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Climate of the Past Discussions

Temperature trends at the Mauna Loa Observatory, Hawaii

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Abstract

Observations at the Mauna Loa Observatory, Hawaii, established the systematic increase of anthropogenic CO_2 in the atmosphere. For the same reasons that this site provides excellent globally averaged CO_2 data, it may provide temperature data with global significance. Here, we examine hourly temperature records, averaged annually for 1977–2006, to determine linear trends as a function of time of day. For night-time data (22:00 to 06:00, LST (local standard time)) there is a near-uniform warming of $0.040\,^{\circ}\mathrm{C\,y^{-1}}$. During the day, the linear trend shows a slight cooling of $-0.013\,^{\circ}\mathrm{C\,y^{-1}}$ at 12:00 (noon, LST). Overall, at Mauna Loa Observatory, there is a mean warming trend of $0.021\,^{\circ}\mathrm{C\,y^{-1}}$. The dominance of night-time warming results in a relatively large annual decrease in the diurnal temperature range (DTR) of $-0.050\,^{\circ}\mathrm{C\,y^{-1}}$. These trends are consistent with the observed increases in the concentrations of CO_2 and its role as a greenhouse gas, and indicate the possible relevance of the Mauna Loa temperature measurements to global warming.

1 Introduction

The observations since 1958 that established the systematic increase of atmospheric CO_2 (Keeling et al., 1976) were carried out at the NOAA Observatory on Mauna Loa (altitude 3397 m a.s.l. (above sea level)), Big Island, Hawaii. It has been argued (Ryan, 2001) that this is an excellent location to make atmospheric measurements because of the isolation from localized anthropogenic and continental sources and sinks. The well-mixed atmosphere at this isolated high-elevation observatory has very small variations in CO_2 concentrations, and the observations have been widely taken as representative of global average values (IPCC, 2007). We suggest that this single high-altitude NOAA station at Mauna Loa Observatory provides a background site for temperature which may be of similar global significance as the CO_2 data obtained there. We will use the high-quality hourly temperature data (NOAA, 2009) from this observatory for the time

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period 1977–2006 to study (a) trends in annual mean temperature data as a function of the hour of the day, and (b) trends in annual mean diurnal temperature ranges (DTR), where the DTR is the difference between the maximum and minimum temperatures in a given 24 h period.

We recognize that temperature trends are often obtained utilizing spatial averages of results from multiple stations, rather than one station. For example, Jones and Moberg (2003) utilized 5159 stations to map global values of surface temperature trends. In another example, trends for averaged stations in the Hawaiian Islands have been given by Giambelluca et al. (2008). Never the less, we believe that the study presented here, using high-quality hourly temperature data obtained from this high-altitude NOAA tropical site, might be consistent with globally averaged temperature trends.

Our paper is organized as follows: In Sect. 2 we describe the 30-year Mauna Loa NOAA observatory temperature hourly data used, including missing observations. In Sect. 3 we give temperature trends for the period of study as a function of time of day and determine a mean rate of temperature warming. We compare this value to IPCC (2007) global temperature trends and warming rates inferred from changes in global CO_2 concentrations. In Sect. 4 we derive the trend in DTR at this observatory and compare it with other studies. We conclude in Sect. 5 with a discussion of the implications of our results.

2 Mauna Loa temperature data

The Mauna Loa Observatory hourly mean air temperature measurements used here are from the NOAA Earth System Research Laboratory (ESRL) station 31 (altitude 3397 m a.s.l.) and are measured in aspirated radiation shields at a height of 2 m above ground (NOAA, 2009). During the 30-year period, 1 January 1997 to 31 December 2006, three different systems were used to collect temperature data (personal communications, 3/2009, Thomas Mefford, Global Monitoring Division, NOAA): (a) 1/1977–12/1983: Thermistor; (b) 1/1984–10/1993: linearized thermistors;

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(c) 10/1993–12/2006: hygrothermometer. Hourly data were based on averages of minute samples from 10/1993 to 12/2006; previous to 1993, longer time periods were averaged.

An important aspect of our data analyses is the treatment of missing data. For the period of record, 1/1/1997–31/12/2006, there were $n = 262\,968$ hourly measurements, of which 9695 values (3.7%) were missing. Missing values were approximately uniformly distributed by year and also as a function of the hour of day. Interpolation to replace missing data was done as follows: (a) If data for the missing hour were available for that same hour within 7 days on both sides, these two values were averaged; (b) If data as described in "a" were not available, values were substituted from the subsequent year for the same hour and day. The two types of interpolation accounted for about 50% each in terms of missing values. The longest gaps were 14/8–15/9/1997 and 29/3–28/4/1984; the first gap was caused by a volcanic eruption at Mauna Loa which severed power lines to the observatory and the second gap was caused by a major lightning strike which affected all projects at the observatory (personal communications, Thomas Medford, NOAA).

3 Temperature trends

Our first objective is to determine, as a function of each hour of the day h, the linear trends of the Mauna Loa temperature data over the 30 years of record, 1 January 1977 to 31 December 2006. We illustrate our data analyses using hourly temperatures T measured at h =12:00 (noon, LST). In Fig. 1, we show the daily temperatures for the period of record at this time of day. Also shown are the annual means of these daily values and the ordinary least-squares best-fit linear trend to these annual values. The slope of this annual trend line for 12:00 has a small rate of annual cooling, $\mathrm{d}T/\mathrm{d}t = -0.014 \pm 0.014\,^{\circ}\mathrm{C\,y}^{-1}$ (uncertainties are ±1 s.e. (standard error) of the slope). Fitting a single linear trend to the 30 years of data can be questioned because of their relatively large scatter. This question is addressed in Sect. 4. In addition to

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scatter, another source of variability (Giambelluca et al., 2008) is large scale synoptic influences such as the Pacific Decadal Oscillation (PDO). We emphasise linear temperature trends in our analyses, so as to compare them with the linear trend in global CO_2 concentration measures at the same site.

Our results as a function of time of day h are given in Fig. 2. In Fig. 2a we give the dependence of T, the mean of all hourly temperatures at a specified time of day, h, for the entire period. The values range from a maximum $T = 11.0 \pm 3.0$°C at $h = 12{:}00$ (uncertainties are ±1 s.d. (standard deviation) of the daily values given in Fig. 1) to a minimum $T = 3.7 \pm 2.2$°C at $h = 05{:}00$. In Fig. 2b we give the dependence of the linear temperature trends for the entire period, dT/dt, as a function of the time of day, h. The values range from a warming trend $dT/dt = 0.040 \pm 009\,°\mathrm{C\,y^{-1}}$ (±1 s.e. of the mean) at h = 02:00 to a slight cooling trend $dT/dt = -0.014 \pm 0.014\,°\mathrm{C\,y^{-1}}$ at h = 12:00 (i.e., the slope of the trend given in Fig. 1). This type of hour of day variability of dT/dt has been considered previously for urban Japanese data (Fujibe, 2009).

The difference between the maximum and minimum slopes for the trend lines (Fig. 2b) is $dT/dt = 0.054\,°\mathrm{C\,y^{-1}}$. At night (22:00 to 06:00 LST) there is a near uniform heating trend with values near $dT/dt = 0.04\,°\mathrm{C\,y^{-1}}$. During the day time, there is a reduction in the morning in the annual warming rate, with a localized minimum (and overall cooling per year) at 12:00 of $dT/dt = -0.014\,°\mathrm{C\,y^{-1}}$, and then an increase again of the warming trend during the afternoon. It is interesting to note the similarity between the shapes of the diurnal variability of the mean temperature (Fig. 2a) and the temperature trends (Fig. 2b) as a function of hour of day. Annual warming over the period of record in Fig. 2b corresponds to low temperatures in Fig. 2a, and relative annual cooling in Fig. 2b to high temperatures in Fig. 2a.

The mean of the Mauna Loa Observatory annual warming and cooling trends given in Fig. 2b gives an overall warming trend (dashed horizontal line) of $dT/dt = 0.021 \pm 0.011\,°\mathrm{C\,y^{-1}}$ (±mean of error bars in Fig. 2b). This compares to Giambelluca et al. (2008) who obtained a mean rate of warming for 1975–2006 averaged over four Hawaii stations with elevations 916–3140 m a.s.l. of $dT/dt = 0.027\,°\mathrm{C\,y^{-1}}$. The mean rate of warming inferred from averaged annual global surface temperature measurements, 1980–2005, by the IPCC (2007) is $\mathrm{d}T/\mathrm{d}t = 0.018 \pm 0.005\,^{\circ}\mathrm{C\,y^{-1}}$. Our value is within the range of those given by the IPCC. This supports our proposal that the Mauna Loa value is representative of the mean rate of global warming. This is in direct analogy to the widely accepted association of the mean rate of increase in the concentration of CO_2, $\mathrm{d}C/\mathrm{d}t = 1.6\,\mathrm{ppmv\ y^{-1}}$ (ppm by volume per year) measured at the observatory (CDIAC, 2009) over the same period, with the rate of increase of CO_2 globally.

We now examine the theoretical relation between changes in global mean atmospheric CO_2 concentrations and changes in global mean atmospheric temperatures. The radiative forcing ΔF has been given as (Myhre et al., 1998)

$$\Delta F = 5.35 \ln\left(\frac{C}{C_0}\right), \tag{1}$$

with ΔF in $\mathrm{W\,m^{-2}}$, C the concentration of CO_2 in ppmv, and C_0 a reference concentration for CO_2. Based on annual mean CO_2 observations at the Mauna Loa Observatory (CDIAC, 2009), we take C_0=334 ppmv for 1977, and C=392 ppmv for 2006. Substitution of these values into (Eq. 1) gives ΔF=0.72 $\mathrm{W\,m^{-2}}$. The change in mean atmospheric temperature ΔT is related to the change in radiative forcing ΔF by (IPCC, 2007)

$$\Delta T = \lambda \Delta F, \tag{2}$$

where λ is the equilibrium climate sensitivity. Studies (IPCC, 2007; Gregory et al., 2002) give a preferred value λ=0.8 [0.5 to 1.2]°C $\mathrm{m^2\ W^{-1}}$. Substituting these values of λ and ΔF=0.72 $\mathrm{W\,m^{-2}}$ into Eq. (2), gives ΔT=0.58 [0.36 to 0.86]°C for the 30-year period 1977–2006 or $\mathrm{d}T/\mathrm{d}t$=0.019 [0.012 to 0.029]°C $\mathrm{y^{-1}}$, very close to the results we obtain for the Mauna Loa Observatory, $\mathrm{d}T/\mathrm{d}t = 0.021 \pm 0.011\,^{\circ}\mathrm{C\,y^{-1}}$.

4 Diurnal temperature range

We now turn our attention to the diurnal temperature range (DTR), obtaining the trend of the annual mean values of DTR at the Mauna Loa Observatory for 1977–2006. We first obtain the maximum and minimum hourly temperatures for each 24 h period, $h = 00{:}00$ to 23:00. These are then averaged over each year, to obtain the annual mean maximum, T_{max}, and annual mean minimum, T_{min}, temperatures (Fig. 3a). The ordinary least-squares best-fit linear slope for the annual T_{max} data is $\mathrm{d}T_{max}/\mathrm{d}t = -0.011 \pm 0.013\,^{\circ}\mathrm{C\,y^{-1}}$ (±1 s.e. of the slope), which is, as expected, close to the trend of $\mathrm{d}T/\mathrm{d}t = -0.014 \pm 0.014\,^{\circ}\mathrm{C\,y^{-1}}$ given in Figs. 1 and 2b for 12:00 (noon, LST). The best-fit linear trend for the minimum temperature is $\mathrm{d}T_{min}/\mathrm{d}t = 0.038 \pm 0.009\,^{\circ}\mathrm{C\,y^{-1}}$, which is close to the night-time trends given in Fig. 2b.

The difference between the annual mean maximum and annual mean minimum temperatures is the annual mean DTR (illustrated for 1977 in Fig. 3a); this is equivalent to taking the mean of the daily DTR values for the year. The annual mean values of DTR are given in Fig. 3b as a function of time t, for the period 1977–2006 at the Mauna Loa Observatory. The ordinary least-squares best-fit linear trend is $\mathrm{d(DTR)}/\mathrm{d}t = -0.050 \pm 0.007\,^{\circ}\mathrm{C\,y^{-1}}$. This is very close to the difference between the maximum and minimum annual trends ($-0.054\,^{\circ}\mathrm{C\,y^{-1}}$) given in Fig. 2b as a function of hour of the day.

The application of a single trend line to the 30 years of data at the Mauna Loa Observatory can certainly be questioned because of the relatively large scatter of the annual data. To partially address this question, we divided the annual DTR data in Fig. 3b into two 15-year periods and obtained the least-squares best-fit trends. For 1977–1991, we obtain $\mathrm{d(DTR)}/\mathrm{d}t = -0.064 \pm 0.021\,^{\circ}\mathrm{C\,y^{-1}}$ (±1 s.e. of the slope) and for 1992–2006, $\mathrm{d(DTR)}/\mathrm{d}t = -0.045 \pm 0.013\,^{\circ}\mathrm{C\,y^{-1}}$. As the number of values decreases in our sample from $n = 30$ to $n = 15$, the s.e. of the slope increases. However, both values are in reasonably good agreement with the 30-year trend given above ($\mathrm{d(DTR)}/\mathrm{d}t = -0.050 \pm 0.007\,^{\circ}\mathrm{C\ y^{-1}}$).

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In the DTR analyses done in this section we have considered T_{max}, T_{min} and DTR to be based on a calendar day (h = 00:00 to 23:00). However, in doing so, there is the possibility that T_{min} for two successive calendar days might be from the same evening (e.g., one value is at 23:00, the other at 01:00). To reduce the possibility of two successive T_{min} values being chosen from the "same" evening, one can also consider an observational day, where the 24 h period considered begins in the morning (e.g., 08:00) or evening (e.g., 19:00). A detailed discussion of the influence of different 24 h periods chosen on T_{max} and T_{min} is given by Janis (2002). We therefore repeated the analyses done in this section, but using an observational day from h = 08:00 to 07:00 (on the next day). We find that the percent difference between individual averaged annual values using calendar days (symbols given in Figs. 3a and b) and observation days (beginning at 08:00), to be 0.0–0.2% for T_{max}, 1.3–5.6% for T_{min}, and 0.5–1.8% for DTR. The changes in the overall trends given in Fig. 3a and b were also considered, and found to be very small, with percent changes to the slope values given in Figs. 3a and b changing by less than 1% (dT_{max}/dt by 0.9%, dT_{min}/dt by 0.0%, and $dDTR/dt$ by 0.2%). We therefore conclude that the choice of 24 h period chosen, when determining daily and annual averages for T_{max}, T_{min} and DTR, has little effect on the overall trends shown in Fig. 3a and b.

We compare our DTR results with those of other studies (Table 1), ranging from analyses done on 1 to 7000 spatially averaged stations. Grant et al. (2005) obtained a DTR trend-line slope for a high altitude station at Mt Washington that is approximately an order of magnitude smaller than our Hawaii results. Although both sites are high altitude, Mt Washington is influenced by a continental location, is closer to anthropogenic influences than the Mauna Loa Observatory, and the period studied is twice as long. Giambelluca et al. (2008) studied records from 21 stations on Hawaii. They spatially averaged the four high-altitude stations (>900 m a.s.l.) over the period 1975–2006 and found a yearly DTR change $\approx -0.036\,^{\circ}\mathrm{C\,y^{-1}}$, slightly less than the value we obtain. Vose et al. (2005) obtained maximum temperatures, minimum temperatures and DTR trends globally for the period 1979–2004, approximately the same period we consider.

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With maximum temperature data averaged over 7018 stations and minimum temperature and DTR data averaged over 6970 stations, they found $dT_{max}/dt \approx 0.0287\,°C\,y^{-1}$, $dT_{min}/dt \approx 0.0295\,°C\,y^{-1}$, and a yearly DTR change $\approx -0.0001\,°C\,y^{-1}$. Differences with our analysis in Hawaii are expected since most stations in the Vose et al. (2005) global study are continental and at low elevations.

5 Discussion

The systematic increase in atmospheric CO_2 has been convincingly demonstrated by measurements made at the Mauna Loa Observatory (Keeling et al., 1976), where the temporal change of annual mean values of CO_2 concentrations 1977–2006 is well represented by a linear trend $dC/dt = 1.6\,ppmv\,y^{-1}$. As discussed above, we have found (Fig. 2b) that there is an overall annual warming trend of temperatures $dT/dt = 0.021 \pm 0.011\,°C\,y^{-1}$ at this observatory for the same period. This is very close to both the average "preferred" value of the IPCC (2007) for the period 1980–2005 of $\overline{dT/dt} = 0.018 \pm 0.005\,°C\,y^{-1}$ and our inferred CO_2 trend analysis value of $dT/dt = 0.019$ [0.012 to 0.029]$°C\,y^{-1}$.

At the Mauna Loa Observatory, we find a systematic dependence of temperature change on the time of day. During the hours of darkness, there is a near-uniform annual rate of heating during the 30-year period 1977–2006. However, during the hours of sunlight there is a systematic decrease in this warming trend during the morning, and a systematic increase in the afternoon (Fig. 2b).

At night, longwave radiation and turbulent sensible heat fluxes dominate heat loss. Increasing presence of green house gases will result in enhanced reradiation back towards the surface and hence warming nocturnal temperatures. During the daytime, shortwave radiation dominates, particularly in tropical regions. It would be expected that the role of green house gases would be greater in the early morning before significant heating enhances boundary layer depth. At the end of the day, the boundary

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layer collapses. A possible explanation for the middle of the day cooling is that the enhanced surface heating is actually resulting in greater mixing and therefore decrease in the near-surface green house gas concentration which would reduce incoming longwave radiation. Relatively strong nocturnal warming can qualitatively explain "why" global warming appears to be concentrated in the high-latitude Arctic (IPCC, 2007).

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Table 1. Diurnal temperate range (DTR) studies compared [m a.s.l. = metres above sea level].

Source	Location	Time Period	Elevation (m a.s.l.)	Number of stations	d(DTR)/dt (°C y^{-1})
Grant et al. (2005)	Mt Washington, New Hampshire	1935–2003	1914	1	–0.0020
Giambelluca et al. (2008)	Hawaii	1975–2006	3–768 916–3400	17 4	–0.012 –0.036
This study	Mauna Loa, Hawaii	1977–2006	3397	1	–0.050
Vose et al. (2005)	Global	1979–2004[a]	Variable	6970	–0.0001

[a] Individual stations had at least 20 years of data.

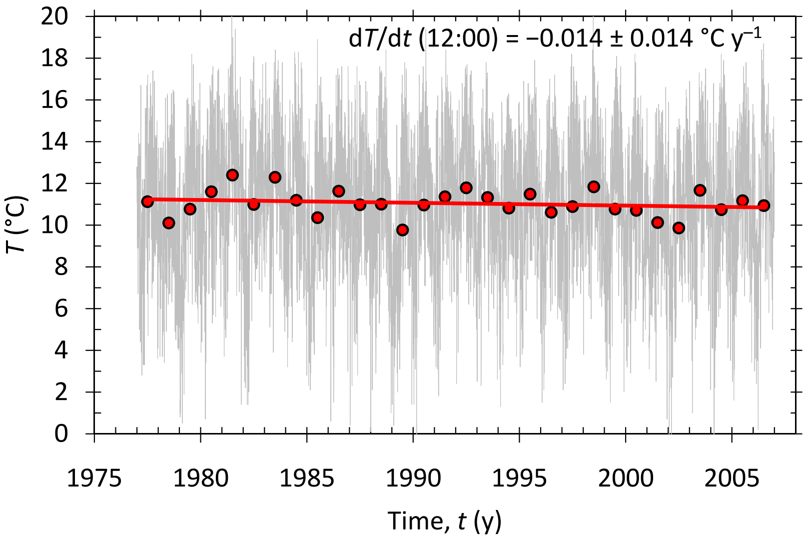

Fig. 1. Temperatures at 12:00 (noon, LST) at the Mauna Loa Observatory, Hawaii, 1977–2006, based on hourly temperature data from NOAA (2009). Shown are the 30-year daily sequence of 12:00 (noon, LST) temperatures T (light grey lines) as a function of time t from 1 January 1977 to 31 December 2006. Also shown (circles) are the annual means of these daily values. The least-squares best-fit line is shown (thick solid line), with slope $\mathrm{d}T/\mathrm{d}t = -0.014 \pm 0.014\,^{\circ}\mathrm{C\,y}^{-1}$ (uncertainties ±1 s.e. of the slope).

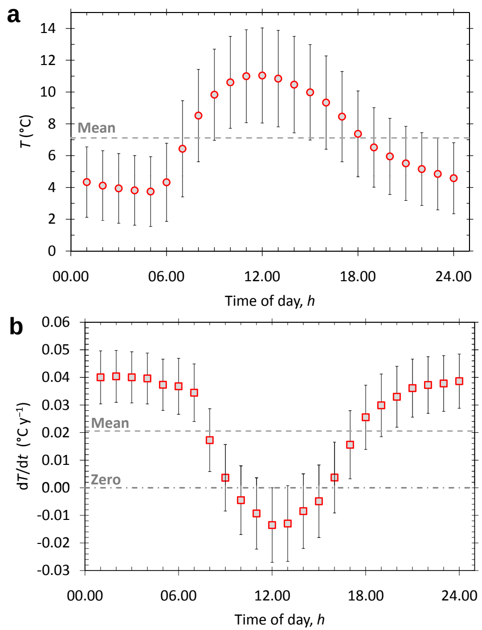

Fig. 2. Mean temperatures and best-fit trend-line slopes for the 30-year Mauna Loa data (NOAA, 2009) as a function of time of day. **(a)** The mean of all temperatures, T, at a specified time of day, h, are averaged for 1977–2006 (circles) (error bars ± 1 s.d. of hourly values for the year). The mean of the time-of-day values is $\bar{T} = 7.11\,^{\circ}\mathrm{C}$ (dashed line). **(b)** Annual mean rates of warming (cooling) $\mathrm{d}T/\mathrm{d}t$ (squares) are given as a function of time of day, h (error bars ± 1 s.e. of the slope). The mean rate of warming (upper dashed line) is $\mathrm{d}T/\mathrm{d}t = -0.021 \pm 0.011\,^{\circ}\mathrm{C\,y^{-1}}$ ($\pm$ average of error bars in Fig. 2b).

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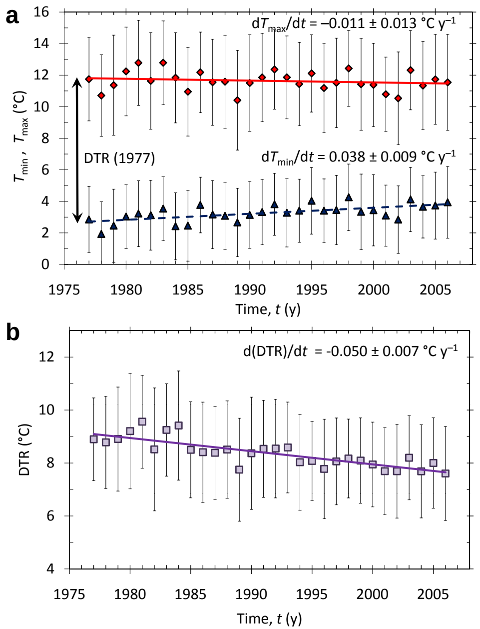

Fig. 3. Mean annual maximum and minimum temperatures, and diurnal temperature ranges (DTR) for the 30-year Mauna Loa data (NOAA, 2009). **(a)** The sequence of annual mean maximum temperatures T_{max} (diamonds) and minimum temperatures T_{min} (triangles) are given as a function of time t for 1977–2006 (error bars ±1 s.d. of daily values for that year). The best-fit linear trends (solid and dashed lines) of the annual values are shown along with their slopes (±1 s.e. of the slope). **(b)** The annual mean values of DTR (squares) are given as a function of time t (±1 s.d. of DTR values for that year). The best-fit linear trend (solid line) of the annual values is shown along with its slope (±1 s.e. of the slope).