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Climate change and precipitation: Detecting changes^(*)

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Abstract

Precipitation is one of the most, if not the most important climate parameter. In most studies on climate change the emphasis is on temperature and sea level rise. Often too little attention is given to precipitation. For a large part this is due to the large spatial and temporal variability of precipitation, which makes the detection of changes difficult. This paper describes methods to detect changes in precipitation. In order to arrive at statistically significant changes one must use long time series and spatial averages containing the information from several stations. In the Netherlands the average yearly precipitation increased by 11% during the 20th century. In the temperate latitudes on the northern hemisphere (40-60°N) the average increase was about 7% over the 20th century and the globally averaged precipitation increased by about 3%. During the 20th century 38% of the land surface of the earth became wetter, 42% experienced little change (less than 5% change) and 20% became dryer. More important than the average precipitation is the occurrence of extremes. In the Netherlands there is a tendency to more extreme precipitations, whereas the occurrence of relatively dry months has not changed. Also in many other countries increases in heavy precipitation events are observed. All climate models predict a further increase of mean global precipitation if the carbon dioxide concentration doubles. Nevertheless some areas get dryer, others have little change and consequently there are also areas where the increase is much more than the global average. On a regional scale however there are large differences between the models. Climate models do not yet provide adequate information on changes in extreme precipitations.

Resumen

La Precipitación es uno de los parámetros más importantes; sin embargo, en muchos estudios de cambio climático se hace énfasis en la temperatura y el nivel del mar, ofreciendo menos atención a la precipitación, especialmente en lo que se refiere a la variabilidad temporal de la precipitación, hechos que hacen que la detección de esos cambios y variabilidades sean difíciles. Este artículo describe métodos para detectar cambios en la precipitación. Para llegar a cambios estadísticos significativos se deben realizar series de tiempo largas y los promedios espaciales que contienen información de varias estaciones; en los Países Bajos la precipitación media anual aumentó en 11% durante el vigésimo siglo, en las latitudes templadas en el hemisferio norte (40-60°N) el aumento medio fue cerca del 7% concluido el vigésimo siglo y el promedio de precipitación global se incrementó cerca de 3%. Durante el vigésimo siglo, 38% de la superficie de la tierra se convirtió en un poco más húmedo, 42% experimentó pequeños cambios (menos del 5%) y 20% se volvió seco. Más importante que la precipitación media es la ocurrencia de extremos: en los Países Bajos hay una tendencia a más extremos de precipitación, mientras que la ocurrencia de meses relativamente secos no ha cambiado.

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También en muchos otros países se observan los aumentos en acontecimientos pesados de la precipitación. Todos los modelos del clima predicen un aumento de la precipitación global si la concentración del bióxido de carbono se duplica; sin embargo algunas áreas siguen secas, otras tienen pequeños cambios y por lo tanto hay también áreas donde el aumento es mucho mayor que el promedio global. En una escala regional sin embargo hay diferencias grandes entre los modelos. Los modelos climáticos todavía no proporcionan la información adecuada en cambios extremos de precipitación.

1. Introduction

From the 15th to the 19th century the carbon dioxide concentration in the atmosphere has been 280-290 ppm. Nowadays it is 380 ppm and increasing rapidly. Already the CO₂ concentration is much higher than it has ever been during the last 160,000 years (Watson et al. 1990, Barnola et al., 1987). The rise in the CO₂ concentration is beyond any doubt due to human activities (Watson et al., 1990), mainly burning of fossil fuels and deforestation. The CO₂ concentration will increase much more in the course of the 21st century. In the business as usual scenario the CO₂ concentration will be doubled compared to the pre-industrial levels somewhere halfway the 21st century. With very rigorous measures it is possible to postpone the doubling till the end of the 21st century.

Carbon dioxide plays an important role in the radiation balance of the earth. Together with water vapor it is the most important greenhouse gas. The greenhouse effect causes the mean temperature on the earth surface to be about 31°C higher than it would be without an atmosphere. There is a wide spread concern that the increase of the CO₂ concentration will influence the global climate. The last decade of the 20th century was the warmest decade of the century and probably also of the last 1000 years (WMO, 1999). During the 20th century the globally averaged temperature increased by about 0.9°C. Barnett et al. (1999) found it very unlikely that recent climate changes are solely due to natural causes. Van Dorland & Van Ulden (1998) attribute about 0.2°C of the temperature rise during the 20th century to natural causes and the rest to human activities.

If we consider the green house forcing from other gases than water vapor, about 64% of the forcing is due to CO₂, about 19% due to methane and about 17% due to other greenhouse gases (Bryant, 1997), like nitrous oxide (6% forcing) and CFC's (10% forcing). The methane concentration in the atmosphere has increased over the 20th century from about 0.8 ppm to 1.6 ppm (Bryant, 1997). Nitrous oxide concentrations have increased by about 10% since pre-industrial times and CFC's were absent in pre-industrial times. The increased concentrations of sulfate aerosols slightly temper the increase of the green house effect (e.g. Van Dorland & Van Ulden, 1998).

Most scientific publications on the increasing green house effect focus on temperature and sea level rise. Generally far too little attention is given to the possible effects of climatic change on precipitation and precipitation distribution. This is surprising, since precipitation is one of the most, if not the most, climate parameter.

For all terrestrial ecosystems water is crucial. The amount of water that is available determines for a large part what kind of ecosystem can develop. Almost all terrestrial ecosystems get their water from precipitation, either directly or indirectly (through rivers). Ecosystems using other sources of water (e.g. dew or the interception of fog) are rare. Also in agriculture the amount of water available is essential in determining what crops can be cultivated (e.g. Boshell et al., 2000). A high variability in the yearly amount of precipitation, which is normal in arid and semi-arid regions, usually is a problem for agriculture, especially when the amount of available water is already marginal.

Although water is crucial too much water can also be damaging, especially in arid and semi-arid regions, where the landscape and the ecosystem usually cannot store large amounts of water. During El Niño events much damage is done to the infrastructure (roads and bridges) in countries like Peru and Ecuador, due to the flooding of rivers and/or mudslides. During the 1982-1983 El Niño event at least 835 people drowned in South America due to floods and over 600,000 people had to be evacuated (Ros-Tonen and Van Boxel 1999). Also an increased incidence of diseases like cholera, malaria and encephalitis during El Niño years can be related to the excessive amounts of water. During the 1997-1998 El Niño event 1237 deaths were attributed to the rains (Ros-Tonen and Van Boxel 1999).

Hurricanes also bring excessive amounts of precipitation. Most hurricane damage results from the excessive rains and the resulting flooding and/or mudslides, although in coastal regions storm surges can also be an important risk factor. In 1998 the fresh water floods resulting from hurricanes Mitch in Honduras and Nicaragua and Georges in Hispaniola caused the loss of thousands of lives (Rappaport 2000). In the USA about 82% of the hurricane related fatalities are the result of floods, most of which are caused by rain-induced floods (Rappaport, 2000).

Until now it is not clear how a climate change, resulting from an increased green house effect, will affect El Niño frequency and magnitude or the amount and strength of hurricanes. A rising global temperature should increase the area of oceans with water temperatures above 27°C, which are suitable for hurricane formation. So far there is however little evidence that hurricane frequency and strength are increasing (Bove et al., 1998). Possibly this is because the temperature rise will be smallest in the tropics. Maybe the current forcing is not yet strong enough to produce statistically significant signals in the behavior of hurricanes.

Despite the fact that precipitation is a very important climate variable, it gets less attention in

climate change studies than temperature and sea level rise (e.g. Barnett et al., 1999). Probably this is because the spatial and temporal variability of precipitation generally is large. This makes it harder to show that the observed trends are statistically significant.

This paper discusses methods to evaluate trends in mean, with emphasis on the statistical significance of the observed trends. Also discussed are methods to detect trends in extreme precipitation. Predictions of precipitation from climate models are compared and used to give an outlook on the changes in precipitation when the carbon dioxide concentration has doubled.

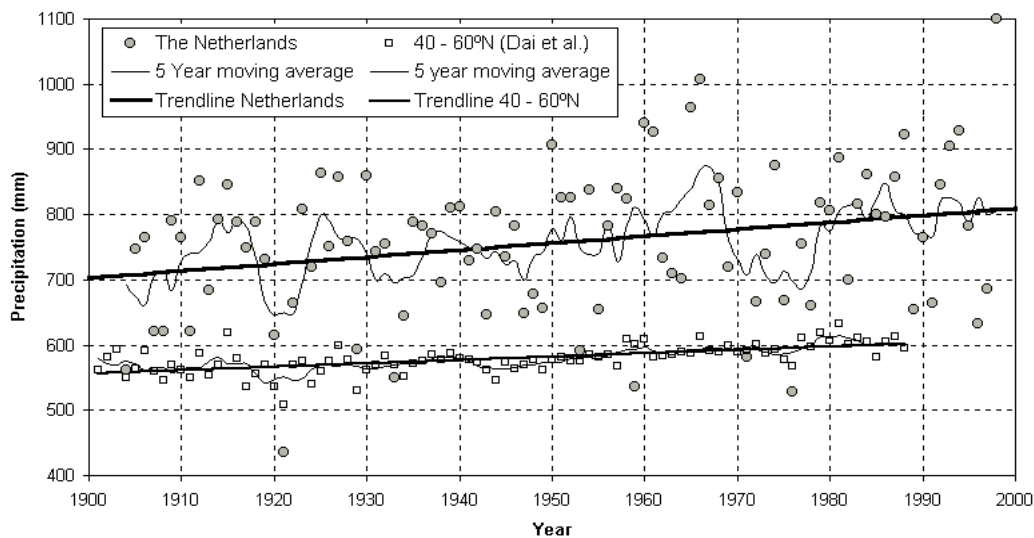


Figure 1. Average precipitation for the Netherlands (13 stations, source of data: Können, 1999) and for the temperate latitudes between 40 and 60°N (data from Dai et al., 1997). Thin line is a five year moving average and the fat line is a trend line.

2. Problems when analyzing precipitation

Precipitation has a very high spatial variability. Two stations relatively close together can have large differences in monthly amounts of precipitation. Part of these differences can be systematic, for example when related to topography. Another part may be erratic because of the limited size of the convective systems producing the precipitation. Evaluating longer averages, like yearly averages, can average out the erratic differences, but systematic differences remain.

The temporal variability of precipitation usually is high, especially in arid and semi-arid regions. Figure 1 shows the yearly precipitation for The Netherlands (average of 13 stations, selected for homogeneity and corrected for wind errors) for the years 1905 till 1998. Despite the fact that The

Netherlands has a humid climate the year-to-year variability is high. In arid and semi-arid regions the temporal variability is much higher. The consequence of this large temporal variability is that one has to analyze long time series (in the order of 100 years) before the observed trends will be statistically significant. In many places such long records are not available.

Another reason to use long time series is that there are several natural cycles that influence precipitation. The most well known are the sun spot cycle, the El Niño cycle (ENSO) and for Europe also the North Atlantic Oscillation (NAO). In order to be sure that the observed trends are not the result of one of these cycles, the record needs to contain several cycles.

Assessing the homogeneity of long time series is generally more difficult for precipitation than for temperature (Jones & Bradley, 1995).

Precipitation records are particularly prone to growth of vegetation and/or building development around the site (Jones & Bradley, 1995). Often meteorological stations are moved, but remain to operate under the same name. Because of the high spatial variability it is likely that moving the station would cause an inhomogeneity in the data series, but because of the high temporal variability it is often hard to assess the homogeneity.

In the beginning the 20th century it was in many places usual to measure precipitation at 1.5 to 2 m height. Nowadays it is more common to measure at 0.4 m height or closer to the surface. Every rain gauge will experience a wind error, which depends on wind speed and rain drop size. Normally the catch is reduced by several percent compared to what should have been caught.

Decreasing the measurement height automatically

reduces the wind speed at measurement height and increases the catch. When analyzing trends, precipitation time series have to be corrected for this error. Special problems arise when measuring in areas with much snowfall. If the precipitation gauge is not heated it will fill up and underestimate the amount of precipitation. If it is heated it can collect snow blowing in from the surroundings and consequently overestimate.

When analyzing precipitation records one should be aware of and if possible correct for errors arising from changes in measurement techniques and inhomogeneities. In order to detect trends the high spatial variability makes it necessary to combine information from several weather stations and because of the high temporal variability one needs long records before any observed trends will be statistically significant.

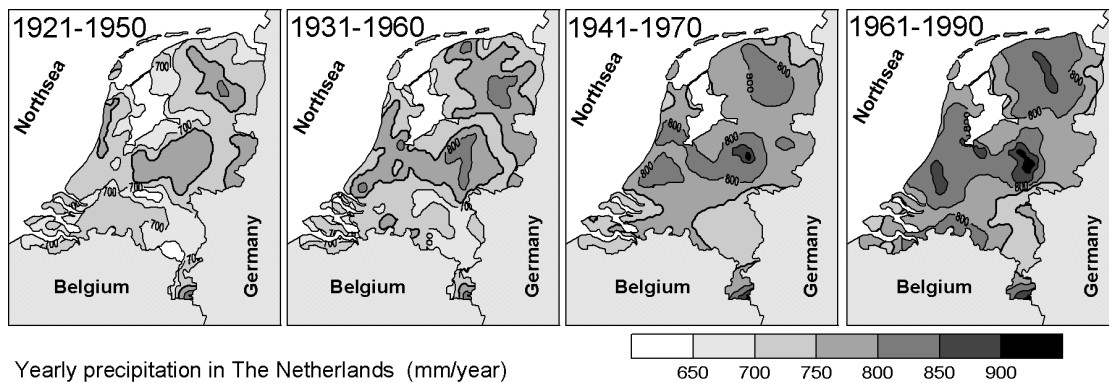


Figure 2. Maps of yearly precipitation for The Netherlands for the periods 1921-1950, 1931-1960, 1941-1970 and 1961-1990.

3. Trends in mean precipitation

A first step in the analysis often is to produce and/or compare precipitation maps like those in figure 2. From the comparison of these maps it seems obvious that the yearly amounts of precipitation have increased.

From the maps it is possible to calculate the percentage of the area with a precipitation of less than 650 mm, 650-700 mm, 700-750 mm etc. These percentages are shown in figure 3. Also from this figure it seems obvious that precipitation has increased. In the first half of the century (1921-1950) 28% of the country had a yearly precipitation of less than 700 mm, 78 % less than 750 mm and the area with more than 800 mm of precipitation was negligible. On the last map (1961-1990) no part of The Netherlands received less than 700 mm, and only 11% of the country less than 750 mm. The area with more than 800 mm yearly has grown to 48% of the country. Despite the fact that the trends are very obvious this type of data is not the most useful for statistical analysis.

In order to access the trends in precipitation during the 20th century we used meteorological data from five stations in The Netherlands from 1904 till 1998 (Van Boxel & Cammeraat 1999a). Table 1 lists mean yearly precipitation, standard deviation and trends calculated for each station. The statistical significance of the calculated trends is tested with ANOVA (F-test, Casella & Berger 1990). The calculated F-value and corresponding uncertainty are also in table 1.

The calculated trends are between 70 to 110 mm/century, which is more than the average increase of precipitation in the temperate latitudes. Despite the large trend, it is only significant for two of the five stations. This is because of the large temporal variability of precipitation. For a part this temporal variability is spatially correlated, but for a part it is not. Therefore it is possible to reduce the temporal variability by taking the average of the five stations. The trend in the average is 87 mm/century and is statistically significant at the 95% confidence level. Later the Dutch Royal

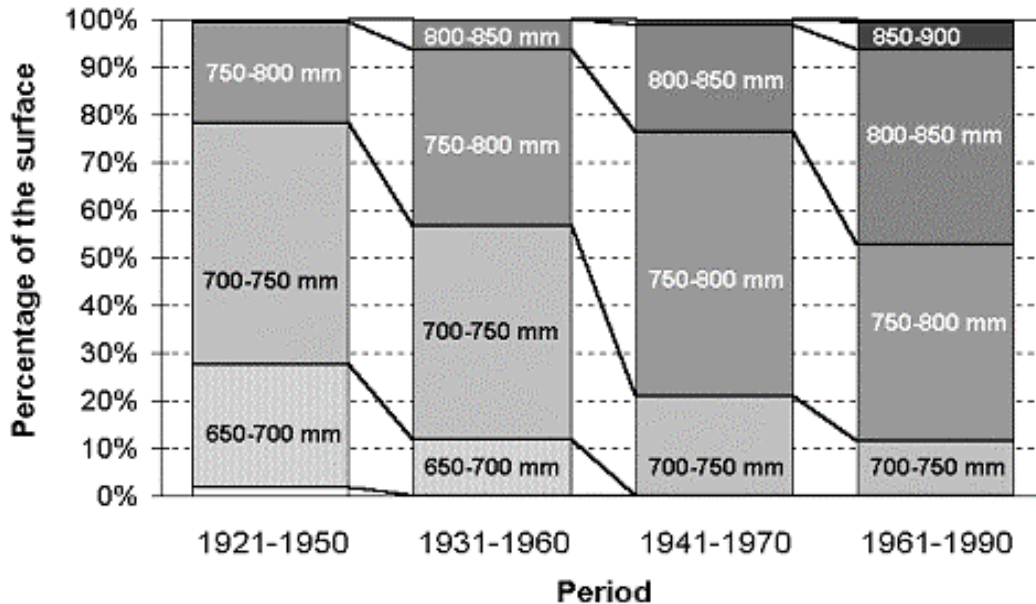


Figure 3. Percentage of the surface of The Netherlands with the indicated amount of precipitation for the periods 1921-1950, 1931-1960, 1941-1970 and 1961-1990.

Meteorological office published the 1906-1998 data of yearly precipitation averaged from 13 meteorological stations, which were selected for homogeneity and carefully corrected for the changed measurement techniques (Können, 1999). These data are shown in Figure 1, together with the calculated trend line. If these data are analyzed we find a trend of 99 mm/century with an uncertainty of $P(F)=2.0\%$. An analysis of the average precipitation of more than 100 stations (Van Boxel & Cammeraat 1999b) yielded a slightly stronger trend (123 mm/century) and a much smaller uncertainty ($P(F)=0.3\%$), but these results were obtained from data not corrected for wind errors.

Also in Figure 1 is the average precipitation for latitudes between 40 and 60°N (data from Dai et al., 1997). Since these data represent the average precipitation over a huge area the temporal variability is much less than that of the average precipitation over The Netherlands (40.000 km²). The trend calculated from these data is 58 mm/century and the $P(F)$ value is less than 0.1%. So by taking the average over a large area, including many meteorological stations, the standard deviation is reduced resulting in larger F -values and a smaller probability that the observed trend is a pure coincidence.

Table 1. Statistical data for the various precipitation series. Trend that are significant at the 90% confidence level ($P(F) < 10\%$) are in bold face.

	De Bilt	Gemert /Volkel	Leeu-warden	Hoofddorp /Schiphol	Winterswijk /Twenthe	The Netherlands		40-60° N
						5 stations	13 stations	
Mean (mm)	783	711	753	768	768	757	760	579
St.deviaton	139	123	106	127	136	116	112	22
Trend (mm/century)	84	70	87	110	84	87	99	52
F-Value	2.6	2.3	5.0	5.6	2.8	4.2	5.4	58.3
P(F)	10.9%	23.2%	2.8%	2.0%	10.0%	4.4%	2.0%	<0.1%

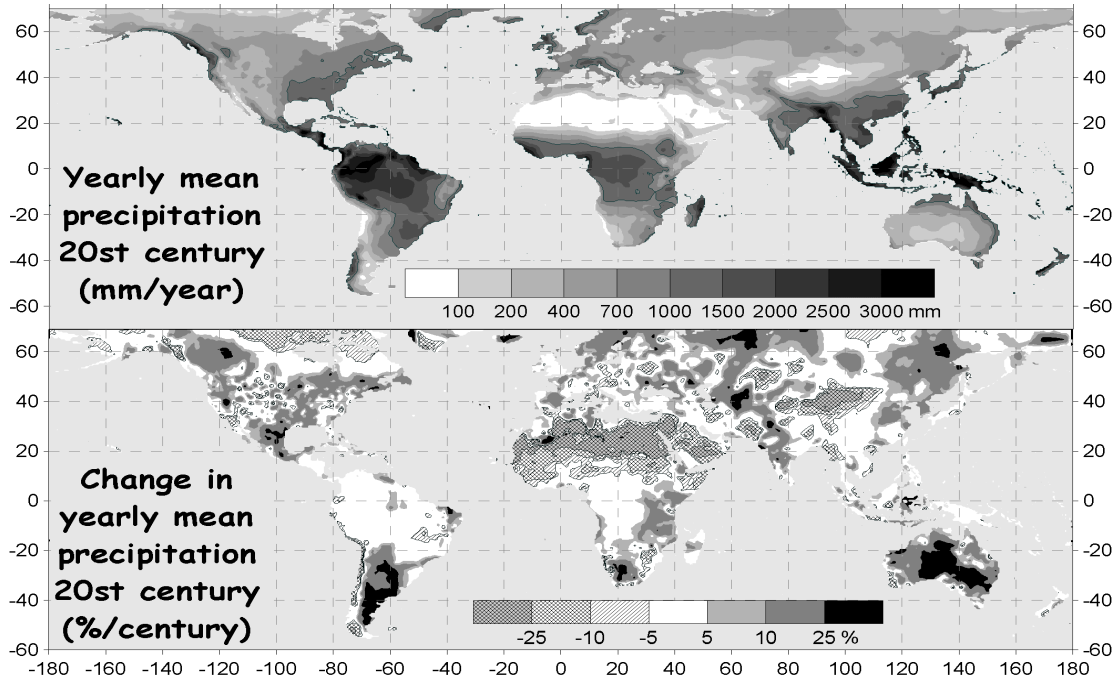


Figure 4. World map of annual mean precipitation and relative change in precipitation during the 20th century (Data from IPCC, 1999).

4. Precipitation world wide

Figure 4 shows the mean annual precipitation over the 20th century for the land surface of the earth. This figure was constructed from data taken from the IPCC website (IPCC 1999; also available on CD-Rom). For a description of these data see New et al. (1999). Since the data set contains data for each ten-year period (1901-1910, 1911-1920, ..., 1981-1990) it is also possible to calculate trends from these data. An increase of for example 50 mm is not very relevant in a humid climate with 1000 mm of precipitation, but crucial in an arid climate with less than 200 mm. That is why the changes are shown as relative changes. The change at each gridpoint is divided by the mean precipitation in that gridpoint.

From Figure 4 it can be seen that a large fraction of the earth surface is getting wetter, however some areas are also getting dryer. 42% of the earth surface experienced little change; the mean annual precipitation changed less than 5% per century. On 38% of the earth surface the precipitation increased by more than 5% per century and 20% became considerably dryer. Much of the area that is getting dryer is concentrated in the arid regions on the northern hemisphere, whereas many of the arid regions on the southern hemisphere are getting wetter.

Figure 5 show the absolute changes (in mm/century) for all latitudes from 55°S to 70°N. Most latitudes are on average getting wetter, with the exception of the latitudes between 8 and 22°N

and between 49 and 54°S, but the latter only represent a relatively small area. Averaged over the entire land surface the increase is 27 mm/century, which compares very well with the results of Dai et al. (1997) who found 24 mm/century.

The changes that were significant at the 5% significance level are indicated by fat dots. Most of the northern hemisphere north of 35°N showed a significant increase in precipitation. This is surprising, since the trend analysis was performed on only nine points, because the input data consisted of 10-year average precipitations from 1901 till 1990. With only nine points a trend has to be very clear in order to be statistically significant.

Also shown in Figure 5 are the changes for the arid regions (defined as having less than 200 mm of precipitation yearly) and the other regions (semi-arid plus humid). Most of the semi-arid and humid regions are getting more precipitation. Many of the arid regions are getting even dryer, but on the southern hemisphere south of 25°S most arid regions are getting wetter.

Worldwide El Niño is the most important single cause of climate variability. This is even more true in the tropics. Therefore when analyzing the precipitation trends in the tropics it is probably necessary to somehow filter out the effects of El Niño on the precipitation in order to reduce the variability. The result could be that trends that are not significant without filtering become statistically significant after filtering.

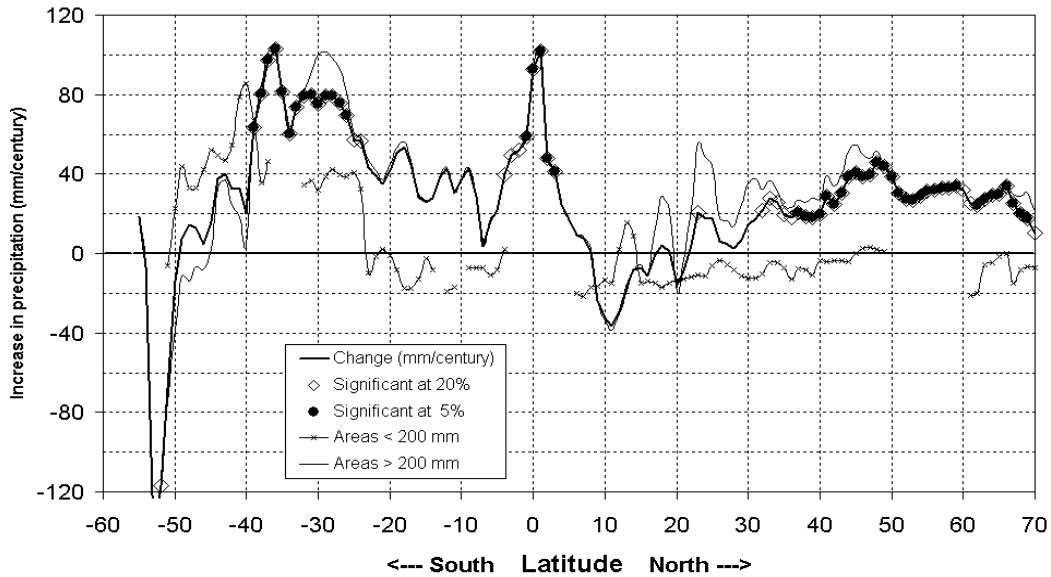


Figure 5. Change in mean annual precipitation with latitude (fat line). Changes that are statistically significant at the 5% significance level are indicated by fat dots. Also shown are changes for arid areas (< 200 mm precipitation) and other areas separately.

5. Trends in the extremes

Often it is not the mean precipitation that is causing most problems, but the extreme precipitations, either excessive rains or draughts. As an illustration table 2 lists some weather events that made it to the newspaper headlines in The Netherlands in October 2000. England was hit again by extreme amounts of precipitation on 2 November and again on 7 December. All these events refer to excessive precipitation. One could ask whether it is a coincidence that we had so many extreme precipitation events. Although it is not possible to prove that individual events are linked to an increasing precipitation, it will be shown that there is a tendency towards more extreme precipitations in many regions.

Table 3: The weather in the newspaper headlines in The Netherlands, October 2000.

1-6 Oct.	Hurricane Keith in Middle America, 17 deaths
7-11 Oct.	Extremely heavy monsoon rains in Asia
12 Oct.	Plumpton (England) 144 mm of precipitation in 24 hours Several cities in England are flooded
11-16 Oct.	Extremely heavy rains in the Alps (France, Switzerland and Italy). Locally more than 500 mm in five days. At least 23 people drowned.
17 Oct	Emergency conditions in Northern Italy, Torino completely shut off.
23 Oct.	Flash floods after heavy precipitation in Murcia, Spain. 5 deaths.
29 Oct.	Strong storm in The Netherlands.

When making a top ten of the ten wettest and ten driest years for the Netherlands (Table 3), it was striking that the dry years were more or less evenly distributed over the century, but all the ten wettest years were after 1950 (1950 included). This is a first indication that not only the mean precipitation is changing, but that there is also a tendency to more extreme precipitations.

In order to explore this hypothesis we examined mean monthly precipitations for The Netherlands. The input data consisted of mean precipitation for The Netherlands (average of more than 100 stations) for each month from January 1904 till

Table 2. Ten wettest and ten driest years for The Netherlands using the KNMI data (13 stations).

Ten wettest years		Ten driest years	
1998	1100	1921	436
1966	1008	1976	528
1965	964	1959	536
1960	940	1933	550
1994	929	1971	582
1961	927	1953	591
1988	923	1929	594
1950	907	1920	614
1993	905	1908	620
1981	888	1911	620

December 1998 (KNMI, 1904-1998; Van Boxel & Cammeraat 1999b). The mean annual precipitation for The Netherlands is about 760 mm and is more or less evenly distributed over the year. So the average month has a precipitation of about 65 mm. The number of dry months (defined as having less than 25 mm precipitation) and the number of wet months (more than 100 mm) were counted for every year and plotted in a graph (Figure 6). Figure 6 also depicts five year moving averages and trend lines for these data.

Some years have no dry (<25 mm) months, whereas others have four, so there is a large scatter. The trend line shows that the number of dry months has not changed in the course of the 20th century.

The trend line for the wet months (>100 mm) shows that the amount of wet months has increased during the 20th century. If we extrapolate the trend line to the year 1900 we find about 0.9 months per year with >100 mm precipitation in the beginning of the century, whereas this number has increased towards 1.9 months per year by the end of the century. Table 4 lists the number of with more than a certain amount of rain, averaged over the century and extrapolated toward the years 1900 and 2000, as well as the ration between the two last.

There is hardly any change at the dry end of the spectrum (30, 40 mm). The frequency of wet and very wet months has increased dramatically. For months with more than 100 mm and more the frequency has at least doubled during the 20th

century. The increase in mean yearly precipitation over the 20th century was mainly the result of more wet and very wet months. As a result there have been several occasions in the last decade of the century, when some polders (areas below sea level) were flooded due to excessive rains. It took several days to pump out the water again.

Also the neighboring countries of The Netherlands show an increase of very wet months. The Belgium meteorological station Ukkel has a precipitation record from 1833 to present. For six of the twelve months of the year the wettest month of the period occurred during the last 10% (17 years) of the period. During the nineties there have been three years with extremely high water levels in the river Meuse, which streams through Belgium. Two of these events caused flooding along the banks of the river in the southern part of The Netherlands.

For the river Rhine (coming from Germany), the average discharge has increased by about 5% during the 20th century, but the peak discharges have increased by about 20%. Also this points to more extreme precipitations, although one also has to bear in mind that the river Rhine has changed during the 20th century.

An increase in heavy precipitation events has also been reported for the USA (Karl & Knight 1998, Karl et al. 1996). Groisman et al. (1999) found that also in the USA increases in extreme precipitation events are responsible for a disproportional share of the observed increases in total annual precipitation. A statistically significant increase

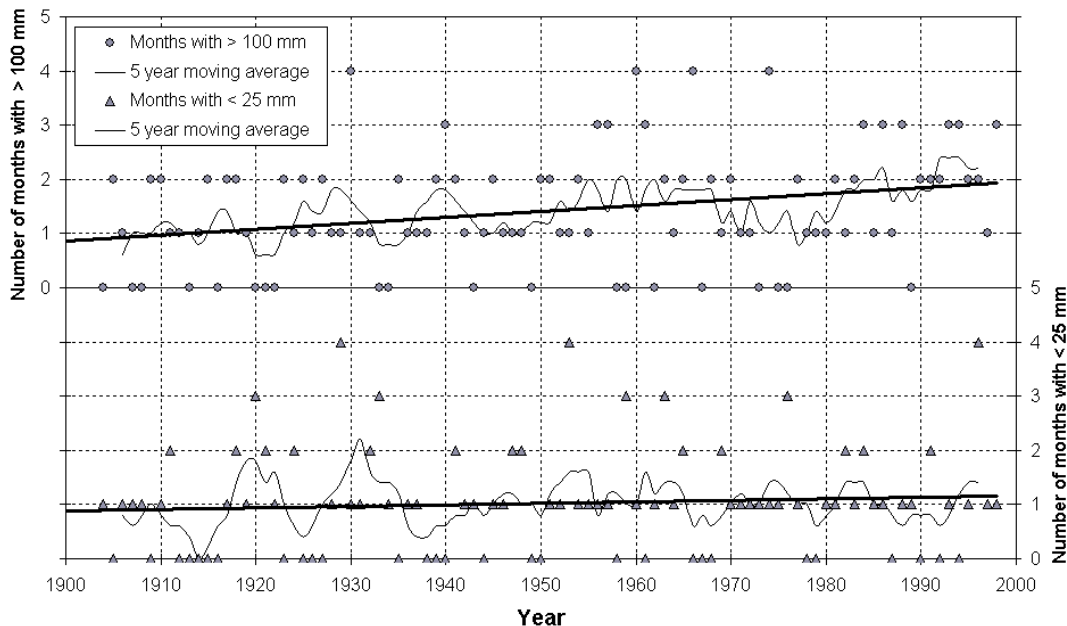


Figure 6. Occurrence of dry months (< 25 mm precipitation averaged over The Netherlands) and wet months (>100 mm) in the Netherlands for the years 1904 till 1998. Also shown are 5-year moving averages and trend lines.

Table 4. Number of months per year with more than mm precipitation, for the entire century, the beginning and the end of the century and the ration between the number at the end and at the beginning of the century.

Precipitation more than:	>30	>40	>50	>60	>70	>80	>90	>100	>110	>120	>130	>140
Century	10.2	8.9	7.2	5.6	4.3	3.0	2.1	1.4	1.0	0.7	0.4	0.2
1900	10.2	8.6	6.4	4.6	3.0	2.1	1.6	0.9	0.5	0.3	0.2	0.1
2000	10.2	9.2	7.9	6.5	5.4	3.8	2.7	1.9	1.4	1.1	0.6	0.3
Ratio 2000/1900			1.2	1.4	1.8	1.8	1.7	2.1	2.8	3.7		

(5% significance level) in the number of days with heavy precipitation has also been reported for Eastern US, European part of former USSR, Asian part of Russia, Southern Canada, several coastal regions of Australia, northern Japan, southwestern South Africa, Natal in South Africa and northeast Brazil (Easterling et al, 2000).

Significant decreases in the occurrence of heavy precipitation events have been reported for Ethiopia, Eritrea, equatorial east Africa and Thailand (Easterling, 2000), southwestern Australia (Suppiah & Hennessy 1998) and the Sahel region of Nigeria (Tahule & Woo 1998). For many of these regions the changes in heavy precipitation events coincide with the changes in mean yearly precipitation (compare with Figure 4).

6. Future climate change and precipitation

If an increased green house forcing leads to higher temperatures, it is very probable that this will also increase evaporation, and therefore also precipitation, since the residence time of water vapor in the atmosphere is only a few days.

The first way to access future climate often is to extrapolate observed trends to the future. The reason for this type of research, however, often is the concern for climatic change. So also the trends might change.

The extent to which the precipitation changes in a given region, will depend very much on how the global circulation is affected by the increased green house forcing. This is calculated by Global Circulation Models (GCM's). With four of these models for the relative change in precipitation are calculated under the condition that if the CO₂ concentration is doubled (Figure 7). These calculations include the effect of an increased sulfate aerosol concentration, that somewhat tempers the increased green house forcing. At first sight the results of the four models look very different, especially when one tries to arrive at conclusions concerning local or regional

precipitation. However there are also a lot of common results.

All models predict an increase of the global mean precipitation, varying from 2% to 5%. Considering the fact that the global mean precipitation has already increased by more than 2% during the 20th century the increase at doubled CO₂ will probably be closer to 5% than to 2%.

In all the models some areas get wetter and other become dryer, although there are more areas getting wetter than areas getting dryer. All models predict an increase in precipitation for the high latitudes on the northern hemisphere and in all model the Mediterranean is getting dryer.

One has to be very careful in the interpretation of the models results for regional studies, since on a regional scale the results of the different models can be completely opposite. At this stage it is very hard to tell which model is better.

The model results as shown in Figure 7 give no information on the changes in extreme precipitation events. This is a disadvantage, since it is usually the extreme events that do most damage. Temporal and spatial resolution of the GCM's is however getting better, because more and more computer power is becoming available. Some of the models are now generating individual storms. It is still too early to say whether the precipitation statistics generated by these storms resemble the real precipitation statistics. However this might be a promising development in the prediction of future climate.

7. Conclusions

When analyzing trends in precipitation (or Climatology in general) it is important to also assess to statistical significance of the observed trends.

Concentrations of the most important green house gases have increased drastically during 20th the century and the artificial (human induced) green house forcing will continue to increase during the 21st century.

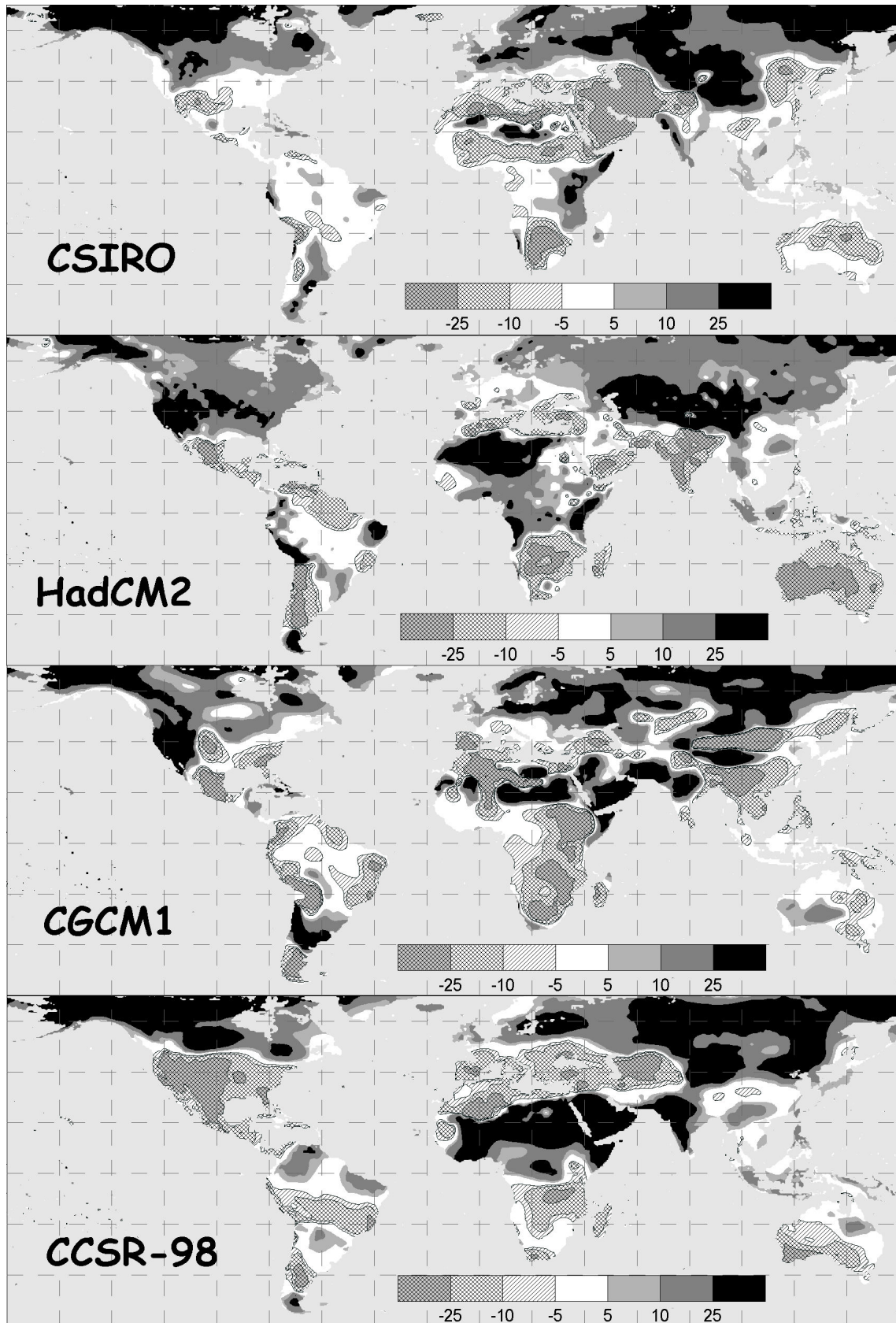


Figure 7. Changes in mean annual precipitation according to four climate models if CO₂ concentration doubles. An increased sulfate aerosol concentration is taken into account (Data from IPCC, 1999).

Over the 20th century mean precipitation in The Netherlands and many other areas in the world has increased. The global mean precipitation increased by about 3%. Over about 38% of the land surface of the earth the increase was more than 5%. On the other hand the mean yearly precipitation decreased by more than 5% over 20% of the land surface of the earth. Especially the arid regions in the northern hemisphere are getting dryer. The increase in mean yearly precipitation is statistically very significant for most of the temperate latitudes on the northern hemisphere.

In many places the increase in mean precipitation is for a large part due to a higher frequency of heavy precipitation events.

All climate models predict a further increase in mean yearly precipitation if the anthropogenic green house forcing further increases (which it will).

To date climate models give little information on the frequency of heavy precipitation events and on a regional scale there are large differences between the various climate models.

Climate models are a very promising tool to assess future climate, but still need a lot of improvement.

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