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How soon will climate records of the 20th century be broken according to climate model simulations?

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ABSTRACT

What will happen to local record values of temperature and precipitation in a world with ongoing global warming? Here we first examine how many of the observed local temperature maxima of 1901–2006 occurred in the years 2001–2006 and compare the observations with model simulations. Then we study whether, and how soon, the models simulate the climate records of the 20th century to be broken in the ongoing 21st century.

In 27% of our analysis area, the highest annual mean temperatures of the whole period 1901–2006 were observed in 2001–2006. For the 22 climate models in our study, this fraction varies from 17% to 70%, with a multimodel mean of 40%. In simulations based on the SRES A1B emissions scenario, the highest annual mean temperature of the 20th century is exceeded on average in 99% of the global area by the year 2080. The same number for the highest (lowest) annual precipitation total is 60% (43%). Monthly and seasonal temperature and precipitation records are also analysed, and the geographical distributions of record value occurrence are related to the distributions of time mean climate change and magnitude of interannual variability.

1. Introduction

During the past century, the global mean temperature increased (as a linear trend) by 0.74 ± 0.18°C (Trenberth et al., 2007). Comparison between model simulations and observations indicates a substantial contribution to this warming from anthropogenic increases in atmospheric greenhouse gas concentrations (Hegerl et al., 2007). More importantly, a larger change is likely during the ongoing century. Depending on the magnitude of greenhouse gas emissions, feedbacks associated with the carbon cycle and the sensitivity of climate to changes in the atmospheric composition, a global mean warming of 1.1–6.4°C is projected from the period 1980–1999 to 2090–2099 by the Intergovernmental Panel on Climate Change (Meehl et al., 2007a).

The change in global mean temperature alone is an insufficient basis for assessing the consequences of the ongoing climate change. First, the changes are geographically variable. For example, in the Arctic temperature increased at almost twice the global average rate in the past 100 yr (Trenberth et al., 2007), and the same area is also projected to experience the largest warming in the future (Meehl et al., 2007a). Second, the impacts of climate change are not determined by changes in time mean conditions alone but are also affected by changes in variability and extremes.

The potential importance of changing climate extremes has made them a field of intense research. This topic was recently reviewed by Trenberth et al. (2007) for the changes observed this far and by Meehl et al. (2007a) and Christensen et al. (2007) for projections of future climate. A brief summary is given below, focusing on some key studies on changes in temperature and precipitation extremes.

As illustrated by Folland et al. (2001), an increase in mean temperature tends to make warm (cold) extremes more (less) frequent and more (less) intense. Both observed and projected changes in temperature extremes tend to follow this qualitative pattern, but changes in variability may introduce asymmetry between the changes in the two ends of the temperature distribution. For example, in accord with an overall tendency toward smaller diurnal temperature range, the decrease in the occurrence of cold nights since the mid-20th century has been generally larger and more widely statistically significant than the corresponding increase in the occurrence of warm days (Alexander et al., 2006; Trenberth et al., 2007). However, both of these changes have been geographically variable, probably partly because of natural climate variability that has accentuated the anthropogenic warming in some areas and counteracted it elsewhere.

Simulations of climate change for the 21st century indicate that, if the projected large global mean warming is realized, this will be accompanied by a large change in temperature extremes.

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Against a background of a great number of studies focusing on individual regions or simulations by individual climate models, the systematic analysis by Kharin et al. (2007) is particularly valuable. These authors compared simulated changes in 20-yr return values of the lowest minimum and highest maximum temperature among 12 atmosphere ocean general circulation models participating in the third Coupled Model Intercomparison Project (CMIP3; Meehl et al., 2007b). Globally averaged, their results suggest a continued larger change in low than high temperature extremes. Under the SRES A1B emission scenario (Nakićenović and Swart, 2000), the multimodel mean globally averaged warming in the 20-yr cold extremes from 1981–2000 to 2046–2065 was 2.3°C, whereas the corresponding change in warm extremes was 1.7°C. This difference is partly explained by a larger simulated time mean warming in winter than in summer in most areas. However, even when accounting for the seasonal cycle of the time mean warming, a disproportionately large increase in cold extremes (indicative of reduced wintertime temperature variability) was found in high-latitude oceans with reduced sea ice and over some mid-latitude areas with reduced snow cover. By contrast, the analysis revealed relatively few systematic differences between the changes in 20-yr warm extremes and in the mean temperature of the warmest summer month.

For precipitation extremes, both observations and model simulations suggest a more complicated nature of changes. Alexander et al. (2006) found that although observations show predominantly positive trends in indicators of heavy short-term (1-to-5-d) precipitation, these changes have been less statistically significant and less geographically uniform than changes in temperature extremes. In simulations of future climate as well, increases in high extremes of daily precipitation predominate, qualitatively as expected from the larger moisture content of a warmer atmosphere (Kharin et al., 2007). These increases also extend to many (although not all) areas that experience a decrease in mean precipitation. However, the link between precipitation extremes and the atmospheric moisture content weakens with increasing timescale. Simulated greenhouse-gas induced changes in both wet and dry extremes of monthly-to-annual precipitation tend to be well correlated with changes in long-term mean precipitation: wet extremes become more severe, especially where the mean precipitation increases, and dry extremes, where the mean precipitation decreases (Räisänen, 2005). Changes in relative variability play a smaller role on these timescales. Nevertheless, in an ensemble-mean sense, models suggest a slight increase in variability in most areas, so that the contrast between wet and dry extremes grows larger in a warmer climate.

For both temperature and precipitation extremes, the simulated changes vary among climate models. As for simulations of the time mean climate change (e.g. Räisänen, 2001), this variation tends to be relatively larger for precipitation than temperature extremes (Kharin et al., 2007). Similarly, changes in average and extreme precipitation are smaller compared with interannual climate variability than the corresponding temperature changes.

In this study, we aim to quantify some aspects of how extremes change in a warming world. Specifically, we focus on record values of temperature and precipitation on the monthly-to-annual timescale. The greater public, in particular, often perceives new climatic records as an expression of climate change. Although this perception is clearly problematic (as new records would be occasionally reported even in an unchanged climate), it is not always totally wrong, because some types of extremes (and thus new climatic records) are expected to become more common as a result of the ongoing anthropogenic climate change. Hence, the question that we pose in this paper is: how soon can we expect record values of 20th century climate to be broken, as the greenhouse-gas induced global warming continues in this century?

After introducing the data sets and methods used (Sections 2 and 3), we first focus in Section 4.1 on temperature observations. Our analysis confirms that new record-high monthly-to-annual temperatures have been observed much more commonly in the first 6 yrs of the 21st century than would be expected in an unchanged climate. Then, in Section 4.2, a similar analysis is made for the same period in the CMIP3 simulations to explore how well climate models are able to reproduce the behaviour seen in the observations. Finally, in Section 4.3, we study the simulated occurrence of new climate records later in the 21st century. In this part we include, in addition to record-high temperatures, also the occurrence of new (high and low) precipitation records, which is excluded from the earlier parts because of worse availability of observational data. In our model-based analysis, we present, on one hand, 'best estimates' of the future evolution (as represented by multimodel mean results), but on the other hand, we also aim to give some idea of the uncertainty associated with differences between climate models and internal climate variability. However, we do not address in this study the sensitivity of our findings to the evolution of future greenhouse gas emissions, which is expected to be small in the next few decades but would become significant in the second half of the 21st century (see Meehl et al., 2007a). Rather, we focus on a single, 'middle-of-line' emission scenario, SRES A1B.

2. Data

We used temperature data from the CRUTEM3v analysis (Brohan et al., 2006), which covers the years from 1850 to 2006, with monthly time resolution. The observations are gridded to a 5° × 5° latitude–longitude grid. However, the time-series of this data are not complete. In large parts of Africa, in particular, observations are only available from the middle of the 20th century, and there are also gaps of varying length in the end of the 20th and the beginning of the 21st century. Similar problems are common in large areas in Asia and South America.

For studying temperature and precipitation records in climate models, we used coupled atmosphere ocean general circulation model simulations from the third Coupled Model Intercomparison Project, CMIP3 (Meehl et al., 2007b). Data for 22 models are used (the 21 models listed by Räisänen, 2007, and BCCR-BCM2.0, Bjerknes Centre for Climate Research, University of Bergen, Norway). For each model, we used one simulation covering the 20th century climate in coupled models (20C3M) and forced by a mixture of anthropogenic forcing factors and (in 15 of the 22 models) variations of solar and/or volcanic activity and one simulation of the 21st century climate. For the 21st century, scenario simulations based on the SRES A1B emission scenario (Nakićenović and Swart, 2000) were used. In terms of the greenhouse gas emissions and resulting global mean warming, A1B is in the mid-range of the SRES scenarios. The CMIP3 data set also includes simulations for the B1 (lower) and A2 (higher greenhouse gas emissions), but these are available for a smaller set of models. By combining the time-series for the 20C3M and SRES A1B simulations, we obtain continuous time-series covering at least the years from 1901 to 2098.

For analysing the variability in the occurrence of records in a stationary climate, we also use pre-industrial control simulations (PICNTRL), in which all external factors are held constant. Furthermore, to study the sampling variability in the simulated occurrence of records in a climate affected by increasing greenhouse gas concentrations, we use an initial-condition ensemble of seven runs for one individual model, CCSM3.

We used the 5° × 5° latitude–longitude grid of the CRUTEM3v observation data in our analysis. The resolution of the CMIP3 models is somewhat finer, ranging from 1.1° × 1.1° to 4° × 5° among the 22 models (Meehl et al., 2007b). The regridding of model data to this analysis grid was made using area-mean-conserving interpolation, in which the input grid boxes were weighted according to their fractional area coverage within the output grid box. Another interpolation option was also explored (choosing the nearest original model gridpoint value to represent the whole 5° × 5° grid cell), but the sensitivity of our findings to the choice of the interpolation method turned out to be modest.

3. Methods

Because the coverage of the CRUTEM3v dataset is incomplete in space and time, we use in our study only those gridpoints that have a sufficiently complete time-series. We formulated three requirements that the time-series of an individual gridpoint had to fulfill. First, there had to be data at least from 75 yr (in all months) in the time period from 1901 to 2000. Second, there had to be data at least from 15 yr in the period 1981–2000 and, third, at least from 5 yr in the period 2001–2006. The selected gridpoints, which qualified all these three requirements, can be seen in Fig. 1. The first and the second requirements are essential for calculating meaningful maxima of monthly, seasonal and annual mean temperatures in the 20th century. The second requirement is especially important because a large fraction of the 20th century temperature maxima were recorded in the last 20 yr of the century. The third requirement is needed for studying how many temperature maxima of the 20th century were already broken in 2001–2006.

In comparing the model results with the observations (Section 4.2), model-simulated time-series are masked by removing the data at the same points in time and space that are missing in the CRUTEM3v time-series. The remaining data are analysed only from the selected grids described above. This comparison has

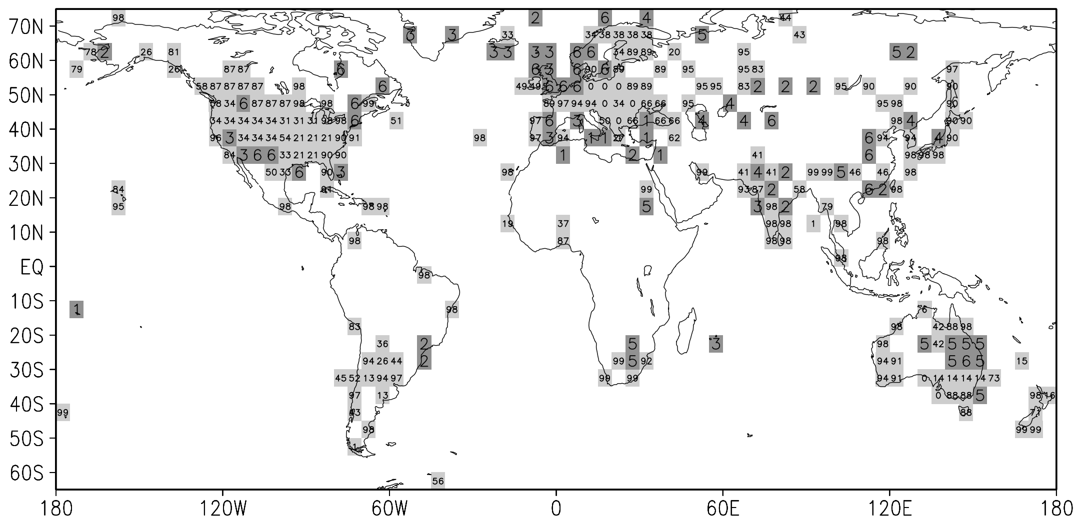

Fig. 1. The years when the highest maximum annual mean temperatures from the period 1901–2006 were observed. Minor size of numbers with light shading indicate the years from 1901 to 2000 and are marked by the numbers 1, 2, . . ., 99, 0. Numbers of larger stature with dark shading represent the years 2001–2006 and are marked by the numbers from 1 to 6.

been made only for temperature and not for precipitation because of worse availability of quality-controlled observational data sets for precipitation. Furthermore, earlier research indicates that the effects of anthropogenic climate change are still much less evident in precipitation than temperature (Hegerl et al., 2007).

In the same section (4.2), we also study whether the observed occurrence of new temperature records in 2001–2006 was outside of what might occur in a stationary climate. The probability that the highest (or lowest) temperature within $N+n$ yr occurs in the latest n yr is $n/(N+n)$, in an unchanged climate. Thus, in that case, about 6% of the record values of 1901–2006 would be expected to occur in 2001–2006 ($N = 100$ and $n = 6$). However, the occurrence of new records is affected by sampling variability, even when the numbers are averaged over a large geographical area. To study this sampling variability, we used the PICNTRL simulations. We chose, if available, for each model the last 212 yr of the PICNTRL simulation, divided this to two 106-year periods and computed how many records of the 106-year period were simulated in the last 6 yr (after applying the observation mask described above). Although the PICNTRL simulations for a few models are shorter than 212 yr, this procedure gave as a total of 40 106-year samples for studying the variability in the occurrence of records in an unperturbed climate.

In Section 4.3, we study how frequently climatic records of the 20th century are broken in simulations of the 21st century climate. Here we include in our analysis the whole global area and use complete simulated time-series from 1901 to 2098. This latter analysis also includes maxima and minima of monthly-to-annual precipitation, in addition to temperature. Along with presenting a number of maps of record value occurrence and geographically averaged numbers (Sections 4.3.1 and 4.3.2), we also provide a more detailed analysis for a few individual grid boxes (Section 4.3.3).

4. Results

4.1. Observed temperature maxima

By using the CRUTEM3v temperature data for the selected grids specified above, we identified, for the whole year, for each four three-month seasons and for each 12 months, the years with the highest and lowest mean temperatures. Figure 1 represents the years when the maximum annual mean temperatures occurred in those grids. In a relatively large number of gridpoints, annual maximum temperatures from the period 1901–2006 occurred between the years 2001 and 2006 (dark shading with large stature in Fig. 1). In total, these gridpoints cover 27% of the analysis area. In most gridpoints (72% of area), the maximum annual temperatures occurred after the year 1980. Studying the regional details, in Europe new annual mean temperature records occurred in 2001–2006 in a large number of grid boxes along the coastlines of the Atlantic Ocean and the Mediterranean Sea. In eastern parts of Australia, the years 2005 and 2006 have been the warmest. In North America, however, the warmest years occurred mostly in the 20th century, for example the year 1987 and some years in the 1930s were commonly the warmest. The latter coincides with a decade characterized by severe heat waves and the famous ‘dust bowl’ drought (e.g. Schubert et al., 2004). Only in some coastal areas and in Arizona, the warmest years occurred in 2001–2006. In most of South America and Africa, observations only become available in the middle of the 20th century, which makes it impossible to estimate reliable temperature records there. The situation is somewhat similar in Asia, but in those scattered gridpoints that qualify for our analysis, the highest annual mean temperatures were quite commonly observed in 2001–2006. It should also be noted that there are gaps in the time-series in many areas; it is possible that some of the records have escaped for that reason.

Minima of annual mean temperature in the time period 1901–2006 occurred nearly everywhere (95% of the area) before 1980. No minimum values occurred in the early 21st century.

The observed occurrence of record values in 2001–2006 (27%) is much larger than the expected value for the occurrence of records in an unchanged climate (6/106 $\approx$ 6%). As shown in the following section, this difference is substantially larger than can be explained by sampling variability.

4.2. Comparison between the observations and model results

To compare the model results with observations, we determined, separately for each model, the area fraction of gridpoints in which the highest monthly, seasonal and annual mean temperatures in 1901–2006 took place between the years 2001 and 2006. Prior to this calculation, the model data were thinned, as described in Section 3, to make the data coverage identical with the CRUTEM3v analysis.

In Fig. 2, we compare the number of monthly temperature records in 2001–2006 (i.e. the number of months, out of 12, in which the record values for the 20th century were exceeded during this period) between the observations (Fig. 2a) and the multimodel mean (Fig. 2b).

It can be seen from Fig. 2a that almost in all Europe, the observed monthly mean temperatures have exceeded the maxima of the 20th century means at least in 1 month and in many places more than in 3 months out of 12, by the end of 2006. The largest number of exceedings (5 or 6 months out of 12) have occurred in coastal areas of the Atlantic Ocean and the Mediterranean Sea, that is, in approximately the same areas where new records of annual mean temperature have been observed in this century (Fig. 1). In Australia, North America and southern South America, typically 1 or 2 months have been warmer in 2001–2006 than ever in the 20th century, but there are also quite many grids where monthly mean temperatures have not exceeded the 20th century maxima in any month, especially in North America. Although there is some correlation between the occurrence of

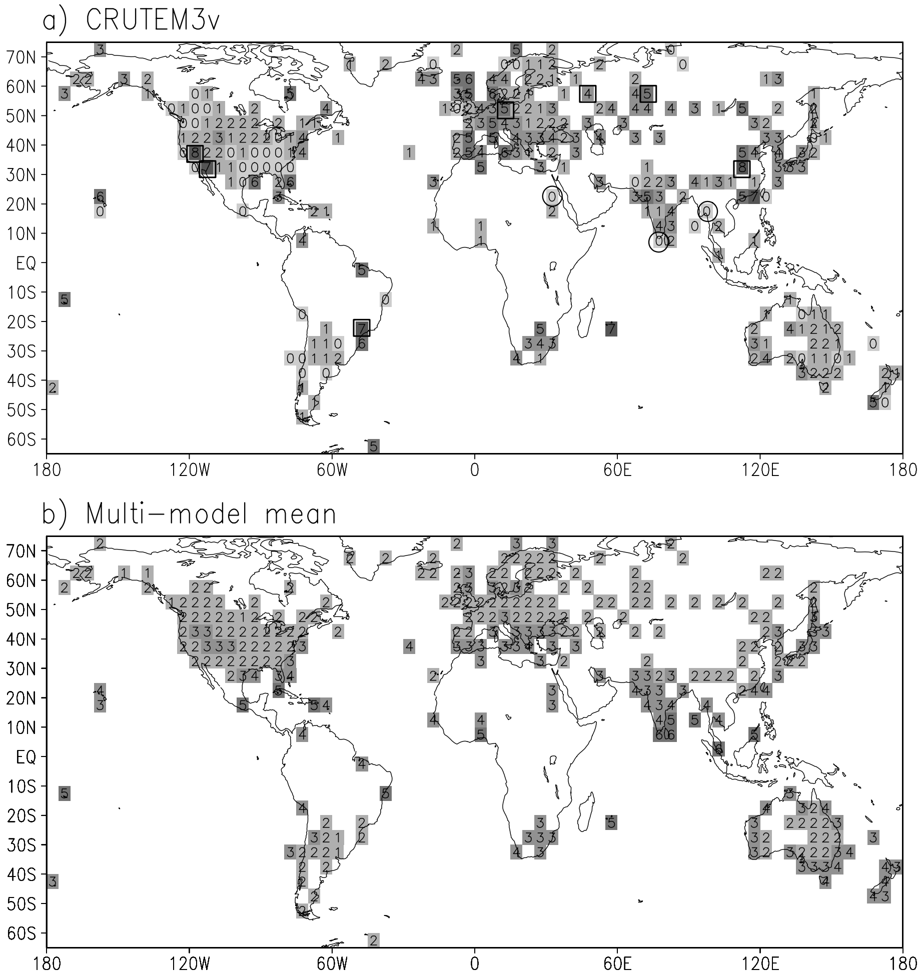

Fig. 2. (a) Number of months (out of 12), in which the observed (CRUTEM3v) monthly mean temperature maxima from the 20th century were exceeded in the years 2001–2006. The squares (circles) indicate the grids where all 22 models simulated a smaller (larger) number of records in this period than was observed. (b) Same as (a) but the numbers represent multimodel means.

new annual mean temperature records (Fig. 1) and the number of new monthly temperature records (Fig. 2a), this correlation is not perfect. For example, although annual mean temperature records were observed in a wide area in eastern Australia in 2005–2006, the number of monthly temperature records in the same area in 2001–2006 was only 1 to 2. Obviously, a year as a whole can be record warm even if this is not the case in any individual month.

Corresponding results for the model simulations are shown in Fig. 2b. In every studied grid, as a multimodel mean, at least one calendar month was warmer in 2001–2006 than ever in the 20th century. Gridpoints where simulated monthly mean temperatures in 2001–2006 exceed the 20th century maxima in 3 or 4 months are mainly located in coastal areas. Only a few grids with five or six exceedings can be found, and all these grids are in low latitudes, in coastal or tropical maritime areas. On the whole, the geographical variation is smaller for the multimodel mean than in observations. However, this is not unexpected, because the averaging over the 22 models smooths out the variations in the individual models. As a geographical average, 2.2 monthly temperature records were exceed in 2001–2006 according to the observations, whereas the same number for the multimodel mean is 2.6, with a range of 1.5–4.2 between the models. A commonality between the observations and the model simulations is that exceedings happened more often in coastal areas. This is likely because interannual temperature variability is smaller along the coasts than further inland, and the probability of occurrence of extremes is therefore more sensitive to the warming of climate in coastal areas (see the discussion in Section 4.3).

Although the number of monthly temperature records differs between the observations and the multimodel mean, the observed number of new records in 2001–2006 is almost everywhere within the range of the model simulations. There are seven grids (marked with squares in Fig. 2a) where the observed number of records exceeds the maximum among the 22 models. Conversely, there are only three grids (marked with circles) where the observed number of records was below the minimum in the models.

We repeated the same analysis for the longer period 1981–2006 and found geographical distributions qualitatively similar to those shown in Fig. 2. The corresponding geographical averages are 6.0 for the observed and 6.8 for the multimodel mean number of new monthly records. For this longer period, however, a larger number of gridpoints were found in which the observed number of records was outside the range of the model simulations. In 8 (23) grids, more (fewer) monthly temperature records were observed in 1981–2006 than occurs in any of the model simulations.

The comparison between the observations and the model simulations is continued in Fig. 3, in which the seasonal cycle of area mean record numbers is studied. The closed circles in Fig. 3 represent the area fraction (%) of the selected gridpoints (within (a) the global area, (b) the Northern and (c) the Southern Hemisphere) where the highest monthly, seasonal and annual maximum temperatures in 1901–2006 were observed between the years 2001 and 2006. The small open circles indicate the individual model values and the large open circle the multimodel mean.

It can be seen from Fig. 3a that there are only four months (January, March, June and July) in which the observed 'global' area fraction of grids with new temperature records in 2001–2006 was larger or about as large as the corresponding multimodel mean value. In the other 8 months and in all four seasons and the annual mean, the observed area fractions are smaller than the multimodel mean. Thus, the models have a tendency

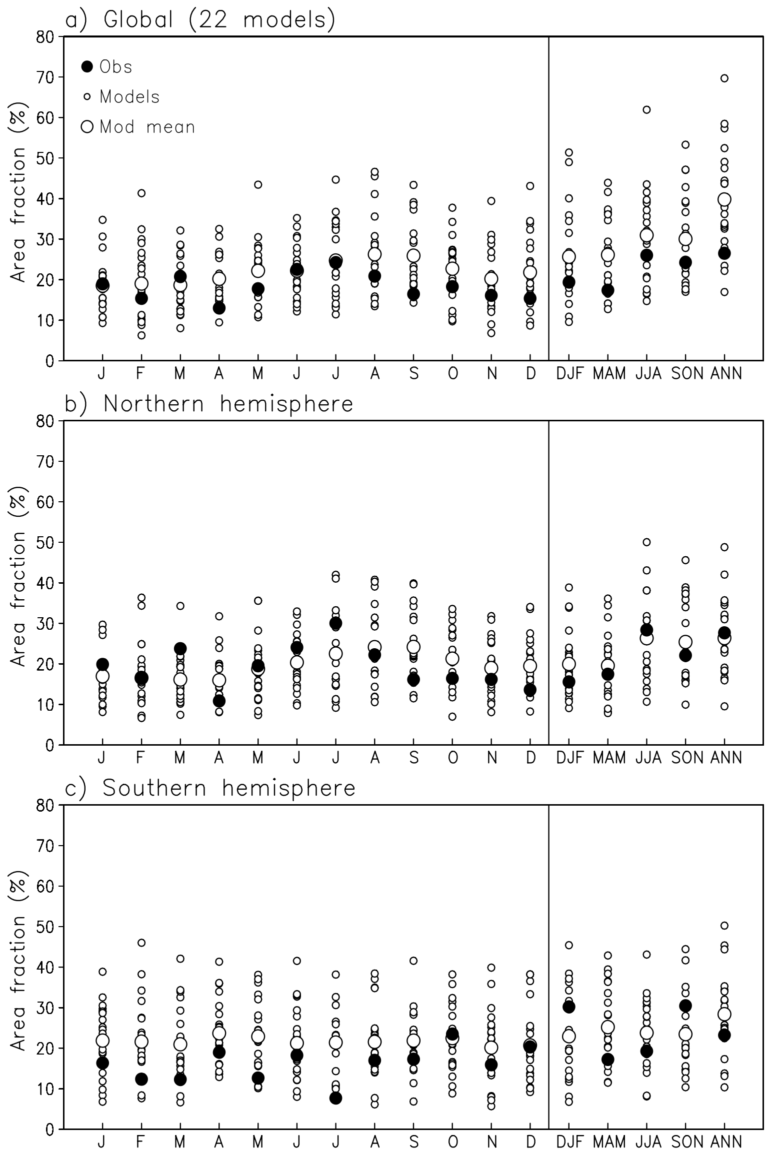

Fig. 3. Area fractions (%) of the selected gridpoints in which monthly, seasonal and annual maximum temperatures of the period 1901–2006 took place between the years 2001 and 2006. Closed circles represent observations and open small (large) circles the values from the 22 models (the multimodel means). (a) includes both hemispheres, (b) the Northern and (c) the Southern Hemisphere.

to oversimulate the number of temperature records during this period. On the other hand, the observed occurrence of temperature records is still within the range of the model simulations. For example, the area fraction of the selected grids where the maximum annual mean temperature of the period 1901–2006 occurred between 2001 and 2006 is 27% in observations and 40% as the multimodel mean, whereas the minimum and the maximum values of the models are 17% and 70%, respectively. There are three models out of the 22 in which the area fraction is less than 27%.

Dividing the analysis to the two hemispheres, the Northern Hemisphere results in Fig. 3b largely resemble the 'global' results in Fig. 3a, obviously because most of our analysis area is in the Northern Hemisphere. However, in the Southern Hemisphere (Fig. 3c) as well, the models mostly overestimate the occurrence of records; only in October, December and Southern Hemisphere summer (DJF) and spring (SON), the multimodel mean values are about as large as the observed values. The observed values are within the range of the model simulations, although the ranges are somewhat wider in the Southern Hemisphere (where the number of grid boxes is relatively small) than in the Northern Hemisphere or the global area.

The tendency of the models to overestimate the recent occurrence of record-high monthly-to-annual mean temperatures also extends to the longer period 1981–2006. For example, the global area fraction (within the analysis area) of grids where the highest annual mean temperature occurred between 1981 and 2006 was 72%, whereas the multimodel mean is 79% with a range of 63%–97% between the individual models.

As mentioned in Section 2, 15 of the models include natural forcing factors (i.e. volcanic and solar activity), whereas the other seven do not (Meehl et al., 2007a). On average, the fraction of area with simulated annual mean temperature records in 2001–2006 is 43% in the models with natural forcing and 34% in the models without natural forcing. The corresponding areas for monthly records are 23% and 20%, respectively. However, the differences between these two model groups are quite small compared with the variability within the groups. According to the Student's *t*-test, the differences between the two model groups are statistically insignificant even at the 10% risk level.

One candidate mechanism for the tendency of the models to overestimate the recent occurrence of record-warm temperatures is internal climate variability, which might have (in principle) reduced the number of observed records. To study the potential importance of this factor, we computed the occurrence of records separately for seven parallel simulations made with the CCSM3 model, which differ only in their initial conditions. It was found (Fig. 4a) that the variation between these simulations was smaller than the variation among the 22 models (implying that genuine intermodel differences also contribute to the scatter seen in Fig. 3) but still substantial enough to be recalled when interpreting the comparison among the models and between the models and the observations. However, internal variability does not appear large enough to fully explain the tendency of CCSM3 to overestimate

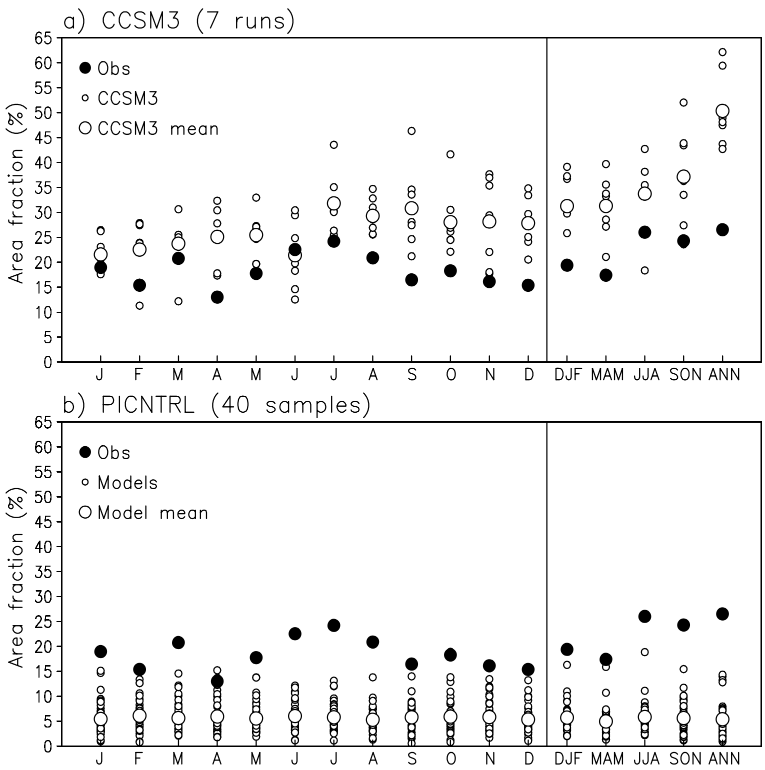

Fig. 4. (a) Same as Fig. 3a but the areas are calculated for seven parallel runs of the model CCSM3 and (b) for 40 samples from the pre-industrial control simulations.

the occurrence of temperature records in 2001–2006, although it should be noted that the overestimate is larger in this model than in the multimodel mean.

Another important question is whether the observed occurrence of new temperature records was exceptional, or whether the large number of records could be explained by internal variability in a stationary climate. To study this, the occurrence of monthly-to-annual temperature records in the last 6 yr of the 40 106-year samples obtained from the PICNTL simulations was computed. The results, shown in Fig. 4b, are unequivocal. Although there is non-negligible variation among the 40 PICNTRL samples around the theoretically expected fraction of 6%, the observed occurrence of records values was, except for April and October, completely above the simulated range. Therefore, we can conclude that the observed number of records that occurred in 2001–2006 was larger than can be explained by pure chance.

As already noted, most models oversimulate the occurrence of monthly-to-annual temperature records in both 2001–2006 and the longer period 1981–2006 (e.g. Fig. 3a). This being the case, it is of interest to study when the simulated number of records (defined here as maxima for the full period 1901–2006) was lower than observed. A decade-by-decade analysis (Fig. 5a) shows that this was the case, in particular, from the 1910s to the 1940s, when fewer than observed monthly temperature records were simulated by all or nearly all models. The difference was particularly marked in the 1930s, which also stands out as a very warm decade in terms of the observed global mean temperature or in the mean temperature calculated over our analysis area (Fig. 5b). In 19 of the 22 models, the mean temperature anomaly of the 1930s was lower than observed.

Nevertheless, differences in area- and time-averaged temperature evolution between the models and the observations only seem to explain partially the corresponding differences in the occurrence of temperature records. For example, although most of the models oversimulate the number of temperature records in 2001–2006, the multimodel mean slightly underestimates the average temperature anomaly during this period. Conversely, the observed occurrence of monthly temperature records in the 1910s was only just within the simulated range, despite no systematic undersimulation of the mean temperature during this period. Thus, we have no full explanation for why the observed frequency of temperature records exceeded the mean number in the models in the early 20th century, whereas the reverse has been true since the 1970s. Potential contributing factors might include regionally significant forcings like land-use change that

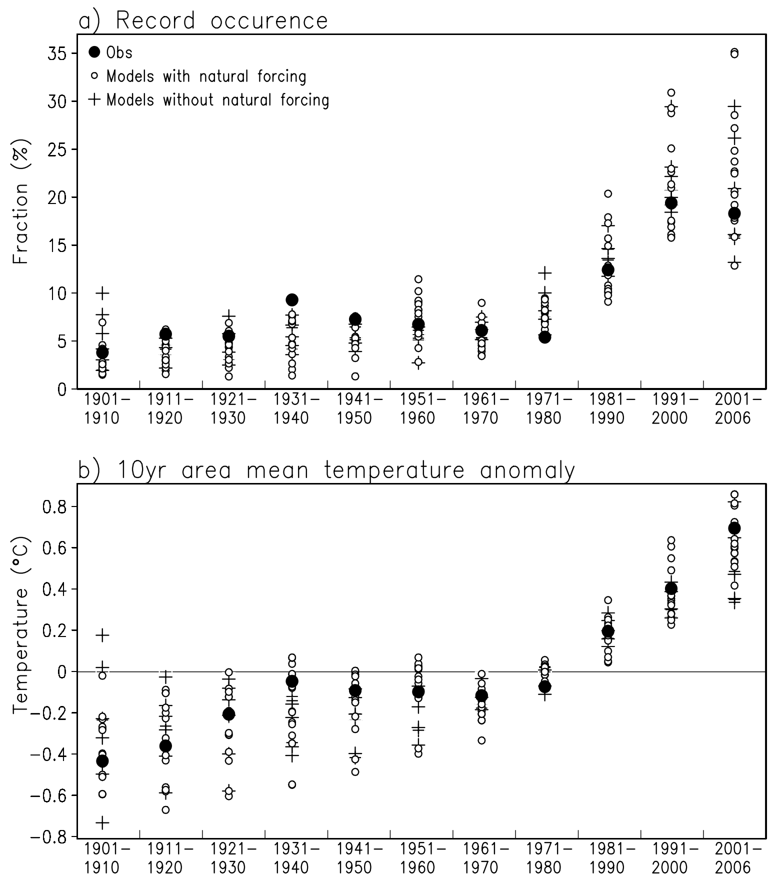

Fig. 5. (a) Observed and simulated fractional (%) occurrence of the monthly temperature records of 1901–2006 as a function of time (as averaged geographically and over the 12 months) and (b) 10-year averages of the area mean temperature anomaly (°C) relative to the mean of 1961–1990. The symbols are explained in the top-left-hand corner of (a).

are missing from the model simulations and also inaccuracy and temporal inhomogeneity of the observational data.

The two model groups with (open circles) and without (plus sign) natural forcing factors are separated in Fig. 5. As noted earlier, there are more records in 2001–2006 in the models with natural forcing, although the difference between the model groups is statistically insignificant. The difference is qualitatively consistent with the fact that the average temperature anomaly (expressed as a deviation from the mean for 1961–1990) in 2001–2006 is higher for the models with (0.6°C) than without (0.5°C) natural forcing. This difference is statistically significant at the 5% level. One possible explanation for this temperature difference is that the volcanic forcing from the Agung (1963) and El Chichón (1982) eruptions cooled the climate in 1961–1990 relative to the beginning of the 21st century, in those models that include this forcing.

4.3. *Occurrence of new record values in simulations of future climate*

In this section, we study how commonly and how soon the 20th century's climate records of annual, seasonal and monthly mean temperature and precipitation are broken in the simulations of the ongoing 21st century. In particular, we focus on the exceedance of the 20th century records by the years 2020, 2050 and 2080. In contrast to the earlier sections, we use in this analysis the whole global area (5° × 5° grid) and complete time-series from 1901 to 2098 for each model. Furthermore, we include both high and low record values of precipitation, in addition to record-high values of temperature. Monthly-to-annual mean temperatures falling below the minima of the 20th century are extremely rare in the simulations of 21st century climate and are therefore not discussed here. Note that to allow a globally complete analysis for both temperature and precipitation, the occurrence of climate records in 2001–2006 is also counted from the model simulations in this section.

4.3.1. Maximum of mean temperature. Figure 6 illustrates the geographical distribution of the multimodel mean number of months (out of 12) in which the simulated 20th century temperature maxima are exceeded within the period 2001–2050. In low latitudes between about 45°S and 40°N, monthly mean temperatures are as a multimodel mean simulated to exceed their 20th century maxima in 11 or even 12 months out of 12. In Antarctica and surrounding sea areas, as well as in the northwest North Atlantic, the average exceedance number is less than 9 (locally down to 6) months out of 12. In the northwest North Atlantic area, six of the 22 models simulate decreasing mean temperature during the 21st century, most probably as a result of the weakening of the thermohaline circulation in these model simulations, which explains the relatively low number of new temperature records there. Elsewhere in northern high latitudes, exceedings can be found in 9 or 10 months out of 12 by the end of 2050. The geographical distribution seen in Fig. 6, with the largest number of new monthly temperature records in low latitudes, concurs with the analysis of Kharin et al. (2007) for daily temperature extremes. These authors found that within the CMIP3 ensemble, the return period for daily maximum temperatures that exceed the present-day 20-year return value shortens in the 21st century most strongly in the tropics.

To understand the geographical distribution in Fig. 6, Fig. 7a shows the simulated multimodel mean annual average warming between the 20th century and the period 2031–2050, whereas Fig. 7b gives the interannual standard deviation of simulated monthly mean temperatures, as calculated from detrended 20th century time-series and based on variances averaged over the 22 models and the 12 calendar months. If the occurrence of new temperature records was primarily determined by the distribution of the time mean warming, then the largest number of new records would be expected over the extratropical Northern-Hemisphere continents and the Arctic Ocean, in stark contrast with the actual distribution seen in Fig. 6. However, the magnitude of interannual temperature variability, which determines

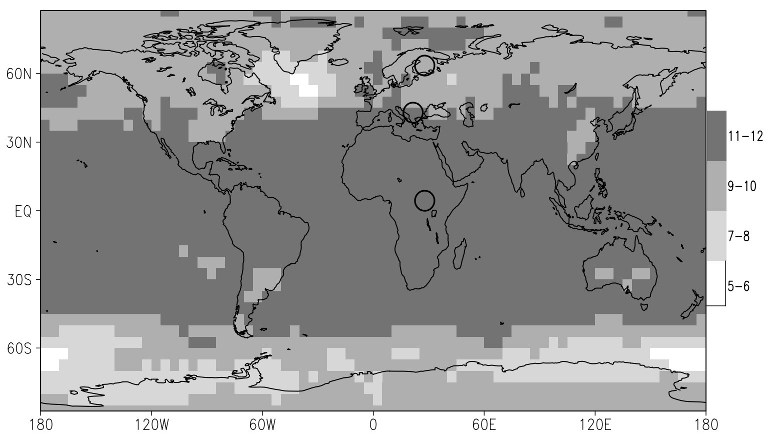

Fig. 6. Multimodel mean number of months (out of 12) in which the highest monthly mean temperature exceeds the 20th century's maximum by the end of 2050. The grids marked by circles indicate the three places that are investigated more closely in Fig. 9 and in Section 4.3.3.

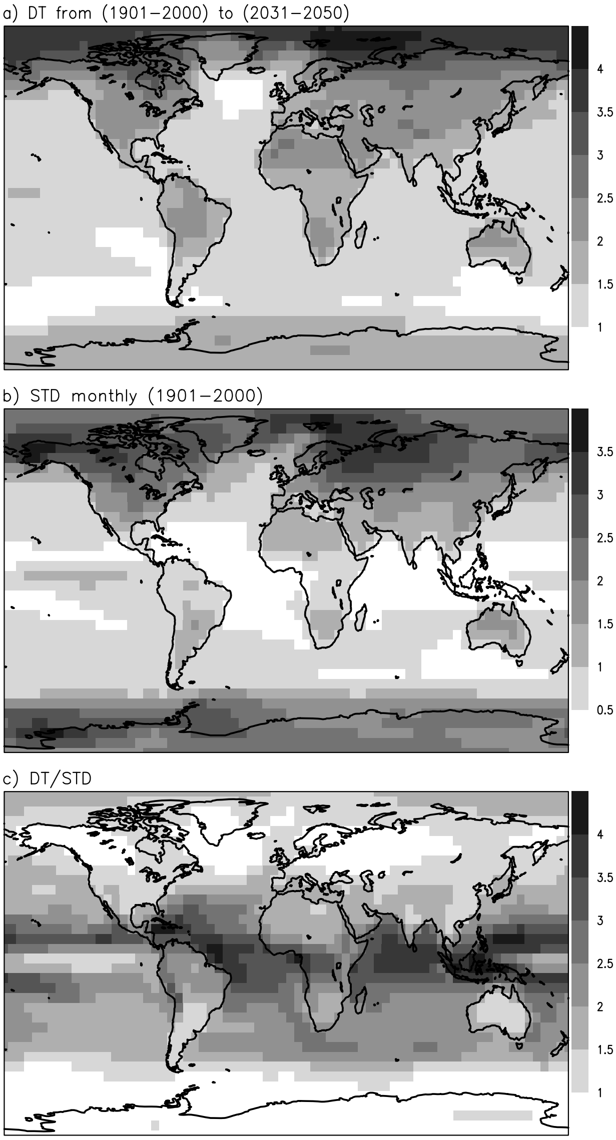

Fig. 7. Multimodel mean of (a) annual mean temperature change (°C) from 1901–2000 to 2031–2050 and (b) average interannual standard deviation of monthly mean temperatures in 1901–2000. Panel (c) represents the ratio between (a) and (b).

Table 1. Multimodel means of the fractions (%) of global area in which the highest monthly, seasonal and annual mean temperatures are above their maxima of the 20th century in at least 1 yr within the years 2001–2020, 2001–2050 and 2001–2080

	2020	2050	2080
Jan	61 (46–83)	89 (80–98)	97 (91–100)
Feb	60 (41–81)	89 (76–97)	96 (90–100)
Mar	61 (44–82)	89 (78–99)	96 (91–100)
Apr	62 (48–83)	90 (80–98)	97 (93–100)
May	65 (51–84)	92 (80–99)	97 (95–100)
Jun	65 (50–85)	92 (83–99)	97 (94–100)
Jul	67 (54–88)	92 (84–99)	97 (94–100)
Aug	67 (50–87)	92 (86–98)	97 (95–100)
Sep	66 (53–85)	92 (86–98)	97 (94–100)
Oct	65 (50–84)	92 (83–98)	97 (94–100)
Nov	63 (47–85)	91 (82–98)	97 (94–100)
Dec	63 (45–84)	91 (81–98)	97 (94–100)
DJF	68 (51–89)	93 (83–99)	98 (94–100)
MAM	69 (55–88)	94 (85–100)	98 (95–100)
JJA	73 (57–93)	95 (87–100)	99 (97–100)
SON	72 (58–90)	95 (89–99)	98 (95–100)
ANN	80 (61–97)	97 (91–100)	99 (96–100)

Note: The range between the 22 models is given in parenthesis.

(inversely) the sensitivity of record value occurrence to the time mean temperature change, decreases sharply from high to low latitudes (Fig. 7b). As a result, the ratio between the mean change and the interannual standard deviation is actually higher in tropical than in extratropical latitudes (Fig. 7c), as is the occurrence rate of new monthly temperature records in these simulations.

By the end of the 21st century, the simulated 20th century temperature maxima are in most models exceeded in all 12 months of the year in an area between about 45°S and 45°N (not shown). Almost everywhere else, this happens at least in 10 months out of 12 (the northwestern North Atlantic is again an exception).

Fractions of the global area (%) in which simulated monthly, seasonal and annual mean temperatures exceed the corresponding maxima of the 20th century by the end of the years 2020, 2050 and 2080 are presented in Table 1. The first numbers are multimodel means and the range among the individual models is shown in parentheses. By the end of 2020, in all individual months the multimodel mean areas are between 60% and 68% of the global area. By the end of 2050, the areas are about 90% and by the end of 2080 at least 96%. Intermodel differences are substantial, with a full range of 30%–40%, in 2020, but they are reduced later when the occurrence of records in all models begins to approach 100%.

On average, new temperature records are simulated slightly more frequently (or earlier) in the Northern Hemisphere summer months than in the Northern Hemisphere winter. As summed over June, July and August, the average simulated number of records by the year 2020 is 2.00 in the Northern and 1.97 in the Southern Hemisphere, whereas the corresponding sums for December, January and February are 1.79 in the Northern and 1.87 in the Southern Hemisphere. Thus, a difference to the same direction occurs in both hemispheres, but it is larger in the Northern Hemisphere. One contributor to this difference is the much larger interannual temperature variability in the Northern Hemisphere extratropical continents in winter than in summer, which reduces the occurrence of new temperature records in winter, despite a maximum in the simulated time mean warming in this season. However, a more detailed regional analysis reveals variations in the seasonal distribution of record occurrence within both hemispheres (not shown).

The areas in which seasonal mean temperatures exceed the 20th century's maximum are slightly larger than the corresponding monthly values, and annual values are even larger, being in the multimodel mean 80% (2020), 97% (2050) and 99% (2080). This is as expected, because the increasing averaging from monthly to seasonal and annual timescales leads to a decrease in interannual variability. Thus, the occurrence of seasonal and annual mean temperature records is more sensitive to the simulated time mean warming than the occurrence of monthly records.

4.3.2. Maximum and minimum of mean precipitation. Multimodel mean numbers of months (out of 12) in which monthly mean precipitation falls below the minimum of the 20th century by the end of 2050 is shown in Fig. 8a. A striking but trivial detail is the lack of new records in Sahara, where precipitation minima of the 20th century are zero in nearly all months in nearly all models, and the corresponding monthly minima of the period 2001–2050 can therefore not fall below them. From the geographical distributions elsewhere, we can see that in broad regions surrounding the horse latitudes around 30°N and 30°S, monthly mean precipitation amounts fall below the minima of the 20th century in 4–6 months and in some areas even in six to eight months out of 12. In other regions, record-low precipitation is simulated to occur in less than four months. Note that, in an unchanged climate and neglecting cases of zero precipitation, one would, on average, expect four of the 12 minima for a 150-year period to occur during its last 50 yr. The actual distribution in Fig. 8a shows that this expectation is exceeded in wide areas in the subtropics and lower mid-latitudes, whereas the reverse is true in high latitudes and parts of the tropics.

The number of months with monthly precipitation exceeding the maximum of the 20th century by the end of 2050 (Fig. 8b) is, on average, larger than the number of months below the minimum. The largest number of exceedings, from 6 to 8 out of the 12 months, occurs in northern and southern high latitudes and the smallest number (locally down to two or three months) of

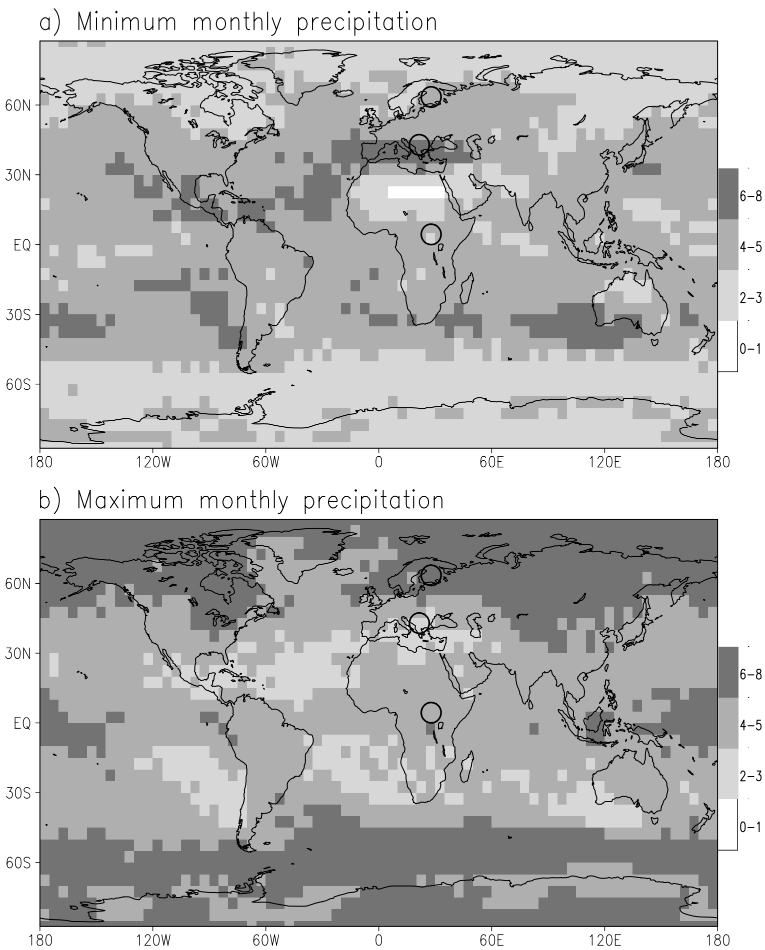

Fig. 8. Same as Fig. 6 but for monthly precipitation amount (a) below the minimum and (b) above the maximum of the 20th century.

Table 2. Multimodel means of the fractions (%) of global area in which the lowest and the highest monthly, seasonal and annual mean precipitation amounts are below their minima (leftmost numbers in columns) and above their maxima (rightmost numbers) of the 20th century in at least 1 yr within the years 2001–2020, 2001–2050 and 2001–2080

	2020		2050		2080	
	MIN	MAX	MIN	MAX	MIN	MAX
Jan	17 (14–21)	21 (17–24)	35 (29–41)	41 (35–47)	45 (36–54)	55 (47–60)
Feb	18 (14–23)	20 (14–27)	35 (29–42)	40 (31–47)	46 (38–53)	53 (43–60)
Mar	17 (14–24)	19 (17–24)	34 (27–41)	40 (33–47)	46 (36–53)	54 (44–62)
Apr	18 (14–21)	19 (15–24)	35 (31–41)	40 (35–44)	46 (41–53)	54 (49–59)
May	18(13–20)	19 (17–23)	35 (27–41)	40 (32–47)	46 (38–56)	53 (44–61)
Jun	19 (15–24)	20 (17–23)	37 (31–44)	39 (33–45)	48 (41–57)	53 (45–59)
Jul	18 (15–22)	20 (17–26)	36 (29–41)	40 (34–46)	48 (38–55)	53 (46–59)
Aug	19 (15–23)	19 (16–23)	37 (33–42)	39 (33–46)	48 (43–55)	52 (44–60)
Sep	18 (15–22)	19 (15–24)	36 (32–43)	39 (31–44)	47 (41–56)	52 (41–58)
Oct	17 (15–19)	20 (15–24)	35 (29–42)	40 (34–46)	45 (37–54)	53 (46–60)
Nov	17 (13–20)	21 (17–24)	34 (26–40)	41 (34–46)	44 (36–53)	55 (47–60)
Dec	18 (15–21)	21 (18–26)	35 (30–40)	41 (38–51)	45 (37–52)	55 (49–63)
DJF	18 (13–22)	23 (13–29)	35 (29–43)	44 (34–53)	45 (38–52)	57 (46–66)
MAM	18 (14–25)	21 (18–27)	35 (29–40)	42 (36–48)	45 (38–51)	56 (47–62)
JJA	19 (13–23)	21 (17–26)	37 (29–43)	42 (35–48)	47 (37–55)	55 (47–60)
SON	18 (14–23)	22 (17–27)	35 (28–42)	42 (33–48)	45 (36–53)	56 (44–62)
ANNUAL	18 (14–21)	24 (17–33)	34 (27–41)	47 (36–54)	43 (34–52)	60 (49–65)

Note: The range between the 22 models is given in parenthesis.

them around 30°N and 30°S. This distribution is nearly a mirror image of the number of record dry months. In areas poleward of 50°N and 50°S, the maximum precipitation in at least 9 of the 12 months is simulated to exceed the maxima of the 20th century by the end of the 21st century, as a multimodel mean (not shown).

The distributions seen in Figs. 8a and b are consistent with the changes in time mean precipitation as simulated by the same models (Meehl et al., 2007a). New record-wet months are simulated most commonly in areas with increasing time mean precipitation, particularly in high latitudes and parts of the tropics, whereas the areas with the largest number of record-dry months in the subtropics and lower mid-latitudes are also simulated to experience a decrease in mean precipitation. This concurs with the analysis of Räisänen (2005), who found that changes in monthly-to-annual timescale precipitation extremes in the CMIP2 data set were primarily controlled by changes in the mean precipitation and only secondarily by changes in interannual variability. The seasonal distribution of record value occurrence also tends to follow the changes in mean precipitation. For example, in northern mid-latitudes where the mean precipitation is simulated to increase in winter but to change little or even decrease in summer, wet records occur more often in winter than in summer, whereas dry records are more common in summer.

Global statistics of the exceedance of the 20th century precipitation records are given in Table 2. In an unchanged climate and neglecting cases with zero precipitation, one would, on average, expect 17% of the 20th century records being broken by the year 2020, 33% by the year 2050 and 44% by the year 2080. The actual multimodel mean numbers for monthly precipitation minima are quite close: during the period 2001–2020 from 17% to 19%; during 2001–2050 from 34% to 37% and during 2001–2080 from 44% to 48% (leftmost numbers of each column in Table 2). The corresponding seasonal and annual values are similar. Intermodel differences in these globally averaged numbers are only 4%–10% in 2020, but increase to 9%–18% later.

Average fractions of the global area in which individual monthly mean precipitation amounts exceed the maxima of the 20th century within the period 2001–2020 are about 20%, within the period 2001–2050 about 40% and within the period 2001–2080 more than 50% (rightmost numbers of each column in Table 2). Again, intermodel differences increase slightly with time. Seasonal and annual values are similar to or a few percentage units higher than the corresponding monthly values, and the range between the models is widest in winter. Thus, globally averaged and as a multimodel mean, new high records of monthly-to-annual precipitation occur more frequently than new low records and more frequently than would be expected in an unchanged climate.

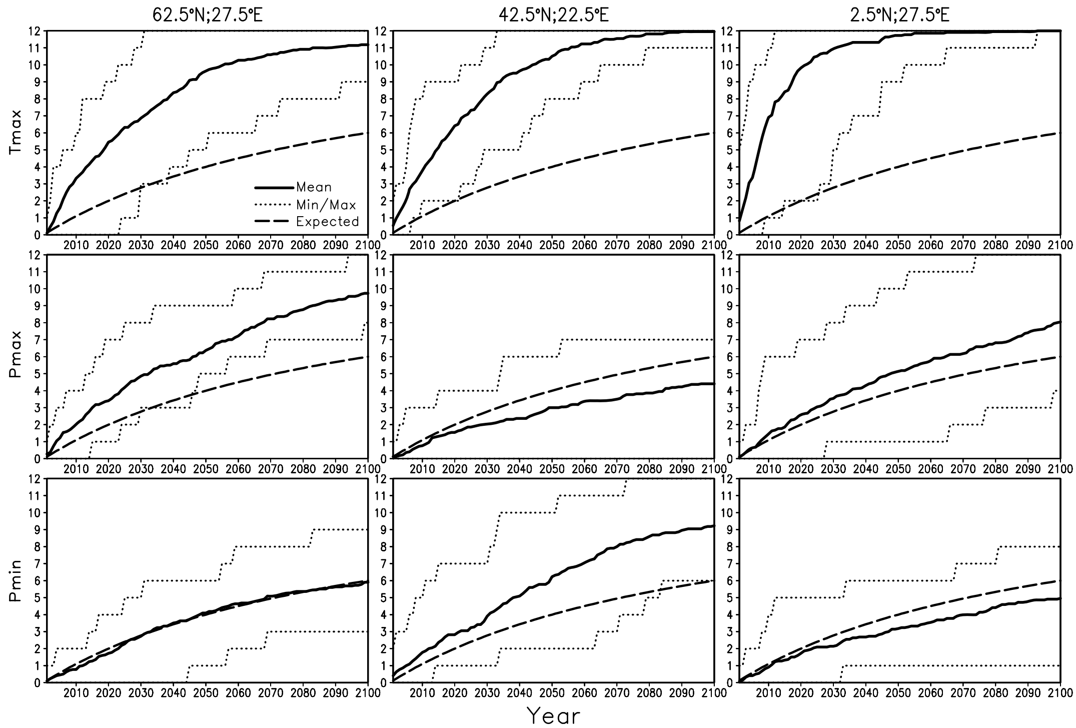

Fig. 9. Local multimodel means (solid lines) and intermodel ranges (dotted lines) for the number of months in which the highest mean temperature (top) and the highest and the lowest monthly precipitation (middle and bottom) are simulated to break the records of the 20th century between the year 2001 and the year on the *x* axis. The expected number of new records in an unchanged climate, which is the same in all panels, is indicated by the dashed lines. Left-hand column: Finland (62.5°N, 27.5°E), mid-column: the Balkan Peninsula (42.5°N, 22.5°E), right-and column: Congo (2.5°N, 27.5°E).

4.3.3. Examples for some locations. In this section, we study how commonly, and how soon, the monthly mean temperature and precipitation records of the 20th century are simulated to be broken in the ongoing 21st century, in three individual locations with different types of climate. We choose the following grids for a closer inspection: the first one in Finland, in Northern Europe (62.5°N, 27.5°E), where the climate is boreal with snowy and cold winters, the second one in the Balkan Peninsula, in Southern Europe (42.5°N, 22.5°E), which belongs to Mediterranean temperate climatic zone, and the third in the Democratic Republic of the Congo, in Africa (2.5°N, 27.5°E), which is characterized by tropical rain forest climate.

The multimodel mean number of monthly temperature records (solid lines in the first row in Fig. 9) increases fast in the African gridpoint. As early as in the ongoing decade, on average, 6 and by the year 2030, 11 of all 12 monthly records of the 20th century are simulated to be broken. As indicated by the range of the model simulations, shown by the dotted lines, all 12 monthly temperature records in this location are broken in all 22 models by the end of the 21st century. In the gridpoint in the Balkan Peninsula, the increase in the multimodel mean number is clearly slower but, in nearly all models, all of the 12 monthly temperature records are simulated to exceed their maxima of the 20th century by the end of the 21st century. In Finland, where natural interannual temperature variability is larger, the increase in the number of simulated monthly temperature records is slower, and on average, one of the 12 20th century records survives to the end of the 21st century.

The simulations indicate that the monthly precipitation amounts will exceed their 20th century maxima more likely in Finland than in the other two places (mid-row, in Fig. 9). The multimodel mean number of record-wet months reaches almost 10 by the end of the 21st century in Finland, and the uncertainty range implied by the variation between the models is quite narrow compared with Balkan and Congo. In Congo, the average number reaches 8 and in Balkan only 4 out of 12 months. In Balkan, the highest individual simulated value is 7 record-wet months by the end of the century and the lowest value is zero, which means that none of the 12 monthly 20th century precipitation maxima is exceeded in the 21st century simulation. In Congo, the uncertainty range is much wider than in Finland, for example, in the middle of the century, the highest model value is 10 and the lowest is 1 month out of 12.

The multimodel mean number of record-dry months by the end of the 21st century exceeds 9 in the Balkan Peninsula and is about 6 in Finland and 5 in Congo. Even in the areas (e.g. in

Finland) where precipitation amounts will increase according to the models, in all likelihood some individual months will still be record dry.

All panels in Fig. 9 also include the expected number of new monthly records in an unchanged climate, which reaches four by 2050 and six by the end of the century. The simulated occurrence of record-warm months is much higher. In all three locations and all 22 models, the expected value is continuously exceeded, beginning from the year 2040 at the latest. In Finland, the number of record-wet months also exceeds the expected value in all models beginning from the year 2046. In the other cases, the differences between the simulations and the expected value are less systematic. Thus, although the multimodel mean number of simulated record-wet months is larger (smaller) than the expected value in Congo (the Balkan Peninsula) and the opposite is true for record-dry months, the range of the simulations extends almost invariably to both sides of the expected value.

5. Summary

In this study, we have focused on the occurrence of new monthly-to-annual timescale temperature and precipitation records in a warming world. Using temperature observations, we first examined how many annual, seasonal and monthly mean temperature records of the 20th century have already been broken in the beginning of the 21st century. To explore how well climate models are able to reproduce the behaviour seen in the observations, the same calculation was also made for an ensemble of climate model simulations. Finally, we used these model simulations to examine what is likely to happen to the 20th century's climate records in a warmer future climate. In addition to exceedings of the 20th century temperature maxima, we studied how commonly, and how soon, the low and high records of monthly, seasonal and annual mean precipitation of the 20th century are broken in model simulations of the 21st century climate. Our main findings are presented below.

5.1. Comparison between observations and model simulations

Observed annual temperatures in the time period 1901–2006 reached their maxima during the years 2001–2006 in 27% of our analysis area (defined in Section 3). The corresponding multimodel mean for the 22 CMIP3 models is 40%, with a range of 17%–70% between the individual models. Although new temperature records have been observed somewhat less commonly in the early 21st century than they occur in most model simulations, the observed number of records has also been much larger than what could be explained by internal variability in an unchanged climate.

In Europe, a large number of the monthly temperature records of the period 1901–2006 occurred in 2001–2006: in coastal areas of the Mediterranean Sea and the Atlantic Ocean, in 5 or 6 months out of 12. In North America, Asia and Australia, however, only a few $5^\circ \times 5^\circ$ grids can be found with four or more new monthly temperature records in the same years. In North America, there are also large areas where none of the 12 monthly temperature maxima of the period 1901–2006 occurred in the first 6 yr of this century.

The observed geographically averaged number of new monthly temperature records in 2001–2006 was 2.2 and the corresponding simulated multimodel mean is 2.6, with a range of 1.5–4.2 between the models. The geographical variation is naturally smaller for the multimodel mean than the observations, due to the averaging over the 22 models. However, in agreement with observations, the gridpoints where monthly mean temperatures in this period most frequently exceed the 20th century maxima are generally located in coastal areas, also in the model simulations.

Unfortunately, the observational time-series are incomplete and do not cover the whole global area. Thus, our study could not reach out everywhere, not even in all land areas.

5.2 Occurrence of new record values in simulations of future climate

In the model simulations for the SRES A1B scenario, the multimodel mean fraction of the global area where the annual mean temperature has exceeded its maximum of the 20th century is 80% by the year 2020, 97% by 2050 and 99% by 2080. The corresponding areas for individual monthly and seasonal temperature exceedings are slightly smaller, but still high. For example, on average 97% of 20th century monthly temperature maxima are exceeded in the models by the year 2080.

The largest number of new monthly temperature records (in 11 or 12 months by the year 2050) is simulated in low latitudes, where interannual temperature variability is modest. At the other extreme, less than nine and locally down to six exceedings of the 20th century monthly maxima are simulated by the end of 2050 near the coast of Antarctica and northwest Atlantic Ocean, where the warming in the models is relatively slow or (in some models) locally non-existent.

The multimodel mean fraction of the global area where annual precipitation amount falls, at least once, below its minimum of the 20th century by the end of 2020 (2050 and 2080) is 18% (34% and 43%). The corresponding monthly and seasonal values are similar. The multimodel mean fraction of the global area where the annual mean precipitation exceeds the 20th maximum by the end of 2020 (2050 and 2080) is 24% (47% and 60%). Monthly and seasonal values are a few percentage units smaller.

The multimodel mean number of months in which monthly precipitation falls below its minimum of the 20th century by the end of 2050 is highest, between 4 and 6 months, in broad regions surrounding the horse latitudes. In the tropics and high latitudes, this number is generally below four. This is consistent with the distribution of the time mean precipitation changes in the models, with a general decrease in precipitation in the subtropics and lower mid-latitudes and a general increase in other areas. Conversely, 20th century record high monthly precipitation totals are exceeded more commonly in the areas where the mean precipitation increases than where it decreases: by 2050 in 6–9 months out of 12 in high latitudes but in only 2 or 3 months around 30°N and 30°S.

Finally, we showed three examples of the variation of the cumulative distributions that characterize the simulated timing and occurrence of new temperature and precipitation records in individual locations. Although a considerable number of new annual and monthly mean temperature maxima will likely occur in all these locations already in the next few decades, the probable timing is substantially affected by the amplitude of natural interannual temperature variability. Thus, for example, new temperature records are simulated to occur sooner in Congo than in Finland, despite the fact that the simulated time mean warming is larger in the latter location (e.g. Fig. 7 and Meehl et al., 2007a).

Changes in low and high records of monthly-to-annual precipitation are strongly dependent on the changes in mean precipitation. In the Mediterranean area, where the models simulate decreasing mean precipitation, cases with record-high precipitation occur quite infrequently in the 21st century simulations, whereas cases with record-low precipitation are much more common. In contrast, in Finland, where the models simulate increasing mean precipitation, the high records are more likely to be broken than the low records.

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