Evaluating the atmospheric drivers leading to the December Flood 2014 in Schleswig–Holstein, Germany

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Abstract. Regional analyses of atmospheric conditions that may cause flooding of important transport infrastructure (railway tracks, highways/roads, rivers/channels) and subsequent adaptation measures are part of topic 1 of the network of experts initiated by the German Federal Ministry of Transport and Digital Infrastructure (BMVI). As an exemplary case study, the December flood 2014 in Schleswig–Holstein, Germany, was investigated. Atmospheric conditions at the onset of the flood event are described and evaluated with respect to the general weather circulation, initial wetness, and event precipitation. Predominantly persistent westerly general weather circulations (GWCs) directed several low pressure systems over the North Sea to Schleswig–Holstein during December 2014, accompanied by prolonged rainfall and finally a strong precipitation event in Southern Schleswig–Holstein causing several inland gauges to exceed their by then maximum water levels. Results show that the antecedent precipitation index (API) is able to reflect the soil moisture conditions and, in combination with the maximum 3–day precipitation sum (R3d), to capture the two main drivers finally leading to the flood: (1) Initial wetness of North Western Schleswig–Holstein, and (2) strong event precipitation in Southern and Eastern Schleswig–Holstein from 21–23 December while both indices exceeded their respective 5–year return periods. Further, trend analyses show that both API and R3d have been increasing during recent years while regional patterns match the north eastward shift of cyclone pathways, leading to higher risk of flooding in Schleswig–Holstein. Within the network of experts, investigations of these and further indices/drivers for earth system changes (e.g. wind surge, sea level rise, and others) derived from observations, reanalyses, and regional climate model data are planned for all German coastal areas. Results can be expected to lead to improved adaptation measures to floods under climate change conditions wherever catchments have to be drained and infrastructures and ecosystems may be harmed.

1 Introduction

In December 2014, predominant westerly general weather circulations (GWCs) caused a Major Baltic Inflow (MIB) event (see e.g. Lehmann et al., 2016; Post and Lehmann, 2016). At the same time, persistent rainfall in combination with an extreme precipitation event from 21–23 December led to the flooding of several catchment areas in Schleswig–Holstein, Germany, located between the North and Baltic Sea. Both events mark independent atmospheric and hydrologic responses to

the GWC illustrating the importance of interdisciplinary research in this area. In this regard, the region Schleswig–Holstein is a potent "blue spot" dealing with multiple drivers for earth system changes in the North and Baltic Sea region. It is affected in many ways by extremes, especially under climate change conditions: (1) Considerable areas in the southern parts lie beneath sea level and have to be drained artificially, (2) long lasting and heavy rainfall events lead to increased flooding

5 possibility of economically relevant parts of the country. The North and Baltic Sea Channel (NOK, http://www.wsa-kiel.wsv.de/Nord-Ostsee-Kanal) for example, also known as "Kiel Canal", is the most important waterway in this region. In fact, with over 30,000 passages per year, it is the busiest artificial waterway worldwide (e.g. Lübbecke et al., 2014). But the NOK is not only important for transportation; it also serves as drainage of several catchments, e.g. the upper Eider basin, while the water level has to be regulated within a few decimetres to keep shipping traffic possible. Therefore, the

10 atmospherical and hydrological conditions have to be monitored carefully concerning extremes and changes thereof.

The physical conditions of the North Sea control both meteorology and hydrology in Northern European coastal regions (see e.g. Attema and Lenderink, 2014): Dominant factors are the actual wind and water levels – including future sea level rise – and the predominant GWC. According to Randall et al. (2007), large scale and prolonged extreme events result from a persistent GWC in conjunction with air-sea interactions (air and soil, respectively). These interactions are of particular

15 importance for coastal areas. Hydrological extremes, like flooding events, thereby are rather caused by unusual and unfavourable combinations of different influencing factors than by extremes of these factors themselves (Klemes, 1993). For instance, storm surges in combination with heavy but not extreme rain fall may lead to problematic drainage situations due to high seaward water levels (see e.g. Wahl et al., 2015). According to investigations by Kew et al. (2013) conducted in the Rhine delta, the probability of extreme surge conditions following extreme 20–day precipitation sums is even 3 times higher

20 than estimated from treating extreme surge and discharge probabilities independently. Also, a combination of initial catchment wetness and a single heavy yet not extreme precipitation event alone may lead to flooding. Berthet et al. (2009) and Pathiraja et al. (2012) show that catchment wetness actually is a crucial parameter in flood forecasting. Given the difficulties in estimating the catchment wetness arising from inadequate records of soil moisture conditions (e.g. Albergel et al, 2013), Woldemeskel and Sharma (2016) point out the role of antecedent precipitation as a surrogate variable for any

25 flood assessment under global warming conditions.

In the following, the observed situation, predominant GWC, and precipitation indices describing soil moisture condition and event precipitation are investigated for the December Flood 2014 in Schleswig–Holstein, Germany. An extensive evaluation concerning the hydrology based on catchment gauge data has already been undertaken by the Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig–Holstein (LKN–SH) and the Landesamt für Landwirtschaft,

30 Umwelt und ländliche Räume Schleswig–Holstein (LLUR–SH) in a separate report (LKN–SH and LLUR–SH, 2015). Therefore, the focus of this paper lies on the atmospheric conditions leading to the flood. The aim is to show that (1) the method of Schröter et al. (2015) to classify nationwide flood events can be applied on a regional scale and that (2) the indices used, namely the antecedent precipitation index (API) and 3–day precipitation sum (R3d), can add useful information about changing local flood regimes in a warming climate. Evidence is presented by investigating the respective significant

trends in recent years. Within topic 1 of the network of experts of the German Federal Ministry of Transport and Digital Infrastructure (BMVI, http://www.bmvi-expertennetzwerk.de), all methods used in this paper are planned to be applied to reanalyses and (regional) climate model data as well. This way, a first glimpse into possible future changes might be achieved without the need to run complex and expensive hydrological models. Further, API and R3d can be derived directly from climate model precipitation output which makes them effective and easy to apply. Therefore, results can expected to be of great value for the work in national and international projects dealing with adaptation of transport and infrastructure under future climate change.

The remainder of this paper is structured as follows: At first, data and methods (chapter 2) are described. An evaluation of the atmospheric drivers leading to the December flood 2014 and a discussion of the findings are offered in chapter 3. Finally, concluding remarks are given in chapter 4 and an outlook in chapter 5.

2 Data and Methodology

2.1 General Weather Circulation

Two different objective General Weather Circulation (GWC) classification methods were compared to describe the situation in SH during December 2014: (1) The modified Lamb Weather Types (LWT, Jenkinson and Collison, 1977) used at the Federal Maritime and Hydrographic Agency (BSH, Löwe et al., 2005) with a model centre over the Central North Sea, and (2) the objective classification (OWTC; Dittmann et al., 1995; Bissolli and Dittmann, 2001) of the German Meteorological Service (DWD) with a model centre over Central Germany. Further differences are the input parameters: While LWT is based solely on sea level pressure data, here the NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996), at 16 grid points over Northern Europe, OWTC input data include air pressure, temperature, wind, and water vapour content on different height levels derived from the current operational GME (Global Model Extended) of DWD (http://www.dwd.de/EN/ourservices/wetterlagenklassifikation/wetterlagenklassifikation). Further, OWTC output parameters include cyclonality on two height levels (950 and 500 hPa) and a humidity index ("wet" and "dry") that describes the precipitable water content of the atmosphere compared to the long term daily mean. LWT output, however, includes a gale index in four categories (from "no gale" to "very severe gale") derived from the strength of the geostrophic flow and the vorticity.

2.2 Precipitation and Soil Moisture Indices

Schröter et al. (2015) have investigated and ranked 76 nationwide flood events concerning their severity and affecting at least 10 % of the German river catchments over a period from 1960 to 2009. Further included were the floods from 1954 and 2013 (Blöschl et al., 2013). The investigations based on the dataset from Uhlemann et al. (2010) using time series of daily mean discharge records at 162 gauge stations of the German Water and Shipment Administration (WSV) and the German Federal Institute of Hydrology (BfG). Additionally, Schröter et al. (2015) used daily precipitation sums from the REGNIE

data set (see e.g. Rauthe et al., 2013) provided by DWD with a spatial resolution of 1 x 1 km to describe the meteorological situation of these events. Basic idea using this approach is the assumption that a combination of extreme initial wetness (i.e. oversaturation of the soil) and a strong but not extraordinary event precipitation leads to flooding. These factors were evaluated by means of two indices: (1) The maximum 3–day precipitation sum (R3d) as trigger of the flood, calculated at

5   each grid point separately within a window of ± 10 days around the onset of the flood event, and (2) the initial antecedent precipitation index (API), calculated from the sum of daily precipitation at each grid point $R_i(x, y)$ and weighted with respect to the time span ($m = 30$ days) of rainfall occurrence prior to the R3d to assure a clear separation of both indices, see Eq. (1):

$$API(x, y) = \sum_{i=1}^{30} k^i R_i(x, y, (m - i)). \tag{1}$$

10   Here, i marks the day prior the R3d and $k = 0.9$ a depletion constant that approximates the decrease of soil moisture due to evapotranspiration and percolation to deeper soil layers. Using this approach, the rainfall at day one prior the R3d is weighted highest.

Both indices were calculated using REGNIE's daily precipitation sums for the December Flood 2014. The constant k was not changed; however, future investigations could include regional soil types at a high resolution (if accessible). Further, it

15   should be noted that the coastal regions were excluded by Schröter et al. (2015) since floods might be affected by the water level conditions in the North and Baltic Sea, i.e. the possibilities for drainage (personal communication K. Schröter). Since sea gauge data did not show any extremes and drainage was possible at all times during the December Flood 2014 (see chapter 3.4), a comparative analysis is justified and might help to point at regional risk potentials, even for spatially limited flood events.

20   Further, the Matlab toolbox WAFO (WAFO–group, 2000) was used for the statistical evaluation: According to Schröter et al. (2015), the yearly maximum 3–day precipitation sums and the respective 30–day antecedent precipitation were calculated at each REGNIE grid point. Then, 5 to 100–year return periods (5-100yrRPs) were derived at each grid point using the Gumbel distribution over the base period 1960–2009.

2.3 Trend Analyses

25   Mean trends above the 95 % significance level for the five highest R3d (R3dfivemax) and API (APIfivemax) values per year were calculated over 30–year running intervals from 1960–89 to 1985–2014 for the Kiel Canal catchment (EZG NOK), Schleswig–Holstein (SH), and all of Germany (D). Instead of the yearly maximum alone, the five highest events per year were chosen as to obtain more reliable and robust statistics. A modified version of the Mann–Kendall test (see Hamed and Rao, 1998) was used to determine significant trends avoiding misleading results due to autocorrelation (in case

30   autocorrelation is greater than zero). All trends were calculated at each grid point separately. Then, area means were derived.

2.4 Gauge Data

Results from gauge data from the LKN-SH and LLUR-SH (2015) report will also be presented to investigate the applicability of the chosen precipitation indices. A map showing maximum water levels at all catchment gauges in Schleswig-Holstein during the December Flood 2014 is kindly provided by Dr. Thomas Hirschhäuser (LLUR-SH). Further in depth analyses of the hydrological situation including discharges and statistical evaluations can be found in the LKN-SH and LLUR-SH (2015) report. Most relevant results thereof are presented in chapter 3.6.

3 Results and Discussion

The December 2014 was predominated by westerly GWCs lasting for several weeks. Therefore, a number of low pressure systems were led from the North Atlantic over Northern Europe in short progression. Exemplarily, the systems ALEXANDRA and BILLIE (11/12/2014) both characterized by wet maritime air and stormy conditions with gusts from 17 to 28 m/s observed all over Schleswig–Holstein (SH) and Hamburg (HH) are shown in Figure 1.

3.1 General Weather Circulation (GWC)

In general, both classification methods show predominant westerly GWCs from 5 December onwards with North Westerly (NW) situations during the heavy precipitation event from 21–23 December (Table 1): OWTC shows humid conditions, LWT "gale". However, differences are apparent during the first precipitation event: The cores of the low pressure systems are centred far north, categorized by LWT as "severe gale" (ALEXANDRA) and "gale" (BILLIE) with South Westerly (SW) cyclonic flow (Fig. 2a/b). OWTC on the other hand categorized a NW anticyclonic flow and dry conditions. An explanation provides the respective model centre; OWTC is focused over Central Germany while LWT is ideally centred in the North Sea. Since most of Southern and Central Germany was unaffected by this precipitation event, most of the model domain was indeed "dry".

It becomes obvious that the use of the classification method is subjected to several factors. Amongst them, the method should be suitable to the region of interest and capture its unique features. In this case, LWT provides slightly better results due to its focus on the North Sea and the fact that OWTC misses wet days during the first precipitation event. Nevertheless, both GWC analyses clearly show that not only one specific weather type but the succession of similar (westerly) types was important to the overall high soil moisture conditions, i.e. in generating prolonged rainfall, especially in Northern Schleswig–Holstein. Additionally, the extreme precipitation event in Southern Schleswig–Holstein was caused by a succession of NW types from 19–23 December (5 days, LWT) and 17–23 December (7 days, OWTC), respectively. Considering the mean life time of the NW type of 1.82 days (base period 1971–2000, Löwe et al., 2013, Table 2–10), the event was extraordinary for this region.

3.2 Precipitation

Above average monthly precipitation amounts between 80 and 160 mm were recorded at the German coasts during December 2014; local monthly means were exceeded by more than double that values and old records were broken. In SH, values of 175 mm up to 225 mm were reached (Fig. 3a) which corresponds to about 225–300 % of the long term means (Fig.

5   3b). All over the rest of Germany, the December 2014 was unremarkable with maximum mean values around or clearly below those of the reference period (1961–1990).

Looking at daily precipitation sums from the REGNIE data set, two main rainfall periods can be distinguished: One from 10–12 December, more pronounced in Northern SH, and one from 18–24 December (Fig. 4). Maximum daily precipitation was detected from 22–23 December in Southern SH and HH with local values exceeding 50 mm corresponding to the

10 standard monthly mean values.

As seen in Figure 4(a–c), the first rainfall period begins in the far North Eastern (NE) SH on 10 December slowly progressing to the south. It further shows that not only SH was affected during this event: Pronounced rainfall was detected north of the Eifel region on 12 December. Figure 4(d–f) displays the main precipitation event from 21 to 23 December. Now, mainly Northern Germany is affected, especially Southern SH on 22 December. Values are comparable to daily precipitation

15 sums from selected DWD stations presented in Figure 5 showing that REGNIE (solid black lines) fits well to the station data (bar plots). Only the highest maximum values are slightly underestimated: Highest values are found at Wittenborn, north of Hamburg, with over 50 mm on 22 December (see Fig. 4e), about 30 mm at Schleswig in Central SH and over 20 mm at Leck in Northern SH on 22 December (see Fig, 4f). The first rainfall period is captured as well with maximum values on 11/12 December respectively (see Fig. 4b/c).

20 ### 3.3 Soil Moisture

Additional investigations using modelled soil moisture data from DWD's Agrometeorological Research Centre (ZAMF) for sandy loam soil and cultivation with sugar beets show highest values in the SH region with up to 139 % nFK in the north for 21 December 2014 (start date of the corresponding event precipitation). Values are decreasing southward, but never below 100 % nFK except for the south of SH (Fig. 6a). The unit [% nFK] describes the saturation in percent effective field moisture

25 capacity of the upper 60cm of soil. If soil moisture exceeds 100 % nFK, the actual water content is higher than usable for plants (DWD, 2016), i.e. most of Northern and Central SH at the onset of the main precipitation event. The south to north gradient is in accordance with precipitation data showing a slow progression of rainfall events from north to south (see chapter 3.2).

ZAMF also provides soil moisture data for loamy sand soil and cultivation with winter grain. Using this data, values in

30 Northern and Central SH are between 105 and 110 % nFK for the same date (Fig. 6b). It should be noted that neither the actual soil differentiation nor the degree of sealing is part of the model chain, and locally, this might be of importance (see

e.g. Apel et al., 2016). Nevertheless, both soil types show the same oversaturated regions in SH with some minor differences in the Fehmarn area (Eastern SH).

3.4 Event Precipitation – R3d

Figure 7 shows the 3–day precipitation sum R3d for the December Flood 2014 in Schleswig–Holstein (Fig. 7a) and its
5   corresponding ratio to the 5–year return period (5yrRP, Fig. 7b). The scaling for R3d is set according to Schröter et al. (2015). Clearly, the main contiguous part of the event precipitation is restricted to Northern Germany with some spots in Central and Southern Germany. It shows rather moderate maximum values of 109 mm north of Hamburg compared to the flood in 2013 with maximum values up to 300 mm (see Schröter et al., 2015, their Fig. 5, left). These differences can be explained mainly with the origin of both events: The flood 2013 was triggered by a quasi–stationary trough over Central
10 Europe in May/June leading low pressure systems with hot and humid air masses at its flanks from SE Europe up north. Additional orographic effects caused by the mountain ridges in Central Europe, large–scale uplifting downstream the low pressure systems, and embedded convective processes finally led to prolonged and extended rainfall (e.g. Belz et al., 2013; Stein and Malitz, 2013; Belz et al., 2014). The December flood 2014 was triggered by low pressure systems with North Atlantic air masses exclusively and appeared in winter when relatively cold air cannot hold as much water.
15 Areas with R3d exceeding the 5yRP are centred north of Hamburg, the Eastern NOK region, the catchments Stör and Krückau, and at the coasts of Mecklenburg–Vorpommern (Fig. 7b). Higher return periods can be found north of Hamburg in the area of Wittenborn (see Fig. 4). Here, values locally exceed even 100yRPs, but due to the fact that the base period only spans 50 years return periods over 100 years are becoming increasingly uncertain (rule of thumb: Two-times the observational time span gives the maximum return period to be statistically sound). Therefore, the cut has been made at 100
20 years. Nevertheless, it shows how extraordinary this event was for this region.

3.5 Antecedent Precipitation Index – API

Figure 8 shows the corresponding values for the antecedent precipitation index API, again, scaled according to Schröter et al. (2015). Maximum API values of 41.5 mm (Fig. 8a) are well below those of the flood 2013 (see Schröter et al., 2015, their Fig. 7, left) and can be found in NW–SH which is in fair agreement with the soil moisture data (see Fig. 6a). In contrast to
25 R3d, the 5yRPs for API are exceeded only in NW–SH (Fig. 8b) with maximum values corresponding to 20yRP.

It is obvious that antecedent precipitation in combination with the maximum precipitation event led to SH–wide flooding in 2014 (Fig. 7/8): Areas that were struck with heavy rainfall did not need additional initial wetness to be flooded, areas with high antecedent precipitation were saturated already and needed only small amounts of additional event precipitation. In this regard, the importance of both indices to describe this flood accurately is illustrated. Furthermore, ongoing investigations in
30 the NOK catchment area suggest that R3d and API are promising indicators/predictors to describe problematic situations in the channel's operational routine. However, since many other influencing factors like wind surge, locking of ships,

dewatering, ferry trafficking, etc. are involved, pin pointing the respective factors to one single event is difficult, and therefore, accurate estimations of the consistency for regional investigations cannot be given at this point yet.

3.6 Gauge Data

The LKN–SH and LLUR–SH (2015) report points out that more than a third (66 out of 184) inland gauges in SH exceeded the up to date Highest High Water level (HHW) during the December Flood 2014 (Fig. 9). Almost all of these gauges are located in areas affected by high R3d values in Southern and North Eastern SH or high API values in North Western SH (see Fig. 7/8).

Furthermore, 14 gauges exceeded high waters with low probability, i.e. 200yr return periods (HW200; according to HWRM-RL, 2007). Two more gauges exceeded their 100yr return periods (HW100), and eight gauges their 10yr return periods (HW10; LKN-SH and LLUR-SH, 2015, their Fig. 46). Regarding discharges, three gauges exceeded their respective 200yr return periods, four more their 100yr return periods, and five more their 50yr return periods (LKN-SH and LLUR-SH, 2015, their Fig. 80). All of these gauges are located in areas affected by R3d or API.

More than 80 % exceeded the Mean High Water level (MHW), while gauges not reaching the MHW were mainly sea gauges located in the North Sea. Return periods of half a year were hardly exceeded here (personal communication Jens Möller, BSH). Therefore, the December Flood 2014 could have been much worse if an additional storm surge would have hindered the drainage of the SH catchments into the North Sea.

3.7 Trend Analyses - R3d & API

Figure 10 shows significant mean 30–year running trends for the North and Baltic Sea channel catchment area (EZG NOK), Schleswig–Holstein (SH), and all of Germany (D) for the five highest R3d and API events per year. Obviously, trends are not only highly dependent on the respective base period, showing considerable interannual variation, but on the area under investigation as well: While trends for R3d are positive in SH (with one exception) and the EZG NOK during the whole period, they become negative during recent years looking at Germany as a whole. Keeping in mind that cyclone pathways and connected extreme precipitation events are shifting north eastwards (e.g. Stendel et al., 2016), SH and the EZG NOK will probably experience more and heavier extreme situations in the future. Furthermore, a clear separation of NE and SW Germany regarding significant R3d trends is evident in recent years, exemplary shown for the period 1983–2012 (Fig. 11a): Trends are positive in NE Germany and negative in SW Germany with only some local spots (e.g. mountainous areas) showing opposing trends. This separation also is in accordance with the shifting cyclone pathways.

API trends (Fig. 11b) are negative for all areas in the beginning, change to high positive values during the 1980ies, and settle on lower values since, but with trends to increase further. Again, D shows smallest values since the NE–SW separation is also evident but not as articulated as for R3d. Nevertheless, API as well can be expected to increase stronger in the Northeast under climate change conditions leading to wetter soil and increased risk of flooding in these areas. Combined with the

higher probability of extreme precipitation events, especially for Northern Germany (SH, EZG NOK), the risk increases even further.

4 Summary and Conclusion

In the end, the December Flood 2014 in Schleswig–Holstein did not turn out as dramatic as it could have been: The flood management worked well, the infrastructure withstood the water masses for the most parts (only a few dyke breaks and a slope slide of about 1.5 km on the freeway A1 were reported). An additional simultaneous storm surge, however, could have caused severe problems, e.g. by cutting off the possibilities for drainage due to high low water levels. The meteorological situation was indeed existent: Persistent westerly weather circulations with frequent low pressure systems partly classified as "gale" or even "severe gale". The fact that all catchments could be drained at all tides and retention areas were utilised to a greater extent (see LKN-SH and LLUR-SH, 2015) may have prevented greater damage.

The indices R3d and API used nationwide by Schröter et al. (2015) can be applied on the regional scale as well and give an accurate evaluation of the initial wetness and the heavy rainfall event that led to the flood in December 2014. Almost all inland gauges exceeding their highest high water values, return periods (HW200, HW100, HW10), and discharges (HQ200, HQ100, HQ50) during this flood are located in areas influenced by R3d and API. API, especially, captures the highest soil moisture conditions modelled by ZAMF at the onset of the R3d event quite well. This is of particular interest for future evaluation of reanalyses and climate models because this method only needs precipitation data as input which makes it a cost effective estimation of the soil moisture without running additional soil models. Since catchment wetness prior to extreme precipitation events is of high importance for flood forecasts (see Berthet et al., 2009; Pathiraja et al., 2012), API seems to be a promising surrogate, especially in case of poor observational soil moisture data (see Woldemeskel and Sharma, 2016). Nevertheless, additional high resolution information about the actual soil type, i.e. in calculating the respective depletion constant, could be an advantage. Other influencing factors/drivers like snowmelt, frost, droughts, etc. could be taken into consideration as well since each catchment exhibits its own system of dependencies (see e.g. Valiuškevičius et al., 2016).

Trend analyses indicate an increasing risk of flood prone situation in Schleswig–Holstein due to increasing R3d and API values over the last decades. Taking sea level rise into account (e.g. Quante et al., 2016; Wahl et al., 2013) leading to increased ground water levels and, therefore, higher initial soil moisture, flood protection and improved drainage of the affected catchments becomes even more relevant.

5 Outlook

Future work within topic 1 of the network of experts will include amongst others evaluating long term changes at gauge stations in the North and Baltic Sea (Möller and Heinrich, 2016) and applying the above described precipitation indices to reanalyses and regional climate models (RCMs). Since precipitation extremes are expected to increase in the future (e.g.

Nikulin et al., 2010; Kharin et al., 2013; Scoccimarro et al., 2013), the number of potentially harmful situations can be expected to increase accordingly. In fact, the trend analyses presented above show that R3d and API are already increasing. How big the impact will be compared to other potent drivers for coastal changes (e.g. wind surge, sea level rise) is one major aspect of this ongoing research.

5 In addition, several other impact studies and pilot projects will investigate future planning and management of transportation under climate change scenarios, e.g. the NOK, Fehmarnsund, and coastal infrastructure. The latter may be harmed by increasing wind induced water levels in the North Sea as well (Gaslikova et al., 2012). New high resolution reanalyses like COSMO–REA6 (Bollmeyer et al., 2015) by the **H**ans–**Er**tel–**Z**entrum (HErZ), based on DWD's operational forecast model **CO**nsortium for **S**mall–Scale **MO**delling limited–area model (COSMO–LAM; Schättler et al., 2011), will improve the

10 hindcast evaluations and serve as input for RCM runs. In a first comparison, Kaiser–Weiss et al. (2015) have already shown advantages over global reanalyses for ground level wind data, especially in coastal and mountainous regions due to the improved spatial (6 x 6 km) and temporal (hourly) resolution. The same might be expected for the evaluation of (extreme) precipitation and derived indices, like R3d and API.

Further investigations could include extending R3d and API to extreme and abnormal events (see Müller and Kašpar, 2014;

15 Müller et al., 2015) via seasonality and a varying size of the catchment areas which is of particular interest for regional investigations. Also, the use of the extreme climate indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI, see e.g. Sillmann et al., 2013a; 2013b) might prove relevant.

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Tables

Table 1: Modified Lamb Weather Types (LWT, BSH) and Objective Classification (OWTC, DWD), December 2014. Letters in LWT indicate from left to right: The classified weather type, cyclonality index ("A" or "C"), predominant wind direction at ground level, and gale index. Characters in OWTC indicate from left to right: Weather type number, predominant wind direction at 700 hPa, cyclonality ("A" or "Z") at 950 and 500 hPa, humidity index ("T" or "F"). LWT gale indices are printed in orange ("gale") und red ("severe gale") letters, OWTC wet weather types in blue letters. "NUL" indicates "no gale".

Date	LWT	OWTC
01/12/2014	SE A SE NUL	38 SO Z Z F
02/12/2014	NE A NE NUL	21 XX Z A T
03/12/2014	A A NE NUL	31 XX Z Z T
04/12/2014	A A SE NUL	**38 SO Z Z F**
05/12/2014	C C SW NUL	**9 SW A A F**
06/12/2014	A A NW NUL	**6 XX A A F**
07/12/2014	SW A SW NUL	4 SW A A T
08/12/2014	NW C NW NUL	15 NW A Z T
09/12/2014	SW A SW NUL	11 XX A Z T
10/12/2014	**SW C SW SG**	5 NW A A T
11/12/2014	**SW C SW G**	15 NW A Z T
12/12/2014	**C C SW G**	**29 SW Z A F**
13/12/2014	NW A NW NUL	4 SW A A T
14/12/2014	**SW A SW G**	**19 SW A Z F**
15/12/2014	SW C SW NUL	**9 SW A A F**
16/12/2014	NW A NW NUL	**19 SW A Z F**
17/12/2014	SW C SW NUL	**40 NW Z Z F**
18/12/2014	SW C SW NUL	**10 NW A A F**
19/12/2014	**NW C NW G**	**10 NW A A F**
20/12/2014	**NW C NW G**	15 NW A Z T
21/12/2014	NW A NW NUL	5 NW A A T
22/12/2014	**NW A NW G**	**10 NW A A F**
23/12/2014	**NW A NW G**	**10 NW A A F**
24/12/2014	C C NW NUL	**9 SW A A F**
25/12/2014	NW C NW NUL	35 NW Z Z T
26/12/2014	A A SW NUL	15 NW A Z T
27/12/2014	C C SE NUL	31 XX Z Z T
28/12/2014	A A NE NUL	2 NO A A T
29/12/2014	A A NW NUL	35 NW Z Z T
30/12/2014	A A NW NUL	5 NW A A T
31/12/2014	A A SW NUL	**7 NO A A F**

Figures
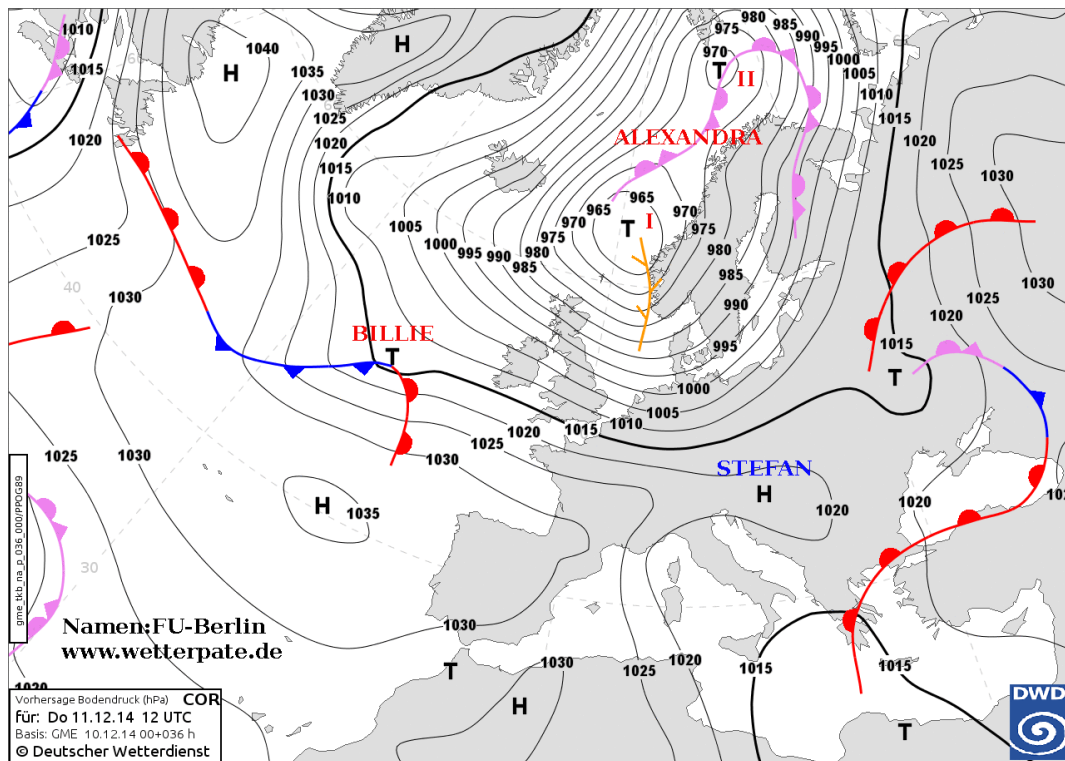
Figure 1: Sea level pressure prediction for Thursday, 11 December 2014 showing the low pressure systems ALEXANDRA and BILLIE in short progression. Image credit: FU–Berlin, www.met.fu-berlin.de (last access: 20 February 2015).
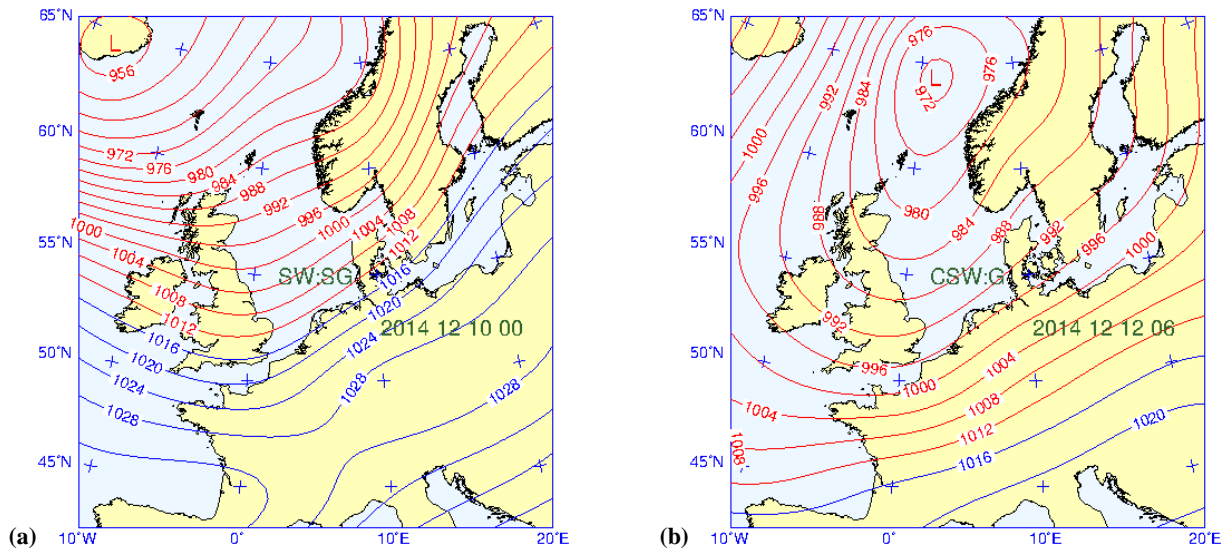
Figure 2: Classification of the general weather circulation (GWC) after the modified Lamb Weather Types used at BSH for (a) the low pressure systems ALEXANDRA (classification: South West (SW) with "severe gale" (SW)) and (b) BILLIE (classification: Cyclonal South West (CSW) with "gale" (G)). Image credit: P. Löwe (BSH Hamburg).
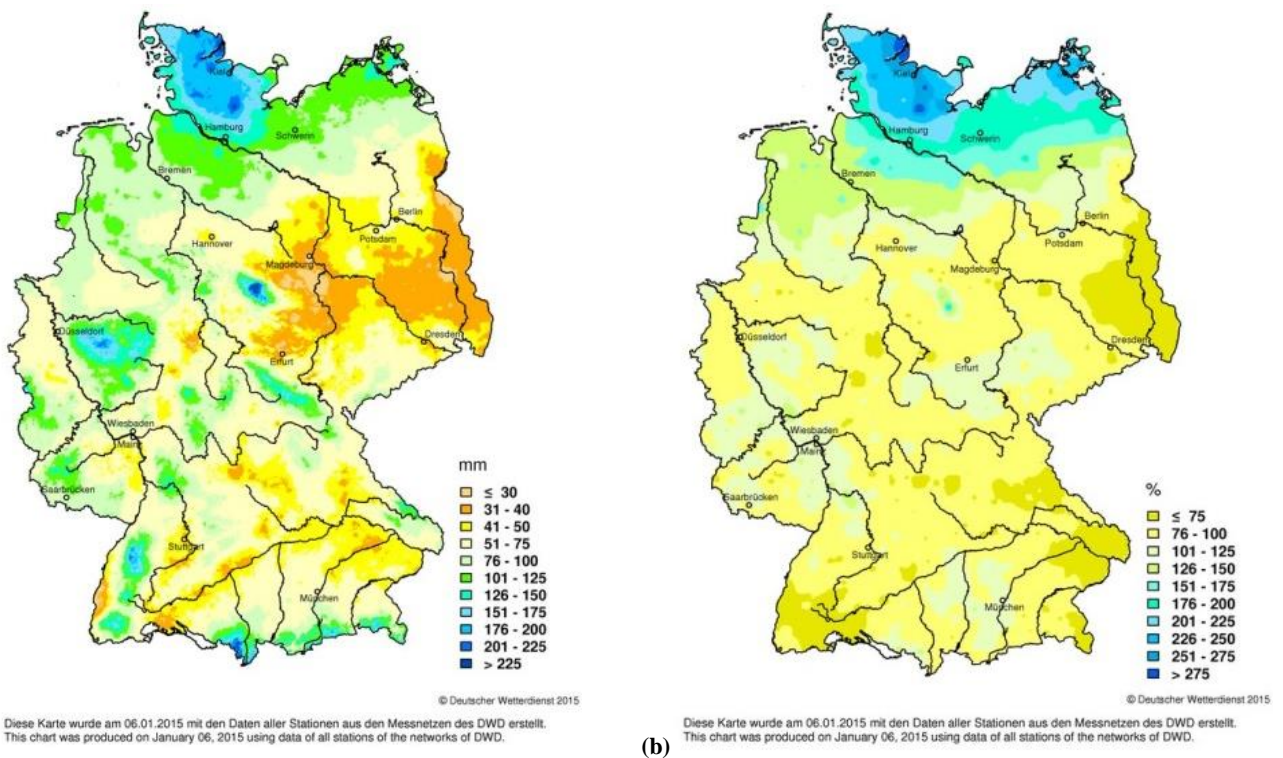
Figure 3: (a) Precipitation sums in Germany in [mm], December 2014 and (b) its differences in [%] to the long term mean 1961–1990. Image credit: DWD, www.dwd.de (last access: 6 January 2015).
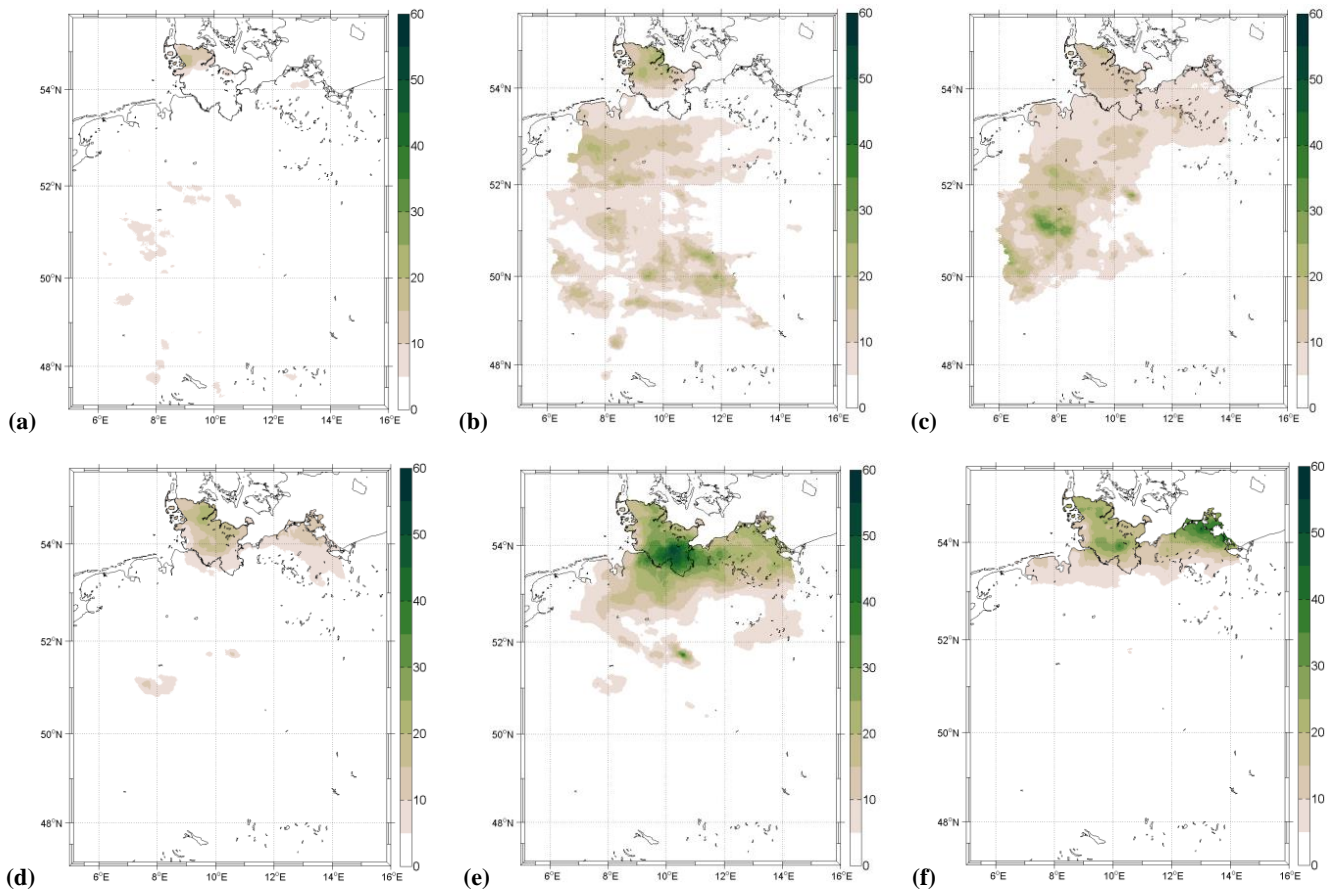
Figure 4: Daily sums of REGNIE precipitation data in [mm] for the first event, 10–12 December 2014 (a–c), and the main precipitation event, 21–23 December 2014 (d–f). The boundaries of Schleswig-Holstein are marked in black.
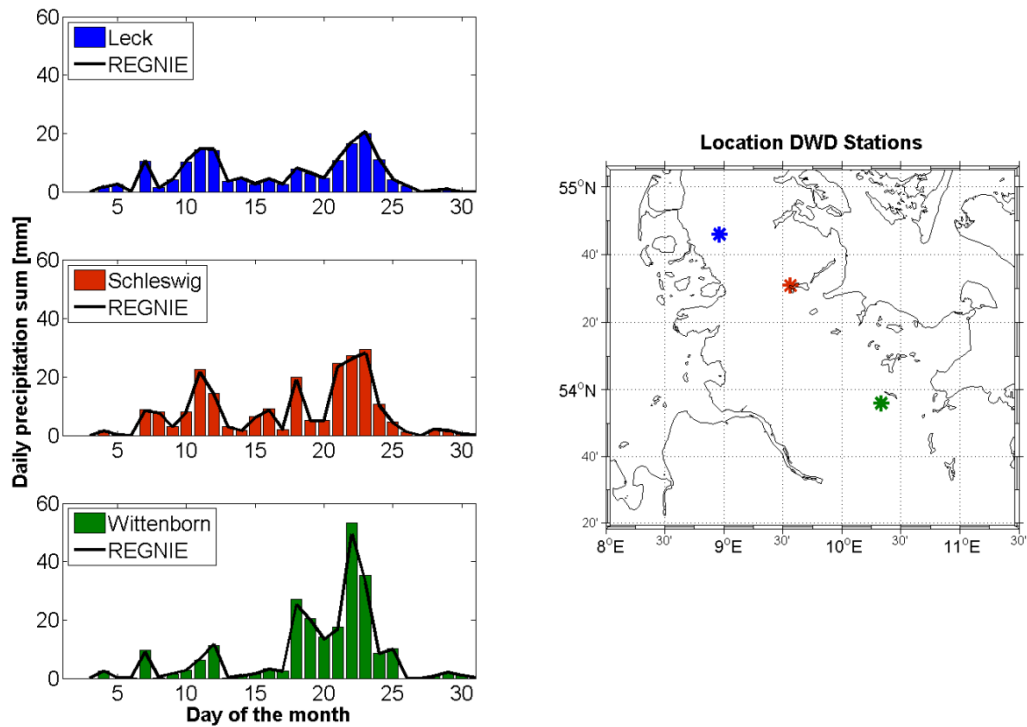
Figure 5: Daily precipitation sums at DWD stations in Northern (Leck), Central (Schleswig) and Southern (Wittenborn) Schleswig-Holstein, December 2014. Black lines indicate REGNIE daily precipitation sums at the closest respective grid points.
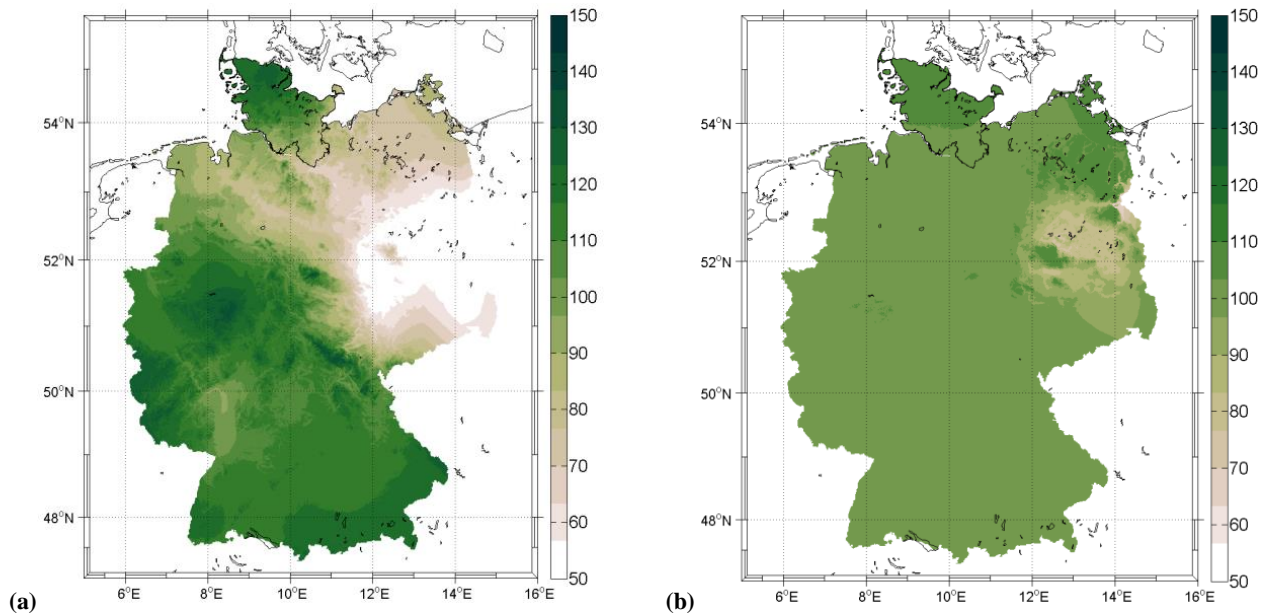
Figure 6: (a) Soil moisture in [% nFK] for sandy loam soil and (b) for loamy sand soil, 21 December 2014 (Model calculations by ZAMF, Braunschweig, Germany). The boundaries of Schleswig-Holstein are marked in black.
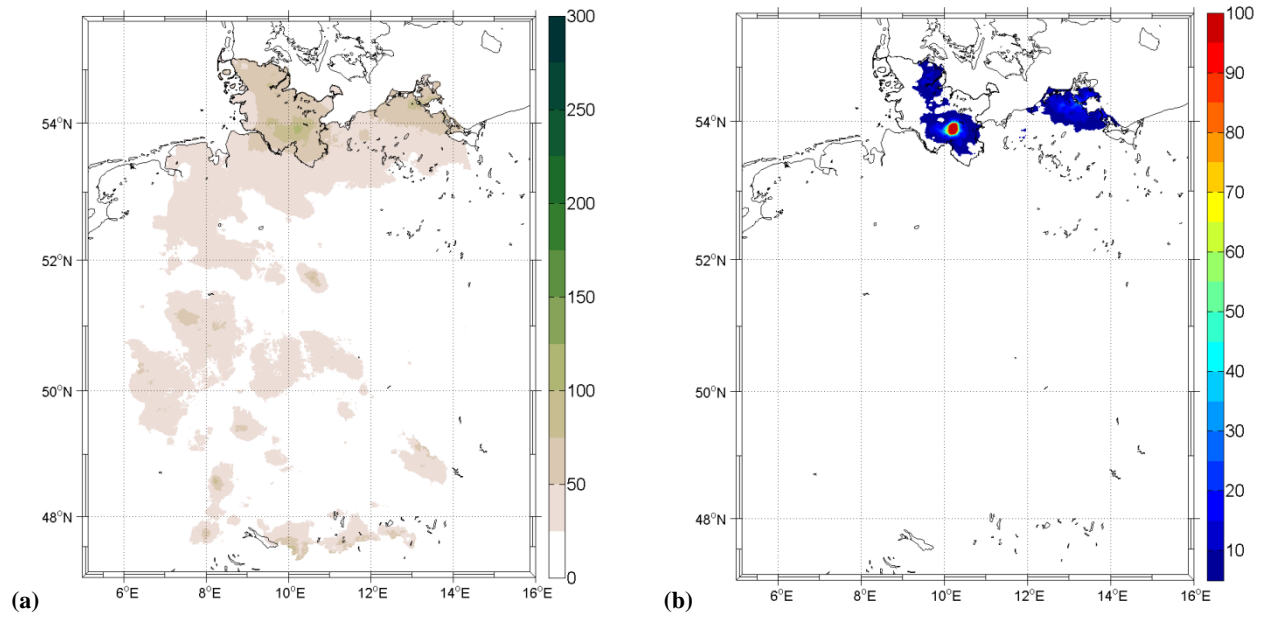
Figure 7: (a) 3–day event precipitation (R3d) in [mm] and (b) corresponding return periods (base period 1960–2009) for the December Flood 2014 in Schleswig–Holstein, Germany, calculated from REGNIE data following the method described in Schröter et al. (2015). The boundaries of Schleswig-Holstein are marked in black.
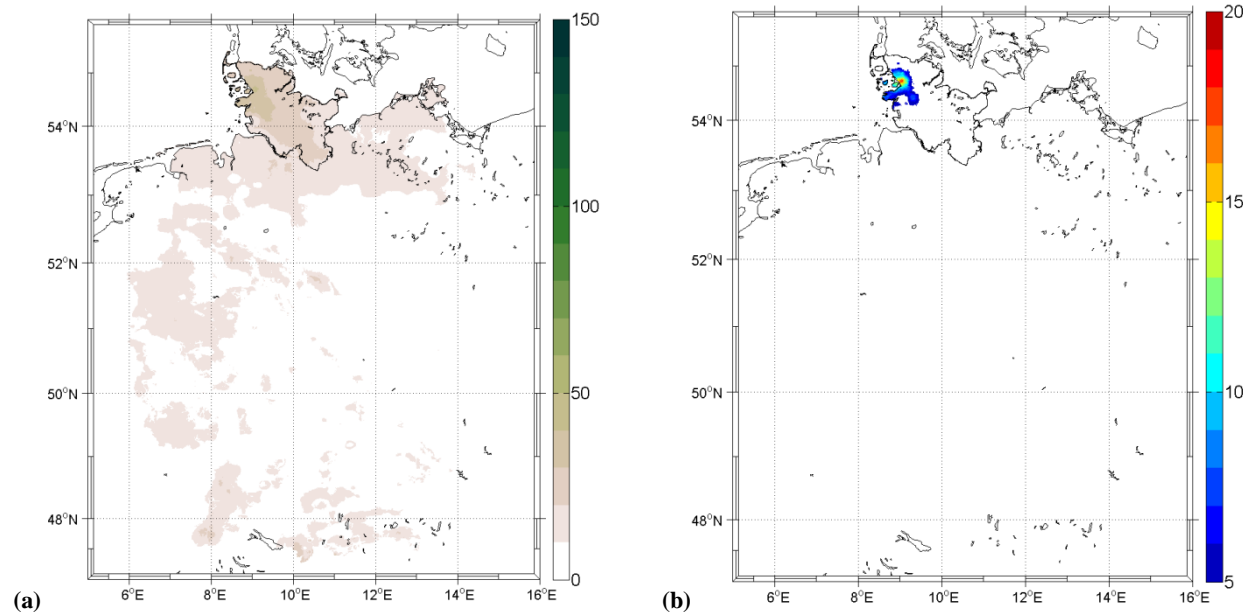
Figure 8: See Figure 7, but for the antecedent precipitation index (API).
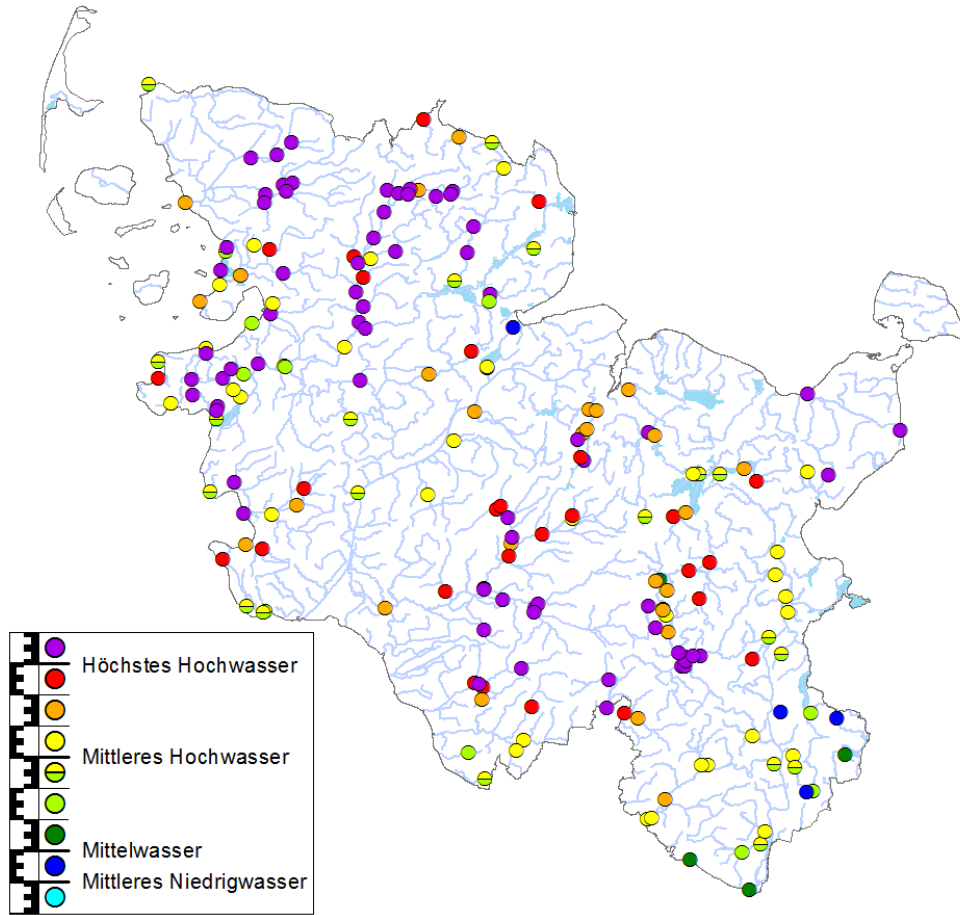
Figure 9: Gauge data in Schleswig-Holstein showing exceedance of highest high water levels (mauve), medium high water levels (yellow to red), medium water levels (green to yellow), medium low water levels (dark blue) and below (light blue) during the December Flood 2014. This map from the LKN–SH and LLUR–SH (2005) report was kindly provided by Dr. Thomas Hirschhäuser (LLUR-SH).
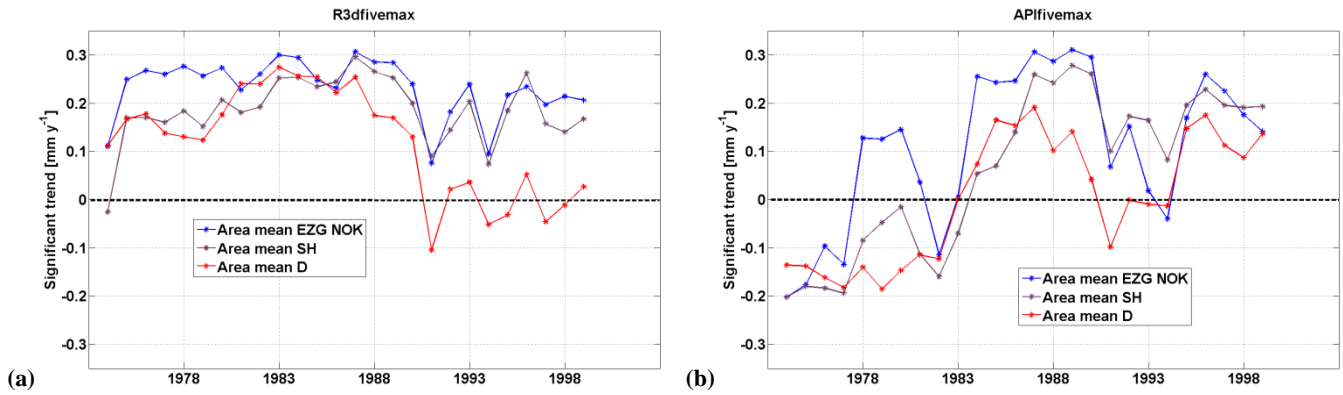
Figure 10: Mean significant trends (above 95 % significance level) over 30–year running intervals from 1960–1989 to 19852–014 in [mm y⁻¹] for the five highest (a) 3–day event precipitation (R3dfivemax) and (b) antecedent precipitation indices (APIfivemax) per year for the Kiel Canal catchment (blue), Schleswig–Holstein (mauve) and all of Germany (red). The centre year of the respective 30–year time slices is marked on the x–axis.
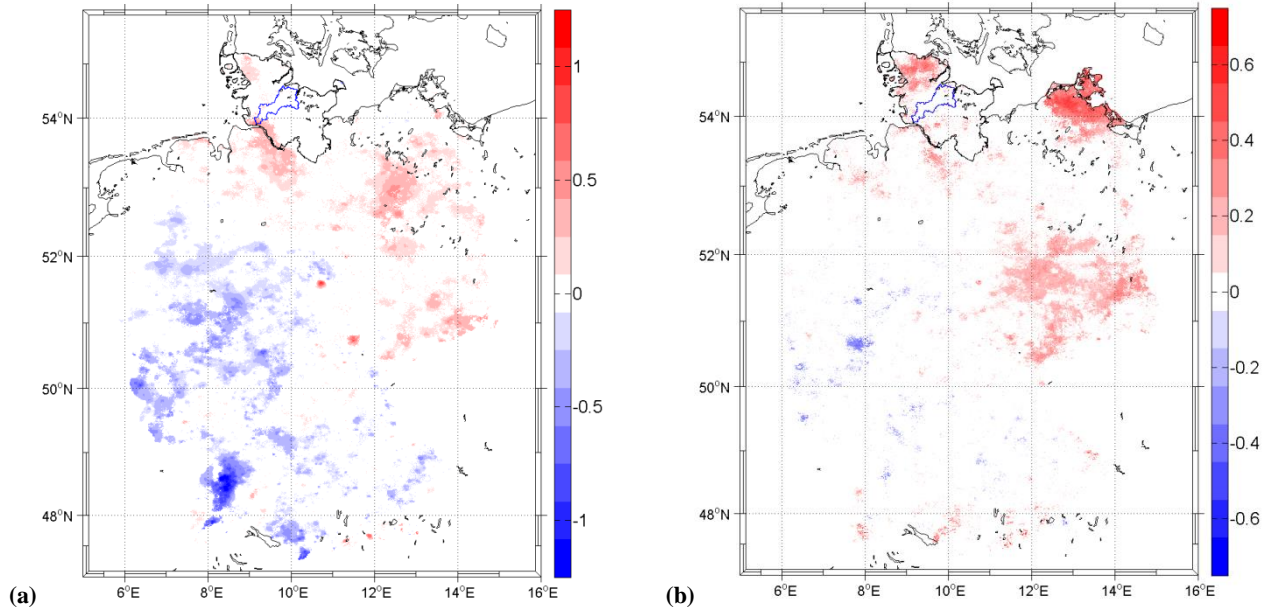
Figure 11: Significant trends (above 95 % significance level) in [mm y⁻¹] for the five highest (a) 3–day event precipitation (R3dfivemax) and (b) antecedent precipitation indices (APIfivemax) per year in Germany, base period 1983–2012. The boundaries of Schleswig-Holstein are marked in black, boundaries of the Kiel Canal Catchment in blue.