A GCM Study on the Maintenance of the June 1982 Blocking in the Southern Hemisphere

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ABSTRACT

General Circulation Model (GCM) experiments have been performed to determine mechanisms that maintained the blocking episode in the Australian–New Zealand region during the period 8–22 June 1982. A control forecast reproduces the persistent ridge. Several mechanistic experiments lead to the following conclusions: (i) The block was not due to orographic forcing, which has only a small local influence on the winter atmospheric circulation in the Southern Hemisphere. (ii) The block was not produced by the sea surface temperature anomalies (SST). By comparing the relative location of low-level atmospheric vorticity and SST anomalies, we are able to show that during June 1982 the atmospheric blocking was the cause of the SST anomalies in the Pacific. (iii) The block was not a response to tropical heating or the Asian Monsoon. There are only weak effects on the block when the tropical heating or heating in the Pacific region is suppressed. (iv) The most important boundary forcing maintaining this blocking ridge is heating associated with the land–sea contrast. The height fields are more zonally symmetric when the land–sea contrast is suppressed. The local land–sea contrast in the Australian region also contributed to maintain the stationary blocking ridge. The sensible heat release in the subantarctic region is an important mechanism that maintains the block. (v) Finally, the daily spectral energetics of the control experiment suggests that the baroclinic amplification of planetary-scale waves forced by synoptic-scale disturbances played an important role in the evolution of this blocking process.

1. Introduction

The forecast of the development, maintenance and breakdown of blocking events is an important problem. It is closely related to the skill with which medium range weather forecasts can be made. Various definitions of blocking have been used. Here, we will use the definition of Dole and Gordon (1983). It requires positive or negative anomalies at a given location exceeding a specific magnitude $M$ and persisting for at least $T$ days. For the winter season, criteria of 100 m and 10 days for 500 mb height anomalies are used to define a block in the Northern Hemisphere (NH). There have been many diagnostic studies on the preferred geographic locations, seasonal variation, life cycle and mechanisms of blocking in the Northern Hemisphere (Rex, 1950a,b; Dole and Gordon, 1983; Shukla and Mo, 1983; Collucci et al., 1981; and others).

In the Southern Hemisphere (SH), large positive or negative anomalies are less persistent than in the NH (van Loon, 1956; Trenberth and Mo, 1985). We will use 500 mb height anomaly criteria of 150 m and 6 days to define SH blocking. Using this criteria, we found that during the 1982 SH winter, pronounced blocking was experienced over the Australian and New Zealand region. During June 1982, the atmospheric circulation was quasi-stationary and dominated by planetary waves 3 and 4 in midlatitudes (Mo, 1985; Noar, 1983). A detailed description of the synoptic development of this block can be found in Noar (1983).

Compared to the numbers of diagnostic and observational papers, there are fewer documented numerical simulations of blocking events. Bengtsson (1981) used numerical models to investigate the predictability of a blocking episode as a function of model resolution and parameterization. Miyakoda et al. (1983) studied the predictability of a NH blocking event in January 1977 as a function of initial conditions and model characteristics. Noar (1983) studied the numerical modeling of the June 1982 blocking in the SH, but his emphasis was on comparing the performance of the model at the National Meteorological Analysis Center at Melbourne to the one at ECMWF rather than on the mechanisms that maintained the block. Ji and Tibaldi (1982) used the ECMWF model to study the mechanisms associated with the Atlantic blocking event of 17–30 December 1978. They found that the orographic forcing was an important factor in maintaining the block, whereas the land–sea contrast was not crucial for this case.

Various theoretical studies throw some light on the mechanisms responsible for the development of blocking. Charney and DeVore (1979) proposed a multiple
Fig. 1. 500 mb geopotential height for (a) 8 June, (b) 14 June and (c) 22 June 1982.
equilibrium theory while Tung and Lindzen (1979) favored a resonant-type mechanism. The local resonant response to orographic or other sources of stationary forcing can produce blocking (Kalnay and Merkine, 1981). Studies also suggest that the effect of the land–sea contrast cannot be ignored (White and Clark, 1975; Kikuchi, 1971). Sea surface temperature anomalies and diabatic heating are also often mentioned as elements important to the maintenance of blocking. Wave–wave interactions have been suggested as one of the possible causes of blocking by Egger (1978) and Wiin-Nielsen et al. (1963). Hansen and Chen (1982) calculated the spectral energetics of two blocking cases in the NH for the winter of 1978/79. They found that blocking developed downstream of intense intermediate or large-scale cyclogenesis and that it could be a result of the baroclinic amplification of planetary waves. A recent diagnostic study of Holopainen and Fortelius (1987) indicated that transient eddies with periods shorter than 6 days played an important role in maintaining the Atlantic block of 16–25 February 1979. Baines (1983) reviewed all possible mechanisms responsible for blockings in the Australian region. He concluded that the Australian region blocking is a local phenomenon rather than a hemispheric one. The possible mechanisms suggested by him are (i) baroclinic instability influenced by local topography or thermal forcing and (ii) a “modon” mechanism aided by thermal forcing associated with the SST patterns.

The purpose of this paper is to study several possible mechanisms associated with the maintenance of the June 1982 blocking in the Southern Hemisphere. We use the GLA Fourth-Order General Circulation Model (Kalnay et al., 1983) to perform a control 15-day forecast of the event. We then compute energy fluxes and the energy balance from both the NMC analysis and the model simulation in order to obtain some guidance as to which processes contributed to the maintenance of the blocking. A series of mechanistic experiments are then performed to assess the actual importance of several possible causes of the blocking.

Section 2 contains a brief description of the June 1982 blocking while section 3 describes the control experimental forecast. In section 4 we present the energy analysis and propose possible mechanisms for the maintenance of the block. In section 5 we discuss several mechanistic experiments in which we changed the orography, sea surface temperature (SST) anomalies, tropical heating, regional heating in the Pacific area, land–sea contrast, and sensible heating in the Antarctic region. Finally, section 6 contains a summary.

2. Observational evidence of the blocking situation of June 1982

June 1982 was characterized by long periods of intense blocking in the Australian–New Zealand region.
The major episodes and synoptic processes associated with this blocking have been described by Noar (1983).

The event began on 1 June 1982 with the intensification of a high near 50°S, 180°. On 2 June, another high intensified near Australia (42°S, 138°E). By 5 June, the ridge near 180° moved to the east while diminishing in strength. On 8 June, (Fig. 1a) the high reestablished itself in a location near 160°E. This type of blocking process was recognized by Wright (1974) and defined as displacement/replacement. The ridge near 160°E became stronger and reached maturity on 13 June. On 14 June (Fig. 1b) the 500 mb pattern had a classic split-flow blocking structure. The stable blocking flow pattern remained stationary for 10 days (8–18 June) and then slowly moved to the east, as shown in Fig. 1c.

We are interested in the maintenance of the blocking, so our discussions will be limited to the 15-day period 8 to 22 June. The mean 500 mb geopotential height field for that period is given in Fig. 2a. All of the data presented here and initial conditions for the model were derived from NMC analyses. However, we have compared this analysis with those of ECMWF and the Australian Bureau of Meteorology and found them to be in good agreement in the blocking region.

A strong blocking ridge dominated the mean circulation in the Australian–New Zealand region, at about 160°E. Weaker ridges were observed at 60°E, 30°W and about 80°W. A Fourier analysis (Table 1) indicates that, during this period, planetary waves 3 and 4 were very strong and were in phase at about the blocking region of 160°E. Planetary wave 2 was also in phase, but made a smaller contribution to the block.

A Hovmöller diagram (time–longitude cross section) for the 500 mb heights (Fig. 2b) shows the time behavior of the blocking ridge during the period of interest. The values plotted are the heights at 50°S minus 5400 m, which was the zonal mean of the height field at 50°S on 8 June 1982. The positive anomaly centered at 160°E is large and stationary for about 9 days. At the end of this period, the anomaly propagates very slowly to the east. Large negative anomalies appear at

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**Fig. 2a.** 15 day average 500 mb geopotential height for 8–22 June 1982 from NMC analysis. Contour interval is 60 m.

**Fig. 2b.** Hovmöller diagram of 500 mb heights minus 5400 m at 50°S for 8–22 June 1982 from NMC analysis. Contour interval is 60 m.
TABLE 1. Amplitudes and phases of first four harmonics at 50°S for the mean 500 mb heights for various experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Amplitudes (m)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Climatology</td>
<td>74</td>
<td>20</td>
</tr>
<tr>
<td>NMC analysis</td>
<td>40.3</td>
<td>35.1</td>
</tr>
<tr>
<td>Control</td>
<td>29.7</td>
<td>45.1</td>
</tr>
<tr>
<td>No mountain, SST of 1982</td>
<td>32.1</td>
<td>37.2</td>
</tr>
<tr>
<td>Reduced tropical heating</td>
<td>43.6</td>
<td>30.9</td>
</tr>
<tr>
<td>No land–sea contrast</td>
<td>63.2</td>
<td>42.8</td>
</tr>
<tr>
<td>No sensible heat near Antarctica</td>
<td>60.8</td>
<td>48.1</td>
</tr>
<tr>
<td>No Australia</td>
<td>46.0</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>26.7</td>
<td>18.7</td>
</tr>
</tbody>
</table>

both sides of the positive anomalies in a typical blocking pattern. A large positive anomaly also occurs at 80°W and persists for 7 days at the end of the period. A strong positive anomaly is located at 80°E at the start of the period, but it propagates quickly eastward and weakens after 4 days.

Figure 3 presents the 15-day averaged zonal wind velocity at the 200 mb level. The easterlies in the tropics are weaker (maximum 16 m s\(^{-1}\)) than shown in the climatology (maximum 25 m s\(^{-1}\)) given by Newell et al. (1972). The westerlies at middle and high latitudes in the SH are much stronger. The jet in the Australian region is about 15 m s\(^{-1}\) stronger than the climatology and is split with a secondary maximum at high latitudes, also typical of a blocking pattern. A strong secondary maximum appears at 50°S, 60°E.

3. Control forecast

In this section, we compare a 15-day control forecast started on 8 June 1982 with observations.

The forecast was performed using the GLA Fourth-Order General Circulation Model (GCM) as documented in Kalnay et al. (1983), which has a resolution of 4° latitude, 5° longitude and 9 vertical levels. The rather coarse resolution is partially compensated by the use of fourth order horizontal differences, so that the model has a short-range forecast skill comparable to that of models of much finer resolution, with 500 mb anomaly correlations remaining above 0.6 for over 5 days in the NH and about 4 days in the SH winter forecasts (e.g., Kalnay et al., 1986a; Baker et al., 1984). The model parameterization of subgrid-scale physical
processes is described in detail in Kalnay et al. (1983) and includes longwave and shortwave radiation with a diurnal cycle, a bulk parameterization of surface fluxes, large-scale supersaturation precipitation, a three-level convective cloud parameterization and cloud radiation interaction. (The climatology of the model is presented in Kalnay et al., 1986b.) In our control forecast, climatological boundary conditions (sea surface temperature, albedo, snow and ice cover, and soil moisture) were used.

Figures 4a and 4b present respectively the 15-day average of the 500 mb height forecast and the corresponding Hovmöller diagram. The model succeeds well in predicting the presence of the blocking ridge at 160°E. Both waves 3 and 4 are strong and they are in phase at the location of the blocking ridge (Table 1). The stationarity of strong positive anomalies at 160°E with strong persistent negative anomalies on both sides is also apparent. At the end of the period, the blocking ridge is somewhat weaker but more stable than was observed and it is slower moving to the east. Two major forecast deficiencies are the overestimation of the intensity of the high near South America at 60°S, 80°W and the lack of ridging in the southern Indian Ocean. In addition, there is a weakening of about 20%–25% in the amplitude of the waves in the course of the forecast.

The 15-day average of the zonal wind field at 200 mb is given in Fig. 5. The easterlies in the tropics over the eastern hemisphere are reproduced well, as is the location of the Australian jet. However, the split jet is somewhat stronger than observed. Figure 6 presents the 15-day average precipitation, with maxima in the South Pacific Convergence Zone, the latitude band from 40° to 50°S, and especially south and east of Australia.

The results have little dependence on the particular initial condition used. A 14-day forecast started on 9 June 1982 resulted in a very similar forecast of the blocking ridge. This ridge, however, is not a characteristic of the model winter integrations. Figure 7 shows the 500 mb heights of the model's climatology, obtained as the average of three 30-day forecasts with three different initial conditions: 15 June 1979, 15 June

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**FIG. 4.** As in Fig. 2 but for the control experiment.
1980 and 15 June 1982. The flow pattern in the SH is very zonal with no blocking ridge in the Australian–New Zealand region.

4. Diagnostic analysis

In this section we perform simple diagnostic analyses attempting to gain some understanding of the mechanisms at work in the maintenance of the block of June 1982.

a. Three-dimensional stationary wave Eliassen–Palm fluxes

Plumb (1985) has recently defined a generalization of the Eliassen–Palm (E–P) fluxes applicable to quasi-

![Figure 5](image)

**Fig. 5.** As in Fig. 3 but for the control experiment.

![Figure 6](image)

**Fig. 6.** Average precipitation rate for the control experiment. Units are mm day$^{-1}$. Values greater than 10 mm day$^{-1}$ are shaded.
geostrophic stationary flow. According to Plumb, the vector
\[
F = p \cos \phi \left[ \bar{\sigma} - \frac{1}{2(\Omega a \sin 2\phi)} \frac{\partial (\bar{v} \bar{\Phi}')}{\partial \lambda} - \bar{u}' \bar{v}' \\
+ \frac{1}{2(\Omega a \sin 2\phi)} \frac{\partial (\bar{u} \bar{\Phi}')}{\partial \lambda}, 2\Omega \sin \phi / S \\
\times (\bar{u}' \bar{T}' - \frac{1}{2(\Omega a \sin 2\phi)} \frac{\partial (\bar{T} \bar{\Phi}')}{\partial \lambda}) \right]
\]
has the property of being parallel to the group velocity. Its divergence in regions of westerly flow indicates export of wave activity, presumably due to a source of stationary forcing. Here (') denotes departure from the zonal mean, (\bar{\cdot}) denotes the 15-day time average, \(T\) is temperature, \(P\) is pressure, \(u, v\) are the components of the horizontal wind vector, \(\Phi\) is the geopotential.

**Fig. 7.** 500 mb heights for the model’s climatology. Contour interval is 60 m.

**Fig. 8.** E–P flux vectors \(F\) for the period 8–22 June 1982 at (a) 300 and (b) 700 mb. Arrows represent horizontal components. The scale factor for the vector is \(2 \times 10^3\) J m\(^{-2}\) for 300 mb and \(4 \times 10^3\) J m\(^{-2}\) for 700 mb. Contours are plotted for vertical component; contour interval is 10 J m\(^{-2}\) for 300 mb and 20 J m\(^{-2}\) for 700 mb. Negative values are shaded.
height, $\phi$ and $\lambda$ are latitude and longitude, $\Omega$ is the Earth's angular velocity, and $S$ is the standard lapse rate (6.5 K km$^{-1}$).

Figure 8a presents the three-dimensional (3-D) E–P flux vectors derived from the analysis at 300 mb, and Fig. 8b the corresponding vectors at 700 mb. Unfortunately, as was the case in the results presented by Plumb (1985), the 3-D E–P flux vectors are more helpful in pinpointing the regions of strong stationary wave energy activity than in indicating their source. At 300 mb the largest horizontal fluxes (indicated by the length of the vectors) are observed in the central Pacific, southern South America and southeast of southern Africa, and in each case the maximum occurs east of a stationary trough. In all these regions, as Plumb observed in the Northern Hemisphere, there is a flux of energy toward the tropics. The only exception is in our region of interest, where the blocking high is associated with a split in the 3-D E–P flux vectors, and there is an indication of horizontal convergence of energy from the tropics.

It is interesting to compare the direction of the vertical fluxes at 300 and 700 mb (Figs. 8a and 8b). At both levels the fluxes tend to be strongly upward in the regions of intense precipitation (Fig. 6)—the South Pacific Convergence Zone (SPCZ), southeast of Africa and south of Australia near 50°S. Only in the blocking region do we see a strong change in sign in the vertical fluxes, with generally upward fluxes at low levels and downward fluxes at upper levels, suggesting that there is also vertical convergence of energy into the blocking high.

In the control forecast, as in the analysis, we observe horizontal fluxes from the tropics toward the blocking

<table>
<thead>
<tr>
<th>Wave</th>
<th>$K(n)$</th>
<th>$P(n)$</th>
<th>$C(n)$</th>
<th>$M(n)$</th>
<th>$R(n)$</th>
<th>$L(n)$</th>
<th>$S(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zonal</td>
<td>132.6</td>
<td>150.3</td>
<td>-25.1</td>
<td></td>
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<table>
<thead>
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<th>Wave</th>
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<th>$P(n)$</th>
<th>$C(n)$</th>
<th>$M(n)$</th>
<th>$R(n)$</th>
<th>$L(n)$</th>
<th>$S(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zonal</td>
<td>180</td>
<td>294.7</td>
<td>-58.6</td>
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**Control run**

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<th>$P(n)$</th>
<th>$C(n)$</th>
<th>$M(n)$</th>
<th>$R(n)$</th>
<th>$L(n)$</th>
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**No land-sea contrast experiment**

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<thead>
<tr>
<th>Wave</th>
<th>$K(n)$</th>
<th>$P(n)$</th>
<th>$C(n)$</th>
<th>$M(n)$</th>
<th>$R(n)$</th>
<th>$L(n)$</th>
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</table>
high at 300 mb (Fig. 9) and even stronger downward fluxes in the region of blocking. A comparison with 700 mb (not shown) also indicates vertical convergence. However, in other regions where the model has not reproduced the stationary waves as well, the agreement between the analysis and forecasted 3-D E–P fluxes is much worse.

Although not absolutely clear, the 3-D E–P fluxes provide some evidence that orographic forcing plays a minor role. The only region with orography where we see significant upward fluxes at low levels is over the southern Andes. Over parts of South America, southern Africa and its surrounding cold waters, where the model predicts minimum surface fluxes of sensible and latent heat, there is a tendency to have negative (downward) vertical E–P fluxes. At high latitudes, there is poleward energy propagation at both levels, suggesting that the Antarctic topography may not be a source of wave activity (Hartman et al., 1984). At 700 mb, near the block over the Antarctic region, fluxes are downward over

Fig. 10. Temporal evolution of the vertical integrated energy conversions for 42° to 58°S for 8–22 June 1983. The left panel shows the evolution for synoptic-scale waves (dashed line). The right panel shows the evolution $R(P_z, P_\lambda)$ for long waves (solid line) and $R(P_z, P_x, \lambda)$ for synoptic waves (dashed line). Units are $10^{-2}$ W m$^{-2}$.

Fig. 11. As in Fig. 2a but for the “no mountains” experiment.
the land but upward over the oceans. This suggests that cold air outbreaks from Antarctica may result in strong sensible and latent fluxes heat, which may be associated with maintenance of the block. Maximum upward fluxes tend to occur east of the cold continents, where the most intense surface fluxes of heat and moisture can be expected, as well as in regions of intense precipitation. All these observations suggest that thermal forcing associated with either land–sea contrast or release of latent and sensible heating dominates the stationary forcing in the Southern Hemisphere winter.

b. Spectral energy transfers

We have seen that during this period the stationary wave pattern was dominated by unusually strong amplitudes of zonal wavenumbers 3 and 4. In order to gain some insight into the processes that gave rise to these waves, we turn now to the spectral energy analysis derived by Saltzman (1970), following the computational procedures of Baker et al. (1977). The energy analysis was performed for the 15-day average of all the atmospheric parameters. In these calculations all terms were averaged over a latitude band from 42° to 58°S and integrated vertically from 100 to 1000 mb.

Table 2 lists for the zonal mean and for each wavenumber \( n \) up to 6, \( K(n) \), the kinetic energy; \( P(n) \), the available potential energy; \( C(n) \), the conversion of \( P(n) \) to \( K(n) \); \( M(n) \), the conversion of \( K(n) \) to zonal mean kinetic energy \( K_z \); \( R(n) \), the conversion of zonal mean available potential energy \( P_z \) to \( K(n) \); \( L(n) \), the rate of transfer of eddy kinetic energy from all other wavenumbers to \( K(n) \); and \( S(n) \), the rate of transfer of eddy available potential energy from all other waves to \( P(n) \). Due to the lack of observations over the Southern Hemisphere, the climatology of the energy cycle is not available. van Loon and Jenne (1972) studied the stationary waves and they found that in midlatitudes, wavenumbers 1 to 3 contain 99% of the variance of the annual mean and wavenumber 1 is the most dominant wave in the Southern Hemisphere.

The first four waves have large eddy kinetic and

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**Fig. 12.** As in Fig. 2 but for the SST of June 1982.
available potential energy, but waves 3 and 4 dominate the baroclinic conversion terms \( C(n) \) and \( R(n) \). The dominant terms in the energy cycle during this blocking period can be summarized schematically as

\[
P_z^{24} \rightarrow P(4) \rightarrow K(4)
\]

where the numbers on top of the arrows are rates of energy transfer \((10^{-2} \text{ W m}^{-2})\).

To examine the importance of possible wave–wave interactions, we calculated the rate of transfer of kinetic and potential energy from wavenumber \( m \) to wave-number \( n \), respectively. Again, we will represent schematically the dominant terms, as obtained in the detailed calculations (not shown)

\[
K(3) \rightarrow 10.7 \rightarrow K(4) \rightarrow 5.1 \rightarrow K(1) \rightarrow 26.3 \rightarrow K(2)
\]

\[
P(3) \rightarrow 5.2 \rightarrow P(4) \rightarrow 9.4 \rightarrow P(1) \rightarrow 6.7 \rightarrow P(2) \rightarrow 3.5 \rightarrow P(1) \rightarrow 4.1 \rightarrow P(2)
\]

The largest transfer of kinetic energy is from wave 1 to wave 2, which gives large \( L(1) \) and \( L(2) \) but opposite sign. All four waves are involved in the transfer of available potential energy. There is no apparent significant transfer of energy between waves 3 and 4.

This analysis suggests that during this period baroclinic processes were important in the quasi-stationary waves 3 and 4, and that there were significant energy transfers between those waves and zonal wavenumber 1. However, since the results are based on the 15-day averaged fields, they do not give any information about

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Fig. 13. (a) 850 mb relative vorticity averaged over 8–22 June 1982. Contour interval is \( 8 \times 10^{-5} \text{ s}^{-1} \). Negative values are shaded. (b) Sea surface temperature anomalies of 22 June 1982. Contour interval is 0.5 K. Negative values are shaded.

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Fig. 14. Schematic diagram of the relationship between slowly varying SST anomalies and the anomalous low-level atmospheric vorticity. Left panels: The atmospheric circulation anomaly drives the SST anomaly. Right panels: The SST anomaly produces the atmospheric anomaly. Top panels: Horizontal advection neglected. Bottom panels: Effect of horizontal advection.
interaction between transient, shorter waves and those planetary waves.

In order to study the energy associated with transient waves, we computed on a daily basis the energy transfers in the latitude band of 42° to 50°S, integrated from 100 and 1000 mb. Figure 10 shows the baroclinic conversion terms $R = P_z \rightarrow P(n)$ and $C = P(n) \rightarrow K(n)$ separated into ultralong waves ($n = 1$ to 4) and synoptic-scale waves ($n = 5$ to 10). It shows that during 8 to 18 June, when the block was steady and strong, shorter baroclinic waves were dominant.

From 18 to 22 June, on the other hand, when the block started to move and decay, the short baroclinic waves were less important in the energy cycle than ultralong waves. This result is not inconsistent with the view that transient baroclinic waves may contribute to the maintenance of blocking, but a more definitive answer would require a three-dimensional analysis similar to that of Holopainen and Fortelius (1987).

5. Mechanistic experiments

In this section we present the results of experimental model integrations designed to test the importance of several possible mechanisms discussed before.

a. "No mountains" experiment

In the SH, the highest mountains are located in South America and southern Africa, both far away from Australia. We have seen from the E-P fluxes of the previous section that orographic forcing may not be important. To test this, we performed a forecast from the same initial condition but eliminated orographic forcing everywhere in the globe. The 15-day average of 500 mb heights for the "no mountains" run is shown in Fig. 11, which should be compared with the control forecast (Fig. 4a). The major changes are in the heating and precipitation fields. The diabatic

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**Fig. 15.** As in Fig. 2 but for the "reduced tropical heating" experiment.
heating and rainfall over the Amazon, Indonesia, central and eastern China are weaker. The Australian jet also decreases in magnitude from 66 to 58 m s\(^{-1}\). In the SH, the differences of flow patterns between two runs are small and the blocking ridge in the Australian–New Zealand region is not affected much. Waves 3 and 4 are still strong and in phase at 160°E. The only significant change occurs near the Andes, with a westward shift of the original lee trough and an enhancement of the ridge (at 30°W) downstream of the Andes. The flow pattern still shows a blocking pattern near the Antarctic peninsula.

As expected, we conclude that orographic forcing is weak and does not contribute to the maintenance of the observed blocking ridge.

b. "Observed June 1982 SST" experiment

In this section, we will assess the role of sea surface and temperature anomalies. We performed a forecast from the same initial condition but using the sea surface temperature of June 1982 instead of the June climatology. The monthly mean SST data were obtained from the NOAA Climate Analysis Center.

Overall, the forecast shows only slight improvements. The 15-day averaged 500 mb heights and the corresponding Hovmöller diagram at 50°S are given in Figs. 12a and 12b, respectively. The flow patterns near the Australian–New Zealand region change very little. In the Southern Hemisphere, there is a significant improvement only in the southern Indian Ocean ridge, which was one of the major deficiencies in the original forecast. Waves 3 and 4 are strong and again in phase. The movement of the block at the end of the period is faster and in better agreement with the observations.

In order to understand why the SST anomalies have not contributed to the maintenance of the Australian–New Zealand blocking, we examine the low-level time-averaged relative vorticity field (Fig. 13a). The presence of the anomalous blocking is very apparent; there is an anticyclonic center south of New Zealand, with a cyclonic center to the north. As was observed in the 500 mb maps, there are stationary cyclonic circulations east and west of the blocking high. The corresponding observed SST anomalies are presented in Fig. 13b. As discussed by Kalnay et al. (1985), the fact that there is a clear correlation between low-level cyclonic vorticity and cold SST anomalies (both shaded) indicates that the SST anomalies were a result of the anomalous quasi-stationary atmospheric circulation. This is because in regions of cyclonic vorticity, where the atmosphere rotates faster than the ocean, the surface stress produces horizontal divergence and cold Ekman upwelling in the ocean (Fig. 14, top left). On the other hand, if the oceanic surface temperature anomalies were driving the atmosphere, one would expect warm SST anomalies to be associated with upward motion and low-level atmospheric cyclonic circulation (Fig. 14, top right).

This argument is strictly valid in tropical regions, where the effects of horizontal advection are negligible. In midlatitudes, as discussed by Hoskins and Karoly.

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![Diagram](image_url)

**FIG. 16.** As in Fig. 3 but for the "reduced tropical heating" experiment.
(1981), if the SST anomalies are driving the atmosphere, there will be a shift of the cyclonic center to the west of the cold SST so that the meridional atmospheric transport of heat opposes the surface heating (Fig. 14, bottom right). Even here, however, it is still possible to detect when the atmosphere drives the ocean, since the horizontal advection of SST by the wind-driven surface currents results in a cyclonic center to the east of the cold water (Fig. 14, bottom left). Such a shift is clearly observed in Fig. 13 south of 30°S, confirming that the atmospheric anomalous circulation is producing the SST anomalies, which therefore do not affect the blocking pattern much.

c. "Reduced tropical heating" experiment

We have ruled out the orographic forcing and SST anomalies as possible causes of the maintenance of the block. Now we are going to study the influence of diabatic heating. In section 4 we showed some evidence of energy fluxes from the tropics near the blocking region. In order to test the importance of this source of diabatic heating, we made a 15-day run strongly suppressing tropical heating by reducing the coefficient of latent heat by a factor of 10 between 20°S and 20°N for all longitudes.

The 15-day averaged forecast of 500 mb heights and the corresponding Hovmöller diagram are given in Fig. 15a and Fig. 15b, respectively. There is very little change in the extratropical height field. The block is not affected, and waves 3 and 4 are still strong and in phase.

The major differences between this run and the control run appear in the upper level zonal wind field. The zonal wind field at the 200 mb level is plotted in Fig. 16. The easterlies cover most of the tropical region, and they are twice as strong for the reduced tropical heating experiment. The westerlies in the midlatitudes are considerably weakened, as could be expected from a reduced Hadley circulation. The locations of maxima of jet in the SH are unchanged, but the maximum over the Australian region reduces to 49 m s⁻¹ compared.

**Fig. 17.** As in Fig. 2 but for the “no land–sea contrast” experiment.
to 66 m s⁻¹ in the control run. Since even in the presence of these significant changes in the subtropical jet the Australian–New Zealand blocking persists, we can conclude that it is not associated with tropical heating and that the upper level jet in the Australian region has no influence on the maintenance of the block.

In a similar experiment we suppressed the heating in the Pacific region between 120°E and 150°W for all latitudes by reducing the coefficient of latent heat of condensation to one-tenth of its original value. The jet in the Australian region is significantly reduced in magnitude but the block in the Australian–New Zealand region remains.

d. "No land–sea contrast" experiment

The blocking ridge is not maintained by orographic forcing, SST anomalies or tropical heating. We per-
formed an experiment to study the influence of the distribution of oceans and continents since the diagnostic study in section 4 suggests that the distribution plays an important role in maintaining the block.

In order to eliminate zonally asymmetric heating associated with land–sea contrast, we treated all ocean and land points as saturated land points. In this experiment, we still keep the orographic forcing. The initial ground temperatures are given as the zonal average of the given latitude, except over elevated terrain where the temperature decreases with a constant lapse rate. Figures 17a and 17b depict the 15-day average of 500 mb height field and its corresponding Hovmöller diagram, respectively. Although the four planetary waves in the midlatitudes are still strong, they are no longer in phase (Table 1) and the blocking is almost entirely gone. The Hovmöller diagram indicates that even the weak ridge present is only a residual from the initial condition.

The major changes are in the temperature and precipitation fields. There is an increase in the meridional temperature gradient because of the absence of the moderating influence of the oceans.

Figure 18 shows the 15-day averaged total precipitation rate. A comparison with the control run (Fig. 6) indicates that the precipitation is more uniformly distributed in the tropics and sub-tropics, except near the Himalayas where orographic effects intensify the rainfall. There are only small changes in the upper level zonal wind field (Fig. 19), $U_{200}$. The middle latitude jet is still located in the Australian region and has same intensity as in the control run.

In Table 2 we present the energetics that are strongly dominated by wavenumber 1. Wavenumbers 3 and 4 have a much weaker baroclinic transfer than in the control run. Again, we can write the dominant terms in the energy cycle schematically as

$$P_2 \rightarrow P(1) \rightarrow K(1) \rightarrow K_2.$$ 

This suggests that the atmospheric circulations in the midlatitude of the SH are dominated by interactions

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**Fig. 20.** As in Fig. 2 but for the “no Australia” experiment.
between wave 1 and zonal flow when the land–sea contrast is suppressed. The wave 1 forcing is probably due to the asymmetric tropical precipitation and to the orography of Antarctica, which has a strong wavenumber 1 component.

e. "No Australia" run

We have seen that land–sea contrast is a necessary factor in the maintenance of blocking in the Australian–New Zealand region. In this section, we will study whether the local land–sea contrast has a strong influence upon the block. We eliminated the presence of land by replacing Australia and New Zealand by ocean with sea surface temperatures extrapolated from the boundaries. Figures 20a and 20b show the 15-day average of 500 mb height and its corresponding Hovmöller diagram. The positive anomalies are considerably weakened compared to the control; they are no longer stationary and move slowly to the east. Figure 20a shows that the ridge is shifted to 180°. Elsewhere, the atmospheric circulation changes little. We conclude that the local heating has considerable influence on the blocking but that its absence does not change the hemispheric circulation patterns significantly elsewhere.

f. "No sensible heat near Antarctica" experiment

The strong upward E–P fluxes over the Southern Ocean near Australia suggested that sensible heating associated with cold air outbreaks from Antarctica could also provide forcing to the block. In order to test this possibility, we suppressed the high-latitude surface fluxes of sensible heat, from 0° to 180° and from 50° to 90°S. Figures 21a and 21b show the 15-day average of 500 mb height for this experiment and its corresponding Hovmöller diagram. The block is much weaker, lasting only about 5 days before collapsing. Since wave 3 is due to the effect of land–sea contrast it remains very strong (Table 1). The other major changes occur at lower levels. For example, the temperature differences between midlatitudes (60°–50°S)

![Diagram of 500 mb geopotential height](image)

**Fig. 21.** As in Fig. 2 but for the "no sensible heat" experiment.
to the pole are about 10 K smaller than the control forecast. The 15-day mean sea level pressure shows that as the polar low situated at 60°S, 90°E deepens, its value drops from 988 mb (control) to 966 mb. This generates larger pressure gradients near Antarctica and strengthens the polar jet. At 850 mb level the polar jet increases from 17 to 27 m s⁻¹. We conclude that the sensible heat resulting from cold air from Antarctica contributes to maintaining the block.

5. Conclusions

During June 1982, a blocking ridge in the Australian–New Zealand region persisted for 15 days. During the period of 8–22 June, planetary waves 3 and 4 were unusually strong, and they were locked in phase at 160°E, where the ridge was located.

Through the use of the GLA fourth-order GCM and diagnostic analysis, we have attempted to determine the mechanisms that maintained the block.

In our “no mountain” experiment, we have shown that orographic forcing has no influence on this block. The precipitation drops in the tropics and the flow pattern near the Andes change, but the block stays strong. This also suggests that the forcing is fairly local. The block has no direct linkage to events near South America.

We show that the block was not produced by SST anomalies. There is a positive correlation between the 850 mb relative vorticity and SST anomalies in the Pacific, showing that the SST anomalies are produced by atmospheric circulations. In addition, we show that the phase shift between cyclonic vorticity and cold SST associated with horizontal advection also implies that the atmospheric anomalies are the cause and not the effect of SST anomalies. Our “SST of 1982” experiment confirms this argument.

In the “no tropical heating” experiment, substantial changes occur in the wind field in the tropics and near Australia, but the block is not changed. This also confirms the suggestion by Baines (1983) that the blocking near Australia is not due to hemispheric resonance of forced Rossby waves because it is a smaller scale phenomenon.

The “no land–sea contrast” experiment leads us to conclude that asymmetric heating due to land–sea contrast is the most important boundary forcing associated with the maintenance of the block. The “no Australia” experiment confirms this result and suggests that local land–sea contrast keeps the block stationary. High-latitude sensible heating associated with cold air outbreaks from Antarctica are also important in maintaining the block.

Energy transfer calculations suggest that short transient waves may have contributed to the maintenance of the block. This possibility will be further investigated using the methodology developed by Holopainen and Fortelius (1987).

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