Mechanisms limiting the southward extent of the South American summer monsoon

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Abstract. An intermediate atmospheric model coupled with a simple land-surface model and a mixed-layer ocean model is used to examine effects that determine the southward extension of summer precipitation over South America. The extent of the continental convergence zone is mainly determined by two mechanisms, which we term ventilation and the "interactive Rodwell-Hoskins mechanism". Ventilation refers to the import into South America of low moist static energy air from the cooler ocean, primarily the Pacific. In the interactive Rodwell-Hoskins mechanism, Rossby-wave-induced subsidence to the west of the diabatic heating interacts with the convection zone. Because of the shape of South America, the interactive Rodwell-Hoskins mechanism is of comparable importance to ventilation. Soil moisture feedback also helps limit poleward movement of the continental convergence zone, but its effect is relatively weak compared to the above two effects. The characteristic northwest-southeast tilt of the continental convergence zone appears to be due to a combination of ventilation and the interactive Rodwell-Hoskins mechanism.

Introduction

The temporal and spatial variation of summertime precipitation in South America depends on the interplay of solar heating, land-ocean contrast, continental convection zones and the neighboring subtropical high pressure regions. A number of studies have examined aspects of the atmospheric dynamics. For instance, *Lenters and Cook* [1997] find that summertime precipitation variability on the Altiplano is related to the position and intensity of the Bolivian high, which in turn is a response to latent heating in the Amazon, central Andes, and the South Atlantic convergence zone (SACZ). They indicate that the effect of topography due to the Andes is secondary. *Lenters and Cook* [1999] further find a close relationship on intraseasonal and interannual timescales between the Altiplano rainfall and the Bolivian high. *Zhou and Lau* [1998] show how South American conditions fit the definition of a summer monsoon circulation induced by strong land-sea thermal contrast.

To understand seasonal movement of continental convection zones, arguably the leading factor in monsoon dynamics, we use an intermediate complexity atmospheric model [*Neelin and Zeng,* 2000] coupled with a simple land-surface model [*Zeng, Neelin, and Chou,* 2000] and a mixed-layer ocean model (*Chou et al* [2001]; CNS hereafter). In CNS a single, rectangular continent is used and an idealized divergence of ocean heat transports is specified as an annual average "Q-flux". Effects that impact the seasonal movement of continental convection zones include: ocean transport, "ventilation", an "interactive Rodwell-Hoskins mechanism" [*Rodwell and Hoskins,* 1996] and soil moisture. When the Q-flux is increased in the tropics, the increased contrast with ocean regions favors land convection, so continental convection zones extend farther poleward. This is consistent with what *Lenters and Cook* [1995] find in their SST experiment. Ventilation is defined as the import of low moist static energy air from ocean regions into continental regions. This ventilation is mainly controlled by westerly winds at midlatitude and a circulation induced by latent heat released from the continental convection. Soil moisture has a relatively weak effect on determining the extension and intensity of continental convection zones. In the subtropical subsidence regions, the continental convection zone cannot be maintained, even with saturated soil moisture. The diabatic heating from continental convection zones induces subsidence to its west and a circulation induced by this subsidence interacts with the convection zones. We call this interaction the "interactive Rodwell-Hoskins mechanism" to emphasize that not only does the heating induce subsidence, but the subsidence can also affect the heating. The interactive Rodwell-Hoskins mechanism along with ventilation is also responsible for an east-west asymmetry of continental convection zones with enhanced rainfall tending to occur at the eastern side of the continent and large dry regions toward the western side.

In this study, we use a realistic continental configuration and prescribed seasonal Q-flux (estimated from a climatological SST experiment) to approximate heat transports in the mixed-layer ocean model. The model climatology is averaged over the last ten years of a twenty year model run in each experiment. With a fixed Q-flux, we can examine the dominant effects, such as ventilation and the interactive Rodwell-Hoskins mechanism, that limit the southward extension of South

American convection zones. First we compare the model climate to observations. Observations used here are precipitation from *Xie and Arkin* [1996], evaporation and sensible heat from the Comprehensive Ocean-Atmosphere Data Set (COADS), radiative fluxes from the Earth Radiation Budget Experiment (ERBE) and *Darnell et al.* [1992], and wind fields from the National Center for Environmental Prediction (NCEP) reanalysis [*Kalnay and coauthors,* 1996]. As a prelude to understanding mechanisms in interannual variability, here we design experiments to examine dominant mechanisms that set the climatological limit of the summer convection zone in South America. The results and discussion are in section 3.

Summer climate in South America

Figure 1 and Figure 2 show January climatology from the model and the observations respectively. Globally, the model precipitation (Figure 1a) is similar to the Xie-Arkin precipitation (Figure 2a) except for a weaker intertropical convergence zone (ITCZ). The corresponding F_{net} (Figure 1b), defined as the net energy absorbed by the atmosphere, is also well simulated compared to the observations (Figure 2b). The wind fields of the model (Figure 1c and Figure 1d) are also in good agreement except for the areas with weaker ITCZ.

Figure 1

Figure 2

Our focus here is on summertime precipitation in South America. The model precipitation in South America is a little stronger than the observed, but the maximum precipitation occurs around the Amazon region in both the model and the observations. A northwest to southeast tilt of the continental convection zone is found in both data sets. The observed precipitation over South America extends a little farther south than the model precipitation because the model does not have orographic precipitation induced by the Andes [*Lenters and Cook,* 1995]. The model simulates the SACZ well. F_{net} in both model and data are similar. The maximum F_{net} values occur toward the south end of South America, which is much farther southward than the corresponding precipitation.

Strong westerly winds dominate at midlatitudes at both low (Figure 1c and Figure 2c) and high (Figure 1d and Figure 2d) altitudes, but the westerly winds at high altitude penetrate farther into the subtropics. At 850 mb, a typical monsoon circulation with a northwesterly flow is found along the eastern side of the Andes [*Zhou and Lau,* 1998]. On the southeastern flank of the South Atlantic high, warm, moist air converges and generates the SACZ. At 200 mb, there is a clear anticyclonic circulation centered at the Altiplano Plateau which is associated with the Bolivian high. A trough to the east of the high associated with the Nordeste low is found. Both the Bolivian high and the Nordeste low produced by the model without the Andes indicates that topography is not necessary for the existence of the Bolivian high and the Nordeste low [*Lenters and Cook,* 1997].

Results

During austral summer, strong solar heating, which is returned from the local surface to the atmosphere, leads to large F_{net} over all of South America with the maxima at the south end of the continent (see Figure 1b and Figure 2b). However, the corresponding precipitation does not extend as far southward as the regional large F_{net}. The precipitation is concentrated in the Amazon. In other words, F_{net} cannot solely control the extension of the continental convection zone in South America. To understand what determines the southward extent of the continental convection zone, we first examine the effect of soil moisture by comparing experiments with interactive soil moisture (Figure 3a) and saturated soil moisture (Figure 3b). When the land hydrology is active, low soil moisture leads to lower evapotranspiration, so the precipitation (Figure 3a) is lower. When soil moisture is saturated, the precipitation increases and extends a little southward as shown in Figure 3b.

Figure 3

Gutman and Schwerdtfeger [1965] first suggested the importance of cold air advection from the west of South America. Due to the Andes, the main contribution of cold air advection is from the upper half of the troposphere over the subtropical Pacific Ocean and the coastal regions. In CNS, $\mathbf{v} \cdot \nabla T$ is found to be more efficient at transporting energy out of a continental area than $\mathbf{v} \cdot \nabla q$. To examine the effect of ventilation, an experiment is performed with suppressed advection terms in the temperature and moisture equations over South America ($\mathbf{v} \cdot \nabla T = 0$ and $\mathbf{v} \cdot \nabla q = 0$). Figure 3c is the result. The precipitation over South America moves southward significantly compared to Figure 3a and Figure 3b. This demonstrates the importance of the ventilation from westerly winds in limiting the southward movement of the South American convection zone. We also notice that the SACZ disappears in this case, suggesting that moisture advection ($\mathbf{v} \cdot \nabla q$) is a factor in producing the SACZ. We note that in simpler models, such as Gill (1980), the neglect of these advection terms appears less important because convective heating is prescribed, whereas here it is simulated.

To further examine the interactive Rodwell-Hoskins mechanism, a fixed f region (9S-56S, 76W-20W) is used to suppress the β-effect and thus Rossby wave dynamics. The value of f at 13.125^0S is used. Effects at the boundary of the region can occur (e.g., just outside the south western boundary in Figure 3d), so several domains were tested. Results over South America are not highly sensitive to the size of this region. The result is shown in Figure 3d. The precipitation extends to the entire South American continent. This distribution is similar to F_{net} in Figure 1d and Figure 2d. We conclude that as the sun moves southward in the southern summer, the extent of the continental convection zone in the control run is decided by ventilation and the interactive Rodwell-Hoskins Mechanism.

A strong east-west asymmetry with a northwest southeast tilt is found in Figure 1a and Figure 2a. This tilt extends into the Atlantic and connects to the SACZ. Similar east-west asymmetric circulations associated with equatorial continents, such as Africa and South America, are also pointed out by *Silva Dias et al.* [1983]. They suggest that the asymmetric circulations can be explained by the properties of Rossby and mixed Rossby-gravity waves which are the result of latent heat released over the Amazon. Current results indicate that this asymmetry of the South American convection zone results from both: ventilation and the interactive Rodwell-Hoskins mechanism. Ventilation advects cold air from the Pacific Ocean and disfavors convection over the western part of South America, so without ventilation (Figure 3c) the east-west asymmetry of precipitation over South America becomes weaker. *Rodwell and Hoskins* [1996] also point out a similar effect due to the horizontal advection terms in their experiment over the Asian continent. When the β-effect is also suppressed (Figure 3d), the east-west asymmetry completely disappears. This indicates that subsidence associated with Rossby wave dynamics also contributes substantially to the asymmetry.

Conclusions

We examine mechanisms governing the southward extent of summertime precipitation in South America. For fixed ocean heat transport, the dominant effects limiting southward extent of precipitation are ventilation and the interactive Rodwell-Hoskins mechanism. In this South American case, the interactive Rodwell-Hoskins mechanism is at least as important as ventilation. This differs from the idealized continent case (CNS) in which ventilation is dominant. This is probably because the narrow southern portion of South America lies westward of much of the tropical convective region and thus is more affected by Rossby wave descent. Soil moisture also has impact on precipitation in South America, but it is relatively weak compared to ventilation and the interactive Rodwell-Hoskins mechanism. In the margin of the continental convection zone, the level of soil moisture cannot be maintained by its water supply, precipitation, so, in turn, precipitation in the interactive soil moisture case cannot move as far southward as in the saturated soil moisture case.

The east-west asymmetry of the continental convection zone in South America is also discussed. Ventilation disfavors convection over the western part of South America but favors convection over the eastern part of the continent. Subsidence induced by latent heat released in the Amazon and SACZ regions further enhances the dryness of the western part of South America and its corresponding circulation. This circulation supplies moisture from the tropics and enhances the convection over the Amazon region (the interactive Rodwell-Hoskins mechanism).

While present results focus on the climatology, the importance of the westerly jet in the ventilation mechanism suggests that interannual variability of the jet stream might affect variability in the southward extent of the continental convection zone.

Acknowledgments. This work was supported under NSF grant ATM-0082529, and NOAA grants NA86GP0314 and NA86GP0361. This is UCLA IGPP contribution 5477.

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(Received July 31, 2000; accepted February 23, 2001.)

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Figure 1. January climatology from the model for (a) precipitation, (b) F_{net}, (c) winds at 850 mb, or (d) winds at 200 mb.

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Figure 2. As in Figure 1 but from observations.

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Figure 3. January precipitation for experiments (a) with interactive soil moisture, (b) with saturated soil moisture in South America, (c) with interactive soil moisture and advection terms suppressed in a region around South America, or (d) with interactive soil moisture, advection terms suppressed and the Coriolis parameter f set to a constant in a region around South America.

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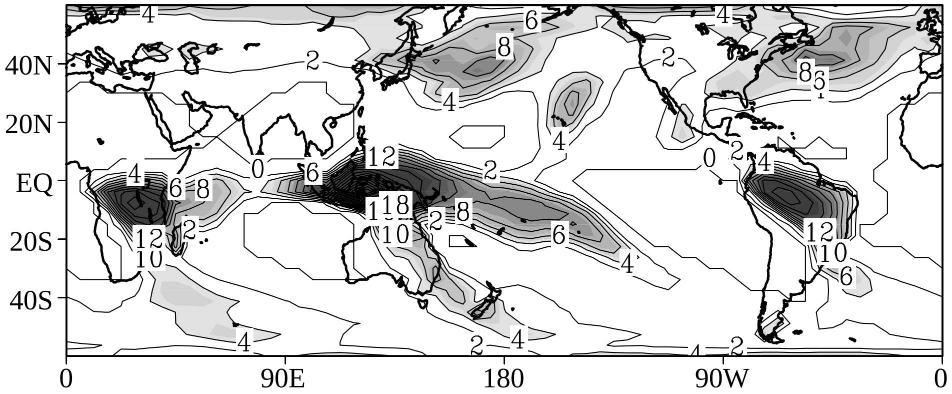
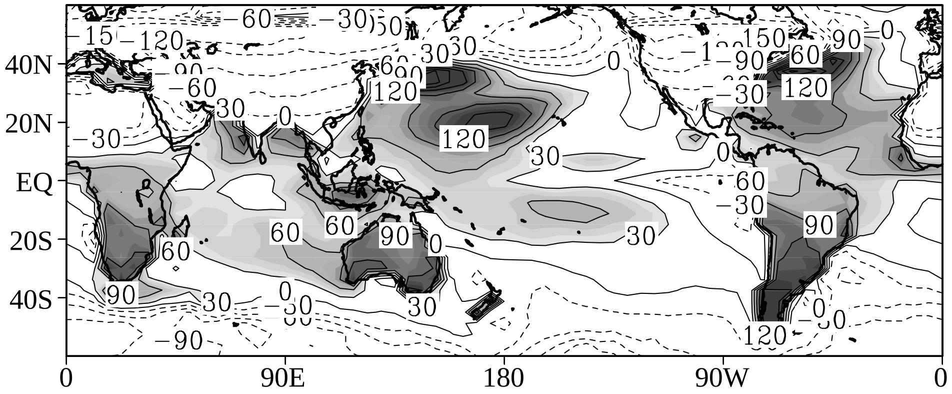
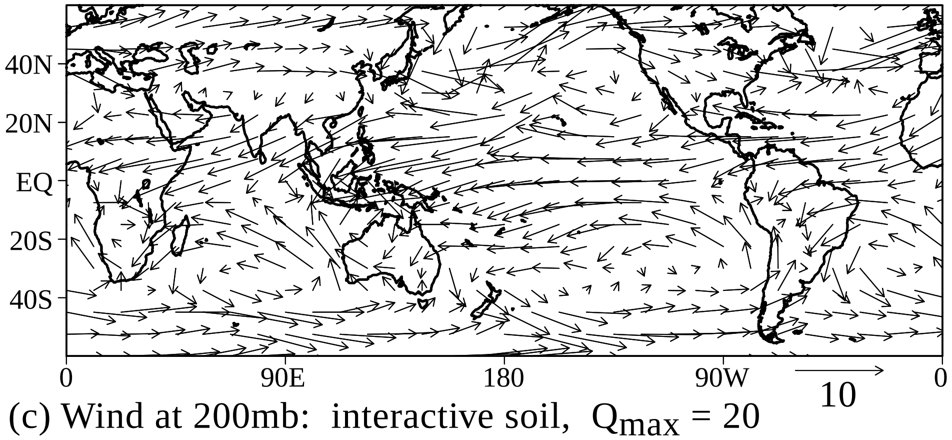
(a) Prec: interactive soil, $Q_{max} = 20$ JAN



(b) F_{net} : interactive soil, $Q_{max} = 20$



(c) Wind at 850mb: interactive soil, $Q_{max} = 20$



(c) Wind at 200mb: interactive soil, $Q_{max} = 20$

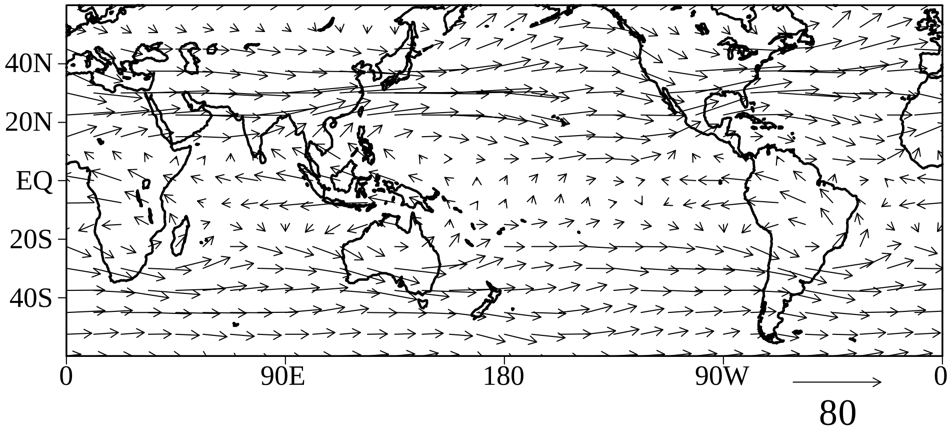
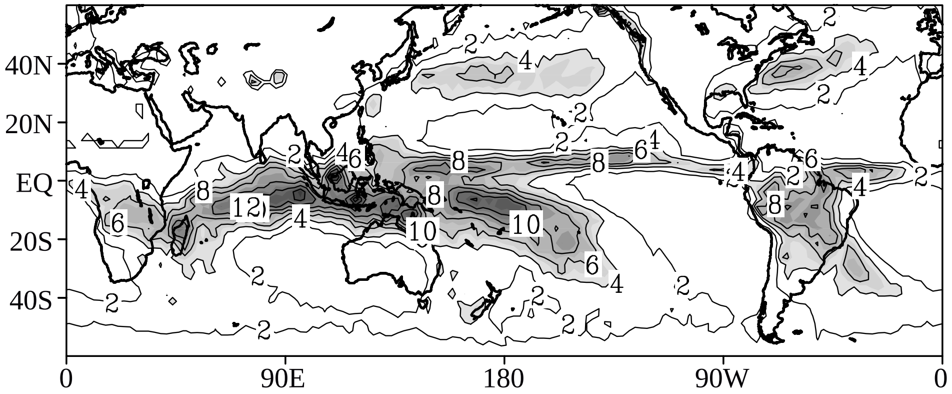
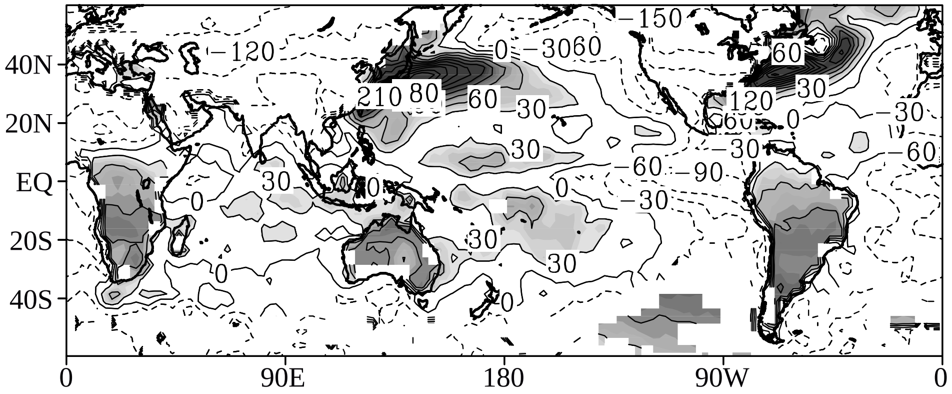


Figure 1

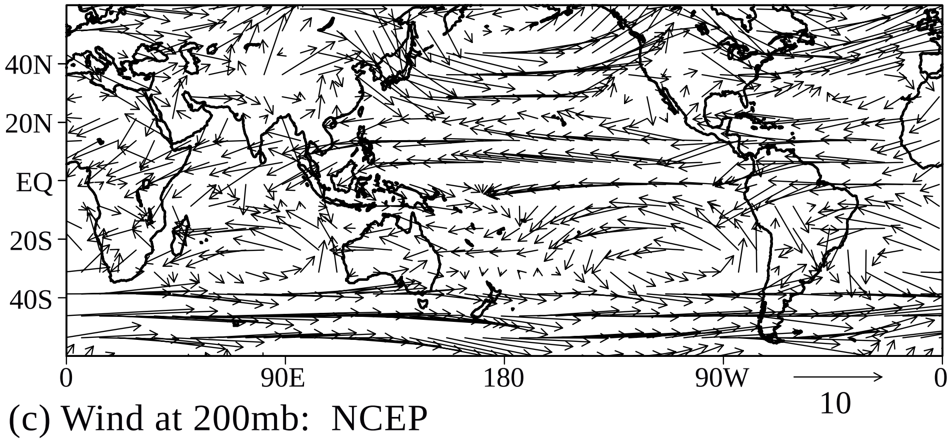
(a) Prec: Xie - Arkin JAN



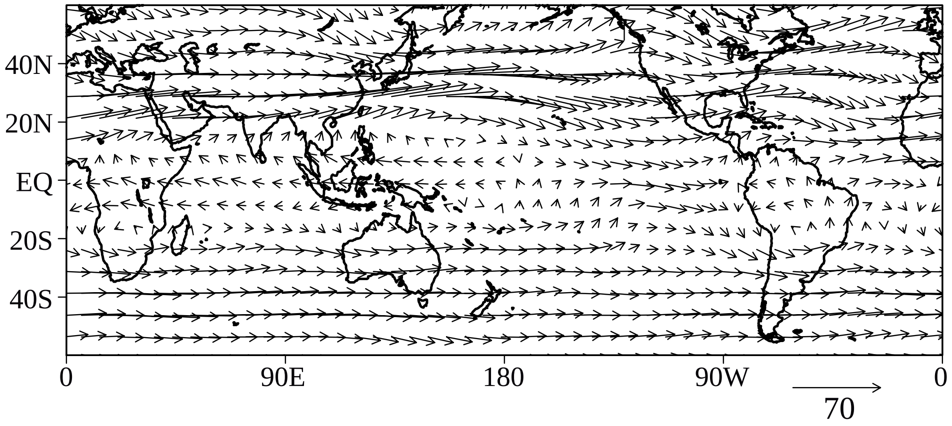
(b) F_{net} : COADS, ERBE and Darnell et al.



(c) Wind at 850mb: NCEP

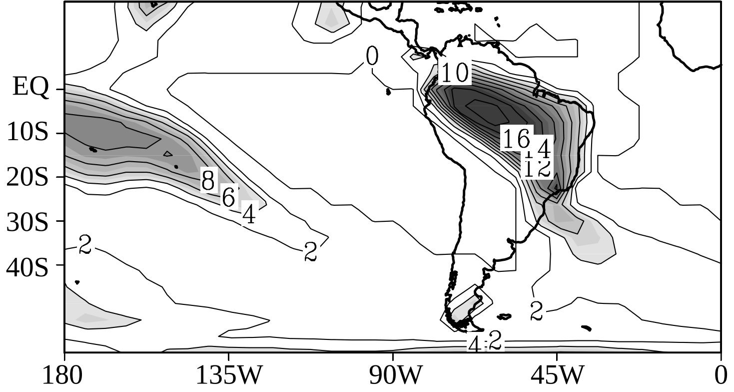


(c) Wind at 200mb: NCEP

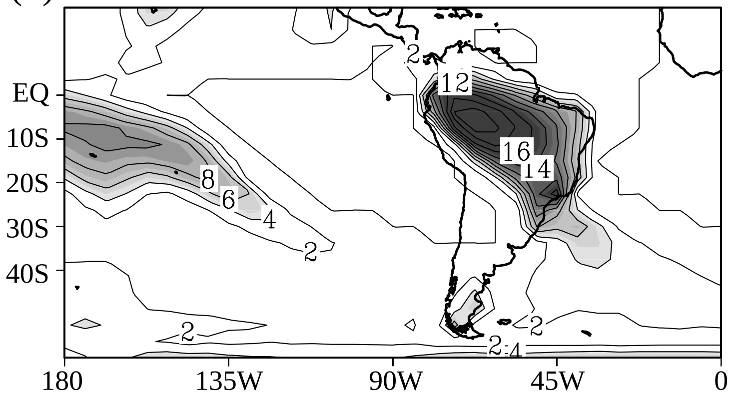


GRL paper 2000GL012138 Neelin_Fig.2

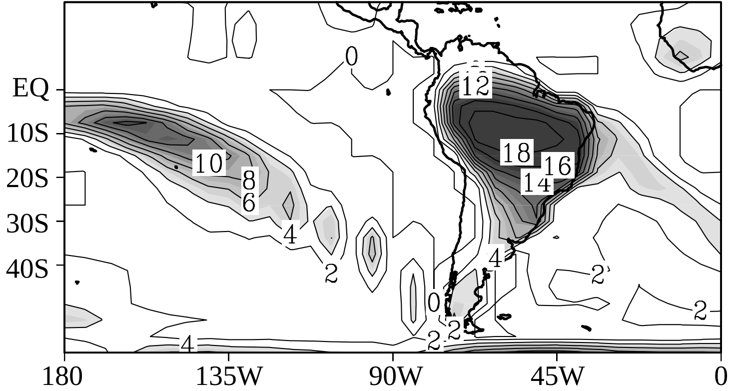
(a) Prec: interactive soil JAN



(b) Prec: sat soil



(c) Prec: no adv, interactive soil



(d) Prec: no adv, fixed f, interactive soil

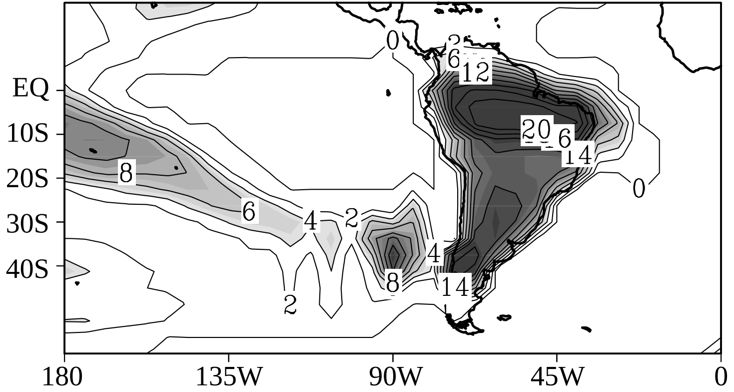


Figure 3