Anomalies in North American Climate: The South Asian-Tropical West Pacific Connection

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Abstract: How do tropical heating fluctuations create North American climate anomalies? We propose some answers using the results from a simplified global atmospheric model. We find that the South Asian-tropical west Pacific area is especially effective at stimulating North American responses. The relatively strong tropical/extratropical interaction between these two areas is the result of two major processes acting on the Rossby wave signal induced by the tropical heating fluctuations. These factors are:

- Wave guiding by the Asian-north Pacific subtropical jet; and
- Wave amplification within unstable regions on the jet flank.

These factors allow relatively small, remote, and short-term tropical fluctuations to have relatively large impacts on North American climate.

Introduction

The extratropical atmosphere is sensitive, over a range of time scales, to fluctuations in tropical atmospheric heating. The extratropical north Pacific/North American (PNA) area seems to be especially responsive to tropical forcing. Thus PNA climate variations are often linked to tropical heating anomalies. However, the mechanisms behind tropical-extratropical interactions are still poorly understood. The major problem is that the atmospheric environment in which the interactions occur is a complex and active medium. Thus the complicated signal propagation and amplification properties of the ambient atmosphere must be considered.

We present a study of some of the mechanisms involved in tropical-extratropical interactions. We focus on short-term summer PNA variations associated with tropical heating anomalies and, in particular, anomalies in the south Asian-tropical west Pacific area. The interaction mechanisms studied are those that occur in a simplified global atmospheric model. Observational analyses provide qualitative support for the simplified model results (Harr *et al* 1991).

The Model

The simplified model used is based on the nonlinear shallow water equations on a global spherical domain. The equations are spectrally formulated with rhomboidal-25 truncation, giving a resolution of 2.8° latitude, 4.7° longitude. The equivalent depth is 2000 meters, which means the model waves have a relatively deep internal mode structure. The ambient atmospheric conditions are taken from the European Centre

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for Medium-range Weather Forecasting (ECMWF) monthly mean analyses for 1979-1987 at 200 mb, with full horizontal variation retained. A steady forcing is applied that maintains the wavy initial state of the model atmosphere in the absence of any anomaly forcing. Dissipation is applied in the form of:

- Relaxation back toward the climatological initial conditions on a 15-day time scale; and
- Biharmonic diffusion.

To produce anomaly solutions, a steady anomaly forcing is applied to the geopotential equation. This forcing is localized in the tropics and simulates one or more heating disturbance in the tropical troposphere. Peak forcing is at the center of the forcing and is equivalent to 3.5 K/day heating. The model with perturbation forcing is integrated to a steady state, which is reached within 20-60 model days. The model response to the tropical forcing is defined as the anomaly solution minus the solution without such forcing.

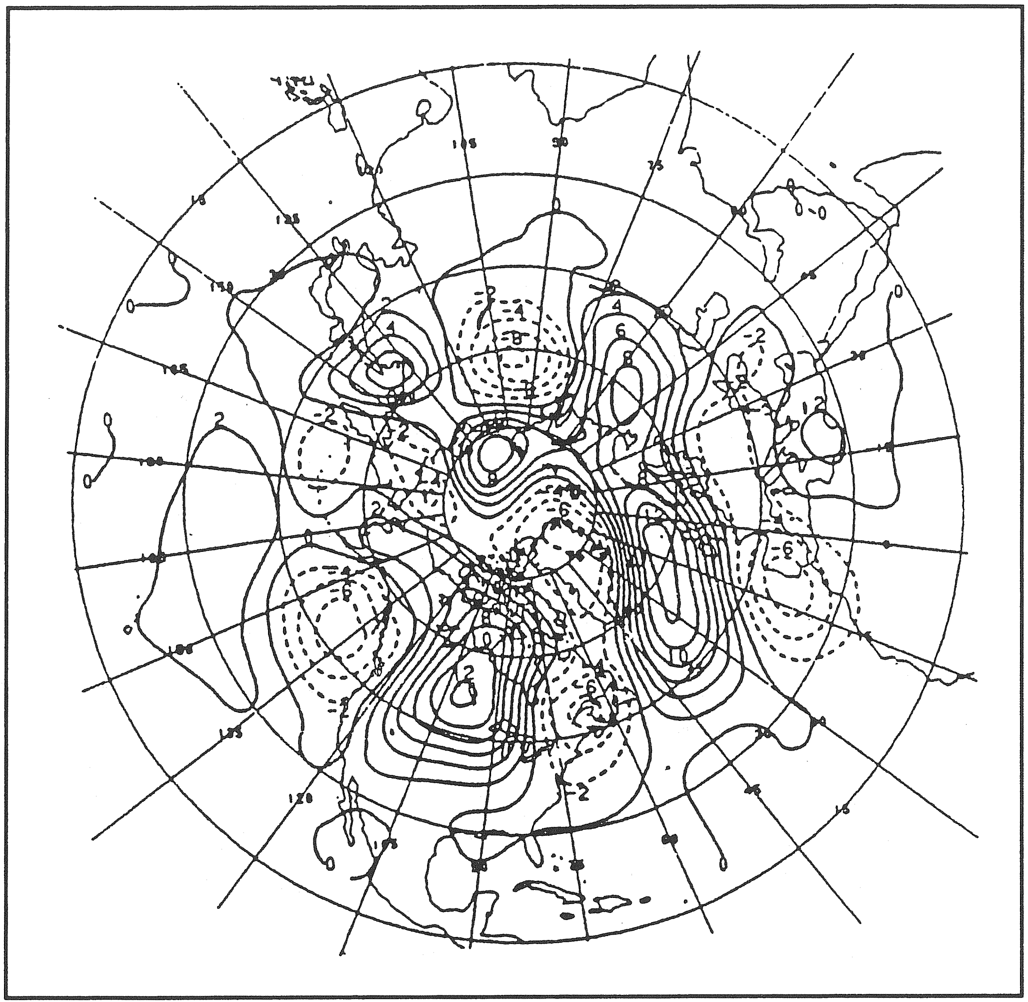
Simulations of the June 1988 Drought

In June 1988 the observed tropospheric geopotential height anomaly field (Figure 1a) showed a marked positive PNA pattern. A positive PNA pattern has height anomalies that are approximately: low over the northeast Pacific, high over North America, and low over the western north Atlantic. A negative PNA pattern would be the same, except for reversed signs (*cf.* Wallace and Gutzler 1981). The positive height anomaly over North America was a dynamical representation of drought conditions observed in June 1988. In addition to the PNA pattern, the June 1988 height anomalies showed a distinct pattern of anomalies of about zonal wave number five stretching across the north Pacific and around the globe at about 45N-60N.

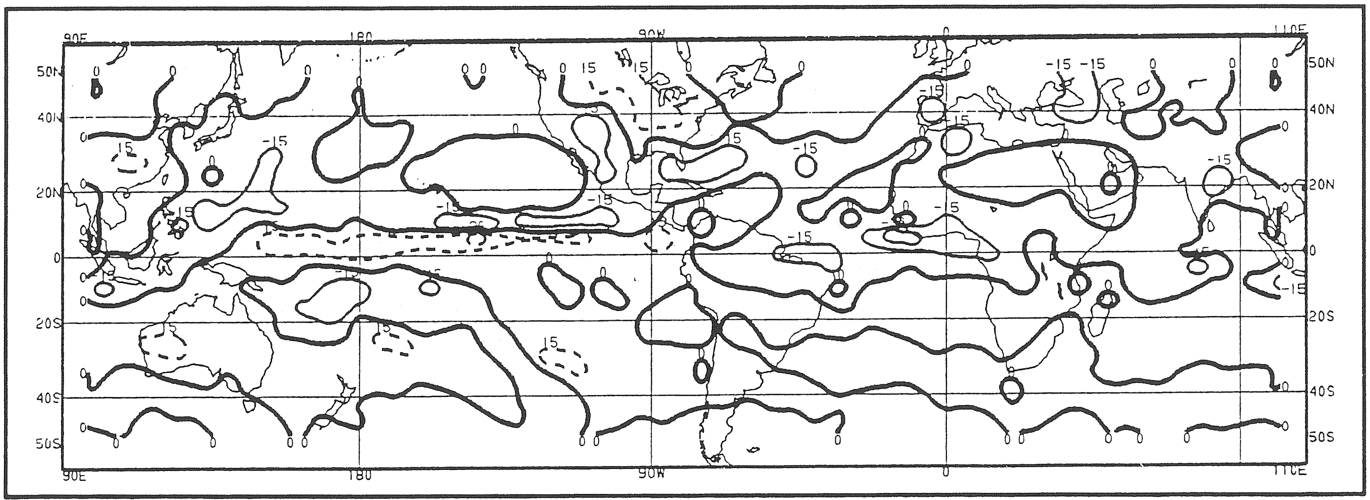
The tropical heating anomalies that may have been influential in developing these height anomalies are implied by the tropical outgoing longwave radiation anomalies (OLRA) for June 1988 (Figure 1b). These show a complex pattern of both anomalous heating and cooling throughout the tropics. The largest and most intense OLRA during June 1988 was a negative one in the west Pacific, corresponding to unusually high tropical cyclone activity. Another prominent negative OLRA is in the east Pacific. This OLRA corresponds to the east Pacific heating anomaly focused on in some other studies of the June 1988 North American drought (*eg*, Trenberth *et al* 1988). (Note: *Negative* OLRAs imply *positive* tropospheric heating anomalies.)

As a case study, we have used the simplified model with a climatological June ambient state to examine the role of these tropical anomalies in forcing the PNA height anomalies. Figure 2 shows model responses to approximations of these two OLRAs in a June ambient flow. Both the

Figure 1. Observed June 1988 anomalies from *Climate Diagnostics Bulletin*, June 1988.



1a — 500-mb geopotential height anomalies. Interval=20 meters; dashed contours= negative anomalies. Note the PNA pattern and zonal wave number five pattern.



1b — Outgoing longwave radiation anomalies (OLRA). Interval=15 W/M2; dashed contours=positive anomalies. Note the indications of anomalous tropical heating where the OLR anomalies are negative (solid contours); for example, in the tropical west Pacific.

west and east Pacific forcings produce reasonable simulations of the observed anomalies over much of the north Pacific, North America, and north Atlantic (Figure 2a,b). The simulation is improved when both of these forcings are included (Figure 2c). In particular, the phase of the low-high-low pattern across North America is improved by including both forcings. The responses to other forcings representative of the June 1988 tropical OLRAs show that most give either a positive or a negative PNA pattern, depending primarily on their sign and longitude.

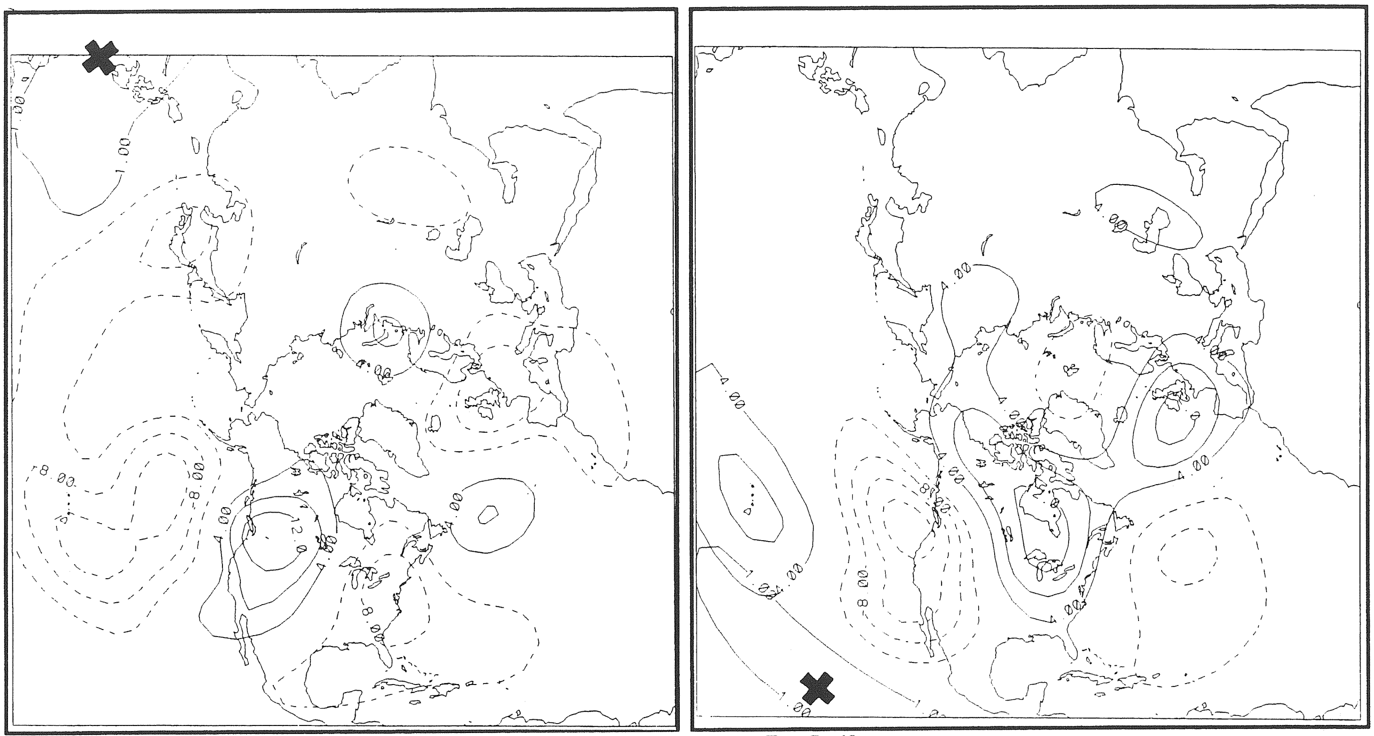
A useful diagnostic tool for interpreting the energetics of these response patterns is the quasi-geostrophic wave activity flux vector developed by Plumb (1985). The vector length shows the intensity of the wave activity; the vector direction shows the wave energy propagation direction; and the vector divergence (or convergence) shows wave activity sources (or sinks). Because these vectors are calculated from a quasi-geostrophic approximation of a wave field, they do not necessarily give a realistic impression of the wave flux *within* the tropics (10S-10N, say). However, *beyond* the tropics, the vectors can give a useful picture of any Rossby wave activity that has arisen due to ageostrophic processes.

The horizontal components of the wave activity flux vectors corresponding to the responses of Figure 2 are shown in Figure 3. The vectors for the west Pacific forcing (Figure 3a) show some northward and eastward propagation out of the forcing area, with zonal propagation along and south of the jet into North America. Near the jet exit, the vector divergence indicates an amplification of wave energy. However, the largest energy source is in the subtropical eastern Pacific, where the vectors are strongly divergent. This part of the Pacific is also the downstream end of a region of potential barotropic instability (in the Rayleigh-Kuo sense). Thus the response to the west Pacific forcing seems to depend on the extraction of energy from the unstable ambient jet (*cf.* Peng and Williams 1986; Crum and Stevens 1990). From this east Pacific area, energy propagates southeastward into the tropics, as well as eastward and northeastward into North America.

The flux vectors for the east Pacific forcing (Figure 3b) show a large propagation of energy from both the forcing area and the unstable subtropical east Pacific area. The flux from the jet exit is much weaker than for the west Pacific forcing case. The northward component of the energy flux into North America is more pronounced for this case than for the west Pacific forcing case. Farther downstream, off the east coast of the United States, there is a marked equatorward component of propagation.

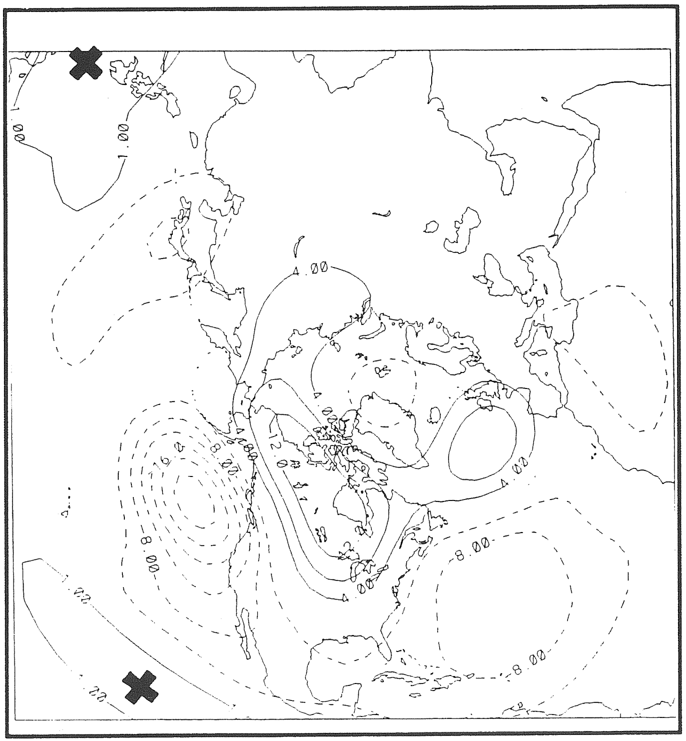
These model results show remote and relatively localized and short-term variations in tropical heating may affect PNA height variations. In particular, the results show heating anomalies in the south Asian and tropical west Pacific areas may have an especially large impact. Such heating anomalies might include intraseasonal variations of the Asian

Figure 2. Model geopotential height responses to idealizations of the tropical west and east Pacific tropical forcings observed in June 1988 for a climatological June ambient state.
Interval = 4m, zero contour omitted. Forcing centers indicated by plus signs.



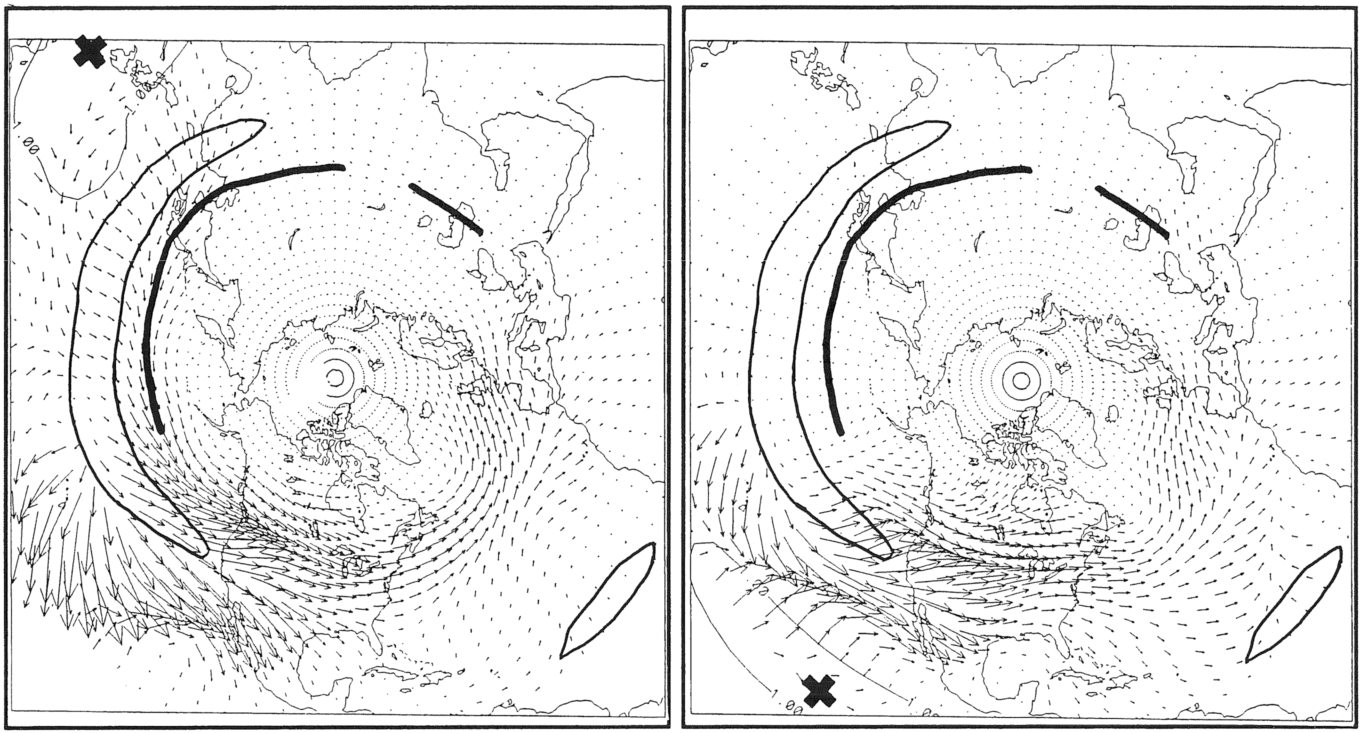
2a — West Pacific.

2b — East Pacific.



2c — Both West and East Pacific.

Figure 3. Wave activity flux vectors (Plumb fluxes) for responses shown in Figure 1(a,b).
Heavy curve shows jet axis (>30 m/s). Closed curves show subtropical areas of potential barotropic instability. Note the waveguiding by the jet and the large energy sources at the jet exit and at the downstream end of the Asian/north Pacific unstable area.



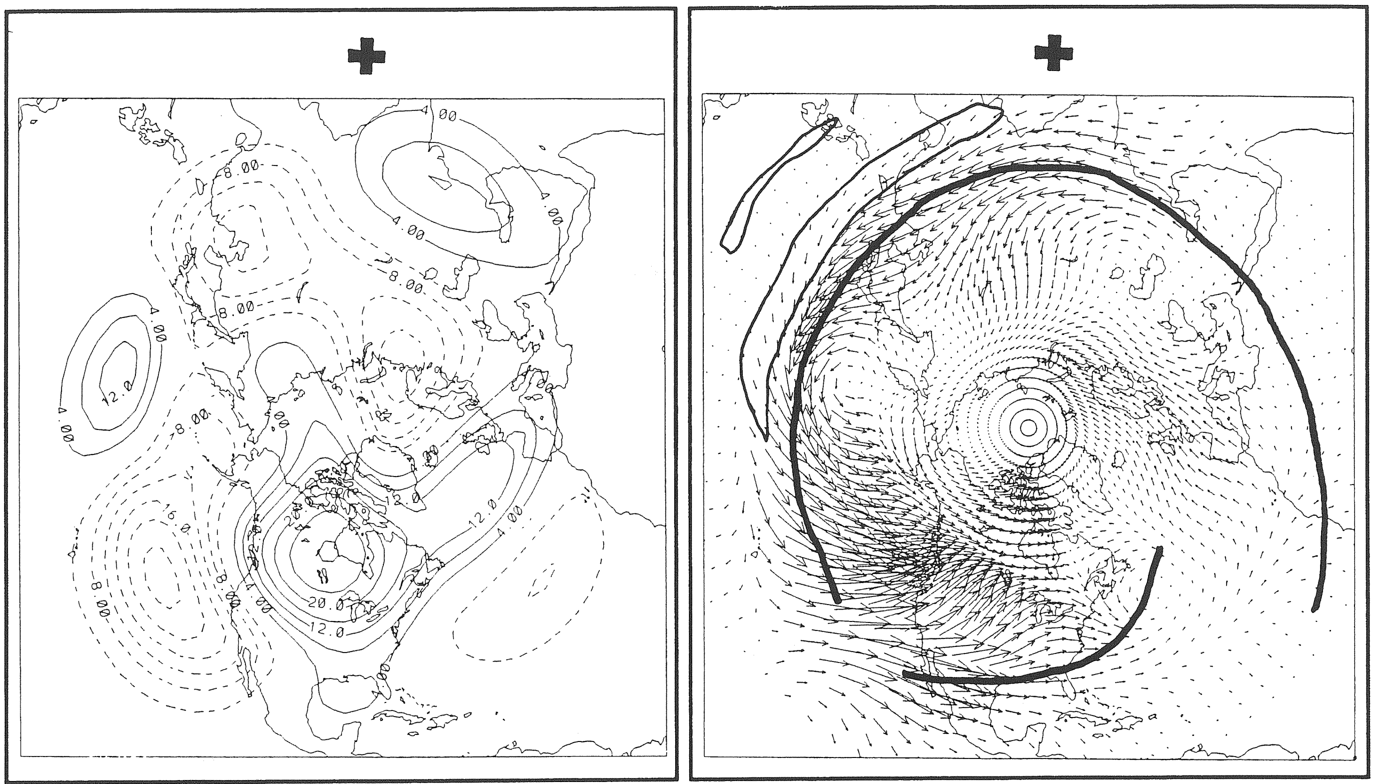
3a — Flux vectors corresponding to Figure 2a.

3b — Flux vectors corresponding to Figure 2b.

monsoon or of west Pacific tropical storm activity. Our observational analyses of tropical-extratropical interactions associated with variations in west Pacific typhoon activity support the basic conclusions of the simplified model (Harr *et al* 1991). This typhoon variability is itself related to tropical intraseasonal oscillations.

These basic conclusions also apply, in large part, to our studies of interactions during the northern winter. One example of a winter result from the simplified model is shown in Figure 4. In this case, a positive tropical forcing is placed just east of Sri Lanka, leading to a strong PNA pattern. The flux vectors show a clear propagation of energy along the jet, with poleward and equatorward propagation near the jet exit. The strongest energy sources are in the subtropics and well to the east of the tropical forcing.

Figure 4. Model height (a) and the corresponding Plumb fluxes (b) for a climatological January ambient state and a forcing centered just east of Sri Lanka (at 7N, 37E, just outside of plot frame).



4a — Plotting as in Figure 2.

4b — Plotting as in Figure 3.

Summary

These results show that widely separated forcings can produce similar PNA responses. Thus PNA patterns are, in general, complex interference patterns arising from both nearby and remote forcings. The results also show that the mechanisms by which a tropical forcing influences conditions in the PNA area depend on the location of the forcing within the ambient flow. The wave-guiding and amplification features of the ambient flow, in particular the Asian-north Pacific jet, tend to organize the responses to widely separated forcings over the PNA area. The high sensitivity of the PNA area comes from its location downstream (in a wave propagation sense) of the subtropical north Pacific wave-guide and amplification regions for Rossby waves. The PNA area is especially responsive to south Asian-tropical west Pacific heating anomalies because these anomalies occur at the upstream end of the wave-guide and amplification areas.

A schematic picture of how remote forcings may exert a large influence in the PNA area is shown in Figure 5. Note that both wave-guiding and amplification on the unstable jet flank are important in producing a PNA response to remote forcing. Figure 5 also shows a southward propagation of energy out of the jet exit and into the Southern Hemisphere. Other model results (not shown) indicate model responses in the eastern tropical Pacific and the southeast Pacific-South American area may be related to energy propagating from the north Pacific jet exit. This may explain the high perturbation kinetic energy observed in the eastern tropical Pacific (Murakami and Unninayer 1977) and some Southern Hemisphere teleconnection patterns (*cf*, Park and Schubert 1991).

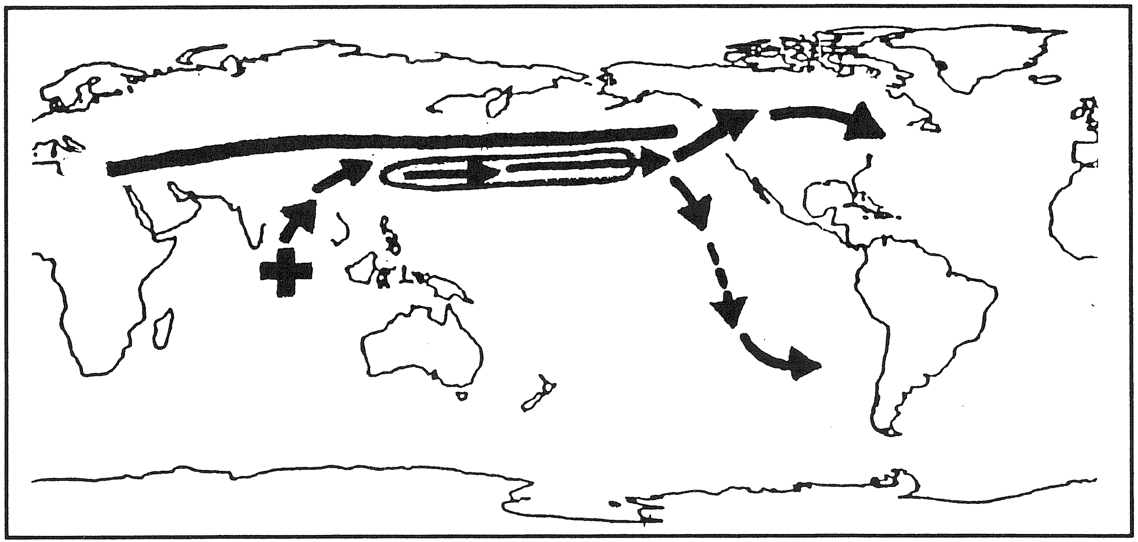


Figure 5. Schematic diagram of tropical-extratropical teleconnection mechanisms influencing east Pacific and North American areas. Plus symbols = tropical heating anomaly; Arrows = Rossby wave energy propagation; Heavy line = jet axis; Closed curve = subtropical area of barotropic instability. The overall chain of events is: (1) poleward propagation out of heating anomaly; (2) waveguiding of energy along jet and through subtropical unstable area; (3) amplification of wave response all the way through the unstable area; and (4) poleward and equatorward propagation at jet exit and at downstream end of unstable area.

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