El Niño: Exploring its Background State

Introduction

The eastern equatorial Pacific is the epicenter of the El Niño-Southern Oscillation. Within the tropics, this region has the largest year-to-year climate variability and is marked by large sea surface temperature (SST) gradients in both north-south and east-west directions. During *normal* periods, a cold tongue extends from the South American coast along the equator, the core temperature increasing gradually toward the west. From the cool water at the equator, sea surface temperatures increase both northward and southward, but more so to the north, where during much of the year a band of warm water is found along 7ºN-10ºN with surface temperatures at or above 27ºC, about 5ºC higher than those at the equator and 1o to 2ºC higher than those at the same latitudes in the southeastern Pacific. This band of warm water — which lies in the region where the Northern and Southern Hemisphere trade winds converge, the Intertropical Convergence Zone (ITCZ) — gives rise to deep convection and heavy rainfall. Studies over the past two decades have revealed that the El Niño-Southern Oscillation (ENSO) originates from an ocean-atmosphere interaction that is sensitive to this background climate state. To predict successfully the swings of ENSO and their global impacts, accurate simulation and understanding of the eastern Pacific climate are therefore needed.

An important feature off the South American coast is the extensive stratocumulus cloud deck in the first kilometer or so above Earth's surface — the boundary layer. This cloud deck shields the surface from incoming solar radiation, keeping the sea surface underneath it cool and affecting the global heat budget. Despite its importance for climate, this cloud deck is poorly simulated in global atmospheric general circulation models (GCMs): the models do not resolve the clouds adequately in either the horizontal or the vertical. The poor simulation of the clouds appears to be the reason why many atmospheric GCMs coupled to ocean models fail to keep the Pacific ITCZ north of the equator for most of the year and fail to keep a strong equatorial cold tongue in the eastern Pacific.

By improving their cloud parameterization schemes, some GCMs have improved their simulation of the cloud deck, yet the clouds are still very different from those observed. Perhaps the reason is that the steep Andes, which rise from sea level to more than 3 km in just 100 km, remain poorly represented in the GCMs, their realistic representation being very costly in computing time. How and to what extent the Andes affect the clouds in the boundary layer and rainfall over the eastern Pacific is yet unknown.

To understand eastern Pacific climate better and especially the role of the Andes, IPRC scientists **Yuqing Wang**, **Shang-Ping Xie**, and **Haiming Xu** are conducting experiments on the region with the IPRC regional climate model (IPRC-RegCM), which has a high resolution and state-of-the-art physics (*IPRC Climate*, **1**, Fall; **2**, No. 2). Below are some preliminary findings of this research on the background climate state in the equatorial eastern Pacific.

Realistic Simulation of the Cloud Deck

Applying the IPRC-RegCM, with 28 vertical levels and fine horizontal resolution (0.5º), to a region in the eastern Pacific large enough for the model physics to develop (150ºW-30ºW, 35ºS-35ºN), resulted in a simulation that reproduced the stratocumulus cloud deck over the Southeast Pacific off South America during austral spring (August, September, and October 1999), the season of the cloud deck's greatest extent. This success now allowed Yuqing Wang and his colleagues to study the dynamical, radiative, and microphysical properties of clouds in the model, and also their interaction with the large-scale circulation. The model simulations of surface winds, precipitation and cloud water path compare favorably with satellite observations (Figure 6). The model captures the major features of the region's boundary layer: the surface mixed layer, the capping temperature inversion (air temperature rising instead of falling with height, capping the height at which clouds can form), and the stratocumulus clouds with their drizzle (Figures 7 and 8). The clouds develop in the lower half of the temperature inversion layer and below, the inversion layer rising toward the west. The strength of the inversion is determined not only by the large-scale subsidence — sinking air — and the local cool sea surface temperature, but also by feedback between the clouds and radiation. A heat budget analysis indicates that the outgoing longwave radiation cools the upper cloud layer at the inversion base, thereby strengthening the tem-

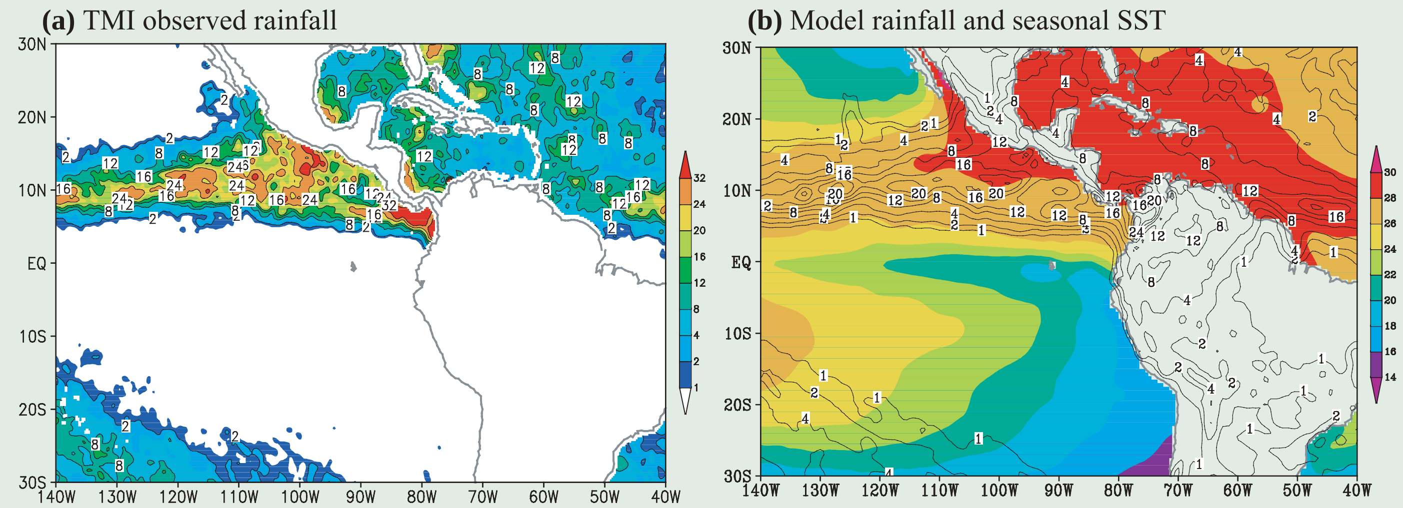

Figure 6. *Mean daily rainfall (mmd-1) from August through October 1999: (a) TMI observations, (b) model results (contours) and seasonal mean SST (colored background).*

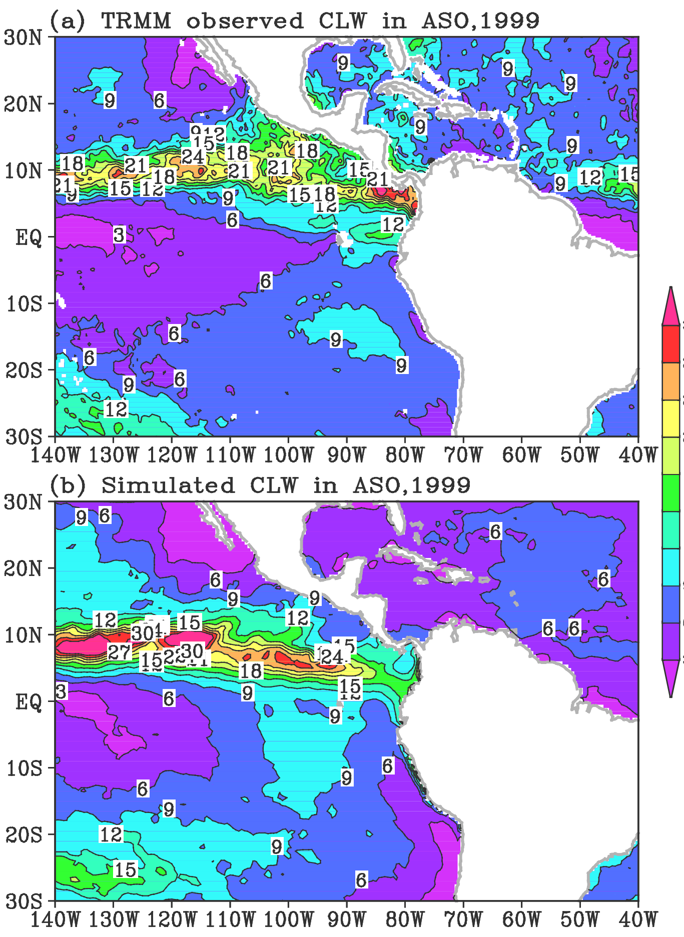

Figure 7. *Vertically integrated cloud liquid water content (10^{-2}mm) averaged over August-October 1999: (a) TMI observations, (b) model results.*

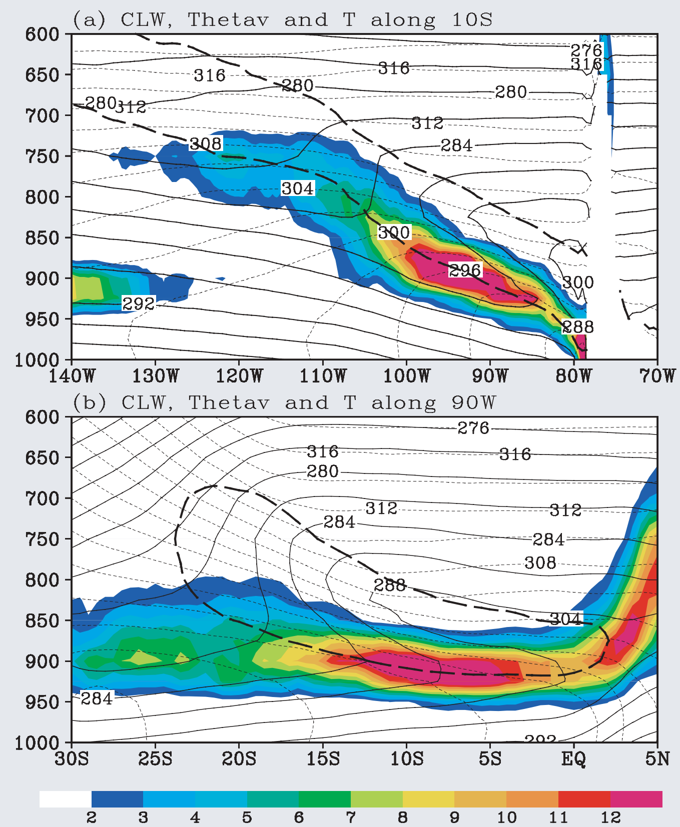

Figure 8. *Cross-sections (a) east-west along 10°S and (b) north-south along 90°W, of August-October 1999, averaged cloud water content (color in 10^{-2}g kg^{-1}); temperature (solid contours in °K); virtual potential temperature (thin dashed contours in °K); and the $d\theta/dp$=8K/100Pa (thick dashed contours), which is a weak criterion for the temperature inversion layer boundaries.*

perature inversion. This cloud-top cooling, in turn, increases local subsidence in and above the inversion layer, which results in greater temperature stratification above the clouds. While of secondary importance, in the model, solar radiation drives a pronounced diurnal cycle in the boundary layer, a cycle that is consistent with observations: the clouds become more dense after sunset and their liquid water content reaches a maximum just before sunrise.

Far-Reaching Effects of the Cloud Deck

Since clouds in the boundary layer greatly reduce the absorbed solar radiation both at the top of the atmosphere and at the underlying ocean surface, they have a general cooling effect and are important modulators of Earth's climate. To understand how the large stratocumulus cloud deck takes part in driving the atmospheric circulation over the eastern Pacific, Yuqing Wang carried out a sensitivity experiment with the IPRC-RegCM, in which he removed the effect of liquid clouds on the radiation budget over the eastern Pacific south of the equator. When the absorption of solar radiation is experimentally removed, the clouds in the boundary layer south of the equator almost disappear and precipitation to the north in the ITCZ decreases by 10-15%, indicating that the stratocumulus clouds over the Southeast Pacific have both local and cross-equatorial effects.

The schematic in Figure 9 shows how the cloud deck affects the north-south circulation over the tropical eastern Pacific at the surface. The clouds impose a net cooling at the cloud top that brings about an anomalous high-pressure system, which, in turn, strengthens the high-to-low pressure gradient and air flow across the equator at the surface and enhances convection in the ITCZ north of the equator. This low-level north-south circulation that develops in response to the low-level atmospheric cooling, strengthens the local Hadley circulation, increasing the surface southeasterly cross-equatorial flow, the mass and moisture convergence and convection in the ITCZ north of the equator, and the large-scale subsidence and cloud deck off the Peruvian Coast. This positive feedback sequence, thus, helps to keep the ITCZ in the tropical eastern Pacific north of the equator.

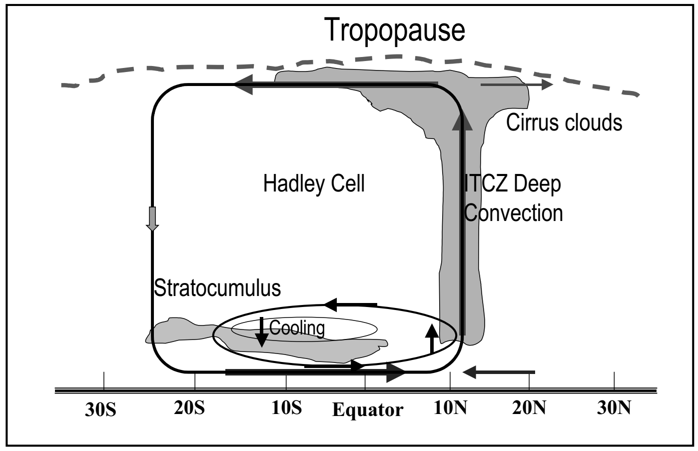

Figure 9. *Schematic showing how the large cloud deck over the Pacific off South America shapes eastern Pacific climate.*

Effects of the Andes

What effects do the narrow and steep Andes have on the stratocumulus cloud deck and on eastern Pacific climate in general? Conducting an experiment with the IPR-RegCM, Xu and Xie removed the Andes. Removal of the Andes produced a very different climate picture from that described above: during Southern Hemisphere spring (August-October 1999) the warm air from the South American Continent flows westward unhindered, lowering the off-shore temperature inversion height and reducing the low-level wind divergence. Both changes greatly decrease cloudiness, allowing more solar radiation to reach the sea surface (Figure 10). Thus, by blocking the warm easterly winds from eastern South America, the Andes help to maintain the wind divergence, the temperature inversion, and hence the stratocumulus cloud deck.

Moreover, a simulation of the Southern Hemisphere fall season (March and early April 1999) with realistic Andes present shows a double ITCZ — that is two bands of deep convection — one north of the equator and one south. The southern ITCZ is in response to the seasonal warming on and south of the equator, and is also seen in observations. Removal of the Andes in a further experiment allows the warm easterlies from South America to converge in the lower atmosphere over the ocean and transient disturbances to travel unhindered westward from the continent. Both effects favor deep convection south of the equator (Figure 11) and prolong the southern ITCZ for three weeks.

These sensitivity experiments were repeated with the orography used in T42 global models (equivalent to a grid spacing of about 2.8º). The results confirm that the overly smooth representation of the Andes in atmospheric GCMs shrinks the stratocumulus cloud cover in austral spring and prolongs the southern ITCZ in austral fall, resulting in a false picture of greater climate symmetry across the equator in the eastern Pacific.

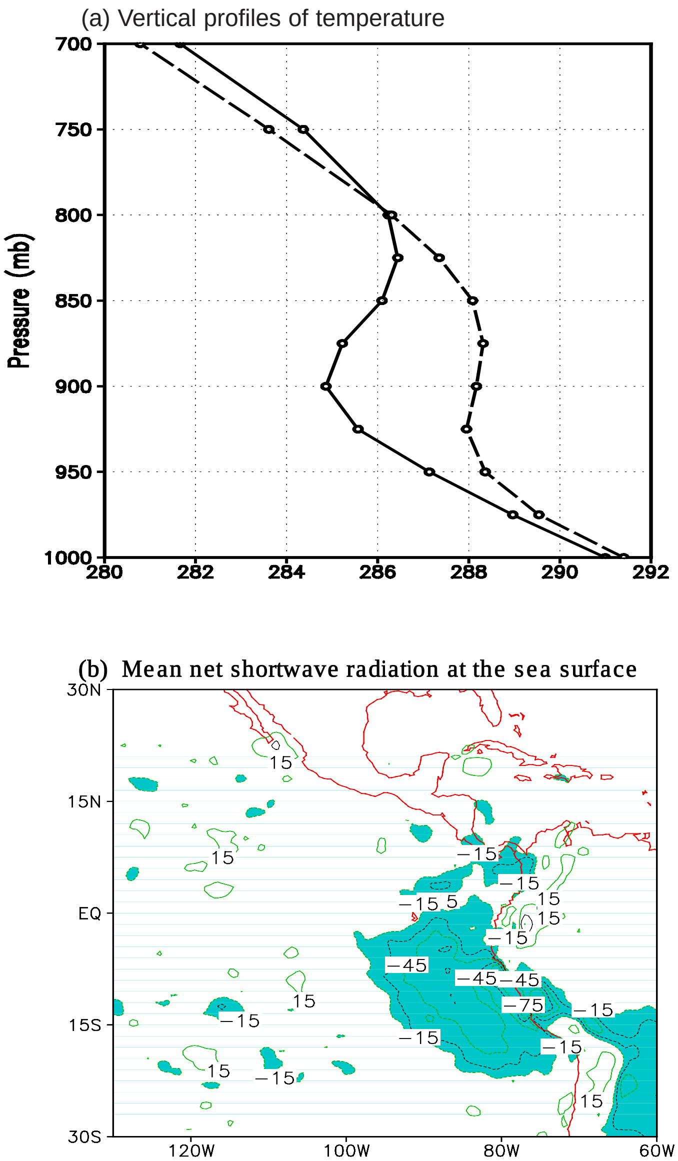

Figure 10a. *Model results of vertical temperature (in K) profiles averaged over 83°W-95°W, 5°S-20°S for the simulations with realistic Andes (solid line) and without the Andes (dashed line).* **10b**. *Differences in the mean net shortwave radiation flux at the sea surface (averaged over August-October, 1999) between the realistic Andes simulation and the simulation without the Andes. Contour interval is 15 Wm^{-2}; values less than -15 Wm^{-2} are colored.*

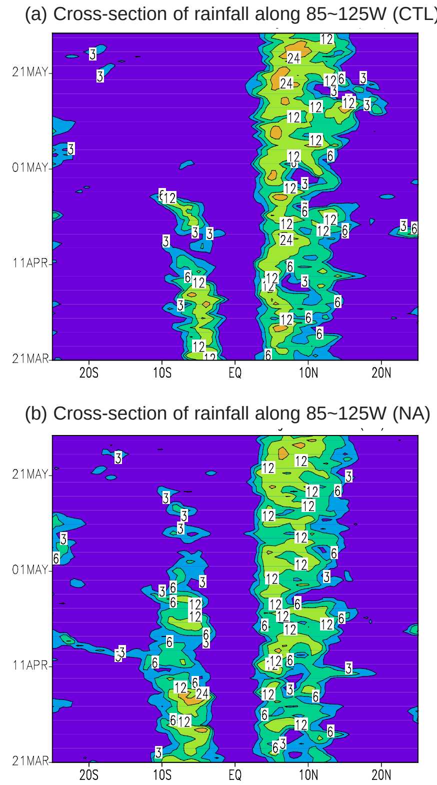

Figure 11. *Cross-sections (averaged between 85°W-125°W) of daily rainfall (in mm) over time and latitude: (a) model results with realistic Andes, and (b) model results without the Andes.*

Conclusion

The ability of the IPRC-RegCM to reproduce the complicated formation of the cloud deck off the Peruvian coast is a significant advance in climate modeling. This rather permanent, low, and unbroken cloud deck acts like a huge white sheet, reflecting sunlight back to space and cooling the atmosphere and the ocean below. The cooling helps to prevent the formation of cumulus clouds that occur elsewhere in warm equatorial regions and helps to keep deep convection and the ITCZ north of the equator in the eastern tropical Pacific except for March and April. In the IPRC model, the sinking air on the leeward side of the Andes contributes to formation and maintenance of the cloud deck and to the northward-displaced ITCZ. The strong interaction among the clouds, the ocean, and the atmosphere reinforces the existing Hadley Circulation. To further understand this interaction between the boundary layer clouds and the ocean, and the influence of the Andes on this interaction, a group of IPRC researchers is now coupling the IPRC-RegCM to a mixed-layer ocean model. In the meantime, the findings so far contribute much to understanding the background state on which the El Niño-Southern Oscillation develops.