The Local Balances of Vorticity and Heat for Blocking Anticyclones in a Spectral General Circulation Model

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ABSTRACT

Blocking anticyclones that appear in perpetual January simulations of a spectral general circulation model are examined. Blocks in three geographical regions are studied: the North Pacific, the North Atlantic and western North America. Local time-averaged balances of vorticity and heat are evaluated for composite cases of blocking. The following common relationships emerged from these budgets.

The time-mean divergence term is, in general, a first-order term in the vorticity balance throughout the troposphere and its pattern over severe orography is closely related to the underlying topography. Above the surface layer, the horizontal advection of time-mean absolute vorticity by the mean wind mainly balances the divergence term with the net effect of the time-mean vorticity forcing being a tendency for the blocking pattern to propagate downstream. The transient eddy vorticity transports act to shift the block upstream and hence they mainly offset the downstream tendency due to the time-mean flow; the magnitude of the eddy vorticity term is typically one-third to one-half that of the divergence or advection terms alone. Frictional dissipation is negligible everywhere except near the ground where it primarily offsets the divergence term.

The horizontal advection of the time-mean temperature field by the mean wind throughout the troposphere is a first-order term in the heat balance and is mainly responsible for maintaining the block's thermal perturbations; it is predominately balanced by adiabatic heating in the free troposphere and by diabatic heating near the surface. Transient eddy heat transports act to dissipate the block's thermal perturbations at all levels, while diabatic heating does not exhibit a systematic relationship with the temperature field at any level.

A quasi-geostrophic diagnosis of the ageostrophic motion field suggests that dynamical processes which strongly affect the vorticity balance may be more important to the maintenance of model blocks than processes which strongly affect the heat balance. The mountains appear capable of influencing the shape of the model blocks, but preliminary results indicate that orographic forcing may not be absolutely essential for the blocking process to occur in the model.

1. Introduction

Blocking is a situation in which the normal eastward progression of migrating midlatitude weather systems is disrupted—or "blocked"—by the development of a high-amplitude, quasi-stationary anticyclone (Huschke, 1959). Known as a blocking ridge or a block, such an anticyclone extends through the depth of the troposphere and typically persists for a week or longer. Because of their long duration and their effect on the movement of synoptic systems, blocks can cause temperatures and precipitation to deviate significantly from their normal patterns. The winter of 1976/77, which in the United States was characterized by record cold in the East and widespread drought in the West (e.g., Edmon, 1980), and December 1983, which in the 48 conterminous United States was the coldest December on record (Quiroz, 1984), featured strong blocking ridges over the West Coast of North America and over Alaska, respectively. These periods provide good examples of the serious economic and social hardships that can be attributed to long-lived intense episodes of blocking and point to the need for better understanding of the blocking phenomenon.

Many observational studies on blocking exist in the literature. Blocking was first noted by Garrett (1904). The implementation of the upper air radiosonde network allowed later researchers to document extensively the climatology and synoptic behavior of blocking (e.g., Namias, 1947; Berggren et al., 1949; Elliot and Smith, 1949; Rex, 1950a,b, 1951; Brezowsky et al., 1951; Sumner, 1954); these early investigations established that blocking in the wintertime Northern Hemisphere primarily occurs over the North Atlantic and North Pacific oceans. More recently, several diagnostic studies of blocking have been conducted (e.g., Sarijarvi, 1977; Hartmann and Ghan, 1980; Colucci et al., 1981; Dole, 1982, 1983; Hanson and Chen, 1982; Hansen and Sutera, 1984; Illari and Marshall, 1983; and Illari, 1984) and the objective identification of blocking events has been shown to be feasible (e.g., Hartmann and Ghan, 1980; Dole and Gordon, 1983; Shukla and Mo, 1983; Lejenas and Okaand, 1983; Knox, 1984).

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Over the years, many theories have been proposed to explain blocking. The early tentative theories considered blocking to be a barotropic process (e.g., Yeh, 1949). In the past decade, a number of other potential mechanisms have been put forward to explain different aspects of blocking. Such concepts as multiple equilibria of atmospheric flows (e.g., Charney and de Vore, 1979; Kallen, 1982), hemispheric resonance of forced Rossby waves (e.g., Tung and Lindzen, 1979), local resonance of forced Rossby lee waves (e.g., Kalnay-Rivas and Merkine, 1981), nonlinear interaction of forced waves and traveling free waves (e.g., Egger, 1978), solitary Rossby waves (e.g., McWilliams, 1980), superposition of forced Rossby waves that have propagated long distances from the tropics (e.g., Karoly, 1983), baroclinic instability of atmospheric flows (e.g., Frederiksen, 1982) and forcing by the cyclone-scale transient eddies (e.g., Austin, 1980) have been proposed as possible explanations of blocking. (A detailed review of blocking mechanisms is beyond the scope of this paper. A good summary of theories that have been recently proposed to account for blocking is given by Baines, 1983.) Even though a large number of plausible mechanisms have been proposed to account for blocking, there is still no generally accepted theoretical explanation for the phenomenon. Hence the need exists for further diagnostic studies to constrain theories.

Remarkably absent from the literature are studies which utilize general circulation models (GCMs) to investigate blocking. According to Knox (1981), this is because previous generations of GCMs proved themselves unable to simulate blocking events with the frequency, persistence, and amplitude of those observed in the real atmosphere. Blackmon and Lau (1980) also commented that the lack of energy at the larger scales and low frequencies which characterize blocking were a major shortcoming of the previous generation of GCMs.

There is increasing evidence, however, that the newest generation of GCMs is able to simulate blocking ridges. Lau (1983) described an outstanding blocking episode that occurred in a 15-year simulation of a GFDL GCM. Chen and Shukla (1983) also reported a blocking event, albeit a rather weak one, that happened in a simulation with a GLAS GCM. On a similar note, several recent forecast experiments (e.g., Bengtsson, 1981; Miyakoda et al., 1983; Tibaldi and Ji, 1983; Tibaldi and Buzzi, 1983; Ji and Tibaldi, 1983) have shown that complex numerical models are capable of reproducing many salient features of blocking ridges.

In a companion paper, Blackmon et al. (1986) compared the climatology, structure and synoptic behavior of blocking in the Northern Hemisphere for a 1200-day perpetual January simulation of the NCAR Community Climate Model (CCM) with that for the earth's atmosphere. In general, a high degree of similarity was found in the blocking characteristics of the model and real atmospheres. The close resemblance between simulated and observed blocks found by Blackmon et al. (1986) suggests that the CCM can be used in quantitative studies of the phenomenon.

There are major advantages in using output from a GCM that reproduces blocking in a realistic manner rather than having to rely entirely upon observational data sets for diagnostic studies of blocking. First, model output is internally self-consistent and the distributions of all model fields are precisely known. For real data, some fields (e.g., divergence, vertical velocity, diabatic heating) are very unreliable or have to be estimated from balance requirements. Second, the sample size for a GCM is potentially much larger than that for observations. In this study, 12 000 days of model output are examined for blocking events. This represents almost an order of magnitude greater sample size than the amount of objectively analyzed upper-air data currently available for the Northern Hemisphere winter (Dec, Jan, Feb) from the National Meteorological Center (NMC). With the model, several realizations of a particular block type in a particular region are more likely to occur and more confidence can be given to statistical results. Lastly, sensitivity experiments can be conducted with a GCM.

In this paper, vorticity and heat budgets for a composite blocking ridge which occurs in a particular region are computed and compared with those that occur in different locations. Blocking in three regions is investigated: the North Atlantic (ATLS), the North Pacific (PACS), and the West Coast of North America (WNAS). In this manner, we hope to isolate those dynamical features that are common to all cases of model blocking from those that are only particular to model blocking in certain regions.

The structure of this paper is as follows. A brief summary of the CCM, its performance characteristics and the various simulations analyzed in this study is contained in section 2. Analysis procedures are described in section 3. In section 4, the local balances of heat and vorticity for model blocking composites are evaluated and results for the model viewed in light of some simple theories that have been proposed to account for blocking. Section 5 concludes the paper with a summary.

2. Model summary

a. Description

The CCM is a sigma-coordinate, spectral model. The model has nine vertical levels ($\sigma = 0.991, 0.926, 0.811, 0.664, 0.500, 0.336, 0.189, 0.074, 0.009$; where $\sigma = p/p^*$, $p$ is pressure and $p^*$ surface pressure). At each level the dependent variables are represented as a sum of spherical harmonics with a rhomboidal truncation at wavenumber 15. The vertical component of vorticity and divergence serve as prognostic variables for the horizontal wind field. The continuity equation and
predictive equations for temperature and water vapor mixing ratio complete the system of prognostic equations. There are 40 Gaussian latitudes between the poles and 48 grid points in longitude, which gives a latitudinal resolution of approximately 4.4° and a longitudinal resolution of 7.5°. A semi-implicitly time scheme is used with a time step of 30 minutes.

The CCM includes the following parameterized physical processes: convective and stable precipitation; fluxes of sensible and latent heat; clear-sky radiative transfer due to shortwave and longwave components; and interactions with subgrid scale motions through diffusion. Clouds are formed in the model interactively and can be either of the convective or nonconvective type. They are allowed in all levels except the lowest one (σ = 0.991) and the top three (σ = 0.189, 0.074, 0.009). If the relative humidity exceeds 80%, clouds are formed and the moisture in excess of 80% is precipitated without evaporation of the condensate in the intervening layers.

Sea surface temperature (SST) and sea ice distribution are held constant and are set to their observed January values, with the possibility of SST anomalies also being superimposed upon the climatological SST field (see section 2c). The solar zenith angle is held constant and is set to its observed mid-January value. The model also includes a spectrally analyzed representation of the earth's topography.

For further details on the model's formulation and history, see Pitcher et al. (1983), Williamson (1983), Ramanathan et al. (1983), McAvaney et al. (1978), Bourke (1974), and references contained within these articles.

b. Performance

Pitcher et al. (1983) have described the results of January and July simulations carried out by the version of the CCM used in this study. They find that, for the most part, the large-scale time-mean features of the observed general circulation are well simulated by the model. Major exceptions are a higher than observed sea level pressure over the wintertime subtropical continents and a tendency for the model's troposphere to be a few degrees colder than that observed. There is also remarkably good agreement between the model's and the earth's stratosphere, especially considering the model's coarse vertical resolution in its stratosphere.

Malone et al. (1984) have examined the characteristics of stationary and transient eddies in the geopotential height field as simulated by the CCM. For January forcing they found that the stationary waves in the Northern Hemisphere generated by the model closely resemble those observed. The geographical patterns of variability and the partitioning of this variability by time scale and zonal wavenumber for the wintertime Northern Hemisphere are also rather realistic.

Mullen (1985) has computed the local balances of vorticity and heat for the CCM's Northern Hemispheric January climatological circulation and compared them with those for observations (Lau, 1979). The model is able to simulate realistically most aspects of the observed climatological balances of vorticity and heat. The most noteworthy difference between the model and reality is in the magnitudes of the vorticity budget terms; the sizes of all of the model's terms tend to be a factor of 2 smaller than those observed. This discrepancy may be some sort of manifestation of the model's relatively coarse horizontal resolution but the exact causes are not known. Except for this global factor of 2 difference in the vorticity budgets, there are no large-scale systematic differences between the model and observations.

Blackmon et al. (1986) found that the model is able to reproduce the two observed oceanic centers of enhanced blocking activity that are located over the North Pacific and North Atlantic oceans. The amount of blocking activity in the model is about the same as that observed over the Pacific but is about 25% less than that observed over the Atlantic. The model does not simulate the third observed continental region of high blocking frequency over northwestern Siberia; the reason for this failure is not known.

To summarize this subsection, the CCM is able to simulate realistically many fundamental features of the observed wintertime general circulation of the Northern Hemisphere. The model's most serious simulation error, as it pertains to this study, is perhaps the lack of low-frequency variance over northwestern Siberia. The inability to simulate adequately the observed amount of blocking activity over Siberia obviously precludes the model's use for examining the phenomenon in this region.

c. Different simulations analyzed

Ten perpetual January simulations, each of 1200 days duration, were screened for blocking ridges. The only difference among these runs is in the specified but fixed SST distribution. Table 1 gives brief descriptions of the nine runs with SST anomalies and lists references where a more thorough description of the SST anomalies associated with these runs can be obtained. Five of the runs involved equatorial Pacific SST anomalies and four of the runs involved midlatitude North Pacific SST anomalies. The magnitudes of these anomalies, except for perhaps the 3W TPAC, 2C MPAC and 2W MPAC experiments, are generally realistic.

As shown by Mullen (1985), the blocking climatologies of the nine individual simulations with anomalous SST forcing along with the average for all ten simulations with different SST distributions are all quite similar to that of the control case in the sense that blocking activity always is locally enhanced over the North Pacific and Atlantic oceans, but absent over
TABLE 1. Summary of various SST anomaly simulations used in this study: the type of SST anomaly, approximate location and magnitude of anomaly, a reference where the time-mean model response to the anomaly is described, and identifier (parentheses) used in text when referring to the anomaly.

<table>
<thead>
<tr>
<th>Anomaly type and identifier</th>
<th>Location</th>
<th>Magnitude (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool tropical Pacific (1C TPAC)</td>
<td>0°, 165°W</td>
<td>−1.5</td>
<td>Blackmon et al. (1983)</td>
</tr>
<tr>
<td>Warm tropical Pacific (1W TPAC)</td>
<td>0°, 165°W</td>
<td>+1.5</td>
<td>Blackmon et al. (1983)</td>
</tr>
<tr>
<td>Warm tropical Pacific (2W TPAC)</td>
<td>0°, 165°W</td>
<td>+3.0</td>
<td>Blackmon et al. (1983)</td>
</tr>
<tr>
<td>Warm tropical Pacific (3W TPAC)</td>
<td>0°, 165°W</td>
<td>+4.5</td>
<td>Blackmon et al. (1983)</td>
</tr>
<tr>
<td>Warm tropical Pacific (W ETPAC)</td>
<td>0°, 112°W</td>
<td>+4.2</td>
<td>Blackmon et al. (1983)</td>
</tr>
<tr>
<td>Cool midlatitude Pacific (1C MPAC)</td>
<td>40°N, 180°</td>
<td>−2.1</td>
<td>Pitcher et al. (1986)</td>
</tr>
<tr>
<td>Cool midlatitude Pacific (2C MPAC)</td>
<td>40°N, 180°</td>
<td>−4.1</td>
<td>Pitcher et al. (1986)</td>
</tr>
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<td>40°N, 180°</td>
<td>+2.1</td>
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<td>Pitcher et al. (1986)</td>
</tr>
</tbody>
</table>

northwestern Siberia. The exact location of the oceanic centers of heightened blocking activity and the level of activity in these regions does vary somewhat among the runs, suggesting SST anomalies might affect the preferred regions and the amount of blocking action in the model. This is probably an indirect effect due to changes in the model's simulated mean state. However, the differences in blocking climatologies between the control run and the SST anomaly simulations seem small; the differences in the location of the oceanic region of enhanced blocking are typically a couple of grid points and the frequency of blocking varies by ≈25%. In fact, differences of this magnitude might even be due to sampling fluctuations. Whether these differences are statistically significant has not been tested.

It is also recognized that the version of the CCM analyzed in this study misses a potentially important feedback mechanism: namely, the dynamic coupling of the ocean and atmosphere. What effect this mechanism would have on blocking characteristics of the model is not known. This question will have to await the development and analysis of GCMs that have a coupled atmosphere and ocean system before it can be answered. However, considering that the typical duration of the model blocks studied here is ~10 days whereas SST anomalies are observed to persist for a period of several months (Namias, 1970; Rasmussen and Carpenter, 1982), it seems reasonable to assume that the effect of a dynamically coupled atmosphere and ocean, at least on the local balances of vorticity and heat in the region near the blocking ridge, would likely be small.

3. Analysis Procedures

a. Definition of blocking

Twice-daily model fields of 500 mb geopotential height were used to identify blocking ridges. This output was on the model’s Gaussian grid. The fields were weakly low-passed filtered to remove brief interruptions due to mobile transient disturbances having periods less than about five days. The low-pass filter and filtering procedure used in this study is the same as that used by Blackmon et al. (1986).

In previous observational studies, the most commonly used methods to identify objectively blocking ridges have been based on temporal anomalies of the 500 mb height field. Yet, such methods can be sensitive to the precise way in which the anomalies are defined. For example, even though the observed frequency and distribution of persistent anomaly events exhibits little sensitivity as to whether contributions to the 500 mb anomaly field due to interannual variability are retained or removed (Dole and Gordon, 1983; Shukla and Mo, 1983), the results for persistent anomaly activity in the CCM depend strongly on whether the anomalies are defined with respect to the mean of all the model simulations used in this study (a procedure somewhat analogous to retaining the interannual variability in the observations) or with respect to the mean for each individual model simulation (a procedure somewhat analogous to removing the interannual variability from the observations). It is because differences in the time-averaged 500 mb height fields between any two of the different SST simulations used in the present study can exceed ±100 m over large areas of the midlatitude Northern Hemisphere (e.g., Blackmon et al., 1983, Fig. 11a) that such a strong dependence on the exact way in which the anomalies are defined is exhibited in the model results. Because of this strong sensitivity to how the anomalies are defined, a procedure for identifying model blocking events that is independent of temporal anomaly fields was deemed necessary for this study. For this reason, an index based on zonal height deviations over a specified region was used to select model blocking episodes.

In this study, blocking is defined as the continuous occurrence at a particular longitude of a large positive 500 mb geopotential height deviation from a regional zonal mean for a relatively long time. A modified version of Hartmann and Ghan's (1980) objective method...
was employed to identify blocking ridges. This analysis was done separately for the PACS (157.5°E–97.5°W), ATLS (60.0°W–30.0°E) and WNAS (172.5°W–67.5°E) sectors. If along the midlatitude band defined by the three Gaussian latitudes (60.0°N, 55.5°N, 51.1°N) the average 500 mb geopotential height at the central longitude (150°W PACS, 15°W ATLS, 120°W WNAS) exceeded the mean in the entire sector by more than a specified amount (200 m PACS and WNAS, 150 m ATLS) continuously for at least seven days, then a blocking event was recorded. The event was defined as continuing until the height at the central longitude became less than the threshold value. Figure 1 shows the latitudinal band for the PACS and ATLS sectors in which this calculation was done. Sixty-seven PACS cases, 42 ATLS cases, and 26 WNAS cases were found in the ten runs. (The chronologies of these cases are given in Mullen, 1985.) The reality of these events was verified by checking twice-daily analyses of unfiltered 500 mb geopotential height. This inspection also revealed that the shapes of these blocks were rather stationary with respect to the twice-daily movement of the ridge line. Admittedly this definition of blocking is somewhat arbitrary, but it does identify large, persistent, quasi-stationary ridges in the 500 mb height field and it is also independent of the time-averaged 500 mb height field.

The central longitudes used to represent blocking in the three geographical sectors were chosen based on the climatological distribution of blocking in the model.
Figure 2 shows the total number of blocking events for all ten SST simulations as a function of longitude, where a blocking event at all longitudes was defined in the same way as it was at 150°W and 120°W for the PAC and WNA sectors, respectively. The diagram indicates two regions of enhanced blocking action. One region is located over the Pacific Ocean between \( \approx 165° \) and 120°W, and the other is located over the Atlantic Ocean between \( \approx 45° \) W and 15°E. These two areas of enhanced blocking activity in the model are consistent with the model results found by Blackmon et al. (1986). The 150°W meridian is the longitude with the highest number of blocking events. For this reason that longitude was chosen to represent blocking in the PACS sector. The 120°W meridian is the easternmost longitude associated with blocking over the Pacific in which the total number of blocking events exceeded 20. For this reason that longitude was selected to represent blocking in the WNA region. Blocking at this longitude is examined in order to investigate a model flow analogous to that for Dole's (1982) negative Pacific persistent anomaly event and that for the boreal winter of 1976/77. The 15°W meridian is the center of the region of enhanced blocking for the Atlantic sector. For this reason that longitude was picked to represent blocking in the ATLS sector. The total number of cases which fulfilled the +200 m anomaly for a local zonal average over 105° of longitude, seven-day criteria at 15°W was only 20. The relatively small number of events which satisfy this criteria in the ATLS sector is not surprising in view of the fact that the model's variability over the wintertime North Atlantic is less than that observed by a small amount (Malone et al., 1984). In order to increase the number of individual blocking events at 15°W, a slightly less stringent amplitude criterion (+150 m anomaly for a local zonal average over 90° of longitude) was employed for the ATLS sector. The use of this less stringent criterion increased the number of ATLS events to 42.

Figure 3 shows the composite averages of 500 mb geopotential height, the standard deviation of bandpass-filtered 500 mb geopotential height \(^1\), and sea level pressure for PACS, ATLS, and WNA conditions. A high amplitude ridge at 500 mb is clearly evident along the central longitude in all of the blocking composites. The storm track is typically shifted \( \approx 15° \) of latitude to the north of its climatological position at the central longitude, and cyclone-scale eddy activity is a minimum along the longitude of the 500 mb ridge line in all of the blocking composites. If allowance is made for differences in analysis procedures, the 500 mb flow and its relationship with the storm path during model blocking episodes bears close resemblance to corresponding ones for Dole's (1982, his Figs. 4.1 and 4.2) persistent-anomaly composites. (Our blocking definition tends to select events centered along the central longitudes whereas Dole's procedure tends to select events centered at the longitude of his key point.) The relationships that exist in the distributions of sea level pressure, 1000–500 mb thickness, and 500 mb geopotential height for these blocking composites—namely, that the geopotential perturbations associated with the block tilt slightly westward with height and that the 1000–500 mb thickness ridge and 500 mb geopotential height ridge closely coincide with one another—are the same as those discussed in Blackmon et al. (1986) and agree closely with those for observed blocking ridges.

b. Computation of vorticity and heat balances

As a means of diagnosing blocking anticyclones in the CCM, vorticity and heat budgets were evaluated. The local, time–mean, isobaric vorticity equation can be written as

\[
\frac{\partial \tilde{\zeta}}{\partial t} = -\nabla \cdot \nabla_p (\tilde{\zeta} + f) - (\tilde{\zeta} + f) \nabla \cdot \mathbf{V} \\
\text{tendency} + \text{advection} + \text{divergence} - \nabla_p : \mathbf{V}^W - \mathbf{F} + R_e \quad (1)
\]

\(^1\) The bandpass filter used in this study is the same as that first used by Blackmon (1976) and later by Malone et al. (1984). The filter retains periods between \( \approx 2.5 \) and 6.0 days. For convenience, their terminology is adopted and regions of maximum bandpass height variance are referred to as "storm tracks" or "storm paths."
Fig. 3. Distributions of 500 mb geopotential height (solid contours every 60 m) and absolute vorticity (dashed contours every $1.0 \times 10^{-3}$ s$^{-1}$) for the (a) PACS, (b) ATLS, and (c) WNAS blocking composites; stippling in these panels represents terrain heights between 500 and 1000 m. Distributions of standard deviation of bandpass-filtered 500 mb geopotential height (contour interval, CI: 5 m) for the (d) PACS, (e) ATLS, and
(f) WNAS blocking composites; heavy dashed line in these panels represents the axis of the storm track in the 1200-day control run where values exceed 50 m. Distributions of sea level pressure (solid contours every 4 mb) and 1000–500 mb thickness (dashed contours every 60 m) for the (g) PACS, (h) ATLS, and (i) WNAS blocking composites.
where
\[ \zeta = k \cdot \nabla_p \times \mathbf{V} \]
and the local, time-mean, isobaric heat balance can be written as
\[ \frac{\partial \bar{T}}{\partial t} = -\bar{\nabla} \cdot \nabla_p \bar{T} - \omega \left( \frac{\partial \bar{T}}{\partial \rho} - \kappa \frac{\bar{T}}{\rho} \right) \]
\[ = \nabla_p \cdot \nabla T^* + \bar{Q} + R_T \]
where
- \( \bar{T} \) is the horizontal wind vector; \( \omega \) is the pressure vertical velocity; \( \nabla_p \) is the horizontal gradient operator and its subscript denotes the constant surface on which the operator is calculated; \( \zeta \) is relative vorticity; \( f \) is planetary vorticity; \( F \) is frictional dissipation; \( \kappa \) is the ratio of the gas constant over the specific heat at constant pressure \( (R/c_p) \); \( Q \) is diabatic heating; and \( R_T \) and \( R_T \) represent residual terms. The values for a composite case of blocking presented here were derived by averaging the means for individual cases, as defined in (1) and (2), assigning equal weight to each case.

The composite values of all terms in (1) and (2) were first evaluated for all of the CCM's nine sigma levels. Twice-daily model output on the model’s Gaussian grid was used. All terms that involve the gradient operator, except the divergence term in (1), were computed using the transformation:
\[ \nabla_p \phi = \nabla_\sigma \phi - \sigma \nabla \ln p^* \frac{\partial \phi}{\partial \sigma}, \]
where \( p^* \) is surface pressure. The pressure-coordinate correction for the divergence was computed assuming thermal wind balance for the correction term (Eq. 7 of Sardeshmukh and Held, 1984). In a manner consistent with the CCM’s numerical formulation, the gradient operator on constant sigma in (3) was evaluated from the spectral coefficients, and the vertical derivative in (3) was evaluated by first-order finite differencing; note that model output must be on the Gaussian grid if spectral operators are used to calculate the gradient operator. The idea of performing an isobaric budget on a model’s sigma levels is not new; Savijarvi (1983) has previously done such an analysis for kinetic energy with output from an ECMWF model and Sardeshmukh and Held (1984) have done such an analysis for vorticity with output from a GFDL model. An excellent discussion dealing with the problem of transforming sigma-coordinate model output to a pressure-coordinate vorticity balance is contained in the paper by Sardeshmukh and Held (1984).

In order to facilitate comparison of model and observed results, the mean composite values of the terms in (1) and (2) were interpolated to mandatory pressure levels, assuming the terms varied linearly with pressure between the model’s sigma surfaces. If the isobaric level was below the ground, then the values of the terms in (1) and (2) were assumed to be zero. Because the balances of vorticity and heat contain nonlinear terms that could introduce horizontal scales beyond the resolution of the model, all terms were truncated at rhomboidal wavenumber 15 in a manner consistent with the model’s numerical formulation before the final results were plotted.

For further details concerning the analysis procedures, see Mullen (1985).

4. The local balances of vorticity and heat

As it turns out, the main characteristics of the vorticity and heat budgets are remarkably similar for blocks in all three regions. Because the key features of these budgets for the PACS composite are, for the most part, representative of those for the ATLS and WNAS blocking composites, results for the PACS composite will be mainly emphasized in this paper. Unless otherwise explicitly stated, the discussion of relationships for PACS blocking also applies to blocking in the other two regions.

a. PACS blocks

1) 300 MB VORTICITY BUDGET

Figure 4a shows the distribution of the time-mean divergence term (DIV) at 300 mb for PACS. The distribution of DIV closely resembles that of the divergence itself (not shown). Cyclonic (anticyclonic) tendencies are located in the region of northwesterly (southwesterly) flow downstream (upstream) of the ridge line, in agreement with observational studies (e.g., Hartmann and Ghan, 1980; Dole, 1982). The peak magnitudes of this forcing in the vicinity of the block and the block’s anticyclonic relative vorticity perturbations \( (\zeta^* \approx 3.0 \times 10^{-3} \text{ s}^{-1}) \) suggest a characteristic time scale on the order of 1.5 days associated with the 300 mb DIV term, implying a residence time about one-seventh the typical lifetime of the composite block at this level. The largest cyclonic tendencies (i.e., upper-level convergence) are located over the central United States, where the upper-level westerlies flow over the eastern slopes of the Rocky Mountains to produce downslope conditions. The dipole pattern, located along the dateline between 50° and 20°N, with anticyclonic forcing to the north and cyclonic forcing to the south, is consistent with a thermally indirect circulation associated with the exit region of the Pacific jet stream (e.g., Blackmon et al., 1977). Similarly, the
Fig. 4. Distributions at 300 mb of (a) the DIV term (CI: \(5.0 \times 10^{-11} \text{s}^{-2}\)), (b) the VADV term (CI: \(5.0 \times 10^{-11} \text{s}^{-2}\)), (c) the VSUM term (CI: \(5.0 \times 10^{-11} \text{s}^{-2}\)), (d) the VEDDY term (CI: \(2.0 \times 10^{-11} \text{s}^{-2}\)), (e) the VTEDY term (CI: \(2.0 \times 10^{-11} \text{s}^{-2}\)), and (f) the VRES term (CI: \(2.0 \times 10^{-11} \text{s}^{-2}\)) for the PACS blocking composite. Solid (dashed) contours denote positive (negative) values; zero contour is omitted. Stippling denotes
region associated with the blocking ridge where time-mean relative vorticity is less than \(-2.0 \times 10^{-3}\) s\(^{-1}\), except in (f) where stippling denotes terrain heights between 500 and 1000 m.
Table 2. Spatial correlation coefficients for selected terms of the vorticity and heat budgets. The value of $T^*$ is estimated from the 850–1000 mb thickness field for the low-level results and from the 200–1000 mb thickness field for the vertically averaged results.

<table>
<thead>
<tr>
<th>Region</th>
<th>DIV</th>
<th>VADV</th>
<th>VSUM</th>
<th>VEDDY</th>
<th>VSUM</th>
<th>HADV</th>
<th>ADIA</th>
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North–south dipole pattern over the central United States is consistent with a thermally direct circulation associated with the entrance region of the Atlantic jet stream.

Figure 4b shows the distribution of the time–mean vorticity advection term (VADV) at 300 mb for PACS. Positive (negative) vorticity advection is present upstream (downstream) of the ridge line, indicating that advection of relative vorticity exceeds the advection of planetary vorticity since these two effects generally oppose one another; this relationship is the same as that observed for real blocks (e.g., Hartmann and Ghan, 1980; Dole, 1982). The characteristic time scale associated with the 300 mb VADV term is on the order of 1.5 days and is about the same as that for the DIV term. Comparison of the DIV and VADV terms reveals that these two time–mean terms strongly offset one another. The spatial linear correlation coefficient between the two terms, which is given in Table 2, is $r_{[DIV, VADV]} = -0.90$. In fact, to a first approximation, the VADV term balances the DIV term in the PACS vorticity budget at the jet stream level.

Although strong cancellation exists between the VADV and DIV terms, their sum (VSUM), which is shown in Fig. 4c, is by no means negligible. This sum provides a measure of the net effect of the time-averaged flow on the vorticity tendencies. Cyclonic (anticyclonic) tendencies are present immediately upstream (downstream) of the ridge line, which indicates that

---

2 The spatial linear correlation coefficient for this calculation and all subsequent calculations is computed for the area indicated in Fig. 1. A cosine of latitude weighting is employed.
the VADV term tends to dominate the DIV term at this level. Hence the net forcing due to the time–mean flow is tending to move the vorticity anomalies associated with the ridge toward the east. The vorticity tendencies due to this forcing are consistent with westerly accelerations near 40°N, 160°W and northerly accelerations near 50°N, 170°W, regions where anomalously suppressed westerly flow and anomalously enhanced southerly flow are located, respectively. Thus, upstream of the ridge the accelerations induced by the time–mean flow act to reverse the circulation anomalies associated with the block. The peak magnitudes of this term and of the vorticity anomalies near the block suggest a characteristic time scale on the order of three days for the pattern to propagate downstream one-quarter of a wavelength. This period is about one-third the typical lifespan of these quasi-stationary features.

The distribution of the convergence vorticity due to transports by the transient eddies (VEDDY) at 300 mb for PACS is pictured in Fig. 4d. In general, the transient eddies are forcing anticyclonic (cylcnic) tendencies approximately one-quarter wavelength upstream of the anticyclonic (cylcnic) anomalies associated with the block. Hence the eddy forcing tends to make the block retrogress and strongly opposes the forcing due to the time–mean motions ($\hat{\mathbf{v}}_{\text{VEDDY}}, \mathbf{VSUM}$) = −0.89, Table 2). A careful comparison of Figs. 4c, d indicates that near the block the peak values of the VEDDY term are about 80–90% those of the VSUM term.

The quadrature relationship that exists between the eddy vorticity forcing and the blocking pattern in the CCM is similar to one described by Illari (1984) for an observed case of blocking. It is not clear, though, whether such a relationship always holds true for all real blocks; Dole (1982) found weak eddy vorticity forcing mainly in phase with the block while Sarjirarvi (1977) reported no obvious relationship between the convergence of eddy vorticity flux and the block. Additional studies are needed in order to determine whether the eddy-mean flow relationship found in the model is a feature that typifies most blocking events.

The distribution of the frictional term (FRICT) at 300 mb for PACS (not shown) indicates that dissipation is everywhere at least one order of magnitude smaller than the two largest terms, the VADV and DIV terms. Since vertical diffusion is nonzero only in the CCM’s lowest five layers ($\sigma \geq 0.500$) and since 300 mb is above the interface of the $\sigma = 0.336$ and 0.500 surface in all regions except over the highest terrain of the Himalayas, it follows that horizontal diffusion is negligible in the vorticity balance at 300 mb during blocking situations.

The distribution of the vorticity tendency term (VTEND) at 300 mb for PACS (Fig. 4e) indicates that the composite block moves eastward over its lifetime. The magnitude of VTEND is small, being less than $0.5 \times 10^{-10}$ s$^{-2}$ everywhere. In fact, for this composite VTEND seems negligible compared to the largest terms in the vorticity budget. Residual terms arise from such effects as interpolation errors, truncation errors, sampling errors (model output is sampled every 12 h whereas time steps are every 30 min), and terms neglected in the synoptically scaled versions of the vorticity equation (1) or the thermodynamic energy equation (2). The magnitude of a residual term compared to that of the other terms serves as measure of the integrity of a budget calculation. Positive (negative) residuals indicate a physically unaccounted source (sink) of the budget quantity. The distribution of the vorticity residual term (VRES) at 300 mb for PACS (Fig. 4f) reveals that the magnitude of VRES is less than $0.5 \times 10^{-10}$ s$^{-2}$ everywhere except around the highest terrain associated with the Rocky Mountains, where anticyclonic (cyclonic) residuals are associated with upslope (downslope) flow. The peak magnitudes of VRES in these regions are $\approx 0.7 \times 10^{-10}$ s$^{-2}$, which is around one-fifth the size of the peak magnitudes associated with the largest terms in the vorticity budget.

Table 3 contains the spatial rms values for all of the terms in (1) and (2). This statistic provides an objective way to estimate the relative importance of the various budget terms and the degree of balance obtained by the budget calculations. Table 3 indicates that, for PACS blocking, the rms of the VRES term is about one-sixth that of the largest vorticity budget terms (VADV and DIV). This suggests that, in the rms sense, the vorticity balance has a signal-to-noise ratio of $\approx 6:1$.

2) Low-level vorticity budgets

The distributions of the vorticity budget terms near the surface for PACS are displayed in Fig. 5. The values in Fig. 5 represent the pressure-weighted vertical averages for the model's two lowest sigma layers (from $\sigma = 0.8685$, the interface of the $\sigma = 0.811$ and $\sigma = 0.926$ layers, to $\sigma = 0.991$). In these two layers the effects of dissipative boundary-layer processes are comparable to those of other dynamical processes.

Figure 5 and Table 2 clearly indicate that the DIV term (Fig. 5a) is the dominant term near the surface. The residence time associated with the low-level DIV

\[ \nabla \cdot (\mathbf{v} \cdot \nabla) f = \nabla \cdot (\mathbf{v} \cdot \nabla)(f + \mathbf{f}) \text{.} \]

This fact was used to compare $\nabla \cdot (\mathbf{v} \cdot \nabla)(f + \mathbf{f})$ with $\rho \nabla^2 \mathbf{f}$ ($\rho$ is the horizontal diffusion coefficient) in order to determine the relative importance of horizontal diffusion compared to a first-order term in the vorticity balance.

The rms values are computed for the same area used to obtain the linear spatial correlation coefficients. A cosine of latitude normalization factor is employed.
Fig. 5. Distributions of the low-level (a) DIV term (CI: $10.0 \times 10^{-11}$ s$^{-2}$), (b) VADV term (CI: $5.0 \times 10^{-11}$ s$^{-2}$), (c) VSUM term (CI: $10.0 \times 10^{-11}$ s$^{-2}$), (d) VEDDY term (CI: $2.0 \times 10^{-11}$ s$^{-2}$), (e) FRICT term (CI: $5.0 \times 10^{-11}$ s$^{-2}$) and (f) VRES term (CI: $10.0 \times 10^{-11}$ s$^{-2}$) for the PACS blocking composite. Solid (dashed) contours denote
positive (negative) values; zero contour is omitted. Stippling denotes region associated with the blocking ridge where the time-mean relative vorticity is less than $-1.0 \times 10^{-3}$ s$^{-1}$ except in (f) where stippling denotes terrain heights between 500 and 1000 m.
## Table 3. Spatial rms values.

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</tbody>
</table>
term is on the order of a half day. As Table 3 indicates, the low-level DIV term is mainly balanced by the FRICT term (Fig. 5e), with the correlation coefficient between the two terms being \(-0.73\) (Table 2). The DIV and FRICT terms in the PACS composite tend to be somewhat correlated with the vorticity perturbations at low levels (Table 2); the DIV term is positively correlated with \(\bar{\xi}[\sigma] = 0.52\) and the FRICT term is negatively correlated with \(\bar{\xi}[\sigma] = -0.49\). (Correlations between these terms are much weaker for WNA blocks.) The low-level VADV term (Fig. 5b) is marked by negative vorticity advection in the region of southerly flow near the Aleutian Islands, which indicates that advection of planetary vorticity tends to dominate the advection of relative vorticity near the surface. The distribution of the low-level VEDDY term (Fig. 5d) is rather noisy; its size is typically one-quarter the size of the DIV term (Table 3) and therefore is of secondary importance to the low-level vorticity budget. The VTEND term (not shown) is almost an order of magnitude less than the DIV term (Table 3) and is negligible at this level. The residual terms at this level (Fig. 5f) are relatively large and imply a signal-to-noise ratio of only \(\approx 1.5:1\) (Table 3); possible reasons for the small signal-to-noise ratios near the surface are discussed in Mullen (1985).\(^5\)

3) Vertically averaged vorticity budgets

The distributions of the vorticity budget terms for PACS, vertically averaged for the entire atmospheric column, are given in Fig. 6. The values in Fig. 6 are pressure-weighted averages for a vertical column that extends from the model’s lowest sigma level (\(\sigma = 0.991\)) to the model’s highest sigma level (\(\sigma = 0.009\)). These vertically integrated results, in essence, represent the barotropic component of the vorticity budget terms for the model.

The vertically averaged DIV term (Fig. 6a) is a first-order term in the vertically averaged vorticity balance (Table 3). Its distribution appears closely related to the underlying orography. Cyclonic (anticyclonic) tendencies tend to be located where downslope (upslope) conditions are present. For example, note the strong cyclonic tendencies near Colorado where downslope conditions exist and the strong anticyclonic tendencies over Alaska where upslope conditions exist. Hence it appears that vortex tube stretching (shrinking) along the leeward (windward) slopes is the dominant divergent effect in regions of strong orographic forcing.

The vertically averaged VADV term (Fig. 6b) is the biggest term in the vertically averaged vorticity balance, its magnitude being about twice that of the DIV term (Table 3). Unlike the situation at the jet stream level, there is little evidence of strong cancellation between the vertically averaged DIV and VADV terms (\(r[DIV, VADV] = -0.08\)). (The degree of cancellation between the vertically averaged DIV and VADV terms is much greater in the ATLS and WNAS composites.) The vertically averaged VADV term generally resembles the 300 mb VADV term and is marked by cyclonic (anticyclonic) tendencies upstream (downstream) of the ridge. The vertically averaged VADV term tends to be large where the flow goes over sloping topography, with cyclonic (anticyclonic) tendencies located over the windward (leeward) slopes; thus in regions of strong orographic forcing, the vertically averaged VADV and DIV terms seem to balance one another closely, much better than the spatial correlation coefficients indicate. (This tendency for strong cancellation over severe orography is even more apparent in the ATLS and WNAS composites, as will be shown later.)

The vertically averaged VSUM term (Fig. 6c) indicates that the net time–mean vorticity forcing tends to cause the blocking pattern to move downstream. Its magnitude is generally somewhat smaller than the VADV term and somewhat bigger than the DIV term (Table 3). Because the size of the VADV term is typically twice that of the DIV term, the vertically averaged VSUM term exhibits large positive correlations with the VADV term (Table 2).

The vertically integrated VEDDY term (Fig. 6d) closely resembles its isobaric counterparts of the free troposphere and, thus, works to retrograde the blocking pattern. This result reflects the fact that the polarity of the eddy vorticity forcing is virtually the same throughout the troposphere. The vertically averaged VEDDY term is typically half as large as the VADV term (Table 3) and tends to offset the net vorticity forcing due to time–mean flow (\(r[VEDDY, VSUM] = -0.59, \text{Table } 2\)).

Because the FRICT term is negligible above the surface layers of the model, the vertically averaged FRICT term (not shown) obviously bears close resemblance to the low-level FRICT term (Fig. 5e). Its magnitude tends to be about half as large as terms involving the time–mean flow but about the same size as the VEDDY term (Table 3). The degree of spatial correlation between the FRICT and VSUM terms is similar to that between the VEDDY and VSUM terms (Table 2). Hence it follows that eddy vorticity transports and frictional dissipation are of comparable importance in counteracting the net vorticity forcing due to the time–mean flow in the vertically averaged vorticity budgets.

The vertically averaged VTEND term (not shown) is typically one-third the size of the largest terms in the tropospherically averaged vorticity balance (Table 3). Its distribution suggests a tendency for the composite

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\(^5\) The relatively large residuals near the surface are undoubtedly due in part to our inability to compute explicitly a correction to the \(\sigma\)-coordinate vertical diffusion of vorticity that converts it into an estimate of the pressure coordinate vertical diffusion. An explicit correction for the surface stress is straightforward to formulate and was used to obtain an estimate of the pressure coordinate surface stress. The results depicted in Fig. 5 and Tables 2 and 3 are based on the FRICT term being estimated in the above manner.
Fig. 6. Distributions of the vertically averaged (a) DIV term (CI: $2.0 \times 10^{-11}$ s$^{-2}$), (b) VADV term (CI: $2.0 \times 10^{-11}$ s$^{-2}$), (c) VSUM term (CI: $2.0 \times 10^{-11}$ s$^{-2}$) and (d) VEDDY term (CI: $2.0 \times 10^{-11}$ s$^{-2}$) for the PACS blocking composite. Solid (dashed) contours denote positive (negative) values; zero contour is omitted. Stippling denotes
block to move downstream over the course of its lifetime.

The vertically averaged VRES term (not shown) possesses characteristics of both the 300 mb and the low-level VRES terms. The tendency for anticyclonic (cyclonic) residuals to reside over the windward (leeward) slopes of the mountains is analogous to the relationship found at the jet stream level. Yet the size of the vertically averaged VRES term is only slightly smaller than those of the largest terms in the vorticity balance and implies a signal-to-noise ratio of \( \approx 2:1 \) for the vertically averaged vorticity budget (Table 3); in this respect, the vertically averaged VRES term is quite similar to its low-level counterpart.

4) 700 MB HEAT BUDGET

The distribution of the time–mean temperature advection term (HADV) at 700 mb for PACS is shown in Fig. 7a. The strongest warm advection exists over Alaska, just slightly to the north of the warmest thermal perturbations. Cold advection is likewise situated over the central United States and the northwest Pacific Ocean where temperatures are locally cold. Hence there is a tendency for the HADV term to increase the lower tropospheric temperature perturbations exhibited by the block (\( r[HADV, T^*] = 0.41; \) Table 2, where an asterisk represents the deviation of a quantity from the zonal mean over the block’s lifetime), in agreement with diagnostics for observed blocks (e.g., Hartmann and Ghan, 1980; Dole, 1982).

The distribution of the adiabatic heating term (ADIA) at 700 mb for PACS is displayed in Fig. 7b. The distribution of this field closely resembles that of the 700 mb vertical velocity field (not shown). The warming (cooling) just downstream (upstream) of the ridge line is associated with downward (upward) vertical motion. The ADIA term shows essentially no correlation with the temperature anomalies (\( r[ADIA, T^*] = -0.02)\). Comparison of the ADIA and HADV terms reveals considerable cancellation between the two terms (\( r[ADIA, HADV] = -0.62; \) Table 2). In regions near steep terrain, peak values of the ADIA term tend to be bigger than those of the HADV term.

The sum of the ADIA and HADV terms (HSUM) represents the total effect of time–mean motions on the temperature field. Figure 7c shows HSUM for PACS. The main effect of the time–mean flow is to warm the region to the east of where the warmest temperature perturbations are located. Thus the time–mean flow, for the most part, acts to shift the warm temperature perturbations of the block toward the east. The characteristic time needed by the time-average flow to create a temperature perturbation with a peak magnitude similar to that of the block itself (\( T^* \approx 8^\circ\)C) is on the order of four days.

The distribution of temperature tendency due to transports by the transient eddies (HEDDY) at 700 mb for PACS is given in Fig. 7d. The eddy heat flux works to destroy the temperature perturbations of the block (\( r[HEDDY, T^*] = -0.59; \) Table 2); the tendency for the eddy heat flux to attenuate the block’s thermal perturbations is also observed for real blocks (e.g., Dole, 1982). The size of the eddy forcing around the ridge is
Fig. 7. Distributions at 700 mb of (a) the HADV term (CI: $10.0 \times 10^{-3}$ K day$^{-1}$), (b) the ADIA term (CI: $10.0 \times 10^{-3}$ K day$^{-1}$), (c) the HSUM term (CI: $5.0 \times 10^{-3}$ K day$^{-1}$), (d) the HEDDY term (CI: $5.0 \times 10^{-3}$ K day$^{-1}$), (e) the DJIA term (CI: $5.0 \times 10^{-3}$ K day$^{-1}$), (f) the temperature tendency due to the model’s convective adjustment process (CI: $5.0 \times 10^{-4}$ K day$^{-1}$), (g) the temperature tendency due to the model’s net radiative heating (CI: $5.0 \times 10^{-4}$ K day$^{-1}$) and (h) the VRES term (CI: $5.0 \times 10^{-1}$ K).
day$^{-1}$ for the PACS blocking composite. Solid (dashed) contours denote positive (negative) values; zero contour is omitted. Stippling denotes region where $T^*$ exceeds 6.0 K, except in (f) where stippling denotes average precipitation rate greater than $5.0 \times 10^{-3}$ m day$^{-1}$ and in (h) where stippling denotes terrain heights between 500 and 1000 m.
typically smaller than that due to terms involving the time-average flow. The zonally elongated dipole structure upstream of the ridge, with warming to the north and cooling to the south of the jet stream axis, is due to enhanced poleward heat fluxes associated with cyclone-scale baroclinic activity along the storm track.

The distribution of the diabatic heating term (DIA) at 700 mb for PACS is presented in Fig. 7e. The diabatic heating is composed of temperature changes due to latent heat release, vertical and horizontal diffusion, and shortwave and longwave radiative transfers. Diabatic warming, due mostly to latent heat release (cf. Figs. 7c, f), is associated with the storm track over the western Pacific and with upslope flow over the southwestern United States. Diabatic cooling, due mostly to longwave radiative transfer (cf. Figs. 7e, g), is mainly confined to continental and Arctic areas. In particular, the strong diabatic cooling over western Canada tends to enhance the existing cold temperatures located there but, in general, there is no evidence of a systematic relation between DIA and \( \overline{T^*} \) (r[DIA, \( \overline{T^*} \)] = 0.00; Table 2). Diabatic processes near the ridge itself are rather weak (\(<1.0^\circ C \text{ d}^{-1}\)).

The distribution of the heat tendency term (HTEND) at 700 mb for PACS (not shown) is consistent with the notion of a slight eastward movement of the block’s thermal field over its lifetime. The peak size

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6 As in the case with vorticity, a correction to the \( \phi \)-coordinate vertical and horizontal diffusion of temperature was not used. As it turns out, \( \phi \)-coordinate vertical and horizontal diffusion are both negligible compared to latent heating and radiative transfers in the free troposphere, which suggests that their pressure coordinate values would also be negligible.
of HTEND is less than one-fifth the peak size of the largest heat balance terms, HADV and ADIA.

The distribution of the heat balance residual term (HRES) at 700 mb for PACS (Fig. 7h) reveals that the HRES term is less than 1.0°C d⁻¹ everywhere within the 3000 km of the block except over the steepest slopes of the Rocky Mountains. In this region, HRES is greater than ±1.0°C d⁻¹ with an anomalous source (sink) of heat along the up slope (down slope) side of the Rockies. Anomalous heating is also evident upstream of the block where synoptic-scale eddy activity is enhanced. This rms size of the HRES term implies a signal-to-noise ratio of ≈3:1 for the 700 mb heat budget (Table 3).

5) LOW-LEVEL HEAT BUDGETS

The distributions of the heat budget terms for the pressure-weighted vertical average for the model's two lowest sigma layers for PACS are given in Fig. 8. As Tables 2 and 3 indicate, the balance of heat near the surface is primarily accomplished by the HADV term (Fig. 8a) offsetting the DIA term (Fig. 8d), although near the center of the blocking ridge the HEDDY term (Fig. 8c) can be as large as either the HADV or DIA terms. In the PACS composite, diabatic heating shows a weak, positive correlation with the thermal field whereas the HADV term does not exhibit any systematic relationship to the thermal field (Table 2). The situation is reversed for ATLS and WNAS blocking, however. The diabatic heating at low levels is predominantly due to surface sensible heat flux (cf. Figs. 8d, e).

The HEDDY term (Fig. 8c) and the ADIA term (Fig. 8b) are typically one-half and one-quarter the size of the HADV and DIA terms, respectively (Table 3). Apparently, the eddy heat transports and adiabatic heating are of secondary importance to the low-level heat balance. Residuals (Fig. 8f) near the ground are negative virtually everywhere, a situation that hints at some sort of systematic error being present in the low-level heat budgets; possible reasons for this error, such as our inability to calculate precisely the model's actual vertical diffusion, are discussed in Mullen (1985). The signal-to-noise ratio for the low-level heat budgets is about 3:1 (Table 3).

b. ATLS and WNAS blocks: Summary of the vorticity and heat budgets

Because of the high degree of similarity in the vorticity and heat budgets for blocks in all three regions, distributions of the vorticity and heat balance terms are not presented here for sake of brevity. Instead, a brief summary of the characteristics of these budgets that are common to blocking in all regions will be given and the most important differences that do exist among the budgets will be pointed out. For a complete documentation of the distributions of the vorticity and heat budgets for ATLS and WNAS blocks, see Mullen (1985).

Virtually all of the key relationships that were previously discussed for the PACS budgets are also very apparent in the ATLS and WNAS budgets. For example, a first-order balance is achieved between the DIV and VADV terms at 300 mb in the ATLS and WNAS vorticity budgets; the VEDDY term at 300 mb is typically one-third the size of the DIV or VADV terms alone, but the eddy vorticity transports are still mainly responsible for offsetting the tendency for downstream propagation of the blocking pattern due to the sum of the DIV and VADV terms. Near the surface, the principle balance of vorticity is brought about by the DIV and FRICT terms. The HADV and ADIA terms are the dominant ones in the 700 mb heat budget with the HADV term being primarily responsible for maintaining the block's thermal perturbations; the HEDDY and DIA terms represent secondary processes. Near the ground, the primary balance of heat is accomplished by the HADV and DIA terms. Most of these relationships can be readily inferred from the information contained in Tables 2 and 3.

Careful inspection of Tables 2 and 3 does suggest at least one important difference between the WNAS budgets and the PACS and ATLS ones. For WNAS blocking, the magnitude of the 700 mb DIA term is about twice that of the HEDDY term. The difference in magnitude indicates that diabatic processes are of greater importance in the 700 mb WNAS heat budget than eddy heat transports. In fact, diabatic heating at 700 mb mainly counteracts the total forcing due to the time-mean flow ($r[DIA, HSUM] = -0.85$; Table 2); this is markedly different than the situation for PACS or ATLS blocking where diabatic and eddy effects are of similar importance and the spatial correlation between DIA and HSUM is much lower.

Other noteworthy differences that exist among the blocking budgets for the different locations seem to be related to differences in the underlying geography. Figure 9 shows the distributions of the vertically averaged DIV and VADV terms for ATLS and WNAS. For example, note the relatively large magnitudes associated with these terms that are located over southern Greenland in the ATLS composite and along the flanks of the Canadian Rockies in the WNAS composite. These large magnitudes are due to strong barotropic flow going over the steeply sloping terrain; such strong orographic forcing in the immediate vicinity of the blocking ridge is absent in the PACS composite (cf. Figs. 6a and 6b).

In Mullen (1985), the local balances of heat and vorticity were evaluated for several other blocking composites for the PACS, ATLS and WNAS sectors. In addition to being categorized by geographical location, blocking ridges were further stratified by either their 500 mb flow configuration (using both objective and manual means) or the SST anomaly experiment in...
FIG. 8. Distribution of the low-level (a) HADV term (CI: $20.0 \times 10^{-1}$ K day$^{-1}$), (b) ADIA term (CI: $10.0 \times 10^{-1}$ K day$^{-1}$), (c) HEDDY term (CI: $10.0 \times 10^{-1}$ K day$^{-1}$), (d) DIA term (CI: $20.0 \times 10^{-1}$ K day$^{-1}$), (e) temperature tendency due to the surface sensible heat flux (CI: $20.0 \times 10^{-1}$ K day$^{-1}$) and (f) HRES term (CI: $10.0 \times 10^{-1}$ K
day\textsuperscript{-1}) for the PACS blocking composite. Solid (dashed) contours denote positive (negative) values. Stippling denotes region where the departure of the 850–1000 mb thickness field from the zonal mean exceeds the hydrostatic equivalent of 12 K.
Fig. 9. Distributions of the vertically averaged DJF term (C; $2.0 \times 10^{-11}$ s$^{-2}$) for the (a) ATLS and (b) WNAS blocking composites, and the VADV term (C; $2.0 \times 10^{-11}$ s$^{-2}$) for the (c) ATLS and (d) WNAS blocking composites. Solid (dashed) contours denote positive (negative) values; zero contour is omitted. Stippling in (a) and (b)
which it occurred. In addition, composites that satisfied different blocking definitions (such as Dole’s persistent anomaly criteria) and a few individual blocking events were examined. Furthermore, vorticity and heat balances at several additional tropospheric levels besides those presented in this paper for the PACS composite were also evaluated by Mullen (1985). In all of the composites and individual cases examined, the main features of the vorticity and heat budgets were essentially the same as those discussed in detail for the PACS composite and summarized for the ATLS and WNAS composites in this paper.

Table 4 and Fig. 10 give a summary of the main characteristics of the vorticity and heat budgets that were common to all cases of model blocking investigated. Table 4 provides information on the phase of the forcing, relative to the vorticity or thermal perturbation, for all of the terms in the vorticity and heat budgets; Fig. 10 provides information on the relative magnitude of the forcing for all of the terms in these budgets. The content of Table 4 and Fig. 10 was inferred from such diagnostics as the tropospheric distributions of budget terms, spatial correlation computations and spatial rms calculations, evaluated for all of the blocking events examined by Mullen (1985).

To summarize, although noticeable differences are apparent among the vorticity and heat budgets for blocking in the different regions, on the whole the major characteristics of these budgets are remarkably similar for all regions. These common features are summarized in Table 4 and Fig. 10. Apparently the main properties of these budgets are robust and are very reproducible for model blocks in all three geographical areas.

c. Discussion

It is of interest to view our results in light of some simple theories that have been proposed to account for the maintenance of blocks. Most of these theories assume that the atmosphere is nondivergent barotropic or that there is some equivalent barotropic level. If a nondivergent mechanism was predominantly at work in the model, the DIV term would be negligible and the VADV term would have to be balanced by the VEddy and FRICT terms. This situation clearly does not occur at the jet stream level or near the surface during model blocking events. At the jet stream level, the DIV and VADV terms are first-order effects in the vorticity balance and strongly offset one another; with characteristic time scales on the order of one day, the magnitudes of these forcings appear to be almost as large as they are in typical nonblocking situations. The divergent component of the wind field plays an essential role in keeping the blocks stationary at this level. At the surface, a somewhat analogous situation exists: The DIV term is the biggest one in the vorticity balance and its magnitude, with a characteristic time scale on the order of a half-day, is far from negligible. Even in the middle troposphere (500 to 700 mb), the DIV term, with a characteristic time scale on the order of two to three days, represents an important forcing. Similarly, if model blocks were only governed by equivalent barotropic dynamics, the HADV term would be negligible. Again, this is clearly not the situation with blocks in the CCM. The HADV term is a first-order term in the heat balance at all tropospheric levels and its magnitude, with a lower-tropospheric characteristic.

denotes terrain heights between 500 and 1000 m; stippling in (c) and (d) denotes region associated with the blocking ridges where the time–mean relative vorticity is less than $-1.0 \times 10^{-5}$ s$^{-1}$.
TABLE 4. Summary of the phase of the terms in the vorticity and heat budgets relative to the vorticity and temperature perturbations, respectively.

<table>
<thead>
<tr>
<th>Level (mb)</th>
<th>Vorticity budget</th>
<th>Heat budget</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-\nabla \cdot (\xi + f)$</td>
<td>$-\nabla \cdot (\xi + f)^T$</td>
</tr>
<tr>
<td>300</td>
<td>downstream</td>
<td>upstream</td>
</tr>
<tr>
<td>500</td>
<td>downstream</td>
<td>out-of-phase</td>
</tr>
<tr>
<td>700</td>
<td>*</td>
<td>downstream</td>
</tr>
<tr>
<td>Surface</td>
<td>*</td>
<td>in-phase</td>
</tr>
</tbody>
</table>

* No obvious relationship exists for the term at the indicated level.

The time scale on the order of three to four days, corresponds to a moderate-sized forcing which is not negligible. Hence, it follows that blocking in the CCM involves important dynamical interactions which are beyond processes contained in the nondivergent barotropic vorticity equation. This is similar to a conclusion reached by Chen and Shukla (1983) for a blocking event in a GLAS model.

An essential feature of both CCM and real blocking anticyclones that must be accounted for by any theoretical mechanism is their relative warmth. It is possible to envision an equivalent barotropic forcing that could be responsible for the block’s warmth. For example, direct warming through subsidence induced by differential eddy vorticity forcing in the vertical, as first suggested by Green (1977), could account for the block’s warm thermal anomalies. However, this effect in the CCM is about an order of magnitude smaller than the warming due to the HADV term (Mullen, 1985; chapter 5). The mechanism predominately responsible for sustaining the model’s warm tropospheric perturbations at all levels is the horizontal advection of time-mean temperature by the time-mean wind. This advection is related to the vertical tilt of the structure: The westward tilt with height of the time-averaged geopotential height field is consistent with warm subtropical air being continuously transported northward into the region of warm temperatures and hence enables the block to maintain its thermal pattern. In other words, baroclinic conversions of the time-mean flow are essential for maintenance of the positive temperature perturbations in the lower troposphere in blocks in the CCM.

Whether the baroclinic processes identified in this study are essential for the maintenance of blocks or whether they are a response to fundamentally barotropic processes occurring in a baroclinic environment (i.e., a mean flow with strong vertical shear) remains...
to be seen. However, some insight into the relative importance of terms that strongly affect the vorticity balance versus terms that strongly affect the heat balance can be gleaned from a comparison of the vertical velocity field with the vorticity advection term and the temperature advection term.

According to quasi-geostrophic (Q–G) theory (e.g., Holton, 1979), only two terms are responsible for the vertical velocity field in the absence of diabatic heating and frictional dissipation: the vertical derivative of the horizontal vorticity advection and the horizontal Laplacian of the horizontal temperature advection. Table 5 gives the covariance at several pressure levels between the actual vertical velocity and the Q–G vertical velocity due to the temperature advection term, the vorticity advection term, and the sum of the temperature and vorticity advection terms. (The numerical procedure used to calculate the Q–G vertical velocities is described in the Appendix.) Table 5 indicates that the covariances for the vorticity advection term are typically three to five times bigger than those for the temperature advection term. The actual vertical velocity field at all levels for model blocking is clearly more related to the Q–G component of the vertical velocity due to the horizontal vorticity advection than that due to the horizontal temperature advection, even though the ageostrophic circulation acts primarily in the thermally direct sense. Hence it appears that the horizontal vorticity advection term plays the dominant role in forcing the ageostrophic circulation. This observation, together with the finding that the VADV and HADV terms are first-order effects in their respective budgets, suggests that the dynamical processes that strongly affect the vorticity balance may be more important to the maintenance of model blocks than processes that strongly affect the heat balance.

There is general agreement in the literature that blocking and, for that matter, stationary long waves are greatly influenced by the earth’s orography. The results for the vorticity budgets in the free troposphere revealed a clear relationship between the divergence term and regions where the flow impinges against steeply sloping terrain. This relationship, along with the fact that the advection term always strongly counterbalances the divergence term over severe orography in the free troposphere, implies that the mountains are capable of influencing the shapes of model blocks through the divergence term.

Even though orography appears capable of influencing blocks, the question remains as to whether orographic forcing is essential for the existence of blocks. Blackmon (personal communication, 1985) has examined a 1200-day simulation of the CCM which was identical to the version of the model used in this study, except that terrain heights were set to zero everywhere. He found that blocking-like structures occurred in the model even in the absence of orography. The results from this zero-orography simulation suggest that mountains are not essential to the blocking process in the model.

The suggestion that orographic forcing is not essential for the formation of blocks is in agreement with the earlier numerical experiments of Kikuchi (1969, 1971). Kikuchi used a two-level, hemispheric, quasi-geostrophic model to investigate the importance of orography and land–sea thermal contrast on blocking. He found that blocking occurred in his model even when orography and land–sea contrast were absent and that the inclusion of these two influences only tended to increase somewhat the duration of the blocks. On the other hand, orography and land–sea thermal contrast were found to be important in determining the preferred longitudes where blocks tended to occur in his model.

One of the most interesting findings of this study is the important role played by the eddy vorticity flux in the maintenance of model blocks. The upper-tropospheric eddy vorticity transports always act to force the blocking pattern upstream and thus tend to oppose the tendency for downstream propagation due to the net time–mean flow forcing. Without this eddy vorticity forcing, the blocking pattern would be blown about one-quarter wavelength downstream by the time–mean flow in a period of just three days.

The idea that transports by the eddies are important for the maintenance of blocks is not new (e.g., Green, 1977; Austin, 1980), but it does contrast somewhat with simple theoretical concepts that ignore the role of the eddies. For example, Charney and de Vore (1979) and McWilliams (1980) obtain time–mean flow solutions, which in some respects resemble blocking pat-
terms, without explicitly considering the effects of transience. Our analysis for the model suggests that transience represents an important process that must be accounted for by any blocking theory.

Shunts (1983) conducted linear and nonlinear experiments with a barotropic model on a beta plane in order to examine the effect of transient eddy forcing on blocking flows. He found that anticyclonic (cyclonic) forcing being located approximately one-quarter wavelength upstream (downstream) of the blocking anticyclone was a natural consequence of eddies propagating through a "split flow" blocking pattern. The pattern of eddy forcing relative to the blocking anticyclone obtained in both his linear and nonlinear experiments is quite similar to that observed in CCM blocks. His results clearly indicate that, once a blocking flow is established, the eddy vorticity transports will tend to cause the block to retrograde and further suggest that, in the presence of transience, it may not even be possible to have an inviscid stationary blocking flow where the VADV term exactly cancels the DIV term. Shunts concludes that vorticity transports by the transient eddies can help maintain blocking patterns by opposing the tendency for the block to be advected downstream by the mean wind. The results for CCM blocks seem consistent with his suggestion.

Because CCM blocks occur in a baroclinic environment, the effect of not only eddy vorticity transports but also eddy heat transports must be considered. Unfortunately, there is difficulty in ascertaining the net effect and the relative importance of transient eddies from just vorticity and heat budgets. The vorticity balance indicates that the eddies tend to maintain the block by opposing the downstream advection due to the mean wind whereas the heat balance indicates that the eddies tend to destroy the block's thermal perturbations. Since vorticity and temperature changes are linked to each other through the thermal wind relationship, it is not clear which eddy forcing, vorticity or heat, is the dominant one. Furthermore, it is hard to distinguish eddy from time–mean effects in the vorticity and heat budgets. For example, the eddy heat flux of the heat balance indirectly contributes to the vorticity balance through the time–mean divergence term because of the secondary circulations induced by the eddies. An analogous coupling exists between the eddy vorticity flux in the vorticity balance and the adiabatic heating term of the heat balance. These eddy-driven secondary circulations, in general, tend to oppose the changes induced by the convergences of transient eddy fluxes.

It is obvious that a thorough treatment of the net effect of transient eddies on the mean flow during blocking situations must take into account not only the convergences of transient eddy fluxes but also the effects of the eddy-induced secondary circulations. In a subsequent paper, a diagnostic technique which implicitly treats the combined effects of eddy flux convergences and the concomitant secondary flow will be used to elucidate further the role of transient eddies during blocking in both the model and real atmospheres.

5. Summary

In this paper, blocking anticyclones that occurred in perpetual January simulations of a spectral GCM were investigated. Blocking ridges were composed by their geographical location and local balances of heat and vorticity were then evaluated for the blocking composites.

The following features of the tropospheric vorticity balance were found to be common to all of the blocking composites. At all tropospheric levels above the surface layer, the divergence term closely cancels the advection term. At the jet stream level, these terms represent strong forcings capable of altering the flow pattern on a time scale on the order of one day; in the middle troposphere, these terms are much weaker except over steeply sloping terrain where orographic forcing is large. In the upper (lower) free troposphere, the advection (divergence) term tends to dominate the divergence (advection) term, with the net result of the two terms being a tendency for the block to shift downstream at all levels of the free troposphere. The transient eddy vorticity fluxes of the free troposphere exhibit a pattern which bears a systematic relationship to the block; the fluxes act in the sense to shift the block upstream and hence they oppose the downstream tendency associated with the time–mean flow forcing. The magnitude of the eddy vorticity flux term is typically one-third to one-half of the divergence and advection terms. Frictional dissipation is negligible above the surface layer. Near the ground, the divergence term is the largest term and it is predominantly balanced by frictional dissipation. The residence time associated with the low-level divergence term is around one-half day.

The following features of the tropospheric heat balance were found to be common to all of the blocking composites. At all levels, horizontal advection of mean temperature by the mean wind is predominantly responsible for sustaining the block's thermal perturbations. The two largest terms in the free troposphere are the horizontal temperature advection and adiabatic heating term. The net effect of the time–mean motions is to cause the block's temperature field to shift downstream. The eddy heat transports at all levels act to dissipate the block's thermal perturbations. Diabatic heating at all levels exhibits no large-scale systematic relationship with the temperature field. Eddy heat transports and diabatic heating tend to be of similar importance above the surface layer. Near the ground, horizontal temperature advection and diabatic heating are the most important processes.
It is important to keep in mind the limitations inherent in any budget study when evaluating our results for the balance of heat and vorticity during model blocking episodes. The fact that a term of a balance requirement is negligible does not necessarily mean that the physical mechanisms reflected in that term may not be important. For example, Boville (1984) has found that some aspects of the simulation characteristics of this version of the CCM are very sensitive to the horizontal diffusion, even though the effect of horizontal diffusion is negligible in both the heat and the vorticity budgets during blocking. Conceivably the blocking characteristics in the CCM may also be critically dependent upon the parameterization used for the horizontal diffusion.

The fact that the CCM is able to reproduce reasonably accurately large-scale, low-frequency phenomena is perhaps the most encouraging result of this investigation. This paper has only examined one important component of low-frequency variability, blocking. This investigation of blocking in the CCM is by no means comprehensive; further examination is warranted. The initiation and breakdown of blocks in the CCM has not been examined in detail, and the potentially important effect of different model resolutions on the CCM's blocking characteristics (see, e.g., Bengtsson, 1981) has not been tested; these are just two topics worthy of further study. Other aspects of low-frequency variability also deserve attention: long-lived cut-off lows that often accompany blocking highs and planetary-scale teleconnection patterns are samples of other important low-frequency phenomena that are realistically simulated by the CCM and could be investigated. Future studies which utilize the CCM have the potential to provide much needed insight into the dynamical processes that are responsible for the low-frequency fluctuations of the atmosphere.

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APPENDIX

Computation of the Quasi-Geostrophic Vertical Velocities

The quasi-geostrophic equation for vertical velocity is obtained by elimination of the local time derivative between the vorticity and thermodynamic equations (e.g., see Holton, 1979; chapter 6) and, ignoring friction and diabatic heating, can be written

\[
\left[ \frac{1}{f^2} \nabla^2 + \frac{\partial}{\partial p} \left( \frac{1}{\sigma} \frac{\partial}{\partial p} \right) \right] \omega
\]

\[= \frac{1}{f_0} \nabla \cdot (\zeta + f) + \frac{R}{p} \frac{1}{f^2} \nabla^2 (\nabla \cdot \nabla T), \quad (A1)\]

\[= F_V + F_T, \quad (A2)\]

where

- \(P\) pressure
- \(\omega\) vertical motion in \(p\)-coordinates \([=dp/dt]\)
- \(\nabla\) horizontal velocity vector
- \(T\) temperature
- \(f\) Coriolis parameter
- \(\zeta\) vorticity
- \(\nabla\) two-dimensional \(\nabla\) operator
- \(\sigma\) static stability \([=\sigma(p) = -1/\rho \partial \ln \theta / \partial p]\]
- \(\theta\) potential temperature
- \(\rho\) density
- \(R\) gas constant for dry air.

Equation (A1) is a diagnostic equation for \(\omega\). The right-hand side of (A1) represents a forcing function for \(\omega\) which we have divided into two parts, \(F_V\) and \(F_T\) in (A2); \(F_V\) is the vertical derivative of the absolute vorticity advection and \(F_T\) is the Laplacian of the thermal advection.

Equation (A2) can be solved for the vertical velocity, \(\omega_V(\omega_T)\), associated with only the vorticity (thermal) advection term \(F_V(\omega_T)\); this can be accomplished by inserting only \(F_V(\omega_T)\) in Eq. (A2), instead of the sum \(F_V + F_T\).

The solution to Eq. (A2) was obtained by the following procedure:

1) The omega forcing of interest \((F_V, F_T, \text{ or } F_V + F_T)\) and the associated omega \((\omega_V, \omega_T, \omega_V + \omega_T)\) were expressed as a sum of zonal harmonic components, with truncation at zonal wavenumber 15. This particular truncation represents the maximum obtainable zonal resolution in the rhomboidal 15 version of the CCM.

2) Equation (A2) was rewritten in terms of the coefficients of individual harmonics. This yielded 31 sets of equations (one for the zonal mean, two for each of the first 15 wavenumbers). Each equation for an individual harmonic component is a separable elliptic equation with latitude and pressure as independent variables.
Fig. A1. The pressure vertical velocity at 500 mb for the PACS blocking composite due to (a) the quasi-geostrophic vorticity advection term (CF: $1.0 \times 10^{-4}$ mb s$^{-1}$), (b) the quasi-geostrophic thermal advection term (CF: $1.0 \times 10^{-4}$ mb s$^{-1}$), (c) the sum of the quasi-geostrophic thermal and vorticity advection terms (CF: $2.0 \times 10^{-4}$ mb s$^{-1}$), and (d) the model's actual field (CF: $2.0 \times 10^{-4}$ mb s$^{-1}$). Solid (dashed) contours denote positive (negative) values; zero contour is omitted.
3) The harmonic coefficients for $F_v$, $F_T$ and $F_{TV} + F_T$ were obtained by Fourier decomposition of the appropriate model fields. A fourth-order finite difference approximation to the equations of each harmonic component was then obtained using the computer subroutine SEPELI described in the NCAR Software Support Library (1976).

4) The vertical velocity field was finally obtained by summation of the solutions for the individual harmonic coefficients.

In Eq. (A2), the horizontal Laplacian was expressed in spherical coordinates, $f$ was allowed to vary with latitude, and the vertical profile of $\sigma$ (function of pressure only) was computed by averaging over the entire Northern Hemisphere of the model. Equation (A2) was solved for the domain extending vertically from $p = 1000$ mb to 100 mb, and meridionally from 2.22° to 86.675°N. The meridional boundaries of this domain are essentially determined by the spacing of the model's Gaussian latitudes. The vertical and horizontal resolutions used were 50 mb and 4.445° latitude, respectively. The Gaussian latitudes for this calculation were assumed to be evenly spaced because the subroutine SEPELI used to solve the equations requires evenly spaced data. Assuming that the Gaussian latitudes are evenly spaced at 4.445° latitude introduces an error of less than 0.01° latitude for all Gaussian latitudes south of 73.3°N and a maximum error of ±0.06° latitude at the northernmost Gaussian latitude. The forcing terms in Eq. (A2) were interpolated from the model's sigma surfaces to the evenly spaced pressure levels, subject to the same constraints described in section 3b. The boundary conditions were assumed to be $\omega$ equals zero at 1000 and 100 mb, and along the northern and southern boundaries.

Figure A1 shows the distributions of $\omega_T$, $\omega_V$, $\omega_{TV}$ and the model's actual $\omega$ at 500 mb for PACS. Comparison of the $\omega_{TV}$ (Fig. A1c) and $\omega$ (Fig. A1d) fields indicates that the quasi-geostrophic calculation produces a rather good approximation to the actual vertical velocity field. The degree of similarity between $\omega_{TV}$ and $\omega$ for PACS is, in general, also displayed for the ATLS and WNAS composites and for all pressure levels between 300 and 850 mb; above 250 mb and below 850 mb the agreement between $\omega_{TV}$ and $\omega$ is not as good due to the artificial nature of the upper and lower boundary conditions ($\omega = 0$). Comparison of $\omega_V$ (Fig. A1a) and $\omega_T$ (Fig. A1b) indicates that $\omega_V$ makes the largest contribution to $\omega_{TV}$; the tendency for $\omega_V$ to dominate $\omega_T$ is apparent in all composites and at all pressure levels between 300 and 850 mb. (See Table 5.)

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