	□	□	□	□

Do you regularly consult weather information from more than one weather provider?

Yes	*No*
□	□

When do you consult weather information from more than one provider?

	Yes	*No*
Depending on the natural hazard	□	□
Depending on the severity	□	□
Depending on personal (travel/outdoor/etc.) plans	□	□
Other reason? (please name)		

In the following, we are interested in your experience with severe weather events and warnings. There will be up to 7 questions to answer.

Have you ever been personally affected by a severe weather event?

Yes	*No*	*Don't know*
□	□	□

If yes, in what ways have you been affected?

	Never	Once	Multiple times
Had travel plans disrupted.	□	□	□
Experienced a power outage.	□	□	□
Felt intense fear for my life.	□	□	□
Suffered property damage.	□	□	□

Suffered an injury or know someone to have been severely injured or killed.	□	□	□

Have you already received one or more severe weather warning(s)?

Yes	*No*	*Don't know*
□	□	□

If you remember the last severe weather warning you have received, how was your experience?

	Yes	*No*	*Don't know*
The event did happen.	□	□	□
The warning level (i.e. the severity of the hazard) was roughly accurate.	□	□	□
The time information (regarding beginning and duration of event) was correct.	□	□	□

If you remember the last severe weather warning you have received, did you change your behaviour in response to the warning message?

Yes	*No*	*Don't know*
□	□	□

Have you already received several warnings from different weather providers (e.g. MeteoSwiss, SRF Meteo, Meteonews, Meteocentrale, etc.) for a same weather event?

Yes	*No*	*Don't know*
□	□	□

If yes, was the information in direct contradiction?

Not at all contradicted	*Somewhat contradicted*	*Very contradicted*	*Don't know*
□	□	□	□

Considering both the likelihood and potential consequences of severe weather events, please indicate, how strongly you agree or disagree with each of the following statements. *Bad weather could pose a threat to…*

	Totally disagree	*Disagree*	*Neither*	*Agree*	*Totally agree*
my personal safety.	□	□	□	□	□
the safety of my friends and family.	□	□	□	□	□
my property.	□	□	□	□	□
my daily life (e.g. work, leisure).	□	□	□	□	□

Next, we are interested in people's general knowledge about (bad) weather and knowledge; including understanding how this knowledge might influence behaviour. There are 3 questions.

True or false: A warning outlook is a forecast of an expected danger and serves as a basis for decision-making (probability >= 70%). A warning is a preview of possible bad weather for the next 5 days (probability >= 40%).

☐ True
☐ False

If it's 20 degree Celsius during the day and the air pressure is high, what type of weather conditions are likely to occur at night?

☐ Cloudy
☐ Rainy
☐ Clear conditions
☐ None of the above

Maximum lead times to warn from bad weather can differ depending on the hazard: For instance, winter storms can be predicted with more than one day in advance, whereas thunderstorms can only be accurately predicted a few hours in advance?

☐ True
☐ False

4) Preferences

Finally, two last questions before we move to the socio-demographic part of the survey.

If you had the choice between one warning or more warnings (i.e. from different weather providers) for a very severe bad weather event (rainfall), what would be your preference? *Which of the following statements most accurately describes your preference?*

For a same weather event, I would like to receive only one harmonized warning from the national authorities.	☐
For a same weather event, I would like to receive several warnings from various weather providers that are visualized differently.	☐
For a same weather event, I would like to receive several warnings from various weather providers that may differ in the message content.	☐
I have no preference.	☐

If you had the choice between one warning or more warnings (i.e. from different weather providers) for a non-severe bad weather event (rainfall), what would be your preference? *Which of the following statements most accurately describes your preference?*

For a same weather event, I would like to receive only one harmonized warning from the national authorities.	☐
For a same weather event, I would like to receive several warnings from various weather providers that are visualized differently.	☐

For a same weather event, I would like to receive several warnings from various weather providers that may differ in the message content.	☐
I have no preference.	☐

5) Socio-demographic Data

In the last part of the survey, we would like to ask 5 questions concerning your person.

What is your sex?

Female	*Male*	*None/Both*
☐	☐	☐

What is your age?

I have or have already had professional or honorary work experience with natural hazards and/or warnings.

Yes	*No*
☐	☐

Please indicate your highest level of education.

Compulsory education	☐
Apprenticeship	☐
Highschool	☐
Vocational school	☐
Professional school	☐
University, ETH	☐

How would you describe your place of residence?

City	Agglomeration community	A town or village centre outside of agglomeration	Rural, outside of village
☐	☐	☐	☐

6) Questions/Comments

Do you have any questions or comments?

If you have further questions or if you are interested in learning the results of this research, please send an email to Philippe Weyrich, philippe.weyrich@usys.ethz.ch

Appendix C

Supplementary Information for the paper "Effects of impact-based warnings and behavioural recommendations for extreme weather events".

C.1) Questionnaire

Note that all questionnaires were identical, but the warning message provided (see Tables 1 and 2 for different warning messages). Here we provide the impact-based warning with the behavioural recommendations. The original questionnaire was in German language. Instructions are in *italic*.

1. Greeting

Dear Sir or Madam,

Thank you for taking the time to complete the online survey on the communication of weather warnings. With the technical support of the Federal Office for Meteorology and Climatology MeteoSwiss, we investigate possibilities for improvement in the communication of severe weather warnings. The interview takes about 10 minutes. Your participation is voluntary and all information is evaluated anonymously and treated in accordance with the provisions of data protection.

If you have any questions, please feel free to contact the Climate Policy Group lead by Prof. Anthony Patt, Department of Environmental Systems Science at ETH Zurich ((+41) 44 632 28 39; philippe.weyrich@usys.ethz.ch).

Thank you very much for your participation,

Philippe Weyrich

2. Questionnaire

In this study, you will have to answer general questions about thunderstorm warnings. You are also introduced into a scenario, in which you receive a warning, and will have to make decisions in response to the warning. A thunderstorm is a complex meteorological phenomenon and is characterized by electric discharges (lightning), heavy rainfall, as well as sometimes, hail and strong winds. In the questions, we always relate to a thunderstorm of category 4 (on a five-point scale), which means a severe to very severe thunderstorm and represents a great to very great danger for the population.

After answering a question or a question block, you can no longer navigate back.

Considering both the likelihood and potential consequences of two natural hazards, heavy snowfall and severe thunderstorms, throughout the year, how do you rate the overall risk to you and your family from thunderstorms compared to snowfall?

1 Snowfall much riskier	*2*	*3*	*4*	*5* About equal	*6*	*7*	*8*	*9*	*10* Thunderstorms

									much riskier
□	□	□	□	□	□	□	□	□	□

3. Warning message and scenario

In the following, you will be introduced into a scenario in which you will receive a weather warning from the Federal Office of Meteorology and Climatology MeteoSwiss. After reading through the warning, you have to take some decisions, as well as evaluate the warning information.

Thunderstorm Scenario

Thunderstorm;
Serious danger
Category 4
Validity: 24.08.2017, 2.30pm – 24.08.2017, 6pm

- Type of thunderstorm: Thunderstorm line
- Movement: pulling from Southwest
- Particularly affected areas: Jura
- Accompanying factors: wind gusts >120km/h, hail 2-4cm, heavy rain >50mm/h

Thunderstorm: In the case of rapidly developing thunderstorms, you have to expect strong wind gusts, as well as hail. Heavy wind often occurs before lightning activity and heavy rain showers.
Source: Radar images and measurements on the ground
Possible Impacts:

- Flash flooding of streams
- Toppling of trees
- Possibility of landslides on steep slopes
- Damage from hail and lightning strikes
- Failure of drainage and sewer systems. Flooding of underpasses, underground garages and cellars
- Disruption to road, rail and traffic
- Danger to vessels on lakes from very strong gusts of wind arising rapidly without warning

General recommendations during a thunderstorm:

- Avoid mountain ridges, exposed trees, groups of trees, masts and towers, all of which are at risk of lightning strikes
- Seek shelter – in a building or car (acts as a Faraday cage)
- If there is no shelter in sight, assume a crouched position
- Do not go hiking in the mountains and renounce to all outdoor activities
- Stay away from metal objects and water
- If a thunderstorm takes you by surprise when swimming, get out of the water immediately
- Drive slowly on flooded stretches of road, or avoid these altogether
- Avoid stream beds and steeply inclined slopes

Imagine it's 2pm on a Sunday afternoon. You are walking in the countryside in the foothills of the Jura Mountains when you get a thunderstorm warning message on your smartphone. You

are walking in a valley and next to a small stream. The following warning applies to your hiking area, is valid from 2.30 pm to 6pm.

Thinking about this warning, how strongly do you agree or disagree with each of the following statements?

	Totally disagree	*Disagree*	*Neither*	*Agree*	*Totally agree*
I would not alter my plans because of the information.	☐	☐	☐	☐	☐
I continue with the hike but avoid potential dangers (keep away from stream beds, towers, etc.) and make sure that a suitable shelter (e.g. building, car) can always be reached quickly.	☐	☐	☐	☐	☐
I immediately interrupt the hike and take care of my own safety.	☐	☐	☐	☐	☐
Check out other information sources (e.g. news, websites of other weather providers, other people) via my smartphone for confirmation or advice.	☐	☐	☐	☐	☐
I pay close attention to the sky, wind, and sounds of possible thunder.	☐	☐	☐	☐	☐

Thinking about this warning, how strongly do you agree or disagree with each of the following statements?

	Totally disagree	*Disagree*	*Neither*	*Agree*	*Totally agree*
The warning is clear and easy to understand.	☐	☐	☐	☐	☐
I believe the message to be credible.	☐	☐	☐	☐	☐
The warning makes me concerned for my safety.	☐	☐	☐	☐	☐
Based on the warning I understand the threats to my safety.	☐	☐	☐	☐	☐
Based on the warning it is clear to me how I should modify my behavior, if necessary.	☐	☐	☐	☐	☐

Moving from this scenario to thinking about thunderstorms in general, please indicate, how strongly you agree or disagree with each of the following statements. *Severe thunderstorms could pose a threat to…*

	Totally disagree	*Disagree*	*Neither*	*Agree*	*Totally agree*
my personal safety.	☐	☐	☐	☐	☐

the safety of my friends and family.	□	□	□	□	□
my property.	□	□	□	□	□
my daily life (e.g. work, leisure).	□	□	□	□	□

4. Experience with thunderstorms and warnings

In the following, we are interested in your experience with thunderstorms and warnings. There will be up to 6 questions to answer.

Have you ever been personally affected by a thunderstorm?

Yes	*No*	*Don't know*
□	□	□

If yes, in what ways have you been affected?

	Never	Once	Multiple times
Had travel plans disrupted.	□	□	□
Had my shopping and other daily activities disrupted.	□	□	□
Suffered a power blackout.	□	□	□
Felt intense fear for my life.	□	□	□
Suffered minor property damage (<1000 CHF).	□	□	□
Suffered major property damage (>1000 CHF).	□	□	□
Suffered an injury.	□	□	□
Known someone to have been severely injured or killed.	□	□	□

Have you already received one or more thunderstorm warning(s)?

Yes	*No*	*Don't know*
□	□	□

If yes, did you change your behaviour?

Yes	*No*	*Don't know*
□	□	□

If yes, what action(s) have you taken?

Protective action	*Seek information*
□	□

If you remember the last thunderstorm warning you had received, how was your experience?

	Yes	*No*	*Don't know*
The event did happen.	□	□	□
The warning level (i.e. the severity of the thunderstorm) was roughly accurate.	□	□	□
The time information (regarding beginning and duration of event) was correct.	□	□	□

5. Knowledge

We are interested in people's general knowledge of thunderstorms; including understanding how this knowledge might influence behaviour. In the following quiz, only one answer option per question is correct. There are 8 questions in total.

Conditions for a thunderstorm are?

□ Enough moisture and a quick rise of air
□ Enough moisture and a quick descent of air
□ Low humidity and a rapid rise of air

What happens in a cold front storm?

□ Warm air pushes under the cold air
□ Moist warm air hits a cold air front
□ Warm air rises and is cooled down by the ambient air

How do you call a storm cloud in technical language?

□ Cumulus cloud
□ Storm cell
□ Cumulonimbus cloud
□ Nimbus cloud

If you count the seconds between the lightning and the thunder, you can obtain the approximate distance of the thunderstorm in km by dividing this number by what?

□ The half
□ Twenty
□ Three
□ Four

If you are engaging in any of the following activities during a thunderstorm, in which case is your risk the highest?

□ Swimming outdoors
□ Playing on computer
□ Biking
□ Hiking

Which of the following descriptions are possible with thunderstorms (in Switzerland)?

□ Wind gusts of over 120 km/h
□ Hailstones with a diameter of more than 5 cm
□ Rainfall of more than 50 mm/h
□ Lightning strikes with temperatures of up to 30000°C
□ All descriptions are correct

True or false: It is possible to predict and warn against heat thunderstorms very accurately in their strength, in time and place, several hours in advance?

□ True
□ False

During a thunderstorm, how should you behave if you find yourself in an open landscape with isolated trees?

- ☐ Assume a crouched position
- ☐ Lay flat on the ground
- ☐ Stand under a tree

6. Sociodemographic data

In the last part of the survey, we would like to ask 4 questions concerning your person.

What is your sex?

Female	*Male*	*Neither/Both*
☐	☐	☐

What is your age?

Please indicate your highest level of education

Compulsory education	☐
Apprenticeship	☐
Highschool	☐
Vocational school	☐
Professional school	☐
University, ETH	☐

How would you describe your place of residence?

City	Agglomeration community	A town or village centre outside of agglomeration	Rural, outside of village
☐	☐	☐	☐

7. Questions/Comments

Do you have any questions or comments? Were there any questions that confused you?

If you have further questions or if you are interested in learning the results of this research, please send an email to Philippe Weyrich, philippe.weyrich@usys.ethz.ch

Appendix D

Supplementary Information for the paper "Responses to severe weather warnings are consistent with an affective decision-making model rather than rational deliberation".

D.1) Supplementary text, figures and tables

We worked together with the providers of the existing Swiss weather app Wetter-Alarm. The application resulted out of a cooperation between the GVB Services AG (which is responsible for the app) and SRF Meteo, which provides the weather (i.e., warnings for frost, thunderstorm, slipperiness, rain, snow and wind among others). The users could receive warnings for three severity levels: moderate (slight risk of damage), severe (increased risk of damage) and very severe (big risk of damage or even risk of death). The standard warnings disseminated in the Wetter-Alarm app included information about the type of hazard, its severity, the timing and location, as well as some general behavioural recommendations (e.g., secure lose items or avoid forests). Figure S1 shows a standard wind warning of medium severity. The impact-based warning included the identical information than the SW, but with an additional impact information of the weather which are shown in Table S2. We developed these messages based on publicly available information on impacts of wind in Switzerland and in close collaboration with the staff of Wetter-Alarm. During the data collection period (from 1.12.2018 to 10.02.2019), 86 different wind warning messages were disseminated for specific regions across Switzerland. The respectively high number of warnings can be explained by the many updates that happen during a warning phase. For instance, forecasters may have to extend the warning area or the timing.

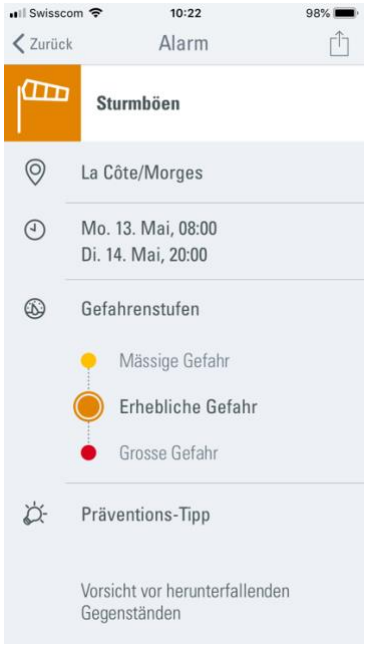


Figure S1. Standard wind warning of medium severity level for the region La Côte/Morges.

Table S1. Socio-demographic characteristics of participants in the field experiment.

Gender	Males: n=1645, 63.1 % Females: n=970, 56.9 %
Age	48.8 years
Completed educational level	34.6 % vocational school, 20.2 % university degree, 19.2 % collage, 18.9 % technical or high school, 7.1 % some compulsory education

Table S2. Additional impact-based information per severity level in the impact-based warnings. Note that we did not observe any very severe (level 3) warnings during the data collection period.

Warning severity level		
Moderate (level 1)	*Severe (level 2)*	*Very severe (level 3)*
Traffic delay	Traffic disruption or restriction	Traffic disruptions or standstill
Overturning of objects	Damage to individual buildings/roofs	Damage to buildings/roofs
Falling of smaller branches	Falling of big branches	Falling trees

D.2) Questionnaire

1. Did you receive the warning via push message?

Yes	No
□	□

2. Have you looked at the wind warning above the survey link?

Yes	No
□	□

Continue only if yes.

3. What feelings did the warning trigger? Please indicate to what extent the following statements apply to you or do not apply.

	Strongly disagree	*Disagree*	*Neither*	*Agree*	*Strongly agree*
I was relaxed.	□	□	□	□	□
I was scared.	□	□	□	□	□
I was worried.	□	□	□	□	□
I was reassured.	□	□	□	□	□
I was angry.	□	□	□	□	□

4. How do you find the information in this warning?

	Strongly disagree	*Disagree*	*Neither*	*Agree*	*Strongly agree*
The warning is clear and easy to understand.	☐	☐	☐	☐	☐
I believe the message to be credible.	☐	☐	☐	☐	☐
The warning makes me concerned for my safety.	☐	☐	☐	☐	☐
Based on the warning I understand the threats to my safety.	☐	☐	☐	☐	☐
Based on the warning it is clear to me how I should modify my behavior, if necessary.	☐	☐	☐	☐	☐

5. Does the weather described in the warning pose a risk to you

Yes	No
☐	☐

6. Does the weather described in the warning affect you in your normal duties*?

Yes	No
☐	☐

*(Any examples of usual activities: work, leisure, commute, shopping and other daily activities, etc.)

7. Have you already responded to the warning?

Yes	No
☐	☐

If yes

6A. How did you react to the warning? Which of the following describes best what you did?

Adapting: I have adapted, but continued with my activitiy(s).	Protecting: I have canceled, or postponed my activity(s) or even taken countermeasures* to protect myself or my property
☐	☐

* (Any countermeasures to protect his/her property: keep the car in the garage, secure loose items around the house, etc.)

If no.

6B. Are you still planning to respond to the warning? Which of the following statements describes best your action-taking?

Nothing/No: I have looked at the warning, but I will continue my activity (s) as usual.	Adapting: I will adapt my activity (s) soon, but continue to do so.	Protecting: I will cancel or postpone my activity (s) soon or even take countermeasures * to protect myself or my property.
□	□	□

* (Any countermeasures to protect his/her property: keep the car in the garage, secure loose items around the house, etc.)

If no.

6C. Why did not you respond to the warning? Which of the following statements best describes the reason for your inaction?

I believe that it is not necessary.	The warning does not affect me locally.	My preparations for the last severe weather warning are already in place, so I have nothing else to do.	I did not see or hear the bad weather warning in time to change my plans.	It is not possible to change my activity (s).	Other
□	□	□	□	□	

8. Have you consulted any other sources of information for confirmation or advice (for example, TV, radio, websites, weather apps, etc.).

Yes	No
□	□

9. Where did you search?

	Yes	No
In the app Wetter-Alarm	□	□
In another weather app	□	□
On websites	□	□
On the radio or TV	□	□
With family, friends or colleagues	□	□

10. Please specify your gender .

Female	*Male*	*Other*
□	□	□

11. Please indicate your age.

12. Please state your highest educational qualification.

Compulsory education	☐
Apprenticeship	☐
Highschool	☐
University, ETH	☐

13. What was the severity level of the warning to which you responded?

1	2	3
☐	☐	☐

14. Have you recently participated in a similar survey on Wetter-Alarm to evaluate a warning?

Yes	No
☐	☐

Do you have any comments / questions?
Thank you for your participation in the study. Your participation helps us to analyze the effectiveness of impact-based warnings compared to standard warnings.