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

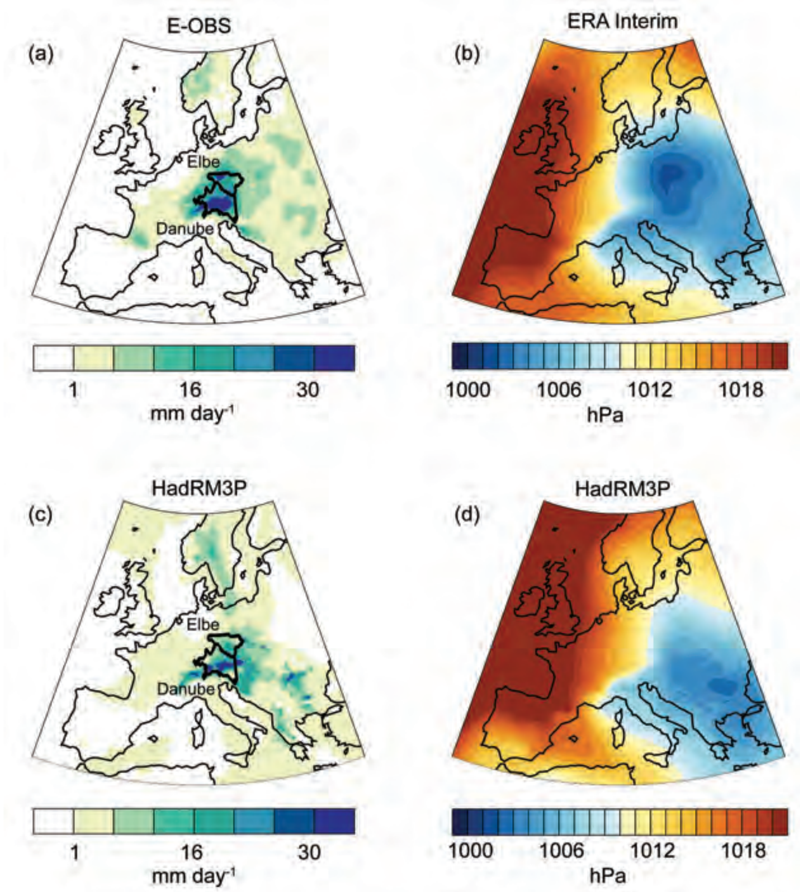

Fig. 20.1. (a) Four-day precipitation average 30 May 2013–02 Jun 2013 in the E-OBS dataset. (b) Mean sea level pressure averaged over the same four-day period in the ERA Interim reanalysis. (c) Average precipitation for the wettest four consecutive days during May–Jun in the all forcings simulations with HadRM3P. (d) Mean sea level pressure averaged over the wettest four consecutive days during May–Jun in the all forcings simulations with HadRM3P. The upper Danube and Elbe catchments are drawn in (a) and (c).

event in central Europe in spring 2013, we make use of the citizen science modeling capability weather@home (Massey et al. 2014). In this study, we perform two types of experiments, the first one simulating the year 2013 under current climate conditions and a second one representing 25 different possible analogous years in a counterfactual world as it might have been without anthropogenic climate change. The Met Office Hadley Centre Atmosphere-only general circulation Model (HadAM3P; Pope et al. 2000), with a nested regional configuration over Europe (HadRM3P), is used to perform these ensemble simulations. Massey et al. (2014) evaluated the ability of the regional climate model (RCM) and showed that the model performs well but tends to underestimate May–June precipitation over central Europe. The first perturbed initial conditions ensemble representing the year 2013 ("all forcings") under present day climate conditions is forced with observed aerosols and greenhouse gas composition as well as SST and sea ice fraction values from 2013 obtained from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) dataset (Stark et al. 2007). The 25 perturbed initial conditions ensembles ("natural") representing the analogous year in the counterfactual experiment are forced with preindustrial atmospheric gas composition and the sea ice extent that corresponds to the year of maximum sea ice extent in each hemisphere of the OSTIA record, which starts in January 1985. The corresponding SSTs are obtained by subtracting 25 estimates of the human influence on SST from the 2013 OSTIA SST values. These 25 SST anomaly patterns are obtained by calculating the difference between nonindustrial and present day simulations for available Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Taylor et al. 2012; see Supplementary Material). Additionally, we also estimate the trend of four-day extremes with the European daily high-resolution (0.25°) gridded (E-OBS version 9.0) precipitation fields (Haylock et al. 2008). For both the model and observation analyses, we consider maximum four-day average precipitation in the upper Elbe (south of 51°N) and Danube (west of 15°E) catchment areas.

Modeling of the event. A question that arises when using the described setup is whether the model is able to simulate the extreme event considered and the factors affecting it. If the model represents the event accurately, this adds confidence in the resulting attribution statement, bearing in mind that no model is a perfect representation of the real world. Statistically, van Haren et al. (2013a,b) showed that state-of-the-art RCMs represent both the climatology and trends in summer mean and extreme rainfall well; there is no trend in observations or model simulations in the region of study. Regarding the mechanism, Fig. 20.1

shows the four-day precipitation average during the event in the E-OBS dataset and the corresponding mean sea level pressure (MSLP) averaged over these four days in the European Centre for Medium-Range Weather Forecasts Re-Analysis, ERA Interim (Dee et al. 2011). To assess the model's ability to simulate this type of heavy precipitation event, we identified the ensemble member in the all-forcings simulations with the wettest four days in the upper Danube and Elbe catchments. As shown in Fig. 20.1c,d, the model is able to represent a similar event to what occurred in spring 2013 in terms of precipitation and MSLP; although, overall, the model appears to slightly underestimate the extent and intensity of the heavy precipitation event. Comparing the maximum four-day precipitation averages between Fig. 20.2a,b and Fig. 20.2c,d for return times up to 100 years indicates that the model underestimates Danube precipitation by about 20% and overestimates the Elbe precipitation roughly the same amount.

Influence of climate change on the floods. There are several methods to attribute whether the odds of an extreme event occurring have been affected by climate change. Here we compare two of these in order to increase the confidence in the resulting statement. Figure 20.2 shows return times for the maximum four-day average precipitation in the E-OBS dataset and in HadRM3P in May–June. Figure 20.2a,b shows that the 2013 event (purple line) was very unusual in these months, with return times larger than 200 years for the upper Danube and Elbe catchments (in agreement with the observation that none of the six larger floods in Bratislava since 1500 occurred in these months; Pekárová et al. 2013). The time series of the maximum four-day average in May or June 1950–2012 is fitted to a generalized extreme value (GEV) distribution with the position parameter μ and scale parameter σ simultaneously varying exponentially with the global mean temperature (smoothed with a four-year running mean) as a first approximation of possible effects of global warming (other choices for the trend give very similar results). The 200 years are the lower bound of the 95% confidence interval estimated with a nonparametric bootstrap (upper blue and red lines). There were events in July and August with higher precipitation, but the impact of heavy precipitation events in the summer months is smaller as a higher proportion of precipitation gets absorbed in the soils. The trends in extremes before 2013 have different signs over the two basins; neither is significantly different from zero at $p < 0.1$. This is also shown in Fig. 20.2a,b where the fitted return times are similar in the 1950 climate (blue lines) and the 2013 climate (lines).

Similar figures are produced from the model simulations with and without climate change (Fig. 20.2c,d). Here, each red dot represents the average

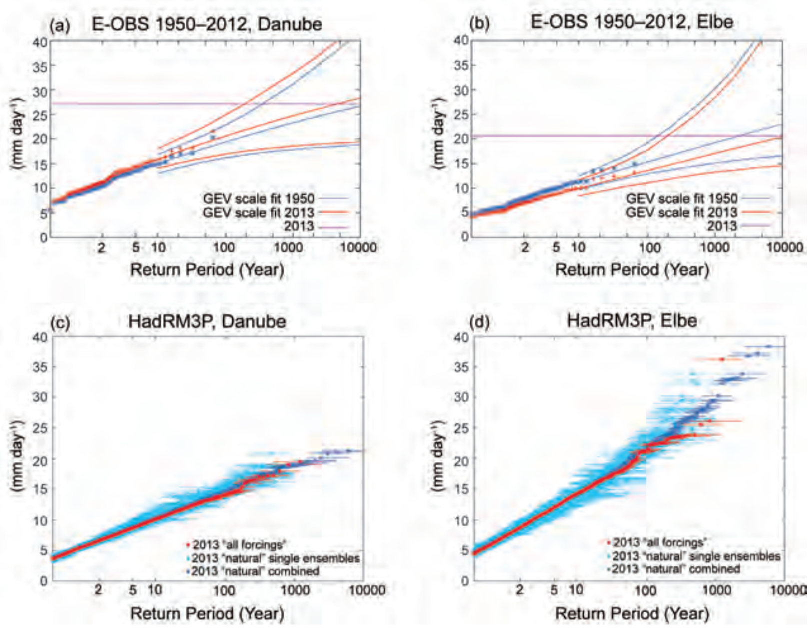

Fig. 20.2. Return time plots for the maximum four-day precipitation average during May–Jun in the E-OBS dataset (a), (b) and in HadRM3P (c), (d) for the upper Danube catchment (left) and the upper Elbe catchment (right). For the E-OBS dataset, red crosses indicate years from 1950 to 2012 after correction for the fitted trend to the year 2013 and the red lines correspond to the 95% confidence interval estimated with a non-parametric bootstrap. Blue crosses and lines represent the same as the red but in the climate of 1950, and the horizontal purple line represents the observed value for May–Jun 2013. For the HadRM3P datasets, the red dots indicate May–Jun possible four-day maximum precipitation events in a large ensemble of HadRM3P simulations of the year 2013, while the light blue dots indicate possible May–Jun four-day maximum precipitation events in 25 different ensemble simulations of the year 2013 as it might have been without climate change. The blue dots represent the 25 natural ensembles aggregated together. The error-bars correspond to the 5%–95% confidence interval estimated with a non-parametric bootstrap.

precipitation over the wettest four-day period in May and June in each of the all forcings simulation ensemble members. Each light blue dot represents the average over the wettest four-day period in May and June in the natural simulations with each of the 25 ensembles forming a separate curve corresponding to the 25 different SST patterns. In addition, all of these 25 natural ensembles have been aggregated and are represented as blue dots. The error bars give the 5%–95% confidence interval of the return periods, derived from bootstrapping several hundred times from the individual ensembles. In the return time plots for the wetter end of the distribution, approximately equal numbers of the 25 different natural simulations (light blue) are found on both sides of the actual conditions curve (red), which is not statistically different from the aggregated natural ensembles (blue). This indicates no evidence that human-induced climate change increased the odds of such an event to occur, nor any evidence that it decreased these odds, in agreement with the E-OBS analysis. Note that this answers a slightly different question from the observational analysis. This analysis considers the odds of an event like the May–June 2013 heavy precipitation happening given the observed SST and sea ice patterns as a function of anthropogenic forcing, whereas the observational analysis only looks at the trend without attribution and without the specific SST and sea ice.

It has been suggested (BfG-DWD 2013) that increased persistence caused by increased CO_2 concentration played a role in the discussed event based on the hypothesis that the decreased meridional temperature gradient would cause more persistent weather patterns at midlatitudes and, consequently, an increased chance of extreme weather like droughts or floods (Francis and Vavrus 2012; Petoukhov et al. 2013). The fact that polar regions warm faster than lower latitudes under global warming and, hence, the meridional temperature gradient decreases, are well-represented mechanisms in current models and, therefore, the model setup can serve as a valuable check on this hypothesis. Given that no change in return times could be detected between the all forcings and the natural simulations, the results do not support the hypothesis that the Arctic warming increases persistence of a weather type and the associated increase in probability for floods in central Europe, in agreement with Wallace et al. (2014) for example. Analyses of historical floods on the Elbe (Mudelsee et al. 2003) and Danube (Pekárová et al. 2013) also find no change in summer floods.

Conclusions. In this study, we quantify the influence of anthropogenic climate change on the heavy precipitation event in spring 2013 in the upper Danube and Elbe catchments with two methods. Both the model-based analysis, with high statistics but possibly systematic errors, and the observation-based analysis, with lower statistics, consistently show that there was no significant effect of the increased greenhouse gas concentrations on this four-day precipitation event. While this study focuses on precipitation, further analyses should focus on runoff or river flows to conclusively attribute the role of climate change on the floods in the two catchments. Flooding results from interactions between weather events, hydrological processes, and infrastructure. While the heavy precipitation event was rare in itself for the time of year, the weather situation during the previous months and the resulting late snowmelt and saturated soils amplified the magnitude of the Danube and Elbe floods.