A FRESH LOOK AT PERSISTENT MID-PACIFIC RIDGING

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Abstract

Persistent ridging in the North Pacific is a major contributing factor to winter weather in Alaska and western Canada. In general, when the axis of a persistent ridge is located near the International Dateline, air temperatures in Alaska are typically cooler than normal. However, if the ridge axis is located in the Gulf of Alaska, temperatures are well above normal. Many of these events also evolve into anticyclones located north of 50ºN. This paper analyzes 10 events of persistent mid-Pacific ridging with respect to planetary waves, wind and outgoing longwave radiation (OLR) anomalies, as well as stratospheric temperature anomalies. These 10 events are also described within the climate environment in which they exist by using monthly climate indices such as the Southern Oscillation index and the Arctic Oscillation Index.

Planetary wave analysis indicates that persistent mid-Pacific ridges occur when planetary wave 2 amplifies simultaneous with a reduction in the amplitude of wave 1. Of prime importance is the reduction in the amplitude of the trough produced by wave 1, which is climatologically located near the dateline. Prior to and concurrent with the formation of a persistent mid-Pacific ridge are significant OLR anomalies over the Indian and western Pacific Oceans. This is linked to a retraction of the jet stream over the mid-latitudes of the western Pacific. Additionally, five of the 10 events displayed major stratospheric warmings over Siberia during the weak prior to onset. Height anomalies are also evident in the stratosphere prior to onset, overall the polar vortex appears to be elongated over Siberia. The limited number of short-wave ridges that amplify and develop into a persistent ridge each winter season suggests that simultaneous multiple forcings are a necessity. This paper suggests that these forcings occur in the tropics, mid-latitudes, as well as in the Arctic.

1. Introduction

During the cooler months of the year, persistent ridging may occur in the vicinity of the International Dateline, resulting in a major shift in the position of the polar jet stream and storm track across the North Pacific. These persistent ridging events typically have a duration of 7 to 14 days and may develop into anticyclones that persist for roughly another week before the Aleutian Low is re-established . During these events as cold dry air moves out of the arctic toward the southeast, that the state of Alaska frequently experiences it's coldest temperatures of the season.

The term "persistent ridge"(PR) is used in this paper instead of the commonly used "blocking", because the latter term has a plethora of definitions in terms of duration and amplitude (see Lupo and Smith 1995 for summary). The emphasis is on PRs that reside in the greater Bering Sea region, which lies roughly between 160°E - 160°W and 45°N - 65°N. This paper focuses on the period from October through April, although ridging over the Bering Sea in the warmer months of the year is a common occurrence as well. The purpose of this study is to enhance the generalized work that has already been done with regard to PR in the mid-Pacific (Rex 1950, Austin 1980, Dole 1989). It is hoped that an analysis of 10 persistent mid-Pacific ridges (MPR) will enable meteorologists to better understand and forecast these events as they occur across the region.

In the following section an overview of the literature on PR is given. Section 3 covers data management issues while in section 4 a description of synoptic patterns prior to and during MPR's is reviewed. The link between MPRs and planetary waves is discussed in section 5. The relationship between MPRs and outgoing longwave radiation (OLR) anomalies over the tropical Indian and western Pacific Oceans, as well as upper tropospheric wind anomalies is explored in sections 6 and 7. Section 8 gives a brief analysis of the conversion of persistent ridges into anticyclones, while section 9 discussions the possible correlation between persistent ridging and stratospheric warm events. Section 10 presents a discussion on the evolution of MPRs in relation to commonly monitored indices, such as the Northern and Southern Oscillation Indices (NOI, SOI), as well as mid-Pacific sea-surface temperature anomalies (PDO).

2. Literature Review

Interest in persistent ridging by the meteorological community dates back to around 1950. Since that time numerous papers have been written on subject, most of which can be categorized into two groups: the climatology of PR, and those that have focused on the dynamics. The main result of the climatological studies is that during the Northern Hemisphere winter, there are two main regions where persistent ridging frequently occurs. The first is over the eastern half of the Atlantic and western Europe centered around the Greenwich Meridian. The second is over the eastern Pacific centered near 150°W (Rex 1950a,b, Quiroz 1986, 1987, Dole 1989, Lejenas and Madden 1992, Lupo and Smith 1995, Renwick and Wallace 1996, Wiedenmann *et al* 2002, Pelly and Hoskins 2003). A third weaker response occurs in the vicinity of the Ural Mountains. These studies have also emphasized the coupling of persistent ridging and the development of a deep low/trough upstream of the ridge. A number of authors have suggested or noted the linkage between PR and the strength and position of the polar jet (Rex 1950a, Dole 1989), higher than normal amplitude planetary waves (Austin, Quiroz 1986, Lejenas and Madden 1992), and stratospheric warmings (Austin 1980, Quiroz 1987).

The study of the dynamics of PR can be subdivided into two classes: case studies and modeling efforts. Case studies have shown the importance of thermal and vorticity advection from the upstream low/trough into the ridge (Hansen and Chen 1982, Illari 1984, Trenberth and Mo 1985, Colucci 1985, 1987, Lupo 1997). A number of these studies have hinted at the dynamic differences between PR occurring in the Atlantic and Pacific basins (Hansen and Chen 1982, Lupo 1997). There are also indications that the relative contributions of vorticity and thermal advection change throughout the evolution of a persistent ridge (Colucci 1985, Lupo 1997).

A number of modeling studies have concentrated on the climatology of persistent ridging found in general circulation models, specifically the role which orography and sea surface temperature (SST) anomalies play in the forcing of a PR via ultra-long planetary waves (Li and Tibaldi 1983, Blackmon *et al* 1986, Mullen 1989). Charney *et al* (1981) used a barotropic model to study the linkage between stationary planetary waves generated by orography and PR. The authors concluded that many but not all PR patterns can be attributed to ultra-long waves 2 and 3. Tung and Lindzen (1979a,b) suggested that persistent ridging occurs when stationary planetary waves generated by orography and land-sea temperature contrasts, which are typically out of phase, resonate as the phase of the two waves are aligned.

Studies of persistent ridging in the Pacific Basin have been conducted by Austin (1980), Dole (1986 &1989), Renwick and Wallace (1996) as well as Bond and Harrison (2000). The general consensus is that MPRs (1) develop in locations where the amplitude of ultra-long planetary wave(s) rapidly increases (although the details of which waves are prominent varies from study-to-study); (2) the upstream low/troughs help the amplification process via thermal and vorticity advection; and (3) there are significant wind anomalies over the western Pacific prior to and during MPR development.

In several related studies, Joung and Hitchman (1982) found that ridging over the mid-Pacific occurred in eight out of 16 cases in which outbreaks of polar air occurred over the southern regions of East Asia. A number of those ridging cases would be considered PR events. Renwick and Revell (1999) studied PR over the South Pacific and found that a divergent wind field in the upper tropical troposphere, resulting from enhanced convection over the east-central Pacific, generated a Rossby wave that appeared to produce a PR in the mid-latitudes. One of the main results of their study was that the location of the divergent wind field with respect to the polar jet stream is fundamental to the whole process.

3. Data Considerations

This study utilizes the NCEP-NCAR reanalysis data set found at the Climate Diagnostics Center website (www.cpc.noaa.gov). The 10 MPR events used in this study were selected from visual inspection of daily mean 500 mb heights. The criteria used to identify a persistent mid-Pacific ridge were as follows: 1) trough-ridge pattern with a zonal daily mean 500 mb height gradient ≥ 200 m occurring within 40° of longitude, for six or more consecutive days. As noted in the Introduction, there are many different definitions of persistent ridging/blocking in use. There are advantages and disadvantages to the various methodologies. These 10 events would also be for example, prominent using Dole's (1986) criteria. 2) The MPR ridge axis transected the Bering Sea region, which ranges from 45°N - 65°N and 150°E - 160°W. 3) The event occurred in the October 1 through April 30 period.

For the synoptic description given in the following sections, emphasis is placed on 500 mb heights and mean sea-level pressure. Both zonal and meridional wind anomalies were analyzed at the 300 mb and 200 mb levels, while 250 mb was selected for streamfunction analysis. Interpolated outgoing longwave radiation (OLR) was used in order to investigate the coupling between tropical forcing and flow anomalies over the mid-latitudes of the North Pacific. Composites of OLR and streamfunction were constructed using a seven day mean for each of the 10 events. These 10 events where then averaged to form the composite. In an effort to clarify the relationship between persistent ridges and stratospheric warmings, temperature anomalies at the 10 mb level were used as an indicator of stratospheric warm episodes. In addition, stratospheric warming bulletins issued by the Free University of Berlin were consulted (ftp://ftp.ngdc.noaa.gov/stp/solar_data/stratwarms). In order to place each MPR event within the "climate environment" in which it occurred, a number of monthly climate indices are used in this paper as well. These indices are available on the Climate Prediction Centers website under "Standardized Northern Hemisphere Teleconnection Indices" (www.cpc.noaa.gov).

4. Synoptic Description of MPRs

Visual inspection of the geopotential heights from the reanalysis data set indicates that MPRs develop in conjunction with a broad spectrum of synoptic weather patterns. Prior to the onset of a MPR the flow across the North Pacific can be nearly zonal, contain of a number of short wave ridges or a high amplitude ridge over the Gulf of Alaska. Of the 10 cases investigated in this study, eight MPR's developed *in situ* as indicated in Table 1. In the two remaining cases, a low amplitude ridge formed some 40-60° of longitude upstream (over eastern Siberia), moved to the east over a three day period, but did not amplify until becoming stationary near 180°.

Table 1: 10 case mid-Pacific ridge inventory

Event	Anti-cyclone	Strat. warm[1]	QBO	Simul. Pr[2]
Mar 24 - Apr 14, 2002	no	no	+west	yes
Jan 1-27, 2000	no	no	-west	yes
Feb 23 - Mar 8, 1999	no	major	west	yes
Mar 4-20, 1997	yes	no	-west	yes
Dec 15-31, 1996	yes	major	+east	yes
Feb 8 - Mar 3, 1994	yes	major	+east	yes
Mar 29 - Apr 11, 1992	yes	major	+east	no
Feb 5-19, 1992	yes	minor	+east	no
Oct 24 - Nov 13, 1990	no	no	west	yes
Feb 20 - Mar 18, 1989	yes	major	-east	no

1) stratospheric warming

2) simultaneous persistent ridge elsewhere in Northern Hemisphere

There were several cases where a developing MPR merged with a pre-existing ridge located in the Gulf of Alaska, to form an extremely broad ridge which stretched across most of the North Pacific. However, the primary ridge axis for these cases remained in the Bering Sea sector (150°E - 160°W). Figure 1 shows a ten event composite of 500 mb heights at day+4 (the beginning of the event is day 0). The composite MPR ridge axis is located around 170°W with a well defined trough over eastern Siberia and Japan.

Equally important to ridge development is the formation of a deep upstream low (or trough), as noted by a number of authors (Illari 1984, Alberta and Colucci 1991). During the amplifying stage of MPR evolution, 500 mb heights in the low/troughs ranged from 4900 m to 5050 m, which is common for developing systems over the western Pacific. As the MPR amplifies, the low/trough is typically 30-40° of longitude upstream, usually within the greater Sea of Okhotsk region (an area bounded by 120-140°E and 40-50°N).

At the surface some of these lows can be traced back three or four days prior to onset (day -4), as they first began to develop in the vicinity of Lake Baikal. However, in other cases the upstream disturbance is not distinguishable from the ambient flow until it is located over the east coast of Siberia. In most of cases there is moderate deepening (10 to 20 mb per day) of the low just prior to the formation of a MPR. i.e.- there is little evidence to suggest that explosive cyclogenesis is a prerequisite to the development of a MPR.

In essence, low/troughs that form upstream of MPR's are important since they act as sources of thermal and vorticity advection (Hartmann and Ghan 1980, Illari 1984, Alberta and Colucci 1991, Lupo 1997). However, these features do not appear to have any characteristics that distinguish them from the majority of disturbances that develop in the region throughout the winter months. Therefore, additional forcings, as will be described in the following sections, must factor into the development of MPRs.

Visual inspection of 500 mb heights also showed that in six of the 10 cases a well-organized *downstream* low/trough was positioned over the Gulf of Alaska or western Canada several days prior to the development of the MPR. In the remaining cases there was a weak depression over the Gulf of Alaska that was not well organized. It was only after the MPR started to mature that the downstream low/troughs in these latter cases began to deepen.

The occurrence of split flow in the upper tropospheric winds was reported by Rex (1950b). During the *developing stages* of an MPR, only four of the 10 cases exhibited signs of a split jet across the Pacific. It is more common for a split jet to appear once the ridge reaches a mature phase, typically several days prior to forming an anticyclone. Split jets do sometimes form on the downstream (east) side of a MPR, as the *downstream* low /trough moves to the south. In the cases where a very broad ridge formed over most of the North Pacific, a split jet typically formed over Mongolia or northern China.

Height analysis also indicates a fairly high correlation with the simultaneous formation of persistent ridging elsewhere in the Northern Hemisphere. During six cases persistent ridges formed over the eastern Atlantic or Europe with one additional case over the Ural Mountains. This result is not unexpected as will be discussed in the next section, since the mid-latitude hemispheric pattern is dominated by wave 2.

A daily composite of heights for each of the 10 events starting at day -8 and continuing through day 0, indicates that at day -8 there are some significant height anomalies in the middle and lower stratosphere (10-70 mb levels), prior to their appearance in the troposphere. These anomalies appear to a limited extent to shift from the stratosphere into the troposphere from day -8 to day 0. Specifically, negative 10 mb height anomalies over Siberia first occur by day -8 but do not become prominent at 100 mb until day -4. The coupling between stratospheric and tropospheric anomalies is beyond the scope of this study, recent work however suggests that the coupling is more prevalent than has been previously thought (Baldwin and Dunkerton 2001). The overall impression is that in the days preceding and at the onset of a MPR, the polar vortex shifts or elongates in such a fashion that results in significant negative height anomalies over central and eastern Siberia, with complementary positive anomalies over Scandinavia.

Once a MPR has developed, the synoptic pattern across the North Pacific exhibits considerable variability from one case to the next. Some MPR's take the form of a single high amplitude ridge with a half- width ranging from 20°-40° of longitude. A number of these are transformed into *omega* patterns (Bluestein 1993) as both the upstream and downstream low/troughs start to "undercut" the ridge in the mid-latitudes. These cases frequently evolve into anticyclones as the East Asian Jet Stream (EAJS) becomes re-established across the central Pacific. Several MPR cases become very broad, spanning most of the middle and high latitudes of the North Pacific. Frequently, these turn into high-over-low patterns as one or more low/troughs are established south of the ridge, generally between 40°-50°N.

As MPR's decay, six cases formed large anticyclones over the Bering Sea or Alaska, one case formed a weak anticyclone over the Chukchi Sea, while the amplitude of two MPR's simply decreased over several days until the flow across the North Pacific became quasi-zonal. In one remaining case, the amplitude of the MPR slowly decreased over a four day period as the ridge slowly moved east into western Canada.

In summary, mid-Pacific ridges develop, mature, and dissipate in a variety of synoptic conditions. This makes forecasting these features based on pattern recognition difficult. As will be illustrated in the following sections of this paper, MPRs only develop when a number of atmospheric parameters work synergistically. The key to forecasting these events is hence the monitoring of those parameters.

5. Planetary Wave Analysis

Each of the 10 events was analyzed with respect to planetary waves in order to assess what role these waves play in the evolution of MPRs. Daily mean 500 mb heights taken along the 55° N latitude circle at 10° longitude intervals, are used as input to a Fourier transform, analogous to the approach used by Eliasen (1958), and Quiroz (1987). 500 mb was selected because it is the level at which most of the previous work has been conducted (Green 1980, Lenjenas and Madden 1992). There is nothing special about the selection of 55° N for analysis, but it does represent however a latitude that is a compromise between predominate eastward moving waves in the lower latitudes and predominate westward waves at higher latitudes (Quiroz 1987) . Since there was no additional data filtering or smoothing, the first 18 waves are preserved. The descriptive analysis that follows focuses on the first four waves.

We should keep in mind that there are limitations to this type of planetary wave analysis, since the amplitude and phases of the various waves under investigation are a function of latitude and well as the height above the earth's surface (Quiroz 1987). Planetary waves do not propagate around the globe following latitude circles, but move north-south as well as vertically as well (Wallace and Hsu 1983). Despite the limitations, both observational (Austin 1980, Colucci *et al* 1981, Hansen and Chen 1982, Dole 1986, Colucci 1987, Quiroz 1987, Lejenas and Madden 1992) and model studies (Tung and Lindzen 1979a,b, Charney *et al* 1981, Ji and Tibaldi 1983) indicate the important role planetary waves play in persistent ridging events.

Figure 2 shows an example of wave amplitude and phase for the March-April, 2002 event. Just prior to the onset of the MPR, wave 1 has a large amplitude, but it decreases substantially several days later. Also notice the retrograde motion of wave 1 during the event. Waves 2 and 4 make the largest contribution to the MPR, since they have the largest amplitudes and each one has a ridge located near the dateline. Table 2 shows each event and the mean amplitude of each of the first four waves over the course of that particular event, as well as the standard deviation of the amplitudes. The 10 event composite is shown at the bottom of the table. Notice that wave 2 dominates while the remaining three waves are of roughly equal amplitude (Colucci *et al* 1981). The climatological amplitude of waves 1 & 2 during the winter months is on the order of 100 m according to the study of Reiter and Westhoff (1981). Wave 1 ridge is normally found near the Greenwich meridian, with a trough over the mid-Pacific, while the ridges for wave 2 are located near 75° E (western Asia) and 105° W (North America). Inspection of each of the 10 events shows that only in the Feb23-March 8, 1999 case, was the amplitude of wave 1 significantly larger than any other wave. In this particular event, the ridge of wave 1 regressed from 80° W to 80° E over an 11 day period, during which its amplitude ranged from 100-200 m, and for a time made a significant contribution to the MPR.

The other nine events are dominated by a wave 2 ridge located between 180° and 160°W. There are times however, when despite a moderate to deep wave 1 trough located over the mid-Pacific, a MPR starts to develop. In those cases, the amplitude of wave 1 decreases significantly over the next several days. Waves 3 & 4 are important as well, however, the amount of time that either one of these wave's ridge is in phase with the observed ridge, is limited in time when compared to wave 2. Planetary wave analysis suggests that waves 2 ,3 and 4 remain nearly stationary (within 20° of longitude) during periods when their amplitudes are considerably larger then their respective climatological average.

Table 2: Wave amplitude for each MPR event

	mean amp (m)	st, dev (m)		mean amp (m)	st, dev (m)
Feb/Mar 1989			Dec/Jan 1997		
wave 1	115	55	wave 1	72	21
wave 2	166	42	wave 2	120	34
wave 3	96	46	wave 3	113	37
wave 4	88	42	wave 4	104	18
Oct/Nov 1990			Mar 1997		
wave 1	53	18	wave 1	107	49
wave 2	98	34	wave 2	136	61
wave 3	42	28	wave 3	84	31
wave 4	98	32	wave 4	100	31
Feb 1992			Feb/Mar 1999		
wave 1	44	15	wave 1	101	30
wave 2	142	53	wave 2	76	18
wave 3	100	27	wave 3	69	33
wave 4	81	29	wave 4	60	27
Mar/Apr 1992			Jan 2000		
wave 1	38	21	wave 1	98	29
wave 2	107	36	wave 2	144	43
wave 3	47	24	wave 3	108	64
wave 4	54	28	wave 4	60	23
Mar/Apr 1992			Mar/Apr 2002		
wave 1	51	22	wave 1	77	40
wave 2	104	51	wave 2	110	26
wave 3	79	40	wave 3	33	12
wave 4	68	26	wave 4	73	22
			composite		
			wave 1	**76**	**28**
			wave 2	**120**	**27**
			wave 3	**77**	**28**
			wave 4	**79**	**18**

It should be noted that the development of a MPR corresponded to a pre-existing planetary wave at the same location for nine out of the 10 cases studied in this paper. The amplitude of the planetary wave increases as the MPR builds. Equally important is the development of the upstream planetary trough. At the *onset* of a MPR, the upstream trough is often more developed than the ridge, in other words the trough is closest to its maximum depth (as a result of the constructive interference of two or three planetary wave troughs), when compared to the amplitude of the ridge.

The December 1996 case is unique in that a MPR developed in conjunction with an eastward traveling wave 5 ridge which moved out of eastern Siberia, and amplified when it reached the Bering Sea. What should be noted about this case is that the Northern Hemisphere pattern two days prior to onset of the event is clearly a wave 5 pattern, hence the spectral analysis indicating a wave 5 ridge co-located with the traveling ridge is simply a reflection of the synoptic pattern around the hemisphere. As the MPR developed wave 4 and then wave 2 became dominate.

With regard to the coupling between planetary waves and the development of a MPR, the following scenario is suggested. A planetary wave ridge of modest to large amplitude should pre-exist near the location where the MPR forms. Typically this will be wave 2 but at times waves 3 & 4, or some combination of these waves. A well developed *planetary* trough should also reside 30°-60° of longitude upstream of the ridge. A *synoptic* low/trough forms over east Asia and subsequently moves into the planetary trough as it deepens. Energy from the synoptic-scale is then transferred (vorticity and thermal advection) to the planetary-scale (Illari 1984, Lupo 1997). As this is occurring, the amplitude of wave 1 trough, which is typically located over the mid-Pacific, should be diminishing as a result of either regression or a decrease in its amplitude. Both the retrogressive nature and the low amplitude of wave 1 during the lifetime of most MPRs, suggests that a traveling component of wave 1 is interfering with the stationary component, an important aspect of the linkage between planetary waves and persistent ridging noted by Quiroz (1987).

Using filtered winter data for a 30 year period, Lejenas and Madden (1992) noted that the frequency at which a retrogressive wave 1 ridge aligned with persistent mid-Pacific ridges is considerably lower than it is over Asia or North America. Their study does not give any indication of the amplitude of wave 1 as it moves from east-to-west across the North Pacific. Of the ten events discussed in this paper, the only one in which a wave 1 ridge made a significant contribution to a MPR was the previously mentioned Feb-Mar 1989 case. There were three other events in which a westward moving wave 1 was superimposed over a MPR. In all three of those events the amplitude of wave 1 was on the order of 30-60 m, in effect wave 1 ridge made little or no contribution to the MPR when compared to waves 2-4.

The results of the planetary wave analysis for these 10 events are similar in many respects to the work of Austin (1980). In her study of two mid-Pacific events, she suggested that MPRs develop when high amplitude ridges of waves 2 & 3 constructively interfere over the mid-Pacific, while the amplitude of wave 1 remains well below its climatological value. She also noted the westward movement of wave 1 during MPR events.

6. OLR Anomalies

In order to investigate any correlation between OLR anomalies and persistent ridging in the mid-Pacific, seven day averaged OLR anomalies were constructed for each of the ten events. A composite of the ten events was then constructed as well. The first selected time period spans the seven day period prior (days -6 to 0) to the development of a MPR, while the second period spans the first seven days of the event (days 1 to 7). The composite for days -6 to 0 shows significant negative OLR anomalies straddling the equator between 70°E and 110°E with a smaller area of positive anomalies lying between 140°E and 170°E as shown in Figure 3. The composite for days 1 to 8 indicates that the area of negative anomalies has shifted to the east and now lies between 100°E and 160°E.

These patterns are consistent with the correlation that Weickmann et al (1985) found between OLR anomalies in the eastern Indian Ocean and extreme western Pacific Ocean (EI/WP) and 250 mb streamfunction anomalies over the Northern Hemisphere, using 28-72 day filtered data. Enhanced convection (negative OLR anomaly) over the EI/WP region causes the East Asian Jet to retract over the western Pacific (Lau and Boyle 1987). In a study of circulation anomalies in the North Pacific using 10 day low pass filtered data, Higgins and Mo (1995) found that OLR anomalies were largest more than a week prior to the onset of seven MPR cases. They argue that the retraction of the EAJS from the western Pacific is linked to the weakening of the west Pacific Hadley cell as well as the production of a Rossby wave of tropical origin.

Table 3: Mean 300 mb zonal wind anomalies (ms^{-1}) for days -1, 0, +1 along the 140° meridian for ten event composite.

25°N	30°N	35°N	40°N	45°N	50°N
-4.7	-6.5	-3.4	-1.0	+8.0	+8.3

Low pressure forms over East Asia and higher than normal pressure over the central Pacific, which essentially provides an environment that is conducive to the formation of a MPR. Inspection of OLR anomalies for each event indicates that five out or the 10 cases had patterns that were duplicates of the composite. Four of the remaining cases were in partial agreement, in other words, they contained an area over the EI/WP that indicated significant negative anomalies but non-existent or weak positive anomalies toward the dateline. One case had a OLR pattern that was for unknown reasons, completely reversed from the composite.

Using results from a barotropic model, Renwick and Revell (1999) made an argument for the coupling of OLR anomalies and persistent ridging in the central and eastern South Pacific. They found that the location of the tropical forcing was of prime importance to the formation of PRs. The authors also noted that the correlation between persistent ridging and OLR anomalies was highest when OLR anomalies led by 10 days. As will be suggested in the next section, there is an important link between OLR anomalies in the EI/WP and the development of mid-Pacific ridging.

7. Wind Anomalies

The association between wind anomalies, particular the EAJS and blocking over the Pacific ocean has been noted by Rex (1950a) and Dole (1986) to name a few. Inspection of a composite three day (days -1, 0, +1) mean of 300 mb zonal winds centered along 140° E (Table 3), indicates that south of 40° N there are substantial negative anomalies, with positive anomalies lying to the north. There is considerable case-to-case variability depending on the position of the upstream low/trough.

Using a 10 case composite, negative wind anomalies over the western Pacific start to develop around day -6, and slowly increase in magnitude reaching 15-20 ms^{-1} by day -2. In the tropics, there are noticeable wind anomalies as well. Stretching from about 140°E to the dateline, speeds of the easterly winds are reduced, and in some areas, easterlies are replaced by light westerlies.

As a further indicator of wind anomalies over east Asia and the western Pacific, streamfunction anomalies were constructed following the technique described by Weickmann et al (1985) for high-pass filtered data. The results are shown in Table 4. The East Asian (EAS) and Pacific (PAC) streamfunction indices clearly show an increase in negative values leading up to day 0. Negative values of both of these indices is indicative of higher than normal heights over Southeast Asia, lower than normal heights in the southwest North Pacific and higher than normal heights over the greater Sea of Okhotsk region.

In an attempt to find precursors to MPR development, 300 mb wind anomalies were analyzed over Asia from days -8 to day -1. Due to large case-to-case variance, the composite (not shown) for each of these days does not reveal a coherent pattern in the vicinity of the West Asian Jet Stream (over Saudi Arabia) or over central Siberia. For example, there are some cases which have + 15 to +25 ms^{-1} wind anomalies over northern Mongolia as the upper tropospheric trough intensifies before reaching the East Asian coast. Other cases however have negative anomalies in the same region or no anomaly at all.

Dole (1986) found that several days prior to the development of high amplitude persistent Pacific trough/ridge couplets, that the EAJS shifts north of its mean climatological position. He also noted the development of a sub-tropical jet in the vicinity of the dateline extending toward the Hawaiian Islands. The wind analysis of the 10 MPR cases supports the findings of Dole and further suggests that the apparent northward shift in the jet is the result of: (1) enhanced convection over the EI/WP which then produces an anomalous circulation center in the southwest Pacific, and facilitates the development of a sub-tropical jet centered near the dateline (Weickmann et al 1985). (2) The positive wind anomalies located over northern Japan are due in large part to the deepening of a trough center over the Sea of Okhotsk.

Once a MPR is in its *mature phase*, wind speeds in the jet core region just off Japan's southeast coast show considerable case-to-case variance. However, the over all trend is that zonal wind speeds at 300 mb are often normal or near-normal, indicating that negative speed anomalies in the jet core *are not* a necessity once a MPR has formed. It is interested to speculate on the role that *downstream* low/troughs might play in the evolution of MPRs. Since large positive upper tropospheric wind anomalies occur in conjunction with downstream lows/troughs located over the eastern Gulf of Alaska and western British Colombia, could these strong winds interact with the elevated terrain of the North America Cordillera, and generate upstream planetary waves that help maintain the ridge?

Table 4: Streamfunction anomaly indices ($10^6\ m^2\ s^{-1}$) for ten event composite.

level=260 mb (sigma=0.258)

Day:	-7	-6	-5	-4	-3	-2	-1	0
EAS	-0.6	-0.1	+0.3	-1.0	-1.0	-2.3	-4.0	-4.3
PAC	-2.0	-1.5	-1.4	-4.5	-6.8	-8.5	-8.4	-6.7

level=170 mb (sigma=0.168)

Day:	-7	-6	-5	-4	-3	-2	-1	0
EAS	-1.2	-1.0	-0.5	-2.3	-3.5	-3.7	-3.6	-4.4
PAC	-2.4	-2.1	-2.3	-5.3	-8.3	-8.3	-6.4	-5.0

8. Conversion to Anticyclones

Visual inspection of the 500 mb heights shows that six of the ten MPRs were transformed into anticyclones located over the Bering Sea or Alaska. This transformation occurred as the previously stationary *upstream* low/trough center, moved toward the ESE, effectively "undercutting" the ridge. Figure 4 shows a composite of 200 mb temperature anomalies for the six cases that were transformed into anticyclones. Notice how the warm anomaly over the Sea of Okhotsk on day -2 moved into the mid-Pacific on day +2. A similar but reversed temperature pattern occurred in the troposphere. During the conversion process the amplitude of the MPR over the Bering Sea was not always decreasing. In some cases, the ridge was simply "undercut" with little change in it's amplitude.

While the *upstream* low/trough moved to the southeast, the *downstream* low/trough typically remained quasi-stationary or moved slightly to the east . The March 1997 event was unique in that the downstream low/trough was positioned over the Gulf of Alaska as the conversion to an anticyclone began. This low subsequently moved to the southwest (simultaneous with small retrogression in wave 2), and merged with the upstream low/trough near 170°W.

In five of the six MPR-to-anticyclone cases, there was clear evidence of jet streaks (300 mb level) moving across the western Pacific from Japan to the dateline. This initiated the redevelopment of the EJAS across the central Pacific, with the flow becoming quasi-zonal or exhibiting a low amplitude wavetrain. The overall conclusion from temperature, height and thickness analysis (not shown) is that upstream low/trough develops into a baroclinic wave, allowing it to move toward the southeast. Why the low/trough becomes unstable at that particular time needs further clarification.

9. Stratospheric Warmings

Labitzke (1965) was the first to note that minor stratospheric warmings preceded PR in the Atlantic by 10 days. Green (1980) analyzed six Pacific PR stratospheric warming cases and found that warmings occur prior, during and after PR. In a more extensive study, Quiroz (1986) examined 25 cases of PR that occurred in the Northern Hemisphere, including seven cases in the Pacific sector, and found that 85% of PR events were in some way linked to stratospheric warmings. Although there was considerable case-to-case variance, he found that on average PRs led warmings by about 3.5 days (however the standard deviation was 7 days).

In the current study, five PR events were concurrent with major stratospheric warming (10 mb level), and one event associated with a minor warming (three of the remaining four events were associated with minor cool anomalies. Table 1 indicates that there is a strong correlation between the east phase of the quasi-biennial oscillation (QBO) and MPRs that occur in conjunction with stratospheric warmings. In five of the six warming cases, the stratosphere at the 10 mb level warmed 7 to 10 days *prior to* the development of the MPR (Figure 5). These warm episodes extended throughout the life of the MPR. Although these warm episodes were generally centered on the North Pole, in five of the six cases the largest warming *prior to* MPR development occurred over Siberia. This is consistent with the aforementioned elongation of the polar vortex. Warm stratospheric air over Siberia should induce lower than normal tropospheric heights over the same region (Hirschberg & Fritsch 1993). Significant changes in the temperature and wind patterns in the stratosphere can of course alter the propagation of planetary waves (Austin 1980). The specific role played by stratospheric warm episodes over Siberia on the subsequent generation of MPR's, should be considered from a hydrostatic and planetary wave perspective.

10. Discussion

In order to further the understanding of why only a limited number of ridges that form each season in the western and central North Pacific amplify and become MPRs, ten short-wave ridges were analyzed with respect to planetary waves, wind and OLR anomalies. These cases ranged from modest to large amplitude ridges that moved from west-to-east across the dateline. The duration of these cases ranged from two to four days.

Planetary wave analysis indicates significant differences between the 10 short-wave ridges and the 10 MPR events. The two primary results from the short-wave ridge analysis are: 1) wave 1 dominates with its *trough* positioned over the mid-Pacific. 2) Wave 2 ridges are rarely aligned with the short-wave ridges. This is in sharp contrast to the data listed in Table 2 for the MPR cases, in which wave 2 is dominate and the amplitude of wave 1 is diminished.

Zonal wind analysis (300 mb) of the 10 short-wave ridge cases does not show the same retraction of the EAJS over the western Pacific as for the MPR cases. However, there are some significant wind anomalies located between 180° and 160°W from day -6 to day -2. By day 0 however, the only significant wind anomalies are associated with the developing disturbance. OLR anomalies in the days prior to the onset of a short-wave ridge do appear over the EI/WP region in most of cases. However, when compared to the MPR cases, the area of large negative anomalies is shifted further east, which may be the reason there are wind anomalies east of the dateline.

Operational climatologists frequently monitor monthly climate indices in an effort to predict long-range weather patterns. Table 5 provides a lists of the values of seven indices *contemporary* with each of the 10 MPR events, in the hopes that some type of "signal" might be apparent. In cases where the event occurred across two months, the monthly values were averaged. Overall, there is a mix of positive and negative values, indicating little correlation between MPRs and most of the indices. There are, however, some areas of note.

Mullen (1989) and Renwick and Wallace (1996) found during negative phases of ENSO (warm episodes), there is a strong tendency for PR to occur in the eastern Pacific with a reduction of events in the western and central Pacific. The data listed as SOI in Table 5, is a two month average centered around the event, shows a mix of results. Note that most SOI values used to determine the phase of ENSO, are a seasonal average (four to six months), and hence mask low-frequency variations. MPRs do occur during El Nino's, however, they occur with considerable less frequency than PR in the eastern Pacific and west coast of North America.

The Pacific Decadal Oscillation (PDO) represents a measure of SSTs across a large area of the central North Pacific. Bond and Harrison (2000) showed that persistent mid-Pacific ridging occurs more frequently when the PDO signal is negative (warm anomalies). The indices listed under PDO in Table 5 once again show a mix of regimes. It is not know why there is not a bias toward negative values in the data set, but one could speculate that since the Bond and Harrison data set ranges from 1958 to 1997, it does not capture short-term (i.e.-decadal) trends within the period. It would be of interest to see if the coupling of ENSO and PDO indices provides a more robust index for pattern anomalies across the North Pacific. Yearly and decadal trends would also be important to consider (Overland *et al* 1999).

Of all the values listed in Table 5, both the Arctic Oscillation (AO) and North Atlantic Oscillation indices show the strongest correlation with MPR's. Both of these indices tend to be in the positive phase during MPR events. The positive phase of the AO indicates a stronger than normal polar vortex with negative sea-level pressure anomalies over the Arctic Basin, a significant positive anomaly over the North Atlantic, with a weaker positive anomaly over the central North Pacific (Baldwin and Bunkerton 2001). These are also consistent with the planetary wave analysis, which indicates that during many MPRs, the northern Hemisphere is dominated by a two wave pattern, with one ridge in the mid-Pacific and the other in the mid-Atlantic. These are the same areas that experience anomalous positive sea-level pressure anomalies.

include

Values of the AO approximately one month prior to each MPR is given as AO -1 in Table 5. Notice the predominance of positive values. The positive phase of the AO (and NAO) has been dominant throughout the 1980's and 1990's, so it is not too surprising that the majority of MPRs occur during this phase. It is, however, one climate element that can be monitored and used to evaluate the potential for MPR development.

In the future, considerable work should be directed toward improving our understanding of MPRs in the context of short-term climate and flow anomalies which frequently occur in the Northern Hemisphere. Specifically, why is mid-Pacific ridging more prevalent during cool phases of ENSO and warm phases of the PDO, and how is it linked to planetary wave amplitude and phases? Is the influence of the Arctic on weather/climate in the North Pacific larger now that it has been in past decades as suggested by Overland *et al* (1999)? What are the trends in the interannual and decadal frequency of persistent mid-Pacific ridging, and how does it factor into the overall climatology of the Pacific Basin (Wiedenmann *et al* 2002)? And finally, what role do stratospheric anomalies play in the evolution of persistent ridging?

11. Summary and Conclusions

This study has investigated 10 cases of persistent mid-Pacific ridging and found that multiple atmospheric parameters must be in alignment in order for these events to develop. MPRs form within a wide variety of synoptic pattens, and frequently there is some type of pre-existing positive height anomaly located over the central North Pacific. There is also evidence that significant height anomalies form in the middle stratosphere over eastern Siberia in conjunction with a elongation of the polar vortex toward Siberia and a reduction in heights just to the north of Scandinavia. And it was found that seven of the ten cases evolved into large anticyclones over the greater Bering Sea region.

There is a high correlation between MPRs and mid-latitude planetary waves. In particular, most but not all MPRs develop near a pre-existing planetary wave, with waves 2-4 dominating. Composite analysis of the 10 events show that wave 2 has the highest amplitude. Of equal importance to MPR formation is the reduction in the amplitude of wave 1, which climatologically is associated with a persistent trough located across the North Pacific.

Significant links between MPRs and OLR anomalies were shown via the use of seven day composite analysis. Wind anomalies associated with the East Asian Jet Stream and in the tropics develop prior to the onset of MPRs and are linked in part to enhanced convection and outflow over the eastern Indian and extreme western Pacific Oceans.

In summary, a MPR will develop if a deep low/trough over east Asia is able to constructively interfere and hence amplify pre-existing planetary waves 2-4. Monitoring the amplitudes and phases of the first four or six planetary waves in real time and as forecast in extended range numerical models will give some indication whether the environment in the mid-Pacific is conducive for the development of a MPR. In conjunction with the movement of a deep low/trough out of eastern Siberia, enhanced tropical convection between 80°E -120°E appears to be linked to the retraction of the EAJS from the west Pacific, which gives the appearance that the EAJS has shifted about 10° of latitude north of its climatological position, giving it more of a southwest-northeast trajectory. The dynamic link between a retracted EAJS and MPR development was beyond the objective of this paper, nevertheless, it may allow an air mass with low potential vorticity, originating in the tropics and sub-tropics to be advected to mid and high latitudes (Pelly and Hoskins 2003).

Finally, it appears that the formation of persistent mid-Pacific ridge is a function of anomalies in the tropics (OLR), mid-latitudes (planetary waves, 300 mb winds) and to some degree the arctic (deeper than normal trough over Siberia, stratospheric warmings). Because all these forcings must occur almost simultaneously, the number of MPRs that form each season is limited.

In the near future we hope to compare and contrast mid-Pacific persistent ridging that occurs during the summer months with the results of the current paper. Due to a greatly reduced EAJS during the summer months, significant differences between winter and summer regimes is anticipated. A study of persistent ridging in the Gulf of Alaska and western North American will be conducted as well.

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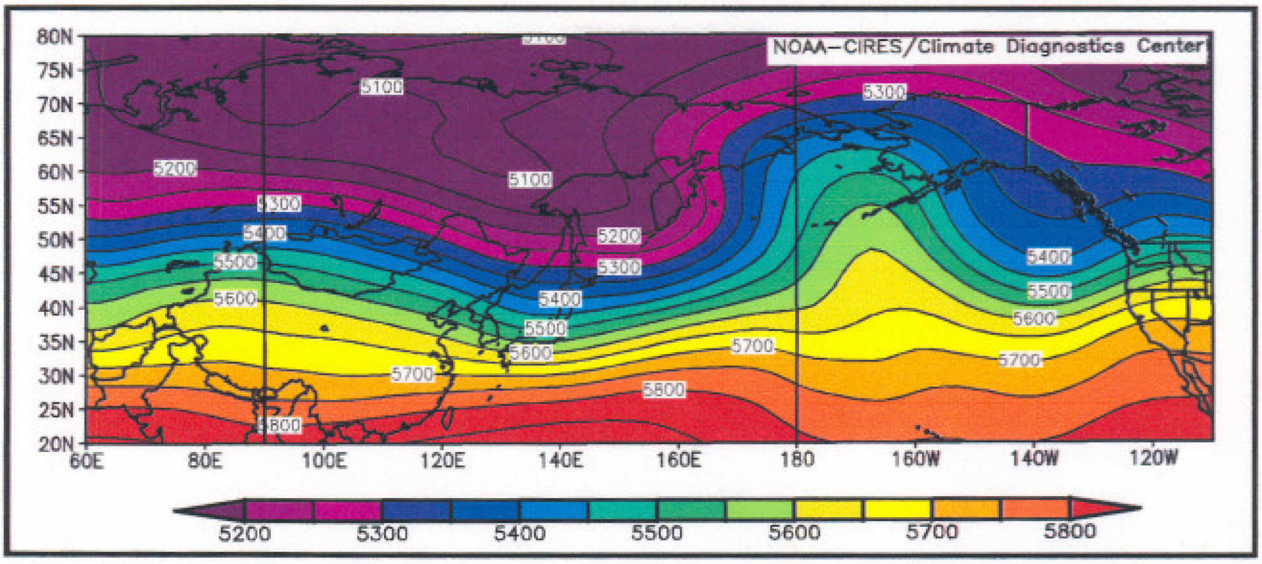

Figure 1: Ten event composite 500 mb heights at day +4 (contour interval of 50 m)

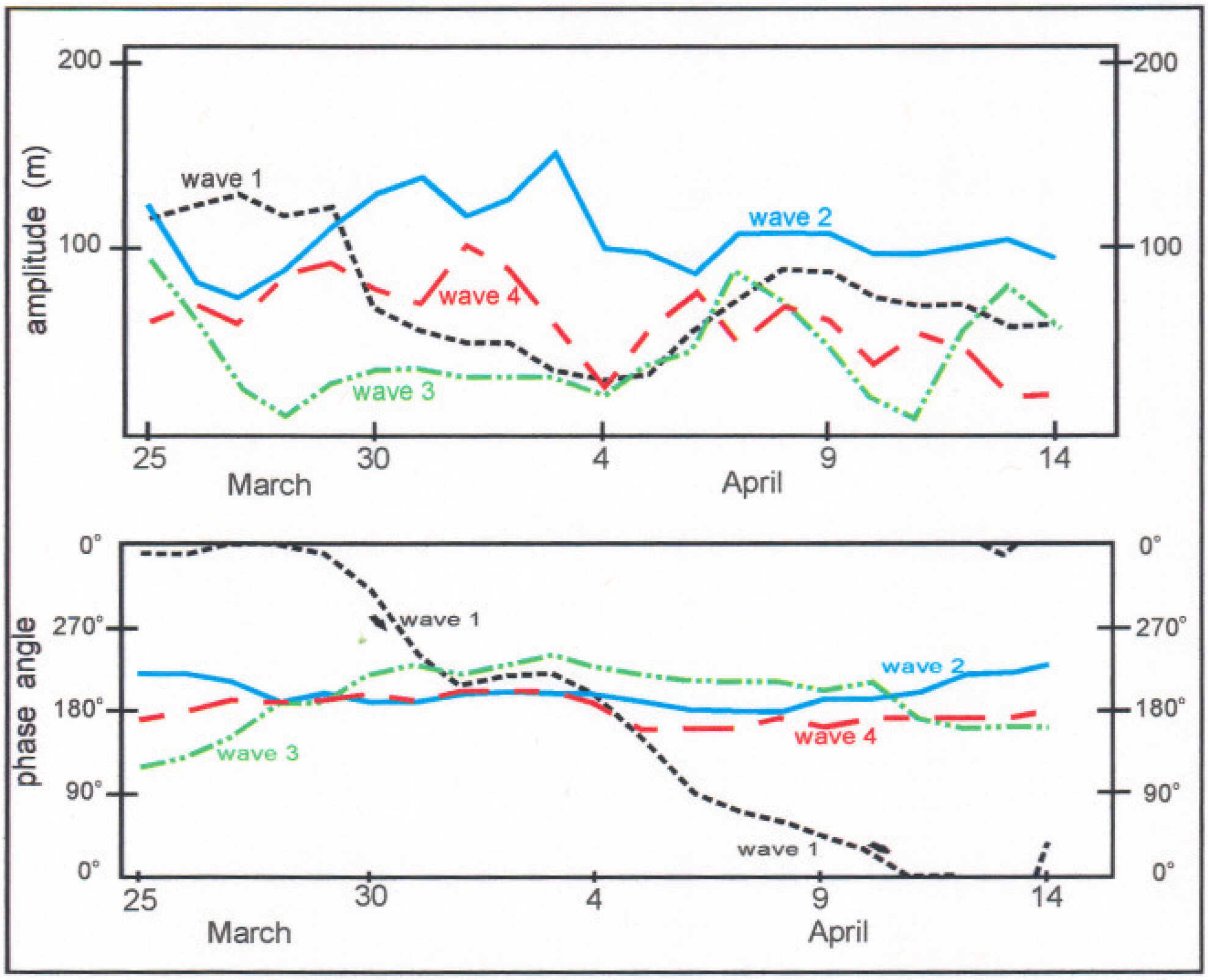

Figure 2: Amplitude (top) and phase (bottom) of waves 1-4 for March 15-April 14, 2002 event

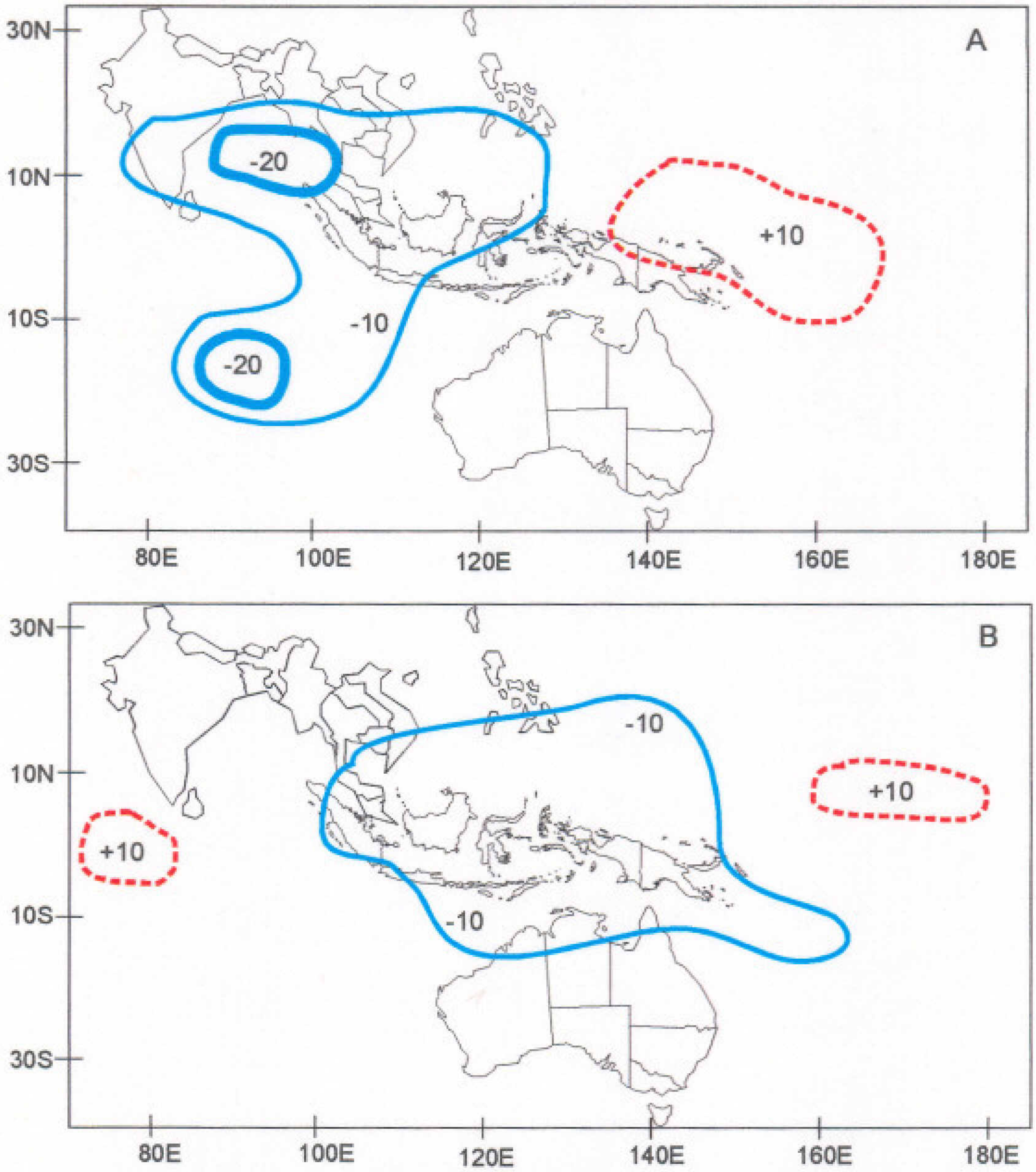

Figure 3: Ten event composite OLR anomalies for: (A) days -6 to 0 (B) days +1 to +7. Contour interval 10 Wm^{-2} with zero contour omitted.

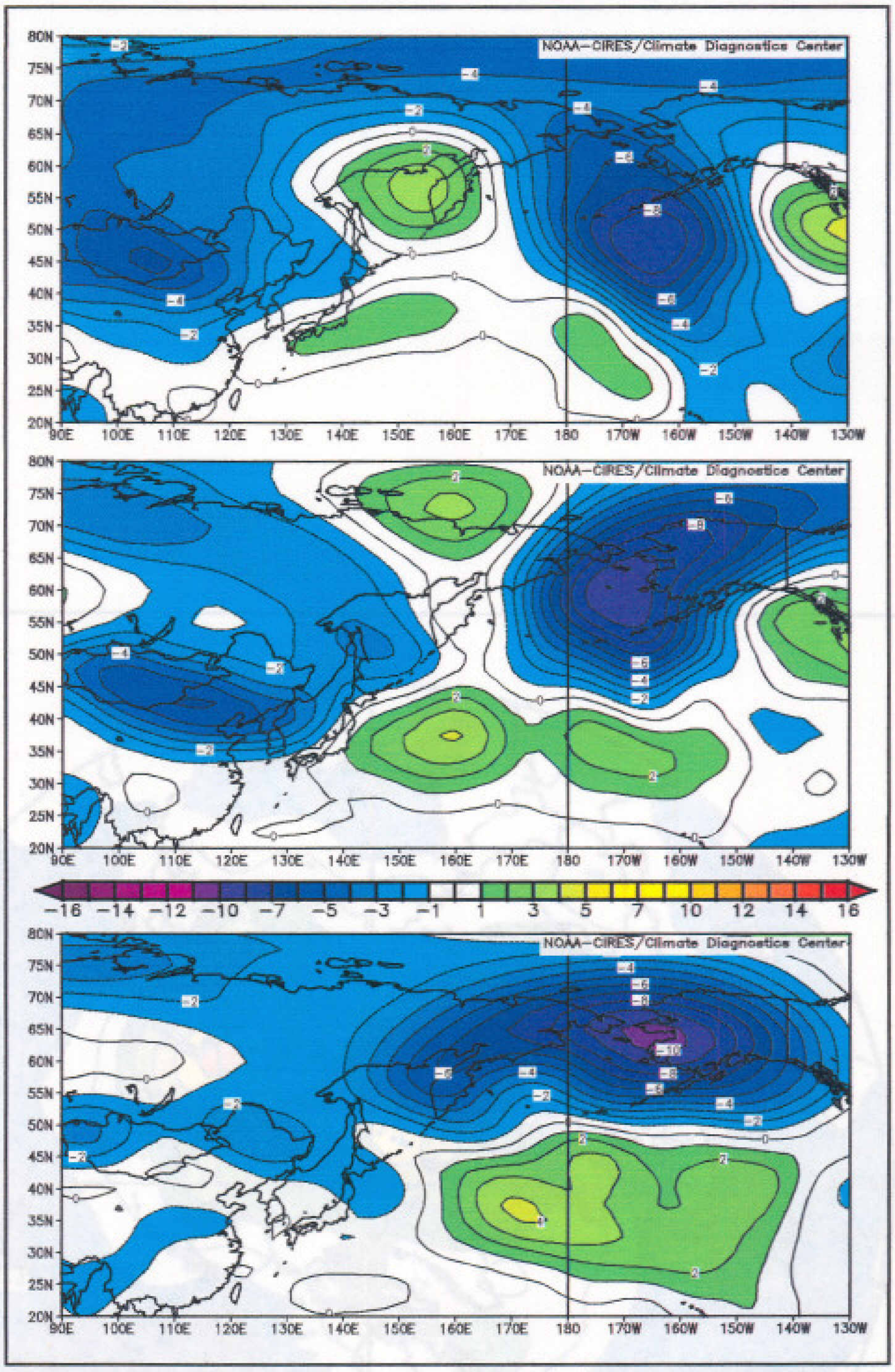

Figure 4: 200 mb temperature anomalies (1° C contour interval) for the six events that evolved into anticyclones. Dashed lines are negative anomalies with solid lines positive anomalies. (top) day -2, (middle) day 0, (bottom) day +2.