Lack of Change in the Projected Frequency and Persistence of Atmospheric Circulation Types Over Central Europe

Journal Article

Author(s):
Huguenin, Maurice F.; Fischer, Erich M.; Kotlarski, Sven; Scherrer, Simon C.; Schwierz, Cornelia; Knutti, Reto

Publication date:
2020-05-16

Permanent link:
https://doi.org/10.3929/ethz-b-000415872

Originally published in:
Geophysical Research Letters 47(9), https://doi.org/10.1029/2019GL086132

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL086132

Lack of Change in the Projected Frequency and Persistence of Atmospheric Circulation Types Over Central Europe

Maurice F. Huguenin[1,2,3], Erich M. Fischer[1], Sven Kotlarski[2], Simon C. Scherrer[2], Cornelia Schwierz[2], and Reto Knutti[1]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland, [2]Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland, [3]Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, New South Wales, Australia

Key Points:
- Climate models project warmer and drier Central European summer conditions under strong global warming independent of the circulation type
- For most circulation types, the models do not agree on the sign and/or magnitude of the projected change in the frequency and persistence
- Current global climate models do not support a general trend towards more persistent weather in Central Europe

Supporting Information:
- Supporting Information S1

Correspondence to:
M. F. Huguenin,
m.huguenin-virchaux@unsw.edu.au

Citation:
Huguenin, M. F., Fischer, E. M., Kotlarski, S., Scherrer, S. C., Schwierz, C., & Knutti, R. (2020). Lack of change in the projected frequency and persistence of atmospheric circulation types over Central Europe. *Geophysical Research Letters*, *47*. https://doi.org/10.1029/2019GL086132

Received 6 NOV 2019
Accepted 24 MAR 2020

Abstract In recent summers, Europe experienced record-breaking heatwaves, wildfires (in Northern Europe), and large-scale water scarcity. Apart from anthropogenic warming, one contribution leading to such exceptionally hot weather was a weaker jet stream allowing a quasi-stationary high-pressure system to persist for many days. Here, we quantify changes in the frequency and persistence of the Central European large-scale circulation types using various climate models. Independent of the circulation type, the models project warmer and drier future summer conditions in Central Europe, but no consistent shift to a more persistent summer or winter circulation. Most of the frequency and persistence changes are small and either within the internal variability or inconsistent across models. The model projections in this study do not support the claim of more persistent weather over Central Europe. Reconciling the results of different approaches and classifications is therefore critical to understand and predict changes in extreme weather over Europe.

Plain Language Summary The atmospheric flow over Central Europe is a key component of both its weather and climate. Recent studies have suggested that the Central European weather patterns are becoming more persistent due to our influence on the climate system. Persistent conditions can lead to record-breaking droughts and heatwaves. It is therefore important to know how the flow conditions (also called circulation types) may change in the future. Here, we use a wide range of global climate models and classify a circulation type for each day. We distinguish between the eight main wind directions and a high- and low-pressure type. Then, we quantify changes in the frequency and length of these circulation types under a strong global warming scenario at the end of the 21st century. In summer, we find a shift to warmer and drier conditions. Our models also show somewhat more persistent summer westerlies. In winter, the changes are not clear. Most of the changes in the circulation are small and likely within the range expected from natural random weather fluctuations. Our study highlights the importance of using many different climate models and other methods to investigate the highly variable Central European circulation today and under a future climate.

1. Introduction

The Central European weather and climate is controlled by the large-scale extratropical atmospheric flow of which the midlatitude westerly jet streams are key components (Woollings et al., 2010). There are two physical processes that give rise to the strength and position of the subtropical and eddy-driven jets: the westerly acceleration of poleward moving air consistent with the local vorticity balance as well as the momentum and heat forcing arising from transient eddies (Peña-Ortiz et al., 2013; Woollings et al., 2010). Most often, there is no spatial separation between individual jet streams (Woollings et al., 2010). As a result of human-induced climate change, the hemispheric lower-tropospheric temperature gradient is projected to weaken, and may thus impact on the jet streams and the atmospheric circulation over the European continent downstream (Blackport & Screen, 2019; Coumou et al., 2018; Coumou & Rahmstorf, 2012; Intergovernmental Panel on Climate Change [IPCC], 2014; Jézéquel et al., 2018; Mori et al., 2019; Steirou et al., 2017).

To study the regional impacts and long-term changes in the atmospheric circulation over Central Europe, the large-scale flow is commonly classified into different circulation types (Demuzere et al., 2011;

Kučerová et al., 2017), each with a characteristic temperature and precipitation signal on the continent. Persistent circulation types are often associated with the occurrence of extreme events resulting in drought and heatwaves in summer (Perkins, 2015; Pfleiderer & Coumou, 2018; Röthlisberger et al., 2016) or heavy snowfall events in winter (Cattiaux et al., 2010; Pfahl & Wernli, 2012). However, the impacts of circulation types on the weather and extreme events are expected to change in a warmer climate (e.g., a future circulation type may bring stronger storm activity due to warmer air being able to hold a higher moisture content; Molnar et al., 2015).

Evidence from observational and modeling studies is now emerging that accelerated warming in the Arctic may affect the Central European circulation by increasing its persistence (Cohen et al., 2014; Coumou et al., 2018; Francis et al., 2018; Pfleiderer et al., 2019; Vavrus, 2018). The increased sea ice loss and subsequent Arctic warming affects the planetary waves, the midlatitude jet streams, and the strength of the storm tracks (Cohen et al., 2012; Coumou et al., 2018). This consequently favors more extreme weather over Europe (Barnes & Screen, 2015; Francis & Vavrus, 2012; Pfleiderer & Coumou, 2018). However, there is currently low confidence in the linkage between Arctic and mid-latitude weather (Barnes & Polvani, 2015; Francis et al., 2018). While Blackport et al. (2019) and Fyfe (2019) present compelling evidence that Arctic warming impacts on the circulation over Eurasia are not responsible for recent severe midlatitude winters, Dai and Song (2020) state that climatic impacts of Arctic warming are probably small outside the high latitudes.

The inherent complexities to simulate changes in the atmospheric circulation caused by sea ice loss and accelerated warming in the Arctic together with changes in the water cycle and land-atmosphere interactions under global warming hinder the scientific consensus in many modeling studies (Barnes & Screen, 2015; Vavrus, 2018). To some degree, this might be caused by the current climate models not robustly supporting the links between sea ice loss, increased heat transfer from the ocean to the atmosphere and the corresponding impact on the atmospheric circulation that carries air from the Arctic into the mid-latitudes (Fyfe, 2019). Difficulties in assessing the impact of Arctic amplification also arise from the short observational time series and the high degree of internal synoptic-scale variability in the midlatitude circulation. Therefore, many questions on changes to the atmospheric circulation over Central Europe remain unanswered.

By classifying the atmospheric flow over Central Europe into different circulation types using a wide range of global general circulation models (GCMs), we can investigate their future changes and surface impacts under global warming scenarios. The different models enable us to capture the high degree of variability in the circulation as well as uncertainties in future changes.

2. Data, Classification Software, and Methods

2.1. Model and Reference Data

To best capture the complex, nonlinear interactions on a global scale, we use coupled ocean–atmosphere GCMs in our analysis. We use daily output from the global Community Earth System Model version 1.2 (CESM12-LE, hereafter CESM; Hurrell et al., 2013) in the large ensemble setup with 84 realizations and a grid spacing of 2.5° × 1.9°. To explore model structural uncertainty in our analysis, we additionally use data from 18 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) with a total of 23 realizations bilinearly regridded to a resolution of 1° (for more information on the CMIP5 models, see Supporting Information Table S1). For both model setups, we use data from the historical period (1960–2005) and from the representative concentration pathway 8.5 forcing scenario (2006–2099). While the GCM's grid resolution over Central Europe is a limiting factor in our analysis, the available data enables us to investigate both current and future Central European climate variability within a large number of ensemble members. Future climate change signals are analyzed for the period 2070–2099 with respect to the historical reference period 1988–2017.

As a reference data set, we use the combined ERA-40/-Interim reanalysis product for the time period 1960–2017 with a spatial resolution of 1° (Dee et al., 2011; Uppala et al., 2005). ERA-40 covers the time period from the 1 January 1960 until the 31 August 2002, while ERA-Interim extends the data set until the 31 December 2017.

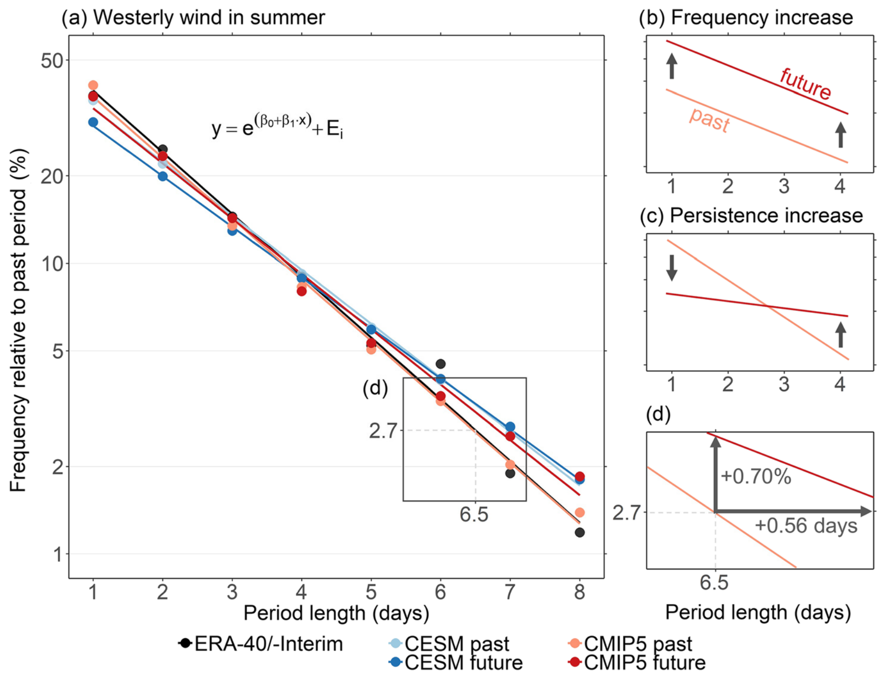

Figure 1. (a) Frequency and length of uninterrupted summer westerly wind periods for the reanalysis (black) and the ensemble mean CESM (blue) and CMIP5 (red) data sets with a logarithmic fit. The equation in black represents the logarithmic regression model $y = e^{\beta_0+\beta_1 \cdot x} + E_i$, where β_0 is the intercept, β_1 is the slope that we define as our persistence measure, and E_i is the error term. (b, c) Schematics of changes to the fit in only the frequency or persistence. (d) Inset for the CMIP5 data showing changes to the persistence fit and its impacts on a continuous 6.5-day long period as an example of the interpretation. Subfigures (b, c, and d) are not to scale.

2.2. The COST733class Classification Software

Following Weusthoff (2011) and Rohrer et al. (2017), we classify the main synoptic-scale circulation types over Central Europe (3°E to 20°E and 41°N to 52°N; Figure S1) with the COST733class software from Demuzere et al. (2011) using daily geopotential height fields on 500 hPa. We use these midtropospheric flow fields as they are more robust compared to ground-based variables over the Alpine region in lower resolution models.

From the COST733class software, we use the Grosswetter-types classification method (cf. also Beck et al., 2007) that determines circulation types according to their correlation with a strict zonal, meridional, or anticyclonic/cyclonic flow pattern with a pressure maximum/minimum in the center of the domain (Weusthoff, 2011). We use the following 10 circulation types: the eight main wind directions west (W), southwest (SW), northwest (NW), north (N), northeast (NE), east (E), and south (S) as well as cyclonic (C) and anticyclonic (A) flow patterns. Our analysis focuses on the summer (June–August) and winter (December–February) seasons.

2.3. A Measure for Persistence

A persistent circulation type is defined as one that prevails over an uninterrupted time period. Figure 1 serves as an example how we construct the persistence measure for all circulation types. The length of a continuous circulation type period and its seasonal frequency (e.g., here for westerly wind in summer; Figure 1a) are well described by a logarithmic regression, implying that the transition probability to another type is largely independent of the length of the period. A 1-day period of westerly wind in summer is nearly twice as frequent as a 2-day period. A logarithmic regression model thus allows us to estimate the decrease in the frequency with increasing duration of a given circulation type. Changes in the slope between past and future time periods are thus equivalent to changes in the persistence. Note that our approach is limited by the data availability for a given circulation type. For example, it cannot be applied to easterly wind as this circulation type only occurs on 1 to 2 days each season (Figures 2a and 2b and S2f). We also require uninterrupted

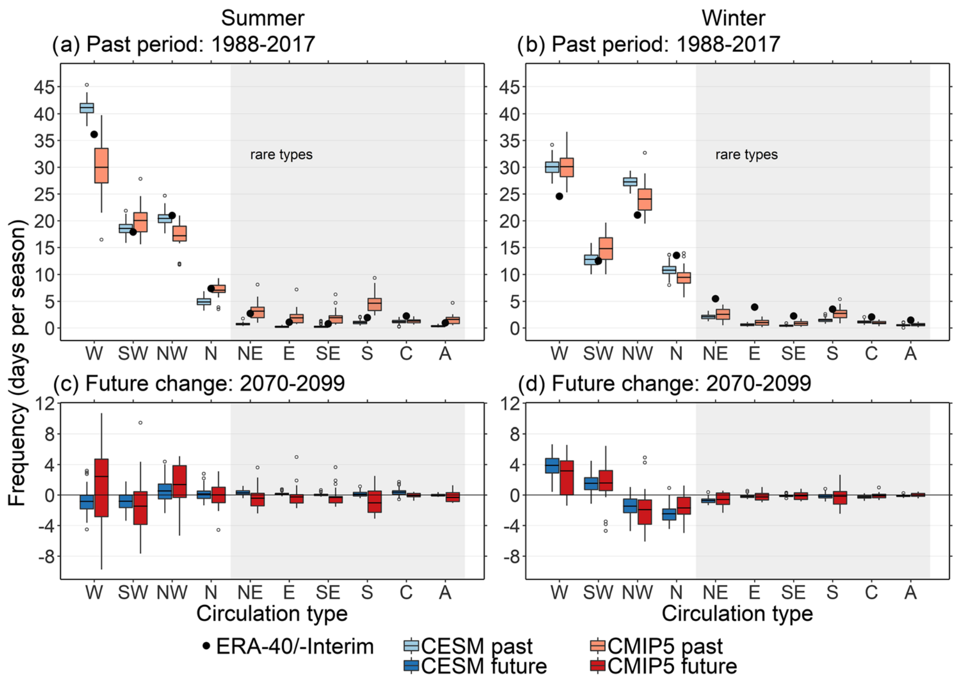

Figure 2. Frequency of the 10 circulation types (days per season) during (a) summer and (b) winter for the period 1988–2017 in both CESM (blue) and the CMIP5 models (red). The frequency in the reanalysis data is given as the black dot. In (c) and (d), the projected changes (days per season) in the models for the future period 2070–2099 are shown relative to the past period. The horizontal line in each boxplot represents the ensemble mean. The gray shaded area indicates the rare circulation types. See section 2.2 for a definition of the circulation types.

periods of the same circulation type for our persistence measure. We analyze all circulation types but focus our interpretation on the four main types.

To calculate a consistent regression model across the reanalysis, the CESM and the CMIP5 data sets for both the past and future time periods, we first remove continuous time periods occurring less than 1% each season and also ensure that we calculate the regression over the same period length for all three data sets. This means that if the reanalysis includes period lengths of up to 5 days and the CESM model has longer periods, we calculate the regression model including up to 5-day periods. We then define the slope parameter of the logarithmic fit β_1 as our persistence measure.

Changes to the regression fit arise from the two combined changes in the frequency and in the persistence: (1) a change in the intercept of the fit β_0 represents a frequency change of a given circulation type (Figure 1b); and (2) a change in the slope results in a frequency change towards short periods and a simultaneous change to longer-term periods, that is, a change in the persistence (Figure 1c). As a change in persistence of a given circulation type is dependent on the frequency, we consider as suggested by Kyselý (2008), changes in the frequency in our calculation of the future persistence. This means that we account for a higher probability of persistence given a future frequency increase of a circulation type (and vice versa). As an illustration of the two effects, Figure 1d shows the changes to a 6.5-day westerly wind period in the CMIP5 ensemble mean. This period is as frequent today as a 7-day period in the future (horizontal arrow), and a 6.5-day period today will be 0.7% more frequent in the future (vertical arrow).

3. Results and Discussion

3.1. Changes in the Frequency of Circulation Types

The large-scale atmospheric flow field over Central Europe is dominated by the four wind directions west, northwest, southwest, and north, which contribute 75% to 80% to the seasonal variability (Figures 2a and 2b). The models reproduce the seasonal frequencies in the reanalysis data set reasonably well (Figures 2a and 2b). For both summer and winter seasons, the results are very similar to those in Rohrer et al. (2017).

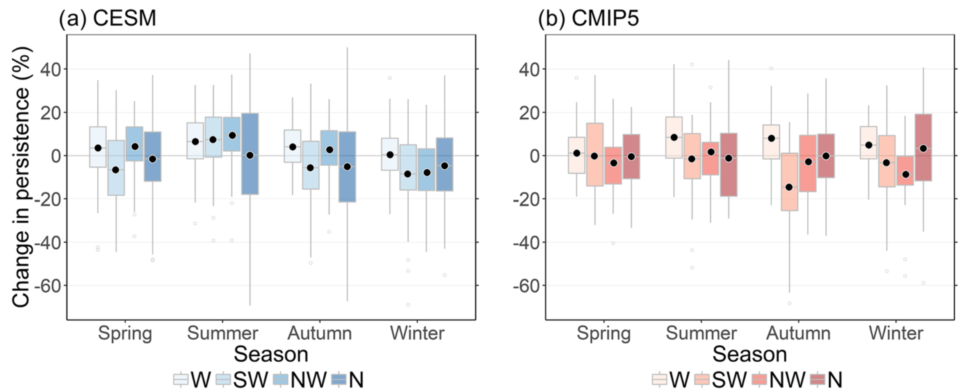

Figure 3. Seasonal future persistence change (%) for the four main circulation types in (a) CESM and (b) CMIP5 relative to the past period as boxplots representing the spread within the ensemble members. The ensemble mean for each circulation type is given as a black dot.

The variability within the CESM ensemble members (blue boxplots) is small compared to the CMIP5 members (red boxplots). While the CESM data only account for internal variability, the CMIP5 models additionally include model uncertainty explaining the larger spread found in this data set.

CESM and CMIP5 also differ in their biases with respect to the reanalysis. In summer, the frequency of westerlies over Central Europe relative to the reanalysis is overestimated in CESM (Figure 2a), likely caused by the too zonal flow in this model (Kwon et al., 2018). The increased frequency of westerlies in CESM is compensated by an underestimation of the northerly flow and the rarer circulation types. In the CMIP5 models, the mean frequencies in summer are reproduced reasonably well, except for an underestimation of westerlies. During the winter season, westerlies and north westerlies are overestimated in both model data sets at the expense of northerly flow and the rarer circulation types (Figure 2b). In winter, all models consistently underestimate the rare circulation types (Figure 2b). This is unfortunate as some of these circulation types (e.g., the anticyclonic circulation) may be conducive to temperature extremes (Black & Sutton, 2006; Pfahl & Wernli, 2012; Brunner et al., 2018).

The observed trends in the frequency of the circulation types over the 1960–2017 period are not significant on the 95% confidence level (Figures S3 and S4) and lie within the variability of the modeled trends (Figure S5). The significance level is in some cases exceeded when considering only a 30-year period (e.g., the frequency of north westerlies significantly decreases with -3.2 days decade^{-1} in summer for 1988–2017). However, these trends turn out to be not robust when considering longer periods. Consequently, we urge cautiousness in assessing trends in the atmospheric circulation over short time intervals.

Projected future changes in circulation frequencies are consistently small and within the range of ± 4 days per season (Figures 2c and 2d). The spread in the frequency changes for the main circulation types within CMIP5, owing to model variability, is considerably larger than in CESM. The only significant change occurring in the future period is an increase in westerlies in winter in the CESM model (Figure 2d). However, this change may in part be overestimated in this model due to the zonal flow bias mentioned above.

3.2. Changes in the Persistence of Circulation Types

The future changes in the persistence measure show a large spread in both CESM and CMIP5, are small, and not significant (Figure 3). In part, this may be caused by the large natural variability within the Central European circulation and the models' difficulties in linking dynamic and thermodynamic changes. This was for instance recognized considering Arctic sea ice loss and its relation to the midlatitude dynamics (Fyfe, 2019). The CESM results indicate an increase in persistence in summer and a decrease in winter (Figure 3a). In CMIP5, potential future seasonal changes are not as clear. Only the westerly circulation type shows an increased persistence over all four seasons in both CESM and CMIP5 with a maximum in summer. In CESM, north-westerly persistence is also projected to increase throughout spring, summer, and autumn (Figure 3a).

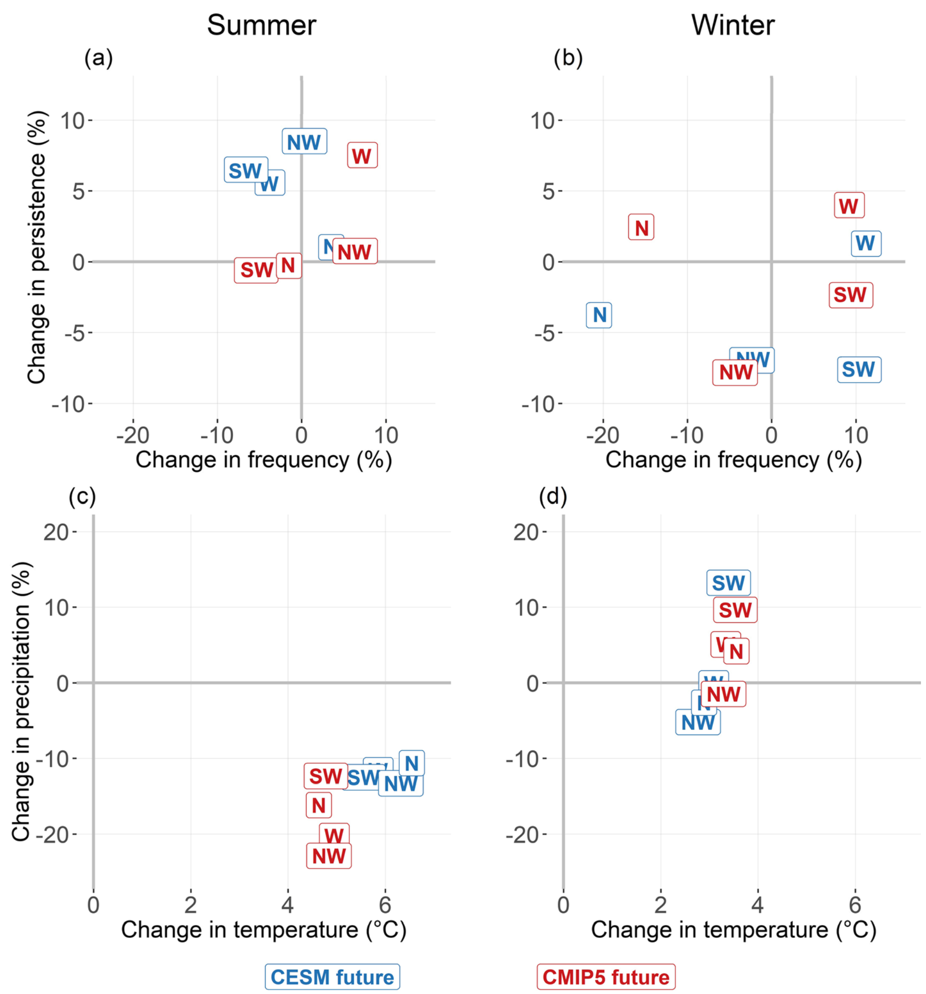

Figure 4. Summary of future 2070–2099 summer and winter (a, b) frequency and persistence (%) as well as (c, d) temperature (°C) and precipitation (%) changes of the main Central European circulation types relative to 1988–2017. Shown here is the ensemble mean for CESM (blue) and CMIP5 (red). For more information on the variability between the ensemble members, see Figures 3 and S6.

3.3. Summary of Frequency and Persistence Changes

The relative future frequency and persistence changes are summarized by way of the ensemble means in Figures 4a and 4b. As introduced above, the models project a small change towards more persistent summer westerlies but generally disagree on the sign and magnitude of the changes for the other circulation types. In winter, evidence for higher persistence is even weaker; persistence can either increase or decrease depending on the circulation type. Considering the large variability across the ensemble members, we argue that projected changes in the frequency and persistence are likely within the range of internal variability or not consistent across models (Figures 3, S6a, S6b, and S7).

The overall small changes in the frequency and persistence might in part arise from the models' current limitations in simulating future changes in the atmospheric circulation. It has been suggested that they underestimate or even miss links between Arctic sea ice loss and the midlatitude circulation (Fyfe, 2019; Mori et al., 2019), that the models might be underestimating changes in the water cycle caused by enhanced evapotranspiration in a warming climate (Pfleiderer et al., 2019), or that they might encounter difficulties in simulating land-atmosphere feedback mechanisms (Hirschi et al., 2011).

In addition to the frequency and persistence changes, we also evaluate future changes in near-surface temperature and precipitation during the occurrence of each circulation type (see Figures S9–S20 for spatial maps). We find an average shift to warmer and drier conditions in Central Europe across all circulation types in summer (Figure 4c), consistent with IPCC (2014), Coumou et al. (2018), and Li et al. (2018). The projected warming signal for the winter season is about 50% smaller than in summer. In part, this increased summer warming signal can be explained by the positive feedback mechanisms between the surface air temperature, soil moisture, evapotranspiration, and clouds in a warmer climate (Seneviratne et al., 2010) and by the influence of lapse rate changes linked to an extending Hadley circulation (Brogli et al., 2019; Kröner et al., 2017). Our results here agree with the statement of more dry-warm summers in Pfleiderer et al. (2019) and the projections of the Swiss Climate Scenarios CH2018 (CH2018, 2018).

4. Conclusions and Outlook

In this study, we classified daily geopotential height at 500 hPa between 1960 and 2100 from a CESM initial condition large ensemble setup and models from the CMIP5 project into 10 circulation types over Central Europe. As a validation data set, we used the ERA-40/-Interim reanalysis product for the time period 1960–2017. Our Grosswetter-types classification method categorized 10 circulation types according to a correlation coefficient with a strictly zonal, meridional, or anticyclonic/cyclonic flow in the COST733class software. We analyzed observed and projected changes in their frequency and expanded from Demuzere et al. (2011), Kučerová et al. (2017), and Rohrer et al. (2017) by considering a larger set of models, allowing for a better assessment of model uncertainty, and by introducing a new persistence measure to assess projected changes in the length of a continuous circulation type for the future time period 2070–2099. We also evaluated the future effects of each individual circulation type on temperature and precipitation impacts.

The projected changes in the frequency and persistence are small across models and circulation types, and the large variability in the signals arises either from internal climate fluctuations or model disagreement. Where simulated changes are stronger, they are usually not consistent across models. The clearest signal is towards somewhat more persistent westerlies in summer. Our results therefore, at least based on the currently available climate models, the chosen weather classification and for Central Europe, do not support the claim that anthropogenic influence on the jet streams makes the weather more persistent (as in Rohrer et al., 2017; Coumou et al., 2018; Francis et al., 2018; Mann et al., 2018; Pfleiderer et al., 2019) and are more in line with studies showing no clear change (Chen et al., 2016; Schaller et al., 2018). Some of these studies that see changes in fact only see a small change that needs many model simulations to become significant. A rigorous intercomparison of different methodological approaches, weather classifications, and model experiments is needed to reconcile the apparent discrepancies in the interpretation of the findings. Before these discrepancies are resolved, the interpretation of past trends and single-weather events as well as explicit or implied extrapolations into the future is speculative at best. Also note that the relation between jet waviness and extreme events is complex and depends on the region (Röthlisberger et al., 2016). We do not conclude from our findings that there is no effect but that current climate models do not agree on changes in the atmospheric circulation.

Future changes in both temperature and precipitation are clearer. The models project a future change towards more hot-and-dry Central European summers independent of the circulation and in winter a shift to warmer conditions with precipitation changes dependent on the circulation type.

Our results show that assessing future changes in the Central European circulation remains a challenging topic, which is best undertaken by using both single and multimodel ensemble setups to capture the large variability and model spread. Complications in arriving at clear signals may also partially arise from the models' limited capacity to correctly simulate interactions between the ocean, sea ice, and atmosphere and its large-scale impacts on the European weather. Some of these deficiencies may be similar in most models (Mori et al., 2019).

We advocate for future research expanding upon our persistence measure to investigate high-impact changes in very rare long-term persistent events. It would be beneficial to evaluate the transitional probabilities for each circulation type and whether they differ for different models. Additionally, it would be helpful to further examine the isolated impact of Arctic sea ice loss and the resulting changes in the temperature gradient on the atmospheric circulation (Gerber et al., 2012; Screen & Blackport, 2019), its implications on the extratropical jet stream, and future Central European weather persistence with the latest model configurations in the CMIP6 project.

Acknowledgments

We thank U. Beyerle for assistance in setting up the COST733class software and his technical support throughout this project. We thank the editor, Alessandra Giannini, and two anonymous reviewers for their constructive suggestions that have improved the manuscript. We thank the University of Augsburg for free access to the classification software and documentation. In addition, we thank the European Center for Mid-Range Weather Forecast (ECMWF) for providing access to the ERA-40/-Interim reanalysis product, and we thank the National Center for Atmospheric Research (NCAR) for the development of the CESM. We acknowledge the World Climate Research Program's Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table S1) for producing and making available their model output. The COST733class output files and analysis scripts are publicly available at https://github.com/mauricehuguenin/europe_circulation_types.

References

Barnes, E. A., & Screen, J. A. (2015). The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *WIREs Climate Change*, *6*, 277–286. https://doi.org/10.1002/wcc.337

Barnes, E. A., & Polvani, L. M. (2015). CMIP5 Projections of Arctic Amplification, of the North American/North Atlantic Circulation, and of Their Relationship. *Journal of Climate*, *28*(13), 5254–5271. https://doi.org/10.1175/JCLI-D-14-00589.1

Beck, C., Jacobeit, J., & Jones, P. D. (2007). Frequency and within-type variations of large-scale circulation types and their effects on low-frequency climate variability in Central Europe since 1780. *International Journal of Climatology*, *27*, 473–491. http://doi.org/10.1002/joc.1410

Black, E., & Sutton, R. (2006). The influence of oceanic conditions on the hot European summer of 2003. *Climate Dynamics*, *28*, 53–66. https://doi.org/10.1007/s00382-006-0179-8

Blackport, R., Screen, J. A., van der Wiel, K., & Bintanja, R. (2019). Minimal influence of reduced Arctic sea ice on coincident cold winters in midlatitudes. *Nature Climate Change*, *9*(9), 697–704. https://doi.org/10.1038/s41558-019-0551-4

Blackport, R., Screen, J. A., van der Wiel, K., & Bintanja, R. (2019). Coincident cold winters in mid-latitudes. *Nature Climate Change*, *9*(9), 697–704. https://doi.org/10.1038/s41558-019-0551-4

Brogli, R., Kröner, N., Sørland, S. L., Lüthi, D., & Schär, C. (2019). The role of Hadley circulation and lapse-rate changes for the future European summer climate. *Journal of Climate*, *32*, 385–404. https://doi.org/10.1175/JCLI-D-18-0431.1

Brunner, L., Schaller, N., Anstey, J., Sillmann, J., & Steiner, A. K. (2018). Dependence of present and future European temperature extremes on the location of atmospheric blocking. *Geophysical Research Letters*, *45*, 6311–6320. https://doi.org/10.1029/2018GL077837

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., & Codron, F. (2010). Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters*, *37*, L20704. https://doi.org/10.1029/2010GL044613

CH2018 (2018). CH2018-Climate scenarios for Switzerland, Technical Report, National Centre for Climate Services, Zurich, 271 pp. ISBN: 978–3–9525031-4-0

Chen, H. W., Zhang, F., & Alley, R. B. (2016). The robustness of midlatitude weather pattern changes due to Arctic sea ice loss. *Journal of Climate*, *29*, 7831–7849. https://doi.org/10.1175/JCLI-D-16-0167.1

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*(9), 627–637. https://doi.org/10.1038/ngeo2234

Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A., & Cherry, J. E. (2012). Arctic warming, increasing snow cover and widespread boreal winter cooling. *Environmental Research Letters*, *7*(1). https://doi.org/10.1088/1748-9326/7/1/014007

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., & Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, *9*(1), 1–12. https://doi.org/10.1038/s41467-018-05256-8

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change*, *2*(7), 491–496. https://doi.org/10.1038/nclimate1452

Dai, A., & Song, M. (2020). Little influence of Arctic amplification on mid-latitude climate. *Nature Climate Change*, *10*(3), 231–237. https://doi.org/10.1038/s41558-020-0694-3

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim Reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Demuzere, M., Kassomenos, P., & Philipp, A. (2011). The COST733 circulation type classification software: An example for surface ozone concentrations in Central Europe. *Theoretical and Applied Climatology*, *105*(1), 143–166.

Francis, J. A., Skific, N., & Vavrus, S. J. (2018). North American weather regimes are becoming more persistent: Is Arctic amplification a factor? *Geophysical Research Letters*, *45*, 11,414–11,422. https://doi.org/10.1029/2018GL080252

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*, L06801. https://doi.org/10.1029/2012GL051000

Fyfe, J. C. (2019). Midlatitudes unaffected by sea ice loss. *Nature Climate Change*, *9*(9), 649–650. https://doi.org/10.1038/s41558-019-0560-3

Gerber, E. P., Butler, A., Calvo, N., Charlton-Perez, A., Giorgetta, M., Manzini, E., et al. (2012). Assessing and Understanding the Impact of Stratospheric Dynamics and Variability on the Earth System. *Bulletin of the American Meteorological Society*, *93*, 845–859. https://doi.org/10.1175/BAMS-D-11-00145.1

Hirschi, M., Seneviratne, S. I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O. B., et al. (2011). Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, *4*, 17. https://doi.org/10.1038/ngeo1032

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The Community Earth System Model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, *94*(9). https://doi.org/10.1175/bams-d-12-00121

IPCC (2014). In Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.), *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, (p. 151). Geneva, Switzerland: IPCC.

Jézéquel, A., Cattiaux, J., Naveau, P., Radanovics, S., Ribes, A., Vautard, R., et al. (2018). Trends of atmospheric circulation during singular hot days in Europe. *Environmental Research Letters*, *13*(5). https://doi.org/10.1088/1748-9326/aab5da

Kröner, N., Kotlarski, S., Fischer, E., Lüthi, D., Zubler, E., & Schär, C. (2017). Separating climate change signals into thermodynamic, lapse-rate and circulation effects: Theory and application to the European summer climate. *Climate Dynamics*, *48*, 3425. https://doi.org/10.1007/s00382-016-3276-3

Kučerová, M., Beck, C., Philipp, A., & Huth, R. (2017). Trends in frequency and persistence of atmospheric circulation types over Europe derived from a multitude of classifications. *International Journal of Climatology*, *37*, 2502–2521. https://doi.org/10.1002/joc.4861

Kwon, Y. O., Camacho, A., Martinez, C., & Hyodae, S. (2018). North Atlantic winter eddy-driven jet and atmospheric blocking variability in the Community Earth System Model Version 1 large ensemble simulations. *Climate Dynamics*, *51*(9-10), 3275–3289. https://doi.org/10.1007/s00382-018-4078-6

Kyselý, J. (2008). Influence of the persistence of circulation patterns on warm and cold temperature anomalies in Europe: Analysis over the 20th century. *Global and Planetary Change*, *62*(1–2), 147–163. https://doi.org/10.1016/j.gloplacha.2008.01.003

Li, C., Michel, C., Graff, L. S., Bethke, I., Zappa, G., Bracegirdle, T. J., et al. (2018). Midlatitude atmospheric circulation responses under 1.5 and 2.0 °C warming and implications for regional impacts. *Earth System Dynamics*, *9*(2), 359–382. https://doi.org/10.5194/esd-9-359-2018

Mann, M. E., Rahmstorf, S., Kornhuber, K., Steinman, B. A., Miller, S., Petri, S., & Coumou, D. (2018). Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification. *Science Advances*, *4*(10). https://doi.org/10.1126/sciadv.aat3272

Molnar, P., Fatichi, S., Gaál, L., Szolgay, J., & Burlando, P. (2015). Storm type effects on super Clausius–Clapeyron scaling of intense rainstorm properties with air temperature. *Hydrology and Earth System Science*, *19*, 1753–1766. https://doi.org/10.5194/hess-19-1753-2015

Mori, M., Kosaka, Y., Watanabe, M., Nakamura, H., & Kimoto, M. (2019). A reconciled estimate of the influence of Arctic Sea-ice loss on recent Eurasian cooling. *Nature Climate Change*, *9*(2), 123–129. https://doi.org/10.1038/s41558-018-0379-3

Peña-Ortiz, C., Gallego, D., Ribera, P., Ordonez, P., & Alvarez-Castro, M. D. C. (2013). Observed trends in the global jet stream characteristics during the second half of the 20th century. *Journal of Geophysical Research: Atmosphere*, *118*, 2702–2713. http://doi.org/10.1002/jgrd.50305

Perkins, S. E. (2015). A review on the scientific understanding of heatwaves-their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research*, *164–165*, 242–267. https://doi.org/10.1016/j.atmosres.2015.05.014

Pfahl, S., & Wernli, H. (2012). Spatial coherency of extreme weather events in Germany and Switzerland. *International Journal of Climatology*, *32*, 1863–1874. http://doi.org/10.1002/joc.2401

Pfleiderer, P., & Coumou, D. (2018). Quantification of temperature persistence over the northern hemisphere land-area. *Climate Dynamics*, *51*(1–2), 627–637. https://doi.org/10.1007/s00382-017-3945-x

Pfleiderer, P., Schleussner, C. F., Kornhuber, K., & Coumou, D. (2019). Summer weather becomes more persistent in a 2° C world. *Nature Climate Change*, *9*(9), 666–671. https://doi.org/10.1038/s41558-019-0555-0

Rohrer, M., Croci-Maspoli, M., & Appenzeller, C. (2017). Climate change and circulation types in the Alpine region. *Meteorologische Zeitschrift*, *26*(1), 83–92.

Röthlisberger, M., Pfahl, S., & Martius, O. (2016). Regional-scale jet waviness modulates the occurrence of midlatitude weather extremes. *Geophysical Research Letters*, *43*, 10,989–10,997. https://doi.org/10.1002/2016GL070944

Schaller, N., Sillmann, J., Anstey, J., Fischer, E. M., Grams, C. M., & Russo, S. (2018). Influence of blocking on Northern European and Western Russian heatwaves in large climate model ensembles. *Environmental Research Letters*, *13*, 054015. https://doi.org/10.1088/1748-9326/aaba55

Screen, J. A., & Blackport, R. (2019). How robust is the atmospheric response to projected Arctic sea ice loss across climate models? *Geophysical Research Letters*, *46*, 11,406–11,415. https://doi.org/10.1029/2019GL084936

Seneviratne, S. I., Corti, T., Davin, E., Hirschi, M., Jaeger, E. B., Lehner, I., et al. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3–4), 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Steirou, E., Gerlitz, L., Apel, H., & Merz, B. (2017). Links between large-scale circulation patterns and streamflow in Central Europe: A review. *Journal of Hydrology*, *549*, 484–500. https://doi.org/10.1016/j.jhydrol.2017.04.003

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., et al. (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, *131*(612), 2961–3012. https://doi.org/10.1256/qj.04.176

Vavrus, S. J. (2018). The influence of Arctic amplification on mid-latitude weather and climate. *Current Climate Change Reports*, *4*(3), 238–249. https://doi.org/10.1007/s40641-018-0105-2

Weusthoff, T. (2011). Weather type classification at MeteoSwiss–Introduction of new automatic classification schemes. *Arbeitsberichte der MeteoSchweiz, 235*.

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*, 856–868. https://doi.org/10.1002/qj.625