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PROGRESS IN PAN AMERICAN CLIVAR RESEARCH: UNDERSTANDING THE SOUTH AMERICAN MONSOON

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ABSTRACT

A review of recent findings on the South American Monsoon System (SAMS) is presented. SAMS develops over a large extension of land mass crossed by the equator with surface conditions that vary from the world's largest tropical forest in Amazonia to a high desert in the Altiplano. The high Andes mountains to the west effectively block air exchanges with the Pacific Ocean, but plentiful moisture transport from the Atlantic maintains intense precipitation that is strongest over central Brazil. There is also abundant precipitation over the subtropical plains of South America in association with moisture transport from tropical latitudes. Furthermore, midlatitude systems are important modulators of the tropical precipitation. The combination of all these factors results in a unique seasonal evolution of convection and rainfall. The findings presented emphasize the system's complexity, and highlight the importance of the South American continent as the core of atmospheric linkages with the adjacent oceans. A discussion on directions for research on SAMS is also presented. There are still outstanding questions on the relative roles played on the system evolution by the orography, local and remote heat sources, and sea surface temperature anomalies. Other remaining questions address the impact of Amazon-deforestation on water and energy cycles over the two largest river basins of South America (Amazon and La Plata).
Keywords: South American Monsoon, South Atlantic Convergence Zone, Predictability, Low-frequency variability.

PROGRESOS EN LAS INVESTIGACIONES DE PAN AMERICAN CLIVAR: ENTENDIENDO EL MONZÓN SUDAMERICANO

RESUMEN

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Se presenta un resumen actualizado acerca del Sistema Monzónico en Sudamerica (SMS). El SMS se desarrolla sobre un continente tropical, con variadas condiciones de superficies que incluyen grandes bosques tropicales (en Amazonia), y el elevado desierto en el Altiplano. Los Andes en el oeste del continente bloquean eficientemente el intercambio de aire con el Océano Pacífico, y canalizan el transporte de humedad desde el Océano Atlántico produciendo intensa precipitación con máximo valores en el centro de Brasil y un maximo secundario sobre las llanuras subtropicales de Sudamerica. Además, sistemas de latitudes medias son importantes moduladores de la precipitación tropical. De la combinación de todos estos factores resulta una singular evolución estacional de la convección y precipitación. Los resultados presentados enfatizan la complejidad del sistema y destacan la importancia del continente Sudamericano como centro de las conexiones atmosféricas con los océanos adjacentes. Una discusión sobre las futuras lineas de investigación a seguir en SMS es también presentada. Existen aun importantes preguntas acerca del papel relativo que ejercen sobre la evolución del sistema la orografía, fuentes de calor locales y remotas y las anomalias de la temperatura de la superficie del mar. El impacto de la desforestación del Amazonas en al balance hídrico y de energía de las dos más grandes cuencas en Sudamerica (de los rios Amazonas y de la Plata) tambien necesita ser estudiado con mayor profundidad.

Palabras clave: Monzón Sudamericano, Zona de Convergencia del Atlántico Sur, Predictabilitdad.

1. INTRODUCTION

A complex variety of regional and remote factors contribute to define the climate of South America. The continental mass extends across the equator from about 10° N to 55° S and has unique geographical features. The high and sharp Andes mountains rise along the Pacific coast on the west. Surface conditions include the world's largest rain forest in Amazonia and driest Desert in Atacama in northern Chile, as well as a high desert in the Altiplano. Climate variability elsewhere significantly impacts the climate over South America. Links between sea surface temperature (SST) anomalies associated with El Niño/Southern Oscillation (ENSO) and rainfall as well as circulation anomalies over the continent have been demonstrated. In turn, climate variability over South America can influence atmospheric patterns in the surrounding oceans and beyond.

The climate of South America, therefore, is a topic of investigation that is scientifically exciting and of extraordinary relevance to the millions who live on the continent. An important obstacle to progress has been the general paucity of surface observations over and around the continent and the inadequacy of available upper-level soundings to resolve key topographically bound circulations, their diurnal evolution, and related horizontal and vertical fluxes of moisture, heat, and momentum. Nevertheless, significant advances toward a better understanding of the climate and increased accuracy in the prediction of its anomalies have been achieved, particularly in the last decade. The availability of high-quality observational datasets produced by reanalysis products at major operational centers has greatly contributed to progress. Studies based on a hierarchy of numerical models of the atmosphere have played a particularly important role in view of data sparcity. Models have helped to gain insight and test hypotheses about the effects on climate of highly complex orography, variable surface conditions, and multiplicity of phenomena with a wide range of space and time scales.

Another key factor towards progress in the understanding and prediction of the South American climate in the last decade has been the establishment of special national and international research programs that have both stimulated interest in the scientific issues and provided support for research efforts. The Pan-American Climate Studies (PACS) program sponsored by the Office of Global Programs of the US National Oceanic and Atmospheric Administration (OGP/NOAA) sharpened the science focus, encouraged international collaborations, and provided resources for pilot projects that currently improve the monitoring of climate variability in the Americas. The Climate Variability (CLIVAR) component of the World Climate Research Programme (WCRP) established the Variability of American Monsoon Systems (VAMOS) panel (see http://www.clivar.org/organization/vamos/), with focus on a better understanding, simulation and prediction of the American monsoons. VAMOS has succeeded in providing scientific motivation for international research programmes on the warm season climate of the Americas, and on fostering the development and implementation of international field projects. US CLIVAR established the Climate Variability and Predictability/Pan-American (CLIVAR/PAN-AM) programme as the US contribution to international CLIVAR through VAMOS. Argentina, Brazil, Chile and Uruguay have also organized national CLIVAR groups. Another major WCRP component, the Global Energy and Water Cycle Experiment (GEWEX), has been involved through its Hydrometeorology Panel (GHP) in the Large-Scale Experiment in the Biosphere and Atmosphere of the Amazon Basin (LBA). The US National Science Foundation (NSF) and several other national science agencies established the Interamerican Institute for Global Change Research (IAI) to encourage and support international groups dedicated to research on the climate of the Americas.

The present paper highlights recent work that provides a better understanding of the South American monsoon system (SAMS hereafter) and warm season climate of South America under the banner of PACS, VAMOS and CLIVAR/PAN AM, although contributions by other programmes have been substantial in some cases. Section 2 describes the main components of SAMS, with a focus on the seasonal cycle of precipitation. Section 3 discusses the variability and predictability of SAMS. Section 4 presents results from numerical models. Section 5 contains an overall summary with emphasis on future directions and challenges.

2. THE SOUTH AMERICAN MONSOON SYSTEM (SAMS)

a) Seasonal mean

Fig. 1 shows the summer rainfall over South America and other outstanding features of the SAMS (see also Zhou and Lau 1998). (In the present paper "seasons" are understood in the Southern Hemisphere context.) The upper levels are characterized by high pressure centered near 15°S, 65°W over the Altiplano and low pressure over northeast Brazil. These features, which are referred to as the "Bolivian high" and "Nordeste trough," are strongest at around 200 hPa. At low levels, easterly flow from the Atlantic Ocean is channeled southward by the Andes mountains into the Chaco Low. This is a climatological feature present throughout the year, but strongest during the summer season. Another important feature in Fig. 1 is the southeastward extension of cloudiness and precipitation from the southern Amazon towards southeast Brazil and the neighboring Atlantic Ocean. This is referred to as the South Atlantic Convergence Zone (SACZ, hereafter).

A spectral analysis of streamfunction and meridional wind at 200 hPa has suggested that the Bolivian high-Nordeste trough system is basically a zonal wavenumbers 2-6 regime with monsoon-like characteristics, i.e., a vertical phase reversal in the midtroposphere and a quarter-wave shift between velocity potential and streamfunction divergence (Chen et al. 1999). The regime has centers of divergence over eastern Brazil and eastern Africa. This is consistent with links between the Bolivian high and condensational heating over the Amazon, and between the Nordeste trough and condensational heating over Africa. Furthermore, the regime is embedded in and modulated by the wave with zonal wavenumber 1, whose center of divergence in the tropics of the Southern Hemisphere is over the western tropical Pacific. A diagnostic calculation involving the equations for velocity potential maintenance (which links velocity potential and diabatic heating) and streamfunction budget (which couples streamfunction and velocity potential) supports the argument that the Bolivian high-Nordeste trough system is generated by local forcing over South America and remote forcing from Africa.

There are very few analyses of rainfall data in South America. Fig. 2 compares precipitation over the Brazilian Amazon during the SAMS and other seasons by using data compiled for the period 1976-1994 by Marengo et al. (2000). This data was provided by 430 stations and interpolated onto a 2.5° longitude by 2.5° latitude grid. To a first approximation, the annual cycle of precipitation tends to follow that of insolation, although there are marked west-east asymmetries. The wet and dry seasons have clear differences (e.g., Kousky 1980, 1988, Horel et al. 1989, Rao and Hada 1990, Rao et al. 1996, Kousky and Ropelewski 1997). The largest values are in the north and northwest

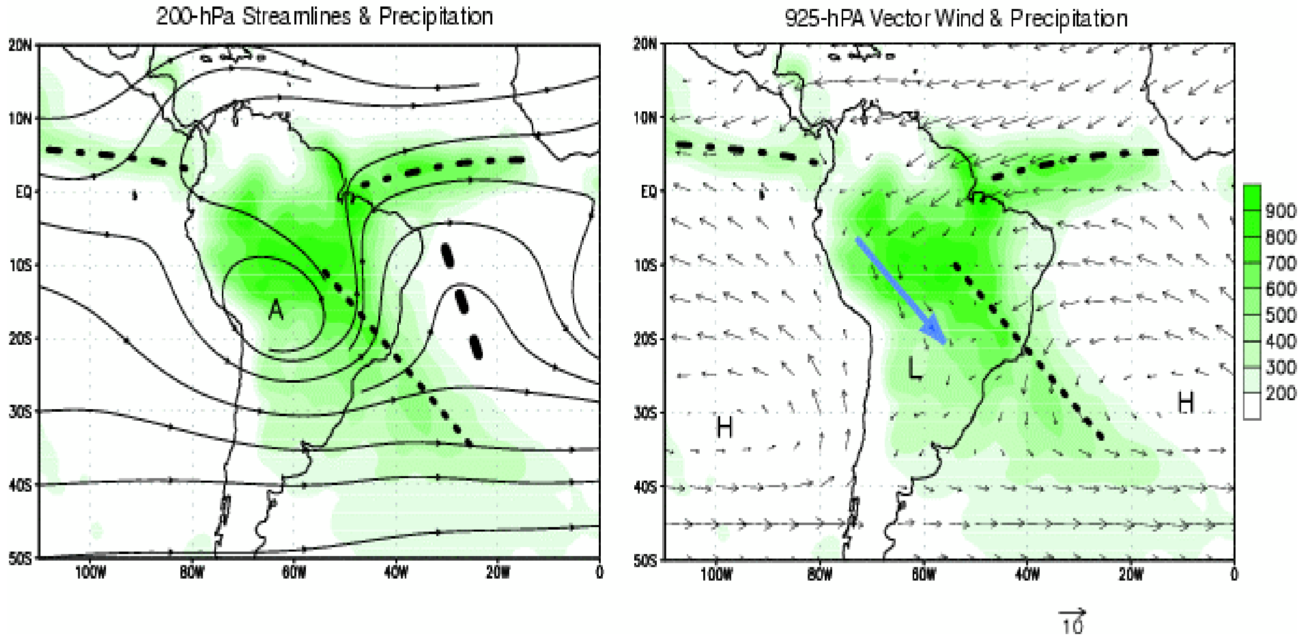

Fig. 1. Schematic illustration of the South American Monsoon System (SAMS). Mean (1979-1995) December-February 200-hPa streamlines (left), 925-hPa vector wind (ms^{-1}, right) and merged satellite estimates and station observations of total precipitation (mm, shading). Circulation data are taken from the NCEP/NCAR Reanalysis archive. The positions of the Bolivian High (A), subtropical surface high pressure centers (H), "Chaco" low (L), low-level jet (thick vector), South Atlantic Convergence Zone (dotted line), Intertropical Convergence Zones (dot-dash line), and "Nordeste" trough (heavy dashed line) are indicated in the respective panels.

during winter while the southeast is quite dry (Fig. 2c) and in the southeast during summer (Fig. 2a), which is also the wettest three-month period, overall. The largest values during the transition seasons are relatively centered in latitude within the region (Figs. 2b and 2d). Rainfall during fall is heavier and more evenly distributed in longitude than in spring. Nevertheless, rainfall in spring can be as intense as in summer at particular locations such as near the mouth of the Amazon River. This appears to result from nighttime convergence of the easterly trades with the land breeze (see also Rao and Hada 1990, Figueroa and Nobre 1990, Marengo and Nobre 2000).

The thick arrow in Fig. 1 represents one of the world's major low-level jets (LLJs): the South American LLJ (SALLJ, hereafter). Warm-season precipitation processes over both South and North America are strongly modulated by LLJs, which develop in the lower troposphere with a horizontal extent in the order of 2000 km and a width of around 500 km. The SALLJ is relatively less known than its North American counterpart: the Great Plains LLJ. The consensus is that the SALLJ and Great Plains LLJ have many common features but also significant differences (Nogués-Paegle and Berbery 2000). Arguably the most intriguing difference, as suggested by global analyses, is that the former is also present in the cold season when the typical thermal forcing mechanisms are weaker, while the latter is primarily a warm season feature (Berbery and Collini 2000). The SALLJ plays an important role in the transport of moisture from the Amazon to La Plata basins.

b) Time evolution

A pictorial view of the establishment and demise of SAMS is given by the sequence shown in Fig. 3 of outgoing longwave radiation (OLR) fields during selected pentads along the calendar year. The development phase of SAMS during spring (September-November) is characterized by a rapid southward shift of the region of intense convection from northwestern South America to the southern Amazon Basin and Brazilian highlands (Planalto). The migration of convection from the Isthmus of Panamá to the central Amazon

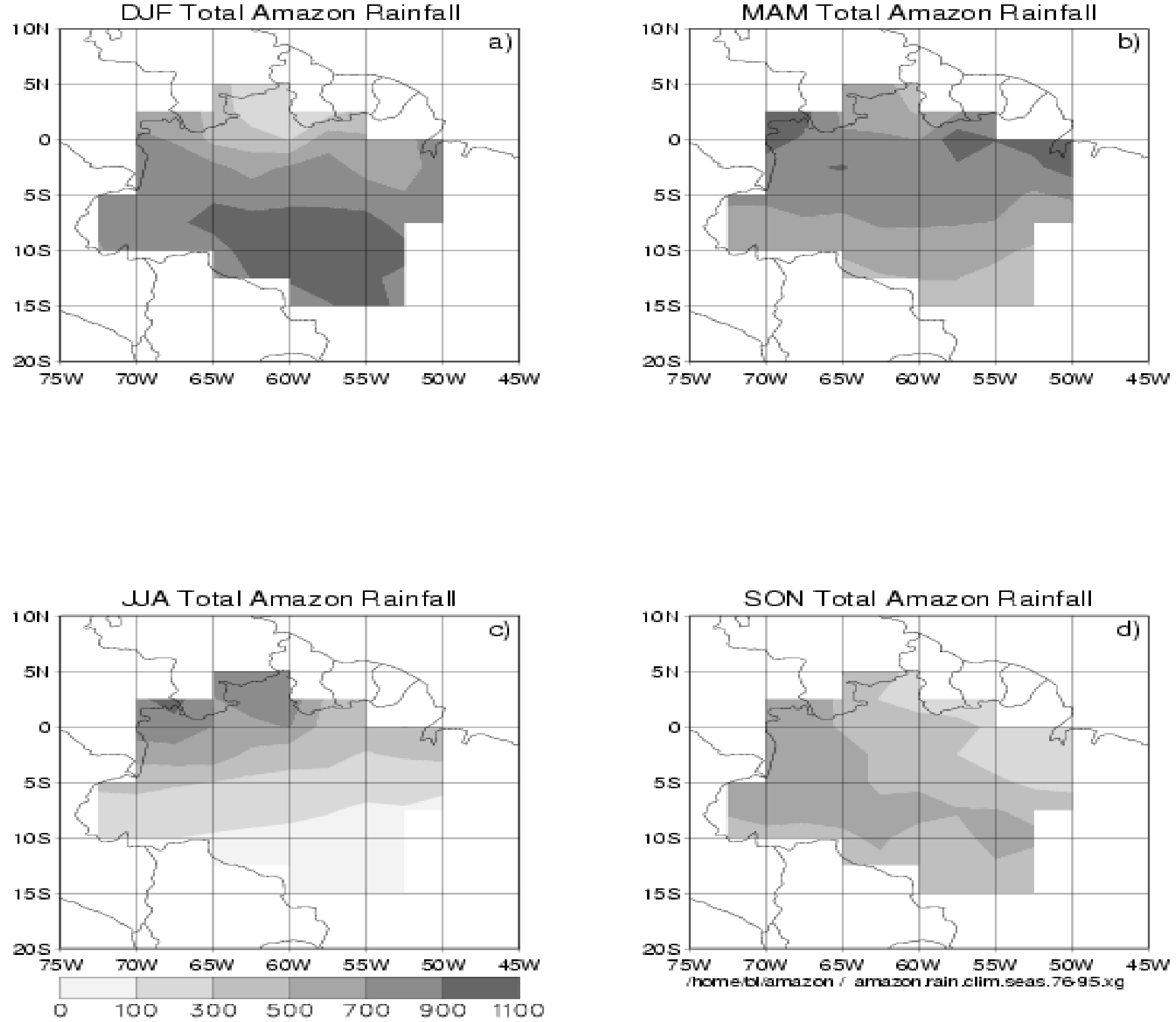

Fig. 2. Climatological monthly mean precipitation (in mm) for a) December-February, b) March-May, c) June-August, and d) September-November.

during spring can occur in as little as one month.The initial displacement of rainfall is lead by a southward reversal of the cross-equatorial flow (Wang and Fu 2002). The Bolivian high-Nordeste trough system establishes as precipitation increases south of the equator becoming most intense during the height of the summer (e.g., Kousky and Ropelewski 1997). The SACZ also evolves in space and time. In December, the SACZ is in its eastwardmost location, in association with high precipitation over much of Brazil, southeasterly flow over eastern Bolivia, and low precipitation in the Altiplano. In January, the SACZ is farther west and precipitation increases over the Altiplano in association with the influx at low levels of moist, unstable air from the northwest along the eastern flank of the Andes. In February, precipitation decreases as this northwesterly flux of moisture is reduced. The decay phase of SAMS continues through fall as convection gradually retreats northward toward the equator.

The mechanisms that control the evolution shown in Figs. 2 and 3 are complex. In the Amazon, Fu et al. (1999, 2001) demonstrated that much of the energy required for convection is provided by static instability processes. The seasonal onset of convection over the equatorial sector is largely in response to the cooling of the

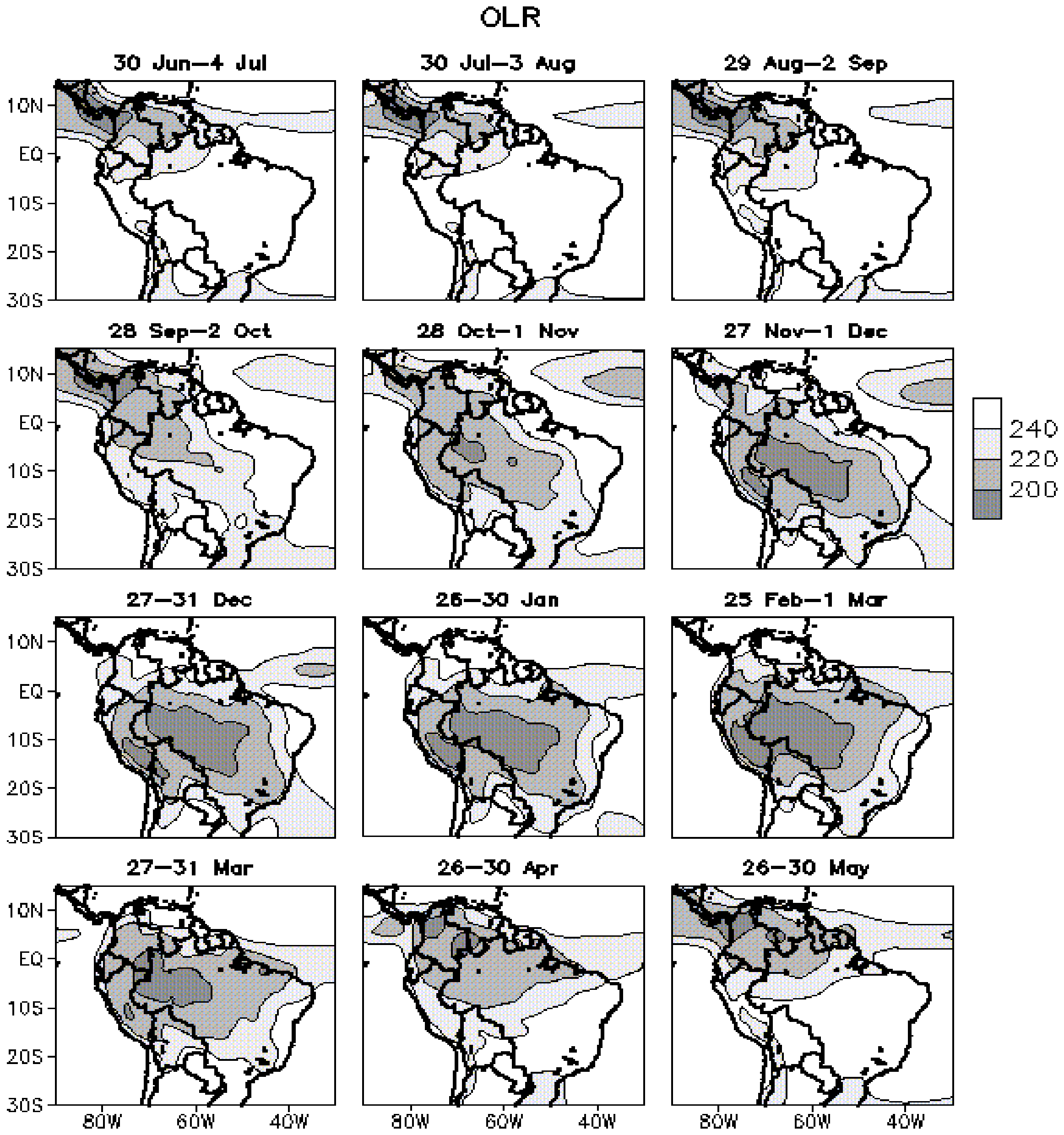

Fig. 3. Average (1979-1995) outgoing longwave radiation (OLR) for selected pentads.

planetary boundary layer (PBL) top and to PBL moistening, which in the eastern and central Amazon is due largely to entrainment. Hence, large-scale atmospheric transport plays a dominant role in the seasonal march of precipitation. Away from the equator, seasonal changes of land surface temperatures are as important as atmospheric transports. Weakening of the inversion starting about two months before onset of the summer rains enable accumulation of potential energy in the lower troposphere. The stretching of the atmospheric column transforms potential energy into divergent kinetic energy. Increase of the upper-level anticyclonic vorticity results from the fast conversion from divergent to rotational kinetic energy, and the rapid establishment of the wet season circulation pattern.

3. VARIABILITY

a) Diurnal modulations

Convection over tropical and sub-tropical South America has a strong diurnal cycle. This is influenced by a number of effects starting from the obvious low-level stabilization and destabilization due to surface radiational cooling during the night and heating during the day. Nevertheless, detailed analyses of the mean diurnal cycle of rainfall (Negri et al. 1994) and convective clouds (Garreaud and Wallace 1997, Sorooshoian et al. 2002) based on high resolution satellite imagery demonstrate that the timing of maximum convection is location dependent and closely linked to regional orographic features such as mountain ranges and concave coastlines.

Recent analyses of wind soundings during summer have revealed intriguing aspects of the SALLJ in central South America that are not easily reconciled by theoretical analyses that have been successfully applied in the North American framework. The principal discrepancies are a deep late afternoon, rather than a shallow early morning, wind maximum at Santa Cruz, Bolivia (Douglas et al. 1999), and substantially enhanced nocturnal cloudiness and rainfall at this foothill site.

The diurnal cycle of moisture budgets over South America are influenced by diurnal oscillations of the SALLJ, convective instability, and land and sea-breezes, as well as solenoidal circulations generated by elevated plateau effects. In addition, explosive mesoscale convective complexes (MCCs) also occur preferentially at night (Velasco and Fritsch 1987). A number of studies have suggested that the diurnal oscillations of the SALLJ and PBL convergence, induced by the sloping terrain, are responsible for modulations of the low level moisture supply on diurnal time scales. The response amplifies near critical latitudes, where the forcing frequency is approximately equal to the Coriolis parameter. The theory suggests a phase shift of approximately 10 hours from 20° to 40° latitude for diurnally forced oscillations (Paegle and McLawhorn 1983). The critical latitude for diurnally forced motions in the PBL response is somewhat variable around 30°N (Smith and Mahrt 1981). The large phase change around that latitude is difficult to resolve over North America, where the Great Plains LLJ develops mainly poleward of 30°N. South America, on the other hand, has extensive mountain ranges and broad valleys from about 50°S to the equator, and an inspection of data from several stations in Argentina around 30°S suggests a nocturnal enhancement of convection (Dickinson 1987).

b) Synoptic variability

An outstanding feature of the warm season precipitation over much of eastern and southern Brazil is the high variability on time scales from a few days out to a few weeks. This variability has been related to changes in the position and intensity of the SACZ (e.g., Casarin and Kousky 1986, Kousky and Cavalcanti 1988; Nogués-Paegle and Mo 1997; Liebmann et al. 1999, Silva and Kousky 2001). The development and decay phases of SAMS are both modulated by incursions of drier and cooler air from the mid-latitudes over the interior of subtropical South America (Garreaud 2000a, Vera and Vigliarolo 2000). Cold fronts associated with synoptic systems that migrate from higher latitudes into northern Argentina and southern Brazil are often accompanied by enhanced deep convection over the western and southern Amazon, and affect the location of the SACZ by increasing the southward flux of moisture (Kousky 1979, 1985, Silva and Kousky 2001).

Over the Altiplano during the summer, widespread rainfall tends to cluster in “rainy episodes” lasting 1-2 weeks, interrupted by dry episodes of similar length when moist convection is suppressed or very isolated. Locally, the occurrence of deep, moist convection is largely controlled by moisture availability in the PBL (Garreaud 2000b). Lenters and Cook (1999) identified three types of events in association with Altiplano rainfall on synoptic time scales (Aceituno and Montecinos 1993, Garreaud 1999). First, low-pressure systems develop over northern Argentina or farther south, with a westward shift of the SACZ and generally dry conditions in the Amazon Basin. Those systems advect warm, moist, unstable air along the eastern flank of the Andes, which triggers convection on the Altiplano that extends eastward into the SACZ. Second, cold-core lows develop over southeastern South America accompanied by an intensification of the SACZ and an upper-level trough over southern Brazil. The Bolivian high is shifted to the southwest and there is anomalous northerly, low-level flow along

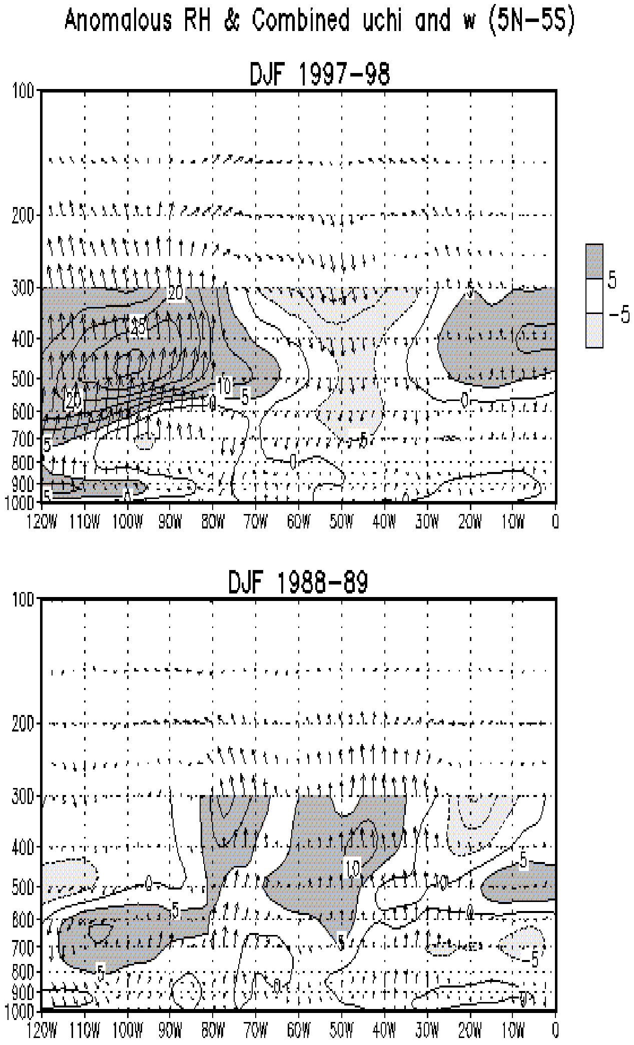

Fig. 4. Longitude-height section of anomalous relative humidity and divergent circulation (5°N-5°S) for December 1997-February 1998 (top) and December 1988-February 1989 (bottom). The divergent circulation is represented by vectors of combined pressure vertical velocity and divergent zonal wind. Shading and contours denote anomalous relative humidity (%). Anomalies are departures from the 1979-1995 base period monthly means.

the flank of the Andes. Third, the SACZ extends westward in association with an anomalous flux of moisture from the eastern Amazon Basin and the South Atlantic toward the central Andes. The Bolivian high strengthens and shifts to the south and much of the Amazon Basin is dry.

c) Intraseasonal variability

Analysis of persistent wet and dry anomalies over tropical and subtropical eastern South America during the austral summer reveals a dipole pattern of rainfall anomalies, with one center over southeastern Brazil in the vicinity of the SACZ and another center over southern Brazil, Uruguay and northeastern Argentina (e.g., Casarin and Kousky 1986, Kousky and Cavalcanti 1988; Kousky and Kayano 1994, Nogués-Paegle and Mo 1997, Silva and Kousky 2001). At times, this seesaw pattern appears to be a regional component of alarger scale system, with the southward extension and strengthening of the SACZ found in association with enhanced tropical convection over the central and eastern Pacific and dry conditions over the western Pacific and the maritime continent (Casarin and Kousky 1986, Nogués-Paegle et al. 2000). Convection is simultaneously suppressed in the region of the South Pacific convergence zone (SPCZ), over the Gulf of Mexico, and in the Atlantic ITCZ. In the opposite phase, there is a strong influx of moisture from the tropics into central Argentina and southern Brazil, which is enhanced by the SALLJ.

The dipole described in the previous paragraph varies on several time scales. Analyses of OLR and velocity potential over tropical and subtropical South America show distinct peaks in the intraseasonal band at 20-25 day and 30-60 day (e.g., Liebmann et al. 1999, Li and Le Treut 1999). The 20-25 day peak has been linked to the remote forcing over southwest Australia, which originates a wave train propagating southeastward, rounding the southern tip of South America and turning toward the northeast. This is one of the components of the Pacific-South American teleconnection pattern (PSA, Mo and Ghil 1987, Szeredi and Karoly 1987a,b, Kidson 1988, Farrara et al. 1989). It has been suggested that this teleconnection pattern impacts the SACZ, which results in a regional seesaw pattern of alternating dry and wet conditions (Nogués-Paegle and Mo 1997, and others). The 30-60 day peak has been linked by most studies to the Madden-Julian oscillation (MJO). Another study based on a rotated EOF analysis applied to data provided by 516 stations in locations ranging from Patagonia to Northeast Brazil during the period 1965-1990 also finds a dipole-type structure in rainfall variability in the 30-70 day band (Grimm et al. 2000a). There is also evidence that the relatively quick onset of seasonal convection over southeastern tropical South America is associated with MJO activity (Vera and Nobre 1999).

d) Interannual variability

The extreme phases of the ENSO cycle have a significant impact on the overall strength of SAMS and the rainfall pattern over tropical South America (e.g. Aceituno 1988, Kousky and Kayano 1994, Ropelewski and Halpert 2000). Connections to the Pacific are established through Rossby-wave trains and through vertical Walker-type circulations. Fig. 4 shows a latitude-height section around the equator for an El Niño and a La Niña event as obtained using the National Center for Environmental Prediction-National Center for Atmosphere Research (NCEP-NCAR) Reanalysis dataset (Kalnay et al. 1996). During the El Niño event (El Niño conditions), the rising motion over tropical South America is weaker than normal (Fig. 4a) and rainfall over the eastern Amazon and Northeast Brazil is below normal (Rao et al. 1986). During La Niña, the rising motion is stronger than average (Fig. 4b) and there is larger than average rainfall in those regions. El Niño years commonly exhibit two tropospheric anomalous warming centers straddling the equator over the central-eastern equatorial Pacific stretching northeastward and southeastward to the Gulf of Mexico and South America, respectively (Rasmusson and Mo 1993, Lau and Zhou 1999). A stronger (weaker) than normal subtropical jet stream over central Chile and north-central Argentina during El Niño (La Niña) episodes is accompanied by wetter (drier) than normal conditions over southern Brazil, Northeast Argentina and Uruguay, and stronger (weaker) than normal low-level southward flux of moisture over subtropical South America east of the Andes. Furthermore, the anomalous mass distribution induced by El Niño is consistent with significant pressure increase over northwestern Africa and subtropical South Atlantic and decrease from the subtropical South Pacific to central South America, reinforcing the summertime regional pressure gradient and resulting in a stronger than normal flux of tropical moisture toward higher latitudes over South America.

Land-sea temperature contrasts in the tropics can affect the evolution of ENSO events. Differences of up to 2°C between the northern South American landmass and the eastern tropical Pacific off the coast have been reported during such events (Pulwarty and Diaz 1993). Deep convection over the Peruvian coast during the austral fall may not only result from warmer SSTs but also as part of the seasonal migration from the Amazon Basin itself. A corresponding eastward displacement of the centroid of deep convection took place during the strong La Niña event of 1988-89. Further studies of the relationships between the demise of the SAMS and the strength of this east-west land-sea temperature contrast and its modulation by cloudiness during ENSO are needed (e.g., Yu and Mechoso 1999).

Linkages between the Pacific Ocean and rainfall anomalies over subtropical and extratropical South America (Pisciottano et al. 1994, Grimm et al. 1998, Grimm et al. 2000b) are often interpreted as the large-scale response to the easterly displaced convection. This response can be described by the leading EOFs of height or streamfunction anomalies, which are referred to as the Pacific-South American modes (PSA1 and PSA2) since they arch over the South Pacific and South America. PSA1 and 2 both have zonal wavenumber 3-type hemispheric patterns in mid to high latitudes, and a well-defined wave train with large amplitude in the Pacific-South American sector (Karoly 1989, Kidson 1999, Mo 2000, Mo and Nogués-Paegle 2001). The PSA1 and PSA2 patterns exhibit characteristics of Rossby wave responses to perturbations in the South Pacific suggesting that their ubiquitous presence on various time scales may be an inherent feature of atmospheric variability similar to the Pacific-North American pattern in the Northern Hemisphere. The PSA 1 pattern appears to be related to ENSO (Mo and Nogués-Paegle 2001), with associated summer rainfall deficits over northeastern South America and enhanced precipitation over southeastern South America (as described above). PSA 2 appears to be associated with the quasi-biennial component of ENSO, which has a period of 22-28 months. The strongest connection between PSA 2 and the tropics is during spring. The associated rainfall pattern over South America shows a dipole pattern with out-of-phase anomalies between the SACZ and the subtropical plains around 35° S.

Over the Altiplano, more than 67% of the interannual variance in monthly mean precipitation is associated with a weakened and northward displaced Bolivian high and a region of cool, dry, southerly flow anomalies at low levels to the east (Lenters and Cook 1999). This pattern developed during the 1986/7 ENSO event, which brought dry conditions to the Altiplano region during January and, especially, February of 1987. The onset of this particular dry period was associated with a single synoptic event: the equatorward penetration of a cold front, which brought dry, stable conditions that inhibited convection on the Altiplano for weeks. Recent studies have examined the physical links between ENSO and rainfall variability in the Altiplano. Vuille et al. (2000) and Garreaud and Aceituno (2001) showed that the generalized warming (cooling) of the tropical troposphere during the warm (cold) phase of ENSO results in an intensification (weakening) of the upper-level westerly winds at subtropical latitudes just east of the central Andes. This leads to a decrease (increase) in the regional moisture transport from the continental lowlands into the Altiplano.

During summer, a large-scale anomalous upper-tropospheric stationary eddy is found to be associated with interannual variations in the intensity of the SACZ in the NCEP/NCAR Reanalysis dataset (Robertson and Mechoso 2000). An anomalous cyclonic eddy accompanies an intensified SACZ with anomalous descent to the southwest and weakened low-level jet east of the Andes. The anticyclonic case is opposite. The wave appears to be a natural mode of atmospheric variability of an essentially extratropical character: the upper-tropospheric vorticity balance is characteristically extratropical, and the vertical structure is equivalent barotropic. This signature is similar to that found by Mo and Nogués-Paegle (2001) for the PSA 2 mode.

A similar (though less localized) stationary Rossby wave was identified by Kalnay and Halem (1981) along the lee of the Andes in 1979 from the First GARP Global Experiment (FGGE) dataset. Subsequent modeling studies by Kalnay et al. (1986) indicated that this wave could exist independently of the Andes, and that tropical heating over either the Pacific or Atlantic sector could generate it. On sub-monthly timescales, Liebmann et al. (1999) found that intensified SACZ episodes are accompanied by a trough to the southwest that is produced by a transient Rossby wavetrain from higher southern latitudes. The interannual SACZ/trough structure may be a rectification of these intraseasonal events, i.e. the product of random sampling of different numbers of submonthly events in any given summer.

Atlantic SST anomalies also influence summer precipitation in South America during summer, when SAMS is active (Moura and Shukla 1981, Mechoso and Lyons 1988, Mechoso et al. 1990, Giannini et al. 2001). SST anomalies over the southwest Atlantic are found to accompany interannual intensifications of the SACZ, with negative anomalies north of about 40°S, and positive ones to the south. The latter coincide with decreased westerly winds, and are thus consistent in sign with the effect of reduced evaporation. The cold anomalies to the north partially underlie the cold atmospheric trough associated with the intensified SACZ; they thus also tend to be consistent with atmospheric forcing, both thermodynamically and through anomalous Ekman pumping (Kalnay et al. 1986). On the other hand, it is plausible that these latter negative SST anomalies may reinforce the overlying atmospheric trough and intensify the monsoonal circulation by strengthening the land-sea temperature contrast. Coupled ocean atmosphere interactions appear to be involved. A simultaneous relationship between SST anomalies in the southwestern Atlantic and precipitation in Uruguay (of the warm-wet or cold-dry types) during summer is shown by Diaz et al. (1998) and Diaz (2000). The mechanisms at work for these associations are a matter of current debate.

In turn, diabatic heating associated with SAMS may exert an important influence on the boreal winter subtropical jet over eastern North America through regional Hadley circulations (Nogués-Paegle et al. 1998). Recent modeling studies have suggested that interannual variations in the North Atlantic Oscillation (NAO) index during boreal winter may be linked to variations in tropical heating associated with SAMS (Watanabe and Kimoto 1999, Robertson et al. 2000, Cassou and Terray 2000).

e) Decadal and longer time-scale variability

A number of studies have reported the existence of decadal and longer time-scale variability in South American rainfall. Most of those studies have related the change of rainfall to regional and global SST variations. Increased cyclonic activity around Newfoundland has been associated with

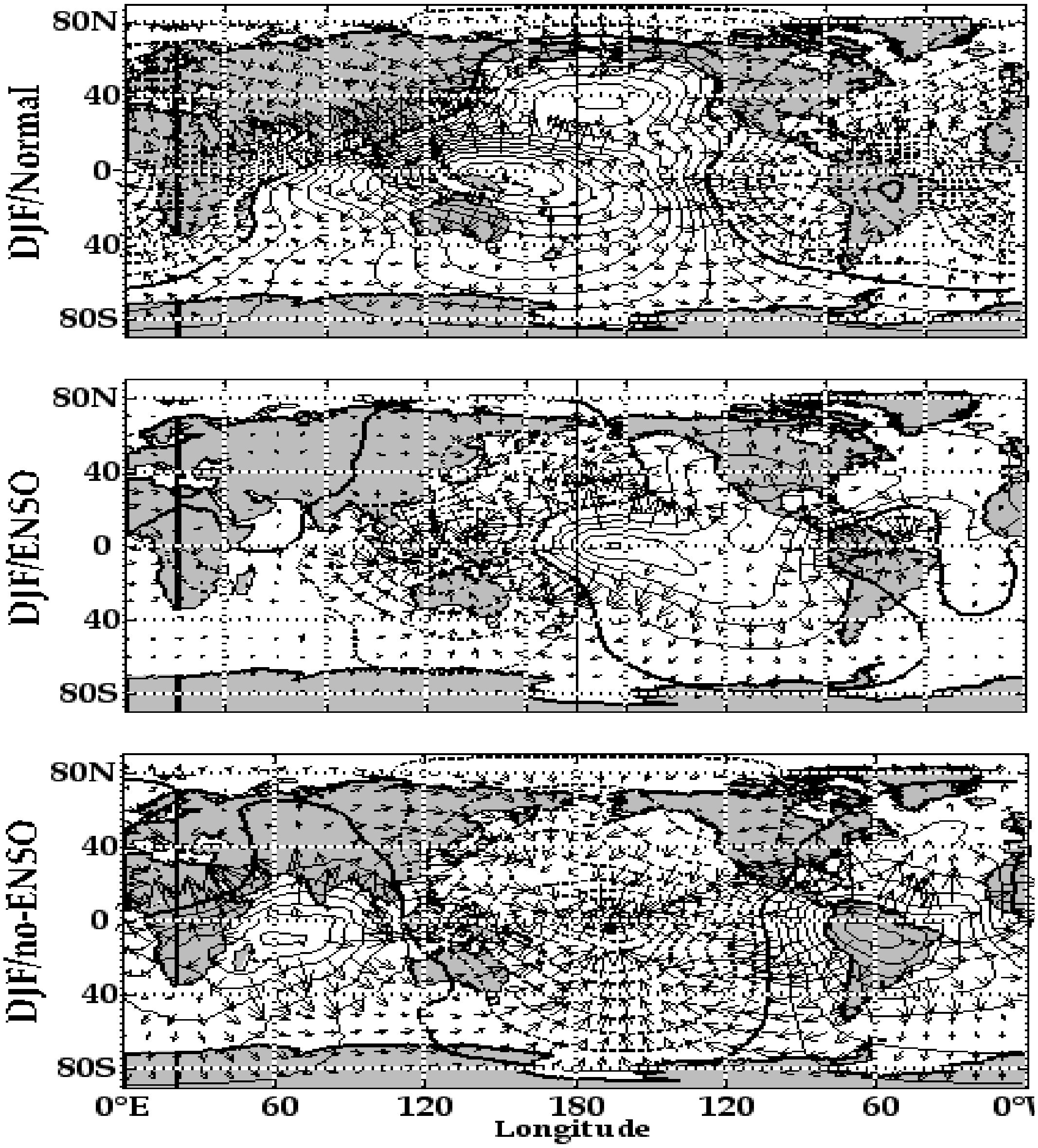

Fig. 5. 200-hPa velocity potential (contours) and irrotational flow (arrows). Upper: the 50-year boreal winter mean (December-January-February). Middle: composite mean departures, for positive minus negative phases of the global ENSO mode. Lower: composite mean departures, for 1978-99 minus 1950-77, of the non-ENSO residual in the Niño3 region. Regions of high-level outflow (low-level confluence) are indicated by diverging arrows and solid contours. Hadley flows (or their departures) are indicated by regions of meridionally oriented arrows north of the equator.

enhanced rainfall in Northeast Brazil (Namias 1972). This implies a relationship with the North Atlantic Oscillation (NAO), which varies on the decadal time scale and is strongest in austral summer. Wagner (1996) used surface and subsurface ship observations and demonstrated a trend of interhemispheric SST gradient in association with a substantial increase in South Atlantic SSTs centered at 20°-30°S in summer. He found a positive correlation between this SST trend and precipitation anomalies over northeast Brazil, and attributed that feature to the southward displacement of the lower tropospheric wind confluence zone. This finding was confirmed by

Marengo et al. (1998), who showed a slow increase of rainfall in northeast Brazil in the historical record, and by Hastenrath (2000) who presented concordant upper level changes in vertical motion and divergent circulations in the NCEP/NCAR Reanalysis dataset. Long-term variations have also been found in historic hydroclimatological records of tropical South America. A negative trend in two regions of western and central Amazonia and a positive trend in eastern Amazonia over the period from 1960s to 1980s was demonstrated by Dias de Paiva and Clarke (1995).

Using CPC Merged Analysis of Precipitation (CMAP) data, Zhou and Lau (2001) showed that the second and the third principal modes of low-passed South American summer rainfall are related to decadal and longer-term variability, respectively. The decadal variation presents a pattern of meridional shift of the ITCZ on both the eastern Pacific and western Atlantic Ocean; such a shift is closely related to the decadal change of the cross-equatorial SST gradient (Nobre and Shukla 1996, Rao et al. 1999) with modifications due to ENSO. The long-term trend shows increase of rainfall over the west coast of Ecuador-Colombia and tropical eastern Brazil and decrease over the surrounding areas and the equatorial North Atlantic Ocean.

The climate change that occurred in the Pacific around the late 1970s and continued since then has usually been associated with the Pacific decadal oscillation (PDO, Mantua et al. 1997). Prior to the mid-1970s (since at least the early 1950s) the eastern Pacific was relatively cool and the central North Pacific warm. After the mid-1970s, the eastern Pacific—both north and south of the equator—has been warm and the central North Pacific cool. Enfield and Mestas-Nuñez (1999) show composite maps of anomalous circulations based on two components of the Niño3 SST index (5°S-5°N, 90°W-150°W): a filtered component (1.5-8 year band) representing canonical global SST variability associated with ENSO and a residual component containing primarily the low-frequency SST change of recent decades (see also Mestas-Nuñez and Enfield 2000). A global complex EOF mode of SST anomalies constructed using an updated version of the Kaplan et al. (1998) SST dataset (1870-1998) reproduces the known canonical aspects of ENSO, including phase propagation of SST within and between ocean basins. The global ENSO mode accounts for about 3/4 of the total SST anomaly variability, while the residual accounts for the rest. Interestingly, about 40- 50% of the amplitudes of the record-setting 1982-83 and 1997-98 El Niño events is accounted for by the residual variability. Related to this, the ranking of the canonical ENSO events changes significantly with respect to the Niño3 index based on data (e.g., 1972-73 is equal to or stronger than 1982-83 and 1997-98). The indices of the canonical ENSO and residual (non-ENSO) variabilities in the Niño3 region were used to obtain the associated winter global composite maps of the tropospheric direct circulation using the NCEP/NCAR Reanalysis dataset for the period 1950-99. The resulting maps of velocity potential and irrotational flow at 850 and 200 hPa, and vertical velocity at 500 hPa show a consistent picture of the 3-D direct circulation for season as well as for the ENSO component and the residual change component. The anomalous winter circulations, composited on the interannual and residual components of the Niño3 variability, are quite different, from both climatology and from each other (Fig. 5). They imply nearly opposite departures from the normal circulation, based on comparable warming phases within the Niño3 region: The zonal Walker circulations at low latitudes are virtually opposite, having decadal subsidence near the dateline in place of the ENSO-related uplift (convection), and decadal uplift over northern South America, in place of ENSO-related subsidence. These results are surprising and significant in at least two respects: the effects of warming in the filtered components are generally opposite, and they are particularly strong in the South American sector. A similar feature was detected by Chen et al. (2001) who suggest that such changes might compensate at least partially the effects of Amazonian deforestation.

f) Variability of river flows

The interdecadal variations of SST anomalies in the Niño3 region are in phase with the interdecadal variations of streamflow anomalies of rivers in southeastern and northwestern South America, although these two regions show opposite responses to ENSO (Genta et al. 1998). In addition, a near-cyclic 15-17-year component in the SACZ was identified in the NCEP/NCAR Reanalysis dataset. The southwest Atlantic SSTs and river flows in the Plata Basin exhibit very similar oscillatory components (Robertson and Mechoso 2000). On interdecadal time scales, SST anomalies associated with the SACZ tend to be monopolar and located north of 30°S. When the SACZ is intensified, the Paraná and Paraguay Rivers tend to swell while the Uruguay and Negro Rivers to the south tend to ebb; this north-south contrast in streamflow anomalies is most marked on the interdecadal time scale. An 8-9-year component has also been identified in the Paraná and Paraguay rivers that is correlated with a similar component in the NAO, with the latter appearing to force the former through changes in the northeast trade winds (Robertson and Mechoso 1998). Statistical analysis of rainfall data from over 40 gauges (Müller et al. 1998) in the upper Paraná Basin showed evidence of increased rainfall after 1970, with the increases associated with increased frequency of rainfall events. The mean annual increase ranged from 8% to 17%. In the upper Paraguay Basin, a comparison by logistic regression of rainfall pattern occurrence, indicated that dry spells were more persistent during the period 1960-70, when river flows were much lower than in the periods before and after; whilst on days when rain fell, it was of lower intensity (Collischonn et al. 2001).

4. NUMERICAL SIMULATIONS AND PREDICTABILITY

a) AGCM simulations

Numerical models are ideal tools for studies leading to better understanding of the individual roles played by the shape and location of continents, topography, and SST distributions in the magnitude and geographical distribution of South American precipitation. This section does not intend to be a comprehensive review of SAMS studies with numerical models or a general discussion on the many problems with the numerical simulation of the major monsoon systems. Rather, the goal is to present recent work in which numerical models have been applied to enhance the basic understanding of selected aspects of SAMS.

In general, AGCMs have difficulties with the narrow and high Andes mountains. These difficulties have contributed to slow down progress towards a reasonable simulation of climatological precipitation over South America by global models. AGCMs based on spectral numerical methods produce spectral noise (Gibbs phenomena) near the Andes (Lenters et al. 1995). The development of techniques to filter topography in such models during the early 1990's allowed for much improved simulations of South American precipitation. Lenters and Cook (1995) used an AGCM with filtered topography (Lindberg and Broccoli 1996) to identify the individual roles of surface features in determining South American precipitation climatology in summer. Three experiments were performed. The one referred to as SST includes realistic January SSTs and global topography, while those labeled mountains and no-mountains include a zonally uniform SST field. Fig. 6 shows selected results from those experiments.

The AGCM simulations shown in Fig. 6 suggest that the presence of the South American continent alone, without topography or longitudinal structure in the SST field, suffices to obtain the summer precipitation maxima in the Amazon, SACZ, and northwestern South America. Precipitation in these regions is associated with maximum low-level wind convergence that are directly related to the interaction of the continental thermal low with the South Atlantic high and the northeasterly trades. The SACZ behavior is more complicated, and precipitation in that region is also enhanced by southeastward moisture advection and moisture flux convergence by transient eddies.

Topography introduces precipitation maxima on the eastern flank of the central Andes and the western flank of the southern Andes (Fig. 6c). Strong precipitation at higher elevations in the central Andes is not primarily due to dynamical mountain effects, but it is associated with strong convergence and convection over the elevated surface. The presence of topography sharpens the SACZ, and strengthens and repositions the Amazonian precipitation maximum. While the presence of longitudinal structure in SSTs is not fundamental to the existence of any of the major precipitation maxima in South America, precipitation in the Amazon and SACZ is very sensitive to SST structure and also to land surface conditions, especially in northeast Brazil. A comparison of Figs. 6a and b, for example,

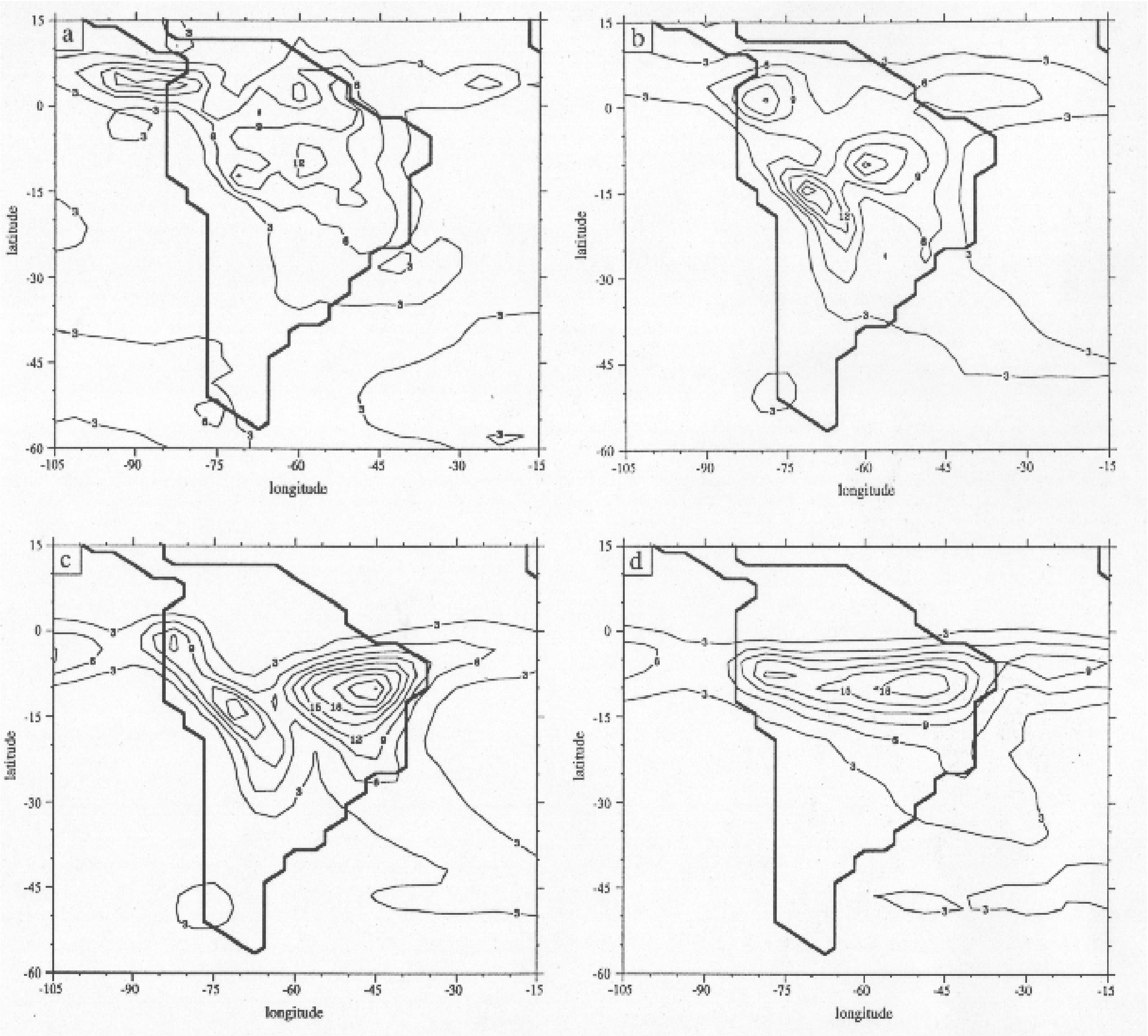

Fig. 6. Precipitation rate for January as (a) observed (from Legates and Willmott 1990); and modeled in the (b) SST, (c) mountain, and (d) no-mountain experiments. Contour is 3 mm^{-1} day.

demonstrates the importance of SSTs in positioning the Amazonian precipitation.

AGCM studies have also confirmed that the Bolivian high is primarily a response to condensational heating over the Amazon, and not to dynamical or thermal effects of the Andes mountains (Lenters and Cook 1997). Gandu and Silva Dias (1998) pointed out that western tropical Pacific heating can affect the intensity and location of the Nordeste trough, and Lenters and Cook (1997) noted that heating over Africa is crucial for "closing" the trough.

The role of tropical Pacific and Atlantic SSTs in shaping the seasonal patterns of the Amazon rainfall and its importance relative to land influence have also been tested explicitly by AGCMs. Fu et al. (2001) suggest that oceanic influences can be as important as those of land in determining the precipitation over the eastern Amazon during the equinox seasons. The seasonality of the land surface dominates that of the precipitation in the western Amazon throughout the year and that in the eastern Amazon during the solstices. These influences are carried out through a direct thermal circulation and propagation of stationary Rossby waves. The direct thermal circulation originates either from the Atlantic ITCZ or from the eastern Pacific ITCZ, and induces subsidence as well as reduced precipitation over

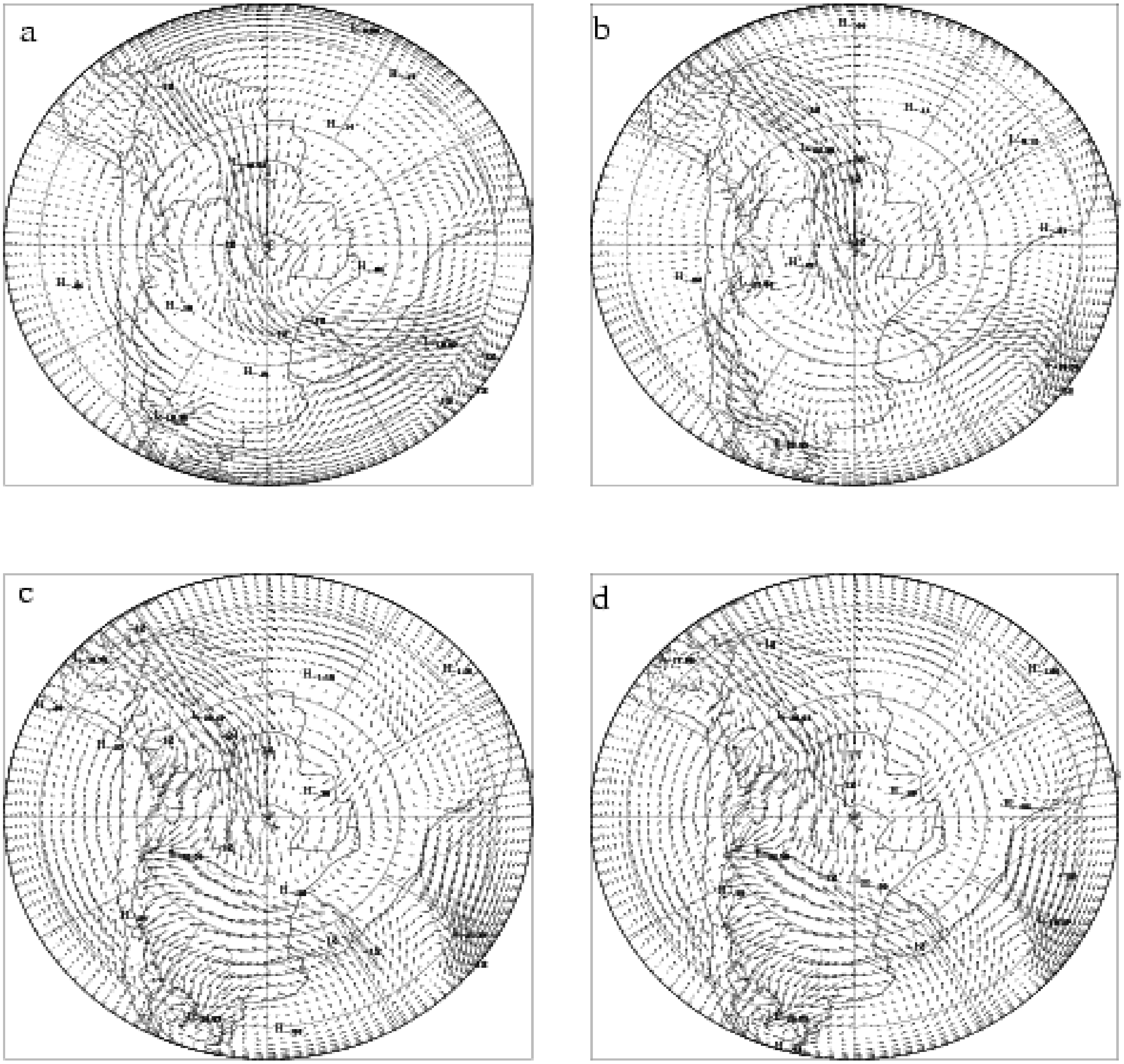

Fig. 7. Six-day averaged simulation of January horizontal wind by the University of Utah variable-resolution model at a) 2,500 m, b) 1,500 m, c) 400 m, and d) 100 m above the surface. There are 128 equally spaced points in the rotated model longitude. Grid points in latitude are separated by 0.5° over the depicted region and by 3° outside this region.

eastern Amazon. Rossby waves are forced by latent heating in the equatorial central Pacific, and propagate as a PSA-like mode into subtropical South America, strengthening the SACZ and suppressing convection over the equatorial eastern Amazon.

Other recent AGCM experiments suggest that east-west contrasts in tropical rainfall are associated with the seasonal cycle of SSTs, primarily in the Atlantic Ocean, which itself lags that of the ITCZ (Fu et al. 2001). The mechanism of influence is through the links between the seasonal cycles of SSTs and Atlantic ITCZ with its associated subsidence. In this regard, fall rather than summer is the rainfall season in northeast Brazil as warmest SSTs in the adjacent Atlantic are consistent with a southernmost ITCZ and weakening of associated subsidence. The seasonal cycle of SSTs in the Pacific Ocean also contribute to the late rainy season in northeast Brazil through its influence on the Pacific ITCZ, which itself is linked to the SACZ and the Nordeste trough.

AGCM experiments have also been performed in which continents were replaced by oceans (Chao 2000, Chao and Chen 2001 a,b). According to these experiments the African and American monsoons are more affected by removal of the corresponding continents than the Asian and Australian summer monsoons. This is consistent with ITCZ's favoring locations of high SST as in the western Pacific and Indian Ocean, or tropical landmass as in tropical Africa and South America.

In terms of prediction skill, a comparison of simulations of 1997/98 El Niño impact on SAMS by AGCMs (Zhou and Lau 2000) showed that the models have more skill over tropical than over subtropical South America. In the former region anomalies are governed by the Walker cell shift that is directly induced by the central-eastern Pacific warming, while in the latter anomalies are mostly caused by anomalous SAMS with large uncertainties due to poorly resolved orographic relief and surface conditions, as well as different solutions by various models intrinsic to the system dynamics.

b) Models with variable resolution

The coarse resolution of constant horizontal grid GCMs precludes adequate detail in regional precipitation patterns. This problem is alleviated with variable grid models that allow resolution of meso-scale features while retaining globally interacting influences. Wang et al. (1999) demonstrate that the latter approach allows for the capture of nocturnal precipitation maximum over the Great Plains of North America. They also demonstrate the importance of two-way interaction between the highly resolved regional domain and the remainder of the global atmosphere to obtain reasonable precipitation simulations. Fig. 7 displays the horizontal wind produced by the University of Utah variable resolution model at four levels between 100 m and 2,500 mb above the surface (see Wang et al. 1999, for model description). The highest horizontal resolution in this case is 55 km. A deep northerly jet core over Bolivia, Paraguay and northern Argentina, and shallow coastal and offshore wind systems are evident.

A stretched coordinate model developed at GSFC/NASA (NSIPP-1) has also been applied to study the role of interactions between regional (e.g., land use and vegetation cover) and large scale processes in determining the seasonal to interannual variability of the atmosphere in the Amazon region (Ferreira et al. 2000). The NSIPP1-climate GCM uses the MOSAIC land surface model (Koster and Suarez 1996), while SSTs are prescribed from observations. All of the variable resolution horizontal grids in use by this model have a uniform resolution region of 20° long x 20° lat over the Amazon, and increasingly coarser resolution away from it. Horizontal resolutions as fine as 0.25° lat x 0.21° long have been used over the Amazon and as low as 4° lat x 4° long in the antipodal point with respect to the Amazon. Simulations with such a grid can be performed 20 times faster than the corresponding uniform grid simulations at a quarter degree global resolution. Uniform grid GCM ensembles show marked differences in predictability around South America in this model (Ferreira et al. 2000). Averages for nine member ensembles indicate that there is not as much intra-ensemble variability over the Amazon as there is over the SACZ region. Inspection of individual ensemble members reveals that the simulated variability over the SACZ region is due to changes in the SACZ orientation and intensity. The stronger intra-ensemble variability (or noise) makes rainfall in the SACZ more unpredictable than rainfall in the Amazon Basin. The stretched coordinate model runs in ensemble mode can help resolve whether this lack of predictability is due to poor resolution of highly variable surface features or to the influence of more unpredictable mid-latitude synoptic scale systems.

c) Simulations with the ETA model

Processes in the mesoscale may affect the long-term variability of the regional climate. This provides a strong motivation for using mesoscale models to study the variability of major monsoon systems. Several studies with mesoscale models have focused on the SALLJ. To study the SALLJ, Berbery and Collini (2000) have adapted to South America the Eta model, which is the mesoscale regional model used at the National Centers for Environmental Prediction (NCEP) for operational short term forecasts over the U.S. They selected a model configuration with a grid spacing of 80 km and 38 vertical levels, initial conditions for the atmosphere and land from NCEP's global data assimilation system, and boundary conditions from the NCEP global model forecasts.

The methodology for analysis of results followed by Berbery and Collini (2000) (see also Berbery et al., 1996) is based on averaging routine short term (12-36-hour) forecasts to produce a "climatology." The results presented here correspond to 45-day period from mid-July to the end of August of 2000. The model reproduces all precipitation centers in an observed climatology for the period (Xie and Arkin 1997, not shown).

Fig. 8 shows the time-averaged vertically-integrated moisture flux field. There is a strong westward moisture flux near the tropics and southeastward transport near the Andes toward northern Argentina-southern Brazil. Precipitation up to 3 mm/day over this region is associated with moisture flux convergence (not shown) downstream of the moisture flux maximum. This winter precipitation appears to be associated with the recurrent passage of cold fronts progressing northeastward east of the Andes from subpolar latitudes, and of upper-level troughs propagating eastward at subtropical latitudes, both of which may develop as cyclogeneses (Necco 1982a). Several authors have documented that the eastern part of South America and adjacent Atlantic Ocean between 20ºS and 35ºS is a preferred region of cyclogenesis (e.g. Necco 1982b). Vera et al. (2002) showed that the second leading mode of austral winter variability on synoptic-time scales over that region is associated with the propagation of upper-level troughs at around 30°S from the Pacific Ocean into the continent. Those systems then intensify at lower levels in the vicinity of the South American coast, and the enhanced moisture transports from tropical latitudes along the eastern portion of the low-level system favors precipitation occurrence. The precipitation produced by those systems accounts for more than 60% of the mean austral winter accumulated precipitation over central and eastern Argentina.

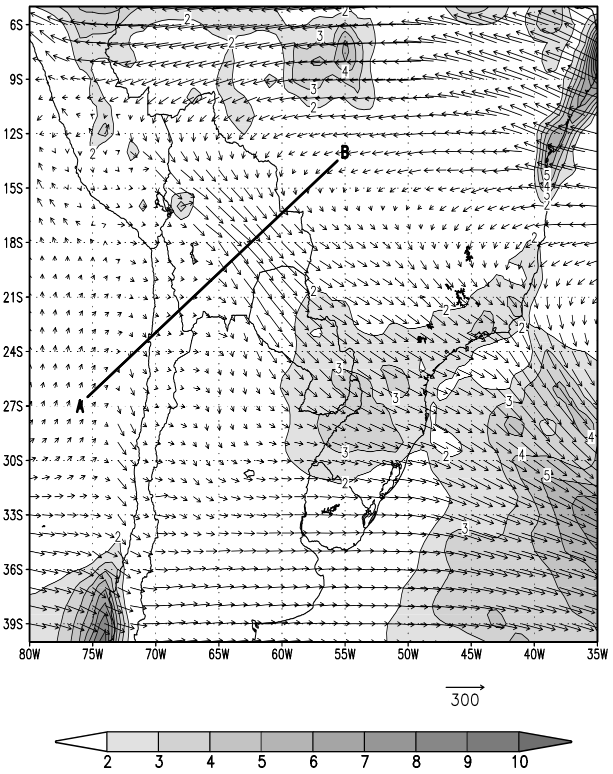

Fig. 8. Vertically integrated moisture flux (arrows) and precipitation (contours and shades) for austral winter 2000. Units are kg (m s)$^{-1}$ and mm day^{-1} respectively. AB represents a line perpendicular to the largest moisture flux east of the Andes.

Fig. 9 presents vertical sections across the maximum moisture flux east of the Andes (line AB in Fig. 8). The wind in a direction perpendicular to line AB (Fig. 9a) shows a maximum east of the Andes at about 700 hPa. This is detached from the upper levels, suggesting a typical low-level jet structure. At the lower levels and particularly over the Pacific Ocean the flow tends to be in the opposite direction, following the predominant circulation of the subtropical anticyclone. The core of the jet is somewhat higher than that during summer (Berbery and Collini 2000), and depicts a weak diurnal cycle that cannot be associated with the summer mechanisms of diurnal oscillations that typically account for changes in wind magnitude and direction at the PBL top. (see, e.g., Bonner and Paegle 1970, reviewed by Stensrud 1996). In this case, the difference between nighttime and daytime winds (Fig. 9b) suggests a decrease of the wind intensity at the lower levels and an increased intensity on the upper portion of the jet, probably representing a vertical shift of the jet's core. As its summer counterpart, this winter LLJ transports much of the moisture from the tropics to the subtropics (Fig. 9c); because of the stratification of moisture, the maximum moisture flux occurs at a somewhat lower level than the wind, between 725 and 825 hPa.

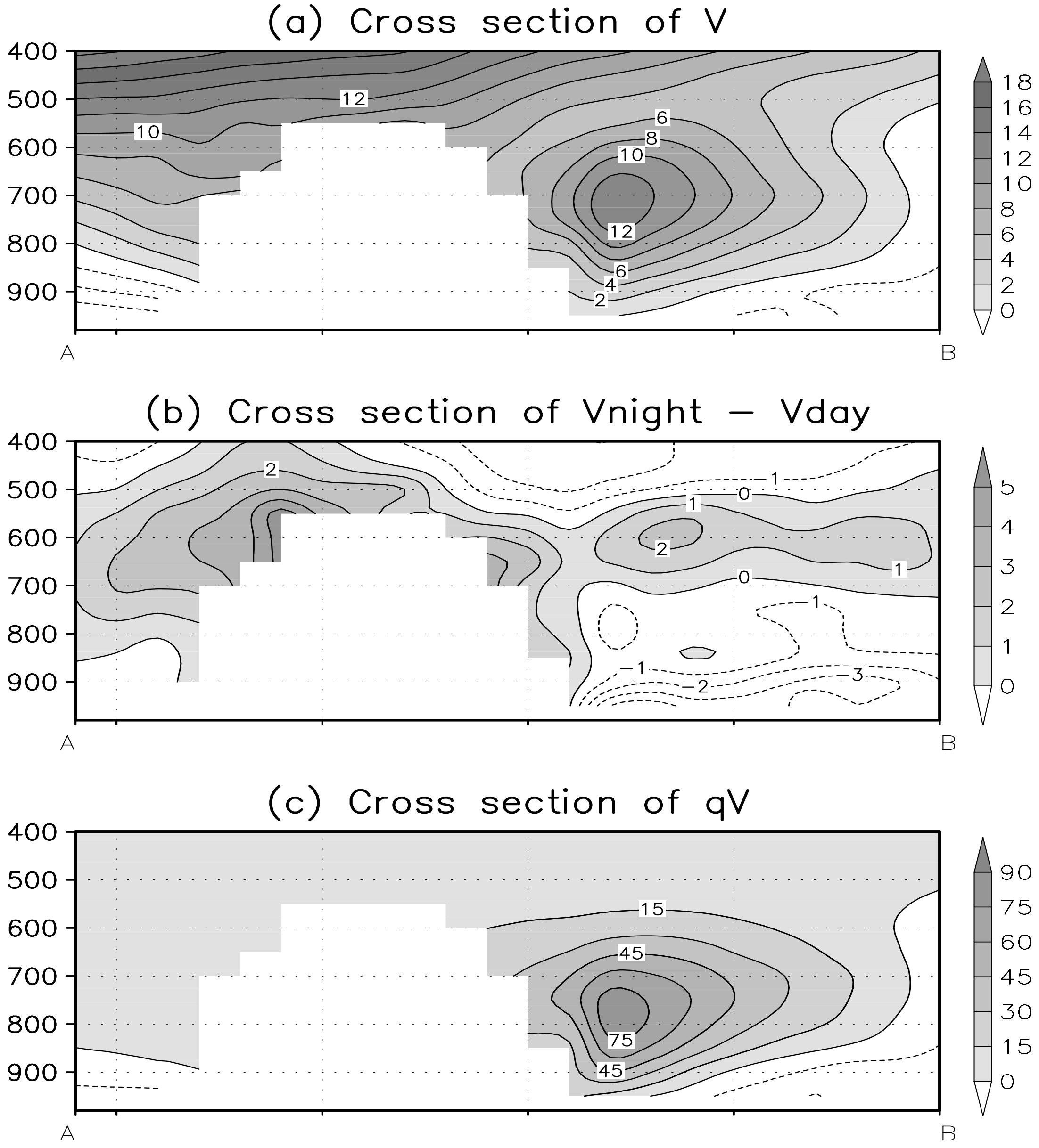

Fig. 9: (a) Cross section of wind perpendicular to line AB in Fig. 8. Contour interval is 2 m s^{-1}; (b) diurnal amplitude of the wind across line AB. Contour interval is 1 m s^{-1}. Nighttime wind is taken from forecasts at 0600 UTC (approximately 0200 LST) and daytime wind from the 1800 UTC forecast (about 1400 LST); (c) same as (a) for the moisture flux. Contour interval is 15 (g kg^{-1}) (m^{-1} s).

d) NCAR Regional Climate Model

Giorgi et al. (1993) used this model (NCAR RegCM) in order to examine the variations in strength of the SALLJ and associated moisture transports in two extreme seasons (1983 and 1985). The RegCM was initialized on January 1 of the two years and then driven at the boundaries by fields from the NCEP/NCAR Reanalysis dataset (Kalnay et al. 1996) at six hour intervals for the five month integrations. Moisture is transported by the diurnally evolving SALLJ from the Amazon Basin towards higher latitudes, into northern Argentina, Paraguay and Southern Brazil, where precipitation peaks during nighttime (Berbery and Collini 2000, Berri and Inzunza 1993, Virji 1981).

The large scale setting in 1983 was dominated by a strong El Niño event, which was associated with a zonal shift in the Walker Circulation and increased anti-cyclonic flow in the Atlantic. Strong southeast trades helped to restrict the southward migration of the ITCZ and led to very dry conditions in Northeast Brazil. The Reanalyses fields show a strong low-level northwesterly flow from the Amazon Basin to southern Brazil during this season, where rainfall was above normal. In 1985 a moderate cold ENSO event was in progress in the equatorial Pacific, while cooler than average temperatures prevailed in the tropical Atlantic, north of the equator and warmer than average temperatures to the south. The Reanalyses fields also show increased northeasterly trades, a strong southward migration of the ITCZ and abundant rainfall in Northeast Brazil and the Amazon. The Bolivian high was well developed and the low-level northwesterly flow from the Amazon towards the southeast was reduced.

The RegCM captures the main circulation features described above in both years, and simulates the substantial increase in rainfall in the northeast in 1985 compared with 1983. Fig. 10 shows the vertically integrated meridional moisture transport (contours) and total field (vectors) for the February-May (FMAM) period in 1983 from (a) Reanalyses driven RegCM and (b) Reanalyses, and for FMAM 1985 from (c) Reanalyses driven RegCM and (d) Reanalyses. In the model, the SALLJ and associated moisture transport takes a more northerly path and extends farther south into northern Argentina than in the reanalyses, showing a more northwesterly transport with an exit into southern Brazil. This difference between the model and reanalyses is evident in both years and may result from the enhanced resolution of the RegCM (60 km). A reduction in the strength of the southward moisture transport is seen in both the reanalyses and the RegCM simulation in 1985 when compared with 1983. A possible mechanism for this change in the SALLJ is as follows. The jet, to a first approximation, is controlled by the east-west pressure gradient between the Atlantic and the Andes. In 1983 the South Atlantic high was strong due to increased subsidence resulting from a shifted Walker Circulation. In 1985 cold conditions resulted in a stronger North Atlantic high and northeast trade winds, and a weaker south Atlantic high. Thus, the low-level northerly flow is strengthened in 1983 by the increased high pressure to the east.

e) Coupled atmosphere-ocean models

Chou et al. (2000) and Chou and Neelin (2001) examined the interaction between land and ocean, as well as land surface hydrological feedback in determining the spatial pattern of the monsoon rainfall. Fig. 11 shows in schematic form mechanisms that they suggest are relevant to the large-scale aspects of summer monsoon systems, as applied to South America. Divergence of ocean heat transports reduces heat input into the atmosphere in surrounding ocean regions and thus tends to favor continental precipitation, as does upper ocean heat storage in the summer season. Transport of low moisture static energy air from ocean to land during summer (and export of high moist static energy air from the continent) is referred to as the “ventilation mechanism.” Numerical experiments suggest this is an important factor in determining the poleward extension of the monsoon rainfall over the continent. A Rossby wave circulation forced by the monsoon convection tends to disfavor convection in the western part of the continent, as postulated by Rodwell and Hoskins (1996). This circulation also acts to promote convection in the eastern part of the continent, so there is a strong interaction between the convection and the Rossby wave circulation. This is referred to as the "interactive Rodwell-Hoskins mechanism." Soil hydrology feedbacks would tend to disfavor land convection but are overruled by the mechanisms that favor land convection zones relative to surrounding oceans. The land hydrology feedbacks provide a secondary factor in tending to reduce the poleward extension of convection over land.

f) Predictability of river flows

The slow cyclic components in the Plata Basin provide a basis for empirical stream flow prediction. Predictability of the Paraná river has been investigated by extracting near-cyclic 25, 9 and 17-year components in summer-season stream flows at Corrientes, over the period 1904-1997, and fitting autoregressive models to each (Robertson et al. 2001). The 9-year component yields successful tercile categorical hindcasts up to 3 years in advance, with below-average flows being more predictable than above-average flows. A prediction including data up to austral summer 1999 suggests increased probability of below-average flows until 2005. Care is needed, however, with long-term predictions based on river flow.

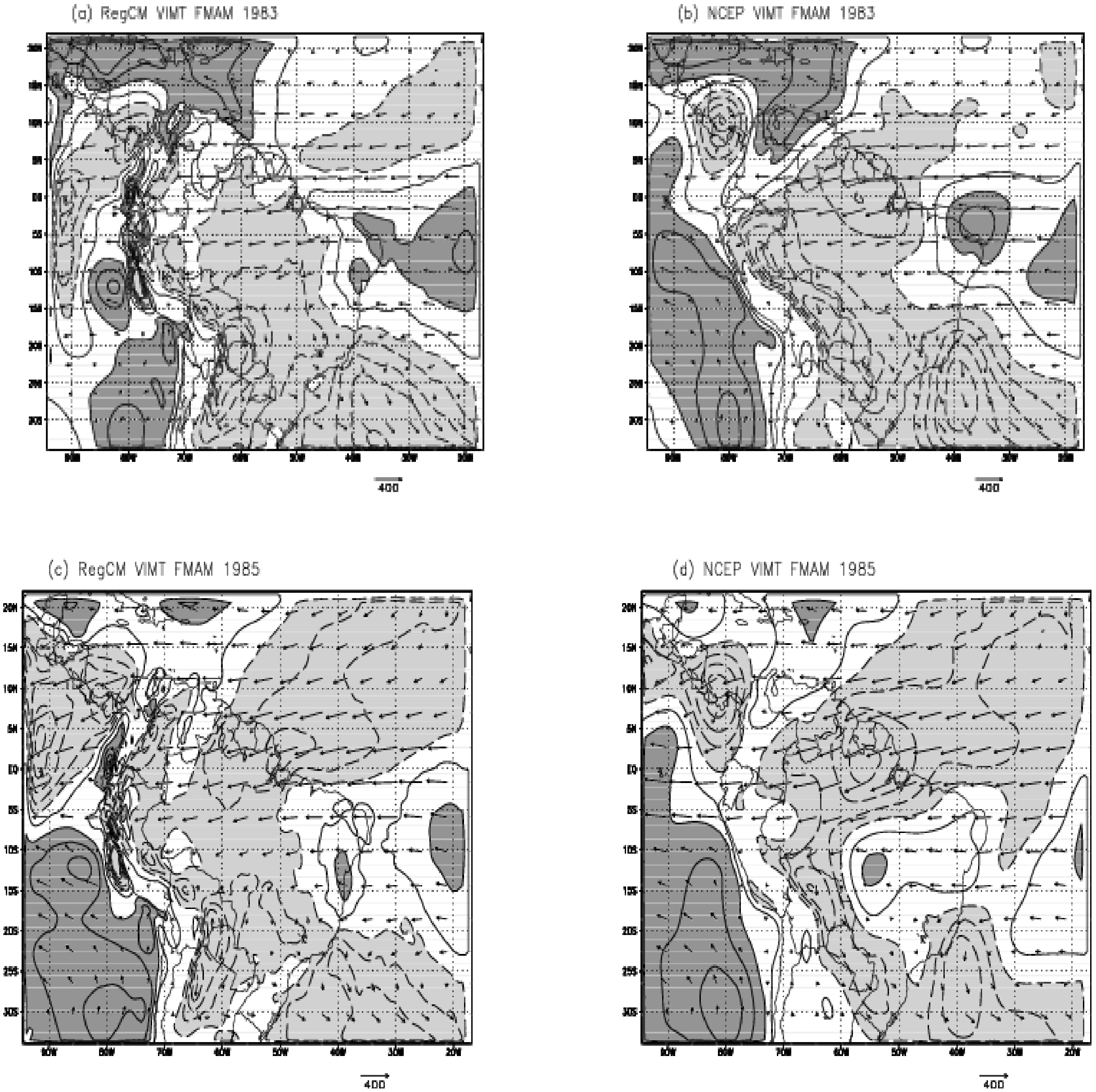

Fig. 10. Vertically integrated meridional moisture transport (shaded, contours from -150 to 150, with 30 kg ($m^{-1}s^{-1}$), and total field (vectors) for FMAM 1983 from Reanalysis driven RegCM (upper left) and Reanalysis (upper right), and for FMAM 1985 from Reanalysis driven RegCM (lower left) and Reanalysis (lower right).

Although runoff integrates effects of climate change over a drainage basin, it is also affected by land-use change, and it is known (Bruijnzeel 1996, Sahin and Hall 1996) that deforestation – which has been widespread in some parts of the Plata Basin – often results in runoff increases. Moreover, annual runoff is not measured directly, but is estimated by means of a calibration curve ("rating curve") from which river discharge is estimated, given daily observations of water level in the river (e.g., Mosley and McKerchar 1993). Because of sediment deposition and/or erosion in river channels as a consequence of deforestation, the rating curve may change with time, and requires constant scrutiny and, if necessary, adjustment. Even without complications arising from land-use change, the uncertainty in the annual flow of the Paraná River at Corrientes (3.8 x 10^6 m^3s^{-1}) has been estimated as roughly equal to the annual flow in Thames (8 x 10^5 m^3s^{-1}; Clarke et al. 2000).

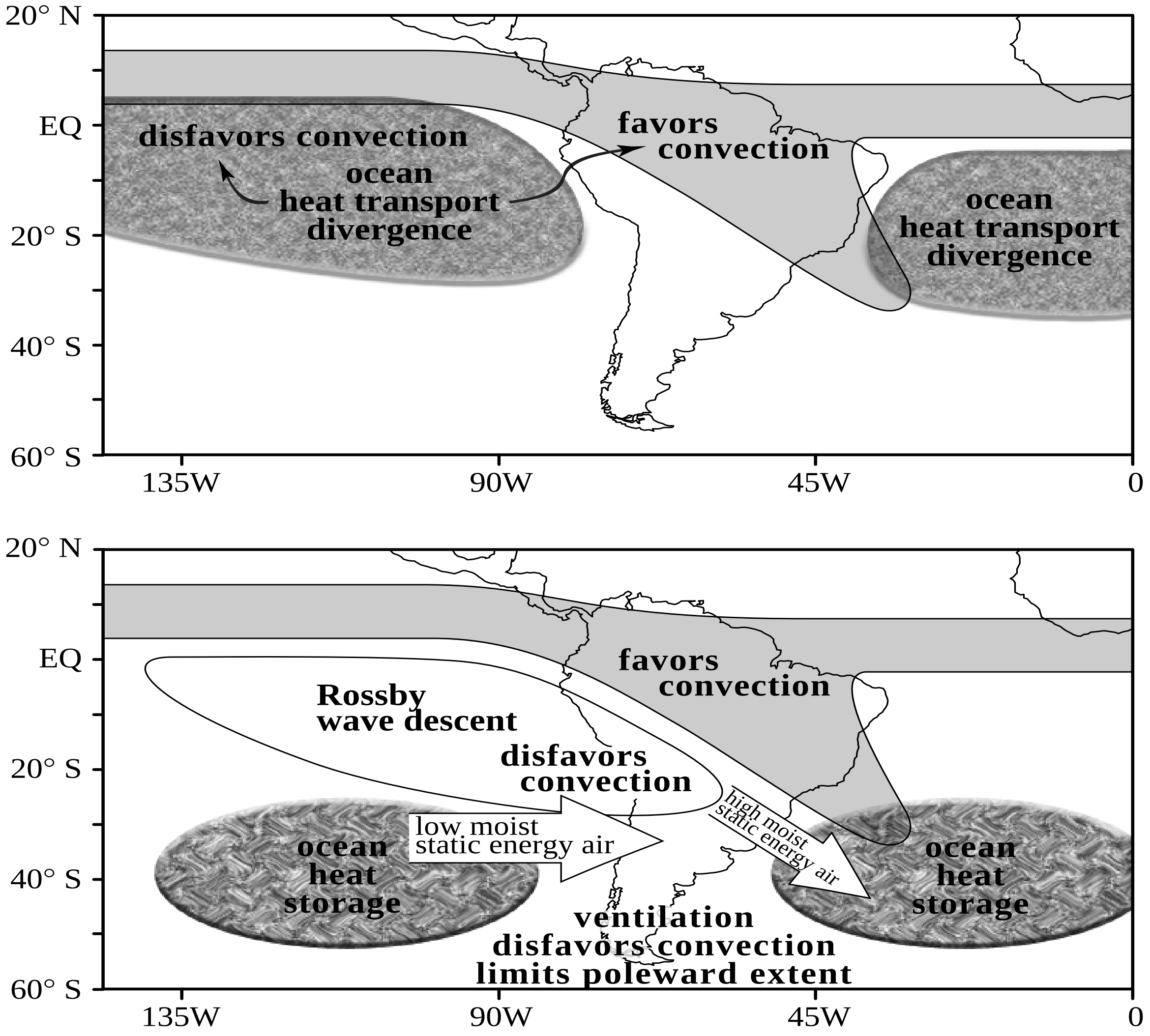

Fig. 11. Schematic of mechanisms relevant to large-scale aspects of the South American summer monsoon, following Chou and Neelin (2001), including the "interactive Rodwell-Hoskins" and the "ventilation" mechanisms.

5. SUMMARY AND DIRECTIONS FOR RESEARCH

a) Bolivian high

General features of the South American Monsoon system (SAMS) are described in the context of the mean seasonal cycle. The evolution of the Bolivian high, which is a major feature of the upper-level circulation during the austral summer, is directly related to the evolving pattern of precipitation. As the Bolivian high intensifies, upper-level cyclonic flow intensifies over the eastern tropical Pacific and central tropical Atlantic. These oceanic troughs are cold core systems characterized by an absence of deep convection. The southward advance of precipitation is rather rapid during late August and September and may be aided by vigorous synoptic systems at higher latitudes in the Southern Hemisphere. *Further investigation of these tropical/intertropical interactions would improve our understanding of the monsoon variability as well, and help us place the South American monsoon system in a global context.*

Many previous theoretical and diagnostic studies have dynamically linked the Bolivian high formation to condensational heating over the Amazon. During El Niño years, there is a tendency for severe drought from Northeast Brazil to the central Amazon, and significantly less release of convective heating in the troposphere over that region. Accordingly, a weaker than average Bolivian high would be expected. Upper-level highs actually increase during strong El Niño episodes throughout the global tropics. *Consequently, there is a need to examine in more detail the thermal versus dynamical impact on the interannual variability of upper-level circulation features, such as the Bolivian high over South America.*

b) SACZ

SAMS includes a zone of enhanced cloudiness and precipitation that extends from southeastern South America southeastward over the adjacent Atlantic Ocean. This feature, known as the South Atlantic Convergence Zone (SACZ) is particularly prominent during late spring and early summer. Intraseasonal variability over South America is strongest over eastern and southern Brazil in association with changes in the position and intensity of the SACZ.

On interannual time scales and longer, the SACZ is associated with an upper-tropospheric eddy circulation that is almost isolated during peak summer, but is strongly teleconnected with ENSO during austral spring. A coherent interdecadal component can be identified that is also present in river flows of the Plata Basin and SW Atlantic SSTs. This interdecadal component is also correlated with SST anomalies over the Pacific that resemble the Pacific decadal oscillation which has a similar time scale, which suggests a global-scale mode (Chao et al. 2000). Further analysis of variability river flows in the Plata Basin also identifies a near-decadal component, unrelated to the SACZ, which appears to be associated with the boreal winter NAO circulation. These slow near-cyclic river flow variations suggest useful predictability several years in advance. *The causes for the amplitude modulation of the near-decadal oscillations of river flow in the Plata Basin during the last century remain to be determined.*

The SACZ location is an important factor that determines features of the continental-scale circulation and moisture fluxes into the South American monsoon regions. In turn, the intensity and positioning of the SACZ is sensitive to continental precipitation features as well as global scale circulation anomalies. *A better, more fundamental, understanding of the SACZ and its connections to the global circulation is needed to advance our understanding and ability to predict the South American monsoon system.*

c) Low-level jets

Observations and model studies have shown that during the warm season a poleward LLJ structure develops over the eastern slopes of the Rockies, but during winter no such circulation feature is observed. Contrary to this behavior, global analyses an regional model short term forecasts reveal that the circulation east of the Andes has a LLJ structure throughout the year. Results presented here suggest that the winter LLJ is the same order of magnitude as the summer one, although it is located at a somewhat higher altitude and displays a much weaker diurnal cycle. The LLJ in winter seems important to feed moisture from the tropics to facilitate the precipitation processes ahead of frontal systems typical for the middle and subtropical latitudes of South America. *Questions remain on the relative importance of orography, convection, elevated heat source and low-level stability in the maintenance and diurnal phasing of this LLJ. More observations are required to resolve this issue due to the extensive data gaps at the core of the jet in a region that encompasses Bolivia, Paraguay, western Brazil and northern Argentina.*

d) Continental scale precipitation

SAMS generally starts weakening during March as solar heating decreases over subtropical South America. Recent studies suggest that a warm Pacific and cold Atlantic Oceans result in a delayed onset and early withdrawal of monsoonal rains over the Amazon Basin. *Many aspects on* the *ENSO impact on the onset and withdrawal of SAMS and the relationships between its interannual and intraseasonal variability remain to be quantified.*

The tropospheric response to equatorial Pacific ENSO anomalies needs to be considered in the context of the response to other remote forcings and time scales. For example, ENSO teleconnections are decadally reinforced over northern and eastern South America with La Nina events plus background warming, both processes conducive to enhanced convection over this region.

The degree to which change observed in background climate during the late 20th century *can be attributed to natural decadal variability, anthropogenic climate change, or a combination of both needs to be ascertained.* That both are occurring simultaneously has become increasingly evident (Andronova and Schlesinger 2000). Many attempts currently underway to understand and predict the impacts on regional climates of interannual variations in SST (notably ENSO) will not succeed without taking into account what is happening to the background climate. Confusion between scientists can easily occur depending upon choices that are made for defining climatologies vis-a-vis the phase of the background variability. *Our community is now challenged to explain these relationships and assure that future prediction models properly account for them.*

e) Modeling

AGCMs have several problems with the simulation of monsoons. These involve processes and phenomena that are particularly difficult to parameterize and capture. It is well known, for example, that AGCMs tend to produce a poor simulation of the diurnal cycle of correction over continents (Yang and Slingo 2001). Analyses of the Asian-Australian monsoon simulation by AGCM show a poor performance with the active/break cycles**.** AGCMs also have difficulties with the simulation of cloud incidence. This is particularly serious if the AGCM is to be coupled to an ocean model. Due to underestimation of stratocumulus cloud coverage, the seasonal cycle of atmosphere-ocean GCMs generally shows large errors in the eastern tropical oceans (Mechoso et al. 1995). Errors in the seasonal cycle contribute to a poor representation of the climate variability (Mechoso et al. 2000). *Numerical models used for seasonal prediction of the South American climate must produce a realistic evolution of ENSO in view of its role as a major modulator of SAMS.*

High and steep Andean topography, such as the Andes mountains, are poorly resolved by global models, in which resolution is constrained by the validity of physical parameterizations as well as by practical considerations of computing resources and time. Filtering techniques used in spectral models tend to preserve the volume of the topography, not its height, because linear dynamical theory (and its comparison with observations) suggests that this is the most important factor for properly simulating the response of the large-scale circulation to mountains. In general, precipitation in the central Andes is overestimated because moister air is allowed over shallow elevations.

This problem of dealing with high variability is ameliorated by modeling at the higher resolutions made possible by regional climate models. Some results suggest that decreasing the grid size produces better precipitation results over the Andes. Nevertheless, even with a resolution of 30-km, Andean peaks that reach to 4 km or more are not resolved and the elevation of the surface is below 3 km everywhere.

Much work is needed to understand dynamical downscaling methods and their capabilities for improving (or degrading) skill in climate forecasts. The relative utility of locally nested and variable resolution global approaches to predictability and climate simulations remains to be determined. Essential to this process is improved monitoring and diagnosis of these regional circulations at higher frequencies and horizontal scales, which will provide useful validation data for regional climate models.

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