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CHANGES IN NEW ZEALAND PAN EVAPORATION SINCE THE 1970s

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ABSTRACT

Several previous studies have reported declines in pan evaporation rate throughout the Northern Hemisphere of about 2–4 mm a^{-2} for various periods since the 1950s. A recent analysis of Australian pan evaporation reported a similar decline and raises the possibility that part of the phenomenon may be related to the greenhouse effect. To assess that possibility, one needs to know whether the decline in evaporative demand is happening in other parts of the Southern Hemisphere. As a first step to addressing the latter question, we examined the trend in pan evaporation at 19 New Zealand sites. We found statistically significant declines in pan evaporation rate at 6 of the 19 sites. There were no sites with statistically significant increases in pan evaporation. When averaged across all 19 sites, the decline in pan evaporation rate was roughly 2 mm a^{-2} (i.e. mm per annum per annum) since the 1970s. Over a 30-year period, this is equivalent to a decline of about 60 mm a^{-1} in annual pan evaporation. These results are generally consistent with those reported throughout the Northern Hemisphere and in Australia. We conclude that the trend for decreasing evaporative demand previously reported throughout the Northern Hemisphere terrestrial surface may also be widespread in the Southern Hemisphere. This may be, in part, a greenhouse-related phenomenon. Copyright © 2005 Royal Meteorological Society.

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

1. INTRODUCTION

In a seminal paper, Peterson *et al*. (1995) reported that pan evaporation had, on average, declined in the United States, former Soviet Union and parts of Asia from the 1950s to early 1990s. Several subsequent studies have largely confirmed these trends. At individual sites, both increases and decreases in pan evaporation are commonly found (e.g. Chattopadhyay and Hulme, 1997; Cohen *et al*., 2002; Roderick and Farquhar, 2004). However, when averaged over a number of sites in a region, clear downward trends have emerged and the reported decline in pan evaporation rate is typically between 2 and 4 mm a^{-2} (i.e. mm per annum per annum) for the United States and Russia for the 1950s to 1990s (Peterson *et al*., 1995; Golubev *et al*., 2001). Measurements from China for 1955–2000 show an averaged rate of decline of about 3 mm a^{-2} (Liu *et al*., 2004). In India, the reported decrease appears to be much larger at about 12 mm a^{-2} for 1961–1992 (Chattopadhyay and Hulme, 1997). Recently, the data have been extended to tropical regions with the report of a declining trend in pan evaporation throughout Thailand over the period 1982–2000 (Tebakari *et al*., 2005). Unfortunately, that study did not report the average trend across all sites. Thus, with the exception of India, the decline in pan evaporation rate over large areas of the terrestrial surface in the Northern Hemisphere, stretching from the tropics to tundra regions is typically about 2 to 4 mm a^{-2}.

The finding that pan evaporation, and hence potential evaporation, has declined despite the well-known increase in near-surface air temperature, seems contradictory at first glance. However, temperature is only one factor that determines the evaporative demand of the atmosphere – the others are vapour-pressure deficit, wind speed and the net irradiance. The change in evaporative demand depends on how those factors change as well as on the change in temperature (Rosenberg *et al*., 1989). This has been most clearly demonstrated in China,

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where a simple temperature-based index, like the Thornthwaite approach, estimates increasing evaporative demand over the last 50 years because of increasing annual average air temperature, but physically based estimates that also use measurements of vapour-pressure deficit, wind speed and net irradiance give a declining trend in evaporative demand in agreement with the observed decline in pan evaporation (Chen *et al*., 2005).

The widespread trend in declining pan evaporation has prompted research into the reasons for the decline. For example, declines in wind speed, like those observed locally in Turkey (Ozdogan and Salvucci, 2004), might be playing a role if widespread. Similarly, declines in vapour-pressure deficit were implicated in the pan evaporation decline in India (Chattopadhyay and Hulme, 1997). There has been a lot of interest in reported

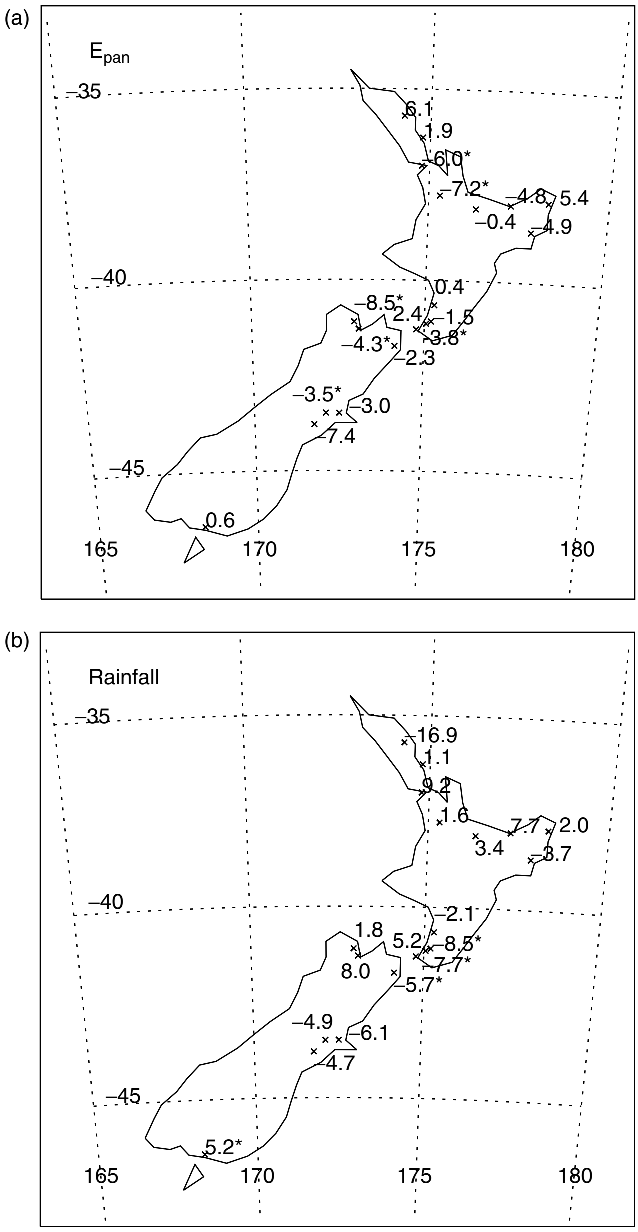


Figure 1. Trends in (a) pan evaporation and (b) precipitation at 19 New Zealand sites. *Denotes a statistically significant ($p > 0.95$) trend. Units are mm a^{-2}

Table I. Trends and averages, indicated by an overbar, in annual pan evaporation rate E_{pan} and annual rainfall rate P over the indicated period (start, end) at 19 sites. Statistically significant trends ($p > 0.95$) are indicated in bold. Trends figures are plus/minus the standard error. The nYrs column depicts the number of years used in the calculations for E_{pan} and P respectively as well as the maximum possible number of years available (e.g. 13/14 means 13 years were used to do calculations out of 14 possible years)

Site[a]	Name	Lon (deg)	Lat (deg)	Ht (m)	Start	End	$\overline{E_{pan}}$ (mm a^{-1})	dE_{pan}/dt (mm a^{-2})	nYrs	$\overline{P}$ (mm a^{-1})	dP/dt (mm a^{-2})	nYrs
A54735	Whangarei, Whau Vly	174.29	−35.71	152	1979	1992	865	6.1 (±5.0)	13/14	1611	−16.9 (±22.8)	14/14
A64282	Leigh 2	174.80	−36.27	27	1972	1998	1313	1.9 (±1.7)	27/27	1136	1.1 (±4.9)	27/27
B86131	Rotorua Aero 2	176.32	−38.11	287	1972	1991	1176	−0.4 (±2.3)	20/20	1368	3.4 (±7.9)	20/20
B87023	Opotiki	177.28	−38.00	6	1980	2003	1145	−4.8 (±2.4)	24/24	1296	7.7 (±5.8)	24/24
C74082[b]	Auckland Aero	174.79	−37.01	33	1972	1997	1225	**−6.0 (±1.6)**	26/26	1107	9.2 (±4.9)	24/26
C75731	Ruakura	175.31	−37.78	40	1973	1996	940	**−7.2 (±1.4)**	21/24	1181	1.6 (±5.0)	24/24
D78931	Ruatoria	178.32	−37.90	61	1977	1996	1085	5.4 (±2.8)	19/20	1770	2.0 (±13.0)	20/20
D87683	Gisborne, Manutuke	177.89	−38.68	9	1972	1991	1184	−4.9 (±3.6)	20/20	950	−3.7 (±5.6)	20/20
E05622	Levin M.A.F.	175.27	−40.65	46	1968	1990	947	0.4 (±1.6)	23/23	1099	−2.1 (±4.1)	23/23
E14272	Wellington,Kelburn	174.77	−41.29	125	1972	2003	951	**−3.8 (±0.8)**	32/32	1237	**−7.7 (±3.7)**	32/32
E15011	Kaitoke	175.19	−41.08	223	1981	1994	888	2.4 (±5.2)	14/14	2065	5.2 (±16.5)	14/14
E15102	Wallaceville	175.05	−41.14	56	1975	2002	1031	−1.5 (±1.5)	28/28	1336	**−8.5 (±3.9)**	28/28
G12191	Motueka, Riwaka	172.97	−41.10	8	1972	1994	1052	**−8.5 (±1.7)**	23/23	1373	1.8 (±7.9)	23/23
G13211	Appleby	173.10	−41.29	17	1972	1996	1271	**−4.3 (±1.7)**	25/25	993	8.0 (±5.1)	25/25
G14711	Grassmere Salt Works	174.15	−41.73	2	1973	2003	1821	−2.3 (±4.4)	29/31	577	**−5.7 (±2.8)**	31/31
H31883	Winchmore EWS	171.79	−43.79	160	1979	1994	1204	−7.4 (±4.9)	14/16	710	−4.7 (±7.2)	16/16
H32412	Darfield	172.14	−43.49	195	1972	2003	775	**−3.5 (±1.3)**	30/32	796	−4.9 (±2.8)	32/32
H32451	Christchurch Aero	172.54	−43.49	37	1972	1993	1340	−3.0 (±5.7)	11/22	640	−6.1 (±5.1)	22/22
I68433	Invercargill Aero	168.33	−46.42	0	1973	2003	997	0.6 (±1.4)	17/31	1113	5.2 (±2.5)	31/31

[a] NIWA site number.
[b] The E_{pan} data for C74082 were measured at station C64971 which is located nearby.

declines in global solar irradiance (Abakumova *et al*., 1996; Gilgen *et al*., 1998; Stanhill and Cohen, 2001; Liepert, 2002) because the expected changes in pan evaporation are similar to observed the changes (Roderick and Farquhar, 2002; Linacre, 2004). The question of aerosol *versus* cloud effects (Ramanathan *et al*., 2001; Farquhar and Roderick, 2003) is likely to be difficult to resolve because of the interaction between clouds and aerosols although progress is being made (Rotstayn, 1999; Liepert *et al*., 2004; Kaufman *et al*., 2005; Ramanathan *et al*., 2005).

Of even more general scientific interest is the speculation that declining evaporative demand might be an intrinsic feature of the greenhouse effect (Farquhar and Roderick, 2003). If that were the case, then the evaporative demand should also be decreasing over terrestrial surfaces in the Southern Hemisphere. However, virtually all of the research to date has been conducted in the Northern Hemisphere, so it has been difficult to assess that possibility. Recently, the first publication on Southern Hemisphere trends reported a decline in pan evaporation rate of about 3 mm a^{-2} from the 1970s to 2002 in Australia (Roderick and Farquhar, 2004). This is quantitatively consistent with reports from the Northern Hemisphere and raises the possibility that a decline in evaporative demand over the terrestrial surface might also be widespread throughout the Southern Hemisphere. To test whether that was likely, we examined pan evaporation (and rainfall) data from a second Southern Hemisphere country, New Zealand.

2. DATA AND METHODS

With the assistance of staff from the National Institute of Water and Atmospheric Research (NIWA), we identified 19 sites (see Table I for a site listing) from the NZ national network that had longer-term measurements of pan evaporation (unscreened Class A pan) and rainfall. Unfortunately, pan evaporation measurements ceased at many of the sites during the mid-1990s (Table I). Consequently, the database contains sites that have different temporal periods. This was not ideal, but the aim was to establish whether there was any evidence for a decline in pan evaporation that was similar to the changes reported in the Northern Hemisphere and in Australia, and for those purposes the data were sufficient.

To construct the time series at each site, we defined a valid month as one having at least 25 daily observations, and the daily average was calculated with the available observations. A valid year was defined as having at least 11 valid months, and the estimate for any missing month was filled in with the long-term average for that month. The linear trend in pan evaporation and rainfall at each site was calculated and the statistical significance of trends was assessed (t-test) at the 95% level (Zar, 1984) (Table II).

3. RESULTS

The calculated trends in pan evaporation and rainfall (Figure 2 for the data at each site) varied from site to site (Table I) with no immediately obvious spatial pattern (Figure 1). Very few of the trends in rainfall were statistically significant (Tables I and II). In contrast, 6 of the 19 sites showed statistically significant declines in pan evaporation (Tables I and II). There was no simple way to calculate aggregate trends in pan evaporation or rainfall across all the sites because the time periods used in the trend estimation varied from site to site (Table I). To give a rough indication, we averaged the trends across all 19 sites and the change in the pan evaporation rate was -2.1 mm a^{-2} while that for the rainfall rate was -0.8 mm a^{-2}.

Table II. Number of sites showing statistically significant changes ($p > 0.95$) in annual pan evaporation and rainfall

	Sites		
	Decrease	No change	Increase
Pan evaporation	6	13	0
Rainfall	3	15	1

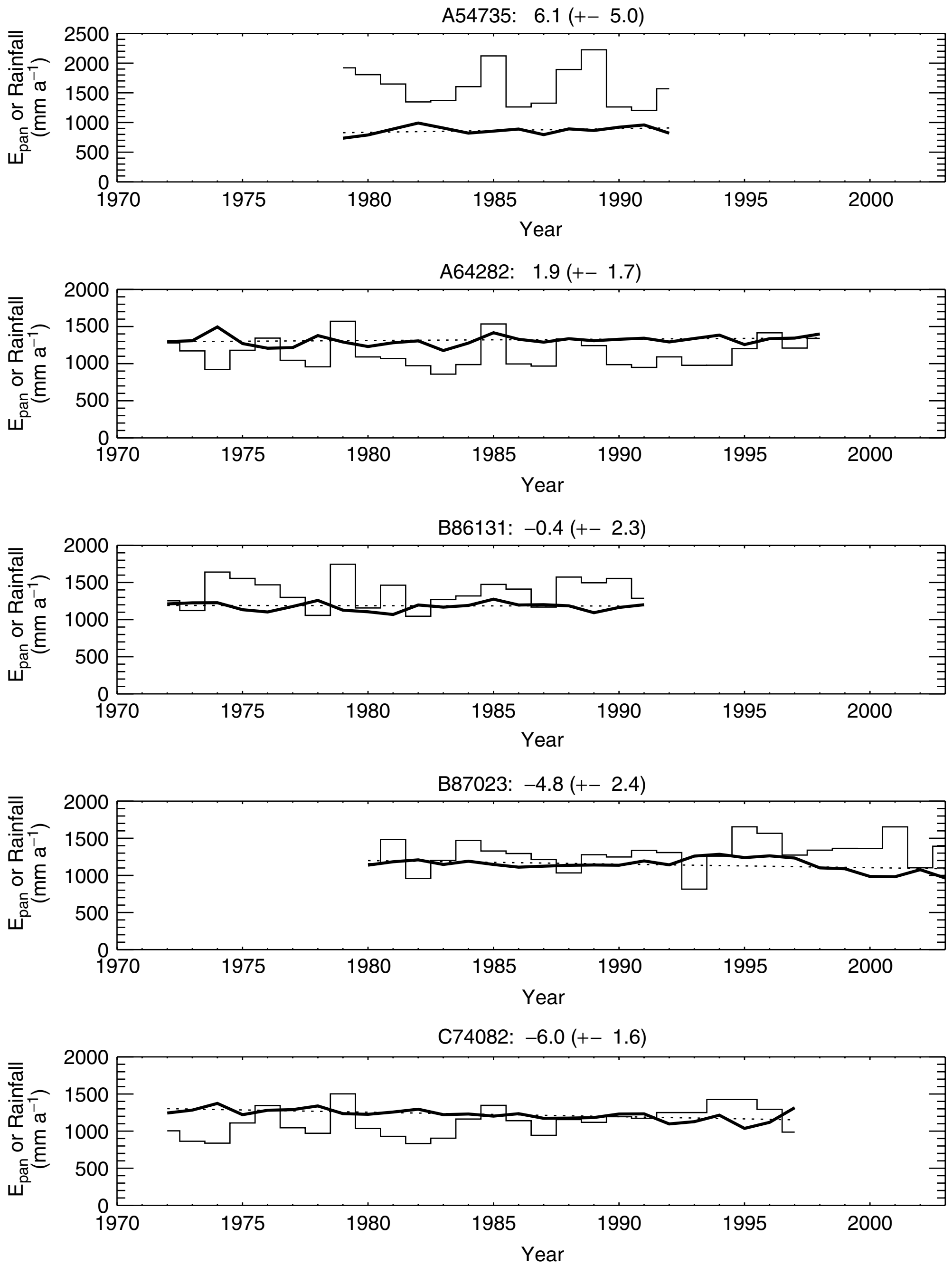


Figure 2. Pan evaporation observations (E_{pan}, thick full line), calculated E_{pan} trend (dotted) and rainfall observations (bars) at 19 New Zealand sites. The title in each panel denotes the NIWA site number (Table I), along with the E_{pan} trend (mm a^{-2}) and the standard error of the trend in brackets. For example, A54735: 6.1 (±5.0) denotes site A54735, and the calculated E_{pan} trend is +6.1 (±5.0) mm a^{-2}

4. DISCUSSION

Observed changes in the near-surface air temperature over New Zealand are very similar to the global pattern of increasing minimum, mean and maximum temperatures with the minimum increasing approximately three

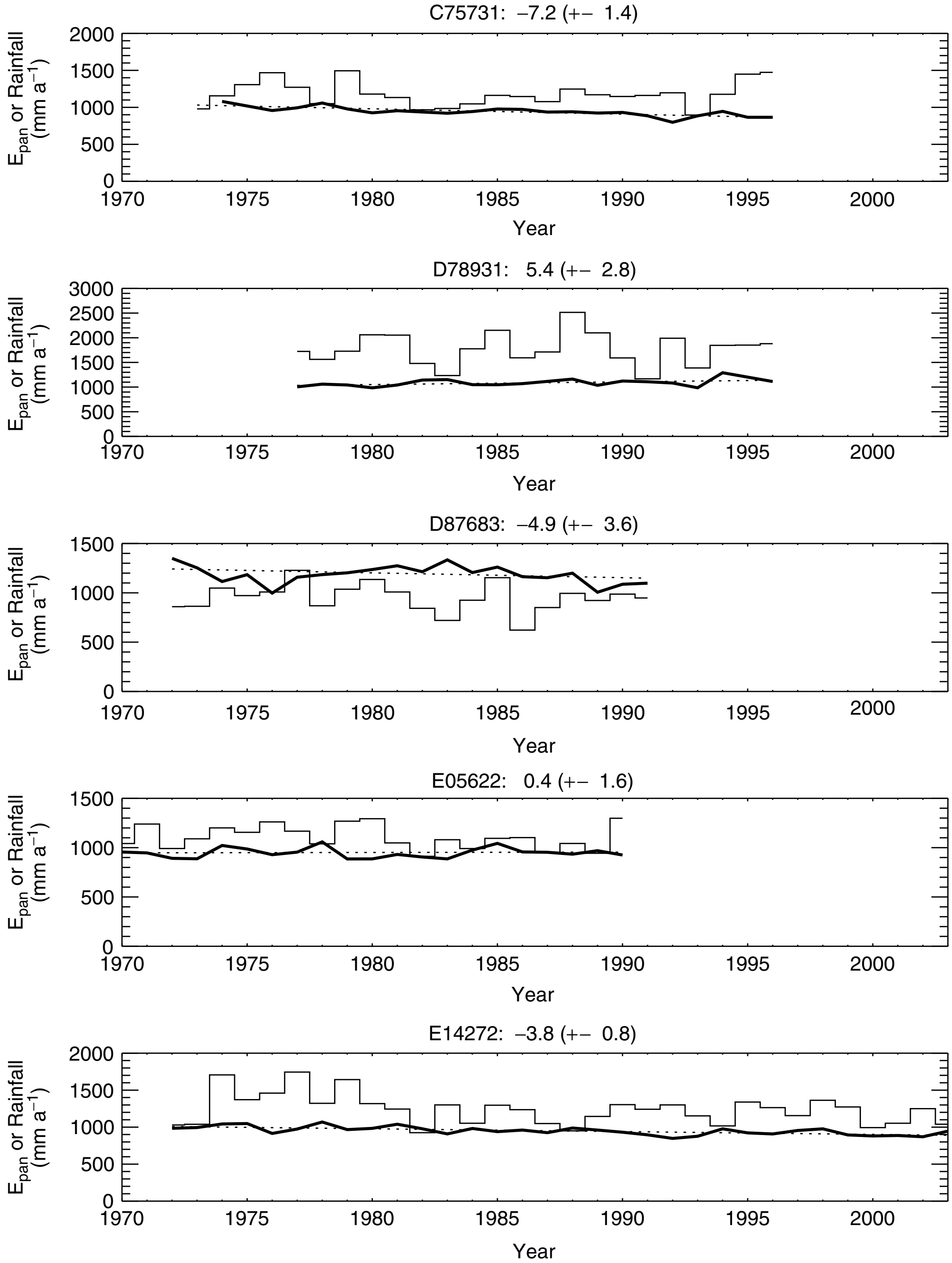
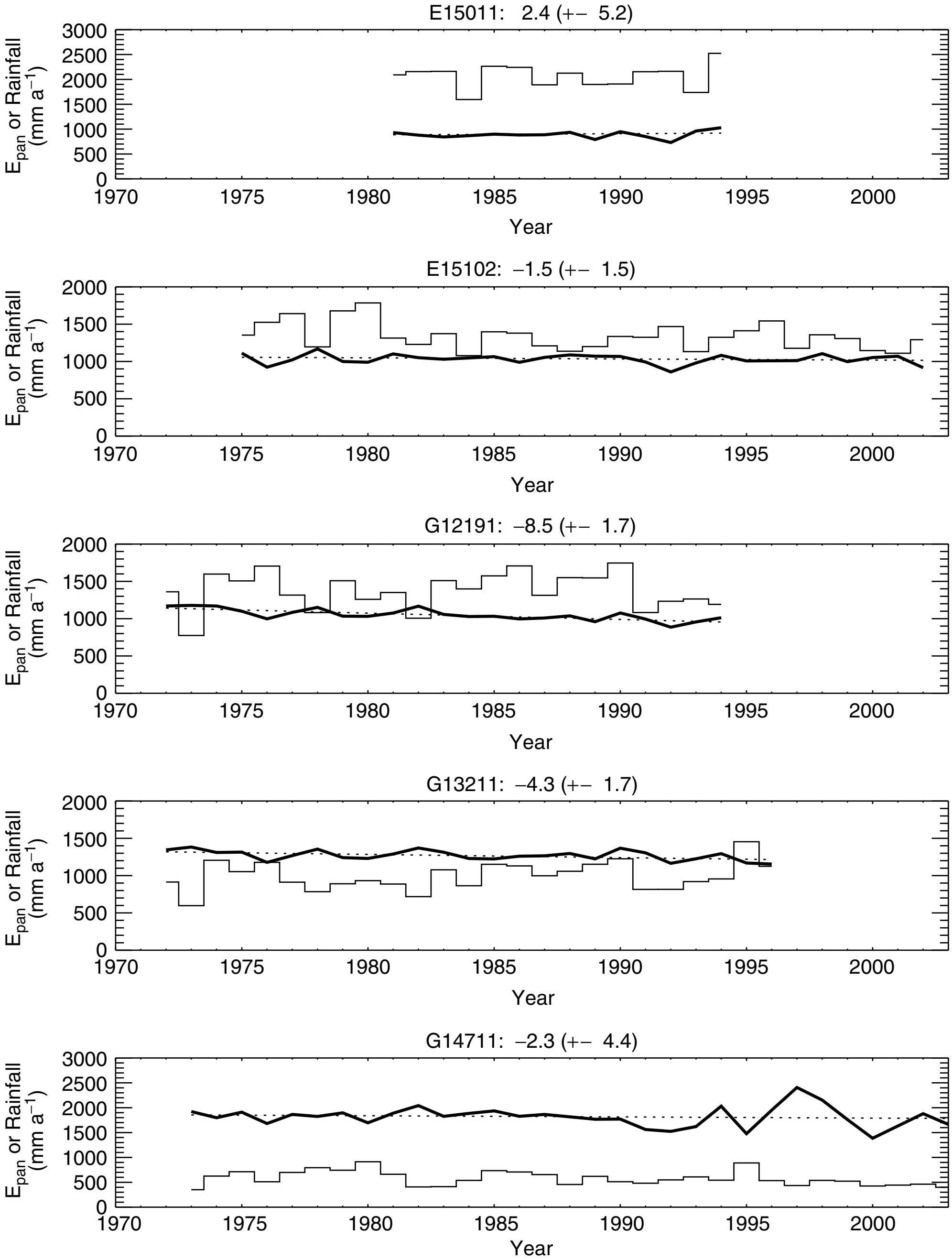


Figure 2. (*Continued*)

times faster than the maximum over the 1951–1998 period (Salinger and Griffiths, 2001). A similar trend also holds for the period since the mid-1970s (Salinger and Mullan, 1999). The gross trends in rainfall and pan evaporation that are reported here for New Zealand are also very similar to those previously reported for several Northern Hemisphere countries, and for Australia (see references listed in Section 1.). In particular, there was variation in the trends from pan to pan, but overall, there were very few sites showing statistically significant changes in rainfall, while several sites showed statistically significant declines in pan evaporation.



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There were no sites showing statistically significant increases in pan evaporation. A rough indicative average for the decline in the pan evaporation rate across all 19 sites was about 2 mm a^{-2} and was generally consistent with the previously reported declines of 2–4 mm a^{-2} from the Northern Hemisphere and from Australia.

In the United States, the decline in pan evaporation has been accompanied by increases in rainfall (Hobbins *et al.*, 2004; Walter *et al.*, 2004). In contrast, the New Zealand data show declines in pan evaporation at sites with both increases and decreases in rainfall (Table I), and this was similar to previous results from Australia

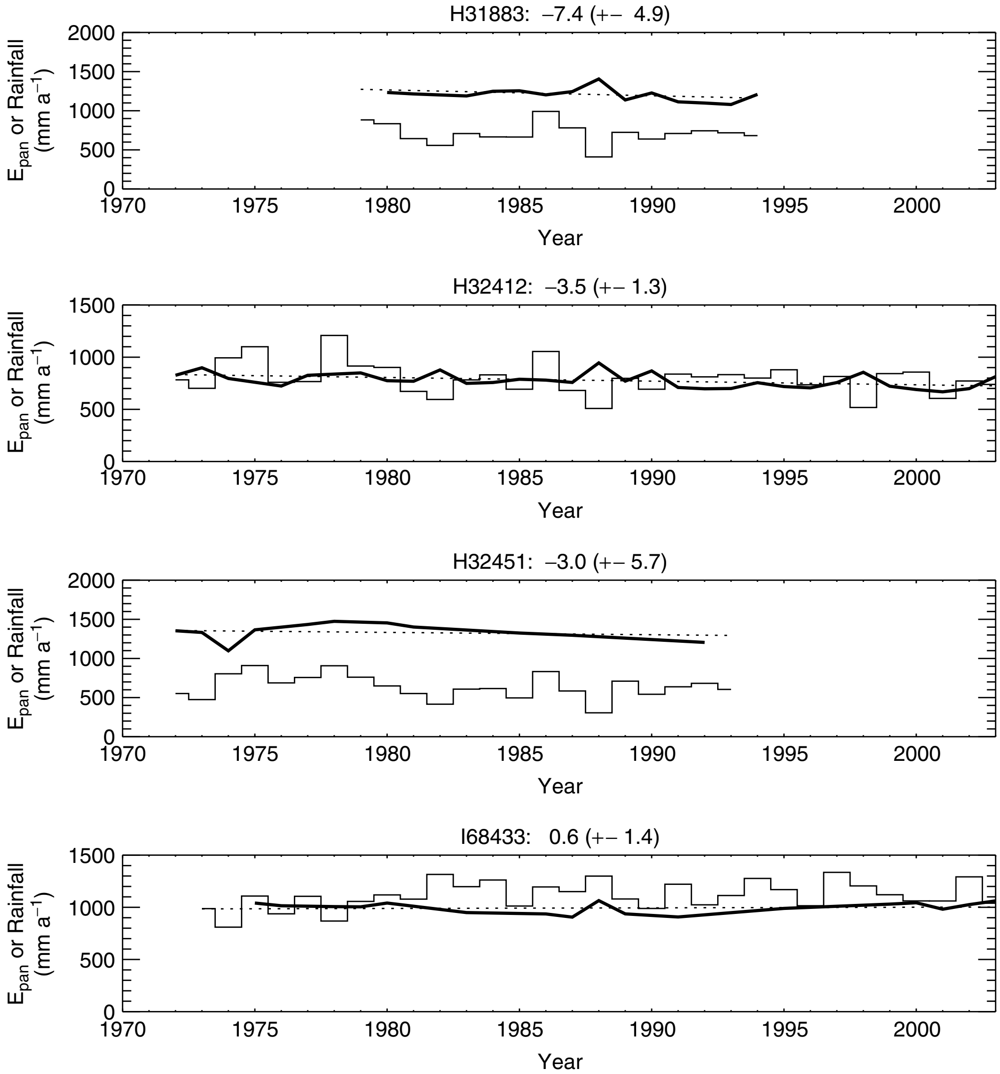

Figure 2. (*Continued*)

(Roderick and Farquhar, 2004), China (Liu *et al.*, 2004) and Thailand (Tebakari *et al.*, 2005). The underlying reasons (i.e. trends over time in temperature, net irradiance, vapour-pressure deficit, wind speed) for declining pan evaporation in New Zealand need to be addressed in a future study.

The results show that the general decrease in evaporative demand that has previously been reported from many parts of the Northern Hemisphere may also be widespread throughout the Southern Hemisphere. Hence, some of the decrease in pan evaporation that has been observed both here and elsewhere may be an effect of greenhouse warming, arising from, for example, an increase in cloud cover (Dai *et al.*, 1997).

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