Climatic Trends in the Southern Hemisphere

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ABSTRACT

Observations of monthly mean sea level pressure, surface air temperature, and 500 mb and 300 mb geopotential heights and temperatures are used to study trends in the Southern Hemisphere from 1951–81.

The winter mean sea level pressure fell over the Indian/Atlantic half of the hemisphere from the 1950s to the 1960s, and rose over the other half. Generally, these trends reversed from the 1960s to the 1970s. The trends are equivalent barotropic.

The trends of temperatures are often regionally dependent. There was a significant warming over Antarctica from the 1960s to 1970s at all upper levels except for a small area on the Indian Ocean side.

1. Introduction

Long-term changes of pressure, heights and temperatures are known to occur in the atmosphere; however, relatively little is known concerning trends in the Southern Hemisphere. Mo and van Loon (1984) recently documented decadal differences in the seasonal cycle of sea level pressure for the periods 1951–58 and 1972–80 due not to change in data coverage or analysis method, but to real climate change. Swanson and Trenberth (1981) compared the mean height and wind fields throughout the troposphere of the Southern Hemisphere for the periods 1957–66 and 1972–78 and discovered an overall pattern to the changes. Some regional changes have also been studied: for example, Kraus (1977) noted an increase of 500 mb heights over Antarctica during the 1960s.

More reports are available on the temperature trends. Trenberth (1976) discussed the temperature trends in the Australian region, and van Loon and Williams (1977) mapped the trend of winter temperatures between 1956 and 1973 over the Antarctic. Angell and Korshover (1978) examined the trends between the surface and 100 mb using 63 radiosonde stations from 1958–77. Several studies of the global temperature trends have been made in recent years because of the potential effect of CO_2 on temperature. In the Southern Hemisphere, Hansen *et al.* (1981) found a cooling trend from 1940–60. However, for the period 1960–70 different studies led to different conclusions. Damon and Kunen (1976), Hansen *et al.* (1981) and Chen (1982) showed a substantial surface temperature increase but Angell and Korshover (1975, 1977) as well as Navato *et al.* (1981) noted a decreasing trend. However, little attention has been paid to the regional dependence of climate trends.

This paper is a study of temperature and pressure trends in winter (June, July and August) and summer (December, January and February), using monthly mean values of observations of sea level pressure and rawinsonde data. This study covers the period 1951–81. It demonstrates that the trends of pressure and temperature are often regionally dependent. The cooling or warming in different regions from the 1960s to 1970s is discussed as well.

Section 2 describes the data. Section 3 documents the trends of sea level pressure and Section 4 the trends of geopotential height fields from the 850 mb to the 200 mb level. Section 5 documents the trends of surface air temperature, and Section 6 the trends of upper-level temperatures. The conclusions are given in Section 7.

2. Data

The station values of monthly mean sea level pressure, surface air temperature and monthly mean upper air rawinsonde observations were obtained from the

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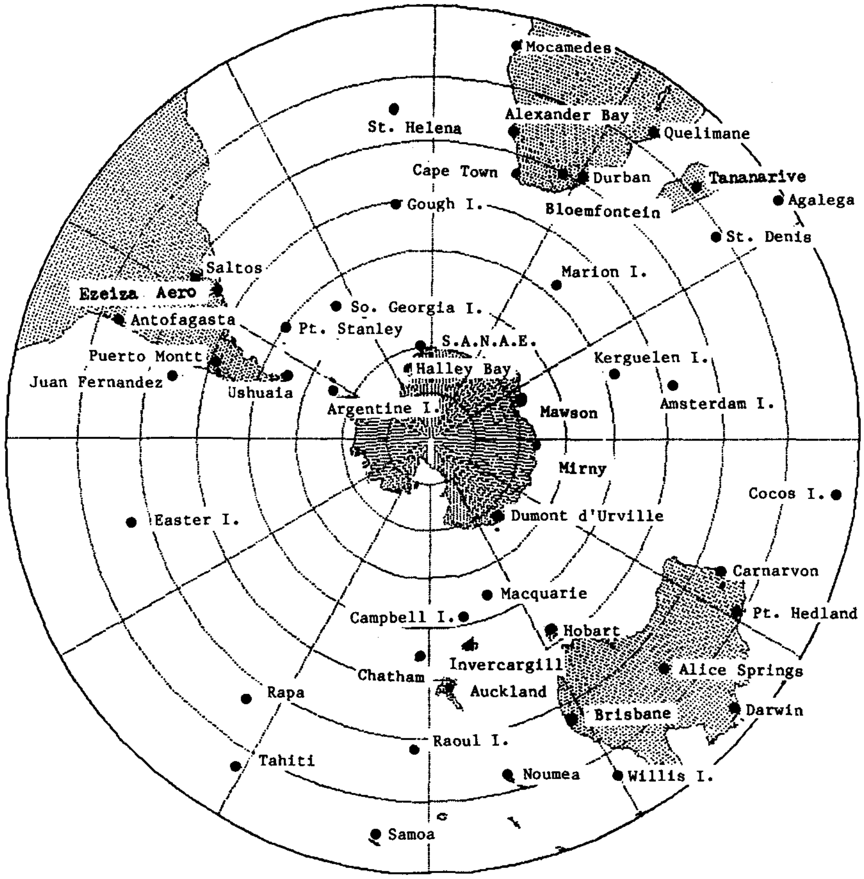

FIG. 1. Names and positions of stations.

National Center for Atmospheric Research. The names and positions of stations used are given in Fig. 1. Stations were chosen to give the best possible coverage. Most of the monthly mean surface data have continuous 30 year (1951–81) records. However, for most high latitude stations, the upper air records started in 1957 or even later.

This study uses seasonal means: June, July, and August for the winter and December, January, and February for the summer season. The trends of the annual means will also be discussed. The normalized anomaly for a given variable Z is defined as the departure from the 1951–81 mean divided by the standard deviation σ, i.e.

$$Z^*(t) = [Z(t) - \bar{Z}]/\sigma,$$

where $\bar{Z}$ is the time average over 31 years and σ is the standard deviation.

To damp the large fluctuations in the data, we have applied the 1-3-1 smoothing to the time series of normalized anomalies. Our results are not sensitive to the smoother used.

3. Sea level pressure

Figures 2 and 3 show the smoothed normalized anomalies of sea level pressure for 31 stations in winter and 30 stations in summer. Except for the stations in high latitudes, the mean sea level pressure fell over the Indian and Atlantic half of the hemisphere from the 1950s to the 1960s, but rose over the other half of the hemisphere. In general, these trends reversed from the 1960s to the 1970s.

At higher latitudes on the Pacific side at Campbell and Macquarie, the sea level pressure increased almost linearly during these 30 years. On the opposite side of the Pacific, for example Stanley, the trend was the reverse.

To bring out the overall trend, the unsmoothed sea level pressure anomalies at each station were fitted into a parabola

$$Z(t) = \bar{Z} + a + bt + ct^2.$$

The mean $\bar{Z}$ and a, b and c are the coefficients of the fitting. When the lowest values of sea level pressure are

FIG. 2. Smoothed normalized anomalies (thin line) of sea level pressure in winter from 1951 to 1981. Thick line gives the parabola fit for unsmoothed anomalies. Vertical scale is in units of one standard deviation, and horizontal scale in units of years labeled in increments of five.

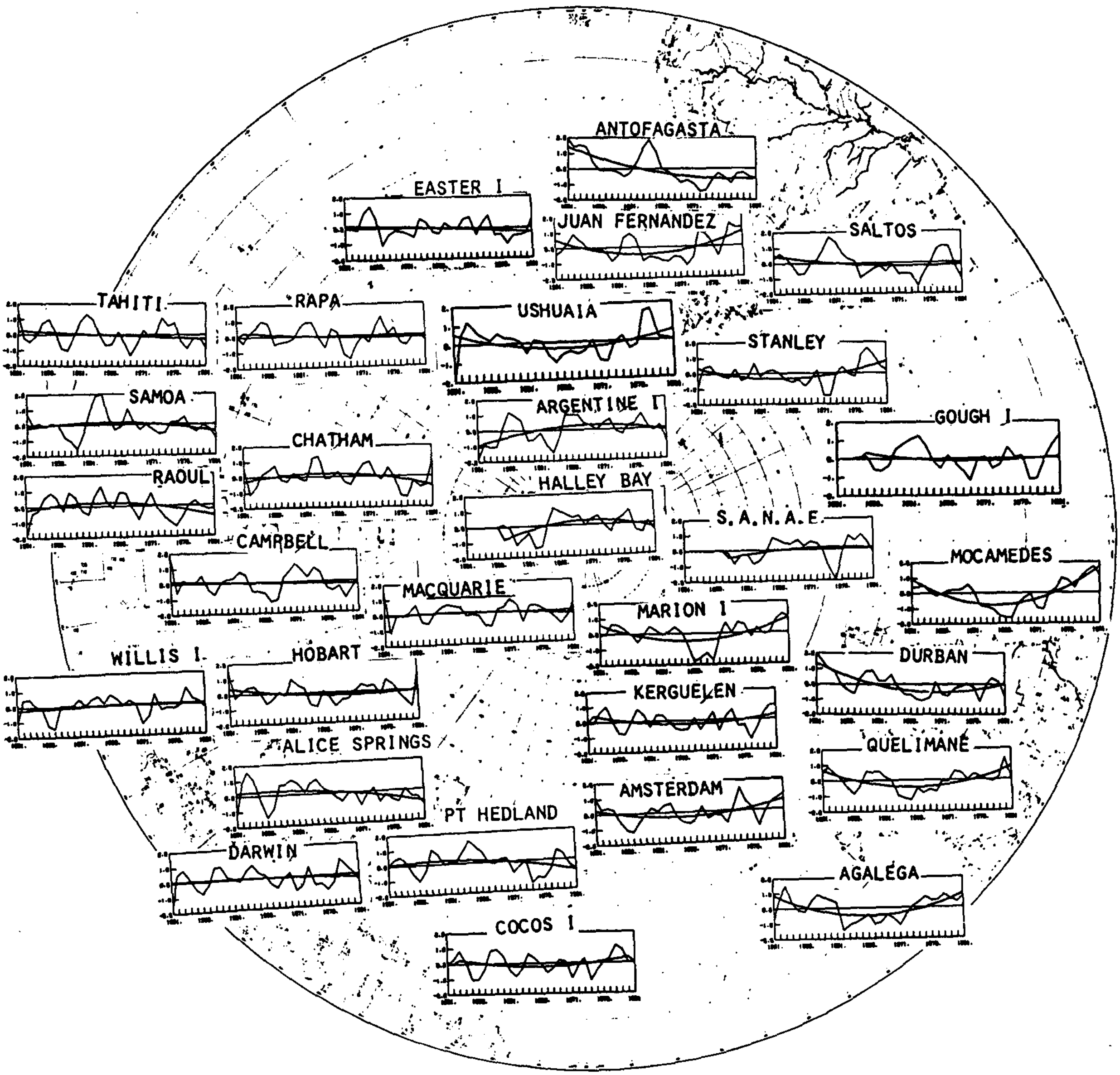

FIG. 3. As in Fig. 2 but for the summer season.

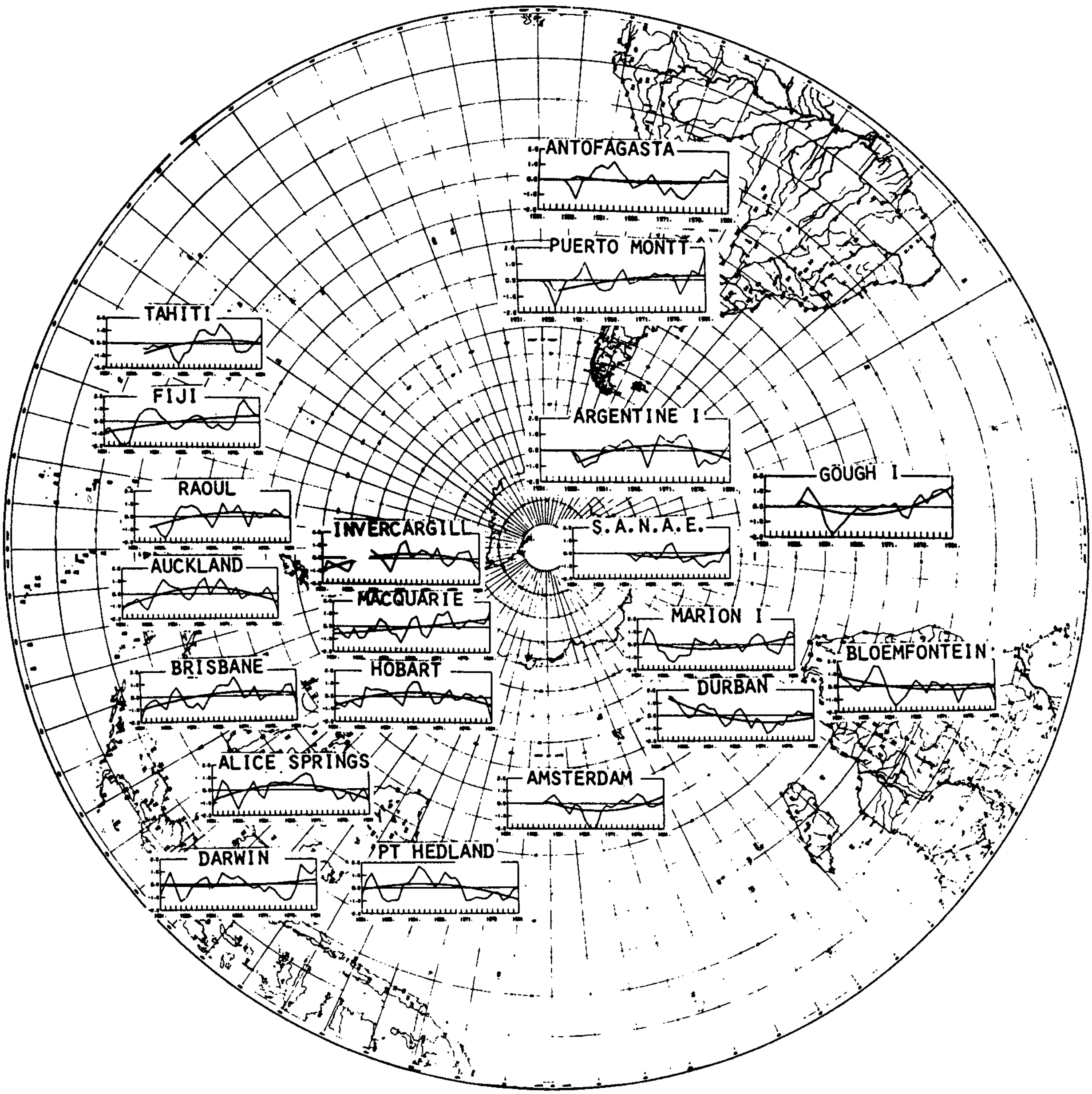

FIG. 4. As in Fig. 2 but for 500 mb height anomalies in winter.

TABLE 1. Means, standard deviations years of records of 500 mb heights and the correlations of 500 mb height anomalies with 300 mb and 850 mb height anomalies for the winter and summer seasons.

		Winter				Summer			
Station	Data period (year)	Mean	Standard deviation	ρ_{300}	ρ_{850}	Mean	Standard deviation	ρ_{300}	ρ_{850}
Alexander Bay	52–81	5780	14.9	0.85	0.83	5864	9.5	0.62	0.61
Bloemfontein	63–81	5785	17.3	0.91	0.70	5866	8.8	0.64	0.27
Durban	60–81	5780	13.6	0.91	0.71	5855	10.7	0.86	0.51
Gough	57–81	5553	29.8	0.95	0.93	5707	29.9	0.95	0.94
Antofagasta	60–81	5821	9.3	0.84	0.71	5868	10.4	0.79	0.44
Puerto Montt	57–81	5549	21.8	0.95	0.80	5707	18.8	0.92	0.72
Argentine I	57–81	5086	34.7	0.99	0.95	5188	29.9	0.96	0.93
S.A.N.A.E.	57–81	4940	48.4	0.97	0.94	5143	34.0	0.92	0.91
Halley Bay	57–81	4922	35.9	0.98	0.96	5118	31.6	0.93	0.91
Fiji	51–81	5865	13.5	0.86	0.73	5859	17.4	0.92	0.73
Tahiti	57–81	5862	17.3	0.94	0.69	5858	14.0	0.86	0.52
Invercargill	51–81	5477	33.2	0.97	0.96	5644	34.6	0.98	0.96
Chatham	56–81	5491	34.9	0.97	0.94	5686	33.6	0.98	0.95
Brisbane	51–81	5707	17.6	0.87	0.77	5832	15.8	0.80	0.72
Hobart	51–81	5517	30.5	0.81	0.96	5686	36.6	0.97	0.94
Macquarie	53–81	5329	34.7	0.96	0.96	5420	16.4	0.96	0.92
Raoul	52–81	5677	33.2	0.97	0.96	5818	18.0	0.54	0.78
Pt. Hedland	51–81	5812	12.3	0.78	0.66	5848	16.8	0.70	0.75
Alice Springs	51–81	5784	10.9	0.75	0.52	5861	16.9	0.58	0.58
Darwin	51–80	5857	8.26	0.84	0.46	5848	13.5	0.87	0.72
Mirny	58–81	4973	86.5	0.99	0.95	5141	39.3	0.98	0.93
Marion I	51–81	5420	35.1	0.97	0.96	5505	41.6	0.98	0.96
Amsterdam	55–80	5612	29.5	0.92	0.87	5777	30.8	0.75	0.81

in the 1960s then a and c are positive but b is negative. This is observed at all stations over Africa, the Indian Ocean, the Atlantic Ocean and South America. When the highest values are in the 1960s, a and c are negative but b is positive. This signature is found at all stations in the Pacific Ocean and over Australia. At high latitudes, the signatures are mixed.

These trends change the amplitude of the dominant half-yearly wave in midlatitudes, as noted in Mo and van Loon (1984), where it is also shown that the trends have a large effect on the planetary waves, especially wave 3. For example, the mean amplitude of wave 3 at 50°S in June was 2.1 mb from 1952 to 1958 (African data set), (2.8 mb from about 1957 to 1966; Taljaard *et al.*, 1969), and 3.2 mb from 1972 to 1980 (Australian data set).

The trends of mean sea level pressure for the summer season are in general weaker. They show the same sig-

TABLE 2. Average 500 mb height, annual means during the periods 1957–69 and 1970–81.

Station	$\bar{Z}_1$ (mean) 1957–69 (m)	$\bar{Z}_2$ (mean) 1970–81 (m)	$\bar{Z}_2 - \bar{Z}_1$ (m)	Error
Argentine Island (65°S, 64°W)	5112.3	5130.2	17.8	6.6
Islas Orcadas (60.7°S, 44.7°W)	5163.4	5180.6	15.3	8.9
S.A.N.A.E. (70°S, 2.4°W)	5004.7	5029.4	24.7	10.4
South Pole (90°S)	4926.5	4974.3	48.1	11.4
Halley Bay (76°S, 27°W)	4995.9	5007.0	11.0	6.5
Byrd Station* (80°S, 119.5°W)	5105.2	5165.2	59.9	14.9
Novolazarevskaja* (70.9°S, 11.8°E)	5131.6	5135.5	4.6	13.6
Mirny (66.6°S, 93°E)	5023.7	5035.0	11.3	8.1
Vostok (72.1°S, 46°E)	4981.1	4995.1	14.0	7.7
Casey (66.3°S, 110.6°E)	5008.0	5028.2	20.2	8.4
Hallett* (72.3°S, 170.2°E)	5107.8	5143.8	36.0	14.1
Mawson (67°S, 63°E)	4990.5	5009.9	19.3	14.1
Macquarie (54.5°S, 159°E)	5342.3	5360.4	18.1	7.6

* For summer months only.

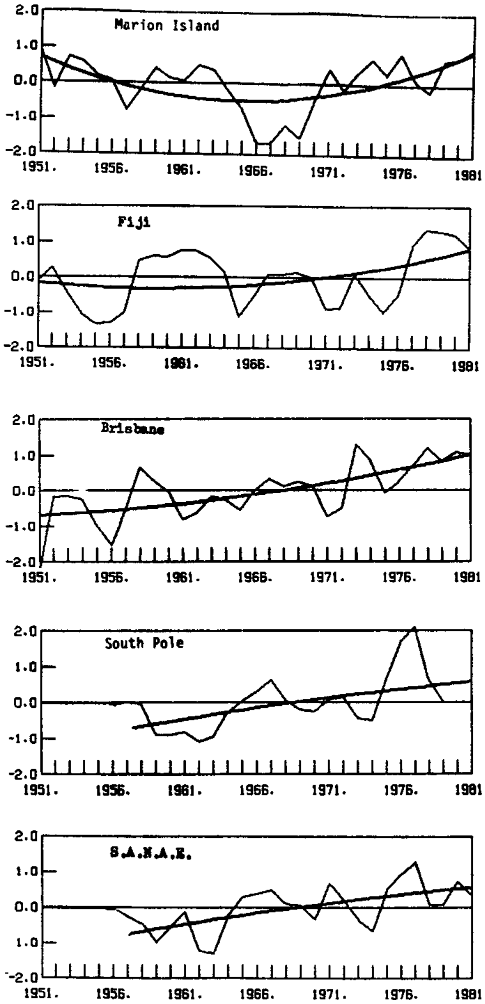

FIG. 5. Smoothed normalized anomalies (thin line) of 500 mb height anomalies for selected stations in summer. Thick line gives the parabola fit for unsmoothed anomalies.

nature as the trends for the winter season. The only station with a large seasonal variation is Stanley where the sea level pressure increased from 1976 to 1981 in the summer season while it fell in winter.

4. Geopotential height fields

Figure 4 shows the smoothed normalized anomalies of 500 mb geopotential heights for 20 stations in winter. The only radiosonde station in the Pacific Ocean east of 140°W is Easter Island at 28°S and its record did not start till 1970. For many stations in South America the records started in the early 1960s, so the trends over that region are uncertain.

Elsewhere, the trends for 500 mb geopotential heights are in general the same as the trends for sea level pressure. The heights fell at the stations in the Atlantic and Indian Oceans and southern Africa from the 1950s to the 1960s and rose on the Pacific side of the hemisphere. These trends reversed from the 1960s to the 1970s. The parabola fit can only serve as a general guide since some stations have no record before 1957.

The trends for 500 mb geopotential heights for the summer are the same as the trends in the winter season; some examples are given in Fig. 5. Means and standard deviations of 500 mb geopotential heights for selected stations can be found in Table 1.

For stations at high latitudes such as Mirny, Macquarie, and S.A.N.A.E., as well as Amundsen-Scott (South Pole), a strong linear trend has been observed. The trend at the South Pole could be due in part to recalculation of the station height (Schwerdtfeger, 1975). This high latitude trend also appears in the annual means from 1957–81. Table 2 gives the annual mean averaged over the periods 1958–69 and 1970–81, as well as their differences. If σ_1^2 is the variance of the first period, σ_2^2 is the variance of the second period, and N_1 and N_2 are the numbers of years used to calculate the means for the two periods, then the error of the difference can be estimated as $(\sigma_1^2/N_1 + \sigma_2^2/N_2)^{1/2}$. The error clearly indicates a large increase in heights throughout Antarctica. This trend was also noted by Kraus (1977) and Trenberth (1979) when they studied the heights from 1958 to 1978.

For stations on the east coast of Australia for example Brisbane (Fig. 5) a linear trend has also been found in the summer season, but the increase of annual mean is not very large.

The trends are equivalent barotropic. Table 1 gives the correlations between the 500 mb height anomalies and the 300 mb height and 850 mb height anomalies for the winter season and the summer season for selected stations.

For most stations there are 31 years of records available. Since there is a low frequency trend, the number of independent samples will be smaller than 31. Assuming 18–29 degrees of freedom, statistically significant at the 99% level, the coefficient needs to be larger than 0.58. Except for small regions in Africa and Australia the coefficients are significant. Figure 6 shows, as examples, the smoothed height anomalies at 200, 300, 500 and 850 mb for the stations Invercargill and Marion Island in winter.

The equivalent barotropical structure for the trends breaks down for stations in the tropics. Trends of sea level pressure and 500 mb height anomalies for selected stations in the tropics can be found in Fig. 7. When the 500 mb heights increased from 1965 to 1981 for all the stations, the sea level pressure fell for stations Songkula, San Juan and Khartoum. For station San Juan, the reversal of trend at the two levels can be found for the whole data period.

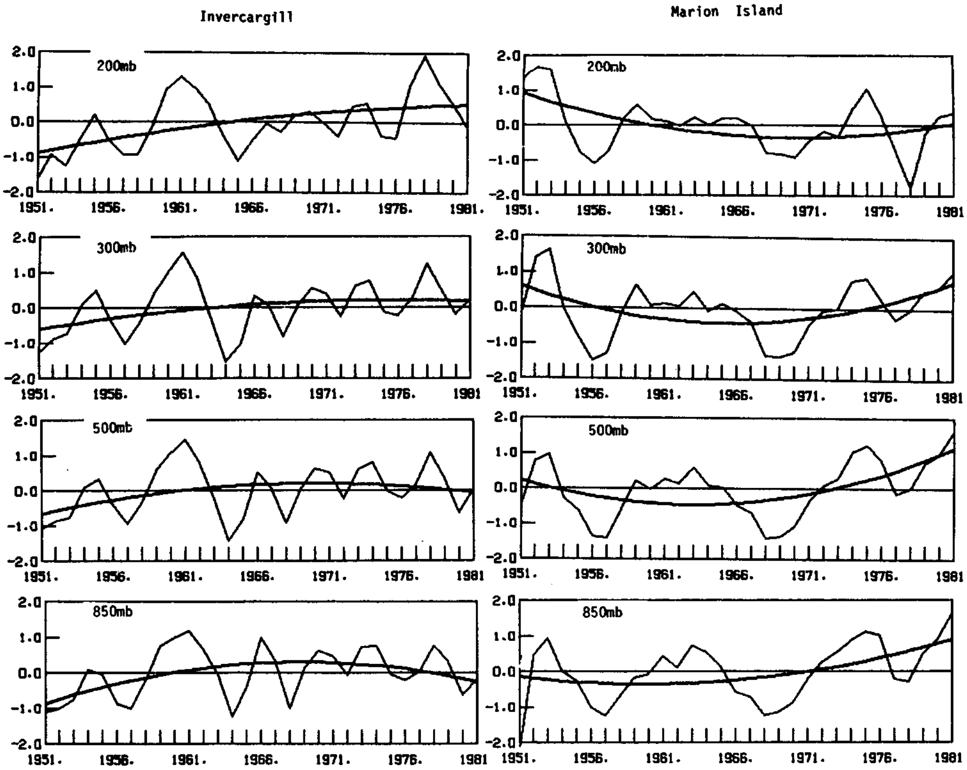

FIG. 6. Smoothed normalized anomalies (thin line) of height fields at 200 mb, 300 mb, 500 mb and 850 mb for the annual means at Invercargill and Marion Island. Thick line indicates the parabola fit using unsmoothed anomalies.

5. Surface air temperature

Figure 8 shows the smoothed normalized anomalies of surface air temperature for 31 stations in winter. The trends tend to be regionally dependent in the first half of the period. There is good evidence for a temperature decrease during the period 1951–65 at stations in the Indian Ocean, e.g. Kerguelen, Cocos Island, Amsterdam. But an increasing trend can be found for most stations from 1965 to 1981 except for Willis, Quelimane and Samoa where the temperature decreased. At some stations, such as Raoul, Alice Springs, Stanley and Rapa, the trend showed no change during this 31 year period.

The trends of surface air temperature for the summer season in general agree with the trends in winter. The temperatures in the 1960s are much lower in summer at stations in and around South America, e.g., Antofagasta, Juan Fernandez and Easter Island. This contributes to a larger temperature increase from the 1960s to the 1970s over that region. Figure 9 shows trends for selected stations in summer. At higher latitudes, the linear warming trend discussed by Angell and Korshover (1978) and Raper *et al.* (1984) shows up in both summer and winter, and it appears in the annual mean as well. However, the abrupt cooling of the annual mean temperature in 1976 reported by them can only be found at some stations, e.g., Casey and Ushuaia, and not at others, e.g., S.A.N.A.E. and Macquarie.

We have also computed the annual means for the periods 1957–68 and 1970–81 and their difference Δ. All stations except Quelimane ($\Delta = -0.566°C$ and error $= 0.16°C$) and Samoa ($\Delta = -0.27°C$ and error $= 0.06°C$) show a temperature increase from the 1960s to the 1970s. The largest increase occurred at the Pole.

For the annual mean temperature, a decreasing trend can be found from the 1950s to the 1960s at stations on the Indian and the Atlantic side of the hemisphere and the reverse trend over the other half of the hemisphere, e.g., Australia and the Pacific Ocean, (cf. Tahiti and Amsterdam in Fig. 10). There is no significant difference between the trends over land and those over sea (Chen, 1982). Due to the sometimes strong regional dependence of the trends, stations should ideally be distributed uniformly over the hemisphere when globally averaged temperatures are studied. There is similarity between the trends of sea level pressure and trends of surface temperature at the stations in the Atlantic and Indian Oceans and South Africa.

6. Upper air temperature fields

Figure 11 shows the smoothed normalized 500 mb temperature anomalies in winter. The temperature at

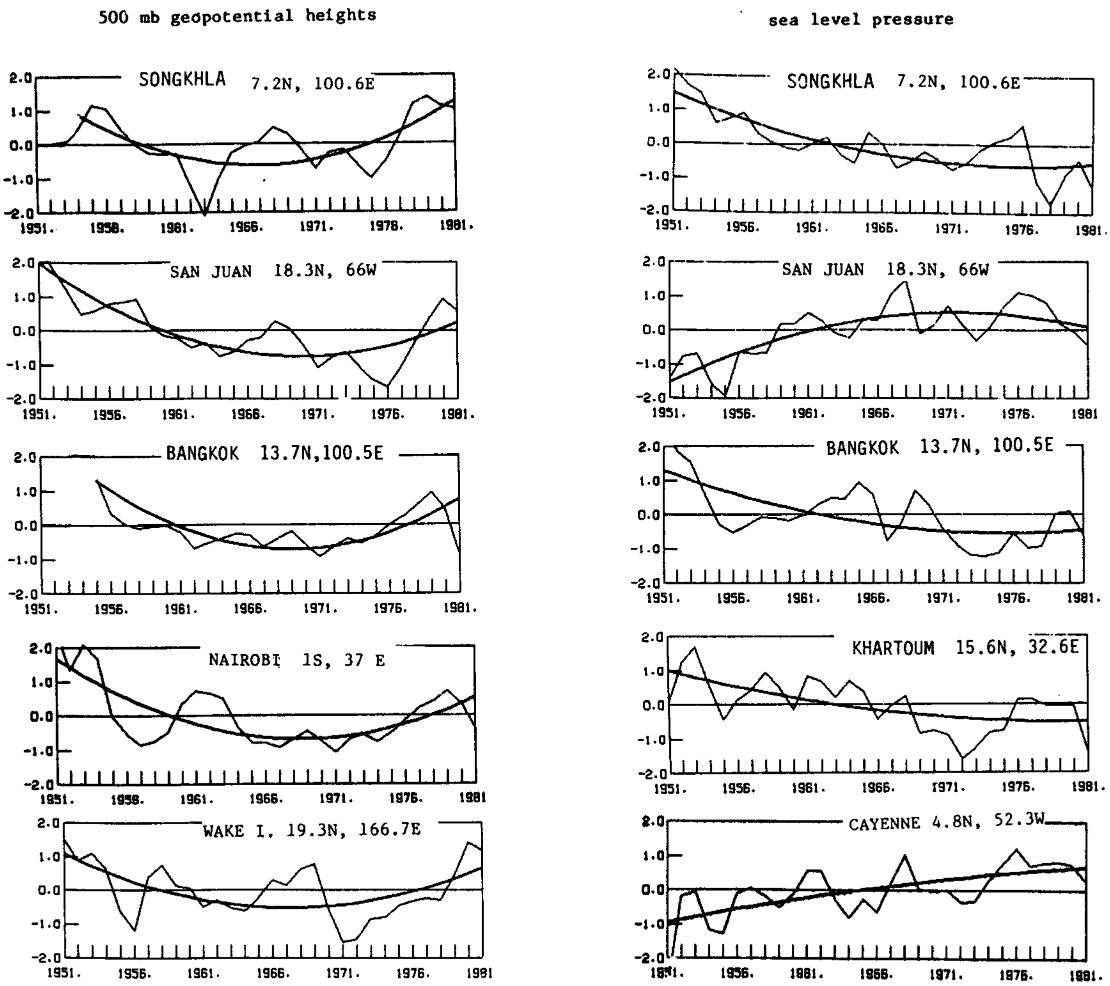

FIG. 7. As in Fig. 5 but for 500 mb height and sea level pressure anomalies for selected stations in the tropics for the winter season.

300 mb in general has the same trend as that of the 500 mb level. Stations in South America and high latitudes started recording in and after 1956 so the trends are uncertain in the 1950s over that area. In general, the temperature decreased during the period 1958–65 for most stations over Australia, the Indian Ocean and Africa (Kukla *et al.,* 1977), but a warming trend can be found for stations in the Pacific Ocean, e.g., Invercargill.

The seasonal change of temperature trends is not very large. The only noticeable difference is in the Australian region where a warming trend started in 1972 for stations such as Darwin, Brisbane and Williamtown.

Table 3 gives the annual mean temperature averaged over the periods 1958–69 and 1970–81, their difference and the estimated errors. Only those stations which showed a significant difference are given. Apart from Antarctic stations along the Indian Ocean; Mawson, Mirny and Novolazarevskaja, where cooling is observed, a significant warming trend occurred in the Antarctic region from the 1960s to the 1970s; this has also been reported by Swanson and Trenberth (1981). This warming trend can be found at all upper levels up to 200 mb. In midlatitude, a warming trend is observed at Amsterdam and Kerguelen in the Indian Ocean; a smaller temperature increase occurred for stations in Australia. However, the cooling trend is present at station Gough over a region in southern Africa where the difference between two periods may not be significant.

7. Conclusions

We have described the trends of monthly mean temperatures and heights from the surface to the 200 mb level. The principal findings are

1) The mean sea level pressure dropped over the Indian and Atlantic Oceans from the 1950s to 1960s

FIG. 8. As in Fig. 2 but for surface air temperature anomalies in winter.

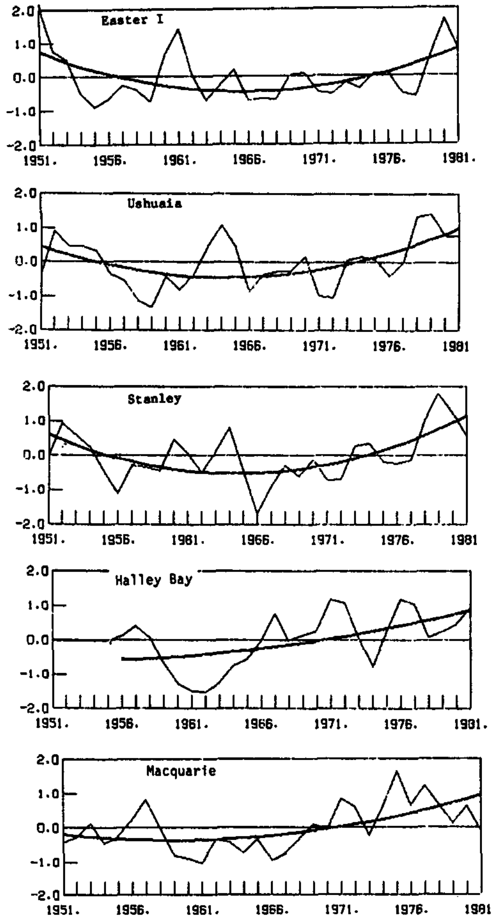

FIG. 9. As in Fig. 5 but for surface air temperature anomalies in summer.

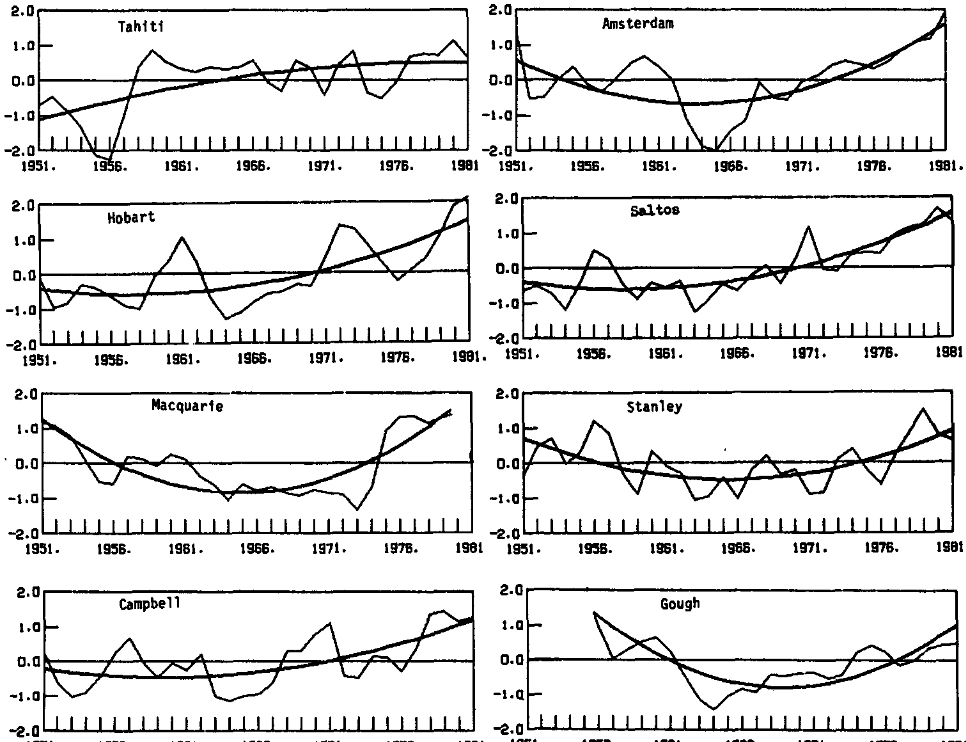

FIG. 10. As in Fig. 9 but for annual mean surface air temperature anomalies.

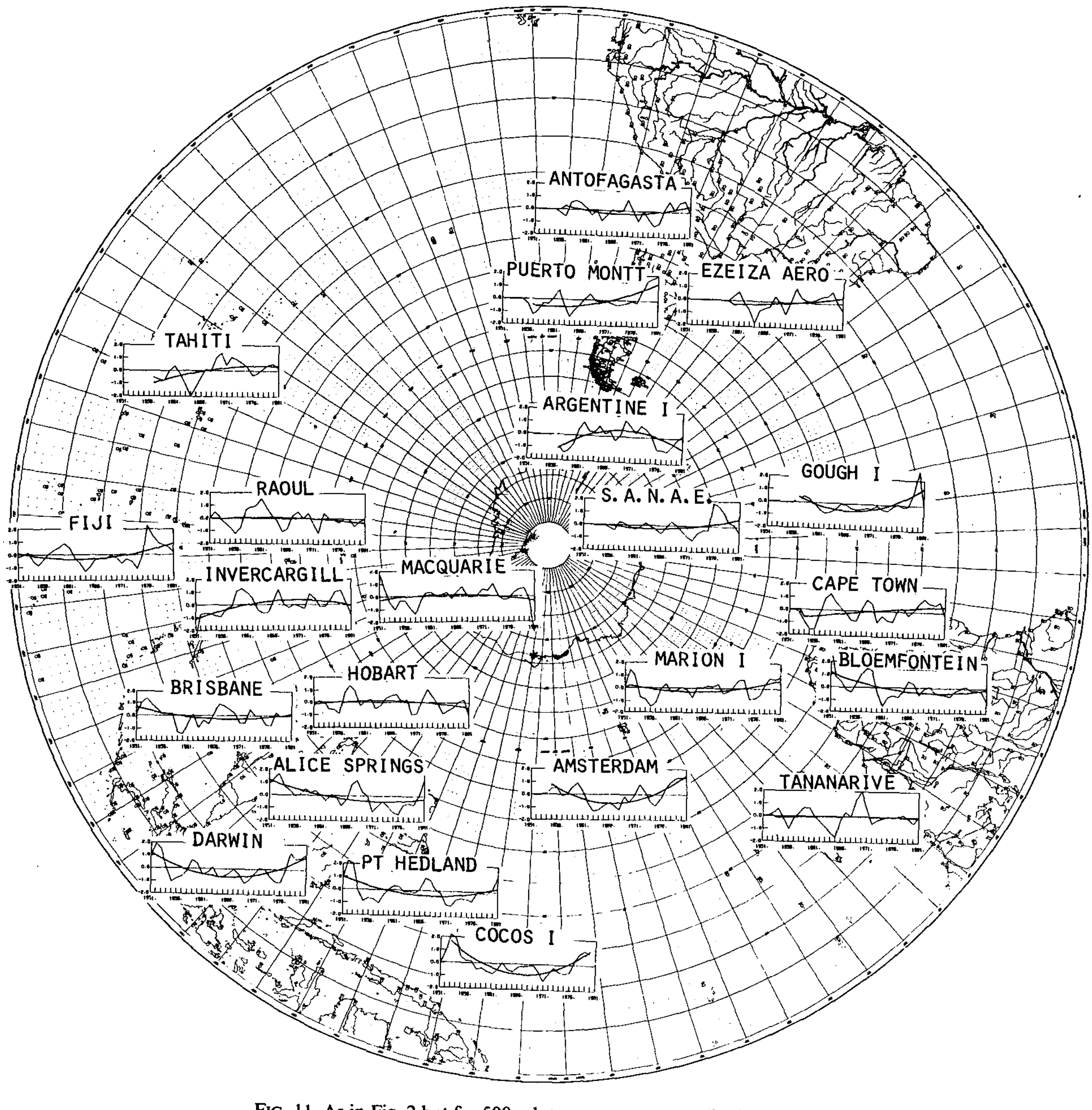

FIG. 11. As in Fig. 2 but for 500 mb temperature anomalies in winter.

TABLE 3. Average 500 mb and 300 mb annual mean temperatures during periods 1957–69 and 1970–81. The actual number of years used in the calculation is given in parentheses if it differs from 12.

	500 mb temperature				300 mb temperature			
Station	$\bar{Z}_1$ 1957–69	$\bar{Z}_2$ 1970–81	$\bar{Z}_2 - \bar{Z}_1$ (°C)	Error (°C)	$\bar{Z}_1$ 1957–69	$\bar{Z}_2$ 1970–81	$\bar{Z}_2 - \bar{Z}_1$ (°C)	Error (°C)
Macquarie	−25.93	−25.55	0.39	0.12	−50.48	−49.65	0.83	0.29
Argentine I	−32.41	−32.00	0.40	0.21	−55.20	−54.50	0.75	0.16
South Pole	−41.74	−40.04 (8)	1.70	0.75	−60.14	−59.34 (8)	0.80	0.31
S.A.N.A.E.	−35.94 (11)	−35.59	0.35	0.39	−57.06 (11)	−54.82	0.23	0.35
Halley Bay	−36.66 (9)	−36.21	0.45	0.19	−58.62	−57.82	0.80	0.23
Novolazarevskaja	−36.50 (9)	−37.08 (7)	−0.58	0.46	−57.30 (9)	−57.96 (7)	−0.66	0.52
Mirny	−34.03	−34.10	−0.07	0.27	−55.30 (11)	−56.05	−0.75	0.36
Vostok	−41.8 (9)	−40.7 (11)	1.1	0.74	−61.0 (9)	−59.77 (11)	1.23	0.80
Casey	−35.14 (8)	−34.38 (7)	0.76	0.25	−56.14 (8)	−55.77 (11)	0.38	0.26
Mawson	−35.41	−35.61	−0.20	0.28	−56.44	−56.73	−0.29	0.34
Marion I	−22.37 (9)	−22.21	0.13	0.36	−46.08 (9)	−46.54	−0.47	0.24
Amsterdam	−16.7 (10)	−15.61 (11)	1.09	0.29	−41.86 (10)	−41.30 (11)	0.58	0.43
Kerguelen	−25.16 (9)	−23.63	1.53	0.36	−46.40 (9)	−47.25 (11)	0.85	0.40
Gough	−18.17	−17.54	0.63	0.15	−42.80 (11)	−43.54	−0.74	0.28
Alexander Bay	−10.51 (11)	−10.51	0.00	0.17	−37.31 (11)	−37.74	−0.43	0.22
Bloemfontein	−11.08 (11)	−11.15	−0.08	0.28	−37.5	−37.78	−0.28	0.35
Durban	−11.25	−11.21	0.04	0.17	−38.00	−38.30	−0.30	0.24
Tahiti	−6.22	−5.40	0.82	0.28	−31.67	−31.15	0.51	0.42
Auckland	−17.49	−17.16	0.33	0.26	−43.85	−43.15	0.71	0.49
Lord Howe	−15.12	−14.9	0.22	0.17	−41.21	−40.34	0.88	0.22
Brisbane	−12.66	−12.18	0.48	0.24	−37.57	−36.97	0.60	0.25
Alice Springs	−9.73	−9.79	−0.07	0.13	−34.40	−34.13	0.27	0.15

and rose over the other half of the hemisphere. For most stations, the trend reversed from the 1960s to the 1970s. For stations at high latitudes the sea level pressure increased linearly.

2) The trends of geopotential height fields in the troposphere are equivalent barotropic.

3) The heights increased almost linearly over Antarctica from 1957–81 at all levels.

4) There was a significant warming over Antarctica from the 1960s to the 1970s at all upper levels except for a small area on the Indian Ocean side.

5) Trends are often regionally dependent. It is unlikely that the behavior of the earth's temperature can be adequately described if the selected stations are not distributed evenly over the globe.

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