Calculated Height Tendencies in Two Southern Hemisphere Blocking and Cyclone Events: The Contribution of Diabatic Heating to Block Intensification

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ABSTRACT

The Zwack–Okossi vorticity tendency equation was used to calculate 500-hPa height tendencies in two intensifying Southern Hemisphere blocking events. The National Centers for Environmental Prediction–National Center for Atmospheric Research gridded reanalyses were used to make each of these calculations. The block intensification period for each event was associated with a deepening surface cyclone during a 48-h period beginning at 1200 UTC 28 July and 1200 UTC 8 August 1986, respectively. These results demonstrate that the diabatic heating forces height rises through the sensible and latent heating terms in these two Southern Hemisphere blocking events. The sensible heating was the larger contributor, second only to (about the same as) the vorticity advection term in the first (second) event. The vorticity advection term has been shown by several studies to be associated with block intensification.

1. Introduction

Over the last several decades, atmospheric blocking events have been studied extensively, but these studies have been carried out primarily using Northern Hemisphere (NH) blocking events (e.g., Tung and Lindzen 1979; Austin 1980; Flierl et al. 1980; McWilliams 1980; Kalnay and Merkine 1981; Frederiksen 1982; Shutts 1983, 1986; Colucci 1985, 1987; Mullen 1986, 1987; Tracton 1990; Mak 1991; Lupo and Smith 1995a,b, 1998; Lupo 1997, 2002; Li et al. 1999; Lupo and Bosart 1999; Swanson 2001; Wiedenmann et al. 2002; Barriopedro et al. 2006; Luo et al. 2007a,b). Southern Hemisphere (SH) events occur much less frequently in comparison with Northern Hemisphere events (e.g., Tibaldi et al. 1994; Wiedenmann et al. 2002), and therefore there have been fewer studies that have examined the dynamic evolution of these events (e.g., Marques and Rao 1999; Sáez de Adana and Colucci 2005; Burkhardt and Lupo 2005, hereinafter BL05). These studies, however, demonstrate that upstream synoptic-scale processes are important contributors to block onset. BL05 specifically find that the synoptic-scale environment during the onset blocking events was very similar to that of Northern Hemisphere events in that upstream synoptic-scale cyclones were prominent features like their Northern Hemisphere counterparts (see, e.g., Tsou and Smith 1990; Lupo 1997; Lupo and Smith 1998; Watarai and Tanaka 2002). Further, BL05 found that the dynamic forcing was dominated by synoptic-scale processes in a manner similar to that of North Pacific Ocean region events (e.g., Nakamura et al. 1997; Colucci 2001). The one difference between Northern and Southern Hemisphere events as posited by BL05, however, is that in the Southern Hemisphere, blocking seems to be the result of the favorable superposition of synoptic- and planetary-scale ridges, whereas in the Northern Hemisphere there seems to be a synergistic wave–wave interaction between the two scales. The work of Luo (2002) and Luo et al. (2007a,b) supports the results of BL05 for the Northern Hemisphere. BL05 further speculate that this may explain the relative differences between the frequency in occurrence, intensity, and persistence in blocking between the two hemispheres.

In the Northern Hemisphere, blocking studies have demonstrated the importance of anticyclonic vorticity advection into the blocking region by an amplifying

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synoptic-scale wave in the onset; however, a few studies (e.g., Tsou and Smith 1990; Alberta et al. 1991; Lupo 1997) suggested a role for temperature advections as well. While there have been many papers over the years that have explored the role of vorticity transport in the support of blocking events, the goal here will be to infer the contribution of the diabatic process, which is typically neglected in the study of blocking events. The authors are not aware of many papers in the literature that examine the possible contribution of the diabatic process to the intensification of a blocking event in the SH. One such study, however, by Sáez de Adana and Colucci (2005) examines more than 10 cases of blocking in the Southern Hemisphere, and their results imply an indirect role for upstream convection in the formation of blocking events using the vorticity and divergence equations. This supports the results of Renwick and Revell (1999), who also infer a role for diabatic heating through upstream convection as well. In the NH, the study of Lupo and Bosart (1999) suggested a positive role for sensible and latent heat release in examining their blocking event, but this was more than offset by the role of radiational cooling.

In examining these SH blocking events, we will explore the issue of the contribution of diabatic processes to the intensification of blocking events that occurred in July and August 1986 in the southeast Pacific Ocean. In a previous study (BL05), the role of diabatic heating could not be assessed properly for this same event given their choice of diagnostic methodologies used. They used the potential vorticity (PV) approach, where the diabatic contribution must be neglected to assume conservation in a dry atmosphere. The idea of examining the direct (e.g., Smith et al. 1984; Tsou et al. 1987; Pauley and Smith 1988; Lupo et al. 1992; Smith 2000) and indirect (e.g., Nuss and Anthes 1987; Pauley and Smith 1988; Neiman et al. 1990; Tan and Curry 1993; King et al. 1995) contributions of diabatic heating to the development of synoptic- and large-scale events is not new. However, the direct contribution of diabatic heating and its relative importance to block intensification on the synoptic or large scales have not been examined extensively. Note here that we refer to those studies in which a direct contribution to development was made as those in which a calculation of the diabatic term was made within the event itself (and contributed positively) (e.g., Lupo et al. 1992). An indirect contribution refers to a calculation demonstrating "preconditioning" [e.g., Nuss and Anthes (1987); Neiman et al. (1990)] or a process that occurs outside the periphery phenomenon examined but that also has an impact on the event being studied (e.g., King et al. 1995)

In section 2, we will describe the data and methods used, and in section 3 we will describe the blocking events and cyclones, which occurred over the southeast Pacific region during late July and August 1986 and which were also described in BL05. In section 4, we will demonstrate, using the Zwack–Okossi (Z–O) vorticity tendency equation (Zwack and Okossi 1986; Lupo et al. 1992), that diabatic processes contributed substantially to two postonset periods of block intensification, and last there is a discussion of these results.

2. Data and methods

a. Data

The dataset used in this analysis was the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses, available through NCAR and archived in their mass storage facilities. The reanalyses are used for this study since they are widely available. The NCEP–NCAR reanalysis dataset is described in Kalnay et al. (1996). This dataset includes global fields of height z (m), temperature (K), relative humidity (%), $\mathbf{u}$ (east–west) and $\mathbf{v}$ (north–south) horizontal wind components (m s^{-1}), and vertical motions ω (μb s^{-1}) on 2.5° longitude × 2.5° latitude grids available on 17 mandatory pressure levels and at 6-h time intervals. There are several surface variables available using the reanalyses as well, including sea surface temperatures (SST, K) and 2-m surface temperature (K). The upper-air reanalyses were interpolated quadratically in natural logarithm of pressure by following the method of Lupo and Bosart (1999).

b. Methods

The following methods for calculating height tendencies using the NCEP–NCAR reanalyses were used. The physics of each forcing mechanism as they contribute to the total vorticity tendency (labeled with T) in the equation below have been discussed in several journal articles (e.g., Zwack and Okossi 1986; Lupo et al. 1992; Lupo and Smith 1995b; Lupo 1997), and therefore they will only be described briefly here. References are given for more details on the parameterizations and methods used to calculate various quantities within the equations presented. Here, we used an extended form (e.g., Lupo et al. 1992) of the Z–O equation, which includes the role of vorticity advection (labeled with V) temperature advection (labeled with Te), adiabatic heating/cooling (labeled with A), frictional forcing (labeled with F), latent heat release (labeled with L), sensible heating (labeled with S), and radiational cooling (labeled with I) in the diabatic heating term:

$$\underset{\mathrm{T}}{\left.\frac{\partial \zeta_{\mathrm{go}}}{\partial t}\right|_{\mathrm{po}}} = \mathrm{Pd}\int_{\mathrm{pt}}^{\mathrm{po}}(\underset{\mathrm{V}}{-\mathbf{V}_h\cdot\nabla_h\zeta_a} + \underset{\mathrm{F}}{\mathbf{k}\cdot\nabla_h\times\mathbf{F}})\,dp - \mathrm{Pd}\frac{R}{f}\int_{\mathrm{pt}}^{\mathrm{po}}\int_{\mathrm{po}}^{p}\nabla_h^2\left(\underset{\mathrm{Te}}{-\mathbf{V}_h\cdot\nabla_h T} + \underset{\mathrm{A}}{S\omega} + \underset{\mathrm{S+L+I}}{\frac{\dot{Q}}{c_p}}\right)\frac{dp}{p}\,dp, \qquad (1)$$

where ω is the vertical motion in (x, y, p) coordinates, $\mathrm{Pd} = 1/(\mathrm{po} - \mathrm{pt})$, and $\mathbf{V}_h$ and ∇_h are the horizontal wind and del (or gradient) operator, respectively. Also, f, ζ, R, p, c_p, $\dot{Q}$, and T hold their conventional meteorological meanings, and ∇^2 is the Laplacian operator. The subscripts "po" and "pt" refer to the surface pressure (or vorticity, when "go" is used) and the pressure at the "top" of the atmosphere, respectively. Other subscripts a, h, and g refer to the "absolute" vorticity, "horizontal" (2D) del operator, and "geostrophic" vorticity, respectively. The static stability is represented as S and is proportional to the lapse rate of the potential temperature. The Laplacian operator represents the curvature in the field or variable to which it is applied [for an example using this equation, see Smith (2000)].

To obtain the 500-hPa vorticity tendencies used in our analysis, we follow the method of Lupo et al. (1992), Lupo and Smith (1995b), and Lupo (1997) and use

$$\left.\frac{\partial \varsigma_g}{\partial t}\right|_{\mathrm{pi}} = \left.\frac{\partial \varsigma_g}{\partial t}\right|_{\mathrm{po}} + \frac{R}{f}\int_{\mathrm{pi}}^{\mathrm{po}}\nabla^2\left(-\mathbf{V}\cdot\nabla T + S\omega + \frac{\dot{Q}}{c_p}\right)\frac{dp}{p}, \qquad (2)$$

where the subscript pi represents the vorticity tendency on any pressure level above the surface.

In Eq. (1), the vorticity tendency at the surface is expressed as a function of dynamic and thermodynamic processes. The forcing processes include the horizontal advection of temperature and adiabatic and diabatic processes coming from the thermodynamic equation, as well as those forcing processes arising from the equations of motion through the vorticity equation, including here, in order, vorticity advection and boundary layer friction.

The diabatic processes included here are latent heat release, sensible heating, and radiational heating/cooling. The parameterization for the sensible heating term is discussed in detail in section 4a below, and the latent heat release includes a convective scheme (e.g., Kuo 1974) and a stratiform component that is proportional to vertical moisture convergence. The radiation scheme includes a longwave radiation parameterization that assumes randomly overlapping clouds (Harshvardhan et al. 1987). The parameterizations for the frictional forcing can be found in Lupo et al. (1992) or Lupo and Smith (1995a).

In the above expressions, all derivative quantities were calculated using fourth-order finite differencing in the horizontal (e.g., Haltiner and Williams 1980) yielding instantaneous vorticity tendencies (s^{-2}). Integral quantities were calculated using the trapezoidal method at 50-hPa increments from the first level above the surface to 100 hPa. In Eq. (1), the vertical motion was solved using the omega equation and by using sequential overrelaxation (Haltiner and Williams 1980), only the procedure was modified to include a fourth-order finite-difference calculation in the relaxation routine. Vorticity tendencies were relaxed in order to give height tendencies ($\mathrm{m\ s}^{-1}$) because height tendencies are a smoother field to examine. The block center-point height tendencies were calculated by area averaging over a 20° latitude × 30° longitude box centered on the anticyclone center point, and then were time averaged over a 48-h intensification period using the mean value theorem [as in Lupo (1997), Lupo and Smith (1998), and BL05]. In the bar graphs, height tendencies were scaled up to meters per day in order to present a unit that can be easily visualized.

3. Synoptic description

The synoptic analysis here will describe briefly the large-scale blocking events and the synoptic-scale cyclone that are the main features of interest for this study. The blocking events occurred during the SH winter (Table 1) and over the South Pacific Ocean region and were the subject of case studies published by Marques and Rao (1999) and BL05. Wiedenmann et al. (2002) showed that this time of the year is close to the climatological peak in block occurrence in the SH and that the southeastern and southwestern Pacific are the two prominent regions for block occurrence. Tables 2 and 3, taken from BL05, showed that the first (second) blocking event intensified from 0000 UTC 28 July (0000 UTC 8 August) to approximately 0000 UTC 1 August (0000 UTC 12 August), and these were parts of a blocking episode that persisted for approximately 1 month. These events were longer lived and stronger than typical SH blocking events. The BL05 study also follows three cyclones that are associated with the midlife cycle period of block intensification for the first event, and the particular cyclone in question is shown on the sea level pressure map for 1200 UTC 29 July 1986 in Fig. 1a (labeled with an "L"), and is the last in the series of

TABLE 1. The climatological characteristics of the two blocking events chosen for this study [for BI, see Wiedenmann et al. (2002)], taken from Burkhardt and Lupo (2005).

Event	Date (start–termination)	Days	BI
1	23 Jul–2 Aug	10.5	3.64
2	3 Aug–16 Aug	13.5	4.06

TABLE 3. As in Table 2, but for the second blocking event.

Phase (dates covering)	Total PV
Onset–intensification 1 (3–5 Aug)	0.075
Maintenance 1 (5–8 Aug)	−0.028
Intensification 2 (8–11 Aug)	0.40
Maintenance 2–decay (11–16 Aug)	−0.018

cyclones. For the second event (not shown), there were two cyclones associated with the midlife cycle intensification period. The synoptic evolution of the development and intensification of the second event was similar to that of the first (BL05). A more complete description of the entire life cycles of these blocking events and cyclones can be found in BL05. However, the main focus in this study is a 48-h intensification period of each blocking event that is associated with the last synoptic-scale cyclone.

Also, in Fig. 1a, there is a tongue of relatively moist air from the tropics feeding into the cyclone of the first blocking event, suggesting that the latent heat release term could have played a substantial role in the development of this cyclone and the intensification of the associated height falls and vertical motions. At 850 hPa, strong cold-air advection into the cyclone region also suggests development of the upstream upper-air trough (Fig. 1b). At 500 hPa, areas of upward vertical motions (shaded, and dotted lines) were associated with the cyclone in question, which is upstream of the blocked region shown here (Fig. 1c). Also, as seen in Fig. 1c, a general region of downward motion can be associated with the blocking event. A jet maximum (Fig. 1d) was located on the upstream flank of this blocking event, and this scenario is a typical signature of block intensification as anticyclonic vorticity is transported into the blocked region as in the scenario described by Tsou and Smith (1990) and Lupo and Smith (1995b). These studies demonstrate that the concurrent intensification of the surface cyclone, upper-air wave, and the upstream jet is associated with the flux of an enhanced anticyclonic vorticity field into the block region. The cyclone was located under a region of the jet maximum that is usually considered to be favorable (poleward exit region or equatorward entrance region) to surface cyclone development because of the presence of upper-level divergence in these regions (e.g., Uccellini et al. 1987). Moreover, the magnitude and location of the vertical motion maximum (Fig. 1c) also suggests some benefit from the coincident coupled jet signature (Fig. 1d) farther aloft (e.g., Rogers and Bosart 1991), a situation that is also known to be favorable for latent heat release and precipitation (Hakim and Uccellini 1992) for cyclone development.

TABLE 2. Average total PV $\times 10^{-7}$ (potential vorticity units per day) for each blocking phase for the first blocking event, taken from Burkhardt and Lupo (2005).

Phase (dates covered)	Total PV
Preblock (20–23 Jul)	−0.70
Onset–maintenance (23–28 Jul)	−3.60
Intensification (28 Jul–1 Aug)	2.90
Decay (1–3 Aug)	−1.70

4. Calculations of 500-hPa height tendencies and discussion

a. Calculations

An examination of the 500-hPa height tendencies over the first part of each intensification period reveals (Fig. 2) that positive height tendencies (rises) were prominent, as expected. For the first event, the vorticity advection term was the dominant contributor to the total tendencies (Fig. 2a); for the second event, the sensible heating term was about equal to the vorticity advection term (Fig. 2b). For the second event, the vorticity advection term was smaller than that for the first event by about one-half, while the sensible heating contribution was larger. The contributions from the stability and latent heat release terms were positive, but they were relatively small for the first event. The latent heating term contributed negatively to the second event. The second largest contributor to the first-blocking-event intensification period was the sensible heating term—a contribution of nearly 8 m day^{-1}. Although this term is only approximately 25% of the vorticity advection term, it was much larger than the other positive contributors.

To determine why the sensible heating term in these cases would be a contributor to block intensification, it is useful to examine the quantities that are part of the diabatic heating term over the 48-h period of study. In this calculation and given the scale of the gridded data, the bulk method was used (e.g., Neiman et al. 1990) to obtain the surface heat flux, which is proportional to the difference in temperature between the 2-m air tem-

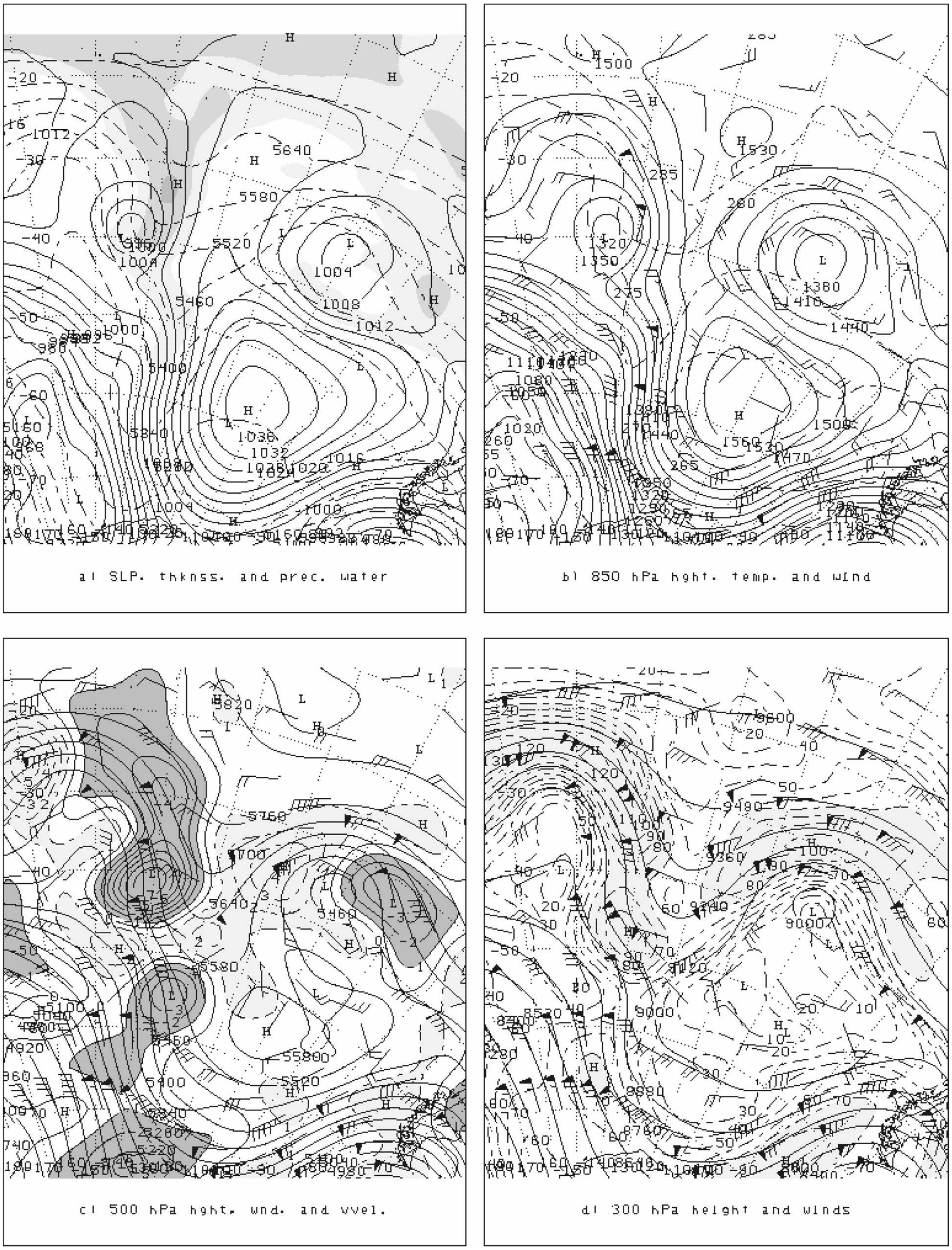

FIG. 1. Synoptic maps of (a) sea level pressure (solid, contoured every 4 hPa), precipitable water (shaded, 12.5 mm), and 1000–500-hPa thickness (dashed, 60 m); (b) 850-hPa height (solid, 30 m), temperature (dashed, 5 K), and wind barbs; (c) 500-hPa height (solid, 60 m), vertical motion (shaded, 1 μb s^{-1}), and wind barbs; and (d) 250-hPa height (solid, 120 m), wind speeds (dashed, 10 m s^{-1}), and wind barbs for 1200 UTC 29 Jul 1986. In (a) the four progressively darker shades represent 20, 30, 40, and 50 mm or more of precipitable water, in (c) the light (dark) shading represents upward (downward) motions stronger than 1 μb s^{-1} (-1 μb s^{-1}), and in (d) the light (dark) shading represents wind speeds greater than 35 m s^{-1} (70 m s^{-1}).

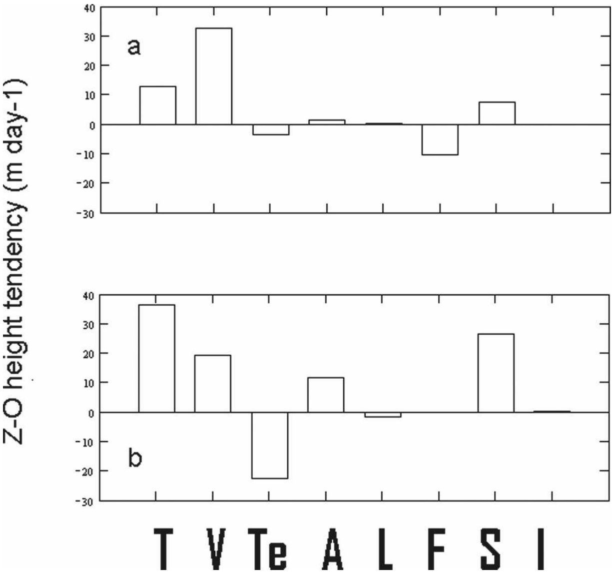

FIG. 2. The block center-point 500-hPa height tendencies (m day^{-1}) for the 48-h period (a) from 1200 UTC 28 Jul to 1200 UTC 30 Jul 1986 and (b) from 1200 UTC 8 Aug to 1200 UTC 10 Aug 1986 as calculated using the Z–O equation. The terms are labeled as follows: T, total Z–O height tendency; V, vorticity advection; Te, temperature advection; A, adiabatic heating/cooling; L, latent heat release; F, friction; S, sensible heating; and I, radiational cooling.

perature and the sea surface temperatures (SSTs). In Fig. 3a for the first blocking event, the SST gradient is relatively zonal across the southeast Pacific. An examination of the 2-m air temperature showed a slight ridging (troughing) on the upstream flank of (within) the blocking event (Fig. 3b). The 2-m temperature distribution may be associated with warm-air (cold air) advection ahead of (behind) the approaching (previous) cyclone. Last, the sensible heat flux (Fig. 3c) throughout the region of the block is positive and shows a ridgelike pattern coincident with the blocking event, with maximum values near the block center during this time. An examination of the time periods between onset and this time (not shown) also demonstrates that the sensible heat flux was generally positive over the block region. An examination of the maps for the second event (not shown) demonstrated that the configuration was very similar.

b. Discussion

The results shown in section 4a are consistent with those of Lupo and Bosart (1999), Lupo and Smith (1995b), and Lupo (1997). Lupo and Bosart (1999) demonstrated that both latent heat release and sensible heating were positive contributors to the warming of the lower atmosphere using a budget analysis based on the first law of thermodynamics over a 10-day period prior to block development. This contribution would have sustained the planetary-scale ridge in place at the time discussed in Lupo and Bosart (1999) just prior to block development. A positive contribution to the heating of the lower atmosphere might directly indicate rising heights above these levels, but caution needs to be taken if vorticity is examined because it is the Laplacian of the heating field [see Eq. (1)] that is the important quantity (e.g., Smith 2000). Smith (2000) demonstrates this behavior by examining a sinusoidally varying latent heat release field; however, this result is not easily applicable here. By examining Fig. 3, it can be inferred qualitatively that the sensible heating in the block region would have contributed to greater anticyclonic vorticities and, thus, height rises. The studies of Lupo and Smith (1995b) and Lupo (1997) also show positive (but very small) height tendencies during most of the development and intensification periods examined. However, these are all Northern Hemisphere events and will be discussed more fully below. Last, the synoptic time scale that we focus on here in order to examine the contribution to block intensification would be analogous to studies that have shown sensible heating to aid in the development of midlatitude cyclones (e.g., Sanders 1986; Nuss and Anthes 1987).

Another physical mechanism by which the diabatic heating could indirectly contribute to block intensification can be inferred from another recent study. Sáez de Adana and Colucci (2005) implied that the upstream divergence induced by upstream tropical convection (and presumably increased ridging aloft) could be associated with the block development. These upstream divergence anomalies (and anticyclonic vorticities) are then advected into the block. They used 14 blocking cases in their study.

In our study, there were no large 500-hPa height rises in these events that were directly due to latent heat release found here for these particular events (Fig. 2). However, a separate calculation of the divergence quantity showed that this term contributed negatively to height tendencies at the block centers. However, our results do show a positive, albeit small, contribution to block development for the first blocking event. For the second event, the latent heating contribution was slightly negative. This could be due to the fact that the latent heat release term was a relatively small contributor for the upstream cyclones (not shown) associated with these blocking events than for previously studied cyclone events (e.g., Lupo and Smith 1995b; Lupo 2002). Our results here, however, demonstrate that the sensible heating contribution was much larger for these two events, as stated earlier. The calculations

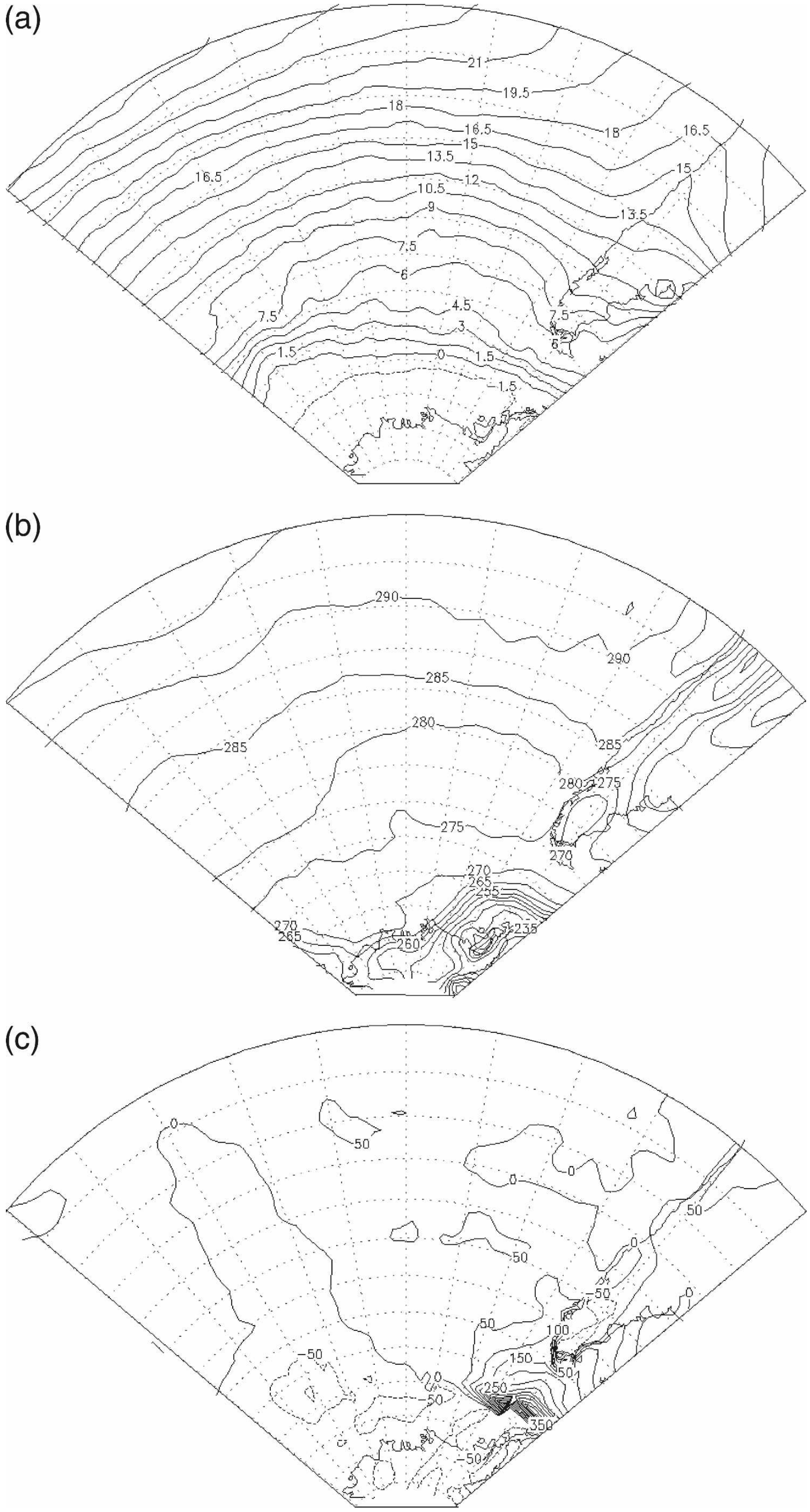

FIG. 3. The mean (a) SST (°C), (b) 2-m surface temperature (K), and (c) sensible heat flux (W m^{-2}) calculated using the bulk method and averaged over the intensification period of a blocking event from 1200 UTC 28 Jul to 1200 UTC 30 Jul 1986.

here also cannot cast doubt on the results of Sáez de Adana and Colucci (2005) because we have not examined their events. Also, our calculation included a direct contribution for latent heat release, whereas the contribution of latent heat release can only be inferred from their study as an indirect contribution.

Block intensity (BI) was shown by Wiedenmann et al. (2002) to be a viable quantity to use as a diagnostic. Here, we examine the potential contribution of sensible heating to block intensity, and we find that, over the life cycles of these events, BI was 3.64 and 4.06 for the first and second blocking events, respectively. An examination of Tables 2 and 3 in BL05 reveals that if the block center height was kept constant then BI was proportional to the gradient between the blocking high and the upstream and downstream troughs. Here, a constant value for the contour following the blocking events [denominator in the BI calculation; see Wiedenmann et al. (2002)] can be used. If the 8 m day^{-1} contribution to the block center-point height due to sensible heating were to be subtracted out for the first (second) block, this would lead to a blocking event that was less intense by approximately 0.2 (0.45) units per day, or 0.4 (0.9) units throughout the period examined here. Although this contribution was small for the first event, it was the second largest following the vorticity advection term. For the second event, it was similar in magnitude to the vorticity advection term. For both events, however, these contributions over a prolonged period of time could have resulted in the difference between a moderate blocking event [as defined by Wiedenmann et al. (2002); BI = 2.0–3.6] or the strong blocking events that actually occurred (Table 1).

In addition, the sensible heating contribution was positive from the block onset time through the intensification time for both events. These results, taken in conjunction with BL05, would suggest that the sensible heating for these events may provide the large-scale preconditioning for the existence of these two blocking events. BL05 (their Table 4), however, demonstrate that the synoptic scale was the main component leading to block strengthening for the first event and that the planetary scale contributed to weakening. This does not preclude individual terms from contributing on a certain scale and then being overwhelmed by other planetary-scale terms or even by the same term on the synoptic scale. For the second event, the scale-interaction term was the prominent positive contributor in a manner similar to that of Northern Hemisphere events.

An examination of four events studied in the Northern Hemisphere (seven development or intensification periods) shows that sensible heating frequently contributed to height rises as in the events studied by Lupo (1997), especially on the planetary scale. Sensible heating was also a positive contributor during the decay phase of the Lupo and Smith (1995b) event. This is similar to what we have observed here for these two SH events, and the commonality among all of these cases was that they were all winter-season cases. The sensible heating term contributed negatively to the intensification periods for the events in Lupo and Smith (1995b, 1998). The Lupo and Smith (1998) event, however, was a summer-season case. Thus, the ocean temperatures might be expected to be cooler than the overlying air. Despite the positive contributions cited for these NH events, the NH sensible heating term (for positive contribution periods, the mean was 2.4 m day^{-1}) did not rise to the prominence found for these Southern Hemisphere events. Nonetheless, for the Northern Hemisphere event studies cited above, the total height tendencies and vorticity advection terms were, in general, stronger than those calculated for these events during intensification. The mean NH total tendency for the block development and intensification periods was 43.2 m day^{-1}, and for the vorticity advection term it was 29.0 m day^{-1}. This result implies that, in these two Southern Hemisphere events, the purported lesser terms (e.g., sensible heating) have risen to greater prominence if they are larger than the diabatic terms in the NH events and the dynamic (vorticity advection) terms in the Z–O equation are similar to those of the NH events or are weaker in the SH.

In addition, it can be argued that the previous cyclone events for both blocking cases brought cooler surface (2 m) temperatures to the blocking region originally and that another process (e.g., temperature transport) may ultimately be responsible indirectly for the sensible heating. This is plausible, since several cyclones traverse the region during the development and intensification periods (see BL05). Studies such as Räisänen (1997) and Lupo (2002) demonstrate that processes in Eq. (1), for example, can be partitioned among the remaining processes. However, it is not straightforward to examine quantitatively which of the other processes are contributing to the sensible heating term. However, Lupo (2002) demonstrated that a particular forcing process can be modulated by the time rate of change of itself through ageostrophic processes. Changes in the surface temperature with time would change the magnitude of the contribution to the sensible heating process through this process.

Last, the results here were consistent with many earlier and recent theoretical studies (e.g., Ghil and Childress 1987; Marshall et al. 2001) that demonstrate that blocking or ridging events can be generated or at least supported by warm surface anomalies and with model studies that show blocking can be forecast better with more faithful representations of the surface and near-surface conditions (e.g., Kung et al. 1993). However, the events studied here represented only one episode and two blocking events and cannot be considered a generalized result. Nonetheless, this study provides further support for these previous studies. Also, previous studies by this group did not demonstrate that the diabatic heating was a consistent significant contributor to the individual development or intensification of blocking events, especially in the Northern Hemisphere. Further studies would be needed to determine whether the results discussed here represent a general result.

5. Summary and conclusions

In this paper, the NCEP–NCAR reanalyses were used to calculate the height tendency fields over a 48-h period for two blocking events and their synoptic-scale cyclones over the southeastern Pacific Ocean. The goal was to demonstrate that the diabatic heating contributed positively to block intensification of these two events in a manner analogous to that of midlatitude cyclones. These blocking events, while stronger and longer lived than a typical Southern Hemispheric event, have been the subject of additional study in other papers (e.g., Marques and Rao 1999; BL05). The Z–O vorticity equation was used as the primary diagnostic tool here because this method partitions forcing processes into individual contributions.

The main conclusions are summarized here:

- The sensible and latent heat release terms contributed positively to the intensification of the first blocking event, whereas the sensible heat term contributed to the second event. Both of these events were previously studied. For the first event, the sensible heating term was much larger than the latent heat release term and was the second largest contributor to intensification behind vorticity advection. In the second event, the sensible heating was of similar magnitude to the dynamic term, and such prominence for the diabatic terms in a blocking event has not been reported in the literature before,
- This contribution from sensible heating can have an impact on the block intensity (it could have resulted in the more robust blocking events studied here), and the contribution of surface or boundary layer heating agrees with the many observational, model, and theoretical studies of blocking events,
- There are two plausible physical explanations for the contribution of diabatic heating to block intensification through sensible heating (direct contribution, as described here), and latent heat release [indirect contribution, as we infer from Marques and Rao (1999) or Sáez de Adana and Colucci (2005)].
- This study and previous studies by this group have not found that diabatic processes were consistent contributors to all blocking events, unlike vorticity advection, and the degree to which diabatic processes do contribute could vary from case to case depending on, at least in this case, the occurrence of nearby synoptic-scale cyclones. This case-to-case variability could be reflective of seasonal or hemispheric differences as well, but further study with more cases would be needed to make this assumption.

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