To the editor

Dear Dr. Rutgersson,
please find enclosed my revised manuscript, Number: esd-2016-73

Author: Dr. Nils H. Schade
Title: Evaluating the atmospheric drivers leading to the December Flood 2014 in Schleswig–Holstein, Germany.

The text has been thoroughly revised according to the criticism and suggestions for changes of the reviewers.

A point-by-point response to the review items and the marked-up manuscript is attached. As you can see from this attachment the criticisms and suggestions have been taken into account. I would like to thank the reviewers for their helpful criticism. Their feedback was important to clarify the main intention of my work.

The following major changes have been made:

1.) Hydrological information about the flood has been added to the manuscript including a new Figure 9 showing gauge exceeding highest high water levels.

2.) A more detailed assessment of the REGNIE performing goodness has been added including a new Figure 5 comparing REGNIE to DWD station data.

3.) Hierarchic levels have been reduced.

4.) The chapters concerning severity indices have been removed since it does not further improve the manuscript. Accordingly, Figures 7b/8b now show return periods instead of index values.

5.) The summary and conclusion chapter has been rewritten to shortly recap the findings and a separate outlook chapter has been introduced.

6.) Administrative and catchment boundaries have been included in Figures 4, 6, 7, 8, and 11.

Finally, I would like my manuscript to be proofread by the editorial office to improve the language. I am hoping the manuscript is then in a more appropriate shape for publication.

Kind regards,

Dr. Nils H. Schade

esd-2016-73-RC1
Schade, N.H.
"Evaluating the atmospheric drivers leading to the December Flood 2014 in Schleswig-Holstein, Germany"

Content:
The author presents a study to estimate the atmospheric drivers of December flood 2014 in Schleswig–Holstein. Different types of classification methods and indices' combination (i.e. antecedent precipitation index & maximum 3 –day precipitation sum) as well as trends assessments were used to analyze spatial and temporal variability of flood events. The applied methodology seems to be technically sound.

General comments:
The paper lacks a discussion on the basis and consistency of the chosen indices. There is a lack of hydrological information about the flood. References provided are not the best way to understand hydrological behavior during 21-23 of December 2014 in general. Conclusions present not relevant information about flood aftermath. A large part of the conclusion is devoted to the future plans. The language sometimes is not fluent and the writing should be checked.

Response to general comments: At first, I would like to thank the anonymous referee #1 for the helpful criticism to improve this manuscript.

Since it is the first attempt to scale the indices down to the regional level, there is not much information concerning consistency yet. This is in fact part of ongoing investigations in the NOK catchment area. Preliminary results show that R3d and API seem to be promising indicators/predictors to describe problematic situations in the channel's operational routine. However, since many other influencing factors like sea level rise, wind surge, locking of ships, dewatering, ferry trafficking, etc. are involved, pin pointing the respective factors to one single event is difficult, and therefore, it is not possible to give an accurate estimation of the consistency for regional investigations at this point yet.

Further, it should be pointed out that this paper was not intended to describe the hydrology in detail since that investigation was already performed by the LLUR/LKN-SH. The focus rather lies on the meteorological information leading to this regionally confined flood event and how well the indices for event precipitation (R3d) and antecedent precipitation (API) can describe the onset of this flood. It was already shown by Schröter et al. (2015) that the indices are well suited to describe the onset of nation-wide flood events.

I fully agree, however, that referring to another investigation is not the best way to understand the hydrology. The revised manuscript now includes the referred picture (with kind permission of the LLUR-SH) showing almost perfect agreement between regions where API and R3d are exceeding their respective 5-year return periods and inland gauges exceeding highest water levels. Further, a passage has been added concerning gauge data to describe the regional concurrence, as well as in the "Data and Methodology" chapter.

The concluding chapter has been removed of non-relevant information. Nevertheless, this work is a starting point for further investigations (or future plans) that will include more in depth analyses and, hopefully, provide important information on how climate change is affecting the indices used in this paper. As mentioned before, this is the first attempt to scale the indices down to the regional level and results seem promising that they might be useful for getting a first glimpse into future changes without the need to run hydrological models (which of course will be the next step for flood protection, adaptation measures, etc.). Therefore, the revised manuscript now includes a separate outlook chapter.

Finally, I would like the revised manuscript to be proofread by the editorial office to improve the language.

These are comments (minor), which needs to be addressed before it is accepted for publication:

1.) P1L28 What is the reason for MIB to be mentioned?

> **Response**: MIB was mentioned to highlight the various responses to the same cause: Persistent westerly circulation. Also, it was intended to tie the analysis more into to the investigations performed within Baltic Earth already and to pique the interest of the community in our work and the work to come. I agree, however, it does not further improve the paper and its purpose. This part will be removed, if the editor decides it is of no further interest to the community.

2.) P1L29 Maybe it's better to use calendar dates

> **Response**: Calendar dates are now used in the revised manuscript.

3.) P2L13 Not whole Europe, may be Northern Europe

> **Response**: The revised manuscript has been changed accordingly

4.) P6L15 Maybe it's better to provide some assessments of the REGNIE performing goodness then to refer on the figures of the reports

> **Response**: A Figure and a passage comparing REGNIE to selected observed station data is included in the revised manuscript.

5.) P6L26 The end of the sentence "only that not differentiated" is unclear. What kind of differentiation?

> **Response**: Soil moisture for sand soil shows the same structure, i.e. almost the same values all over Schleswig-Holstein whereas loam soil is clearly wetter in the Northern parts and drier in the South. The respective passage has been removed in the revised manuscript to avoid unclearness.

6.) P7L6 To name a source of information

Response: The source of information has been added in the revised manuscript.

7.) P8L1 A verb (may be "need") is missing

Response: Yes, indeed. It has been added in the revised manuscript

8.) P8L3 "affecting the drainage of affected catchments". Maybe it's better to re-write this part of the sentence to avoid unclearness.

Response: The respective passage has been rephrased in the revised manuscript to avoid unclearness.

9.) P8L20 Unmistakably is very strong form of certainty. May be it's better to use another word when talking about the future.

Response: You're right; those strong forms better be avoided. Thanks for pointing it out!

10.) P9L34 References proving additional meltwater runoff in the future are needed

Response: Admittedly, it was an assumption on my part. The passage has been removed in the revised manuscript.

11.) Maps should contain major catchment boundaries (including Kiel channel watershed)

Response: All respective figures in the revised manuscript now include boundaries of Schleswig-Holstein and the Kiel Canal catchment to make the figures easier to understand.

esd-2016-73-RC2
Schade, N.H.
"Evaluating the atmospheric drivers leading to the December Flood 2014 in Schleswig-Holstein, Germany"

Content:
In this article, atmospheric conditions were studied, which caused the severe flooding in Schleswig-Holstein in December 2014. The topic is interesting and important having a direct value for human activity. Two classifications of large-scale atmospheric circulation and two indices of precipitation and moisture conditions were used.

General comments:
The main disadvantage of the paper is its descriptive nature. A number of characteristics and maps have been presented but their analysis, synthesis and discussion is lacking. The objectives, tasks and hypotheses of the study are not clearly formulated. I'll answer to the general questions of the journal and then I'll make my more detail comments and suggestions. 1. Does the paper address relevant scientific questions within the scope of ESD? Partly. 2. Does the paper present novel concepts, ideas, tools, or data? Some. 3. Are substantial conclusions reached? Partly. 4. Are the scientific methods and assumptions valid and clearly outlined? Yes. 5. Are the results sufficient to support the interpretations and conclusions? Yes. 6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes. 7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes. 8. Does the title clearly reflect the contents of the paper? Yes. 9. Does the abstract provide a concise and complete summary? Yes. 10. Is the overall presentation well structured and clear? Yes. 11. Is the language fluent and precise? Revision of the language is needed. 12.Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes. 13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? No. 14. Are the number and quality of references appropriate? More or less, yes. 15. Is the amount and quality of supplementary material appropriate? Yes.

Response to general comments: At first, I would like to thank the anonymous referee #2 for the helpful criticism to improve this manuscript.

The revised manuscript has been rewritten with more emphasize on analyses, synthesis and discussion to state the objectives, tasks and hypotheses of the study more clearly (as also pointed out in the response to RC1).

Further, I would like the revised manuscript to be proofread by the editorial office to improve the language since both referees are pointing out language revision.

Remarks and suggestions

1.) The term “westerly situation” widely used in this paper seems a bit strange for me. I think that “westerly circulation” is meant here. Classifications of general weather situations are more like circulation classifications (page 3 line 13).

Response: The term “westerly situation” has been changed in the revised manuscript to “westerly circulation”

2.) Page 1 line 18. I prefer to use “precipitation event” instead of “event precipitation”.

Response: The term “event precipitation” was defined by Schröter et al. (2015) as the highest 3-day precipitation sum at the onset of the flood. For consistency reasons I would prefer to keep it.

3.) Page 1 line 27. There should be December, not Dezember.

Response: Indeed!

4.) Page 2 line 13-14. The sentence should be revised. Which physical conditions of the North Sea are the dominant factors?

Response: The sentence has been rewritten.

5.) Page 3 line 14. What does mean the abbreviation BSH?

Response: “Federal Maritime and Hydrographic Agency” has been included in the revised manuscript.

6.) I have a question how much the used circulation classifications were objective or subjective. It is written that the second classification was objective. But is the Jenkinson-Collison classification subjective?

Response: The Lamb Weather Types (LWT) in the original form are indeed subjective. Jenkinson and Collison developed an automated system to “objectify” LWT, allowing classification based on sea level pressure data solely. Therefore, the Jenkinson-Collison classification is objective as well. It is now stated in the revised manuscript.

7.) Page 3 line 21. I am not sure which term is used in English: "cyclonality" of "cyclonicity". Please, make clear it.

Response: "Cyclonality" is the correct term.

8.) In the section 2.2 many data sources were listed. Which variables were used in this study, it was not indicated.

Response: The REGNIE dataset includes only daily precipitation sums (on a 1 km by 1 km grid) which were used in this study to calculate the precipitation indices. The chapter has been rewritten in the revised manuscript to clarify.

9.) Trend analysis was not mentioned in the introduction. Why it was included into this study? Trends are not related to the 2014 flooding event. The significance of the trends is not estimated at all. Without it we cannot talk about trends.

Response: "trend analysis of the indices investigated" was mentioned on page 3 line 9, but I admit, it can easily be overlooked. The introduction has been rewritten to clarify that trends for the precipitation indices were included to point at potential future problems that may come with increased antecedent precipitation (-> higher soil moisture -> higher chance of flooding due to persistent precipitation) and increased event precipitation (-> higher chance of flooding due to higher precipitation sum). Concerning significance, only present significant trends (Mann-Kendall Test) are presented in the analyses, see chapter 2.3, page 5. However, supplementary information including figures showing maps of the p_value ≤ 0.05 could be added to the revised manuscript if the editor decides it is necessary.

10.) It is not correct to express wind speed using the Beaufort scale. It will be better to do it using m/s.

Response: Well, I would not say it is incorrect to use the Beaufort scale, since wind speed observations over sea have been estimated in Beaufort for a long time and, in fact, when comparing those observations with today's measurements, it is always recommended to use the Beaufort scale. But I admit that it is better to use m/s in this context.

11.) I think that there are too many subchapters in the chapter 3. I recommend to use two hierarchic levels, not three.

Response: The hierarchic levels haven been changed in the revised manuscript.

12.) Page 5, line 24. There is written that the LWT seems more appropriate. How much is this statement justified? On which facts is it based?

Response: Actually, it is due to the fact that LWT is centred close to the area of interest and offers the slightly better suited general weather situation for this specific case. Further, OWTC misses wet days during the first precipitation event. The passage has been rewritten in the revised manuscript.

13.) A misunderstanding is related to the title 3.1.4 Gauge data. Are the data from rain gauges? In fact, there is information about water level measurements. Gauge data were not described in the section of data and methods.

Response: No, these are not rain gauges. As pointed out in the response to RC1, there are additional passages in the revised manuscript including information about gauge data from the report of the LKN-SH and LLUR-SH (2015).

14.) Page 8 lines 3-4. This sentence was not understandable for me.

Response: The passage has been rewritten in the revised manuscript.

15.) It was difficult to understand the use of severity indices. What they show and how they could be compared?

Response: The severity indices are measures to compare flood events in their extent and extremeness. I admit chapter 3.2.3 does not really improve the manuscript in this regard. The chapter has been removed in the revised manuscript, together with passages in the "Data and Methodology" chapter.

16.) The main results of the study are not clearly and shortly concluded

Response: As pointed out in the response to RC1, the concluding remarks have been extensively rewritten according to the focus of the paper.

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

Nils H. Schade[1]

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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 ~~the Expertennetzwerk~~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 ~~situation~~circulation, initial wetness, and event precipitation. Predominantly persistent westerly ~~situations~~ 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 ~~event~~ precipitation event in ~~southern~~Southern Schleswig–Holstein causing several inland gauges to exceed their by then maximum water levels. ~~An additional storm surge hindering drainage of the catchments into the North and Baltic Sea could have been fatal.~~ 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~~North ~~west~~Western Schleswig–Holstein, and (2) strong event precipitation in ~~southern~~Southern and ~~eastern~~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 ~~are~~ have been increasing during recent years while regional patterns match the north eastward shift of cyclone pathways ~~during recent years~~, leading to higher risk of flooding in Schleswig–Holstein. Within the ~~Expertennetzwerk~~network of experts, investigations of these and further indices/drivers for earth system changes (e.g. wind surge, sea level rise, ~~land cover changes,~~ 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~~, e.g. in other Baltic Sea regions~~.

1 Introduction

In Dec~~z~~ember 2014, predominant westerly general weather ~~situations~~ circulations (~~GWS~~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 ~~during the Christmas Holidays~~ led to the flooding of several catchment areas in Schleswig–Holstein, Germany, located between the North and Baltic Sea. Both events mark ~~exemplary~~ independent atmospheric and hydrologic responses ~~within the causality chain~~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 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 atmospherical and hydrological conditions have to be monitored carefully concerning extremes and changes thereof.

The physical conditions of the North Sea ~~are the dominant factor controlling~~control both meteorology and hydrology in Northern European coastal regions (see e.g. Attema and Lenderink, 2014)~~.~~: ~~Of particular importance~~Dominant factors are the actual wind and water levels – including future sea level rise – and the predominant ~~GWS~~GWC. According to Randall et al. (2007), large scale and prolonged extreme events result from a persistent ~~GWS~~GWC in conjunction with ~~the~~ air-sea interactions ~~between air and sea~~ (air and soil, respectively). These interactions are of particular 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~~s~~ 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 ~~for~~in the Rhine delta, the probability of extreme surge conditions following extreme 20–day precipitation sums is even 3 times higher than estimated from treating extreme surge and discharge probabilities ~~as~~ 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. ~~Further, g~~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 flood assessment under global warming conditions.

In the following, the observed situation, predominant ~~GWS~~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, 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 ~~event~~ precipitation sum (R3d), can ~~provide~~ 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 ~~the Expertennetzwerk~~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 ~~will~~ 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~~:~~. ~~Therein, the observational basis is presented in chapter 3.1, the statistical analysis of the precipitation indices following the method of Schröter et al. (2015) in chapter 3.2, as well as a trend analysis of the indices investigated.~~ Finally, concluding remarks are given in chapter 4 and an outlook in chapter 5.

2 Data and Methodology

2.1 General Weather ~~Situation~~Circulation

Two different objective General Weather Circulation~~Situation~~ (~~GWS~~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~~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~~Central Germany. Further differences are ~~due to~~ 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~~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 ~~provided by DWD~~ 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 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):

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

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 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.

~~Schröter et al. (2015) further defined indices to classify the severity S_X^k of each event k investigated as aggregated measure S_X^k for each parameter X, in this case, the event precipitation (P) and the initial wetness (W): All values $X_{x,y}^k$ (X here stands for either R3d or API) at each grid point *(x, y)* that exceeded the values of the respective 5y return period were divided by the latter, their ratios summed up, and finally normalized by the number of REGNIE grid points Γ in Germany, following Eq. (2):~~

~~$S_X^k = \frac{100}{\Gamma} \sum_{x,y} \left\{ \frac{X_{x,y}^k}{X_{x,y}^{5\,y\,RP}} \right\} \mid X_{x,y}^k \geq X_{x,y}^{5\,yr\,RP}$ (2)~~

~~Now, all events can be ranked and compared. The floods in June 2013 (see Belz et al., 2013; Stein and Malitz, 2013, Belz et al., 2014), holding as the heaviest and severest event in the last 60 years, and July 1954 were special in the sense that both represent the extremes in case of the severity of event precipitation P (July 1954, P = 55.2) and initial wetness W (June 2013, W = 114.1).~~

~~For the following investigations REGNIE was used as well and, f~~Further, the Matlab toolbox WAFO (WAFO–group, 2000) was used for the statistical evaluation~~ of the extreme precipitation indices.~~: 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.~~ to compute the severity indices.~~

2.3 Trend Analyses

Mean trends ~~at~~ 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 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

~~3.1 Observed Situation~~

The December 2014 was predominated by westerly ~~GWS~~GWCs lasting for several weeks. Therefore, a number of low pressure systems were led from the North Atlantic over N~~n~~orthern 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 ~~8 to 10 Bft~~ 17 to 28 m/s observed all over Schleswig–Holstein (SH) and Hamburg (HH) are shown in Figure 1.

3.~~1.~~1 General Weather ~~Situation~~ Circulation (~~GWS~~GWC)

In general, both classification methods show predominant westerly ~~GWS~~GWCs from 5 December onwards with ~~north~~North ~~west~~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~~South ~~west~~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~~Central Germany while LWT is ideally centred in the North Sea. Since most of S~~s~~outhern and ~~c~~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. ~~Here, the LWT seem more appropriate.~~ Nevertheless, both ~~GWS~~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~~Northern Schleswig–Holstein. Additionally, the extreme precipitation event in ~~southern~~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.~~1.~~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. 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~~Northern SH, and one from 18–24 December (Fig. 4). Maximum daily precipitation was detected from 22–23 December in ~~southern~~Southern SH and HH with local values exceeding 50 mm corresponding to the standard monthly mean values.

As seen in Figure 4(a–c), the first rainfall period begins in the far ~~north~~North ~~east~~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 N~~n~~orthern Germany is affected, especially ~~southern~~Southern SH on 22 December. Values are comparable to ~~those~~

daily precipitation sums from selected DWD stations presented in ~~(LKN SH and LLUR SH, 2015, their Fig. 1~~Figure 5~~)~~ showing that REGNIE (solid black lines) fits well to the station data (bar plots). Only the highest maximum values are slightly underestimated~~performs well.~~: 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).

3.~~1.~~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. ~~5~~6a). The unit [% nFK] describes the saturation in percent effective field moisture 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~~Northern and ~~central~~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.~~1.~~2).

ZAMF also provides soil moisture data for loamy sand soil and cultivation with winter grain. Using this data, values in ~~northern~~Northern and ~~central~~Central SH are between 105 and 110 % nFK for the same date (Fig. ~~5~~6b)~~, only not that differentiated~~. 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~~Eastern SH).

~~3.1.4 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 (see their Fig. 27). All of these gauges are located in areas affected by high event precipitation and/or high antecedent precipitation (see following chapter 3.2). Further, 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). 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.~~

~~3.2 Precipitation Indices~~

3.~~2.1~~4 Event Precipitation – R3d

Figure ~~6~~7 shows the 3–day precipitation sum R3d for the December Flood 2014 in Schleswig–Holstein (Fig. ~~6~~7a) and its corresponding ratio to the 5–year return period (5yrRP, Fig. ~~6~~7b). The scal~~e~~ing for R3d is set according to Schröter et al. (2015). Clearly, the main contiguous part of the event precipitation is restricted to ~~northern~~Northern Germany with some spots in ~~central~~Central and ~~southern~~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~~Central 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~~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.

Areas with R3d exceeding the 5yRP are centred north of Hamburg~~ in the area of Wittenborn (see Fig. 4)~~, the ~~eastern~~Eastern NOK region, the catchments Stör and Krückau, and at the coasts of Mecklenburg–Vorpommern (Fig. ~~6~~7b). Higher return periods can be found ~~were exceeded only locally, i.e.~~ north of Hamburg in the area of Wittenborn (see Fig. 4)~~(not shown)~~. 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 years. Nevertheless, it shows how extraordinary this event was for this region.

3.~~2.2~~5 Antecedent Precipitation Index – API

Figure ~~7~~ 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. 6~~5~~a). In contrast to R3d, the 5yRPs for API are exceeded only in NW–SH (Fig. 8~~7~~b) with maximum values corresponding to 20yRP~~. Higher return periods were not reached during this flood~~.

It is obvious that antecedent precipitation in combination with the maximum precipitation event led to SH–wide flooding in 2014 (Fig. 7~~6~~/~~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. ~~Further~~In this regard, ~~it illustrates~~ the importance of both indices to describe this flood accurately is illustrated. Furthermore, ongoing investigations in 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 sea level rise, 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. ~~and points at potential risks in case an additional storm surge would be present during the course of a similar event, affecting the drainage of affected catchments. Nevertheless, areas that were affected the most experienced strong event precipitation in December 2014.~~

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.

~~3.2.3 Severity Indices~~

~~Nationwide, the December Flood 2014 ranks with P = 3.3 for the event precipitation and W = 0.6 for the antecedent precipitation which is at least significant for the event precipitation index: It exceeds the wetness index by a factor of 5. Compared to the events in 1954 (P = 55.2) and 2013 (W = 114.1) the December Flood 2014 is of little relevance. On the regional scale, however, it affected SH as a whole (API in the northwest, R3d in the east and south) which makes this flood event particularly noteworthy (Fig. 6/7). Taking climate change into consideration, situations like this can be expected to increase in strength and occurrence. First hints can be seen in the following trend analyses conducted for API and R3d, respectively.~~

3.~~2.4.~~7 Trend Analyses - R3d & API

Figure ~~8~~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~~unmistakably~~ 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. ~~9~~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. ~~9~~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 ~~coastal areas~~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~~Northern Germany (SH, EZG NOK), the risk increases even further.

4 ~~Concluding Remarks~~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). ~~, fire departments and voluntary aides reacted fast. The most significant damage to the transport ways appeared to be a slope slide on freeway A1 on a distance of about 1500 m (personal communication). Nevertheless, the initial wetness in combination with strong event precipitation could have caused more severe damage. Undercutting of the railway tracks Hamburg – Kiel/Flensburg would have led to considerable restrictions for train services and transportation since this route is the main connection up north. Some fields close to the tracks were already flooded and under surveillance during the whole event. Bridges and Tunnels in the area are old and water levels up to 45 cm above the previous maximum put the infrastructure under enormous pressure. Furthermore, a~~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 ~~situations~~ 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) ~~provide useful information~~ 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. ~~should~~ 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~~ separately or in combination~~ 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 ~~the Expertennetzwerk~~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 ~~testing the applicability~~applying ~~of~~ the above described ~~severity~~ precipitation indices ~~in~~to reanalyses and regional climate models (RCMs). ~~s~~Since precipitation extremes are expected to increase in the future (e.g. Nikulin et al., 2010; Kharin et al., 2013; Scoccimarro et al., 2013), ~~and~~ 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. ~~This holds especially true for other Baltic Sea regions, where river systems and catchments have to deal with an additional meltwater runoff.~~

In addition, ~~S~~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 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 ~~the above described indices~~ R3d and API to extreme and abnormal events (see Müller and Kašpar, 2014; Müller et al., 2015) ~~including~~ 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), Dec~~z~~ember 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

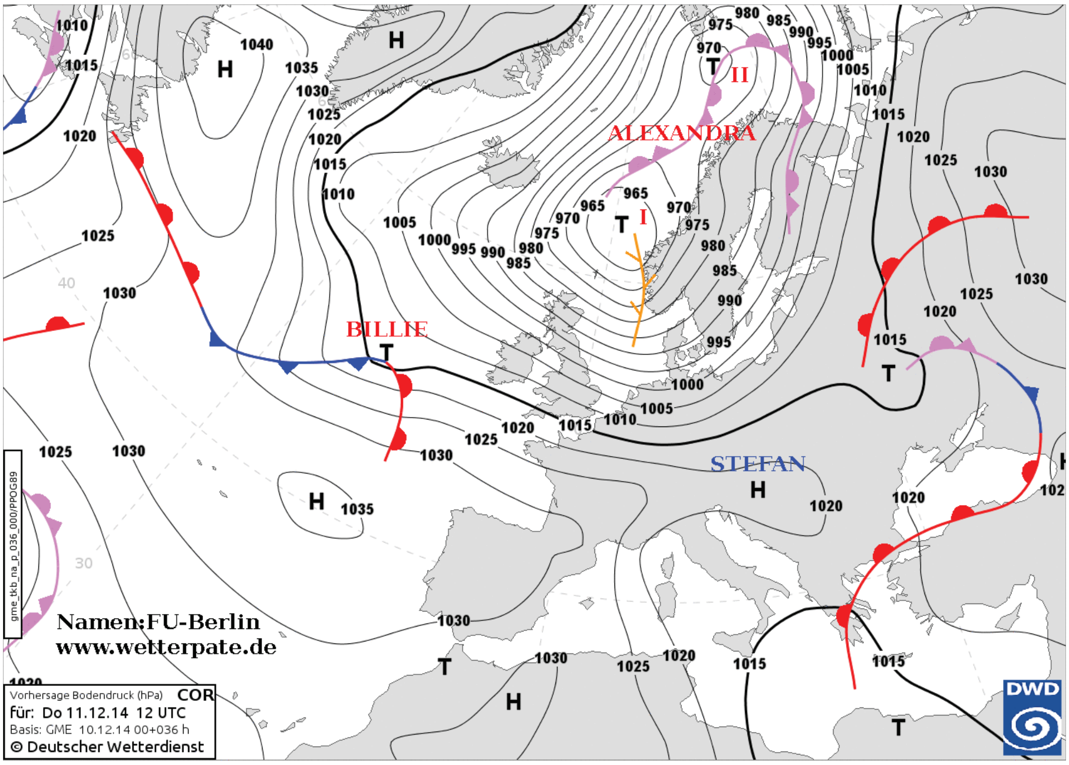
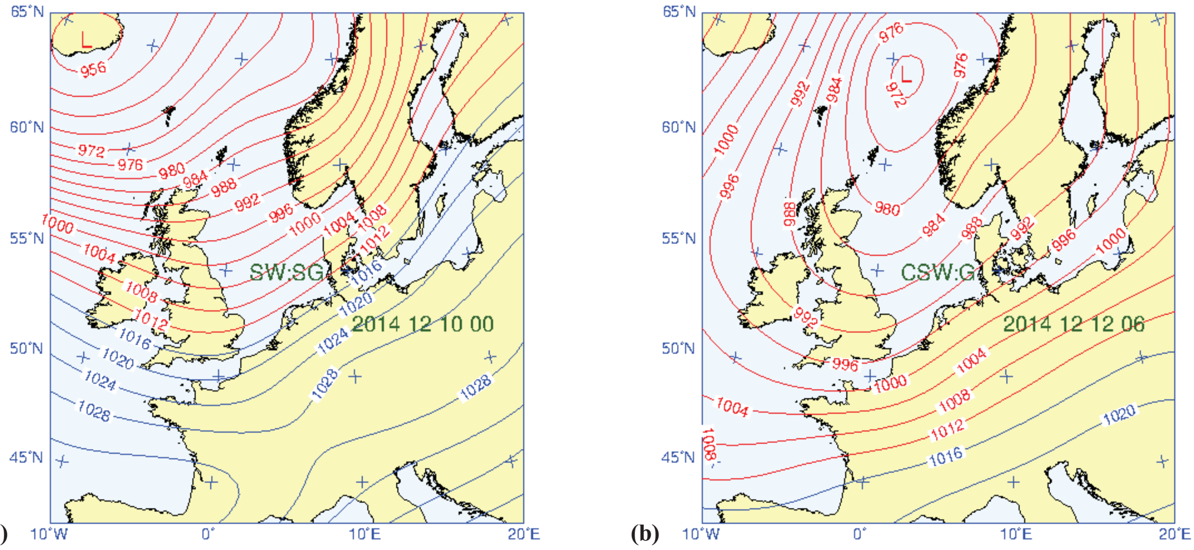
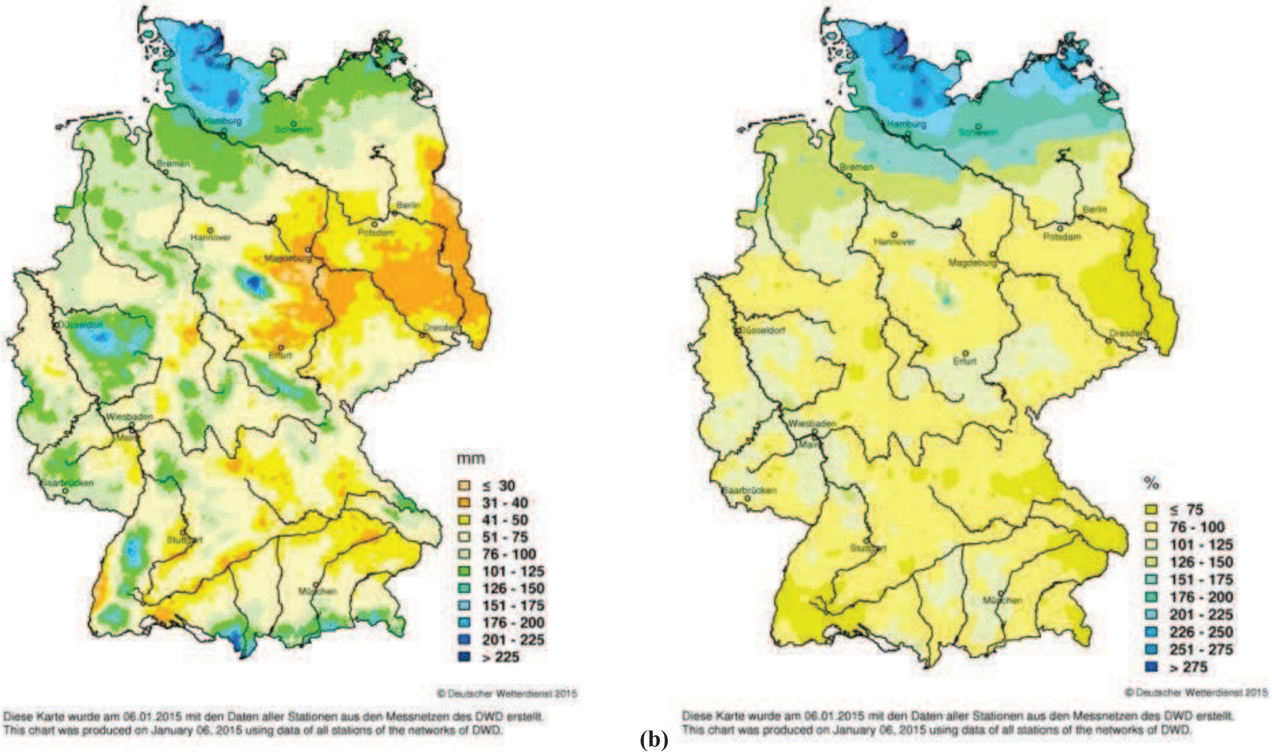


Figure 1: Sea level pressure prediction for Thursday, 11 December 2014 showing the low pressure systems ALEXANDRA and BILLIE in short progression. Image credit: FU–Berlin, www.met.fu-berlin.de (last access: 20 February 2015).



(a) **(b)**

Figure 2: Classification of the general weather ~~situation~~circulation (~~GWS~~GWC) after the modified Lamb Weather Types used at BSH for (a) the low pressure systems ALEXANDRA (classification: South ~~west~~West (SW) with "severe gale" (SW)) and (b) BILLIE (classification: Cyclonal ~~south~~South ~~west~~West (CSW) with "gale" (G)). Image credit: P. Löwe (BSH Hamburg).



(a) **(b)**

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).

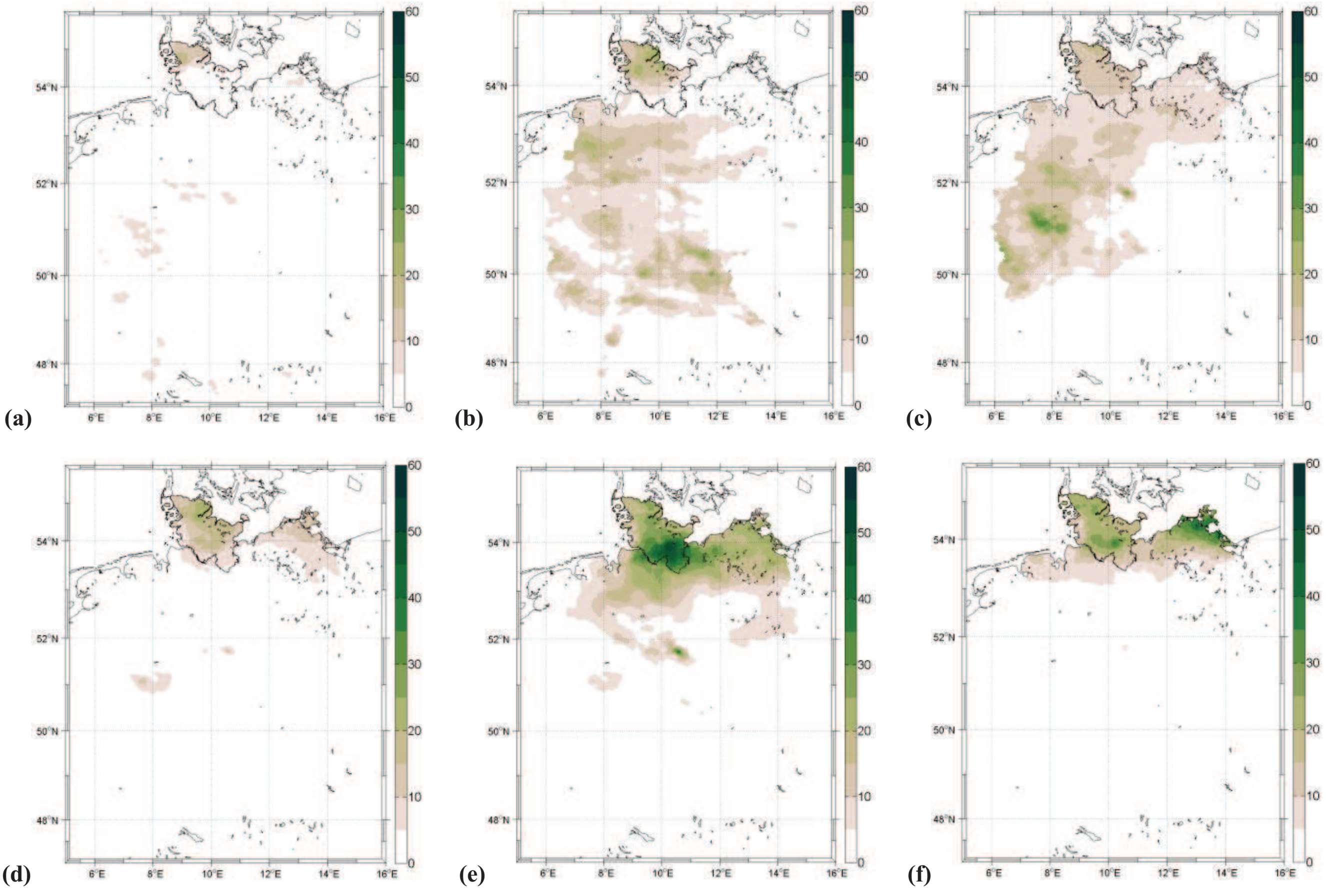


Figure 4: Daily sums of REGNIE precipitation data in [mm] for the first event, 10–12 December 2014 (a–c), and the main precipitation event, 21–23 December 2014 (d–f). The boundaries of Schleswig-Holstein are marked in black.

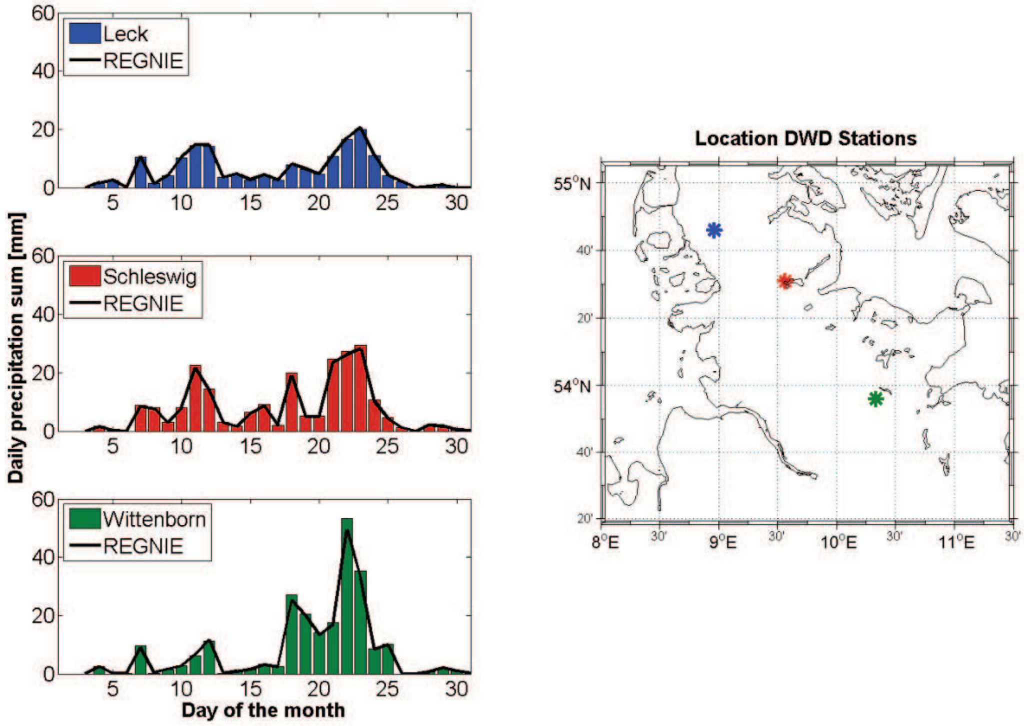
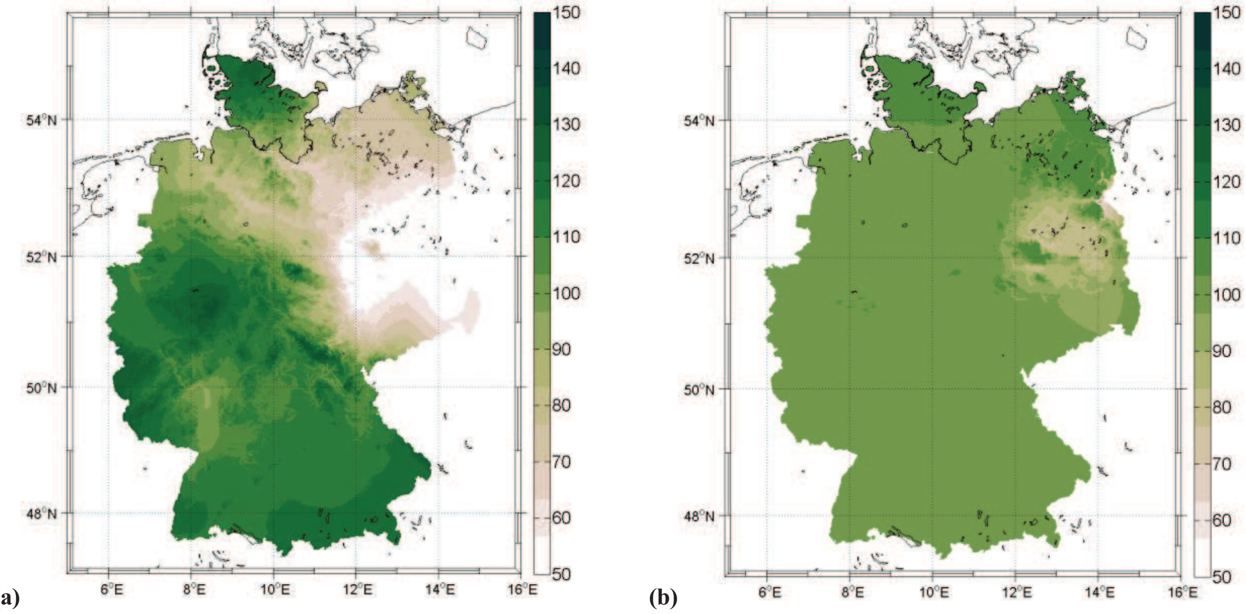
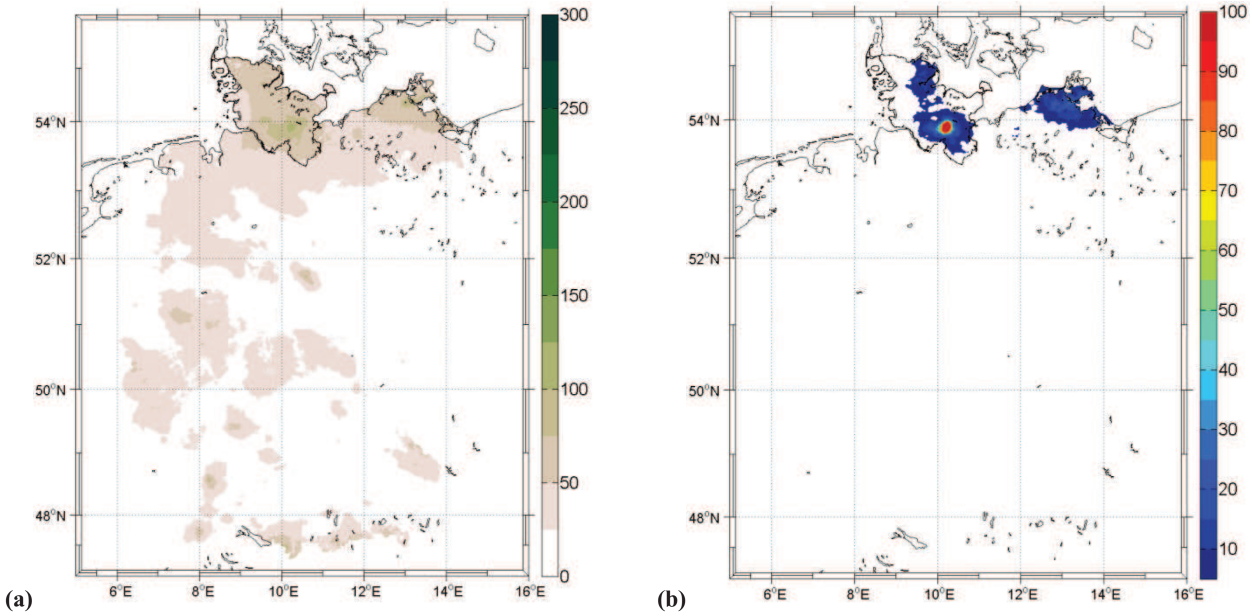


Figure 5: Daily precipitation sums at DWD stations in Northern (Leck), Central (Schleswig) and Southern (Wittenborn) Schleswig-Holstein, December 2014. Black lines indicate REGNIE daily precipitation sums at the closest respective grid points.



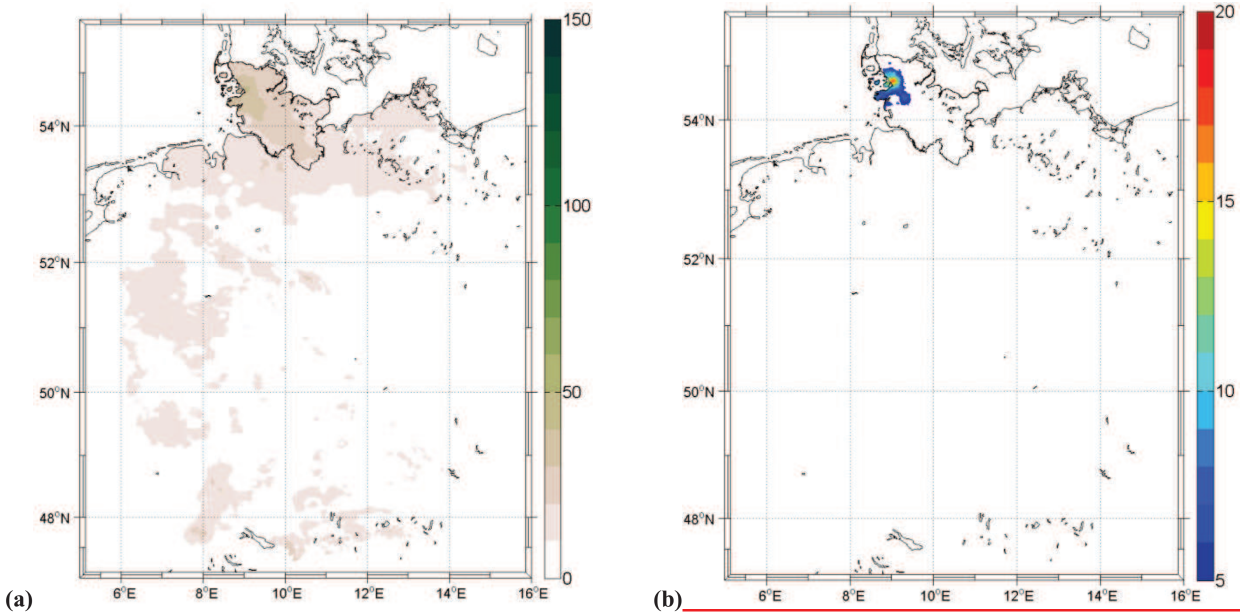
(a) (b)

Figure 6~~5~~: (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.



(a) (b)

Figure ~~6~~7: (a) 3–day event precipitation (R3d) in [mm] and (b) ~~its ratio to the 5y~~ 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.



(a) (b)

Figure ~~7~~8: See Figure ~~6~~7, but for the antecedent precipitation index (API).

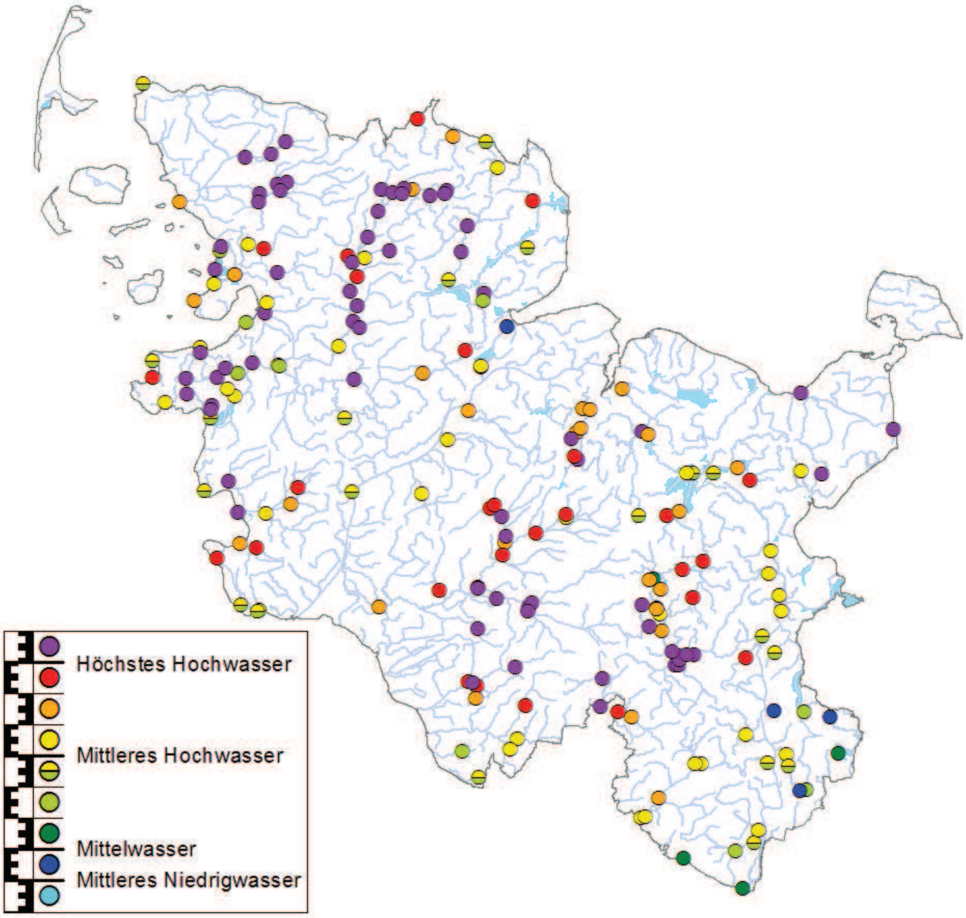
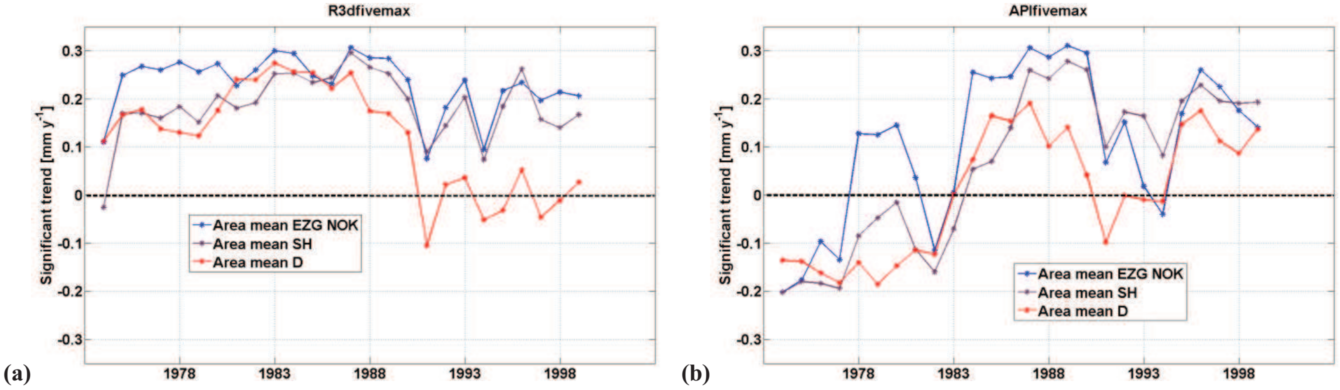
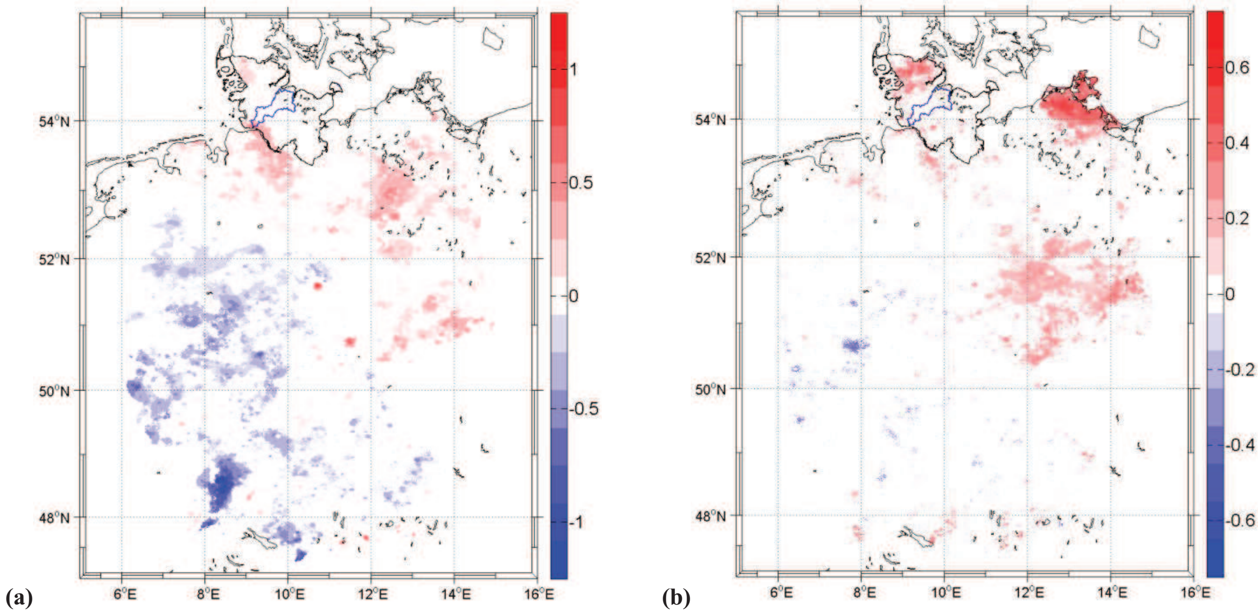


Figure 9: Gauge data in Schleswig-Holstein showing exceedance of highest high water levels (mauve), medium high water levels (yellow to red), medium water levels (green to yellow), medium low water levels (dark blue) and below (light blue) during the December Flood 2014. This map from the LKN–SH and LLUR–SH (2005) report was kindly provided by Dr. Thomas Hirschhäuser (LLUR-SH).



(a) (b)

Figure ~~8~~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.



(a) (b)

Figure ~~9~~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.