



Revisiting the parameterization of potential evaporation as a driver of long-term water balance trends

Michael T. Hobbins,¹ Aiguo Dai,² Michael L. Roderick,¹ and Graham D. Farquhar¹

Received 4 March 2008; revised 10 April 2008; accepted 16 April 2008; published 20 June 2008.

[1] We examine the effects of two different parameterizations of potential evaporation on long-term trends in soil moisture, evaporative flux and runoff simulated by the water balance model underlying the Palmer Drought Severity Index. The first, traditional parameterization is based on air temperature alone. The second parameterization is derived from observations of evaporation from class-A pans. Trends in potential evaporation from the two parameterizations are opposite in sign (\pm) at almost half the stations tested over Australia and New Zealand. The sign of trends in the modelled soil moisture, evaporative flux and runoff depends on the parameterization used and on the prevailing climatic regime: trends in water-limited regions are driven by precipitation trends, but the choice of parameterization for potential evaporation is shown to be critical in energy-limited regions. **Citation:** Hobbins, M. T., A. Dai, M. L. Roderick, and G. D. Farquhar (2008), Revisiting the parameterization of potential evaporation as a driver of long-term water balance trends, *Geophys. Res. Lett.*, 35, L12403, doi:10.1029/2008GL033840.

1. Introduction

1.1. Background

[2] Simple water balance models are often used to assess land surface moisture conditions. A typical example is the water balance model underlying calculations of the Palmer Drought Severity Index (PDSI) [Palmer, 1965]. Routinely used in the US to assess developing drought conditions, this model was recently extended on a worldwide, long-term basis leading to the conclusion that many regions have become drier and more drought-affected during recent decades [Dai et al., 2004]. In the PDSI, the water-balance is calculated using a bucket model, yielding a moisture anomaly from which the non-dimensional, monthly drought index is derived. In the bucket model, soil fills with precipitation (*Prcp*) and empties through actual evapotranspiration (ET_a) and *Runoff*. At each model time step, the maximum possible ET_a is the minimum of the evaporative demand, herein denoted potential evaporation (E_p), and the available water.

1.2. Water- and Energy-Limited Environments

[3] E_p and ET_a can be considered in the classical framework of the limitations on ET_a . In environments with a limited supply of soil-water to evaporate, ET_a is less than

E_p . In these “water-limited” environments, it is changes in the availability of water (through *Prcp*), and not of energy, that dominate changes in ET_a . As water availability increases, ET_a converges towards E_p until they are equal in wet environments. Here only the availability of energy limits ET_a , and in such “energy-limited” environments, increasing *Prcp* will not change ET_a but will increase soil moisture and/or *Runoff*. Increasing the availability of energy alone at energy-limited sites will raise ET_a and consequently depress soil moisture and/or *Runoff*. Most regions in the world lie in the continuum between the water and energy limits, reaching either only seasonally. The method used to estimate E_p (and hence constrain ET_a) influences the water balance calculation and the resulting conclusions on long-term trends, hence it is the effects of different E_p formulations on long-term water balance variables that motivate this paper.

1.3. E_p Trends

[4] In the traditional formulation of the PDSI bucket model, evaporative demand is derived from an approach that can be traced back to *Thornthwaite* [1948] and is solely a function of air temperature (T_{air}). Consequently, as T_{air} steadily increases with global warming, the calculated value of E_p in the model also steadily increases. In contrast, the measurements of pan evaporation (E_{pan}) that are better physical representations of E_p show widespread declines over the last 30-50 years [Peterson et al., 1995; Chattopadhyay and Hulme, 1997; Golubev et al., 2001; Hobbins et al., 2004; Liu et al., 2004; Roderick and Farquhar, 2004, 2005; Tebakari et al., 2005; Wu et al., 2006]. Similarly, calculations of reference ET [Allen et al., 1998] (also see auxiliary material¹) using observations of solar radiation, T_{air} , humidity, and wind speed also show declines [Thomas, 2000; Chen et al., 2005; Shenbin et al., 2006], in general agreement with the E_{pan} record in China. The poor performance of T_{air} -based E_p in predicting observed evaporative demand was further highlighted in China, where rising T_{air} but declining E_{pan} were found across eight of the 10 river basins [Chen et al., 2005].

[5] The key point here is that E_p is less affected by changes in T_{air} than by changes in surface radiation, wind speed, and humidity deficit [Roderick et al., 2007]. Indeed, when formulating the PDSI, *Palmer* [1965] recognized the importance of all of these dynamics driving the more physically complete *Penman* [1948] E_p -formulation, but justified his choice of an equation for E_p based solely on T_{air} by an appeal to expediency, having previously noted, “. . . *Thornthwaite*’s empirical formula can be used for any location at which daily maximum and minimum temperatures are recorded. It is this simple universal applicability

¹Environmental Biology Group, Research School of Biological Sciences, Australian National University, Canberra, A.C.T., Australia.

²National Center for Atmospheric Research, Boulder, Colorado, USA.

Table 1. Magnitude, Range, Direction, and Significance of Temporal Trends for the Inputs and Both Parameterizations' Outputs Across the Two Sets of Stations^a

Parameterization	Variable	Trend Statistics			Trend Direction (# p ≤ 0.05)	
		Mean ± Stdev	Min	Max	+ve	-ve
<i>Australia, 27 stations, 1975–2004</i>						
Observed	<i>Prcp</i>	0.10 ± 3.92	-10.31	6.84	14 (1)	13 (1)
	<i>T_{air}</i>	0.01 ± 0.01	-0.01	0.03	22 (6)	5 (0)
	<i>E_{pan}</i>	-2.67 ± 7.62	-17.48	10.95	10 (3)	17 (7)
<i>E_p</i> ^{PDSI}	<i>E_p</i>	1.14 ± 1.25	-0.59	3.83	20 (6)	7 (0)
	<i>ET_a</i>	0.45 ± 3.02	-9.37	6.71	16 (2)	11 (1)
	<i>SM</i>	-0.27 ± 0.99	-3.75	0.99	13 (0)	14 (2)
	<i>Runoff</i>	-0.50 ± 1.72	-7.52	1.25	17 (0)	10 (0)
<i>E_p</i> ^{Pan}	<i>E_p</i>	-2.00 ± 5.72	-13.11	8.22	10 (3)	17 (7)
	<i>ET_a</i>	0.15 ± 3.20	-9.66	6.76	14 (1)	13 (1)
	<i>SM</i>	-0.05 ± 0.94	-3.94	1.17	14 (0)	13 (2)
	<i>Runoff</i>	-0.14 ± 2.02	-6.68	6.24	18 (0)	9 (1)
<i>New Zealand, 8 stations, 1974–2003</i>						
Observed	<i>Prcp</i>	-3.24 ± 6.34	-12.16	4.88	3 (0)	5 (4)
	<i>T_{air}</i>	0.02 ± 0.01	-0.01	0.04	7 (3)	1 (0)
	<i>E_{pan}</i>	-1.77 ± 2.21	-4.74	0.89	3 (0)	5 (2)
<i>E_p</i> ^{PDSI}	<i>E_p</i>	1.03 ± 0.98	-0.49	2.54	7 (3)	1 (0)
	<i>ET_a</i>	0.51 ± 1.55	-2.14	2.51	6 (2)	2 (0)
	<i>SM</i>	0.19 ± 0.64	-1.55	0.39	5 (1)	3 (1)
	<i>Runoff</i>	-3.58 ± 5.80	-12.90	4.75	3 (0)	5 (4)
<i>E_p</i> ^{Pan}	<i>E_p</i>	-1.24 ± 1.55	-3.32	0.62	3 (0)	5 (2)
	<i>ET_a</i>	-0.89 ± 2.77	-5.58	2.36	4 (1)	4 (2)
	<i>SM</i>	-0.05 ± 0.61	-0.94	0.88	5 (1)	3 (2)
	<i>Runoff</i>	-2.21 ± 4.83	-8.83	4.83	3 (0)	5 (3)

^aUnits are mm/year² for trends in *Prcp*, *E_{pan}*, *E_p*, *ET_a*, and *Runoff*; °C/year for trends in *T_{air}*; and mm/year for trends in *SM*. Means and standard deviations are across the 27 stations in Australia and eight stations in New Zealand. Numbers in parentheses count trends significant at 95%.

rather than any claim to outstanding accuracy which has led to the widespread use of this method” [Palmer and Havens, 1958]. In fact, Thornthwaite [1948], too, expected his *T_{air}*-based approach to be replaced by a more physically based method as the necessary theory was developed and supporting data became more widely available. As evaporation from a water surface inside a pan integrates all these factors [Rotstayn et al., 2006], its measurements have long been widely used as a physical measure of *E_p* in agricultural and engineering applications. While other workers have examined the sensitivity of long-term PDSI to various model features [e.g., Karl, 1986], no-one has yet examined the effects of using such a physically based *E_p*.

[6] Clearly, the declining trend in physically based measures of *E_p* compared to the increasing trend implied by calculations based solely on *T_{air}* might lead to different conclusions about trends in drying [Moonen et al., 2002]. In this paper, we examine that proposition by running the PDSI water balance model at 35 sites across Australia and New Zealand. At each site, the model is run twice. In the first run, we calculate *E_p* per the standard PDSI implementation using *T_{air}* measurements. In the second run, *E_p* is based on pan evaporation observations. No other forcings (e.g., *Prcp*) and model parameters are changed, thereby isolating the effect of different formulations of evaporative demand on the outputs of the water balance model (*ET_a*, soil

moisture, and *Runoff*) and hence on the modelling of drought.

2. Methods and Materials

2.1. Description of the Water Balance Model

[7] The PDSI bucket model uses a two-layer soil column, with the water content at field capacity set as 25.4 mm (1 inch) for the upper layer, where it is assumed freely available for evapotranspiration, and that for the lower layer (or root zone) prescribed by the analyst. Evaporative demand in the PDSI is traditionally set as a time-series of *T_{air}*-based *E_p*. *Prcp* is partitioned into recharge, filling first the upper soil layer and then the lower layer, until the soil column fills; *Runoff* occurs when whole-column soil moisture is at field capacity and evaporative demand (i.e., *E_p*) from both layers has been met. When *Prcp* and upper-layer soil moisture cannot meet *E_p*, the soil dries in two stages: moisture in the upper soil-layer completely evaporates at the potential rate (i.e., *E_p*), then that in the root-zone declines at a rate depending on root-zone soil moisture and unmet *E_p*. Note that the physiologic response of vegetation to water limitation is modelled in this two-layer soil column, not in the parameterization of evaporative demand. The water-equivalent depth of the bucket (*AWC*) was set using the same 2.5° × 2.5° global grid used by Dai et al. [2004] (see Figure S1a).

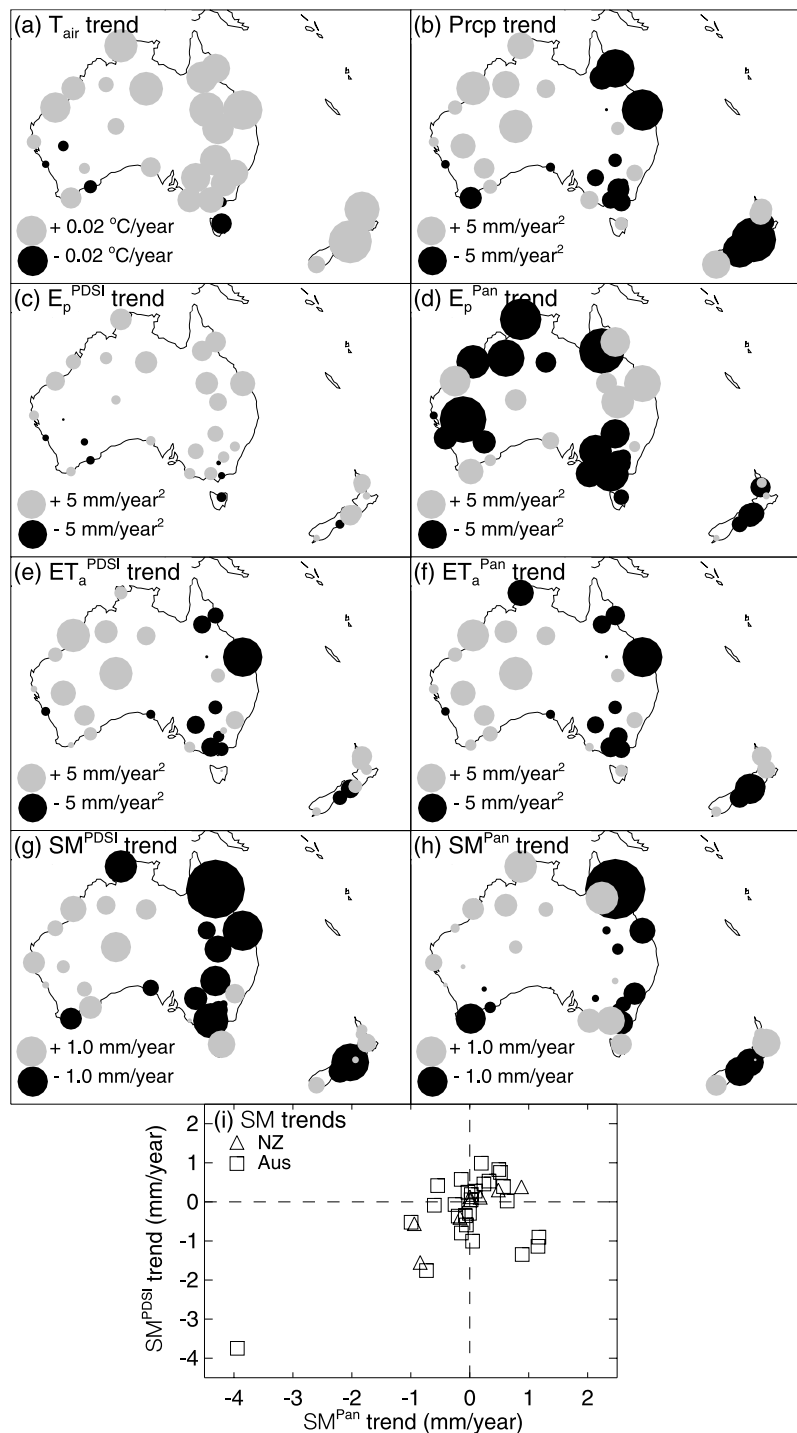


Figure 1. Annual trends at 27 stations in Australia and eight in New Zealand over the periods 1975–2004 (Australia) and 1974–2002 (New Zealand). Maps show direction and scale of trends for (a) T_{air} , (b) $Prcp$, (c) E_p^{PDSI} , (d) E_p^{Pan} , (e) ET_a^{PDSI} , (f) ET_a^{Pan} , (g) SM^{PDSI} , and (h) SM^{Pan} . Grey circles indicate positive trends, black circles negative, with areas proportional to trend magnitudes. In (i) the station-trends in SM^{PDSI} (Figure 1g) are plotted against those in SM^{Pan} (Figure 1h).

2.2. Data and Study Area

[8] We chose Australia and New Zealand as our study area. This represents a wide climatic range because Australia is primarily water-limited and New Zealand energy-limited (see section SI.3 and Figure S3). Australian stations were restricted to the 27 sites with monthly T_{air} , $Prcp$, and E_{pan} data used by Roderick *et al.* [2007] that were also part of the High Quality Annual T_{air} data network [Della-Marta

et al., 2004]. The period of analysis for Australian data was 1975–2004. We selected the eight New Zealand sites for which long-term monthly $Prcp$, T_{air} , and E_{pan} records were available from the National Institute of Water and Atmospheric Research (NIWA). Analysis periods varied across the New Zealand sites but were constrained to within 1974–2003 (see Table S2).

[9] As the soil moisture-accounting in the PDSI bucket model requires continuous monthly input time-series, missing data were filled as follows: (i) when only one or two months' data were missing from a year, these monthly data were scaled from their climatological monthly means according to the proportion in the rest of the year; or (ii) when over two months' data were missing from a given year, all months of that year were replaced by their climatological means. In the worst case (E_{pan} for New Zealand), less than 3% of data were infilled. For further details on data sources, see section SI.2.

2.3. Two Estimates of E_p

[10] Our first estimate of E_p is that used operationally in the PDSI by NOAA [Dai *et al.*, 2004], and here denoted E_p^{PDSI} (see equations (S1)–(S3)). The constant heat factors (B and H , see equation (S2)) required for E_p^{PDSI} were prescribed using the $2.5^\circ \times 2.5^\circ$ global grids from Dai *et al.* [2004] (see Figures S1b and S1c). Our second E_p estimate uses observed monthly E_{pan} multiplied by the traditional pan coefficient k , i.e., $E_p^{\text{pan}} = k.E_{pan}$. While k has been shown to vary seasonally [Allen *et al.*, 1998], the widely adopted value of 0.7 [Stanhill, 1976] was used for the unscreened New Zealand pans. For the Australian pans, k was set to 0.75 to account for the 7% reduction in E_{pan} due to the bird-guards [van Dijk, 1985].

2.4. Model Calculations

[11] In running the PDSI bucket model, initial SM was specified equal to AWC , for the following reasons: first, it is standard PDSI procedure to initiate the model run with maximum moisture in both soil layers; second, a sensitivity analysis (not shown) indicated that the effects of initial conditions disappeared within two years. Nonetheless, to eliminate bias and minimize the effects of high initial SM conditions, the models were run for two years prior to the analysis period. Trends were defined as the slope of an Ordinary Least Squares regression through annual time-series, with the significance of annual trends determined by t -tests. As the model conserves mass, the trends in the component fluxes ($Prcp$, ET_a , and $Runoff$) sum to the second time-differential of SM . We report the first time-differential of SM as it is of greatest climatological interest.

3. Results

[12] The observed trends in the input time-series— T_{air} (for the E_p^{PDSI} run), $Prcp$ (for both runs), and $k.E_{pan}$ (for the E_p^{pan} run)—are shown in Figures 1a, 1b, and 1d, respectively, and closely match previous results for Australia and New Zealand [Roderick and Farquhar, 2004, 2005]. The difference between the two E_p measures is apparent in Figures 1c and 1d. Note that of the 35 sites, most (27) show increases in E_p^{PDSI} , in line with the general increase in T_{air} shown in Figure 1a. In contrast, only 13 sites showed increases in E_p^{pan} .

[13] ET_a -trends in Australia (Figures 1e and 1f) generally follow the $Prcp$ -trends (Figure 1b). This result is expected because Australia is largely water-limited (section SI.3 and Figure S3), so trends in moisture supply, not in evaporative demand, largely determine the ET_a -trend. However, in New Zealand, whether ET_a -trends increased or decreased depended on the E_p parameterization. Again,

this result is expected because at energy-limited sites, ET_a is sensitive to changes in E_p . Clearly, ET_a^{pan} in New Zealand responds to dynamics in evaporative demand missing from the E_p^{PDSI} parameterization. While differences exist between the scale and direction of SM -trends, both parameterizations generate generally declining SM in eastern Australia and central New Zealand, with increases in western Australia and northern and southern New Zealand (Figures 1g and 1h). Again, in Australia, both models generate spatial patterns of SM -trends more closely resembling trends in $Prcp$ than in E_p . Figure 1i shows the relations between SM -trends between the two parameterizations at all stations mapped in Figures 1g and 1h. Clearly, there is little relationship between the SM -trends predicted using E_p^{PDSI} and E_p^{pan} : at seven of the 35 stations, they are of different signs, and five of these stations are located in important agricultural and/or populated regions of southwestern Western Australia, New South Wales, and Victoria.

[14] The potential for mismatch between the hydrologic trends estimated by the two parameterizations is further demonstrated at Darwin (the northernmost station in the Australian set), which is energy-limited on an annual basis. Here moisture supply is increasing ($dPrcp/dt = +4.4 \text{ mm/year}^2$), but the E_p -parameterizations' respective drivers are in conflict: warming leads to increasing E_p^{PDSI} ($dT_{air}/dt = +0.02^\circ\text{C/year}$, $dE_p^{\text{PDSI}}/dt = +2.8 \text{ mm/year}^2$), but E_{pan} is decreasing ($dE_p^{\text{pan}}/dt = -10.4 \text{ mm/year}^2$) due to declining wind speeds and solar radiation [Rayner, 2007; Roderick *et al.*, 2007]. The decline in the energy available for evaporation is captured by the E_p^{pan} observations, but not by the E_p^{PDSI} calculations because the latter do not respond to solar radiation or wind speed. Thus, the two parameterizations drive the PDSI bucket model to indicate opposite trends in ET_a ($dET_a^{\text{PDSI}}/dt = +1.1 \text{ mm/year}^2$, $dET_a^{\text{pan}}/dt = -4.2 \text{ mm/year}^2$), which leads to the soil drying in the case of E_p^{PDSI} ($dSM^{\text{PDSI}}/dt = -1.1 \text{ mm/year}$) and wetting in the case of E_p^{pan} ($dSM^{\text{pan}}/dt = +1.2 \text{ mm/year}$).

4. Discussion

[15] In assessing the likely ecohydrologic impacts of climate change, projections of continental drying must be reconciled with observations of declining evaporative demand. The PDSI, upon which much support for many of these conflicting projections is based, is an index based on a hydrologic model that predicts evaporative demand from the direct effect of surface warming only. However, the effects of other accompanying changes, such as those in surface radiation, wind speed and humidity, likely play an important role over many land areas [Roderick *et al.*, 2007].

[16] Here we have compared long-term trends in ET_a and SM from the PDSI bucket model forced by two parameterizations of E_p : one based on T_{air} alone; the other derived from observations of a physical metric of evaporative demand (i.e., E_{pan}) that responds to the appropriate dynamics— T_{air} , humidity, wind speed, and net available energy [Rotstajn *et al.*, 2006]. The primary attraction of the T_{air} -based E_p^{PDSI} is simplicity: only T_{air} data are required, and such data are widely available in time and space, including historical global grids at many spatio-temporal resolutions. That historical T_{air} -trends are more certain than trends in radiation, humidity, and wind speed, demonstrates the value

of the E_{pan} record: these variables are physically integrated into E_{pan} measurements. Here we have shown that T_{air} -based E_p cannot predict the directions of observed trends in evaporative demand: 46% of the long-term trend directions predicted by E_p^{PDSI} are opposite to those observed in E_{pan} across Australia and New Zealand.

[17] It is important to note that using T_{air} -based parameterizations in climate change analyses—particularly in deriving trends in drought dynamics—invokes retrograde assumptions about the relationships of T_{air} to all other evaporative drivers. In fact, using T_{air} -based E_p produces an apparent paradox with declining E_{pan} in Australia, which has been resolved by Roderick *et al.* [2007] as caused by reductions in wind speed and some regional changes in solar radiation—both drivers unaccounted for in a T_{air} -based E_p . It can be no surprise then that T_{air} -based predictions of drying under warming contradict a gathering wealth of reports of decreasing evaporative demand in the face of global warming.

[18] More subtle interactions between trends in the surface water balance arise in energy-limited regions than in water-limited regions, so the answer to the question “does warming mean drying?” depends critically on accompanying changes in $Prcp$ and also on the climate regime in question. Our Budyko-based climatological analysis (see Figure S3) indicates that, over water-limited regions such as most of Australia, trends in ET_a are largely determined by trends in $Prcp$, and not in E_p . However, this conclusion does not assist in the essential regional analyses: it is in the southern and eastern regions of Australia—areas that are wetter (i.e., more energy-limited) than the continental mean and, crucially, where most people live and most agricultural production occurs—that the differences in direction and scale of SM -trends between parameterizations are most apparent. Here, the E_p parameterization choice is crucial.

[19] Our conclusions regarding the disjunction between drying predicted by T_{air} -based parameterizations and observations of wetting are also implicit in the results of Robock *et al.* [2005], who, working with a large-scale set of observed soil moisture in the Ukraine from 1958 to 2002, found that decreasing summer $Prcp$ under a warming trend had still resulted in increased summer soil moisture.

5. Conclusions

[20] Our comparison of different E_p formulations in the PDSI bucket model has highlighted the problems with the T_{air} -based parameterization of evaporative demand classically used in a well-established water balance model (i.e., E_p^{PDSI}). We find that, in energy-limited regions, what constitutes drying under E_p^{PDSI} frequently shows as wetting under E_p^{Pan} . While the analysis here is limited to Australia and New Zealand, our station selection covers a broad climatic range, so we expect our findings—wetting often projected by a physically based parameterization where drying had previously been projected by one that is T_{air} -based—to apply elsewhere, as over the last few decades declining E_{pan} has been widely observed in the face of globally rising T_{air} .

[21] The PDSI model could be parameterized with potential evapotranspiration, such as that from the Pen-

man-Monteith approach. However, the limited availability of data on humidity, solar radiation, wind speed, and surface resistance currently preclude such an observational study on a global or even continental basis, although work progresses on developing such datasets [Dai *et al.*, 2005]. In the meantime, however, results from a multi-model ensemble-mean (see Figure 10.12 in the IPCC AR4 WG1 report [Meehl *et al.*, 2007]) indicate patterns of projected trends in ET_a broadly similar to those in $Prcp$ over much of the global land surface.

[22] Our continent-wide results warn against an oversimplistic treatment of evaporative demand in water balance models and highlight the urgent need for a more rigorous approach to assessing long-term changes in the terrestrial water balance. The effects of this over-simplicity may be obscured in water-limited regions as evapotranspiration there is strictly constrained by water availability. However, more rigorous analyses are particularly wanting over regions where evapotranspiration is limited frequently or consistently by the availability of energy, and where this empirical study shows important dependencies of ET_a and SM on E_p . Meeting this need over more than select regions presents the hydroclimatological community with the same challenge originally laid down by Penman [1948], Thornthwaite [1948], and Palmer [1965]: to develop reliable global datasets of radiation, humidity and wind as well as air temperature and precipitation to permit physically sound estimations of water balance trends.

[23] **Acknowledgments.** We acknowledge funding support from a Gary Comer Award. We acknowledge the BoM and NIWA and especially the numerous observers whose work formed the ultimate basis of this study. The National Center for Atmospheric Research is sponsored by the U.S. National Science Foundation. Dai is also partly supported by NCAR's Water Cycle Program.

References

- Allen, R. G., L. S. Pereira, D. Raes, M. Smith (1998), Crop evapotranspiration: Guidelines for computing crop water requirements, *FAO Irrig. Drain. Pap.*, 56, Food and Agric. Org., Rome.
- Chattopadhyay, N., and M. Hulme (1997), Evaporation and potential evapotranspiration in India under conditions of recent and future climate change, *Agric. For. Meteorol.*, 87, 55–73.
- Chen, D., G. Gao, C.-Y. Xu, J. Guo, and G. Ren (2005), Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China, *Clim. Res.*, 28, 123–132.
- Dai, A., T. Trenberth, and K. E. Qian (2004), A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, 5, 117–130.
- Dai, A., T. Qian, K. E. Trenberth (2005), Has the recent global warming caused increased drying over land?, paper presented at 16th *Symposium on Global Change and Climate Variations/Symposium on Living with a Limited Water Supply*, Am. Meteorol. Soc., San Diego, Calif.
- Della-Marta, P., D. Collins, and K. Braganza (2004), Updating Australia's high-quality annual temperature dataset, *Aust. Meteorol. Mag.*, 53, 75–93.
- Golubev, V. S., J. H. Lawrimore, P. Y. Groisman, N. A. Speranskaya, S. A. Zhuravin, M. J. Menne, T. C. Peterson, and R. W. Malone (2001), Evaporation changes over the contiguous United States and the former USSR: A reassessment, *Geophys. Res. Lett.*, 28, 2665–2668.
- Hobbins, M. T., J. A. Ramirez, and T. C. Brown (2004), Trends in pan evaporation and actual evapotranspiration across the conterminous US: Paradoxical or complementary?, *Geophys. Res. Lett.*, 31(13), L13503, doi:10.1029/2004GL019846.
- Karl, T. R. (1986), Sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their calibration coefficients including potential evapotranspiration, *J. Clim. Appl. Meteorol.*, 25, 77–86.
- Liu, B., M. Xu, M. Henderson, and W. Gong (2004), A spatial analysis of pan evaporation trends in China, 1955–2000, *J. Geophys. Res.*, 109, D15102, doi:10.1029/2004JD004511.

- Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 749–845, Cambridge Univ. Press, Cambridge, U. K.
- Moonen, A. C., L. Ercoli, M. Mariotti, and A. Masoni (2002), Climate change in Italy indicated by agrometeorological indices over 122 years, *Agric. For. Meteorol.*, *111*, 13–27.
- Palmer, W. C. (1965), Meteorological drought, Res. Pap. 45, 58 pp., U. S. Dep. of Comm., Washington, D. C.
- Palmer, W. C., and A. V. Havens (1958), A graphical technique for determining evapotranspiration by the Thornthwaite method, *Mon. Weather Rev.*, *86*, 123–128.
- Penman, H. L. (1948), Natural evaporation from open water, bare soil and grass, *Proc. R. S. London, Series A*, *193*, 120–146.
- Peterson, T. C., V. S. Golubev, and P. Y. Groisman (1995), Evaporation losing its strength, *Nature*, *377*, 687–688.
- Rayner, D. P. (2007), Wind run changes: The dominant factor affecting pan evaporation trends in Australia, *J. Clim.*, *20*(14), 3379–3394, doi:10.1175/JCLI4181.1.
- Robock, A., M. Mu, K. Vinnikov, I. V. Trofimova, and T. I. Adamenko (2005), Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet), *Geophys. Res. Lett.*, *32*, L03401, doi:10.1029/2004GL021914.
- Roderick, M. L., and G. D. Farquhar (2004), Changes in Australian pan evaporation from 1970 to 2002, *Int. J. Climatol.*, *24*, 1077–1090.
- Roderick, M. L., and G. D. Farquhar (2005), Changes in New Zealand pan evaporation since the 1970s, *Int. J. Climatol.*, *25*, 2031–2039.
- Roderick, M. L., L. D. Rotstain, G. D. Farquhar, and M. T. Hobbins (2007), On the attribution of changing pan evaporation, *Geophys. Res. Lett.*, *34*, L17403, doi:10.1029/2007GL031166.
- Rotstain, L. D., M. L. Roderick, and G. D. Farquhar (2006), A simple pan-evaporation model for analysis of climate simulations: Evaluation over Australia, *Geophys. Res. Lett.*, *33*, L17715, doi:10.1029/2006GL027114.
- Shenbin, C., L. Yunfeng, and A. Thomas (2006), Climatic change on the Tibetan plateau: Potential evapotranspiration trends from 1961–2000, *Clim. Change*, *76*, 291–319.
- Stanhill, G., (1976), The CIMO international evaporimeter comparisons, WMO Publ. 449, 38 pp., World Meteorol. Org., Geneva, Switzerland.
- Tebakari, T., J. Yoshitani, and C. Suvanpimol (2005), Time-space trend analysis in pan evaporation over Kingdom of Thailand, *J. Hydrol. Eng.*, *10*, 205–215.
- Thomas, A. (2000), Spatial and temporal characteristics of potential evapotranspiration trends over China, *Int. J. Climatol.*, *20*, 381–396.
- Thornthwaite, C. W. (1948), An approach toward a rational classification of climate, *Geogr. Rev.*, *38*, 55–94.
- van Dijk, M. H. (1985), Reduction in evaporation due to the bird screen used in the Australian class A pan evaporation network, *Aust. Meteorol. Mag.*, *33*, 181–183.
- Wu, S., Y. Yin, D. Zheng, and Q. Yang (2006), Moisture conditions and climate trends in China during the period 1971–2000, *Int. J. Climatol.*, *26*, 193–206.

A. Dai, National Center for Atmospheric Research, P.O. 3000, Boulder, CO 80307, USA.

G. D. Farquhar, M. T. Hobbins, and M. L. Roderick, Environmental Biology Group, Research School of Biological Sciences, Australian National University, Canberra, ACT 0200, Australia. (michael.hobbins@anu.edu.au)