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# PLANETARY AND SYNOPTIC SCALE INTERACTIONS IN SOUTHEAST PACIFIC BLOCKING USING POTENTIAL VORTICITY DIAGNOSTICS: MORE EVIDENCE FOR THE PAUCITY OF WAVE-WAVE INTERACTIONS IN SOUTHERN HEMISPHERE BLOCKING

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## 1. INTRODUCTION

Climatological studies of blocking in the Southern Hemisphere (SH) demonstrate that blocking events are less common (e.g. Lejenas, 1984; Renwick 1998), and are weaker (e.g. Wiedenmann, et al., 2002; *hereafter WLMT02*) throughout the SH when compared to their NH counterparts. WLMT02 implied that the relative roles in the interaction between planetary-scale and synoptic-scale waves may partially explain the relative paucity of SH blocking. However, the same study demonstrated that blocking events in the South Pacific sector occur with equal frequency and persistence as those in the northern Pacific. Trenberth and Mo (1985) also suggested that the difference in climatological behavior of blocking events between the two hemispheres may be a result of differences in the dynamics that develop and maintain blocking events.

Briefly, the dynamic support for blocking events comes from the influx of anticyclonic vorticity advection into the blocking region by an amplifying synoptic-scale wave, however a few studies (e.g., Tsou and Smith, 1990; Alberta et al., 1991; Lupo 1997) suggested a role for temperature advections as well. The dynamic forcing mechanisms that contribute to the growth and maintenance of blocking events have also been partitioned into synoptic, planetary-scale, and scale interaction processes in several studies as well (e.g., Tsou and Smith, 1990; Tracton, 1990; Marques and Rao, 1999; Colucci, 2001). Then, studies have demonstrated that the importance of synoptic and planetary-scale forcing was different for the growth and maintenance of north Atlantic and north Pacific blocking events (e.g., Nakamura et al., 1997; Colucci, 2001). Nakamura et al. (1997) found that north Atlantic blocking events are primarily dependent on planetary-scale processes while north Pacific events are more dependent on synoptic-scale fluxes of potential vorticity (PV) for growth and maintenance. Lupo and Smith (1995b) (*hereafter LS95b*) and Colucci (2001) found that north Atlantic blocking events were also dependent on interactions between synoptic and planetary-scale processes. Lupo (1997) also demonstrated the importance of synoptic-scale processes relative to the planetary-scale component in the north Pacific region.

Recently, Burkhardt and Lupo (2005) demonstrate that in the SH, the synoptic-scale was crucially important to the growth, intensification, and maintenance of two southeast Pacific blocking events. They show, however, that there is a strong negative correlation between the synoptic-scale and scale interaction components. They speculate that this may indicate that in the SH, the wave-wave interactions between the planetary and synoptic-scales may not be mutually beneficial (non-linear), and thus, this may explain why blocking events there are weaker, less persistent, and less frequently than NH events. In the NH, the synoptic-scale and scale interaction terms are frequently of the same sign.

The objective of this study was to examine another SH blocking case study in order to provide additional case study evidence in support of Burkhardt and Lupo (2005). The blocking event chosen for study here occurred in the south Pacific during July 2001.

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## 2. METHODS AND ANALYSES

### *2.1. Analyses*

The data set used here was the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) gridded re-analyses (Kalnay et al., 1996). These data were archived at NCAR and obtained from the mass-store facility in Boulder, CO. These re-analyses were the 2.5$^o$ by 2.5$^o$ latitude-longitude analyses available on 17 mandatory levels from 1000 to 10 hPa at 6-h intervals. These analyses include the standard atmospheric variables geopotential height, temperature, relative humidity, vertical motion, $u$ and $v$ wind components and surface information. The mandatory level data were interpolated quadratically in ln [p] to 50 hPa level-increments, and these more closely resemble raw sounding information (Lupo and Bosart, 1999).

### *2.2. Methods*

The blocking criterion of Lupo and Smith (1995a) (*hereafter LS95a*) was used here, and this can be summarized as a combination of the Rex (1950) subjective criterion and the Lejenas and Okland (1983) objective criterion, with the exception that a “block” is defined as persisting for five days or more. The Rex (1950) criterion used subjective map analysis, and in his study it was desirable that highly meridional split flow persists for 10 days or more. The Lejenas and Okland (1983) criterion is a zonal index plotted on a time-longitude or Hovmoller diagrams, and persistent weak or negative "non-translating" values can also represent blocking (LS95a). A thorough description of the blocking criterion used here can also be found in WLMT02.

The diagnostic techniques used here are described in Burkhardt and Lupo (2005). Briefly, PV framework was used as the analysis and map display tool, which included the use of dynamic tropopause (DT) maps (Morgan and Neilsen-Gammon, 1998). PV was calculated on 300 hPa surfaces since these PV fields are similar to those calculated on an isentropic surface (e.g., Lupo and Bosart, 1999). This PV calculation, although not strictly conserved, is still an effective diagnostic tool and is given here as:

$$PV = g\left[\hat{k}\cdot\left(\frac{\partial\vec{V}}{\partial p}\times\nabla\theta\right)+\zeta_a\frac{\partial\theta}{\partial p}\right] \quad (1),$$

where $\zeta_a$ is the absolute vorticity vector along the vertical axis, θ is potential temperature, g is acceleration due to gravity and V is horizontal wind speed, respectively. The change in block center point PV was calculated assuming that this quantity is conserved (e.g., Lupo and Bosart, 1999). The development of a particular blocking event is equivalent to the advection of PV,

$$\frac{\partial PV}{\partial t} = -\vec{V}\cdot\nabla PV \quad (2).$$

In examining these blocking events and assessing the role of the synoptic-scale versus that of the planetary-scale forcing, the methodology of LS95b, or Colucci (2001) (*and references therein*) was used. The filtered analyses were used in partitioned forms of (1) and (2) derived by substituting for each variable X;

$$X = \overline{X} + X' \quad (3),$$

where the first (second) term on the right-hand-side of (3) is the planetary (synoptic)-scale component, respectively. Thus, a scale-partitioned form of (2) is given by;

$$\frac{\partial PV}{\partial t} = \left.\frac{\partial PV}{\partial t}\right|_P + \left.\frac{\partial PV}{\partial t}\right|_S + \left.\frac{\partial PV}{\partial t}\right|_I = P + S + I \quad (4),$$

where P, S and I are the planetary-scale, synoptic-scale, and scale interaction PV advections, respectively. The forcing term in (2), which is a product term, mathematically gives rise to scale interaction terms (I) in (4) via the product rule (e.g., Colluci, 2001).

A second-order, two-dimensional Shapiro (1970) filter was used 1250 times on the variables in the data set in order to separate the planetary-scale wavelengths from the synoptic-scale wavelengths. Applying this filter results in a response function, which retains 2%, 44%, 80% of the signal for waves having a wavelength of 3000, 4500, and 6000 km at 45 degrees N (or S) latitude, respectively. More details regarding the use of the filtering procedure can be found in LS95b.

## 3. SYNOPTIC AND DYNAMIC ANALYSIS

### *3.1 climatological comparison and synoptic analysis*

The blocking event chosen for study was a southeast (SE) Pacific region event that occurred during July 2001. The climatological characteristics of the blocking event are shown in Table 1, and for comparison, the Burkhardt and Lupo (2005) events are also listed. This blocking event was slightly weaker overall than the two blocks studied previously. This time of the year represents the SH winter season, which is the part of the season when blocking events occur most frequently and are most persistent and strongest. This blocking event can be classified as a strong blocking event (e.g., WLMT02) when compared to their SH counterparts.

*Table 1.* The characteristics of the two blocking events chosen for study here (*for BI see* WLMT02).

| Event | Dates (Start / Termination) | Days | Block Intensity (BI) |
|---|---|---|---|
| | | | |
| 1 | 23 July – 2 August 1986 | 10.5 | 3.64 |
| 2 | 3 – 16 August 1986 | 13.5 | 4.06 |
| 3 | 13 - 24 July 2001 | 11.0 | 3.33 |

The development phase of this blocking event possessed all the characteristics of blocking events studied by LS95b and references cited therein. On 1200 UTC 11 July 2001, an upstream surface cyclone was approximately 35 degrees longitude upstream of the blocking system, which was within one-half wavelength (e.g., Lupo and Bosart, 1999). This cyclone event was strengthening and slowly moving eastward. At the same time, the 500 hPa ridge was also intensifying and met the blocking criteria used here by 0000 UTC 13 July 2001. The synergistic strengthening of this cyclone and synoptic-scale wave (as shown by many of the referenced papers), the quasi-stationary downstream ridge, and the jet maxima on the western (and southwestern) flank of the blocking event likely contributed to enhancing the anticyclonic vorticity advection into the blocking region These signatures are key components in the development or intensification of blocking events.

Then, two prominent cyclones developed upstream of the block, one began explosive development around 0000 UTC 13 July, 2001, and intensified from 1000 hPa to 963 hPa by 1200 UTC on the eastward flank of the block. The blocking event intensified reaching a peak BI of 6.03 at 0000 UTC 16 July, 2001 (Fig. 1). A second, more modest developing cyclone occurred late in the lifecycle of this event resulting in modest re-intensification late in the block lifecycle. Again, this continued interaction with subsequent cyclones was similar to the many studies that demonstrate this interaction in NH events (e.g., Tracton, 1990; Lupo and Bosart 1999; Burkhardt and Lupo, 2005).

This blocking event decayed after 1200 UTC 22 July 2001, and this period was characterized by falling central heights (Fig. 2). The decay period was not associated with upstream cyclones, and developing cyclone during the decay period was located too far upstream to have any impact. This blocking event remained quasi-stationary during its lifecycle, being located near 120° W at onset, but drifting to near 65° W during the decay period.

### *3.2. dynamic analysis*

In order to examine the overall dynamic behavior of this event, a phase diagram is used in order to examine the behavior of the SH flow. This is a standard technique in dynamic analysis of physical systems (e.g., Lorenz, 1963; Mokhov et al. 2004 and references therein) and is based on the principle that a well-behaved oscillating system such as a swinging pendulum (without any damping mechanism) would result in a circular set of trajectories on a phase diagram of pendulum position versus the change in position with respect to time. The balance of forces that describes such a simple system results in a Sturm-Liouville equation of the form;

$$\ddot{X} + \omega^2 X = 0 \quad (5),$$

which has a general solution of the form;

$$X(t) = A(t)\sin[\omega(t) + \phi(t)] \quad (6),$$

where X(t) represents a time series of some variable, A(t) the amplitude, and ω(t) the frequency, and ϕ(t) the initial phase in the oscillating system.

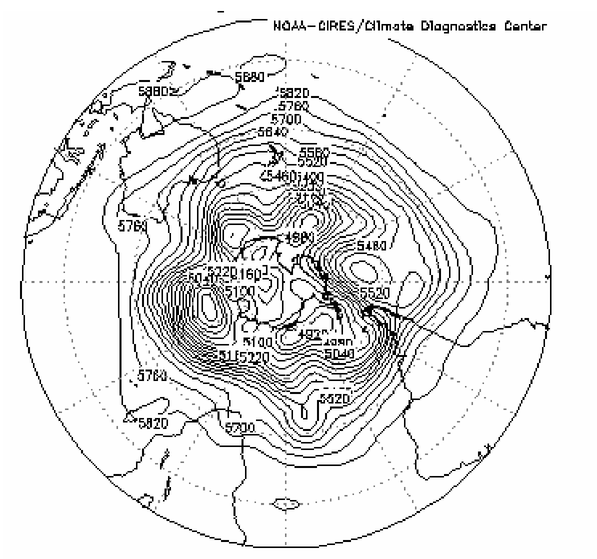


*Figure 1.* The 0000 UTC 16 July 2001 500 hPa NCEP re-analysis plot for the Southern Hemisphere. The contour interval is 60 dam.

Fig. 3 is a plot of the mean 500 hPa planetary-scale height versus the change in the mean 500 hPa planetary-scale height with respect to time. The height fields were averaged over a stationary box within the blocking region that is 30° latitude by 40° longitude. The diagram in Fig. 3 looked similar regardless of the size of the box used within the SH mid-latitude flow with only changes in the magnitude of the height tendency being noted (not shown), that is, the height tendencies were larger in general for smaller boxes. The planetary-scale height fields were used in order to eliminate synoptic-scale and sub-synoptic-scale processes.

The period of time covered in Fig. 3 is the entire month of July 2001. This trajectory is difficult to follow as plotted, thus, in order to examine this trajectory, the month is broken down into three parts based on the block lifecycle. The trajectory plotted in Fig. 4 suggests that the large-scale flow field was relatively stable, or in equilibrium, during the first part of the month, and spiraled inward until shortly before block onset. This corresponds to general height falls through about the 10th of July. Then, the flow becomes unstable as the red trajectory moves away from the spiral during block onset. This corresponds to the beginning of rising heights in Fig. 2. The blue trajectory indicates that the flow does become more stable, making a complete loop before block decay, and then moves into a different orbit (green trajectory) after block decay.

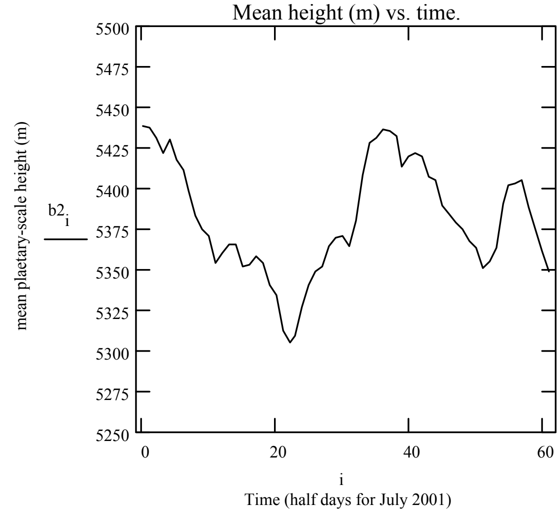


*Figure2.* The mean twice-daily height values for July 2001, beginning with 0000 UTC 1 July, 2001.

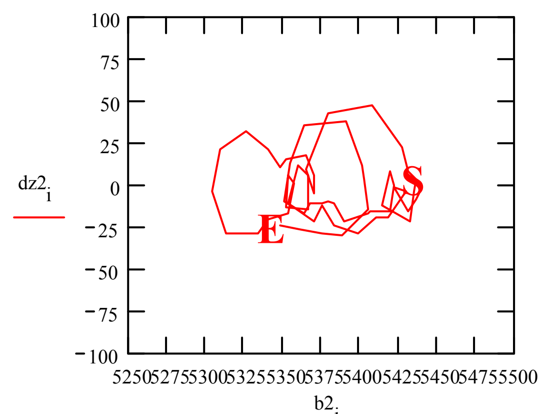


*Figure 3.* A phase diagram of mean 500 hPa height (m) (abscissa) and the first derivative of mean height with respect to time (m day$^{-1}$) (ordinate) for a stationary box (100° W to 140° W and 30° S to 60° S) in the mid-latitude Southern Hemisphere flow. The start and end points of the trajectory are marked S and E, respectively.

A brief analysis of the total PV tendencies will be presented here since many of the findings mirror those of previous studies. The total PV tendencies presented in Table 2 are nine point averaged center point PV tendencies calculated using Eq. 2. In order to filter out small scale and computational noise, the center point tendencies were integrated over particular phases of each blocking event following, for example, Lupo (1997) and Burkhardt and Lupo (2005). Table 2 demonstrates that, as expected, intensification periods corresponded to increasing PV values since, in the SH, PV is a negative quantity. Increasing (decreasing) PV in the SH represents the positive (negative) advection of PV in the absence of non-conservative forcing mechanisms (e.g., diabatic heating or friction) or sources and sinks of PV, and higher PV values or anticyclonic (cyclonic) PV advection are associated with block intensification (decay). Positive PV advection during block intensification (not shown) into the block center (in the SH) was associated with block intensification. Also, high θ (low pressure) advections on the dynamic tropopause (DT) were also associated with block intensification. The block center was also located within the equatorward exit region of the poleward jet maximum, and this region would be favored for anticyclogenesis in a SH straight line model jet maximum.

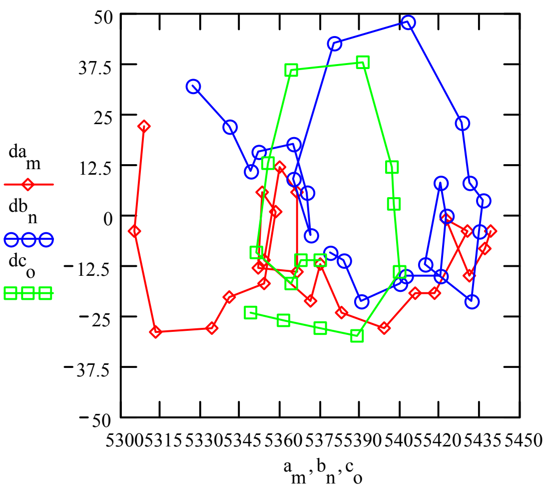


*Figure 4.* Phase plots for July 2001, where the abscissa is central height within the blocking region and the ordinate is the change in height with respect to time. In a) the red, blue, and green trajectories represent the first, second, and third 10 day period in July 2001, respectively. In b) the month is broken up according to the period before block onset (red, solid), during the block lifecycle (blue, dotted), and after block termination (green, dashed)

When the PV tendencies were partitioned into their planetary, synoptic, and interaction components (Table 2), the synoptic scale PV tendencies at the block center point were generally positive contributors throughout the block, while the interaction tendencies were a negative contributor, or countered the block development. The planetary-scale PV tendencies were smaller and generally positive (negative) for the first (second) part of the blocking event. These findings are also similar to those of Burkhardt and Lupo (2005), who found that the synoptic-scale and interaction tendencies were generally larger than those on the planetary-scale for the SH blocking events. This study and Burkhardt and Lupo (2005) suggested that intensification and decay was generally governed by the combined total of the synoptic and interaction tendencies, especially for these southeast Pacific region blocking events. They also suggest that, in general, the synoptic-scale and interaction tendencies opposed one another for most of the block lifecycle, another result similar to that of Burkhardt and Lupo (2005). The results implied that the interactions between the planetary-scale and synoptic-scale were not synergistic. It is apparent that the synoptic-scale and the interaction tendencies were of opposite sign throughout each block life cycle. Thus, the interactions between the planetary and synoptic scales were not necessarily beneficial to each other in these two SH blocking events.

*Table 2.* Average scale partitioned PV (by wavelength) and total PV x $10^{-7}$ PVU day$^{-1}$ for each blocking phase from the July, 2001 blocking event.

| Phase | P | S | I | Total |
|---|---|---|---|---|
| | | | | |
| Pre-block | 8.90 | 3.50 | -14.80 | 13.60 |
| Intensification | 2.60 | -4.30 | 5.30 | 2.21 |
| Maintenance | -2.30 | 2.60 | -9.20 | -4.10 |
| Decay | 4.50 | 31.80 | -23.3 | 5.20 |
| | | | | |
| Block Life | 0.90 | 4.90 | -9.00 | 6.64 |

In order to investigate further the interactions between scales in these two events, the center point PV tendencies for each scale were correlated versus each other and versus the total PV tendency. Only the synoptic-scale and the scale interactions were highly correlated with each other (-0.62), and the correlation was negative (Fig. 5) when examining plots of the PV tendencies with time throughout the block lifecycles. The correlations are statistically significant at the 95% confidence level and these were tested using the Z-score test assuming the null-hypothesis, or that no relationship is assumed to exist between the two *a priori*. This is similar to the Burkhardt and Lupo (2005) result.

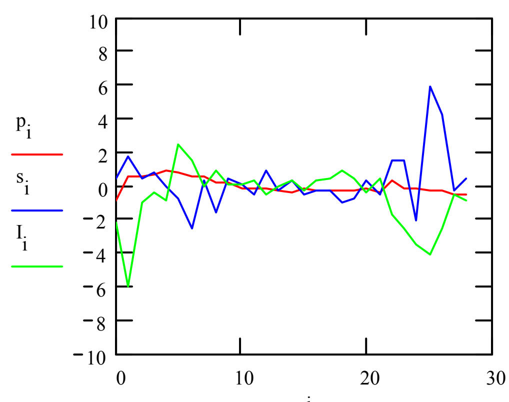


*Figure 5.* The PV advection by the planetary-scale (red), synoptic-scale (blue), and scale interactions (green) versus time. The units on the ordinate (abscissa) are $10^{-11}$ PVU s $^{-1}$ (half-days following 0000 UTC 10 July, 2001).

## 4. DISCUSSION

In section 3.1, it was shown that the synoptic evolution of this SH blocking events was similar to that of two previously examined SH blocking events and their NH counterparts. Specifically, the upstream forcing associated with the development of surface cyclones, the concurrent amplification of the associated synoptic-scale upper air wave, and phase locking with a quasi-stationary planetary-scale wave contributed to the onset and intensification of blocking. Many of the studies referenced here have suggested that this model which represents block onset being associated with the influx of anticyclonic vorticity or lower PV air for the NH. Subsequent upstream cyclone development contributed to the further intensification of the blocking event into its life time, and that the same model describes the cycle of intensification and weakening often observed in longer lived blocking events (e.g., Tracton, 1990; Lupo 1997; Lupo and Bosart, 1999; Burkhardt and Lupo, 2005). Then, the synoptic evolution of these observed SH events was also similar to the early model results of Kalnay and Merkine (1981), Frederiksen (1982), or Shutts (1983), which demonstrated the importance of the contribution of synoptic transients to block formation and maintenance.

Further, an analysis of the individual upstream cyclone events during the block lifecycle demonstrated that the results of Lupo and Bosart (1999) applies to this SH event as well. This study suggested that cyclonic development within one-half to one-quarter wavelength upstream of the block center (or ridge axis) contribute to the intensification of the event itself. Thus, the same key features which can be identified on routinely available maps by operational community for forecasting the onset and intensification of blocking in the NH can also be identified for SH.

The synoptic analysis suggested that as long as there was upstream forcing feeding into the blocking region, the events persisted. The phase diagram in Fig. 4 suggests, however, that the blocking episode came to an abrupt end when a new equilibrium was being established in the SH flow in late July, 2001 (green trajectory). While this suggests that the planetary-scale flow may behave differently during the block lifecycle than it did after block decay, we cannot comment here whether or not this represents multiple equilibria as suggested by, for example Charney and DeVore (1979), or Nitsche et al. (1994).

A re-analysis of the NH events studied by LS95b and Lupo (1997) suggested a similar recurrence for their events. For the NH events, the wave-amplitude index (e.g., Lupo 1997) was used in order to identify periods of large-scale flow that were described as "high" or "low" amplitude flow, and which represents "vacillation" in the mid-latitude wave amplitudes as discussed by Lorenz (1963), (more recently) Haines and Holland (1998), and others. These blocking events, generally, did not survive the transition from one quasi-equilibrium state to another, especially if the transition in the planetary-scale flow is large. This may be due to a breakdown in the planetary-scale jet stream as it becomes unstable and transitions from one equilibrium to another. It also suggests that even if the role of planetary-scale PV forcing is small, the planetary-scale provides a key contribution to block maintenance even if this contribution is "preconditioning" or providing a favorable background for block development as posited by several references in this work.

An examination of the partitioned PV processes revealed that the character of the scale-interactions was different when comparing NH blocking to SH events. Previous studies of the wave-wave interactions involved in blocking lifecycles focused on the large-scale. For example, Gottwald and Grimshaw (1999a,b) discuss blocking from the perspective of the interactions between long waves and/or solitary waves ("solitons") when explaining the dynamics of blocking events. Other recent studies have focused on the interactions between planetary and synoptic scale waves, or more specifically, the phase locking of the two scales. The studies referenced above for NH events suggest that the wave-wave interactions between the planetary-scale wave and the amplifying synoptic-scale wave were critical for block onset or further development, and as such represent a non-linear or synergistic amplification. This would occur if amplification or block intensification occurred such that the planetary-scale, synoptic-scale, and interactions all contributed positively to wave development. This is especially true for the north Pacific blocking event studied in Lupo (1997). This type of mutually beneficial wave-wave interaction between the different wave scales in the intensification of blocking events shares many of the characteristics of resonant Rossby wave triads as described by Lynch (2003), and which is analogous to a swinging spring system. However, that study also concedes that there are potential difficulties in providing an atmospheric analog to their system.

Blocking events also intensified in the NH as long as either the synoptic or planetary-scales along with the positive contribution from the interaction term results in block development (e.g., LS95a; Colucci, 2001). This situation would also represent a non-linear amplification between ridges of two different scales, and the positive contribution from the synoptic-scale and interactions are similar to the observational results of Lupo (1997) for Euro-Atlantic blocking. Thus, the onset and intensification of NH events are generally associated with non-linear amplification between the two scales reflected by the positive contribution from the interaction term, and not just the superposition of the amplifying synoptic-scale wave and the quasi-stationary planetary-scale wave as they locked into phase. In either case described above, there is a mutually beneficial interaction between the scales.

This contrasts with the result found for the two SH events examined in Burkhardt and Lupo (2005) and the blocking event here. As shown in section 3.2, the synoptic and interaction terms were generally of opposite sign throughout the block lifecycle. Thus, there was generally little contribution to ridge or block development that occurred as a result of the interaction between the two scales during onset or intensification periods. In the SH then, blocking would appear to be generally a manifestation of the superposition between the waves of two different scales (constructive interference) as they lock into phase. Since there appears to be little (or less frequent) synergistic link between the synoptic and planetary-scales, this may account for the relative infrequency of blocking in the SH as well as the fact they tend to be weaker and less persistent than NH events as found by the climatological study of WLMT02. Also, they found a correlation between the intensity and duration of NH events, which provides further evidence that the mutual wave-wave interactions in these events were beneficial to the blocking events, whereas no similar correlation found for SH events in that same study would support the conclusion here that these events were the result of the superposition of each scale.

## 5. SUMMARY AND CONCLUSIONS

The planetary and synoptic scale interactions in a blocking event over the southeast Pacific Ocean region were studied here using the NCAR NCEP re-analyses and the PV system as the diagnostic tool. This event was stronger and more persistent than typical SH events, and as such provided this study with a clear portrayal of their synoptic and dynamic lifecycle.

A synoptic analysis demonstrated that this blocking event followed the same pattern as many observational and model studies of NH events, or that upstream cyclogenesis and the associated synergistically amplifying short wave phase locking with a quasi-stationary planetary-scale wave contributed to the onset and further intensification of these events. Block maintenance or decay occurred when there was no contribution from these upstream events, whether they occur too far upstream of the blocking event or too close to the center point. Thus, those features that can be identified in an operational environment and that contribute to the block lifecycle for NH events can also be identified in the SH.

The dynamic analysis produced a couple of key results. First, it appeared that the SH blocking episode of July 2001 came to an abrupt end when the planetary-scale flow transitioned from one equilibrium state to another that was different from the blocked state. A re-analysis of some NH events implied a similar phenomenon could be identified in these previously studied events. This result is consistent with one of the conclusions of Haines and Holland (1998), whose model results lead them to speculate that blocking regimes may persist as long as the large-scale flow remains balanced and does not become unstable and break down or transition to a new state. Then, the importance of the planetary-scale in preconditioning or providing a favorable background is confirmed for the SH, even if the individual scale-partitioned PV tendencies are small.

A second key result is that the synoptic-scale was the largest and most important contributor to block onset and maintenance. This result is similar to that found for Burkhardt and Lupo (2005) for south Pacific region blocking events, and reinforces the importance of amplifying synoptic-scale transients in the maintenance of blocking events as found by many studies for the NH.

The final key result was that, in spite of the importance of synoptic-scale transients in Pacific region blocking events, the nature of the wave-wave interactions between the planetary and synoptic-scales may be different in each hemisphere. In the NH, the interaction component of the forcing tends to be positive suggesting that the phase locking between the planetary-scale wave and the amplifying synoptic-scale wave takes place in a non-linear or synergistic fashion (active interaction). In this SH event, the interaction component of the PV tendency correlated negatively with the synoptic-scale component, and were, at every stage, opposing block intensification. This indicates that the phase locking between the scales generally resulted in the superposition of the two waves of different scales, but nothing more. In conjunction with the climatological results of WLMT02, this difference in the behavior of planetary-synoptic-scale interactions may account for the tendency of SH blocking events to occur less often, and be less persistent and intense than their NH counterparts.

## 6. ACKNOWLEDGMENTS

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