

Climate change and circulation types in the Alpine region

Journal Article**Author(s):**

Rohrer, Marco; Croci-Maspoli, Mischa; Appenzeller, Christof

Publication date:

2017-02-13

Permanent link:

<https://doi.org/10.3929/ethz-b-000129189>

Rights / license:

[Creative Commons Attribution-NonCommercial 3.0 Unported](#)

Originally published in:

Meteorologische Zeitschrift 26(1), <https://doi.org/10.1127/metz/2016/0681>

Climate change and circulation types in the Alpine region

MARCO ROHRER^{1,2,3*}, MISCHA CROCI-MASPOLI¹ and CHRISTOF APPENZELLER¹

¹Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland

²Institute for Atmospheric and Climate Sciences, ETH Zurich, Zurich, Switzerland

³Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Bern, Switzerland

(Manuscript received June 16, 2015; in revised form March 22, 2016; accepted April 29, 2016)

Abstract

The frequency of circulation types over the Alpine region is explored using 20 different global and regional climate model chains. The projected changes in these circulation types are investigated for the 21st century using the SRES A1B scenario. The multi-model approach relies on the climate models from the ENSEMBLES project and circulation type classifications provided by the COST Action 733. For the latter, the two circulation type classifications GWT (Grosswetter-types) and CAP (Cluster Analysis of Principal components) are selected. GWT is applied to sea level pressure and geopotential height at 500 hPa whereas CAP is applied to sea level pressure. Overall, the ensemble of climate models captures the frequency of individual circulation types well, as shown by the comparison of circulation types from climate models and re-analysis data between 1980 and 2009. Discrepancies occur during winter (DJF) when westerlies are overestimated both at the sea level and at the 500 hPa geopotential height level. The model spread is largest during summer. The frequency of circulation types is simulated best during spring and autumn irrespective of the applied circulation type classification.

The analysis of circulation types in the climate projections indicates that in winter easterlies are expected to decrease mostly at the benefit of westerlies until the end of the 21st century. In summer projected changes depend on the height level considered. At sea level westerlies are projected to decrease while easterlies increase markedly in their frequency. This change is not occurring on the 500 hPa geopotential height level.

Keywords: synoptic climatology, circulation type classification, climate change, COST 733, Alpine climate

1 Introduction

Large-scale weather patterns largely determine local weather and climate conditions and, as a consequence, play a crucial role for society and economy. Circulation type classifications (CTCs) are widely used to examine these weather patterns. Circulation types describe similar and recurrent states of the atmosphere over a defined time interval and area (PHILIPP *et al.*, 2010).

Modern computers enable to use automated and objective CTCs, which allow to classify the atmospheric circulation for large datasets of observed and simulated climate. Hence this systematic and reproducible classification of circulation types can be used to objectively quantify past, present and future changes in the atmospheric circulation concerning its patterns, frequency and persistence (HUTH *et al.*, 2008). In this respect CTCs have been proven to be useful tools to validate the performance of climate models (e.g. HUTH, 1997; DEMUZERE *et al.*, 2009; PASTOR and CASADO, 2012).

Due to their coarse resolution, climate models are known to better simulate the large-scale circulation than surface variables (YARNAL *et al.*, 2001; BENESTAD *et al.*, 2008). Several studies show that circulation types may correlate with surface weather variables like precipitation (e.g. SCHIEMANN and FREI, 2010), temperature

(e.g. BLENKINSOP *et al.*, 2009) or natural hazards (e.g. storms, SCHIESSER *et al.*, 1997; floods, PRUDHOMME and GENEVIER, 2011; hail, KUNZ *et al.*, 2009). Therefore, they provide a potential downscaling tool to assess surface variables (with respect to their mean and their extreme values) that are not or only poorly resolved in climate models. In this regard CTCs may serve as valuable proxies for atmospheric circulation in a future climate (e.g. DEMUZERE *et al.*, 2009; PONGRACZ *et al.*, 2010; LORENZO *et al.*, 2011). In addition, their link to surface weather variables potentially delivers more insight on the future development of local to regional weather (e.g. temperature, PLAVCOVA and KYSELY, 2013) and extreme events (e.g. storms, PINTO *et al.*, 2010; hail, KAPSCH *et al.*, 2012; temperature and precipitation, RIEDIGER and GRATZKI, 2014).

To the author's knowledge, no study exists that examines projected climate change specifically over the Alpine region with the aid of circulation types and a multi-model approach. Nonetheless, several studies assessed how Switzerland and the Alpine region may be affected by climate change during the 21st century. Most prominently, the Swiss Climate Change Scenarios CH2011 report, released by the CH2011 initiative, provides a detailed overview (CH2011, 2011). The CH2011 report relies on the results of the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4; IPCC, 2007), the EU ENSEMBLES project

*Corresponding author: Marco Rohrer, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland, e-mail: marco.rohrer@giub.unibe.ch

Table 1: The ENSEMBLES models used in this study. The Regional Circulation Model (RCM) is denoted together with the driving Global Circulation Model (GCM) and their sensitivity where required. The data availability of the daily mean sea level pressure (SLP) and 500 hPa geopotential height (Z500) fields is indicated by an “X”.

GCM	Sens	RCM	Institute	From	To	SLP	Z500
BCM	HIRHAM		Met. No	1951	2050	X	X
	RCA		SMHI	1961	2100	X	X
HadCM3	Q0 (std)	CCLM	ETH Zürich	1951	2099	X	
		PROMES	UCLM	1951	2050	X	X
		RRCM	VMGO	1951	2050	X	X
		HadRM3Q0	Met Office	1951	2100	X	X
		HIRHAM	Met. No	1951	2050	X	X
	Q16 (high)	RCA3	C4I	1951	2099	X	X
		HadRM3Q16	Met Office	1951	2100	X	X
	Q3 (low)	RCA	SMHI	1951	2098	X	X
		HadRM3Q3	Met Office	1951	2100	X	X
	ECHAM5		REMO	MPI	1951	2100	X
		HIRHAM	DMI	1951	2099	X	
		RACMO	KNMI	1950	2100	X	X
		RCA	SMHI	1951	2100	X	X
		REGCM3	ICTP	1951	2100	X	X
ARPEGE		ALADIN	CNRM	1950	2100	X	X
		HIRHAM	DMI	1951	2100	X	X
CGCM3		CRCM	OURANOS	1951	2050	X	X
IPSL		CCLM	GKSS	1963	2050	X	

(VAN DER LINDEN and MITCHELL, 2009) and several methodological studies (e.g. BUSER et al., 2009; FISCHER et al., 2012).

This study uses the same projection data as the CH2011 initiative to assure highest consistency. Emphasis is placed on the projected changes in the evolution of the seasonal frequency of circulation types using two different CTC methods, Grosswetter-types (GWT) and Cluster Analysis of Principal components (CAP) at two height levels in the troposphere. A multi-model approach using a suite of global and regional climate model chains (hereinafter referred to as model chains) from the ENSEMBLES project is chosen in order to provide additional information regarding climate change in the Alpine region.

2 Methods

Daily circulation type time series are derived for the Alpine region (41°–52° N, 3°–20° E) from the mean sea level pressure (SLP) and the 500 hPa geopotential height (Z500) fields of a total of 20 model chains of the EU ENSEMBLES project (VAN DER LINDEN and MITCHELL, 2009) running from 1951 to 2050 or 2100 (Table 1). These model chains correspond to the selection of the CH2011 initiative (CH2011, 2011). For Z500 only 17 model chains are available on a six hourly resolution. To compute daily circulation types, the daily mean is calculated prior further examination. All model

chains use the Special Report on Emissions Scenarios (SRES) A1B greenhouse gas emission scenario (NAKICENOVIC and SWART, 2000) that projects a fast growing economy but a moderate increase of greenhouse gases due to rapid introduction of new and more efficient technology.

The two classification schemes GWT and CAP from the COST 733 Action “Harmonisation and Applications of Weather Type Classifications for European Regions” CTC catalog (PHILIPP et al., 2014) are applied. These classification schemes are chosen due to the high skill in resolving precipitation in the Alpine region (SCHIE-MANN and FREI, 2010). In addition, they are in operational use at MeteoSwiss (WEUSTHOFF, 2011) and therefore observation based data is available for the observation period.

GWT classifies the daily synoptic situation according to the correlation coefficients obtained by the comparison with a strictly zonal, meridional and cyclonic flow pattern. In theory, CAP performs a principal component analysis with a subsequent cluster analysis. This study uses predefined circulation types derived from ERA-40 re-analysis data (UPPALA et al., 2005) between 1957 and 2002 and assigns every model day to the nearest composite pattern in terms of Euclidian distance. This procedure has the drawback that circulation types derived from ERA-40 are used to classify the ENSEMBLES model data, which may have a different data structure. On the other hand, this approach enables the direct

Table 2: Synoptic description of the CAP9 circulation types (slightly adapted from WEUSTHOFF, 2011).

CT	Synoptic description
NEi	NorthEast, indifferent
WSWcf	WestSouthWest, cyclonic, flat pressure
W NEU	Westerly flow over Northern Europe
Ei	East, indifferent
A Alps	High Pressure over the Alps
NEc	NorthEast, cyclonic
WSWc	WestSouthWest, cyclonic
A CEU	High Pressure over Central Europe
W SEUc	Westerly flow over Southern Europe, cyclonic

comparison of circulation types of model data with re-analysis data. GWT is calculated for 10, 18 and 26 circulation types for both SLP and Z500 fields whereas CAP is derived for 9, 18 and 27 circulation types only for the SLP field. This study shows the results of GWT with 10 circulation types (referred to as GWT10SLP and GWT10Z500 respectively) and CAP with 9 circulation types (referred to as CAP9SLP). Detailed information about the applied CTCs can be found in PHILIPP *et al.* (2010) and references therein. GWT circulation types are abbreviated according to the prevailing wind direction or cyclonicity (N=North, E=East, S=South, W=West, A=anticyclonic, C=cyclonic). A short synoptic description of each circulation type for CAP9SLP is given in Table 2.

Because model resolution can influence the circulation types (e.g. DEMUZERE *et al.*, 2009), models are re-gridded to a $1^\circ \times 1^\circ$ regular longitude-latitude grid in order to compare model data to observation-based re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The analysis is performed on a seasonal basis; March–May (MAM, spring), June–August (JJA, summer), September–November (SON, autumn) and December–February (DJF, winter). In line with the CH2011 initiative, the period from December 1979 to November 2009 (in the following termed 1980–2009) is chosen as the reference period. Model data is compared to the re-analysis based classification catalog established at MeteoSwiss (WEUSTHOFF, 2011) to investigate the accuracy of the simulated atmospheric circulation. This catalog is based on the centroids calculated for the whole ERA-40 period (1957–2002) and uses ERA-40 data (until August 2002) and ERA-interim data (since September 2002; DEE *et al.*, 2011).

Two different statistical methods are used to detect significant trends in the circulation types (i.e. p -value < 0.05). First, the significance of the differences between the reference (1980–2009) and the projected period (2070–2099) are tested with the Wilcoxon signed-rank test. Second, the trends obtained by logistic regression are examined between 1995 and 2085 for each circulation type using the median of the model ensemble.

3 How well are circulation types represented in climate models?

The model chains are generally able to capture the frequency of circulation types for the reference period 1980–2009 over the Alpine region. The largest deviations between re-analysis and model data are found during winter as shown for CAP9SLP (Fig. 1a), GWT10SLP (Fig. 1c) and GWT10Z500 (Fig. 1e). The models overestimate westerly circulation types in winter, in some cases significantly. This is in contrast to easterly circulation types, which are generally significantly underestimated in the models during winter. These findings are in line with previous studies by e.g. RIEDIGER and GRATZKI (2014), BLENKINSOP *et al.* (2009) or VAN ULDEN and VAN OLDENBORGH (2006).

The spread of the models is by far the largest during summer for SLP based CTCs. As a consequence, the model spread inhibits a detection of significant deviations of the modeled frequency from the observed frequency. Nevertheless, the absolute deviations are in many cases considerable. PLAVCOVA and KYSELY (2011; 2013) also found that the model spread is largest during summer. Two CAP9SLP circulation types (A CEU and W SEUc) do not occur during summer in the re-analysis data. This is correctly represented by the majority of the models (Fig. 1b). RIEDIGER and GRATZKI (2014) found an even stronger westerly overestimation in summer than in winter. Reasons for the mismatch with the results of this study can be manifold such as a subset of the models used, a slightly different domain centered over Germany and a different methodology taking into account the 950 hPa and 500 hPa geopotential height fields. This points out that the used CTC can influence the obtained results as also noted by e.g. CAHYNOVA and HUTH (2014).

Simulated and observed frequencies of circulation types best agree during autumn (Table 3; ROHRER, 2013). Only indifferent easterlies (Ei) are significantly underestimated in CAP9SLP. GWT detects any significant deviation neither on sea level nor on the Z500 level. These results are in line with the study of BLENKINSOP *et al.* (2009).

GWT is a correlation based CTC which solely provides a correlation index for zonality, meridionality and cyclonicity and subsequently derives the circulation types according to predefined thresholds. Because these thresholds are the same on the sea and Z500 level, the availability of GWT classifications at both levels allows a comparison of their flow characteristics.

Most evidently, the westerly and northwesterly circulation types clearly dominate at the Z500 level (Fig. 1e and 1f), whereas meridional and easterly circulation types are far more abundant at sea level (Fig. 1c and 1d). Model spread is much smaller at the Z500 level than at sea level. This is particularly evident during summer. The most notable difference between the two levels is that westerlies occur more often during summer than during winter at the Z500 level, in contrast to the sea

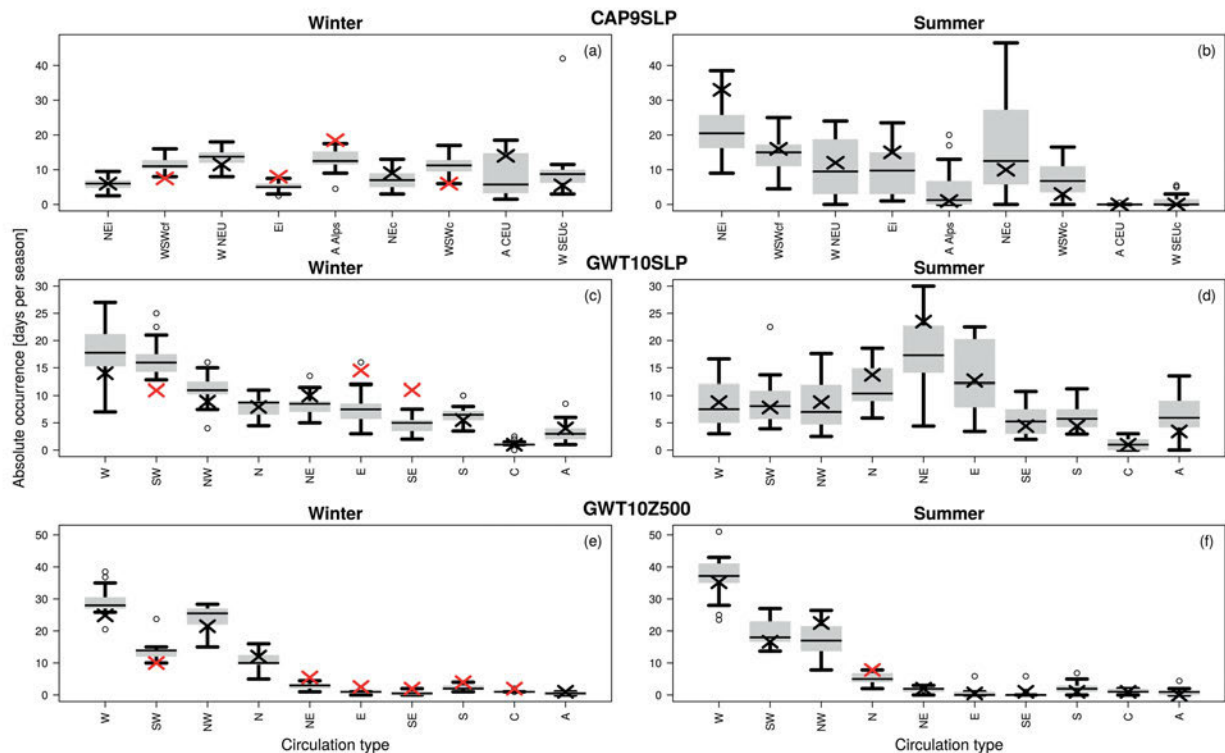


Figure 1: Comparison of the frequency of each circulation type [days per season] between ECMWF re-analysis data (crosses) and the 20 ENSEMBLES models (boxes) over the Alpine region for the period 1980–2009. The winter (left) and summer (right) season for CAP9SLP (top row), GWT10SLP (middle row) and GWT10Z500 (bottom row) are shown. Red crosses indicate where the re-analysis lies outside the 90 % confidence interval of the models.

level where the opposite is true. Furthermore, purely anticyclonic situations rarely occur over the Alpine region at the Z500 level whereas they are more abundant at sea level, especially during summer.

The daily classification catalog of GWT on the sea and Z500 level is used to evaluate quantitatively how closely linked these two levels are. Analyses of the ECMWF re-analysis data reveal that on 22 % of the days between 1980 and 2009 the same circulation type prevailed on both levels (hereafter referred to as matching days). A sensitivity test using the whole available time period (1957–2012) leads to the same result (22 %).

The percentage of matching days seems to be very low with only every fourth to fifth day having the same wind direction on the sea and Z500 level. However, the strict separation in eight wind directions plus an anticyclonic and a cyclonic type does not provide an intelligent algorithm to detect synoptic situations with a similar wind direction. In a synoptic situation where the prevailing wind direction is on the border between two classes, the Z500 level may be classified differently than the sea level despite being almost identical. With a less restrictive matching rule where the adjacent wind directions are allowed (i.e. NW, W, SW for a W flow), the percentage of matching days rises from 22 % to 54 % for the ECMWF re-analysis.

Analyzing the percentage of matching days on a seasonal basis shows that the correlation between Z500 and SLP circulation types is higher during winter (28 %

matching days) than during summer (14 % matching days). This may be indicative of the more dominant role of regional features such as convection and heat lows. The generally smaller north-south pressure gradient over Europe during summer probably also contributes to this finding.

Most model chains simulate the percentage of matching days accurately (mean 23.6 % and 90 % confidence interval 15.8–28.0 %). In addition, the seasonal fluctuation of matching days is clearly visible in the model simulations. In the period 1957–2012, when observation-based classifications are available, no trend in the number of matching days is detected either for re-analysis or for the model chains.

4 Projected changes in the seasonal frequency of circulation types

Two different methods are used to test the significance of the modeled trends, the Wilcoxon signed-rank test and logistic regression. Due to their different methodology, it is expected that not all trends are detected by both methods. If both statistical methods detect a trend in a circulation type, the trend is assumed to be robust. Hence, in the following section only trends found in both statistical frameworks are discussed. Additionally

Table 3: Summary of all significant trends (p -value < 0.05) obtained by the delta changes approach using the reference period 1980–2009 and the projection period 2070–2099 for CAP9SLP (a), GWT10SLP (b), GWT10Z500 (c). Significant positive trends are indicated by a “++” sign for the delta change approach and are colored red for logistic regression, significant negative trends by a “--” sign for the delta change approach and colored green for logistic regression. If both statistical frameworks detected a significant trend, the corresponding box is framed. If a circulation type occurs less than 3 days per season, the significant trends are denoted by a single “+” or “–”, colors are lighter and the framing of the boxes is thinner.

(a) CAP9SLP

Season	WSWcf	WSWc	W NEU	W SEUc	NEc	NEi	Ei	A Alps	A CEU
Winter					--	--			
Spring		--		--	--				+
Summer	--		--		++				
Autumn		--							

(b) GWT10SLP

Season	W	SW	NW	N	NE	E	SE	S	C	A
Winter	++			--	--	--				
Spring				++						
Summer	--	--	--	--	++	++		--		++
Autumn		--				++			-	++

(c) GWT10Z500

Season	W	SW	NW	N	NE	E	SE	S	C	A
Winter	++		--	--					-	
Spring	++	--	++		--		-	--		-
Summer	++	--						-	-	
Autumn								--		

only trends for circulation types are discussed that occur more often than three days per season in the observation-based data. Details are given in Table 3, as well as in Figs. 2 and 3.

Most prominently, at the sea level a general increase of easterlies at the expense of westerlies is found during summer until the end of the 21st century (2070–2099). This trend is represented by a significant increase of northeasterlies (NE) and easterlies (E) at the expense of all other wind directions except southeast (SE) in GWT10SLP. This trend is less pronounced in CAP9SLP. Nevertheless, it is represented by a significant increase of cyclonic northeasterlies (NEc) and a significant decrease of two westerly circulation types (WSWcf and W NEU) in CAP9SLP (Table 3, Fig. 2). The second statistical framework used in this study, logistic regression, adds confidence to aforementioned findings (Table 3, Fig. 3). One possible explanation for these projected trends may be the development of a low pressure anomaly (i.e. a heat low) over the Mediterranean as proposed by HAARSMa et al. (2009). In addition, these results are in line with the study by VAN ULDEN and VAN OLDENBORGH (2006) and by PLAVCOVA and KYSELY

(2013), who found that many climate models (global and regional) project more easterlies and anticyclonic situations at the expense of westerlies in Europe during summer.

In contrast, GWT10Z500 reveals a significantly increasing frequency of westerlies (W) during summer, whereas southwesterlies (SW) significantly decrease (Fig. 2 and 3, Table 3). The opposite response on the Z500 level compared to sea level in the course of the 21st century may be explained by a similar mechanism as proposed by HAARSMa et al. (2009) who note that the vertical extent of the Mediterranean heat low is around 800 hPa and that the high-pressure anomaly over the British Isles tilts toward the south with increasing height. RIEDIGER and GRATZKI (2014) find an increase of southwesterly circulation which is not in line with results of this study. This study shows that the response to climate change in the following century may be completely different at SLP and Z500. RIEDIGER and GRATZKI (2014) use different classification scheme which combines the 500 hPa and the 950 hPa geopotential height field. This may mask some trends found in this study, especially as they are of opposite sign on the two examined levels.

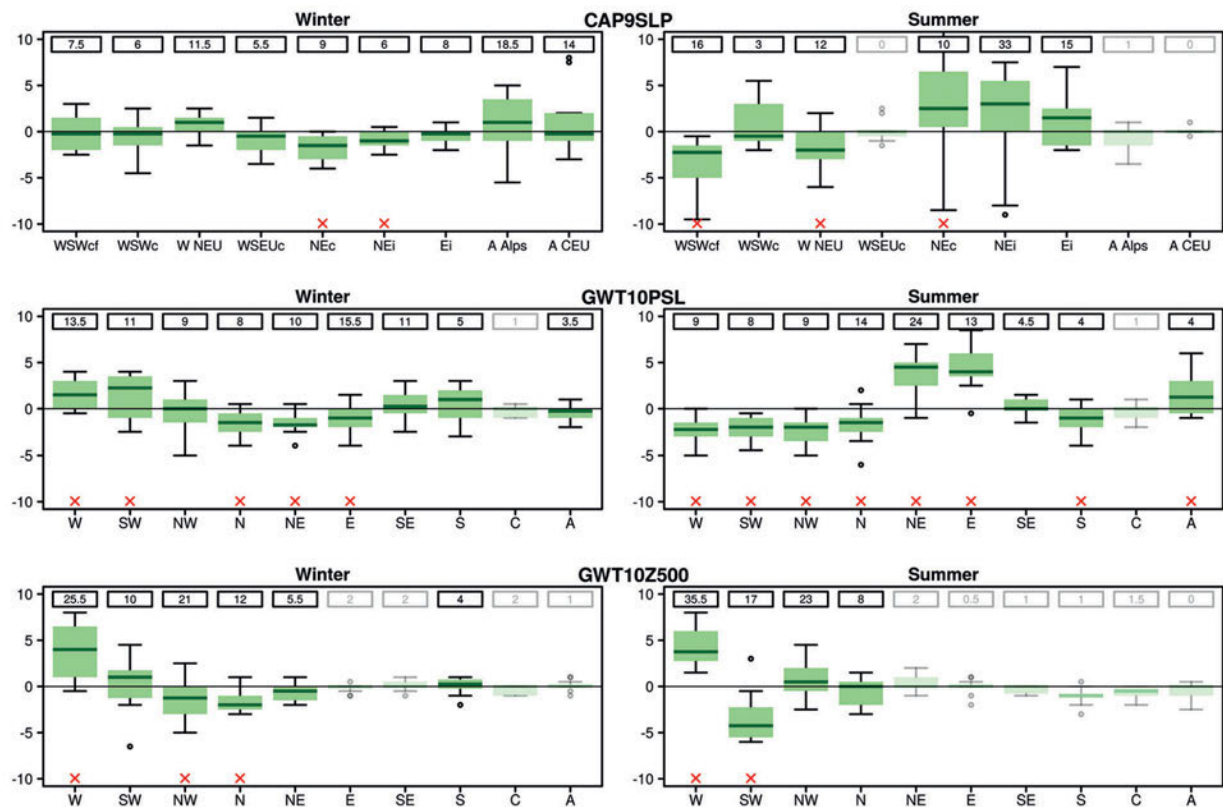


Figure 2: Projected changes in the occurrence frequency in absolute number of days of each circulation type for CAP9SLP (top row), GWT10SLP (middle row) and GWT10Z500 (bottom row). Changes are derived by the delta change approach for winter (left column) and summer (right column) until the end of the 21st century (2070–2099). The number above the boxplot denotes the occurrence of the corresponding circulation type during the reference period (1980–2009) using ECMWF re-analysis data. The red “x” on the bottom depicts circulation types for which significant changes (p -value ≤ 0.05) are detected. If a circulation type occurs no more than 3 days per season, the boxplot is transparent and significant changes are not shown.

The expected future changes in the frequency are slightly smaller during winter compared to summer. While CAP9SLP detects a significant decrease of (north) easterlies (NEi, NEc), GWT10SLP indicates significantly more frequent westerlies (W) and less frequent northerlies to easterlies (i.e. N, NE and E; Fig. 2 and Table 3). Logistic regression does not find a significant increase of westerlies in both SLP based classifications but agrees on the significant decrease of (north)easterlies. Closer examination showed that logistic regression also detects positive trends for westerly circulation types but none is significant at the 0.05 level. This is in good agreement with PLAVCOVA and KYSELY (2013). The significant decrease of easterlies and northeasterlies at the ground level cannot be found at the Z500 level. In agreement with SLP based classifications, westerlies (W) are projected to increase at the expense of northerlies (N).

In spring and autumn no consistent trends are found at sea level in CAP9SLP and GWT10SLP except for southwesterlies, which occur less frequently during autumn (Fig. 2 and 3, Table 3; WSWc in CAP9SLP, SW in GWT10SLP). CAP9SLP indicates a general decrease of cyclonic circulation types during spring with significantly decreasing trends in three out of four cyclonic circulation types (WSWc, W SEUc and NEc).

This is largely in agreement with results from PLAVCOVA and KYSELY (2013) who found an increasing tendency of anticyclones over central Europe instead of decreasing cyclonic activity during spring and decreasing south(east)erlies instead of southwesterlies as proposed in this study. However, this study only found this trend by the Wilcoxon signed-rank test and not by the logistic regression. During autumn PLAVCOVA and KYSELY (2013) propose an increase of anticyclonic situation over Central Europe (centered over Czech republic) and some models show an increasing frequency of southwesterlies which is not in line with the results presented in this study.

During autumn GWT10Z500 shows a similar picture with only a significant decrease of southerlies (S). In contrast, spring is marked by a significantly higher abundance of (north)westerlies (NW and W) compensated by a significant decrease of southern wind directions (SE, S and SW). Trends from both transitional seasons resemble the trends for summer more than those for winter.

Regarding the projected frequency of purely anticyclonic situations over the domain, increasing tendencies are found in every season by at least one classification at sea level. However, ROHRER (2013) notes that an artificial high pressure anomaly over elevated terrain (mainly

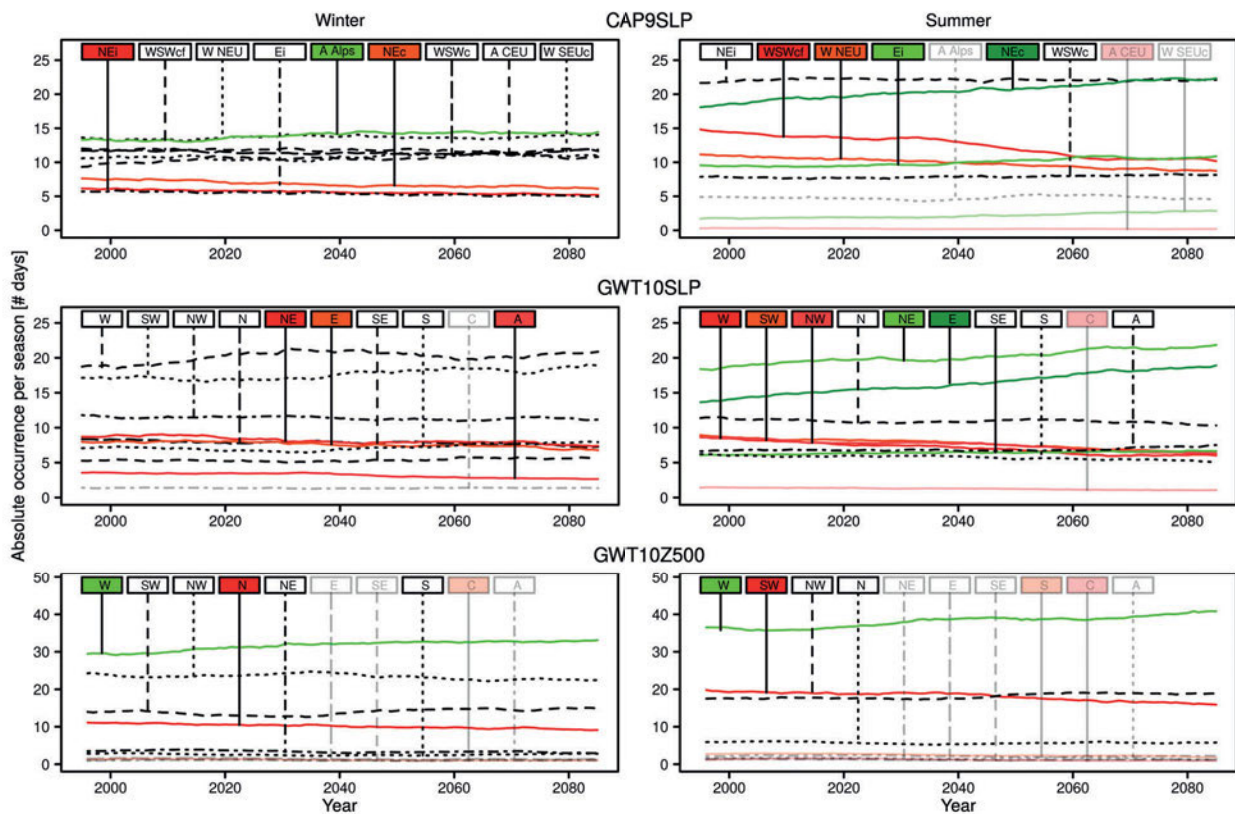


Figure 3: Logistic trend analysis for CAP9SLP (top), GWT10SLP (middle) and GWT10Z500 (bottom) for winter (left) and summer (right). Each panel depicts the trend of the absolute occurrence of a circulation type per season in days between 1995 and 2085. Significant trends (p -value < 0.05) are colored red (negative trend) or green (positive trend). For the reason of clarity the 30-years-running mean of the occurrence of each circulation type is shown. Circulation types occurring less than 3 days per season in the observation based classification are transparent.

the Alps which are in the center of the domain) is more likely to be responsible for these changes than a physical climate change signal. The anomaly seems to originate from the extrapolation from surface level to sea level which is the more inaccurate the higher the terrain is. No significant changes in the frequency of anticyclonic circulation types are detectable at the Z500 level except in spring. However, note that this circulation type rarely (i.e. 0–1 days per season) occurs in any season.

5 Discussion and Conclusions

Projected changes in the atmospheric circulation over the Alpine region are examined using nested global and regional climate model simulations. The two objective circulation type classification methods GWT and CAP are applied in a multi-model framework provided by the ENSEMBLES project. The expected changes are estimated in a comparable approach as by the CH2011 initiative.

First, the ability of 20 climate model chains to simulate the atmospheric circulation during the period 1980–2009 is analyzed by comparing the seasonal frequencies of the circulation types in the climate models with ECMWF re-analysis data. Overall it is found

that the climate models are able to capture atmospheric circulation. However, westerlies (easterlies) are significantly overestimated (underestimated) during winter at the sea level as well as at the 500 hPa geopotential height level. Wintertime southwesterlies are significantly overestimated in all three classifications used in this study. In summer the spread of the models is largest at both levels. This is due to the larger influence of small- to mesoscale phenomena (e.g. convection) during summer which is modeled differently depending on the applied regional climate model. Atmospheric circulation is best modeled during spring and autumn where the deviations between the observation-based data and the models are smallest for all circulation type classifications.

The overestimation (underestimation) of westerlies (easterlies) in midlatitudes is a common finding in studies examining the atmospheric circulation in climate models. Studies using climate model data from the Coupled Model Intercomparison Project phase 3 (CMIP3; MEEHL et al., 2007), which are the driving global climate models for the ENSEMBLES project, find a bias in the climatic mean state in the North Atlantic-European (NAE) domain. The westerly bias, with its accompanied too strong meridional pressure gradient over the mid-latitudes, also results in a lack of blockings in the NAE domain (e.g. SCAIFE et al., 2010) or too zonal extratrop-

ical cyclone tracks in winter (e.g. [ULBRICH et al., 2008](#)). These biases in the mean state of most global climate models trigger the overestimation found in this study.

A comparison between the 500 hPa geopotential level and sea level showed that 22 % of days between 1980 and 2009 are classified to the same circulation type on both levels. This percentage is higher during winter and lower during summer. Generally, the model spread is substantially lower at the 500 hPa geopotential level and westerly wind regimes are more dominant compared to the sea level.

Assessing the projected changes in the seasonal frequency of circulation types for the 21st century leads to two main findings. First, easterlies (westerlies) are expected to become significantly more (less) frequent during summer at sea level. These findings may be related to Mediterranean soil moisture depletion ([HAARSMA et al., 2009](#)). The significantly increasing frequency of westerly winds at the 500 hPa geopotential height level is in line with this hypothesis as the Mediterranean heat low is confined to the lower atmosphere.

During winter, easterlies are projected to significantly decrease until the end of the 21st century (2070–2099), while there are tendencies, although only partly significant, towards more abundant westerlies at both the sea level and the 500 hPa geopotential height level. Southwesterlies are projected to significantly increase, whichever classification method is applied. This decrease of easterlies is in line with the projected decrease of blockings in the North Atlantic domain in CMIP3 simulations (e.g. [SILLMANN and CROCI-MASPOLI, 2009](#); [BARNES et al., 2012](#)). [VAN DER LINDEN and MITCHELL \(2009\)](#) also report a tendency towards a more positive NAO state in future, which is in line with more westerlies in Central Europe and less blockings in the North Atlantic domain. However, in the newer CMIP5 simulations ([TAYLOR et al., 2012](#)) the future changes in blocking frequency are less pronounced. [ZAPPA et al. \(2013\)](#) showed that the representation of extratropical cyclones, another important atmospheric feature in the midlatitudes, improved from CMIP3 to CMIP5. This may alter the results obtained by this study.

The newly released CORDEX data ([JACOB et al., 2014](#)) may deliver more insight in this regard. Results from the recent fifth IPCC assessment report indicate that although CMIP5 overall performs better than CMIP3, the general direction of trends in atmospheric circulation remain the same in both model generations ([COLLINS et al., 2013](#)). In short, although more recent models show smaller trends, the main message of this paper still remains valid.

Spring and autumn are not expected to experience major circulation changes at sea level. In contrast, during spring westerlies and northwesterlies are projected to significantly increase at the 500 hPa geopotential height level.

The projected future frequency of high pressure systems over the domain is not discussed as [ROHRER \(2013\)](#) notes that most models show a high pressure anomaly

over elevated terrain rendering a profound prediction on how the frequency of high pressure systems may evolve difficult. These high pressure anomalies are in fact likely to be remnants of the extrapolation over elevated terrain.

Note that the focus of this paper was on projections towards the end of the current century. Earlier projection periods have also been analyzed (not shown; see [ROHRER, 2013](#)). Many of the trends discussed only occur to be significant during the last projection period. In the first projection period (2020–2049) the contribution of natural variability relative to the global warming signal is large and hence the signal-to-noise ratio is small.

Finally this study highlights the importance of using several climate models instead of only a single one to assess climate change. Single models may deliver misleading results due to its individual flaws and inhibit a reliable quantification of model uncertainty, which in turn a multi-model approach provides.

6 Acknowledgements

This study was partly funded by the Federal Office for the Environment and the Swiss National Science Foundation via the project EXTRA-LARGE (Contract number 143219) under the guidance of STEFAN BRÖNNMANN. We greatly acknowledge TANJA WEUSTHOFF and OLIVIA ROMPPAINEN-MARTIUS for their valuable comments. The CH2011 data were obtained from the Center for Climate Systems Modeling (C2SM) and additional model data were downloaded from the ENSEMBLES data portal. Circulation types were calculated with the aid of the COST733 classification software provided by the COST 733 Action “Harmonisation and Applications of Weather Type Classifications for European Regions”. The Swiss National Supercomputing Center (CSCS) is acknowledged for their data storage capabilities.

Abbreviations

A	Anticyclonic
A Alps	High pressure over the Alps
A CEU	High pressure over Central Europe
C	Cyclonic
CAP	Cluster analysis of principal components
CAP9SLP	CAP with nine circulation types on sea level pressure
CH2011	Swiss Climate Change Scenarios 2011 report
CMIP3	Coupled Model Intercomparison Project phase 3
CMIP5	Coupled Model Intercomparison Project phase
COST	European cooperation in science and technology

CTC	Circulation type classification
DJF	December-January-February, winter
E	East
Ei	East, indifferent
ECMWF	European center for midrange weather forecasts
ERA	European center for midrange weather forecasts re-analysis
GWT	Grosswetter-Typen
GWT10SLP	GWT with ten circulation types on sea level pressure
GWT10Z500	GWT with ten circulation types on 500 hPa geopotential height
IPCC	Intergovernmental Panel on Climate Change
JJA	June-July-August, summer
MAM	March-April-Mai, spring
MeteoSwiss	Federal Office of Meteorology and Climatology
N	North
NAE	NorthAtlantic-European
NE	NorthEast
NEc	NorthEast, cyclonic
NEi	NorthEast, indifferent
NW	NorthWest
S	South
SE	SouthEast
SON	September-October-November, autumn
SW	SouthWest
SLP	Sea level pressure
SRES	Special report on emission scenarios
W	West
WSWc	WestSouthWest, cyclonic
WSWcf	WestSouthWest, cyclonic, flat pressure
WNEU	Westerly flow over Northern Europe
WSEUC	Westerly flow over Southern Europe cyclonic
Z500	500 hPa geopotential height

References

- BARNES, E., A.J. SLINGO, T. WOOLLINGS, 2012: A methodology for the comparison of blocking climatologies across indices, models and climate scenarios. – *Climate Dyn.* **38**, 2467–2481.
- BENESTAD, R.A., I. HANSEN-BAUER, D. CHENG, 2008: Empirical-statistical downscaling. – World Scientific Publishing Company, 228 pp.
- BLENKINSOP, S., P.D. JONES, S.R. DORLING, T.J. OSBORN, 2009: Observed and modelled influence of atmospheric circulation on central England temperature extremes. – *Int. J. Climate* **29**, 1642–1660.
- BUSER, C.M., H.R. KÜNSCH, D. LÜTHI, M. WILD, C. SCHÄR, 2009: Bayesian multi-model projection of climate: bias assumptions and interannual variability. – *Climate Dyn.* **33**, 849–868. DOI:10.1007/s00382-009-0588-6.
- CAHYNOVA, M., R. HUTH, 2014: Atmospheric circulation influence on climatic trends in Europe: an analysis of circulation type classifications from the COST733 catalogue. – *Int. J. Clim.*, published online April 7, 2014. DOI: 10.1002/joc.4003.
- CH2011, 2011: Swiss Climate Change Scenarios CH2011, published by C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC. – Zurich, Switzerland, 88 pp. ISBN: 978-3-033-03065-7.
- COLLINS, M., R. KNUTTI, J. ARBLASTER, J.-L. DUFRESNE, T. FICHEFET, P. FRIEDLINGSTEIN, X. GAO, W.J. GUTOWSKI, T. JOHNS, G. KRINNER, M. SHONGWE, C. TEBALDI, A.J. WEAVER, M. WEHNER, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. – In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. STOCKER, T.F., D. QIN, G.-K. PLATTNER, M. TIGNOR, S.K. ALLEN, J. BOSCHUNG, A. NAUELS, Y. XIA, V. BEX AND P.M. MIDGLEY (Eds.). – Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- DEE, D.P., S.M. UPPALA, A.J. SIMMONS, P. BERRISFORD, P. POLI, S. KOBAYASHI, U. ANDRAE, M.A. BALMASEDA, G. BALSAMO, P. BAUER, P. BECHTOLD, A.C.M. BELJAARS, L. VAN DE BERG, J. BIDLOT, N. BORMANN, C. DELSOL, R. DRAGANI, M. FUENTES, A.J. GEER, L. HAIMBERGER, S.B. HEALY, H. HERSBACH, E.V. HOLM, L. ISAKSEN, P. KALLBERG, M. KÖHLER, M. MATRICARDI, A.P. McNALLY, B.M. MONGE-SANZ, J.-J. MORCRETTE, B.-K. PARK, C. PEUBEY, P. DE ROSNAY, C. TAVOLATO, J.-N. THÉPAUT, F. VITART, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. – *Quart. J. Roy. Meteor. Soc.* **137**, 553–597. DOI:10.1002/qj.828.
- DEMUZERE, M., M. WERNER, N.P.M. VAN LIPZIG, E. ROECKNER, 2009: An analysis of present and future ECHAM5 pressure fields using a classification of circulation patterns. – *Int. J. Climatol.* **29**, 1796–1810. DOI:10.1002/joc.1821.
- FISCHER, A.M., A.P. WEIGEL, C.M. BUSER, R. KNUTTI, H.R. KÜNSCH, M.A. LINIGER, C. SCHÄR, C. APPENZELLER, 2012: Climate change projections for Switzerland based on a Bayesian multi-model approach. – *Int. J. Climatol.* **32**, 2348–2371. DOI:10.1002/joc.3396.
- HAARSMAN, R.J., F. SELTEN, B. VAN DEN HURK, W. HAZELEGER, 2009: Drier Mediterranean soils due to greenhouse warming bring easterly winds over summertime central Europe. – *Geophys. Res. Lett.* **36**, L04705. DOI: 10.1029/2008GL036617.
- HUTH, R., 1997: Continental-scale circulation in the UKHI GCM. – *J. Climate* **10**, 1545–1561.
- HUTH, R., C. BECK, A. PHILIPP, M. DEMUZERE, Z. USTRNUL, M. CAHYNOVA, J. KYSELY, O.E. TVEITO, 2008: Classifications of atmospheric circulation patterns: Recent advances and applications. – *Ann. N.Y. Acad. Sci.* **1146**, 105–152. DOI: 10.1196/annals.1446.019.
- IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. SOLOMON, S., D. QIN, M. MANNING, Z. CHEN, M. MARQUIS, K.B. AVERYT, M. TIGNOR, H.L. MILLER (Eds.). – Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

- JACOB, D., J. PETERSEN, B. EGGERT, A. ALIAS, O.B. CHRISTENSEN, L. BOUWER, A. BRAUN, A. COLETTE, M. DÉQUÉ, G. GEORGIEVSKI, E. GEORGOPOULOU, A. GOBIET, L. MENUET, G. NIKULIN, A. HAENSLER, N. HEMPELMANN, C. JONES, K. KEULER, S. KOVATS, N. KRÖNER, S. KOTLARSKI, A. KRIEGSMANN, E. MARTIN, E. MEIJGAARD, C. MOSELEY, S. PFEIFER, S. PREUSCHMANN, C. RADERMACHER, K. RADTKE, D. RECHID, M. ROUNSEVELL, P. SAMUELSSON, S. SOMOT, J.F. SOUSSANA, C. TEICHMANN, R. VALENTINI, R. VAUTARD, B. WEBER, P. YIOU, 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. – *Reg. Env. Change*, **1–16**, 563–578. DOI: [10.1007/s10113-013-0499-2](https://doi.org/10.1007/s10113-013-0499-2).
- KAPSCH, M.-L., M. KUNZ, R. VITOLO, T. ECONOMOU, 2012: Long-term trends of hail-related weather types in an ensemble of regional climate models using a Bayesian approach. – *J. Geophys. Res.* **117**, D15107. DOI: [10.1029/2011JD017185](https://doi.org/10.1029/2011JD017185).
- KUNZ, M., J. SANDER, C. KOTTMEIER, 2009: Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. – *Int. J. Climatol.* **29**, 2283–2297. DOI: [10.1002/joc.1865](https://doi.org/10.1002/joc.1865).
- LORENZO, M.N., A.M. RAMOS, J.J. TABOADA, L. GIMENO, 2011: Changes in present and future circulation types frequency in northwest Iberian peninsula. – *PLoS ONE* **6**, e16201. DOI: [10.1371/journal.pone.0016201](https://doi.org/10.1371/journal.pone.0016201).
- MEEHL, G.A., C. COVEY, K.E. TAYLOR, T. DELWORTH, R.J. STOUFFER, M. LATIF, B. McAVANEY, J.F.B. MITCHELL, 2007: THE WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. – *Bull. Amer. Meteor. Soc.* **88**, 1383–1394. DOI: [10.1175/BAMS-88-9-1383](https://doi.org/10.1175/BAMS-88-9-1383).
- NAKICENOVIC, N., R. SWART (Eds.), 2000: IPCC Special report on emissions scenarios. – Cambridge University Press, UK, 570 pp.
- PASTOR, M.A., M.J. CASADO, 2012: Use of circulation types classifications to evaluate AR4 climate models over the Euro-Atlantic region. – *Clim. Dyn.* **39**, 2059–2077. DOI: [10.1007/s00382-012-1449-2](https://doi.org/10.1007/s00382-012-1449-2).
- PHILIPP, A., J. BARTHOLY, C. BECK, M. ERPICUM, P. ESTEBAN, X. FETTWEIS, R. HUTH, P. JAMES, S. JOURDAIN, F. KREIENKAMP, T. KRENNERT, S. LYKODIS, S.C. MICHALIDES, K. PIANKO-KLUCZYNSKA, P. POST, D.R. ALVAREZ, R. SCHIEMANN, A. SPEKAT, F.S. TYMVIOS, 2010: Cost733cat – A database of weather and circulation type classifications. – *Phys. Chem. Earth* **35**, 360–373. DOI: [10.1016/j.pce.2009.12.010](https://doi.org/10.1016/j.pce.2009.12.010).
- PHILIPP, A., C. BECK, R. HUTH, J. JACOB, 2014: Development and comparison of circulation type classifications using the COST 733 dataset and software. – *Int. J. Climatol.*, published online. DOI: [10.1002/joc.3920](https://doi.org/10.1002/joc.3920).
- PINTO, J.G., C.P. NEUHAUS, G.C. LECKEBUSCH, M. REYERS, M. KERSCHGENS, 2010: Estimation of wind storm impacts over western Germany under future climate conditions using a statistical-dynamical downscaling approach. – *Tellus* **62A**, 188–201. DOI: [10.1111/j.1600-0870.2009.00424.x](https://doi.org/10.1111/j.1600-0870.2009.00424.x).
- PLAVCOVA, E., J. KYSELY, 2011: Evaluation of daily temperatures in Central Europe and their links to large-scale circulation in an ensemble of regional climate models. – *Tellus* **63A**, 763–781. DOI: [10.1111/j.1600-0870.2011.00514.x](https://doi.org/10.1111/j.1600-0870.2011.00514.x).
- PLAVCOVA, E., J. KYSELY, 2013: Projected evolution of circulation types and their temperatures over Central Europe in climate models. – *Theor. Appl. Climatol.* **114**, 625–634. DOI: [10.1007/s00704-013-0874-4](https://doi.org/10.1007/s00704-013-0874-4).
- PRUDHOMME, C., M. GENEVIER, 2011: Can atmospheric circulation be linked to flooding in Europe? – *Hydrol. Process.* **25**, 1180–1190.
- PONGRÁCZ, R., J. BARTHOLY, A. PHILIPP, C. BECK, A. KERN, 2010: Application of different weather pattern classifications to simulated future climate conditions for Central Europe. – American Meteorological Society. Meeting deliverable, https://ams.confex.com/ams/90annual/techprogram/paper_164338.htm
- RIEDIGER, U., A. GRATZKI, 2014: Future weather types and their influence on mean and extreme climate indices for precipitation and temperature in Central Europe. – *Meteorol. Z.* **23**, 231–252. DOI: [10.1127/0941-2948/2014/0519](https://doi.org/10.1127/0941-2948/2014/0519).
- ROHRER, M., 2013: Climate Change and Circulation Types in the Alpine Region. – Scientific Report MeteoSwiss **91**, 80 pp.
- SCAIFE, A.A., T. WOOLLINGS, J. KNIGHT, G. MARTIN, T. HINTON, 2010: Atmospheric Blocking and Mean Biases in Climate Models. – *J. Climate* **23**, 6143–6152. DOI: [10.1175/2010JCLI3728.1](https://doi.org/10.1175/2010JCLI3728.1).
- SCHIEMANN, R., C. FREI, 2010: How to quantify the resolution of surface climate by circulation types: an example for Alpine precipitation. – *Phys. Chem. Earth* **35**, 403–410.
- SCHIESSER, H.H., C. PFISTER, J. BADER, 1997: Winter Storms in Switzerland North of the Alps 1864/65–1993/94. – *Theor. Appl. Climatol.* **58**, 1–19.
- SILLMANN, J., M. CROCI-MASPOLI, 2009: Present and future atmospheric blocking and its impact on European mean and extreme climate. – *Geophys. Res. Lett.* **36**, L10702, DOI: [10.1029/2009GL038259](https://doi.org/10.1029/2009GL038259).
- TAYLOR, K.E., R.J. STOUFFER, G.A. MEEHL, 2012: An Overview of CMIP5 and the Experiment Design. – *Bull. Amer. Meteor. Soc.* **93**, 485–498. DOI: [10.1175/BAMS-D-11-00094.1](https://doi.org/10.1175/BAMS-D-11-00094.1).
- ULBRICH, U., J.G. PINTO, H. KUPFER, G.C. LECKEBUSCH, T. SPANGHEHL, M. REYERS, 2008: Changing Northern Hemisphere Storm Tracks in an Ensemble of IPCC Climate Change Simulations. – *J. Climate* **21**, 1669–1679. DOI: [10.1175/2007JCLI1992.1](https://doi.org/10.1175/2007JCLI1992.1).
- UPPALA, S.M., P.W. KALLBERG, A.J. SIMMONS, U. ANDRAE, V.D. BECHTOLD, M. FIORINO, J.K. GIBSON, J. HASELER, A. HERNANDEZ, G.A. KELLY, X. LI, K. ONOGI, S. SAARINEN, N. SOKKA, R.P. ALLAN, E. ANDERSSON, K. ARPE, M.A. BALMASEDA, A.C.M. BELJAARS, L. VAN DE BERG, J. BIDLOT, N. BORMANN, S. CAIRES, F. CHEVALLIER, A. DETHOF, M. DRAGOSAVAC, M. FISHER, M. FUENTES, S. HAGEMANN, E. HOLM, B.J. HOSKINS, L. ISAKSEN, P.A.E.M. JANSSEN, R. JENNE, A.P. McNALLY, J.F. MAHFOUF, J.J. MORCRETTE, N.A. RAYNER, R.W. SAUNDERS, P. SIMON, A. STERL, K.E. TRENBERTH, A. UNTCH, D. VASILJEVIC, P. VITERBO, J. WOOLLEN, 2005: The ERA-40 re-analysis. – *Quart. J. Roy. Meteor. Soc.* **131**, 2961–3012. DOI: [10.1256/qj.04.176](https://doi.org/10.1256/qj.04.176).
- VAN DER LINDE, P., J.F.B. MITCHELL (Eds.), 2009: ENSEMBLES: Climate change and its impacts: summary of research and results from the ENSEMBLES project. – Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. 160 pp.
- VAN ULDEN, A.P., G.J. VAN OLDENBORGH, 2006: Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in Central Europe. – *Atmos. Chem. Phys.* **6**, 863–881.
- WEUSTHOFF, T., 2011: Weather type classification at MeteoSwiss: Introduction of new automatic classification schemes. – *Arbeitsberichte der MeteoSchweiz* **235**, 46 pp.
- YARNAL, B., A.C. COMRIE, B. FRANKS, D.P. BROWN, 2001: Developments and prospects in synoptic climatology. – *Int. J. Climatol.* **21**, 1923–1950.
- ZAPPA, G., L.C. SHAFFREY, K.I. HODGES, 2013: The ability of CMIP5 models to simulate North Atlantic extratropical cyclones. – *J. Climate* **26**, 5379–5396, DOI: [10.1175/JCLI-D-12-00501.1](https://doi.org/10.1175/JCLI-D-12-00501.1).