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averaged warming signal over western Europe, with the remaining 37% ($\pm 29\%$) explained by the direct impact of changes in anthropogenic radiative forcings from GHG and aerosols. The results further suggest that the anomalous atmospheric circulation, and associated low rainfall, were also influenced both by changes in SST/SIE and by the direct impact of changes in radiative forcings; however, the magnitude

of the forced signals in these variables is much less, relative to internal variability, than for surface air temperature. Further evidence suggests that changes in North Atlantic SST were likely an important factor in explaining the striking contrast between the European summers of 2013 and that of 2012. A major area for further work is to understand more completely the mechanisms that explain these influences.

19. CONTRIBUTION OF ATMOSPHERIC CIRCULATION TO WET SOUTHERN EUROPEAN WINTER OF 2013

PASCAL YIOU AND JULIEN CATTIAUX

Winter 2013 was the second wettest since 1948 in southern Europe. This is partially explained by the atmospheric circulation. We suspect the warm Atlantic Ocean to have amplified the precipitation extreme.

Introduction. Southern Europe witnessed anomalously high precipitation amounts, associated with anomalously low temperatures, during the winter of 2013. The goal of this paper is to put this regional event into the context of long-term variability. In Europe, studies have highlighted North Atlantic atmospheric dynamics as the main driver of winter precipitation and temperatures on both intra-seasonal and inter-annual time scales (e.g., Cattiaux et al. 2010; Vautard and Yiou 2009). Here, we focus on the contribution of large-scale circulations the winter 2013 precipitation anomalies using the same flow-analogue approach as in the analysis of summer 2012 North European precipitation by Yiou and Cattiaux (2013).

Data. We use in situ measurements provided by the European Climate Assessment dataset at 5231 stations over the period 1948–2013 (Klein-Tank et al. 2002). We compute anomalies relative to a 1971–2000 climatology. The daily climatology is obtained by averaging over each calendar day in 1971–2000, then smoothing by splines. We selected 510 stations on the basis of (a) an altitude lower than 800 m, longitudes between 10°W–40°E, and latitudes between 30°–72°N; (b) the availability of more than 70% of daily values between 1 January 1971 and 31 December 2000 for a reliable estimate of the climatology; and (c) the availability of more than 90% of daily values between 1 January 2013 and 31 December 2013 for a reliable estimate of the 2013

anomalies. We averaged precipitation values over Southern Europe (10°W–20°E; 35°–50°N, see Fig. 19.1) after selecting (d) only one station per 0.5° × 0.5° latitude/longitude box for spatial homogeneity, hence leaving 45 stations in that region. Although we mainly focus on cumulative precipitation, we also computed the precipitation frequency (or fraction of wet days) for each month as in Vautard et al. (2007) and Vautard and Yiou (2009). The precipitation frequency is the empirical probability in a given month of observing a daily precipitation amount larger than 0.5 mm. It provides an indicator of the temporal continuity of precipitation.

Observed rainfall anomaly. Anomalously high precipitation amounts are observed in Southern Europe (e.g., France, Spain, and Italy) in February–March 2013 (Fig. 19.1, upper panels). These anomalously high amounts culminate in March 2013. Those winter wet conditions contrast with drier than usual conditions in Northern Europe (e.g., United Kingdom, Netherlands, Germany, and Scandinavia). The precipitation frequency during winter 2013 (from 1 January to 31 March 2013) also has positive anomalies in Southern Europe, indicating that the rain episodes lasted for prolonged periods of time (Supplementary Fig. S19.1). Therefore, the generally wet conditions mainly concern the southern part of Europe for winter 2013 (mainly February and March). Besides, cold anomalies were observed over

Western Europe during this season (Supplementary Fig. S19.2).

The highest daily precipitation amounts on average over Southern Europe occurred in February and March (Fig. 19.2a), as did the longest winter spells of precipitation (32 days). Part of that precipitation was snow, which caused havoc in French public transportation, especially in the middle of March 2013, and broke local records of snow amounts in the French Pyrenees. On average over Southern Europe during the whole winter season (JFM), 2013 is the second wettest winter since the beginning of our record (1948) behind 1979. This points to the exceptional character of the Southern Europe 2013 winter. The temperatures were also anomalously low in February and March in Southern Europe, contrasting with Eastern Europe, especially in February (Supplementary Fig. S19.2), but the temperature anomaly was close to the median (e.g., 33rd coldest year on record), therefore, justifying our focus on precipitation. The temperature anomalies are not as well reconstructed by the circulation analogues in February 2013, especially over France. This is explained

by the fact that the February cold temperatures were due to persisting snow cover (e.g., in France) rather than the atmospheric circulation itself.

Contribution of the atmospheric circulation. The contribution of large-scale dynamics to the precipitation anomalies of 1948–2013 is estimated from the same flow-analogue approach as used in Cattiaux and Yiou (2012) or Yiou and Cattiaux (2013). For each day, we selected the 20 days with the most correlated sea level pressure (SLP) among days of other years but within a moving window of 60 calendar days to account for seasonality (see Yiou et al. 2007 for details). SLP anomalies are derived from the NCEP–NCAR reanalyses (Kistler et al. 2001) and are considered over the period 1948–2013 and the area (80°W–20°E, 22.5°–70°N).

For each station and each day, we computed the mean of the 20 analogue composites. The mean analogue precipitation of winter 2013 (averaged over 20 analogue days) is higher than usual in Southern Europe, both in terms of precipitation amount (Fig. 19.1) and frequency (Supplementary Fig. S19.1).

Spatial patterns of analogue precipitation follow the observed ones, albeit with lower amplitudes (Fig. 19.1). The spatial correlations are 0.61, 0.64, and 0.79 in January to March, respectively. On a daily time scale over Southern Europe, the precipitation analogues closely follow the observed averages (Fig. 19.2a; temporal correlation $r = 0.57$; p -value $< 5 \times 10^{-3}$). This confirms that the large-scale atmospheric circulation influences the precipitation amounts at the intraseasonal scale.

In order to further describe the circulation patterns of the winter 2013, we used the clustering approach of Michelangeli et al. (1995), and adapted by Yiou

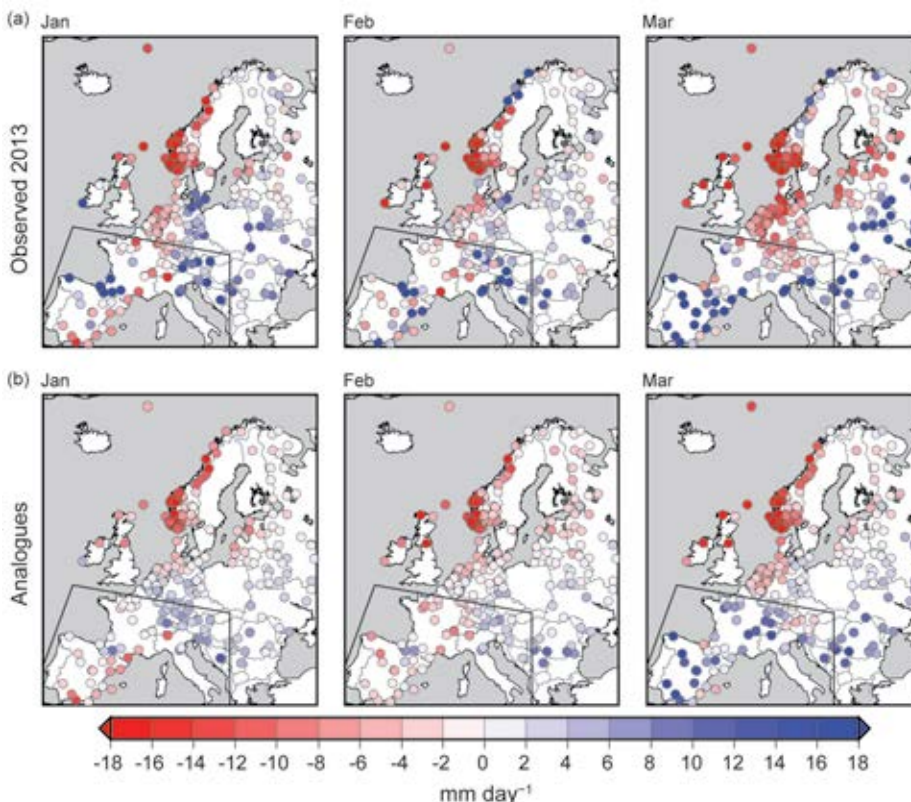


FIG. 19.1. Anomalies of precipitation over Europe (in mm day^{-1}) for the winter months in 2013 (Jan–Mar). The colored points represent the 510 ECA&D stations we retained. The polygon outlines the region over which the averages are computed (10°W–20°E; 35°–49°N). (a) Observed precipitation anomalies. (b) Mean precipitation obtained from 20 analogues of circulation.

et al. (2008), to derive the four preferential winter weather regimes over the North Atlantic region and the period 1948–2013. The rationale for this analysis, which complements the flow-analogue approach, is to visualize the atmospheric circulation temporal variability and associate episodes of high precipitation with circulation patterns (Fig. 19.2a). The weather regimes are computed from SLP anomalies during 1948–2013. These four weather regimes correspond to anomalies in the flow and affect the advection of temperature and humidity (Fig. 19.2c–f). We find that the wet spells over Southern Europe correspond with episodes of the Atlantic Ridge (AR) in February and the negative phase of the North Atlantic Oscillation (NAO–) in March, which yields a weak pressure dipole over Iceland and the Azores (Fig. 19.2d–e). When the circulation yields anticyclonic patterns over Scandinavia (blocking), daily precipitation amounts fall to low values.

Trends of precipitation. We computed the linear trends of the seasonal average precipitation over the outline region (Fig. 19.2b) for the period between 1971 and 2013. The trends for all seasons are not statistically significant (p -values > 0.1). The mean analogue precipitation for winter is well correlated ($r = 0.86$, p -value $< 10^{-15}$) with the observed average (Fig. 19.2b), and the analogues yield a negative winter trend found in the

observations, although it is not statistically significant (p -value = 0.26). The winter 2013 median analogue

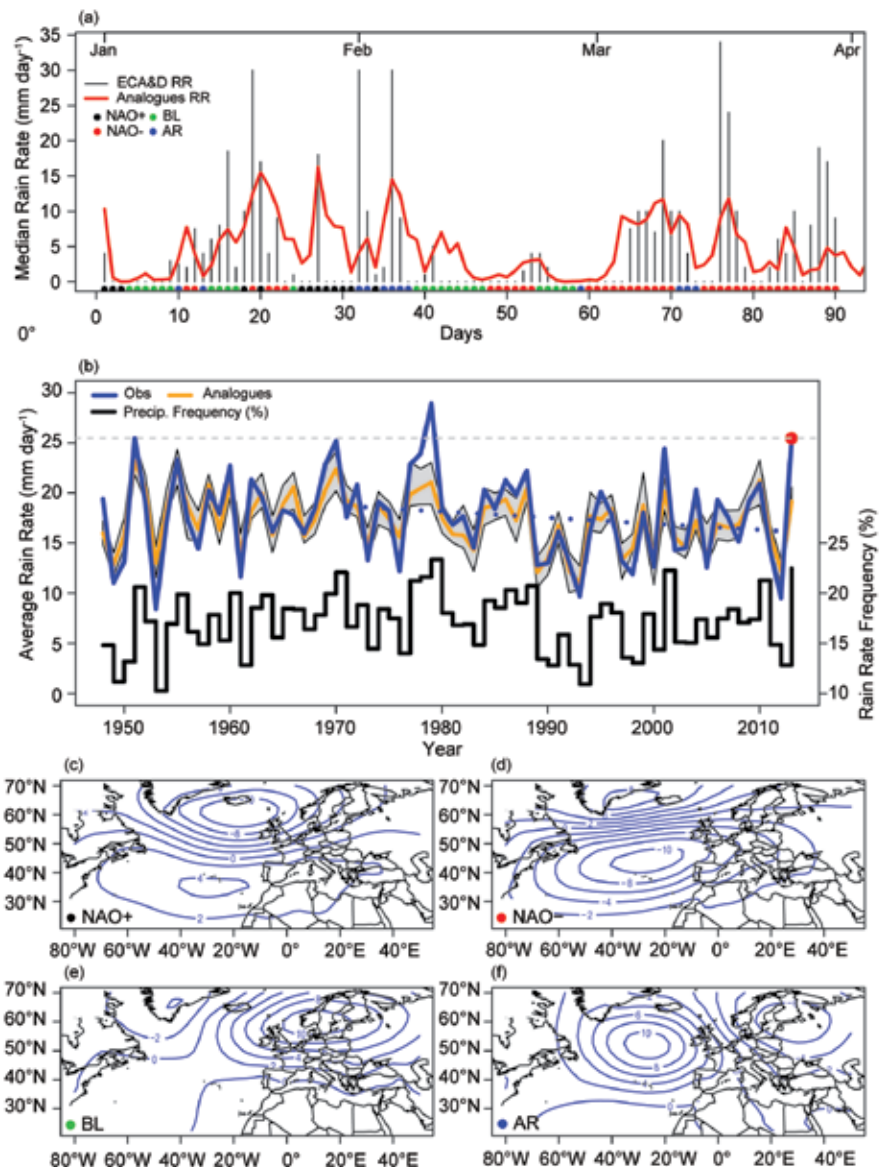


FIG. 19.2. Temporal evolution of precipitation in the outlined Southern Europe region and winter weather regimes. (a) Temporal evolution of precipitation in Jan–Mar 2013 (black vertical lines). The thick red line represents the median of analogue composites across stations and the 20 analogues. The colored points at the bottom of the panel indicate the daily weather regime. (b) Time series of average precipitation for winter (JFM, blue) between 1948 and 2013. A red dot and a horizontal dashed line indicate the value for 2013. Dotted lines are the linear trends between 1971 and 2013. The orange line represents the precipitation mean over Northern Europe stations of the median of analogues (in %). The gray shading is the 10th and 90th percentile of the precipitation analogues. The black line represents the average precipitation frequency (in %) in Jan–Mar. (c–f) Summer weather regimes computed from a classification of NCEP sea level pressure data. We use the terminology of Michelangeli et al. (1995): positive North Atlantic Oscillation (c: NAO+), negative North Atlantic Oscillation (d: NAO–), Scandinavian Blocking (e: BL), and Atlantic Ridge (f: AR). The isolines represent anomalies with respect to a 1971–2000 climatology.

precipitation amount is only the 18th highest of the analogue time series, showing that even if the atmospheric conditions were favorable to wet conditions over Southern Europe, they do not fully explain the exceptional character of the precipitation anomaly. We conjecture that a potential amplifying cause could be that the oceanic air masses carried by regimes of westerly winds were moister than usual due to warmer SSTs in the Northeast Atlantic (between 0.5 and 1.5 K above normal). We performed an additional analysis by searching circulation analogues among the years of warm Northeast Atlantic SST (i.e., above the 1971–2000 average). The mean monthly European precipitation amounts reconstructed from such “filtered” analogues exceed those of “regular” analogues, picked over 1948–2012 (not shown). Although this is not a definite proof, this pleads in favor of this mechanism.

Conclusions. Our analysis suggests that the high precipitation amounts were mainly caused by the cyclonic conditions (NAO– and Atlantic Ridge) that prevailed during the late winter (February and March) over the North Atlantic. Such conditions brought moist air over Southern Europe. This conclusion is drawn from the significant correlations over Europe between the observed and the analogue precipitation, deduced from the North Atlantic atmospheric circulation. The extreme precipitation amounts, not fully explained by the atmospheric circulation, are conjectured to be due to a warmer Northeast Atlantic with more moist air (Trigo et al. 2013).

The trend in winter precipitation over Southern Europe is negative but not statistically significant. The frequency of cyclonic regimes over Scandinavia (NAO– and Atlantic Ridge) has also slightly decreased, albeit not significantly (not shown).

20. THE HEAVY PRECIPITATION EVENT OF MAY–JUNE 2013 IN THE UPPER DANUBE AND ELBE BASINS

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An observation-based analysis and large simulation ensembles show no evidence that climate change made heavy precipitation in the upper Danube and Elbe basins in May–June, such as observed in 2013, more likely.

Introduction. After an anomalously cold, cloudy, and rainy spring in central Europe, regions in Germany, Switzerland, Austria, and the Czech Republic received large amounts of precipitation between 30 May and 2 June 2013, with some places receiving the usual monthly precipitation amount within one or two days (CIB 2013). As shown in Fig. 20.1a, the maximum precipitation fell in the upper Danube and Elbe catchments, which led to severe flooding along these rivers in the following weeks. Grams et al. (2014) identified that during the four-day event, three consecutive low pressure systems moved from east to west over central Europe, due to a Rossby wave breaking, with the Alps acting as a wall. Thus, the low pressure systems remained stationary—a rare weather situation that occasionally occurs in summer but is extremely unusual in spring. Hydrological processes, in particular the late snow melt and saturated soils

in some regions in Germany even before the event caused by the unusual spring weather, played an important role in the ensuing Danube and Elbe floods (BfG-DWD 2013). It has been suggested that Arctic warming has increased the chances of flooding on the Elbe and Danube (Petoukhov et al. 2013). However, Hirabayashi et al. (2013) showed that floods in central Europe should decrease with climate change, even as flooding in other parts of Europe has been attributed to anthropogenic warming (Pall et al. 2011). In this study, we analyze whether and to what extent anthropogenic climate change changed the odds of high precipitation in the upper Elbe and Danube catchments in May–June.

Methods. To obtain the very large ensembles of regional climate simulations needed to quantify the role of anthropogenic climate in the heavy precipitation