Model based assessment of climate change impact on inland flood risk in coastal areas caused by compounding storm tide and precipitation events

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Abstract. In addition to storm surges, inland flooding due to intense rainfall becomes an increasing threat at coastal lowlands. In particular, the coincidence of both types of events poses great challenges to regional water boards since their technical drainage capacities are limited. The evaluation of historical inland flood events at the German North Sea coast at the gauge Knock near Emden shows that in the past mainly moderate storm series in combination with large-scale, heavy precipitation led to an overload of inland drainage systems, whereas storm tides and precipitation alone could be handled well. Evaluation of the drivers of inland flood events simulated for the control period of two climate models confirms that a combination of storm tides and precipitation leads to highest drainage system overloads. Moderate system overload is also caused by heavy precipitation events alone rather than by storm tides without precipitation. Scenario projections based on a set of combinations of two highly resolved climate models and two emission scenarios suggest that the intensity of compound events of rainfall and storm tides will increase consistently against the background of mean sea level rise for all investigated climate change projections, while simulated system overload is higher for RCP8.5 compared to RCP2.6 scenario. Comparable to the past, future compound events will cause more potential damage compared to single extreme events. Such behaviour can be expected to induce an increasing frequency and intensity of inland drainage system overloads along the North Sea coast if timely adaptation measures will not be taken.

1 Introduction

Drainage management at flat coasts is a traditional challenge to be able to use the dike hinterland for human activities such as agriculture, settlements or trade (Bormann et al., 2020). The inhabitants of the marsh area along the North Sea started building dikes and sea walls more than 1000 years ago in order to protect the productive landscape against tidal inundations and storm floods. Due to the humid climate and the resulting rainfall excess of inland areas, a concurrent development of an efficient drainage system was necessary (Bormann, 2018). Tidal gates and pumping stations were built to convey the excess water from the hinterland to the sea. Such drainage management has been improved over the past decades (Spiekermann et al., 2018, 2023), keeping all areas productive during the year and protecting low-lying coastal areas against inland flooding. Similar

30   systems for coastal protection and inland drainage were also developed in other low-lying coastal areas around the world, such
      as the Netherlands (van Alphen et al., 2022; Ritzema and Stuyt, 2015), the United States of America (Titus et al., 1987),
      Australia (Waddington et al., 2022) and New Zeeland (Kool et al., 2020).

      Climate change projections suggest that global sea level rise will continue until end of the 21st century and beyond (IPCC,
      2021). Coastal areas therefore are identified as highly threatened areas (IPCC, 2022). Low-lying coasts are particularly

35   vulnerable because water hazards may come from two sides (Bormann et al., 2018, 2020). Both, sea level rise and intense
      rainfall events will have an increasing impact on flooding until end of the century. Recent studies indicate that climate change
      also might intensify the pronounced seasonality in runoff generation along the North Sea coast (Bormann and Kebschull, 2023;
      Bronstert et al., 2023), leading to increasing drainage demands in the future if drainage standards shall be kept at least at the
      status quo.

40   However, water boards along the North Sea coast are increasingly operating their systems at the edge of their capacity as
      consequence of increasing climate variability and extreme events (Spiekermann et al., 2018, 2023). Water boards therefore are
      aware that the effects of climate change will place even greater demands on drainage infrastructure in the future (Bormann et
      al., 2018, 2020, 2022). In addition to the individual events mentioned above, compound events in particular pose a special
      challenge for flood protection and inland drainage. If, for example, storm tide (Pugh and Woodworth, 2014) and high rainfall

45   events occur at the same time, even a combination of moderate single events often leads to an overload of the inland drainage
      system (Santos et al., 2021; Kool et al., 2020; van den Hurk et al., 2015). At the German North Sea coast of Lower Saxony
      such an event was last observed in February 2022, when a series of storm depressions (Ylenia, Zeynep, Antonia) was
      accompanied by days of heavy rainfall. Consequently, regional flooding occurred although drainage systems worked at the
      edge of their capacity.

50   Climate change adaptation and flood risk management must explicitly consider the flood generation mechanism of such events
      (van den Hurk et al., 2015), especially if climate change will intensify as projected by the IPCC (2021, 2022). Available studies
      mainly focus on the coincidence of storm tides and high regional river discharges. Heinrich et al. (2023) investigated the
      coincidence of storm tides and high river discharge at European coasts. While they found a significantly increased likelihood
      of simultaneous storm tides and high river discharge for westward facing estuaries, they did not identify a frequency higher

55   than expected by chance of such compound events for other estuaries including the northward facing Ems estuary. Similarly,
      Svensson and Jones (2002) analysed the dependence of storm tides, river flow, and precipitation in the UK. They identified
      more compound flood events on the western coast compared to the eastern coast.

      Paprotny et al. (2020) demonstrated that large-scale hydrodynamic models are capable of representing observed compound
      flood events in northwestern Europe. Thus, model-based tools can be useful for the projection of climate change impacts.

60   Bevacqua et al. (2019, 2020) predicted a strong increase in the occurrence rate of compound flooding events for the future,
      especially for northern Europe, mainly due to the stronger precipitation as the result of a warmer atmosphere carrying more
      moisture. A similar result was obtained by Heinrich et al. (2023b), but attributed mostly to future rising mean sea level.

So far, integrative scenario-based climate impact assessments are not available with regard to the above-described compound events causing local to regional flooding at shallow coasts. Available analyses focus either on the impacts of storm floods (e.g., van Alphen et al., 2022; Waddington et al., 2022) or on changes in runoff generation (e.g., Bormann et al., 2018; Bormann and Kebschull, 2023) or are based on statistical approaches (Santos et al., 2021). This is mainly due to the fact that the usually available (daily) temporal resolution of long term climate projections is not sufficient to drive regional hydrodynamic ocean models to represent tidal water level dynamics, because they require regional wind fields in high temporal resolution. Similarly, process based runoff generation models require precipitation intensities in sufficient resolution.

In this study, we fill this gap by driving a runoff generation model and a regional hydrodynamic ocean model with the same regionalized climate scenarios in hourly temporal resolution, enabling consistent coupled projections of compound events. We use climate projections of two climate models quantifying the effects of two different emission scenarios and analyse this small ensemble with regard to change signals in in the impact of storm tides and runoff generation on the overload of a regional drainage system at the German North Sea coast.

2 Material and methods

2.1 Target area

The target area of this study is located in the northwestern part of East Frisia (northern Germany) and includes the area of the water board Emden (Figure 1). Coastal water boards are responsible for the regulation of water flow in the regional drainage networks, consisting of canals, ditches, tidal gates and pumping stations. They guarantee both water drainage in wet periods, but also regulation of discharge in dry periods. The area of the water board Emden is bordered by the Ems estuary, the Dollart and the North Sea. The water board has an area of 465 km², from which 1/3 is located below sea level (Spiekermann et al., 2018). The landscape is dominated by marsh soils, mainly used for dairy farming (grassland). But the region also has residential and commercial area, and tourism plays an important role in regional economy.

Since a permanent and reliable drainage is the prerequisite for the settlement and use of the area, the water board maintains a watercourse network of 1,100 km in length, which conveys the runoff to the two tidal gates and pumping stations Knock and Greetsiel. Depending on the sea water level, either free drainage is possible (currently approx. 1/3 of the drainage volume) or pumping is required (currently approx. 2/3 of the drainage volume). In the case of extremely high sea water levels, the pumping capacity drops significantly due to the increasing geodetic head (Bormann et al., 2023).

Specific inland flood risk is caused in periods when high sea water levels and heavy rainfall coincide. In such situation high runoff generation and reduced pumping capacities can lead to drainage system overload and inland flooding.

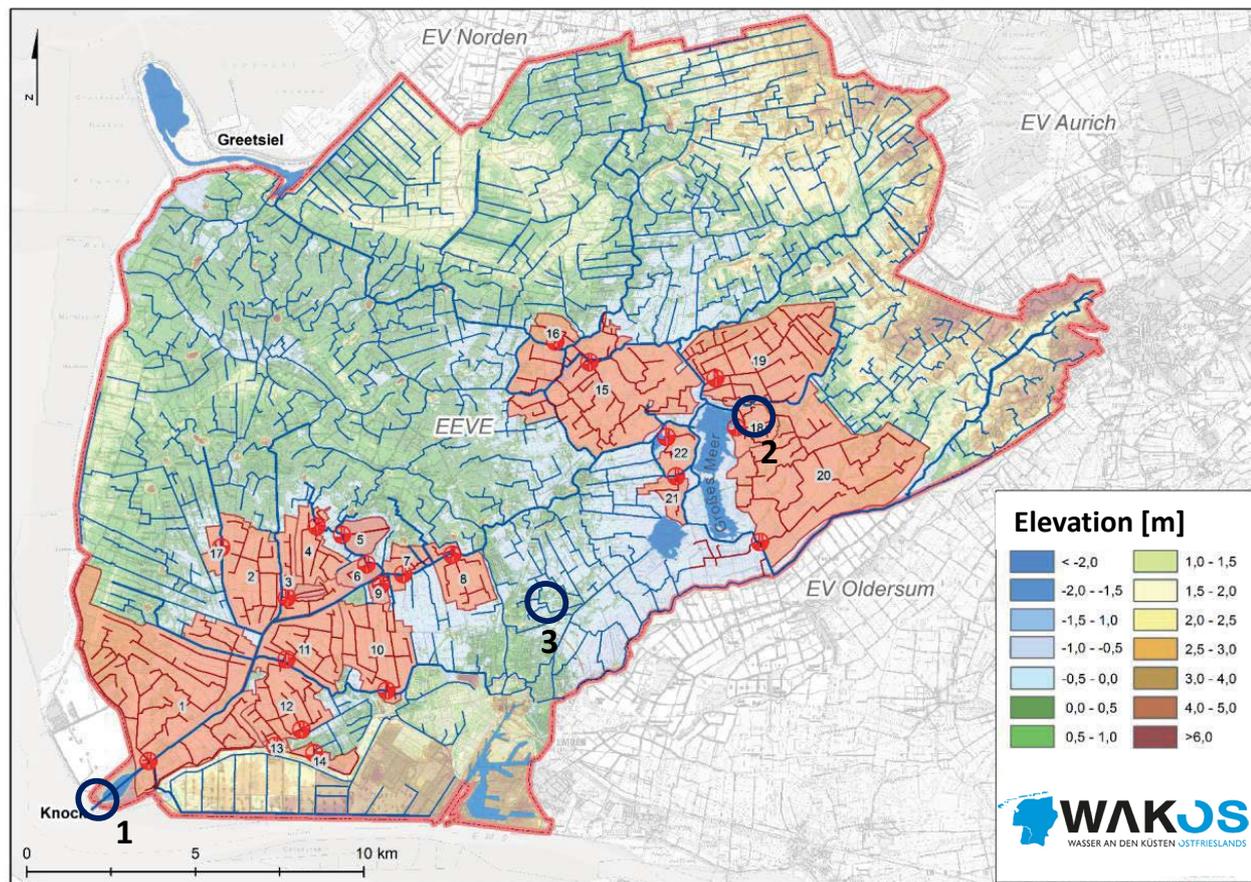



Figure 1: Topography of the water board Emden. Orange areas are low-lying pump-areas. 1: gauge Knock; 2: gauge Bedekaspel; 3: DWD weather station Emden. Data source: extract from the basic geodata of the Lower Saxony surveying and cadastral administration (LGLN; www.lgln.niedersachsen.de).

2.2 Data

For the analyses of historic events, a regional 20-year time series (2000-2019) on sea water levels, inland water levels and weather data was available for the water board Emden in high temporal resolution:

- Sea water levels in 1 minute resolution at gauge Knock (location 1 in Figure 1; source: state agency NLWKN; www.nlwkn.niedersachsen.de);
- Inland water levels in 15 minutes resolution at gauge Bedekaspel (location 2 in Figure 1; source: Emden water board; www.entwaesserungsverband-emden.de);
- Precipitation in daily resolution at station Emden (location 3 in Figure 1; source: German Weather Service; www.dwd.de).

105 As forcing for the impact modelling, four data sets from the Euro-CORDEX initiative were available that provide regional climate projections for Europe at 12.5km (0.11°) resolution (Jacob et al. 2014). For these data sets, the regional climate model REMO (Jacob et al. 2007) in two different versions (REMO2009 and REMO2015) was driven by the output of two global climate models (HadGEM2-ES; Jones et al. 2011 and MPI-ESM-LR; Giorgetta et al. 2013) that is part of the CMIP5 ensemble (Taylor et al. 2012). For both regionalizations, hourly model output was available for a historic period and two emission

110 scenarios (RCP8.5 and RCP2.6) in the following combinations:

- HadGEM2-ES, regionalized by the regional climate model Remo2009 (1950-2099; RCP2.6 and RCP8.5) referred to as HadGEM in the following, and

- MPI-ESM-LR, regionalized by the regional climate model Remo2015 (1950-2100; RCP2.6 and RCP8.5) referred to as MPI in the following.

115 Bias correction was carried out for the simulated temperature and precipitation of both dynamic climate models. A monthly linear scaling (Shrestha et al., 2017) was applied to the control period (1971–2000) to correct a long-term overestimation of precipitation and temperature. In order to reproduce seasonality in precipitation and temperature correctly, monthly specific bias correction factors were applied to the model data for all months of the year.

2.3 Classification and determination of compound events

120 Compound events are defined by the joint impact of several events on one system. Zscheischler et al. (2020) suggested a typology of meteorological compound events. They distinguish between

1. Multivariate compound events: simultaneous occurrence of *different events* affecting the same system,

2. Spatial Compound Events: occurrence of events in *different regions* affecting the same system,

3. Temporal compound events: several *consecutive events* affecting the same system, and

125 4. Preconditioned compound events: events that occur only under *certain conditions*.

This typology is similar to the definition of the IPCC (2012). It describes compound events as combinations of (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different type(s)

130 (Seneviratne et al., 2012).

In this study, the coincidence of storm tides and high-yield precipitation on the North Sea coast is investigated for the Emden water board (East Frisia). Practical experience of the water board shows that system overload at the North Sea occurs especially when intense precipitation falls over a longer period of time during a period in which the pumping capacity is reduced by high sea levels (Spiekermann et al., 2018, 2023). This is due to the technical limitation of the pumping capacity installed in the dike

135 line.

Compound events in the observations were identified based on van den Hurk et al. (2015) by selecting the 15 largest events according to sea level (mean sea level over a 5 tides period), precipitation (antecedent 3 day precipitation sum) and highest

inland water levels (maximum daily value). For the model-based analyses, compound events were identified by an adjusted
method, since inland water level could not be simulated due to the complex drainage system. As for the observations, the 15
largest events were selected for the highest sea levels (average sea level over a period of 5 tides) and precipitation events
(antecedent 3 day precipitation sum), but highest simulated system overloads of the inland drainage system replaced inland
water levels. System overloads were calculated as sum of the current system overload at a distinct day and runoff generation
minus pump-capacity of that day (which depends on average sea level; for details see following section on model-set-up). By
selection of the characteristic three days period, a potential delay between precipitation and system overload is taken into
account (concentration time resp.).

2.4 Model set-up

While the analysis of compound events based on observations could be carried out straight forward according to the literature
(van den Hurk et al., 2015), for the evaluation of climate change projections a new model-set-up was necessary. Extreme
precipitation events and high water levels of storm tides were derived from simulations directly, but due to the complexity of
the coastal drainage system, inland water levels could not be simulated for the water board area; instead, system overload was
estimated as follows (Figure 2). A storage-approach represents the volume of the coastal drainage system. Runoff-generation
simulated by the SIMULAT water-balance-model (Diekkrüger and Arning, 1995; Bormann, 2008) is the only input, and pump-
capacity the only output term. We assume that there is no exchange of water between the area of the Emden water board and
the neighbouring water board areas, and that there is no limitation of lateral water flow within the water board area through
canals and ditches. The time-variable drainage capacity then depends on the sea level simulated by the regional hydrodynamic
ocean model TRIM-NP (Kapitza et al. 2008), the inland water level (assumed to be constant at current level) and the parameters
of the pumps. Since both models (SIMULAT and TRIM-NP) are driven by the same climate projections, consistent
representations of possible future conditions are simulated.

2.4.1 SIMULAT model

The physically based hydrological model SIMULAT (Diekkrüger and Arning, 1995; Bormann, 2008) is a continuous
hydrological SVAT (soil-vegetation-atmosphere-transfer) scheme, initially developed to simulate local-scale hydrological
processes. Basic equations included in SIMULAT are the Richards' equation to calculate soil water flux and the Penman-
Monteith equation the potential evapotranspiration (PET). Actual evapotranspiration (ETA) is calculated from PET taking into
account the actual soil moisture status (approaches of Feddes et al. (1978) for transpiration and Ritchie (1972) for evaporation).
Further processes considered by SIMULAT are the separation of rainfall into surface runoff and infiltration (performed by a
semi-analytical solution of the Richards' equation (Smith and Parlange, 1978)), interflow (based on Darcy's law), groundwater
recharge and the snowmelt (degree-day approach). A plant growth model is not included; instead, average seasonal
development of plant parameters necessary for the Penman-Monteith equation is estimated by linear interpolation of values
given from the literature (see Bormann and Kebschull, 2023). Soil parameters are derived by the pedotransfer-function of

170   Rawls and Brakensiek (1985). At the scale of hydrological response units (HRU) derived for the Emden water board by
       Bormann et al. (2018) based on the available spatial data sets, runoff generation is calculated by accumulating all three runoff
       components (surface runoff, interflow, and groundwater recharge) for each daily time step. At the water board scale, runoff
       generation is calculated for all HRU and afterwards weighted per unit area. Runoff routing is not considered since hydraulic
       gradients are mainly affected by the operation of the drainage system and therefore temporarily variable. We assume that the
175   concentration time is considerably smaller than the maximum duration of the events analyzed in this study (3 days). SIMULAT
       was successfully calibrated and validated for the Emden water board (Bormann et al., 2018), and for neighboring water boards
       (Bormann and Kebschull, 2023) by comparing runoff generation simulated by the model against the estimated drainage rates.
       For the climate change impact analysis, SIMULAT is driven by hourly climate variables of the regionalized climate models
       MPI and HadGEM, namely air temperature, air humidity, wind speed, global radiation and precipitation. As output, SIMULAT
180   calculates daily runoff generation rates.

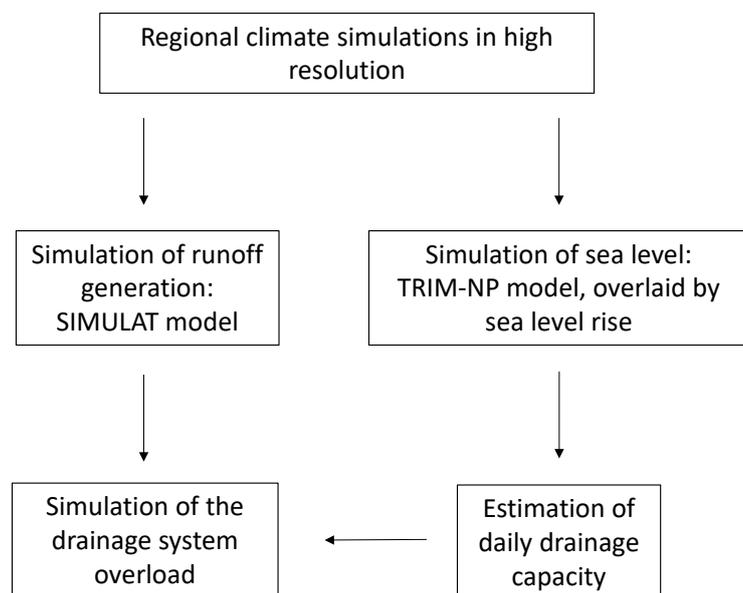



**Figure 2: Model-chain for the projection of future compound events: Regionalized climate projections drive a regional
runoff-generation model (SIMULAT) and a regional hydrodynamic ocean model (TRIM-NP); estimation of daily**
185   **drainage capacity from sea water levels enables the comparison against runoff generation, resulting in projections of
drainage system overload.**

2.4.2 TRIM-NP model

For the high-resolution modelling of water levels in the German Bight and the attached estuary of the river Ems (Figure 1),
the hydrodynamic numerical model TRIM-NP (Casulli et al 1998, Kapitza 2008) is used. TRIM-NP is a 3D finite-difference

190 model, which solves the Reynolds-averaged Navier-Stokes equations on a Cartesian grid. It allows for wetting and drying. For the simulations in this study, the model is used in a 2D barotropic mode with nested grids. The coarsest grid with 12.8 km resolution covers northeastern Atlantic, North Sea and Baltic Sea. Three further grid refinements are nested one-way towards the 1.6 km resolution over the Germen Bight. The FES tidal signal (Layard et al 2006) is applied at the lateral boundaries of the coarsest grid. For the climate change impact analysis, TRIM-NP is driven by hourly 10m-height wind components and sea

195 level pressure from the regionalized climate models MPI and HadGEM. The output sea level variations for the period 1950-2100(2099) are stored with 20 min resolution for the German Bight (Gaslikova 2023). For further model details and applicability for the climate change scenarios see also Gaslikova et al 2013. The resulting high frequency sea level variations are additionally superimposed by regionalized long-term projections of the mean sea level rise (IPCC, 2021). In particular, for the period 2020-2100 the median of the regional RCP2.6 and RCP8.5 projections for Delfzijl from the IPCC AR6 Sea-Level

200 Projection Tool (Garner et al. 2021, Fox-Kemper et al. 2021) are used. The dataset is complemented with the observed annual mean sea level at Norderney (WSV, 2021) for the historical period 1971-2019.

2.4.3 Drainage capacity

The drainage capacity of a coastal outlet structure consisting of a tidal gate and a pumping station (such as station Knock for the Emden water board; Figure 1) depends on both individual drainage capacities which apply as a function of total dynamic

205 head between inland water level and sea level. While for low sea level gravity-driven flow through the tidal gate is possible, water needs to be pumped against high sea level.

Pump capacity depends on total dynamic head which is defined as is the work to be done by a pump, per unit weight, per unit water volume. Based on an estimation of gravity driven flow through the tidal gate (provided by the state agency; NLWKN) and the pump parameters (provided by the Emden water board), a drainage capacity function was derived for the station Knock

210 as 3rd order polygon (see Figure 3). As inland water levels are managed to remain as constant as possible, pump capacity decreases with increasing sea water levels

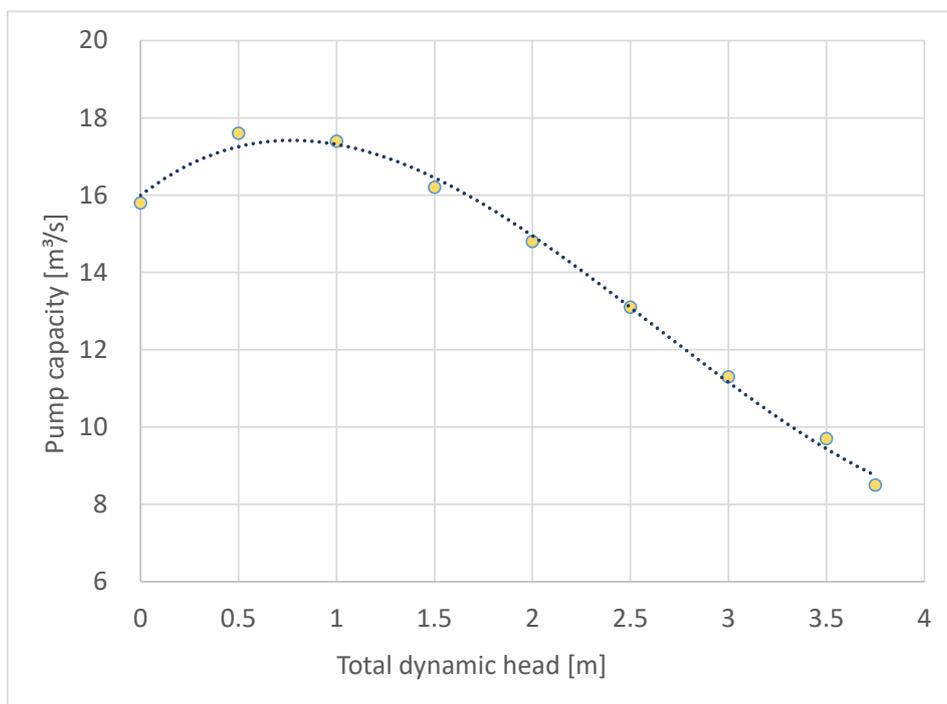



Figure 3: Drainage function for station Knock (3rd order polygon).

3 Results

3.1 Identification of compound events based on historical data

The water level in the inland water system is regulated to keep the inland water level constant. The difference between the observed and the intended (regulated) inland water level thus provides a proxy for the drainage system (over)load. To analyze possible compound effects, the events with the 15 largest inland water anomalies were selected and plotted together with the observed mean sea level over five tides and the antecedent three-day precipitation sum. In addition, the 15 largest sea level and precipitation events were also selected and plotted together with the observed inland water level anomalies (Figure 4). The analysis reveals that either the co-occurrence of very high sea levels together with very high precipitation events, or the joint occurrence of moderate sea levels and precipitation sums lead to the largest observed deviations from the regulated inland water level (in total nine of the 15 largest events). This is in agreement with the results and conclusions presented by van den Hurk et al. (2015). Moreover, a tendency can be inferred that precipitation is a somewhat more important driver as five of the 15 highest inland water level anomalies were associated with high precipitation only while sea level heights were smaller. In addition, Figure 4 reveals that sea level and precipitation do not represent the sole drivers of inland water anomalies as some of the events with rather similar combinations of precipitation and sea levels were associated with rather different inland water heights.

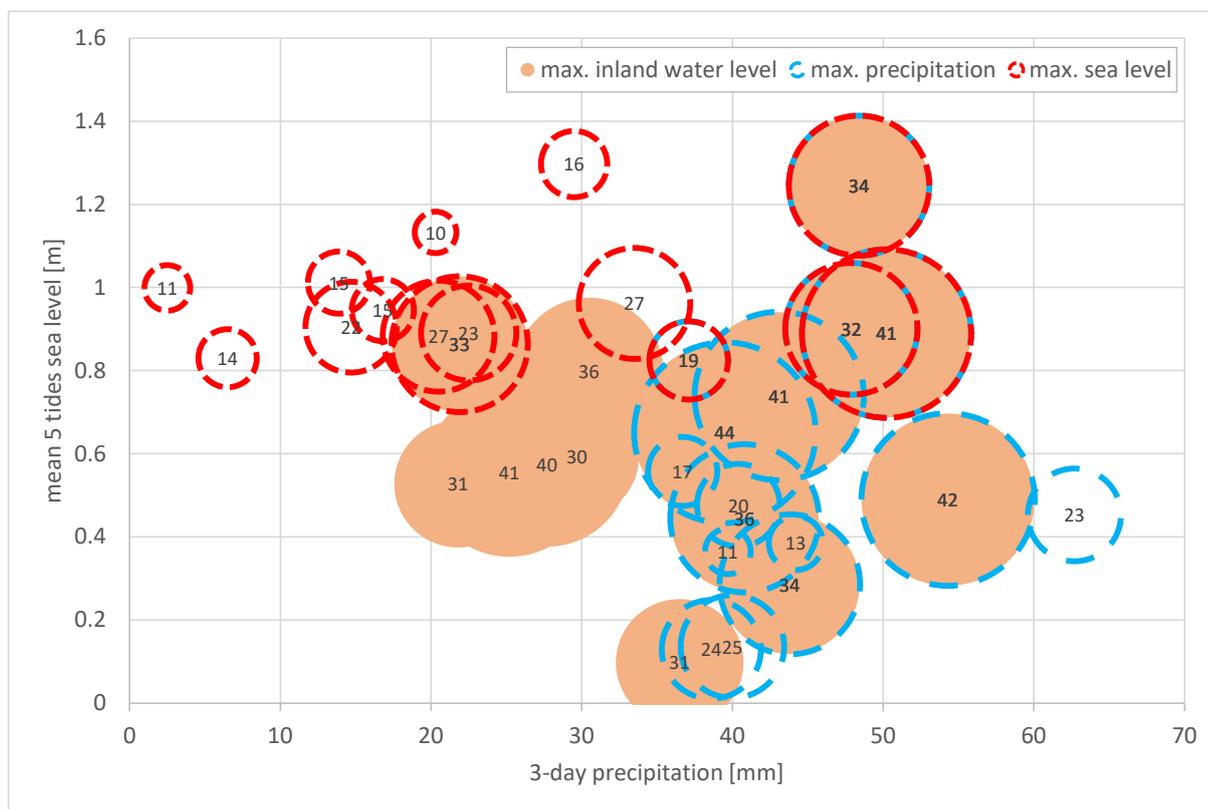



Figure 4: Inland water level anomaly as difference from the regulated inland water level [cm] for the 15 highest sea level (mean sea level over a 5 tides period; red circles) and precipitation (antecedent 3 days precipitation sum; blue circles) events in the period 2000-2019. Additionally, the 15 highest inland water level anomalies in the same period are shown (orange circles). The diameter of the circles is proportional to the size of difference between the observed and the intended regulated inland water level.

3.2 Identification of compound events based on scenario simulations

3.2.1 Control period of the climate simulations

The analysis of compound events from the impact models driven with data from the two downscaled climate models (HadGEM, MPI) for the control period (1971-2000) reveals that the model set-up is able to reproduce the structure of compounding sea level and precipitation events contributing to inland flooding as obtained from the observations. Repeating the analysis done for the observations (Figure 4) for the 1971-2000 control period yields in the same three different groups of events (Figure 5), as derived from observed data (section 3.1). Note that instead of inland water level anomaly simulated drainage system overload was used in the analysis of model data.

For the control period, the overlap of largest 5-day mean sea levels to highest inland drainage system overloads and highest precipitation events is small, while most of the largest precipitation events contribute to high inland drainage system overloads,

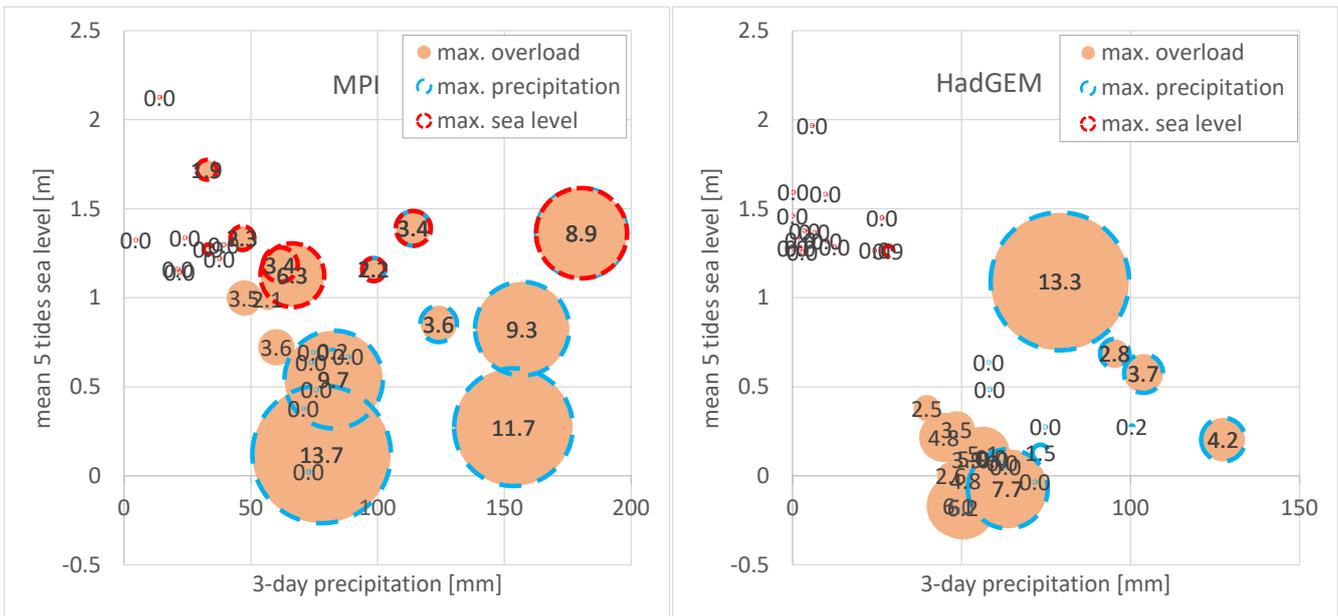
245 as found for the observed data set. Largest system overloads are neither caused by the maximum sea level nor by the largest precipitation sum. The largest system overloads (13.7 million m³ for MPI model, and 13.3 million m³ for HadGEM model) are generated by a combination of moderate events of both drivers. However, obviously both precipitation sums and sea levels are larger in the simulations compared to the data. This may partially be due to the shorter time-period of observational data, compared to the simulations.

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Figure 5: Simulated drainage system overload [10⁶ m³] for the 15 highest sea level (mean sea level over a 5 tides period; red circles) and precipitation (antecedent 3 days precipitation sum; blue circles) events in the period 1970-2000 derived from the simulations driven by the MPI (left) and HadGEM (right) model data. Additionally, the 15 simulated drainage system overloads in the same period are shown (orange circles). The diameter of the circles is proportional to the

255 **magnitude of the modeled drainage system overload.**

For precipitation, the overestimation of the simulation can also be caused by individual small-scale convective summer events, which do not cover the whole water board area and therefore do not induce a system overload in reality. Therefore, the same evaluation of compound events was repeated with a focus on events in the winter half year, only (October to March; Figure 260 6).

Figure 6: As Figure 5 but for the winter half-year (October to March) only.

3.2.2 Impact of climate change on water balance terms

All climate scenarios applied in this study are featuring a temperature increase until the end of the 21st century. Regional warming is projected for all seasons while increase in temperature seems to be larger in winter than in summer. For East Frisia, the temperature rise projected by the HadGEM model exceeds that of the MPI model (Ley et al., 2023). Compared to temperature, the projected patterns in precipitation are much more variable, depending on the season, the emission scenario, the model and on the time-period considered in the future. While on the annual scale both climate models and both emission scenarios considered in this study project a more humid future, change signals are model and scenario specific on a seasonal scale (Figure 7). Here, the HadGEM model projects a stronger increase in winter precipitation for the far future (end of the 21st century) which can be expected to be a major driver of future compound events.

Also for the evapotranspiration calculated by the SIMULAT model, the projected changes depend on the climate model and the scenario. While projections based on the HadGEM model show an increase for both scenarios and time-periods in summer and autumn, the signal is not that clear for the climate projections based on the MPI model (figure 7). The difference in the projected evapotranspiration can be mainly attributed to the differences in the temperature projections.

Figure 7: Scenario and model specific changes in monthly precipitation (top) and in monthly evapotranspiration (bottom).

3.2.3 Impact of sea level rise on drainage capacity and frequency of system overload

The drainage capacity at tidal gauge Knock was calculated based on the simulations of the TRIM-NP model overlaid by long-term sea level rise (Figure 8). Sea level extremes associated with the storm events show strong inter-annual and inter-model variability with no significant trends in water level upper percentiles for the 21st century for any realization. Secular sea level rise, thus, is the main driver of substantial changes in high water levels for future scenarios. The magnitude of sea level changes

285 is strongly dependend on the chosen pathway scenario (here RCP2.6 and RCP8.5) with a minor influence of the driving climate model (MPI or HadGEM).

Figure 8: 30-year running mean of annual 99.9 percentiles of water level at gauge station Knock for different projections with and without mean sea level rise (SLR).

290

In general, high water levels disable free drainage and reduce the pump capacity which depends on the pressure head between inland water level and sea level. The climate projections show a long-term decrease in drainage capacity (Figure 9), which is in agreement with the projected increased sea level (Figure 8). While the decrease for the control period is relatively weak (especially for the HadGEM model), it accelerates in particular for the RCP8.5 scenario in the second half of the 21st century,

295 while decrease in drainage capacity is weaker for the RCP2.6. Such a decrease can be expected to contribute to a future increase in drainage system overload even if precipitation extremes will not increase for the future.

As expected from the projected increase in winter precipitation and the decrease in drainage capacity, the projected number of days with drainage system overload increases for all investigated combination of climate models, emission scenarios and future time-periods. Compared to the control period, the increase is higher for the RCP8.5 than for the RCP 2.6 scenario, and higher

300 for the far future (end of the century) than for the near future. Generally the number of days with system overload are higher in the simulations driven by the HadGEM than by the MPI model (Figure 10).
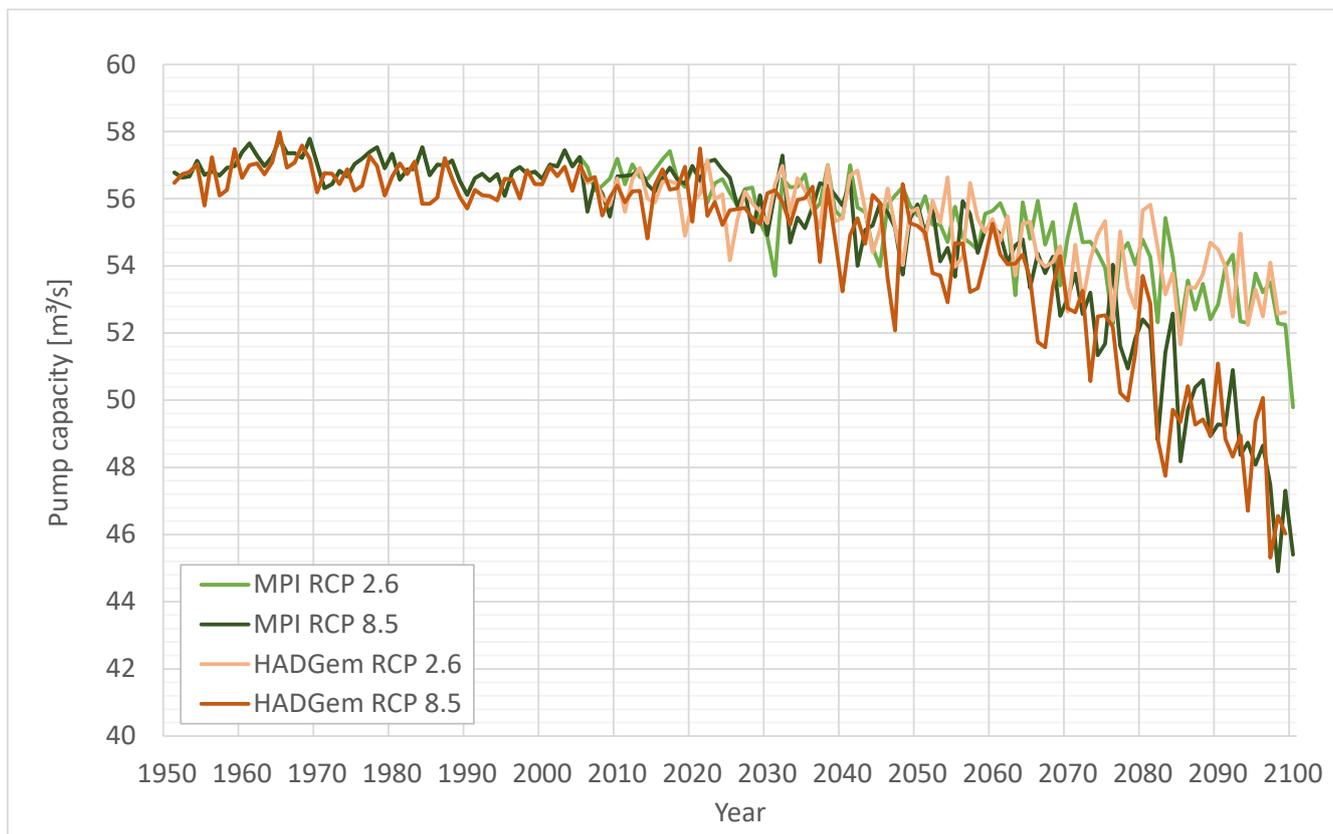
Figure 9: Impact of sea level rise on the estimated annual pump capacity at gauge station Knock
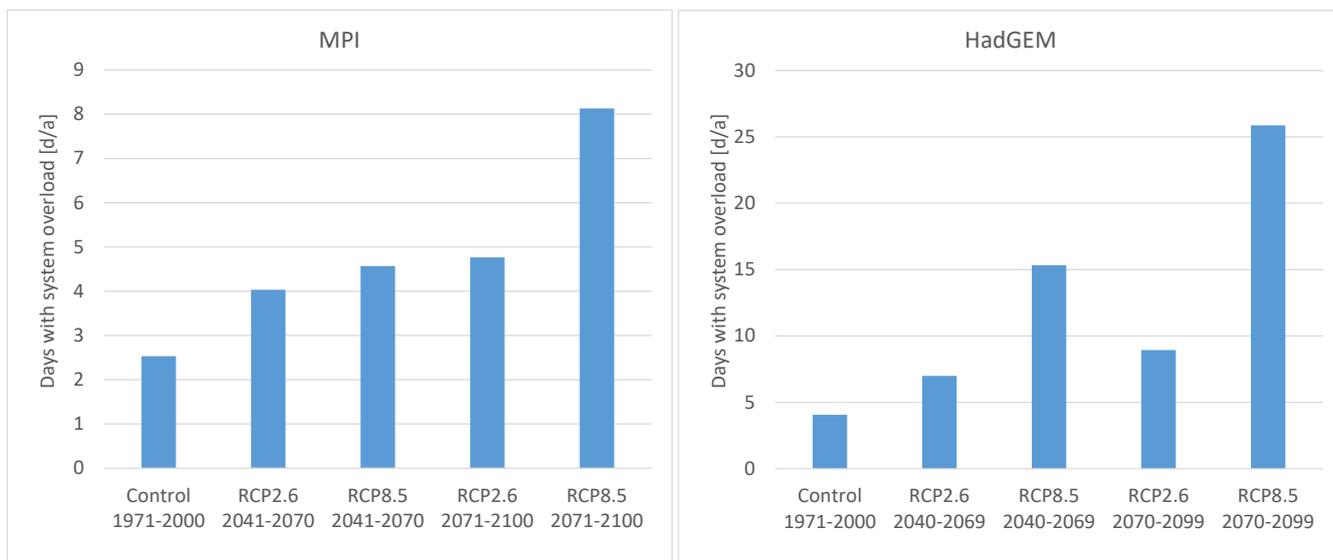
Figure 10: Projected number of days with drainage system overload at station Knock obtained from the different models and scenarios for the mid and the end of the 21st century (MPI: left; HadGEM: right).

3.2.4 Analysis of scenario calculations on compound events

310 As for the control period, the largest 15 winter events (October to March) of drainage system overload, sea level and precipitation were selected from the 30 year time periods centered around the mid and the end of the 21st century. The pattern of contributing drivers was analyzed for a small ensemble of two climate models (HadGEM, MPI), for two concentration pathways (RCP2.6, RCP8.5) and for two different time periods (near future, far future).

The projections based on the HadGEM (Figure 11) and MPI models (Figure 12) indicate that for all combinations of scenarios
315 and models and for both investigated time periods highest system overloads are not generated by the largest individual events (5-tide mean sea level , 3-day precipitation) but by compound events of moderate or intense precipitation and coastal sea levels. By the end of the century and for all projections, the inland flood generation mechanisms are independent of the climate model used. The patterns of contributing drivers and the compound events are similar for the simulations driven by both climate models (Figures 11, 12): Moderate 5-tide coastal sea levels in combination with intense precipitation generate the highest
320 drainage system overloads. As for the control period, flood generation seems to be more sensitive to intense precipitation compared to the sea level during a storm tide. For the simulations based on both climate models, most of the storm tides do not lead to significant drainage system overloads, while the intense precipitation events do.

As indicated by the development of contributing drivers, especially for the pessimistic representative concentration pathway RCP8.5, compound events probably become more intense and more frequent until end of the 21st century. The magnitude of
325 drainage system overload will become significantly larger with intensification of the single drivers (concerning the max. system overload: by a factor of 5 for the HadGEM model, and by a factor of 3.5 for the MPI model). Also the "moderate" events contributing to the compound events will be more intense in future. For the RCP8.5, drainage system overload is expected to be significantly larger by the end of the century compared to the near future. Analyzing the projections for the more optimistic emission scenario RCP2.6, the results indicate that the generation mechanisms of compound events remain
330 constant, while the magnitude of system overload does not increase from near to far future for both climate models. Drainage system overload within RCP2.6 simulations seems to be mainly caused by intense rainfall situations.

While the generation mechanisms of future compound events seem to be consistent for the two climate models used, the magnitude of the driving precipitation events and their timing differs (Figures 11, 12). While for the MPI model the antecedent precipitation is higher (mainly generated by rainfall events in late autumn), antecedent precipitation of the HadGEM model is
335 smaller (mainly generated by precipitation events in winter).
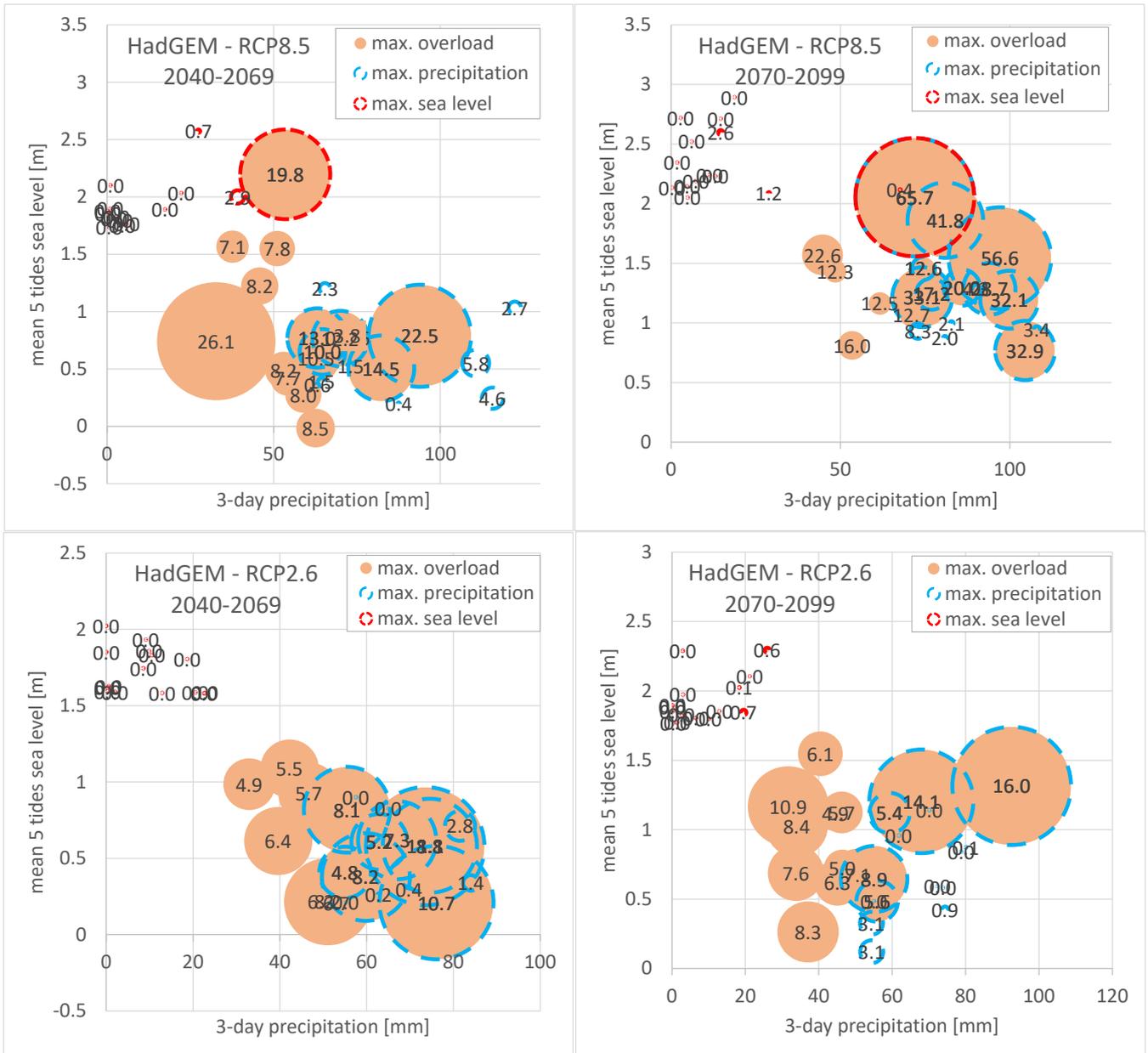
Figure 11: Simulated drainage system overload [10^6 m^3] for the 15 highest sea level (mean sea level over a 5 tides period; red circles) and precipitation (antecedent 3 days precipitation sum; blue circles) events in the winter half-year (October to March) in the period 2040-2069 (left) and 2070-2099 (right) for the RCP8.5 (top) and RCP2.6 (bottom) scenario derived from the simulations driven by the HadGEM model data. Additionally, the 15 simulated drainage system overloads in the same period are shown (orange circles). The diameter of the circles is proportional to the magnitude of the modeled drainage system overload.
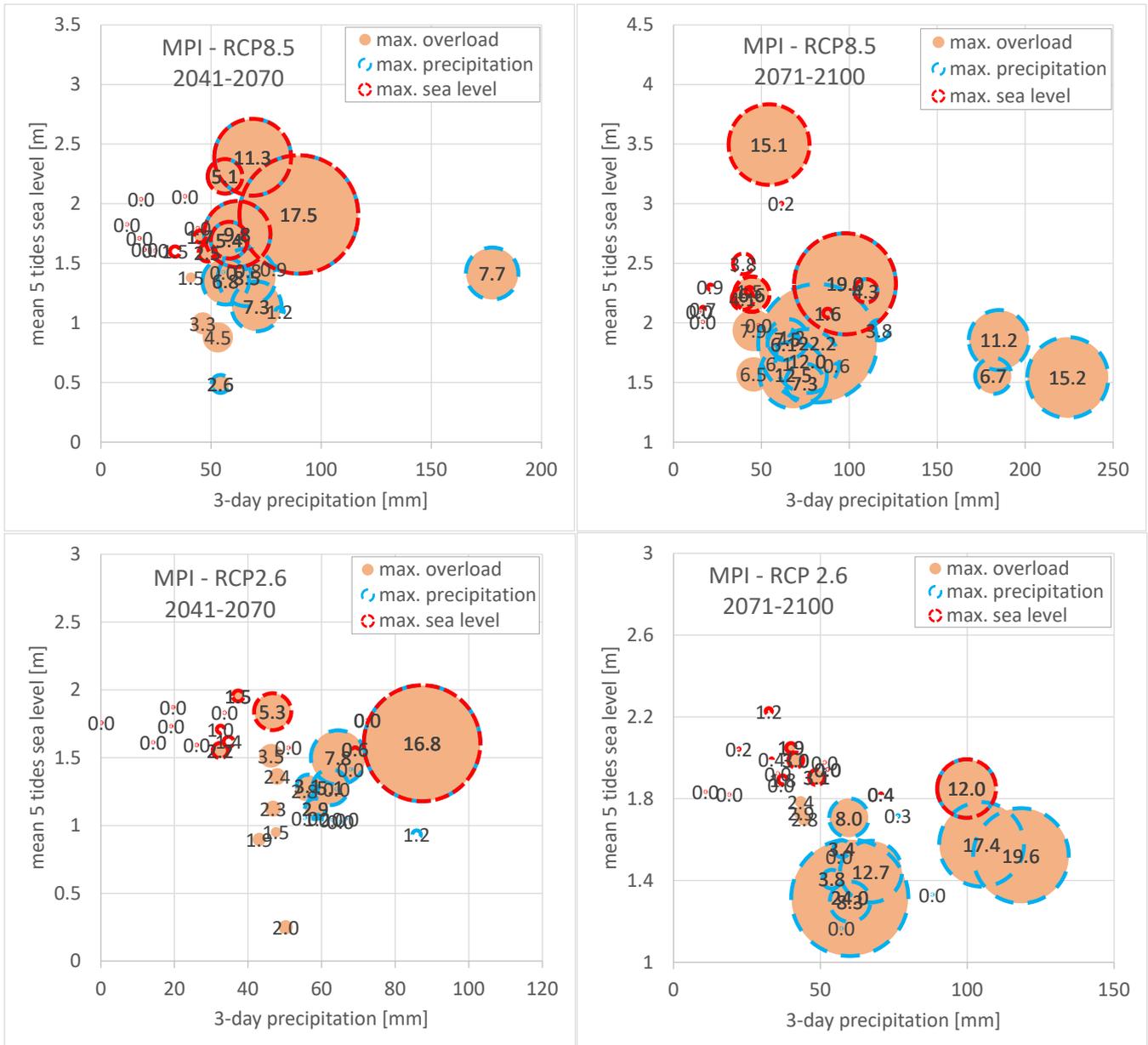
Figure 12: As Figure 10 but for the simulations driven by the MPI model. Note that periods for the analyses are shifted
345 **by one year compared to Figure 10 because of the shorter duration of the HadGEM simulation.**

4 Discussion

The analysis of historic data revealed that compound events of moderate storm tides and heavy rainfall caused inland coastal flooding due to an overload of the drainage system of the Emden water board, rather than individual drivers. This is in

agreement with observations and analyses from the Dutch coast (van Hurk et al., 2015) and from the UK (Svensson and Jones,
350 2002), although compound events of storm tides and high river discharge are not observed more frequently for the Ems estuary
than to be expected by chance (Heinrich et al., 2023). Heinrich et al. (2023) found that only rivers along the westward-facing
coasts of Europe experienced an increased probability of simultaneous storm tides and high river discharges. For the area of
coastal water boards the exposition of the coastline seems to be of minor importance as long as they are exposed to the west
or northwest, since the location of water board areas usually is close to the dike (to the North Sea), compared to the headwaters
355 of the rivers flowing into the North Sea. So we assume that the findings of our study are transferable to large parts of the Dutch,
German and Danish low lying North Sea coast.

Individual projections on climate change impact on winter precipitation (Figure 7), runoff generation (Bormann and Kebschull,
2023) and sea level rise (IPCC, 2021) suggested that drainage of coastal regions might become a greater challenge for the
future (see also Spiekermann et al., 2023). The question arose whether, as observed for the past, compound events ca be
360 assumed to cause the largest system overloads (inland flood events) also in the future, or whether the importance of contributing
drivers might change. The simulation results of the modelling experiment emphasize that the generation mechanisms and the
resulting patterns of current inland flooding at the North Sea coast can be simulated at the water board scale by the model set-
up applied in this study. This is essential for the predictability of future compound events under climate change conditions,
needed for the adaptation to long-term climate change impacts. The model projections indicate that the flood generation
365 mechanisms remain stable for future time-periods under climate change conditions. The results based on the small ensemble
also suggest that, in accordance with Seneviratne (2012), compound events of moderate individual drivers will be an important
source of inland flood risk until end of the 21st century. The simulation results based on both climate models are consistent
concerning runoff generation mechanisms despite model specific differences in the projections (e.g., precipitation projections,
Figure 7), indicating that such behavior might also by confirmed by larger model ensembles. However, this needs to be
370 confirmed by future studies as soon as larger climate ensembles are available in high temporal resolution.

The magnitude of drainage system overloads is expected to increase significantly for the RCP8.5 scenario by the end of the
century while intensity for system overload seems to remain constant for the projections based on the more optimistic
representative concentration pathway RCP2.6. This is in accordance with other climate change impact studies on hydrological
systems in Germany (Brasseur et al., 2023).The intensity of precipitation events seems to be the more important driver
375 compared to the average sea level during one or a series of storm tides. Nevertheless, as long as rainfall amounts and intensities
will not exceed those represented by the climate projections, moderate rainfall alone - without any restriction in drainage
capacity - is not expected to lead to large floodings in shallow coastal inland regions along the North Sea coast until end of the
21st century.

The projections emphasize that climate change adaptation will be required also for all scenarios considered. In accordance
380 with Cioffi et al. (2018), existing drainage infrastructure will be not sufficient to cope with the consequences of climate change,
even for more optimistic emission scenarios (RCP2.6). As shown by this study, adaptation thereby does not only need to
consider the individual impacts of sea level rise (Bormann et al., 2023; NLWKN, 2007) and runoff generation (Bormann and

Kebschull, 2023), but explicitly potential impacts of compound events, because highest drainage system overload must be expected by such type of combined events.

385 Despite the representation of past events, the study suffers from some uncertainties. First, the ensembles of climate models and climate change scenarios is small. It remains possible that combinations of other climate models and emission scenarios lead to a different climate change signal. This needs to be reviewed using a larger ensemble as soon as more long-term climate model simulations are available that provide forcing data for the impact models in at least hourly resolution. Second, the storage based representation of the water spatially distributed in the water board area neglects internal flow processes. Better

390 data on such internal flow processes and state variables could reduce this uncertainty. Nevertheless, as long as the management of the anthropogenic drainage system is not following clear and systematic rules, being influenced by unknown or even erratic individual decisions, a process-based simulation of the drainage system will probably fail. And third, while for precipitation and temperature a bias correction of the climate scenario simulations was required (input for SIMULAT), no bias correction was carried out for the wind speed (input for TRIM-NP). This might cause some inconsistency concerning the driving forces

395 of this study which could be quantified by model intercomparison with/without systematic bias correction. Finally, the observed and simulated data show that a combination of the largest individual events (one or more storm tides and rainfall event) must not necessarily cause the biggest system overloads in the simulations. Probably there are still other influencing factors (such as a high saturation of the water board area, e.g. caused by a longer rainfall memory) which are not yet considered by the approach presented above.

400 **5 Conclusions**

The results of this study clearly indicate that highest overload of coastal drainage systems currently is and in future will be caused by compound events of storm tides and heavy rainfall. While intense rainfall in particular poses a big challenge for coastal drainage systems, the simultaneous occurrence of storm tides and rainfall will pose major problems for the defence systems. Therefore, the dimensioning of coastal and flood protection measures as well as the related risk management explicitly

405 must take such events into account to avoid flood events and resulting damages.
However, such type of compound events is considered explicitly neither in current risk management nor in long-term planning of climate change adaptation in Germany. So there is a need to rethink the question of to what kind of events and hazards a society needs to adapt. While this study can contribute to emphasize that compound events need to be considered for adaptation planning and risk management, for a quantitative assessment larger climate model ensembles in high temporal resolution need

410 to be considered in future studies..

Data availability: The data used in this paper are available from the authors upon request.

Author contributions: The conceptualization of the study was carried out by HB and RW. The simulations were performed by
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of the manuscript.

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