


Knowledge for Climate

Future Weather




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Content

1 Summary

The impact of climate change will manifest itself in our future weather. In the project *Future Weather* we investigated a number of these impact relevant weather conditions in the (present and) future climate. We focussed primarily on changes in precipitation extremes on different scales ranging from intense showers at local scales to multi-day precipitation extremes over the Rhine catchment area. On an intermediate scale, regional differences in precipitation within the Netherlands are studied. Finally, we considered a worst case scenario of a combined wind and discharge extreme. Besides quantitative results, we also put effort into understanding these extremes on a process level. Noteworthy results are: i) increased evidence that shower intensities increase strongly with warming and could even double at the end of this century, ii) a quantification of the relative importance of natural variations in comparison with climate change for multi-day precipitation extremes important for extreme discharges, iii) better understanding and improved modelling of the influence of the North Sea on regional precipitation, and iv) evidence that the probability of a simultaneous occurrence of high river discharge and storm surge is a factor 4 higher than previously assumed. In this report we describe, and provide background information on the science of, these findings.

2 Samenvatting

De invloed van klimaatverandering uit zich in het toekomstige weer. In het project *Future Weather* onderzoeken we een aantal weerscondities in het (huidige en) toekomstige klimaat met een grote maatschappelijke impact. We richten ons voornamelijk op neerslag extremen: van de intensiteit in buien op een locale schaal tot meerdaagse neerslag extremen in het Rijnstroomgebied. Op een tussenliggende schaal is er gekeken naar regionale verschillen in neerslag binnen Nederland. Als laatste is een *worst case* scenario van een optreden van een storm tegelijk met een afvoerpiek van de Rijn onderzocht. Naast kwantitatieve resultaten hebben we ook een procesmatig beter begrip van deze extremen. De belangrijkste resultaten zijn: i) een sterkere onderbouwing dat de intensiteit van buien sterk met de temperatuur toeneemt, en zelfs zou kunnen verdubbelen aan het eind van deze eeuw, ii) een betere kwantificering van de rol van natuurlijke variaties in verhouding tot klimaatverandering voor meerdaagse neerslag extremen die van belang zijn voor de afvoer van de Rijn, iii) een toegenomen begrip van, en betere modellen voor, de invloed van de Noordzee op regionale neerslag, en iv) aanwijzingen dat de kans op een gelijktijdig optreden van een hoge rivierafvoer en stormvloed 4 keer zo groot is als voorheen aangenomen. In dit rapport beschrijven we deze resultaten en geven daarnaast wetenschappelijke achtergrond informatie.

3 Introduction

This report describes a number of the highlights from the project KKF1a *Future Weather* which has been financed by the Dutch program Knowledge for Climate ("Kennis voor Klimaat"). The project ran from September 2009 to December 2011. The title of the project, *Future Weather*, is chosen as this research primarily focuses on a number of weather conditions which cause substantial societal impacts, and the question of how these weather conditions may change in the future.

Future Weather includes high resolution modeling of the climate using hydrostatic regional climate models targeted at scales of 10-1000 km, and using global climate models targeted at scales of 200 km to the continental and global scale. In addition, we performed a case study with an even higher resolution model that explicitly resolves atmospheric convection, a so-called non-hydrostatic model. Besides the output of these modeling systems we also look closely at the observations.

Much of the research is motivated by questions in relation to the development and subsequent application of the Dutch climate scenarios, which were issued by KNMI in 2006. These scenarios – hereafter KNMI'06 – consisted of 4 scenarios which are characterized by the strength of the global temperature rise and whether or not atmospheric circulation patterns over Europe will change (see box). In the first release of KNMI'06 only scenarios for winter and summer in the year 2050 were given, but in later editions scenarios for the year 2100 and the other seasons were added. To keep the text concise we will use the term "year 2050" or just "2050" and "2100", which does not refer to a specific year but to a climatological period around the year mentioned. Generally such a climatological period is defined as a 30-years period, although we note that even 30 years may be too short to capture all natural climate variability (see Section 4). Thus, the year 2050 refers to a climate around the year 2050 as given by the period 2035-2065.

The main research in *Future Weather* focuses on precipitation extremes at different spatial and temporal scales, and on potential differences of regional precipitation change within the Netherlands. The largest scale studied here is represented by multi-day precipitation extremes over the Rhine catchment

KNMI'06 scenarios

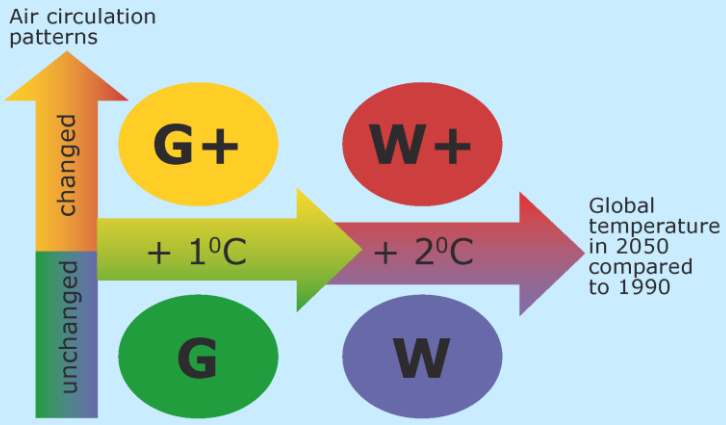
In 2006 KNMI issued a new set of climate scenarios. These were based on analysis of a set of global and regional climate model simulations, combined with observations and constraints based on understanding of the climate system. The overall climate scenarios are described in Van den Hurk et al. [2007], and more detailed information of the weighting between modeling results and physical understanding is described in Lenderink et al. [2007]. The website of the KNMI'06 scenarios can be found under http://www.knmi.nl/climatescenarios/

The KNMI'06 scenarios were well received by both the impact modeling community in the Netherlands and the scientific community worldwide. However, after issuing these scenarios in 2006, a number of weaker points and/or restrictions became clear. Such limitations are unavoidable at present and are a consequence of the compromise made between "what is asked for" and "what we know and how certain we are about it". On the one hand, they follow from how we dealt with limitations in available data, modeling results and observations, and incomplete understanding of the physics of the climate system. On the other hand, they follow from new user requests.

area. Extreme precipitation for typically 5 to 20 days determine to a large extent the peak discharges of the Rhine, and are therefore important to determine the safety norms of the river dikes. The present safety norms are based on return periods of 1250 years. In the KNMI'06 climate scenarios it is implicitly assumed that changes in the multi-day extremes for winter are approximately equal to the mean precipitation changes. This has been achieved by selecting model results that approximately satisfied this criterion, and this decision was based on physical arguments. Nevertheless, results of climate models often show that multi-day extremes could increase more (or less) than mean precipitation and/or one day extremes. However, these results were usually based on relatively short model integrations of order 30 years, and on this time scale the role of natural variability – variations that occur irrespectively of human induced climate change – for these type of extremes is substantial. In *Future Weather* we investigate in detail for precipitation extremes over the Rhine catchment area what the relative importance is of natural variability compared to the signal due to climate change.

Framework of the KNMI'06 scenarios

The KNMI'06 scenarios are characterized by two steering variables: on the one hand the strength of the global temperature rise, on the other hand the strength of atmospheric circulation changes for western Europe. Projections of the global mean temperature change are determined by future greenhouse gas concentrations and model uncertainty concerning the response of the global climate models to increasing greenhouse gas concentrations. The latter is referred to as *climate sensitivity*, which is strictly the global mean temperature response to a doubling of CO_2 concentrations. For the end of this century, the uncertainty in greenhouse gas concentrations and the uncertainty in the climate sensitivity are approximately equally important; they explain an approximately equal portion of the spread in the projected global mean temperature rise in climate model simulations. The other steering variable is the strength of the atmospheric circulation change over western Europe, which is chosen because this strongly affects many aspects of our climate. In winter, most climate models project a strengthening of the westerly flow leading to milder and wetter winters, whereas in summer a weakening of the westerly winds is simulated leading to warmer but drier summers. There are, however, also climate models that project little changes in the westerly flow for western Europe. Our understanding of the mechanisms leading to future atmospheric circulation changes is at the moment too limited to say which of the climate models is more accurate in this respect. Therefore, both possibilities are taken into account. Together, this leads to four climate scenarios as shown below



Besides looking at the distribution of extremes in multi-day precipitation, we also investigated the probability of occurrence of a wind storm after a period of extreme precipitation. This is particularly important for the *Maeslantkering* which protects the Rotterdam area from flooding in the case of storm surge. In present calculations of the safety norms it is assumed that the probabilities of storm surges and extreme river discharges are independent. However, as both type of events occur under similar atmospheric circulation patterns, this assumption is under doubt. Here, we investigate the validity of this assumption for the present-day climate.

On a regional scale we look at differences in precipitation within the Netherlands. In the KNMI'06 scenarios it was assumed that changes in precipitation due to climate change over the Netherlands were uniform in space. (The same assumption has been made for all other variables as well.) Thus, the spatial structure of precipitation in 2050, or 2100, are the same as in the present-day climate. After the release of the KNMI'06 scenarios an exceptional summer occurred. The early summer of 2006 was record warm until end of July, and was followed by an extremely wet August month. In particular, in the coastal areas approximately 240 mm of rain fell, which is 3 times the climatological mean in August. Analysis of this event showed that approximately one third of this precipitation amount was caused by the high sea surface temperature – approximately 2 degree above climatology at the start of August – resulting from the very warm early summer. In addition, analysis of the trend over the last 50 years showed that the coastal area has become wetter relative to inland areas. We investigated whether this trend is systematic, and whether we could expect similar changes in the regional precipitation differences in the future.

Intense events of local precipitation have a large influence on society. They are associated with local flooding, erosion and water damage, and may have impacts on transport and safety. It is commonly expected that precipitation extremes will increase as the climate warms (see box). In an earlier study it was found for data from De Bilt that hourly precipitation extremes increase at a rate of 14 % per degree, which is (much) more than commonly thought. In addition, from a simulation with the KNMI regional climate model RACMO evidence was found that hourly extremes in the future could also increase at the same rate. Yet, it was not known how robust these results were across different observational data sets and different models that project future changes. This, and the question whether we already observe a trend in the intensity of showers, is investigated in *Future Weather*.

During the execution of the project, two exceptional precipitation events happened, both in summer. First, on the 26th and 27th August 2010 more than 130 mm precipitation was recorded in the eastern part of the Netherlands, leading

to severe local flooding. The KNMI station Lievelde recorded 138 mm on the morning of 27th of August; the third highest daily precipitation amount recorded at a Dutch precipitation station after 1950. In the E-OBS observational data set, which is based on observations aggregated on a grid of 25 km, it is even the most extreme event. Second, on the 28th June 2011, during a severe shower, 79 mm of rain was recorded between 20 and 21 local time at the KNMI automatic observational station at Herwijnen. This is the highest hourly precipitation extreme ever recorded at a KNMI station in the Netherlands. At the end of this report we will discuss which processes attributed to these extremes, and speculate on how these extremes could change in the future.

Of course, the results obtained in *Future Weather* are not fully conclusive and a number of issues remain and new questions emerged. Therefore, we finish with a number of research questions and topics that should be further explored. Some of those questions will be addressed in the following KvK project "*Theme 6: High quality climate projections*", in this report often abbreviated to "*Theme 6"*, which runs from 2011-2015.

Precipitation extremes and global warming

Precipitation extremes are generally expected to increase with global warming. The reason for this expectation is a rather basic one: warmer air can hold more moisture, which potentially allows more rain to accumulate in a downpour. This follows from a fundamental equation, termed the Clausius-Clapeyron (CC) relation, which gives approximately a 7 % increase of the maximum water vapour content per degree temperature rise. In earlier work, it has been argued that extreme precipitation should follow this CC scaling. However, the general consensus at present is that – while CC scaling provides a basic guideline – many processes could lead to deviations from CC scaling. As such, changes in the atmospheric circulation patterns from the large (500-5000 km) scale up to the cloud scale (~1 km) could play a role. The extent to which these processes could lead to deviations from CC scaling is further explored in this report.

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A record breaking precipitation event, with an hourly precipitation sum of 79 mm, occurred in Herwijnen on 28th June 2011.

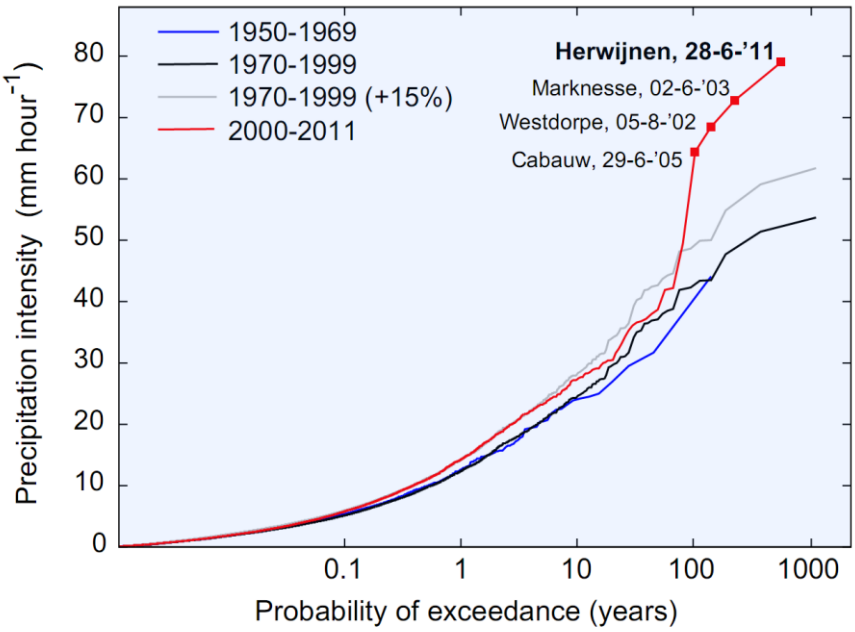

Figure 1. Distribution of hourly (on clock hours) precipitation extremes in the Netherlands for three different time periods. For this plot we used all measurements at ~30 observational stations in The Netherlands; the number of stations varies with time, but the total number of observations is approximately equal in the 1970-1999 and 2000-2011 time period. The four highest measurements are indicated by the small red squares; all of them occurred after the year 2000. In addition, we also plotted the distribution from 1970-1999, assuming an expected increase of 15% in intensity (grey line). This expectation is based on the observed temperature increase and the observed relation between temperature and precipitation intensity (see Sections 7 and 8).

4 Rhine catchment precipitation extremes.

In *Future Weather* we studied multi-day precipitation extremes in the Rhine catchment area. In particular, extreme precipitation lasting 10 to 20 days in the catchment area of the Rhine in Germany and Switzerland lead to peak discharges in The Netherlands, which could be a threat to society. (We note that the melting of snow is also important for the Rhine discharge. The main melt of snow in the Alps, which is now in late spring/early summer, is expected to occur earlier in the season when the climate warms. This could affect the probability of the simultaneous occurrence of high snowmelt and extreme precipitation, and therefore the probability of extreme river discharge. This is however not studied here.)

Not all changes seen in climate model simulations are a signal of (human induced) climate change. A major and commonly made pitfall of the interpretation of the outcome of climate models is the attribution of a change, which is due to natural variability, to greenhouse gas warming.

Natural Variability

The climate systems shows natural variations on different time scales, from variations from year-to-year to variations for 10 year periods and longer. Variations that occur irrespectively of human induced greenhouse warming are called natural variability. The amount of natural variability depends on the variable looked at and the time and spatial scale. For the globally averaged temperature it is rather small on a 10-year period; in the absence of human induced climate change the average temperature over two 10-year periods are approximately equal. By contrast, for example, for winter storms in the Netherlands the amount of natural variability is considerable; in one 10-year period several severe storms could hit the Netherlands, whereas in other 10-year periods there could be (almost) no storms. Therefore, it is obvious that to base safety norms of the coastal defense – the present norm is a probability of failure once every 10.000 years or less for highly populated areas – on an observational data set of only 10 years is not a good idea. (Extrapolating to such long return periods is done using advanced statistical methods based on extreme value theory). Over longer periods natural variability tends to average out. Yet, even on a period of 30 years – a period normally used to determine a climatology – natural variability can be substantial.

Estimates of changes in discharge of the Rhine (as well as other main rivers) are often based on the output of regional climate model simulations. The primary reason for this is that the terrain of the catchment area is generally complex with, for instance, substantial topography. Clearly, regional climate models with a typical resolution of 25 km do a much better job at resolving the complex terrain than global climate model with a resolution of 200 km. Yet, there is a downside to the use of regional climate model simulations. In many cases

changes in extreme discharges are computed from comparing two 30-year periods with each other, for instance between a *control period* 1970-2000 with the *future period* 2070-2100. (This is because long integrations with regional climate models are computationally very expensive, and usually take 1-3 months on a present-day supercomputer.) It should be no surprise that, by comparing two 30-year periods with each other, the role of natural variability in, for instance, a 10-day precipitation extreme could be substantial. Therefore, it may be difficult, if not impossible, to separate out the signal due to climate change from the noise due to natural variability.

In an earlier study with a small ensemble of regional climate model simulations (50 km resolution) coupled to a discharge model, it was found that natural variability indeed strongly affected the estimates of changes in extreme discharges [Lenderink et al. 2003]. For instance, it was found that for a climate change signal of a 10 % increase, there is a 20 % probability that a *decrease* in the 100-year discharge extreme is obtained from the model results. This finding is obtained by comparing 30-year control periods with a 30-year future periods, and the 100 year discharge level is determined by means of extrapolation using a statistical fit (Gumbel distribution; Coles [2001]) to the data. The main limitation of this study, however, was that these results were obtained with a rather small sample of only three model simulations for present-day and future climate.

In *Future Weather* we investigated in much more detail how important natural variability is compared to the climate change signal by using a much larger ensemble of climate model simulations [Kew et al. 2010]. This ensemble is based on a global climate model (ECHAM5). This model has been run at a relatively low resolution of approximately 150-200 km, and thus relatively low computational costs, which allowed the generation of a very large ensemble of 17 members (the Dutch ''ESSENCE'' project). We looked at multi-day precipitation extremes directly, instead of the Rhine discharge.

In this large model ensemble we considered changes in 1-day up to 20-day precipitation extremes. Here, we show results for winter as high river discharges occur mostly in the winter season. As a measure of extreme the 99th percentile is chosen; this is approximately an extreme occurring once every season. Although peak discharges are caused by even more extreme (and rare) events, the amount of model data does not allow us to look at more rare events.

The percentage change between the control period 1961-1991 and the future period 2070-2100 is computed. In the full ensemble of 17 simulations the mean response in the 99th percentile is approximately 11% for 1-day extremes and +6% for 20-day extremes (grey and blue thick stippled horizontal lines in Figure

2, respectively). At the same time, the mean precipitation increases by about +12 %. As these changes are based on 17 members in total, which is about 500 years of simulation for both the control period as well as the future period, the influence of natural variability is low. Yet, we note that the difference between the 1-day and the 20-day extremes could be due to chance or natural variations; the lower boundary of the shaded area of 1-day precipitation extremes (left panel in Figure 2) still overlaps with the upper boundary of the shaded area for 20-day precipitation extremes (right panel in Figure 2) with an ensemble size of 17 members. In the remaining text we will omit this subtlety and refer to these number as the climate change signal.

We continue to look at natural variability. The influence of natural variability is estimated by a re-sampling method by which a very large number (~10.000) of ensemble members can be generated. We will call this large artificially created ensemble a “super” ensemble. In this manner the spread due to natural varia-

Natural variability strongly affects estimates of the change in 1 and 20-day precipitation extremes in winter. From a single climate model simulation (ensemble size of 1) the climate change signal in a large-scale 20-day precipitation extreme *cannot* be inferred.

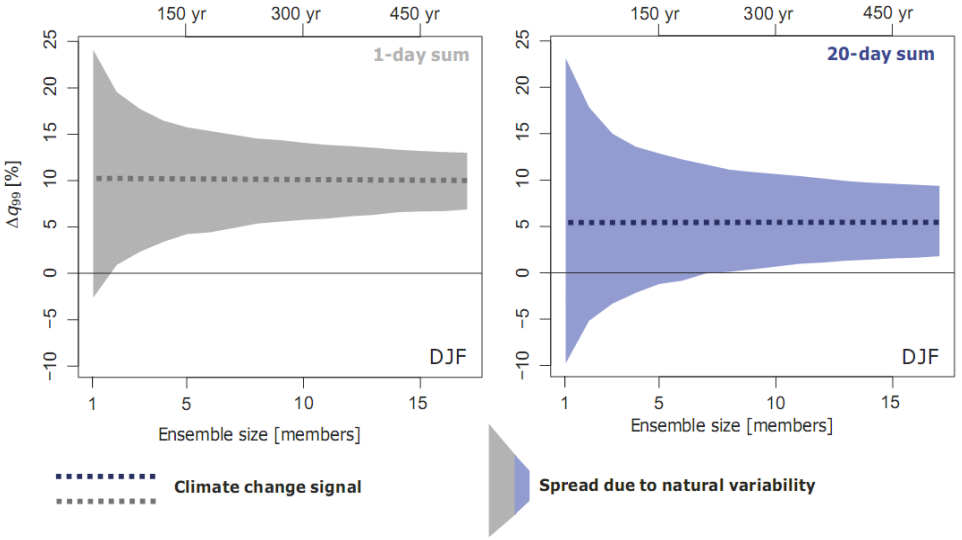

Figure 2. Change in the 99th percentile (Δq_{99}) of 1-day and 20-precipitation sums as a function of the number of model simulations (ensemble size *n*). Changes are in percentage (future period 2070-2100 with respect to the control period 1961-1991) for winter and the northern part of the Rhine catchment area. The 99th percentile is the precipitation extreme occurring approximately once a season. Horizontal stippled lines are the climate change signal derived from all (17) ensemble members. Shaded areas show the expected (95%) range of the spread in obtained change in a (smaller) model ensemble due to natural variability (see main text for details). In particular, for small ensemble sizes (that is, only few model simulations) the spread due to natural variability is dominant. For a 1-day precipitation extreme one needs 2 climate simulations (equivalent to 60 years for both control and reference period) to detect (with 95 % probability) the positive change due to climate change. Yet, for a 20-day precipitation extremes one needs 8 simulations (equivalent to 240 years). This is partly attributed to the smaller climate change signal and partly to the stronger natural variability for 20-day precipitation extremes.

bility can be estimated more reliably than by considering the difference between the 17 model integrations separately.

The blue/grey bands in Figure 2 indicate the spread in outcomes in the generated super ensemble. To be precise, it is the range covered by 95 % of the artificially generated ensemble. For instance, taking only one climate integration (indicated by ensemble size 1) we could expect a simulated change between -9 and +23 % in the 20-day precipitation extreme. A single simulation is therefore of no use in estimating the signal due to climate change. Taking 10 model integrations, which is effectively 300 years for both the control and the future period, the expected range is reduced to +1 tot +11 %. To be able to detect a positive change one needs 8 ensemble members in this case. For 1-day extremes the situation is far better and one only needs 2 ensemble members. This is to a large extent due to the larger climate change signal for 1-day precipitation extremes (+11 % versus +6 % for 20-day precipitation extremes) and to a lesser extent to the smaller role of natural variability as expressed by the smaller bandwidth of the grey/blue shaded areas.

The climate change signal in the ESSENCE ensemble is comparatively low compared to the values given in the KNMI'06 scenarios. In these scenarios the change for mean winter precipitation in 2100 ranges between +7 and +28%, whereas for 10-day precipitation the range is between +8 and +24 %. For a larger climate change signal the situation is better, and it is easier to distinguish the climate change signal from natural variability.

In the development of the KNMI'06 scenarios it was assumed that that the change in *the* 10-day large scale precipitation extreme in winter is approximately equal to the change in mean precipitation. This assumption has been made based on physical arguments, and was to some extent at odds with a number of model simulations. The results presented here show that the major reason why large differences between changes in extreme and in mean precipitation are obtained in short climate integrations is natural variability. Averaged out over longer periods (more ensemble members) both changes become approximately equal (although not necessarily the same). Therefore, the results obtained in *Future Weather* provide support for the assumption of comparable changes in mean and 10-day extreme precipitation in the winter season.

Dealing with natural variability and uncertainty

Considering these results one could argue that "if the natural variability is so large why care about a comparatively small climate change signal?". The same argument applies when comparing the climate change signal to uncertainty about an index (e.g. the 100 year return period) in the present-day climate. This is complex question, and we do not claim to have a definite answer. However, we would like to note here two – we think – important arguments. These arguments are not independent, but for means of simplicity we present them separately here.

First, climate change and natural variability have a different nature. Natural variability (and likewise uncertainty) is approximately random, whereas a climate change signal is systematic. Suppose that a certain adaptation measure (for instance, height of the river dikes) has proven successful over an extended past, which implies a low risk at least in relative terms. If we know that the climate change signal increases the probability of weather conditions leading to an impact (for instance, a critical discharge level), this implies that our risk increases due to climate change, no matter how (un)certain we are about our risk in the present-day climate.

Second, the time scale matters. Both the typical re-occurrence time of the climate event causing impacts and the lifetime of (investments in) adaptation infrastructures are important. These time scales are often longer than the time scale affected by natural variability, or the time scale for which natural variability has been estimated. In the case of a river discharge, one could argue that this time scale is actually 1000 years as we are interested in the probability of approximately one event in a 1000-year time period. (If we would have 1000 earths with the same climate, than on average in each year the threshold should be exceeded in one of these earths.) As natural variability is approximately random it (slowly) averages out over longer time scales. Therefore, the longer the time scale the more important is the climate change signal* compared to natural variability.

*Here, we made the implicit assumption that the climate change signal is reasonably robust across different return periods. Although there is no hard general proof for this assumption, for many variables this is reasonable based on model results and physical arguments.

To reverse the argument, if we would have to make investments for the next 10-30 years, and if these investments relate to events occurring relatively often and having relatively small impact, then it would make much more sense to look at natural variability than at climate change.

In general, what will happen in the next 10-30 years is strongly affected by natural variability, and less affected by climate change. However, the change in probability of a very rare, high impact extreme in the more distant future is determined primarily by the climate change signal. In this respect, it is important to realize that apparently small changes in temperature or precipitation could lead to unexpectedly large changes in the return period of rare and extreme events [see e.g. Rahmstorf and Coumou, 2011].

Whether natural variability or climate change, or (as in most cases) both, are important depends on the application. Therefore, we think that it is important that the user has at least a basic understanding of the issues discussed here.

River flooding

5 Combined wind and precipitation extremes

The storm surge barrier near Hoek van Holland, the Maeslantkering, protects the densely populated Rotterdam area when high sea levels occur due to wind storms, the tide and pressure effects. It closes automatically when the water level is predicted to exceed the mean sea level by more than 3m. A worst case scenario is that of simultaneous occurrence of extreme storm surge and extreme discharge of the rivers Lek and Rhine. In the event of an extreme discharge alone, the barrier should remain open to prevent the damming of excess water. In the event of a surge, the barrier should be closed to protect the densely populated Rotterdam area.

In present estimates of the probability of such a worst case scenario, it is assumed that the storm surges and high discharges are independent events. But since both rainfall events and winds storms are caused by the same weather systems – synoptic low pressure systems often called depressions – this assumption of independency could be challenged. Because both events are rare it is, however, difficult to establish their dependency. A complicating factor is also that extremes in the Rhine river discharge in The Netherlands are caused by a preceding period of order 10-20 days with high precipitation (or snow/ice melt) in the Rhine catchment, which is mainly in Germany and Switzerland.

In *Future Weather* we investigated whether such a dependency between storm surges and high discharge could be important. As both events have a long return period we have to rely on a long time series generated by a model; the observational time series is much too short. For this time series we took the winter months from the period 1950 to 1980 of all 17 members of the ESSENCE ensemble of global climate model simulations. Even though this is a long time series of in total 500 years, we are only able to look at events occurring approximately once every winter season: that is, the 99th percentile. These events are relatively extreme, but they are less extreme than the events that cause severe impacts, which typically occur approximately once every 10 years or even less frequently. Despite this we will call them extreme events in the following. As in the previous section, we only looked at high discharges caused by extreme precipitation, and as a simple proxy for the discharge we used the *n*-day precipitation sum (with *n* between 1 and 20 days) of the period preceding the wind maximum.

After a 10-day period with abundant rain there is a ~4 times larger probability on a storm from the North-North-West (NNW) (red diamond compared to blue diamond).

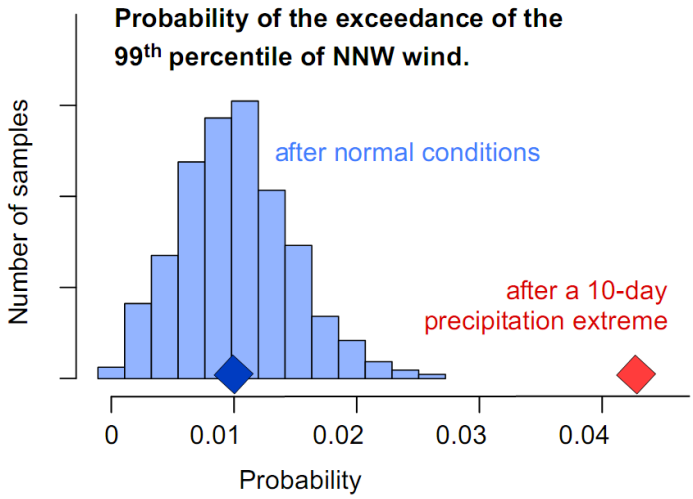

Figure 3. Probability of the exceedance of the 99th percentile of NNW wind. After a 10-day precipitation extreme the probability of exceedance is approximately 0.04 (red diamond), which is a factor 4 higher than the probability of 0.01 (by construction) in the full data set (blue diamond). The increase in probability is outside the range that could be expected due to chance because of the much smaller sample size (blue bars).

Figure 3 shows the probability of exceeding the 99th percentile of wind from the NNW (North-north-west) direction. By definition this probability is 0.01 in the full data set (blue diamond). But, for all days following a 10-day *precipitation* sum exceeding the 99th percentile, this probability turned out to be approximately 4 times larger (red diamond). As the number of days from which the latter probability is computed is 100 times smaller then the full data set, this probability has to be compared with samples of the same number of days from the full data set. These samples are drawn many times randomly (implicitly assuming independence) from the full data set and the resulting distribution is shown by the blue bars in Figure 3. This distribution spreads around a probability of 0.01 with maximum values around 0.025. Therefore, the obtained increase in probability of a wind storm after a 10-day precipitation extreme (from 0.01 to 0.04) is not due to random sampling and is statistically significant.

The enhanced probability of a NNW storm after a multiday precipitation extreme is reasonably robust, and can be understood from the typical sequence of atmospheric circulation conditions over the North Atlantic and West Europe (see Kew et al. 2011). It is found after periods of extreme precipitation over up to 20 days. Further analysis showed that it is mainly due to a shift in wind direction. For wind speed it is only found after a relatively short period, up to a few days, of extreme precipitation [Kew et al. 2011].

There are several limitations of this research. Severe impacts obviously do not occur with a once a year event, which is studied here. A major remaining question is therefore how these findings extend to more extreme events. Also, we looked at two rather simple proxies of storm surge and high river discharge. More detailed modeling with higher resolution atmospheric models and more realistic surge models and hydrological models of the Rhine are required to establish the robustness of these results. The results here apply to the output of one climate model only, and the validity of these results, while being physically plausible, needs to be confirmed with different models (and observations). Finally, it is not known how climate change could affect the joint probability of extreme discharge and storm surge.

In broader perspective, the research presented here (and in other sections of this report) reveal how complex and challenging it is to provide relevant information that allows society to adapt to (risks in) the present-day climate and to climate change. Questions from society often, and in connection with safety almost always, involve high spatial (and temporal) resolution, a combination of models (meteorological and impact models), and complex statistics (due to the rarity of the events and the large role of natural variability). Scientific studies, like the ones presented here, only provide answers to parts of the problem. This could sometimes lead to misinterpretation of the results by users of climate information (see box on the next page). The challenge is therefore to integrate and asses the results of different studies to provide an optimal (given present-day knowledge) answer to the users request. To do so, expert knowledge is compulsory (see box on next page).

A climate service

Let's consider a user who is interested in the question how the 100-year discharge of a large river (like the Rhine) could be affected by climate change. Scientist "A" investigates this with a complex discharge model, forced by output from a single (30-years) run of a very high resolution climate model for present-day and future climate. Scientist "B" investigates this with a simple discharge model, forced by a large ensemble of climate model integrations. Which scientist is likely to provide the most useful information concerning the question posed by the user?

Undoubtedly, most users would trust the results of scientist "A" more, because these results are based on models that have a more realistic description of local processes, the topography, or just plainly because the results look more realistic. However, as shown in the previous section, for these type of extremes (governed by the succession of a number of active low pressure systems) 30-year periods are too short to separate the signal due to climate change from the noise due to natural variations. This implies that the change the user is seeing in the climate simulation of scientist "A" is likely not a climate change signal, but results primarily from natural variations. How counterintuitive it may seem, for this user it would be much better to consider to coarse resolution output of a big ensemble of climate models integrations and trust the results of scientist "B".

However, let's now assume that the river basin is much smaller, and that extremes in the discharge are caused by summer showers. In that case, scientist "A" is likely to provide more useful information.

There is therefore no standard recipe on how to provide the most useful information to users. Sometimes a relatively low resolution model could give useful information, sometimes high resolution modeling is needed, but more often it is a combination of both (and knowledge about observations as well). The choice on how to value different sources of information is based on expert judgment, where knowledge about the relevant processes plays a key role. This is the main challenge of "providing climate services".

As said, there are applications where we think that high resolution is the key to progress. This is where we continue in the next sections.

6 Regional precipitation in the Netherlands

The North Sea exerts a strong influence on the climate of the Netherlands. In spring the North Sea is cold compared to the land. At the same time atmospheric circulation types with flow from the west to northwest occur relatively frequently. With such circulation conditions, when the cooler air from the sea moves above the warmer land, the atmospheric column is destabilized – warmer surface air tends to rise in a cooler atmosphere – and showers develop. These showers rain out typically one or a few hours after they have been formed, thus leading to precipitation further inland. A minimum in cloud cover occurs over the coastal area in spring, and thus a maximum in sunshine duration, results for the same reason. In autumn, the situation is reversed. The North Sea is several degrees warmer than the land, and showers develop above the warmer water. These showers rain out mainly in the coastal area of the Netherlands. Averaged over the Netherlands, precipitation amounts are typically 70 mm month^{-1} in the months September to November. In the coastal region, less than approximately 30 km from the sea, precipitation amount are 20 to 30 mm month^{-1} higher (see Figure 4; left panel).

The KNMI regional climate model RACMO2 captures the spatial differences in

RACMO reproduces the observed precipitation climatology for the Netherlands well

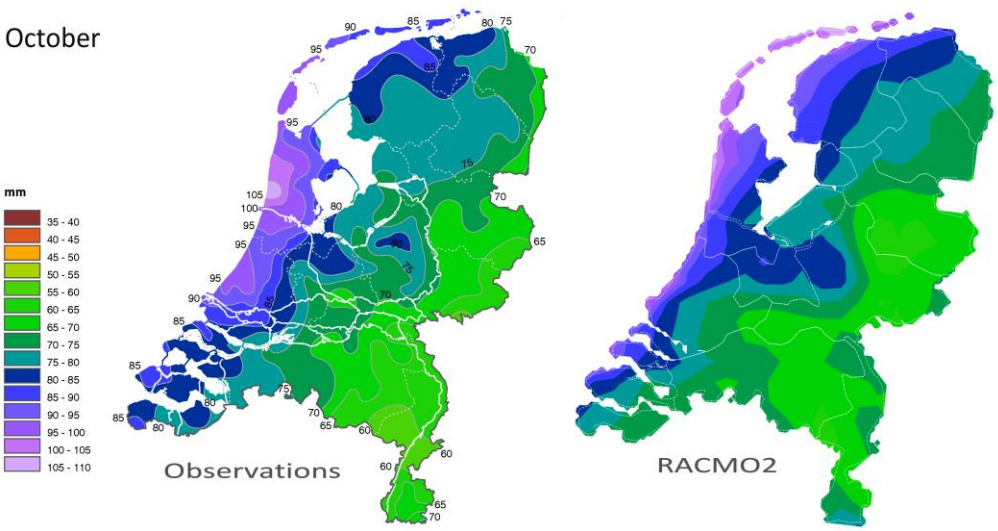

Figure 4. Observed climatology (1970-2000) of precipitation in October (left, from the Dutch "klimaatatlas") versus modelled precipitation in a simulation with RACMO2 for the period 1996-2010. The time periods are different because high resolution sea surface temperature used in RACMO are only available after 1996. The model captures most of the observed structures in precipitation over the Netherlands. The maximum in precipitation (in the observations in *Noord Holland*, near IJmuiden) however is located too far too the northwest in RACMO2, and the zone of high precipitation amounts along the coast is too narrow.

observed precipitation climatology in the Netherlands to a good degree. These model integrations, executed in *Future Weather*, have been run with a high horizontal resolution of 10 km, and a realistic prescription of sea surface temperatures. The North Sea temperature is derived from satellite observations, which are only available after 1996. For October the general features in the observations - a gradient of wet conditions in the west and northwest of the Netherlands to drier conditions in the southeast – is represented in the model output (Figure 4).

Looking carefully, however, there are subtle differences between RACMO2 results and the observations. Some of these differences are due to the fact that we are comparing different time periods here; the model results are from 1996 to 2010 (because the high resolution sea surface temperature derived from satellites are only available after 1996) and the observations are from 1971-2000. But one feature which is likely not related to the difference in time periods is the location of the maximum precipitation. In the observations this maximum is extending approximately 10-20 km inland; in the model results it is at the coastline (in fact, precipitation amounts above sea are even higher). This feature is robust, and has for example also been found in model simulations for August 2006. In August 2006 precipitation amounts along the coast were 220 mm, which is three times the climatological mean. This precipitation maximum of 220 mm was reproduced by RACMO2, yet the location was shifted approximately 30 km seaward.

Analysis of August 2006 showed that the coastal precipitation was affected by the anomalous warm sea surface temperature of the North Sea. At the beginning of July sea water temperatures were more than 2 degree warmer than normal due to the long period of very warm weather in early summer. Model simulations with RACMO2 showed that the warm sea surface temperature increased coastal precipitation by approximately 30 % [Lenderink et al. 2009].

The observed long term in precipitation from 1950 to present also shows a wettening of the coastal area relative to the area further inland, in particular in (late) summer (see Figure 5). At the same time the North Sea temperature has increased by more than one degree. Although it is not proven that the relative increase in coastal precipitation is due to the temperature increase, this is likely to be the case considering the physics described above.

How will the trend in coastal precipitation continue in the future*? In Future Weather* we looked into results of a large ensemble of 19 regional climate model (RCM) simulations [Attema and Lenderink, 2011]. These regional models were run at a resolution of 25 km – twice as high as the 50 km resolution (four times as many grid cells) used for the KNMI'06 scenarios – for the period 1950

to 2100. This ensemble shows a rather wide range in future projections of the coastal effect. On average there is a small positive trend of approximately 2 mm month^{-1} by the end of this century. This appears small, but we note that with a coastal zone of 50 km as used here, the observed coastal effect in Autumn is also only about 9 mm month^{-1}. So, the median of the long term projected trend in summer (black line) is about 20-25% of the observed coastal effect in autumn (right axis in Figure 5).

Regional climate models show on average a small trend toward a wetter region near the coast in summer (compared to inland). Yet, the observed trend over the last decades appears much larger.

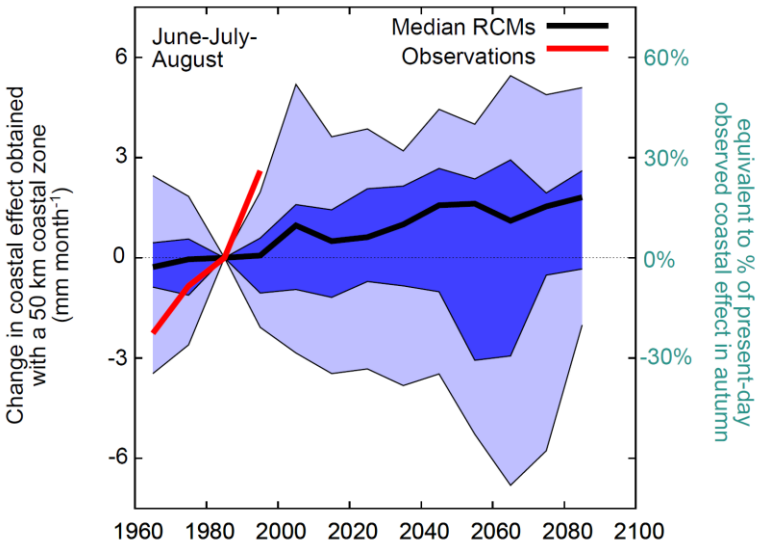

Figure 5. Time series of the coastal effect in precipitation with respect to 1990 in a large ensemble of regional climate models in comparison with the observed trend. Here, the coastal effect is defined as the precipitation in a coastal area (less than 50 km from sea) minus the inland precipitation (more than 50 km from sea); positive values indicate an increase in coastal precipitation compared to inland precipitation. For the model results the median of the regional climate models (black line), the spread given by 50 % of the models (dark blue area) and the full ensemble spread (light blue area) are shown.

The observed trend over the last 50 years (red line in Figure 5), however, is more than twice as large as the long term projected trend by the models. The trends in the RCM results (as well as the observations) are with respect to 1990. The strong divergence of the envelope of the model results near 1990 is due to natural variability. It is seen that the observed trend is just at the border of this envelope spanned by the RCM result. Therefore, although we think it is unlikely, we cannot rule out the possibility that the observed trend in coastal effect is almost entirely due to natural variability rather than a systematic trend.

There are several limitations of the RCM models that could aversely affect the projected trends. First of all, the most obvious limitation is the resolution. With

25 km the coastal effect is just resolved. Second, the regional models have been forced by sea surface temperatures directly derived from the global climate model simulations. These models, with a typical resolution of 200 km, hardly resolve the North Sea. Therefore, the quality of the sea surface temperature of the North Sea derived from these global climate model simulations is obviously doubtful. Third, coastal effects in precipitation heavily depend on convective precipitation – see photo of a convective cloud in the box on parameterization on the next page – and the dynamics of these convective clouds are not resolved by the model, but are represented in a simplified way.

In *Future Weather* we developed a version of RACMO2 with a high resolution of 10 km and the inclusion of a more realistic prescription of the North Sea. This was done by including a so-called slab ocean model into RACMO2. As shown in Figure 6, with the slab ocean model we are able to reproduce the satellite observations to a very good degree.

In the following project *Theme 6* we will use the slab model in long climate integrations with RACMO2. The goal is to further investigate how regional differences in precipitation may change in the future. Presently, these integrations are under way.

As said earlier, convective precipitation which plays an important role in coastal precipitation is not explicitly resolved by RACMO2 but parameterized (see box on parameterization). This causes problems with the phasing in space and time of convective precipitation. This is a general problem in present-day regional and global climate models. Despite this we note that RACMO results are generally close to the observations as shown for instance in Figure 4. In fact, in a recent intercomparison of 15 European regional climate models in the ENSEMBLES project, RACMO2 turned out to give the overall best performance for the reproduction of the present-day climate [Christensen et al. 2010].

Parameterization of convective clouds

Processes in convective clouds take place on scales from millimeters to several kilometers, but present-day regional climate models only resolve scales of 10 km and larger. Clearly something has to be done to represent these cloud processes that are not resolved, and this "something" is called parameterization. In a parameterization an estimate of the effect of the processes in convective clouds in terms of the quantities resolved by the model is computed. For instance, the transport of heat and moisture in the convective cloud is expressed as a *parameterized* function of the mean vertical gradients of heat and moisture in the atmosphere and a measure of vertical instability. These parameterizations are based on measurements and physical understanding; they can be rather complex and they appear to work reasonably well in the daily practice of numerical weather prediction. Yet, it is also known that in climate models parameterizations of clouds are responsible for a major, if not the largest, source of uncertainty. The spread in the response of the global mean temperature to a doubling of CO_2, the so-called *climate sensitivity*, in global climate models is *primarily* determined by uncertainty in cloud parameterizations [Dufresne and Bony, 2008]. Here, we look at a different aspect. The result of RACMO2 show that the lifetime of convective clouds is not well represented. Showers develop too strongly above the warm sea water and rain out too quickly. As a result the maximum precipitation amount in Autumn is located just above sea, whereas in the observations this maximum is above land.

These convective clouds are responsible for a major uncertainty in global and regional climate models. This is because they are very complex and only simplified prescriptions of their effect, so called parameterizations, are included in the models.

With a simple "slab" ocean model developed in *Future Weather* we are able to reproduce the temperature from satellite observations, and improve significantly on the sea surface temperature from ERA interim.

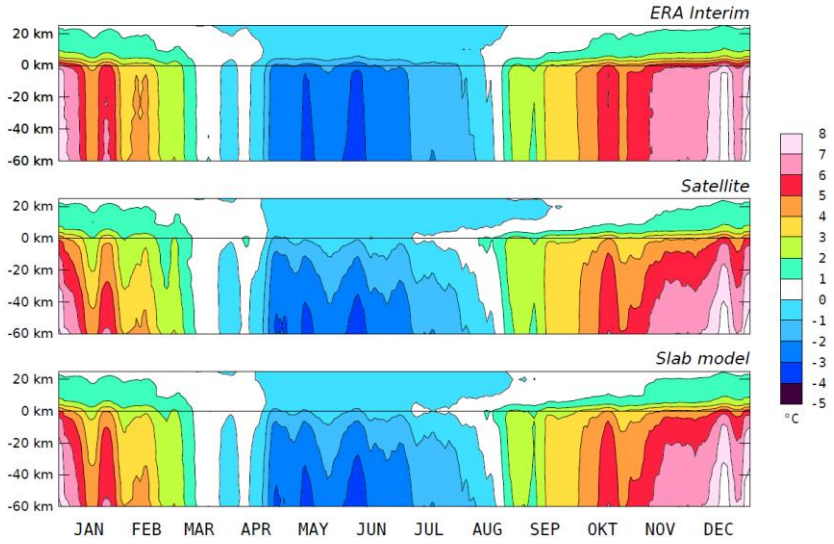

Figure 6. Climatology (average over 1996-2010) of temperature anomaly with respect to the average land temperature. The vertical axis is the distance to the coastline, with negative (positive) values over sea (land). Upper panel is based on the re-analysis (ERA-interim) of the European Centre for Medium Range Weather Forecasting (ECMWF); middle panel is the best estimate derived from high resolution satellite observations, and the lower panel is a simulation with the newly developed slab ocean model. The main feature of a relatively warm North Sea in autumn and winter, and a cold North Sea in spring and summer is present in all panels. Yet, the temperature gradients along the coast are weaker in the satellite observations and in the slab ocean model compared to those in ERA-interim.

Given these limitations of present-day (regional) climate models, it is of interest to investigate the behavior of a new generation of atmospheric models that explicitly resolves the organized turbulent motions in convection. These so-called non-hydrostatic models are, however, still in their infancy. The increase in recent years of computer power makes the application of these models now possible. Over the last several years they have been introduced into weather forecasting, and the first examples of applications in climate research are also emerging. In *Future Weather* we used the non-hydrostatic model RAMS to investigate the case of August 2006.

Precipitation in the very high resolution non-hydrostatic model RAMS compared to observations. Further development for this new model type is still needed

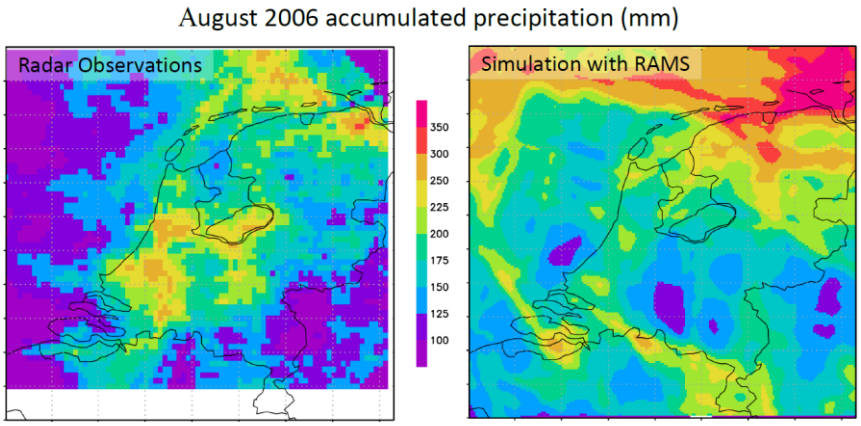

Figure 7. Observed (left) and modeled precipitation with the non-hydrostatic model RAMS (right) for the month August 2006. The observed precipitation is derived from rain radar data which is calibrated with observations of approximately 300 surface stations. Observations (far) above sea are unreliable.

Figure 7 shows the observed and modeled precipitation sum with RAMS for the month of August 2006 (Ter Maat, 2012). This run has been carried out using satellite derived sea surface temperatures. Simulated precipitation amounts are in the right order of magnitude. Yet, the model appears to have problems with the location of the precipitation maxima. This could be partly caused by the unpredictable (chaotic) behavior of convective clouds. Also, errors in the model and errors in the modeling setup are likely to be partly responsible. In general, the results are worse than those obtained with the hydrostatic model RACMO2 [Lenderink et al. 2009]. But, it is important to note that this is one of the first examples of the application of such a model in a climate mode. It is therefore likely that the results of these types of models will improve considerably in the near future.

Besides this experiment, the sensitivity of RAMS to the sea surface temperature and the land surface initialization has been explored. A considerable influence of the sea surface temperature is found, which confirms earlier results with RACMO2 [Lenderink et al. 2009]. Besides that, it was found that the timing and location of convection is dependent on the soil moisture initialization. These results deserve further investigation. Work on non-hydrostatic modeling will therefore continue in *Theme6*.

7 Local precipitation extremes

Extreme events of intense precipitation have a huge influence on society. They are associated with flooding, erosion, water damage, and may impact on transport and safety. It is commonly expected that precipitation extremes will increase as the climate warms.

The primary reason why precipitation extremes are expected to increase is that a warmer atmosphere can hold more moisture before saturation occurs. This increase in the *moisture-holding* capacity of the atmosphere with temperature occurs at a rate given by the Clausius-Clapeyron relation: approximately 7 % per degree temperature rise. If the relative humidity in the future climate remains approximately the same as in the present-day climate – which is generally expected based on model results and also physical arguments [see e.g. O'Gorman and Muller, 2010] – the amount of water vapour in the atmosphere will increase at the same rate per degree temperature rise. Now, the commonly used argument is that in extreme showers all water vapour in the air (or a constant fraction thereof) is converted to rain. Hence, extreme precipitation should follow the Clausius-Clapeyron (hereafter CC) relation.

However, despite the conceptual understanding as outlined above, there is no obvious reason why extremes should follow the CC relation exactly. For instance, changes in the dynamics of the atmosphere and the convective cloud, the vertical profile of the atmosphere, and the size of the convective cloud could well cause deviations from the CC scaling.

Figure 8 shows hourly precipitation extremes as a function of atmospheric humidity, where we took the dew point temperature as a measure of humidity

Dew point temperature
If we cool an air parcel (at constant pressure) then at a certain temperature condensation will occur. This temperature is called the dew point temperature, and is a measure of the *absolute* humidity of the air. An increase of one degree in dew point temperature is approximately equal to an increase of 7 % in absolute humidity as given by the CC relation. Another property of the dew point temperature is that if the temperature rises one degree, and if the relative humidity remains unchanged, then the dew point temperature will also rise one degree. The difference between the temperature and dew point temperature, sometimes called dew point depression, is therefore a measure of the *relative* humidity of the air. For the Netherlands dew point temperatures between 12 and 20 °C are common in summer. If the dew point rises above 20 °C it feels very humid and quite uncomfortable.

(see box). This figure is derived from data from approximately 30 stations over the Netherlands (1995-2010) and a long time series from Hong Kong (1886-2010). The data is first divided into bins of two degrees wide according to the dew point temperature. In each bin different extremes are computed. These are the 90th, 99th, and 99.9th percentiles, representing the precipitation intensity occurring once every 10, 100 and 1000 hours of precipitation.

Clearly extremes of hourly precipitation follow a stronger dependency on the dew point temperature in Figure 8 than predicted by the CC relation; they follow a dependency of approximately 14 % per degree for dew point temperature between 10 and 22 °C.

A 14 % per degree dependency of precipitation intensity on temperature has been found earlier for data from De Bilt [Lenderink and Van Meijgaard, 2008]. In *Future Weather* we looked at how robust this relation is. It turns out that by taking the dew point temperature instead of air temperature, a much more robust relation is obtained. As such, data from Hong Kong shows an almost identical relation between dew point temperature and precipitation intensity (see Figure 8). Similar results were also found for data from Switzerland and Belgium [Lenderink and van Meijgaard, 2010; Lenderink et al. 2011].

The intensity of extreme showers, as measured by hourly precipitation sums, follows a dependency of 14 % per degree. A doubling of intensity occurs each 5.3 degree temperature rise.

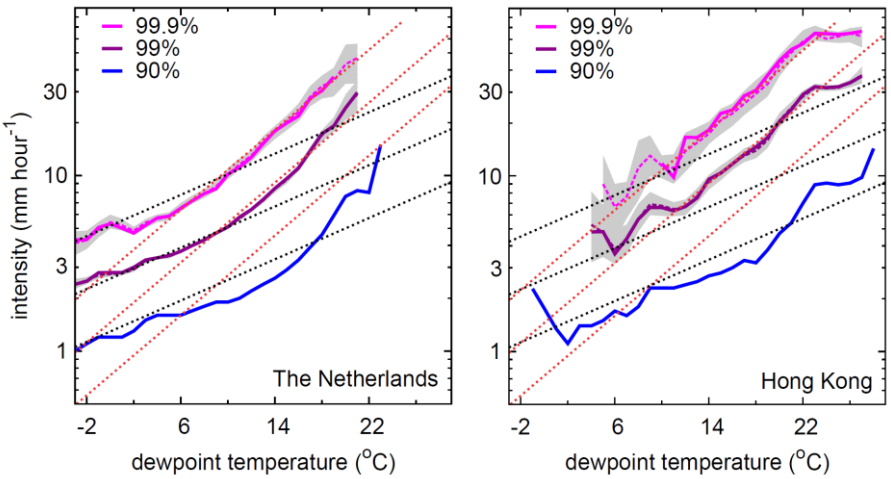

Figure 8. Extremes of hourly precipitation as a function of the dew point temperature in data from The Netherlands (left) and Hong Kong (right). The vertical axis is logarithmic, so that exponential relation of 7 % (black stippled) and 14 % (red stippled) per degree are straight lines. Shown are the 90th, 99th and 99.9th percentiles of hourly precipitation, which represent events that occur once per 10, 100, and 1000 hours of precipitation, respectively. The most extreme events presented, the 99.9th percentile level shown by the magenta line, reveal a dependency close to 14 % per degree over a large temperature range. The dew point temperature is taken 4 hours before each precipitation event to exclude the influence of the shower itself on the dew point temperature.

How could the scaling relations in Figure 5 be of guidance when considering climate change? The idea is roughly as follows:

- First, it is commonly found, and to some degree understood, that changes in relative humidity are relatively small as the climate warms. Exceptions are continental areas in summer where large scale drying out of the soil occurs. This plays a role in eastern and southern Europe, but for the Netherlands this is not likely a major factor, and this is confirmed in experiments with regional climate models [Lenderink et al. 2011]. Thus, we can safely assume that the relative humidity remains approximately constant. This implies that a temperature increase of say 3 degrees in summer by the end of this century is accompanied by a 3 degrees dew point temperature rise.
- Second, our simplified view of climate change is that each extreme precipitation event occurring in the present climate will occur under similar atmospheric conditions in the future climate, yet with the exception of the higher values of temperature and dew point temperature. By “similar atmospheric conditions” we mean, amongst others, similar atmospheric flow conditions (the high and low pressure systems) and vertical instability of the atmosphere. We then assume that the effect of humidity on precipitation intensity is captured by considering a fixed percentile, for example the 99% percentile, in Figure 8. (The latter assumption is not trivial, and there is some debate about this in the literature. We think, however, that there is reasonable support for this assumption.) This means that each extreme precipitation event follows approximately a 14 % per degree increase. Thus, taking the aforementioned 3 degrees warming, this implies that each extreme precipitation event in the present climate becomes $(1.14)^3 \approx 1.48$ times more intense in the future climate.

The intensity of extreme hourly precipitation is at present 10 to 15% higher than normal. This increase is very likely attributed to a warming of 1 degree in The Netherlands.

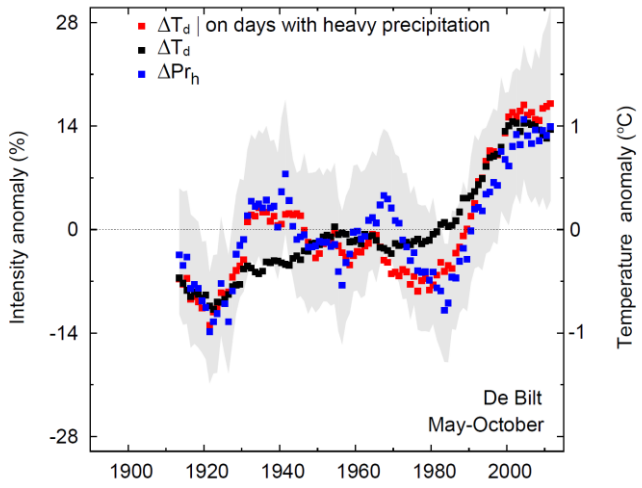

Figure 9. Time series of anomalies in extreme hourly precipitation (blue squares) in De Bilt in comparison with anomalies in dew point temperature on days with heavy rain (red dots) and the average dew point temperature (black dots). Results are averages from the period May to October. The grey band reflects the uncertainty in the estimates of the precipitation extreme anomalies (98 % range). Variations in rain intensity (blue) closely follow variations in dew point temperature (red), except for the period near 1970. Higher dew point temperature in recent years, closely tied to the observed warming of the Netherlands, have led to more extreme hourly precipitation.

In *Future Weather* we also looked at whether the dependency of hourly extremes on dew point temperature is already reflected in observed trends. The observed increase in temperature in the last 50 years is approximately 1 degree in the summer half year. As the relative humidity did not change much, this implies a one-degree rise in dew point temperature (black squares in Figure 9). We therefore expect an increase in hourly precipitation extremes of approximately 14 %, and this is indeed observed (blue squares). Moreover, there is a very close correspondence between long term variations in dew point temperature on days with heavy rain and variations in precipitation intensity; the blue and red squares in Figure 9 follow very similar variations. The optimal correspondence between the red and blue symbols is obtained with a dependency of precipitation intensity on dew point temperature of 10-14 % per degree (plotted in Figure 9 is 14 % per degree).

Finally, we investigate possible future changes of hourly precipitation extremes in regional climate model projections. Figure 10 shows the change, 2071-2100 with respect to 1971-2000, in hourly precipitation extremes in three model simulations. Two simulations are with the KNMI regional climate model RACMO2. Differences between these two are caused by the different global climate model simulations, ECHAM5 and MIROC, which are used to force the regional climate model. The other simulation is from a different regional climate model, CLM, which is forced by (again) a different global climate model. The results of the regional climate model simulations show a widely varying response from almost no increase in hourly precipitation extremes in CLM to a very drastic increase of +60-80% in RACMO2 driven by MIROC.

An analysis of these regional climate model projections showed that a major part of the spread in outcome can be explained by how precipitation extremes in the model respond to humidity changes. In general, RACMO2 appears to capture the observed relations between hourly precipitation extremes and humidity (such as shown in Figure 8) better than CLM. Yet, both models appear to misrepresent the observed dependencies for high values of temperature and dew point temperature.

Extremes of hourly precipitation in the regional climate models are primarily determined by parameterization schemes, in particular those involved with convective clouds (see box in Section 6). The results in *Future Weather* suggest

Regional climate model simulations show a wide range in projected increases of hourly precipitation extremes for the end of this century: from almost no increase (left) to +60-80% (right panel).

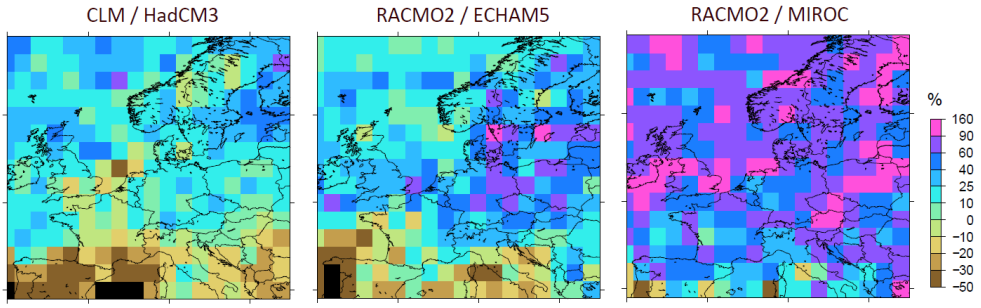

Figure 10. Change in hourly precipitation extremes in summer derived from three different regional climate model simulations (RCM name / GCM driver). Changes are in percentage between 2071-2100 and 1971-2000. The block pattern is not the native model resolution (which is 25 km), but results from the analysis technique where changes in 2° by 2° (latitude-longitude) blocks are computed at the same time.

that the ability of these schemes to represent the essential physics involved with intense precipitation is limited.

Future scenarios of hourly precipitation extremes based on present-day climate modeling results are therefore not very trustworthy. In the following KvK program "*Theme 6*" we will therefore investigate precipitation in a new generation of climate models. These models are based on so-called Non-Hydrostatic (NH) dynamics, that operate on approximately 2 km resolution and which start to resolve the dynamics of convective clouds.

We could use the observed relation in Figure 8 to establish future scenarios. Of course, such an extrapolation should be considered with care, but we think it is useful to present it alongside the modeling results. The increase in mean summer temperature in the KNMI'06 scenarios for the end of this century ranges between +1.7°C and +5.6°C. With the found dependency of 14 % per degree, and assuming constant relative humidity, this implies that hourly precipitation extremes could increase between +25 and +108 %. A doubling of precipitation intensity by the end of this century therefore appears possible.

8 Two recent events of extreme precipitation

8.1 26-27 august 2010

On the 26th and early morning of 27th of August 2010 a series of showers produced more than 130 mm of rain in the eastern part of the Netherlands. This caused severe local flooding, and the return value of this event has been estimated to be more than 1000 years [Brauer et al., 2011]. These showers were embedded in a frontal system that approached from the southwest (Figure 11).

24 hours with rain resulted in severe flooding in the eastern part of the Netherlands

To understand this type of precipitation extreme it is important to know where the water that rained out during this event originated from. In summer the atmosphere typically contains 20 to 30 litres of water per m^2, in the form of water vapour, when integrated from the surface to the top of the atmosphere. Converted to rain this is equivalent to 20 to 30 mm. Therefore, it is clear that in this case only part of the rain that fell was contained locally in the atmosphere,

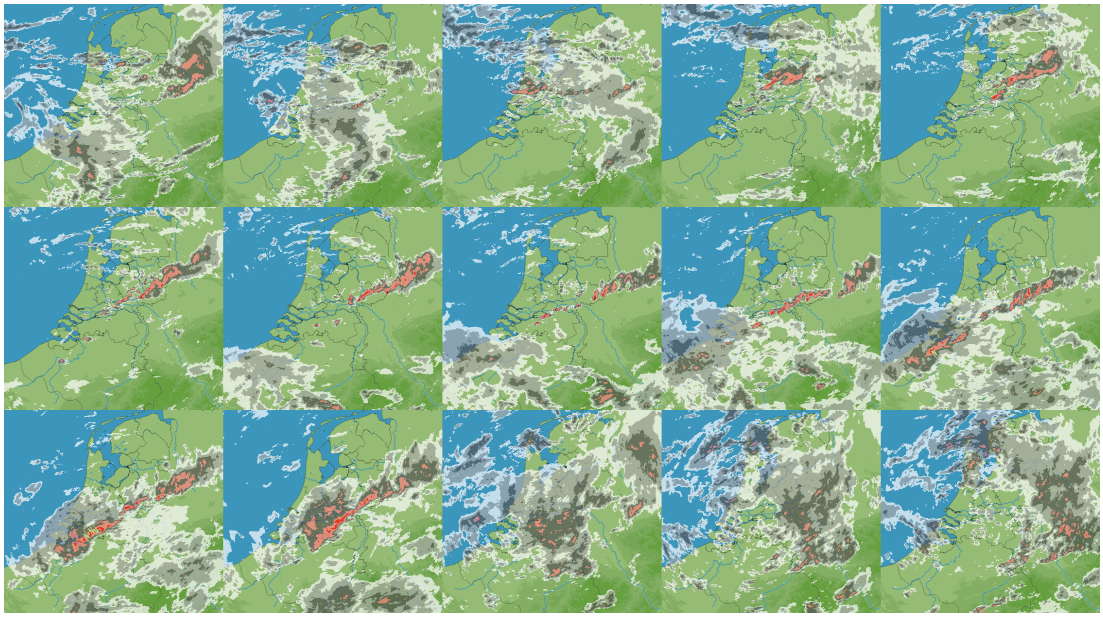

Figure 11. Rain radar images running from 1200 local time (LT) 26 August 2010, with steps of one hour (left-to-right, top to bottom) until 0200 LT 27 August. A relatively thin line of high precipitation intensity (red colours) oriented in the southwest-northeast direction, and slowly moving in the northeast direction, is embedded in a larger area with lighter precipitation (white and grey colours). During this event more than 130 mm of precipitation fell in the eastern part of the Netherlands.

and that the transport of water vapour by the atmospheric motions must have been important.

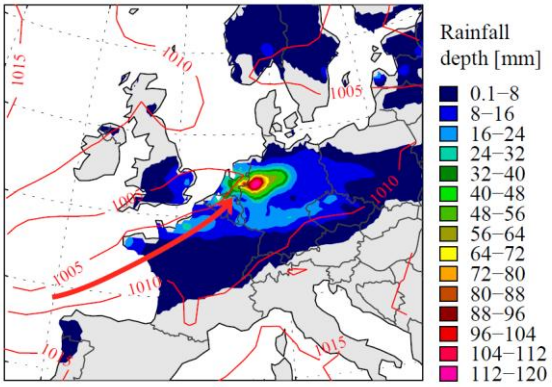

Figure 12. Accumulated precipitation and atmospheric surface pressure on the 26th of August 2010 (reproduced with permission from Brauer et. [2010]). The red arrow shows the transport of warm and moist air at the south side of an elongated low pressure system. We note that a simulation of the regional climate model RACMO for this case underestimated the maximum precipitation amount by approximately 30%, which is likely caused by the underrepresentation of the convective rain band as shown by the rain radar images.

A further analysis of this case showed that a substantial part of the rainwater originated from the subtropics (Figure 13). The transport of water vapour from the subtropics occurs in so-called atmospheric rivers. These are narrow bands of high atmospheric humidity, and they occur under specific atmospheric circulation conditions. In this case an elongated low pressure system southwest of the British Isles channeled the transport of warm and moist air from the subtropics to the Netherlands.

Thus, for this extreme event a clear connection between water evaporated in the sub-tropic and rainfall in The Netherlands has been established. This connection is through atmospheric rivers, the occurrence of which are highly dependent on the atmospheric flow conditions.

From our understanding of this event, and considering the other findings in *Future Weather*, what can we say about how this event would look in the future? This is an interesting case as several scales and processes appear to apply here:

1. This extreme is connected to a frontal system belonging to a synoptic low pressure system. Results in Section 4 (not explicitly shown here) and results from the literature [O'Gorman & Schneider, 2009] imply

that we could expect a 3-7 % increase per degree temperature rise for these type of large scale extremes.

2. Embedded in this larger scale system is a small band of convection. Results in Section 7 show that a 10 to 14 % increase in intensity of these convective showers appear reasonable, which is much higher than the aforementioned 3-7 % increase for large scale extremes. The dew point temperature during this event was about 17 °C, and during two hours more than 20 mm fell. As a major part of the precipitation sum fell in these intense convective showers, it appears that convective scaling could be applicable for this event.

3. It is unclear how the transport of moist air from the sub-tropics could change. On the one hand, this is dependent on whether and how the atmospheric circulation changes. On the other hand, as the climate warms – and in particular the subtropical Atlantic ocean - the area with warm and moist air in the subtropics moves northward. Thus, in the

An atmospheric river channels moisture from the subtropics to the Netherlands

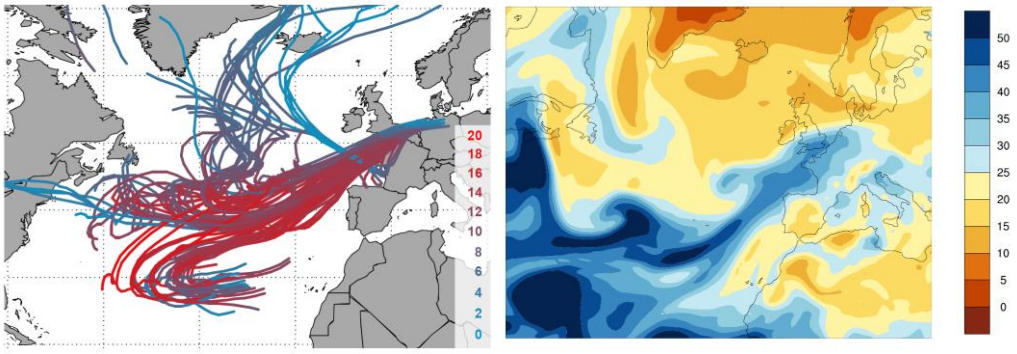

Figure 13. Left: Tracking of air parcels that produced the heaviest rain on the 26th. Moist parcels are red, whereas drier parcels are cyan. It is shown that a large part of the moist parcels originated from the sub-tropics. Right: vertically integrated water vapor content of the atmosphere (in units of kg/m^2, equivalent to mm's of rain when all water vapor is converted to rain). A small band – an atmospheric river – transports very moist air from the subtropics to the Netherlands.

future the Netherlands will be closer to the source of moist air and therefore this type of event could occur more frequently and/or become more intense. This might lead to unexpected changes.

To summarize, as different processes on different temporal and spatial scales played a role in this event, it is hard to project how it could change in the future under global warming. We think it is likely that the precipitation amount will increase between the large scale scaling of 3-7 % per degree warming and the local convective scaling of 10-14 % per degree. In the following project *Theme 6* we will look more in detail how these intermediate scale precipitation extremes could change. In addition, the possibly stronger influence of the subtropics on our climate (through atmospheric rivers) could give rise to unforeseen changes.

8.2 28 June 2011

The showers that occurred on the 28th June 2011 were extraordinary. In Vught, located 15 km north of Eindhoven, a downburst associated with these showers caused severe wind damage, and further north in Herwijnen 79 mm of rain fell in one (clock) hour, between 2000 and 2100 local time. It turns out that this hourly precipitation sum was the highest recorded at any observational station in the Netherlands (Figure 1 in the Introduction). Notably, the 4 highest observations were all recorded in the last 10 years. Despite the fact that the station density in the last 15-20 years is higher than before, this is a remarkable finding.

The time evolution of temperature, dew point temperature and 10 minute precipitation is shown in Figure 14. It is shown that just before the shower the temperature was around 30 °C. But more importantly, with a dew point temperature of close to 23 °C in the last few hours before the shower the absolute humidity of the air was unusually high for the Netherlands. At the onset of the shower the temperature dropped by almost 10 degrees in 10 minutes time. Also the dew point temperature decreased by several degrees, but not as dramatically as the temperature itself. The drop in dew point temperature, hence absolute humidity, is most likely caused by the transport of drier air from aloft to the surface due to the turbulent motions of the convective cloud.

The high value for the dew point temperature, and the high vertical instability of the atmosphere caused by a frontal zone approaching from the south west, resulted in heavy convection and strong precipitation. During three 10 minute intervals precipitation amounts were approximately 20 mm.

With high afternoon temperatures, and a dew-point near 22 °C, conditions for heavy precipitation were favorable.

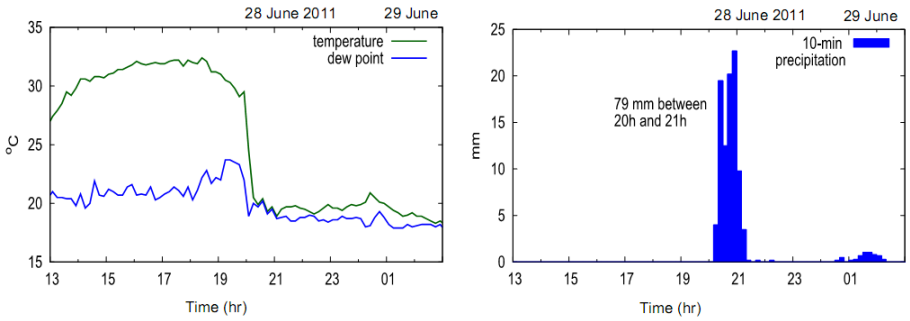

Figure 14. Time evolution of temperature and dew point temperature (left) and 10 minute precipitation (right) observed at Herwijnen on the 28th of June 2011.

Finally, we discuss how such an event could change in the future. In Section 7 we showed that hourly precipitation extremes are generally expected to increase at a rate of 10-14 % per degree. However, the results from Hong Kong presented in Figure 8 show that the increase in intensity with dew point temperature breaks down at a dew point of 23 °C. For higher dew point temperatures the intensity does not increase further with temperature. It is not known whether such a limitation also exists for the Netherlands, although this appears likely. As the dew point temperature in this event is close to the threshold of 23 °C, we may expect no further increases of the intensity with global warming.

Yet, the event on 28th June 2011 could be viewed as a prototype of events that may occur more frequently in the future climate. In the present climate the far majority of extreme convective precipitation occur for dew point temperatures below 20 °C. With a typical predicted warming at the end of this century for western Europe of 3 °C, many more precipitation events will occur close to the threshold of 23 °C. From the present-day distribution the estimated increase in frequency is approximately a factor 5. This could imply that events like “Herwijnen” will be become a much more common feature of summer time precipitation by the end of this century.

9 Outlook

What did we learn in this project, what are the limitations, and what should be further explored? Here we summarize these points:

1. For large scale precipitation extremes connected to synoptic scale (>500 km) low pressure systems which occur mostly in the winter season, it was shown that the role of natural variability is large even on a 30-year time scale. When the natural variability was averaged out, it turned out that extremes increased at a rate similar to the mean precipitation change in winter. Typical increases are 3-7 % per degree warming, which are consistent with the KNMI'06 scenarios.

2. For the present-day climate, It was shown in that the probability of a NNW storm surge is larger after a period of 5-20 days of extreme precipitation in the Rhine catchment than climatology. The probability of a simultaneous occurrence of a high river discharge and NNW storm surge could be a factor 4 higher than in the case that these events are independent (as commonly assumed). This could have considerable implications for the safety norms. Yet, we would also like to note two limitations of this study. First, these results are obtained in a model with relatively coarse resolution. Second, in order to have sufficient statistics we could only look at moderate extremes occurring approximately once a year.

3. A small tendency towards a wetter coast in summer has been found in a large ensemble of regional climate model integrations. At the end of this century this increase in coastal effect is about 30 % of the observed present-day coastal effect in autumn. However, major drawbacks of these results are the relatively coarse resolution (25 km in the model ensemble) and the prescribed temperature in the North Sea. In addition, the observed trend over the past 50 years already exceeds the predicted value for the end of this century. It is not know whether this is a systematic trend, or part of a natural variation. Here, we further developed the KNMI regional climate model towards an even higher resolution (10 km) and included a more realistic prescription of the North Sea to be able to study these questions in the next project *Theme 6*.

4. For hourly precipitation intensity on a local scale, we found more evidence for a 10-14 % increase per degree warming. In recent years, the

intensity of summer showers appears to be 15 % higher than before 1990, which is likely attributed a one-degree warming of the Netherlands. Extrapolating this relation to the future, increases of up to 100 % in intensity appear possible by the end of this century (with a warming of 5 degrees, which is approximately the upper range in the KNMI'06 scenarios).

Whether we can extrapolate observed relations to such high temperatures is obviously uncertain – although results from Hong Kong suggest that it may work reasonably well – and therefore we also looked for evidence in regional climate models. Unfortunately, models appear to be very uncertain at predicting changes in hourly extremes with changes between close to zero and up to 60-80%. What is even worse is that the models fail to reproduce the observed relations for high temperatures, casting serious doubt on their ability to predict future changes. A major cause of these model deficiencies is related to the fact that these model do not resolve the physics of convective clouds that give rise to extreme precipitation intensities; instead they use simplified prescriptions, so-called parameterizations. These parameterizations of cloud processes are still one of the major sources of uncertainty in climate model projections, not only on the regional scale but also on the global scale [Dufresne and Bony, 2008]. In *Theme 6* we will therefore continue this work in a atmospheric model in which convection is explicitly resolved.

5. We studied precipitation extremes on two totally different scales: local intensity on an hourly time scale and multi-day precipitation on a scale of hundreds of km. In between there is a whole range of time and spatial scales, which are relevant for different users such as, for instance, the water boards. The event on the 26-27 August 2006, as discussed in this report, underlined the importance of these intermediate scales. We do not have sufficient insight into how these intermediate-scale precipitation extremes could change. They are affected by processes acting on different scales. Convective processes are likely to give rise to increases in the order of 10-14 % per degree warming, yet large scale processes give rise to changes that are 2-3 times smaller. In addition, the influence of non-local processes, such as the occurrence of atmospheric rivers channeling moist air from the sub-tropics to our regions, are poorly understood and could give rise to unforeseen changes. These intermediate scales are therefore a real challenge. In the project *Theme 6* we continue this research. However, we also note that, given the complexity and the early state of understanding and modeling of the processes involved, much research is still needed.

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To develop the scientific and applied knowledge required for Climate-proofing the Netherlands and to create a sustainable Knowledge infrastructure for managing climate change

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