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The horizontal structure of monthly fluctuations of the southern hemisphere troposphere from station data

Imre Szeredi and David J. Karoly, Department of Mathematics,
Monash University, Clayton, Australia

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The horizontal structure of monthly fluctuations of the southern hemisphere troposphere has been investigated using station data and the dominant modes of variation are described. Monthly mean rawinsonde data for the period 1950-1979 from 32 stations in the region from 10°N to the South Pole were analysed using principal factor and compositing techniques.

Two dominant modes are found; a zonally-symmetric tropical mode associated with variations of height at low latitudes and zonal wind in the subtropics, and a zonally-symmetric mode associated with out-of-phase variations of height between middle and high latitudes. The station network has restricted the analysis to the largest scale modes only. Although several other modes were found, their horizontal structure could not be resolved well with the station data.

Introduction

There have been a number of recent studies (for example, Wallace and Gutzler 1981; Horel 1981; Blackmon et al. 1984) which have identified and documented the horizontal structure of low-frequency fluctuations, with periods longer than about a month, of the northern hemisphere (NH) tropospheric circulation. These fluctuations are associated with variations of weather regimes and with local climatic anomalies on monthly and seasonal time-scales. Study of the horizontal structure has helped to identify the relationships between the anomalies in one region and those in other regions at large distances. The typical structure associated with these fluctuations in the NH has large horizontal scale and several centres of action often over a large meridional band. They appear to be associated with changes in amplitude of the time-mean planetary waves or small phase variations of the planetary waves. These studies have used numerical analyses of the circulation as their primary data with some verification of the results using station data. Most have used monthly means of daily analyses to isolate the low frequency variations.

There have been fewer studies of the horizontal structure of fluctuations of the southern hemisphere (SH) circulation. These have generally concentrated on monthly mean surface data (Kidson 1975a,b; Pittock 1980a,b, 1984) or daily analysed mid-tropospheric data (Rogers and van Loon 1982). Mo and White (1985, hereafter referred to as MW) and Trenberth (1980) have used monthly mean analyses to investigate the low frequency variation of the SH troposphere. Trenberth (1980) was primarily interested in interannual variations associated with a weak quasi-biennial oscillation in the SH zonal mean circulation. MW have used the correlations between monthly mean 500 hPa geopotential height at different grid-points to perform a teleconnection analysis of the extratropical SH troposphere. They identified several modes of spatial variation of geopotential height, including a zonally symmetric structure with opposite variations in middle and high latitudes, a zonal wave-number three pattern in middle latitudes in winter and a regional continent-ocean contrast in summer. They used correlations between a limited number of stations to verify the structure of some of their modes. As a minor part of their study, they also computed the principal components of the correlation matrix of monthly mean height in summer and winter and found the leading component to be a zonally symmetric pattern with opposite variations between Antarctica and middle latitudes.

The relatively short period of SH numerical analyses available is a major deficiency of these studies of low-frequency variations. Less than nine years of data were available for Trenberth (1980) and MW. Also, the numerical analyses are less reliable at low latitudes and these studies have considered extratropical regions only.

In this study, we have used monthly mean rawinsonde station data for the SH to identify the dominant modes of low-frequency variation of the large-scale circulation and to describe the horizontal structure of these modes. The station data are available for a longer period than the numerical analyses, with most stations used having data available for twenty years or more. We have used data from stations south of 10°N so that low-frequency variations in the tropics can be linked with those in the SH. The sparse and uneven distribution of the stations in the SH means that only the very large-scale horizontal structure can be described well.

This study is an extension of our earlier investigation of the vertical structure of monthly fluctuations of the SH troposphere (Szeredi and Karoly 1987; hereafter referred to as SK). There it was shown that a large fraction of the variance of monthly fluctuations of height, temperature and wind at all levels at any station could be represented in terms of the variations of a small number of 'key' variables at a single level. In particular, monthly mean height and two wind components at 300 hPa could be used to represent more than about 75 per cent of the variance at extratropical stations and more than about 45 per cent of the variance at tropical stations. For this reason, we have selected height and zonal wind at 300 hPa as the variables to be used for the horizontal structure analysis. Although the analysis was also carried out for meridional wind, the results have not been included because there were no obvious modes of variation of the meridional wind which could be described well using the station network available.

As in SK, the analysis here has been based on the use of principal factor analysis. This technique has been used by Horel (1981) to describe the horizontal structure of low-frequency variations in the NH. It has the advantage over the teleconnection analysis of MW that the individual modes of variation can be separated and ranked in terms of the fraction of total variance they represent.

A description of the data and the analysis techniques is given in the next section. This is followed by a description of the dominant modes of variation of height and zonal wind. Two dominant modes have been identified which are zonally symmetric; a tropical mode and a mode associated with out-of-phase variations in middle and high latitudes. Time-series for these modes are then presented along with their correlations with prescribed indices. Maps of composites are shown which are based on these time-series and the indices in order to confirm the factor analysis results.

Data and analysis techniques

World monthly mean rawinsonde data for the period 1950-79 from *Monthly Climatic Data for the World* (National Climatic Data Center 1950-1979) were obtained from the National Center for Atmospheric Research, Boulder, Colorado. Only stations south of 10°N were considered here. For some months and stations, the tape contained several versions of the data and, in such cases, the latest version was retained. Data greater than four standard deviations from either side of the long-term means for each month were considered outliers and discarded. To remove the seasonal cycle, time-series of anomalies were obtained by subtracting the long-term monthly means from the individual monthly values for all months. In addition the data have been detrended by subtracting the least-squares straight line trend fitted to the data. Detrending was considered necessary because of the existence of different long-term trends in different regions which could have affected the results. Based on the results of the vertical structure analysis described in SK, we have used height and zonal wind at 300 hPa as the primary variables for the horizontal analysis. The network of 32 stations used for this study is listed in Table 1. They were selected from stations having records greater than approximately 100 months in length on the basis of providing good spatial coverage, with stations separated by at least 1000 km. The analysis has been based on the correlations between stations in order to better capture the relationships between variations at different stations and not have to take account of the geographical variability of variance. The increase in the variance of height with latitude would mean that a covariance-based analysis would weight high latitude structures more highly and not represent as clearly the relationships between low and high latitudes.

This study employs mainly the multivariate statistical technique known as principal factor analysis (PFA) and for a more detailed coverage, the reader is referred to Harris (1975), Morrison (1967) and Harman (1976). This technique was used in SK and a description was given there. The IMSL (1982) set of subroutines was used to perform the calculations. The great advantage of the technique is its ability to compactly summarise the interrelationships within a set of a large number of variables by identifying the dominant groups of variables with similar fluctuations. These groups of variables are called factors. For small data sets the interrelationships can be deduced from the correlations themselves but for larger numbers of variables this is much more difficult. Since there are more variables in this horizontal structure analysis the technique is more useful here than in the vertical structure analysis in SK.

Because of the generally lower correlations between variables and lower proportions of variance explained by the factors relative to those in SK, the results here are more sensitive to the method employed in calculating the factors. The analysis procedure was altered to take

Table 1. List of stations used in the horizontal structure analysis.

STATION	*ID*	*LAT (°N)*	*LONG (°W)*	*ELEV (m)*	*RECORD PERIOD*
Trivandrum	43371	8.5	283.0	64	1950-79
Kerguelen	61998	−49.3	289.8	18	68-79
Nairobi	63741	−1.3	323.2	1798	50-79
Abidjan	65578	5.2	3.9	40	57-79
Salisbury	67774	−17.8	31.0	1472	70-79
J. G. Strijdom	68112	−22.5	342.5	1718	58-79
Cape Town	68816	−34.0	341.4	46	50-79
Gough Island	68906	−40.4	9.9	54	57-79
Marion Island	68994	−46.9	322.1	22	50-79
Rio de Janeiro	83746	−22.8	43.3	42	67-79
Antofagasta	85442	−23.5	70.4	122	57-79
Easter Island	85469	−27.2	109.4	41	70-79
Puerto Montt	85799	−41.4	73.1	8	57-79
Ezeiza Aero	87576	−34.8	58.5	20	60-79
Argentine Island	88952	−65.3	64.3	10	57-79
S.A.N.A.E. Station	89001	−70.3	2.4	62	57-79
Casey Station	89611	−66.3	249.5	16	58-79
Truk	91334	7.5	151.9	2	57-79
Nadi	91680	−17.8	182.5	16	50-79
Pago Pago	91765	−14.3	170.6	3	67-79
Tahiti	91938	−17.6	149.6	2	57-79
Invercargill	93844	−46.4	191.7	1	50-79
Darwin	94120	−12.4	229.1	21	50-79
Townsville	94294	−19.3	213.2	4	50-79
Port Hedland	94312	−20.4	241.4	11	51-79
Forrest	94646	−30.8	231.9	162	56-79
Williamtown	94776	−32.8	208.2	9	50-79
Laverton Airport	94865	−37.9	215.2	14	50-79
Mawson	94986	−67.6	297.1	14	55-79
Norfolk Island	94996	−29.1	192.1	110	50-79
Macquarie Island	94998	−54.5	201.0	7	51-79
Cocos Island	96996	−12.1	263.1	1	53-79

account of this following the techniques used by Horel (1981). Various methods for obtaining the factors were used and only the *major* structures which were found to be independent of the particular method are described here. For example, different numbers of factors were rotated obliquely and compared to unrotated factors. Oblique rotation was used because it is a less constrained method of obtaining a simpler factor structure than orthogonal rotation. It was found that the correlations between obliquely rotated factors were small, usually less than 0.15, so the factors were still approximately orthogonal. Examples shall be shown later to illustrate the effect of rotation.

The objective means used to compare the factors obtained by different methods and to identify the common structures was to determine the pattern correlation between pairs of factors. Factors with 'large' pattern correlation were grouped as having common structure. As a guide, a minimum pattern correlation of approximately 0.7 is useful because around 50 per cent of the spatial variance of one factor is then accounted for by the other factor. Any common structures identified in this way are thus concluded to be stable and real in the sense that they are independent of the analysis technique and so a product of the data.

Generally five but up to eight different methods have been used to calculate the factors, with the biggest difference in methods being whether rotation was included as a processing step. Firstly, both rotated and unrotated principal factors were obtained using the Kaiser-Guttman (KG, eigenvalue ⩾ 1.0) criterion, then factors were selected by fixing the number to be calculated. This was done by allowing the program package to choose the minimum number of factors it could achieve. In other words, an estimate of the rank of the correlation matrix was made, generally leading to half to two-thirds the number of factors obtained by using the KG criterion. Finally, another set of factors was obtained which was calculated by obliquely rotating the first half to one-third of the original unrotated KG selected factors. As an example, consider winter 300 hPa height. There are 32 stations from which data were available and thus 32 height variables. Using the KG criterion, nine factors were obtained and then, by estimating the rank of the correlation matrix as well, a second set of six factors was calculated. These two sets of factors were rotated obliquely to obtain two additional sets of factors. A fifth set was calculated from the original unrotated nine factors by obliquely rotating the first five factors only. Further sets can be obtained by rotating, instead of five, some other number of factors.

There were only minor differences between most of the unrotated factors, i.e. those obtained using the KG criterion with or without rank estimation beforehand, and so the pattern correlations between the corresponding factors were also approximately one. In some cases, therefore, there were really only four *different* sets of factors to compare in order to determine the stable factors and common structures.

Another technique employed in this analysis was that of compositing. Where PFA identifies structures by weighting all fluctuations of variables proportional to their magnitudes, compositing places more emphasis on the extreme departures to determine spatial patterns and is thus less sensitive to the smaller variations. Compositing involves calculating the average of a data field from selected times (months) at the extremes of a time-series of an index describing a particular event or variation in the atmosphere.

In this study, the irregular and, in places, sparse network of stations restricts our investigations to the largest horizontal scales. Another problem with an irregular network such as this is that the factors may be biased towards regions where there is a denser network of stations. This would arise because of the tendency for higher positive correlations between variables that are located closer together. This was used as a criterion for selecting the stations for analysis from the available ones so that the density of stations was as uniform as possible. The highest concentration of stations used in the analysis occurs in the Australasian region, but, as the results will show, this is not a problem for the leading factors.

To provide the best available coverage of stations over the hemisphere, five stations with data periods shorter than twenty years have been used. The inter-station correlations were computed using slightly different periods for different station pairs. The impact of these different record lengths on the factors is difficult to assess. The results which follow suggest that there are no anomalous features in the spatial patterns at any of the five stations with shorter record lengths.

In the following two sections, the stable factors for height and zonal wind at 300 hPa are described. Because of the possibility of different results associated with the seasonal variation of the circulation, the results for summer (December, January and February) and winter (June, July and August) have been considered separately.

Geopotential height

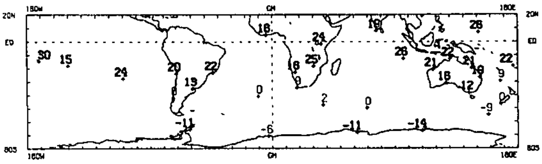
Summer

The leading factor from all methods for the fluctuations of monthly mean height in summer has all tropical stations varying in phase, accompanied by weaker variations of the opposite sign for the extratropical stations. Using the different methods, this pattern explains between 17.5 per cent and 26.4 per cent of the variance with an average of 21.3 per cent. Some variation in the amplitudes of the structures at Easter Island and South America is found using different methods and some methods show this mode to be bordered by the Greenwich Meridian in the west and the central Pacific in the east. The two patterns shown in Fig. 1 represent extremes of this variation and they have the lowest pattern correlation of all pairs (0.79) from the different methods used. The average correlation was 0.88. They also illustrate the effect rotation can have on the patterns as the second pattern is an obliquely rotated version of the first. In subsequent diagrams, only the rotated factors are shown. This leading pattern is in agreement with the tropical Pacific part of the leading NH winter rotated principal component obtained by Horel (1981, his Fig. 5(a)). Based on analysed height data, his factor represented the Pacific/North American pattern and explained 7.8 per cent of the variance.

The pattern which explains the second largest proportion of variance – between 8.1 per cent and 12.3 per cent and on average 9.8 per cent – is also stable to the different methods, and is shown in Fig. 2. The pattern

Fig. 1 Leading (a) unrotated and (b) rotated factor for monthly anomalies of 300 hPa height in summer.

a) First factor, unrotated, summer, Z 300 hPa



b) First factor, rotated, summer, Z 300 hPa

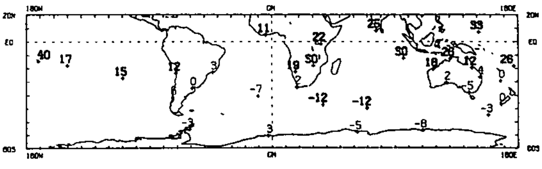
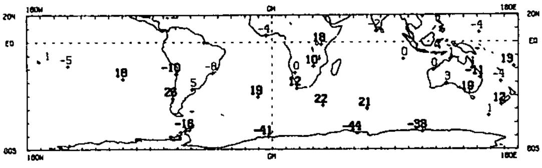


Fig. 2 Second rotated factor describing mid-latitude/ antarctic mode of summer 300 hPa height.

Second stable factor, summer, Z 300 hPa



correlation for this structure ranged from 0.51 to 0.99 and averaged 0.74. This pattern describes an out-of-phase relationship between the mid-latitude stations and the antarctic stations. It appears weaker for the South American stations where one also finds the correlations with the antarctic stations to be lower in magnitude. The leading summer height pattern of MW (their Fig. 15(b)) is similar to this, indicating a zonally symmetric out-of-phase variation between middle and high latitudes.

Another pattern which was stable explained the third most amount of variance and described a complicated smaller scale structure between South America and Africa. The time-series in these regions were shorter and possibly less reliable. The fraction of total variance represented by the first six factors is given in Table 2. This shows that the first and second summer factors are distinct in terms of the error formula of North et al. (1982) whereas the third and lower factors are not. There may be some degeneracy in the third and lower eigenvalues, possibly leading to some mixing of the factor patterns. Table 3 indicates that rotation has redistributed the variance more evenly towards the lower factors.

Winter

The variations of monthly mean height in winter in the SH are less clearly described in terms of the factor patterns than in summer. There are fewer stable patterns and each pattern explains less variance. The fractions of variance given in Table 2 indicate that only the leading factor can be considered distinct from the lower factors.

As in summer, a tropical in-phase variation is stable and explains the most variance; from 12.2 per cent to 18.3 per cent depending on the method, and averaging 13.0 per cent although this is less than the summer pattern. The rotated factor is shown in Fig. 3(a). The eastern Pacific and South American region have lower amplitudes in winter than in the corresponding summer pattern.

The second stable pattern described, as in summer, an out-of-phase structure between middle and high latitude and is shown in Fig. 3(b). This pattern is less zonally symmetric than the corresponding summer pattern, not including Africa and Indian Ocean stations. It bears some resemblance to the leading winter pattern in MW (their Fig. 15(a)). The pattern is stable, but this appears mainly due to the largest amplitudes in the antarctic remaining unchanged with different methods. At the other stations, for example, Argentine Island, there is some variability in the amplitude. The variance explained was between 6.0 per cent and 9.8 per cent averaging 7.9 per cent while the pattern correlation lay between 0.75 and 0.99 with an average among the different versions of 0.85.

A third stable pattern was found which explained a smaller fraction of the variance. While its influence was widespread, its structure showed smaller scale variations which were not well resolved by the station network. It is possible that this pattern may have been associated with the zonal wave-number three variations in winter identified by MW.

Table 2. Percentage variance explained by first six unrotated principal factors for (a) summer and (b) winter geopotential height at 300 hPa. For summer and winter, 8 and 9 factors respectively had eigenvalues greater than 1.0.

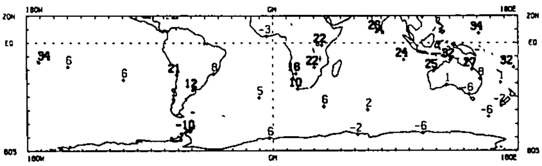
	(a) S-Z300		*(b) W-Z300*	
Factor	*% variance explained ± error*	*Cumulative variance explained*	*% variance explained ± error*	*Cumulative variance explained*
1	26.41 ± 5.30	26.41	18.26 ± 3.64	18.26
2	12.35 ± 2.47	38.76	10.50 ± 2.10	28.76
3	7.94 ± 1.59	46.70	8.18 ± 1.64	36.94
4	6.78 ± 1.36	53.48	7.75 ± 1.55	44.69
5	5.32 ± 1.06	58.80	6.31 ± 1.26	51.00
6	4.85 ± 0.97	63.65	5.54 ± 1.11	56.54

Table 3. As in Table 2 except for rotated factors.

	(a) S-Z300		*(b) W-Z300*	
Factor	*% variance explained ± error*	*Cumulative variance explained*	*% variance explained ± error*	*Cumulative variance explained*
1	20.01 ± 4.00	20.01	12.49 ± 2.50	12.49
2	10.89 ± 2.18	30.90	8.22 ± 1.64	20.71
3	8.86 ± 1.77	39.76	8.10 ± 1.62	28.81
4	7.30 ± 1.46	47.06	7.73 ± 1.54	36.54
5	6.84 ± 1.36	53.90	7.25 ± 1.44	43.79
6	5.93 ± 1.18	59.83	6.74 ± 1.34	50.53

Fig. 3 (a) First and (b) second rotated factors for winter 300 hPa height.

a) First factor, winter, Z 300 hPa



b) Second stable factor, winter, Z 300 hPa

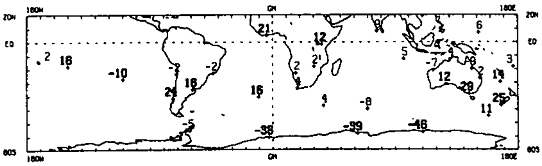
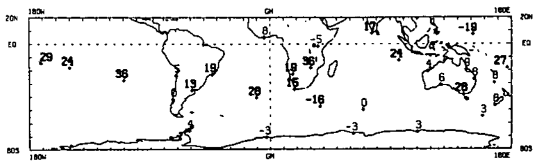
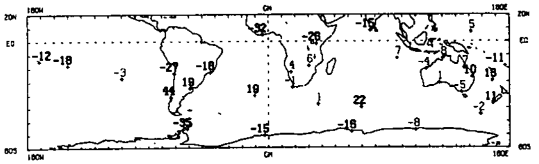


Fig. 4 (a) First and (b) second stable factors for summer 300 hPa zonal wind.

a) First factor, summer, U 300 hPa



b) Most stable factor, summer, U 300 hPa



Zonal wind

Summer

In contrast to results for the height factors, the summer factors for zonal wind are less stable to different methods than the winter patterns. In particular, the leading factor is more difficult to define in summer than in winter. Also, the pattern which explained the most variance was not necessarily the most stable pattern.

The pattern explaining the most variance was stable and is shown in Fig. 4(a). Among the different methods, the correlation between different versions of the leading factor varied from 0.45 to 0.99 (average of 0.69). It shows an in-phase variation for all subtropical stations, with small amplitudes at high latitudes. The variance explained by versions of this pattern ranged between 10.0 per cent and 17.1 per cent and averaged 13.2 per cent. The factor which explained the second largest fraction of variance described a structure over Australia, but it was not found with all methods.

The most stable summer pattern (Fig. 4(b)), explaining the third largest amount of variance, has a two node structure confined mainly to the region between South America and Africa, with anomalies of the same sign in low latitudes and Antarctica but of opposite sign in middle latitudes. Between 6.3 per cent and 8.9 per cent with an average of 7.4 per cent of the variance was explained. The correlations varied between 0.75 and 0.99, averaging 0.83. Applying the error formula of North et al. (1982) to the variances listed in Table 4, it is possible that there is a degeneracy in the eigenvalues leading to a mixture in the patterns with the next factor. This next factor described a complicated two node variation over Australia which was not stable.

The variations of the zonal wind associated with the leading factor are on the equatorward side of the long-term mean zonal jet at 300 hPa in summer. The leading summer height and zonal wind factors are related since changes of the meridional height gradient in the subtropics associated with the tropical height factor would lead to changes in the zonal wind through geostrophic balance.

Winter

The most stable winter pattern, shown in Fig. 5, is an out-of-phase mode between northern and southern Australia. Between 9.5 per cent and 13.1 per cent of the variance is explained by this mode depending upon the procedure for obtaining the factors. The average was 11.3 per cent and the average pattern correlation was 0.88 (ranging from 0.74 to 0.99). This pattern appears to be associated with variations of the long-term mean subtropical jet in winter.

There is some evidence for other patterns but their definition is more dependent on the procedure for obtaining the factors. For example there were stable patterns found for the South American and African region but they showed comparatively small space-scales relative to the station network.

Table 4 shows the amounts of variance explained by the first six principal factors of zonal wind. The leading summer factor explains more variance than the winter factor and is the only distinct factor. All other factors for both seasons overlap insofar as they are within each others error range. The cumulative variance explained by the first six factors is the same for both seasons.

Table 4. As in Table 2 except for zonal wind. A total of 9 and 11 factors were found for summer and winter respectively.

Factor	*(a) S-U300* % variance explained ± error	*(a) S-U300* Cumulative variance explained	*(b) W-U300* % variance explained ± error	*(b) W-U300* Cumulative variance explained
1	17.10 ± 3.42	17.10	13.06 ± 2.61	13.06
2	10.51 ± 2.10	27.61	11.76 ± 2.35	24.82
3	8.37 ± 1.67	35.98	10.74 ± 2.15	35.56
4	6.46 ± 1.29	42.44	8.34 ± 1.67	43.90
5	6.33 ± 1.27	48.77	7.03 ± 1.41	50.93
6	5.68 ± 1.14	54.45	6.74 ± 1.35	57.67

Time-series and composite analysis

To give an indication of the time-scale of variation of the major patterns found previously, time-series of the factors were obtained. The factors having the largest space-scales will be examined: the tropical pattern and the middle to high latitude out-of-phase pattern. Indices of these modes were constructed also and correlated with the factor time-series. Following this, composites were calculated based on extreme values of the factor time-series and the indices.

Time-series

A time-series for each factor was obtained by multiplying the normalised value (because correlations have been used) of the variable at each station by the factor amplitude at that station and summing over all stations for that particular date. The time-series of a factor is thus a linear combination of the time-series of all the (normalised) variables, and the factor amplitudes are the weights assigned to each variable. For some dates, there were missing data at some stations and if more than one-third of the variables having large factor amplitudes had missing data at a particular date, the factor time-series was not calculated. There were more missing data during the 1960s compared with the 1970s, when less than 10 per cent of data was missing for any one date.

First the time-series of those patterns describing the tropical mode are presented. In Fig. 6(a) the time-series of the leading factor for summer height is shown. This pattern, describing the tropical in-phase variation, shows more variability for yearly time-scales than for monthly time-scales. The time-series for the leading factor for winter 300 hPa height, describing a similar horizontal structure to the leading summer factor, is shown in Fig. 6(b), and it appears to vary over shorter time-scales than in summer. The leading summer zonal wind factor also described a tropical in-phase variation.

Fig. 5 Most stable factor for winter 300 hPa zonal wind.

First factor, winter, U 300 hPa

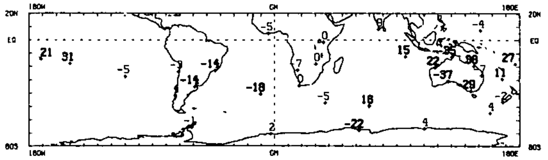
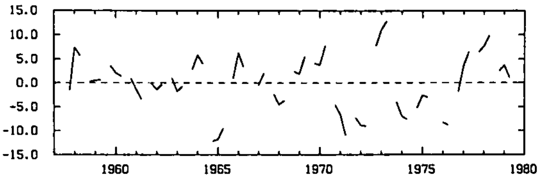
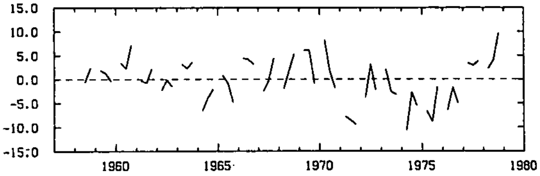


Fig. 6 Time-series of (a) summer tropical height factor shown in Fig. 1(b), (b) the winter tropical height factor shown in Fig. 3(a), and (c) the summer tropical wind factor in Fig. 4(b). In all time-series diagrams, each tick mark indicates January of the year so summer is centred on the tick marks and winter is between the tick marks.

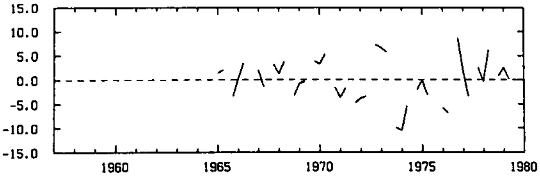
a) summer, Z 300 hPa



b) winter, Z 300 hPa



c) summer, U 300 hPa



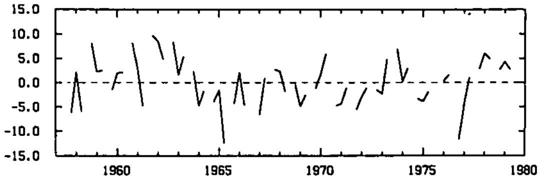
Its time-series (Fig. 6(c)) shows more monthly variability than for summer height.

Correlations were calculated between these time-series and a Southern Oscillation Index (SOI). The difference in normalised surface pressure anomalies between Tahiti and Darwin was calculated for the period 1964-79 and then deseasoned and linearly detrended. The correlations between this index and the time-series for the tropical patterns are shown in Table 5. The summer height factor, denoted S-Z300PF1, has a correlation of 0.54 which is significant at the 99 per cent level assuming 22 degrees of freedom or one in every two months independent. In addition, minima of the SOI correspond to maxima in the time-series of this factor. A SO event appears to be associated with higher 300 hPa heights in the tropical eastern hemisphere. The summer zonal wind factor time-series (S-U300PF1) also shows a significant correlation with the SOI indicating westerly anomalies in the subtropical SH at 300 hPa accompanying a SO event. The time-series of the winter height pattern (W-Z300PF1) has a low correlation with the SOI. The leading winter zonal wind factor time-series (W-U300PF1, not shown) has a correlation of -0.42 with the SOI. This is the only relationship between the factors and the SOI in winter.

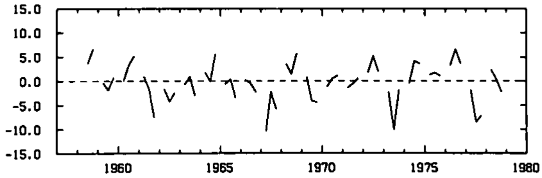
The other major pattern is the out-of-phase structure between middle and high latitudes. The time-series for the second stable summer height factor is shown in Fig. 7(a). Compared with the tropical mode, this higher latitude variation shows more high frequency variability within a season and thus less persistence on monthly time-scales. The time-series for the winter middle to high latitude variation (Fig. 7(b)) exhibits even more variability on monthly time-scales than for summer. Visual comparison of summer time-series with the time variation of the equivalent component in MW reveals a rough correspondence (allowing for sign) for some years such as the 'low' years of 1978-79 and 'high' year 1977, found in MW. The time-series for the winter mode in MW does not appear to resemble the corresponding time-series here (Fig. 7(b)).

Fig. 7 **Time-series of the (a) summer north – south factor shown in Fig. 2 and (b) winter north – south factor shown in Fig. 3(b).**

a) summer, Z 300 hPa



b) winter, Z 300 hPa



An index of this mode, which we shall call the north-south index (NSI), was calculated using the nine stations that consistently had large amplitudes for this mode and is defined as:

$$\mathrm{NSI} = \mathcal{Z}_{68906} + \mathcal{Z}_{68994} + \mathcal{Z}_{61998} + \mathcal{Z}_{94865} + \mathcal{Z}_{93844} - (\mathcal{Z}_{88952} + \mathcal{Z}_{89001} + \mathcal{Z}_{94986} + \mathcal{Z}_{89611}),$$

where $\mathcal{Z}$ indicates that normalised 300 hPa height anomalies at the stations were used. This index describes a see-saw type variation in the height field where middle latitude stations experience a rise in 300 hPa height at the same time as there is a fall in height at the coastal antarctic stations. Macquarie Island (94998) was not included because it had variable amplitude in some of the factors for this mode, indicating that it may be lying near the node line. Time-series of this index were calculated for both summer (NSIS) and winter (NSIW) and both have more variability on monthly time-scales than on annual time-scales.

Correlations between this index and the factor time-series are listed in Table 5. Assuming 30 degrees of freedom, the summer height mode has a very high correlation with NSIS which is significant at the 99.5 per cent level but in winter the correlation is small – only 0.19 – suggesting that, in winter, these stations do not well describe the mode represented by the factor. In summer, the linear combination represented by the north-south index describes very well the variability of the second stable summer mode.

Table 5. Correlations between time-series of the principal factors and an index of the Southern Oscillation and with the north-south index (NSI).

S-Z300PF1	−0.54 (43)	SOI
W-Z300PF1	−0.17 (44)	SOI
S-U300PF1	−0.65 (42)	SOI
W-U300PF1	−0.42 (42)	SOI
S-Z300PF2	0.91 (62)	NSIS
W-Z300PF2	0.19 (61)	NSIW
S-U300PF3	−0.56 (42)	NSIS

Composite analysis

In this section, the large-scale structure of the two major patterns discussed previously are investigated using composite maps. This is a complementary technique to factor analysis, where the starting point is now from the time variation of the factor and the data field is sought as a check on the factor patterns.

In all composite maps to follow, the data fields are unnormalised (i.e. dimensional) anomalies and boldface numbers for height indicate significant anomalies at the 95 per cent level based on a one-sided Students' 't' test and 30 degrees of freedom (Spiegel 1961). Monthly anomalies were used to form the composite maps for both height and wind data. The dates were selected by looking for 'obvious' cutoff levels in the time-series rather than fixing the number of dates that contribute to the compositing. Due to the relatively short time-series, it was felt that a criterion such as choosing dates in the highest and lowest quartile, while being objective, was nevertheless somewhat arbitrary.

In this section, two modes of variation shall be examined: the Southern Oscillation and its variation at 300 hPa, and the north-south out-of-phase variation at middle to high latitudes.

Firstly, the factors can be easily checked by compositing from the factor time-series. In general, the statistically significant values of the composites better resembled their corresponding factors in summer than in winter. This applies to both the tropical and the higher latitude north-south mode. Figure 8 shows the composites obtained from minimum values of the time-series in Fig. 6(a) and Fig. 7(a) representing the summer tropical and higher latitude modes respectively. They are quite similar to their factor patterns in Fig. 1(b) and Fig. 2.

The Southern Oscillation (SO)

A strong SO event is indicated by low values of the SOI for the SH summer months. Composites were made for geopotential height and zonal and meridional wind at 300 hPa from the following extreme SOI dates: 6512-6602, 7212-7302, 7712-7802; and the resulting map is shown in Fig. 9. It shows an increase in height at 300 hPa in the tropical eastern hemisphere region along with some decrease at higher latitudes. Stations such as Townsville and those in the eastern Pacific and South American regions appear relatively uninfluenced. This map is very similar to the leading summer height pattern shown in Figs 1(a) and (b) and the composite map in Fig. 8(a), with deviations of the same sign throughout the tropics. It is also in agreement with the results of Horel and Wallace (1981) for 200 hPa height. The westerly wind anomalies in the tropical Pacific are similar to those found by Arkin (1982) at the 200 hPa level and are in agreement with those found in the leading summer wind factor.

Compositing 300 hPa height for the winter months prior to the above summer months produced a map (not shown) which has fewer statistically significant features than in summer and has a more complicated smaller scale structure. This is especially so at the Pacific stations where the anomaly at Easter Island is of opposite sign to Tahiti and Puerto Montt and northern Australia.

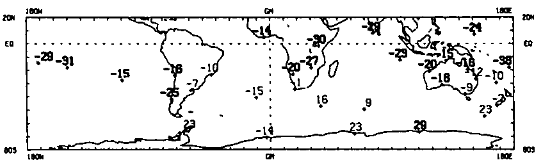
The middle-high latitude variation

The purpose of compositing based on the summer and winter time-series of the NSI is to examine the relationship this mode has with the lower latitudes. The maps should have large amplitudes at the nine stations but it is the amplitudes at the other stations that are of more interest.

Positive and negative values of the summer north-south index (NSIS) produced composite maps (Fig. 10) which were very similar to the factor analysis results at middle to high latitudes. The important feature is the weak relationship and the sharp boundary this mode has with tropical stations where magnitudes of the deviations are far less though the sign remains the same.

Fig. 8 Composite map of height anomalies (in gpm) based on minimum values of the time-series of (a) the summer tropical height factor and (b) the summer north-south factor.

a) Composite map, first factor, summer, Z 300 hPa



b) Composite map, second stable factor, summer, Z 300 hPa

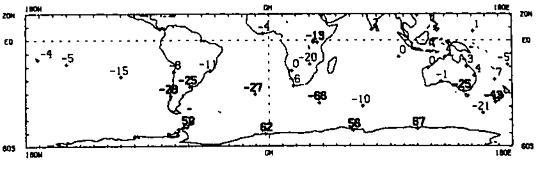


Fig. 9 Composite map of height (in gpm) and zonal and meridional wind (in m/s) anomalies based on minimum values of the Southern Oscillation Index.

Composite map, min. extrema of SO index for Z,U,V 300 hPa

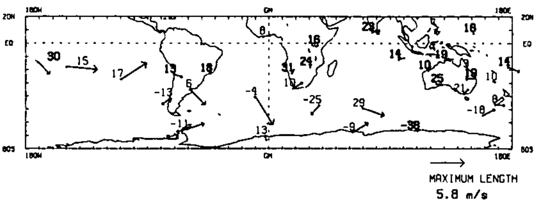
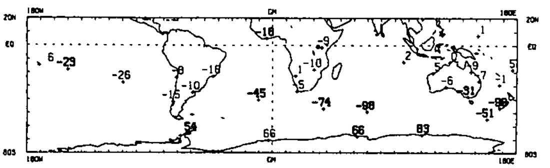


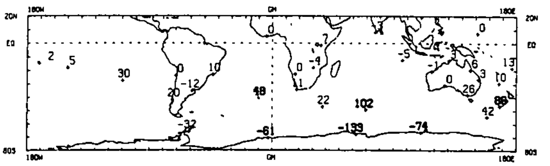
Fig. 10 Composite map of height anomalies (in gpm) based on (a) minimum and (b) maximum values of the index NSI for summer.

Composite map, north-south index, summer, Z 300 hPa

a) min extrema



b) max extrema



The smaller amplitude anomalies in South America suggest that there are important zonal variations in the structure of the mode. It appears that the tropical atmosphere has little influence on this mode in summer. In the same way, patterns (not shown) were generated from NSIW and showed a weaker signal for this mode, although its influence extended further equatorward. This agrees with the correlations in Table 5 suggesting that this mode as shown in Fig. 2 or 8(b) is stronger in summer than in winter.

Discussion and summary

First we shall make a broad comparison of the results presented above with those from related studies, bearing in mind that such comparisons between different studies are dependent, to some extent, on the geographical region and number of variables used in each study. Comparing the results of Rogers and van Loon (1982), Trenberth (1980) and MW with those found here (Table 2), it is evident that, for both seasons more variance is explained by the first few factors/components for monthly mean data than for daily data. The leading eigenvector for daily data explains 10.2 per cent and 8.2 per cent for summer and winter respectively (see Rogers and van Loon 1982, Table 2). For monthly analysed data (see MW, Table 1), the corresponding percentages are 20.9 per cent and 21.2 per cent, and for the station data presented here, the leading height factor explained 26.4 per cent in summer and 18.3 per cent in winter. For data from all year round, 21.9 per cent of the variance is in the first component (Trenberth 1980). There appears to be more variance explained in the leading SH factor/component than for the NH for monthly data, although there have been no northern hemisphere results published for station data. From Table 1 of Horel (1981) up to 16 per cent of the variance is accounted for by the leading factor in their winter data sets. The leading modes/components in the SH are zonally symmetric whereas in the NH they have wave-like structures.

The leading height pattern, an in-phase variation throughout the tropics, is the same for both seasons. There is evidence that it may be associated with the Pacific/North American pattern in the NH winter (SH summer) (see Horel 1981, Fig. 5(a), his leading (NH) winter component). The time-series for this factor showed more variance on annual time-scales than on monthly time-scales. The time-series of the summer pattern has a correlation with the SOI of 0.54. Using the SOI, composite patterns have been obtained for minimum values of the index which closely resemble the factor patterns. Thus not only is the time-series of the leading factor strongly correlated with this index, but the composite fields on extreme SOI are very similar to the factors themselves. This supports the view that the Southern Oscillation is the most important influence in the SH summer on the low frequency fluctuations of the circulation at low latitudes. However, the time-series of the winter pattern has a correlation of only 0.11 with the SOI suggesting that there is less influence of the SO on the low latitude circulation in the SH winter.

The second height pattern (Fig. 2), describing a see-saw between the antarctic stations and the mid-latitude stations, is well known and exists also in the daily data in both summer and winter (see Rogers and van Loon 1982, Figs 2(b) and 3(b)) as well as in analysed monthly data (see MW, Figs 15(a) and (b)). There are some differences in the shape of this factor from those obtained by MW which are not explainable by an irregular network. In terms of variance explained, the pattern is weaker in winter than in summer. This was also found to be the case with results obtained by others for analysed data. The time-series for this factor showed quite large variations from month to month. The indices NSIS and NSIW defined using selected stations have quite different correlations with the time-series of the factor pattern for summer and winter. A very high correlation was found with the summer factor time-series with over 80 per cent of the variance explained, while the correlation was negligible with the winter factor time-series. Compositing based on both maximum and minimum of NSIS produced patterns that very closely resembled the summer factor. The composites showed almost no interaction with the tropical latitudes.

Only two stable factors were found for zonal wind in summer. The leading factor has largest amplitudes in the tropics over Australia and the Pacific Ocean, and was associated with the leading summer height mode and the SO. The second factor is associated with the middle latitude jet over South America and possibly represents north-south shifts in the position of jet maximum. The main winter pattern (Fig. 5) has largest amplitudes in the vicinity of the subtropical jet located over Australia and the western Pacific Ocean. This factor had a negative correlation with the SOI, indicating that, in winter, a SO event is associated with a strengthening of the jet and extension of the jet further east over the Pacific.

In summary, two major patterns arising in both summer and winter have been found; a tropical mode associated with the Southern Oscillation and a zonally symmetric mode of opposite variations in middle to high latitudes. The tropical patterns vary over longer time-scales than the higher latitude patterns while for both modes the time-scales for winter appear to be shorter than for summer. In addition, several more regional patterns occurring in only one or other of the two seasons have been suggested by the results but their more complex structure could not be identified clearly using the station network.

The results in this analysis must be qualified because of the use of the coarse network of stations available, particularly at higher latitudes. In order to provide a more even distribution, analysed data must be used. A study of the low frequency variations of the SH troposphere using a 15-year set of numerical analyses is in progress.

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