Synoptic and Mesoscale Processes in the South American Monsoon

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14. SYNOPTIC AND MESOSCALE PROCESSES IN THE SOUTH AMERICAN MONSOON

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The general features of the South American monsoon system (SAMS) are reviewed, but particular emphasis is put on its synoptic and mesoscale processes. During austral summer, the daily precipitation variability over tropical South America results mainly from the combined action of equatorial trades, easterly tropical disturbances, and the equatorward incursions of midlatitude synoptic wave systems. In the subtropics and western Amazon basin it is largely explained by frequent northward incursions of mid-latitude systems, affected by the Andes topography. There are different types of influence from frontal systems, which lead to different spatial organization of tropical convection, and different development of mesoscale convective systems (MCSs). MCSs are strongly modulated by the diurnal cycle and by transient synoptic systems, as well as influenced by mesoscale effects such as jets and other topographically forced circulations and surface atmosphere interactions. There are also mesoscale features associated with aerosols and land cover (deforestation). The jet with most extensive influence in the SAMS is the South American low-level jet east of the Andes. There are major regional differences in the structure, intensity, and diurnal cycle of rainfall systems. While the La Plata Basin (LPB) is particularly dominated by large and intense MCSs, the rainfall in the Amazon Basin comes partly from smaller MCSs and partly from frequent showers and thunderstorms. The diurnal cycle of convective cloudiness during the summer rainy season is generally tied to the diurnal march of the insolation, but is also influenced by regional factors. The peak is at afternoon/early evening in most of the monsoon region, while a nocturnal precipitation maximum is observed in the subtropical plains (LPB). Monsoon precipitation and its extreme events are modulated by several intraseasonal oscillations, including the Madden-Julian oscillation. The maximum intraseasonal variability is concentrated in Central-East Brazil, including the South Atlantic Convergence Zone. The frequency and intensity of extreme precipitation events is also modulated by other climatic oscillations, such as the El Niño-Southern Oscillation.

1. Introduction

Although the large-scale circulation patterns associated with the South American Monsoon System (SAMS) are driven by seasonally varying large-scale distributions of sensible and latent heating, with the Andes Mountains and other orographic features playing an important role in the dynamics of the monsoon system, there are numerous synoptic and mesoscale

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features embedded within these large-scale circulation patterns. These features are responsible for the day-to-day weather and high impact rainfall events. As extreme rainfall events that affect the most populous regions in South America are most frequent in the summer monsoon season, understanding synoptic and mesoscale processes in the SAMS and improving their forecast has important practical consequences. Some of these features and the factors that can affect their frequency and intensity are here briefly described, with mention of forecast issues and remaining challenges.

2. General Features of SAMS

In the austral summer, as the major heating zone migrates to the subtropics, a thermal low-pressure system develops over the Chaco region, in central South America. The low-pressure system over northern Argentina and western Paraguay is a climatological feature present throughout the year, but is strongest during the summer.

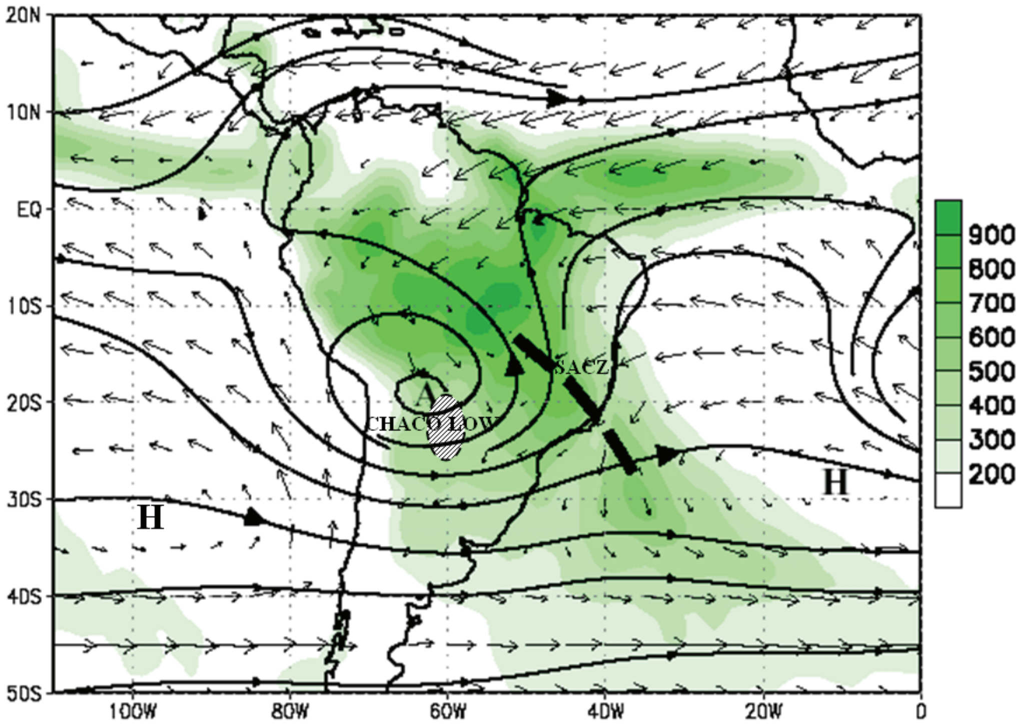

Figure 1. Main features of the SAMS. December-February mean (1979-1995) 925 hPa vector wind and 200 hPa streamlines from the NCEP/NCAR reanalysis archive, and merged satellite estimates and station observations of precipitation (mm, shading). The position of the upper-level Bolivian High (A) and the subtropical Atlantic and Pacific surface high pressure centers (H) are indicated. The approximate axis of the South Atlantic Convergence Zone (SACZ) is indicated by the heavy dashed line, and the center of the Chaco Low is indicated by the ellipse.

As the southwest-northeast inter-hemispheric pressure gradient between the South American low and the northwestern Sahara strengthens, and the tropical northeasterly trade winds increase in intensity (Fig. 1), the cross equatorial flow penetrates the continent, carrying moisture. The flow becomes northwesterly, is channeled southward by the Andes Mountains, and turns clockwise around the Chaco low. Low-level wind and moisture convergence associated with the interaction of the continental low with the South Atlantic high and the northeasterly trade winds result in enhanced precipitation in the Amazon, Central and Southeast Brazil (Lenters and Cook 1995; Zhou and Lau 1998). The southeastward extension of cloudiness and precipitation towards the Atlantic Ocean is referred to as the South Atlantic Convergence Zone (SACZ) (Kodama 1992), whose location is probably anchored by the Brazilian highlands in central-east South America (Grimm *et al.* 2007). As the SACZ enters its most active stage (December-January-February, DJF) the upper level anticyclonic center moves southward from the Amazon, setting up the "Bolivian high" (Fig. 1). East of this high and over the Atlantic Ocean close to the coast of Northeast Brazil, the "Nordeste trough" develops (Virji 1981; Kousky and Ropelewski 1997).

3. Synoptic Features

During austral summer, the daily precipitation variability over tropical South America results mainly from the combined action of equatorial trades, easterly tropical disturbances, and the equatorward incursions of midlatitude synoptic wave systems.

The day-to-day variability of rainfall over subtropical South America and western Amazon basin is largely explained by frequent northward incursions of mid-latitude systems to the east of the Andes. Although synoptic disturbances are particularly large and frequent in winter, they are also present during summer, and often reach sufficiently low latitudes to affect the South American monsoon system (e.g., Garreaud and Wallace 1998; Seluchi and Marengo 2000; Garreaud 2000). The deep northward intrusion of midlatitude systems is affected by the Andes topography, which plays a significant dynamical role on the structure and evolution of the synoptic systems that cross South America. In particular, cold fronts tend to be directed northward immediately to the east of the Andes, fostering the advance of cold air incursions (cold surges) well into subtropical (and sometimes tropical) latitudes. During wintertime the major effects of the incursions are temperature drops and strong meridional winds. In summer the largest impact is on the precipitation, through the equatorward propagation (~10 m s^{-1}) of a northwest-southeast oriented band of enhanced convection ahead of the leading edge of the cool air, which tends to be followed by an area of suppressed convection. This synoptic scale banded structure, which maintains its identity for about 5 days, is the dominant mode of the day-to-day variability of the deep convection, contributing ~25% of summer precipitation in the central Amazonia and ~50% over subtropical South America (Fig. 2). These bands also influence convection in the SACZ, lending support to the role of transient disturbances in the maintenance of the SACZ (Lenters and Cook 1995). As in wintertime, the incursions occur with a periodicity of about 7 days.

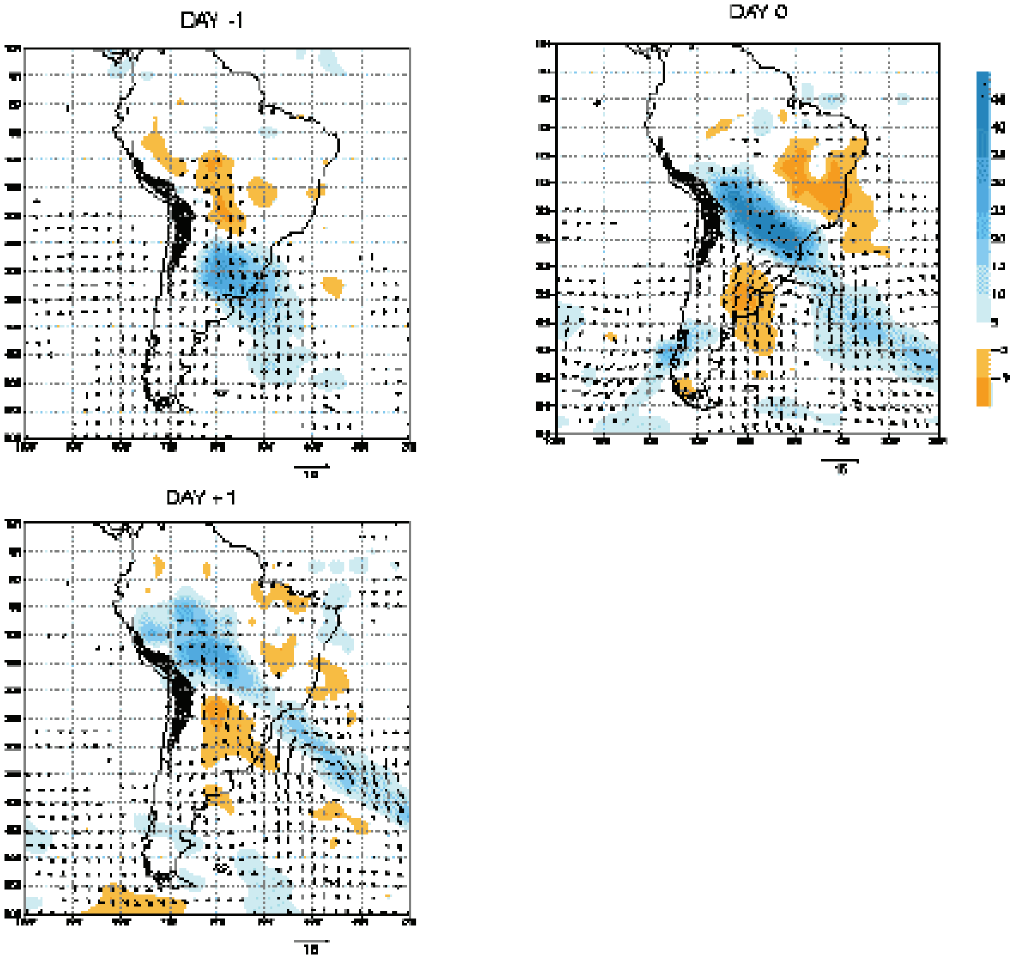

Figure 2. Composite maps of low-level wind (average between 1000-850 hPa) and convective index anomalies (CI=230-OLR, if OLR ≤ 230 W m^{-2}, CI=0 otherwise) anomalies for days -1, 0, and +1, based on the dates with intense convection over the subtropical plains of the continent (25°S, 60°W). Black area indicates terrain elevation in excess of 3000 m. The interval in the color bar on the right is 5 W m^{-2}, starting from 0 at the bottom of the white bar. (from Garreaud and Wallace 1998)

Detailed observations of convective activity in southwestern Amazon Basin during the wet season of 1999 (Rickenbach *et al.* 2002) revealed the changing character of precipitation associated with the variability provided by the northward incursion of the remains of extratropical fronts. Siqueira and Machado (2004) identified three different types of frontal system influences in South America from the point of view of spatial organization of tropical convection. Type 1 is frequent throughout the year, especially in austral summer, and is characterized by the penetration of a cold front in subtropical South America that interacts with tropical convection and moves with it into lower tropical latitudes. Type 2 is also more frequent in austral summer and is characterized by Amazon convection and enhancement of a quasi-stationary northwest–southeast oriented band of convection extending from the

Amazon basin to subtropical South America along the passage of a cold front in the subtropics. When the type 2 pattern remains longer than 4 days over South America, it often characterizes the SACZ. Type 3, which is more frequent in austral winter, is represented by a quasi-stationary cold front in subtropical South America and midlatitudes, without significant interaction with tropical convection. Siqueira *et al.* (2005) indicate that there are significant differences in mesoscale convective system (MCS) horizontal dimensions and vertical development for the three types of frontal system interaction with tropical convection.

4. Mesoscale Features

Deep convection during the South America monsoon season frequently undergoes mesoscale organization in certain regions. Mesoscale convective systems are strongly modulated by the diurnal cycle and by transient synoptic systems, as well as influenced by mesoscale effects such as jets and other topographically forced circulation and surface atmosphere interactions.

The jet with most extensive influence in the SAMS is the South American low-level jet (SALLJ) (Stensrud 1996; Paegle 1998, and references therein), embedded within the northwesterly winds along the Andes Mountains (Fig. 1). The SALLJ plays an important role in the transport of moisture from the tropics to the subtropics, producing enhanced rainfall in its exit region. The strongest winds are near Santa Cruz, Bolivia. The SALLJ, unlike LLJs in other parts of the world, is present throughout the year (Berbery and Barros 2002; Marengo *et al.* 2004). The explanation for this characteristic resides in the mechanical blocking effect of the Andes orography, which causes stationary Rossby waves in the zonal circulation (Byerle and Paegle 2002; Campetella and Vera 2002). This mechanical effect tends to produce an orographically bound cyclone throughout the year, with poleward flow east of the mountains. The variability of the SALLJ may be partly explained by changes in the zonal circulation (Byerle and Paegle 2002). Changes in sensible and latent heating also modulate the SALLJ and are important in explaining the observed diurnal cycle (Berbery and Collini 2000). The SALLJ events are conditioned by synoptic variability, and can be separated into two groups with different synoptic evolutions: (1) events in which the LLJ extends farther south, at least to 25°S; (2) events in which the jet leading edge is north of this threshold (Nicolini *et al.* 2002). The LLJs in the first category are stronger and associated with high moisture convergence and precipitation in southeastern South America (SESA) and low precipitation in the SACZ, while those in the second one are weaker and associated with enhanced precipitation in the SACZ and suppressed precipitation in SESA. This behavior leads to a dipole-like variability between SESA and SACZ. During summer (DJF) the first category is less frequent than the second one. This dipole-like behavior is also described in Sections 5 and 6.

Mesoscale Convective Complexes (MCCs) occur frequently during October-April in SESA, as shown in Fig. 3, especially between 20°S and 40°S, over a region comprising western South Brazil, Northeast Argentina and Paraguay (Velasco and Fritsch 1987; Silva Dias 1987). These MCCs have, on average, area around 5×10^5 km^2 and lifetime of 12 hours. Their intensification is related to the position of the upper-level subtropical jet, and its interaction with the low-level warm and moist northerly wind. MCCs are more abundant during SALLJ events. They preferentially initiate in late afternoon and mature during nighttime, which may be partially explained by the diurnal variability of the SALLJ, with late afternoon-evening maximum and by the nocturnal convergence over the Paraná River basin valley. Large MCSs and MCCs develop east of the Andes, and move preferentially southeastward in association with the northerly low-level jet and enhanced moisture flux convergence (Machado *et al.* 1998; Nicolini *et al.* 2002). Salio *et al.* (2007) and Anabor *et al.* (2008) show that the environment, internal structure and propagation features of the large MCS in subtropical South America is similar to the ones observed in the North American mid-west region downwind from the Rocky Mountains. The associated maximum of meridional moisture flux occurs just to the east of the Andes, between the surface and 700 hPa, sharply decaying eastward. More than 80% of these systems occur during SALLJ events that penetrate farther south of the SALLJ mean maximum (15°S-20°S) (Nicolini *et al.* 2002). According to TRMM data, SESA contains the most extensive "hot spot" of the most intense thunderstorms on Earth (Zipser *et al.* 2006, their Fig. 3).

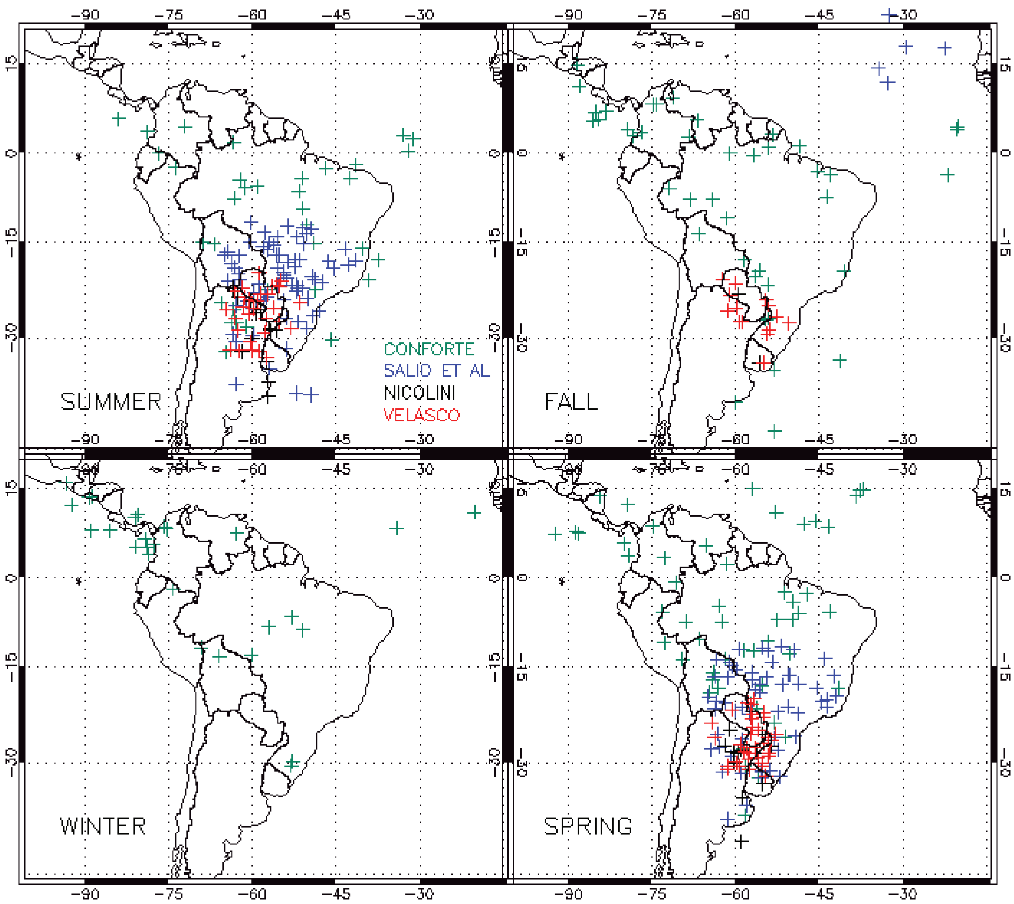

Figure 3. Compilation of the MCCs location as given by the works of Velasco and Fritsh (1987), Conforte (1997) Torres (2003), and Salio *et al.* (2007). Prepared by J. C. Conforte.

There are major regional differences in the structure, intensity, and diurnal cycle of rainfall systems. While the La Plata Basin, in SESA, is particularly dominated by large and intense MCSs, the rainfall in the Amazon Basin comes partly from smaller MCSs and partly from frequent showers and thunderstorms. In this region, most convective systems are smaller (average area less than 1×10^5 km^2) and have shorter lifetime (3-6 hours) than MCCs (Carvalho and Jones 2001; Carvalho *et al.* 2002a; Nieto Ferreira *et al.* 2003).

There are also differences in structure of the MCSs related to larger scale synoptic situations. A basic difference between the two more frequent types of summer frontal incursions identified by Siqueira *et al.* (2005) and listed in the previous section, is that Type 2, often evolving into SACZ, shows larger horizontal extent with weaker vertical development than Type 1. Rickenbach *et al.* (2002) also showed, for the particular case of 1999, that MCSs during SACZ were significantly larger in areal coverage with weaker rainfall intensity and weaker vertical development of the convective cells, when compared to other periods without the SACZ influence. Anagnostou and Morales (2002) showed that the amplitude of the diurnal cycle of rainfall during SACZ episodes is smaller than in other periods. Cifelli *et al.* (2002), Silva Dias *et al.* (2002a) and Albrecht *et al.* (2005) focus on the differences in dynamical evolution and internal cloud microphysical structure of a few MCS in different large scale situations. Several authors (e.g., Williams *et al.* 2002; Silva Dias *et al.* 2002b; Andreae *et al.* 2004; Martins *et al.* 2009) have pointed out that the aerosol number concentration may have a role in influencing the cloud microphysical structure through their portion acting as cloud condensation nuclei. The larger vertical development and strength of vertical currents in the Amazon Basin are associated with larger aerosol concentrations in a more continental regime. During SACZ events, or after a few days of frequent and widespread rainfall events, the smaller number of aerosols present in the atmosphere would lead to a more maritime behavior of convection. Freitas *et al.* (2007) show that in a seasonal sense, the numerical reproduction of rainfall amounts and temperature variations over South America is possible through a careful representation of the biomass burning emissions of aerosol, the turbulent and convective transports of aerosol and their interaction with radiation. This indicates a very complex interaction of large scale structure and cloud processes controlling the amount of rainfall.

The diurnal cycle of convective cloudiness during the summer rainy season, as documented by satellite products, is tied to the diurnal march of the insolation, but is also influenced by regional factors (Garreaud and Wallace 1997; Sorooshian *et al.* 2002). The peak is observed at afternoon/early evening in most of the monsoon region, consistent with the more suitable thermodynamic conditions during this part of the day, while a nocturnal precipitation maximum is observed in the subtropical plains, which might be ascribed to the diurnal cycle of the SALLJ (Berbery and Collini 2000) and the decrease of the intensity of the compensating subsidence associated with the SACZ (Silva Dias 1987; Gandu and Silva Dias 1998). SALLJEX (Vera *et al.* 2006) has helped to illustrate the characteristics of the diurnal cycle of the SALLJ. Another example of regional convection tied to the diurnal cycle is the afternoon genesis in the northeastern coast of South America and subsequent inland propagation of squall lines in the Amazon Basin (Kousky 1980; Cohen *et al.* 1995; Garreaud and Wallace 1997).

The documentation of mesoscale circulations that may exhibit a diurnal oscillation is hampered by the lack of observations with adequate temporal and spatial resolution. The LBA campaign has been helpful over the Amazon region to provide insight on this issue. Most of the studies of mesoscale circulations in the Amazon Basin have focused on the effect of deforestation on local circulations and ultimately on clouds and rainfall. A few studies (e.g., Oliveira and Fitzjarrald 1993; Silva Dias *et al.* 2004; Lu *et al.* 2005) have looked into the local circulation associated with large rivers and the impact on cloudiness and eventually on rainfall. The impact of the surface fluxes of sensible and latent heat in neighboring areas with different vegetation types will result in a thermal circulation flowing from colder to warmer areas in low levels. Areas of deforestation surrounded by forest will experience a convergence during daytime which leads to increased cloudiness and may affect rainfall (Souza *et al.* 2000; da Silva and Avissar 2006). During the dry season, satellite images (Cutrim *et al.* 1995; Negri *et al.* 2004) show enhanced shallow cumulus cloud over the deforested areas. In the wet season the available soil moisture in the deforested area maintains the evapotranspiration. Silva Dias *et al.* (2002a) show that cumulus clouds develop first over the forest in the wet season. However, Laurent *et al.* (2002) mention that the more intense rainfall of the afternoon and evening are initiated over mountains. Durieux *et al.* (2003) compared cloudiness over square areas of about 250 km x 250 km with and without deforestation by using infrared satellite images. They show different results in the dry and wet seasons. During the dry season there are more low clouds over deforested areas in the afternoon and less deep convection at night. During the wet season, convection is stronger at night over scenes that include deforestation. A conceptual model for increased rainfall in regions with deforestation is discussed by Avissar *et al.* (2002) and Correia *et al.* (2007). The main feature of this model is that with deforestation there is an increase in local temperatures leading to a lowering of surface pressure and increased moisture convergence. Up to some quite uncertain threshold of deforestation, the increase in moisture convergence over-compensates the loss in evapotranspiration associated with the removal of the forest and substitution for grasses or other types of agriculture, and precipitation increases. For complete deforestation the estimate varies around 30-40% decrease in precipitation (e.g., Nobre *et al.* 1991).

5. Active and Break Monsoon

The onset of the monsoon precipitation is followed by active and break periods. The onset itself has been studied from the seasonal forecast point of view by Gan *et al.* (2005), who introduced indices based on low level and upper level wind direction changes, and by Liebmann *et al.* (2007), who looked into the ability of a GCM ensemble to forecast the date of rainfall initiation. In both cases the observed date has a wide spread, similar to model spread. Drummond and Ambrizzi (2008) suggest teleconnections to the Indian and Pacific oceans which may explain some of the variability observed in the onset and variability of the South American monsoon.

Monsoon precipitation is modulated in several intraseasonal time-scales (periods of 10-20, 20-30, and 30-70 day). This means that precipitation over South America results from a complex interaction of different time scales (Nogués-Paegle *et al.* 2000). The maximum intraseasonal variability is concentrated in Central-East Brazil, including the SACZ.

Ferraz (2004) examined the intraseasonal modes of summer (November through March) precipitation variability. The first mode features a strong center in Central-East Brazil, with the SACZ on its southern edge, and weaker oscillations of opposite signs in the subtropical plains (SESA), featuring a significant "dipole"-like relationship between precipitation anomalies in Central-East Brazil/SACZ and the subtropics to the south (Grimm *et al.* 2000). The dipole structure appears even stronger in OLR analyses (e.g., Casarin and Kousky 1986; Nogués-Paegle and Mo 1997; Nogués-Paegle *et al.* 2000). This mode is present in all intraseasonal time-scales.

The local circulation anomalies associated with the first mode are consistent with a seesaw pattern in precipitation (Fig. 4). In one extreme phase of the pattern, a cyclonic anomaly directs the northwesterly moisture flux into Central-East Brazil (SACZ) and decreases the southward transport. In the opposite phase, an anticyclonic anomaly enhances the moisture flux towards the subtropical plains. Coherent with this pattern, low-level zonal westerly (easterly) winds over central Brazil during summer are associated with an active (inactive) SACZ and net moisture divergence (convergence) over SESA, implying a weak (strong) SALLJ (Herdies *et al.* 2002; Jones and Carvalho 2002; Gan *et al.* 2004). The SALLJ is also modulated by intraseasonal fluctuations of the zonal flow above the Andes, which drive fluctuations of the orographically bound cyclone east of the Andes. A relationship of this sort could be used in a forecast scheme of SALLJ variations (Byerle and Paegle 2002; Wang and Fu 2004).

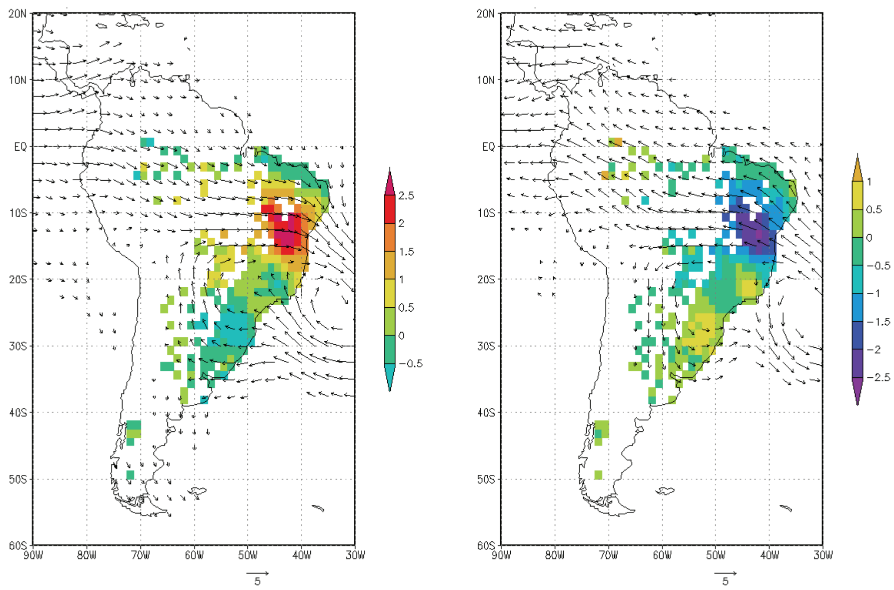

Figure 4. Composites of rainfall anomalies and vertically integrated moisture flux for wet (left) and dry (right) phases of the first rotated mode in the 30-70 day band. (from Ferraz 2004)

The origin of the circulation anomalies associated with the first modes of precipitation variability on intraseasonal time-scales over South America is not yet completely understood. These anomalies seem to be related to tropics-tropics teleconnections or to wave trains propagating from the Pacific Ocean, rounding the southern tip of South America and turning northeastward, as part of larger scale systems, and originated or modified by associated convection in West and Central Pacific (Grimm and Silva Dias 1995; Nogués-Paegle *et al.* 2000; Grimm and Ambrizzi 2009). The first mode in the 30-70 day band seems to originate in the convective anomalies associated with the Madden-Julian Oscillation (MJO) in western and Central Pacific, where the SPCZ is enhanced and shifted eastward. Grimm and Silva Dias (1995) have shown that convective anomalies in the Central Pacific can lead to enhanced rainfall in Central-East Brazil/SACZ. Liebmann *et al.* (2004a) have shown that SACZ rain events preferentially occur around 25 days after the peak in MJO convection in the western tropical Pacific, while events downstream of the SALLJ tend to occur around 2 days after this peak in convection. Also, Carvalho *et al.* (2004) found that the MJO plays an important role in modulating the persistence of intense SACZ events. Therefore, it is important to forecast the MJO. Since MJO behavior is difficult to predict in global numerical weather prediction models, the use of statistical forecast models (e.g., Jones *et al.* 2004) may be warranted. Analogously, the MJO phase also influences the skill of medium- to extended-range weather forecasts over South America (Jones and Schemm 2000).

Kiladis and Weickmann (1992) associated tropical convection in the Pacific Ocean with circulation anomalies that propagate first poleward and then equatorward over South America, and analyzed cases in which SACZ variations (in the 6-30 day time scales) are forced by westerly perturbations originating in the extratropics. Enhanced convection is activated by upper-level troughs and occurs in the upward motion induced by the advection of cyclonic vorticity ahead of the trough axis, as in a midlatitude baroclinic wave. The troughs are accompanied by the intrusion of cold fronts into the tropics from higher southern latitudes. Regions in which upper-level westerly flow lies near a tropical convergence zone (as the SPCZ and the SACZ) are prone to larger interaction between westerly disturbances and tropical convection. Also Liebmann *et al.* (1999) related submonthly modulation of the SACZ to extratropical waves propagating into South America.

In addition to the remote influences, the evolution of the summer monsoon can be influenced by regional factors. Grimm *et al.* (2007) showed that the seasonal evolution of the monsoon in part of South America, including the SACZ, can be influenced by the soil moisture anomalies at the beginning of the season, which are able to produce temperature anomalies and circulation anomalies shaped and enhanced by orography in Central-East Brazil, and influenced by sea surface temperature anomalies off the southeast coast of Brazil.

6. Modulation of Extreme Precipitation Events by Climate Variability

Some important synoptic and mesoscale features responsible for heavy precipitation are significantly affected in intensity and frequency by climate variability, of which the most important example is El Niño - Southern Oscillation (ENSO). Grimm and Tedeschi (2009) disclosed significant ENSO signals in the frequency and intensity of extreme events over extensive regions of South America during different periods of the El Niño (EN) and La Niña (LN) episodes. Although changes in intensity show less significance and spatial coherence than in frequency, they are consistently combined with changes in frequency in several regions, especially in SESA. Outstanding examples of this modulation are given here for the beginning and peak of the summer monsoon season, focusing the most populated regions.

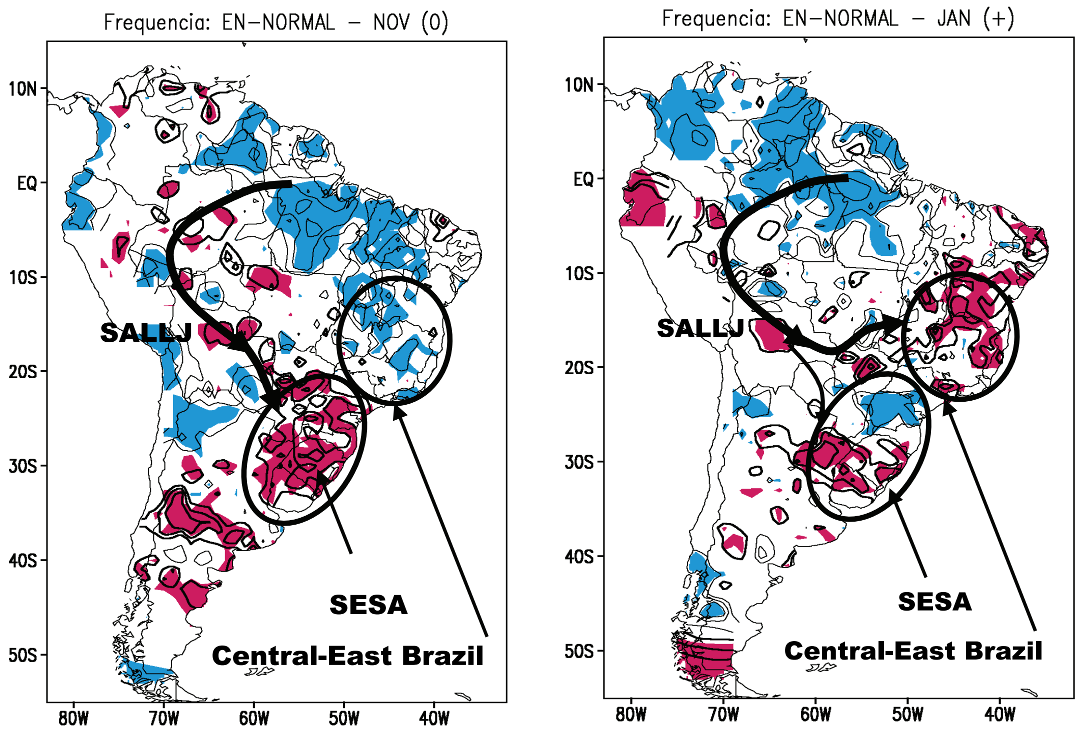

Figure 5. Differences between numbers of extreme rainfall events in El Niño years and neutral years in November (left panel) and January (right panel). Extreme events are defined as three-day running mean precipitation above the 90th percentile. Contour interval is 1 event. Positive (negative) differences significant over the 90% confidence level are represented by red (blue) color. Schematic moisture flux is indicated. (adapted from Grimm and Tedeschi 2009)

At the beginning of the summer monsoon season (in October and November) the number of extreme events decreases in Central-East Brazil (including the SACZ region) in EN episodes (Fig. 5, left) and increases in LN episodes (not shown). On the other hand, in the same period, the extreme events are increased (reduced) in SESA during EN (LN) episodes. During November of EN years there are, on average, 6.3 extreme rainfall events over part of southern Brazil, while there are only 1.2 extreme events in November of LN years. The MCCs, that are already frequent in SESA in spring (Fig. 3), have their frequency and intensity enhanced during EN episodes (Velasco and Fritsch 1987). Yet the severe events in

Central-East Brazil are not favored at the beginning of the monsoon. The reason for this opposite behavior resides in the anomalous circulation patterns produced by ENSO. During EN, subsidence prevails over Central Brazil, due to a perturbed Walker circulation, while a pair of cyclonic/anticyclonic nearly equivalent barotropic anomalies are produced by Rossby wave propagation over western/eastern subtropical South America. At upper levels, these anomalies enhance the subtropical jet and the cyclonic advection over SESA, while at lower levels they produce moisture divergence in Central Brazil and enhance the SALLJ with its northerly advection of moisture into SESA (Grimm 2003). Opposite anomalies prevail during LN episodes (Grimm 2004).

On the other hand, in peak summer (January) of EN episodes the number of extreme rainfall events is increased in Central-East Brazil (Fig. 5, right), and extreme precipitation is favored in the SACZ (Carvalho *et al.* 2002b, 2004). Yet in SESA the number of extreme events is reduced in the northernmost part of the region, but remains enhanced in northern Argentina. Impacts during LN are approximately opposite. The reversal of ENSO impact on Central-East Brazil from November to January is connected to the inversion of the regional circulation anomaly over southeast Brazil (southern part of Central-East Brazil), which directs moisture either to southern Brazil or to Central-East Brazil (Grimm 2003, 2004, and schematic moisture flux in Fig. 5). A hypothesis for this inversion is tested and discussed in Grimm *et al.* (2007) and Grimm and Zilli (2009), involving surface-atmosphere interaction and the effect of orography in Central-East Brazil. The influence of local processes is favored by the weakening of the ENSO teleconnection to subtropical South America through extratropical latitudes in peak summer (Grimm 2003; Cazes-Boezio *et al.* 2003).

ENSO-related significant changes in the frequency of extreme rainfall events are much more extensive than changes in monthly rainfall, because ENSO influence seems to be stronger on the categories of more intense daily precipitation (Grimm and Tedeschi 2009). This is an important aspect, since the most dramatic consequences of climate variability are brought about by its influence on extreme events. The ENSO influence also extends to extreme drought events or monsoon failures, as can be seen during January of La Niña events in Central-East Brazil (Grimm 2004).

7. Research and Observational Activities Needed

In spite of the considerable progress that has been achieved in the last decade in numerical weather prediction, forecasts of rainfall on a daily basis over most of tropical South America still show considerable shortcomings especially during the monsoon season. The development of mesoscale convective systems defies the ability of forecasts to produce accurate patterns of rainfall. In part this can be attributed to the resolution and convective parameterizations used. In an ideal case, convective systems should be modeled with kilometer scale resolutions and explicit cloud microphysics parameterizations. Even so, the physical assimilation of data on clouds and precipitation is essential in order to achieve good results in precipitation forecasts in the 24-48 hour time frame. As stated by Palmer *et al.* (2008), day to day systematic changes in precipitation and therefore in diabatic heating fields produce planetary wave anomalies in both the tropics and the extratropics via the atmospheric teleconnectivity. These anomalies affect and are affected by ocean-atmosphere interactions in seasonal time scales, which may then feed back to the original anomalies in precipitation produced by mesoscale convective systems. The monsoon system dynamics lies in the heart of this chain of multiple scale processes, being affected by both ends of the time scale. In this sense, progress in the understanding and prediction of the onset, demise, break periods, and intensity of the monsoon needs a multiple scale approach as well as an approach to mesoscale convective system modeling that takes into account their dependence on land use and land cover changes as well as their dependence on atmospheric concentration of aerosol.

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