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CHANGES IN AUSTRALIAN PAN EVAPORATION FROM 1970 TO 2002

MICHAEL L. RODERICK and GRAHAM D. FARQUHAR*
Cooperative Research Centre for Greenhouse Accounting, Research School of Biological Sciences, Institute of Advanced Studies, The Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

Contrary to expectations, measurements of pan evaporation show decreases in many parts of the Northern Hemisphere over the last 50 years. When combined with rainfall measurements, these data show that much of the Northern Hemisphere's terrestrial surface has become less arid over the last 50 years. However, whether the decrease in pan evaporation is a phenomenon limited to the Northern Hemisphere has until now been unknown because there have been no reports from the Southern Hemisphere. Here, we report a decrease in pan evaporation rate over the last 30 years across Australia of the same magnitude as the Northern Hemisphere trends (approximately -4 mm a^{-2}). The results show that the terrestrial surface in Australia has, on average, become less arid over the recent past, just like much of the Northern Hemisphere. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: climate change; enhanced greenhouse effect; hydrological cycle; pan evaporation; potential evaporation; water cycle

1. INTRODUCTION

The moisture balance at the terrestrial surface can be described as a balance between the atmospheric supply (rainfall) and atmospheric demand (potential evaporation) (Budyko, 1948, 1974; Penman, 1948). In applications such as those in ecology, hydrology, agriculture and engineering, the potential evaporation is taken to be proportional to the rate at which water evaporates from a pan located at the surface, known as pan evaporation. Because of the widespread applications, pan evaporation is routinely measured by various agencies (Stanhill, 2002) and those data are used together with rainfall measurements to characterize the surface moisture balance, and changes in it.

Changes in terrestrial rainfall around the world have been well documented, and the general trend has been for increases over most regions (with notable exceptions in parts of Africa) over both the last 50 and 100 years (Folland *et al*., 2001). In contrast, little attention has been given to changes in potential evaporation. However, there has long been an expectation, e.g. by the Intergovernmental Panel of Climate Change (IPCC; e.g. Stocker *et al*., 2001) and others (e.g. Robock *et al*., 2000), that potential evaporation will increase as the average air temperature near the surface increases. This expectation is based on an implicit assumption that, as the air temperature increases, everything else is held constant. That is, the potential evaporation would increase as the air at the surface warmed if there were no change in the vapour content of the air and windspeed were unchanged. However, data reported by the IPCC show that as the average surface temperature has increased there has also been a marked increase in the vapour pressure (Folland *et al*., 2001). Accordingly, the average relative humidity in air adjacent to the surface appears to remain very nearly constant (Roderick and Farquhar, 2002). This is not unexpected — the original work of Arrhenius (1896) assumed constant

* Correspondence to: Graham D. Farquhar, Cooperative Research Centre for Greenhouse Accounting, Research School of Biological Sciences, Institute of Advanced Studies, The Australian National University, Canberra, ACT 0200, Australia;
e-mail: farquhar@rsbs.anu.edu.au

relative humidity as surface temperature changed. If the relative humidity does remain near constant, then it follows from physical principles that potential evaporation will be insensitive to changes in the *average* surface temperature (Monteith and Unsworth, 1990: 187).

Empirically, one can evaluate trends in potential evaporation using measurements of pan evaporation. To date, the scientific community has been mostly interested in the gross trends in pan evaporation. Accordingly, most of the previous studies have been based on averages across many pans and there are some sites where pan evaporation has increased and others where it has decreased. Nevertheless, the first published report showed that, on average, pan evaporation had decreased over the USA, Former Soviet Union and Eurasia for the period 1950 until the early 1990s (Peterson *et al*., 1995). Subsequent reports have confirmed this to be a general trend throughout the Northern Hemisphere. For example, over the same period, decreases in pan evaporation have been reported in India (Chattopadhyay and Hulme, 1997), China (Thomas, 2000) and Italy (Moonen *et al*., 2002), although some mixed trends have also been reported, e.g. East Asia (Xu, 2001), and a slight increase at a single pan in Israel (Cohen *et al*., 2002).

The reported changes in rainfall and potential evaporation are large enough for the consequent changes in surface moisture balance to be readily observed. However, to interpret the changes we must distinguish between actual and potential evaporation (Budyko, 1974). Actual evaporation is the evaporation that occurs from the environment surrounding the pan. In a dry environment, actual evaporation is less than potential evaporation because it is the supply of water (rainfall) that is limiting. In contrast, in a wet environment, the available energy is limiting and actual evaporation is usually equated to the potential evaporation. Hence, when using the supply–demand framework, sites are separated into water-limited (rainfall less than potential evaporation) and energy-limited (rainfall greater than potential evaporation) categories (Budyko, 1974). (Note that potential evaporation is approximately 0.7 times the pan evaporation, where the factor of 0.7 is known as the pan coefficient (Linacre, 1993a,b).) At energy-limited sites, a decrease in pan evaporation, at constant rainfall, implies that actual evaporation will decrease and runoff and/or soil moisture will increase. Importantly, all of these predicted changes have been observed in Russia over the last 50 years (Robock *et al*., 2000; Golubev *et al*., 2001; Peterson *et al*., 2002). Conversely, in a water-limited environment, actual evaporation is limited by available water and not energy, and changes in actual evaporation are dominated by changes in rainfall (Budyko, 1974; Choudhury, 1999; Milly and Dunne, 2002). Nevertheless, a general trend for water-limited sites is that, at constant rainfall, a decline in pan evaporation will result in an overall increase in biological productivity because of a reduction in the moisture deficit (i.e. the supply of water is more capable of meeting the atmospheric demand). Hence, it is no surprise that model-based estimates show an increase in carbon uptake for the USA over the last century (Nemani *et al*., 2002), given that the average trend in that region has been for more rainfall and less pan evaporation (Peterson *et al*., 1995; Groisman *et al*., 2004). Further, the trend for more rainfall and less potential evaporation in the USA implies that runoff must have increased. This has been observed (Lins and Slack, 1999; Groisman *et al*., 2004).

The trends in rainfall and pan evaporation described above show that the terrestrial surface in the Northern Hemisphere has, on average, become less arid. What is of particular interest here is that, as noted above, Arrhenius (1896) based his greenhouse calculations on the assumption of constant relative humidity. This assumption has proved to be insightful. While as yet overlooked, it is important to note that Arrhenius (1896) also asserted that the calculated warming as a result of increasing atmospheric CO_2 would decrease the diurnal temperature range. (Note that Arrhenius apparently thought this to be self-evident and did not give an explanation.) Certainly, the diurnal temperature range has decreased because the nights are getting warmer faster than the days (Karl *et al*., 1993; Easterling *et al*., 1997). This also appears be a necessary condition for the average relative humidity to remain constant (Roderick and Farquhar, 2002). With the relative humidity being constant, this leaves net irradiance and windspeed as possible reasons for the decline in pan evaporation. There is strong evidence that a decline in sunlight at the surface (Stanhill and Cohen, 2001) has played an important role in the decline in pan evaporation in the Northern Hemisphere (Roderick and Farquhar, 2002) and there has been speculation that this may be an intrinsic feature of the enhanced greenhouse effect (Farquhar and Roderick, 2003). Of course, if the Northern Hemisphere decline in pan evaporation is related to the enhanced greenhouse effect, then there should also be a decline in pan evaporation in the Southern Hemisphere. However, there are as yet no reports of trends in pan evaporation and the associated changes in aridity from the Southern Hemisphere, and so we investigated changes in pan evaporation and rainfall across Australia.

2. DATA AND METHODS

Data used in the analysis were acquired from the Bureau of Meteorology (BoM), which routinely measures evaporation from standardized US Class A pans at selected sites throughout Australia. The BoM pan evaporation network was expanded in the late 1960s, and the existing network was more or less complete by the mid 1970s. Daily rainfall is also recorded at these sites. For the period 1970–2002, we identified 30 sites in the BoM database having both long-term annual pan evaporation measurements and complete rainfall records. A list of the stations is available in the Appendix (Table A.I). To test whether the results and subsequent interpretation were sensitive to the time period, we also analysed pan evaporation and rainfall over the period 1975–2002. There were two reasons for choosing this second, shorter period. First, there were a further 31 sites with complete records for the shorter period. Second, during the mid 1970s many parts of Australia experienced unusually high rainfall and there was a concurrent reduction in pan evaporation (presumably due to high cloud cover, low sunlight and increased relative humidity during the wet period), whereas in 2001–02 many parts of Australia were in drought and pan evaporation was elevated (presumably due to low cloud cover, high sunlight and a reduction in relative humidity during the drought). Hence, for the period 1975–2002, pan evaporation was generally low at the start and high at the end. Thus, any emergence of a trend towards declining pan evaporation rate for the period 1975–2002 would be particularly robust. Both data sets (1970–2002, 30 sites; 1975–2002, 61 sites) were analysed separately for trends in annual pan evaporation and annual rainfall at each site. The significance of the trends was assessed (t-test) at the 95% level (Zar, 1984).

3. RESULTS

The results show that the trends in pan evaporation varied from site to site with perhaps a trend for the decreases in pan evaporation to be strongest in the northwest and southeast (Figure 1; also see Figure A.1 in the Appendix for the 1970–2002 time series at each site). For the 1970–2002 period, about half of the sites (14 out of 30) showed statistically significant declines in pan evaporation and three sites showed statistically significant increases (Table I). In contrast, very few of the trends in rainfall were statistically significant (Table I, Figure 3). When averaged over all 30 sites, the trend in annual pan evaporation rate for the period 1970–2002 was -4.3 ± 1.8 mm a^{-2} and was statistically significant ($p > 0.95$; Figure 2). The trend in rainfall for 1970–2002 when averaged over all sites was not statistically significant (Figure 2). The same general trends were also found for the 1975–2002 period (Figures 1, 3, and 4).

Table I. Number of sites showing statistically significant changes ($p > 0.95$) in annual pan evaporation and rainfall in the two reporting periods

	Sites		
	Decrease	No change	Increase
1970–2002 (30 sites)			
Pan evaporation	14	13	3
Rainfall	2	28	0
1975–2002 (61 sites)			
Pan evaporation	23	33	5
Rainfall	0	60	1

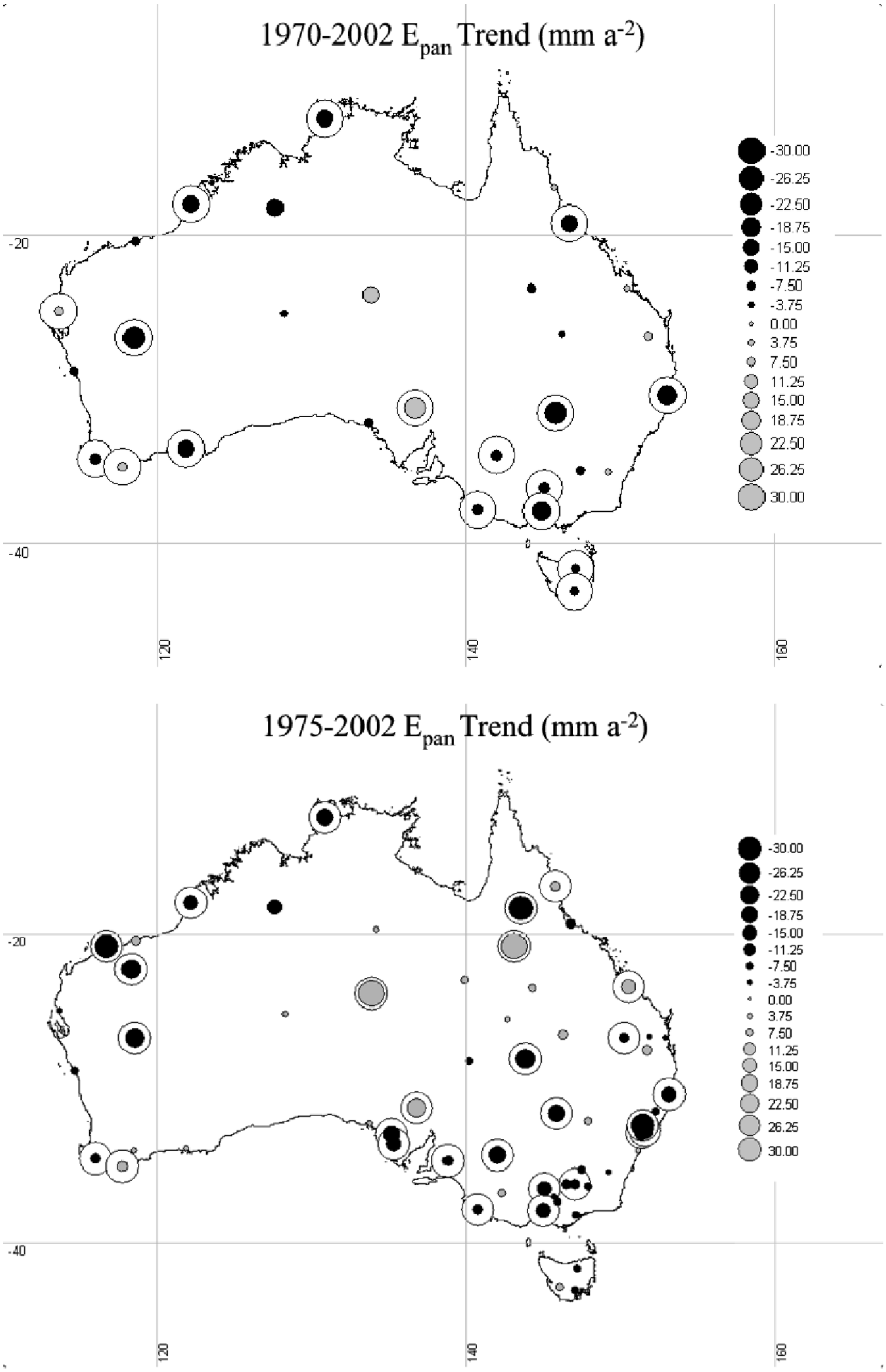

Figure 1. Trends in annual pan evaporation rate E_{pan} for 1970–2002 (30 sites) and 1975–2002 (61 sites). Dots enclosed by a circle denote a statistically significant ($p > 0.95$) trend

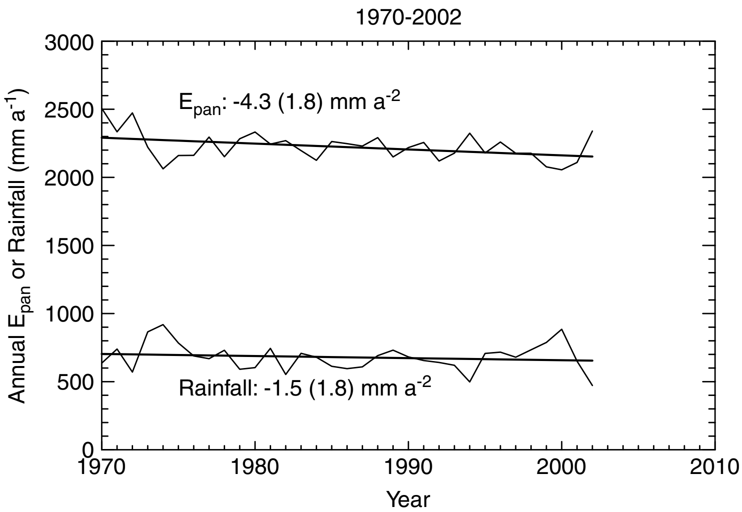

Figure 2. Overall trends in annual pan evaporation rate E_{pan} and annual rainfall rate averaged over 30 sites for 1970–2002. (Standard error shown in brackets. E_{pan} trend is significant ($p > 0.95$) but the rainfall trend is not significant)

4. DISCUSSION

The absence of any major trends in rainfall during either period (1970–2002, 1975–2002) is not surprising given the large year-to-year variability that is typical of rainfall records, both in Australia and elsewhere. It is also consistent with continental summaries of Australian rainfall that show a (not statistically significant) trend of -0.3 ± 1.8 mm a^{-2} for 1970–2002 (BoM, 2003). Although there was some regional variation, pan evaporation declined on average by $\sim$4 mm a^{-2}. The fact that pan evaporation has been decreasing while the average maximum air temperature in Australia has been increasing (Nicholls, 2003) is not contradictory because, as noted above, the rate of pan evaporation is not very sensitive to changes in either average maximum air temperature or average air temperature. Although there were some important differences between sites, our results show that, on average, Australia has become less arid over the last 30 years, not because rainfall has changed, but rather because potential evaporation, and hence the atmospheric demand for water, has decreased.

Although there were no previous reports of pan evaporation trends in Australia, there were many hints that it might be declining. For example, the observed decline in the diurnal temperature range across Australia is consistent with Northern Hemisphere trends (Plummer *et al*., 1995; Nicholls, 1997). In turn, this suggests an increase in cloudiness (Dai *et al*., 1999) and an associated general decline in evaporative demand similar to that which has occurred in many parts of the Northern Hemisphere (Roderick and Farquhar, 2002). Confirmation of this, at least for a region of Australia, is available in a more detailed agro-ecological study that reported increases in cloud cover, minimum temperature and absolute vapour pressure, as well as declining sunlight, across parts of northeast Australia over the period 1957–95 (McKeon *et al*., 1998). Other parts of the Southern Hemisphere have also shown similar trends. For example, decreases in sunlight and diurnal temperature range, along with increases in rainfall and minimum temperatures, have been reported in the Pampas region of Argentina for the period 1960–90 (Viglizzo *et al*., 1995). These trends suggest a decrease in potential evaporation just like that in Australia, and in the Northern Hemisphere.

The observed decrease ($\sim$4 mm a^{-2}) in the Australian pan evaporation rate is about the same magnitude as the averaged trends that have been reported in the Northern Hemisphere over the last 30–50 years (see references cited above). The fact that potential evaporation has decreased in many regions of the world, despite the well-known increases in average air temperature at the surface, highlights the need for a reassessment of the ecological and hydrological impacts of climate change (Moonen *et al*. 2002). In particular, the terrestrial surface in the Northern Hemisphere, and in Australia, has become less arid on average. Further, the evidence

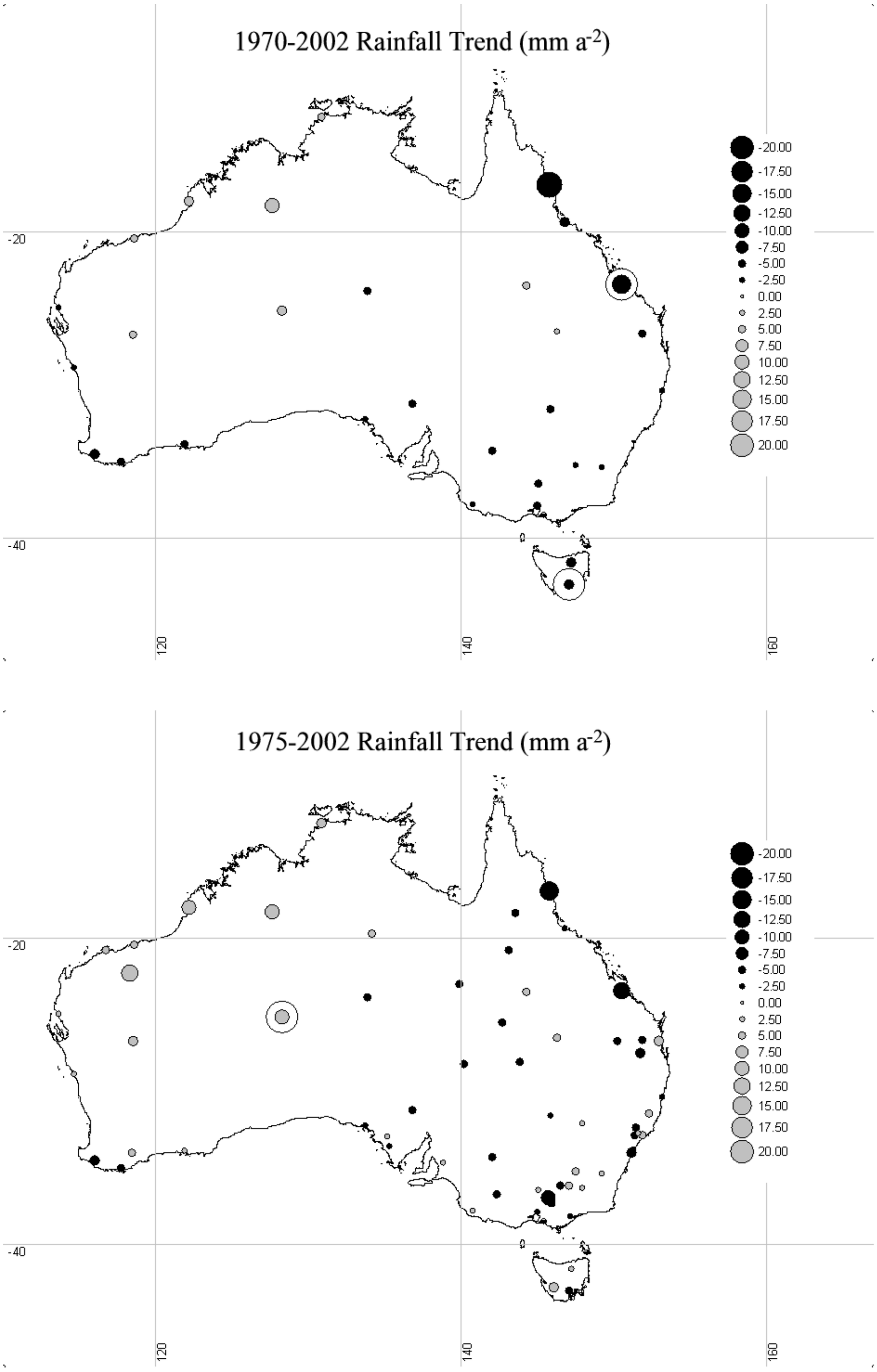

Figure 3. Trends in annual rainfall rate for 1970–2002 (30 sites) and 1975–2002 (61 sites). Dots enclosed by a circle denote a statistically significant ($p > 0.95$) trend

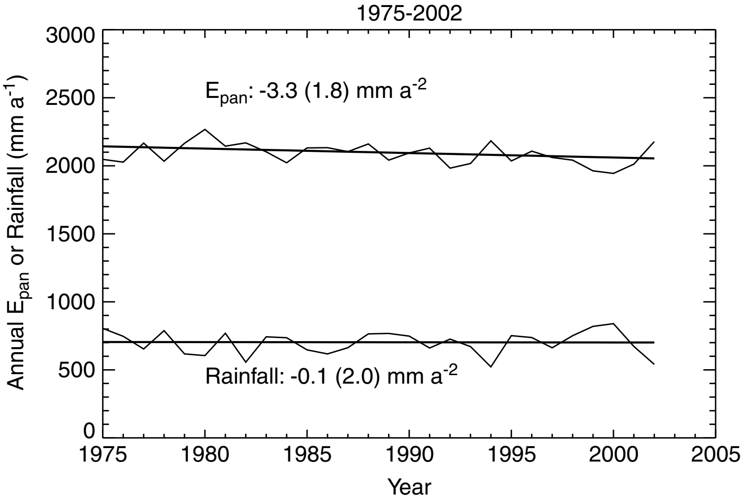

Figure 4. Overall trends in annual pan evaporation rate E_{pan} and annual rainfall rate averaged over 61 sites for 1975–2002. (Standard error shown in brackets. E_{pan} trend is significant ($p > 0.90$) but the rainfall trend is not significant)

from the Northern Hemisphere that was noted in Section 1 shows that the expected ecological and hydrological changes are already occurring.

How the trend for decreasing potential evaporation relates to the enhanced greenhouse effect must await a more complete investigation of trends in pan evaporation in other parts of the Southern Hemisphere, and an investigation of the underlying physical reason(s) for the trends. In terms of the surface energy balance, there are three possibilities to explain a decline in pan evaporation: decreases in one or more of vapour pressure deficit of the air, net radiation and windspeed (Penman, 1948; Monteith and Unsworth, 1990). For Australia, the observed decrease in diurnal temperature range (Plummer *et al.*, 1995; Nicholls, 1997) is much the same as in the Northern Hemisphere and implies that the vapour pressure deficit has remained near constant (Roderick and Farquhar, 2002). Assuming that this is the case, then a decrease in net radiation and/or windspeed must be involved. In the Northern Hemisphere, decreased sunlight has proved to be an important component of the decrease in pan evaporation (Roderick and Farquhar, 2002). However, declines in windspeed may also play a role, and we note a recent summary report showing a slight decrease in windspeed in the USA since 1960 (Groisman *et al.*, 2004).

Whatever the underlying physical reason(s), the principal advantage of using evaporation pans is that they integrate all the various physical effects (Stanhill, 2002). Accordingly, it is now clear that many places in the Northern Hemisphere, and in Australia, have become less arid. In these places, the terrestrial surface is both warmer and effectively wetter, and a good analogy to describe the changes in these places is that the terrestrial surface is literally becoming more like a gardener's 'greenhouse'.

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APPENDIX

Table A.I. Trends and averages, indicated by overbar in annual pan evaporation E_{pan} and annual rainfall P at 30 sites for 1970–2002.[a] Significant trends ($p > 0.95$) indicated in bold. Trend figures are plus/minus the standard error

Num[b]	Name	Lon (deg)	Lat (deg)	Height (m)	$\overline{E_{pan}}$ (mm a^{-1})	$d(E_{pan})/dt$ (mm a^{-2})	$\overline{P}$ (mm a^{-1})	$d(P)/dt$ (mm a^{-2})
2012	Halls Creek Airport	127.66	−18.23	422	3126	−10.2 ± 6.1	621	8.0 ± 4.2
3003	Broome Airport	122.23	−17.95	7	2761	**−10.2 ± 3.0**	656	4.9 ± 6.4
4032	Port Hedland Airport	118.63	−20.37	6.4	3250	−5.5 ± 4.7	315	2.5 ± 2.8
6011	Carnarvon Airport	113.67	−24.88	4	2612	**5.1 ± 2.4**	230	−1.1 ± 1.9
7045	Meekatharra Airport	118.54	−26.61	517	3531	**−20.2 ± 3.9**	257	3.1 ± 2.0
8051	Geraldton Airport	114.7	−28.8	33	2446	−2.2 ± 2.7	446	−0.7 ± 1.8
9592	Pemberton	116.04	−34.45	174	1147	**−6.6 ± 1.6**	1115	−5.9 ± 4.2
9741	Albany Airport	117.8	−34.94	68	1393	**5.3 ± 1.3**	794	−1.8 ± 1.8
9789	Esperance	121.89	−33.83	25	1712	**−9.7 ± 2.8**	618	−2.1 ± 2.1
13 017	Giles Meteorological Office	128.29	−25.04	598	3471	−1.7 ± 5.9	314	4.4 ± 3.2
14 015	Darwin Airport	130.89	−12.42	30.4	2622	**−12.8 ± 2.2**	1797	3.1 ± 7.6
15 590	Alice Springs Airport	133.89	−23.8	546	3051	11.6 ± 7.8	330	−1.8 ± 3.4
16 001	Woomera Aerodrome	136.8	−31.16	166.6	3029	**19.8 ± 4.4**	192	−3.0 ± 1.8
18 012	Ceduna Amo	133.71	−32.13	15.3	2260	−3.0 ± 3.2	278	−0.5 ± 1.4
26 021	Mount Gambier Aero	140.77	−37.75	63	1324	**−7.6 ± 1.4**	705	−0.6 ± 1.9
31 011	Cairns Aero	145.75	−16.87	3	2221	0.0 ± 2.9	2056	−17.0 ± 9.6
32 040	Townsville Aero	146.77	−19.25	7.5	2601	**−9.7 ± 3.6**	1080	−3.9 ± 9.0
36 031	Longreach Aero	144.28	−23.44	192.2	3028	−3.5 ± 5.9	439	1.5 ± 3.0
39 083	Rockhampton Aero	150.48	−23.38	10	2173	0.6 ± 3.2	794	**−11.6 ± 5.0**
40 112	Kingaroy Prince Street	151.85	−26.55	441.9	1643	3.3 ± 2.5	802	−3.2 ± 3.2
44 021	Charleville Aero	146.26	−26.41	302.6	2612	−0.8 ± 5.2	477	0.4 ± 2.9
48 027	Cobar MO	145.83	−31.49	260	2405	**−17.7 ± 4.9**	424	−2.4 ± 3.0
59 040	Coffs Harbour MO	153.12	−30.31	5	1683	**−13.4 ± 1.7**	1652	−0.9 ± 7.4
70 014	Canberra Airport	149.2	−35.3	578.4	1673	0.9 ± 3.0	629	−1.0 ± 3.0
72 150	Wagga Wagga AMO	147.46	−35.16	212	1793	−4.2 ± 3.0	600	−1.0 ± 2.9
76 031	Mildura Airport	142.08	−34.23	50	2171	**−8.0 ± 3.4**	290	−2.2 ± 1.8
80 091	Kyabram (Institute of Sustainable Agriculture)	145.06	−36.34	104.5	1570	**−7.9 ± 2.1**	466	−1.9 ± 2.7
86 071	Melbourne Regional Office	144.97	−37.81	31.2	1214	**−15.7 ± 1.7**	650	−3.6 ± 2.4
91 104	Launceston Airport	147.2	−41.54	170	1292	**−4.8 ± 1.7**	640	−3.9 ± 2.3
94 069	Grove Research Station	147.07	−42.99	60	980	**−5.0 ± 1.8**	743	**−5.5 ± 2.4**

[a] The same table of the 61 sites for 1975–2002 is available on request from the authors.
[b] BoM site number.

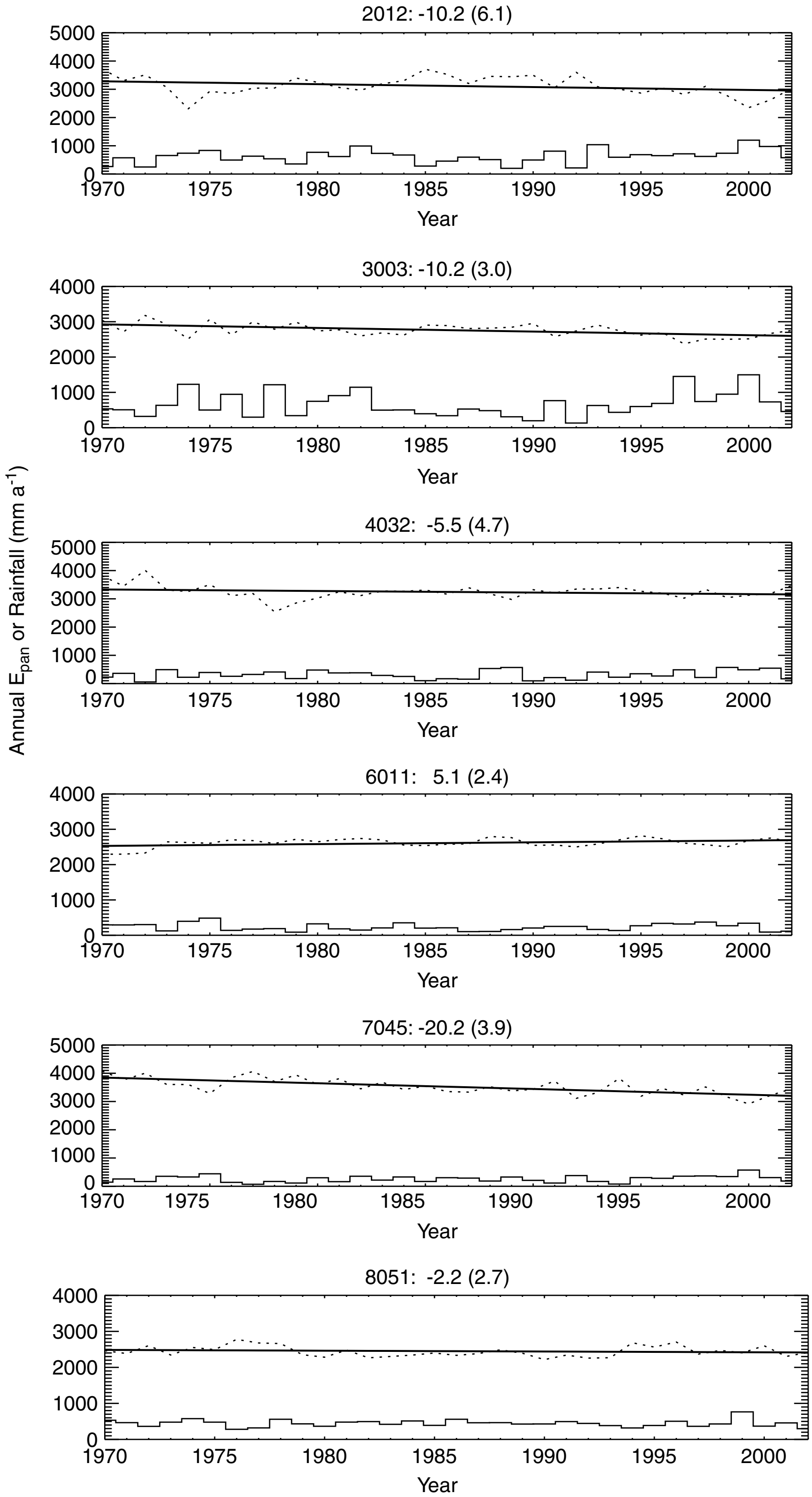


Figure A.1. Annual pan evaporation observations E_{pan} (dotted), calculated E_{pan} trend (full line) and rainfall (bars) for 30 sites from 1970–2002. The title in each panel denotes the site number (see Table A.I) along with the E_{pan} trend (mm a^{-2}) and the standard error of the trend in brackets (e.g. 2012: −10.2 (6.1) denotes site 2012, trend in E_{pan} is -10.2 ± 6.1 mm a^{-2})

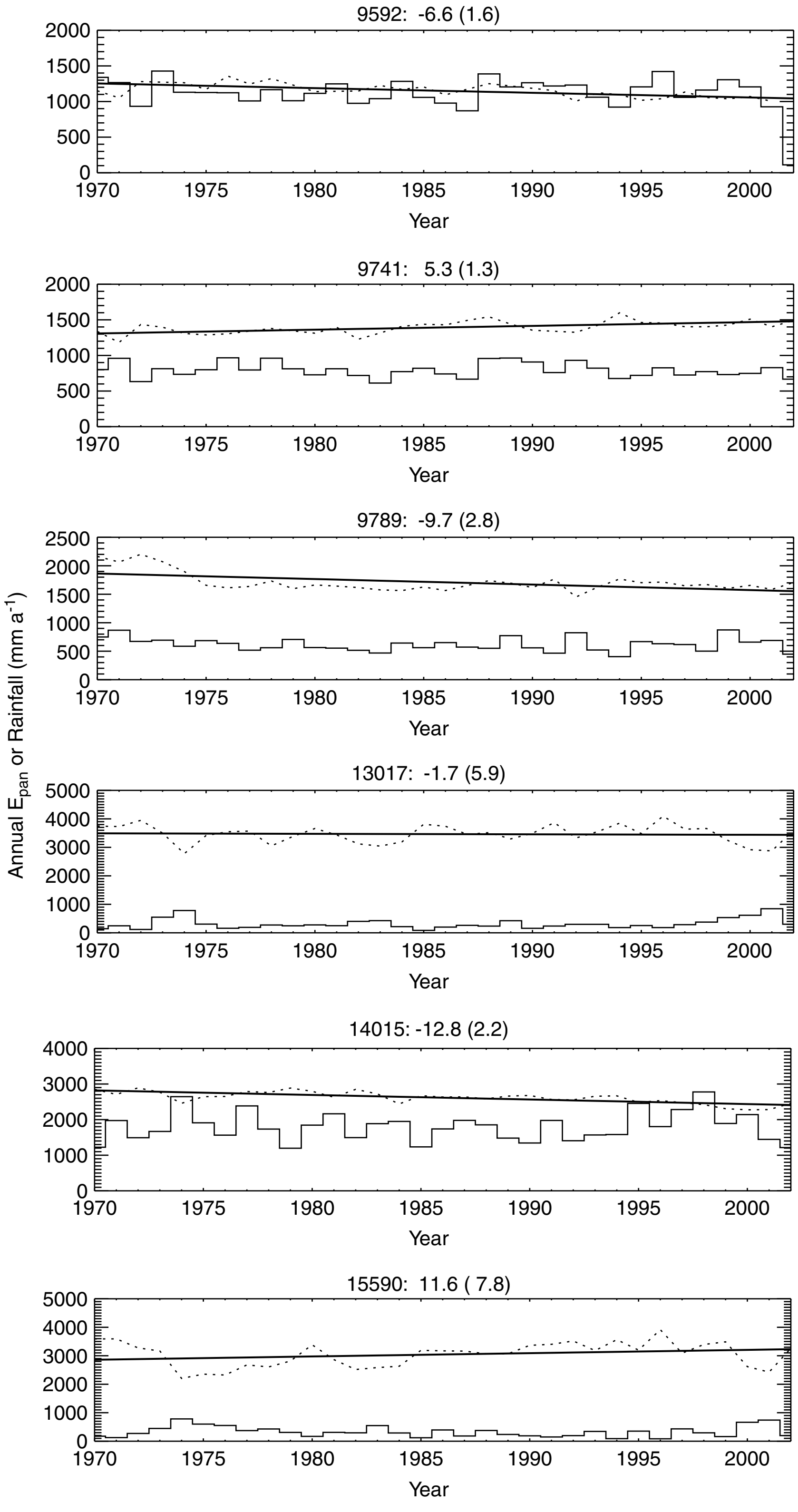
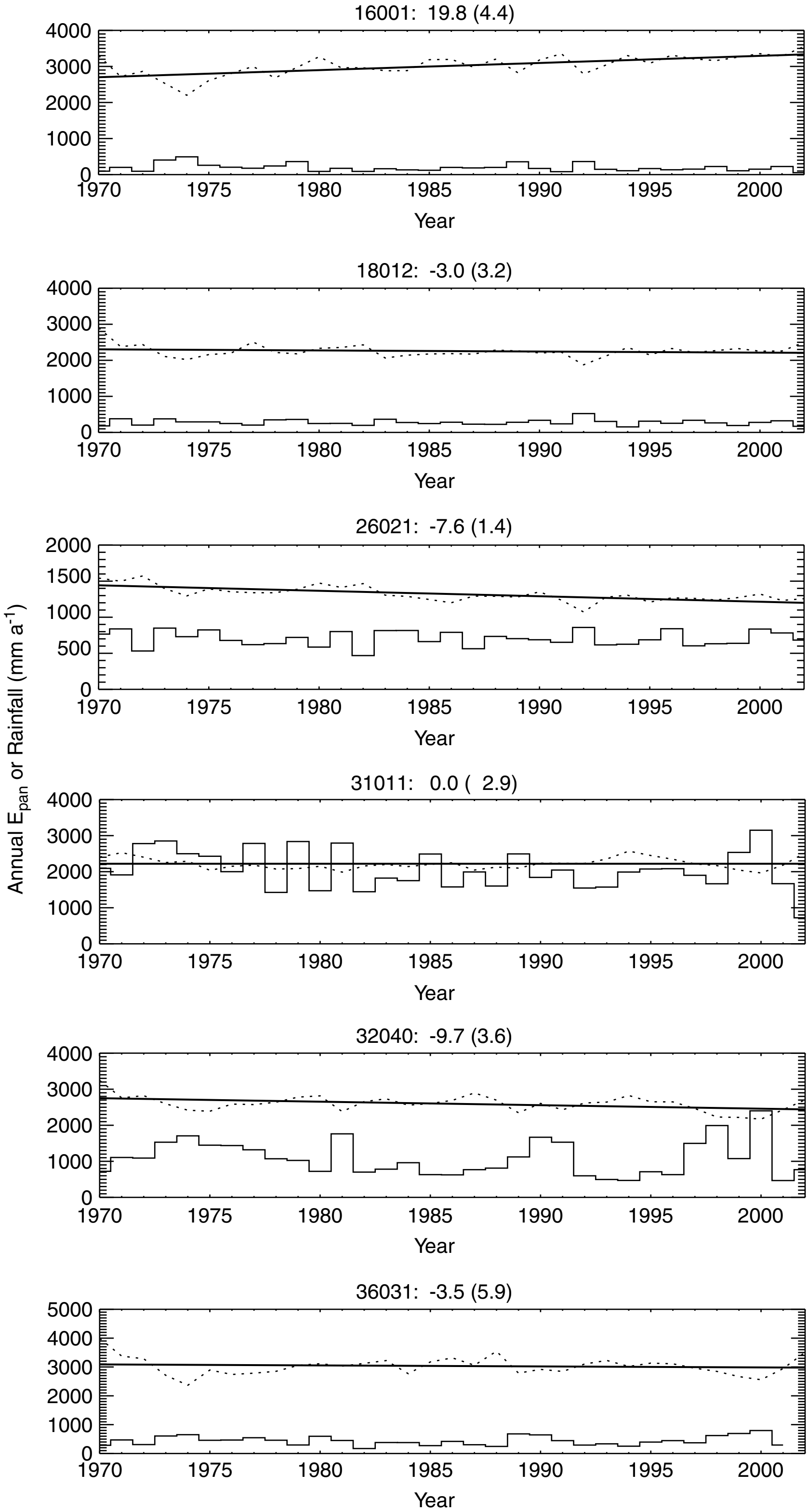


Figure A.1. (*Continued*)



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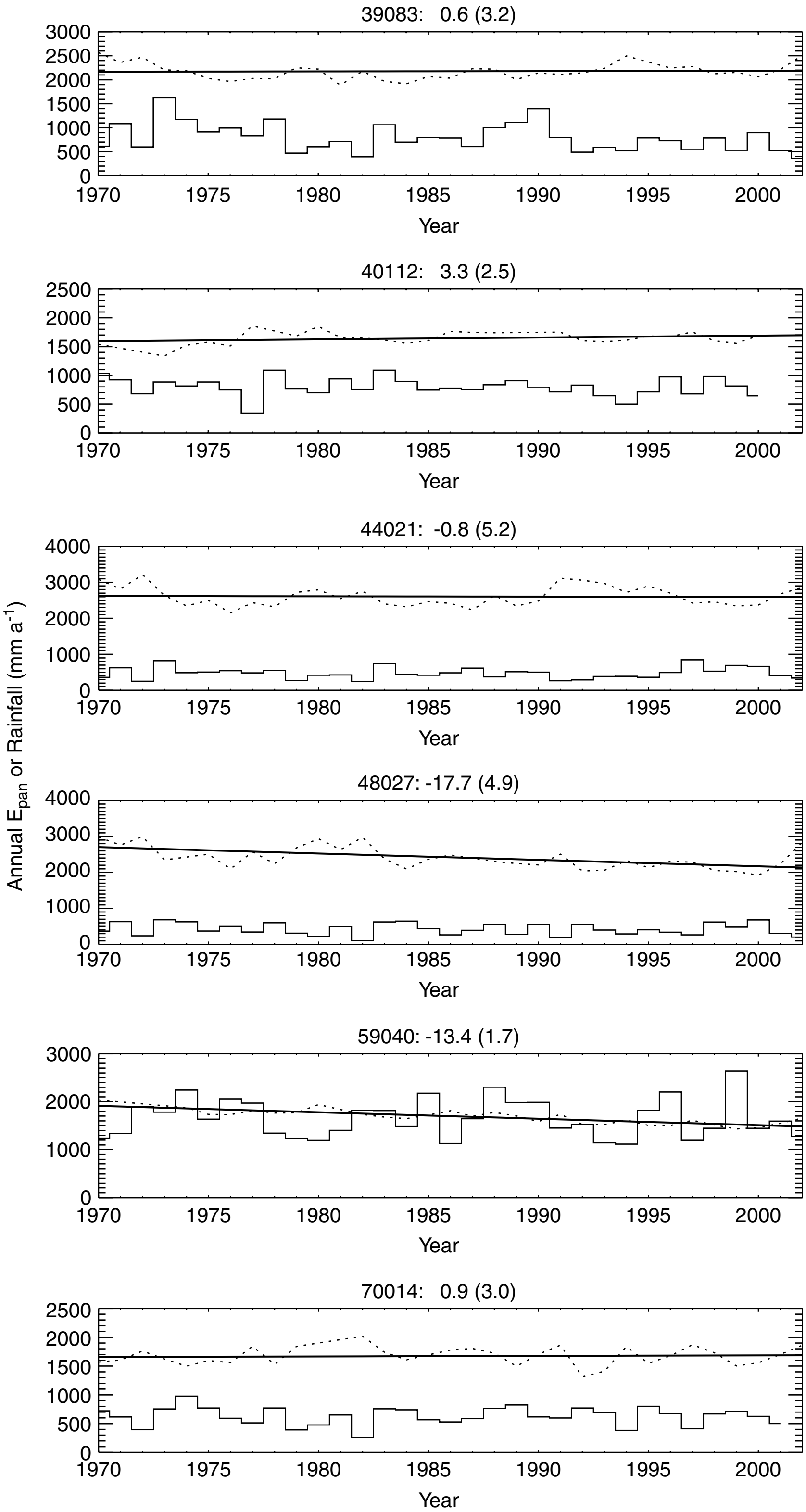

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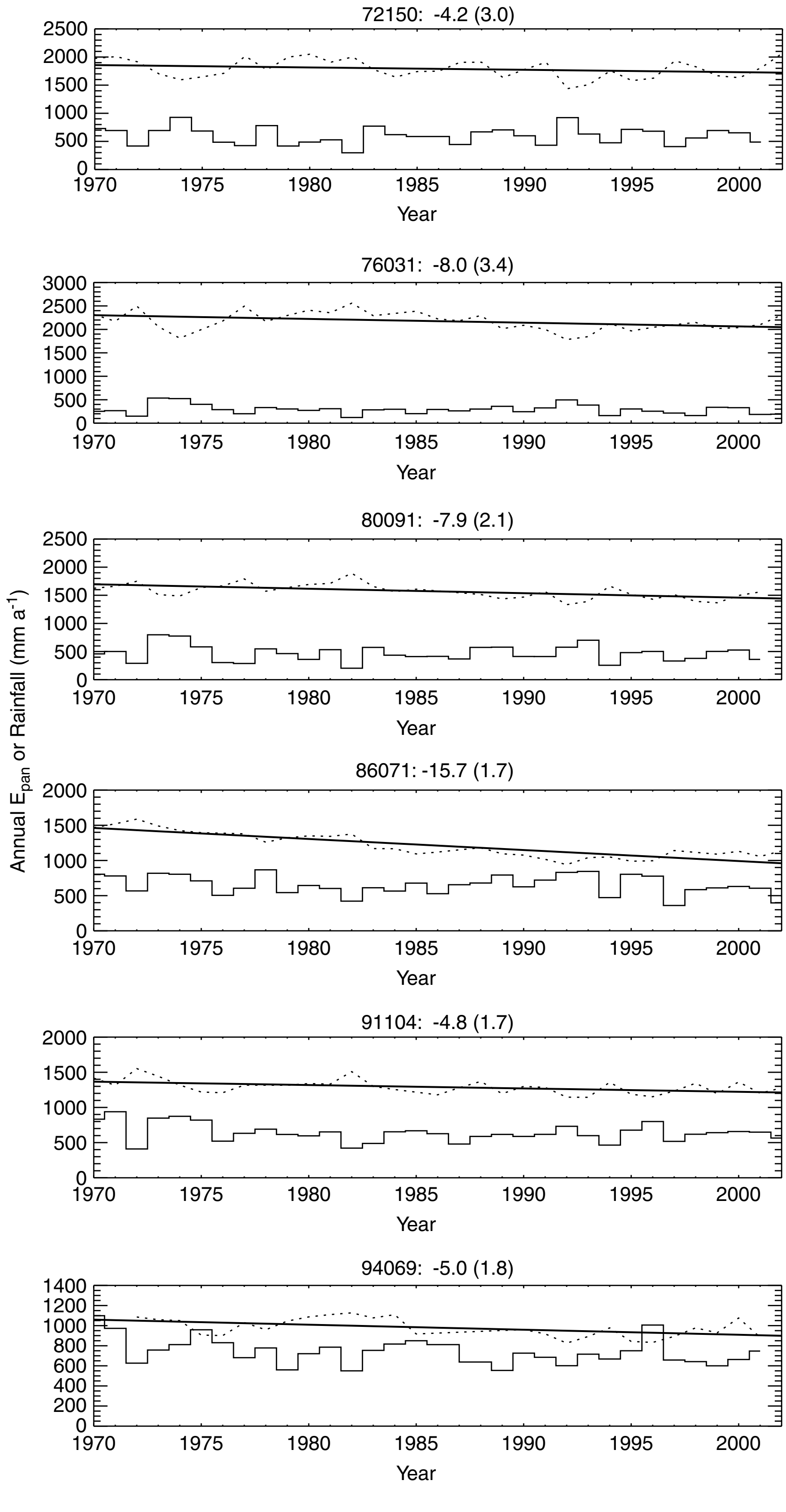

Figure A.1. (*Continued*)

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