Variability and Triggering Factors of Observed Global Mean Land-Surface Precipitation since 1951

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Introduction

Precipitation is a major branch of the global water cycle. All water evaporated from the earth's surface is to fall down on earth sooner or later. Evaporation itself is directly linked to the global energy cycle. Thus, global mean precipitation is a measure for the intensity of the global water and energy cycle.

The intensity of evaporation depends on the surface air temperature (SAT), which itself is driven by global natural and anthropogenic forcing and internal climate variability. It is well known that external forcing like fluctuations in solar constant, explosive volcanism and anthropogenic greenhouse gas heating drive SAT (IPCC, 2001a). Furthermore, internal climate variations like the El Nino-Southern Oscillation phenomenon ENSO can clearly be seen in SAT. Thus, a considerable fraction of SAT variability can be explained by these external forcing and internal climatic variations. Evidence for these links is provided by statistical investigations (e.g. Schönwiese et al., 1997), conceptual models (e.g. energy balance models, EBM, e.g. Grieser et al., 2001) as well as detailed atmosphere-ocean general circulation models (AOGCM, e.g. Cubasch and Meehl, 2001). As a major result of these investigations an anthropogenic global warming attributable to enhanced greenhouse gas emissions became visible which may continue in the future. However there remains a great deal of discussion between climatologists, politicians, and stakeholders of many communities on the amplitude of the threat following to global warming (IPCC, 2001b).

One major topic in this discussion is the high vulnerability of human life and property to changes in the hydrological cycle. Enhanced evaporation in semiarid and arid regions can crucially affect water resources and may lead to potable water shortage and crop lost. Heavy precipitation on the other hand may lead to an enhanced number of floods with direct damage to human life and properties.

From a conceptual point of view it is assumed that global warming leads to higher evaporation rates and increases the water-holding capacity of the atmosphere. Therefore the atmospheric moisture content should increase followed by enhanced precipitation (Trenberth, 1998).

It is the aim of this work to investigate the variability of observed global mean land-surface precipitation (hereafter PGL) of the period 1951 to 2000. In a first step the mean annual cycle is separated from the overall variability. In a second step it is tested whether or not a significant long-term trend exists that may be attributed to an enhanced global water cycle and thus to global climate change. In a third step it is discussed whether natural or anthropogenic external forcing or internal climate variability influencing the global mean surface air temperature may also be related to global mean precipitation. In order to test the conceptual point of view that higher global mean temperatures lead to higher global mean precipitation a direct statistical link between both these variables is investigated.

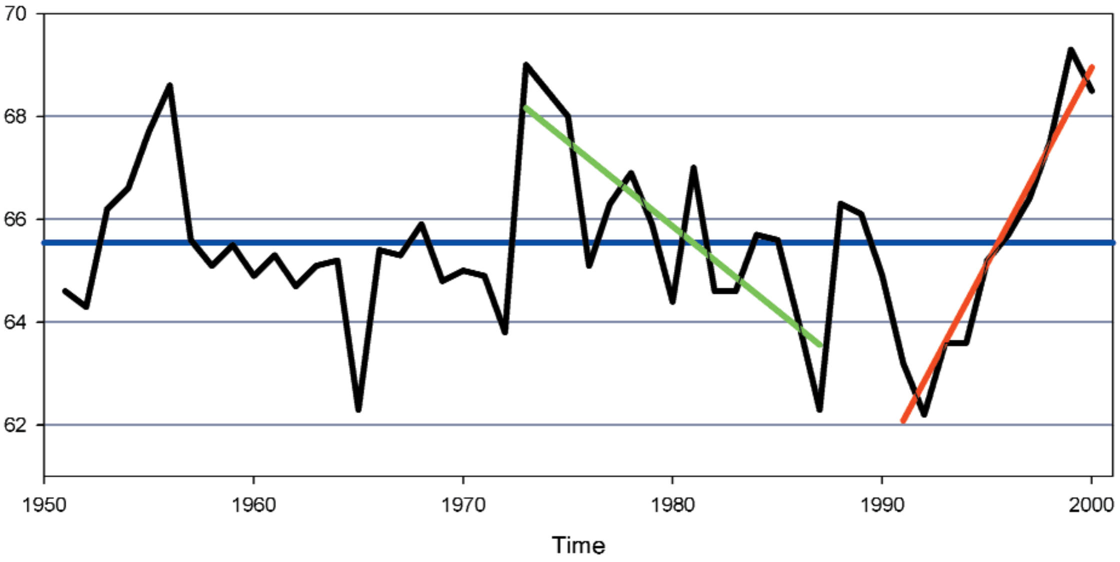

Fig. 1 Time series of annual mean monthly precipitation sums of the global land surface (Greenland and Antarctica omitted). Blue line: linear trend for the whole period 1951 to 2000, green line: linear trend for the period 1973 to 1987, red line: linear trend for the period 1991 to 2000.

Data

On a global scale different gridded data sets of observed precipitation are available. Each of these data sets has its particular advantages and disadvantages. For the question under consideration here a dataset providing constant accuracy over time should be preferred. For the period 1951 to 2000 the recently published VASCLimO v1.1 data set of the Global Precipitation Climatology Centre (GPCC, Beck et al., 2005) is most suitable since it is the only one that consists of gauge observations of long nearly gap free and homogeneous station records. Antarctica and Greenland are left out because of lack of data. From the data set with .5° resolution a global mean time series is generated by averaging over all 65,617 grid-box time series. Each grid box gets a weight according to its grid-box size and land fraction. The time series of annual mean monthly precipitation sums is shown in Fig. 1.

In order to investigate a possible link to other variables the monthly record of sunspot numbers (SSN; NGDC, 2005) is used as a proxy for variations in incoming solar radiation and the Southern Oscillation Index (SOI; CAS, 2005) as a characterisation of the El Nino-Southern Oscillation phenomenon. Also observed global mean temperature SAT (Jones and Moberg, 2003) is taken into account. Finally a link to explosive volcanism is analysed on the basis of the 5 most pronounced eruptions within the period 1951 to 2000 (s. Tab. 1, Grieser and Schönwiese, 1998).

Table 1 The five volcano eruptions with a Volcanic Explosivity Index VEI>5 within the period 1951 to 2000. Date classifies month and year of eruption.

Name	Date	Country	Approx.VEI
Agung	3/1963	Lesser Sunday Islands	5.9
Fernandina	6/1968	Galapagos	5.4
Fuego	10/1974	Guatemala	5.3
El Chichon	4/1982	Mexico	5.8
Pinatubo	6/1991	Philippines	6.1

The VASClimO v1.1 precipitation data set for the 600 months of the period 1951 to 2000 reveals a mean monthly precipitation sum of 65.55 mm/month (i.e. litres per month and square meter). The lowest precipitation sum is observed in February 1965 (47.3mm), the highest precipitation sum occurred in August 1988 (91.3mm). Though these extremes differ by nearly a factor of 2, the standard deviation of the time series is only 8.01 mm/month. Thus the coefficient of variation is about 12.2%.

Part of this variability can be explained just by the way precipitation is expressed. Here mm/month is used as usual for the products of the Global Precipitation Climatology Centre (GPCC). However, the length of a month varies from 28 to 31 days, i.e. by about 10% and this may explain a considerable amount of variability in time series of monthly precipitation sums. Therefore another measure of precipitation may be more adequate: the precipitation rate in mm/day. Monthly precipitation sums can easily be expressed as monthly averages of daily precipitation rates by division by the number of days of the concerning month. As a result the coefficient of variation of monthly means of the precipitation rate is 11.5% compared to 12.2% if monthly sums are used.

The precipitation rate consists of two independent parts: the mean annual cycle and the deviations from the mean annual cycle. The mean annual cycle is characterized by values below 2.1mm/day for all months except June to September. The minimum elongation of 1.92mm/day occurs in November whereas the maximum elongation with 2.59mm/day takes place in July. Both, July and August, the months with the highest precipitation rates, have 31 days. On the other hand February, the shortest month, has a low precipitation rate. If the lengths of the months are not taken into consideration the annual cycle of precipitation appears magnified. Fig. 2 shows the mean annual cycle of monthly precipitation sums and the rescaled annual precipitation rate for comparison.

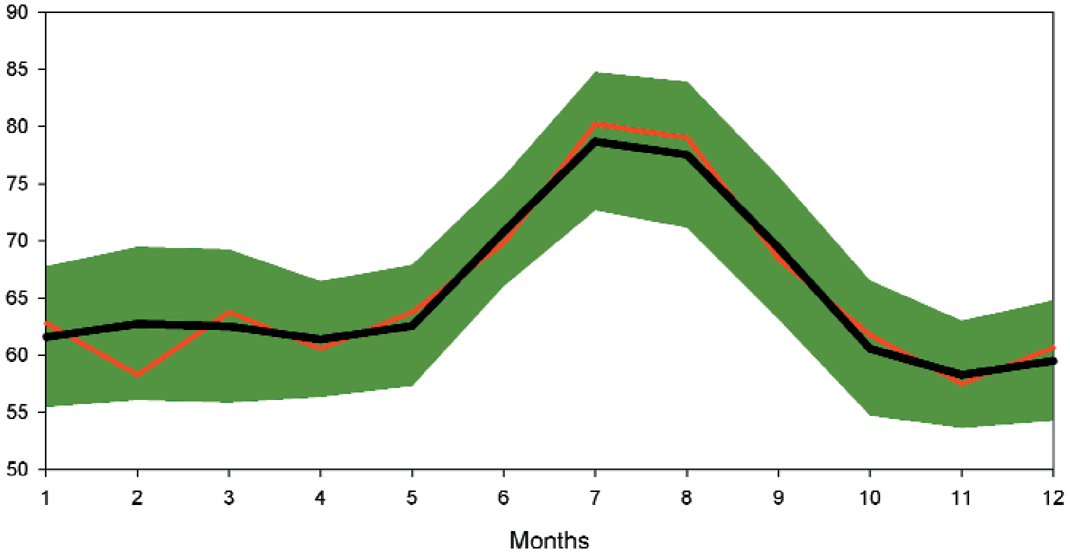

Fig. 2 Mean annual cycle of global mean land-surface precipitation with (black line) and without (red line) consideration of different length of month. The green area is an estimate of the 90% range of variability of deviations from the mean annual cycle.

The pronounced mean annual cycle in land-surface precipitation explains nearly 78% of the time-series variance, whereas deviations from the mean annual cycle explain only 22% of variance (see Fig. 2). To put it in other words: the standard deviation of the mean annual cycle (.219mm/day) is about twice as large as the standard deviation of the fluctuations (.117mm/day). The latter is about 5.4% of the long term mean of 2.153mm/day.

These fluctuations may contain signals of external forcing or internal climate variability. They may be linked to fluctuations of the surface air temperature.

Trends and long-term variability

As a first step it is tested whether part of the variance of precipitation can be attributed to long term trend and thus to climate change. In order to investigate long term changes it is sufficient to deal with annual mean monthly precipitation sums as provided in Fig. 1. The linear trend of the whole period from 1951 to 2000 is of the order of .0038mm/month/year. The explained fraction of variance is about 10^{-7} and thus it can be concluded that no 50-year trend exists in the record. However, decadal variability may be rather pronounced. Two examples are provided in Fig. 1: The linear trend for the decade 1991-2000 is .76mm/month/year. The explained fraction of variance is 92.6% and thus highly significant. Also highly significant is a negative trend of about 15 years from 1973 to 1987. This time the trend magnitude is about -.33mm/month/year which explains 65.7% of the variance.

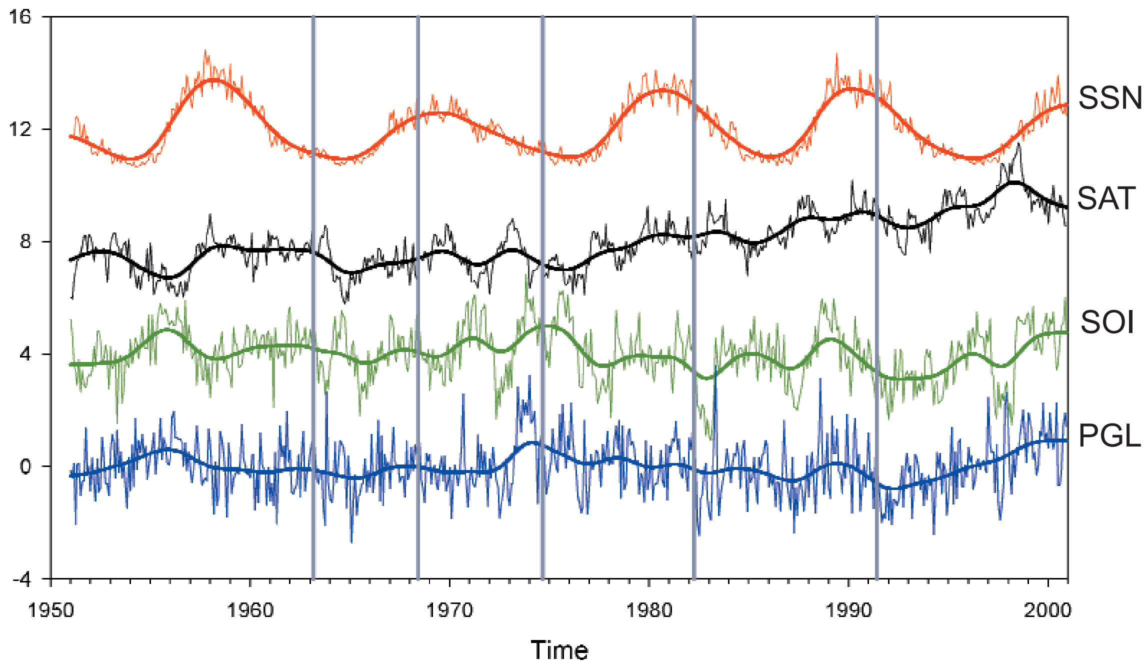

Fig. 3 Standardized monthly time series (thin lines) and low-pass filtered time series (Gaussian, 4 years, heavy lines) of monthly mean global land-surface precipitation rate (blue), standardized southern oscillation index SOI (green), standardized global mean surface air temperature SAT (black) and standardized sunspot numbers SSN (red) from 1951 to 2000. Time series are shifted for better visibility. Gray vertical lines mark times of major volcanic eruptions.

Aside the question whether PGL is increasing the question arises whether its variability changes. In order to investigate this question, the 50 year period is subdivided into two 25-year periods. The standard deviation of the second period (1976-2000) is 1.75mm/month. It is not significantly higher than the standard deviation of the first sub-period (i.e. 1.59mm/month).

Therefore it can be concluded that no significant long-term change in global land-surface precipitation and its variability is found. No indication of an enhanced global water cycle can be determined from this data set.

Links to other climate variables and external forcing

Figure 1 clearly reveals that PGL variability happens to occur mainly on time scales up to decades. The question arises whether the variability is in line with internal climate variability, i.e. the El Nino Southern Oscillation phenomenon (ENSO) and variations of natural external forcing like solar radiation expressed as variations in sunspot numbers (SSN) or strong volcanic eruptions, characterized by high values of the volcanic explosivity index (VEI). Furthermore, the hypothesis is tested whether a direct link between SAT variations and variations in PGL exists.

As discussed above, a fraction of the variability of climatological time series may be due to mean annual cycles. Furthermore also the variances themselves may feature an annual cycle. In order to ensure independency of the annual cycles in both, mean and standard deviation, all time series are standardized with respect to each calendar month. Therefore the resulting time series as depicted in Fig. 3 are free of an annual cycle in both mean and variance.

All the time series of Fig. 3 consist of 600 monthly values. In order to investigate possible relations between PGL variations on the one hand and SOI, SSN and SAT on the other hand, Pearson correlation coefficients r are calculated. The square of this coefficient is the fraction of variance r^2 that both time series have in common. If white-noise time series of a length of 600 values of uncorrelated variables were analysed, r^2 would be below .45% for 90% of the cases. Thus all cases with $r^2>0.45\%$ are called significant on a 90% level of significance.

The fraction of common variances r^2 for PGL and SOI is 18.38% and thus highly significant. For PGL and SSN it is .05%, and for PGL and SAT it is 0.21%. On the basis of the standard statistical test it has to be concluded that PGL and SSN are uncorrelated and so are PGL and SAT.

However, correlations may be hidden by others. SOI explains a considerable faction of the variance of PGL which can be subtracted from the original time series. The resulting time series of the fraction of precipitation not explained by SOI can again be subject to a correlation analysis. It reveals that a small but significant correlation to SAT with $r^2=0.71\%$ is found. The correlation to SSN, however, becomes even smaller.

VEI – The Volcanic Explosivity Index

VEI is defined by Chris Newhall and Steve Shelf (1982) in order to help volcanologists to scale and to compare the eruptions of different volcanoes. Aside the volume of erupted material also the plume height and frequency of eruption are considered. The scale is open-ended and starts from 0, for non-explosive eruptions. From a climatological point of view only the stratospheric mass loading is of interest since it resides long enough to alter the atmospheres radiation budget for months. Grieser and Schönwiese (1999) therefore introduced a climatologically corrected VEI which is proportional to the logarithm of stratospheric mass loading. This climatologically corrected VEI is used here.

Correlation analysis is not adequate in order to investigate a possible link between explosive volcanism and PGL. This is due to the fact that only 5 major volcanic eruptions occurred during the period of interest. Each of these eruptions provokes a stratospheric aerosol cloud which has an impact to the Earth's energy budget during the months following the eruption (Grieser and Schönwiese, 1998; Bissolli, 2001). In order to deal with the hypothesis that those volcanic eruptions affect global mean precipitation, fourfold tables are used which allow for a contingency test.

All months are grouped into two groups, the months following an eruption and the others. All precipitation sums are also grouped; one group consisting of precipitation sums higher than average, one with the precipitation sums lower or equal average. Based on this grouping a parameter-free consistency test can be performed which results in the significance of the statement “precipitation is likely to be reduced after a volcanic eruption”.

Up to now nothing is said on the exact meaning of “after a volcanic eruption”. It is a period characterized by a start month and an end month. Both are not given a priori. Instead, start and end month are varied. The end month is varied in the interval from start month +0 to start month +18 months, allowing interval lengths of 1 to 19 months. The start months is varied from -12 months to +12 months with respect to the month of eruption. Of course, for start times before the month of eruption and short interval lengths no signal should be observable. All together the test is performed 475 times; 25 start months (-12 to 12) times 19 end months (start month +0 to start month +18).

Highly significant statistical links are found if the start month is set not later than 3 months after the month of eruption and for period lengths of 2 to 16 months (Fig. 4). Therefore it can be concluded that explosive volcanism has a significant impact on global land surface precipitation. On top of that the period for which strong volcanic eruptions significantly decrease PGL is approximated to be up to 16 months.

Summary and Conclusions

A recently published gridded dataset of observed global monthly land-surface precipitation on .5° grid for the period 1951 to 2000 is used in order to investigate the variability of global mean land-surface precipitation. It is found that a pronounced mean

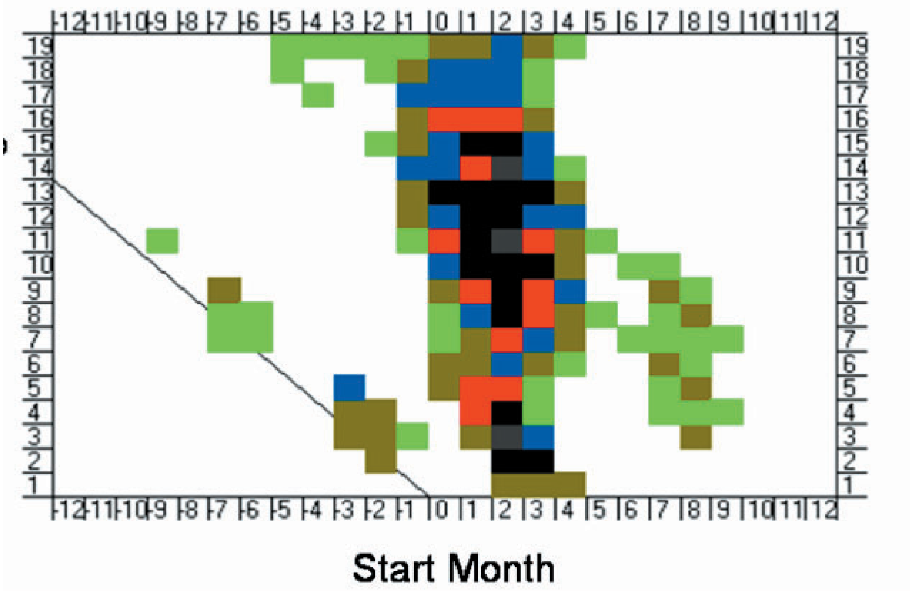

Fig. 4 Significance of reduced global mean land-surface precipitation (PGL) after strong volcanic eruptions based on 475 contingency tables. Abscissa indicates the start month with respect to the volcanic eruption. Ordinate indicates the period length. Colors indicate significance: white <90%, green < 95%, brown < 97.5%, blue < 99%, red < 99.5%, black < 99.9%, gray >=99.9%. The area in the lower left corner of the plot should not reveal significant results by definition.

annual cycle with high precipitation rates from July to September explains nearly 80% of the total variability. These months coincide with the season where the intertropical convergence zone (ITCZ) is north of the equator. Land fraction is higher there than south of the equator. This may explain at least part of the annual cycle. For further investigations the annual cycle is removed.

No trend-like behaviour is found within the 50-year period and thus no indication of an enhanced global water cycle. However, one has to keep in mind that global mean land-surface precipitation is investigated which only accounts for about 25% of the total global precipitation. The other 75% of precipitation occur over the world oceans.

Though no linear trend is found in the global mean land-surface precipitation, there are significant local and regional trends within the data set used (see Beck et al., 2005). Beck et al. (2006) found an increase in the area covered by dry climates. Taking this into account the precipitation in non-dry climates has to have increased in order to compensate for respective area reductions.

Global mean land surface precipitation is statistically linked to the El Nino-Southern Oscillation phenomenon which explains about 18% of the precipitation variability. No statistical link to the variation of sunspot numbers is found. Strong volcanic eruptions, however, significantly decrease global mean land-surface precipitation for up to 16 months after eruption.

A statistical link to global mean surface air temperature is hardly visible. Thus, the data do not support the concept that on a global scale higher mean temperatures lead to noticeable higher evaporation and, in consequence, higher precipitation. This may be due to the fact that on one hand highest temperature variability happens to occur outside the tropics. Therefore, global mean temperature variations mainly reflect extra-tropical temperature variability. On the other hand high precipitation variability happens to occur due to local convection cells mainly within the tropics. Thus it may be possible that global mean land-surface precipitation mainly probes a different part of the globe than global mean surface air temperature. However, this does not mean that there is no link between these climate variables. It may be hidden by other more pronounced mechanisms, leaving it open to future research to investigate what drives global mean land-surface precipitation.

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