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Climate change in the Netherlands

Supplements to the KNMI'06 scenarios

Contents


ROTTERDAM

Abstract

The general scenarios for future climate change in the Netherlands, which KNMI issued in 2006, are not overruled by recent scientific developments. Also according to the present-day knowledge, the four KNMI'06 scenarios together describe the most likely changes in the Netherlands, including associated uncertainties. This conclusion emerges from an evaluation of research from the past few years, in which specific attention has been paid to the consequences for climate change in our region.

Important recent scientific developments include: the observed rapid warming of the Netherlands and Western Europe, the observed rapid decrease of large ice sheets on West-Antarctica and Greenland, and new research on precipitation patterns on the local and regional scale. This research is no reason to change the KNMI'06 scenarios now. Our assessment is that the changes, as far as they can be determined now, fall largely within the four KNMI'06 scenarios.

Recent results indicate which scenarios are more likely than others. The rapid warming in the Netherlands and Western Europe is best accounted for in the W/W+ scenarios. The increase in the intensity of heavy showers is well described in the G/W scenarios. Besides possible long-lasting periods of drought, as in the G+/W+ scenarios, periods of wetness will likely occur more frequently, as in the G/W scenarios, in particular in the coastal zone.

Existing uncertainties have become more transparent by new research. There are indications that climate change may be more extreme than anticipated. Extreme scenarios (sometimes called 'worst case' scenarios) can be useful if the risks are large, for example if the safety of the coast is at stake, as for the Delta Committee. However, relatively little scientific evidence exists for these extreme scenarios. For example, it is unclear whether the accelerated melt of the Greenland and West-Antarctic ice sheets will continue (and if yes to what extent). The KNMI'06 scenarios describe the most likely sea level rise along the Dutch coast. There is no reason to change these scenarios now.

The recent results provide guidance for the follow-up research that must lead to a next generation of KNMI climate scenarios for the Netherlands around 2013, following on the fifth IPCC report which will be published that year. It has become more clear which aspects of climate models are useful for the prediction of local climate change in the future, where improvements are possible and necessary, and which related choices need to be made.

Finally, this publication provides scenario information for the transition seasons (spring and autumn) and for the individual months, together with probabilities for extreme showers under both present and future climate conditions, to complement the KNMI'06 figures published earlier. In addition, a toolbox is made available which generates complete time series of climate variables that match each of the four KNMI'06 pictures of the future.

Changes in the climate of the Netherlands according to the KNMI'06 scenarios

- temperature will continue to rise; mild winters and hot summers will become more common;
- on average, winters will become wetter and extreme precipitation amounts will increase;
- the intensity of extreme rain showers in summer will increase, however the number of rainy days in summer will decrease;
- the calculated change in wind is small compared to the natural fluctuations;
- the sea level will continue to rise.

1 Introduction

1.1 Objective and contents

The KNMI'06 climate scenarios (Van den Hurk et al., 2006) are three years old by now, and frequently used in studies on the impacts of climate change in the Netherlands and adaptation to these changes (*Figure 1*). They provide guidance for the policy of local, provincial and national governments in the area of, among others, spatial planning, national security and water management. The scenarios are part of the National agreement on water management (NBW-Actueel), the climate agreement between the Provinces and the State, the advice of the Delta Committee, and the Draft National Water Plan.

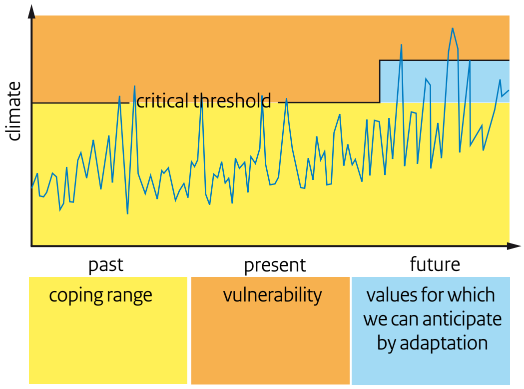

Figure 1. *Schematic diagram for adaptation to climate change. Adaptation is the accommodation of natural systems and societal sectors to the effects of climate change. The diagram illustrates how the critical threshold shifts to higher values as a result of adaptation measures. In this way, society is better prepared to deal with higher values of, for example, precipitation amount. Source: Willows and Connell (2003).*

However, the development of knowledge about the climate system and the changes therein continues. In an international context, KNMI participates in research on climate change with the aid of models and observations. KNMI has recently developed the global climate model EC-Earth, increased detail in the regional climate model RACMO, and intensified the monitoring of the climate using station observations and satellites.

The next generation climate scenarios for the Netherlands is planned for about 2013

The next generation climate scenarios for the Netherlands is planned for about 2013. This brochure draws up the balance sheet by:

- assessing the implications of recent research results (in the areas of observations and modelling) for the application of the KNMI'06 climate scenarios of 2006 (Chapters 2 and 3);
- presenting additional data on future climate change in the Netherlands in response to questions from society (Chapter 4), and;
- outlining the roadmap towards the next generation of KNMI climate scenarios for the Netherlands (Chapter 5).

1.2 KNMI'06 climate scenarios

Climate scenarios are consistent and plausible pictures of the future climate. They are intended as a tool for climate impact studies and adaptation measures. The KNMI'06 scenarios provide four pictures of climate change in the Netherlands around 2050 and 2100 (relative to the period 1976-2005). Together, these four scenarios describe the most likely changes with accompanying uncertainty for important climate variables, such as temperature, precipitation, wind and sea level.

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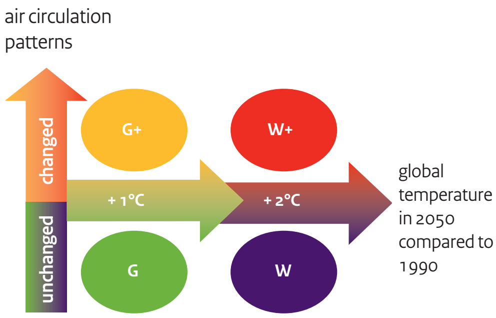


Figure 2. *Classification of the four KNMI'06 climate scenarios.*

The KNMI'06 scenarios have been constructed by combining information from global and regional climate models from all over the world. In these models the scientific knowledge on the operation of the climate system is brought together. Observations have been used to assess which global and regional climate models best describe the climate of Western Europe. Additionally, observations have been used to translate the changes of model variables into local weather characteristics that are relevant for users, such as the warmest summer day per year or the daily extreme precipitation amount occurring once every 10 years.

The scenarios differ in the degree of global temperature rise and the degree of change in atmospheric circulation patterns above the Netherlands (**Figure 2**). The W/W+ scenarios are characterised by a strong increase in the global mean temperature, whereas this increase is moderate in the G/G+ scenarios. In the G+/W+ scenarios, a change in the atmospheric circulation above the Atlantic Ocean and Western Europe leads to extra warm and wet winters (**Figure 3**), whereas the summers are extra warm and dry. In the G/W scenarios, the influence of circulation changes is small.

The KNMI'06 climate scenarios portray a plausible and coherent picture of climate change in the Netherlands. They show that the likely changes in extreme weather events are different from changes in the average weather.

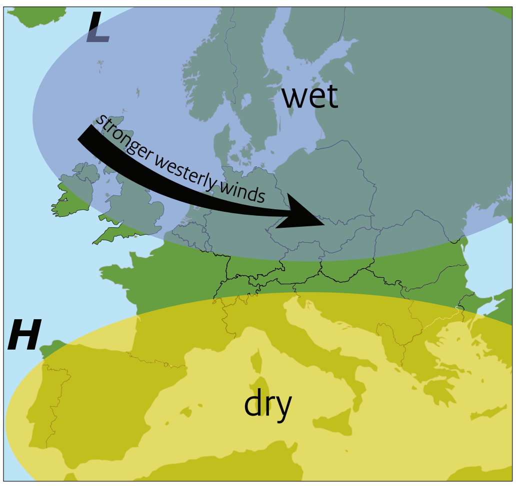
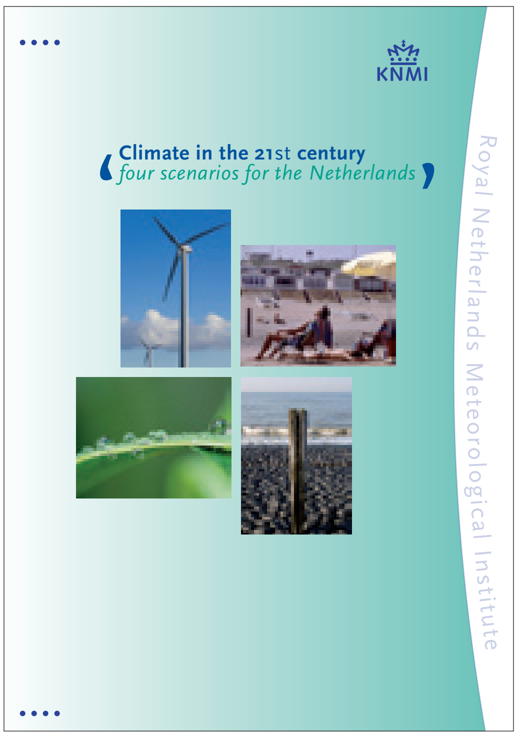


Figure 3. *Change in atmospheric circulation patterns in the G+/W+ scenarios for winter.*



The KNMI'06 scenarios assume that the regional differences in the climate of about 2050 and 2100 will be similar to the differences that already occur in the present-day climate.

For example, in the scenarios with changes in the atmospheric circulation the temperature increase on heat wave days is stronger than on average summer days. Summer precipitation occurs less frequently in these scenarios, but heavy showers that do occur become more intense.

The Netherlands is characterised by regional differences in climate. However, in the KNMI'06 scenarios no regional difference is made in climate change. In other words: the projected changes in the north are the same as in the south. Also, no local urban heat island effects are included. The changes in the city are the same as in the countryside. Potential changes in regional differences and urban heat island effects could not be determined well, or were small compared to the spread between the different scenarios. The KNMI'06 scenarios assume that the regional differences and the urban heat island effects in the climate of 2050 and 2100 will be similar to the differences that already occur in the present-day climate.

Predictability at the medium range time scale (10 to 20 years)

Climate scenarios typically have a time horizon of 50 to 100 years. In that respect, they differ from weather forecasts, which reach ahead until 10 days and seasonal forecasts which reach ahead until one year. However, the time horizon is not the only difference;the type of information also differs. Climate scenarios are not concerned with predicting the weather on a certain day or in a certain season, but only with the average weather and the probability of extremes in the long run ***(Figure 4)****.*

For the intermediate range, decadal predictions are currently under development. These are predictions for fluctuations in the climate in the next 10 to 20 years. They are made on the basis of slow natural climate fluctuations, expected concentrations of greenhouse gasses and particulate matter (aerosols), and a correct assessment of the initial conditions. Research on the quality of these predictions is ongoing.

Slowly varying components of the climate system form the physical basis for decadal predictions. The oceans, sea ice, snow and soil moisture provide 'memory' in the climate system. If the present conditions of these components can be determined (by observations), if the likely evolution is known, and if we understand how they affect the weather, meaningful predictions could be derived. This applies in particular for the state of the tropical ocean and the Atlantic Ocean. Observations with buoys in the oceans are being used to produce and verify decadal predictions.

Clearly, also the steadily increasing amount of greenhouse gasses in the atmosphere provides an important contribution to the predictability on time scales of 10-20 years. 'Warmer than at present' is a skillful prediction almost everywhere. The rate of warming, the associated uncertainty margins, and other changes, will become more clear when decadal predictions have been developed further. Remaining unknown factors are the activity of the sun and volcanic eruptions, because these are unpredictable.

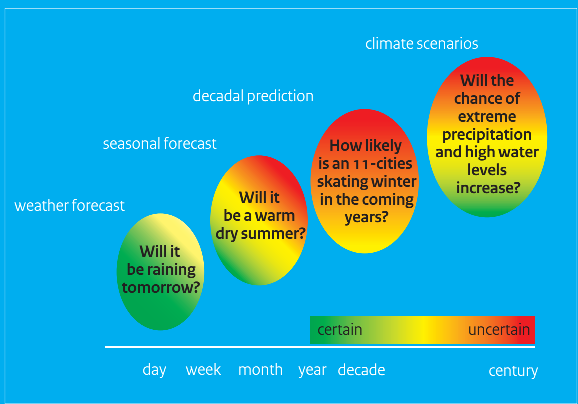
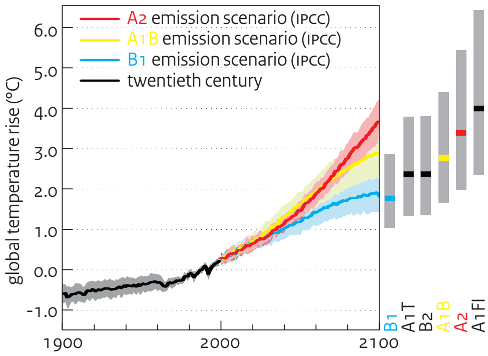


Figure 4. *Schematic diagram of the difference between weather forecasts, seasonal forecasts, decadal predictions and climate scenarios. The uncertainty in the prediction is indicated with colours, varying from green (certain), via yellow to red (uncertain). The differences between the predictions are not only caused by the fact that the time horizon differs, but also because the type of information is different. Weather forecasts say something about a particular day, whereas scenarios sketch out the possibilities over a longer period of time. In between are seasonal forecasts and decadal predictions, which describe the chances of future events in particular seasons and decades. The text in the circles provides an example of a typical user question.*



***Figuur 5.** Increase in global mean temperature (relative to the average between 1980 and 1999) as calculated with a large number of global climate models under different IPCC emission scenarios (A2, A1B, B1). To the right are the best estimates for 2100 for all IPCC emission scenarios (B1 until A1FI), with the mean value of all calculations indicated by the horizontal dash, and the band of likely (> 66% chance) model outcomes in grey. Source: IPCC, 2007[1].*

[1] *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure SPM.5. Cambridge University Press.*

1.3 Relation with IPCC emission scenarios

Climate models make use of projections of future emission of greenhouse gasses and particulate matter (aerosols). Associated with these projections are story lines of how the world population, economy and technology will develop. These emission scenarios cannot be coupled one-to-one to the KNMI'06 climate scenarios.

The model calculations in ***Figure* 5** are performed for the 2007 report of the Intergovernmental Panel on Climate Change (IPCC, 2007), the panel of the United Nations that periodically assesses and summarizes the knowledge of the climate in support of policy making. The different climate models each show a somewhat different response of the climate system – the climate sensitivity – to the emission of greenhouse gasses. By considering all these different models and emission scenarios, an impression of the emission and model uncertainty is obtained. Around 2050, the differences in the global mean temperature rise between the different emission scenarios are relatively small (about 0.5°C) compared to the bandwidth of model projections for the same emission scenario (about 1°C). The bands of calculated temperature rise per emission scenario overlap largely. This implies that the biggest uncertainty in 2050 is due to the limited knowledge of the climate system, and the associated differences in model calculations of the climate sensitivity. For 2100, the different emission scenarios show a more clear distinction, but the range for each emission scenario is at least as wide due to the uncertainty in climate sensitivity. Because KNMI intended to cover a large part of the total uncertainty with the climate scenarios, global temperature rise has been chosen as starting point for the scenario classification rather than emission scenarios.

By means of the global mean temperature, an indirect relation between the KNMI scenarios and emission scenarios can be identified. Each of the four KNMI'06 scenarios may occur under each IPCC emission scenario for 2050. For 2100, the G/G+ scenarios (2°C global temperature rise) are most representative for a low B1 emission scenario under an average estimate for the climate sensitivity, whereas the W/W+ scenarios (4°C rise) are representative for a high A1FI scenario.

Each of the four KNMI'06 scenarios can occur under each IPCC emission scenario for 2050.

1.4 Uncertainties and probabilities

Like almost every prediction for the future, predictions of the future climate in the Netherlands are also uncertain. This comes about by:

- uncertainty about socio-economic developments, and the associated uncertainty about emissions of greenhouse gasses and particulate matter and about land use;
- uncertainty due to external factors, such as solar activity and volcanic eruptions;
- model uncertainty due to limited knowledge of the climate system and limited computer power;
- uncertainty due to possible chaotic (strongly nonlinear) behaviour of the climate system (internal variability).

Because of the uncertainties we develop scenarios rather than predictions.

Because of these uncertainties we develop scenarios rather than predictions. The four KNMI'06 scenarios have been developed as a generic set for a wide group of users. Together, they cover a wide band of possible changes. Based on the current knowledge they describe the bandwidth of most likely outcomes. More precise probability statements about the future climate in the Netherlands are not yet possible.

Extreme scenarios

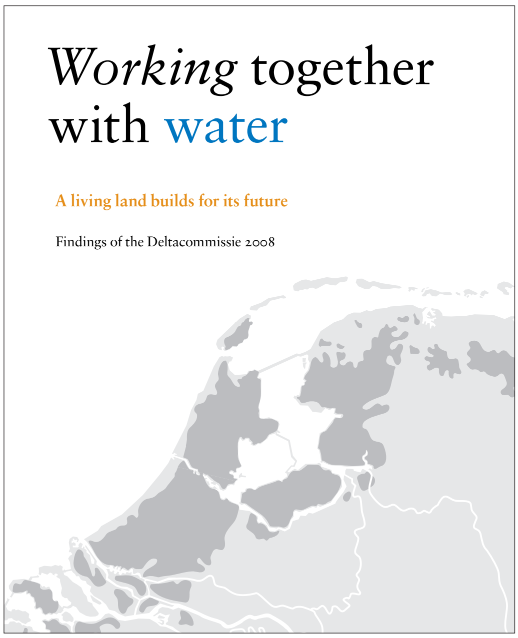
Due to various causes climate change can eventually evolve less extreme than presently foreseen or more extreme. The latter can occur gradually as well as suddenly (this means within several decades). For example, the greenhouse gas emissions could increase faster than in the most extreme IPCC emission scenario. Also, the global temperature rise can be higher than the upper limit that is now projected, because of a higher climate sensitivity than expected. Large sudden changes can occur if critical thresholds (so called 'tipping points') are exceeded, for example by release of methane from the ocean floor or tundra areas, by the disappearance of ice sheets on Greenland and West-Antarctica or by the melt of the polar ice at the North Pole during summer (Lenton et al., 2008).

Climate scenarios reflect the scientific knowledge of a particular moment in time. Absolute lower or upper boundaries, for example for temperature rise or sea level rise, cannot be provided. Generally, the more extreme the scenario is, the lower the probability that the scenario will become reality. But also extreme climate changes with low probability but large impacts can be important. In a risk approach (in which risk is defined as probability × damage), additional and more extreme scenarios than the KNMI'06 scenarios can be required, dependent on the type of investment and the time horizon to which the investment applies. In a cost benefit analysis or a vulnerability analysis, for example answering the question at what point in time standing policy is no longer adequate, a whole spectrum of possible climate changes can be required. For specific users and applications KNMI and other parties have developed additional climate scenarios.

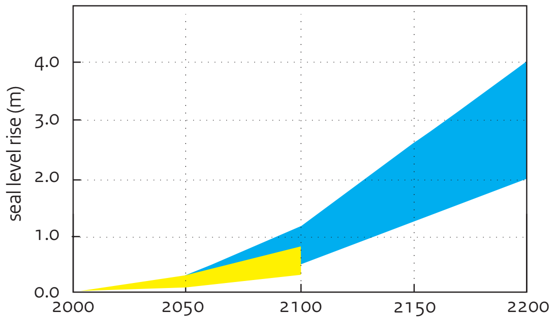
By introducing probability statements in the next generation KNMI climate scenarios it is in principle possible to position extreme scenarios beside the general scenarios. In June 2009, a new generation of climate change scenarios has been issued in the United Kingdom, in which probability statements are provided for different climate variables on a local scale (Jenkins et al., 2009). These probability statements do not include the total uncertainty. Many of the above mentioned extreme scenarios are still left out, because they are not included in the model simulations. Also, only a limited set of emission scenarios has been used. Besides, it is unclear how the probability information for different variables must be combined, for example to determine the joint probability of temperature and precipitation extremes.

In about 80% of the model calculations that have been used by the IPCC, the global mean warming for the used emission scenarios in 2050 is between 1°C and 2°C (relative to 1990). These values have been chosen as the starting points for the G/G+ and W/W+ scenarios, respectively. However, the climate in the Netherlands does not depend solely on the global temperature rise, but also on regional and local processes, such as the changes in the air circulation patterns. These regional and local processes introduce additional uncertainty, which can only be quantified to limited extent at this moment. This implies that no exact statement can be made about the bandwidth of the four KNMI'06 scenarios when taken together.

However, when developing the KNMI'06 scenarios, attention has been paid that at least two thirds of the model results for the seasonal mean temperature and precipitation changes in our region is covered



by the four scenarios. For other variables, such as evaporation, wind and sea level, and for changes in extremes, such quantitative conditions have not been set, because of lack of model results or because model results were deemed insufficiently reliable. For these variables the bandwidth of the changes has been estimated on the basis of the model spread and understanding of the changes.



***Figuur 6**. Scenarios for sea level rise. The predicted increase in sea level for the Dutch coast in 2050, 2100 and 2200 (baseline year is 1990, effects of soil subsidence not included). Source: Delta Committee (2008).*

The Delta Committee scenario depicts a 'plausible upper limit' and in that respect can be positioned as an extreme scenario supplementing the KNMI'06 scenarios which describe the most likely outcomes.

1.5 Relation with Delta Committee scenarios

After the publication of the KNMI'06 scenarios, various more extreme climate scenarios have been published, each with their own objective. The Delta Committee (2008; see also Kabat et al., 2009) issued a climate scenario for local sea level rise which according to their information is intended as 'reference for long-term (2100 and later) robustness test of required measures and investments'. In view of this objective, the Delta Committee has determined a 'plausible upper limit' for the sea level rise. KNMI has contributed substantially to this work (Katsman et al., 2009).

For 2050, the Delta Committee makes use of the KNMI'06 scenarios, but for 2100 there are differences (***Figure 6***). The main difference is the estimate of the contribution of the melting and calving of the ice sheets of Greenland and Antarctica. The Delta Committee emphasises the upper limit of the possible melt and this limit is significantly higher than the most likely contribution that KNMI accounts for in the KNMI'06 scenarios.
Also, the starting point of the Delta Committee is a global warming of 2 to 6°C in 2100, the band width of the IPCC calculations for A1FI in ***Figure 5***, whereas the KNMI'06 scenarios start from a more likely global warming of 2 to 4°C in 2100 (relative to 1990). This yields additional expansion of ocean water in the Delta Committee scenarios and consequently additional sea level rise.

The Delta Committee scenario for the sea level rise along the Dutch coast in 2100 depicts a 'plausible upper limit' of the possibilities (55 to 120 cm, excluding 10 cm land subsidence) and in that respect can be positioned as an extreme scenario supplementing the existing KNMI'06 scenarios which describe the most likely outcomes (35 to 85 cm, excluding subsidence).

2 Scientific developments

2.1 Emissions and concentrations of greenhouse gasses

In the period 2000-2007, the worldwide carbon dioxide (CO_2) emissions increased four times faster than during 1990-2000 (***Figure 7*, *left figure;*** *Global Carbon Project, 2008*). This growth exceeds the highest long-term emission scenario of the IPCC. No figures are available yet about the tempering influence of the economic recession in 2008 and 2009.

In the period 2000-2007, the worldwide carbon dioxide emissions have increased four times faster than during 1990-2000.

The increase in emission is partly compensated by an increase in natural sinks of CO_2 by the oceans and the vegetation on the land (Global Carbon Project, 2008). However, the increase in emission dominates, which results in a rapidly growing amount of CO_2 in the atmosphere (***Figure 7, right figure***). In the period 2000-2007 the CO_2 increase has on average been 33% higher than over the period 1980-2000. The present concentration of CO_2 is 385 ppm (parts per million). This is well over 100 ppm above the pre-industrial concentration. The evolution of the CO_2 concentration in the atmosphere until now is still within the bandwidth of the calculations with the IPCC emission scenarios on which the KNMI'06 scenarios are based, but close to the upper limit.

2.2 Global temperature

The global mean temperature in the period 2000-2008 is 0.17 to 0.22°C above the average in the period 1990-2000 and 0.7 to 0.8°C above the temperature at the end of the 19th century (Hansen et al., 2001). According to the IPCC it is very likely that the major part of the global warming in the past decades can

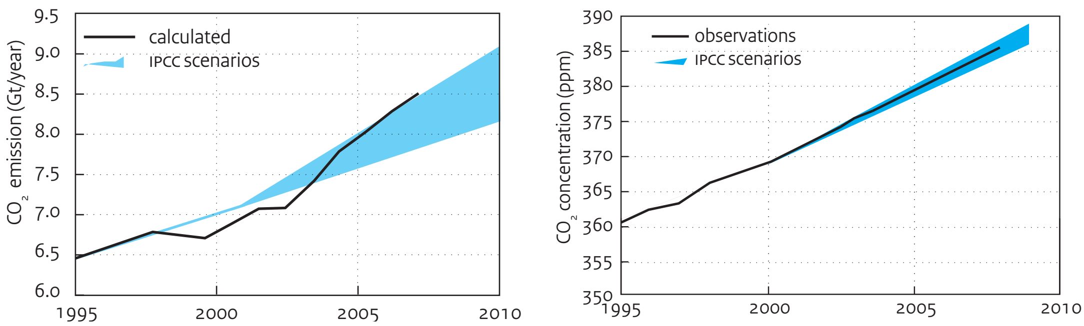


Figure 7. *Calculated CO_2 emissions (left) and observed CO_2 concentrations (right) compared to the IPCC emission scenarios and concentration calculations. Source: Global Carbon Project (2008).*

New emission scenarios

The IPCC emission scenarios for the short to medium term will be improved on a number of important points. First, the fast increase in emissions of greenhouse gasses and particulate matter from rapidly developing economies such as China and India will be better described. This increase has been significantly underestimated in the current scenarios (Ohara et al., 2007). Secondly, it is expected that improved estimates of aviation and shipping emissions will become available. Third, the new scenarios are extended with greenhouse gasses and aerosol particles that have not been included explicitly in the current scenarios. This applies to pollutants such as ozone, particles of soot and organic carbon, which can strongly affect the climate on a regional scale.

For the next generation KNMI climate scenarios (about 2013) and for the next report of the IPCC a new kind of scenario will be used. Rather than scenarios for the emissions of greenhouse gasses, the evolution of the concentration of greenhouse gasses in the atmosphere will be considered, the so-called representative concentration pathways (RCPs; Moss et al., 2009). Starting point for the development of these scenarios is the strength of the total disturbance of the global climate system (the radiative forcing) by humans.

An important advantage of these new scenarios is the connection with the so-called stabilisation scenarios. In these scenarios society strives to limit the climate change through an active climate policy. Within the European Union there is agreement that the global mean temperature rise should not exceed 2°C relative to the pre-industrial level, in order to avoid dangerous, large scale and irreversible climate impacts. In order to limit (at 50% probability) the global mean temperature rise to 2°C, stabilisation of greenhouse gasses at a concentration of 450 ppm CO_2-equivalent [1] is required. To meet this target a considerable worldwide emission reduction is required, and the emission level in 2040 needs to drop 25 to 60% below the level of 1990 (IPCC, 2007).

[1] CO_2-equivalent concentration is a measure in which the effect of other greenhouse gasses is translated to the equivalent of the effect of CO_2

be attributed to human influence on the climate. Due to natural fluctuations, which are partly related to El Niño and variations in the activity of the sun, not all recent years are equally warm. But all years from 2001 onwards belong to the top 10 of warmest years since the beginning of the observations at the end of the 19th century.

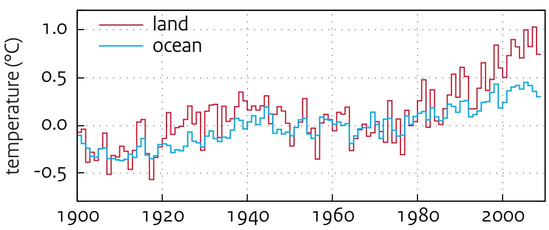


Figure 8. *Annual mean temperature on earth based on observations broken down into land surface and ocean. Alternative series for the global temperature generally show the same evolution. Source: NASA GISS. (Hansen et al., 2001).*

All years from 2001 onwards belong to the top 10 of warmest years globally since the beginning of the observations at the end of the 19th century.

The temperature rise in the most recent years seems to be lower than in the period 1975-2000. This can be explained by natural fluctuations; a systematic difference in the rate of temperature rise cannot be detected statistically. The difference is entirely due to the oceans. Land temperatures have risen with the same rate as before (***Figure 8***). The sea surface temperature has decreased in the seas of South-east Asia and in parts of the northern Pacific Ocean. It is likely that in the Southern Ocean around the South Pole the sea surface temperature also decreased. However, the latter is uncertain because of the relative poor quality of the observations. The decrease in the northern Pacific Ocean is in areas where large natural fluctuations between subsequent decades occur. The decrease near South-east Asia is outside the band of natural fluctuations; the cause of this decrease remains yet unknown.

Modelling of the global climate

*The sensitivity of the global temperature for the increase of greenhouse gasses remains uncertain (**Figure 5**). The spread that climate models exhibit has hardly changed during the past 10 years, despite scientific research: at a doubling of CO_2-concentrations the temperature in the majority of models increases between 2°C and 4.5°C (IPCC, 2007). However, a (much) stronger or (somewhat) less strong temperature response cannot be excluded.*

This uncertainty is largely determined by the uncertainty of how clouds adapt in a future climate. This applies in particular to (sub)tropical clouds over the oceans. Modelling cloudiness is complicated, because many processes, such as radiation, turbulence and cloud micro-physics, act on a (very) local scale and as a result require a simplified description in global climate models.

The uncertainties in polar regions are also large. The unexpected fast melt of sea ice at the North Pole during recent summers has emphasised the shortcomings of the present global models. Mixing and transport of ocean water, transport of moist and heat through the air, cloudiness and sea ice dynamics play an important role in the polar areas. Many of these processes act at small scales and are difficult to describe in climate models.

The warming of the earth can initiate processes that, in turn, strengthen the warming in the long run. Examples of these feedback mechanisms are the full melting of the sea ice at the North Pole in summer, destabilization of the land ice on Greenland and West-Antarctica and large scale changes in ecosystems, such as the disappearance of the Amazon rain forest, with considerable effects on the carbon cycle. Long-term feedbacks through the uptake and emission of CO_2 by, in particular, the oceans and the biosphere, are still missing in most climate models. Strong feedbacks can also occur through adaptation of the vegetation to climate changes. These can lead to changes in evaporation, cloudiness and precipitation. The research on these feedback mechanisms does not provide a clear picture yet, but the implications for the longer term can be large. Research on climate change in the past million years provides evidence that a warming of eventually 6°C at a doubling of the CO_2 concentration is among the possibilities (Hansen et al., 2008).

The warming is not equal on every location on earth. The Poles warm stronger than the tropics, and the continents generally warm stronger than the oceans. As a result, the atmospheric circulation patterns on earth could also change. Due to changes in the atmospheric circulation patterns in the (sub)tropics, wind regimes can shift to the north. As a result, the Netherlands may be more affected by westerly winds during winter. During summer, a strong warming of the continent due to drying, may cause more easterly winds in the Netherlands. The knowledge on the causes of these changes in circulation patterns has increased strongly in the past few years, but how exactly they will occur is still uncertain.

Although the uncertainties have not decreased in all cases (see the climate sensitivity example above), important progress has been made in recent years. The fundamental knowledge on the way the climate system operates and its predictability has grown. Given the increased spatial resolution of global climate models, small scale processes can be better described. Also, the current satellite observations provide opportunities for model evaluation and improvement, in particular related to cloud processes. In short, the current combination of high resolution observations and models opens new possibilities for more robust and more confident climate predictions.

2.3 Ice sheets on Greenland and Antarctica

Observations show that on the edges of the Greenland and West-Antarctic ice sheets the loss of ice has increased during recent years (Ramillien et al., 2006). However, locally strong fluctuations occur (Van der Wal et al., 2008). In some areas the rate of loss of ice has reduced recently. The small scale, dynamical processes which cause these fluctuations in ice loss are not yet well understood nor adequately represented in models. Therefore, it is difficult to construct scenarios for the future contribution of ice loss from ice sheets to sea level rise.

The fluctuations in the ice loss on the edges of the Greenland and West-Antarctic ice sheets are not yet well understood.

Given the rapid developments in this area of research, the long-term contributions of the Greenland and Antarctic ice sheets to sea level rise in the KNMI'06 scenarios may have to be adjusted in the future. An indication of the size of this adjustment can not be given now. Because the observational time series will gradually become longer and the research on this subject will intensify, we expect the uncertainties to decrease considerably in the coming years.

2.4 Self-gravitation and sea level rise

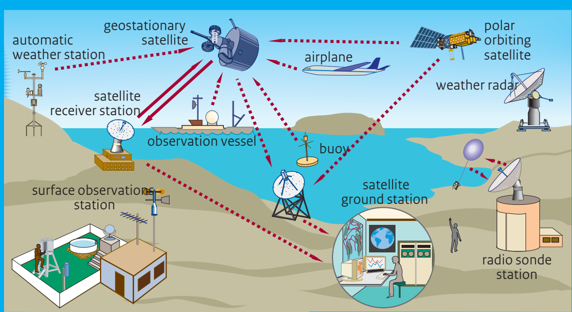
When (part of an) ice mass on land melts, the released fresh water ends up in the ocean. However, this melt water is not distributed evenly over the oceans, because of the 'self-gravitation effect' (Farrell and Clark, 1976). Ocean water is attracted to the ice mass on land by gravitation. The sea level is therefore relatively high near an ice sheet. If (part of) the ice on land melts, the sea level will rise averaged over the globe. But also, the attraction force of the ice mass on the ocean water reduces, because of loss of mass. Due to the decreased attraction force the sea level does not rise but falls in an area close to the ice sheet *(area A in **Figure 9**)* when the ice mass shrinks. Further away from the ice sheet (area B) the sea level does rise, but less than without a change in gravitation effect. Far from the ice sheet (area C) the sea level rise is larger than in case of an unchanged gravitation effect.

Observations

Observations form the basis of our knowledge about climate change. Through so-called climate monitoring it can be determined whether the changes agree with climate scenarios issued earlier. Besides, observations provide an important contribution to the understanding, and therefore the modelling, of the climate system.

Satellite observations become increasingly important. Apart from the strongly increased technical capabilities of astronautics, the observational series are becoming more valuable because they cover several decades by now. As a result, potential long-term trends can be better distinguished from short duration fluctuations. For example, using satellite observations we will be able to better quantify the changes in the ice sheets of Greenland and Antarctica in the near future.

By combining satellite observations with observations from soundings, buoys and tide gauges in the oceans the sea level is monitored. These observations show that the sea level rises gradually. Over the past century, the sea level along the Dutch coast has risen by 20 cm without clear signs of a local acceleration in recent decades. Evidence does exist for accelerated global mean sea level rise (IPCC, 2007).



Averaged over the globe, self-gravitation has no net effect on the sea level; this process only causes the ocean water to be distributed unevenly. The distance between the Netherlands and Greenland is such that the sea level rise along the Dutch coast due to the melt of this ice sheet is only one fourth of the global average sea level rise (the Netherlands is in area B). Antarctica is far away from us. If this ice sheet shrinks the self-gravitation effect causes a somewhat

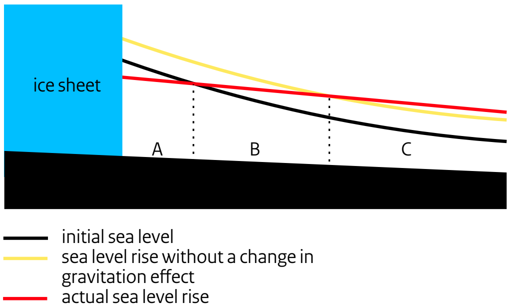


***Figure 9**. Illustration of the effect of self-gravitation on the local sea level in case of ice loss. In area A the sea level falls; in area B the sea level rise is smaller than in case of an unchanged gravitation effect; in C the sea level rise is larger than in case of an unchanged gravitation effect.*

Averaged over the globe, self-gravitation has no net effect on the sea level; self-gravitation only causes the ocean water to be distributed unevenly.

larger sea level rise for the Netherlands than would be seen in case of an unchanged gravitation effect (the Netherlands is in area C).

In the KNMI'06 scenarios the self-gravitation effect has been excluded. In the next generation KNMI scenarios the effect will be included, but its inclusion will likely hardly affect the KNMI'06 scenarios for sea level rise along the Dutch coast.

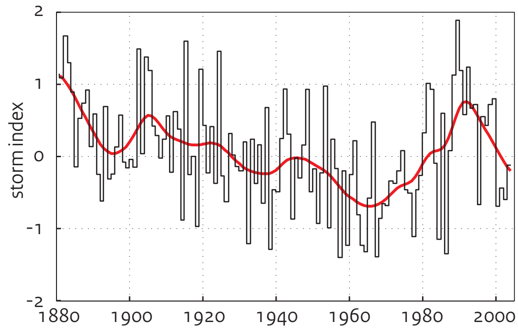


***Figure 10**. Storm activity over the British Isles, North Sea and Nordic Sea. The black line is a measure of the annual number of heavy wind storms in every year and the red line follows a 30-years running mean. Source: IPCC, 2007.*

2.5 Wind storms and surges

Subtle changes in the atmosphere may have a large effect on the wind storm climate. A small change in the position and strength of the storm track over the Atlantic Ocean - the band of strong westerlies at about 10 km height in which wind storms develop and are carried along - can be of great importance. The storm climate exhibits strong variations by nature. Even from one decade to the other large differences occur (***Figure 10***). Furthermore, severe storms are rare, which makes the detection of systematic trends difficult.

The KNMI'06 scenarios describe only a small influence of climate change on the wind storm climate of the Netherlands. This picture is confirmed by new research (Sterl et al., 2009). Models provide evidence that the natural fluctuations in the wind storm climate are larger than the changes caused by the greenhouse effect.

For risk of flooding not only the strength of the wind storms is important, but also the wind direction. Northerly winds cause the highest surges of sea water along the Dutch coast. There is no evidence, however, for more or stronger winds from northerly

Ensembles of climate simulations

Nowadays, climate scenarios are more often based on a large number of simulations with one or more climate models - a so-called ensemble. Until recently, scenarios used to be based on only a few model simulations. In that case natural fluctuations can easily be misunderstood for a systematic trend. The KNMI'06 scenarios are a first step towards scenarios based on an ensemble of model simulations. This development will continue in future scenarios. Natural fluctuations and the results of human behaviour can be better distinguished and quantified by using ensembles. The probabilities of rare events, like strong wind storms, can be better determined too. Ensembles also offer the possibility to assess changes in the variations from day-to-day, or from year-to-year, and therefore the probabilities of, for example, heat waves and cold spells, as well as long wet or dry spells.

> *The KNMI'06 scenarios describe only a small influence of climate change on the wind storm climate of the Netherlands. Recent research confirms this.*

directions. The height of extreme storm surges in the future will therefore not be higher than at present. However, there appears to be a tendency towards more (south-)westerly winds (Sterl et al., 2009).

2.6 Observed rapid warming in the Netherlands

Based on observations, Van Oldenborgh et al. (2009) found that the temperature in the Netherlands and surrounding countries has increased twice as much as the global average over the past years. This increase appears to be systematic and it is very likely that a natural fluctuation on the time scale of 10 years is not the cause.

Several causes for the stronger warming in the Netherlands exist. For winter, there is an increase in westerly winds. For summer, there is an increase of incoming solar radiation due to a decrease in cloudiness, which is likely caused by drying over the continent, and due to a decrease in air pollution (less aerosol particles). These processes are not well simulated in climate models, and therefore the difference between the global temperature rise and the local warming in the Netherlands in the past 50 years is systematically underestimated.

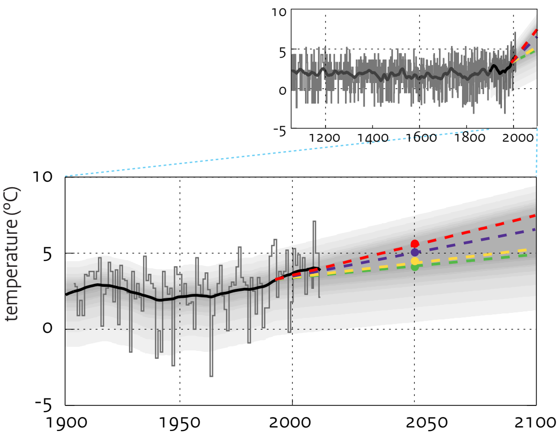


Figure 11. *Winter temperatures in De Bilt between the year 1000 and 2008, and the four climate scenarios for 2050 (coloured dots). The values before 1900 are based on a temperature reconstruction for the 'Low Countries' (Shabalova and Van Engelen, 2003). This reconstruction is based on historical evidence and instrumental data for the period since 1706. The thick black line is a running 30 year mean. The coloured and stippled lines connect every climate scenario with the base year 1990. The grey band indicates the year-to-year variations that are derived from the observations.*

Probability of extremes in a changing climate

Design criteria for safety of infrastructure are often based on observations of extreme events in the current climate. Events that occur only once every 10 years or even once every 10,000 years are of particular importance. Observational series are rarely longer than 100 years, and often shorter. Therefore, it is often necessary to extrapolate statistically (using so-called extreme value distributions) to return periods outside the observational series. In practice, it is assumed that the climate is stationary. This no longer seems adequate now. Based on model results and observed trends, IPCC (2007) concludes that some extremes will occur more often and/or become more intense.

It is possible to account for changes in the frequency and strength of extremes (Klein Tank et al., 2009). Together with international partners KNMI investigates the required statistical methods. In addition, it is explored whether local extremes, which pose great difficulties to climate models, can be associated with larger scale phenomena that are better simulated by the models.

Statements about very rare events in the future climate are inevitably uncertain. The uncertainty about future climate change plays an important role in this. But the statistical extrapolation techniques, which are also used for the current climate, form another source of large uncertainty as well. This applies, for example, to the extreme precipitation conditions, that are associated with the discharge of the river Rhine and which is exceeded with a probability of once every 1250 years. The latter is regarded as the so-called design discharge. The current design discharge determined for the river Rhine is 16,000 m3/s, but with a 95% confidence interval of 13,000 to 18,500 m³/s (Delta Committee, 2008). Similarly, large margins exist in extreme wind storm conditions over the North Sea that occur once in 10,000 years; the safety standard as set down in Dutch national law.

The rapid warming in the Netherlands and Western Europe is best accounted for in the W/W+ scenarios.

In the KNMI'06 scenarios the relation between global warming and warming in the Netherlands is derived from global and regional climate models. Only the G+/W+ scenarios with changes in the atmospheric circulation patterns show a stronger local warming, up to about 1.5 times the global average temperature rise in summer. The observations over the last fifty years suggest a factor 2. Whether this trend will continue in the future is questionable, however.

The strong warming in the Netherlands is partly caused by factors that cannot be easily extrapolated to the future. The increase in westerly winds has been large over the past decades. The mechanisms behind this change are not yet fully understood, and it is therefore unclear whether this trend will continue at the same rate. The same applies to the decrease in cloudiness. We can be more certain about the decrease in air pollution. It is unlikely that the air will continue to become cleaner with the same rate of change. In the observations almost no decrease in the concentration of aerosol particles can be seen after 2000. In the long run, potential changes in the North-Atlantic Ocean and the warm 'Gulf Stream' could also have a strong effect on the temperature in the Netherlands.

The annual average temperature in the Netherlands over the past 10 years (1999-2008) has been 0.8°C higher than the base temperature around 1990 (the average between 1976 and 2005). Compared to this, the changes in the G/G+ scenarios for 2050 (between 0.9 and 1.3°C) are small (***Figure 11***), although these relate to the average over 30 years rather than 10 years. Using the G/G+ scenarios implies that the temperature in the Netherlands will not rise much more until 2050. This could occur, for example when the temperature in the next 10 years is lower than in the past 10 years, but is less likely.

The rapid warming in the Netherlands and Western Europe is best accounted for in the W/W+ scenarios. Scenarios with even higher temperature rise may be useful when for a particular application high temperatures cause a great risk (see the box on page 10).

2.7 Extreme winter precipitation in the Rhine basin

According to recent research the observed increase in winter precipitation in the temperate zones of the Northern Hemisphere (including large parts of Western Europe) is associated with the human influence on climate (Zhang et al., 2007). The KNMI'06 scenarios describe a further increase in winter precipitation in future.

In the KNMI'06 scenarios, the 10-day precipitation extremes during winter increase with the same percentage as the daily extremes. This picture remains unchanged.

Peak discharges of the river Rhine often occur during prolonged periods with abundant rainfall in winter in the catchment area (about 10 days or more). Therefore, not only the change in precipitation intensity on individual days is important, but also the extent to which days with high precipitation amounts occur more (or less) clustered. A change in clustering is possible according to some climate models, but highly uncertain. Different climate models show contradictory results. Therefore, it is assumed in the KNMI'06 scenarios that the 10-day precipitation extremes will increase with roughly the same percentage as the daily extremes. For the winter season, the latter increase is almost the same as the increase in mean winter precipitation.

2.8 Drying of the soil

Due to the temperature rise the evaporation will increase, as long as sufficient soil moisture is available and the net radiation will not decrease. According to the KNMI'06 scenarios the evaporation will have increased with 3 to 15% by the summer of 2050. If not compensated by increased rainfall or water management measures, this will result in drying of the soil. Most climate models simulate an increased drying of the countries in the Mediterranean in the 21st century. For the Netherlands, the model calculations are less conclusive. Due to drying of the soil, summertime temperatures may rise even more resulting in a further increased probability of summer heat waves (e.g. Sterl et al., 2008).

The summer drying of Southern Europe also has consequences for the climate of Western and Central Europe. Firstly, drier and warmer air is advected to

Due to the drying of the soil, the temperature can rise additionally which causes the probability of summer heat waves to further increase.

the Netherlands with southerly winds. Secondly, as a result of the higher temperatures over Southern Europe air circulation patterns may change such that the easterly winds over Western and Central Europe become more frequent. These easterly winds will also advect drier and warmer continental air. These changes are depicted in the G+/W+ scenarios.

2.9 Shower intensity during summer

At higher temperatures the air can contain more water vapour. If the relative humidity of the atmosphere doesn't change substantially, the amount of water vapour in the atmosphere will increase by about 7% per degree Celsius temperature rise. During showers a large part of the available water vapour will be transformed into rain. Therefore, it is expected that showers are more intense at higher temperatures. This is why all KNMI'06 scenarios show an increase for the extreme daily amounts of rainfall in summer. Precipitation observations at De Bilt (The Netherlands) show an increase in hourly intensities during extreme showers in summer. The increase is about 14% per degree Celsius temperature rise (**Figure 12;** Lenderink and Van Meijgaard, 2008). This relationship is considerably stronger than expected on the basis of the amount of water vapour alone. It is likely that the additional increase is the result of stronger turbulence in a shower cloud. This causes water vapour to transform into rainfall more quickly and more moisture to convey from the surroundings into the cloud.

It is likely that the rainfall intensity per hour during extreme showers will increase more strongly than the extremes of the rainfall amount per day. For the daily amounts, the available total amount of water vapour in the atmosphere is a limiting factor. Showers become more intense while it is likely that their duration decreases.

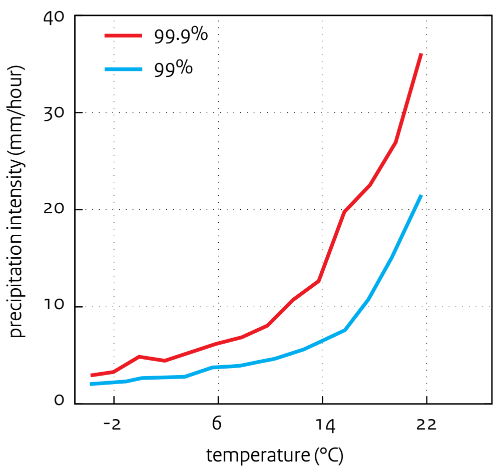


__Figure 12__. Hourly precipitation intensity as a function of the daily mean temperature based on the observations at De Bilt (The Netherlands). The 99% and 99.9% percentiles are the extremes that are exceeded on average once every 100 and 1000 precipitation hours. At higher temperatures (the summer half of the year) the extreme shower intensity strongly increases with increasing temperature (about 14% per °C).

High resolution climate modelling for the Netherlands

Information about climate change at the local scale is important for climate adaptation. In general, the uncertainty increases when the spatial scales become smaller. Also, the change in local precipitation amounts is more uncertain than the change in local temperatures. For summer, it is uncertain whether the average precipitation amount increases or decreases in the Netherlands. We are certain, however, about an increase in temperature. There are limitations of the predictability at the local scale, in particular for precipitation. But there are important exceptions.

According to recent research (Lenderink and Van Meijgaard, 2008), the change in precipitation is strongly dependent on the spatial scale, in particular during summer. Local showers will show a stronger increase in intensity than the increase of the daily amounts averaged over a larger area. Also, an increased temperature of the North Sea can lead to more, and more extreme, precipitation at the coast compared to inland. Because these local precipitation processes are strongly linked to the temperature, it is likely that the predictability is relatively high.

The regional climate models that have been used for the KNMI'06 scenarios had a spatial resolution of 50 km, which makes them inadequate to provide meaningful information on the local scale. Research using higher resolution models, in combination with observations, is underway to better quantify these local precipitation processes (__Figure 13__).

It is likely that the rainfall intensity per hour during extreme showers will increase more strongly than the extremes of the rainfall amount per day.

For the KNMI'06 scenarios no information was available from climate models about changes in precipitation amount per hour. Therefore, for practical applications it was assumed that the hourly intensities increase at the same rate as the daily amounts (see section 4.3). It is likely that this assumption is invalid for extreme showers during summer. The above relationship in the observations of the current climate cannot be used directly for statements about shower activity in a future climate, because other factors, such as changes in the air circulation patterns and potential soil drying, need to be included as well.

For summer, the margin for precipitation extremes in the KNMI'06 scenarios is relatively large; the G/W scenarios show a strong increase in the extreme daily amounts, because they are based on the upper limit in a large number of different climate models. Because of the high margin in the G/W scenarios, it is likely that the increase in extreme rainfall intensity per hour in the future will not be (much) higher than the increase in the extreme daily amounts given in the G/W scenarios. The values in the G+/W+ scenarios for the increase in the extreme daily precipitation amounts are likely to underestimate the increase in the extreme precipitation intensity per hour. Not only can the precipitation intensity strongly increase with temperature; it is also likely that the other phenomena that are closely linked to showers, such as hail, thunderstorms, wind gusts and tornadoes, will increase in strength and/or occur more frequently.

2.10 Coastal precipitation in summer and autumn

The temperature of the North Sea has a discernable influence on the precipitation distribution in the Netherlands. In Kattenberg (2008) the effect of the North Sea temperature on the precipitation in the Netherlands has been discussed at length. Lenderink et al. (2008) provide evidence that, under certain air circulation patterns, up to about 15% more precipitation can fall along the coast per degree Celsius temperature rise of the North Sea. These are mostly conditions in which cold and unstable air is transported over a warm North Sea. This effect is strongest up to about 30 km inland, and occurs in particular in the second half of the summer and in the autumn.

Similar to the land surface (see section 2.6), the temperature of the North Sea also seems to increase faster than the global average temperature. However, this is more difficult to assess because long and uniform time series of North Sea temperatures are scarce. Observations show that the coastal area has on average become wetter during late summer and autumn compared to the inland area. A causal relationship with the increasing North Sea temperatures is likely.

The starting point of the KNMI'06 scenarios is one single value for the temperature and precipitation

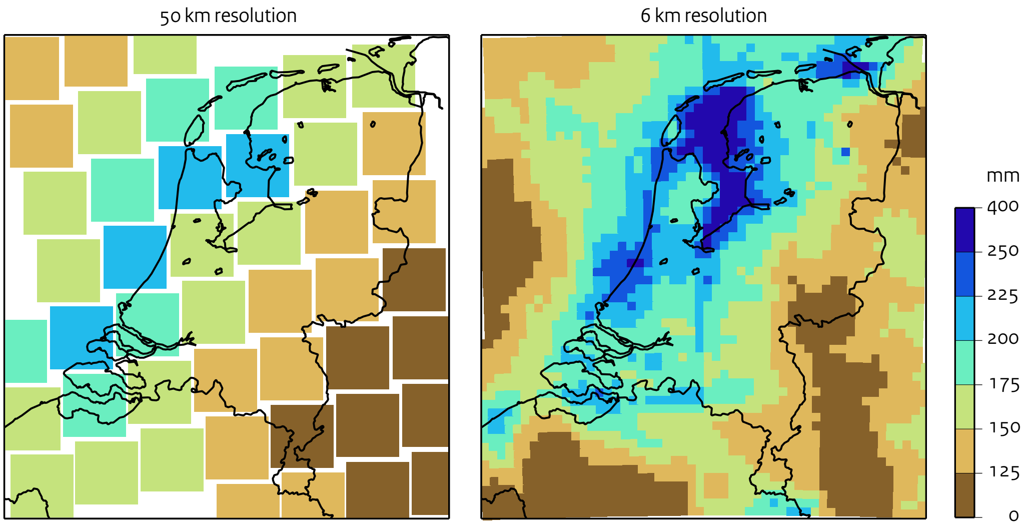


***Figure 13**. Model simulation of the precipitation distribution in August 2006 based on the regional climate model RACMO. Left: the 50 km resolution version, which has been used for the KNMI'06 scenarios. Right: a 6 km resolution version, which is currently used by KNMI to investigate regional differences in climate change within the Netherlands.*

changes for the whole of the Netherlands. The climate models used for the KNMI'06 scenarios do not include a realistic description of the local temperatures of the North Sea water. Also, the spatial resolution used for the scenarios is insufficient to distinguish coastal precipitation from precipitation inland. Long climate simulations with regional models in which the effect of the North Sea water is realistically simulated are not available yet. This implies that statements about the future precipitation in late summer and autumn in the coastal area are indicative.

Since the G/W scenarios have been based on the upper limits of the model results used, these scenarios contain sufficient margin to include the effect of the warm North Sea.

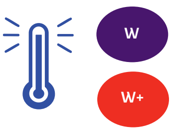
Besides long periods of drought, as in the G+/W+ scenarios, one needs to account for short duration periods with extreme precipitation in the coastal area, such as in the G/W scenarios.

If the G+/W+ scenarios are used, it is likely that the influence of the warmer sea water on the precipitation in the coastal area is underestimated. For these scenarios the local temperature rise of the North Sea will be relatively high. The G+/W+ scenarios are based on models that show a strong drying above land, and a strong suppression of shower activity. For the coastal area, with the North Sea as a source of moisture, this is not realistic. It is likely that the coastal area will see less decrease of the average precipitation amount during summer, and a stronger increase of the extreme daily amounts than the average over the Netherlands in the G+/W+ scenarios. Besides long periods of drought, as described in the G+/W+ scenarios, one needs to account for short duration periods with extreme precipitation in the coastal area, such as described in the G/W scenarios.

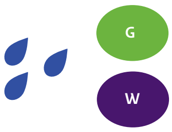
3 Implication for KNMI'06 climate scenarios

> *The KNMI'06 scenarios describe the most likely changes in the climate according to the present-day state of knowledge.*

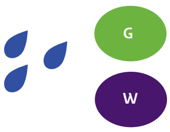
The new research results outlined in the previous sections give rise to reconsider the climate scenarios from three years ago. The KNMI'06 scenarios remain useful for the majority of studies and questions on impacts and adaptation in the Netherlands, because they still provide the most likely changes in the climate with accompanying uncertainty according to the present-day state of knowledge. Yet, the following new guidance for usage applies:



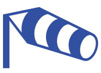
The temperature in the Netherlands is increasing rapidly. This rapid warming is caused by factors that are insufficiently understood, and therefore cannot be simply extrapolated into the future. It appears that the lower temperature rise in the G/G+ scenarios is less likely than the higher temperature rise in the W/W+ scenarios.



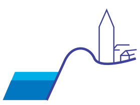
Evidence exist for a stronger increase of the intensity of heavy showers under rising temperatures during summer than the increase of the extreme daily amounts that are provided in the KNMI'06 scenarios. It is likely that the G/W scenarios contain sufficient margin to compensate for the difference. This is particularly relevant for applications which focus on short duration heavy precipitation events.



It is plausible that the regional differences in extreme precipitation within the Netherlands, as seen in the observations, will be amplified in the future. The changes in (extreme) precipitation during summer in the G+/W+ scenarios seem low for the coastal area. For this part of the country, one needs to account for the combination of drought in the G+/W+ scenarios and short periods with precipitation extremes according to the G/W scenarios.



New research confirms that, even when averaged over 30 years, the natural fluctuations in extreme winds are larger than the changes caused by the enhanced greenhouse effect. There are no indications for more or stronger winds from northerly directions in future, which cause the largest surge of sea water along the Dutch coast.



The accelerated loss of ice from the Greenland and West-Antarctic ice sheets in recent observations is not yet well understood or modelled. Also, there is uncertainty about the redistribution of ocean water due to the self-gravitation effect. According to current knowledge, an adjustment of the KNMI'06 scenarios for the sea level rise, in order to better account for these effects, would not yield a change in the sea level scenario values.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4 Supplementary KNMI’06 scenario values

4.1 Transition seasons

The KNMI’06 climate scenarios provide the changes in temperature, precipitation, etc. for winter (December, January, February) and summer (June, July, August). Meanwhile, the changes in each particular month have also been derived (***Figure 14***) by means of interpolations and model analyses. The monthly values are also determined for the transition seasons spring (March, April, May) and autumn (September, October, November). These additions to the KNMI’06 scenarios are given in ***Table 2*** (inside back cover) together with the values for winter and summer published earlier.

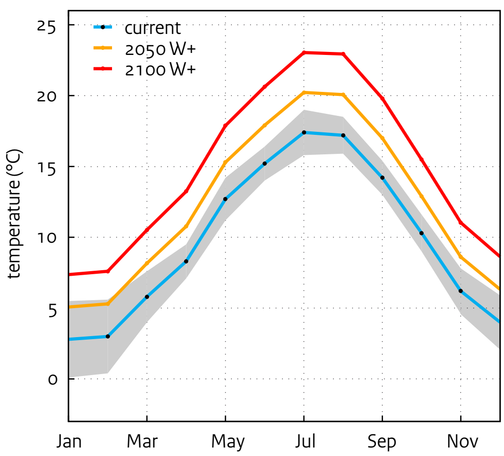


Figure 14*. Annual cycle of temperature for the current climate (De Bilt, 1976-2005) and the future climate around 2050 and 2100 for the W+ scenario. The grey band provides an indication of the year-to-year variations in the current climate. Temperatures which are normal in July and August under present conditions, will be exceeded during more than 5 months on average per year under the W+ scenario in 2100.*

4.2 Time series of daily values

Many studies on the effects of climate change make use of meteorological time series of temperature, precipitation amount, etc. on subsequent days. However, no associated time series for the climate around 2050 and 2100 have been provided within the KNMI’06 scenarios. These scenarios only describe the changes relative to the climate around 1990.

The KNMI’06 scenarios have been constructed by combining the results of different climate models. Therefore, no climate model exists for which the results exactly agree with one of the KNMI’06 climate scenarios. Comparison with observations also shows that climate models often contain systematic errors that are large enough to make the simulated time series of these models inadequate for direct use in impact studies.

Instead, time series for the future can be derived by adjusting local time series from the past in such a way that the transformed series match a chosen climate scenario. For the KNMI’06 scenarios, a software program has been made available through the Internet, which performs this transformation for daily values of temperature and precipitation. In the new time series, not only the seasonal averages are brought in agreement with the scenarios, but also the (moderate) extremes.

A consequence of the method used is that the time series for the future still contain many characteristics of the historical record. For example, the sequence of warm and cold days remains unchanged. The same holds for the sequence of dry and wet days, even though the change in the number of wet days has been taken into account. Using time series that have been transformed this way has shortcomings for studies in which changes in for example the length of dry spells, multi-day precipitation extremes, or warm and cold spells are important. Work is underway to provide an alternative in the form of representative time series of 'future weather' derived from special climate model simulations (see section 5.2).

4.3 Precipitation extremes

To avoid flooding, the water management sector in the Netherlands has a need for statistics on extreme precipitation amounts which are exceeded with a particular frequency. These statistics are required for the whole year, for every location in the country, and for different precipitation duration and return periods. Also, the change in these statistics in the future is important. The KNMI'06 scenarios provide information about the extreme daily precipitation amounts and the extreme 10-day precipitation amounts, which are exceeded with a probability of once every 10 years (or events with a return period of 10 years). Information about changes in short duration precipitation or more extreme events is not provided.

Expanding the information given in the KNMI'06 scenarios, ***Table 1*** provides the annual precipitation statistics for durations of one hour up to 10 days for different return periods, both for the current climate and for 2050 based on the four KNMI'06 scenarios. The values for the scenarios have been derived from transformed observational series (see section 4.2). In view of the results of section 2.9, it is recommended to use the G/W scenarios for the extreme 1-hour rainfall in the whole of the Netherlands in impact studies. The changes in the extreme 1-hour rainfall are the same as the changes in extreme daily amounts.

According to recent research (Buishand et al., 2009), significant regional differences exist in extreme precipitation for the current climate, which are not directly related to the differences in the total precipitation amounts in a year. For the extreme daily precipitation amounts that are exceeded with a probability of once in 10 years, the differences between the most wet and dry parts of the country are currently almost as large as the changes in the scenarios for 2050.

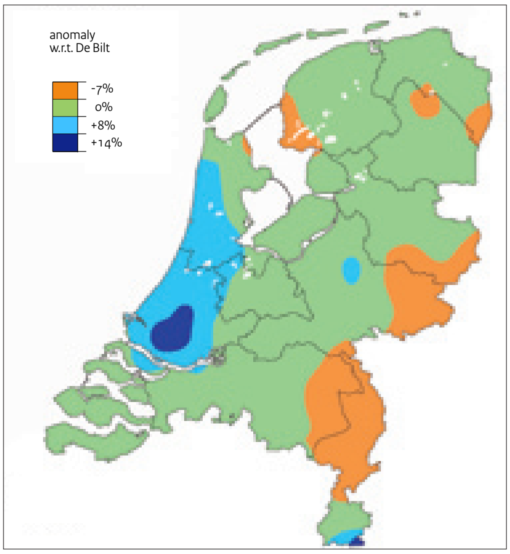
Figure 15 (left figure) shows the regional differences in extreme precipitation. The differences are percentage differences relative to De Bilt. The percentages are valid for the 1-day and 10-day amounts in ***Table 1***, but not for the extreme 1-hour rainfall. Station and rain radar observations show no clear regional differences for extreme hourly precipitation amounts. From this figure it is clear that the statistics of De Bilt are valid for a large part of the country, but that extreme precipitation is up to 14% higher in an area in the west of the country. This maximum for extreme precipitation is more outspoken than the maximum for the total precipitation amount ***(Figure 15, right figure)***. The relation with the earlier described coastal effect on the precipitation in late summer and autumn (see section 2.10) and possible urban heat island effects are subject of research.

In the future, changes in the regional precipitation patterns may occur due to drying over the European continent (see section 2.8) and higher temperatures of the North Sea water (see section 2.10).

__Table 1__. Year statistics for precipitation extremes (mm) in the current climate based on the observations at De Bilt (1906-2003) and the future climate around 2050 (based on 13 transformed observational series, 1906-2008, which together are representative of De Bilt) for different return periods and durations. For a duration of 1 hour the G+/W+ scenarios are not shown because of the results in section 2.9.

precipitation duration	1 hour					1 day					10 days				
return period	current	G	G+	W	W+	current	G	G+	W	W+	current	G	G+	W	W+
1 year	14	15	-	17	-	33	36	35	39	36	80	85	81	89	82
10 years	27	30	-	33	-	54	60	57	66	60	114	122	116	130	119
100 years	43	48	-	53	-	79	88	84	98	88	143	154	146	164	150

For precipitation events that occur relatively often, there is evidence of change already over the past decades. The majority of station observations in the Netherlands and surrounding areas show an increase in the number of days per year with at least 20 mm precipitation between 1946 and 2008 (**Figure 16**). Since 1950, the precipitation thresholds which are exceeded on average once per year in the Dutch records have increased by about 10%. As a result, the values in ***Table 1*** may be too low for the present-day conditions for a return period of one year. For more extreme events (1x per 10 years and 1x per 100 years), no significant changes can be detected in the observations.



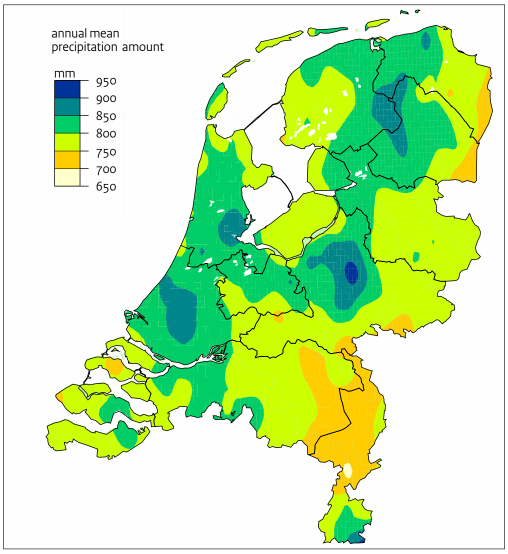


***Figure 15**. Regional differences in the extreme value statistics of precipitation (left; based on observational series from 141 stations, 1951-2005). The colour indicates the difference in extreme precipitation relative to De Bilt. For comparison, a map of regional differences in annual mean precipitation amount (right; based on 283 stations, 1971-2000).*

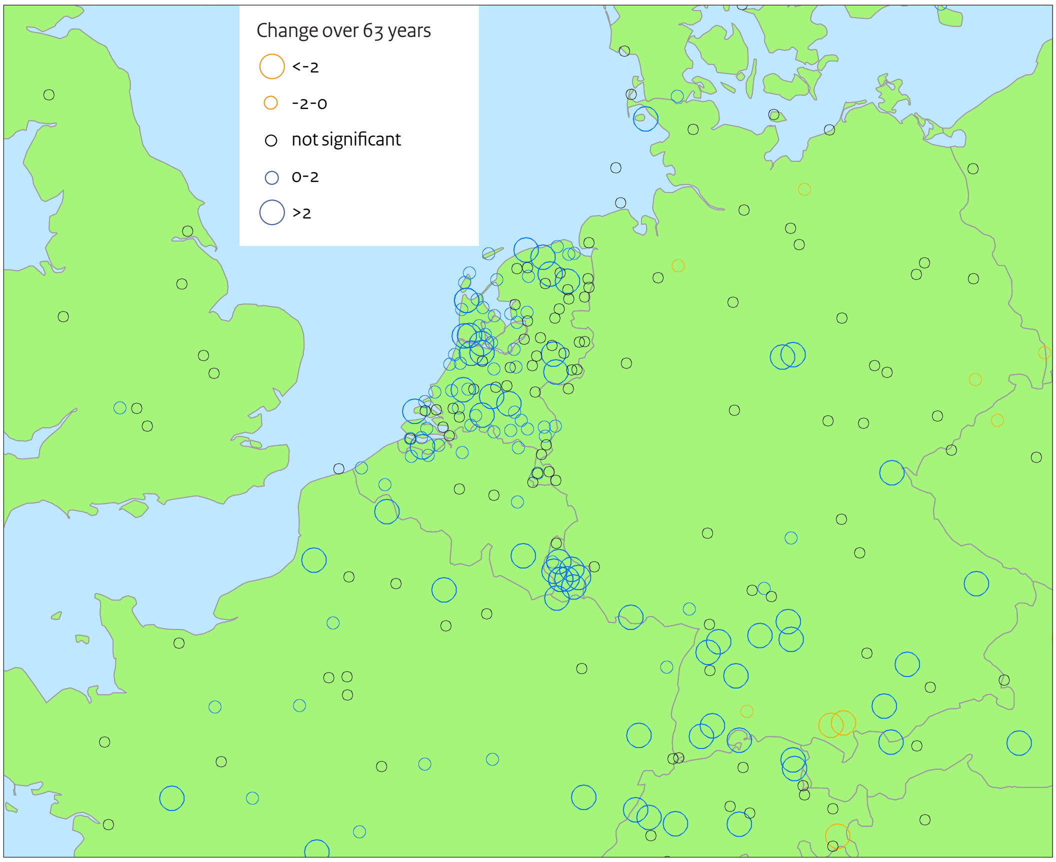


***Figure 16.** Trends in the number of days per year with at least 20 mm precipitation, observed at weather stations between 1946 and 2008. Source: eca.knmi.nl*

5 Outlook to the future generation KNMI climate scenarios

5.1 Time line and (inter)national coordination

Much of the research on climate change is performed in the framework of large international climate research programmes, of which the World Climate Research Programme and the European Framework Programme are the most important ones. Through active participation in these programs, KNMI obtains access to the most recent results of climate research on an internationally acknowledged level. These programs also form important suppliers for the IPCC.

When issuing the new generation climate scenarios, KNMI will link up with the cycle of IPCC assessment reports. For the next IPCC report a large number of simulations with climate models will be performed in the coming years. The analyses of these simulations, combined with the analyses of new observations, form the basis for the next IPCC report. This report will probably be published in 2013. Therefore, the next KNMI climate scenarios are also planned for 2013, which guarantees that the new research results, which will be available at that time, can be included.

Part of the research is also performed in the framework of national climate programs such as Sustainable Earth from NWO (Netherlands Organisation for Scientific Research), Climate Changes Spatial Planning, Living with Water, and Knowledge for Climate. A strong relation exists with the programme Scientific assessment and policy analysis from VROM (Ministry of Housing, Spatial Planning and the Environment). The next generation KNMI climate scenarios are an important part of the execution of the national adaptation policy, as laid out in the Draft National Water plan. The required long-term climate research links to the Delta programme, which will be drawn up in the coming years.

Various countries in Western Europe have developed their own national climate scenarios in the past years. In each of these countries the calculations with climate models performed for the IPCC have been used as the starting point. However, the methodology for construction of the national scenarios differs from country to country. The KNMI'06 scenarios are unique in two ways:

1. Most of the countries make use of the emission scenarios as a basis for the national climate

scenarios. KNMI has used the global temperature rise, because this provides a better insight into the combined uncertainties about greenhouse gas emissions and the response of the climate system.

2. In most countries it is still common practice to base scenarios on only a few model simulations. The KNMI'06 scenarios have been based on a large number of model simulations, which guarantees the consistency with the IPCC report as much as possible.

The different approach in each country limits the mutual comparison of climate impact studies and adaptation strategies. This is why KNMI now has close contact with Belgian and German colleagues about mutual coordination of our respective climate scenarios. In Belgium this has lead to a joint project, in which scenarios for Flanders are linked up with the KNMI'06 scenarios.

5.2 Choices

New research leads to new insights. Therefore, KNMI, in consultation with the user community, issues new climate scenarios on a regular basis. KNMI aims for one set of general climate scenarios that suits a wide user community. This facilitates mutual comparison and integration of impact studies and adaptation strategies. Besides, there is room for additional scenarios for specific applications, such as risk analyses, cost/benefit analyses and vulnerability analyses.

When developing new climate scenarios, user participation is important. In view of the diversity of user groups (from policy makers, scientists to operational institutions) choices have to be made, in dialogue with the user community. Questions for the set of general climate scenarios are:

- **How many scenarios will we issue, and within which framework?**
  The KNMI'06 scenarios use the global temperature change and the change in atmospheric circulation patterns over the Netherlands as starting points. This lead to four scenarios. Will this choice include the major part of the relevant uncertainty, also according to the newest model results? Uncertainty about the increase of the temperature of the North-Atlantic Ocean due to a possible change in the warm 'Gulf Stream', could for example be a reason to introduce a third steering variable and, consequently, additional scenarios.

- **Which characteristics of local climate change will we provide?**
  Instead of only providing the changes in the means and moderate extremes, as in the KNMI'06 scenarios, probability distributions and/or time series can be produced for the future climate, which address the requirements of the most important user communities. KNMI explores the possibilities of deriving representative time series of 'future weather' on the basis of special climate model simulations that match a particular climate scenario. This will provide a more complete and consistent picture of the future climate, including year-to-year variations and possible changes in for example long-lasting heat waves and multi-day precipitation extremes.

- **Do we focus on improved quantification of the probabilities or on higher resolution and spatial detail?**
  Better quantification of the probabilities requires large numbers of model simulations. Because the computer power is limited, this will come at the expense of the spatial resolution of the model and therefore at the expense of regional detail, and the possibility of providing information on small scale processes, such as the intensity of showers. Evidence exists for significant differences of climate change within the Netherlands, in particular in the precipitation climate between the coastal area and inland. The research on this issue is however still in its infancy and requires considerable effort in the area of regional modelling. Whether the emphasis should be on probabilities or higher resolution is unclear, because both developments are desired.

- **For which variables can meaningful probability statements be made?**
  Methods for probability statements in a risk-based approach currently receive large international attention. Probability statements may be possible for the global temperature rise. This rise depends primarily on the emission scenario used and the climate sensitivity. For climate changes in the Netherlands many more factors are important. Thus probabilities can be determined less easily. This holds in particular for statements about changes in the probability of rare events (extremes), which are being used in water management, among others.

- **How do we deal with difficult to quantify, but potentially important processes?**
Examples of these processes are the accelerated melt of ice sheets due to dynamical processes (see section 2.3), and the climate feedback mechanisms associated with biological and chemical processes (see section 2.2). The new generation climate models, which will be used for the next IPCC report, and which will act as input for the new KNMI scenarios, will include these processes partially.

- **Is there a possibility to construct scenarios including time evolution?**
For questions related to investments it is important to know when the climate will have

Scenarios for air quality

The consequences of climate change for air quality are not yet well known. Certain chemical constituents which play a role in air quality have an influence on the climate as well. Examples are ozone, which is a greenhouse gas, and aerosol particles, which affect cloud formation and reflect solar radiation.

Many meteorological factors affect the air quality. Most chemical reactions in the atmosphere intensify at higher temperatures. This is why episodes of smog often coincide with heat waves ***(Figure 17)****. The warming of the climate system results in an increase in the amount of water vapour in the atmosphere. This can lead to a stronger breakdown of air pollution. Changes in air circulation patterns can transport more clean air from the sea, or more polluted air from nearby source areas, such as the Ruhr area, Belgium or Southern England. More frequent high pressure systems with low wind speeds (as in the G+/W+ scenarios) can lead to more smog episodes. Changes in cloudiness also affect the rate of smog formation. If it rains more frequently, particulate matter will be washed out more easily. As a result, the concentrations in the air decrease. Thus, the influence of the weather and the climate on the air quality is diverse and the net effect of climate change is not immediately clear.*

Climate change will potentially lead to changes in the needs and behaviour of people, such as a decrease of heating during winter and an increase of the use of air conditioning during summer. Such factors affect the anthropogenic emissions of greenhouse gasses. Climate change has an effect on the vegetation and therefore also on the natural emissions from the vegetation and the soil. Natural emissions are important for the air quality. The emission of volatile organic constituents from plants and trees provides a considerable contribution to smog formation during heat waves. At higher temperatures, more nitrogen oxides are also released from the soil. Nitrogen oxides contribute to ozone formation.

Recently, model calculations have been performed in cooperation with TNO and RIVM to analyze the effect of temperature on the ozone concentration. Most model results show that for Western Europe an increase in temperature leads to an increase in the exceedance of hourly average threshold values for ozone. Measurements confirm the strong correlation between temperature and ozone ***(Figure 17).*** *Only a few studies have considered the effect of climate change on small aerosol particles.*

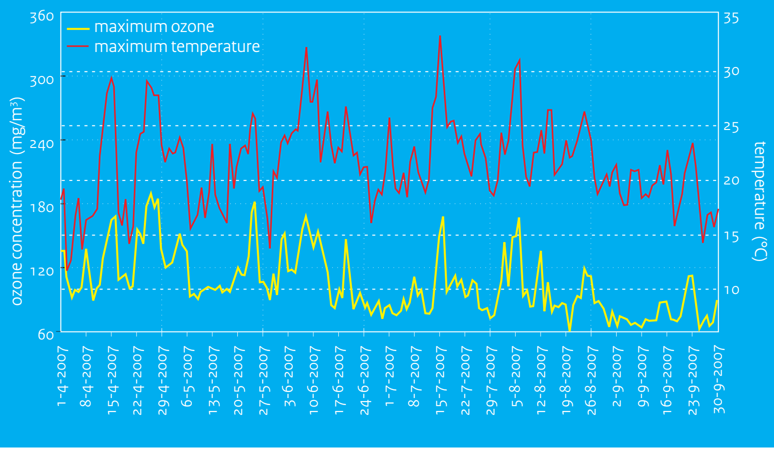


Figure 17*. Country average values of maximum ozone concentration and maximum temperature in the summer of 2007. Source: RIVM (2007).*

changed such that measures have to be taken or existing policies have become inadequate. For this purpose, scenarios with a fixed time horizon (such as 2050 and 2100 in the KNMI'06 scenarios) are less useful.

- **Will we issue decadal predictions for the coming 10 to 20 years?**
  The predictability of the climate for the coming 10 to 20 years is part of public attention. However, the uncertainties in this new field of research are large (***Figure 4***). KNMI investigates whether or not there is sufficient predictability for this time horizon for the Netherlands.

- **For which climate related variables will scenarios be developed?**
  Examples of climate related variables are air quality and evaporation. Both variables are influenced by the climate, and both variables do affect the climate, but they are also strongly dependent on external factors, such as land use and socio-economic factors. In cooperation with (inter)national partners, KNMI investigates if and in what form scenarios for these variables can be made.

Not every request from users can be realized in practice. Climate research is a scientific field in motion and we do not know beforehand how our knowledge will develop in the coming years. KNMI will have to make choices and intends to involve stakeholders in these choices.

Scenarios for evaporation

Scenarios for the actual evaporation are not equal to the scenarios for the reference evaporation provided in KNMI'06. If a soil moisture shortage develops as a result of a precipitation shortage, than the actual evaporation can strongly decrease whereas the reference evaporation remains high or even increases. Changes in the actual evaporation are related to changes in the soil, land use and water management. Also, the increase in the CO_2 concentration of the air plays a role, because of its effect on the growth and evaporation of plants.

*In cooperation with Public Works and Water Management (RWS-Waterdienst) and the Netherlands Environmental Assessment Agency (PBL) the potential changes in actual evaporation under the KNMI'06 scenarios have been investigated. From this exploratory study, which used a set of detailed hydrological model instruments, it was deduced that the G/W scenarios will lead to an overall increase of the actual evaporation accumulated over the year in 2050. In the G+/W+ scenarios, in which the summer precipitation decreases, a decrease in actual evaporation is almost only seen in some dune areas along the Dutch coast caused by a shortage of soil moisture (**Figure 18**). The change in actual evaporation in the sandy areas of the East, Central area and South, which are most vulnerable for drought, is small.*

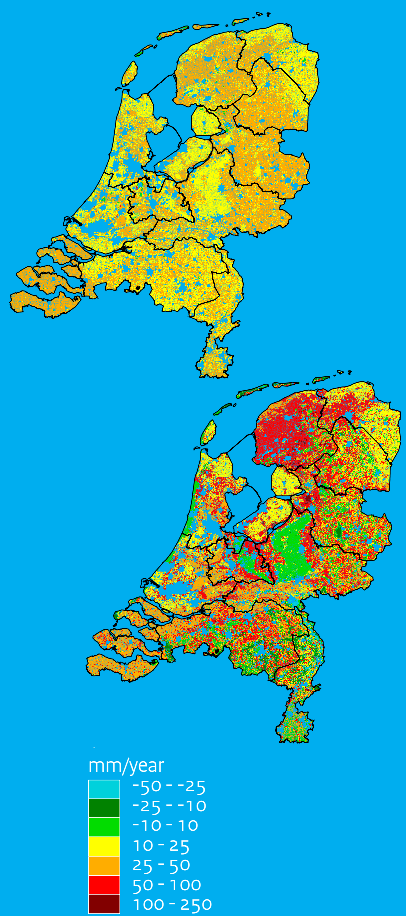


***Figure 18**. Change in the actual evaporation (mm/year) for the KNMI'06 scenarios W (left) and W+ (right) calculated with a detailed water balance model. Source: Public Works and Water Management (RWS-Waterdienst)/ Netherlands Environmental Assessment Agency (PBL).*

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