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Tales of Future Weather

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Society is vulnerable to extreme weather events and, by extension, to the human impact on future events. As climate changes weather patterns will change. The search is on for more effective methodologies to aid decision-makers both in mitigation to avoid climate change and in adaptation to changes. The traditional approach employs ensembles of climate model simulations, statistical bias correction, downscaling to the spatial and temporal scales relevant to decision-makers, and then translation into quantities of interest. The veracity of this approach cannot be tested, and it faces in-principle challenges. Alternatively, numerical weather prediction models in an altered climate setting can provide tailored naritives of high-resolution simulations of high-impact weather in a future climate. This Tales of Future Weather approach will aid in the interpretation of lower resolution simulations. Arguably, it potentially

provides a complementary and more realistic and more physically consistent pictures of what future weather might look like.

Introduction

Science-informed policy is aided by robust, reliable insights into the changes in weather likely to be experienced by individuals, by sectors and by nations. Vulnerability to high impact weather, whether it takes the form of weather extremes or changes in local climate which, while not necessarily extreme in the meteorological sense, carry significant societal consequences, has generated a demand for local climate information. In response, climate services targeting a variety of lead times are being considered world-wide[1]. The extent to which this demand can be met with high fidelity remains unclear[2,3,4]. In this paper we propose a novel alternative methodology compared to current approaches, and discusses its strengths and weaknesses.

Quantitative information of a probabilistic nature at local scales would prove of great value if robust, actionable, trustworthy, and reliable (hereafter, "decision-relevant") information on the probability of future weather phenomena could be provided. Such information, if decision-relevant, would aid evaluation of the effectiveness of measures for coping with future events[5]. One traditional methodology for constructing such information, hereafter called MoCoDoT (model-correct-downscale-translate), is to use a current generation of climate models to simulate events on global and regional scales, downscale these simulations to generate local geophysical information and then translate the results into quantities of interest. The downscaling procedure is usually one-way, it attempts to correct for biases in the global climate model which provided the original simulation but does not allow feedbacks to the global model or insure consistency at the local scale. The local climate information thus generated is then used to provide information for decision makers. An example is flood risk assessment using socio-economic models to compute the damages of flooding and the costs and benefits of protective measures[6]. While desirable, obtaining the probabilities of future events may be considered beyond the pale when multi-model ensembles do not provide a good proxy for the true probability of future events[3]; this is widely acknowledged to be the case[7]. The aim of this Perspective, which expresses the views of the authors, is to propose an alternative approach that takes a qualitatively different path using both climate models and weather models to better focus on specific weather events; events that expose the vulnerability of society. It then examines the strengths, weaknesses and benefits of this new approach to science as well as decision making.

The linking of severe weather events to rising greenhouse gas concentrations in the atmosphere, along with a number of recent demonstrations of societal vulnerability to severe weather, has led to significant media and scientific attention. Hurricanes Katrina, Sandy and Haiyan, the European heat waves in 2003, 2006 and 2010, floods in Asia and Australia in 2011, floods in central Europe in 2013 and floods in the UK in the winter of 2013/2014 are vivid examples. Mitigation measures are considered to reduce the impacts to which society is exposed, while adaptation measures can reduce the vulnerability of society to those phenomena that do occur. The understanding and advancement of each is aided by decision-relevant information about future weather, ideally in terms of reliable probability distributions. Yet the common MoCoDoT approach described above is severely hampered by the inherent difficulty of predicting climate, given the existence of non-linear feedbacks in the climate system and structural model error/inadequacy in today's best climate models[3,7,8]. Many phenomena of importance in the evolution of the climate system are simply not simulated within climate models; while the Tales approach cannot supply these missing feedbacks into the climate simulation, it does allow decision-makers access to simulations of the high-impact weather phenomena and allows climate scientists an additional means to identify internal inconsistency.

Further, the traditional MoCoDoT approach does not easily support methods used by many potential users of climate information. The decision-relevant aspects of high-impact weather events that are not necessarily extreme in the meteorological sense, often involve multi-dimensional, non-linear combinations of several variables. This is the case, for instance, when design criteria for infrastructure are based on benchmark synoptic events from the past; the design aim is for the infrastructure to survive the range of behavior up to these thresholds. The frequency with which such thresholds will be exceeded will without doubt change in a different climate. Realistic representation of synoptic events under projected future climate conditions could prove more relevant to and more digestible by those planning for changes in high-impact weather. Such information could then be more easily considered alongside other determinants of societies' vulnerability such as wealth, resilience and perceptions[9].

The paper is structured as follows. The next section contains an assessment of the forecast skill of current climate models. In the two sections that follow, a methodology is presented which emphasizes local vulnerability and which focuses on simulating weather events and their impact in a future climate as realistically and coherently as possible. This is achieved through active participation of stakeholders in the process and the use of high-resolution weather models that are well-evaluated and calibrated for representing synoptic weather events in an initialized forecast setting using observational data. With these models high impact events are deduced. Important parts of the methodology include the choice of relevant events, the selections of boundary conditions, and the interdisciplinary construction of storylines which is discussed in the penultimate section. The storylines could be obtained from a number of sources including climate models and physical understanding, while the relevant events and boundary conditions should be chosen to inform the needs of stakeholders, guided by conditions seen in past events. The paper concludes with a discussion section, in which we argue that the "tales of future weather" approach (hereafter, Tales) can alleviate many of the challenges to interpretation faced by the MoDoCoT approach.

While the Tales methodology cannot account for fundamental inadequacy in today's best weather models, we argue it can provide information which remains of use even as climate models develop and simulations of the 21st century themselves change. The Tales approach informs users about climate change impacts by making use of both catalogues of past weather analogues and realistic synoptic weather events possible in future climates.

Climate forecast quality

The value of climate predictions with the MoCoDoT method relies on the fidelity of multi-decadal forecasts from climate models. Predictability of meteorological variables beyond the limits provided by the background observed climatological information itself is difficult to achieve for two distinct reasons: first the actual loss of information given the apparently chaotic nature of the system, and second the structural imperfections in weather and climate models. Predictability is certainly lost if the probabilities extracted from models become indistinguishable from those of the (seasonally varying) climatology; this decay might happen in a few weeks if only the atmosphere was modelled, or extend to months, years or decades when slower oceanic processes which impact the atmosphere are simulated realistically[10,11,12]. On longer time scales, predictability might arise from external forcing or realistically simulated internal variability[3,13]. Processes which are not simulated realistically result in model-based probabilities that need not resemble targeted climatological probability distributions. The time scales on which such model inadequacy dominates the forecast is more easily identified in forecasts that can be evaluated empirically[12,14]. While it is widely appreciated that model-based simulation adds significant skill to probability forecasts of weather out to about two weeks[15], their value added on seasonal to annual timescales is less clear[10,16]. On decadal time-scales there is currently little if any evidence that they significantly outperform the probability forecasts of empirical models[14], with the possible exception of the North Atlantic circulation[12]. On daily to weekly time scales today's models are clearly superior to empirical models at local scales.

Multi-decadal climate forecasting is much more complicated than weather forecasting because (i) "confirmation" is no longer possible given the timescales[4] of interest and (ii) there is no relevant observed "climatology" with which to compare the forecast. The diversity of simulations under today's models does not reflect the uncertainty in our future[3,4] even under the assumption of a given emission scenario. And, of course, large uncertainties remain in emission scenarios themselves.

These caveats rule out interpreting the simulations as literally true potential futures: taking today's climate simulations as reflecting conditions over the next century at face value. However it is done, downscaling introduces a new layer of additional uncertainty to the numbers generated . Clearly the criterion for optimising climate change related decisions is not to be found in assuming there is skill in a naïve interpretation of a downscaled ensemble of climate model simulations[5,17].

Perhaps the highest impact MoCoDoT application, generating probability distributions of detailed and high resolution (up to 5 kilometers) climate forecasts for use in planning energy, water, transport and social impacts, is found in the British UKCP09 project. This project is fully probabilistic, with output probabilities established within a "Bayesian framework"[18]. The limitations of any approach that uses climate model output in this way have been outlined above and discussed in literature[2,3,19]. An alternative approach that also relies on downscaling is to provide a limited set of scenarios that span a range of plausible realisations of future climate. The Dutch climate scenarios (KNMI'06 and KNMI'14 released in 2006 and 2014)[20,21] are examples of such an approach. These scenarios are also based on global and regional model output and statistical downscaling procedures. In this case a limited set of physically consistent scenarios are constructed, without providing probabilistic information. Other recent examples of regional climate scenarios are CH2011[22] for Switzerland, using global and regional model output to generate 3 scenarios distinguished by emission pathways, and the "climate change in Australia" scenarios[23].

Given structural model error and the nature of the climate forecasting problem, one can never expect to provide decision-makers with robust, reliable probability forecasts that have been proven effective in past applications. One can do more, however, than downscale and compute relative frequencies from large model ensembles exposed to a particular forcing. 'What if' scenarios and "analogue" simulations, tales of future weather informed by weather model simulations, offer a complementary methodology which can more fully explore the uncertainty of future climate for decision makers today. A Tales approach is more resilient in several relevant and important aspects.

Tales of Future Weather

In general, scenarios describe a system under hypothetical conditions. In climate science these hypothetical conditions are guided by the range of expected changes to the dominant drivers of the climate system. Scenarios account for uncertainties both in the drivers and in the system's response to them. They can be regarded as storylines in which information on both socio-economic and climate change are combined in one narrative, providing heuristic tools that can enhance social learning and engage stakeholders[24].

The details of the description of the hypothetical climate conditions will vary according to the problem of interest. One approach is to provide general statistical terms; this is the usual way climate change scenarios are presented. We suggest that a better approach provides storylines of realistic synoptic weather events in present and future climate settings related to local vulnerability. Such detailed descriptions of synoptic weather in a future climate and its impact has considerable value to users: it is vivid, it can be related to relevant past weather analogues, it can be easily linked to the every day experience of the users, and it allows exploring vulnerabilities in a realistic synoptic weather setting. Relating such information on extremes to everyday experiences is linked to higher levels of concern of extreme weather[25], which is necessary for decision-making.

How might one construct tales of future weather to inform adaptation decisions and mitigation policy? The use of global high resolution atmosphere models that resolve the synoptic scales (model grid spacing currently about 10 km and expected to improve in the nearterm), the reliability of which are well understood within the frame of numerical weather prediction, allows a more physically coherent expression of what weather in an altered climate could feel and look like[26]. It is possible to provide a limited set of future weather scenarios that explore a range of plausible realizations of future climate. The scenarios are imposed onto the boundary conditions (sea surface temperatures, atmospheric composition, land use etc.) of a high resolution model. The boundary conditions may be obtained from traditional coupled climate model simulations of future climate but they could equally well be inspired by other sources, including paleoclimate data, sensitivity experiments with coupled models, archives of past meteorological analyses and forecasts, or even simple constructions of physically credible possibilities. The synoptic patterns related to the 2003 heat wave or the 2013 floods in Europe, for instance, could be simulated repeatedly using expert elicited patterns of changes in sea surface temperatures and radiative forcing representative of a warmer world. In this way a wider range of plausible realizations of an alternative climate can be considered than with traditional coupled climate model experiments.

An important difference of the Tales approach with MoCoDoT is that the selection of boundary conditions is tailored to the specific case of interest; users are part of the process through the identification of the event types of interest. Another advantage is that the impacts of biases in the climate model simulations can be investigated, and both the effectiveness of current approaches and the impact of known deficiencies can be evaluated. Specifically, the consistency of the local environments produced in the Tales' simulations can be compared with those indicated in the coarse grained climate model which inspired that Tale, allowing new tests of internal consistency with lead time. The dynamic coherence of the global high resolution weather model provides spatial coherence and physical consistency across both space and time within each Tale. Even today's best weather models remain, of course, imperfect; nevertheless the range of extreme events that they can simulate realistically is extended significantly beyond the lower resolution "extreme" "weather" simulated in today's global climate models.

Such synoptic resolving simulations are technically feasible, as shown in earlier studies[26,27,28,29]. In particular regional high resolution models have been used at time and spatial scales of interest to explore changes in weather phenomena. The novelty of our approach, however, includes the transdisciplinary of the construction of Tales presented in the next section. Also, we advocate the use of global higher resolution models in the large scale forcing of regional climate, as errors in that forcing may create a large errors in the simulated regional climate changes[30].

Transdisciplinary Story Lines

Storyline development requires an inter- and transdisciplinary approach. The actors include the users of climate information, the climate system specialists, numerical weather prediction experts, and the communicators of climate scenario information. The scene that will be portrayed in a scenario depends highly on the particular vulnerabilities of the system as perceived by the users involved; there is no common approach to describing it. We can, however, describe a number of the relevant elements for a storyline on the implications of future weather. Box 1 describes an example of coastal defence in a low lying delta to illustrate the different elements. The approach, however, is generic, taking the local vulnerability as a central element and does not rely on this specific case set in the midlatitudes.

1) The drivers of vulnerability

Traditionally emission scenarios have been related to storylines[31]. The current Representative Concentration Pathways (RCPs)[32] provide a collection of alternative future emission pathways without direct simulation (and thus omitting potentially important feedbacks). Current research[33] explores the implications (and tests the internal consistency) of combining a given RCP with a given Shared Socioeconomic Pathway (SSP). The aim is to ease consideration of adaptation measures and non-climate drivers of vulnerability (such as urbanisation trends, land management policies and issues around air quality) within the narrative.

2) Description of relevant analogues from current and past climate

Past extreme weather events are stored in our collective memory. In Europe the dry summer of 1976 and the hot summers of 2003, 2006 and 2010 stand out. In the USA hurricanes Katrina and

Sandy will not soon be forgotten. These extreme weather events expose the vulnerability of society. In hydrology, 'representative standard years' (such as 1976 for Europe[34]) are used to investigate sensitivities of water management systems to dry weather conditions. It is interpreted as an analogue for a possible future dry summer. Historical 'reference years' ensure physical consistency and consistent spatiotemporal variability. Their disadvantages include the fact that return times are badly defined and that the available characteristics of an event (timing, spatial structure, compound conditions) are dictated by the observation network that was in place on the day. In the Tales approach, a thorough synoptic description of a relevant analogue, the mechanisms at play and the consequences of the weather extreme, and a description of possible future synoptic events are essential parts of the storyline. Earlier research[25,35] has shown that societal actor's prior experience of similar extreme weather events influence adaptive measures and preparedness for future extremes. An adequate description of the physical mechanisms and implications of relevant analogues from the past can positively influence adaptive capacity. This results in the following elements in the Tales approach that describe the analogues:

2a Statistical description of the analogues

The statistical characteristics of an event provide information on the severity of the event as compared to other events in current climate. The impact of recent trends in climate can be included in the statistical analysis. We will not be able to assess the changes in frequency for the events in the future.

2b Physical description of the analogues

A synoptic description of a relevant analogue, accompanied with a description of the physical mechanisms at play, contributes to an understanding of the event and to the plausibility of the scenario. An example is the high amount of rainfall along the Dutch coast in August 2006. The preceding record-warm month warmed the North Sea and lead to enhanced moisture convergence and convection near the coast[36]. The drought in the UK in March 2012 followed by a month of high precipitation is another example. Box 1 describes an example of a compound event of high precipitation followed by a storm surge in 2012 in the Netherlands.

2c Consequences of the analogue

The consequences of an event can be put in the context of the vulnerability of society to extremes. Having historic analogues allows these to be considered in much greater detail. The example of extreme rainfall in the coastal area mentioned above exposed the vulnerability of the urban water management system and vulnerability of agriculture in greenhouses in the west of The Netherlands. Communicating such a link of the weather event to impacts and consequences on key sectors is a key to effective adaptive responses; it increases preparedness for environmental risks[37].

3) Description of synoptic weather patterns in a future climate setting

Rather than attempting to describe quantitatively the changes in the statistics of weather which are themselves uncertain, Tales provides specific cases of synoptic weather events in a future climate setting. The boundary and initial conditions of the atmospheric model used to create the synoptic events constrain the setting. As noted above, these can be derived from traditional climate model simulations, yielding the advantages of higher resolution and the use of a well-evaluated and calibrated weather model. Tales, however, can also consider a wider range of plausible boundary conditions. Alternative boundary conditions for the high resolution model can be chosen to reflect: a) the interests of the users in terms of the types of events likely to be relevant to their decisions, and b) a wider scientific perspective on the potential large scale consequences of climate change than that which can be obtained from coupled climate model ensembles. The high resolution models can be used in two different ways. Events of interest can be selected from long simulations under either present-day or alternative boundary conditions. A second approach is to conduct many short simulations designed explicitly to study synoptic events of interest. In the latter case, interesting initial conditions can be chosen via data assimilation to drive the model near synoptic events of interest[37]. This approach may provide probabilities for changing impacts/extremes given certain types of weather patterns, but it cannot provide probabilities for the changing likelihood of such patterns.

Regional high resolution models with boundary conditions reflecting a future state have been used before[27]. Also, in Japan, USA/UK (e.g. Athena[39] project), and The Netherlands (Future Weather project using EC-Earth[40, 26]) high resolution global atmosphere models are already being used with boundary conditions from a future climate scenario though without the user focus described above. These provide a good technical basis for describing plausible future synoptic weather events.

4) Wider scientific perspectives on the future climate setting

Scientific findings are important for generating plausible storylines and for designing the NWP model simulations. For instance, recent studies show that the increase in extreme rainfall with temperature is much stronger than expected from the Clausius-Clapeyron relation. Physical mechanisms have been identified to explain the effect[41]. Similarly, changing spatial gradients depending on the land use, land-sea contrast or orography are relevant for explaining plausible changes in regional climate. Other examples are the possible change in stationary eddy patterns in the atmosphere driven by melt of Arctic sea ice in summer and the shift in stationary wave patterns and weather regimes due to weakening of the jet stream[42,43]. A wider perspective can include a description of climate surprises which could plausibly be generated by nonlinear feedbacks, for example a description of the effect of a collapse of the thermohaline circulation in the Atlantic Ocean, or disruption of the monsoon circulation. The relevance of each Tale can be debated within the context of our knowledge of the weather model's performance in the present climate. Such discussions, involving both decision makers and scientists, will aid our ability to interpret the future weather we may (chose to) face.

Discussion

In this paper we have argued for a novel, complementary approach to delivering climate change information for use in society. The traditional MoCoDoT approach (model the entire climate system, "correct" for biases, downscale to the scales of interest and finally translate into terms suitable for application) has limitations[2,9,17]. Firstly the simulation models are known not to provide high fidelity representations of processes which are expected to be important. Secondly, the nature of the problem means that the impact of such shortcomings can be neither confirmed nor quantified. A third issue relates to communication of decision-relevant information. Climate impacts often depend on the simultaneous combination of weather variables (concurrent values of temperature, humidity, wind speed and pressure, for example) that need to be analysed in combination over time. In many professions, design constraints are phrased in terms of "reference" years or as events which represent the type of conditions which the system is expected to withstand. The Tales methodology enables this approach, and does so over wider range of boundary and initial conditions than that provided by traditional climate modelling; one can even "zoom in" on a case of particular interest to decision makers. Of course, one must acknowledge that high resolution weather models cannot simulate realistically all high-impact events of interest; structure errors in weather models persist and some can be identified in practice. Nevertheless, we can deploy the whole of our scientific understanding to question what are credible boundary conditions governing the future. This approach allows interaction with users from the very beginning. The use of weather prediction models that are well-calibrated with observations and for which the skill is known for phenomena of interest, and thus have a theoretical and empirical basis, reduces but does not eliminate the impact of systematic model error; it also increases the range of tests of internal consistency available to us. The Tales approach extends the MoCoDoT approach by allowing us to further explore and better evaluate the known range relevant and plausible conditions.

Current projections regarding detailed changes in climate system are largely derived from climate models. As the value of these models for climate forecasts cannot reliably be expressed in statistical terms, one has to arrive at *qualitative* judgments on the methodological virtue of modelling exercises. Determining the methodological virtue of a finding *a priori* is not straightforward. The broader the relevant peer community, the more likely it is that the different epistemic values held by different groups of experts will impact the assessment of methodological quality. Criteria such as (1) theoretical basis, (2) empirical basis, (3) comparison with other simulations and (4) acceptance/support within and outside the direct peer community are relevant in expressing the level of methodological reliability, or 'pedigree'[44,45,46]. The Tales approach addresses these issues by avoiding a naïve realist interpretation of climate model simulations as forecasts, by focusing on individual meteorological events which are more easily communicated and utilised, and by allowing closer comparison with the core science, and our physical understanding. That is, we advocate to use well-evaluated and calibrated physics-based models with empirical data. In these ways storylines relating to weather events of the past, present and future can be generated, enriching the climate science discussion beyond the analysis of results obtained from coordinated model ensembles like CMIP5.

Our approach allows exploration of the consequences of a set of specific weather cases. Precise probabilities are neither available nor required, although the weather events must, of course, be examined and deemed physically plausible. A discussion of the basis for that plausibility will accompany the storyline allowing its assessment by users deciding whether it is a suitable basis for action. Scientific insight and criticism of plausible events directly relevant to the decision maker is ingrained in the process.

Robust, decision-relevant probabilities were not available under traditional approaches. The structure of the storyline approach ensures that the nature of the information is obvious within Tales. While our method accepts the fact that today's climate models cannot produce long-term decision-relevant probability forecasts, this in no way suggests climate models have no value; indeed they still play a key role. Models are valuable tools in generating and testing the understanding which helps us create the storylines. The emphasis is on their use to generate plausible background conditions for weather phenomena consistent with larger scale changes in the climate system.

The development of storylines is founded in physical process understanding as this is the basis for confidence in plausible future physical climates. Just as importantly, their insights must be expressed in a manner meaningful to policy and decision makers. This translation creates the need for transdisciplinary collaboration in targeting plausible weather events future and investigating their societal consequences. Stakeholders are not end recipients of authoritative information from scientists but become co-producers of the scenarios. A truly interactive process of co-development of scenarios raises both scientific and stakeholder perspectives transparently, and deals with each in a balanced manner.

After consideration of the Tales approach and further testing of the proposed methodologies for different cases for which local vulnerability to climate change is assessed, we call for a careful re-evaluation of the design of climate model experiments. Long time frame (multi-decadal to centennial) simulations remain informative for the study of physical interactions involving slow feedbacks in the Earth system which can be simulated with sufficient fidelity. For the provision of regional scale information on any time scale, however, we suggest a new emphasis on high resolution time slice experiments driven by as wide a range of plausible large scale / global settings. Some, but not all, of these settings can be based on traditional modelling directly from global climate models, those experiemnts will come with the bonus of informing our view of thethe internal consistency of envisioned future impacts. The information from traditional climate model ensembles can complement the Tales approach; Tales embraces the traditional approach where traditional modelling provides a framework for the narratives, it aids traditional modelling through tests of internal consistency, and it allows decision makers access to more usable information which is more relevant to their needs. In short, a Tales approach improves the use of our current scientific understanding to better imagine what weather the future might hold.

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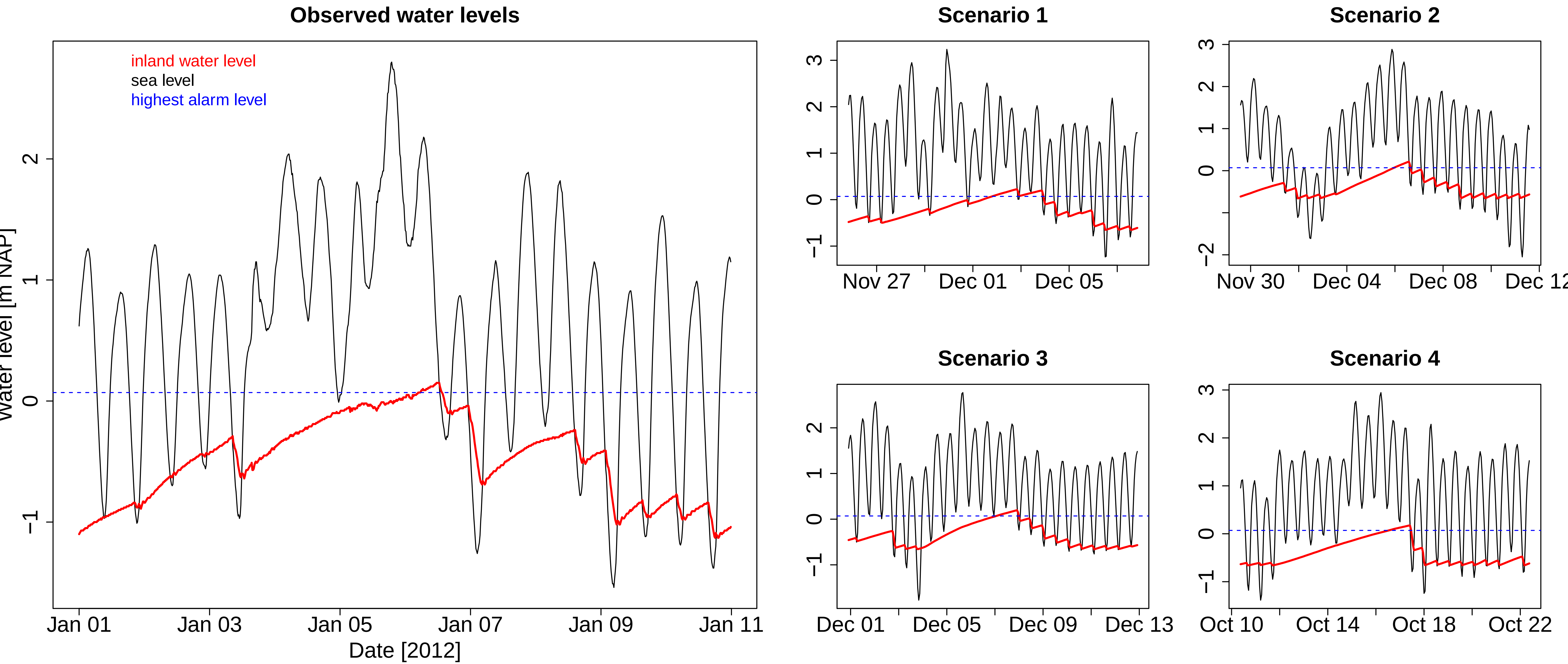
Box: A Tale on a compound event in a low lying Delta

Even in the highly managed hydrological system of The Netherlands, large decisions on infrastructure changes are often incident-driven. This box describes elements of a Tale of Future Weather for decision-makers on local water management in the region. An event in early January 2012 exposed the vulnerability of the northern parts of the Netherlands to flooding. 20-30 mm/day of rain fell during a few consecutive days due to passing of synoptic pressure systems. The sluicing capacity from the inland waterways to the North Sea is 10 mm per day, but strong north-westerly winds at the end of the period of high rainfall created a surge that prevented sluicing at low tide (Figure Box). This led authorities to order evacuation of the region and there was a call for extra measures to protect for future events like these. The return times of the precipitation event and of the winds were very modest (3-7 years). The event is an example of a compound event where neither precipitation nor surge were extreme, but the two in combination had a large hydrological impact for this region. Such events are not well simulated in most global climate models because of the synoptic details. Simulations were made with a global atmospheric model derived from a global numerical weather prediction model (EC-Earth) at very high resolution of about 20 km. Future boundary conditions were obtained by adding sea surface temperature anomalies obtained from a climate model to current sea surface temperature conditions[26]. The model was combined with a simple hydrological model. Figure Box 1 shows four selected time series from those simulations similar to the analogue (excluding a scenario of future sea level rise). This figure demonstrates that complex synoptic events with large hydrological impact similar to the one observed are well captured in such simulations, and thus provide input to the Tale. Further information, including expert knowledge on physical understanding on potential changes in storminess[7,26,47,48] and on the changes in the hydrological cycle when temperature rises[7,49], can also be included; so can 'what-if' scenarios on future sea level rise[50,51]. The Tales approach allows the exploration of local vulnerability using information from these more physically coherent synthetic events. The Tales approach also includes information on the local vulnerability and identified regions of interest. In large parts of the Groningen and Friesland provinces, the water drainage system depends on passive sluicing at low tide rather than pumping;and the storage of water in inland lakes is not possible here. These aspects complement the details of the synoptic information for assessing the local vulnerability of the region to climate change. The model information of this specific case added with 'what-if' scenarios of sea level rise and on changes in extreme rainfall have been provided to water managers and aid in designing adaptation measures in a realistic setting now.

Figure caption:

Figure B1. Example of restricted discharge options leading to flooding as shown by observed time series of the water level (meters above a mean sea level denoted by NAP) at the North Sea side (black) and inland side (red) at the “R.J. Cleveringsluizen” sluices, Lauwersoog (53,24^{o}N, 6,13^{o}E) in early January 2012. The purple line section denotes the period of elevated alert conditions and the dashed line indicates the highest alarm level. A similar set of four events, excluding the impact of sea level rise, derived snap shot weather simulations with an Numerical Weather prediction model using boundary conditions of the second half of the 21st century are shown on the right.



Observed water levels
inland water level
sea level
highest alarm level
Water level [m NAP]
Date [2012]
Jan 01
Jan 03
Jan 05
Jan 07
Jan 09
Jan 11
Scenario 1
Nov 27
Dec 01
Dec 05
Scenario 2
Nov 30
Dec 04
Dec 08
Dec 12
Scenario 3
Dec 01
Dec 05
Dec 09
Dec 13
Scenario 4
Oct 10
Oct 14
Oct 18
Oct 22