ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Analysis of a compounding surge and precipitation event in the Netherlands

To cite this article: Bart van den Hurk *et al* 2015 *Environ. Res. Lett.* **10** 035001

Environmental Research Letters

OPEN ACCESS

RECEIVED
14 November 2014

REVISED
22 January 2015

ACCEPTED FOR PUBLICATION
4 February 2015

PUBLISHED
26 February 2015

LETTER

Analysis of a compounding surge and precipitation event in the Netherlands

Bart van den Hurk[1], **Erik van Meijgaard**[1], **Paul de Valk**[1], **Klaas-Jan van Heeringen**[2] **and Jan Gooijer**[3]

[1] KNMI—Royal Netherlands Meteorological Institute, De Bilt, The Netherlands
[2] Deltares, Delft, The Netherlands
[3] Water board Noorderzijlvest, Groningen, The Netherlands

E-mail: bart.van.den.hurk@knmi.nl

Keywords: compounding events, coastal water management, flooding

Abstract

Hydrological extremes in coastal areas in the Netherlands often result from a combination of anomalous (but not necessarily extreme) conditions: storm surges preventing the ability to discharge water to the open sea, and local precipitation generating excessive water levels in the inland area. A near-flooding event in January 2012 occurred due to such a combination of (mild) extreme weather conditions, by which free discharge of excessive water was not possible for five consecutive tidal periods. An ensemble of regional climate model simulations (covering 800 years of simulation data for current climate conditions) is used to demonstrate that the combined occurrence of the heavy precipitation and storm surge in this area is physically related. Joint probability distributions of the events are generated from the model ensemble, and compared to distributions of randomized variables, removing the potential correlation. A clear difference is seen. An inland water model is linked to the meteorological simulations, to analyze the statistics of extreme water levels and its relationship to the driving forces. The role of the correlation between storm surge and heavy precipitation increases with inland water level up to a certain value, but its role decreases at the higher water levels when tidal characteristics become increasingly important. The case study illustrates the types of analyzes needed to assess the impact of compounding events, and shows the importance of coupling a realistic impact model (expressing the inland water level) for deriving useful statistics from the model simulations.

Introduction

The adaptation to climate conditions by societies across the planet is frequently challenged by large impacts of weather extremes. However, the magnitude of the impact is rarely uniquely determined by the value of a univariate meteorological quantity such as rainfall, wind speed, or temperature. In practice it is a combination of circumstances that lead to a high impact event, either of meteorological nature only (heavy rains in combination with a wind driven storm surge, a long drought in combination with high temperatures) or a mixture of meteorological conditions and non-meteorological issues (such as high population density, poor infrastructure). It is of high relevance to consider the contribution of compounding circumstances and processes when analyzing high impact events and their possible trends.

In the IPCC Special Report on climate Extremes (SREX, Seneviratne *et al* 2012) compounding events are defined as (among other definitions) ‘combinations of events that are not themselves extreme but lead to an extreme event or impact when combined’. Leonard *et al* (2014) reviewed the SREX definitions, and emphasized the necessity of establishing a statistical relationship between the different events. More generally, compounding events are governed by a solid definition of the relevant spatial and temporal scales. In addition, quantitative assessments of the intensity and occurrence frequency of compounding events and possible trends therein require a proper modelling framework. Taking the global scale as sampling domain it will be easy to demonstrate the simultaneous occurrence of two arbitrary events, but the spatial and temporal characteristics of these events determine the actual impact on society.

The analysis of the statistical properties of compounding events requires the modelling of joint probabilities. Various examples exist in literature (see Leonard *et al* 2014 for an extensive review), making use of statistical tools such as copulas (e.g. Lian *et al* 2013), Bayesian networks (Gutierrez *et al* 2011), bivariate extreme value models (Zheng *et al* 2013) or physical modelling (Kew *et al* 2013, Klerk *et al* 2014).

Diagnosing extreme events from a limited observational record is a challenge, and can sometimes be bypassed by pooling observations from multiple stations (Zheng *et al* 2013) or using large physical model ensembles (Kew *et al* 2013). Under the constraint that the joint occurrence of relevant processes or metrics is modelled well, long simulations of 'virtual' weather events lead to a solid estimation of the statistical properties of these joint occurrences. In addition, coupling to impact assessment modules allows focusing on the events that have a high impact on the society (Berkhout *et al* 2013), and can be used to analyze non-stationary systems, for instance due to climate change or altered land use or infrastructure arrangements (Hazeleger *et al* 2015).

In this paper we illustrate the application of a regional climate model (RCM) ensemble to analyze the compounding occurrence of heavy precipitation and storm surge conditions in a Dutch coastal polder area. Its water balance is determined by the difference in local rainfall runoff and the amount of discharge to the sea under low tide conditions. A near flooding event in January 2012 exposed the vulnerability of this area to these compounding events. The meteorological model, coupled to a local water balance model, is used to quantify the effect of correlation between rainfall and storm surge on inland water levels, for relevant time scales. Analyses for future climate conditions are to be described in a follow-up paper.

Description of the area and the near flooding event in 2012

Water management in the Netherlands is organized in regional water boards, that are more or less aligned with hydrological units. The water board Noorderzijlvest (1440 km^2) is situated in the North of the Netherlands, and the average altitude is similar to the mean sea level. Via two main outlets the excessive water is discharged through a combination of pumps and inland storage reservoirs to the Lauwersmeer, and from there drained off into the North Sea by gravitation during low tides.

In January 2012 a series of active low pressure systems passed over the North Sea from West to East producing >60 mm rain accumulated over 5 days, and five consecutive tidal periods in which storm surges did not permit any gravitational drainage to occur (figure 1). The soil in the entire area was already

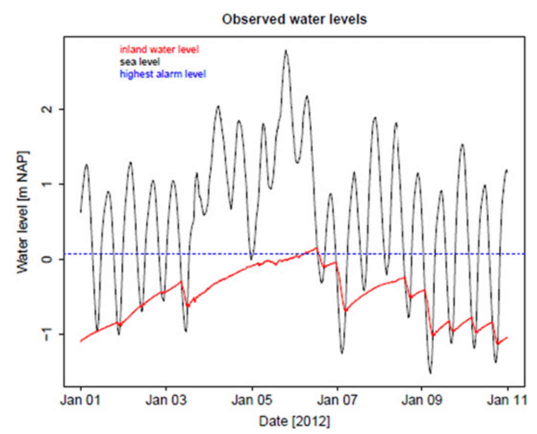

Figure 1. Observed water level in the North Sea (black line) and inland water level close to the Lauwersmeer outlet to the North Sea (red line) during the first 3 weeks of January 2012. Between 4 and 7 January five consecutive low tide episodes did not allow any discharge of inland water to the North Sea. The blue dotted line refers to the warning level leading to precautionary measures (+7 cm NAP). Part of this figure has been published before by Hazeleger *et al* (2015).

saturated owing to above normal rainfall in the preceding weeks. High inland water levels (particularly close to the water outlet channel at Lauwersmeer) exceeding the warning level of +7 cm Normal Amsterdams Peil (NAP) led to precautionary measures such as evacuation and the use of emergency overflow areas. The 5 day precipitation amount had a return period of approximately 10 years, similar to the return period of the storm surge level. However, an accurate estimate for the return period of the combined occurrence could not be derived from observations due to the limited record length.

Data and methodology

To get a robust estimate of the return period of the combined events, the compounding rainfall and storm surge events leading to the situation as described above have been analyzed using an ensemble of RCM simulations (operated at high spatial resolution similar to numerical weather prediction applications), driving a hydrological management simulator generating time series of inland and North Sea water levels. Precipitation output was corrected with a nonlinear bias correction scheme, and storm surge was empirically derived from simulated outbound wind conditions.

The atmospheric model

The RCM used is RACMO2 (Van Meijgaard *et al* 2008, Van Meijgaard *et al* 2012), forced with information from the global climate model EC-Earth (Hazeleger *et al* 2012). After spinning-up the ocean component of the global climate model, an ensemble was produced by perturbing the initial atmosphere state of EC-Earth in 1850 and running each member until 2000

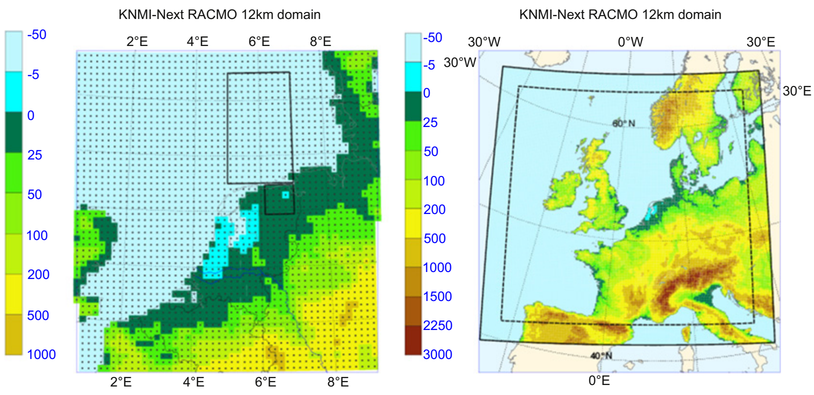

Figure 2. Grid spacing (left) and simulation domain (right) of the RACMO2 RCM. Initial and boundary conditions are provided by the EC-Earth climate model. Boxes in left panel show areas of analyzed precipitation in the target domain (lower box), and wind speed used to generate coastal storm surge (upper box).

assuming historic greenhouse gas concentrations. A corresponding RACMO2-ensemble was generated by downscaling each of the EC-Earth members for the period 1950–2000, giving $16 \times 50 = 800$ years of weather representing present day climate conditions. The RCM uses prescribed sea surface temperatures generated by EC-Earth, and dynamically resolves all meteorological processes at 5 min time steps and 12 km resolution in the domain interior as shown in figure 2.

Precipitation data

Hourly precipitation was derived by averaging RACMO2 output from all grid points enclosing the Noorderzijlvest area (see figure 2). A common feature in many GCM driven RCM simulations is a systematic bias in precipitation, dependent on biases in the driving GCM, the precipitation processes in the RCM, and resolved hydrological feedbacks. Hourly precipitation observations between 1998 and 2012 were obtained from *in situ* station data at Lauwersoog. Using rainfall radar data, an area reduction factor was applied following Overeem *et al* (2010), to account for the scale-dependence of the relationship between rainfall intensity and return period. A nonlinear bias correction (van Pelt *et al* 2012) was applied of the form

$$P* = \frac{E_o}{E_c}\left(P - P_c^{90}\right) + a\left(P_c^{90}\right)^b, \quad P > P_c^{90},$$

$$P* = aP^b, \quad P < P_c^{90}, \tag{1}$$

where excess E_c is the mean precipitation of all precipitation events exceeding the modelled 90th percentile value (P_c^{90}), E_o the same for the observations, P^* is the corrected precipitation amount and a and b are empirically derived bias correction coefficients inferred from observed and modelled 60 and 90 percentile values of precipitation P. The bias correction is applied to 5 day precipitation sums, which avoids problems with biases in frequency of occurrence of wet intervals (Leander and Buishand 2007). Moreover, the 5 day interval represents the appropriate time scale for the analysis applied here (see subsequent sections). Experiments with a bias correction based on 99 percentile values do not lead to very different results (not shown). Results for 5 day distributions of observed, simulated and bias corrected precipitation are displayed in figure 3 (right panel), clearly showing that the bias corrected return levels adequately match the observed return levels for return periods up until the observational record length. To accommodate application of a local water balance model which requires precipitation input on the sub-daily scale (see subsequent sections), 3 hourly bias corrected precipitation series are derived by multiplying all 3 hourly amounts contained in a 5 day interval with the same bias correction factor as was obtained for that given 5 day interval. This guarantees that the 5 day characteristics of the bias corrected series are preserved, but cannot be interpreted as a genuine bias correction on the 3 hourly scale. Obviously, although the match between the bias corrected and observed return levels at the 3 hourly scale is less adequate as was found for the 5 day series, the original model output is considerably improved.

Wind and storm surge

RACMO2 simulations were not coupled to a dynamic wave model, but instead an empirical relationship between 3 hourly instantaneous wind speed u and direction φ and storm surge S was derived using a regression equation of the form (van den Brink *et al* 2004)

$$S = \alpha u^2 \sin(\varphi - \beta), \tag{2}$$

where α and β are regression coefficients. The regression equation was calibrated using wind data from RACMO2 model from the North Sea box (see figure 2) and local surge data at station Lauwersoog. Comparison between the observed and modelled frequency distribution of the storm surge leads to a good

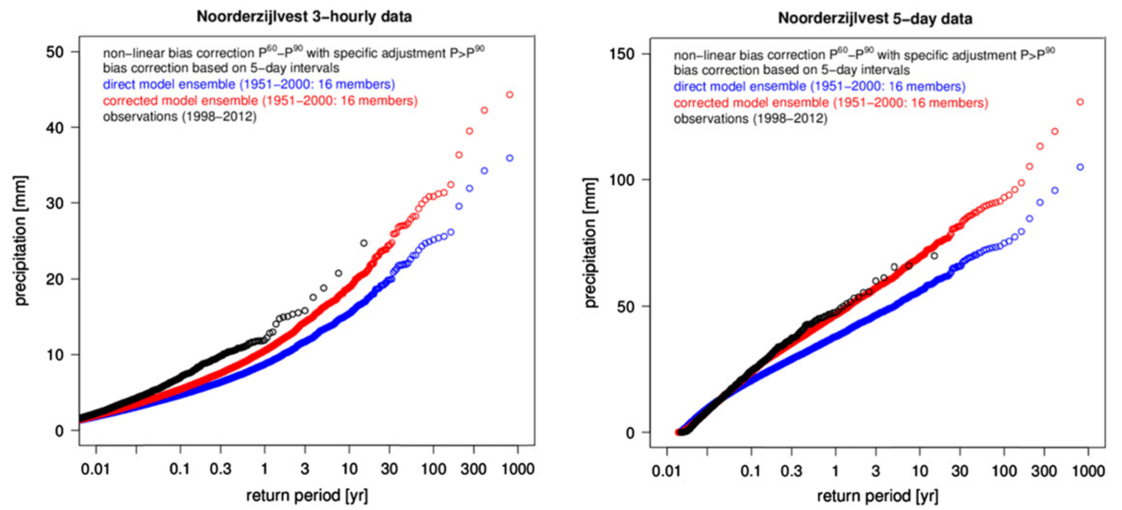

Figure 3. Observed, modelled and bias corrected precipitation accumulated over 3 hourly (left) and 5 day (right) intervals.

correspondence for high surges for 3 hourly averaged values (not shown).

The historical astronomical tide between 1950 and 2000 was added to the modelled storm surge data, to generate a time series of sea level at the North Sea coast. Note that this astronomical tide is not correlated to the meteorological phenomena analyzed here, and therefore does not affect the statistics of compounding events. However, the astronomical tide does play an important role in the occurrence of high water levels, as will be discussed below.

Simulation of the regional hydrological balance

RACMO2 time series of bias corrected hourly precipitation, uncorrected total surface evaporation (collected over the same domain as precipitation) and sea level were used as a forcing to the so-called RTC-Tools water balance tool. RTC-Tools is an open source real-time control modelling tool (see http://oss.deltares.nl/web/rtc-tools/home). It is used to describe the dynamics of the water level in the Noorderzijlvest area, accounting for effects of precipitation, evaporation, soil moisture and ground water storage, and horizontal transport of water via the managed water system. It consists of a number of interacting modules representing subsystems in the water management domain, optimized for rapid simulations and data processing, and also used in the daily operations of the water board.

RTC-Tools is used to calculate the inland water level at a number of locations in the Noorderzijlvest area, including Lauwersmeer (figure 1). Figure 4 shows examples of simulations of the water level at this location, in combination with sea level at Lauwersoog (equivalent to figure 1). The simulations show qualitatively similar events as observed in January 2012, when a multi-day storm surge prohibited discharge of high rainfall amounts into the North Sea. A further examination of the 800 years of simulation data is discussed in the next section.

Results

Compounding precipitation/surge events

Figure 5 demonstrates the existence of a correlation between heavy precipitation and storm surge. The joint probability distribution resulting from the 800 year RCM simulations (hereafter referred to as the reference simulation) is compared to the distribution of a set of randomized data in which the correlation is removed by combining precipitation and wind-induced surge from non-corresponding RCM ensemble members (hereafter referred to as the shuffled simulations): by selecting precipitation and wind sequences from different combinations of ensemble members we have composed ten sets of shuffled simulations, each with a record length of 800 years. Results are shown for averaging periods of variable length: 1, 2.5, 5 days. The difference between these joint probability distributions, highlighted in colour in the figure, illustrate the physical correlation between the plotted quantities: in these areas the probability of finding a combination of a high precipitation and high storm surge is larger in the reference simulation than in the set of shuffled simulations. We find such enhanced probabilities generally in the upper right (and lower left) corners of the diagram, while the off-diagonal areas show opposite behaviour (not colour-coded).

From the results shown in figure 5 it is not entirely clear whether the dependence between rainfall and storm surge in the Netherlands varies with the return time of the events. The increase in coloured surface area as one moves into the upper right direction suggests an increasing dependence with increasing return time, but beyond the 99% contour this relationship is

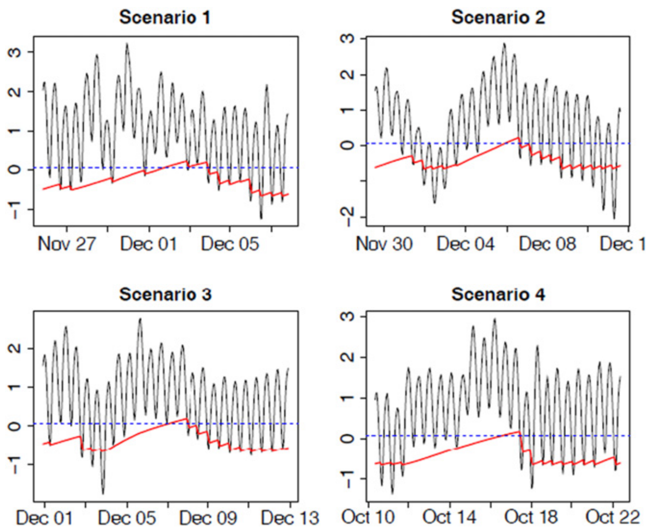

Figure 4. Snapshots of high water level events simulated by the hydrological water management model RTC-Tools using RACMOs output as forcing. Shown are four arbitrary episodes ('scenarios') leading to water levels exceeding the highest warning level, indicated by the horizontal dotted line. Part of this figure has been published before by Hazeleger *et al* (2015).

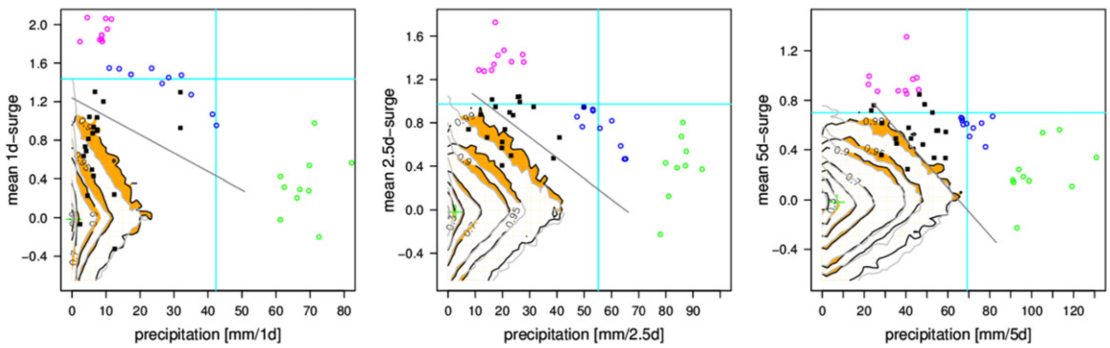

Figure 5. Joint probability distribution of accumulated precipitation in the Noorderzijlvest area and mean surge height for (left) 1, (middle) 2.5 and (right) 5 days intervals. Heavy contours denote the area enclosing indicated percentage of data (30, 50, 70, 90, 95 and 99% contours are shown) from the reference RCM simulation, while light contours show these data from the RCM 'shuffled' simulations (see text). The orange coloured area marks the joint probabilities that are lower for the shuffled data, pointing at physical correlation between the two quantities. The ten events with the most extreme wind-induced surge are plotted in each figure panel (magenta points), similarly for the most extreme precipitation events (green points), and a combination of high wind-induced surge and high precipitation (blue points). The black squares represent the 20 events corresponding to the highest inland water level. The vertical and horizontal lines (cyan) represent the 10 year return periods of precipitation and wind-induced surge for the chosen accumulation period, respectively. The slant grey line, obtained from one and the same prescription in each of the panels, is added for reference.

not clear. Modelling such dependence using bivariate extreme-value models applied to the observations can result in overestimation of compound events (Zheng *et al* 2014). This emphasizes the added value of employing climate models to assess the joint dependence analysis.

The existence of a correlation in the high tails of both precipitation and storm surge points at a common cause: one or multiple active low pressure systems which set up a strong Northerly wind leading to a storm surge, while at the same time the associated frontal systems produce high amounts of precipitation (see below for a further exploration of these events).

In the analyses shown in figure 5 we have taken the *mean* storm surge in the indicated time interval. The water balance characteristics of the Noorderzijlvest area are, however, not governed by the mean sea level within a time interval, but by the sequence of tidal lows within that period. Examining the relationship between accumulated precipitation and the single *minimum* sea level in the accumulation period does not show a clear correlation structure when the accumulation period is chosen to be 5 days. This single minimum is hardly related to the average storm characteristics in a 5 day interval, and also does not affect the local water balance greatly. Therefore, the mean sea level, which is strongly correlated to the mean level of the tidal lows in that period, is a more appropriate measure to analyze. For shorter time intervals, containing only one or two tidal lows, a stronger relationship between mean and single minimum sea level within that period exists.

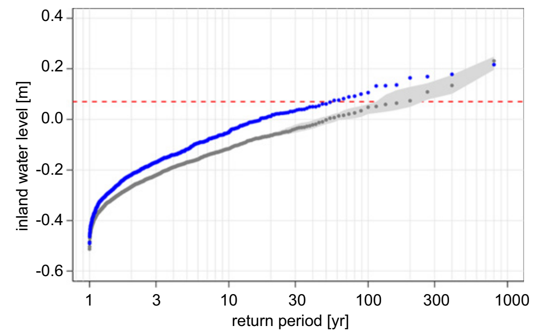

Figure 6. Return level of inland water level at Lauwersmeer using the original (blue) and shuffled (grey) RACMO2 time series as forcing. In the shuffled simulations the simultaneous occurrence of high precipitation and high storm surge is governed randomly, and a bootstrap is applied to the shuffling operation to generate an uncertainty estimate of ±1 standard deviation (grey band). The red dashed line indicates the highest warning level for this station.

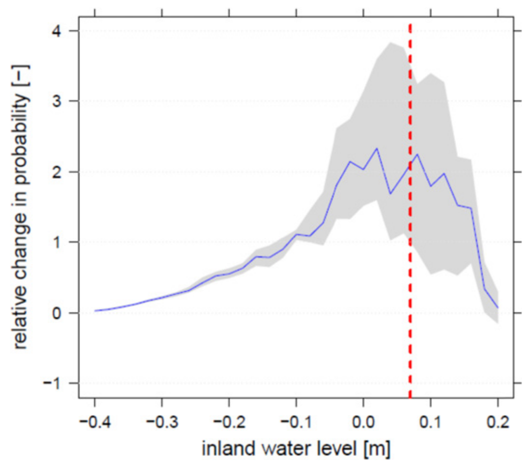

Figure 7. Effect of removing the compoundig occurrence of high precipitation and storm surge levels on the inland water level at Lauwersmeer. Shown is the relative difference in probability of reaching an inland water level derived from the reference simulation and the set of shuffled simulations as a function of the inland water level itself. The grey band shows the uncertainty range obtained by bootstrapping the shuffled RACMO2 time series. The red dotted line marks the warning level of +7 cm NAP.

The different averaging time scales shown in figure 5 display similar correlation characteristics: removal of the correlation leads to lower population densities of events in the upper right sections of the diagram. In neither of the averaging intervals delays between surge and precipitation are taken into account. Klerk *et al* (2014) point at the importance of discharge delays for much larger hydrological systems such as the Rhine area. There it takes several days for excessive rainfall associated to meteorological systems generating strong storm surges to reach the river outlet at the coast. Kew *et al* (2013) show that the role of this delay is strongly reduced when taking 20 day averaging intervals, and at this time scale the importance of compounding surge and rainfall extremes is still relevant. Due to the much smaller areal size of the Noorderzijlvest area and its immediate proximity to the coast this delay does not play a major role.

The bias correction applied to the RCM rainfall data (equation (1)) does affect the shape of the correlation structure of figure 5 by repositioning the precipitation data on the horizontal axes. However, the chronology of the precipitation events (and thus their correlation with surge events) is unaffected by this bias correction.

Effect of compounding extremes on inland water level

Calculations with RTC-Tools, yielding 800 years of time series of inland water levels, were carried out with both the reference simulation and a bootstrap of the set of ten shuffled simulations, in each of which combinations of storm surge and precipitation data were taken from arbitrary non-corresponding RACMO2 ensemble members. This collection of shuffled data sets allows an uncertainty assessment of the joint occurrence probability.

The compounding occurrence of heavy precipitation and storm surge has a distinct impact on the frequency distribution of high inland water levels. Figure 6 displays the return period of the inland water level for both the reference simulation and the set of shuffled simulations. The reference simulation (including the compounding occurrence) leads to higher inland water levels for all return periods exceeding once per year. The indicated warning level is exceeded on average only 1/150 years in the randomized simulations (without compounding occurrence), while this warning frequency is more than two times more frequent in the reference simulation.

The effect of the compounding occurrence is demonstrated in figure 7, which shows the relative difference in probability of reaching a given inland water level derived from the reference simulation and the set of shuffled simulations, respectively. This probability ratio is expressed as a function of the inland water level calculated with RTC-Tools. For inland water levels below the warning level of +7 cm NAP the removal of the compounding occurrence results in a reduction of the probability of reaching the indicated inland water level by up to a factor 2. The increase of the relative difference with water level is not just a statistical artefact created by a reduction of the sample size with increasing water levels: in fact, an uncertainty estimate generated by a bootstrapping technique does not support the zero-hypothesis that the relative difference in probability of reaching an inland water level is independent on the water level. Thus especially for high water levels—just below the warning level—the effect of compounding events is of importance. This is supported by the results shown in figure 5, where, in particular for high precipitation and storm surge levels (conditions leading also to high inland water levels), a

correlation between these meteorological phenomena is apparent.

However, for higher inland water levels the effect of the correlation between surge and rainfall is reduced, and ultimately disappears for very high water levels. This is also illustrated in figure 5, where the precipitation and surge levels for the events of the 20 highest water levels is indicated (black squares). These events are all positioned in the upper right section of the panels, but not necessarily in the outer range of the distribution.

For these events the astronomical tide appears to play an important role. The astronomical tide is governed by oscillations in the geometry between Earth, Moon and Sun. At spring tide the amplitude between high and low tide is largest, while at neap tide the amplitude is smallest, implying relatively low levels of high tide, but also relatively high levels of low tide. Paradoxically, the latter phenomenon can, dependent on the magnitude of the wind-induced surge, seriously constrain the amount of gravitational drainage of inland water from the Lauwersmeer to the North Sea. Closer inspection of the highest inland water levels reveals that indeed these are usually found under neap tide conditions (not shown), contributing to discharge limitations under conditions with relatively low levels of wind-induced surge. Since the astronomical tide is not correlated to the meteorological conditions, also the effect of removing the correlation between surge and rainfall is small for the events with the highest inland water levels.

Meteorological situation during extremes

Events with extreme 5 day mean wind-induced surge at Lauwersoog primarily occur during the months October–December. Synoptically they can be characterized by deep and extensive low pressure systems moving from Iceland to central or Northern Scandinavia with significant anti-cyclonic development across Ireland and the British Isles in their rear track. This situation gives rise to strong winds between West and North across the central and Northern section of the North Sea with an associated long wind fetch. Typically, during a 5 day period one or two such low pressure systems pass by. Precipitation in the Noorderzijlvest area is produced by frontal systems, but usually amounts are not excessive because strong upper air flows in these conditions rapidly push the frontal systems across the relatively small-scale area. In these situations a prolonged cyclonic flow of unstable air often extends far South into Central Europe resulting in huge amounts of orographically induced precipitation on the lee side of the low-mountain ranges in Belgium and Germany and, in particular, the high-mountain range of the Alps.

A summary of the meteorological situation corresponding to extreme wind-induced surge is shown in figure 8 (left panel), displaying a composite of precipitation, surface pressure and wind speed for the ten highest storm surge events (indicated by magenta symbols in figure 5).

The right panel in figure 8 shows the composite of the ten most extreme simulated precipitation events in the Noorderzijlvest area (green symbols in figure 5). The majority of these events occur during the summer months. Synoptically, a common feature of these events is that a slow-moving medium-sized low pressure system is positioned close to the area, mostly over Northern Germany or Southern Denmark, such that associated frontal bands near the centre of low pressure produce considerable amounts of precipitation during multiple days in the same location. Interestingly, the preferential position of the centre of low pressure gives rise to a North–Westerly/Northerly flow over the North Sea, and thus positive wind-induced surge at Lauwersoog. This outcome is indicative of the feature that for this type of stagnant low pressure systems the most active bands with precipitation are found in the South–Westerly quadrant of the system, which is where Noorderzijlvest is located relative to Northern Germany. Eventually, these systems recede, often in Easterly direction, or simply dissipate over time. The onset of this type of synoptic pattern is less unequivocal, as the low pressure systems giving rise to these high precipitation events do not follow a preferential track of motion but are found to originate from a variety of directions.

Synoptically, the combination of high 5 day mean surge and precipitation amounts forms a kind of hybrid of the extreme wind-induced surge events and extreme precipitation events. These events are found year-round, but the preferential period ranges from end of July–October. The central panel in figure 8 shows a composite by selecting events with a surge height exceeding 0.8 m (about 10% above the 10 year return period) and 5 day precipitation sum above 90 mm (about 20% above the 10 year return period). Compared to the extreme wind-induced surge events (left panel in figure 8) the low pressure systems in this sample are smaller in horizontal extent and less deep in central pressure. The low pressure systems move predominantly from Scandinavia across Eastern Europe in Southerly/Southeasterly direction, but occasionally travel from France over Germany in Northeasterly direction. Precipitation during these events is primarily produced by frontal bands on the Western/South Western edge of the pressure system and probably enhanced by late summer high sea surface temperatures. The low pressure systems and associated frontal zones move faster than those associated with extreme precipitation events (right panel in figure 8). Due to the prevalent Northerly flow over Germany in this synoptic sample the location with maximum precipitation is found over the Sauerland low-mountain range.

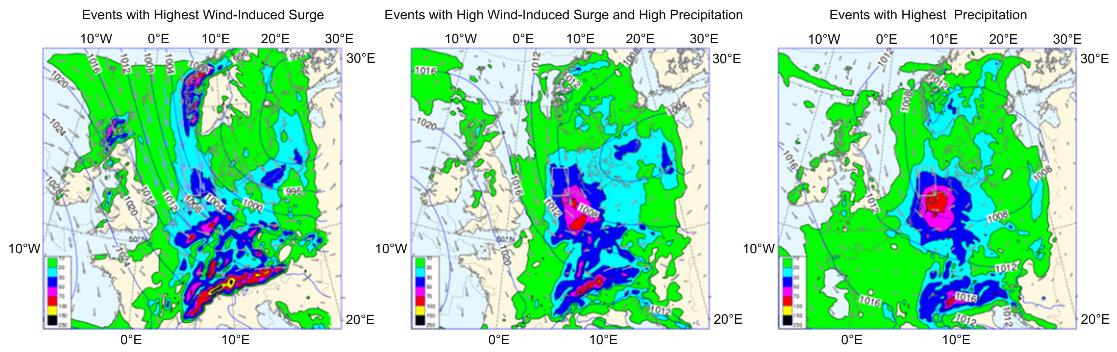

Figure 8. Composite synoptic structure of typical high surge events at Lauwersoog and/or high precipitation events at Noorderzijlvest obtained from the full 16 times 50 years of RACMO simulations. Shown are samples of events corresponding to extreme wind-induced surge (left panel), extreme precipitation (right panel), and a combination of high wind-induced surge and high precipitation (central panel). Each sample is composed from the ten most extreme events, corresponding to those shown in the right-hand panel of figure 5. Each event is composed as a 5 day mean field for mean sea level pressure and near surface wind and 5 day accumulated field for precipitation. The black and grey box indicate the target domains used in determining precipitation and wind-induced surge, respectively, comparable to figure 2.

Discussion and conclusions

The compounding occurrence of multiple meteorological events leading to critical inland water levels in a Dutch coastal polder area is shown to be a factor of importance. Safety measures to protect the inhabitants against disruptive circumstances are guided by the assessment of the probability of occurrence of such events. Insights in the role of correlated phenomena are crucial for this assessment.

Here we demonstrate that high surge and high rainfall events tend to be mutually related by their common dependence on the meteorological situation. While peak storm surges occur in the winter season as a result of deep cyclones, high precipitation events are mainly found during stagnant summer depressions. The meteorological conditions that lead to a combination of these two are dominantly found around the fall season, and result in a physically based correlation structure that affects the occurrence of inland high water levels. Extreme inland water levels are further enhanced during neap tide conditions, that is uncorrelated to meteorological phenomena.

The analysis of climate records supporting the assessment of current or expected impacts of extreme weather conditions on society should take the notion of compounding events into account. Typical analyses of climate change driven trends in weather extremes impacting on society consider univariate meteorological quantities such as extreme precipitation, wind, or storm surge (e.g., IPCC 2013). However, this focus on univariate phenomena enhances the risk of overlooking important combinations of phenomena, or may overemphasise risks when compounding compensating effects are in place. Addressing compounding extremes puts the specific local vulnerabilities central to the analysis of interest (e.g. Brown *et al* 2012, Berkhout *et al* 2013), and offers new ways of making relevant assessments of climate driven changes in risks.

The focus on local conditions is central to the analysis of compounding extremes, as is illustrated in this case study. Time scales, phenomena, spatial scales, infrastructural operations and non-correlated physical phenomena such as astronomical tide all play a role. This makes the study of compounding events and their impacts conceptually challenging: every local situation is unique, and requires a context specific set-up.

The application illustrated here is associated with a number of potential caveats, that should be taken into account.

First, the analysis is heavily based on (long simulations with) a local water balance model and a RCM driven by forcings from a global climate model, which are all shown to be imperfect. Inland water level calculations rely on assumptions regarding the drivers of the regional water balance in the catchment area. Bias corrections are needed to adjust the precipitation record, and empirical data are needed to estimate storm surge data. A systematic bias in the correlation between the occurrences of these phenomena may likewise be present in the model time series, and may affect the results significantly. However, due to the lack of long-term reliable observational records, and to the complex nature of the interaction between atmospheric circulation, wind driven storm surge, heavy precipitation and soil saturation, the detection and removal of a bias in this interaction is not straightforward. Further work in this direction should increase our confidence in the modelling tools proposed and applied in this paper.

Second, although an 800 year simulation record was available, the confidence range of the joint occurrence of events with a return period of 10 years or longer is still fairly wide. The statistical confidence can be improved by extending the simulation record

length, although it must be recognized that the quality of model simulations of extreme events with such long return periods is difficult to assess.

Third, some prior assumptions about the functioning of the local water system are necessary before analyzing the effect of compounding extremes. In our illustrative case study we explored the effect of different time scales and effects of astronomical tide, but inevitably have not considered a number of other important components that may be of relevance. One such component is the precipitation history that affects the available water storage capacity in the soil and open reservoirs, which may have played a significant role in the January 2012 event. Other components, not explored here but potentially important, are the horizontal water transport characteristics in the area, the effect of winds on open water in the polder area, temperature anomalies affecting evaporation or convection etc. A formal analysis of all potentially important compounding events is hardly possible without having (observationally based) evidence on the full functioning of the system.

The use of a model set-up as applied here opens the way to analyze effects of systematic changes in the climatic or infrastructural conditions. Future climate simulations are available for the RACMO2/EC-Earth configuration, and analysis of these is subject of ongoing research. However, the credibility of future assessments depends strongly on the confidence we have in the quality of such model-based future assessments, which is difficult to support from observational evidence. For the case study explored here it is evident that assumed changes in the mean sea level play a strong role in the frequency of high inland water levels. A good physical understanding of the underlying mechanisms that potentially lead to a change in the occurrence of compounding events can be supported by such model analyses.

Acknowledgments

This study is financially supported by the Dutch Ministry of Infrastructure and Environment. Discussions with Marc de Rooy, Frank Hallie, the Dutch Delta Program and colleagues from HKV—Lijn in Water and water board Noorderzijlvest are highly appreciated.

References

Berkhout F, Van den Hurk B, Bessembinder J, De Boer J, Bregman B and Van Drunen M 2013 Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments *Reg. Environ. Change* **14** 879–93

Brown C, Ghile Y, Laverty M and Li K 2012 Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector *Water Resour. Res.* **48** W09537

Gutierrez B T, Plant N G and Thieler E R 2011 A bayesian network to predict coastal vulnerability to sea level rise *J. Geophys. Res. Earth Surf.* **116** F02009

Hazeleger W *et al* 2012 EC-Earth V2.2: description and validation of a new seamless Earth system prediction model *Clim. Dyn.* **39** 2611–29

Hazeleger W, Van den Hurk B J J M, Min E, Van Oldenborgh G J, Petersen A C, Stainforth D A, Vasileiadou E and Smith L A 2015 Tales of future weather *Nat. Clim. Change* **5** 107–13

IPCC 2013 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T Stocker *et al* (New York: Cambridge University Press)

Kew S F, Selten F M, Lenderink G and Hazeleger W 2013 The simultaneous occurrence of surge and discharge extremes for the Rhine delta *Nat. Hazards Earth Syst. Sci.* **13** 2017–29

Klerk W J, Winsemius H C, Van Verseveld W, Bakker A M R and Diermanse F D 2014 The co-incidence of storm surges and extreme discharges within the rhine-meuse delta *Environ. Res. Lett.* submitted

Leander R and Buishand T A 2007 Resampling of regional climate model output for the simulation of extreme river flows *J. Hydrol.* **332** 487–96

Leonard M *et al* 2014 A compound event framework for understanding extreme impacts *Wiley Interdiscip. Rev. Clim. Change* **5** 113–28

Lian J J, Xu K and Ma C 2013 Joint impact of rainfall and tidal level on flood risk in a coastal city with a complex river network: a case study of Fuzhou City, China *Hydrol Earth Syst. Sci.* **17** 679–89

Overeem A, Buishand T A, Holleman I and Uijlenhoet R 2010 Extreme value modeling of areal rainfall from weather radar *Water Resour. Res.* **46** W09514

Seneviratne S *et al* 2012 Changes in climate extremes and their impacts on the natural physical environment *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* ed C Field, V Barros, T Stocker and Q Dahe (Cambridge: Cambridge University Press) pp 109–230

Van den Brink H W, Können G P, Opsteegh J D, van Oldenborgh G J and Burgers G 2004 Improving 10^4-year surge level estimates using data of the ECMWF seasonal prediction system *Geophys. Res. Lett.* **31** L17210

Van Meijgaard E, Van Ulft L H, Van de Berg W J, Bosveld F C, Van den Hurk B J J M, Lenderink G and Siebesma A P 2008 *The KNMI regional atmospheric climate model RACMO, version* 2.1. *KNMI Technical Report 302* pp 1–43 (www.knmi.nl/publications/fulltexts/tr302_racmo2v1.pdf)

Van Meijgaard E, Van Ulft L H, Lenderink G, De Roode S R, Wipfler L, Boers R and Timmermans R 2012 Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe Final Report, National Research Programme Climate Changes Spatial Planning KvR 054/12 pp 1–44

Van Pelt S C, Beersma J J, Buishand T A, van den Hurk B J J M and Kabat P 2012 Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations *Hydrol. Earth Syst. Sci.* **16** 4517–30

Zheng F, Westra S, Leonard M and Sisson S A 2014 Modelling dependence between extreme rainfall and storm surge to estimate coastal flooding risk *Water Resour. Res.* **50** 2050–61

Zheng F, Westra S and Sisson S A 2013 Quantifying the dependence between extreme rainfall and storm surge in the coastal zone *J. Hydrol.* **505** 172–87