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# A cloud-based reconstruction of surface solar radiation trends for Australia

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With 7 Figures

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**Summary**

Despite its importance to climate change, reliable and calibrated measurements of solar radiation are available only after 1992 for Australia. In this study we extend the data base from 1967 to 2004 by the development of a cloud-based solar radiation model. Results show no significant change in the majority of stations, although slightly more than one quarter of the stations report a significant decrease of solar radiation with a maximum of just less than one percent per decade. Trend analyses also detect an upturn in many of the southern stations in the late eighties which appear to relate to changes in middle and high cloud cover.

## 1. Introduction

Solar radiation and its associated changes play an important role in determining global climates via both the energy balance of the earth-atmosphere system and the earth's surface. An important research goal is to examine how measured solar radiation at the earth's surface ($K_S$) varies over time using a network of reliable radiometric measurements from data sets such as the Global Energy Balance Archive or the Baseline Surface Radiation Network (Gilgen et al., 1998; Ohmura et al., 1998). Global monitoring of solar radiation trends have shown decreases throughout most of the twentieth century (Gilgen et al., 1998; Liepert, 2002; Dutton et al., 1991; Ohmura and Lang, 1989; Stanhill and Cohen, 2001). More recent studies (Wild et al., 2005) report increasing global trends after the late eighties or early nineties. This paper addresses these issues within the Australian context by examining changes in cloud coverage as related to solar radiation transmission by the atmosphere.

Causes for the reported trend are varied and no clear picture has emerged. Using data from the International Satellite Cloud Climatology Project (ISCCP), Pinker et al. (2005) report increases in surface solar radiation over the globe. Direct aerosol effects, both natural and anthropogenic can also induce substantial decreases in $K_{S.}$ Large decreases in aerosol forcing, of up to $14\,\mathrm{W\,m^{-2}}$ in $K_S$ have been measured as a result of anthropogenic sources (Ramanathan et al., 2001).

Indirect aerosol effects can also be important by increasing the number of cloud condensation nuclei (CCN) and increasing cloud nucleation. Increases in CCN imply lower mean cloud droplet size if liquid water is held constant. As a result cloud albedo will increase, cloud precipitation efficiency will decrease and cloud lifetimes will increase (Ramanathan et al., 2001). This indirect effect has been verified experimentally in a number of case studies using aircraft observations (Heymsfield and MacFarquhar, 2001; Gultepe et al., 1996).

Reliable measurements of $K_S$ for Australia only extend until the early nineties and as a result, earlier records are not suitable for trend analysis (B. Forgan, pers. comm.). In this study we provide a data set for the period 1967–2004 using a cloud model of solar radiation. Sunshine duration records were also available but the data set is much more limited than cloud cover and better results were obtained using cloud data at different levels. An added advantage of using this approach is that it provides a greater understanding of causes leading to solar radiation changes – cloud cover and cloud level.

The following sections describe the data set, the model and its validation, and trends obtained. They are followed by a discussion of causes and implications of these trends, and conclusions.

## 2. Methodology

### *2.1 Data set*

Data consisted of three-hourly cloud cover observations. There are a total of 29 stations in Australia with these data, mostly obtained from airports or Bureau of Meteorology regional offices (Table 1 and Fig. 1). These data are obtained at three-hourly intervals by trained Bureau of Meteorology staff following common observational guidelines. Cloud cover data are obtained in oktas at each of three levels: low, medium and high as well as total. Cloud cover estimates at each level assume that the estimate is representative of the entire sky at that level regardless of lower-level clouds blocking the view of the observer. In case that the cloud view at one level is totally blocked by cloud layers at a lower level, then it is assumed that the coverage of the totally-blocked cloud level is zero. Therefore it is possible for the sum of cloud cover at each level to be greater

**Table 1.** Stations used in the analysis

| Station | Station number | Latitude | Longitude | Start | End | Years |
|---|---|---|---|---|---|---|
| Adelaide Airp | 1 | 34.95 S | 138.52 E | 1967 | 2004 | 38 |
| Albany Airp | 2 | 34.94 S | 117.80 E | 1967 | 2004 | 38 |
| Alice Springs Airp | 3 | 23.71 S | 133.87 E | 1967 | 2004 | 38 |
| Brisbane Airp | 4 | 27.42 S | 153.11 E | 1967 | 2004 | 38 |
| Broome Airp | 5 | 17.95 S | 122.23 E | 1967 | 2004 | 38 |
| Cairns Airp | 6 | 16.87 S | 145.74 E | 1967 | 2004 | 38 |
| Canberra Airp | 7 | 35.30 S | 149.20 E | 1967 | 2004 | 38 |
| Carnarvon Airp | 8 | 24.89 S | 113.67 E | 1967 | 2004 | 38 |
| Ceduna Met Office | 9 | 32.13 S | 133.70 E | 1967 | 2004 | 38 |
| Charleville Airp | 10 | 26.41 S | 146.25 E | 1967 | 2004 | 38 |
| Darwin Airp | 11 | 12.42 S | 130.89 E | 1967 | 2004 | 38 |
| East Sale Airp | 12 | 38.12 S | 147.13 E | 1967 | 2004 | 38 |
| Esperance | 13 | 33.83 S | 121.89 E | 1970 | 2004 | 36 |
| Mt. Gambier Airp | 14 | 37.74 S | 140.77 E | 1967 | 2004 | 38 |
| Giles Met Office | 15 | 25.03 S | 128.30 E | 1967 | 2004 | 38 |
| Halls Ck Airp | 16 | 18.23 S | 127.66 E | 1967 | 2004 | 38 |
| Hobart Airp | 17 | 42.84 S | 147.50 E | 1967 | 2004 | 38 |
| Kalgoorlie Airp | 18 | 30.78 S | 121.45 E | 1967 | 2004 | 38 |
| Launceston Airp | 19 | 41.54 S | 147.20 E | 1967 | 2003 | 37 |
| Long Reach Airp | 20 | 23.44 S | 144.28 E | 1968 | 2003 | 37 |
| McKay Met Office | 21 | 21.12 S | 149.22 E | 1967 | 2003 | 38 |
| Meekatharra Airp | 22 | 26.61 S | 118.54 E | 1967 | 2004 | 38 |
| Melbourne Reg Office | 23 | 37.81 S | 144.97 E | 1967 | 2004 | 38 |
| Mt. Isa Airp | 24 | 20.74 S | 139.48 E | 1967 | 2004 | 38 |
| Onslow | 25 | 21.64 S | 115.11 E | 1967 | 2004 | 33 |
| Perth Airp | 26 | 31.93 S | 115.98 E | 1967 | 2004 | 38 |
| Pt Hedlam Airp | 25 | 20.37 S | 118.63 E | 1967 | 2004 | 38 |
| Rockhampton Airp | 28 | 23.37 S | 150.48 E | 1967 | 2004 | 38 |
| Williamstown Airp | 29 | 32.79 S | 151.84 E | 1967 | 2004 | 38 |

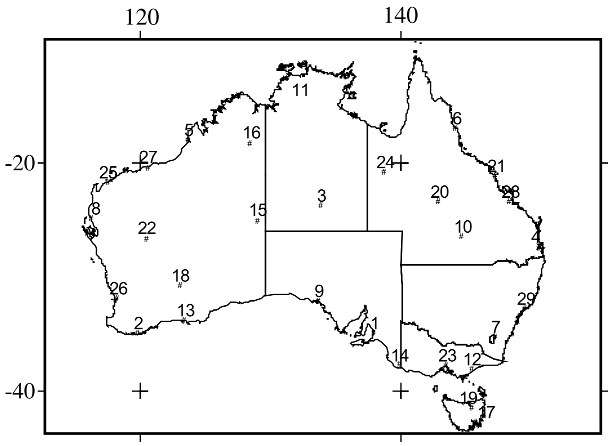



**Fig. 1.** Map of the Australian continent showing the location of 29 Bureau of Meteorology stations recording 3-hourly cloud cover at three levels. See Table 1 for name and coordinates

than total cloud cover as seen by the observer at the ground.

Cloud observations extended from 1967 until 2004 for a total of 38 years, although there were a number of stations with missing data (Table 1). Following Reiss and Thomas (2001), a gap of a single year was replaced by the average of the neighbouring years. Cloud cover for the total sky and at each level is averaged over the entire year and is used as an index of sky opacity.

Solar radiation data were available from the Bureau of Meteorology pyranometer network. Accurate, calibrated measurements were taken from 17 stations starting in the early to mid-nineties. This data set is narrowed down further since there were only six stations out of the 17 with concurrent cloud and pyranometer measurements (Table 2). Nevertheless the stations cover a range of climate types that are typical of Australia – tropical climate with a dry season in winter (Broome, Cairns, Darwin), dry desert climate (Alice Springs), and two locations (Adelaide, Mt. Gambier) with a climate dominated by westerly systems in winter.

**Table 2.** Stations with concurrent solar radiation and cloud data measurements. These data sets formed the basis of the cloud radiation model described below

| Station | Start year | End year | No. of years |
|---|---|---|---|
| Alice Springs | 1994 | 2003 | 9 |
| Darwin | 1994 | 2003 | 6 |
| Broome | 1997 | 2003 | 7 |
| Cairns | 1998 | 2003 | 5 |
| Mt. Gambier | 1994 | 2003 | 9 |
| Adelaide | 1995 | 1997 | 3 |

Daily total solar irradiance for each station was averaged into yearly means and grouped together with corresponding cloud observations. A total of 39 years of data were obtained from six stations having concurrent solar radiation and cloud observations.

## *2.2 Radiation model*

There are a variety of approaches that use cloud data in the calculation of solar radiation (Iqbal, 1983). Some of the early work (London, 1957; Laevastu, 1960) only considered total cloudiness in their work, which estimated yearly insolation over the globe. Later studies pointed out the importance of cloud type in affecting cloud transmission of solar radiation (Haurwitz, 1948; Vowinckel and Orwig, 1962). At short time scales of one hour to one month, cloud type is crucial for an accurate estimation (Davies et al., 1975; Suckling and Hay, 1977; Kasten and Czeplak, 1980; Dissing and Wendler, 1998).

In Australia Paltridge and Proctor (1976) used cloud type to estimate monthly mean of daily solar radiation using the relationship:

$$K_{\mathrm{Sm}} = K_0\left(1-\sum_{\mathrm{i}} a_{\mathrm{im}} c_{\mathrm{im}}\right)\left(1-\phi_{\mathrm{Wm}}-a(1-c_{\mathrm{m}})\right) \tag{1}$$

where the subscripts m and S stand for surface and monthly average, $K_{\mathrm{Sm}}$ is the irradiance at the earth's surface, $K_0$ is the mean daily incoming extraterrestrial solar radiation for the month, $a_{\mathrm{im}}$ and $c_{\mathrm{im}}$ are the albedo and cloud cover for cloud layer i, $a$ is a planetary clear sky albedo term, and $c_{\mathrm{m}}$ is total cloud cover. Atmospheric absorption by water vapour and other gases in the atmosphere, denoted by $\phi_{\mathrm{Wm}}$, was derived using the solar absorption parameterisations of Lacis and Hansen (1974) as a function of precipitable water vapour. For any station and month, $\phi_{\mathrm{Wm}}$ is given as:

$$\phi_{\mathrm{Wm}} = 1 - \frac{\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_0(1-\varphi_{\mathrm{Wm}})\cos Z\,dZ}{\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_0 \cos Z\,dZ} \tag{2}$$

where $I_0$ is the solar constant, $Z$ is solar zenith angle, $\varphi_{\mathrm{Wm}}$ is the absorption parameterised using monthly average precipitable water vapour and solar zenith angle $Z$, this last term calculated during mid-month.

Essentially the first term in the brackets of Eq. 1 represents depletion by cloud albedo, the second term depletion by atmospheric gases and clear sky albedo in the fraction of sky not covered by clouds. Mean albedos of 0.35, 0.55, 0.60 and 0.50 were used for cirrus (type 1), for altocumulus and altostratus (type 2), for low cloud 1 (type 3) and low cloud 2 (type 4), respectively. According to Paltridge and Proctor (1976), this relationship may be used to estimate monthly average solar radiation with an error of under 10%.

Rewriting Eq. 1 in terms of a normalised transmission gives

$$\frac{K_{\mathrm{Sm}}}{I_0 \cos Z} = (1 - a - \phi_{\mathrm{Wm}}) + \alpha_1 c_{1\mathrm{m}} + \alpha_2 c_{2\mathrm{m}} + \alpha_3 c_{3\mathrm{m}} + a c_{\mathrm{m}} + \sum_{\mathrm{i}=1}^{3} \beta_{\mathrm{i}} (c_{\mathrm{m}} \times c_{\mathrm{im}}) \quad (3)$$

where $\alpha_{\mathrm{i}} = -a_{\mathrm{im}}\,(1 - \phi_{\mathrm{Wm}} - a)$ and $\beta_{\mathrm{i}} = -a a_{\mathrm{im}}$ $(\mathrm{i} = 1, 2, 3)$. Equation 3 lends itself to a multiple regression analysis with $c_{1\mathrm{m}}$, $c_{2\mathrm{m}}$, $c_{3\mathrm{m}}$, $c_{\mathrm{m}}$ and their interactions $c_{\mathrm{m}} \times c_{\mathrm{im}}$ as independent variables and a normalised transmission as the dependent variable (left hand side of Eq. 3). The main benefit of this approach is that regression coefficients are directly related to cloud albedos, therefore avoiding the necessity to arbitrarily assign values for them.

Two modifications were done to Eq. 3 for the regression analysis. As mentioned earlier, all values were reduced to yearly averages (monthly subscript m eliminated) and a gaseous absorption term was also included. The regression models had the following forms, with and without the absorption term:

$$S_0 = \alpha_0 + \alpha_1 c_1 + \alpha_2 c_2 + \alpha_3 c_3 + \alpha_4 c + \varepsilon_0 \quad (4)$$

and

$$S_{wv} = \alpha_0 + \alpha_1 c_1 + \alpha_2 c_2 + \alpha_3 c_3 + \alpha_4 c + \varepsilon_{wv} \quad (5)$$

where now all the terms represent yearly averages, $S_0 = K_s/K_0$ and $S_{wv} (= K/(K_0/T_{wv}))$ are solar radiation transmission without (and with) water vapour absorption respectively. The term $S_0$ is the ratio of the daily average solar irradiance ($K$) to the extra-terrestrial value for that day and location ($K_0$). In turn $T_{wv}$ represents a transmission of solar radiation after absorption by water vapour and other atmospheric gases and is the yearly average of the monthly transmission: $T_{wv} = \sum_{\mathrm{i}=1}^{12} (1 - \phi^{\mathrm{i}}_{\mathrm{Wm}})$, where $\phi^{\mathrm{i}}_{\mathrm{Wm}}$ is the absorptivity term in the $i$th month. Error terms are $\varepsilon_0$ and $\varepsilon_{\mathrm{W}}$, which are assumed to follow some normal distributions. In theory Eq. 5 should prove more accurate than Eq. 4 as water vapour absorption differences in individual stations are accounted for.

In comparing the performance of Eq. 4 vs 5, we have focused on the main effects (linear terms) of $c_1$, $c_2$, $c_3$ and $c$ on the normalised transmission ($S_0$ or $S_{wv}$), while neglecting the interactions of $c_{\mathrm{i}} \times c$ (the secondary terms), as they increase only minimally the explained variances in the normalised transmission (i.e. explained variance increased from 94.3 to 95.14% for $S_0$ and 89.5 to 91 for $S_{wv}$). Moreover, results in Table 3 indicate that the regression model performance is not enhanced by inclusion of water vapour absorption. Therefore, the regression model with no absorption is used throughout Australia to determine an index of transmission.

Results shown in Table 3 warrant further discussion as it appears to diminish the importance of water vapour absorption. Certainly the $\mathrm{T_{wv}}$ term is written explicitly in most models which estimate solar radiation (Paltridge and Proctor, 1976; Davies et al., 1975; Iqbal, 1983). However results from the regression analysis argue that much of the depletion by water vapour absorption is already taken up in the form of increased depletion by higher cloud cover and higher cloud

**Table 3.** Results of the multiple regression analysis shown in Eqs. 4 and 5. Number of data pairs equals 39. Coefficients $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$ represent contributions by total, low, middle and high cloud cover, respectively. Coefficient $\alpha_0$ is the regression constant

| | $\alpha_0$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $R^2$ | SE |
|---|---|---|---|---|---|---|---|
| No absorption | 0.8220 | −0.1968 | −0.2152 | −0.1031 | −0.2230 | 0.943 | 0.014 |
| With absorption | 0.9362 | −0.4064 | −0.1148 | −0.0161 | −0.0555 | 0.895 | 0.023 |

opacity. Thus the explicit introduction of water vapour absorption information does not improve the model regression.

A second point to consider is that the cloud albedos from the regression are significantly lower than the averages used by Paltridge and Proctor (1976). Cloud albedos vary widely with liquid water content, thickness and liquid droplet radius (Paltridge and Platt, 1976; Houghton, 1985), so that it is expected that use of mean albedos would only coarsely approximate the real values at any point in time. More importantly, albedo values are obtained from uniform overcast conditions, quite different from partial cloud cover where side reflection from clouds would add to the downward solar radiation. In addition, given the nature of cloud observations as mentioned earlier, it is possible for coverage by low, middle and high clouds to exceed total cloud cover. However the regression model would assign coefficients for all clouds present, regardless if the sum of the three layers exceeds the total cloud coverage as seen at the surface. This process is also likely to lower the regression coefficients. In summary, it is useful to view the coefficients not as cloud albedos, but as coefficients related to cloud albedos which provide the best estimate of surface irradiance.

Note that Eq. 4 is applied to the entire cloud data set as described in Table 1 and spanning a period of 38 years. The model uses data based on cloud observations essentially unchanged since 1967 and it is expected that the Eq. 4 should be a fairly robust index of atmospheric opacity in the absence of significant changes in aerosols. This fact was further confirmed by using "leave-one-station out"; cross-validated results (Fig. 2a and b). In other words, a regression model based on Eq. 4 was constructed leaving one station out, and then applying the regression to the independent data set from the station. As may be noticed in Fig. 2a and b, the technique reproduces yearly and decadal fluctuations satisfactorily. The regression model to fit the entire cloud data set as described in Table 3 and spanning a period of 38 years turns out to be:

$$S_0 = 0.822 - 0.215c_1 - 0.103c_2 - 0.223c_3 - 0.197c$$
$$R^2 = 0.94 \quad S.E. = 0.014 \quad n = 39 \tag{6}$$

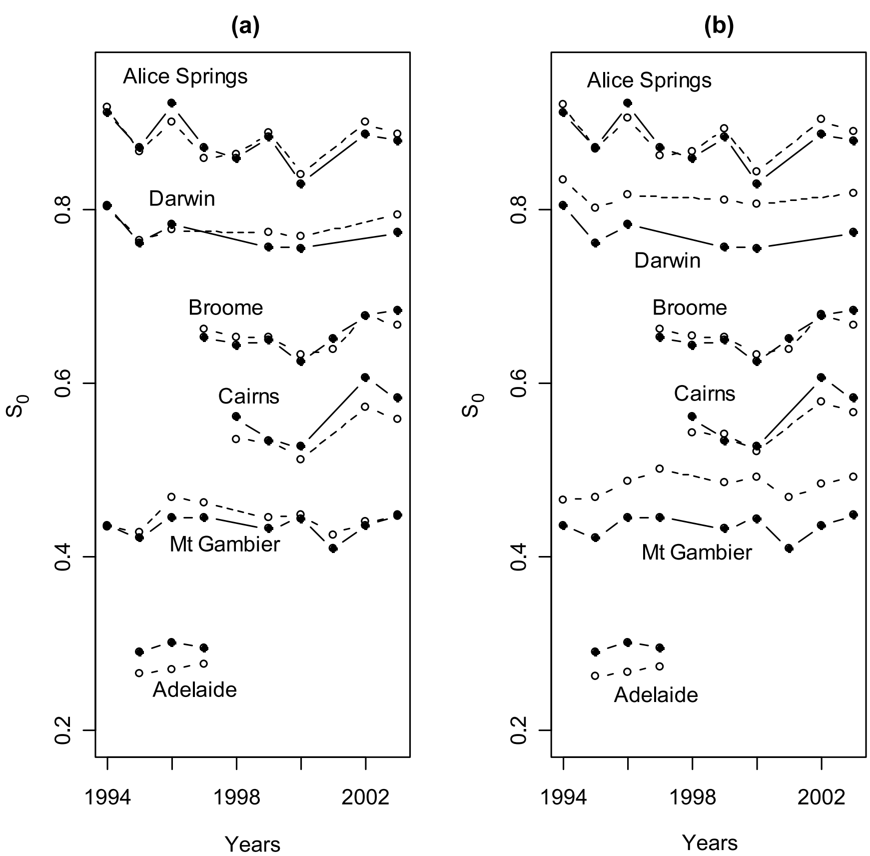



**Fig. 2.** (**a**) A comparison between observed (solid line) and reconstructed (dashed line) solar radiation transmission using multiple regression analysis in equation 6 for pooled data over 6 stations: Alice Springs, Darwin, Broome, Cairns, Mt. Gambier and Adelaide; (**b**) "Leave-one-station out" cross-validated results of reconstructed solar radiation ($S_0$) for each of the six stations. For easing of viewing Alice Springs, Darwin, Mt. Gambier and Adelaide have been offset by 0.2, 0.2, 0.1 and 0.3. These results indicate that it is feasible to use Eq. 6 to reconstruct the solar radiation transmission $S_0$ based on cloud cover $c_1$, $c_2$, $c_3$ and total cloud cover $c$ for other stations in Australia

**Table 4.** Statistics for clear sky transmission of daily solar radiation. There is no significant trend at the 5% level of confidence in all stations with the exception of Kalgoorlie. The last column represents decadal changes in transmission ($\Delta T$)

| Station | Slope | Intercept | $T_{stat}$ | $n$ | $\Delta T$ |
|---|---|---|---|---|---|
| All data | $4.0 \times 10^{-7}$ | 0.751 | 0 | 1027 | 0.001 |
| Darwin | $3.56 \times 10^{-7}$ | 0.717 | 1.3 | 70 | 0.01 |
| Broome | $2.34 \times 10^{-7}$ | 0.746 | 0.8 | 86 | 0.008 |
| Adelaide | $2.75 \times 10^{-5}$ | 0.842 | −0.5 | 16 | 0.09 |
| Mt. Gambier | $1.72 \times 10^{-7}$ | 0.728 | 0.4 | 88 | 0.006 |
| Alice Springs | $-3.2 \times 10^{-7}$ | 0.782 | −0.1 | 74 | 0.001 |
| Cairns | $8.35 \times 10^{-7}$ | 0.729 | 0.2 | 78 | 0.003 |
| Kalgoorlie | $1.02 \times 10^{-5}$ | 0.744 | 3.4 | 80 | 0.04 |
| Rockhampton | $-2.50 \times 10^{-6}$ | 0.754 | −1.0 | 95 | 0.009 |
| Mildura | $3.51 \times 10^{-6}$ | 0.748 | 1.1 | 99 | 0.01 |
| Geraldton | $-2.1 \times 10^{-6}$ | 0.767 | −0.8 | 93 | −0.007 |
| Wagga | $1.38 \times 10^{-6}$ | 0.750 | 0.4 | 82 | 0.005 |
| Tennant Ck | $-1.96 \times 10^{-6}$ | 0.776 | 0.9 | 93 | 0.007 |

with $c_1$, $c_2$, $c_3$ and $c$ being low, middle, high and total cloud cover, respectively. The relationship was be used to reconstruct the solar radiation transmission of all 29 stations over Australia.

### *2.3 Changes in aerosol load*

Aerosol changes might affect the transmission trends but unfortunately there are no consistent and uniform aerosol measurements for the Australian region over the study period. It is however possible to provide an indication of changes in aerosol transmission by observing clear sky trends using instrumental records. To accomplish this task, 12 stations with concurrent cloud and pyranometer data were chosen from the list in Table 1. The maximum daily solar radiation ($K_{max}$) was selected for each month and the ratio of $K_{max}$ to the extra-terrestrial value for that day and location ($K_0$) was plotted vs day number with the starting date being 1 January 1994. The choice of maximum solar radiation for the month will eliminate most of the cloud effects, as corroborated by comparison with stations containing cloud data. Therefore the regression trend line will indicate changes due to non-cloud processes operating in the atmosphere.

Results in Table 4 show that, with the exception of Kalgoorlie, none of the trends are significant at the 0.05 level of significance. It is likely that local effects dominate in the case of Kalgoorlie, a location known for its industrial metal smelting operations. Higher transmission over time would indicate cleaner air, perhaps a result of stricter emission control measures. Figure 3 shows transmission when all data are pooled together. There is some scatter but very little evidence of a trend.

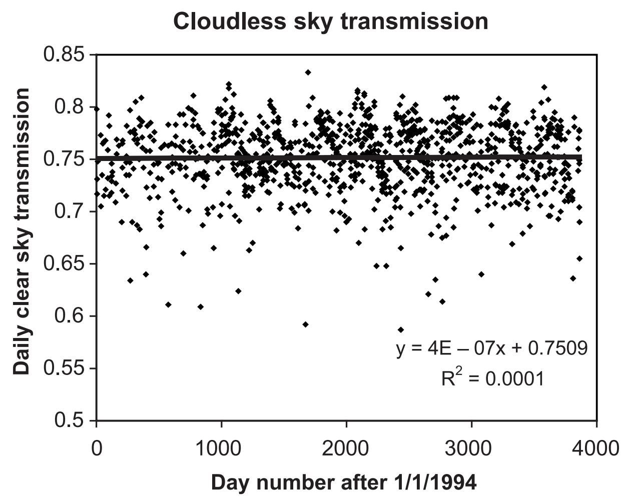



**Fig. 3.** Daily transmission of cloudless solar radiation for Australian stations. All data have been pooled together

There is some additional data supporting the argument that there have been no consistent changes in Aerosol Optical Depth (AOD) of sufficient magnitude to influence surface solar radiation. Daily AOD data from a Multi-shadow band radiometer (MFRSR) have been taken at the University of Tasmania, Hobart for the time period 1994 to 1999. These show decadal increases of 0.01 in the visible bands, but they are not statistically significant at the 95% level of confidence. Wilson and Forgan (2002) examined AOD data at Cape Grim, northwestern Tasmania (40.68 S; 144.688 E) for a 14 year period from

**Table 5.** Statistics for regression trends between yearly $K/K_0$ and total cloud and cloud type cover using Eq. 6. Columns 2 and 3 represent a linear trend for the entire data set. Columns 4 and 5 represent results from a change point analysis as discussed in the text. D and I represent increasing and decreasing trends. Also shown is the year of change. All data in bold are significant at the 0.05 level of confidence

| Station | Slope (year$^{-1}$) | *p*-value | Change point | *p*-value |
|---|---|---|---|---|
| Adelaide Airp | **−0.00037** | **0.05** | 1978 | 0.24 |
| Albany Airp | **−0.00048** | **0.001** | **D-1991-I** | **0.01** |
| Alice Springs Airp | 0.00029 | 0.25 | 1989 | 0.2 |
| Brisbane Airp | −0.00044 | 0.09 | 1982 | 0.15 |
| Broome Airp | 0.00027 | NS | **D-1983-I** | **0.07** |
| Cairns Airp | −0.00012 | NS | **I-1993-D** | **0.04** |
| Canberra Airp | 0.00026 | 0.25 | 1995 | 0.38 |
| Carnarvon Airp | −0.00030 | 0.25 | 1996 | 0.24 |
| Ceduna Met Office | −0.0011 | NS | 1982 | 0.26 |
| Charleville Airp | 0 | NS | 2000 | 0.47 |
| Darwin Airp | **0.00095** | **0.008** | **D-1981-I** | **0.01** |
| East Sale Airp | −0.00031 | 0.15 | 1983 | 0.11 |
| Esperance | **0.000386** | **0.03** | **D-1990-I** | **0** |
| Mt. Gambier Airp | 0.00030 | 0.15 | **D-1992-I** | **0.03** |
| Giles Met Office | **−0.00060** | **0.04** | **1994-D** | **0.03** |
| Halls Ck Airp | −0.00043 | 0.25 | 1972 | 0.1 |
| Hobart Airp | **−0.00067** | **<0.001** | **D-1990-I** | **0** |
| Kalgoorlie Airp | **−0.00068** | **0.002** | **1985-D** | **0.01** |
| Launceston Airp | **−0.00053** | **0.01** | **D-1987-I** | **0.06** |
| Long Reach Airp | −0.00014 | NS | 1971 | 0.19 |
| McKay Met Office | −0.00037 | 0.20 | 1986 | 0.12 |
| Meekatharra Airp | 0 | NS | 1975 | 0.27 |
| Melbourne Reg Office | **−0.00088** | **<0.001** | **1983-D** | **0** |
| Mt. Isa Airp | **−0.00076** | **0.02** | **1972-D** | **0.04** |
| Onslow | 0.000514 | 0.08 | 1988 | 0.1 |
| Perth Airp | −0.00019 | 0.25 | 1977 | 0.13 |
| Pt Hedlam Airp | −0.00039 | 0.12 | 1972 | 0.16 |
| Rockhampton Airp | −0.00036 | NS | 1990 | 0.24 |
| Williamstown Airp | 0.00011 | 0.15 | 1980 | 0.22 |

1986 to 1999. Tropospheric AOD show no long-term trend, although stratospheric AOD increased temporarily over a period of a few years as a result of the Mount Pinatubo volcanic eruption.

### 2.4 Yearly trends in transmission

Equation 6 was applied to reconstruct the solar radiation transmission $S_0$ of all 29 stations over Australia, and we use these reconstructed data to determine their trends and statistical significance. Results are shown in Table 5. Column 2 represents the slope of the relationship (year$^{-1}$) followed by their *p*-value in column 3. Slopes significant at the 5% level of confidence or more are denoted in bold.

There were ten stations with significant trends. Of these, eight had decreasing trends (Adelaide, Albany, Giles, Hobart, Kalgoorlie, Launceston, Melbourne and Mt. Isa) and two had positive trends (Darwin, Esperance). The magnitude of the negative slopes vary from just under one percent per decade (−0.00088 year$^{-1}$) for Melbourne to just under one half percent per decade (−0.00037 year$^{-1}$) for Adelaide. Positive slopes are higher in Darwin (0.000953 year$^{-1}$) and lower in Esperance (0.000386 year$^{-1}$).

Visual examination of the records also revealed a trend reversal in some stations. To examine this process, a mathematical technique known as Mann-Whitney-Pettitt change point test (Pettitt, 1979) was applied to the transmission records. This method has been used to identify the change point year in precipitation in Ireland (Kiely, 1999) and extreme rainfall in southwest Western Australia (Li et al., 2005). Column four of Table 5 shows the year of change points, with D and I indicating decreasing or increasing trends, respectively before or after the reversal. Also shown are the $p$-values associated with the trends, bold for significant at 0.05 level of significance or larger.

There are now 12 stations that had significant reversal in trends, with 7 out of the 12 showing decreasing trends followed by increasing trends (Albany, Broome, Darwin, Esperance, Mt. Gambier, Launceston, Hobart). Two stations (Kalgoorlie and Mt. Isa) showed sharper increasing trends followed by slightly decreasing trends. One station (Cairns) had an increasing trend followed by a decline, while the remaining two show no trends initially, but decline after a certain date (Giles and Melbourne). The years of reversal also show some interesting features. The stations along the southern coast show a reversal and increasing trends in the early nineties (Albany, Esperance, Mt. Gambier, Hobart, Launceston), while in the north coast the reversal and increasing trends occur earlier in the early eighties (Darwin and Broome).

### *2.5 Yearly trends in cloud levels*

Cloud levels were next examined for trends, as they influence transmission of solar radiation. Data were grouped into mid-latitude (Albany, Esperance, Mt. Gambier, Hobart and Launceston), tropical (Broome, Cairns and Darwin) and continental stations (Giles, Kalgoorlie and Mt. Isa). Only stations exhibiting change points in transmission of solar radiation were examined (Table 5, column 4 and 5).

**Table 6.** Results of the Mann-Whitney-Pettitt test for the change point year in annual cloud levels at the eleven stations during 1967–2004. Here decimal numbers in brackets are $p$-values associated with the identified change point years. Significant changes at the 0.05 level are marked in bold

| Station | Low | Middle | High |
|---|---|---|---|
| Albany | **1988** (≈ 0) | 1972 (0.17) | **1988 (0.02)** |
| Esperance | **1990 (0.03)** | **1988 (0.05)** | 1997 (0.14) |
| Mt. Gambier | 1989 (0.13) | 1977 (0.08) | **1994 (0.01)** |
| Hobart | 1988 (0.17) | **1988 (0.01)** | **1988** (≈ 0) |
| Launceston | 1983 (0.11) | 1990 (0.12) | **1987 (0.02)** |
| Broome | 1987 (0.09) | 1988 (0.32) | **1976 (0.05)** |
| Cairns | 1992 (0.08) | 1988 (0.11) | 1993 (0.07) |
| Darwin | **1982 (0.03)** | **1990** (≈ 0) | **1990** (≈ 0) |
| Giles | 1996 (0.25) | **1988 (0.03)** | **1990 (0.01)** |
| Kalgoorlie | 1987 (0.06) | 1984 (0.06) | 1974 (0.13) |
| Mt. Isa | 1972 (0.39) | 1972 (0.07) | **1988 (0.04)** |

Yearly cloud cover was further partitioned into low, medium and high levels so as to determine the degree of spatial coherence. Table 6 shows the change-point years and their $p$-values for the 11 selected stations during 1967–2004. The most common change-point year is around 1988. The signal is not as clear in low cloud levels, as the $p$-value of the test statistics is only significant for three out of 11 stations (Albany in 1988, Esperance in 1990 and Darwin in 1982). The signal is clearer at the significance level of 0.1, as three more stations are added (Broome in 1987, Cairns in 1992 and Kalgoorlie in 1987). It is evident that the year 1988 is the most common at all levels, so this change-point year is adopted in the remaining analysis for cloud levels at all stations.

To quantify the change in cloud levels since the selected change point year of 1988, we estimate the slopes for the periods before and after the change point: 1967–1988 and 1989–2004. We also plot the time series of cloud levels and estimated trends before and after change-point year 1988 (Fig. 4) to visualize how trends changed after 1988.

Table 7 and Fig. 4 show that all but one station exhibit weak increasing trends in low cloud levels after the change point year 1988. In addition, both mid and high cloud levels exhibit significant decreasing trends since 1988.

In tropical stations, low clouds have increased since 1988 with Cairns experiencing a significant increasing trend (0.0025 $\text{year}^{-1}$), and Broome and Darwin with weak increasing trends. No consistent signal appears in the middle and high level cloud before or after the change point. With regards to continental data, there is no clear signal with the exception of significant increasing high cloud cover in all three stations (Giles, Kalgoorlie and Mt. Isa) prior to 1988, followed by decreasing trends in one (Kalgoorlie) or non-significant increases in the other two.

In summary, there is a detectable stepwise change in some mid-level and high-level clouds in and around 1988. Comparing trends before and after the change, we find that low cloud levels have increased after 1988 except for the continental station of Mt. Isa; and mid and high level clouds at mid-latitude have significantly decreased since 1988. These mid-latitude decreasing trends for mid and high cloud levels are not replicated consistently in tropical and continental stations.

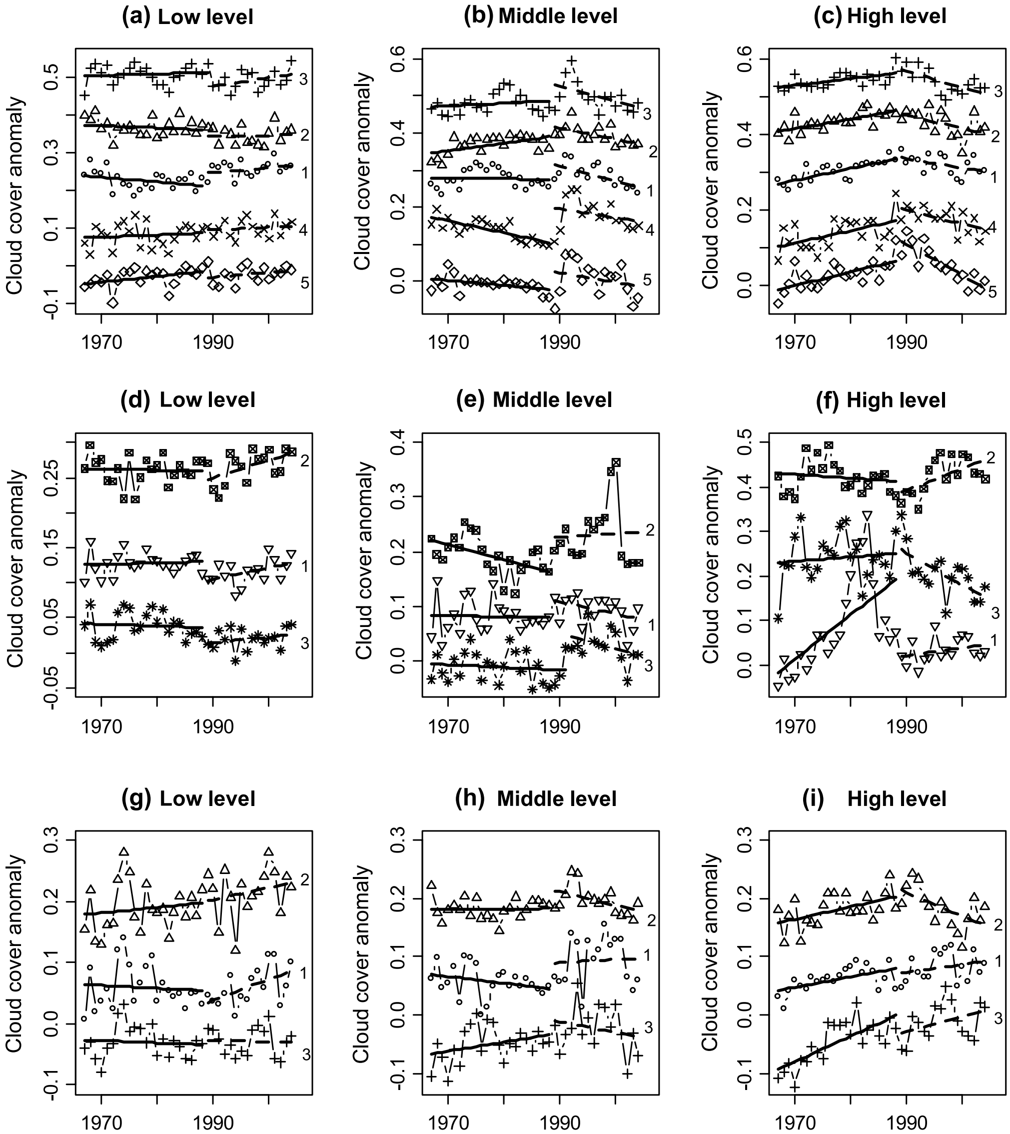



**Fig. 4.** Anomalies of yearly cloud cover calculated by subtracting yearly average cloud cover from the long term mean. Figures (**a**), (**b**) and (**c**) show mid latitude data at stations: Albany (1), Esperance (2), Mt. Gambier (3), Hobart (4) and Launceston (5); Figures (**d**), (**e**) and (**f**) show tropical data over stations: Broome (1), Cairns (2) and Darwin (3); Figures (**g**), (**h**) and (**i**) show inland data over stations: Giles (1), Kalgoorlie (2) and Mt. Isa (3). For easing of viewing Mt. Gambier, Albany, Hobart and Launceston have been offset by 0.1, 0.2, 0.3 and 0.4. Similarly Cairns and Darwin data have been offset by 0.1 and 0.2, and Giles and Mt. Isa have been offset by 0.05 and 0.15, respectively. There is a common stepwise change point year around 1988 in the trend. The linear trends before and after 1988 are superimposed in the yearly cloud cover anomalies

### *2.6 Seasonal trends in transmission*

In this section we partition the cloud data into winter and summer averages and repeat the above procedures for transmission trends and change points. Summer months are defined as October to March inclusive, while winter months represent the rest of the year, April to September inclusive. As in the previous analysis, the high quality surface radiation data set is used (Table 2), and mean extra-terrestrial radiation is calculated for the winter and summer half years. Regression relationships are then derived for daily solar radiation transmission vs cloud level and total cloud coverage:

$$S_\mathrm{s} = \frac{K_\mathrm{S}}{K_{0\mathrm{S}}} = 0.8313 - 0.2677C_{1\mathrm{S}} - 0.2094C_{2\mathrm{S}} - 0.0518C_{3\mathrm{S}} - 0.1392c_\mathrm{S}$$

$$R^2 = 0.92 \quad S.E. = 0.018 \quad n = 43 \tag{7}$$

**Table 7.** A comparison of estimated trends in cloud levels between pre-change period 1967–1988 and post-change 1989–2004. Significant trends are marked in bold

| Station | Low | | Middle | | High | |
|---|---|---|---|---|---|---|
| | Before 1988 | After 1988 | Before 1988 | After 1988 | Before 1988 | After 1988 |
| Albany | −0.0013 | 0.0013 | ≈0 | **−0.0041** | **0.0031** | **−0.0025** |
| Esperance | −0.0006 | 0.0001 | **0.0021** | **−0.0030** | **0.0026** | **−0.0034** |
| Mt. Gambier | 0.0001 | 0.0009 | 0.0008 | **−0.0041** | **0.0018** | **−0.0042** |
| Hobart | 0.0006 | 0.0007 | **−0.0033** | −0.0023 | **0.0033** | **−0.0039** |
| Launceston | 0.0016 | 0.0012 | **−0.0013** | −0.0026 | **0.0037** | **−0.0083** |
| Broome | 0.0002 | 0.0017 | −0.0002 | −0.0022 | **0.0101** | 0.0019 |
| Cairns | −0.0001 | **0.0025** | **−0.0027** | 0.0006 | −0.0009 | **0.0050** |
| Darwin | −0.0003 | 0.0008 | −0.0005 | −0.0029 | 0.0010 | **−0.0073** |
| Giles | −0.0005 | **0.0034** | −0.0011 | 0.0006 | **0.0018** | 0.0013 |
| Kalgoorlie | 0.0009 | 0.0020 | 0.0001 | **−0.0024** | **0.0022** | **−0.0041** |
| Mt. Isa | −0.0004 | −0.0003 | 0.0016 | −0.0019 | **0.0044** | 0.0025 |

$$S_w = \frac{K_W}{K_{0W}} = 0.7987 - 0.2715C_{1W} - 0.1910C_{2W} - 0.0601C_{3W} - 0.1496c_W$$

$$R^2 = 0.94 \quad S.E. = 0.021 \quad n = 43 \tag{8}$$

where now subscripts S and W stand for summer and winter, respectively, $K$ and $K_0$ are the seasonal averages of the daily measured and extra-terrestrial irradiance respectively, $C$ is total cloud cover and subscripts 1, 2, 3, refer to low, medium

**Table 8.** Statistics for regression trends between $K/K_0$ vs total cloud and cloud type cover for winter and summer (Eqs. 7 and 8). $p$-Values at the 5% level of confidence or less are marked in bold

| Station | Summer | | Winter | |
|---|---|---|---|---|
| | Slope (year$^{-1}$) | $p$-value | Slope (year$^{-1}$) | $p$-value |
| Adelaide Airp | −0.000231 | NS | −0.000065 | NS |
| Albany Airp | **−0.000458** | **0.02** | −0.000284 | 0.11 |
| Alice Springs Airp | **−0.000760** | **0.04** | −0.000108 | NS |
| Brisbane Airp | −0.000077 | NS | −0.000623 | 0.08 |
| Broome Airp | 0.000201 | NS | 0.000270 | NS |
| Cairns Airp | −0.000125 | NS | 0.000156 | NS |
| Canberra Airp | 0.000368 | NS | 0.000166 | NS |
| Carnarvon Airp | −0.000229 | NS | −0.000438 | 0.16 |
| Ceduna Met Office | −0.000266 | NS | 0.000275 | NS |
| Charleville Airp | 0.000021 | NS | 0.000155 | NS |
| Darwin Airp | **0.001053** | **<0.001** | **0.001063** | **0.009** |
| East Sale Airp | −0.000135 | NS | −0.000077 | NS |
| Esperance | 0.000534 | 0.07 | **0.000557** | **0.03** |
| Mt. Gambier Airp | 0.000312 | NS | **0.000477** | **0.05** |
| Giles Met Office | **−0.000863** | **0.01** | −0.000129 | NS |
| Halls Ck Airp | −0.000435 | NS | 0.000170 | NS |
| Hobart Airp | **−0.000478** | **0.05** | **−0.00075** | **<0.001** |
| Kalgoorlie Airp | **−0.000875** | **0.01** | −0.000596 | 0.08 |
| Launceston Airp | **−0.000875** | **0.01** | −0.000283 | 0.10 |
| Long Reach Airp | −0.000122 | NS | 0.000257 | NS |
| McKay Met Office | −0.000258 | NS | −0.000267 | NS |
| Meekatharra Airp | −0.000029 | NS | 0.002268 | NS |
| Melbourne Reg Office | **−0.001065** | **<0.001** | **−0.000766** | **0.01** |
| Mt. Isa Airp | **−0.000931** | **0.03** | −0.000135 | NS |
| Onslow | 0.000593 | 0.08 | **0.000687** | **0.05** |
| Perth Airp | −0.000044 | NS | −0.000157 | NS |
| Pt Hedlam Airp | −0.000356 | NS | −0.000327 | NS |
| Rockhampton Airp | −0.000070 | NS | **0.000640** | **0.04** |
| Williamstown Airp | −0.000053 | NS | −0.000295 | NS |

**Table 9.** Results of the Mann-Whitney-Pettitt test for change-point year in the reconstructed annual, winter (April–Sep.) and summer (Oct.–Mar.) solar radiation transmission series of all 29 stations over Australia and associated *p*-values. The significant change-point year at the level 0.01 or less are marked in bold

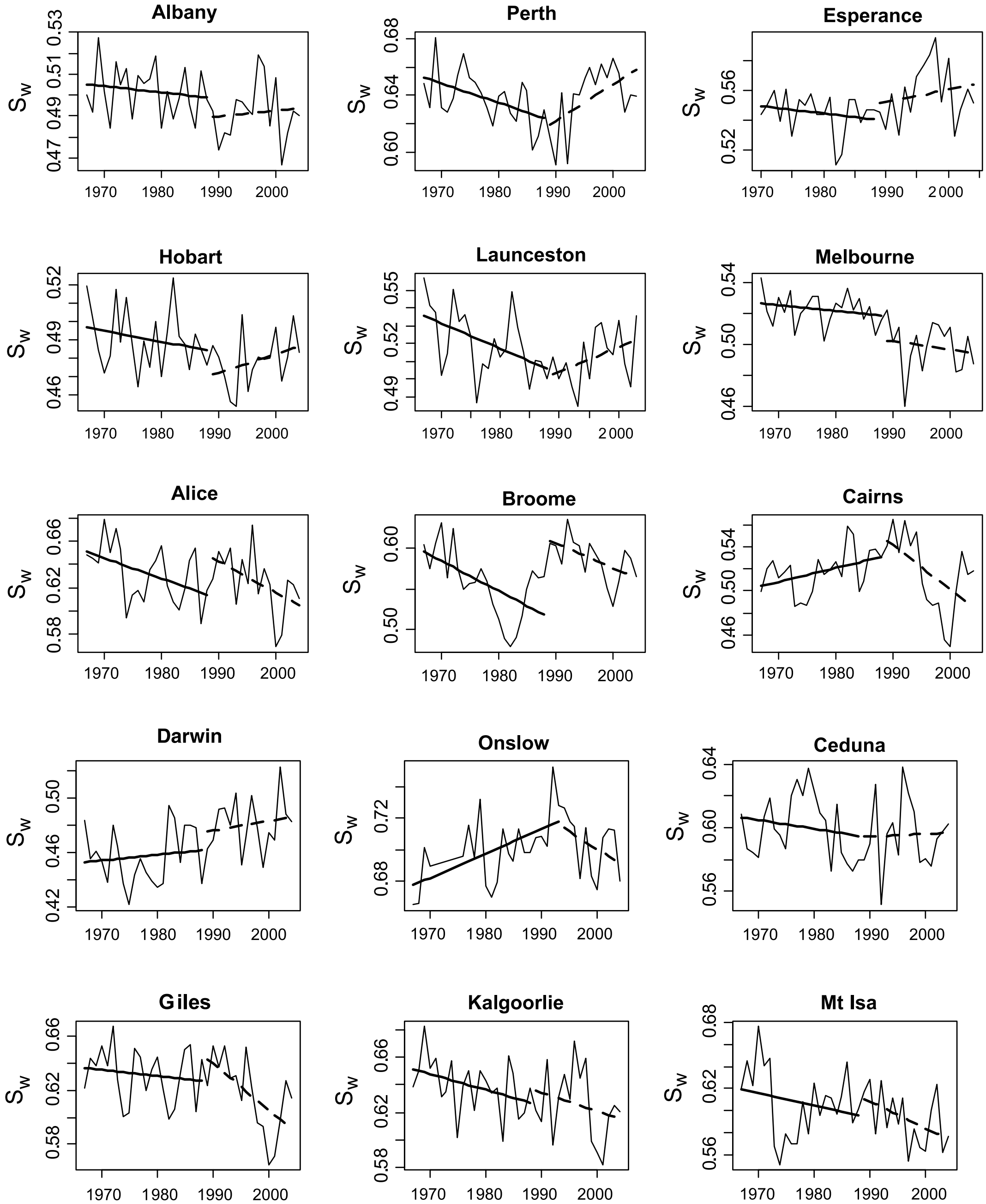
| Station | Annual | *p*-value | Winter | *p*-value | Summer | *p*-value |
|---|---|---|---|---|---|---|
| Adelaide Airp | 1978 | 0.24 | 1982 | 0.24 | 1986 | 0.61 |
| Albany Airp | **D-1991-I** | **0.01** | **1988** | **0.09** | **1990** | **0.04** |
| Alice Springs Airp | 1989 | 0.2 | **1973** | **0.06** | 1972 | 0.45 |
| Brisbane Airp | 1982 | 0.15 | 1970 | 0.32 | **1982** | **0.02** |
| Broome Airp | **D-1983-I** | **0.07** | **1988** | **0.06** | 1993 | 0.11 |
| Cairns Airp | **I-1993-D** | **0.04** | **1994** | **0.05** | 1978 | 0.39 |
| Canberra Airp | 1995 | 0.38 | 1976 | 0.24 | 1992 | 0.34 |
| Carnarvon Airp | 1996 | 0.24 | 1997 | 0.32 | 1986 | 0.13 |
| Ceduna Met Office | 1982 | 0.26 | **1982** | **0.06** | 1992 | 0.18 |
| Charleville Airp | 2000 | 0.47 | 1978 | 0.37 | 2000 | 0.44 |
| Darwin Airp | **D-1981-I** | **0.01** | **1988** | **0.02** | **1988** | **0.01** |
| East Sale Airp | 1983 | 0.11 | 1982 | 0.45 | 1992 | 0.25 |
| Esperance | **D-1990-I** | **0** | **1990** | **0.06** | **1990** | **0.02** |
| Mt. Gambier Airp | D-1992-I | **0.03** | 1992 | 0.13 | **1992** | **0.02** |
| Giles Met Office | **1994-D** | **0.03** | **1996** | **0.02** | 1991 | 0.32 |
| Halls Ck Airp | 1972 | 0.1 | 1997 | 0.16 | 1998 | 0.42 |
| Hobart Airp | **D-1990-I** | **0** | **1988** | **0.07** | **1988** | **0.01** |
| Kalgoorlie Airp | **1985-D** | **0.01** | **1985** | **0.06** | **1983** | **0.05** |
| Launceston Airp | **D-1987-I** | **0.06** | **1984** | **0.06** | 1973 | 0.18 |
| Long Reach Airp | 1971 | 0.19 | 1971 | 0.39 | 1993 | 0.11 |
| McKay Met Office | 1986 | 0.12 | 1986 | 0.49 | 1985 | 0.26 |
| Meekatharra Airp | 1975 | 0.27 | 1998 | 0.18 | 1974 | 0.22 |
| Melbourne Reg Office | **1983-D** | **0** | **1988** | **0** | **1988** | **0.02** |
| Mt. Isa Airp | **1972-D** | **0.04** | **1972** | **0.05** | 1970 | 0.47 |
| Onslow | **1988** | **0.1** | **1985** | **0.1** | **1990** | **0.09** |
| Perth Airp | 1977 | 0.13 | **1994** | **0.1** | 1979 | 0.46 |
| Pt Hedlam Airp | 1972 | 0.16 | 1972 | 0.32 | 1985 | 0.21 |
| Rockhampton Airp | 1990 | 0.24 | **1989** | **0.06** | 1990 | 0.33 |
| Williamstown Airp | 1980 | 0.22 | 1996 | 0.61 | 1982 | 0.23 |

and high cloud cover, respectively. As expected, both relationships exhibit a high coefficient of variance and low standard error.

Table 8 presents results for the regression trends. In summer, 22 out of 29 stations exhibit negative trends, with eight of these being significant. There is only one station, Darwin Airport which exhibits a significant positive trend in summer. In winter 16 stations show decreasing trends and 13 increase, but only seven stations exhibit significant trends, with the majority exhibiting positive trends. Only Hobart and Melbourne exhibit significant negative trends.

Change point analysis is presented in Table 9 for both winter and summer. To better observe the trends, we have relaxed the significance level to 0.1. Examining the winter values, it is seen that there were 16 significant change points, seven of which occurred between 1989 and 1990. The rest of the change point dates are scattered in years before 1988–1990 (5) and years after 1988–1990 (4). The change point pattern for summer also confirms the significance of 1988 as a change point year. Of the nine significant change points calculated, six occurred in the period 1988–1990. We can then conclude that 1988 is the most common change point year.

In the subsequent analysis we use a common change point year 1988 for all series that exhibited significant change points and calculate trends before and after the change point year. Results are presented for winter (Fig. 5) and summer (Fig. 6). Examining the winter time series first, it may be noticed that all the southern stations with the exception of Melbourne and Ceduna show decreasing trends until 1988, followed by increasing trends afterwards (Albany, Perth, Esperance, Hobart, Launceston). Continental stations (Alice Springs, Mt. Isa, Giles, Kalgoorlie) show decreasing or constant trends until 1988, followed by higher decreasing trends.



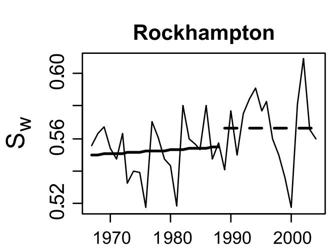




**Fig. 5.** Significant changes in the reconstructed winter (April–Sep.) solar radiation transmission ($S_w$) for 16 stations over Australia during 1967–2004 and the superimposed fitted linear trends before and after change point year (1988) at each station

Results for Queensland coastal stations are mixed (Cairns, Rockhampton), while along the north coast, Darwin exhibits an increasing trend after 1988. No clear pattern emerges in the summer time series for significant change points (Fig. 6). Three out of the nine south coast stations show increasing trends after 1988 (Esperance, Mt. Gambier and Melbourne), while two show de-

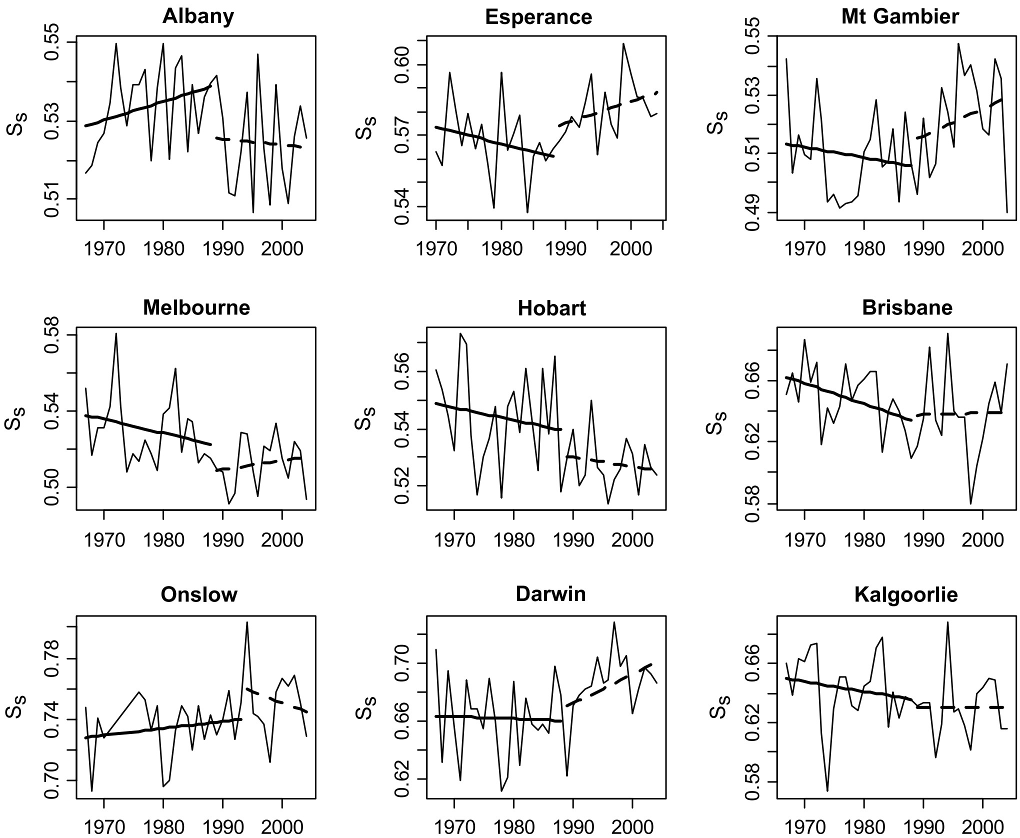



**Fig. 6.** Significant changes in the reconstructed summer (Oct.–Mar.) solar radiation transmission ($S_s$) for 9 stations over Australia during 1967–2004 and the superimposed fitted linear trends before and after change point year (1988) at each station

creasing trends (Albany and Hobart). As before, Darwin shows increasing trends after 1988.

In summary, estimates of decreasing yearly cloud cover anomalies observed in southern stations after 1988 (Table 7 and Fig. 4a–c) are supported by increasing winter solar radiation transmissions, but this effect is not evident in the summer time series. Continental stations show decreasing transmissions in winter, which is supported by yearly increases in low cloud cover after 1988 (Fig. 4).

## 3. Discussion

The motivation behind this study stems from a knowledge gap in Australian solar radiation trends prior the early nineties. Wild et al. (2005) present evidence of recent increases in solar radiation globally, which also include data from Australian station. Measurements prior to 1992 are not available for Australia, so that it is not possible to determine if Australian radiation records also underwent a long-term decrease followed by an increase sometime in the late eighties or early nineties. This information can only be provided by modelled solar radiation using proxy data, which is the approach followed in this study.

To accomplish this task several options were considered – data on total cloud cover, cloud cover at three levels, and sunshine duration. The fist option was by far the most numerous and had the longest record. However the technique proved highly inaccurate as solar radiation transmission is dependent on cloud type (Haurwitz, 1948; Vowinckel and Orwig, 1962). Sunshine duration was also considered but was rejected as the data recording methodology was changed by the purchase of new paper with a lower burn threshold around 1980 (Forgan, personal Communication).

Our model uses observations of cloud cover and height, essentially unchanged in its methodology since its first use in 1967 by the Australian Bureau of Meteorology. A yearly cloud transmission relationship is developed using cloud data (three levels and total cloud cover) and calibrated pyranometer data. The regression model is then used to estimate yearly solar radiation transmission over the entire data set.

With the exception of Kalgoorlie, known for its mining and industrial operations, no significant trend for cloudless conditions was obtained from individual pyranometer data. These results disagree with the world-wide increase in measured clear sky global radiation after 1992 (Wild et al., 2005). All-sky global radiation has been reported as increasing in the last few decades over Germany (Power, 2003), but decreasing in South Africa (Power, 2005). Data for China (Liang and Xia, 2005) and the United States (Lieper and Tegen, 2002) show a decrease up to 1990, and a recovery afterwards. Aerosol forcing has been given as the likely cause for these global radiation trends. However many of the stations are in the northern hemisphere and are under the influence of large population and industrial centres. The changes picked up in our study due to direct aerosol effects are small and not statistically significant, and certainly much smaller than those produced by cloud cover changes.

Nineteen out of the 29 stations used report a drop in yearly solar radiation transmission, with eight of these being statistically significant. By contrast there were eight stations showing increases, with only two of these being significant. Our results imply a small increase in cloud amount. Jones and Henderson-Sellers (1992) also reported a small increase in total cloud amount over Australia, but their study period was longer (1910–1989). Despite the reported solar radiation change point in many stations in the late eighties and early nineties, the overall pattern is still one of increasing cloud cover and decreasing transmissions.

Statistical analysis revealed a number of years when trends in transmission underwent changes. Only 12 out of a possible 29 changes proved significant. Of these, the majority (7) showed decreasing followed by increasing trends, two stations showing sharp decreasing trends followed by slightly decreasing trends, one increasing followed by a decreasing trend, and two with no trend followed by decreasing trends. Furthermore, five out of the seven stations reporting decreasing/increasing trends are spatially coherent as they are located in southern Australia and are under the influence of westerly synoptic systems. Further examination of individual cloud levels showed that the change points in these five stations occurred between 1987 and 1992, these being related to rapid increases in middle and high level clouds followed by gradual cloud cover decreases afterwards.

Solar radiation transmissions were also derived for winter and summer half years following the same analysis as with the yearly transmissions. Winter transmission for most of the southern stations also exhibit decreases until 1988, followed by increases afterwards. However no clear pattern emerges in the summer transmission in the southern stations. These results indicate that processes occurring in winter are likely to be related to yearly cloud decreases observed after the late eighties in the southern stations. The other outstanding feature is the decreasing summer transmission in continental stations after 1988, a feature likely to be related to increasing low cloud cover.

There is no clear explanation for the rapid cloud cover changes in the five southern stations. The cloud acquisition procedure has remained the same since its inception in 1967, making it unlikely to be related to errors or changes in data acquisition. One possible explanation could be the Mt. Pinatubo volcanic eruption occurring in June 1991, dumping debris and ash into the stratosphere, which spread world-wide (McCormick et al., 1995; Luo et al., 2002). The reported rapid spread of these aerosols throughout the globe is similar to the near step change reported in middle and high-level clouds for the southern stations (Fig. 4b and c). The question we wish to address here is if the aerosol load associated with this volcanic eruption is sufficient to induce substantial decreases in yearly solar transmission.

A sensitivity test was performed to examine the importance of this large but transient AOD signal in affecting surface solar irradiance. The Streamer radiative transfer model was used with an eight stream DISORT algorithm option (Key and Schweiger, 1998). A cloud scene was chosen typical of conditions for Hobart, Tasmania. It contained low, middle and high cloud levels, with coverage of 0.5, 0.2 and 0.1 and cloud thickness of 0.5, 0.2 and 0.1 km, respectively. Yearly average of daily solar irradiance was calculated for Hobart, and for background tropospheric and stratospheric aerosols with a 600 nm AOD (used as input in Streamer) ranging from 0.02 to 0.16. This yearly AOD range essentially covered all values measured by Wilson and Forgan (2002) at Cape Grim, Tasmania. Although their reported AOD figures were estimated for 500 nm, their AOD values were essentially constant with wavelength and as a first approximation we have taken the AOD at 500 and 600 nm to be equal.

On a yearly basis, a maximum transmission ($K/K_0$) of 0.776 was obtained with an AOD of 0.02, and a minimum of 0.754 with an AOD of 0.16. These differences are not large, amounting to a maximum of 2.8% over the full range of AOD values that were measured. Their low impact on surface solar irradiance may be further illustrated by plotting transmissions from the cloud regression model (Eq. 6), which assumes a constant aerosol load, and the resultant transmissions that may be expected if the atmosphere were to undergo a change in transmission of ±2.8% resulting from a change in AOD of 0.02 to 0.16. These results, expressed as error bars in transmissions are only approximate figures as they are based on a single idealised cloud scene

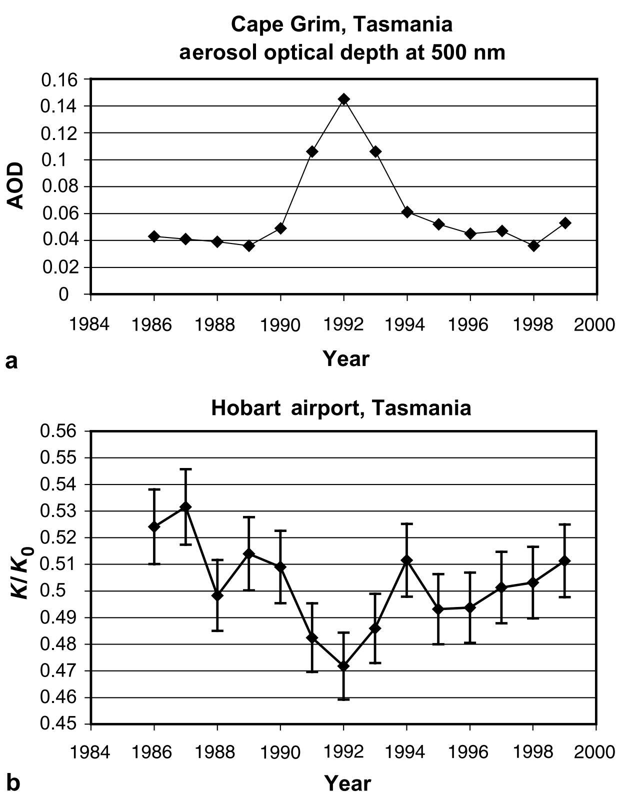



**Fig. 7.** (**a**) Yearly aerosol optical depth for Cape Grim, Tasmania which has been adapted from Wilson and Forgan (2002). (**b**) Yearly transmission calculated by the cloud regression model for Hobart, Tasmania. Error bars denote expected change in transmission due to a maximum change in AOD of ± 0.02 to 0.16

as described in the previous paragraph. Nevertheless they are useful qualitative indicators of the impact of *direct* aerosols effects on surface solar irradiance.

Figure 7b shows the transmission results from the cloud model for Hobart, Tasmania, with no explicit dependence on aerosol, for the period 1986 to 1999, which corresponds to the time interval of AOD measurements at Cape Grim. Superimposed on these transmission figures are the percentage change from the streamer model. These AOD changes, represented by the error bars, are small compared to those induced by cloud cover, and certainly are unlikely to influence the decadal change in transmission seen in Fig. 7b.

A second possibility is that the stratospheric aerosol layer could have been misinterpreted as cirrus or altostratus cloud during weather observations. This is unlikely as firstly, the anomaly was reported throughout a series of stations and not just one as expected if it were an error by an individual observer. Secondly, the anomaly appeared in middle level clouds as well as cirrus. It would be more difficult to misinterpret a middle level cloud compared to cirrus cloud because of its increased bulk and opacity.

Could aerosol indirect effects be acting? There are some studies that examine how volcanic eruptions may affect cirrus cloud properties. Luo et al. (2002) analysed three satellite-based cirrus data sets for evidence of responses to the Mt. Pinatubo eruption. They concluded that there is no evidence that the volcanic event had a systematic effect on tropical cirrus properties. Lohmann and Feichter (2005) and Lohmann et al. (2003) used the ECHAM global circulation model and also concluded that the effect of Mt. Pinatubo aerosols on cirrus properties is small. On a regional scale, however, lidar measurements support Mt. Pinatubo aerosols enhancing cirrus cloud formation (Sassen, 1992) via a scenario involving mixing of stratospheric sulphuric acid droplets with tropospheric air containing ammonia gas. In a recent paper, Kaufman and Koren (2006) use global surface-based measurements from the Aerosol Robotic Network (AERONET) to link global cloud cover with aerosol type, with increasing (decreasing) cloud cover related to aerosol low (high) absorption optical thickness.

The above literature argues that there is no strong, unambiguous link between the

Mt. Pinatubo eruption and the enhancement of cirrus cloud formation. It is clear that the cloud anomalies are not generated from local surface heating as they deal with middle and high level clouds. The pattern suggests poleward/equatorial shifts in synoptic systems, perhaps in response to solar forcing (Lohmann et al., 2004; Haigh, 1999), and in combination with a Mt. Pinatubo enhancement effect. However in the United States no significant relationship was obtained between solar forcing and a solar radiation model using sunshine duration (Stanhill and Cohen, 2005). Other cyclic processes are suggested, such as the Southern Annular Mode (SAM) resulting in strengthening or weakening of the southern hemisphere westerlies (Thompson and Solomon, 2002; Kidson, 1999; Burnett and McNicoll, 2000).

## 4. Conclusion

In summary, there is no clear trend that emerges in yearly transmission of solar radiation as the majority of these stations (19) recorded non-significant trends. Eight out of the ten stations with significant trends recorded decreases, with the majority of the stations located in the southern end of the continent. These southern stations exhibited a weak upturn in the late eighties, the trends before and after the upturn were particularly evident in the winter half year, and were related to changes in middle and high level clouds. Possible causes for the effect include the Mt. Pinatubo eruption, SAM effects or a combination of both. A future study will examine these processes in more detail.

### Acknowledgement

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