Interannual Variability of the Southern Hemisphere Circulation: Representativeness of the Year of the Global Weather Experiment

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(Manuscript received 29 January 1983, in final form 29 August 1983)

ABSTRACT

An analysis has been made of the intraseasonal and interannual variability of mean circulation and eddy statistics for both summer and winter in the Southern Hemisphere. Total variance fields of geopotential height, the north–south and east–west wind components and poleward transient eddy momentum fluxes at 500 mb are analyzed along with their contributions from two broad frequency bands covering 2–5 day and 8–64 day period fluctuations. Largest interannual variability occurs between 40–60°S in association with the main jet stream in summer or the polar jet stream in winter and the main belt of eddy activity within each season.

The circulation and eddy statistics during the year of the Global Weather Experiment (GWE) are compared with the means and standard deviations over all years from 1972–80, and contrasted with individual years. The GWE summer of 1978–79 is contrasted with 1976–77, and the 1979 winter is contrasted with 1980. The year of the GWE was characterized by an exceptionally deep circumpolar trough, an increase in westerlies between 45–70°S and a decrease to the north, with a southward shift in the main westerly jet during summer 1978–79 and a considerably enhanced and southward shifted polar jet but weaker subtropical jet in winter 1979. Associated with these changes was a southward shift in storm tracks and high frequency eddy activity throughout the year. In both seasons anomalous convergence of momentum by the eddies into the jets was such that it would have helped sustain the abnormal distribution of westerlies against surface friction.

Many of the anomalies in the circulation statistics during the GWE are statistically significant, most notably in winter, and their reality is supported by station data and the dynamical consistency of the relationships between the anomalous mean flow and storm tracks. In addition, the deficit of mass over the Southern Hemisphere revealed by sea level pressures in April–July 1979 is compensated by the surfeit that occurred in the North Hemisphere. Although the vastly improved observations during the GWE may have contributed to the size of the anomaly, they cannot account for the systematic change in location of the features of the flow. The circulation during the GWE appears to have been at one extreme of the large natural interannual variability that is so much a feature of the Southern Hemisphere flow. The atypical nature of the circulation should be borne in mind in analyses based solely on the GWE over the Southern Hemisphere.

1. Introduction

The operational year of the Global Weather Experiment (GWE), otherwise known as the First GARP1 Global Experiment (FGGE), took place from December 1978 to November 1979. During this period a number of special observing systems were in place and a special effort was made to intensively observe the global atmosphere (Fleming et al., 1979a,b). Of special interest in the Southern Hemisphere (SH) was the presence of drifting buoys providing continual observations of sea level pressures over the southern oceans for the first time.

The existence of such comprehensive global observations of the atmosphere ensures that intensive analyses will be performed on the data from the GWE; for example, Lyne et al. (1982), and results of these studies will be used as a basis for testing the veracity of General Circulation Models of the atmosphere. It is therefore very important to establish, as best we can, the degree to which the year of the GWE can be regarded as typical.

Differences in the analyzed circulation during the GWE arise from both real changes in the circulation and from changes due to the improved data base. It is difficult to separate these effects, especially in analyzing eddy statistics. It is clear that the analyzed circulation during the GWE was quite different in several respects from previous years. Great care is therefore needed in using results based solely upon the GWE. Guymon and Le Marshall (1981) and Bengtsson et al. (1982) attributed the differences mostly to the improved data base. However, there is strong evidence from station data and other analyses (Tucker and Physick, 1980; Streten and Pike, 1980; Tucker, 1981; Trenberth and van Loon, 1981; van Loon and Rogers, 1981) that the real circulation in the Southern Hemisphere throughout the GWE was quite anomalous. These aspects are explored further here.

In this paper, we use mainly the operational Aus-

1 GARP is the Global Atmospheric Research Program.

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tralian World Meteorological Centre analyses to estimate the year-to-year variability in summer and winter of certain mean, variance and covariance fields that reflect changes in the mean flow and eddy characteristics. The contributions to the total variances or covariances of two frequency bands corresponding to the high frequency 2–8 day period baroclinic eddies and the lower frequency 8–64 day period fluctuations are also presented. The high frequency fluctuations reveal the locations of “storm tracks” (Blackmon et al., 1977; Trenberth, 1981b, 1982; Physick, 1981), whereas the 8–64 day band reveals locations of blocking-type phenomena and other low frequency fluctuations (Trenberth 1981b, 1982). The storm tracks defined in this way include not only tracks of cyclonic but also anticyclonic disturbances. They generally indicate regions of vigorous transient baroclinic eddy activity.

We present the mean and standard deviations of the zonal mean profiles of the eddy statistics. Thus we can define confidence intervals which may be used for testing whether a given sample of data, whether from a general circulation model or any other source, is a member of the same population. Here, the statistics for the year of the GWE are compared with those over all years including the GWE, and contrasted with the other years using a Student t-test. Such a comparison has only been carried out at 500 mb since analyses at other upper levels are less reliable (Trenberth, 1981b). However, for both summer and winter, years that show a marked contrast to that of the GWE are chosen in order to compare the dynamical consistency of changes in the relationships between the mean flow and eddy statistics. The GWE summer of 1978–79 is contrasted with 1976–77 and, winter 1979 is contrasted with 1980.

Marked contrasts between circulation regimes in adjacent years have been noted previously. Trenberth (1975) pointed out the distinct differences between 1971 and 1972 in the Australasian region. Trenberth (1979, 1980a,b, 1981a) and Swanson and Trenberth (1981a,b) have documented interannual and longer period variability of the Southern Hemisphere circulation. Trenberth (1979, 1980a, 1981a) and Swanson and Trenberth (1981b) found that the zonal mean flow in the Southern Hemisphere exhibits greater variability than that in the Northern Hemisphere and noted a tendency for quasibiennial fluctuations to be present in the zonal mean anomaly fields with a systematic progression of the anomalies from low to high latitudes. Trenberth (1981a) showed this behavior to be primarily present in the Australasian sector and Swanson and Trenberth (1981b) found it to have a barotropic structure. The large magnitude of the interannual variability in the Southern Hemisphere was not properly considered by Guymer and Le Marshall (1981), Trenberth and van Loon, (1981) or Bengtsson et al. (1982).

The data used and the method for computing the eddy statistics are the same as given in Trenberth (1982) and are briefly outlined in Sections 2 and 3. Section 3 also includes details of the statistical analysis used as a basis for assessing how anomalous the circulation was during the GWE. In order to provide an overall perspective, some monthly mean fields are presented in Section 4. The zonal mean fields of various statistics for summer and winter are presented in Section 5 along with the estimated variability in each field and the corresponding fields for the GWE. In Section 6 the contrast between different years is drawn. The results are discussed in Section 7.

2. Data

The main data set used in this study consists of the 0000 GMT analyses from the World Meteorological Centre in Melbourne, Australia. It is identical to that used by Trenberth (1982) and extends from May 1972 to November 1980. Trenberth (1981b and 1982) discussed the problems and overall quality of the data. The sparseness of the observational network in the SH leads to uncertainties and shortcomings in the analyses and, for this reason, only 0000 GMT 500 mb analyses are considered in detail here.

Data were transformed from the polar stereographic grid to a 5° latitude–longitude grid extending from 10°S to the pole. Only geopotential height z and the geostrophic wind components u and v are included. Most of the results are based on a coarser grid of 10° latitude by either 10° longitude in low and middle latitudes or 20° longitude south of 60°S.

Owing to the method of analysis, given in Section 3, we define each season to be 128 days long. Then, in order to avoid some missing data, we define summer to be from 4 November to 11 March and winter from 15 May to 19 September [see Trenberth (1982)]. Thus there are 9 winters and 8 summers in our data set.

Since the GWE was from December 1978–November 1979, it does not include a complete summer of consecutive days as we have defined it. However, we will refer to the summer of 1978–79 as the summer of the GWE.

Two other data sets have been used in Section 4 in order to throw further light on the main analyses. First, in an attempt to obtain a global perspective, we have included pressure data from the United States Navy sea level pressure analyses from 20–90°N as archived in the historical series at NCAR (Trenberth and Paolino, 1980). These analyses are available from 1899–1979 although they are considered less reliable prior to 1925. Second, as ground truth over a longer time span at 500 mb, we use station monthly mean rawinsonde observations at 500 mb, as made available through NCAR.

3. Method

We follow the standard notation of dividing each variable $z$ into
\[ z = \bar{z} + z', \]

where the overbar is the long term mean and \( z' \) the departure from the mean. We use the notation \( [z] \) to indicate the zonal mean of \( z \).

The mean annual cycle for the period May 1972–January 1978 has been analyzed by Trenberth (1979, 1980b, 1981a) and Swanson and Trenberth (1981a). The first four harmonics were used to remove the annual cycle from the daily data.

Following Trenberth (1981b and 1982), the variances and covariances were analyzed into frequency bands using Lorenz' (1979) "poor man's spectral analysis" technique. The latter requires the length of data to be a power of 2 and hence 128 day "seasons" were used. The resulting spectral estimates are combined into frequency bands representing the 2–8 day and 8–64 day period fluctuations (Trenberth, 1981b). Since the technique is applied to each season individually, all variances, covariances, spectra and cospectra are relative to the mean for each season. We average these to obtain the mean intraseasonal eddy statistics over all years. We have then separately determined the interannual variability of the mean fields and the eddy statistics. Chervin (1980) has advocated computations of statistics which make distinctions such as this.

If \( X \) is any variable such as a mean \( \bar{x} \), variance \( \bar{x}^2 \), or covariance \( \bar{x'y} \) for each season, and there are \( n + 1 \) years, we estimate the population mean \( \bar{X}_n \) and standard deviation \( \sigma \) by

\[
\bar{X}_n = \frac{1}{n+1} \sum_{i=0}^{n} X_i, \quad (1)
\]

\[
\sigma = \left[ \frac{1}{n} \sum_{i=0}^{n} (X_i - \bar{X}_n)^2 \right]^{1/2}. \quad (2)
\]

These provide the best overall estimate of the mean and variability.

In order to rigorously test whether the various statistics during the GWE year are significantly different from those in other years, we consider the following. Let \( X_0 \) be the variable being tested (the value for the GWE). Assume that \( X_0, X_1, \ldots, X_n \) are independent Gaussian variables with the same true standard deviation and \( X_1, \ldots, X_n \) have the same mean. We set up a null hypothesis that \( X_0 \) has the same true mean as \( X_1, \ldots, X_n \). We define

\[
\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i, \quad (3)
\]

\[
s^2 = \frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})^2. \quad (4)
\]

Then

\[
t = \frac{X_0 - \bar{X}}{s} \left( \frac{n-1}{n+1} \right)^{1/2} \quad (5)
\]

is distributed as student's t with \( n - 1 \) degrees of freedom. This is a special case of the test between the means of two samples but where one sample contains only one value (e.g., Panofsky and Brier, 1968, p. 63).

Comparing (1) and (2) with (3) and (4), we find

\[
\bar{X}_n = \frac{X_0 - \bar{X}}{n+1},
\]

\[
X_0 - \bar{X}_n = \frac{(X_0 - \bar{X}) n}{n+1}, \quad (6)
\]

\[
\sigma^2 = s^2 + \frac{(X_0 - \bar{X})^2}{n+1}. \quad (7)
\]

In a table, presented later, we compare the normalized departures from the means of the two samples compiled with and without \( X_0 \), defined as

\[
b = \frac{X_0 - \bar{X}}{s}, \quad d = \frac{X_0 - \bar{X}_n}{\sigma}. \quad (8)
\]

We reject the null hypothesis if \( t > t_c \), where \( t_c \) is a critical value of \( t \). It corresponds to a normalized departure from the mean \( b \) of, from (5),

\[
b_c = t_c \left( \frac{n+1}{n-1} \right)^{1/2}. \quad (9)
\]

Therefore, from (6), (7), (8) and (9), the corresponding critical value of the normalized departure \( d \) for rejection of the null hypothesis is

\[
d_c = t_c \left[ \frac{n^2}{(n+1)(n-1+t_c^2)} \right]^{1/2}. \quad (10)
\]

For the specific cases in question, \( n = 7 \) for summer or \( n = 8 \) for winter, and we choose the two-tailed 95% confidence interval (see Hayashi, 1982) for which \( d_c (n = 7) = 1.75 \) and \( d_c (n = 8) = 1.78 \). It may seem curious that the critical value of \( d_c \) increases slightly as \( n \) increases. However, this arises because the test being performed here is with \( b_c \) rather than \( d_c \). We use the latter only because our statistics are plotted in units of \( d \), although we have computed statistics both ways (Table 2, for instance). Any normalized departures from the overall mean in excess of \( d_c \) would be cause to reject the null hypothesis and would be an indication that the GWE year was indeed extreme. Such a test does not, of course, tell us whether the extreme is due to changes in data coverage, short term changes in climate, or other effects. In Section 5 the statistical significance of the results will be assessed but the interpretation will be delayed until Section 7.

4. Monthly mean fields

Figure 1 shows a 6 year mean zonally averaged geostrophic westerly wind component for January and July. Latitude–time sections of these fields have previously been presented by Swanson and Trenberth.
placed south of average. In July 1979, and in winter as a whole, the double jet structure became more pronounced than usual with a weaker subtropical jet and a stronger and poleward-displaced polar jet.

In order to gain an overall perspective of the anomalies in the mean fields throughout the GWE, Fig. 3 shows latitude–time sections of the monthly mean zonally averaged sea level pressure and 500 mb geopotential height anomalies. Here, the anomaly is the departure from the mean of all other values for the same month from May 1972 to November 1980. A remarkable aspect of Fig. 3 is the persistence of the anomalies, as shown by the fact that no smoothing has been used. We note the negative anomalies at both levels near the center of the circumpolar trough at 65°S throughout the GWE. It appears that July was more extreme than any other month during the GWE. The extreme value of the pressure anomaly of −13 mb occurred at 70°S in July.

Skepticism over the reality of the features shown in Fig. 3a (e.g., Guyma and LeMarshall, 1981) can be partially allayed by considering the global distribution of sea level pressure and making use of the conservation of mass of dry air. For instance, in Fig. 3a, the anomaly in sea level pressure in April 1979 was nearly everywhere negative and, area averaged over 7.5–90°S, was

(1981a). They differ by up to 3 m s$^{-1}$ south of 20°S from corresponding cross sections based on an earlier ∼10 year period given by van Loon (1972) (Trenberth, 1979; Swanson and Trenberth, 1981a). The differences are mostly real and reflect long-term changes in the circulation; therefore Fig. 1 can only be considered representative of the 1972–78 period. In particular, the double jet structure in winter was more evident in van Loon’s analyses.

Global cross sections similar to Fig. 1 but for the analyzed rather than geostrophic wind have been given by Bengtsson et al. (1982) and Lync et al. (1982) for January and either June or July 1979. As an indication of the overall flow during the GWE and the changes, Fig. 2 shows the fields for January and July 1979 (adapted from Bengtsson et al.) along with their differences from Fig. 1. In both months the departure pattern is remarkably similar. Departures well in excess of +5 m s$^{-1}$ near 60°S are accompanied by negative departures of −5 m s$^{-1}$ near 40°S. Maximum departures coincide with the level of the jet stream, but the latitudinal structure is very similar at all levels. In view of the geostrophic assumption in Fig. 1, these departures should be interpreted with caution. However, later, in Figs. 4 and 10 we confirm the pattern shown in Fig. 2 using only geostrophic winds. Thus, in January 1979 and for the summer as a whole, the jet was dis-

![Fig. 1. Meridional cross section of the six year mean zonally averaged geostrophic wind (m s$^{-1}$) for January 1973–78 and July 1972–77.](image1)

![Fig. 2. Meridional cross section of the zonally averaged wind (m s$^{-1}$) in 1979 for (a) January and (b) July (adapted from Bengtsson et al., 1982). Also shown as dashed contours are the differences from Fig. 1.](image2)
−1.5 mb. The corresponding anomaly over the Northern Hemisphere from 17.5°–90°N was +1.3 mb. Unfortunately, we do not have adequate data over the tropical belt to complete the picture. Here, identical methods and data periods (May 1972–November 1980) were used in both hemispheres. Exact compensation in pressures between the hemispheres should not be expected because it is necessary to remove the effects of the corrections to sea level and water vapor (Trenberth, 1981c). Studies to do this are currently in progress and results will be reported at a later date.

The largest anomalies in Fig. 3a averaged over 7.5–90°S occur in the winter half-year with anomalies of −1.5, −0.6, −1.0, −1.1 and +0.6 mb in April through August 1979. Over 17.5°–90°N in the Northern Hemisphere the corresponding anomalies were +1.3, +0.3, +0.9, +0.8 and −0.5 mb. Based upon the 55 year period 1925–79, the latter correspond to +2.5, +1.1, +2.6, +1.6 and −0.9 standard deviations. In April and June 1979, these are significant at above the 98% level. Although an exact balance is not achieved, the degree of compensation is very good and provides encouraging support for the reality of the Southern Hemisphere analyses.

A longer term perspective on Fig. 3b can be provided to some extent by station data. The monthly mean rawinsonde observations as made available through NCAR have been searched for reliable stations with long records that include 1979. We have selected four widely spaced stations near 40 and 70°S that have been averaged to provide a rough idea of the zonal mean at each latitude and the gradient between 40 and 70°S. The stations used were Amsterdam Island (37.8°S 77.6°E), Christchurch (43.5°S 172.5°E), Commandante Espora (38.7°S 62.2°W) and Gough Island (40.4°S 9.9°W) at an average latitude of 40.1°S, and Mawson (67.6°S 62.9°E), Wilkes (66.3°S 110.6°E), Argentine Island (65.3°S 60.6°W) and Halley Bay (75.5°S 26.6°W) at an average latitude of 68.2°S. These stations are not optimally placed to pick up the regional anomalies shown by van Loon and Rogers (1980) but they are all we have. Unfortunately, other desirable stations with good records like SANAE and McMurdo Sound had most 1979 months unavailable. Data from 1955 to 1980 were used but the average was computed only if all stations were present. This reduced the number of years to between 14 and 20 for each zonal mean and 12 to 17 for the gradient, depending on the month. Table 1 presents the number of years used to compute the mean and standard deviation and gives for the year of the GWE the anomaly and the anomaly normalized by the standard deviation. Here the mean and standard deviation include the GWE year, unlike Fig. 3. This factor inflates the values in Fig. 3 by 12.5%.

The overall pattern in Table 1 is similar to that in
Table 1. The anomaly $z'$ (gpm) departure normalized by the standard deviation $z'/\sigma$, and the number of years $N$ that went into the mean and standard deviation for (1) the four stations near 40°S, (2) the four stations near 70°S, and (3) the gradient, for the year of the GWE, at 500 mb.

<table>
<thead>
<tr>
<th>Month</th>
<th>12</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z'$</td>
<td>-1</td>
<td>37</td>
<td>-10</td>
<td>14</td>
<td>-1</td>
<td>7</td>
<td>45</td>
<td>41</td>
<td>19</td>
<td>23</td>
<td>8</td>
<td>-7</td>
</tr>
<tr>
<td>$z'/\sigma$</td>
<td>-0.0</td>
<td>1.4</td>
<td>-0.4</td>
<td>0.7</td>
<td>-0.0</td>
<td>0.3</td>
<td>2.8</td>
<td>1.7</td>
<td>0.8</td>
<td>1.0</td>
<td>0.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>$N$</td>
<td>14</td>
<td>16</td>
<td>19</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>17</td>
</tr>
</tbody>
</table>

$70^\circ$S

| $z'$  | -20 | -4 | -23 | -11 | -9 | -31 | -62 | -88 | -30 | 13 | -4 | 41 |
| $z'/\sigma$ | -0.4 | -0.1 | -0.7 | -0.3 | -0.3 | -1.8 | -1.7 | -1.6 | -0.5 | 0.3 | -0.1 | 1.2 |
| $N$   | 17 | 18 | 16 | 17 | 19 | 17 | 18 | 17 | 19 | 19 | 20 | 17 |

$40-70^\circ$S

| $\Delta z'$ | 30 | 53 | 9 | 25 | 4 | 30 | 105 | 124 | 46 | 18 | 11 | -49 |
| $\Delta z'/\sigma$ | 0.5 | 0.9 | 0.2 | 0.5 | 0.1 | 0.6 | 2.1 | 1.6 | 0.6 | 0.3 | 0.3 | -1.1 |
| $N$   | 14 | 12 | 14 | 15 | 17 | 14 | 16 | 16 | 15 | 15 | 15 |

Fig. 3b. The departures from the mean are, however, smaller at 70°S which probably reflects 1) the unrepresentative nature of the 1972–80 period commented on earlier; and 2) the absence of stations where the anomalies were analyzed to be largest. As in Fig. 3, the largest anomaly in the gradient occurs in July 1979 although the anomaly is most significant in June 1979. A stronger than normal gradient and thus stronger westerlies in all months except November 1979 are confirmed.

5. Zonal mean fields at 500 mb

In the following figures, the mean latitudinal profile is shown by the solid curve along with the interannual variability, as indicated by ±1σ, shown by the shaded region. The heavy dashed curve shows the corresponding profile for the season during the GWE. Where the profile during the GWE departs significantly from the mean for the other years, as given by the test outlined in Section 3, the variable, along with the values of the normalized departures and their confidence level are given in Table 2.

The mean profiles themselves are not discussed or interpreted in detail, since this aspect has already been addressed by Trenberth (1981b and 1982).

a. Summer

Figure 4 shows $\bar{\bar{u}}$ the zonal mean westerly wind component at 500 mb averaged over the 8 summers 1972–73 to 1979–80. Strongest winds occur at 45°S and the interannual variability is largest from 45–50°S. The departure from the long-term mean of the 500 mb $\bar{\bar{u}}$ in the 1978–79 summer as a whole in Fig. 4

Table 2. Significant departures of the circulation variables for the GWE year from the average for other years. For each variable, the latitude, frequency band if appropriate, $b = (X_0 - \bar{X})/\sigma$ the normalized departure from the mean of other years, $d = (X_0 - \bar{X})/\sigma$, the normalized departure from the mean of all years, and CL the confidence limit exceeded in the t-test are given.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Latitude (°S)</th>
<th>Band</th>
<th>b</th>
<th>d</th>
<th>CL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\bar{u}}$</td>
<td>40</td>
<td></td>
<td>-3.0</td>
<td>-1.8</td>
<td>95</td>
</tr>
<tr>
<td>$\bar{\bar{u}}$</td>
<td>50</td>
<td></td>
<td>2.2</td>
<td>1.5</td>
<td>90</td>
</tr>
<tr>
<td>$\bar{\bar{v}}$</td>
<td>50</td>
<td>2–8</td>
<td>-4.5</td>
<td>-2.1</td>
<td>99</td>
</tr>
<tr>
<td>$\bar{\bar{v}}$</td>
<td>Total</td>
<td></td>
<td>-5.5</td>
<td>-2.2</td>
<td>99.5</td>
</tr>
</tbody>
</table>

Winter

| $\bar{\bar{u}}$ | 40            | 3.4  | 2.0 | 98 |
| $\bar{\bar{u}}$ | 60            | -3.8 | -2.1| 98 |
| $\bar{\bar{u}}$ | 70            | -6.6 | -2.4| 99.9|
| $\bar{\bar{u}}$ | 80            | -4.1 | -2.2| 99 |
| $\bar{\bar{u}}$ | 50            | 3.3  | 2.0 | 95 |
| $\bar{\bar{u}}$ | 60            | 4.6  | 2.2 | 99.5|
| $\bar{\bar{u}}$ | 80            | -3.8 | -2.1| 98 |
| $\bar{\bar{v}}$ | 30            | 2–8  | -2.6| -1.8| 95 |
| $\bar{\bar{v}}$ | 60            | 8–64 | 3.1 | 1.9 | 95 |
| $\bar{\bar{v}}$ | 30            | 2–8  | -2.6| -1.8| 95 |
| $\bar{\bar{v}}$ | 60            | 2–8  | 2.2 | 1.6 | 90 |
| $\bar{\bar{v}}$ | 20            | 2–8  | -2.3| -1.6| 90 |
| $\bar{\bar{v}}$ | 30            | 2–8  | -3.4| -2.0| 98 |
| $\bar{\bar{v}}$ | 40            | 2–8  | -2.3| -1.6| 90 |
| $\bar{\bar{v}}$ | 60            | 2–8  | 3.1 | 1.9 | 95 |
Fig. 4. Meridional profile of the summer zonal mean 500 mb wind (solid curve) plus and minus one standard deviation (shaded) and the corresponding profile for the GWE year (dashed) in m s⁻¹.

is very similar to the January 1979 departure shown in Fig. 2. Only at 40°S where the \([u]\) departure is \(-1.8 \sigma\) is the 95% confidence limit exceeded. At 50°S the departure is in the opposite sense and larger in absolute value than at 40°S but it only exceeds the 90% confidence limit.

The meridional profiles of several intraseasonal variance fields are shown in Figs. 5, 6, 7 and 8. In Figs. 5–7 the total mean variance is presented along with the contributions from the 2–8 day and 8–64 day period bands, for \([z^2]\), \([u^2]\) and \([v^2]\). In Fig. 8 \([u]^2\) the variance in the zonal mean wind is shown. The corresponding values of \([v]^2\) are, of course, zero. Note that Fig. 8 should not be confused with the ±1σ shown in Fig. 4. The latter represents the interannual

Fig. 5. Meridional profile of the variance of geopotential height for summer, geopotential dam²; mean (solid curve), plus and minus one standard deviation (shaded), and the profile for GWE (dashed). Shown are the total variance and the contributions from the 2–8 day and 8–64 day period bands. The scale of the latter is offset.

Fig. 6. As in Fig. 5 but for the variance of the westerly wind component in m² s⁻².

Fig. 7. As in Fig. 5 but for the variance of the northerly wind component in m² s⁻². Here there is no offset in the scale for the 8–64 day profile.
Fig. 8. Meridional profiles of the total variance of the zonal mean wind $\overline{u^2}$ within the summer season in m$^2$ s$^{-2}$. The mean (solid) plus and minus one standard deviation (shaded) and the profile for the GWE (dashed) are shown.

variance of $\overline{u}$, whereas Fig. 8 shows the mean variance of $\overline{u}$ within each season and the variability of the variance from year-to-year.

Maxima in $\overline{u^2}$ and $\overline{v^2}$, and the col in $\overline{u^2}$, especially in the 2–8 day band, at 50°S are associated with the storm-track located just south of the strongest winds at 500 mb. Whereas most of the variance of $v$ occurs at high frequencies, the contributions from each frequency band are comparable for $u$ and $v$. This is discussed more fully by Trenberth (1981b, 1982) and is related to the larger east–west scales of motion occurring at lower frequencies. To some extent, this is revealed by Fig. 8 since the fluctuations in $\overline{u}$ are, of course, hemispheric in scale. At 60°S the intraseasonal variations in $\overline{u}$ constitute 16% of the total in Fig. 6.

In Fig. 9 the meridional flux of momentum by the eddies $\overline{u'v'}$ is shown. Largest contributions come from the 2–8 day band and maximum convergence of westerly momentum is into the 45–60°S latitude band, thereby helping to maintain the strong westerlies against surface frictional dissipation (Trenberth, 1981b, 1982).

In all of Figs. 4–9, maximum interannual variability occurs between 40–60°S in association with the belt of strongest westerlies and maximum eddy activity within each season.

For the 1978–79 summer of the GWE, the variance fields are not exceptional, although a stronger storm track than average is indicated. However, the departures in $\overline{u'v'}$ are highly significant and exceed the 99.5% confidence level at 50°S for the total field (Table 2). As a consequence, there is convergence of more than usual westerly momentum into the 50–60°S belt, which is also highly statistically significant: this was evidently helping to maintain the southward shift in the mean jet (Figs. 2 and 4). Further elaboration is given in Section 6.

Fig. 9. Meridional profiles of the meridional flux of momentum $[u'v']$ for summer. The total and the contributions from the 2–8 day and 8–64 day bands are shown with the mean (solid) plus and minus one standard deviation (shaded) and the GWE profile (dashed) in m$^2$ s$^{-2}$.

b. Winter

Figures 10–15 present the winter fields corresponding to Figs. 4–9 for the nine winters 1972–80.

The mean wind $\overline{u}$ at 500 mb (Fig. 10) shows only a broad belt of westerlies between 30–60°S and maximum values are less than in summer (Fig. 4). However,
as seen in Figs. 1 and 2, the meridional profile is rather different at other levels. At low levels, the maximum winds are near 50°S but in the upper troposphere, strongest winds are in the subtropical jet at 30°S. At 500 mb parts of both systems are present as a double jet structure which is more pronounced regionally, particularly in the Australia–New Zealand region (see Swanson and Trenberth, 1981a and Fig. 19). The double jet is also more pronounced in some years than others and was more prominent in the earlier analyses of van Loon et al. (1971) compared with the 1972–78 period analyzed by Trenberth (1979). It was also much more prominent in the 1979 winter, as shown in Fig. 2 and Fig. 10. Largest interannual variability occurs in the 40–60°S region (Fig. 10) in the vicinity of the polar jet.

The departure pattern of the 1979 winter, given in Fig. 2 for July, is also evident for the whole winter in Fig. 10 but with reduced amplitude. Highly significant departures from the mean for other years are present in the $\bar{z}$ and $\bar{u}$ fields throughout the 35–80°S belt (Table 2). It seems that the mean flow field for the winter of the GWE was highly atypical.

The general relationships among $[\bar{u}]$, $[z^2]$, $[u^2]$ and $[v^2]$, with the latter shown in Figs. 11–13, are much the same as in summer but not quite as well defined.

Maximum values of $[u^2]$ and $[z^2]$ at high frequency occur near 45–50°S in the col in the $[u^2]$ profile as expected for storm tracks, but the relationships are much better defined locally (Trenberth, 1982). Again, the $v$ field, unlike the $u$ and $z$ fields, is dominated by the higher frequencies and smaller scales.

The interannual variability of the variance fields in winter tends to be greatest at 50–65°S in association with the polar jet stream. Variability associated with the subtropical jet is seen only in $[u^2]$ (Fig. 14). The contribution of the fluctuations in the zonal mean $[u]$
to $[\overline{w}]$ are given in Fig. 14 and constitute 20% of the total at 60°S. Interannual variability of $[\overline{u}]$ is quite uniform with latitude.

Figure 15 presents the winter profiles of $[\overline{u}\overline{v}]$. As in summer, largest contribution comes from the 2–8 day band and maximum convergence of westerly momentum is into the 40–60°S region, thereby serving to sustain the surface westerlies against surface friction (Trenberth, 1982). Interannual variability of the momentum flux is largest throughout 30–60°S.

Table 2 shows the variables that in winter 1979 depart significantly from the mean for other years. Aside from $[\overline{u}]$ at 60°S in the 8–64 day band, all of the significant departures occur at high frequency in the 2–8 day band. The pattern is quite systematic, with decreases in $[\overline{z}^2]$, $[\overline{u}^2]$ and $[\overline{v}^2]$ north of 40°S but increases at 60°S, a pattern quite consistent with the changes in $[\overline{u}]$. Corresponding changes in 1979 also occur in $[\overline{u}\overline{v}]$ with a marked decrease in poleward momentum flux at 30–40°S but an increase at 50°S in the 2–8 day band. However, none of the changes in $[\overline{u}\overline{v}]$ itself are statistically significant. On the other hand, the change in convergence of westerly momentum flux in the 2–8 day band at 45°S is statistically significant at the 95% confidence level. Overall, the 1979 change in convergence in momentum by the eddies acts to reduce the westerlies from 30–45°S and increase them from 50–65°S, a pattern very consistent with the observed distribution of westerlies (Fig. 2).

6. Contrasts of circulation in different years

We have seen that a distinctive anomaly occurred in the mean flow fields throughout the GWE, with winds stronger than usual from 50–65°S but weaker than usual at 40°S. Although the circulation in the Southern Hemisphere has a great deal of zonal symmetry and can be usefully summarized by the zonal mean profiles given in Section 5, there are nonetheless very significant regional variations in the distribution of storm tracks and blocking, as revealed by the eddy statistics (Trenberth, 1981b, 1982). Owing to the short record, there are insufficient years of data available to enable us to composite flow regimes of contrasting character and to obtain statistically significant results. Nevertheless, it is illuminating to contrast aspects of individual flow regimes and to examine the consistency of the changes from the viewpoint of our physical understanding.

Therefore, in this section we contrast the flow during the GWE with that in another year and consider some of the regional aspects of the circulation. Exact opposites are, of course, impossible to find, and presumably another important consideration is the degree of persistence of a regime. For instance, we expect that large-scale low-frequency fluctuations within a season would affect the location of storm tracks and therefore, for the seasonal average, blur the usually distinctive spatial patterns associated with the high frequency eddy statistics. In spite of this consideration, the contrasting years were selected solely on the basis of the character of the mean flow.

a. Summer

The greatest contrast in circulation in the summers appears to be between the GWE summer of 1978–79
and 1976–77. Fig. 16 presents the 500 mb mean $\bar{u}$ field for all eight summers. In Fig. 17 the departures from this mean are shown for the two summers in question (note that the northern boundary is at 10°S in Fig. 16 but at 20°S in Fig. 17). The unusually weak westerlies that occurred at 50–60°S in 1976–77 have previously been commented on by Trenberth (1979), Trenberth and van Loon (1981), and van Loon and Rogers (1981). In addition, December 1978 was noteworthy for the many record high surface temperatures that were experienced over much of Antarctica associated with two warm air intrusions (Sinclair, 1981).

A striking aspect of the departure patterns in Fig. 17 is their predominantly zonal character. The zero line is near 40°S in 1976–77 and 45°S in 1978–79, and departures well in excess of ±2 m s$^{-1}$ occur in each case. Whereas the jet was located about 3° latitude south of average in 1978–79 (Fig. 2), it was several degrees north of average in 1976–77. Consequently, in this case, there is little to be gained in looking at the regional changes of the eddy statistics; the dominant changes are revealed in the zonal averages.

Differences between the circulation in the two years for zonal mean quantities are shown in Fig. 18. The contrast in $[\bar{u}]$ at the top of Fig. 18 shows changes between the years as large as 6 m s$^{-1}$ near 50°S and −3 m s$^{-1}$ near 35°S. Together these correspond to about a 5° latitudinal shift in the position of the jet. Based upon average conditions over all years, we have previously noted the strong tendency for storm tracks to be located about 5° south of the jet (Trenberth, 1981b, 1982), and have also seen similar results in the Northern Hemisphere by Blackmon et al. (1977). During the summer, the main storm track in the Southern Hemisphere on average tends to be located along ~50°S at all longitudes (Trenberth, 1982, and see Figs. 5–7). Consequently, we might expect to see a reduction in high-frequency eddy activity north of ~50°S and

![Figure 16](image16.png)

**Fig. 16.** Mean $\bar{u}$ field at 500 mb for the 128 day summer season (m s$^{-1}$). Values greater than 20 m s$^{-1}$ are shaded.

![Figure 17](image17.png)

**Fig. 17.** Departures from the mean field of Fig. 16 of the $\bar{u}$ field for summer of (a) 1976–77 and (b) 1978–79; m s$^{-1}$. Negative departures are shaded.
Fig. 18. Differences between zonal mean quantities for the summers of 1978–79 minus 1976–77. Shown from top to bottom are \( \bar{u} \), m s\(^{-1}\); \( \bar{v} \) in the 2–8 day band, m\(^2\) s\(^{-2}\); \( \bar{z} \) in the 2–8 day band, gpm; and the eddy convergence of momentum \( \partial (\bar{u} \bar{v}) / \partial t \) as given by Eq. (11) in (m s\(^{-1}\)) day\(^{-1}\).

an increase to the south in 1978–79 compared to 1976–77.

The key indicators of the storm track location are the 2–8 day frequency band of \( \bar{z} \) and \( \bar{v} \), and their differences in the two contrasting regimes are also shown in Fig. 18. We see that there is indeed a marked increase in these quantities south of 50\(^\circ\)S and a large decrease in \( \bar{v} \) north of 50\(^\circ\)S but only a small reduction in \( \bar{z} \) north of 45\(^\circ\)S. A comparison with Figs. 5 and 7 shows that both years are contributing significantly to produce this signature.

Another characteristic feature of storm tracks is strong convergence of westerly momentum into the center of the storm track by the eddies (Blackmon et al., 1977; Trenberth, 1981b, 1982). Consequently, at the bottom of Fig. 18 we have plotted

\[
\frac{\partial (\bar{u})}{\partial t} = - \frac{1}{a \cos^2 \phi} \frac{\partial}{\partial \phi} (\bar{u} \bar{v} \cos^2 \phi) + \cdots . \tag{11}
\]

It is not possible to reliably evaluate the other terms in the momentum equation. However, for averages over a season, the left-hand side of (11) must be small and the eddy convergence of momentum is offset by other terms such as the Coriolis torque associated with the mean Ferrel cell. The latter acts to decelerate the westerlies aloft but increases them near the surface and thus compensates for losses due to surface friction. There is good qualitative agreement between the observed change in \( \bar{u} \) and the change in convergence of momentum by the eddies, thereby indicating that the southward shift of the jet during the GWE was partially maintained against surface friction by the eddy momentum convergence (see also Trenberth, 1982).

The overall interrelationships between the jet and the storm track, as revealed by the eddy statistics, have therefore carried over into the individual years, showing a consistent pattern that is quite remarkable.

b. Winter

The greatest contrast with the 1979 winter of the GWE occurred in 1980, but the contrast is not as good as found for the summer season. The winter flow is generally more complicated owing to large departures from the zonal symmetry. For instance, Fig. 19 presents the mean \( \bar{u} \) field over the 9 years and reveals the double jet structure in the New Zealand region. The departures from this mean for the winters of 1979 and 1980 are shown in Fig. 20.

In spite of the double jet structure regionally, there is a fairly strong zonal character to the departure patterns in Fig. 20. In 1979 we note departures over 5 m s\(^{-1}\) in several places between 50–60\(^\circ\)S, and opposite departures occur near 60\(^\circ\)S, south of Australia, during 1980. However, near the Greenwich meridian, maximum departures of over 4 m s\(^{-1}\) in 1980 occur at 50\(^\circ\)S close to the zero line in 1979. Overall, the zero line is near 45\(^\circ\)S in 1979 but closer to 55\(^\circ\)S in 1980.
mean during 1979 (Fig. 10) but enhanced in amplitude. The eddy activity associated with the main storm track, as revealed by the differences between the 2–8 day $\tilde{z}^2$ and $\tilde{u}^2$ fields (Fig. 21), underwent a pronounced southward shift and was much stronger at 60°S while decreasing at 40°S. Convergence of westerly momentum by the eddies into the storm track, as given by (11) and shown at the bottom of Fig. 21, is qualitatively similar to the differences in $\tilde{u}$ and apparently was acting to sustain the anomalous pattern of westerlies against surface friction.

The pattern of changes in the zonal mean fields in the contrasting winter regimes (Fig. 21) is notably similar to Fig. 18 which contrasted the two different summer regimes. Once again, the interrelationships between the mean flow and eddy statistics apparent in the mean over all years (Trenberth, 1982) has carried over into the anomalous individual years.

In order to explore the regional aspects of this relationship, the 2–8 day band contribution to $\tilde{z}^2$ is shown for 1979 and 1980 along with their differences in Fig. 22. The main storm tracks, as indicated by the locus of maxima in Figs. 22a, b have been accentuated by the heavy dashed line in each case. During the winter of 1979, the storm track was south of 50°S everywhere and was generally 5–10° south of the storm track in 1980. In the South Pacific, there is evidence of a double track during 1980, but the southernmost

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**Fig. 20.** Departures from the mean field of Fig. 19 of the $\tilde{u}$ field for winters of (a) 1979, and (b) 1980; m s$^{-1}$. Negative departures are shaded.

The double jet structure present in 1979 (Figs. 2 and 10) is therefore even less evident during 1980 than in Fig. 1.

The contrast in the circulation during the winters of 1979 and 1980 is first shown by considering several zonal mean quantities in Fig. 21. The differences in $\tilde{u}$ are very similar to the departure from the overall

**Fig. 21.** Differences in the zonal mean quantities for the winters of 1979 minus 1980. From top to bottom are shown $\tilde{u}$, $\tilde{u}^2$, $\tilde{v}^2$, 2–8 day, $\tilde{z}^2$, 2–8 day, and $\tilde{a}[\tilde{u}] / \tilde{t}$; as for Fig. 18.
branch is greatly enhanced and the only track in evidence during 1979. The regional contrast between these patterns is shown by their differences in Fig. 22c. Again we note that the change is consistent with a general southward shift in the high frequency baroclinic eddy activity during 1979 relative to 1980.

7. Discussion and conclusions

In comparing the circulation and eddy statistics for the seasons of the GWE both with their means based on eight summers or nine winters and with values from contrasting regimes in other individual seasons, we observe that a very consistent pattern has emerged. The year of the GWE was characterized by an increase in westerlies south of \( \sim 45^\circ \text{S} \) and a decrease to the north, indicating a southward shift in the main westerly jet in summer and a considerably enhanced polar jet in winter. Associated with this was a southward shift in storm tracks throughout the year, in a manner consistent with expectations based upon relationships between the mean flow and the location of tracks of high-frequency baroclinic eddies. The latter are revealed by the mean statistics over several years of observations in both the Northern Hemisphere (Blackmon et al., 1977) and Southern Hemisphere (Trenberth, 1981b, 1982), and from theoretical arguments based upon baroclinic instability (e.g., Frederiksen, 1979, 1980; see Trenberth, 1981b, for a full discussion).

It is clear from Table 2, that the circulation statistics during the GWE, especially in winter, were exceptional. As noted in the Introduction, it is difficult to say how much of this is attributable to the vastly improved observations taken during the GWE. It would be surprising, indeed, if the enhanced observational network did not contribute probably to somewhat larger variances and covariances. This factor may account for some of the very high levels of significance found in Table 2, but it does not account for the systematic change in location of the features of flow. In addition, some confidence in our results is obtained from a comparison of eddy statistics at 500 mb based upon the Australian analyses with those based upon station data using the GFDL approach (Oort, 1982). The latter does not reveal the Australian eddy statistics at 500 mb to be deficient in any way. On the contrary, over the oceans they appear to be superior (Trenberth, 1982). Rather, it seems clear that, for the most part, the circulation during the GWE year was at one extreme of the natural interannual variability that is so much a feature of the Southern Hemispheric circulation.

Interannual variability of the flow was previously known to be large in the Southern Hemisphere and, in particular, persistent contrasting flow regimes tend to occur in alternate years as part of a quasi-biennial oscillation. The differences between the circulation during the winters of 1979 and 1980 are further evidence of this. The latter contrast is fortuitous since global analysis systems established for the GWE have continued and global 1980 analyses are therefore widely available. Although the density of drifting buoys dwindled in 1980, satellite soundings and cloud wind observations continued and the observational base in the Southern Hemisphere was still quite good. More comprehensive comparisons of the two years in three dimensions will therefore be possible.

Apparently, the consistency of the changes in the individual years is related to the degree of persistence of the regimes and their extreme nature. Edmon (1980) was unable to find such clear relationships between the mean flow and the eddies in contrasting the circulation and eddy statistics of two Northern Hemisphere winters.

As well as changes in location, it seems that there can also be large changes in the magnitude of the intraseasonal variances from year to year. In the Southern Hemisphere we suspect that some of this may be due to deficiencies in the analyses since variances of geopotential height at 50^\circ \text{S} were relatively low for 1972–74 but then have increased in more recent years as satellite sounding data have been more widely exploited. Nevertheless, Carleton (1980) has also found very large fluctuations from year to year in the count of cyclogenetic cloud vortices during winter over the Southern Hemisphere, based upon satellite imagery. There are only 5 winter seasons, 1973–77, of cloud vortex data available, and a cursory comparison with our eddy statistics reveals little correspondence, but this is not surprising since the vortex tally does not take the intensity of each storm into account.

Further support for the view that most of the exceptional nature of the circulation during the GWE was real comes from independent analyses of observed parameters at stations with long records. Tucker and Physick (1980), Stretten and Pike (1980), Tucker (1981) and van Loon and Rogers (1981) have all confirmed the unusual nature of the flow during the GWE, and we have provided further evidence with Table 1.

The anomalous nature of the circulation during the GWE was evidently not confined to just the Southern Hemisphere. The monsoon circulations during both the winter monsoon experiment (WMONEX) (Greenfield and Krishnamurti, 1979) and summer monsoon experiment (SMONEX) (Fein and Kuettnner, 1980) were below normal in intensity and the summer monsoon was almost two weeks late in arriving. In addition, preliminary analyses show that the deficit of mass over the Southern Hemisphere from April to July 1979 was compensated by unusually high pressures over the Northern Hemisphere. In April and June of 1979, these “hemispheric” departures were highly statistically significant.
Since it seems that many aspects of the circulation, at least over the Southern Hemisphere, were atypical during the GWE, great care is needed in treating results from only that year as representative of long-term mean conditions. In view of the difficulty most general circulation models have had in sustaining sufficiently strong westerlies over the middle latitudes of the Southern Hemisphere, it may prove even more difficult to reproduce the mean flow during the GWE. Until it is known why such large anomalies occur, modelers should be alert to the large natural variability of the Southern Hemisphere circulations.

Acknowledgments. This research was sponsored by the Climate Dynamics Program, Division of Atmospheric Sciences, National Science Foundation under Grant ATM82-11560. Many computations were made using the computing facility at the National Center.
for Atmospheric Research. The author thanks Gary Swanson for performing some of the computer programming, and Dr. Y. Hayashi for providing suggestions on the statistical analysis.

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