Atmospheric blocking and storm tracks during SOP-1 of the FROST Project

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Atmospheric blocking is a significant feature of the winter circulation in the southern hemisphere. The frequency of blocking activity was at first found to reach a maximum in the Tasman Sea and New Zealand region during winter, but evidence is emerging of higher frequencies of blocking activity in the eastern Pacific. FROST, the Antarctic First Regional Observing Study of the Troposphere, provided an opportunity to study the effects of all sources of data (including ‘late’ observations) on meteorological analyses over the Southern Ocean and the Antarctic region, and the probable impacts of these data on the performance of numerical weather prediction models. The first of three special observing periods (SOPs) was held in July 1994. Analyses for this period (SOP-1) have demonstrated that atmospheric blocking was a significant feature in the Pacific sector of the Southern Ocean (150°E -75°W) and that it had a major influence on the paths followed by cyclones, apparently contributing to the crossing of the Antarctic coast by vortices on several occasions. The blocking activity was evident in the eastern half of the Pacific (75°W - 150°W) during the first half of the month but relocated to the southwest Pacific (150°W - 150°E) towards the end of the month.

Introduction

The occurrence of atmospheric blocking continues to pose difficulties for weather forecasters and atmospheric modellers in the southern hemisphere. Baines (1990) suggests that atmospheric blocking on the synoptic scale is arguably the most significant problem for weather forecasting when viewed globally. He asserts that this results from ‘its general unpredictability, and the large length scales and lifetimes of the phenomenon’ (Baines 1990, p. 124). This is despite the steady improvement in numerical weather forecasting models demonstrated by e.g. Simmons (1986), Seaman et al. (1995), and Bourke et al. (1995), and generally acknowledged by professional weather forecasters.

Apart from the intrinsic interest in blocking and the demands of day-to-day weather forecasting, the
phenomenon can result in major anomalies of temperature and precipitation, leading to serious economic and social impacts in winter and summer seasons. Rex (1950b) and Gill (1982) have discussed major anomalies of temperature and rainfall that have occurred over Europe in times of major blocking events. Pook (1994) has referred to the effect on water storage and hydro-electric resources in western and southwestern Tasmania resulting from winter drought caused by persistent blocking in the winter of 1989. Summer blocking patterns can have equally serious impacts, as discussed by Green (1977).

In addition to rainfall and temperature anomalies, Schwerdtfeger (1984) has referred to the dramatic change in wind conditions from stormy westerlies to moderate northeasterlies which occurred during a ten day period in June 1952, when an intense block persisted between the Falkland and South Shetland Islands. He comments that these synoptic situations are unique in offering the opportunity for 'a few days of weak, or not more than moderate, surface winds, welcome for oceanographic work, disembarking on islands, and other outdoor activities' (Schwerdtfeger 1984; p. 156).

Early studies of blocking in the southern hemisphere (e.g. van Loon 1956; Wright 1974; Lejenas 1984) found that the phenomenon occurs most frequently in three preferred locations to the east or southeast of the continents. Of these three regions the sector which includes the Tasman Sea and the southwest Pacific was seen to be the dominant zone for blocking activity. Blocks appear as local enhancements of the climatological low index circulation in this region, with frequency maxima in winter and early spring, and again in summer (Hirst and Linacre 1981).

A comprehensive comparison of blocking statistics for the northern and southern hemispheres has been given by Coughlan (1983). While acknowledging characteristics common to blocking activity in each hemisphere, he drew attention to significant contrasts between the patterns of blocking in the two hemispheres. Apart from the preference for three dominant regions of blocking in the southern hemisphere contrasting with two in the northern hemisphere, the mean latitude of blocking action in the south was found to be 45°S compared to 56°N in the north.

Sinclair (1996) employed an automated procedure to locate and track anticyclones in the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis set for the period 1980-89. In contrast to previous studies of blocking, his analysis found that there were just two regions where intense and persistent blocks occurred. Both of these regions were in the Pacific Ocean, one to the southeast of New Zealand and the other southwest of South America, near 110°W. A subsequent study by Sinclair (1997), using the ECMWF dataset extended to 1994, found a higher incidence of blocking days in the southeast Pacific than in the New Zealand region, with approximately 50 per cent of the southeast Pacific blocks occurring after 1991. These analyses suggest that blocking is more common in the eastern and central Pacific Ocean than previously thought, with the frequency of blocking in this region having increased during the period since 1980. However, as the high latitude region of the South Pacific Ocean to the east of the date-line is almost totally devoid of conventional meteorological observations (Streten and Zillman 1984) there exists the possibility that this observed increase stems from improvements in remote sensing and atmospheric modelling of the region. Nevertheless, the apparent increase in blocking frequency has been accompanied by changes in the structure of the semi-annual oscillation of surface pressure (SAO) in the South Pacific Ocean sector during the same period. Van Loon et al. (1993) and Hurrell and van Loon (1994) have reported that there has been a decrease in the amplitude of the second harmonic of the annual pressure wave relative to the two preceding decades.

**Blocking definitions**

A systematic effort to set down criteria by which the phenomenon of blocking could be identified was accomplished by Rex (1950a). Taking advantage of the upper-air network which had been established over the northern hemisphere by the middle of the century, he identified five necessary conditions for an atmospheric block to occur. These are:

- the basic westerly current (at 500 hPa) must split into two branches;
- each branch current must transport an appreciable mass;
- the split-jet system must extend over at least 45 degrees of longitude;
- a sharp transition from zonal flow upstream to meridional flow downstream must be observed across the current split; and
- the pattern must persist with recognisable continuity for at least ten days.

Owing to the unavailability of comprehensive upper-air data for the southern hemisphere, van Loon (1956) developed a set of three basic requirements for satisfactorily defining a blocking situation from mean sea-level pressure data. Wright (1974) identified a more common form of blocking in the Australasian region than that which the narrow definition of van Loon (1956) could permit. He developed an alterna-
tive definition of blocking to take account of the occurrence of a 'process which may be called one of displacement and replacement' (Wright 1974, p. 3). The four criteria of his definition are:

- the basic westerly current splits into two branches;
- the 5-day mean 500 hPa ridge at 45°S (defining the longitude of the block) has a rate of progression of less than 20 degrees of longitude per week and progresses no more than 30 degrees of longitude during the entire blocking occurrence;
- the ridge of high pressure at the longitude of blocking is at least 7 degrees south of the normal position of the subtropical high pressure belt (as derived by Taljaard et al. 1969) and is maintained with recognisable continuity; and
- the occurrence lasts for at least six days.

Trenberth and Mo (1985) developed an objective method to determine the temporal frequency and spatial distribution of blocking in the southern hemisphere. Essentially, their objective definition of blocking requires a large positive anomaly (e.g. ≥ 10 dam) of 500 hPa geopotential height to persist for at least five days. The anomalies calculated in their analysis were obtained after removing the annual cycle in a similar manner to that of Trenberth and Swanson (1983).

Indices of blocking action

In addition to the application of the definitions in the previous section, attempts have been made to develop objective indices of blocking action. For the southern hemisphere, Wright (1974) and Noar (1983) have described a blocking index (BI) which was developed by the Extended Forecast Section of the Australian Bureau of Meteorology. The BI was originally defined as:

\[
BI = U_{27.5} + U_{57.5} - (U_{42.5} + U_{47.5})
\]  

...1

where \(U_x\) represents the zonal component (m s\(^{-1}\)) of the mean geostrophic wind at the latitude (°S) specified by the subscript, calculated from the five-day mean 500 hPa field. Hence the index measures the relative influences of the zonal components of the geostrophic wind at middle, high and low latitudes. High values of BI indicate situations in which the high and low latitude westerly winds are strong or the mid-latitude westerly flow is weak, or a combination of both. Configurations of this type correspond to blocking activity but the index is unable to convey information on the degree of meridionality of the flow or the latitudinal separation of the zonal wind maxima. More recently, this index has been modified by the addition of zonal components at several latitudes. The modern BI has the following form (Wright 1994):

\[
BI = 0.5(U_{25} + U_{30} + U_{55} + U_{60} - U_{40} - U_{50} - 2U_{45})
\]  

...2

where \(U_x\) represents the zonal component of the mean 500 hPa wind at latitude \(x\).

An alternative index of blocking, derived from observed locations of the polar wind maximum (PWM) and the subtropical wind maximum (STWM) – the two main dynamic features associated with the blocking mechanism – has been put forward by Gibson (1995). This index is defined as:

\[
B_i = 3[\sin \Phi_{pi} - \sin \Phi_{si}] - [\sin \Phi_{p(i+1)} + \sin \Phi_{p(i-1)}]\n+ [\sin \Phi_{s(i+1)} + \sin \Phi_{s(i-1)}] - [\sin \Phi_{p} - \sin \Phi_{s}]
\]  

...3

where \(B_i\) is the value of the blocking index at longitude \(i\), and \(\Phi_{pi}\) and \(\Phi_{si}\) are the corresponding values of \(\Phi_p\) and \(\Phi_s\), the (time-mean) latitudes of the STWM and the PWM, respectively, at longitude interval \(i\), and \(\Phi_p\) and \(\Phi_s\) are the hemispheric mean average values of \(\Phi_{pi}\) and \(\Phi_{si}\). The values of \(\Phi_{pi}\) and \(\Phi_{si}\) are usually determined at longitude intervals of 10°, and all averages are obtained by taking the sines of the latitude angles, averaging them, and then taking the arc sine of the result. Since blocking events are, by definition, persistent over several days, the values of \(\Phi_{pi}\) and \(\Phi_{si}\) are usually time-averaged, typically for a period of three days.

This index reflects contributions from three components: (a) the area within a longitude segment bounded by the STWM and the PWM; (b) the curvatures of the time-meaned STWM and PWM (positive contributions when the STWM has cyclonic curvature, and the PWM has anticyclonic curvature), and (c) the hemispheric mean value of the area between the STWM and the PWM – this is subtracted in order to eliminate seasonal variations in the value of the index which arise from the larger interannual movement of the STWM as compared to the PWM. Components (a) and (b) will clearly have large positive values in a blocking situation.

In this paper we apply the definition of Wright (1974), the geopotential anomaly method and indices of blocking action to investigate the incidence of blocking during the first special observing period (SOP-1) of the First Regional Observing Study of the (Antarctic) Troposphere (FROST).

The FROST project

FROST is a project designed to study the effects of all sources of data (including 'late' observations) on meteorological analyses over the Southern Ocean and Antarctic region and the probable impacts of these data on the performance of numerical weather prediction models (Turner et al. 1996). The first of three spe-
cial observing periods (SOPs) was held in July 1994. Although the subtropical ridge is located to the north of the FROST analysis region, which was confined to latitudes south of 50°S, blocking anticyclones are not uncommon features in these higher latitudes and the frequency of occurrence of blocking in the hemisphere reaches a maximum in the Tasman Sea and New Zealand region during winter (Wright 1974; Hirst and Linacre 1981; Lejenäs 1984; Trenberth and Mo 1985).

Synoptic analyses for SOP-1 have demonstrated that atmospheric blocking was a significant feature in the Pacific sector of the Southern Ocean and had a major influence on the paths followed by cyclones, apparently contributing to the crossing of the Antarctic coast by vortices on several occasions.

In addition to the first analysis set for July 1994, re-analysis of a ‘special week’ in SOP-1 (22 - 28 July 1994) was conducted with the addition of late data which included verified observations from AWS, some drifting buoys, AVHRR imagery from NOAA satellites and Operational Linescan (OLS) imagery and Special Sensor Microwave/Imager (SSM/I) data from the Defense Meteorological Satellite Program (DMSP). Visible and infrared imagery from DMSP have been analysed over the data-sparse Indian Ocean and Australasian sectors of the Southern Ocean using the semi-objective technique reported by Guymer (1978). The technique has been employed to locate cyclonic vortices over the ocean and, in some cases, as an aid to making estimates of the intensities of these systems. As well, the technique has been used to determine the structure, orientation and intensity of key features in the 1000-500 hPa thickness field.

Of particular significance to the re-analysis has been the ability to track weather systems inland over the Antarctic continent using the DMSP OLS thermal infrared channel, as well as the visible channel, with its ability to detect reflected moonlight during the polar night. For the most part, cyclonic systems appeared to remain north of the Antarctic coast but cloud bands from these systems were observed to move inland at regular intervals. Towards the end of the ‘special week’, several vortices identified on cloud imagery were observed to move across the coast of East Antarctica and penetrate well inland.

The Pacific blocking events

By the austral winter of 1994 the tropical sea-surface temperature (SST) pattern in the South Pacific Ocean was displaying characteristics of a developing El Niño (Beard 1995). Positive SST anomalies had developed in the central and eastern tropical Pacific Ocean and anomalously cold surface water was evi-

dent to the northwest of Australia and in the waters surrounding Indonesia. Negative SST anomalies were apparent in the subtropical waters of the western and eastern Pacific.

Early in July 1994, an anticyclone made its first appearance for that month at high latitudes in the central South Pacific Ocean. Thereafter, a persistent high pressure system became established in the central and eastern Pacific Ocean sector during the first half of SOP-1. The high was flanked in the western Pacific Ocean by a complex low pressure system which remained anchored to the north of the Ross Sea. By the middle of July an anticyclone with central MSLP above 1020 hPa was analysed south of 60°S in the eastern Pacific sector. This maintained its identity until 21 July, after which it gradually dissipated. The surface high was accompanied by a thermal involution in the 1000-500 hPa thickness field and the slow movement and equivalent barotropic structure was typical of a blocking pattern. In Fig. 1(a) the MSLP pattern is shown for 0000 UTC 12 July, with the 500 hPa analysis for the same time shown in Fig. 1 (b).

The mean geopotential at 500 hPa during SOP-1 revealed anomalous behaviour in the eastern South Pacific Ocean. Figure 2 shows the July 1994 mean SOP-1 500 hPa heights for the southern hemisphere at 45°S and 55°S from the Australian GASP model. Comparison with the long-term means from the
Australian NMC analysis over a 20-year period (also shown) demonstrates the distortion of the pattern during July 1994. The predominance of the ridge near 90°W (270°E) is a striking feature, particularly at 55°S, where the peak value of 5391 gpm is significantly higher than that of the ridge at 165°E in the climatological means (5327 gpm). It is also notable, however, in the SOP-1 data that the normally dominant ridge in the Tasman Sea -New Zealand region is not greatly diminished from its mean value, although it is displaced slightly westwards at 45°S. The 500 hPa geopotential height anomalies for the month of July 1994 have been extracted for latitudes 45°S and 55°S, and are illustrated in Fig. 3. There appears to have been a significant difference in wave number at the latitudes considered during this event. In Fig. 3 at 55°S the dominant wave number appears to have been 2 and the pattern was essentially stationary or retrogressive. At 45°S the dominant number is 3, and the pattern is progressive during the second half of the month.

The Hovmöller representation of the 500 hPa daily height anomaly at 45°S and 55°S from the Australian GASP model throughout the month (Fig. 4) indicates the persistence of positive anomalies of at least 20 dam in the eastern Pacific from 2 to 10 July. The anomaly reached 40 dam at its peak at 55°S on 6 July. Positive anomalies of the order of 20 dam or more made their first appearance in the western Pacific on 24 July at 55°S and remained anchored in the region until the end of the month. At 45°S, however, this ridge was never stationary and, after relocating to the date-line on 17 July, it slowly migrated into the central Pacific during the second half of the month.

The blocking definition of Wright (1974) requires that the 500 hPa ridge at 45°S in the five-day running mean progress less than 20 degrees of longitude per week and no more than 30 degrees of longitude during the entire blocking occurrence. Our five-day mean anomaly at 45°S (not shown) satisfies this criterion for the episode in the eastern Pacific at the start of the month but the progress is too rapid for the second event at the end of the month.

According to Beard (1995) the Bureau of Meteorology’s BI indicated above-average blocking activity centred on approximately 90°W during SOP-1 and slightly below-average blocking in the New Zealand region. The daily Hovmöller representation of BI for July 1994 in his Fig. 10 reveals that the most significant blocking activity occurred in the eastern Pacific Ocean early in the month and persisted until the middle of July. Thereafter, the maximum BI values tracked westwards and were located near the date-line after 20 July with a secondary maximum emerging in the eastern Pacific by 27 July.
In Fig. 5 daily values of Gibson’s blocking index B are plotted (at intervals of 10° of longitude) in the form of a Hovmöller diagram for the period June 30 (Julian Day 181) to August 1 (Julian Day 213). The values have been calculated using Eqn 3, and using as input three-day mean positions of the STWM and the PWM, obtained from daily analyses of the positions of the wind maxima on hemispheric 500 hPa charts—the GASP 1200 UTC charts were used for this purpose. (For the sake of convenience, the arithmetic B values have been multiplied by 100.) Since synoptic experience has shown that a value of B greater than 30 is usually associated with a significant blocking event, those areas on this diagram where B ≥ 30 have been cross-hatched, indicating the times and regions where significant blocking activity is occurring.

The patterns revealed in Fig. 5 are in broad agreement with those presented in Beard (1995), in that they show major blocking activity taking place in the Eastern Pacific (and the Western Atlantic) sectors early in July, while persistent blocking is seen to occur near the date-line after July 21, and a new centre of activity appears at 280°E (80°W) from the 27th to the 31st. However, there are some differences between the two pictures of blocking activity—in particular, it appears that the fully flow-based index B is more capable of precise location of blocking systems, and can also pick up blocking events which may be only weakly reflected in the patterns based on Wright’s index. An example of this is the blocking event shown in Fig. 5 as occurring in the Tasman Sea sector at the beginning of July, and then drifting eastward to the date-line before dissipating after July 5.

Monthly mean values of B (as a function of longitude) have been calculated, and are shown in Fig. 6. This figure reveals a typical southern hemisphere winter pattern, with the strongest overall blocking activity located near the date-line, and with significant activity extending across the Pacific sector, but with little or no activity in the Atlantic and Indian Ocean sectors. Again, a comparison of this figure with Fig. 2 reveals the advantage of using a flow-based index (as compared to one based on heights observed at fixed latitudes) — in particular, the two peaks of activity in the eastern Pacific are clearly resolved in Fig. 6, but are not apparent in Fig. 2.

**Storm tracks**

The interaction between the blocking pattern and individual cyclones in the complex low pressure trough in the western Pacific is clearly shown in Fig. 7. These three thermal infrared images from consecutive orbits of a Defense Meteorological Satellite
Fig. 5  Hovmöller diagram of daily values of Gibson’s Blocking Index (B) for the period 30 June (Julian Day 181) to 1 August (Julian Day 213) 1994.

Fig. 6   Monthly mean values of Gibson’s Blocking Index - B (as a function of longitude) for the month of July 1994

Program (DMSP) satellite indicate that the waves consistently moved southwards towards the Antarctic coast. One of the vortices (A) was observed to move southeastwards at 20 m s⁻¹ (72 km/h; 38.9 kn) over three successive orbits on 11 July 1994 from approximately 1600 UTC to 1915 UTC.

During the 'special' re-analysis week from 22 to 28 July, blocking relocated to the western Pacific and strong pressure rises recorded on the automatic weather stations (AWSs) over the high plateau of Antarctica demonstrated that an intense ridge had extended across East Antarctica (Pook and Cowled, forthcoming). During this period, lows approaching the Australian sector from the west were observed to stall and move towards the Antarctic coast. On 27 July two vortices crossed the coast and moved rapidly inland over the high plateau (Fig. 8). At the same time, intense lows continued to move slowly eastwards through the Atlantic and Indian Ocean sectors of the Southern Ocean.
Fig. 7  DMSP thermal infrared imagery of a chain of vortices in the southwest Pacific Ocean on 11 July 1994 from successive orbits of satellite F10 at (a) approximately 1555 UTC, (b) 1735 UTC and, (c) 1915 UTC. Labels A and B identify vortices which moved rapidly southeastwards.

Fig. 8  DMSP images of cyclonic vortices over East Antarctica at approximately, (a) 2300 UTC 26 July 1994, (b) 0140 UTC 27 July 1994, and (c) 0220 UTC 27 July 1994.
Number of cyclones analysed in 2 x 30° latitude sectors during July 1994 in, the western Pacific between 150°W and 180°, and eastern Pacific, between 90°W and 120°W.

The number of vortices analysed on the FROST analysis set in the eastern and western sectors of the Pacific varied throughout the month of July as the influence of blocking changed (Fig. 9). The SOP-1 analyses provide clear evidence of the influence of atmospheric blocking on storm tracks in the Southern Ocean and an association between blocking events and the migration of lows across the Antarctic coast.

Discussion and concluding remarks

There is convincing evidence that an intense and persistent blocking episode occurred in the eastern Pacific during the initial phase of SOP-1. The latitude at which the surface and 500 hPa anticyclones became established was considerably further south than the latitude zone which has previously been associated with blocking in the southern hemisphere but is similar to that reported by Sinclair (1996). In this case, the mean displacement from the equator of the blocking events in the eastern Pacific was similar to that found in the northern hemisphere by Coughlan (1983). The location of the blocking activity in the eastern Pacific for a significant portion of the month confirms that this sector can be associated with extended blocking events. Persistent blocking in the eastern Pacific on this occasion was accompanied by the presence of an intense and complex low pressure system in the western Pacific to the north of the Ross Sea in Antarctica. Parish and Bromwich (1998) have demonstrated how a similar synoptic configuration in late June and early July of 1988 was associated with drainage of air from Antarctica through the Ross Sea resulting in pressure decreases of 20 hPa or more across a large portion of Antarctica.

This paper has demonstrated the capacity for blocking action to significantly distort storm tracks over the Southern Ocean and steer cyclones towards and, in some cases, over the Antarctic continent. As these systems provide a mechanism for the advection of relatively warm, moist air onto the Antarctic Plateau, blocking appears to be a major controlling influence on precipitation in the dry interior of the Antarctic. This result has significant implications for weather forecasting for activities on the Plateau and, as well, may be useful in determining the mass balance for particular regions of the continent. It also suggests that there may be possibilities for inferring previous circulation anomalies from palaeclimatic studies, including ice core analysis.

References


Rex, D.F. 1950b. Blocking action in the middle troposphere and its


