Sea Level Rise: a literature survey

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Ir. G.H.P. Oude Essink

TU Delft
Delft University of Technology

Faculty of Civil Engineering
Department of Sanitary Engineering and Water Management
Section Water Management

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Faculty of Civil Engineering, Delft University of Technology

Foreword

Up till the beginning of the 'Industrial Revolution', global changes of climate had natural causes. These changes were due to a number of climatological mechanisms. An important consequence of was the change of atmospheric temperature, which among others determines the level of the sea. The time scale of this natural process was in the order of millennia.

However, because of human activities since the beginning of the 'Industrial Revolution' at roughly 1850, the concentration of atmospheric trace gases influencing this temperature is rapidly increasing. Consequently, the temperature of the atmosphere may increase more than is natural in the near future, and as a result, sea level may rise. Especially for populations, such as the Dutch, living in low-lying countries, it is essential to know how fast this rise may be in the future. By analyzing data how sea level changed in the past, more insight should be gained in how the sea level will rise in the coming century. Moreover, scientists are developing climate models that predict future sea level rise.

Possible effects of future sea level rises on water management will be discussed in the author's thesis: Water Management Impacts of Sea Level Rise. A Sensitivity Analysis of the Groundwater Flow Regime in the Netherlands. A two-dimensional groundwater flow model is used to simulate the impact of sea level rise on the groundwater flow regime.

Summary

In order to assess the impact of sea level rise on Water Management, it is useful to understand the mechanisms that determine the level of the sea. In this study, a *literature survey* is executed to analyze these mechanisms.

Climate plays a central role in these mechanisms. Climate mainly changes due to a disturbance in the balance of incoming and outgoing energy. The disturbance in the

balance is accomplished when a.o. the concentration of trace gases (called together the Greenhouse gases or the effective CO_2-concentration) alters. Before the Industrial Revolution, natural processes only determined the effective CO_2-concentration. However, since the Industrial Revolution the effective CO_2-concentration has rapidly increased because of human activities, and has thus enhanced the global warming. This mechanism of global warming is called the *greenhouse effect.*

Some feedback mechanisms such as ice and snow, water vapour and permafrost (permanently frozen soils) have amplified the greenhouse effect, while on the other hand a feedback mechanism such as oceans has counteracted the greenhouse effect. A doubling of effective CO_2-concentration in the atmosphere is to be expected by the middle or end of the next century, depending on changes in emissions. It is generally expected that this doubling of the CO_2-concentration will enhance the greenhouse effect. Consequently, the atmospheric temperature will rise some degrees.

If the temperature rises, sea level rises due to the following processes: thermal expansion of ocean water; melting of mountain glaciers and small icecaps; and ablation (melting and runoff, evaporation) of the polar ice sheets of Greenland and Antarctica. It is even possible that a great part of the West Antarctic Ice Sheets may disintegrate, and thus, sea level may rise several meters.

The sea level can change tens of meters within a geologically short time (in the order of millennia). This can be seen when sea level changes in the past are analyzed. However, since the present era is an interglacial, the sea level is already high, and as a result, the sea level might not rise more than several decimeters within the coming century, taking only natural physical processes into account.

Scientists have predicted different changes in future sea level. However, the present range of predictions for the coming century are rather consistent. Most prognoses are in the range between 40 and 100 cm for the coming century, although there are still prognoses with much higher values, up to more than 1.5 meter per century. In these particular cases, the prognoses depart from the assumption that the West Antarctic Ice Sheets should quickly be disintegrated.

However, still quite a number of the above mentioned mechanisms are based on only assumptions. Therefore, in order to supply scientific evidence how the mechanisms act, it is necessary to investigate the following aspects: the causes of climate change during long times periods; the most important feedback mechanisms (such as oceans and clouds); and the processes that contribute to a possible disintegration of the West Antarctic Ice Sheets.

1 Introduction

As the Netherlands is a low-lying country, sea level rise would effect the society of the Dutch environmentally, socially and economically. The effects of sea level rise on Water Management have to be estimated in time, so that society can react on those impacts.

For this reason, it is important to know within what range of future sea level rise can be expected. One way to estimate future sea level rise is to analyze the changes in sea level rise during the past over several time periods: decennia, centuries, millennia and even millions of years.

Although much research is accomplished concerning the causes of sea level rises, many important aspects that determine the sea level rise are not easily understood and can not easily be described.

First, climate on the Earth is not only changing due to natural causes, but also due to human activities, especially since the beginning of the 'Industrial Revolution'. The geosphere-biosphere system (Priem, 1989) activates natural processes which cause changes in climate. These natural processes alter the atmospheric temperature, causing warm and cold periods on the Earth. Well-known periods are the Ice Ages during the last million years. On the other hand, human activities, such as extra emission of gases (e.g., CO_2 and methane), accelerate temperature rise of the atmosphere. It is difficult to determine which part of sea level rise is the consequence of which cause since the beginning of the 'Industrial Revolution': natural processes or human activities.

In addition, many climatological mechanisms influence temperature rise such as ice and snow, water vapour, clouds, oceans and permanently frozen soils (permafrost). Some of these mechanisms amplify temperature rise, other mechanisms counteract it.

Finally, sea level rise is related to temperature rise. For instance, ocean water will warm up and as a result expand (this is called thermal expansion), while glaciers and icecaps will melt. Moreover, an uncertain cause of sea level rise may be the disintegration of polar ice sheets on West Antarctic (Thomas, 1986; Oerlemans, 1989). Furthermore, some physical processes may cause a fall in sea level, such as the accumulation of water on polar ice sheets of Central Antarctica.

Because of these many uncertainties in mechanisms, the most relevant mechanisms that determine the level of the sea are investigated in this literature study. At this moment, no exact prognoses of sea level rise for the coming centuries can be given, since at present the order of magnitude of possible sea level rise and natural variation of the sea level is the same. Here, facts and causes of sea level rises in the past are presented. Nevertheless, also some scenarios of future sea level rises for the coming centuries are given.

The *eustatic* sea level rise depart from the assumption (of Suess in 1885) that on the ocean surface no slope could exist and that vertical displacements of the ocean surface occur uniformly throughout the world. However, changes in sea level are influenced by *glacio-isostatic* effects which accompany the present deglaciation phase, with uplift movements in areas of ice melting and subsidence in a wide peripheral belt. (Pirazolli, 1991).

By contrast, when sea level rise is mentioned in this literature study, in fact the ***relative sea level rise*** regarding to the land-surface is meant, For instance, isostatic uplift or subsidence movements of the crust of the Earth has the same effect as sea level rise. Therefore, also regional circumstances concerning the isostatic uplift or subsidence movements highly determine the *relative* sea level rise (Robin, 1986).

The most relevant mechanisms of sea level changes are discussed in this literature study. In chapter 2, a brief summary of the climate change in the world is given. In chapter 3 follows a discussion of causes of temperature rise and greenhouse effect in relation with feedback mechanisms. Chapter 4 gives the physical processes which determine sea level in case of temperature rise. In chapter 5 the sea level changes in the past during some different time periods are described. Chapter 6 summarizes some prognoses of future sea level rises, calculated by scientists during the last few years. In this chapter, also the scenarios of future sea level rises are given. Finally, the conclusions and recommendations are summarized in chapter 7.

2 Causes of climatic change

Since the creation of the Earth, climate has been changing. During the first hundred million years, the upper layers of the Earth's crust were liquid. Slowly, the Earth's crust cooled down to temperatures that made life possible. Even now, the Earth is still cooling down. The scope of this literature study is focussed on the climate change during the last million years. At this moment, the general condition of the Earth's crust is determined by a complex self-regulating *geosphere-biosphere system* (Priem, 1989). The system includes the following components: atmosphere, biosphere (these are all biological processes: the aspect 'life'), oceans, ice sheets, land-surface properties and the Earth's crust itself. These components are closely related to each other.

Solar radiation warms up the Earth. External changes in global climate are forced by various processes that change the flows of radiation energy within the geosphere-biosphere system. Either the absorption of solar radiation or the trapping of long-wave radiation by trace gases in the atmosphere may change. An important consequence of climate change is a change in *global mean equilibrium surface temperature*. Five possible reasons for change in global climate are (Dickinson, 1986):

1. a change in solar output. Solar output is known to vary both on very long time scales, as well as on short time scales (days to years),

2. a change in the geometry of the Earth's orbit around the sun (the *Milankovitch cycles*),

3. a change in the fraction of incoming (short-wave) energy at the top of the atmosphere that is absorbed by the surface or atmosphere,

4. a change in the amount of net outgoing (long-wave) energy at the top of the troposphere, and

5. a change in the amount of heat stored in the deep oceans.

It is very difficult to detect which change is the effect of what reason, because the global temperature is a combination of the five reasons that have different response-time scales. The reasons 1. and 2. are beyond the scope of this literature study. On the contrary, the reasons 3., 4. and 5. are closely related to the *geosphere-biosphere system* on the Earth and they may be the causes of changes in mechanisms such as the greenhouse effect. Therefore, the reasons are discussed in chapter 3.

3 Causes of temperature change

First, the physical process that takes place in the atmosphere of the Earth causing the greenhouse effect is briefly described. Then the origin of present atmospheric trace gases are divided into two components: natural processes and human activities. Furthermore, the most important feedback mechanisms are discussed, and finally, prognoses of CO_2-concentration and atmospheric temperatures for the coming century (using figures of the Villach Conference in Austria 1985 and the IPCC[1] in 1990) are summarized.

3.1 Relation between temperature rise and greenhouse effect

Radiation of the sun warms up the atmosphere. A part of the radiation is absorbed by the Earth's surface (short-wave energy), while another part (the reflection coefficient, called *albedo*) of the radiation is emitted as long-wave radiation. The amount of the short-wave energy absorbed by the Earth's surface depends on the state of the geosphere-biosphere system.

Temperature changes, if the balance between the absorption and radiation of energy at both long-wave and short-wave lengths is disturbed. The concentration of trace gases in the atmosphere is the most important aspect that keeps the incoming and outgoing energy in balance.

In case the concentration of trace gases is increasing, more emitted energy will be trapped in the atmosphere. This process is called the *greenhouse effect.* A higher level of trace gases (the so-called *Greenhouse gases*) is considered as the main contributor that warms up the atmosphere of the Earth.

3.2 Origin of the concentration of Greenhouse gases in the atmosphere

The most important atmospheric Greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), ozone (O_3), methane (CH_4) and chlorofluorocar-

[1]The Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC) is set up jointly by the World Meteorological Organization and the United Nations Environment Programme in 1988. It is an assessment of how human activities may be changing the Earth's climate through the greenhouse effect. Several hundred of international scientists participated in the preparation and review of this assessment. The editors of chapter nine Sea Level Rise are R.A. Warrick and J. Oerlemans

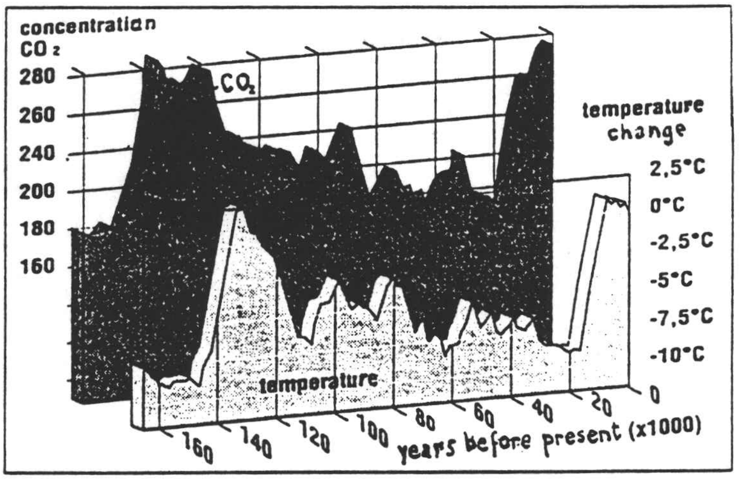

Figure 1: *There is a clear relationship between the CO_2-concentration and the temperature change, during the last 160000 years. The data are based on ice samples, bored in the station Vostok in Antarctica (Barnola et al., 1987. From: S. Zwerver, 1989.*

bons ($CFCs$). All the trace gases together, except water vapour, are called the *effective CO_2-concentration*, since of these gases carbon dioxide is the most important gas from the viewpoint of affecting climatic change. The other gases occur in much smaller concentrations than the CO_2-concentration, for instance 1.7 ppm ('parts per million') N_2O related to 350 ppm CO_2 (Korevaar, 1989).

Greenhouse gases originate from both natural processes as well as human activities. Water vapour is purely a natural factor (whose concentration widely varies in space and time), while CFCs, being of strictly anthropogenic origin, are purely artificial. The other trace gases have concentrations that are influenced by human activities, but may also vary naturally as parts of the feedback of the climate system as a whole (Dickinson, 1986).

3.2.1 Natural processes

The concentrations of trace gases in the atmosphere have been built up in several millions of years. Thanks to the greenhouse effect of these gases, the mild climate has made the Earth livable for some 3.5 billion years. Without these Greenhouse gases, the Earth would now have a temperature of about -18 ^oC.

Up till the Industrial Revolution, the CO_2-concentration was the result of the complex self-regulating geosphere-biosphere system. An enormous amount of CO_2 is stored as bicabonate in ocean water and as carbonate and biomass in sedimentary rocks, together some two hundred thousand times the amount of CO_2 in the atmosphere (Priem, 1989). In this system, the biosphere plays a crucial role. In case the atmospheric CO_2-concentration will fall substantially below the present level, a worldwide cold period will set in. For instance, during the last Ice Age, the CO_2-concentration was 30 per cent lower than at the beginning of the 'Industrial Revolution'. This is detected in air bubbles, locked in old ice-layers in Antarctica (fig. 1). The geosphere-biosphere system reacts as follows (Priem, 1989).

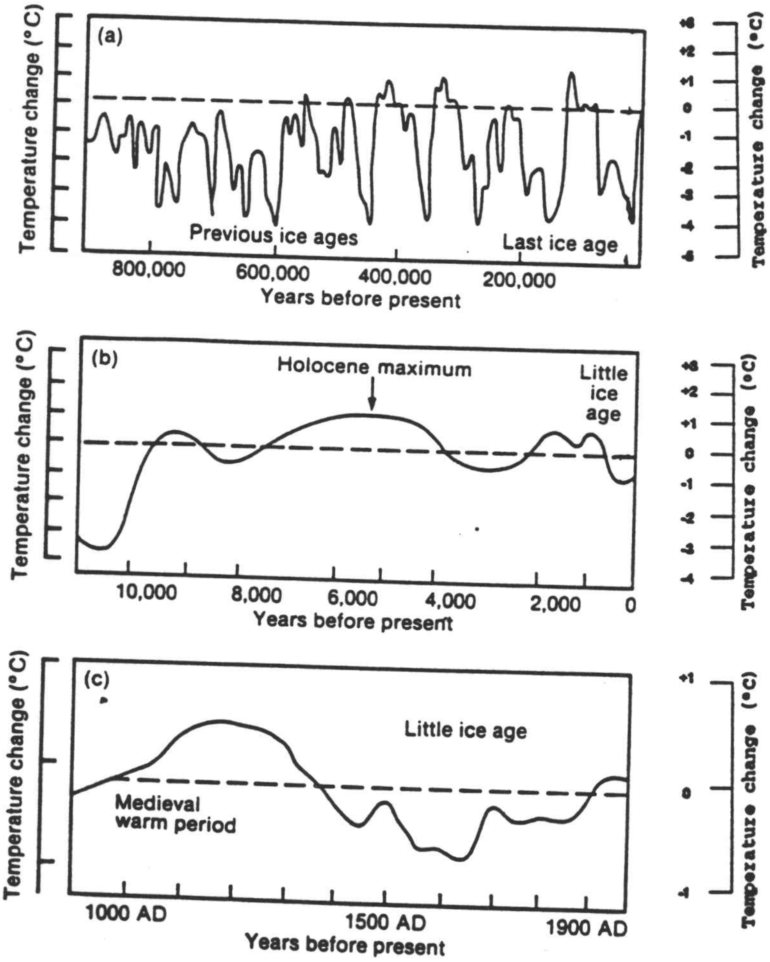

Figure 2: *Schematic diagrams of global temperature variations since the Pleistocene on three time scales: (a) the last million years, (b) the last ten thousand years, and (c) the last thousand years. The dotted line nominally represents conditions near the beginning of the twentieth century. Modified from IPCC, 1990.*

During the cold period, the sea will absorb extra CO_2 and the biological activity as well as the intensity of the chemical erosion at the surface of the Earth will decrease. As a result, less CO_2 will be withdrawn from the atmosphere by formation of carbonate and biomass. Meanwhile, the supply of CO_2 will not be influenced by the current cold at the surface of the Earth, because of volcanic eruptions and geological processes in the Earth's crust. According to this simplified scenario, after a while the CO_2-concentration in the atmosphere will rise again, and thus the climate will warm up. In the course of this process, feedback mechanisms will counteract the increase of the CO_2-concentration in the atmosphere. However, the regulating processes in the geosphere-biosphere system will act too slow to counteract the present increase of CO_2-concentration substantially.

The warming up and cooling down of the Earth is a natural process. Fig. 2 shows the change in global temperature on three time scales.

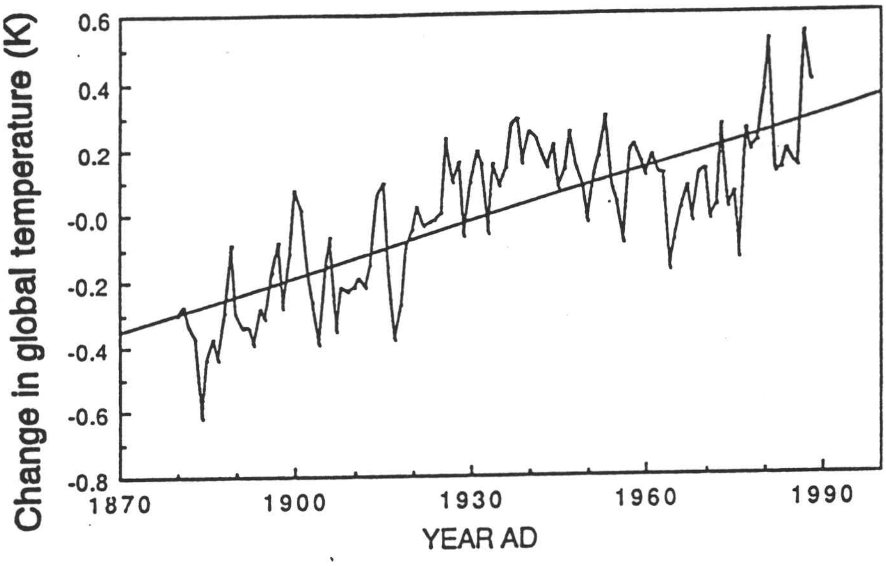

Figure 3: *Change in global mean air temperature (near the surface) over the last 110 years. From: Oerlemans, in press.*

3.2.2 Human activities

Since the beginning of the 'Industrial Revolution', the concentration of trace gases has rapidly increased as a result of intensive human activities. It is common knowledge that the year 1850 is marked as the moment the concentration of trace gases increased rapidly, due to the 'Industrial Revolution'. However, recently excavated ice samples from Greenland indicate that the increase of trace gases started earlier, around 1810. Wahlen *et al.* suppose that this increase of trace gases is the result of changes in land use and deforestation.

Anyway, since 1850, the concentration of CO_2 increased by about 30 per cent (Oerlemans, in press). Consequently, energy is absorbed and the atmospheric temperature has risen (fig. 3). At this moment, the CO_2-concentration annually increases about 0.4 per cent, the N_2O-concentration 1 per cent, the CH_4-concentration 0.25 per cent and the $CFCs$-concentration about 5 per cent (Korevaar, 1989). This is especially due to large-scale burning of biomass and fossil fuels (coal, mineral oil and natural gas). Some important polluters are industry (e.g., coal mining), traffic and agriculture (e.g., rice cultivation).

It should be noted that the global warming could be the effect of the recovery from the 'Little Ice Age', rather than a direct result of human activities. The 'Little Ice Age' began about 450 years ago and came to an end only in the 19^{th} century (see fig. 2).

3.3 Feedback mechanisms

Feedback mechanisms are processes that influence the change in the concentration of the trace gases and consequently the temperature, because they are components in the geosphere-biosphere system. If it is assumed, that the concentration of trace gases increases and that as a result the temperature rises, these feedback mechanisms can either counteract or amplify these rises. Nevertheless, it is still quite unclear how most feedback mechanisms react to changes in the climate exactly. There are too many uncertain aspects and parameters in these feedback mechanisms, while scientific research on interaction between these mechanisms is still in development. However, in the following six sections some characteristics of the most important feedback mechanisms are summarized:

1. **Influence of ice and snow**
   Much of the solar radiation is absorbed at the Earth's surface. Therefore, the reflection coefficient at the surface (the so-called *albedo*) is the most important factor in determining the actual amount of absorbed solar radiation. The albedo may vary from as low as 0.02 [−] to higher than 0.95 [−], depending on the kind of surface (Dickinson, 1986). In general, ice and snow surfaces have much higher albedos than most land surfaces and all (liquid) oceans. Therefore, in case the temperature rises because of a higher concentration of trace gases, ice and snow will melt, and thus the extent of ice and snow surfaces on the world decreases. The incoming solar radiation is reflected less, and as a result, the temperature at the Earth's surface rises even more. This feedback mechanism amplifies the process of warming up the Earth.

2. **Influence of water vapour**
   An increase in the effective CO_2-concentration will raise the temperature. Therefore, more water vapour will enter the atmosphere. The absorption of outgoing energy increases, and consequently the temperature rises even more. This feedback mechanism also amplifies the warming up of the Earth. According to some scientists (Rind *et al.*, 1991), the influence of water vapour is not overestimated in the *general circulation models* (GCMs) and has the same order of magnitude as the influence of the effective CO_2-concentration.

3. **Influence of clouds**
   Especially this item is unclear, because the following parameters of clouds are difficult to assess: cloud-thicknesses, fractional covers, altitudes of the tops of the clouds, liquid water contents, drop sizes and spacial scales. It is possible that future change in cloud properties could alter the net radiation budget of the climate system by either more absorption of outgoing energy or possibly more reflection of incoming energy. Hence, clouds could either amplify or counteract the effect of the increased effective CO_2-concentration (Dickinson, 1986).

   Ramanathan and Collins (1991) investigated the influence of clouds by measuring with satellites the radiation at the top of the atmosphere during the 1987 El Niño event. They found in that specific case-study that especially highly reflective cirrus clouds counteract the greenhouse effect.

4. **Influence of oceans**
   Still little is known about the role of oceans if trace gases increase. Scientists are familiar with the fact that oceans can absorb large amounts of the CO_2-concentration, but the precise saturation level is unknown. A first assessment of the saturation level is that about half of what mankind emits in the atmosphere is

absorbed by oceans (Zwerver, 1989). If so, oceans are a positive feedback mechanism: they counteract the rise of the effective CO_2-concentration and consequently temperature.

Another important aspect of oceans in case of climate change may be the possibility that the *direction* of some ocean streams alters, which has great affects on 'local' climate. For instance, the North Atlantic Drift (Gulfstream) is essential for the climate in Western Europe.

5. **Influence of permafrost**
   By warming up permafrost, which are permanently frozen soils at high northern latitudes (such as in Canada and Siberia), more methane (CH_4) will enter the atmosphere. This will amplify the greenhouse effect.

6. **Influence of volcanic activities**
   Volcanic eruptions bring large amounts of dust particles in the atmosphere. Together with the dust particles of the burning of fossil fuels and forests, the volcanic dust will reflect incoming energy, and as a result, the greenhouse effect could be counteracted. Furthermore, the dust particles form the cores of cloud drops that will probably reflect sunlight (see also item 3.).

3.4 Future effective CO_2-concentration and temperature rise

Although the observed global-scale warming experienced over the past century is compatible with model estimates of the magnitude of greenhouse effect, it is not yet possible to detect statistically the effects of changing CO_2-concentration and other trace gas levels on climate (Wigley *et al.*, 1986).

For the future development of the effective CO_2-concentration, several scenarios are possible. However, an evaluation of results from climate models leads to the conclusion that the increase in global mean equilibrium surface temperature due to increases of CO_2-concentration and other Greenhouse gases equivalent to the doubling of the atmospheric CO_2-concentration is likely to be in the range of 1.5-4.5 $°C$. Although no value within this range of uncertainty can be excluded, it is plausible that the increase may be found in the lower half of this range. This range is valid in case the present trend of emission of Greenhouse gases continues. The upper bound scenario implies that the effective CO_2-concentration might double by the middle of the next century, while the lower bound scenario implies that doubling of the effective CO_2-concentration will not be reached until after 2100.

The well-known scenario is formulated at the Villach Conference Austria 1985 (Bolin *et al.*, 1986) as follows: 'a doubling of the atmospheric CO_2-concentration, or equivalent, increases the global mean equilibrium surface temperature between 1.5 and 4.5 $°C$'. The temperature scenario for the coming century of the Villach II conference with a probability range is illustrated in fig. 4. The last scenario that is presented here is from the Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC), sponsored by the World Meteorological Organization and the United Nations Environment

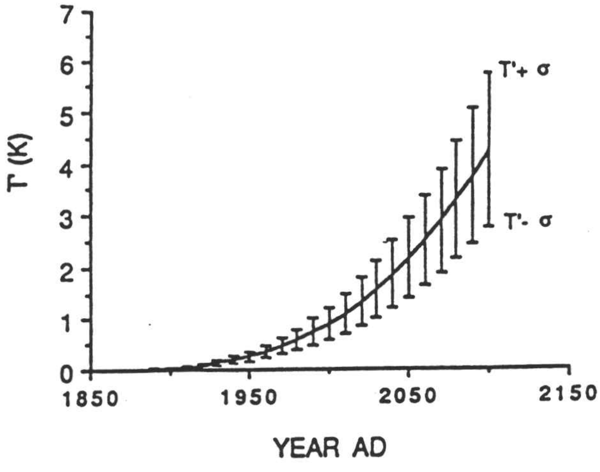

Figure 4: *The temperature scenario: the outcome of the Villach II discussion. Vertical bars indicate the standard deviation. From: Oerlemans, 1989.*

Programme. In 1990, the IPCC predicts 'under the IPCC Business-as-Usual (Scenario A) emissions of Greenhouse gases, a rate of increase of global mean temperature during the next century of about 0.3 ^oC per decade (with an uncertainty range of 0.2 ^oC to 0.5 ^oC per decade), which is greater than that seen over the past 10.000 years...'

Furthermore, the IPCC employs three other *policy emission scenarios* of the Greenhouse gases for the coming century. In these scenarios, a broad range of possible controls to limit the emission of Greenhouse gases are generated, and levels of technological development and environmental controls are varied. The rate of increase in global mean temperature is for:

1. scenario A, 'Business-as-Usual': 0.3 ^oC per decade with an uncertainty range of 0.2 ^oC to 0.5 ^oC per decade,
2. scenario B, 'Low Emission': 0.2 ^oC per decade,
3. scenario C, 'Control Policy': just above 0.1 ^oC per decade,
4. scenario D, 'Accelerated Policy': about 0.1 ^oC per decade.

4 Relation between temperature rise and sea level rise

An important consequence of increase of global mean atmosphere temperature is sea level rise. The following four physical processes are connected to the rise of atmospheric temperature, and contribute to the change in sea level: (1) thermal expansion of ocean water, (2) melting of mountain glaciers and small icecaps, (3) accumulation on and ablation of polar ice sheets of Greenland and Antarctica, and (4) disintegration of the West Antarctic Ice Sheets.

The ablation means that accumulation of ice on the polar ice sheets of Greenland and Antarctica evaporate or melt and subsequently run off.

4.1 Thermal expansion of ocean water

Thermal expansion of ocean water is an important factor contributing to sea level rise. Thermal expansion is dependent on the salt concentration and highly dependent on the temperature level. For instance, a layer of ocean water of 100 m thickness at a temperature of 25 ^oC will expand 3 cm per degree temperature rise, while a layer of ocean water of 100 m thickness at a temperature of 0 ^oC will only expand 0.5 cm.

Because warming up of deep ocean layers is a long time scale process (at least some centuries), sea level rise by thermal expansion for the coming centuries would only be determined by the upper ocean layers of only a few hundred meters thickness.

subsectionMelting of mountain glaciers and small icecaps Although mountain glaciers and small icecaps only contain a small part of the total ice mass on Earth (see table 1), they are located in warmer climates than polar ice sheets of Greenland and Antarctica. Therefore, the ice masses are more active and react to climate change more quickly (Oerlemans, 1989).

Since the beginning of the 'Industrial Revolution', a great number of mountain glaciers has shown a withdrawal of their tongues. In fig. 5, a few long records are displayed, showing variations in glacier length. Despite the fact that data of essential mountain glaciers such as in the Andes, Himalaya and Alaska are rare, the impression is that the withdrawal is worldwide (see fig. 6). Even though still many aspects need more attention, it is clear that glacier tongues are withdrawn.

The mean reason for this withdrawal is that temperature rise melts glacier tongues. Furthermore, glacier tongues are quite sensitive to radiation, because the albedo of the ice surfaces is large, about 0.3. When the temperature rises, the balance in net radiation budget of the climate system alters. If so, the incoming short-wave radiation is more intensive than before, because of two processes. First, if the concentration of $CFCs$ increases, the thickness of the ozone layer reduces, and as a result the incoming radiation increases. Second, since the beginning of this century, the number of volcanic activities has been small. As a result, less dust is in the atmosphere, and hence, the incoming radiation is stronger (Oerlemans, in press).

4.2 Accumulation on and ablation of polar ice sheets

The polar ice sheets of Greenland and Antarctica will also react to climate change. These ice sheets of Greenland and Antarctica differ from the mountain glaciers and small icecaps due to other physical characteristics (see table 1). A higher atmospheric temperature will not immediately imply decreases of ice masses on these ice sheets. This depends on the surface temperature above the polar ice sheets.

For most geographical and climatological conditions (when surface temperature is not too low), increasing air temperature indeed implies decreasing ice masses. This is the case for the Greenland Ice Sheet and the edges of the Antarctic continent. By contrast, for the coldest polar regions, particularly over Central Antarctic, the annual surface air temperature is very low and it limits snow (or rime) accumulation. When the annual surface air temperature above Central Antarctica will increase, the saturation vapour

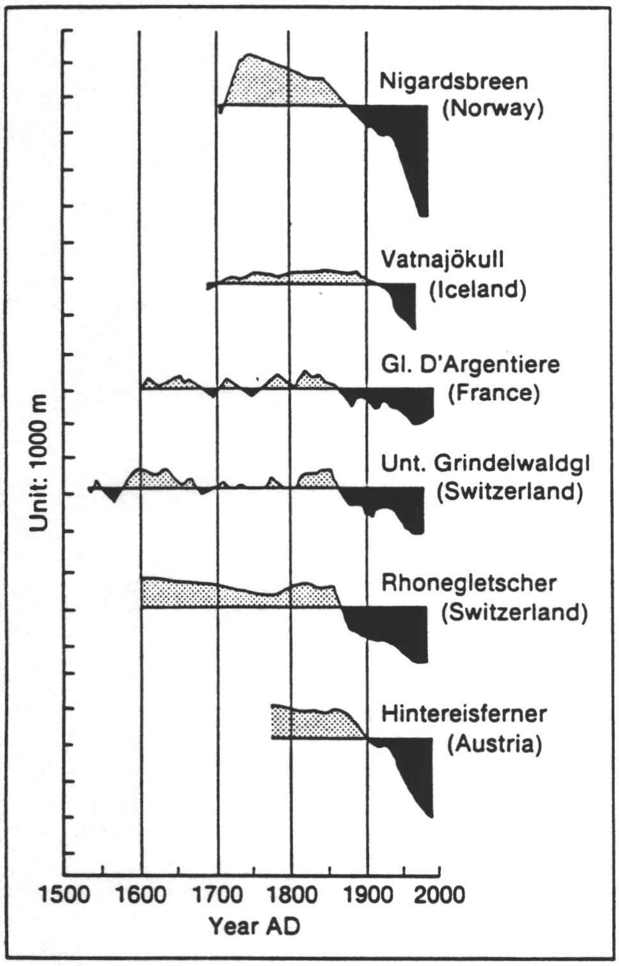

Figure 5.

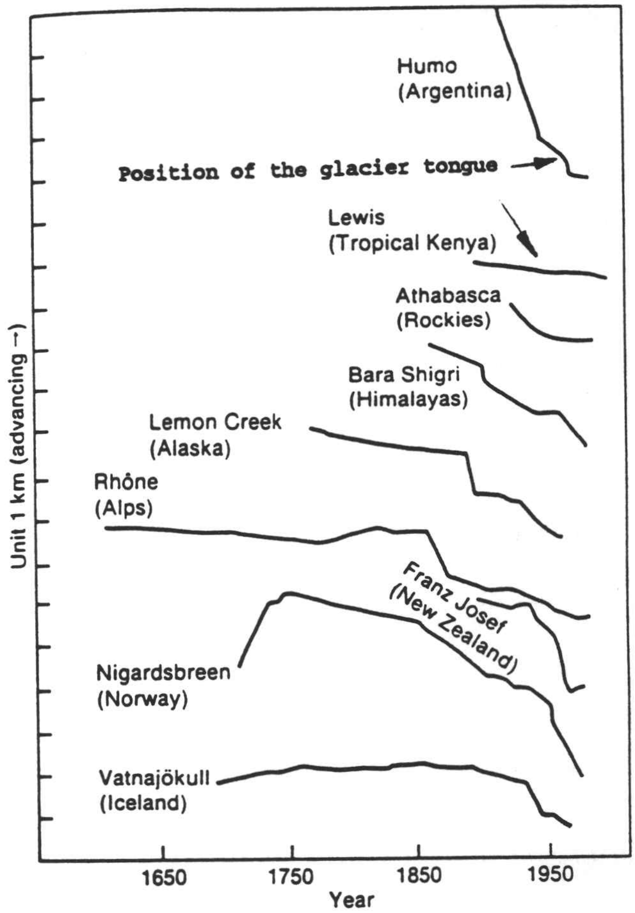

Figure 6.

Figure 5: *Historic variations in the length of some glaciers. The position of the glacier tongue is given, relative to the axis that is determined by the averaged position of the glacier tongue during the whole record. The area between the position of the glacier tongue and the average position is painted black. Data from Bjornsson (1979); Ostrem et al. (1977); Kasser (1967, 1973); Kasser & Haeberli (1979); Muller (1977); Vivian (1975) and Haeberli (1985). From: IPCC, 1990.*

Figure 6: *Historic fluctuations in the length of some glaciers throughout the world over the last three centuries (after Grove 1988, and other sources). From: IPCC, 1990.*

pressure increases also. Scientists suggest that as a consequence, the atmosphere above Central Antarctica can contain more water vapour, and ice masses accumulate. This leads to the situation that ice masses would increase with air temperature.

Present computations suggest that the net effect is small: the accumulation of snow on Central Antarctic and the ablation on Greenland and the edges of the Antarctica continent are somewhat in balance. However, this is a temporary situation. In the long run (centuries to millennia, if the warming would last that long), mass loss on Greenland

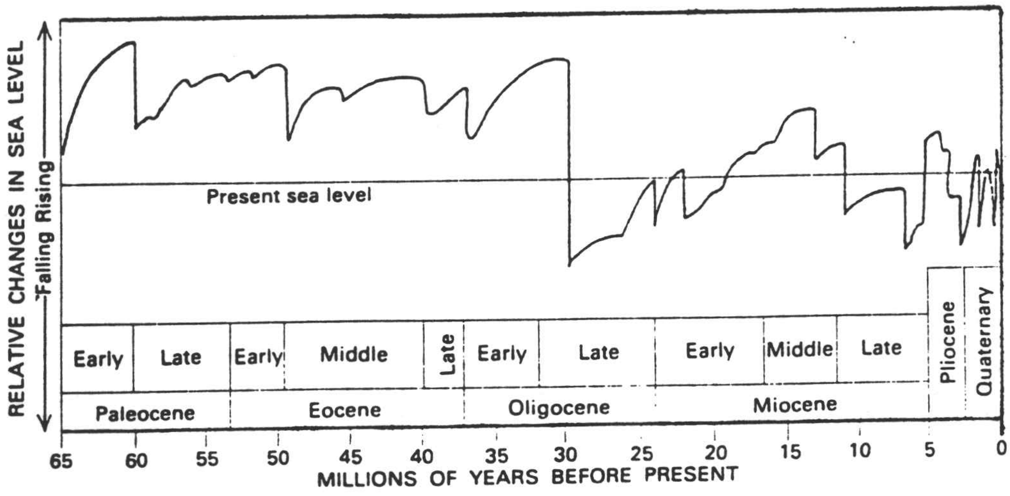

Figure 8: *Sea level curves during the Cenozoic: Tertiary and Quaternary periods. Modified from Vail, Mitchum, and Thompson, 1977, figure 3. From: Meisler et al., 1984.*

in a sea level rise of 5 to 6 meters within a few centuries. Still, many aspects need more research, although the present consensus is that the early estimations of the sensitivity of the WAIS were too large.

5 Sea level changes in the past

Since the creation of the Earth climate, atmospheric temperature and thus sea level have changed. By analyzing sea level changes in the past during different time periods, the mechanisms involved are understood more. Therefore, scientists may be able to give more reliable prognoses of sea level rises.

In this chapter, the sea level changes in the past during four different time periods are presented: (1) changes during the Cenozoic: Tertiary and Quaternary periods, (2) changes during a part of the Quaternary period, (3) changes during the Holocene and finally, (4) changes during the last centuries.

5.1 Changes during the Cenozoic: Tertiary and Quaternary periods

Fig. 8 shows the relative sea level changes during the Tertiary and Quaternary periods. It is easy to see that sea level during the Early Tertiary period was in general higher than during the Late Tertiary period.

5.2 Changes during a part of the Quaternary period

The cycles on the Earth of cold periods (Ice Ages) followed by warm periods (interglacial eras) have occurred already many million years, as it appears in fig. 9, where the globally estimated mean summer temperature (July) in the Netherlands is shown. The Quaternary is characterized by an alteration of several warmer and colder phases.

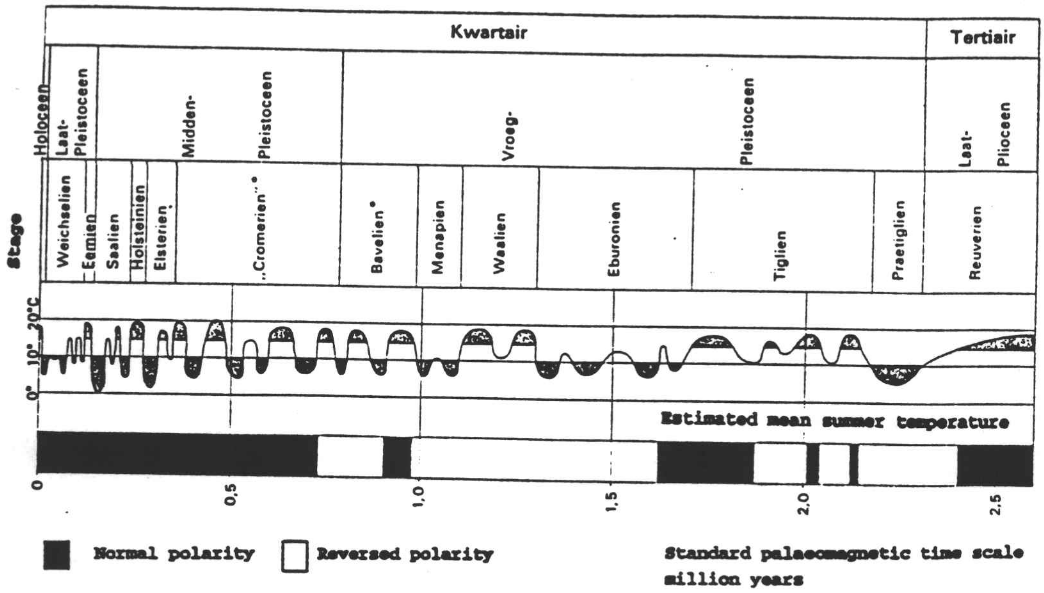

Figure 9: *Global palaeomagnetic climatological curve of the Netherlands. The time-scale relies on palaeomagnetic data. The temperature curve is inferred from pollen analytic data. From: Zagwijn et al., 1986.*

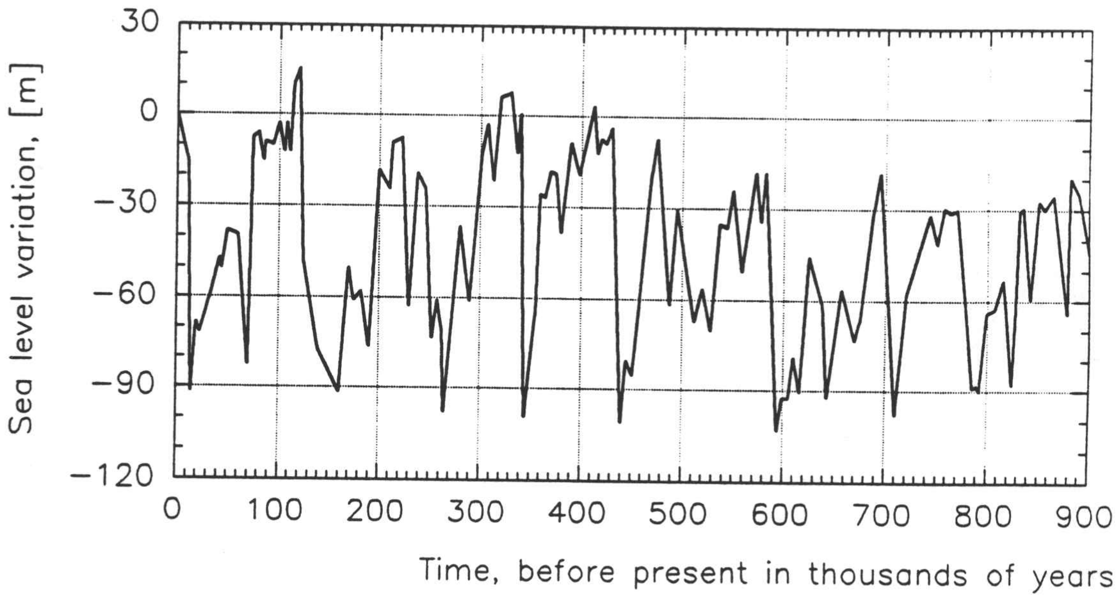

Figure 10: *Sea level curves. Modified from Zellmer, 1979, figure 17. From: Meisler et al., 1984.*

The uppermost cold phases (Elsterian, Saalian, Weichselian) comprise some interphases of less severe cold. Fig. 10 displays the sea level during the last 900.000 years. During these last 900.000 years, the mean sea level was approximately 45 meters below present mean sea level. It is obvious that the present sea level has a high position.

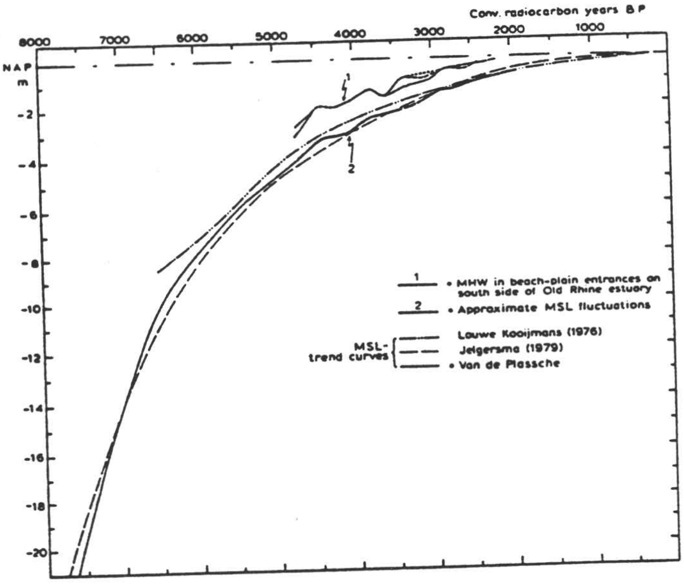

Figure 11: *Time-depth diagram with sea level trend curves for the Netherlands, developed by Louwe Kooijmans (1976), Jelgersma (1979) and Van de Plassche (1982). From: van de Plassche, 1982.*

5.3 Changes during the Holocene

At this moment, the Earth finds itself in an interglacial era. The last Ice Age, the Weichselian, lasted for 60.000 years. Since the beginning of the Holocene era (about 10.000 year ago), the climate has become warmer. As a result, sea level has risen. In fig. 11 the time-depth diagram with the sea level trend curves during the last 8000 years for the Netherlands (van de Plassche, 1982) is shown. It shows that during the last millennia, sea level rose less than during the first millennia of the Holocene. Keeping this in mind, it is unlikely that sea level will rise several tens of meters during the coming millennia, because relatively small amounts of ice masses are still stored in mountain glaciers, icecaps and on polar ice sheets of Greenland and Antarctica. For instance, in case the total ice sheet of Greenland will completely melt away, the sea level will 'only' rise about 7.5 m (see table 1).

5.4 Changes during the last centuries

Finally, the mean sea level of Amsterdam, Brest, Den Helder and 'Global', illustrated in fig. 12, explicitly shows a deviation in the trend of sea level rise, since approximately the beginning of the 'Industrial Revolution'.

Table 2 shows the results of some scientists who have estimated the change of the sea level during the last century. It shows that the sea level has risen about 10 à 15 cm per century in the period 1880-1980. Barnett's estimations show that the last fifty years sea level has risen faster than the first fifty years of the period 1880-1980. Nevertheless, the rise of sea level over this period is never more than a few decimeters. The estimations of the IPCC have the same tenor. It judges that 'the average rate of rise over the last 100

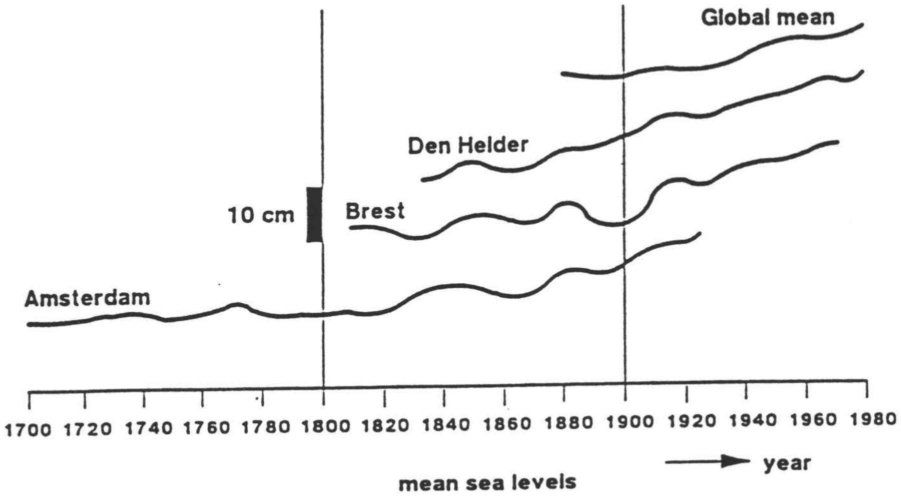

Figure 12: *Mean isostatic sea levels of Amsterdam, Brest, Den Helder and Global mean, put together in one figure. The Global mean sea level is derived by Gornitz et al. (de Ronde, 1988).*

Author	Rate [cm/century]	Comments
Thorarinsson (1940)	> 5	Cryologic Estimate
Gutenberg (1941)	11 ± 8	1807-1939 (many stations)
Kuenen (1950)	$12 - 14$	-1942 Different Methods
Lisitzin (1958)	11.2 ± 3.6	1807-1943 (six stations)
Wexler (1961)	11.8	Cryologic Estimate
Fairbridge and Krebs (1962)	12	1900-1950 (selected stations)
Emery (1980)	30	1935-1975 (many stations)
Gornitz *et al.* (1982)	12⋆	1880-1980 (many stations)
Klige (1982)	15	1900-1975 (many stations)
Barnett (1983)	15.1 ± 1.5	1903-1969 (selected stations)
Barnett (1984)	14.3 ± 1.4†	1881-1980 (many stations)
Barnett (1984)	22.7 ± 2.3†	1930-1980 (many stations)
Gornitz & Lebedeff (1987)	12 ± 3†	1880-1982 (130 stations)
Barnett (1988)	11.5	1880-1986 (155 stations)

†= Value plus 95 % confidence interval.

⋆ = 12 cm/century is the uncorrected value: 10 cm/century is corrected for crustal motion (long range trends, e.g., residual isostatic uplift of continents).

Table 2: *Estimates of mean 'global' sea level increase. From: Barnett, 1983, Robin, 1986 and IPCC, 1990.*

years has been 10-20 cm per century' and that 'there is no firm evidence of accelerations in sea level rise during this century (although there is some evidence that sea level rose faster in this century compared to the previous two centuries).'

Therefore, it is believed that the sea level shall not rise more than several decimeters for the coming century.

6 Future sea level rise

In this chapter the two processes that determine the prognoses of the future sea level rises are mentioned first. Second, for one prognosis the different contributions to the sea level rise (see also chapter 4) are specified, followed by some prognoses of future sea level rises. Finally, some future sea level rise scenarios are given.

It is difficult to prove what part of the sea level rise is the result of climatic changes caused by human activities or by natural processes. For instance, in order to detect the specific part of sea level rise caused by mankind, scientists should demonstrate about one millimeter sea level rise per year in a wave-amplitude of about two meters. Therefore, it will probably take quite a few years before scientists can *statistically* prove the sea level is rising because of human activities. Nevertheless, many scientists have tried to prognosticate the sea level rise especially for the coming century.

6.1 Processes of future sea level rise

The two important processes that determine the prognoses of sea level rise are:

- **Sea level rise because of natural processes**
  There can be detected two *response-time scales*: a *short* one and a *long* one.
  Changes in climate at a short response-time scale are in the order of decennia or a century. Decennia do not have the same mean temperature. Some decades can be considered as warm comparing to the mean temperature during a century. Some short response-time scale processes are associated with upper oceanic layers and adjustment of small glaciers. Response-time scales of the order of a century are associated with deeper oceanic layers and larger glaciers.
  Changes in climate at long response-time scales are in the order of millennia. Although the sea level has not risen much during the last millennia (see fig. 11), still a steady state situation is not reached. Two long response-time scale processes are the melting of continental ice sheets and resultant adjustment of the Earth's crust to changing ice loading (Robin, 1986). For instance, since the end of the last Ice Age Scandinavia is rising and, at this moment, some parts near the Dutch coast (Noord-Holland and the area near Rotterdam) are falling more than 8 cm per century (Noomen, 1989).

- **Sea level rise because of human activities**
  Changes in climate that are accomplished by human activities, such as the extra emission of Greenhouse gases, amplify the greenhouse effect. Therefore, the sea level is rising extra in this century; above the sea level rise caused by natural processes. The response-time scale is short, only in the order of decades.

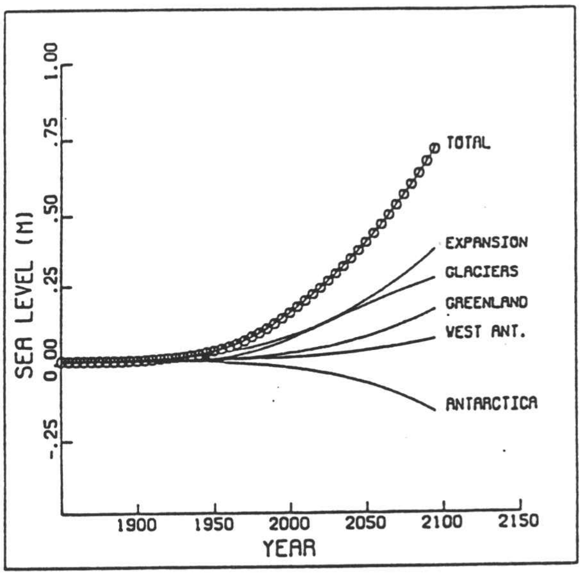

Figure 13: *Estimated contributions to changing sea level for the temperature scenario of fig. 4. From: Oerlemans, 1989.*

6.2 Several contributions of future sea level rise

Some scientists, such as Oerlemans (1989, in press), estimate the future sea level rise by dividing the contributions into the four sections of chapter 4: (1) thermal expansion of ocean water ('Expansion'), (2) melting of mountain glaciers and small icecaps ('Glaciers'), (3) accumulation on and ablation of polar ice sheets ('Greenland' and 'Antarctica'), and (4) disintegration of West Antarctic Ice Sheets ('West Antarctica'). In fig. 13 the estimated contributions to changing sea level of the temperature scenario of fig. 4 are shown. The most important contribution seems the thermal expansion of ocean water. The contributions of Greenland and West Antarctica Ice Sheets largely compensate each other. Since in fig. 4 a standard deviation is given, the probability densities of sea level rise can be determined. This is done in fig. 14: it indicates how rapid uncertainties of the present prognoses of future sea level rise grow in time (Oerlemans, 1989).

However, there are also scientists who suggest that global warming could lead to an ice-sheet growing. For instance, Miller and De Vernal (1992) examined a recent geological record of 130.000 years to present. They found that accumulation on polar ice-sheets (ice-sheet growth) occurred for climate conditions at the begin of the last glacial cycle, under climate conditions rather similar to present. Furthermore, they suggest that accumulation on polar ice-sheets could dominate all other contributions during global warming, resulting in a possible sea level fall of 70 cm per century.

6.3 Prognoses of future sea level rise for specific years

It is easy to understand that the prognostications of sea level rises by scientists are not very consistent, since so many mechanisms that determine the sea level rise are quite

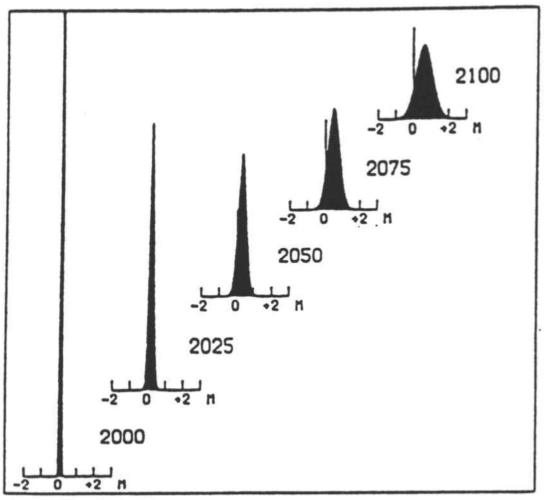

Figure 14: *Probability densities of sea level stand relative to 1985, for some selected times. From: Oerlemans, 1989.*

Author	2000	2025	2050	2075	2100
Historic Extrapolation[1]	2-3	4.5-6.8	7-10.5	9.5-14.3	12-18
Hoffman *et al.* (1984):[2]					
- Mid-Range Moderate Scenario	8.8	26.2	52.3	91.2	144.4
- Mid-Range High Scenario	13.2	39.3	78.6	136.8	216.6
(Robin (1986) [3]		25.1	52.6	70.8	89.1)
Oerlemans (1989)		20.5	33.0	50.5	65.6

Table 3: *A comparison of estimates of future sea level rise, in cm relative to 1980, except for Oerlemans, which is relative to 1985.*

unclear. Therefore, it becomes clear that the range of prognoses is broad, after analyzing quite a few prognoses of sea level rises.

Table 3 summarizes a few estimates of the global future sea level rise at specific years. Because many prognoses are calculated with different scenarios and parameters, a straightforward comparison is not entirely possible.

1. The historical sea level rises are estimated by Barnett (1983) and Gornitz *et al.* (1982): 10 à 15 cm per century in the period 1880-1980. The data are based on measurements of sea level changes with tidal gauges at particular locations over the past century.

2. Hoffman *et al.* (1984) made projections of sea level rises for the next century at intermediate years. They assumed that the glacial contribution would be one to two times the contribution of thermal expansion. By using special case scenarios for changes in Greenhouse gases, the sea level could rise as much as 345 cm ('High Scenario') and as little as 56.2 cm ('Conservative Scenario') in the year 2100. Here, the two 'Mid-Range Scenarios' are summarized: 'the Mid-Range Moderate Scenario' and 'the Mid-Range High Scenario' (Hoffman, 1984).

3. Robin (1986). These prognoses are calculated from the sea level-time regression (linear relationship) used by Robin to estimate sea level rise for a 3.5 K warming (Oerlemans, 1989).

RIVM: IMAGE					
Greenhouse gases scenarios	2000	2025	2050	2075	2100
Scenario A: unrestricted trends	6.7	21.1	38.9	61.1	86.5
Scenario B: reduced trends	6.3	18.7	33.6	50.5	67.8
Scenario C: changed trends	6.0	17.8	28.8	41.3	53.8
Scenario D: forced trends	5.8	15.8	24.5	33.2	41.8

Table 4: *Four scenarios of future sea level rises in the period 1985-2100, as input in the model IMAGE (in cm relative to 1985). From: Rotmans & den Elzen, 1988.*

Here follow some other estimations of sea level rises without projections at specific years:

- Revelle estimated in 1983 that the sea level rise is likely to be 70 cm in 2085 relative to 1980, ignoring (and not adding) the impact of a global warming on Antarctica, although he notes that the latter contribution is likely to be 1 to 2 m per century after 2050 (Titus, 1987).
- The USA National Academy of Science Polar Research Board (1985) implies a sea level rise between 50 and 200 cm in 2100, relative to 1980 (Titus, 1987).
- Robin (1986) estimated (based on a linear relation between sea level change and global temperature trend) that: 'the prediction of global warming of $3.5°C \pm 2.0°C$ due to CO_2 doubling over the next century would lead to a sea level rise of 80^{+85}_{-60} cm'.
- In the statement of the Villach Conference, Austria in 1985 stands: 'on the basis of observed changes since the beginning of this century, global warming of $1.5°C$ to $4.5°C$ would lead to a sea-level rise of 20-140 centimeters' (Bolin, 1986).

In two impact studies that estimate the effects of climate change on society, the following future sea level rises are presented:

- the Netherlands National Institute of Public Health and Environmental Protection (RIVM) uses the simulation model IMAGE to research some socio-economic consequences of the greenhouse effect for the Dutch society. In this model, four different scenarios for emissions of the most important Greenhouse gases are used to determine the future sea level rise (see table 4):
- in 1987, the UNEP (United Nations Environment Programme) and the Government of the Netherlands gave the onset for a study of the consequences of sea level rise and possible countermeasures for the Netherlands. The project is called: *ISOS, Impact of Sea level rise On Society. A case study for the Netherlands*, (Delft Hydraulics, 1988). In this study, the following three scenarios of sea level rises are proposed for the period 1990-2090: (1) the high scenario 85 cm, (2) the middle scenario 60 cm, and (3) the low scenario 35 cm.

Intergovernmental Panel on Climate Change				
Greenhouse gases scenarios		2030	2070	2100
Scenario A: Business-as-Usual	high	29	71	110
	best estimate	18	44	66
	low	8	21	31
Scenario B: Low Emission	best estimate	16	32	47
Scenario C: Control Policy	best estimate	15	29	40
Scenario D: Accelerated Policy	best estimate	14	26	34

Table 5: *Four scenarios of future sea level rises in the period 1990-2100, determined by the IPCC (in cm relative to 1990). From: IPCC, 1990.*

Finally, the prognoses of the IPCC are given in table 5. The IPCC employs simple models to calculate the rise in sea level to the year 2100, relative to 1990. The best estimate of global mean sea level rise under the IPCC Business-as-Usual emission scenario is about 60 cm over the next century with an uncertainty range of 30 to 100 cm per century. In table 5, also the best estimations of sea level rise of the three other *policy emission scenarios* of the Greenhouse gases are given.

6.4 Scenarios of future sea level rise

As could be seen in subsection 6.3, many prognoses of future sea level rise are possible, and therefore, some *sea level rise scenarios* are used. The selected sea level rise scenarios are:

1. no sea level rise,
2. a sea level fall of -60 cm per century,
3. a *natural* sea level rise of 15 cm per century,
4. a sea level rise of 60 cm per century, according to the IPCC,
5. a sea level rise of 100 cm per century,
6. an *extreme* sea level rise of 150 cm per century,

The groundwater flow model, which is employed to assess the impact of sea level rise on the groundwater flow regime, has the ability to insert the sea level rise as a boundary condition according to *pumpperiods*.

7 Conclusions and recommendations

Solar radiation is partly absorbed by the Earth's surface and partly reflected to the atmosphere. An important disturbance in the energy balance is accomplished when the fraction of solar radiation reflected (the so-called albedo) alters or when the outgoing energy is trapped in the atmosphere. Climate changes especially because of disturbances in the balance of incoming (short-wave) and outgoing (long-wave) energy. The concentration of trace gases in the atmosphere influences the energy balance. The higher the concentration of trace gases in the atmosphere, the more energy is absorbed by the atmosphere. As a result, the atmosphere will warm up. This last aspect is called the greenhouse effect.

From trace gases, the CO_2 is, except from water vapour, the most important Greenhouse gas. Therefore, the total concentration of trace gases is called the effective CO_2-concentration.

If the temperature rises, feedback mechanisms such as ice and snow, water vapour and permafrost significantly amplify the greenhouse effect. On the other hand, scientists believe that the feedback mechanism oceans counteracts the greenhouse effect, because large amounts of CO_2 and heat can be stored in the deep oceans. Furthermore, the influence of the feedback mechanism clouds is still too unclear to estimate its effect on temperature rise, although some scientists have evidence that clouds counteract the greenhouse effect.

Up till the beginning of the Industrial Revolution, a complex self-regulating geosphere-biosphere system had determined the concentration of the trace gases. However, from about 1850 on, human activities have increased the effective CO_2-concentration in the atmosphere due to deforestation, changes in land use, and burning of biomass and fossil fuels. Scientists estimate that as a result of human activities, between 2050 and 2100 the effective CO_2-concentration in the atmosphere will have doubled compared to the beginning of the Industrial Revolution. As a result of the established greenhouse effects, the temperature will then have risen approximately 3 $°C$, with an uncertainty range of 1.5-5.5 $°C$.

An important consequence of global mean temperature is sea level rise. Under natural conditions, the following physical processes contribute to sea level rise: accumulation on polar ice sheets, thermal expansion of ocean water and melting of mountain glaciers and small icecaps.

When the results of quite some scientists are summarized, the majority of the future sea level rises is predicted between the range of 40 and 100 cm for the coming century. The main contributor to the future sea level rise for the coming century will be the thermal expansion of ocean water, while the accumulation on and ablation of polar ice sheets are supposed to be in balance.

Meanwhile, some scientists, such as Hoffman in 1984, accept much higher estimates of future sea level rise. This is partly due to their assumptions on whether or not the West Antarctic Ice Sheets will rapidly disintegrate, as a result of rapid temperature rises. This could result in a 5 to 6 meter sea level rise within a few centuries.

The reason, that a sea level rise of only approximately several decimeters for the coming century may probably be expected, is because this era is an interglacial. Therefore, only relatively small amounts of ice masses are stored. For instance, by analyzing the sea level changes during the last three millennia, it can be seen that the sea level has not risen more than a few decimeters. By contrast, by analyzing sea level changes at the beginning of the Holocene (some millennia further in the past), one can detect that sea level can also vary several tens of meters within a geologically short time (millennia).

Recommendations

For this moment, the scientific committee have to confirm statistically, that human activities amplify the greenhouse effect on a different time scale than natural processes do, decades instead of millennia. Then it may be not too late for policymakers to seriously counteract the impacts of sea level rise by formulating realistic response strategies. Thus, in order to predict more reliable sea level rise for the coming century, the scientific committee have to do more research on especially the following items:

- the influence of the feedback mechanisms on the greenhouse effect; especially of the feedback mechanisms 'oceans' and 'clouds',
- the causes of climate change during the large time periods. A new Ice Age might counteract the greenhouse effect,
- the physical processes that contribute to a possible disintegration of the West Antarctic Ice Sheets,
- the observations of sea level rises for both the past and the future, and
- the global models that simulate the complex climate system of the Earth.

References

Barnett, T.P. Recent Changes in Sea Level and Their Possible Causes. *Climatic Change* **5**: 15-38, 1983.

Barnola, J.M., Raynaud, D., Korotkevich, Y.S. & Lorius, C. Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature.* vol.**329**. 408-411. 1 october 1987.

Barth, M.C. & Titus, J.G. (eds). *Greenhouse Effect and Sea Level Rise. A Challenge for this generation.* New York: Van Nostrand Reinhold. 1984.

Bolin, B., Döös, B.R., Jäger, J. & Warrick, R.A. (eds). *The Greenhouse Effect, Climate Change, and Ecosystems.* John Wiley & Sons. 1986.

Delft Hydraulics & Rijkswaterstaat. Impact of Sea level rise On Society. A case study for the Netherlands. *United Nations Environment Programme. Government of the Netherlands. H 750-phase I.* Delft Hydraulics & Rijkswaterstaat. December 1988.

Dickinson, R.E. How Will Climate Change? The Climate System and Modelling of Future Climate. In: *The Greenhouse Effect, Climate Change, and Ecosystems.* Edited by B. Bolin, B.R. Döös, J. Jäger, & R.A. Warrick. John Wiley & Sons. 1986.

Gornitz, V., Lebedeff, S. & Hansen, J. Global Sea Level Trend in the Past Century *Science.* vol. **215**. 1611-1614. 26 march 1982.

Hoffman, J.S. Estimates of Future Sea Level Rise. In: *Greenhouse effect and sea level rise: A challenge for this generation.* Edited by M.C. Barth, & J.G. Titus. New York: Van Nostrand Reinhold. 1984.

IPCC Scientific Assessment. Climate Change. *Working Group 1 of the Intergovernmental Panel on Climate Change, sponsored by the World Meteorological Organization and the United Nations Environment Programme.* Edited by J.T. Houghton, G.J. Jenkins & J.J. Ephraums. Cambridge: Cambridge University Press. 1990.

Korevaar, R. EG loopt warm voor aanpak broeikaseffect. (in Dutch). *Toegepaste Wetenschap T.N.O.* 47-51. February 1989.

Meisler, H., Leahy, P.P. & Knobel, L.L. Effect of eustatic sea-level changes on saltwater-freshwater in the Northern Atlantic Coastal Plain. *U.S. Geological Survey. Water-Supply Paper 2255*, 1984.

Miller, G.H. & De Vernal, A. Will Greenhouse warming lead to Northern Hemisphere ice-sheet growth ? *Nature.* vol. **355**. 244-246. 16 january 1992.

Noomen, P. Bodembeweging in Nederland. (in Dutch). In: *Zeespiegelrijzing en bodemdaling; welk scenario wordt werkelijkheid ?* Symposium 12 april 1989, Delft University of Technology. Delft, 1989.

Oerlemans, J. A projection of Future Sea Level. *Climatic Change* **15**: 151-174, 1989.

Oerlemans, J. in press. Effects of Climatic Factors. In: *Coastal Lowlands. Hydrology and Watermanagement of deltaic areas.* Edited by A. Volker, R.H. Boekelman, M.A.A. Mulder & P.C. Koppen. Delft.

Pirazzoli, P.A. & Pluet, J. World Atlas of Holocene Sea-level Changes. *Elsevier Oceanography Series*, vol. **58** 1991.

Plassche, O., van de. Zeespiegelbewegingen in Nederland gedurende de laatste 7000 jaar. (in Dutch). In: *Nederlandse organisatie voor zuiver-wetenschappelijk onderzoek, jaarboek 1982, bijlage.* 1982a.

Plassche, O., van de. Sea-level change and water-level movements in the Netherlands during the Holocene. *Mededelingen Rijks Geologische Dienst, volume* **36-1** 1982b.

Priem, H.N.A. De grootste milieu-catastrofe. (in Dutch). In: *N.R.C. Handelsblad, Wetenschap en Onderwijs.* February 28, 1989.

Ramanathan, V. & Collins, W. Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño. *Nature.* vol.**351**. 27-32. 2 may 1991.

Rind, *et al.* Positive water vapour feedback in climate models confirmed by satellite data. *Nature.* vol.**349**. 500-503. 7 february 1991.

Robin, G. deQ. Changing the Sea Level. Projecting the Rise in Sea Level Caused by Warming of the Atmosphere. In: *The Greenhouse Effect, Climate Change, and Ecosystems.* Edited by B. Bolin, B.R. Döös, J. Jäger & R.A. Warrick. John Wiley & Sons. 1986.

Ronde, J.G., de. Past and future sea level rise in the Netherlands. *Workshop on sea level rise and coastal processes.* Palm coast, Florida, 9-11 march, 1988.

Rotmans, J. & den Elzen, M.G.J. Simulatiemodel voor een aantal maatschappelijke gevolgen van het broeikaseffect voor Nederland. (in Dutch). *Rapport nr. 758471008. National Institute of Public Health and Environmental Protection (RIVM).* 1988.

Thomas, R.H. Future Sea Level Rise and its early detection by satellite Remote Sensing. In: *Globaal overzicht van Nederlands onderzoek naar zeespiegelstijging.* Delft Hydraulics, 1986.

Titus, J.G. The Causes and Effects of Sea Level Rise. In: *Impact of Sea level rise On Society. Report of a project-planning session, Delft 27-29 August 1986.* Edited by H.G. Wind. A.A. Balkema/Rotterdam/Brookfield/1987.

Wigley, T.M.L., Jones, P.D. & Kelly, P.M. Empirical Climate Studies. Warm World Scenarios and the Detection of Climatic Change Induced by Radiatively Active Gases. In: *The Greenhouse Effect, Climate Change, and Ecosystems.* Edited by B. Bolin, B.R. Döös, J. Jäger & R.A. Warrick. John Wiley & Sons. 1986.

Zagwijn, W.H., Beets, D.J. & Berg, M. van den. Atlas van Nederland. Deel 13. Geologie. *Staatsuitgeverij, 's Gravenhage.* 1985.

Zwerver, S. Maatregelen tegen broeikaseffect hoeven niet veel te kosten. (in Dutch). Part of the report: 'Een paar graden meer ?'. In: *N.R.C. Handelsblad, Wetenschap en Onderwijs.* March 31, 1989.

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19. **Noppeney, R.M.**: De invloed van stagnante zones op dispersie. (november 1988)

20. **Noppeney, R.M.**: Gevoeligheidsonderzoek Alarmmodel Rijn; De invloedslengte van samenvloeiingen bij dispersie. (november 1988)

21. **Noppeney, R.M.**: De verspreiding van olie op rivieren benaderd met het Taylor-model. (november 1988)

22. **Noppeney, R.M.**: De invloed van near-field processen op een far-field dispersie beschrijving. (november 1988)

23. **Ellen, T. van** : De invloed van afvoerfluctuaties op de verspreiding van een verontreinigingsgolf. (juni 1989)

24. **Blanken, J.G. den:** Afscheidssymposium prof.ir. A.C.J. Koot. (januari 1989)

25. **Hooykaas, L.J., Donze, M. en Klapwijk, Sj.P.** : Fosfaatbalans van de polder Reeuwijk en de Reeuwijkse plassen. (januari 1989)

26. **Verwoerdt, P. en Mazijk, A. van:** De één-dimensionale dispersievergelijking van Taylor bij een opdeling van de rivier in vakken. (maart 1989)

27. **Mazijk, A. van:** Gevoeligheidsonderzoek Alarmmodel Rijn; eindrapportage. (mei 1989)

28. **Blanken, J.G. den en Hoogh, M.P.A.J. de:** Desinfectie van behandeld afvalwater met chloor: vergelijking van eenpunts- en tweepuntsdosering;
deel 1: Tekst, bijlage A, B en C.
deel 2: Bijlage D, E, F en G.
(mei 1989)

29A. **Verstappen, G.G.C.:** Gedrag van organische micro-verontreinigingen in rivieren. (juli 1989)

29B. **Mooren, J.J.M. en Heide, J. van der:** Leaching of heavy metals from thermally decontaminated soils. (maart 1989)

30. **Nieuwstad, Th.J., Wortel, N.C., Bout, F.N. van den en Alting, B.J.:** Een vergelijking tussen ladingsgewijze en continue zuivering van afvalwater. (juni 1989)

31. **Kramer, J.P., Wouters, J.W. en Kop, J.H.:** Dynasand Filtratie. (juli 1989)

32. **Nieuwstad, Th.J.:** Treatment of municipal wastewater in a pilot-scale airlift-loop reactor. (December 1989)

33. **Ankum, P.:** Polders; achtergronden, ontwerp en toekomstige ontwikkelingen. (juni 1990)

34. **Brandsma, T.:** Evaporation in Hydrology and Meteorology. (July 1990)

35. **Mooren, J.J.M.:** Het uitlooggedrag van kunstmatig samengestelde en verontreinigde grond. (2 delen) (augustus 1990)

36. **Singh, S.N., Boekelman, R.H., Rientjes, T.H.M. en Dam, J.C. van:** Behaviour of groundwater of the polder Groot-Mijdrecht.

37. **Boekelman, R.H. en Rientjes, T.H.M.:** Workshop hydrological models. (September 1990)

38. **Stavrides, N., Rientjes, T.H.M. en Dam, J.C. van:** Network optimization, a simple approach applying GIS and MLR.

39. **Duindam, P., Morales, C. and Heide, J. van der:** Investigacion sobre los desechos solidos de la ciudad de Masaya, Nicaragua. (enero 1991)

40. **Heide, J. van der:** Evaluacion hidraulica de plantas potabilizadoras de filtracion rapida en Nicaragua. (junio 1991)

41. **Heide, J. van der:** Metodologia de potabilizacion de agua superficial en Nicaragua. (abril 1992)

42. **Veldkamp, R.G.:** Randvoorzieningen van rioolstelsels kritisch beschouwd. (oktober 1991)

43. **Kruithof, J.C., Schippers, J.C. and Dijk, J.C. van:** Abastecimiento de Agua Potable de Agua Superficial en los años Noventa. (febrero 1992)

44. **Rietveld, L.C. and Matsinhe, N.P.:** Pilot Plant Studies on Slow-Sand-Filtration and Up-Flow-Roughing Filtration in Mozambique, (January 1993)

45. **Brandsma, T.:** Evaporation and Climate Change. (February 1992)