The linkages between the El Niño phenomenon in the tropical Pacific and atmospheric–oceanic changes throughout the world are explored using an extensive series of specially designed model experiments.

Pursuant to various theoretical investigations (e.g., Hoskins and Karoly 1981) and observational studies (e.g., Horel and Wallace 1981), considerable attention was devoted to the impact of tropical Pacific (TP) sea surface temperature (SST) forcing in El Niño–Southern Oscillation (ENSO) episodes on the midlatitude atmospheric circulation, especially in the North Pacific–North America sector. It has been demonstrated that atmospheric general circulation model (GCM) experiments with prescribed, temporally fixed SST anomalies in the ENSO region have considerable success in reproducing the observed atmospheric response (e.g., Blackmon et al. 1983). The realism of these simulations was enhanced by prescribing anomalous SST patterns in the TP that change from month to month in accordance with observational records in the 1962–76 period (Lau 1985). The model being used is a low-resolution GCM developed at the Geophysical Fluid Dynamics Laboratory (GFDL). This experimental design facilitates a more in-depth investigation of the evolution of the atmospheric signals through different seasons during the entire ENSO cycle. By examining two parallel model runs with independent initial conditions, but with identical sequences of SST forcing, the reproducibility of atmospheric signals generated by ENSO forcing was assessed. It was noted that responses of the tropical atmosphere to the prescribed TP SST changes are rather similar in the two runs, whereas the extratropical wavelike pattern in the Pacific–North America region exhibits more variability from one run to the other. This study may be viewed as a primitive forerunner of the modern-day multimember ensemble approach, with the number of members (two) being admittedly small because of computing resource limitations at that time.
It has long been recognized that observed SST anomalies accompanying ENSO events are not confined to the TP, but have significant amplitude in other parts of the World Ocean. The strong correlation between SST variations observed in the deep tropical east-central Pacific and those located in the North and South Pacific, the Atlantic basin, and the Indian Ocean is illustrated in Fig. 1a. A natural question to ask is what are the relative roles of the SST forcing at various sites in generating the atmospheric response? To address this issue, a suite of experiments using the GFDL GCM was conducted, with the domain of time-varying anomalous SST forcing being placed in the TP [the Tropical Ocean–Global Atmosphere (TOGA) runs], midlatitude Pacific [the Midlatitude Ocean–Global Atmosphere (MOGA) runs], and throughout the ice-free World Ocean [the Global Ocean–Global Atmosphere (GOGA) runs]. For all oceanic grid points lying outside the domain of anomalous SST forcing, the surface conditions were constrained to evolve through identical seasonal cycles, with no interannual variability being introduced. These model integrations, as well as some of the runs to be described later in this lecture, were performed under the auspices of the National Oceanic and Atmospheric

![Observation](image1)

![Model](image2)

Fig. 1. (a) Temporal correlation coefficient between spatially averaged SST anomalies in the ENSO region (rectangular box in the equatorial Pacific) in the Nov–Jan season and global SST anomalies in the subsequent Feb–Apr season. The SST data in all regions are based on observations from the 1950–99 period. (b) As in (a), but for correlation between the prescribed SST anomalies in the same ENSO region and global SST anomalies simulated by an oceanic mixed-layer model in the MLM experiment. The thick black boundary in (b) indicates the domain of SST prescription using observed data in that experiment. [From Alexander et al. (2002).]
Administration’s (NOAA) Equatorial Pacific Ocean Climate Studies (EPOCS) program (Hayes et al. 1986) and the decade-long (1990–2000) NOAA–universities consortium for investigating atmospheric variability associated with perturbed boundary conditions (Held and Lau 2002). The findings from the TOGA–MOGA–GOGA experiments have been summarized by Lau and Nath (1994). They reported that the SST anomalies in the TP (as considered in the TOGA runs) play a dominant role in forcing the atmospheric wave train in the North Pacific–North America sector, whereas the anomalous SST forcing in the midlatitude North Pacific (MOGA runs) yields only a weak response that is out of phase with the signal generated by TOGA. The strong similarity between the extratropical atmospheric patterns generated in GOGA and TOGA confirms that, among the different sites in the World Ocean, the TP is particularly influential in modulating midlatitude atmospheric variability.

**MODEL SIMULATION OF THE “ATMOSPHERIC BRIDGE” LINKING ENSO FORCING AT TP AND SST VARIABILITY ELSEWHERE.** Interest also turned to the causes for the near-global extent of the SST anomalies associated with ENSO. In view of the short time lag (on the order of months) between the SST signals in the TP and those in other sites, the global-scale atmospheric circulation was proposed as the primary pathway for communicating oceanic changes in the ENSO region to oceanic sites elsewhere. The chain of processes associated with this atmospheric bridge mechanism proceeds as follows. TP SST anomalies related to ENSO affect the local precipitation and flow patterns, thus altering the spatial distribution of heat sources and sinks, which influences the atmospheric conditions around the globe. These widespread atmospheric anomalies in turn lead to changes in the underlying ocean through modulation of the local air–sea fluxes and surface currents. Some of these ideas have already been proposed in the early studies of Alexander (1992) and Luksch and von Storch (1992) on the concomitant SST changes in the North Pacific during ENSO events. A systematic investigation was performed at GFDL using a set of GCM experiments that were designed to diagnose various facets of the atmospheric bridge mechanism. The basic experiment is a variant of the TOGA experiment described previously. As before, observed month-to-month SST variations were prescribed in the TP. However, at each ice-free grid point lying outside of this forcing domain, a simple oceanic mixed-layer model was employed to compute the local SST changes, mainly by taking into account the perturbed surface heat and radiative fluxes. Hence, the atmosphere is forced by SST changes prescribed in the TP, whereas simplified two-way air–sea coupling is incorporated outside that forced domain. This experimental setup is therefore suited for delineating the contributions of the atmospheric bridge to the global characteristics of the atmosphere–ocean system during ENSO. In the early version of this experiment [labeled as TOGA-Mixed Layer (TOGA-ML); Lau and Nath 1996], the domain of the prescribed SST forcing for the 1946–88 period extended across the entire width of the TP between 25°S and 25°N, and the oceanic mixed layer was represented by a slab with a constant depth of 50 m. A four-member ensemble has been obtained with this design. In the later version [labeled as Mixed Layer Model (MLM); Alexander et al. 2002], a smaller SST forcing domain extending from 172°E to the South American coast, and from 15°S to 15°N, was employed. A more realistic oceanic mixed layer with variable depth was used to simulate oceanic variability outside the region of prescribed SST changes. An ensemble of 16 members, with each run extending over the 1950–99 period, has been generated.

The correlation chart of SST variations at individual grid points versus those prescribed in the central equatorial Pacific, as computed using the output from the MLM experiment, is presented in Fig. 1b. Comparison of this pattern with its observational counterpart (Fig. 1a) reveals many similarities, thus illustrating the prominent role of the atmosphere in linking ENSO forcing to SST variability at distant sites. The processes contributing to the atmospheric bridge between ENSO in the TP and the extratropical North Pacific and North Atlantic are described in detail in Lau and Nath (2001). That study confirms that the modulations of the surface heat fluxes at midlatitude sites are primarily attributable to local changes in surface wind speed, air temperature, and humidity during ENSO events, in accord with the bulk aerodynamic law. The atmosphere–ocean changes in the Indian Ocean–tropical western Pacific (the IWP sector) that are related to ENSO have been examined by Klein et al. (1999) and Lau and Nath (2003), among others. These investigations indicate that, in addition to sensible and latent heat transfers, changes in the shortwave radiative flux also play a significant role in determining the SST response at various tropical sites to the bridge mechanism. Variations in these short-wave fluxes are driven by changes in cloud cover accompanying precipitation systems, the locations of which are largely governed by the spatial distribution of meridional and zonal overturning atmospheric circulation cells in various phases of ENSO.
THE ATMOSPHERIC BRIDGE AT WORK IN THE TROPICAL WESTERN PACIFIC. The ENSO signals in the tropical western Pacific sector are used here as an example for illustrating the impacts of the atmospheric bridge mechanism on the atmosphere–ocean system. Figure 2 shows the patterns of horizontal wind, SST, sea level pressure, and precipitation based on observations (left panels) and output from the MLM experiment (right panels). These anomaly charts are obtained by subtracting the composite over outstanding La Niña events from the composite over prominent El Niño events and, hence, describe the typical behavior in the boreal winter season in the mature warm phase of ENSO cycles. In El Niño episodes, positive sea level pressure perturbations and dry conditions are seen over much of the tropical western Pacific, with an anomaly center over the South China and Philippine Seas (Figs. 2b and 2d). The anticyclonic surface flow pattern near this center leads to southwesterly surface wind anomalies off the Chinese coast between 15° and 30°N (arrows in Figs. 2a and 2c). These wind changes are oriented opposite to the local climatological northeasterly monsoon flow in the cold season. The resulting anomalous positive temperature and moisture advections, as well as a decrease in wind speed, lead to suppression of sensible and latent heat loss from the ocean to the atmosphere. These effects are further augmented by increases in shortwave radiative flux, due to the reduction in cloud cover under the prevalent dry conditions over the western TP. These ENSO-induced perturbations of the surface heat fluxes in turn generate warm SST anomalies in the South and East China Seas, and the maritime region south of Japan (shading in Figs. 2a and 2c). The notable correspondence between the simulated atmospheric and oceanic signals (Figs. 2c and 2d) and their observational counterparts (Figs. 2a and 2b) confirms that the essential interactive processes in the coupled air–sea system associated with the atmospheric bridge in the western TP sector are well captured by the MLM experimental design.

FEEDBACK EFFECTS OF ENSO-INDUCED SST ANOMALY IN THE INDO-WESTERN PACIFIC SECTOR ON THE ATMOSPHERIC CIRCULATION. Studies of the tropical atmospheric bridge indicate growth of the SST anomalies in the IWP sector to considerable amplitudes during the boreal summer after the ENSO events have attained maturity in the TP. This finding has sparked considerable interest in the feedback effects on the global climate.
atmospheric circulation of warm SST anomalies generated in the IWP sector during El Niño events through the bridge mechanism. This issue was explored by Lau et al. (2005) using a new set of SST sensitivity experiments that are analogous to the TOGA experiment, but with the domain of time-varying SST forcing being shifted from the TP to the IWP sector (the IWP experiment). The prescribed space–time development of the oceanic forcing in the IWP domain is based on SST data generated in the MLM experiment for that region. The atmospheric response to the ENSO-driven SST forcing in the IWP during the summer is characterized by a pair of zonally extended upper-tropospheric pressure ridges spanning almost the entire latitude circles at approximately 35°N and 35°S (see Fig. 2f in Lau et al. 2005). The pattern is similar to that associated with droughts in the U.S. Great Plains (Schubert et al. 2004). The evidence presented in Lau et al. (2005, their Fig. 8) indicates that the zonal extension of the anomalous pressure ridges over the North and South Pacific may partially be attributed to dynamical effects of the intensified synoptic-scale eddy activities in those regions on the local time-mean circulation.

**INTERACTIONS BETWEEN ATMOSPHERIC RESPONSES TO SST FORCINGS IN THE INDO-WESTERN PACIFIC AND EAST-CENTRAL TROPICAL PACIFIC.** In view of the marked sensitivity of the atmospheric circulation to SST anomalies in the IWP, it is of interest to examine the atmospheric responses to various combinations of SST forcings in the IWP and TP sectors. Specifically, La Niña episodes in the TP are correlated with positive, zonally elongated geopotential height anomalies in the upper troposphere along the latitude belts centered at about 40°N (e.g., see right panels in Fig. 4 in Lau et al. 2008). It is hence anticipated that the atmospheric response to La Niña events in the TP would be reinforced by the response to warm SST changes in the IWP. Conversely, the response to El Niño conditions in the TP tends to be weakened in the presence of warm anomalies in the IWP.

The above notions have been tested in two different contexts by conducting and comparing model runs similar to the TOGA and IWP experiments. The first study (Lau et al. 2006) is concerned with the warm and dry anomalies that prevailed over a large portion of the Northern Hemisphere throughout the 1998–2002 period (Hoerling and Kumar 2003). The SST conditions during this period are characterized by a persistent La Niña event in the TP, and warm anomalies in the IWP. The atmospheric anomaly pattern is dominated by circumglobal 200-hPa pressure ridges centered at 35°N and 35°S. Experiments have been performed by prescribing observed, time-varying SST forcings during the 1998–2002 period in the IWP and TP sectors separately. The results confirm the constructive interference between the atmospheric responses to the SST anomalies in the two sectors. The evidence presented in Lau et al. (2006) supports the claim in Hoerling and Kumar (2003) that warm anomalies in the IWP and cold anomalies in the TP constitute the “perfect” SST pattern for widespread droughts and above-normal air temperatures.

The second study (Lau et al. 2008) evaluates the impacts on future ENSO behavior of the secular warming trend of the SST field in the IWP. The rise of basinwide SSTs in this region is one of the most prominent signals of climate change in the past several decades (e.g., Vecchi and Soden 2007). The SST trend in the IWP in the first half of the twenty-first century, as projected by a coupled GCM at GFDL, was used to perturb the boundary conditions in that region. The atmospheric response in this experiment (Fig. 3a) has been examined in conjunction with a TOGA-like run with prescribed La Niña forcing in the TP only (see response in Fig. 3b), and with a run in which SST changes are incorporated in both the IWP and TP domains (see response in Fig. 3c). This series of model experiments indicates that, as a result of cooperation between responses to warm SST in the IWP and cold SST in the TP, the atmospheric signals associated with La Niña events (such as droughts over North America) will become progressively stronger in the next several decades, as warming proceeds in the IWP.

**ENSO MODULATIONS OF THE ASIAN MONSOONS.** ENSO events are known to exert considerable influences on the evolution and intensity of the monsoon systems over South and East Asia. Of particular interest is the observational evidence on the earlier-than-normal monsoon onsets in La Niña events, and delayed onsets during El Niño. These relationships have been reported for the monsoons affecting both the Indian subcontinent (e.g., Joseph et al. 1994) and East Asia (e.g., Wu and Wang 2000). Moreover, the onset of the Asian monsoons is characterized in most years by the well-defined spatial development of atmospheric and oceanic signals from west to east in the South China Sea and tropical northwestern Pacific, and from south to north in the Indian sector. Lau and Nath (2009, 2012) reported that some of the above observed characteristics are well reproduced in the MLM experiment. Diagnosis of the output from this experiment has also yielded useful insights into the mechanisms contributing to monsoon onsets and
ENSO–monsoon interactions. For instance, the spatial evolution of monsoon-related signals may be partially attributed to the local coupling between the atmospheric flow and the underlying SST pattern, both of which are linked to ENSO processes in the TP through the atmospheric bridge mechanism. Furthermore, the relative roles of local and remote SST forcings in determining the timing of monsoon onsets have been delineated by adopting a methodology similar to that based on the TOGA/IWP experiments, that is, partitioning the World Ocean into smaller domains and simulating the atmospheric responses to these subdomains individually. These results indicate that the effects of remote SST forcing from the TP region are critically dependent on the behavior of the ENSO cycle in that region, whereas the contributions of local SST forcing are governed by processes associated with the atmospheric bridge mechanism.

INVESTIGATION OF THE RECENT HIATUS IN GLOBAL WARMING BY APPLYING THE TOGA-ML/MLM PARADIGM. Recent records indicate that the global annual-mean temperature has stopped rising in the past 15 years, contrary to expectation of a continuing warming trend due to the greenhouse effect. The basic experimental design for TOGA-ML/MLM has been used to identify a mechanism for this “hiatus” in global warming. Noting the prolonged La Niña–like conditions in the TP region through much of the recent decade, Kosaka and Xie (2013) conducted a suite of GCM runs by prescribing the time-varying SST conditions within the eastern TP, and allowing for full air–sea coupling outside the TP. The historical evolution of radiative forcing associated with changes in the atmospheric composition was also prescribed. This experimental setup is hence very similar to the TOGA-ML/MLM simulations described earlier. The results presented by Kosaka and Xie indicate that their experiment is capable of reproducing the recent hiatus in global warming, thus implying a significant role for the decadal cooling in the TP region in the global temperature trend. Further diagnosis of their model output illustrates that the global impact of SST forcing from the TP region may be attributed to the spreading of atmospheric teleconnection signals far beyond the TP zone. The occurrence of the hiatus phenomenon in the boreal winter season is consistent with the much stronger teleconnectivity between SST forcing in the TP and the Northern Hemisphere atmospheric circulation in that phase of the seasonal cycle. The cause of the persistent oceanic cooling in the TP in the past decade is still under active investigation, and may be linked to strengthening of the overlying trade winds during the same era. The intensified surface winds are in turn accompanied by increased equatorial upwelling, enhanced subduction in the overturning cells near the ocean surface, and larger subsurface ocean heat uptake (England et al. 2014). The decade-long SST cooling in the TP and the associated changes may hence be viewed as one facet of the natural climate variability of the coupled atmosphere–ocean system. This interpretation is buttressed by the multitude of TOGA-ML/MLM-style experiments analyzed by this and other authors.

CONCLUDING REMARKS. In this lecture, a synopsis has been offered of the range of problems that could be fruitfully addressed by applying various treatments at the air–sea boundary in GCMs. One class of treatment entails the prescription of observed SST changes in selected forcing domains (such as the TOGA–MOGA–GOGA suite), aimed at evaluating the effectiveness of SST forcing at different locations.
in forcing atmospheric changes. Another class of treatment is the prescription of SST forcing in a region that has been demonstrated to generate prominent atmospheric anomalies (specifically, the central and eastern TP regions), and allowing for two-way air–sea interactions at all grid points lying outside of that region. This experimental setup (as best represented in the TOGA-ML or MLM runs) is suited for delineating various facets of the atmospheric bridge mechanism. A third class of treatment (of which the IWP experiment is a prime example) is the prescription of oceanic forcing in certain regions outside of the TP using SST data generated in simulations of the atmospheric bridge, with the goal of investigating the feedback of these oceanic anomalies on the atmospheric circulation. Different combinations of the above treatments have yielded helpful insights into the primary role of SST changes in the TP region in setting the pace of atmosphere–ocean variability around the globe, and on time scales spanning from interannual fluctuations to multidecadal trends.

To facilitate comparison and interpretation of model outputs generated from different experimental designs, nearly all results presented here are based on products from models developed at GFDL. It should be noted that analogous studies on the role of SST forcing at various sites as a “pacemaker” of global climate variability have been conducted with GCMs at many other research institutions. Particularly noteworthy is the series of multimodel investigations on the impacts of SST anomalies on various aspects of the atmospheric circulation, as performed under the auspices of the U.S. Climate Variability and Predictability Program (CLIVAR) International Climate of the Twentieth Century (C20C) project (e.g., Scaife et al. 2009; Kucharski et al. 2009; Zhou et al. 2009).

Throughout this long series of model studies, the overall scheme for incorporating different classes of experiments, the detailed design of individual runs in each of these classes, and the strategy for analyzing the output from the myriad model runs are essentially motivated and guided by observational evidence of phenomena in the real climate system. The credibility of the model-based findings has been assessed by comparison between model output and the available observational data. In some instances, the model results have provided new clues for interpreting and reexamining the observations. This synergy between the observational and modeling approaches has led to continued progress in research endeavors on the nature of climate variability related to ENSO.

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