

# 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 datasets used to determine the evapotranspiration (ET) component. Here, we make an assessment of the issues with the PDSI in which several other sources of discrepancy emerge not the least of which is how precipitation has changed and is analyzed. As well as an improvement in precipitation data available, accurate attribution of drought causes requires accounting for natural variability, especially El Niño-Southern Oscillation (ENSO) 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 apt 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 blurred. Here we attempt to clarify underlying aspects of this socially and ecologically relevant topic. We discuss what the expectations should be and thus prospects for the future and we provide some recommendations for resolving outstanding issues.

## **What is drought?**

As noted by the Intergovernmental Panel on Climate Change (IPCC) AR4 (Fourth Assessment Report)<sup>1</sup>, “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’ “. AR4 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, ET and runoff to drought from climatic factors. More generally, water availability is a general societal and environmental concern, which brings in also the demand side, and thus there are other possible definitions related to water scarcity. The IPCC SREX “extremes” report<sup>2</sup> includes a valuable discussion of drought or “dryness”, drought drivers and drought indices that complements that here.

Drought can be quantified and described in absolute terms, such as through the amount of soil moisture or lake levels, or through relative measures, such as the Palmer Drought Severity Index (PDSI) in various forms, and these can be compared<sup>3,4</sup>. Because drought is defined by one tail of the probability distribution function of a drought measure, such as soil moisture content or streamflow, a small reduction in the mean (e.g., -5%) will translate into a much larger increase in drought frequency based on other drought definitions<sup>5</sup>. 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 carbon dioxide and other heat-trapping gases in the atmosphere – global warming if you will – there is the strong expectation for a general increase in potential evapotranspiration (PET) that is directly related to the increase in surface heating. This will likely 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. For the historical period, other variations (including unforced natural climate changes in surface humidity and wind speed) can be important for the

apparent drying trend. Nevertheless, climate model projections suggest drying over many areas in low- and mid-latitudes under increasing greenhouse gases<sup>5-10</sup> (GHGs). More specifically, there is a strong tendency for the wet areas to get wetter and dry areas get drier, and with a poleward expansion of the subtropical dry zones<sup>11</sup>. Model projections, however, do not show large systematic long-term trends in surface relative humidity and wind speed in response to long-term GHG forcing.

For the most part, droughts over recent years appear to be natural in terms of where and when they occur<sup>10,12</sup>. That is to say anthropogenic climate change factors 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 the drought more quickly and with greater intensity.

Meanwhile, where it rains it rains harder because a warmer atmosphere can hold more moisture<sup>11,13</sup>. 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<sup>14-16</sup>.

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 changes are underway: an expansion of the tropics, a poleward shift in the main storm tracks in mid-latitudes<sup>11</sup>, and/or changes in the seasonality of rains<sup>1</sup>. Moreover this pattern is predicted in climate models<sup>1,2,6-9</sup>. 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 this pattern in many places<sup>17</sup>, although the model-predicted seasonality change in precipitation appears to be evident in observations<sup>18</sup>. Further, changes in the character of precipitation to more intense heavy rains but longer dry spells, as observed and expected<sup>19</sup>, means 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 paper in *Nature* by Sheffield et al.<sup>20</sup> “*Little change in global drought over the past 60 years*” was published at almost the same time as *Nature Climate Change* published a completely different view: “*Increasing drought under global warming in observations and models*” by Dai<sup>5</sup> (published online in August 2012). How can two research groups arrive at such disparate and seemingly contradictory conclusions?

The essence of the Sheffield et al. paper 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, within the papers, the differences between Sheffield et al. and Dai results are not that great. Sheffield et al.<sup>20</sup> 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<sup>4,21</sup>. 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 infiltrates to deeper ground layers or runs off the land and how much is evaporated or transpired by plants, i.e. ET. As noted in AR4, “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 affects 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 whether it is realized depends on available moisture.

## Issues with ET and baseline period

Several drought indices, such as the Standardized Precipitation Index (SPI<sup>22</sup>) 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 they are limited because they do not deal with the ET side of the issue. The concept of the SPI has been extended<sup>23,24</sup> and a new drought index formulated, the Standardized Precipitation Evapotranspiration Index (SPEI), based on precipitation and PET 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 (PDSI\_Th) use the “Thornthwaite method” to account for ET effects. PDSI\_Th 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<sup>25</sup>, that uses local climate data to calibrate the index so that the categories conform better to those originally intended by Palmer. The fact that this PDSI formulation is called an “index” of drought recognizes that it is a useful but relative metric, but just how it relates to absolute drought at any location has to be treated with care. Several studies have, however, shown quite good relationships between the PDSI and both observed streamflow and measured soil moisture<sup>3,4</sup>. Moreover, many local factors are systematic and thus are not a factor in examining changes over time.

A more “realistic” and complex approach to estimating PET in the PDSI<sup>4,7,20,21</sup> is the method outlined by Penman in 1948 and modified by Monteith to give the Penman-Monteith (PM) formulation that incorporates the effects of wind, humidity, plus solar and longwave radiation. Unfortunately, most of these fields are not as 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, which plays a central role in ET and depends a lot on how clouds have changed. The role of the surface water vapor pressure deficit in PM, and issues in ET more generally are reviewed by Wang et al.<sup>26</sup> A review of changes in surface winds<sup>27</sup> 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<sup>4</sup> and van der Schrier et al.<sup>21</sup> attempted to provide these evaporation components of the “forcings” of the PDSI and the results turn out to depend critically on the forcings. Sheffield et al.<sup>20</sup> 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. 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.” While 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 for temperature.

Both climatologies and changes in ET over time have been extremely difficult to determine reliably<sup>27</sup>. An evaluation was made of global land ET estimates<sup>28</sup> from 30 various observationally-based estimates from upscaled in-situ data, satellite remote sensing retrievals, and land surface models, as well as

atmospheric reanalyses and also from 11 climate models. The observational spread was over  $\pm 20\%$  and hence the uncertainties are unduly large. The regional uncertainties are even greater. The differences stem not only from different formulations and parametric representations of ET but also from the different datasets and forcing fields used. Yet these estimates were all for a recent period after 1989 when such datasets exist. For climate change studies over longer time periods, the formulations and associated biases may be important, but the input datasets 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. use a base period of 1950-2008. Dai used 1950-79, which is a relatively wet period, and that colors the results. The ideal base period should sample natural variability fully, and the 1950-79 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 aspects are included. This changes 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 resulting datasets.

Some of the issues have been addressed<sup>21,29</sup>. Global maps of monthly scPDSI for the period 1901-2009 were produced<sup>29</sup> based on the CRU TS3.10.01 datasets (see methods) using both ET formulations. The findings are that the scPDSI has 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 also included. The leading mode of variability in the new dataset represents a trend towards drying conditions in some parts of the globe between 1950 and 1985, and increasing temperature and PET explain part of the drying 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. They<sup>29</sup> conclude that this is the principal reason for different published interpretations of the scale of recent global drying and not the ET formulation. But it seems there is more to it.

As well as the above issues, Sheffield et al.<sup>20</sup> uncovered some minor problems with the results of Dai<sup>4</sup> related to how his datasets had been updated after 2004 but none that obviously explain most of the differences in the results. Moreover, it is evident that there are major 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 appears that another significant factor affecting the differences in published conclusions relates to differences in the underlying precipitation datasets used.

## Issues with precipitation datasets

The discrepancies among the previous studies are also likely due to the precipitation datasets used. Sheffield et al.<sup>20</sup> used four different precipitation datasets: CPC-Prec/L, GPCCv4, CRU TS3.10 and U. Delaware v2.01. Van der Schrier et al.<sup>21,29</sup> used an improved version of the CRU dataset (CRU TS3.10.01) while Dai<sup>4,5</sup> explored other datasets (see Methods). CRU has very recently updated their precipitation dataset and analysis to version 3.21. The global mean land precipitation anomalies from several datasets (Fig. 1) are fairly consistent from 1950 to 1990 (although mean alignment is guaranteed for the base period 1961-90). However, differences become readily apparent after 1991 when fewer station data are available for all datasets. The much greater number of GPCC stations does not guarantee improved

coverage if the additional 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 dataset. Many of the stations used by GPCP 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<sup>30</sup>. In Fig. 1, the numbers of stations available/used is indicated for different datasets (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).

The CRU TS3.10.01 dataset, which has data from fewer than 1500 rain gauges in recent years, differs substantially from the GPCP and GPCP precipitation products that have many more gauge data (Fig. 1). CRU TS3.10.01 effectively had a 'wet bias' with respect to the other datasets 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 that 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 GPCP and GHCN estimates from 30°S to 60°N. The U. Delaware dataset diverges from all the other datasets after around 1995, showing a drying trend. This was noted earlier<sup>31</sup> 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 analyzing precipitation data have been explored<sup>32</sup> and there are merits in several approaches (i) analyzing anomalies in mm (as done by Dai and GPCP); (ii) analyzing per cent anomalies (as done by CRU); and (iii) analyzing standardized anomalies, all of which work best under certain circumstances and 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 out of a mean about 800 mm (5%) and this translates into differences in PDSI of up to 0.3 (Fig. 3) (excluding the U. Delaware estimate); see also Sheffield et al.<sup>20</sup> for the spread in PDSI in using several precipitation datasets. These differences in turn are enough to change the area of the global land under drought (for the bottom 20% of the PDSI) by some 6% or so, thereby potentially greatly altering perceptions about changes in drought depending on which precipitation dataset is chosen.

## Variability versus trends

The most common source of episodic droughts around the world is ENSO. During El Niño events there are major droughts over Australia, Indonesia, southeast Asia, parts of Africa and the northeast of Brazil because the main rainfall areas in the tropics move off-shore over the tropical Pacific in conjunction 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 Niños. Droughts occur because the atmospheric circulation becomes favorable, often as teleconnections, and often 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 promoting risk of heat waves and wild fires<sup>33</sup>. 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 ENSO impacts on ET through changing wind speed have not been extensively analyzed.

Hence ENSO is the primary source of variability in the tropical and global precipitation record<sup>34</sup> and therefore variations in ENSO affect perceptions about changes in drought<sup>12,35</sup> 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<sup>36</sup>. The overall trend in global land precipitation since the 1980s is upwards as a result of more La Niñas in recent years, but the 1950 to 1970s period was relatively wet and there is no simple linear trend. The trend is less for GPCP and GPC datasets (Fig.1).

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

## Conclusions and recommendations

While all groups have contributed to 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, is the disparities among precipitation datasets. The recent development of the CRU TS3.21 updated precipitation dataset has already narrowed these. In future, some of these issues may be addressed by a more comprehensive effort to obtain precipitation fields using remote sensing as well as in situ data under the banner of the Global Precipitation Mission (<http://pmm.nasa.gov/GPM>). Nevertheless, the general availability of precipitation data and differences in the primary precipitation datasets 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 likely not possible to determine reliable decadal and longer term trends in drought attributable to climate change without first accounting for the effects of ENSO and Pacific decadal variability.

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 GPCP but they are not permitted to pass these on. We urgently recommend that this should be addressed. At the same time, higher temporal resolution precipitation data, 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. With regard to ET, there remains merit in simpler formulations that can account for some aspects of drought related to atmospheric demand for moisture via temperature dependencies provided their shortcomings are recognized. However, improvements in the observation and modeling

of ET and all its forcings at large scale are also required<sup>26</sup>. 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 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will likely increase, although there may be regional exceptions. Climate change is adding extra 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 the major time that human-induced warming effects accumulate on land is during drought because the “air conditioning effects” of water are absent. Climate change may not manufacture droughts, but it could exacerbate them and it will likely expand their domain in the subtropical dry zone.

## Methods: Data

The precipitation data used here come from:

1. The Climatic Research Unit CRU TS3.21, CRU TS3.10.01: (29);  
<http://www.cru.uea.ac.uk/cru/data/hrg/>
2. University of Delaware v3.02, (31);  
[http://climate.geog.udel.edu/~climate/html\\_pages/archive.html](http://climate.geog.udel.edu/~climate/html_pages/archive.html)
3. GPCC, v6, Global Precipitation Climatology Centre, (38);  
[ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata\\_v6\\_doi\\_download.html](ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata_v6_doi_download.html)
4. GHCN-M v2; (39); <http://www.ncdc.noaa.gov/temp-and-precip/ghcn-gridded-products.php>
5. GPCP v 2.2: Global Precipitation Climatology Project, (40)  
[http://precip.gsfc.nasa.gov/gpcp\\_v2.2\\_data.html](http://precip.gsfc.nasa.gov/gpcp_v2.2_data.html).

The CRU TS3.10.01, CRU TS3.21, U.Del and GPCC datasets were consistently processed on the same 0.5°x0.5° grid, excluding land regions with permanent ice cover (Greenland) and extreme aridity. For the GPCP dataset (2.5°x2.5°) only land gridboxes were used for computing the area averages, excluding Greenland. For the GHCN anomalies (5°x5°) averages were computed using all available grid boxes with data. Dai<sup>4</sup> mainly used the GPCP and GPCC datasets as well as the CPC dataset.

For GPCC up to 40,000 stations have been used although with a drop in the past decade and especially after 2009 (Fig. 1). CRU 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 dataset does not use the daily SYNOP sources (used by other datasets) because a determination of how many days can be used for a complete month has to be made. All datasets show a reduction in station numbers in the last two decades, but this should not be taken to mean the network is degrading.



## References

1. Trenberth, K. E., *et al.* Observations: Surface and Atmospheric Climate Change, in *Climate Change 2007: The Physical Science Basis. Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon *et al.*, pp. 235–336, Cambridge University Press, Cambridge, UK and New York, NY, USA, (2007).
2. Seneviratne, S. I., *et al.* Changes in climate extremes and their impacts on the natural physical environment, in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, edited by C.B. Field, *et al.*, pp. 109-230, Cambridge University Press, Cambridge, UK and New York, NY, USA (2012).
3. Dai, A., Trenberth, K. E., & Qian, T. A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, **5**, 1117–1130, (2004).
4. Dai, A. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *J. Geophys. Res.*, **116**, D12115 doi:10.1029/2010JD015541 (2011).
5. Dai, A. Increasing drought under global warming in observations and models. *Nature Climate Change*, **3**, 52-58, doi:10.1038/nclimate1633 (2013).
6. Wang, G. L. Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment. *Clim. Dyn.*, **25**, 739-753 (2005).
7. Burke, E. J., Brown, S. J., & Christidis, N. Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *J. Hydrometeorol.*, **7**, 1113-1125 (2006).
8. Seager, R., *et al.* Model projections of an imminent transition to a more arid climate in southwestern North America. *Science*, **316**, 1181-1184 (2007).
9. Sheffield, J., & Wood, E. F. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim Dyn*, **31**, 79-105 (2008).
10. Dai, A. Drought under global warming: a review, *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 45-65 (2011).
11. Seager, R., Naik, N., & Vecchi, G.A. Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. *J. Climate*, **23**, 4651–4668. doi:10.1175/2010JCLI3655.1 (2010).
12. Hoerling, M., Eischeid, J., & Perlwitz, J. Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. *J. Climate*, **23**, 2131–2145. doi: 10.1175/2009JCLI3420.1 (2010).
13. Giorgi, F., Im, E.-S., Coppola, E., Diffenbaugh, N. S., Gao, X. J., Mariotti, L., & Shi, Y. Higher hydroclimatic intensity with global warming. *J. Climate*, **24**, 5309–5324 doi:10.1175/2011JCLI3979.1 (2011).
14. Nicholls, N. The changing nature of Australian droughts. *Climatic Change*, **63**, 323-336 (2004).
15. van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R.A. M., Liu, Y.Y., Podger, G. M., Timbal, B. & Viney, N. R., The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, *Water Resour. Res.*, **49**, doi:10.1002/wrcr.20123 (2013).
16. Lewis, S. C., & Karoly, D. J. Anthropogenic contributions to Australia’s record summer temperatures of 2013. *Geophys. Res. Lett.* doi: 10.1002/grl.50673 (2013) (in the press).
17. Seager, R., & Vecchi, G. A. Greenhouse warming and the 21st Century hydroclimate of southwestern North America, *PNAS*, **107**, 21277–21282, doi:10.1073/pnas.0910856107 (2010).
18. Chou, C., Chiang, J. C. H., Lan, C. W., Chung, C. H., Liao, Y. C., & Lee, C. J. Increase in the range between wet and dry season precipitation. *Nat. Geosci.*, **6**, 263-267 (2013).
19. Trenberth, K. E., Dai, A., Rasmussen R. M. & Parsons, D. B. The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205-1217 (2003).
20. Sheffield, J., Wood, E. F. & Roderick, M. L. Little change in global drought over the past 60 years, *Nature*, **491**, 435–438, doi:10.1038/nature11575 (2012).
21. van der Schrier, G., Jones, P. D. & Briffa, K. R. The sensitivity of the PDSI to the Thornthwaite and Penman–Monteith parameterizations for potential evapotranspiration. *J. Geophys. Res.*, **116**, D03106 (2011).
22. Orlovsky, B., & Seneviratne. S. Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections, *Hydrol. Earth Syst. Sci.*, **17**, 1765–1781, doi:10.5194/hess-17-1765-2013 (2013).

23. Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Climate*, **23**, 1696–1718. doi:10.1175/2009JCLI2909.1 (2010a).
24. Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., & El Kenawy, A. A new global 0.5° Gridded Dataset (1901–2006) of a multiscalar drought Index: Comparison with current drought index datasets based on the Palmer Drought Severity Index. *J. Hydrometeorol*, **11**, 1033–1043. doi:10.1175/2010JHM1224.1 (2010b).
25. Wells, N., Goddard, S. & Hayes M. J. A self-calibrating Palmer Drought Severity Index. *J. Clim.*, **17**, 2335–2351 (2004).
26. Wang, K., & Dickinson, R. E., A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability, *Rev. Geophys.*, **50**, RG2005, doi:10.1029/2011RG000373 (2012).
27. McVicar, T.R., *et al.*, Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *J. Hydrology*, **416-417**, 182-205 (2012).
28. Mueller, B., *et al.* Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations, *Geophys. Res. Lett.*, **38**, L06402, doi:10.1029/2010GL046230 (2011).
29. van der Schrier, G., Barichivich, J., Briffa, K. R. & Jones, P. D. A scPDSI-based global dataset of dry and wet spells for 1901-2009. *J. Geophys. Res.*, **118**, 4025–4048 doi:10.1002/jgrd.50355 (2013).
30. Lorenz, C., & H. Kunstmann, H. The hydrological cycle in three state-of-the-art reanalyses: Intercomparison and performance analysis. *J. Hydrometeorol.*, **13**, 1397-1420, doi: 10.1175/JHM-D-11-088.1 (2012)
31. Nickl, E., Willmott, C. J., Matsuura, K. & Robeson, S. M. Changes in annual land-surface precipitation over the Twentieth and early Twenty-first century. *Annals Assoc. Amer. Geogr.*, **100**(4) 729–739 (2010).
32. Jones, P. D., & Hulme, M. Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *Intl. J. Climatol.*, **16**, 361-377 (1996).
33. Mueller, B., & Seneviratne, S. Hot days induced by precipitation deficits at the global scale, *Proc. Natl Acad. Sci.*, **109**, 12398–12403. Doi:10.1073/pnas.1204330109 (2012).
34. Gu G., Adler R. F., Huffman, G.J., & Curtis, S. Tropical rainfall variability on interannual-to-interdecadal/longer-time scales derived from the GPCP monthly product. *J. Clim.*, **20**, 4033–4046 (2007).
35. Vicente-Serrano, S.M., *et al.* A multi-scalar global evaluation of the impact of ENSO on droughts. *J. Geophys. Res.*, **116**, D20109, doi:10.1029/2011JD016039 (2011).
36. Boening, C., Willis, J. K., Landerer, F. W., Nerem, R. S. & Fasullo, J. The 2011 La Niña: So strong, the oceans fell, *Geophys. Res. Lett.*, **39**, L19602, doi:10.1029/2012GL053055 (2012).
37. Dai, A., The influence of the inter-decadal Pacific oscillation on U.S. precipitation during 1923–2010. *Clim. Dyn.*, **41**: 633-646. Doi: 10.1007/s00382-012-1446-5 (2013b).
38. Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U. & Ziese, M. A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present, *Earth Syst. Sci. Data*, **5**, 71–99, doi:10.5194/essd-5-71-2013 (2013).
39. Parker, D. E., Hilburn, K., Hennon, P. & Becker, A. Precipitation, in “*State of the Climate in 2011*”. *Bull. Amer. Meteor. Soc.*, **93**, S26-S27 (2012).
40. Huffman, G. J., Adler, R. F., Bolvin, D. T., & Gu, G. J., Improving the global precipitation record: GPCP version 2.1, *Geophys. Res. Lett.*, **36**, L17808, doi:10.1029/2009GL040000 (2009).

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### Competing financial interests

The authors declare no competing financial interests.

Figures

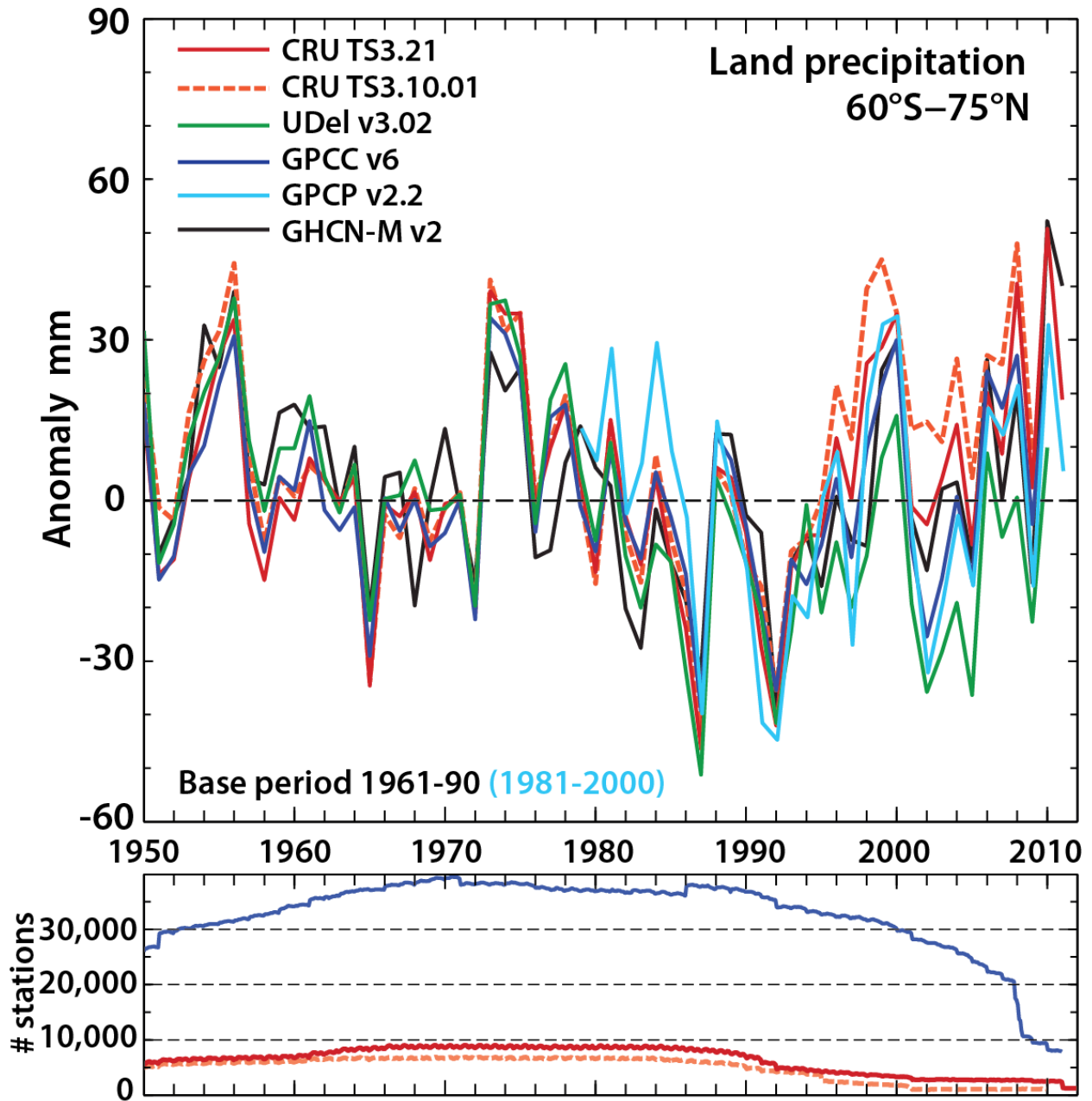


Fig. 1. Time series of global land (60°S to 75°N) precipitation departures from the annual mean of about 800 mm for 1961-90 in mm for several datasets: CRU TS3.21 (red), CRU TS3.10.01 (dashed red), University of Delaware v3.02 (green), GPC v6 (blue), GPCPv2.2 (sky blue), GHCN-Mv2 (black). The lower panel shows the number of stations that went in to the GPC and CRU datasets. The base period is 1961-90 except for GPCP where 1981-2000 is used.

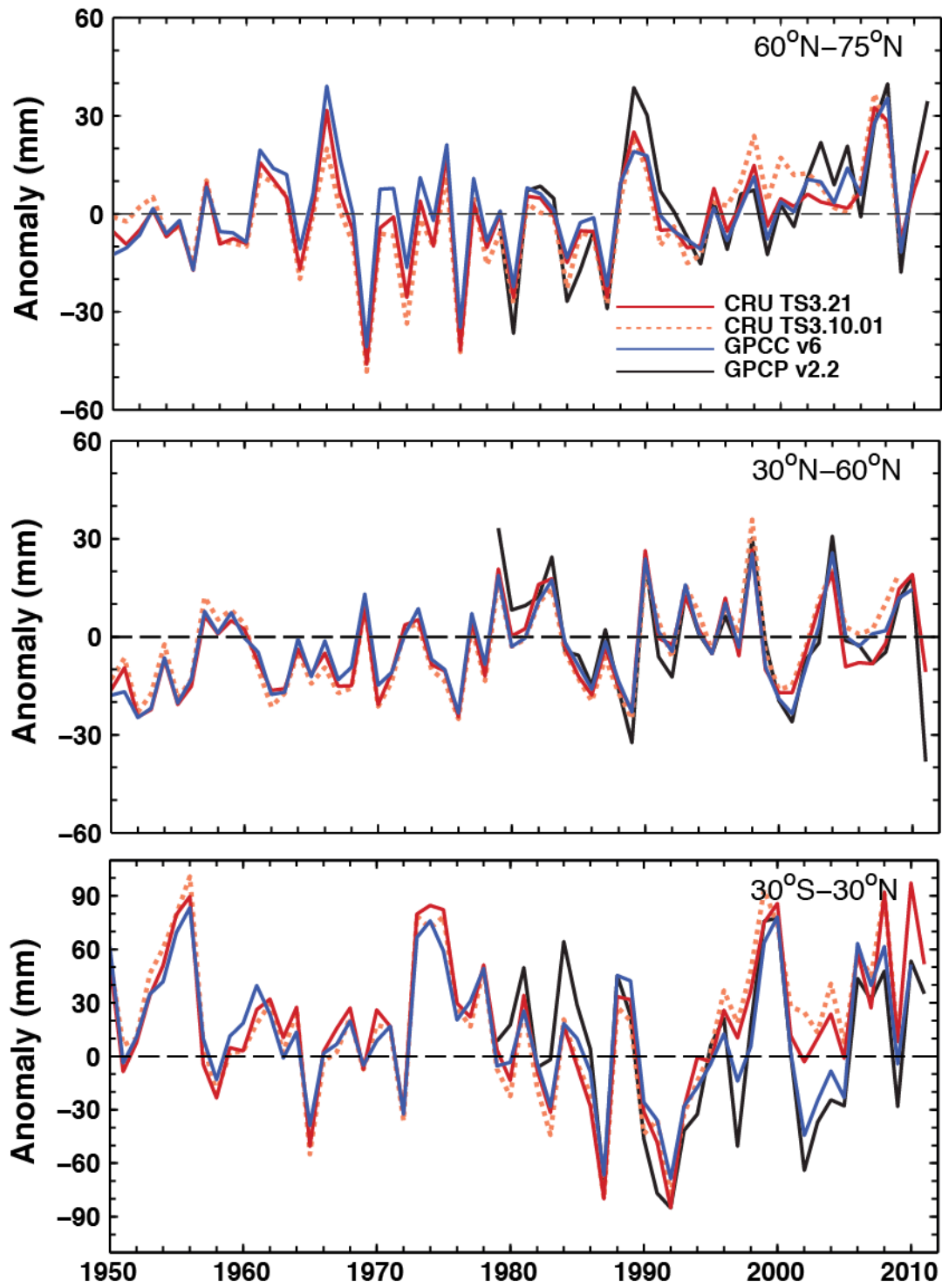


Fig. 2. Time series of mean precipitation for zones indicated in mm for CRU, GPCP and GPCP datasets with a base period of 1981-2000.

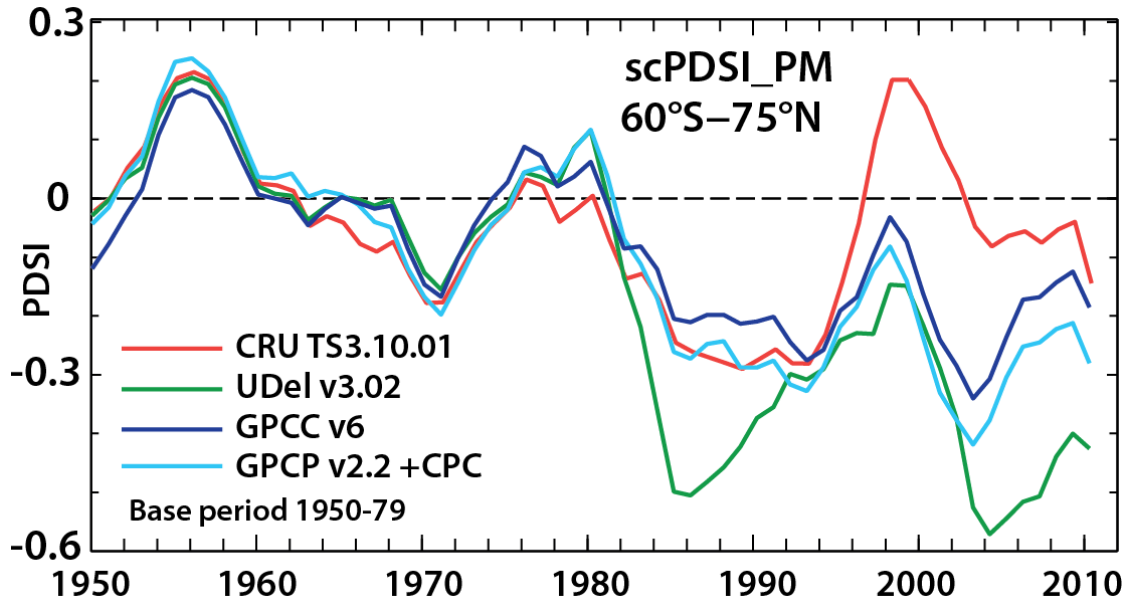


Fig. 3. Time series of 5-yr smoothed global-mean, annual scPDSI\_PM calculated using the same climate forcing except for the precipitation data, which came from four different data sets. All except the CRU TS3.10.01 precipitation case show a statistically significant drying trend ( $p < 0.05$ ). Note the CPC+GPCP precipitation data were used by Dai<sup>4,5</sup>. Sheffield et al.<sup>20</sup> used earlier versions of all four precipitation datasets.