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Global warming and changes in drought

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Several recently published studies have produced apparently conflicting results of how drought is changing under climate change. The reason is thought to lie in the formulation of the Palmer Drought Severity Index (PDSI) and the data sets used to determine the evapotranspiration component. Here, we make an assessment of the issues with the PDSI in which several other sources of discrepancy emerge, not least how precipitation has changed and is analysed. As well as an improvement in the precipitation data available, accurate attribution of the causes of drought requires accounting for natural variability, especially El Niño/Southern Oscillation effects, owing to the predilection for wetter land during La Niña events. Increased heating from global warming may not cause droughts but it is expected that when droughts occur they are likely to set in quicker and be more intense.

How is drought changing as the climate changes? Several recent papers in the scientific literature have focused on this question but the answer remains unclear. Here we attempt to understand this socially and ecologically relevant topic. We discuss what the expectations for changes in drought should be, and thus the prospects for the future, and we provide some recommendations for resolving outstanding issues.

What is drought?

As mentioned in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), "in general terms, drought is a 'prolonged absence or marked deficiency of precipitation', a 'deficiency of precipitation that results in water shortage for some activity or for some group' or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance'." The report[1] goes on to note that "drought has been defined in a number of ways. 'Agricultural drought' relates to moisture deficits in the topmost one metre or so of soil (the root zone) that impacts crops, 'meteorological drought' is mainly a prolonged deficit of precipitation, and 'hydrologic drought' is related to below-normal streamflow, lake and groundwater levels." These differences emphasize the relative roles of precipitation, evapotranspiration (ET) and runoff in drought caused by climatic factors. More generally, water availability is a societal and environmental concern, which also brings in the demand side, and thus there are other possible definitions related to water scarcity. The IPCC SREX report[2] includes a valuable discussion of drought or 'dryness', drought drivers and drought indices that complements that given here.

Drought can be quantified and described in absolute terms (such as the amount of soil moisture or lake levels) or through relative measures (for instance, PDSI in various forms), and these can be compared[3,4]. Because drought is defined by one tail of the probability distribution function of a drought measure, such as soil moisture content or stream flow, a small reduction in the mean (for example, −5%) will translate into a much larger increase in drought frequency based on other drought definitions[5]. Consequently, this difference has caused some confusion regarding the magnitude of drought changes, and using the percentiles of soil moisture or streamflow instead of mean values to define drought and its changes may represent a better approach in this case.

With human-induced climate change from increased CO_2 and other heat-trapping gases in the atmosphere — global warming — there is the strong expectation of a general increase in potential ET (PET) that is directly related to the increase in surface heating. This will probably result in an increase in actual evaporation, or evapotranspiration in plants, only if adequate moisture is available. So potentially there is more drying, but in drought situations part of any extra energy goes into raising temperatures, thereby amplifying warming over dry land. This also assumes other things remain equal. Of course they do not. Between 1900 and the present, other variations (including unforced natural changes in surface humidity and wind speed) have been important for the apparent drying trend. Nevertheless, climate model projections suggest that drying would occur over many areas in low- and mid-latitudes under increasing greenhouse gas (GHG) concentrations[5–10]. More specifically, there is a strong tendency for the wet areas to get wetter and dry areas to get drier, with a poleward expansion of the subtropical dry zones[11]. Model projections, however, do not show large systematic long-term trends in relative surface humidity and wind speed in response to long-term GHG forcing.

For the most part, droughts over recent years seem to be natural in terms of where and when they occur[10,12]. That is to say, the anthropogenic factors of climate change are not yet important in the location and timing of droughts. But when they do occur, it is expected that the extra heat from global warming will increase the rate of drying, establishing drought more quickly and with greater intensity. Meanwhile, where it rains, it will rain harder because a warmer atmosphere can hold more moisture[11,13]. Australia is just one location where it is clear that drought and heat go together and both have increased from both human and natural causes[14–16].

These are the most basic expectations for changes in drought as the climate changes. But changes in atmospheric circulation that affect moisture regimes can also occur and there is evidence that some are underway: an expansion of the tropics, a poleward shift in the main storm tracks in mid-latitudes[11] and/or changes in the

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seasonality of rains[1]. Moreover, this pattern is predicted in climate models[1,2,6–9]. Yet it is still early days to be seeing such a pattern distinctly and indeed there is sufficient variability in the atmospheric circulation to mask these changes in many places[17], although the model-predicted change in seasonal precipitation seems to be evident in observations[18]. Furthermore, changes in the character of precipitation to more intense heavy rains but longer dry spells, as observed and expected[19], mean that more water runs off leaving less behind to replenish soil moisture.

Disparate results

Two recent papers looked at the question of whether large-scale drought has been increasing under climate change. A study in *Nature* by Sheffield *et al.*[20] entitled 'Little change in global drought over the past 60 years' was published at almost the same time that 'Increasing drought under global warming in observations and models' by Dai[5] appeared in *Nature Climate Change* (published online in August 2012). How can two research groups arrive at such seemingly contradictory conclusions?

The essence of the study by Sheffield *et al.* is that a traditional metric of drought based on historical meteorological observations — the PDSI —is flawed in its original formulation. The authors explore a differently formulated version that results in "little change in drought over the past 60 years" in contrast to other conclusions that used the conventional PDSI. However, the differences between the results obtained by Sheffield *et al.*[20] and Dai[5] are not that great. Sheffield *et al.*[20] are not the first to conclude that the conventional PDSI is flawed and requires careful interpretation. Two earlier papers reported results using exactly the same PDSI formulation but with varying results[4,21]. So there are obvious reasons to be cautious in making conclusions about how drought is changing globally. However, to understand the difficulties and uncertainties it is necessary to review some of the basics about drought metrics and the PDSI in particular.

Fundamentally, drought relates to the amount of water available in soils or hydrological systems. It obviously depends a lot on precipitation, but it also depends on how much water infiltrates to deeper ground layers or runs off the land and how much is evaporated or transpired by plants (that is, ET). As noted in the Fourth Assessment Report[1] "The most commonly used index of drought is the PDSI that uses precipitation, temperature and local available water content data to assess soil moisture." The air temperature controls the water-holding capacity of the atmosphere, and thus influences the atmospheric demand for moisture, which strongly influences ET. The latter also depends on surface humidity and wind, which affect whether the moisture is carried away or not. The PET depends on the available energy from the sun or downwelling infrared radiation, wind speed, and cloudiness, and its realization depends on available moisture.

Issues with ET and baseline period

Several drought indices, such as the Standardized Precipitation Index (SPI; ref. 22) are based on precipitation alone and provide a measure only for water supply. They are very useful as a measure of precipitation deficits or meteorological drought, but are limited because they do not deal with the ET side of the issue. The concept of the SPI has been extended[23,24] and a new drought index formulated — the Standardized Precipitation Evapotranspiration Index (SPEI) — on the basis of precipitation and PET data to overcome this issue. The PDSI takes this one step further by accounting for the balance of precipitation, ET and runoff, and has the ability to incorporate local soil and possibly vegetation properties, making it a fairly comprehensive and flexible index of relative drought. The original SPEI and the original formulation of PDSI use the 'Thornthwaite method' [4,20,21] to account for ET effects. This approach considers only monthly precipitation amounts and temperatures but has the major advantage that it is easily calculated because these data are readily available for most global land areas. The disadvantage is that it cannot account for changes in solar and infrared radiation, humidity and wind speed, which we discuss below.

Advances in recent years include a 'self-calibrating' version, the scPDSI[25], that uses local climate data to calibrate the index so that the categories conform better to those originally intended by Palmer. This PDSI formulation is a useful but relative metric, thus the way it relates to absolute drought at any location has to be treated with care. Several studies have, however, shown quite good co-variability between the PDSI and both observed streamflow and measured soil moisture[3,4]. Moreover, many local characteristics are systematic and thus not a factor for examining changes over time.

A more realistic and complex approach to estimating PET in the PDSI is the method outlined by Penman in 1948 and modified by Monteith to give the Penman–Monteith (PM) formulation[4,7,20,21] that incorporates the effects of wind and humidity, plus solar and longwave radiation. Unfortunately, global fields of most of these data are not readily available and they generally suffer from temporal and spatial inhomogeneities in the observations. Indeed there are major concerns about the reconstruction of solar radiation data, as incoming energy plays a central role in ET and depends a lot on how clouds have changed. The function of the surface water vapour pressure deficit in the PM formulation, and issues in ET more generally, are reviewed by Wang and Dickinson[26]. An evaluation of changes in surface winds[27] finds decreases in many areas, but the confidence in wind trends is low because long, homogenized records are rare, and instrumentation is sensitive to maintenance and siting issues. Dai[4] and van der Schrier *et al.*[21] attempted to provide these evaporation components of the 'forcings' of the PDSI and the results turn out to depend critically on the forcings used. Sheffield *et al.*[20] stated that "Recent studies have claimed that there is little difference between the PDSIs that use the Thornthwaite and PM algorithms (PDSI_Th and PDSI_PM, respectively) but this can be attributed to inconsistencies in the forcing data sets and simulation configuration…" Accordingly, discrepancies arise from the highly uncertain forcing data.

Sheffield *et al.*[20] carried out a detailed comparison of various forcing data for the PDSI calculations and claim that "PDSI_PM gives a better estimate of the true trend in global drought because of its more comprehensive physics." Although this may be true in principle, it can be offset by the uncertainties in the drivers of those physics for which the observational estimates are less reliable and have less spatial coverage than temperature data.

Both climatologies and changes in ET over time have been extremely difficult to determine reliably[27]. An evaluation was made of global land ET estimates[28] using 30 observationally based analyses from upscaled in-situ data, satellite remote sensing retrievals, land surface models and atmospheric reanalyses, and also from 11 climate models. The observational spread was greater than ±20% and hence the uncertainties are unduly large. The regional uncertainties are even greater. The discrepancies stem not only from the different formulations and parametric representations of ET used, but also from the different data sets and forcing fields applied. Yet these estimates were all for the period 1989–1995, for which such data sets exist. For climate change studies over longer time periods the formulations and associated biases may be important, but the input data sets employed remain a key concern.

Another important issue that has emerged in recent research is the choice of the baseline period to define and calibrate the PDSI moisture categories. Sheffield *et al.*[20] use a base period of 1950-2008. Dai[5] used 1950–1979, which is a relatively wet period, and that colours the results. The ideal base period should sample natural variability fully, and the 1950–1979 period does not include the North American dust bowl era of the 1930s, for instance (but all the necessary data are not always available). However, there is also a problem in using 1950–2008, because any recent anthropogenic climate change effects are included. This alters the ranges of observed variability against which the longer-term variations that characterize changes are scaled. Hence it greatly reduces any prospects of identifying a climate change signal in the results of the analysis.

Some of these issues have been addressed[21,29]. Global maps of monthly scPDSI for the period 1901–2009 were produced[29] based on the CRU TS3.10.01 data sets (see Methods) using both ET formulations. The scPDSI was found to have a similar range of variability in diverse climates making it a more suitable metric for comparing the relative availability of moisture in different regions. The more physically based Penman–Monteith parameterization for PET was adopted but also calculated using the actual vegetation cover rather than a simple reference crop, and a treatment of seasonal snow effects was included[29]. The leading mode of variability in the new data set represents a trend towards drying conditions in some parts of the globe between 1950 and 1985, and increasing temperature and PET explain part of this trend. However, local trends in most of the drying regions are not statistically significant. When the calibration period does not include the most recent part of the record (when anthropogenic warming is most evident) trends towards more extreme conditions are amplified. The study concluded that this is the principal reason for different published interpretations of the scale of recent global drying and not the ET formulation[29]. But it seems there is more to it.

As well as the above issues, Sheffield *et al.*[20] uncovered some minor problems with the study by Dai[4] related to how his data sets had been updated after 2004 but none that obviously explain most of the differences in the results. Moreover, it is evident that there are important issues with the other forcing data for the more complex and comprehensive form of PDSI, and thus there remains some merit in the simpler but self-calibrated version of PDSI_Th — provided that it is recognized that it is an index, and it is not extended into the future. However, it seems that another significant factor affecting the differences in published conclusions relates to differences in the underlying precipitation data sets used.

Issues with precipitation data sets

The discrepancies between the previous studies are also probably due to the precipitation data sets used. Sheffield *et al.*[20] used four different precipitation data sets: CPC-Prec/L, GPCCv4, CRU TS3.10 and U. Delaware v2.01. Van der Schrier *et al.*[21,29] used an improved version of the CRU data set (CRU TS3.10.01), whereas Dai[4,5] explored other data sets (see Methods). The Climate Research Unit (CRU) has very recently updated their precipitation data set and analysis to version 3.21. The global mean land precipitation anomalies from several data sets (Fig. 1) are fairly consistent from 1950 to 1990 (although mean alignment is guaranteed for the base period 1961–1990). However, differences become readily apparent after 1991, when data from fewer stations are available for all data sets. The much greater number of Global Precipitation Climatology Centre (GPCC) stations does not guarantee improved coverage if the extra stations are all in the same area. It may be argued that fewer, more homogeneous, records provide more reliable time series and this has been the rationale behind the construction of the CRU data set. Many of the stations used by GPCC are not available for use by others. Coverage certainly affects the analyses of precipitation anomalies but continuity, or more strictly lack of temporal continuity, is more of an issue[30]. In Fig. 1, the numbers of stations available/used is indicated for different data sets (see Methods). Real-time monitoring is becoming a vital part of developing climate services, but the amount and timing of data released by countries is extremely variable. Access to greater numbers of station data can often be achieved much later, but not in near real-time from the more traditional CLIMAT and SYNOP sources (see Methods).

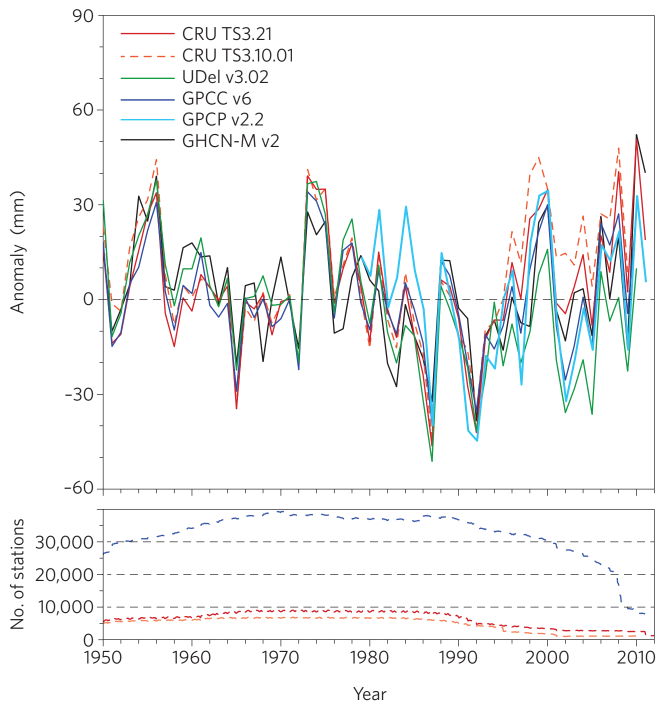

Figure 1 | Time series of global land (60° S to 75° N) precipitation departures from the annual mean for several data sets. The lower panel shows the number of stations that were used for the GPCC and CRU data sets. The base period is 1961–1990 except for GPCP, where 1981–2000 was used.

The CRU TS3.10.01 data set, which has measurements from fewer than 1500 rain gauges in recent years, differs substantially from the GPCC and Global Precipitation Climatology Project (GPCP) precipitation products that have many more gauge data (Fig. 1). This data set effectively had a 'wet bias' with respect to the other data sets in the global average since around 1996. The problem occurred especially at northern latitudes and the tropics (Fig. 2). Maps for 2002 (not shown) reveal the biggest differences in tropical South America, Indonesia and parts of Africa. This issue has been reduced in the newer version (CRU TS3.21), which has an increased number of stations in these regions and globally (>2400 stations during the 2000s). However, CRU TS3.21 values are still somewhat higher than GPCC and Global Historical Climatology Network (GHCN) estimates from 30° S to 60° N. The University of Delaware data set diverges from all the other data sets after around 1995, showing a drying trend. This was noted earlier[31] and attributed to issues in the data from the Global Surface Summary of the Day (GSOD) archive and better sampling of dry areas.

The anomaly time series given in Fig. 1 show very different trends after about 1990. Methods of analysing precipitation data have been explored[32] and there are merits in several approaches: analysing anomalies in mm (as done by Dai and GPCC); analysing per cent anomalies (as done by CRU); and analysing standardized anomalies. All of these methods work best under certain circumstances — generally when the field is fairly coherent, but when there are large gradients and diverse regimes involved differences can be substantial, especially in trends. The only way the correct answer can be known is by using more stations and better coverage, although constraints can be derived from other hydrological variables in the context of a water budget.

The global land precipitation differences (Fig. 1) in recent years range up to about 40 mm around a mean of 800 mm (5%) and this

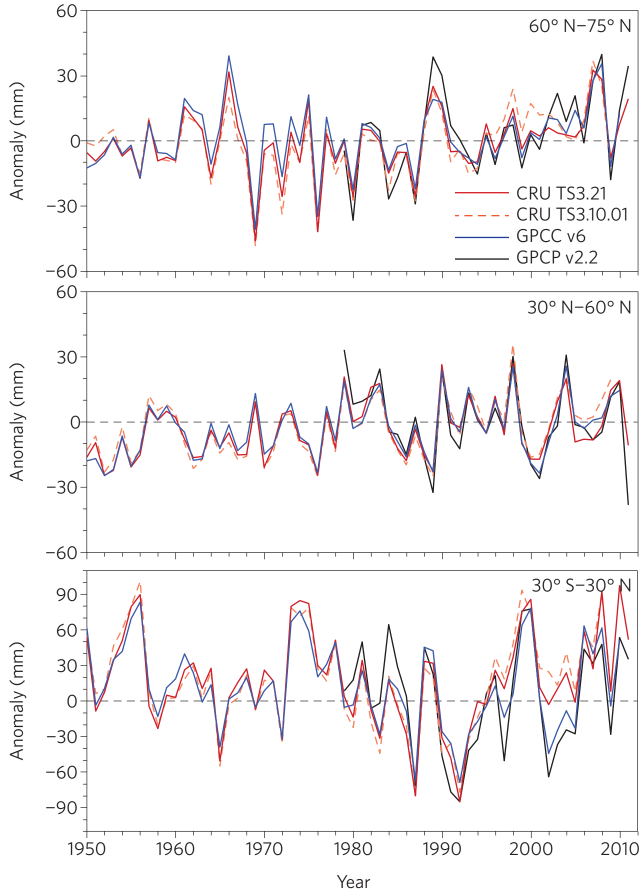

Figure 2 | Time series of mean precipitation for zones indicated with a base period of 1981–2000. The legend applies to all panels.

translates into differences in PDSI of up to 0.3 (Fig. 3) (excluding the Univ. Delaware estimate); see Sheffield *et al.*[20] for the spread in PDSI in using several precipitation data sets. These differences in turn are enough to change the area of global land under drought (for the bottom 20% of the PDSI) by some 6% or so, thereby potentially causing a large shift in perceptions about changes in drought depending on which precipitation data set is chosen.

Variability versus trends

The most common source of episodic droughts around the world is the El Niño/Southern Oscillation (ENSO). During El Niño events there are major droughts over Australia, Indonesia, southeast Asia, parts of Africa and the northeast of Brazil. This is a result of the main rainfall systems in the tropics moving off-shore over the tropical Pacific combined with the much warmer than normal waters, often leaving weakened monsoons behind. In the La Niña phase, dry areas are more common in Peru, Ecuador and over the oceans, in places where it is wet during El Niño events. The atmospheric circulation creates favourable conditions for drought, often through teleconnections, which can be initiated by sea surface temperature anomalies. They occur in anticyclonic (high pressure) conditions where gentle subsiding air suppresses clouds and rainstorms and the sunshine dries out the soils and vegetation, ultimately increasing the risk of heat waves and wild fires[33]. With anticyclonic conditions in the drought area, the nature of the atmospheric circulation means that cyclonic conditions prevail elsewhere. Hence somewhere else in the world low-pressure cyclonic regimes must exist as part of an atmospheric wave or monsoonal overturning atmospheric flow, and the air generally rises and provides unsettled cloudy and rainy weather. Evaporated moisture moves from the anticyclonic to the cyclonic regions, which tends to make dry areas drier and wet areas wetter. These changes also affect wind speeds and other variables that impact ET, but the impacts of ENSO on ET through changing wind speed have not been extensively investigated.

Thus ENSO is the primary source of variability in the tropical and global precipitation record[34] and therefore variations in ENSO affect perceptions about changes in drought[12,35] and their possible links to climate change. Recent years, such as 2010 and 2011, were especially wet on land in association with La Niña conditions and led to a 5 mm drop in global sea-level as excess precipitation deposited water on land, especially in Australia, filling up Lake Eyre[36]. The overall trend in global land precipitation since the 1980s is upwards as a result of more La Niña events in recent years, but the 1950s to 1970s were relatively wet and there is no simple linear trend. The trend is less for GPCP and GPCC datasets (Fig.1).

Sheffield *et al.*[20] and van der Schrier *et al.*[21] did not consider the influence of ENSO, but this was explored in detail by Dai[4]. Indeed, precipitation on land is controlled to a large degree by ENSO: in general with more La Niña phases, as experienced in recent years, there is more rain on land. The Interdecadal Pacific Oscillation and associated Pacific Decadal Oscillation in turn modulate ENSO and greatly influence precipitation regimes especially across the western United States[37]. That says nothing about whether the extent and intensity of drought is greater or not when it occurs, and so the signals from ENSO and the Pacific Decadal Oscillation should be removed to the extent possible before looking at trends associated with climate change, although residual effects will probably remain. Other outstanding issues relate to whether ENSO and the Pacific Decadal Oscillation have been affected by climate change.

Conclusions and recommendations

Although all groups have contributed to our knowledge about drought, the uncertainties have not always been adequately appreciated. There are various drought indices and metrics, as discussed here, and the PDSI model itself contains uncertainties. There remain substantial issues on how to best deal with changes in ET, although these are well documented in the literature. What is more surprising, and disappointing, are the disparities between precipitation data sets. The recent development of the CRU TS3.21 updated precipitation data set has already narrowed these. In future, some of these problems may be addressed by a more comprehensive effort to obtain precipitation observations using remote sensing as well as *in situ* data under the banner of the Global Precipitation Measurement mission[38]. Nevertheless, the general availability of precipitation data and differences in the primary precipitation data sets continue to be a concern.

The other major issue is the role of natural variability, especially ENSO, which biases the land precipitation towards wetter conditions, and with less drought globally under La Niña conditions. Hence it is probably not possible to determine reliable decadal and longer-term trends in drought due to climate change without first accounting for the effects of ENSO and the Pacific Decadal Oscillation.

The recommendations from this assessment are that it would be highly desirable for countries to allow a lot more of their precipitation data to be publicly available. Many of these data are used by GPCC but they are not permitted to pass these on. We urgently advocate that this should be addressed. At the same time, precipitation data with higher temporal resolution, such as hourly data, are greatly needed to document extremes and runoff issues. We also strongly encourage further 'data rescue' efforts to recover past data by preserving data at risk of being lost owing to deterioration of the storage medium, and digitizing the data into computer readable form for easy access. With regards to ET, simpler formulations, which can account for some aspects of drought related to atmospheric demand for moisture

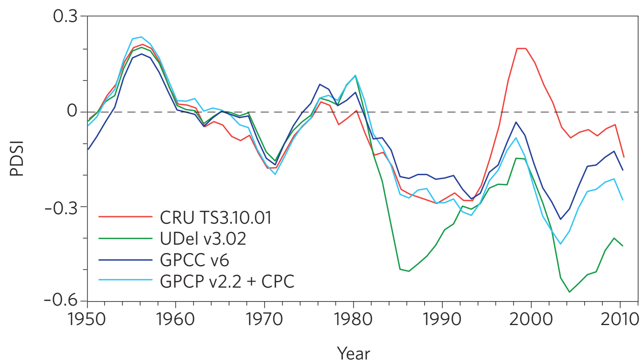

Figure 3 | Time series of 5-year smoothed global-mean annual scPDSI_PM, calculated using four different precipitation data sets. All other inputs are the same for each series. The base period used was 1950–1979. All except the CRU TS3.10.01 precipitation case show a statistically significant drying trend ($p<0.05$). Note the CPC+GPCP precipitation data were used by Dai[4,5]. Sheffield *et al.*[20] used earlier versions of all four precipitation data sets.

through temperature dependencies, still have merit provided their shortcomings are recognized. However, improvements in the observation and modelling of ET and all its forcings at a large scale are also required[26]. Research projects are underway to improve knowledge, forcings and model capabilities with respect to ET, soil moisture and surface water, and further progress is essential if we are to adequately depict the changing face of drought and water resource availability.

Changes in the global water cycle in response to the warming over the twenty-first century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will probably increase, although there may be regional exceptions. Climate change is adding heat to the climate system and on land much of that heat goes into drying. A natural drought should therefore set in quicker, become more intense, and may last longer. Droughts may be more extensive as a result. Indeed, human-induced warming effects accumulate on land during periods of drought because the 'air conditioning effects' of water are absent. Climate change may not manufacture droughts, but it could exacerbate them and it will probably expand their domain in the subtropical dry zone.

Methods

The precipitation data used are available and described in refs 29,31,39–46. The CRU[29,42] TS3.10.01, CRU TS3.21, U.Del[31,43] and GPCC[39,44] data sets were consistently processed on the same 0.5° x 0.5° grid, excluding land regions with permanent ice cover (Greenland) and extreme aridity. For the GPCP data set[41,45] (2.5° x 2.5°) only land gridboxes were used for computing the area averages, excluding Greenland. For the GHCN anomalies[40,46] (5° x 5°) averages were computed using all available grid boxes with data. Dai[4] mainly used the GPCP and GPCC data sets as well as the CPC data set.

CLIMAT is a code for promptly reporting monthly climatological data assembled at land-based meteorological surface observation sites to data centres at the end of each month. Surface synoptic observations (SYNOP) is the code used for reporting weather observations made by manned and automated weather stations, typically every six hours.

For GPCC up to 40,000 stations have been used although with a drop in the past decade and especially after 2009 (Fig. 1). The CRU data set typically has between 5000 and 7000 stations in CRU TS3.10.01, increasing somewhat up to about 10,000 at times for CRU TS3.21, but dropping after 1991. However, coverage for CRU TS3.21 is a substantial improvement in the past decade, although 2011 values are still tentative. The CRU data set does not use the daily SYNOP sources (used by other data sets) because a determination of how many days can be used for a complete month has to be made. All data sets show a reduction in station numbers in the last two decades, but this should not be taken to mean the network is degrading.

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Additional information

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Competing financial interests

The authors declare no competing financial interests.