Persistent North Pacific Circulation Anomalies and the Tropical Intraseasonal Oscillation

R. WAYNE HIGGINS AND KINGTSE C. MO

Climate Prediction Center, NOAA/NWS/NCEP, Washington, D.C.

(Manuscript received 11 March 1996, in final form 27 June 1996)

ABSTRACT

A composite analysis of multiyear (1985–93) global reanalyses produced by the NCEP/NCAR and the NASA/DAO is used to show that the development of persistent North Pacific (PNP) circulation anomalies during NH winter is linked to tropical intraseasonal oscillations. The development is initiated over the tropical west Pacific by anomalous convection (characterized by an east–west dipole structure) one to two weeks prior to the extratropical onset time in both reanalyses. As tropical heating moves eastward toward the central Pacific, anomalous divergent outflow associated with the local Hadley circulation generates an anomalous Rossby wave sink (source) in the subtropics, consistent with the retraction (extension) of the Pacific jet. Prior to onset the signature of the forced anomalies is a pair of cyclonic (anticyclonic) circulation anomalies centered near the node of the tropical heating dipole. Wave trains extending from the region of anomalous convection into the extratropics set the stage for the subsequent rapid development of the PNP anomalies. After onset, the mature PNP anomalies extend equatorward to feed back (through modifications to the moisture transport) on the tropical precipitation anomalies. Throughout the evolution, the tropical precipitation anomalies and the extratropical PNP anomalies evolve coherently with tropical intraseasonal oscillations in both reanalyses.

1. Introduction

Efforts to identify and describe large-scale persistent atmospheric flow anomalies (e.g., Wallace and Gutzler 1981; Dole and Gordon 1983; Dole 1986a,b; Dole and Black 1990; Higgins and Schubert 1996) found in the exit regions of the major midlatitude jet streams have done much to advance our understanding of intraseasonal variations having timescales of a week or more. These, and other studies, suggest that persistent anomalies are recurrent low-frequency “modes” with striking case to case structural similarity. The fully established persistent anomaly patterns project strongly upon the leading atmospheric teleconnection patterns (Wallace and Gutzler 1981) and are linked to long-lived extremes in surface weather (e.g., Dole 1986a).

Explanations of the physical mechanisms responsible for persistent anomalies have generally been based on the similarity of these structures to the response to tropical/subtropical forcing and/or unstable modal structures found in various simplified models (e.g., Simmons et al. 1983). In this study we examine the linkage between observed persistent atmospheric flow anomalies over the North Pacific and the tropical intraseasonal oscillation (IO) in an attempt to isolate the possible forcing of persistent anomaly events by tropical heating.

There is strong evidence for the linkage between the extratropical circulation and tropical heating on interannual timescales from studies of El Niño–Southern Oscillation (e.g., Horel and Wallace 1981; Geisler et al. 1985; Lau 1985; Lau and Boyle 1987; Rasmusson and Mo 1993). On intraseasonal timescales several studies have focused on the linkage between the Madden-Julian oscillation (MJO) and the extratropical circulation. Statistically significant links between the outgoing longwave radiation (OLR) tied to the MJO and fluctuations in the east Asian jet during NH winter were found by Weickmann et al. (1985) and Knutson and Weickmann (1987). Lau and Phillips (1986) found evidence for a quadrature relationship between east–west dipole convection anomalies associated with the MJO (Weickmann 1983; Lau and Chan 1985) and extratropical wave trains. Their results suggested a mutual forcing over the Indian Ocean and western Pacific in which the extratropical wave trains both force and respond to tropical convection. There is also evidence for a linkage between tropical convection and the extratropical circulation at higher frequencies (Livezey and Mo 1987; Liebmann and Hartmann 1984; Liebmann 1987; Kiladis and Weickman 1992).

In addition to the observational evidence, there is also a strong theoretical framework for the response of the large-scale circulation to tropical convection (e.g., Matsuno 1966; Webster 1972) and for the role of the extra-
tropical circulation in forcing tropical convection (e.g., Lau and Li 1984; Liebmann and Hartmann 1984; Zhang and Webster 1992). A central issue to the problem of tropical–extratropical interaction concerns wave propagation between hemispheres (Webster and Holton 1982; Webster 1973a,b; Tomas and Webster 1994). These and other studies indicate that wave energy can propagate most freely into the deep Tropics in regions of westerly flow; during northern winter this should be most evident in the eastern Pacific where tropical westerlies are the strongest.

Studies that have focused on the life cycles of persistent midlatitude flow anomalies have generally produced little evidence of a strong connection to tropical forcing. Black (1996) argued that anomalous wave sources were local to the persistent anomaly region and that remote forcing played little or no role during the life cycle of persistent North Pacific anomalies. Higgins and Schubert (1994) and Black and Dole (1993) illustrated the importance of forcing by synoptic-scale eddies and large-scale transient development, respectively, during the lifecycle of persistent events. On the other hand, a recent study by Higgins and Schubert (1996) (hereafter HS96) analyzed simulations from a general circulation model and found that tropical heating on intraseasonal timescales was phase locked with the development of persistent North Pacific anomalies. Overall, their results were not inconsistent with the idea that, on the intraseasonal timescale, the primary role of the Tropics is that of a catalyst or initiator of midlatitude modes (e.g., Sardeshmukh and Hoskins 1988), which then grow through local energy exchanges with the mean jet (Simmons et al. 1983; Branstator 1985).

Attempts to study the role of the Tropics in persistent anomaly development have been limited by many factors including the lack of observations over the oceans, inconsistencies in the divergence or heating fields in analyses, and/or GCM deficiencies in the simulation of low-frequency variability. Recently, the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and the Data Assimilation Office (DAO) at NASA’s Goddard Space Flight Center have completed multyear (1985–93) global reanalyses. The reanalyses provide a valuable product for the research community because they are produced with state-of-the-art fixed assimilation systems and large input databases. The reanalysis datasets and the assimilation systems used to produce them are documented in Kalnay et al. (1996) and Schubert et al. (1993), respectively.

This study capitalizes on the reanalysis datasets, to diagnose the role of remote tropical forcing in persistent anomaly development over the North Pacific. Our goal is to show that tropical forcing plays an important role in the initiation of persistent North Pacific (PNP) anomalies (in a composite mean sense) thereby providing a focus for ensuing studies on the precise nature of the source mechanisms. In this study we consider intraseasonal variability greater than about 10 days; no attempt is made to separate the Madden–Julian oscillation (i.e., the 30–70-day band) from higher-frequency tropical oscillations, though this may be a necessary refinement in order to fully understand the tropical–extratropical linkage (e.g., Kiladis and Weickmann 1992). The reanalyses produce quite realistic Pacific anomaly events and provide sufficient occurrences of the anomalies to allow defining statistically reliable composite anomalies. In data sparse regions, where the reanalyses depend heavily on the model and analysis scheme, the intercomparison becomes important. Agreement between the reanalyses will increase the reliability of the results, while differences will serve as our basic measure of uncertainty. The current study considers only persistent anomaly events in the North Pacific during NH winter. In a companion paper (K. Mo and R. Higgins 1997, manuscript submitted to J. Climate, hereafter MH97) we examine persistent anomaly events in the South Pacific during SH winter and make some comparisons to the results presented here.

Section 2 describes the reanalysis datasets and the analysis technique. A comparison of selected climate statistics highlighting the quality of the reanalyses is given in section 3. Section 4 presents the composite mean circulation features during the mature phase of PNP events including related features in the Tropics and subtropics. Section 5 establishes the linkage between the tropical IO and PNP events with a focus on the composite evolution prior to onset. Section 6 uses a 200-hPa vorticity budget to describe a potential physical mechanism for the developments. A summary and discussion are given in section 7.

2. Data and analysis technique

The primary data used in this study are daily averaged global gridded fields (precipitation, geopotential heights, winds and specific humidity at standard pressure levels) from the NCEP/NCAR and the NASA/DAO reanalyses for eight 90-day winter seasons (starting 1 December) extending from 1985/86 through 1992/93. The NCEP (DAO) data are on a 2.5° × 2.5° (2° × 2.5°) latitude–longitude grid. The precipitation is obtained from the 0–6- (0–3-) hour accumulations during the forecast cycle for the NCEP (DAO). Daily averages of the NOAA satellite OLR for the same period are used to represent tropical convection and to “validate” tropical precipitation patterns from the reanalyses.

Anomalies are defined as deviations of the field from the local seasonal cycle (defined as the grand mean plus annual and semiannual harmonics for each reanalysis separately). The anomaly time series are low-pass-filtered (Blackmon and Lau 1980) to remove periods less than approximately 10 days. Persistent anomaly cases are selected using the threshold crossing procedure of Dole and Gordon (1983). The 500-hPa height anomaly threshold and duration criteria used are (+100 m, 10 days) and (−100 m, 10 days) for positive and negative persistent anomaly cases, respectively. Individual case onset and termination dates are determined by applying

Unauthenticated | Downloaded 12/10/21 01:40 PM UTC
the selection criteria at the specific regional local maximum in persistent anomaly occurrence (the "key" point). For the North Pacific cases the key point is 50°N, 162.5°W in both reanalyses.

Composite evolution fields for cases of a given sign are obtained by averaging over all cases relative to the time when the height anomaly at the key point first crosses the threshold magnitude (100 m); this time is designated as the onset day or "day 0." Lagged composites of various fields were constructed each day for the 30-day period from 10 days prior to onset (day −10) to 19 days after onset (day +19).

In section 6 we use the one-level vorticity balance diagnostic approach of Sardeshmukh and Hoskins (1988) to examine a possible physical mechanism linking anomalous tropical forcing to the extratropical PNP anomalies. The equation can be written as

$$\frac{d\zeta}{dt} + \mathbf{v}_o \cdot \nabla (\zeta + f) = S + \mathbf{k} \left( \frac{\partial \mathbf{v}}{\partial p} \times \nabla \omega \right) - \mathbf{\omega} \cdot \nabla \zeta + F,$$

where $\zeta$ is the relative vorticity, $\mathbf{v}$ is the horizontal vector wind, $\mathbf{v}_o$ is the rotational wind, $\omega$ is the vertical velocity, $f$ is the Coriolis parameter, and $F$ is the friction term, which is negligible for the scale of interest (Mo and Rasmusson 1993). Here, $S$ is the effective Rossby wave vorticity source (hereafter RWS)

$$S = -\nabla \cdot [\mathbf{v}_s (\zeta + f)],$$

in which $\mathbf{v}_s$ is the divergent wind. Here, $S$ includes contributions from both vortex stretching and the advection of absolute vorticity by the divergent wind; that is,

$$-\nabla \cdot [\mathbf{v}_s (\zeta + f)] = -(\zeta + f) \mathbf{\nabla} \cdot \mathbf{v}_s - \mathbf{v}_s \cdot \nabla (\zeta + f).$$

For the NCEP, calculations were in the spectral domain and a spatial smoothing (Sardeshmukh and Hoskins 1984) using wave 20 was applied to $S$. This approach was used by Rasmusson and Mo (1993) to link circulation changes in the extratropics to tropical convection during ENSO and by Berbery and Paegle (1993) to study intraseasonal interactions between the Tropics and the SH extratropics. Prior to compositing, the seasonal cycle is removed from each term in (1) and a low-pass filter is applied.

3. Seasonal mean and variance

This section presents a comparison of selected climate statistics highlighting the quality of the reanalyses, par-
Fig. 2. Hovmöller diagrams of the 200-hPa zonal mean zonal wind for March 1985–November 1993 in (a) the NCEP reanalysis and (b) the DAO reanalysis and (c) the difference (NCEP – DAO). The contour intervals are (a) 5 m s\(^{-1}\), (b) 5 m s\(^{-1}\), and (c) 1 m s\(^{-1}\). In (a)–(c) the shading corresponds to areas where the values are less than zero.

particularly as it relates to the discussion in the following sections. Figure 1 compares the seasonal mean 200-hPa eddy (zonal mean removed) streamfunction (Figs. 1a and 1b) and the precipitation (Figs. 1c and 1d) for DJF 1985/86–1992/93. The streamfunction patterns show generally good agreement (e.g., the Hudson Bay trough, the Gulf of Alaska ridge, the east Asian trough) though there are features with significant differences in amplitude (e.g., the subtropical ridge southeast of Asia). The precipitation maps both show well organized intertropical convergence zones (ITCZs) over the equatorial Pacific, southern Africa, and Brazil. The ITCZ over the
The equatorial Pacific is somewhat broader in the NCEP reanalysis. Rainfall over the maritime continent is somewhat heavier and more coherent and the south Pacific convergence zone (SPCZ) is stronger in the DAO reanalysis. The winter storm tracks in the NH have somewhat more precipitation in the NCEP reanalysis. Some large regional differences are found in the lee of the mountains (e.g., over South America east of the Andes) suggesting that both reanalyses have difficulty resolving topographically related features. For the 8-winter period, global mean precipitation rates are 2.43 mm day$^{-1}$ (2.65 mm day$^{-1}$) in the DAO (NCEP). The precipitation from both reanalyses for this period is compared to standard climatologies and satellite estimates in Mo and Higgins (1996).

In Fig. 1 we showed eddy streamfunction, rather than streamfunction itself, because there are systematic differences in the zonal mean circulation. An examination...
of the 200-hPa zonal mean zonal wind (Fig. 2) illustrates these differences. The zonal mean fields (Figs. 2a and 2b) are similar but the difference field (Fig. 2c) shows appreciable systematic differences, especially in the high latitudes of the SH. The differences shown here are also fairly large in the gradient regions of the subtropics and tend to follow the annual cycle. They are likely related to differences in the regional Hadley circulation (not shown; see Mo and Higgins 1996) and in the vertical distributions of atmospheric heating and vertical velocity (recall that the vertical resolutions are different). We note that differences at the equator may be significant with respect to oceanic coupling. In view of these differences, we often remove the zonal mean before intercomparing fields; hereafter, quantities with the zonal mean removed are referred to as eddies.

In the Tropics the IO is associated with the systematic eastward movement of low-frequency large-scale convection and circulation anomalies (Madden and Julian 1972). It has been shown to be predominantly a wave-number one phenomenon (Slingo and Madden 1991) but with some variance also concentrated at wavenumber two (Rui and Wang 1990; Hendon and Salby 1994). The degree to which the reanalyses capture tropical IOs is relevant in this study since they appear to play an important role in the initiation of the PNP anomalies (see sections 5 and 6). The signature of the IO at the equator in the DAO (Fig. 3a) and the NCEP (Fig. 3b) reanalyses during an El Niño year (1987) shows similar features (including periodicity, amplitude, and phase) during all seasons. Substantial interannual variability of the IO is captured in both reanalyses: while the El Niño year (1987) shows a very robust IO, the La Niña year (1988) shows a very weak and disorganized oscillation (Schubert et al. 1995).

The basic patterns of low-frequency variability (LFV), as represented by the standard deviation of the low-pass-filtered 500-hPa eddy height anomalies for the NH winter are similar in the reanalyses (Figs. 4a and 4b); both show the largest LFV over the eastern North Pacific and North Atlantic Oceans in the exit regions of the midlatitude jets. There is also a band of higher variability centered near 60°S. Most contributions to the total standard deviation are from the low frequency band shown here; contributions from synoptic-scale eddies are much smaller and concentrated in the storm tracks. The areas of largest LFV are also the regions where the largest number of (large amplitude) persistent anomaly events occur. The geographical distribution of the sum of positive and negative persistent anomalies at each
grid point (cases selected using the procedure described in section 2) is similar in both reanalyses (Figs. 4c and 4d). The locations of the centers over the NH oceans agree quite well with earlier studies, but the center over northern Russia identified in Dole and Gordon (1983) is not evident in the reanalyses suggesting the possibility for considerable interannual variability. The number of events decreases (increases) when the anomaly threshold and duration criteria are increased (decreased) but the geographical distribution remains roughly the same. The preferred locations for persistent anomalies in the NH seem to show little seasonal dependence, though their numbers decrease dramatically during NH spring and summer (when the same selection criteria are used). Maxima in the South Pacific near 170°E and 130°W (Figs. 4c and 4d) are investigated in MH97.

4. Persistent North Pacific circulation anomalies

Based on the geographical distribution of persistent events (Figs. 4c and 4d), we select PNP events using the key point (162.5°W, 50°N). Examination of Table 1 shows that our selection criteria yield 6 Pacific positive (hereafter PP) and 8 Pacific negative (hereafter PN) cases for the 8-winter period (DJF 1985/86–1992/93) and that all of these events are in common in the reanalyses. PNP events occurred (by our definition) on roughly 36% of the days during this 8 NH winter period. During DJF, the duration of PP events ranges from 12 to 33 days in both reanalyses with an average duration of 20.3 (20.5) days in the DAO (NCEP) reanalysis. The duration of PN events ranges from 13–31 (11–21) days in the DAO (NCEP) reanalysis with an average duration of 19.6 (17.2) days. Overall, 99.2% (87.9%) of the days satisfying the PP (PN) selection criteria are in common to both reanalyses during DJF. Table 1 also suggests that events not in common to both reanalyses tend to have shorter durations, independent of season.

HS96 showed that the circulation features associated with PP events were similar to those associated with PN events but with the sign reversed, especially over the North Pacific. Here we exploit this antisymmetry by presenting the composite difference (positive minus negative) for all days in DJF satisfying the selection criteria.

Composites of 200-hPa eddy streamfunction anomalies during the mature phase (Fig. 5) show that the main PNP anomaly center is accompanied by a strong subtropical anomaly of the opposite sign and by significant downstream development across North America in both reanalyses. There is also evidence of weaker wave trains in the SH extending toward South America. The shading indicates regions where the features are statistically significant at the 95% level (based on a two sided t test with a null hypothesis of zero mean). The composites may be interpreted as a single basic pattern with one polarity associated with blocking and the other with a regionally intensified zonal flow. Near the date line a pair of zonally elongated subtropical anomalies of uneven strength straddles the equator.

The impact on the location and strength of the Pacific jet is considerable (Fig. 6); PP (PN) events are associated with a zonally retracted (extended) Pacific jet and a weaker (stronger) jet core near 30°N. The largest anomalies are found in the left jet exit region (cycloic shear side) on the southern flank of the main PNP anomaly center in each case (see Keyser and Shapiro 1986

<table>
<thead>
<tr>
<th>Type</th>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Duration</th>
<th>Month</th>
<th>Day</th>
<th>NCEP</th>
<th>DAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>85</td>
<td>1</td>
<td>11</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>85</td>
<td>2</td>
<td>28</td>
<td>10</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>85</td>
<td>6</td>
<td>24</td>
<td>18</td>
<td>6</td>
<td>24</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>85</td>
<td>8</td>
<td>14</td>
<td>26</td>
<td>8</td>
<td>12</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>85</td>
<td>11</td>
<td>5</td>
<td>24</td>
<td>11</td>
<td>6</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>85</td>
<td>11</td>
<td>7</td>
<td>11</td>
<td>11</td>
<td>7</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>87</td>
<td>1</td>
<td>12</td>
<td>19</td>
<td>7</td>
<td>19</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>88</td>
<td>1</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>89</td>
<td>1</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>89</td>
<td>2</td>
<td>23</td>
<td>2</td>
<td>2</td>
<td>23</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>89</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>89</td>
<td>6</td>
<td>25</td>
<td>17</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>90</td>
<td>2</td>
<td>8</td>
<td>12</td>
<td>2</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>90</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>23</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>90</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>90</td>
<td>11</td>
<td>19</td>
<td>11</td>
<td>5</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>90</td>
<td>12</td>
<td>22</td>
<td>12</td>
<td>11</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>91</td>
<td>3</td>
<td>26</td>
<td>3</td>
<td>3</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>91</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>10</td>
<td>18</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>92</td>
<td>2</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>99</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>92</td>
<td>12</td>
<td>33</td>
<td>12</td>
<td>14</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>85</td>
<td>1</td>
<td>12</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>85</td>
<td>***</td>
<td>***</td>
<td>13</td>
<td>3</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>85</td>
<td>5</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>30</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>86</td>
<td>1</td>
<td>19</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>86</td>
<td>1</td>
<td>14</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>86</td>
<td>***</td>
<td>***</td>
<td>3</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>86</td>
<td>***</td>
<td>***</td>
<td>6</td>
<td>2</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>86</td>
<td>12</td>
<td>24</td>
<td>12</td>
<td>8</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>87</td>
<td>1</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>87</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>19</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>87</td>
<td>9</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>17</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>87</td>
<td>11</td>
<td>13</td>
<td>11</td>
<td>27</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>88</td>
<td>1</td>
<td>17</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>88</td>
<td>2</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>21</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>88</td>
<td>8</td>
<td>20</td>
<td>8</td>
<td>8</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>89</td>
<td>***</td>
<td>***</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>90</td>
<td>9</td>
<td>17</td>
<td>9</td>
<td>14</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>91</td>
<td>1</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>31</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>91</td>
<td>***</td>
<td>***</td>
<td>5</td>
<td>4</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>91</td>
<td>9</td>
<td>20</td>
<td>9</td>
<td>10</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>92</td>
<td>1</td>
<td>21</td>
<td>1</td>
<td>2</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>92</td>
<td>***</td>
<td>***</td>
<td>5</td>
<td>26</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>92</td>
<td>***</td>
<td>***</td>
<td>6</td>
<td>14</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>92</td>
<td>10</td>
<td>18</td>
<td>14</td>
<td>10</td>
<td>18</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>
for a review of jet structure). Zonal wind anomalies associated with the west Atlantic jet indicate a meridional displacement poleward (equatorward) during PP (PN) events. Near the date line there are tropical westerly (easterly) anomalies during PP (PN) events. During PP events the anomalous tropical westerlies may enhance the propagation of wave energy into the deep Tropics over the eastern Pacific (e.g., Webster and Holton 1972). The meridional wind anomalies (Fig. 7) show a quadrupole (four-celled) structure over the North Pacific. The subtropical anomalies near 20°–25°N indicate a weaker (stronger) regional Hadley circulation during PP (PN) events in both reanalyses. These features are consistent with the linkage to the tropical IO to be described later.

Comparisons of streamfunction (Figs. 5a and 5b) and precipitation (Figs. 8a and 8b) anomaly composites show that the main PNP anomaly center is accompanied by precipitation anomalies consistent with the shift of the storm track. For PP events, the precipitation is enhanced (suppressed) to the northwest (southeast) of the main anomaly center. The precipitation composites also show positive anomalies to the south of the main anomaly center and a dipolelike feature just south of the equator (poles over Indonesia and near the date line). Since forecast products depend on model physics, we also show the observed OLR anomaly (OLRA) composite mean differences (Fig. 8c) for verification (these data were not assimilated). The OLRA also show this dipolelike feature along (and just south of) the equator with enhanced convection (negative OLRA) from 80° to 140°E and suppressed convection (positive OLRA) from 160°E to 160°W. Other notable features in each composite are the suppressed convection along the ITCZ and eastern edge of the SPCZ and the pattern of anomalies along the west coast of North America. Weickmann
(1983) and Lau and Chan (1985) showed that the intraseasonal variability of tropical convection is dominated by a similar dipole (e.g., Fig. 10 in Lau and Chan 1985). The tropical and subtropical rainfall anomalies and OLRA are consistent with variations in the subtropical regional Hadley circulation described in Fig. 7. The midlatitude streamfunction anomalies and the associated tropical precipitation anomalies are indicative of a strong connection between the PNP anomalies and the Tropics.

Another view of the tropical–extratropical teleconnection during PNP events is presented in Fig. 9, which shows that the mature phase is associated with a coherent pattern of anomalous moisture transport spanning the Tropics and extratropics in both reanalyses. Composite daily maps (not shown) indicate that after onset the PNP anomalies gradually push equatorward into the Tropics leading to modified tropical moisture transports that help to reinforce the tropical precipitation anomalies. In the NH subtropics, the anomalous moisture transport is dominated by a cyclonic circulation centered east of the date line near 20°–25°N. Strong easterly moisture transport anomalies are found just south of the equator on either side of the date line with westerly anomalies generally confined to the equatorward flanks of the NH subtropical cyclonic circulations. The divergence of the anomalous moisture flux (Figs. 9c and 9d) shows convergence (divergence) into regions of heating (cooling). Calculations of the separate terms in the moisture flux convergence show that these patterns are primarily determined by the anomalous winds.

5. Linkage to the tropical intraseasonal oscillation

The precipitation anomaly and OLRA patterns in Fig. 8 represent activity during the mature phase of the PNP life cycle (i.e., when the extratropical circulation features are already well established and when the energy sources are local to the key region). We find, however, that linkages to tropical convection appear to be strongest well prior to onset when the heating anomalies over the west Pacific are strong enough to set up dynamical interactions between the tropics and the midlatitudes (see section 6). Examination of lagged composites of pentad mean OLRA and 200-hPa velocity potential anomalies (Fig. 10) shows that the dipole heating anom-
Fig. 7. Composite mean (all PNP anomaly days) 200-hPa meridional wind (contours) and meridional wind anomalies (shaded) for PP events in (a) the DAO reanalysis and (b) the NCEP reanalysis and for PN events in (c) the DAO reanalysis and (d) the NCEP reanalysis. The contour interval is 4 m s\(^{-1}\). The zonal mean has been removed from the meridional wind anomalies and dark (light) shading corresponds to areas where the values are greater than 2 m s\(^{-1}\) (less than \(-2\) m s\(^{-1}\)).
enhanced) tropical convection in both reanalyses (Figs. 12 and 13). This configuration of heating and circulation anomalies has been noted in other studies (e.g., Sardeshmukh and Hoskins 1988; Park et al. 1995). Just prior to onset, an anomaly of the opposite sign appears at the same location in the NH while the original SH anomaly persists and appears to extend east-northeastward. Relatively weak wave trains extend from the trop-ical heating across the North Pacific and (to a lesser extent) the South Pacific; MH97 find that the SH wave trains are more evident in individual cases suggesting that these waves are not as stationary.

Careful inspection of the preonset evolution of individual cases often shows a gradual eastward shift of a midlatitude anomaly located directly northeast of the NH member of the cyclonic (anticyclonic) pair discussed above and of opposite sign; this behavior is apparent in the composites (Figs. 12 and 13) starting about day 8. The onset phase is characterized by the retrogression of anomalies west of North America where they merge with the “forced” anomalies to become a rapidly growing north–south dipole over the eastern North Pacific.

The largest differences between the reanalyses are in the details of the preonset evolution; while both reanalyses show large-amplitude streamfunction anomalies directly north of the tropical forcing plus a series of downstream anomalies extending toward North America, the amplitudes and locations of the maxima and minima differ. In view of the slightly different position and intensity of the tropical convection in each case, the difference in the evolution of the initial NH response is not too surprising. Park et al. (1995), for example, show that the forced response to imposed tropical heating is sensitive to the phase of the heating with respect to the Pacific jet. The best agreement between the reanalyses occurs during and after the onset phase (also see Fig. 5) when local energy sources associated with the mean flow (e.g., Dole and Black 1990) and synoptic-scale eddies (e.g., Higgins and Schubert 1994) or effective Rossby wave sources that develop outside the Tropics and also depend on the mean flow (Sardeshmukh and Hoskins 1988) appear to dominate. Throughout the evolution the streamfunction and OLRA tend to exhibit a zonally elongated structure in the Tropics.

So far we have suggested that PNP anomalies evolve coherently with tropical IOs in a composite mean sense. One may wonder how well this teleconnection holds for individual events. To explore this, we considered several aspects of the tropical precipitation anomalies associated with each PNP event: 1) Were large precipitation anomalies present over the tropical Pacific prior to onset? 2) Did they exhibit a dipole structure characteristic of the IO? 3) Did the anomalies evolve eastward in a manner consistent with the tropical IO? Spatial (x–y) maps of the OLRA during the preonset (day −10 to day 0) and mature (day 0 to day +10) phases and Hovmöller (longitude–time) diagrams were produced for each case. These maps showed that in 12 cases (out of 14) there were large precipitation anomalies (often exceeding 4 mm day$^{-1}$) and OLRA (often exceeding 50 W m$^{-2}$) exhibiting a dipole structure and coherent eastward evolution. All of the qualifying cases also showed tropical heating anomalies of the “correct” sign near the date line during the mature phase.
6. Vorticity budget at 200 hPa

Previously we showed that the tropical upper-tropospheric divergence fields from the reanalyses are consistent with satellite measured OLR during PNP events suggesting that a reasonable vorticity balance might be achieved. In this section we show that the balance is reasonable and then use it to discuss a possible mechanism for the initiation of PNP anomalies. Our objective is to demonstrate the relevance of the Rossby wave source (RWS) in the linkage between remote tropical forcing and the extratropical PNP anomalies.

The vorticity balance prior to and during PNP events was analyzed in the NCEP and the DAO reanalyses. The balances are similar in both reanalyses, so only the NCEP results are presented. Lagged composites of all terms in the vorticity equation (1) were produced for both PP and PN events from day −10 to day +19. The composite mean balance for both preonset (day −10 to day −1) and onset/mature (day 0 to day +9) phases was examined. In agreement with Sardeshmukh and Hoskins (1987) and Mo and Rasmusson (1993), we find that the vertical advection and twisting terms at 200 hPa are small and generally confined to the deep Tropics where the vertical velocity is large. The tendency term is also quite small throughout the evolution. Thus, the vorticity balance is mainly between the RWS and the advection of absolute vorticity by the rotational flow during both phases (see Figs. 14 and 15). This balance is illustrated for the mature phase on Fig. 14, which shows composites of the RWS (Fig. 14a), the advection term (Fig. 14b), and the sum of the RWS, twisting, vertical advection, and tendency terms (Fig. 14c); similar results are obtained during the preonset phase though the largest RWS anomalies are located farther to the west (Fig. 15b). From this balance we conclude that the analyzed divergent and rotational components of the flow are reasonably accurate since the budget residual (the difference between the RWS and the advection of vorticity by the rotational wind) is small. While the RWS is small in the deep Tropics, it is much larger in the subtropics where a dipole pattern appears on the anticyclonic shear side of the Pacific jet. A dipole
Fig. 10. Map sequences of 200-hPa velocity potential anomalies and NOAA/OLRA represented as the composite difference (PP – PN) for pentads centered at day +8, day +3, and day +2 in (a) the DAO reanalysis and (b) the NCEP reanalysis. In each panel the zonal means have been removed. Velocity potential anomalies are contoured every $1 \times 10^{-6}$ m$^2$ s$^{-1}$ and the zero contour has been omitted. OLRA are contoured every 10 W m$^{-2}$ and light (dark) shading correspond to areas where OLRA are greater than 10 W m$^{-2}$ (less than −10 W m$^{-2}$).
in the opposite sense is located in midlatitudes on the cyclonic shear side of the jet. The RWS anomalies in the subtropics and midlatitudes form a quadrupole pattern consistent with the jet retraction (extension) and the subsequent development of the PNP anomalies.

Prior to onset the circulation anomalies in the Pacific jet entrance region are primarily rotational (cf. Figs. 15a and 15b) though there is considerable advection of absolute vorticity in the subtropical western Pacific by both divergent and rotational components of the wind. The collocation of divergent and rotational wind anomalies in this region prior to onset suggests a rapid conversion of divergent outflow (associated with the tropical heating anomalies) into rotational flow consistent with the vorticity balance. The RWS anomalies in the subtropical western Pacific (near 20°–25°N) are mainly due to advection of vorticity by the divergent flow, though vorticity stretching also contributes; prior to onset these anomalies gradually move eastward toward the date line together with the anomalous convection. On the cyclonic shear side of the jet the RWS anomalies are mainly due to vorticity stretching associated with secondary regions of divergence and convergence not directly associated with the tropical forcing. As mentioned earlier, the overall pattern of RWS anomalies forms a quadrupole during and after onset consistent with the jet retraction (extension). These results are generally consistent with those of Sardeshmukh and Hoskins (1988), who pointed out the importance of advection of vorticity by the divergent component of the flow and how it moves the RWS into the subtropics, even with the anomalous divergence confined to the deep tropics.

The relationships discussed above between the tropical heating anomalies, the tropical IO, the subtropical RWS, and the Pacific jet both prior to and during PNP events are summarized for the composite flow in the Hovmoeller (longitude–time) diagrams of Fig. 16. The developments appear to be initiated over the tropical western Pacific by anomalous convection (characterized by an east–west dipole structure) 1–2 weeks prior to onset (Fig. 16a). The tropical heating anomalies evolve coherently with the tropical IO (Fig. 16b), which exhibits a large local wave number 1 response that peaks about 3 days before onset. As the suppressed convection (positive OLRA) moves toward the central Pacific prior to onset, the 200-hPa anomalous convergence in the deep Tropics increases as indicated by the meridional component of the divergent wind west of the date line (Figs. 16c and 15b); similar arguments hold for the PN events but with the opposite sign. The anomalous convergence is accompanied by a weakening of the local Hadley circulation in the subtropics (Fig. 11). Prior to onset, advection of vorticity by the anomalous inflow moves an anomalous vorticity source (positive RWS) into the subtropics on the anticyclonic shear side of the jet entrance region (Figs. 16c and 15b). Farther downstream an anomalous vorticity sink (negative RWS) appears just prior to onset and peaks about one week later. During the evolution the subtropical RWS anomalies combine with midlatitude RWS anomalies over the North Pacific to form a quadrupole pattern (Fig. 14a) consistent with the jet retraction (extension) as indicated by the large zonal wind anomalies in the jet exit region (Fig. 16d) and the increasing rotational wind anomalies (Fig. 15a).

Thus, the key result of our study is that anomalous remote forcing from the Tropics appears to play an important role in the development of PNP anomalies prior to onset. In particular it generates a subtropical RWS, which in turn is at least partly responsible for the retraction (extension) of the Pacific jet exit region, and the formation of the PNP anomalies. The tropical forcing should not be viewed as the proximate source for the PNP anomalies, but rather as a catalyst for the developments. Our results are consistent with earlier studies of PNP anomalies which emphasized the importance of local source mechanisms during the onset and mature phases.

7. Summary and discussion

The NASA/DAO and NCEP/NCAR reanalyses were used to examine the linkage between PNP circulation anomalies and the tropical IO during NH winter. Many of the conclusions drawn here confirm earlier results based on a multyear simulation with the NASA/DAO GCM (HS96) but there are a number of new ones especially concerning the mechanism for the tropical–extratropical linkage prior to onset. The key findings of this study are 1) well-defined tropical precipitation anomalies occur in the western Pacific more than a week prior to the development of the composite PNP anomalies in both reanalyses, 2) the tropical heating anomalies evolve coherently with the tropical IO, 3) fluctuations in the local winter Hadley cell generate an anomalous RWS in the subtropical Pacific, 4) subtropical and extratropical RWS anomalies form a quadrupole pattern consistent with the retraction (extension) of the Pacific jet exit region and the preonset extratropical “response,” and 5) the mature PNP anomalies extend into the Tropics to feed back (through modifications to the moisture transport) on the tropical precipitation. These tropical–extratropical linkages are similar in many respects to those during ENSO episodes (Rasmusson and Mo 1993). The difference, however, is that during PNP events the tropical convection is associated with the tropical IO and the timescale is roughly 15–20 days. Tropical convection associated with ENSO events is more stationary and has interannual timescales.

Prior to onset the signature of the initial developments is a pair of cyclonic (anticyclonic) subtropical circulations near 120°E in both reanalyses. The NH member of this pair is part of a North Pacific wave train that emanates from a region of heating/cooling anomalies in the tropical western Pacific and develops into (or merges
Fig. 11. Map sequence of the 200-hPa vector wind anomalies and NOAA/OLRA in the NCEP reanalysis represented as the composite difference (PP − PN) at day −8, day −6, day −4, day −2, day 0, and day +2. The standard vector length is 30 m s⁻¹, and light (dark) shading corresponds to areas where OLRA are greater than 10 W m⁻² (less than −10 W m⁻²).
Fig. 12. Map sequence of 200-hPa eddy (zonal mean removed) streamfunction anomalies in the NCEP reanalysis represented as the composite difference (PP − PN) at day −8, day −6, day −4, day −2, day 0, and day +2. In each panel the three levels of light (dark) shading indicate positive (negative) anomalies significant at the 95%, 99%, and 99.9% levels, respectively. The contour interval is $4 \times 10^{-4}$ m² s⁻¹.
Fig. 13. Same as Fig. 12 except for the DAO reanalysis.
Fig. 14. Composite mean (day 0 to day +9) 200-hPa vorticity budget terms during persistent anomaly events represented as the difference between PP and PN events in the NCEP reanalysis: (a) RWS anomalies, (b) advection of absolute vorticity by the rotational wind, and (c) sum of the RWS, vertical advection of absolute vorticity, and twisting terms minus the vorticity tendency. In (a)–(c) the contour interval is $10 \times 10^{-11}$ s$^{-2}$, the zero contour has been omitted for clarity, and the dark (light) shading indicates positive (negative) anomalies.

Fig. 15. Map sequences of (a) 200-hPa rotational wind anomalies and (b) 200-hPa divergent wind anomalies and RWS anomalies represented as the composite difference in the NCEP reanalysis for pentads centered at day 28, day 33, and day 48. On each panel, the time mean absolute vorticity (contoured every $2 \times 10^{-11}$ s$^{-2}$) is also shown. The standard vector length for the rotational (divergent) wind anomalies is 25 m s$^{-1}$ (5 m s$^{-1}$). The dark (light) shading corresponds to areas where the RWS anomalies are greater than $5 \times 10^{-11}$ s$^{-2}$ (less than $-5 \times 10^{-11}$ s$^{-2}$).

with) the growing extratropical PNP anomaly in the Gulf of Alaska region during the onset phase. There is also evidence for a similar, though less well defined, composite wave train extending from Australia into the SH midlatitudes.

During the preonset stage the composite tropical heating pattern has the signature of an east–west dipole centered over the Indonesia/west Pacific region. As the tropical heating anomalies traverse the western Pacific, the local Hadley circulation is suppressed (enhanced) as indicated by dramatic fluctuations in the divergent outflow in the Tropics and subtropics. The anomalous RWS generated by this outflow is dominated by the vorticity advection term and located in the subtropical western Pacific on the anticyclonic shear side of the jet. As indicated by the vorticity balance, this source is consistent with a rapid conversion of divergent to rotational flow in the subtropical western Pacific. Beginning with the onset phase, this subtropical RWS combines with midlatitude sources to form a quadrupole pattern consistent with the retraction (extension) of the Pacific jet exit region and the development of the PNP anomalies. Late in the period, the equatorward extension of the PNP anomalies results in anomalous moisture transports and divergence, which help maintain the phase locking between the Tropics and the extratropics. During this time IOs often appear to reduce their eastward propagation speed as tropical heating anomalies weaken rapidly east of the date line.

While the composite global signal during the onset and mature stages of PNP anomalies shows a remarkable degree of coherence in the circulation anomalies extending both downstream over North America, and southward into the Tropics and subtropics of the SH in both reanalyses, the preonset phase shows some differences. In particular, there are differences in the amplitude and location of the initial extratropical wave trains, apparently resulting from differences in the tropical heating anomalies in each case. However, the present results are consistent with previous observational and modeling studies that suggest that the primary role of the Tropics is that of a catalyst or initiator of middle-latitude modes, which grow primarily by energy exchanges with the zonally asymmetric climatological basic state and/or synoptic-scale eddies. The fact that we obtain a coherent preonset wave train shows that the initiation of these events is not entirely random but, instead, is tied to tropical IOs, which have a well-defined evolution.

The main weakness of the current approach is that it composites all PNP events and thus potentially weakens the tropical signal by including anomalies that are not initiated by IO events or that are in different phases of development. Preliminary examination of the individual events in our composites shows a strong tropical–extratropical linkage (as described here) in roughly 80% of the NH winter events. However, the robustness of the PNP events in the absence of the IO and the precise nature of the mutual interaction during the extratropical developments is still not entirely clear. The complete 40+ year NCEP reanalysis will be an excellent resource for additional studies of the relative importance of remote versus local energy sources for the persistent
FIG. 16. Hovmöller (longitude–time) diagrams of (a) NOAA/OLRA, (b) 200-hPa velocity potential anomalies, (c) 200-hPa RWS and divergent wind anomalies, and (d) 200-hPa zonal wind anomalies represented as the difference between PP and PN composites from DJF in the NCEP reanalysis. The anomalies are averaged in latitude as follows: (a) 20°S–equator, (b) 20°S–equator, (c) 15°–20°N, and (d) 30°–40°N. The contour intervals are (a) 5 W m⁻², (b) 0.5 × 10⁻⁶ m² s⁻¹, (c) 0.5 × 10⁻⁸ m² s⁻¹, and (d) 5 m s⁻¹. The standard vector length in (c) is 5 m s⁻¹. In (a)–(d) the zero contour has been omitted for clarity. The dark (light) shading corresponds to areas where the values are (a) negative (positive), (b) negative (positive), (c) positive (negative), and (d) positive (negative).
events, as well as for other studies such as the seasonal-to-interannual variability of these events. Moreover, these issues will likely not be resolved by diagnostic studies, but will require carefully designed model experiments.

The strong tropical–extratropical linkage demonstrated here has important consequences for the ability of GCMs to simulate the observed low-frequency variability of the atmosphere (especially in data sparse regions, such as the tropical Pacific). In particular, it appears that GCMs must produce a proper simulation of tropical IOs in order to obtain the correct distribution and amplitude of midlatitude variability. Recent studies by Slingo et al. (1995) and Park et al. (1990) have performed detailed comparisons of the ability of GCMs to simulate the MJO. The large differences between GCMs found in these studies highlights the difficulty we face in obtaining realistic simulations of low-frequency variability. This is consistent with recent forecast studies (e.g., Ferranti et al. 1990), which have suggested that for prediction beyond the medium range the impact of the Tropics on the extratropics cannot be ignored especially during periods of intense tropical low-frequency variability.

Finally, users of the reanalysis products may wonder to what extent the reanalyses represent an improvement over existing (in the case of NCEP) archived analyses. The GCM used for the NCEP reanalysis is the same over existing (in the case of NCEP) archived analyses. To the extent that resolution is important in capturing persistent anomaly events, the GDAS may be better than the reanalysis. However, the GDAS system is not “frozen” so there will be discontinuities in forecast and analysis products related to changes in the GCM. The reanalyses provide the most valuable resource for studying the historical archives because they are produced with fixed assimilation systems and large input databases.

Acknowledgments. We would like to thank George Kiladis for the OLR data. Vernon Kousky and Jerry Bell provided valuable comments that have helped to substantially improve the manuscript. The authors are also indebted to Siegfried Schubert, Chester Ropelewski, Randall Dole, Robert Black, and Richard Rood for insightful discussions. Thanks also go to Wesley Ebisuzaki, Julian Wang, and Muthu Chelliah for help in preparing the NCEP reanalysis data. This work was partially supported by the NOAA Office of Global Programs under the Pan American Climate Studies (PACS) project and the CDAS/Reanalysis project and by Interagency Agreement S-41367-F under the authority of NASA Headquarters.

REFERENCES


——, and T. J. Phillips, 1986: Coherent fluctuations of extratropical


