P2.27 EFFECTS OF THE ANDES ON THE EASTERN PACIFIC CLIMATE: REGIONAL MODEL SIMULATION

Haiming Xu*, Shang-Ping Xie and Yuqing Wang
International Pacific Research Center, University Of Hawaii, Hawaii

1. INTRODUCTION

The stratus clouds often observed off the west coast of South America constitute the largest deck of stratus over subtropical oceans (e.g., Klein and Hartmann 1993), and play an important role in the regional and global climate by substantially reducing the amount of solar radiation absorbed by the ocean (e. g., Hartmann et al. 1992). Coupled ocean-atmosphere models have shown that this radiation cooling acts to strengthen the SST gradients in both the meridional and zonal directions, with far-reaching consequences to the basin-wide climate of the Pacific Ocean (Philander et al.1996; Yu et al. 1999; Gordon et al. 2000. These low level clouds have a net radiation cooling effect on the atmosphere and affect the global radiation budget. Despite their climatic importance, these low-level clouds are poorly simulated in global GCMs because of insufficient horizontal and vertical resolutions and inadequate parameterization. The deficiencies in simulating stratus clouds appears to be responsible for the failure of many coupled GCMs to keep the Pacific ITCZ north of the equator and maintain the adequate strength of the equatorial cold tongue.

The influence of the Andes on the global and regional climate has been extensively investigated by using GCMs (Kalnay et al. 1986; Walsh 1994;Gandu et al. 1991; Lenter et al. 1995,1997). In spite of the above modeling studies about the effects of the Andes, the impact of the Andes on the eastern Pacific climate, particularly on the stratus clouds in the southeastern Pacific are not well understood. The major reason is that atmospheric GCMs, on one hand, did not enough horizontal resolution to resolve the steep and narrow Andean mountains, on the other hand, were not capable of reproducing some major climate features in the eastern Pacific such as stratus clouds and boundary temperature inversion over the southeastern Pacific due to their insufficient vertical resolution and inadequate parameterization.

In addition, current GCMs and coupled GCMs have difficulty in reproducing the double ITCZ in the eastern Pacific. Mechoso et al (1995) examined the seasonal cycle over the tropical Pacific simulated by 11 coupled ocean-atmosphere general circulation models (GCMs) and found that current state-of-the-art GCMs share troublesome systematic errors. One of these errors is that a long persistent double ITCZ is simulated on both sides of the equator in the eastern Pacific. We hypothesize that the simulated long persistent double ITCZ might also be related to the poor representation of the steep and narrow Andes in GCMs.

In this paper, we will use a high-resolution regional climate model to investigate the effect of the steep and narrow Andes on the eastern Pacific climate. Particularly we will focus on the effect of the Andes on stratus clouds over the southeastern Pacific in the cold season and precipitation in the eastern Pacific in the warm season

2. DESCRIPTION OF THE RCM AND EXPERIMENTAL DESIGN

2.1 A brief description of the RCM

In this study, we use a regional climate model developed at International Pacific Research Center (IPRC), University of Hawaii. See Wang et al (2002) for a detailed description and model performance over East Asia.

The model is a primitive equation model with sigma as the vertical coordinates. The model resolution in this study is 0.5º in longitude/latitude and 28 vertical levels with 10 levels below 850 hPa. The model domain is from150 ºW to 30ºW and 35ºS to 35ºN, which includes tropical regions of the eastern Pacific Ocean, north and south Americas and western Atlantic Ocean

2.2 *Design of numerical experiments*

A series of numerical experiments were designed to explore the effects of the Andes on the eastern Pacific climate, which are listed as follows,

1) Control run. All forcing mechanisms were incorporated in the domain. The time-dependent sea surface temperature (SST) was interpolated from 1˚×1º grid of the weekly mean observed data (Reynolds and Smith 1994) and updated at each model step. The lateral boundary conditions were constructed based on the relaxation method and updated at each time using the NCEP/NCAR reanalysis every 6 hours. In order to study the effects of the Andes on the stratus and the precipitation in the cold and warm season respectively, the model was initialized on 1 September and 1 March 1999 and integrated for three months respectively.

2) No-Andes run. This experiment is identical to the above Control run except with the Andes completely removed. We remove the mountains on the west side of South American continent, which includes the northern,

* *Corresponding author:* Haiming Xu, IPRC, SOEST, Univ. of Hawaii, Honolulu, HI 96822; e-mail: hxu@hawaii.edu

central and southern Andes by setting the topographic height 0.5 m.

3) T42 topography run. This experiment is identical to the Control run except with the T42 resolution topography employed in an effort to evaluate whether the unrealistic representation of the topography in current GCMs leads to poor simulation of stratus clouds and precipitation in the southeastern Pacific.

3. COLD SEASON

3.1 CLOUD

Figure 1 shows the cloud liquid water content difference between the control and No-Andes runs. It can be seen that a large positive value area covers the most part of the southeastern Pacific off the west coast of South America, and it extends as far westward as to about 95ºW and 25ºS southward with two SSE-NNW-oriented high value belts along the coast, one is just near the coast with its maximum value of 0.05 mm and the other one is about 1000 km off the coast with its maximum value of 0.04 mm, indicative of marked increase of stratus clouds due to the effect of the Andes. It is estimated that the Andes leads to 30% increase of cloud liquid water content on area average in the coastal region east of 95ºW.

3.2 PBL structures

Klein and Hartmann's (1993) observational study has shown that the stratus cloudiness are related to changes in static stability with a 6% increase in stratus fractional area coverage corresponding to each 1ºC increase in static stability. Their study also showed that the temperature inversion at the top of the boundary layer appeared to play a central role in the existence of stratus cloud. The vertical profiles of temperature averaged over the southeastern Pacific (83ºW-95º, 5ºS-20ºS) are shown in Figure 2 for both the control (solid) and No-Andes (dashed) runs. It can be seen that a well-maintained temperature inversion is found at the top of planet boundary layer (PBL) in the control run with its base and top located at 900mb and 825mb respectively. Below the inversion a well-mixed layer is maintained. In the No-Andes run, an interesting feature is that the temperature within the PBL is much higher than that in the control run, especially the temperature increases as much as 3ºC around 900mb and the temperature inversion is much weak when compared with the Control run. The base and top of the inversion also become lower than those in the Control. The warming in the PBL causes the temperature inversion to weaken in the No-Andes run.

3.3 Large-scale adjustment

The wind flow and temperature patterns at 900mb show that in the control run easterly winds dominate over the South America east of the Andean mountains. Over the southeastern Pacific, southeasterly winds prevail with maximum winds over about 1000km off the west coast. A high temperature center occurs over the central part of South America with its central value more than 24ºC, the temperature is much higher than that over the southeastern Pacific where relative low temperature is found with its range from 10 to 18 ºC because of the underlying cold SST.

As the Andean range is removed in the RCM, the easterly winds over the South America move across the

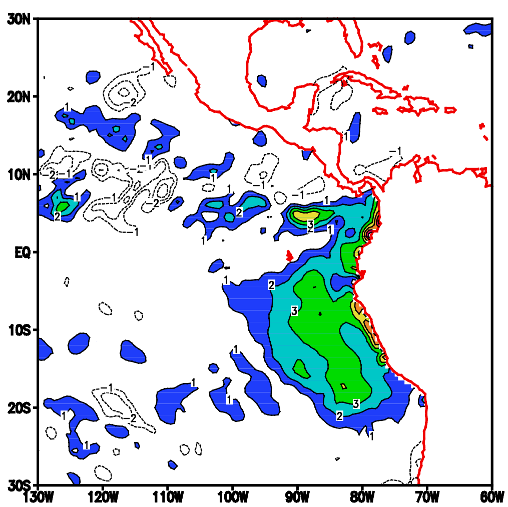

Fig.1. Difference of vertically integrated liquid water between control and No-Andes runs, averaged for August-October, 1999. Contour interval is 1 and the unit is 10^{-2} mm. Areas with positive values greater than 1 are shaded.

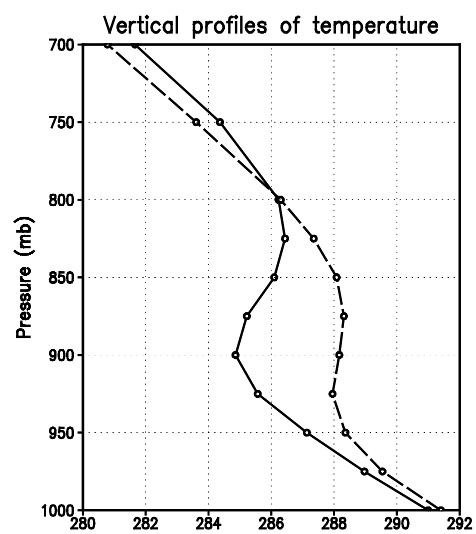

Fig. 2. Vertical profiles of temperature averaged over 83W-95W, 5S-20S for control (solid line) and No-Andes run (dashed line).

originally Andean region and even reach the southeastern Pacific. The southeasterly winds over the southeastern Pacific markedly increase, especially near the coast due to the intrusion of the easterly winds from the continent. Simultaneously the warm center over the continent expands towards the west with a warm ridge extended to the southeastern Pacific. The analysis of the thermodynamic energy equation at 900mb reveals that the horizontal advection term is the major reason for the warming over the southeastern Pacific. Therefore, without the blocking of the Andes the easterly winds can directly move the continental warm air into the southeastern Pacific, resulting in the lower-tropospheric warming there and associated weakening of the PBL's temperature inversion.

3.4 T42 topography run

The standard resolution in current AGCMs is T42. In order to test whether the poor simulation of stratus cloud in current AGCMs is related to the unrealistic representation of the steep and narrow Andean mountains, we rerun the RCM with the same conditions as the control run except the T42 resolution topographic height employed. The difference of the vertically integrated liquid content between the Control and T42 topography runs indicates that a large positive value area covers most part of the southeastern Pacific with its maximum value of 0.02mm, indicative of remarkable increase of stratus clouds due to the relative realistic representation of the Andes in the Control run when compared with the T42 topography run. It is also suggested that the coarse resolution and the associated poor representation of the narrow and steep Andes in the current AGCMs is possibly a major factor for underestimation of the stratus clouds over the southeastern Pacific, and the development of high-resolution models will possibly improve the simulation of the stratus clouds.

4. WARM SEASON

4.1 Oceanic ITCZ

In order to demonstrate whether the presence of the Andes affects the double ITCZ in the eastern Pacific, we present the time-latitude sections of the precipitation along 85ºW-125ºW for the observations, control and No-Andes runs (Figure 3). The double ITCZ is evident in both the observations and the Control run. Both the position and magnitude of the double ITCZ are in good agreement except that the simulated northern ITCZ is wider and extends much northwards. Apart from the above exceptions, the disappearance dates of the southern ITCZ in both the observations and control run are roughly in agreement. In the No-Andes run (Figure 3c), however, the simulated southern ITCZ persists much longer, almost 20 days longer than that in the control run. Our finding also implies that the long persistent double ITCZ in current AGCMs and CGCMs is possibly related to the poor representation of the steep and narrow Andean mountains in their simulations.

The precipitation difference between the Control and No-Andes runs for April and May indicates the

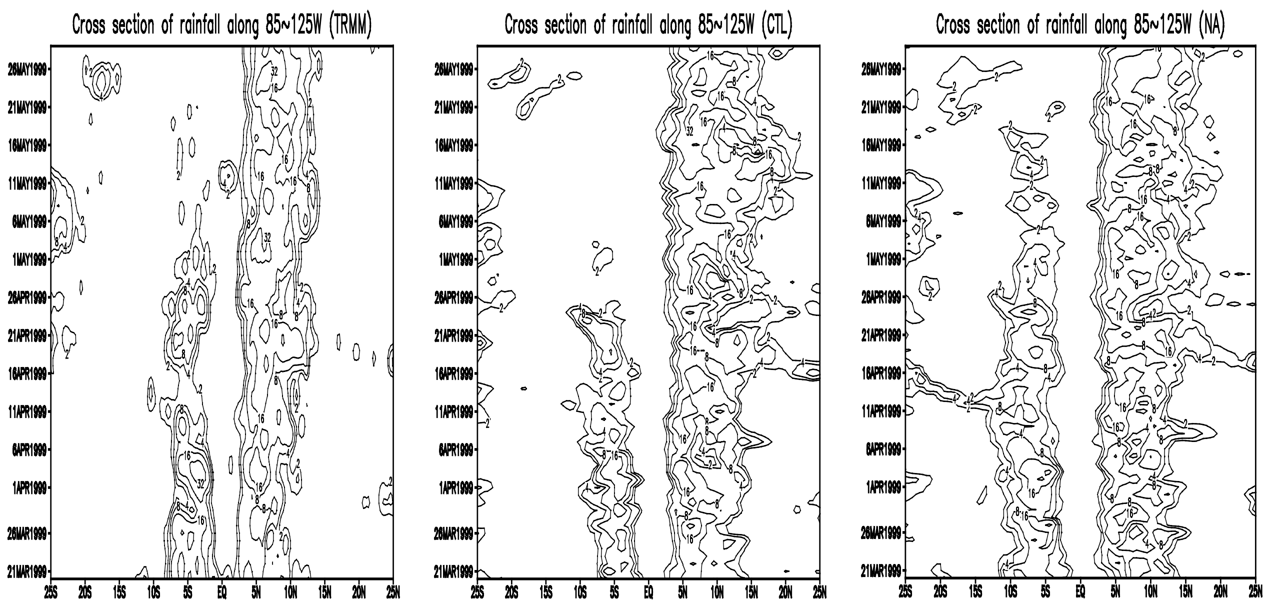

Figure.3. Time-latitude sections of zonally averaged precipitation (mm/day) between 85ºW and 125ºW for TMI observations (a), control (b) and No-Andes (c) runs, respectively.

presence of the Andes can strengthen the northern ITCZ and weaken the southern one, acting to enhance the climatic asymmetries in the eastern Pacific.

The main cause of the effect of the Andes on the double ITCZ attributes to the blocking of the Andes. On one hand, the Andes hinders the easterly winds east of the Andes to enter into the southeastern Pacific, and allows a rather strong divergence to dominate the west coast, on the other hand, the presence of the Andes also blocks dynamic disturbances developed in the South America to shift into the southeastern Pacific, which is clearly shown in the time-longitude sections of 950mb vorticity along 4ºS-12ºS (omitted). Both of them act to hinder the initiation and development of cumulus convections off the west coast of Peru. On the contrary, while the Andean mountains are removed in the RCM, the easterly winds directly shift into the southeastern Pacific. As a result, the originally divergence field off the coast has been changed into a convergence field, a favorable situation for the development of cumulus convections. In addition, dynamics disturbances are excited and developed in the northern South America, and when the Andes is removed these disturbances can continue to migrate towards the west and even reach as far as to the tropical southern Pacific. These disturbance systems redevelop as they move into the southeastern Pacific because of a favorable convergence condition in the PBL near the coast, which help initiate ocean convection and maintain the strong southern ITCZ. The enhanced southern ITCZ in turn affects the northern one through the Hadley cell.

4.2 T42 topography run

The precipitation difference between the control and T42 topography reveals that the difference pattern is quite similar to the difference pattern between the control and No-Andes runs with positive values over the most parts of South America and negative values over the southern tropical Pacific, indicating the underestimation of the steep and narrow Andes in current GCMs can really lead to stronger southern ITCZ. Cross section of the precipitation along 85-125ºW also shows that the simulated ITCZ in the T42 topography run lasts much longer than in the control though it is weak when compared with the No-Andes. It is suggested that a long persistent double ITCZ in the eastern Pacific, at least, partially attribute to the poor representation of the steep and narrow Andes.

5. CONCLUSION AND DISCUSSION

A regional climate model developed at International Pacific Research Center (IPRC), University of Hawaii, is used to study the effects of the narrow and steep Andes on the stratus cloud deck over the southeastern Pacific in the cold season (August-October) and on precipitation in the warm season (March-May), respectively.

In the cold season, comparison of the control and the No-Andes runs indicates that the presence of the high Andes substantially enhance the cloud deck over the southeastern Pacific. It is found that the presence of the Andes blocks low-level warm easterly winds from South America, leading to the development of divergence and an enhanced temperature inversion off South America that favor the formation of stratus clouds. On the contrary, without the Andean mountains, the warm eastern winds to the east side of the Andes can directly move into the southern Pacific, and simultaneously this intrusion of the warm eastern winds lowers the height and weakens the strength of the PBL's temperature inversion by warming the air above PBL in the southeastern Pacific and leads to the occurrence of a convergence field instead of the originally divergence field near the coast. Both of them act to hinder the formation and maintenance of the stratus clouds. Comparison of the control and T42 topography runs shows that the model with coarse resolution topography markedly underestimates the stratus clouds in the southeastern Pacific, suggesting that the poor simulations of stratus clouds in current state-of-the art GCMs, at least, partially attribute to the poor representation of the steep and narrow Andean ranges.

In the warm season, comparison of the control and the No-Andes runs shows that the presence of the Andes not only changes the precipitation in the South America but also modifies the precipitation in the eastern Pacific. The presence of the mountains acts to enhance the northern ITCZ and weaken the southern one. Without the mountains, the simulated double ITCZ maintains almost 20days longer than that in the control. The major reason is that the presence of the mountains, on one hand, hinders the easterly winds east of the Andes to enter into the southeastern Pacific, and allows a rather strong divergence to dominate the west coast, on the other hand, blocks dynamic disturbances in South America to shift into the southeastern Pacific. Both of them act to obstruct the initiation and development of cumulus convections in the tropical southern Pacific. Without the Andean mountains, the reversed situation occurs. Comparison of the control and T42 topography runs also indicates that the model with coarse resolution topography substantially overestimates the southern ITCZ, implying that the poor representation of the steep and narrow Andes in current global GCMs is a likely cause of persistent double ITCZ in their simulations.

As mentioned earlier, one limitation of these experiments is that sea surface temperatures are fixed and do not respond to changes in the atmosphere. In reality significant changes in stratus clouds off the west coast of South America near Peru could cause significant changes in local sea surface temperatures in this region through the modification of radiation budget. Local significant changes in sea surface temperature patterns might affect the trans-Pacific gradient of surface temperatures, which might force larger remote changes than was shown in the current experiments. In fact, coupled GCM simulations have shown that stratus clouds near the coast of Peru are a key component of the interhemispherically asymmetric features that characterize the annual mean climate of the eastern equatorial Pacific, including the cold SST off Peru and the absence of a southern ITCZ (Philander et al.1996; Yu et al. 1999; Gordon et al. 2000). Seemingly regional effects of the Andes are likely to lead to a basin wide adjustment of the Pacific climate including its ITCZ by exciting coupled waves that propagate westward (Xie 1996; Xie and Satio 2001).

REFERENCES

Bretherton, C.S., 1993: Understanding Albrecht's model of trade-cumulus cloud fields. *J. Atmos. Sci*., **50**, 2264-2283.

Gandu, A.W., and J.E. Geisler, 1991: A primitive equations model study of the effect of topography on the summer circulation over tropical South America. *J. Atmos. Sci.,* **48**, 1822-1836.

Gordon, C.T., A. Rosati, and R. Gudgel, 2000: Tropical sensitivity of a coupled model to specified ISCCP low clouds. *J. Climate*, **13**, 2239-2260.

Hartmann, D.L., M.E. Ockert-Bell, and M.L. Michelsen, 1992: The effect of cloud type on earth's energy balance: Global analysis. *J. Climate*, **5**, 1281-1304.

Kalnay, E., K.C. Mo, and J. Paegle, 1986: Large-amplitude, short-scale stationary Rossby waves in the Southern Hemisphere: Observations and mechanistic experiments to determine their origin. *J. Atmos. Sci*., **43**,252-275.

Klein, S.A., and D.L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate*, **6**, 1587-1606.

Lenters, J.D., and K. H. Cook, 1995: Simulation and diagnosis of the regional summertime precipitation climatology of South America. *J. Climate*, **8**, 2988-3005.

Lenters, J.D., and K. H. Cook, 1997: On the origin of the Bolivian high and related circulation features of the South American Climate. *J. Atmos. Sci.,* **54**, 656-677.

Ma, C.-C., C.R. Mechoso, A.W. Robertson, and A. Arakawa, 1996: Peruvian stratus clouds and the tropical Pacific circulation—a coupled ocean-atmosphere GCM study. *J. Climate*, **9**, 1635-1645.

Norris, J.R., 1998: Low cloud structure over the ocean from surface observations. Part II: Geographical and seasonal variations. *J. Climate*, **11**,383-403.

Philander, S.G.H., D. Gu, D. Halpern, G. Lambert, N.-C. Lau, T. Li, and R.C. Pacanowski, 1996: The role of low-level stratus clouds in keeping the ITCZ mostly north of the equator. *J. Climate*, **9**, 2956-2972.

Reynolds, R.W., and T. M. Smith, 1994: Improved Global Sea Surface Temperature Analyses Using Optimum Interpolation. *J. Climate*, 7, 929–948.

Walsh, K., 1994: On the influence of the Andes on the general circulation of the southern Hemisphere. *J. Climate*, **7**, 1019-1025.

Wang, Y., O.L. Sen, and B. Wang, 2002: A highly resolved regional climate model (IPRC–RegCM) and its simulation of the 1998 severe precipitation events over China. Part I: Model description and verification of simulation. *J. Climate*, (revised).

Xie, S.-P., 1996: Westward Propagation of Latitudinal Asymmetry in a Coupled Ocean–Atmosphere Model. *J. Atmos. Sci.,* **53**, 3236–3250.

Xie, S.-P., 1996: Effects of seasonal solar forcing on latitudinal asymmetry of the ITCZ. *J. Climate*, **9**,2945-2950.

Xie, S.-P., and S.G.H. Philander, 1994: A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340-350.

Xie, S.-P., and K. Saito, 2001: Formation and variability of a northerly ITCZ in a hybrid coupled AGCM: Continental forcing and ocean-atmospheric feedback. *J. Climate*, **14**,1262-1276.

Yu, J.-Y., and C.R. Mechoso, 1999: Links between annual variations of Peruvian stratocumulus clouds and of SST in the eastern equatorial Pacific. *J. Climate*, **12**, 3305-3318.