Organization of Extratropical Transients during El Niño

MARTIN P. HOERLING

Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, Colorado

MINGFANG TING

Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

(Manuscript received 30 April 1993, in final form 29 September 1993)

ABSTRACT

Four observed El Niño–Southern Oscillation (ENSO) events are studied to determine the mechanisms responsible for the anomalous extratropical atmospheric circulation during northern winter. A parallel analysis of a GCM’s response to El Niño is performed in order to assess if similar mechanisms are operative in the model atmosphere. The observed stationary wave anomalies over the Pacific/North American (PNA) region are found to be similar during the four winters despite appreciable differences in sea surface temperatures. The anomalous transient vorticity fluxes are remarkably robust over the North Pacific during each event, with an eastward extension of the climatological storm track leading to strong cyclonic forcing near 40°N, 150°W. This forcing is in phase with the seasonal mean Aleutian trough anomaly suggesting the importance of eddy–mean flow interactions. By comparison, the intersample variability of the GCM response over the PNA region is found to exceed the observed inter–El Niño variability. This stems primarily from a large variability in the model’s anomalous transients over the North Pacific.

Further analysis using a linear stationary wave model reveals that the extratropical vorticity transients are the primary mechanism maintaining the stationary wave anomalies over the PNA region during all four observed ENSO winters. In the case of the GCM, the organization of transient eddies is ill defined over the North Pacific, a behavior that appears more indicative of model error than the unpredictable component of seasonal mean storm track anomalies. A physical model is proposed to explain the robustness of the tropical controlling influence of the extratropical transients in nature. A simple equatorial Pacific heat source directly forces a tropical anticyclone whose phase relative to the climatological tropical anticyclone leads to an eastward extension of the subtropical jet stream. This mechanism appears to be equally effective for a heat source located either in the central or eastern Pacific basin.

1. Introduction

 Whereas the basinwide warming of tropical Pacific sea surface temperatures (referred to as El Niño in the current study) accounts for much of the tropical atmosphere’s interannual variability, its influence on the extratropical atmosphere is less clear due to the large “natural” (unforced) variability there. Nevertheless, several extratropical regions possess potential long-range predictability, and thus individual seasonal means may be controlled by long-lived boundary forcings. These regions include the northeast Pacific and western North America where a statistically significant enhancement of the total (forced and unforced) interannual variability relative to the estimated natural variability is found (e.g., Madden 1976; Chervin 1986). The statistical results are consistent with diagnostic studies that reveal a strong teleconnection between tropical Pacific sea surface temperatures (SSTs) and wintertime climate anomalies over the Pacific/North American (PNA) region (e.g., Bjerknes 1966, 1969; Horel and Wallace 1981; van Loon and Madden 1981; Yarnal and Díaz 1986).

 The dynamics of the teleconnection between tropical and extratropical latitudes continues to be a central problem in climate research. Theoretical studies have shown that propagation of energy from a tropical heat source and interaction with the zonally varying flow can induce stationary wave anomalies that resemble those observed during El Niño winters (Hoskins et al. 1977; Webster 1981; Hoskins and Karoly 1981; Simmons 1982; Simmons et al. 1983; Branstator 1985). Such patterns are also well reproduced in atmospheric general circulation models (GCMs) forced with prescribed El Niño–like SST anomalies (e.g., Shukla and Wallace 1983; Blackmon et al. 1983; Lau 1985; Palmer and Mansfield 1986; Hoerling et al. 1992). The GCM results argue for the feasibility of dynamically predicting extratropical seasonal means subject to an independent determination of the SST forcing. An important caveat, however, is that while GCMs appear of
sufficient fidelity to reproduce the salient features of tropical–midlatitude interactions, these results by themselves do not ensure useful predictions. Progress on this matter will require a better understanding of the dynamics of the seasonal anomalies in both nature and GCMs.

To determine the origin of circulation anomalies over the PNA region, recent linear modeling studies have used a more complete representation of the atmospheric forcing during El Niño. Using observed data, Kok and Opsteegh (1985) and Ting and Hoerling (1993, hereafter referred to as TH) showed that the extratropical wave train anomalies during the 1982/83 and 1986/87 El Niño winters were maintained by transients, and not by a steady tropical heat source. A major contribution came from extratropical transients, presumably associated with anomalous storm track structure. Held et al. (1989) arrived at a similar conclusion based on their composite analysis of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM response to El Niño. A different picture emerges, however, from TH's analysis of the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM1) simulation for 1986/87. Hoerling et al. (1992) showed that the CCM1 simulation agreed well with observations during that winter, especially the rainfall anomaly patterns over the tropical Pacific and the magnitude of stationary wave anomalies over the PNA region. Yet, diabatic and transient forcings were found to be of comparable importance in maintaining the extratropical wave train in CCM1, contrary to the dominant transient contribution inferred from observations.

It remains to be determined whether a general statement can be made about the origin of extratropical stationary wave anomalies during El Niño. For example, considerable variability of the wintertime extratropical response during El Niño is observed despite Horel and Wallace's (1981) analysis which suggests a preference for a PNA pattern. During strong El Niños, for example, Livezey and Mo (1987) find that the West Pacific Oscillation, the Tropical/Northern Hemisphere pattern and the PNA pattern are all almost as likely to occur. Given the inter–El Niño variability in SSTs and the fact that several modes of extratropical response are observed, it is quite possible that the relative importance of individual atmospheric forcing mechanisms can vary among El Niños. Concerning prediction, growing evidence suggests that the extratropical anomalies during El Niño are not simply steady responses to tropical forcing but involve strong synoptic eddy–mean flow interactions, and as such a GCM's fidelity may have to be considerably greater than previously supposed.

The purpose of this study is to examine the dynamics of observed and simulated atmospheric responses during several recent large-scale warmings (and coolings) in the tropical Pacific, and for each event determine the origin of the extratropical wave train. We are particularly interested to find out whether a single forcing mechanism consistently accounts for the extratropical flow anomalies in both model and nature, and if so, how this mechanism is related to tropical SST anomalies. The observational part of the analysis is for the 1982/83, 1986/87, 1988/89, and 1991/92 events, whereas the GCM-based analysis is for simulations of the 1982/83 and 1986/87 El Niños using the NCAR CCM. The five-member ensemble mean CCM response for the 1986/87 winter season was already studied in TH where it was found that the dynamics of the model response differed from nature. The model dynamics may have been significantly blurred, however, by compositing over five cases. Indeed, the dispersion among the five GCM seasonal responses to the same SST forcing was found to be quite large, and one wonders whether this variability is indicative of nature and thus representative of the limitations in predicting the atmospheric response. It thus becomes relevant to examine the dynamics of the stationary wave anomalies within each realization and compare the results to observations. Through this approach we hope to provide a more rigorous assessment of the ability of a GCM to predict the extratropical response to El Niño.

2. Methodology

a. GCM experiments

The NCAR CCM1 with triangular truncation at wavenumber 31 is used to simulate the atmospheric response to the 1982/83 and 1986/87 El Niños. A detailed description of the experimental design and the model's wintertime (December, January, and February) climate appears in Hoerling et al. (1992). Briefly, two anomaly experiments are performed in which global SSTs evolve as observed for the periods July 1981 through November 1983 and July 1985 through November 1987. Five independent realizations that differ only by their initial atmospheric conditions have been run for each 30-month period. The model's seasonal mean wintertime response is computed as the difference between each realization and CCM1's 10-yr control climatology. Diabatic and transient forcing anomalies are computed directly from the model's once-daily archive as described in TH.

b. Observational analyses

The observed circulation data are derived from the National Meteorological Center's (NMC) once-daily global initialized analyses. To facilitate comparison with the GCM, the NMC data are converted into CCM format as described in TH. Circulation and transient vorticity forcing anomalies are computed for the three warm-phase El Niño–Southern Oscillation (ENSO) winters during 1982/83, 1986/87, and 1991/92 and for the cold phase of ENSO during 1988/89. Transients
are defined herein as departures from the 90-day seasonal means as in Kok and Opsteegh (1985) and Held et al. (1989). The anomalies are computed with respect to a 5-yr NMC wintertime climatology covering the 1986/87 through 1990/91 period used previously in TH.

It is difficult to derive reliable estimates of the diabatic heating anomalies for the above ENSO winters due to various changes in NMC's assimilation model during the past decade. We use instead outgoing long-wave radiation (OLR) data as a proxy for the diabatic forcing. The OLR anomalies are computed relative to a 17-yr winter mean covering the period 1974/75 through 1990/91.

c. Linear baroclinic model

A linear, primitive equation, stationary wave model is used to determine the origin of wave train anomalies in the CCM and observations. The model is formulated in sigma coordinates with vertical discretization identical to the CCM. All experiments employ a zonally asymmetric base state. The wavy base state and forcings (diabatic and transient vorticity fluxes) are allowed to retain zonal scales up to wavenumber 6 and meridional scales up to wavenumber 15. The forcings are treated as fixed sources in the primitive equation model, and the forced responses are compared to CCM and observed stationary wave anomalies.

Dissipations employed in the prognostic equations are identical to those used previously in TH. These include a subgrid-scale horizontal diffusion as in CCM1, a boundary-layer Rayleigh friction and Newtonian damping with time scales of 0.35 and 2 days at the lowest and next lowest levels, respectively, and a vertical diffusion having a 1000-day time scale applied in the vorticity, divergence, and temperature equations. We also include a 10- and 5-day damping in the free atmosphere for the momentum and temperature equations, respectively, and a thermal diffusion in the temperature equation. The former acts to parameterize nonlinear effects, while the latter parameterizes thermal transient effects. The reader is referred to TH for a complete description of the linear model, and to Ting and Held (1990) for a description of the numerical schemes used to solve the dynamical system.

The linear model solution can be very sensitive to the particular choice of dissipations when a three-dimensional base state is used (Branstator 1992). We have made two independent checks to ensure that the conclusions drawn from our linear experiments are not sensitive to the choice of dissipations. First, the linear model solution when subjected to the total CCM forcing is compared to the anomaly pattern produced by the CCM (see section 3c for more detail). The linear model with the above choices of dissipations is able to reproduce most essential features of the CCM anomaly pattern. Second, several sensitivity experiments have been performed for different choices of dissipations that reflect uncertainties in their values. For example, we have deleted the 5-day damping in the temperature equation, given the fact that the thermal diffusion already partially accounts for nonlinear effects. The resulting linear model response is about 20% stronger, but otherwise identical in pattern to that shown in section 3c. Importantly, the reduction of thermal damping does not change the relative importance of diabatic and transient forcings. Similarly, removing the thermal diffusion from the temperature equation while retaining the 5-day damping yields a solution that is almost identical to one that includes thermal diffusion. We thus conclude that the qualitative results shown herein are not affected by reasonable choices of dissipation.

3. Results

a. Observations of the atmospheric anomalies during four recent ENSOs

Tropical Pacific sea surface temperature anomalies based on Reynolds (1988) are shown in Fig. 1 for the mature winter phases of the three warm events and one cold event of the past decade. The anomalies are computed relative to the period 1983–1992. These events are noteworthy for their large-amplitude, basinwide scale of anomalous equatorial Pacific SSTs, and should be distinguished from the more classic El Niño events in which anomalous SSTs are confined to coastal sections of South America (e.g., Deser and Wallace 1987). The 1982/83 event (Fig. 1a) is among the strongest of the century with maximum anomalies occurring east of 130°W, while the more moderate warmings during 1986/87 (Fig. 1b) and 1991/92 (Fig. 1d) exhibit maximum positive anomalies farther west near 160°W. The strong cold event of 1988/89 (Fig. 1c) possesses many features of the moderate warm events, but of opposite sign. These include on-equatorial maxima centered near 160°W and a forked pattern of opposite-signed anomalies branching from the equatorial west Pacific into the subtropical central Pacific. Furthermore, as will be shown, the atmospheric anomalies over the Pacific sector during the 1988/89 winter also resembles that occurring during the warm events, albeit of opposite sign. Thus, for ease of comparison with the three warm events so as to illustrate common aspects of the atmospheric anomalies during these particular ENSO winters, all subsequent anomaly maps for 1988/89 are scaled by −1. Although somewhat arbitrary, the zero-order approximation that the atmosphere responds linearly (in sign) to tropical Pacific SST anomalies is supported by several climatological studies of the atmospheric response to El Niño and La Niña (Yarnal and Diaz 1986; Kiladis and van Loon 1988; Kiladis and Diaz 1989).

Tropical Pacific OLR anomalies exhibit a simple wavenumber 1 pattern for all four winters (Fig. 2), consisting of a central basin surplus (deficit) and a
Fig. 1. December–February sea surface temperature anomalies for (a) 1982/83, (b) 1986/87, (c) 1988/89, (d) 1991/92. Contour interval is 0.4°C and negative contours are dashed.
FIG. 2. December–February outgoing longwave radiation (OLR) anomalies for (a) 1982/83, (b) 1986/87, (c) 1988/89, (d) 1991/92. Contour interval is 10 W m$^{-2}$ and negative contours are dashed. Panel (c) is multiplied by $-1$. 
western basin deficit (surplus) of rainfall during the warm (cold) phase of ENSO. An additional common feature is the northwest-southeast tilt of the OLR anomaly dipole across the tropical Pacific. The strong central Pacific anomaly is on the equator, whereas the somewhat weaker anomaly over the west Pacific is shifted 10° north of the equator.

Several differences in the individual OLR anomaly patterns in Fig. 2 can be related to inter-El Niño variability in SST forcing. Notably, enhanced convection is farther east during 1982/83 (Fig. 2a) compared with the two moderate El Niños (Figs. 2b and 2d) consistent with the shift of warm SSTs into the eastern equatorial Pacific during the strong event. Also, a 10° eastward shift of negative OLR anomalies during 1991/92 relative to 1986/87 is consistent with a similar eastward shift of warmest SSTs during 1991/92 (see Fig. 1). On the other hand, the amplitude of SST and OLR anomalies are not simply linearly related. Over the convectively active central Pacific, the magnitude of OLR anomalies is slightly greater during 1986/87 than 1991/92 despite the appreciably greater positive SST anomalies during the latter winter. The situation also appears to be complicated over the convectively suppressed tropical western Pacific. Note, for example, the small areal extent and weak magnitude of positive OLR anomalies over this region during 1986/87 compared to the other two warm ENSOs. Yet, the west Pacific SST anomalies are very similar for the three El Niño winters. The more complicated local SST/OLR relationship here may be due to the remote influence of the convectively active regions over the central Pacific or Indian Ocean sectors. Also, since intraseasonal convective events are observed to acquire their maximum intensity over the Indian Ocean/western Pacific region (e.g., Lau and Chan 1985; Knutson and Weickmann 1987), some of the inter-El Niño variability here may reflect the influence of such low-frequency phenomena rather than steady SST forcing.

Figure 3 illustrates the streamfunction tendency associated with the climatological and anomalous transient vorticity fluxes defined as

\[ T = -\nabla^2(\nabla \cdot \overline{\zeta}), \tag{1} \]

where \( V \) is the velocity vector, \( \xi \) is the relative vorticity, the bar represents a 90-day average, and primes denote departures from the time average. All fields are shown at sigma = 0.245 (roughly 250 hPa), and the zonal mean has been removed. Despite the inter-El Niño variability in SSTs and tropical diabatic forcing for these four ENSOs, the anomalous transient behavior (Figs. 3a–3d) over the North Pacific is remarkably robust in that a maximum forcing is consistently centered near (40°N, 150°W). The sense of this forcing is to locally induce cyclonic (anticyclonic) circulation over the northeast Pacific during the warm (cold) ENSOs, and may be viewed simply as an eastward shift of the climatological center of maximum cyclonic forcing (Fig. 3e) from 175°W to nearly 150°W during the ENSO winters. A major contribution over the northeast Pacific occurs through high-frequency transients with periods less than 10 days (not shown), suggesting that the anomalous transient forcing is associated with an extension (contraction) of the climatological storm track during the warm (cold) ENSOs. A second center of anomalous cyclonic (anticyclonic) forcing during the warm (cold) phase of ENSO is evident south of Hawaii. Although its precise location shows considerable variability, its longitude seems to follow the location of equatorial OLR anomalies. It is difficult to make any general statement on the anomalous transient behavior elsewhere.

The upper-tropospheric stationary wave anomalies over the PNA region are quite similar during the recent ENSOs (Fig. 4). Over the subtropical Pacific, twin anticyclones are observed during the three warm events (Figs. 4a, b, d), whereas twin cyclones are observed during the cold event (Fig. 4c). The similarity in subtropical anomalies among these four events appears to be consistent with the robustness observed within a larger sample of ENSO winters. Horel and Wallace's (1981) analysis for the 1951–1978 period demonstrates that up to 50% of the variance of the seasonal mean 200-hPa heights over the subtropical Pacific is explained by a Line Island rainfall index. That rainfall anomalies in this region may have controlled the subtropical circulation anomalies during the recent events is suggested by the fact that the longitude of twin anticyclone anomalies closely follow the OLR anomalies (see Fig. 2). During 1986/87 in particular, the tropical anticyclones are shifted some 30° west of those in the other warm events, consistent with the westward-shifted negative OLR anomalies. In contrast, the positions of stationary wave anomalies over the North Pacific exhibit less variability, being centered at 150°W in all four cases. A similar robustness characterizes the transient vorticity forcing anomalies (see Fig. 3), and provides further observational evidence for the coupling between the extratropical oceanic storm tracks and low-frequency circulation patterns, as described by Lau (1988).

The similarity of midlatitude PNA-sector anomalies among these four events appears somewhat remarkable in light of the conventional view of a more variable extratropical response to El Niño. Recall that Horel and Wallace (1981) find only 35% of the variance of seasonal mean 200-hPa height variability in this region to be explained by equatorial Pacific SSTs. It is important to recall, however, that their period of study includes many different types of ENSO events, as opposed to the exclusively basinwide events studied herein. That the atmosphere here may respond quite differently to the classical coastal-type El Niño versus the basinwide warming is suggested by the modeling results of Palmer and Mansfield (1986). Nonetheless, the observational results confirm the notion that many
Fig. 3. December–February streamfunction tendencies at sigma = 0.245 due to anomalous transient vorticity flux convergences for (a) 1982/83, (b) 1986/87, (c) 1988/89, (d) 1991/92, and (e) climatological transient vorticity flux convergences. Contour interval is 10 m$^2$ s$^{-1}$ and negative contours are dashed. Zonal mean is removed and fields are truncated at R15. Panel (c) is multiplied by $-1$. Map projection centered at 150°W and 40°N.
processes in addition to tropical SST anomalies contribute to midlatitude low-frequency variability. As such, though it is tempting to claim that SST forcing is the underlying cause for the patterns in Fig. 4, we must recognize that processes purely internal to the atmosphere could have generated those patterns. In this regard, it is important to note that the eddy streamfunction depictions of such patterns in Fig. 4 do not contain the zonal mean anomalies. We find the zonal mean extratropical anomalies to differ apprecia-
b. GCM simulations of the atmospheric response to El Niño

Each realization of the NCAR CCM1 for the 1982/83 and 1986/87 El Niño winters is shown in Figs. 5 and 6, respectively. As for observations, we consider the GCM's behavior over the PNA region only. The model's tropical anomalies during both winters are highly reproducible, as revealed by the recurrence of twin anticyclone anomalies southeast of Hawaii. Since the tropical circulation is known to be strongly diabatically forced, the similarity of anomalies is evidence for CCM1's robust convective response to the imposed SSTs. Figure 7 illustrates the ensemble averaged heating anomalies for each event, and we have verified that individual samples deviate little from their respective means (not shown). Despite a robust convective response, intersample variability of the upper-level tropical circulation anomalies is not negligible. For the 1986/87 simulations in particular, the Northern Hemisphere tropical anticyclone center shifts from 165°W over the Hawaiian Islands in experiment 1 (Fig. 6a) to 135°W in experiment 2 (Fig. 6b). This purely initial condition sensitivity in CCM1 is as large as the boundary-forced sensitivity in nature as implied by differences between the 1982/83 and 1986/87 observed streamfunction anomalies (Fig. 4).

The model's extratropical anomalies are more variable than those simulated over the tropics. Over the northeast Pacific, experiments 4 and 5 for 1982/83 (Figs. 5d,e) exhibit cyclonic anomalies with large amplitude in fair agreement with observations, whereas experiment 1 (Fig. 5a) fails to simulate an anomalous low. Large variability of the North American anticyclone anomaly is also evident during 1982/83, with a center over Alaska in experiment 2 and centers over eastern Canada in experiments 4 and 5. Although CCM1's anomalies over the PNA region are more reproducible during 1986/87, experiment 3 (Fig. 6c) deviates from the other experiments, possessing an extratropical wave train nearly in quadrature with the other four realizations.

Large intersample variability of the simulated extratropical response during El Niño has been noted in other GCM studies (e.g., Shukla and Wallace 1983). The cause for this variability has not been determined, although both Geisler et al. (1985) and Palmer and Mansfield (1986) find that the robustness of their GCM's extratropical response diminished as equatorial Pacific SST anomalies shifted eastward. Our results are similar in that the anomalies over the PNA region for 1982/83 are less reproducible than for 1986/87, although a sample size of 5 is not adequate to define the spatial variability of the response.

Of greater interest to this study is the comparison of modeled intersample variability with observed inter-El Niño variability. For the Pacific/North American region as a whole, CCM1's intersample variability is clearly as large as the variability observed among the four recent ENSOs. Of course, a different choice of observed ENSOs may lead to a different conclusion. For example, Palmer and Mansfield (1986) found their model's intersample variability to be appreciably less than the difference between observed atmospheric responses for the 1982/83 and 1976/77 El Niño winters.

Nevertheless, it is important to determine the reasons for dispersion among the GCM samples. If the GCM variability is indicative of the natural (i.e., unpredictable) variability of seasonal means, then the GCM results offer a pessimistic view of seasonal predictability. On the other hand, the model results may have spurious origins due to errors in representing the chain that couples tropical SSTs and extratropical stationary waves. As such, the predictable component of the atmospheric response in the GCM may be considerably less than that implied by the observations in Fig. 4.

We have already noted that CCM1's tropical heating anomalies are strongly controlled by the anomalous SST forcing, much as in nature, and thus the model's intersample variability is unlikely due to changes in diabatic forcing. In contrast, CCM1's transient vorticity fluxes exhibit a wide spectrum of behavior during individual realizations. As shown in Figs. 8a–8e for the 1986/87 simulations, the transient forcing anomalies vary greatly in amplitude and sign over the North Pacific, contrary to the recurrent signal in the observed ENSOs (see Fig. 3). Observe, however, that for each realization there is a reasonable correspondence between the eddy streamfunction anomalies and the transient forcing anomalies over the extratropical Pacific. A similar situation occurs in the 1982/83 simulations (not shown). This appreciably larger variability in the GCM transient anomalies versus those observed cannot be simply attributed to an error in CCM1's mean transient behavior, as is evident from the close agreement between the modeled (Fig. 8f) and observed (Fig. 3e) climatological transient forcings.

A more concise view of the contrast between model and observations is given in Fig. 9 where the ensemble average of CCM1's 1982/83 and 1986/87 transient forcing anomalies are compared with the average of those observed during the four recent ENSOs. Over tropical latitudes, the model's mean forcing due to transient vorticity flux anomalies (Figs. 9b,c) agrees closely with that observed (Fig. 9a). Much less agreement is found over the North Pacific due in part to the large cancellation between individual realizations. Indeed, CCM1 exhibits almost no mean cyclonic forcing anomaly over the North Pacific. One can discern,
however, ensemble mean cyclonic forcing of moderate amplitude over the far eastern Pacific and the southwestern United States. This feature is also evident in observations and appears related to the formation of a secondary storm track during El Niño (see Ting and Hoerling 1993).

c. Linear baroclinic model experiments

A more rigorous assessment of CCM1’s transient behavior in relation to the tropical heating is gained by contrasting the responses of a steady-state linear baroclinic model to the GCM’s transient vorticity and diabatic forcings for each realization. In this study, as in TH, we generally find the baroclinic model to faithfully reproduce CCM1’s stationary wave anomaly in the individual experiments for the 1986/87 winter when linearized about CCM1’s wavy climatological flow and forced with its global vorticity transients and heating anomalies (Fig. 10; note that the contour level is double that in Fig. 6). An exception is for experiment 3 where the linear model response is a poor proxy for the GCM stationary wave anomaly over the PNA region (not shown). The cause for failure in this case is not fully understood. A possibility is that the anomaly pattern in experiment 3 is indicative of regime behavior in CCM1. To the extent that such behavior is dominated by nonlinear dynamics (e.g., Molteni et al. 1990) our linear diagnosis would be expected to fail. We focus our attention on the remaining four GCM realizations for the 1986/87 El Niño winter. The ability of the linear model to reproduce the primary features of the GCM pattern for these realizations justifies further diagnosis of the separate influences of diabatic and transient forcing.
FIG. 8. December–February streamfunction tendencies at sigma = 0.245 due to anomalous transient vorticity flux convergences for the individual realizations of CCM1 for 1986/87 [panels (a)–(e)], and due to CCM1's climatological transient vorticity flux convergence (f). Contour interval is 10 m^2 s^{-2} and negative contours are dashed. Zonal mean is removed and fields are truncated at R15. Map projection as in Fig. 4.
Figure 9. December-February streamfunction tendencies at sigma = 0.245 due to anomalous transient vorticity flux convergences for the ensemble mean of (a) four observed ENSOs, (b) CCM1 1982/83, and (c) CCM1 1986/87. Contour interval is 10 m² s⁻² and negative contours are dashed. Zonal mean is removed and fields are truncated at R15. Map projection as in Fig. 4.

Figure 11 presents the linear model response to CCM1’s tropical (20°N–20°S) Pacific (120°E–120°W) diabatic forcing only. The primary features evident in each panel are the wave train emanating from the tropical west Pacific and the twin anticyclones located symmetrically about the equator near 160°W. As has been previously shown in TH for the ensemble mean response, the former feature is induced primarily by anomalous cooling over the Indonesian/Philippine sector, whereas the latter is both a local response to the anomalous heating over the equatorial central Pacific and a remote response to anomalous west Pacific cooling (see Fig. 7). The reproducibility of these stationary wave responses over the PNA region is indicative of
the strong coupling between SST anomalies and rainfall anomalies over the tropical Pacific in CCM1.

Yet, as is implied in Fig. 12 by the large intersample variability of the linear model's response to CCM1's extratropical (north of 20°N) vorticity transients, only modest coupling exists between the CCM's tropically forced stationary wave and its North Pacific storm track. Indeed, the response to transient forcing in experiment 5 (Fig. 12d) is opposite in sign to the wave train induced by tropical Pacific heating. The transient-induced response for the remaining experiments is grossly in phase with the tropically forced stationary wave, although the individual centers of action vary greatly in location and magnitude. Note, for example, the strong transient-induced cyclone near Vancouver Island in experiment 4 (Fig. 12c), while a considerably weaker forced cyclone is located near the Aleutian Islands in experiment 2 (Fig. 12b). These results for the
GCM contrast with the strong reproducibility of transient eddy activity during the four recent El Niño winters (see Fig. 3).

This large intersample variability leads us to conclude that the linear model response to CCM1’s ensemble mean extratropical transient vorticity forcing studied in TH is effectively a residual of large differences between individual realizations. While we believe the ensemble mean transient behavior to be indicative of CCM1’s equilibrium response to the 1986/87 El Niño, the small residual amplitude of this mean forcing relative to the large amplitude of individual samples is unlikely to render it statistically significant. Furthermore, the reproducibility of CCM1’s stationary wave response over the PNA region during 1986/87 as revealed in Fig. 6 cannot be ascribed to an organized behavior of storm track transients, being instead attributable to the recurrence of strong tropical forcing.

Fig. 11. Zonally asymmetric streamfunction anomalies at sigma = 0.245 for linear model response about CCM1’s zonally varying climatology and subjected to CCM1’s 1986/87 anomalous Pacific sector (120°E–120°W) diabatic heating within 20°S and 20°N. Contour interval is 1 x 10⁶ m² s⁻¹. Map projection as in Fig. 4.
A strikingly different picture emerges from the linear model diagnosis of the forced response to extratropical transients during the observed ENSOs (Fig. 13). In these experiments the model is linearized about NMC's wavy climatological flow. A transient-induced wave train over the PNA region characterizes all four ENSO winters. The slight phase shift between individual winters, for example, a 20° westward shift of centers over the North Pacific during 1986/87 (Fig. 13b) relative to 1991/92 (Fig. 12d), is consistent with similar phase shifts of the seasonal mean stationary wave anomalies (see Fig. 4). With regard to amplitude, the transient forced waves account for much of the total seasonal mean stationary wave anomalies over the PNA region. This is consistent with our previous analysis for the 1986/87 winter (Ting and Hoerling 1993) in which we diagnosed separately the contributions due to extratropical transients and tropical heating, and showed...
that the extratropical transients were the primary mechanism maintaining the extratropical stationary wave anomaly. We are unable to perform a complete analysis on the maintenance of stationary waves during the other three winters used herein due to data limitations that adversely influence diagnosis of the heating. We have, however, used the OLR anomalies to derive a proxy for the heating anomalies in a manner similar to Kok and Opsteegh (1985). The linear model's extratropical response to the diabatic forcing (not shown) was found to be less than 20% of the amplitude of the transient-induced response for each El Niño event. The empirical procedure used to derive the heating fields together with the sensitivity of the response to details
of such forcing places considerable uncertainty on these latter calculations. Nonetheless, our results are quite suggestive of the primary role played by extratropical transients during these four ENSO winters.

4. Tropical controlling of extratropical transients

Held et al. (1989) suggested a process by which the extratropical transients can be organized by tropical SST anomalies. They argued that a tropically forced wave train of only modest amplitude may be sufficient to displace the downstream portion of the oceanic storm track. The anomalous transients in turn force a wave train of large amplitude that is in phase with the tropically forced response. Implicit in this description is that the transients are slaves to the tropically induced wave train. Thus, if the heating anomaly is displaced farther into the eastern Pacific, perhaps in response to a farther east positioning of equatorial SST anomalies, one would expect the anomalous transients to follow suit. Yet, the observational results presented herein suggest otherwise with quite similar extratropical transient anomalies during several ENSOs despite large differences in equatorial SST anomalies. It is thus unclear what mechanism acts in nature to control the behavior of extratropical transients under the influence of various distributions of tropical forcing.

We explore the efficacy of the tropical forcing to control the extratropical transients by performing a series of idealized linear model experiments. A diabatic heat source having a parabolic vertical structure with maximum heating at 350 hPa and an elliptical horizontal structure with major axis on the equator is imposed on NMC and CCM wavy climatologies [see Fig. 4 in Ting and Sardeshmukh (1993) for an illustration of this idealized heating]. The vertically averaged heating corresponds roughly to a 10 mm day$^{-1}$ rainfall anomaly, and the horizontal scale attempts to reproduce the pattern of negative OLR anomalies shown in Fig. 2. The heat source is positioned at various locations along the equatorial Pacific.

Figure 14 illustrates in bold contours the steady linear response to heating at 170°W and 130°W, corresponding to the range of OLR anomalies observed during the recent ENSOs. For clarity, only positive contours of the model response are shown, and these have been superimposed on the appropriate wavy base state. Consistent with Gill's (1980) simple analytic solution, the upper-level linear response includes a tropical anticyclone whose center is shifted west of the maximum heating and that has a zonal scale greater than that of the imposed heat source. The pattern of the tropical response is similar for diabatic forcing centered at both longitudes (compare upper and lower panels), although the anticyclonic center is shifted farther east for the case of eastward displaced heating. The tropical responses are also quite similar for either the NMC (left panels) or the CCM (right panels) base states. This latter insensitivity differs from the results of Ting and Sardeshmukh (1993) who found the tropical response to be quite sensitive to the choice of either a GFDL GCM or a European Centre for Medium-Range Weather Forecasts (ECMWF) observed wavy base state. This apparent contradiction is partly explained by the differences between the CCM and GFDL model base states. An additional consideration is that the sensitivity in Ting and Sardeshmukh (1993) is due partly to the different modal structures of the three-dimensional base states. With the inclusion of an additional thermal diffusion due to the transients in the current linear model study, modal behavior does not seem to play a significant role. Whether linear modal behavior is relevant for the atmosphere is still an open question that is beyond the scope of this study.

Of particular interest in Fig. 14 is the eastward phase shift of the anomalous tropical high relative to its climatological counterpart for heating centered at either 170°W or 130°W. In both instances, the tropical high and by continuity the subtropical jet on its northern flank are extended eastward toward the date line. Through this simple process of jet stream extension, the oceanic storms are more likely to invade the eastern North Pacific. To a first approximation, this eastward shifting of the extratropical transients may not be especially sensitive to the precise location of the equatorial rainfall anomalies (and the underlying SST anomalies) within the band spanning the eastern portion of what is commonly called the Niño 4 region to the central portions of the Niño 3 region.

Whereas a simple jet extension in response to equatorial Pacific heating may be a plausible dynamical mechanism for organizing extratropical transients in nature, the situation in the GCM is evidently more complicated. One distinction between the GCM and nature is the greater sensitivity of the model's climatological flow to forcing from the equatorial west Pacific. For the 1986/87 winter in particular, the results in Fig. 11 and in TH show a large-amplitude wave train originating from the region of suppressed rainfall over Micronesia in CCM1, whereas little sensitivity to the diagnosed west Pacific cooling anomaly occurred in nature. The phase of the cooling-induced wave train in CCM1 is such as to shift the subtropical Pacific jet poleward (and not eastward), a response that may make interaction with the equatorial central Pacific heat source less effective.

5. Discussion and summary

The dynamics of the atmospheric response during El Niño has been examined, with emphasis on the extratropical anomalies over the Pacific/North American region. Diagnostics were performed to assess the origin of the wintertime stationary wave anomalies during three recent warmings (1982/83, 1986/87, 1991/92) and one cooling (1988/89) of the tropical Pacific, and
within a series of GCM simulations for the 1982/83 and 1986/87 warm events. The purpose was twofold: to ascertain whether a single mechanism was consistently responsible for the extratropical anomalies in nature and whether such a mechanism was faithfully reproduced in the GCM.

When allowance was made for the sign difference in the atmospheric anomalies for the cold and warm
events, qualitatively similar stationary wave patterns were observed over the PNA region during the four ENSO winters. The tropical Pacific anomalies showed the largest inter-El Niño variability, being very sensitive to the precise location of the SST and accompanying rainfall anomalies. The extratropical North Pacific showed surprisingly less variability. Particularly reproducible were the anomalous transient vorticity fluxes, whose structure and frequency were indicative of an eastward-shifted Pacific storm track.

The five-member ensemble of NCAR CCM1 simulations for 1982/83 and 1986/87 exhibited intersample variability over the PNA region that was as large as that among the recent observed ENSO winters. While the CCM had a highly reproducible tropical convective response to the SST anomalies, the model's extratropical transients varied greatly. Indeed, the five-case sample size was found to be barely adequate to diagnose the GCM's equilibrium transient eddy response over the North Pacific.

A linear baroclinic stationary wave model was used to quantify the role of transients in maintaining the extratropical stationary wave anomalies. For observations, the response to transient vorticity forcing was consistent and highly organized during all four ENSO winters. Vorticity transients north of 20°N accounted for much of the sign distribution and amplitude of the total stationary wave anomaly over the North Pacific and North America. This result was found to be consistent with the important effects of transients found by Kok and Opsteegh (1985) during 1982/83 and in the GFDL model experiments studied by Held et al. (1989). In contrast, comparatively little organization of the transients was evident in the CCM, despite a consistently large-amplitude wave train induced over the PNA region by the model's tropical diabatic forcing.

We explored a possible mechanism by which events in the tropics can control the behavior of transient eddies in extratropics. A simple steady equatorial heat source was found to be sufficient to initiate a process that included a forced tropical anticyclone phase shifted slightly east of the climatological west Pacific high, and a resultant eastward extension of the subtropical Pacific jet. This mechanism appeared to be effective in displacing the climatological deformation zone of mid-latitudes eastward. Through this process we argued that individual extratropical cyclones would be more likely to penetrate into the northeast Pacific, thereby leading to an eastward extension of the wintertime storm track.

It was further found that this process could be as effectively initiated by an equatorial heat source positioned near the date line, as by one located at 130°W. This helped to explain the reproducibility in extratropical transient eddy behavior during the several observed ENSOs, despite the large SST variability.

Of course, these idealized experiments alone do not prove that tropical forcing caused the anomalous transient behavior in the extratropics during the recent ENSO winters. Additional experiments using time-dependent dynamical models would be required to test our claim that the observed transient eddies in the extratropics were indeed organized by tropical SST's. Indeed, other processes could also act to organize the extratropical transients, including suppressed rainfall over the tropical west Pacific, orographically induced stationary wave anomalies, zonal mean zonal wind changes, or extratropical SST anomalies. The efficacy of these and other mechanisms occurring within a wide class of ENSO events requires further investigation.

The extratropical transients were shown to be much more variable in the CCM simulations during El Niño, and this appears to have increased the model's intersample variability. Indeed, if the spread of individual members in CCM1's ensemble were used as a measure of predictive skill in extratropics, a more pessimistic view emerges than that offered by the recent observed ENSO winters. Stated otherwise, a statistically significant signal of the equilibrium response to El Niño requires a large sample of CCM1 simulations. The cause for dispersion in the CCM is not clearly known, although symptomatic of this behavior was an inability to efficiently couple the anomalous tropical heating with the subtropical Pacific jet and its accompanying storm track.

An important problem to which our paper is relevant is the dynamical prediction of seasonal mean climate anomalies. We are intrigued by the recurring atmospheric patterns over the PNA sector during the four recent El Niño winters. Notwithstanding the possibility that the recent events may not be inclusive of a large El Niño population, it is relevant to question whether existing AGCM's are capable of reproducing a similar robust behavior. In this regard we are encouraged by the forecast experiments reported by Molteni et al. (1993), which demonstrate a quite accurate seasonal mean response within ECMWF model runs for the 1988/89 winter. Our paper claims that the predictable component of the extratropical response that appears to exist in nature can be forfeited in AGCMs due to model error. The model error may actually be quite subtle. Our diagnosis of observations argues for a much more complicated picture of the extratropical response to El Niño than suggested by theoretical analysis. The chain between tropical and extratropical latitudes involves many vital links including the three-dimensional distribution of tropical heating (and cooling) anomalies, the resultant energy dispersion through a wavy ambient flow, an incipient stationary wave response, and synoptic eddy--mean flow interactions that strongly feed back upon the stationary waves. Additionally, zonal mean flow anomalies may also be important. One can easily imagine a modest misrepresentation of a link leading to sizeable errors in the GCM's extratropical response.

We take an optimistic (although not unrealistic) view that skill on seasonal time scales can be signifi-
stantly enhanced by model improvement. This view is to be contrasted with prospects at the medium range (≈ 10 days), where additional skill is unlikely to accrue due to the "chaotic" behavior of individual eddies beyond several days. Although synoptic eddy–mean flow interactions are also important on the seasonal time scale, we argue that the envelope of such activity can be tropically controlled at low frequency during El Niño. As such, given a useful forecast of the SST anomalies and an accurate atmospheric GCM, the extratropical behavior may at times be deterministic well beyond the medium range, and seasonal predictions may be feasible.

Acknowledgments. We appreciate the generosity of Dr. Maurice Blackmon in providing the GCM datasets used in this study. We also appreciate the assistance of Drs. John Bates and George Kiladis, who provided us with the SST anomalies and OLR anomalies used to construct Figs. 1 and 2. Support provided by the Equatorial Pacific Ocean Climate Studies Program (EPOCS) and NOAA’s Climate and Global Change Program is gratefully acknowledged. The comments of two anonymous reviewers helped to clarify several points in the paper. This work has also benefited from discussions with Drs. Prashant Sardeshmukh, Michael Alexander, and Clara Deser.

REFERENCES


Unauthenticated | Downloaded 05/25/22 10:54 AM UTC