The American Monsoon Systems

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Abstract

This paper examines similarities and differences among major features of the North and South American monsoon systems. Over both North and South America the summertime circulation shows upper-level anticyclone/low-level heat low structures. These develop at different distances from the equator. It is argued that ascent to the east where convective and subtropical convergence zones develop, and subsidence over the cool waters of the eastern Pacific where stratocumulus decks provide a radiative heat sink to the tropical atmosphere are integral and unifying aspects of both monsoon systems. The intraseasonal and interannual variability of the systems are contrasted. The reported links between anomalies in soil conditions and sea surface temperatures are marginal, and consistently long-range predictability is low. Ropelewski et al. (2004) and Grimm et al. (2004) focus on each of the American monsoon systems in companion papers.

1. Introduction

Whilst there could be some debate as to whether the seasonal changes in the atmospheric circulation over the Americas satisfy the conditions set by Ramage (1971) for an "official monsoon label", there is no doubt that in this particular case the issue reduces to reaching quantitative thresholds while qualitative criteria are met.

The warm season flow over the Americas shows the classical monsoon-type surface low pressure /upper-level anticyclone and intense low-level inflow of moisture from the ocean. The flow is affected by large-scale land-sea surface temperature contrasts, as well as by land-atmosphere interactions related to elevated terrain and land surface conditions (e.g. soil moisture and vegetation). Associated seasonal changes in regional precipitation show the shift from low or relatively low to very intense.

We will refer to the North American and South American warm season circulations in the tropics as the North American and South America Monsoon Systems (NAMS and SAMS, respectively). Both the NAMS and SAMS provide a useful framework for describing and diagnosing warm season climate. Climate anomaly patterns during the warm season can be characterized in terms of changes in the intensity and/or features of either the NAMS or SAMS. For example, the summertime precipitation regime over North America during the 1988 spring/summer drought or the 1993 summer flood closely mimics a weakening and amplification of the NAMS, respectively.

Our focus in this paper is on the similarities and differences among major features of the NAMS and SAMS. Ropelewski et al. (2004) and Grimm et al. (2004) give a closer examination of each individual system in companion works. Higgins et al. (2003), Paegle et al. (2002) and Vera et al (2004) are other relevant recent papers on the subject to which the reader is referred for an extensive bibliography. We start in section 2 with an overview of the monsoon systems over the Americas. Sections 3 and 4 outline the intraseasonal and interannual variability of the systems, respectively. Section 5 discusses the dynamics of the systems, and section 6 deals with predictability aspects.

2. Structure of the monsoon systems over North and South America

The Americas form a landmass of great meridional extent, reaching unbroken from over 50S to over 70N. The equator intersects South America, which forms a cone, narrowing down with increasing latitude. The west coast of Central and North America tilts in the northwest/southeast direction, while that of South America in the tropics does not have such a pronounced tilt. High mountain ranges extend along the Pacific coast of both continents. The Andes, in particular, effectively block the influence at low levels of the Pacific Ocean on the climate of South America.

Another key feature that affects, and is affected by, the monsoon systems is the sea surface temperature (SST) of adjacent oceans (Fig.1). During the warm season, tropical North American is flanked to the west by the eastern Pacific warm pool extending to about 20N and by the cold Pacific waters off-California north of that latitude, and to the east by the warm waters of the Gulf of Mexico and Caribbean. Tropical South America

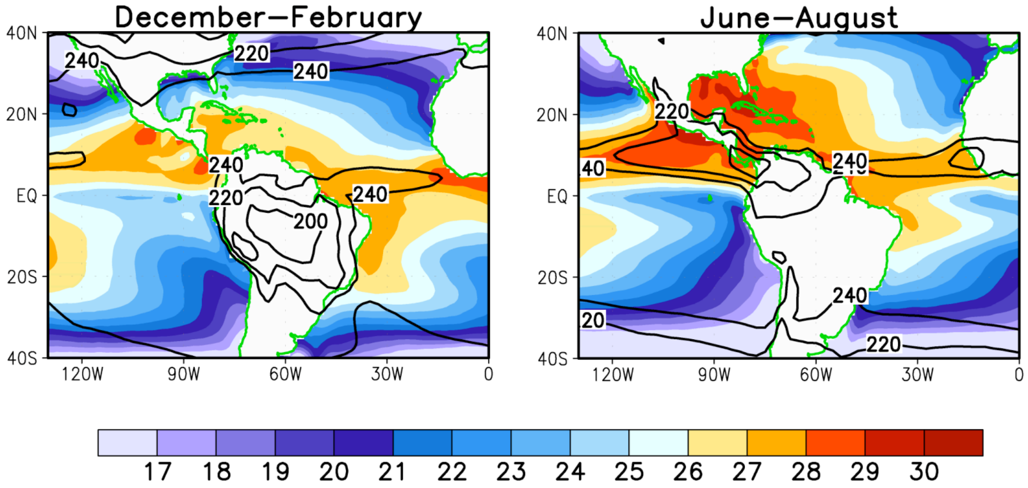

Figure 1. Distributions of sea surface temperature (ºC, shading) on outgoing longwave radiation (Wm^{-2}, contours) for December-February (left panel) and June-August (right panel). (Courtesy V. Kousky.)

is flanked by the cold Pacific waters off Peru and Ecuador and by the warm waters of the tropical Atlantic. Consistently with the continental spread across the equator, the seasonal evolution of precipitation shows a migration in latitude with maximum values around the equator during the equinoxes.

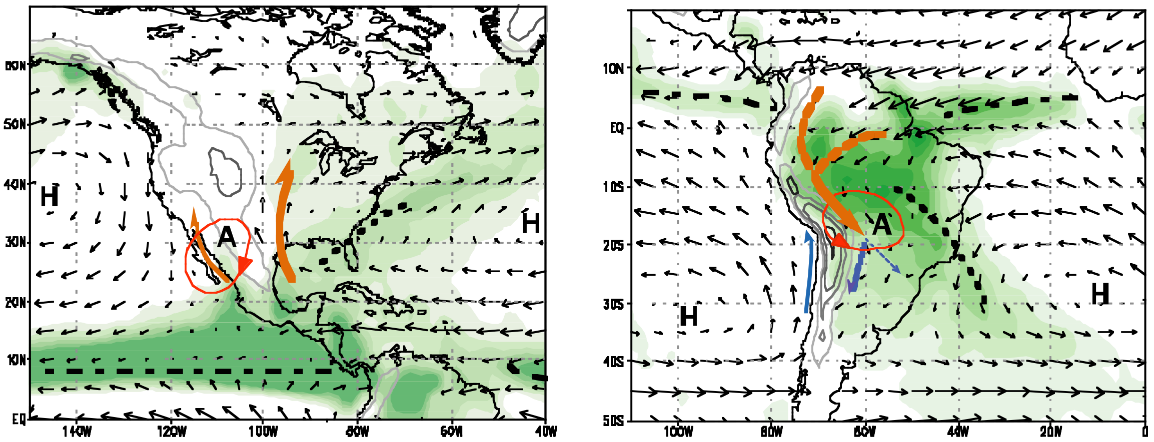

Figure 2.

Figure 2. Schematic illustration of the North and South American monsoons systems (left and right panels, respectively). Shading indicates precipitation and dashed lines indicate convergence zones. Small arrows show low-level (900 hPa) winds, and thick arrows represent low-level jets. An "H" shows a subtropical surface high center, and an "A" indicates the monsoon anticyclone. (Adapted from V. Kousky.)

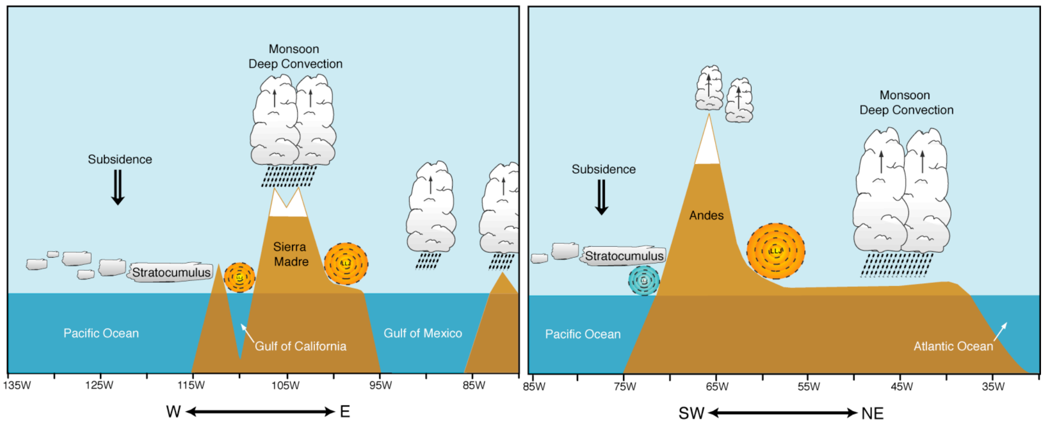

Figure 3. Schematic vertical section for the corresponding summer season at around 30N (left panel) and southwest-northeast (right panel). Regions of deep convection and low-level jets are indicated. (Panel for NAMS adapted from W. Higgins.)

Figures 2 and 3 show schematically the major features of the warm season circulation over North and South America. The NAMS is characterized by a region of intense precipitation emanating from the eastern Pacific intertropical convergence zone (ITCZ), extending northward over Mexico to the southwest United States (U.S.), with largest values over the western slopes of the mountain range. High values of precipitation also extend northeastward over the Gulf of Mexico, reaching up along the eastern flank of North America, and merging into the North Atlantic storm track. There is also a relative maximum to the southwest of the Great Lakes. The continental east-west contrast between the arid west and the humid east is a key characteristic of a monsoonal circulation, which we elaborate upon in section 5. The upper-level monsoon anticyclone associated with the NAMS shifts northward with season from southwestern Mexico to northwestern Mexico and southwestern United States. Moisture transport onto the North American continent is associated with broad-scale advection from the Gulf of Mexico, and with important low-level jets (LLJs) over the Gulf of California and east of the Rockies. The latter LLJ is a warm season, primarily nocturnal, feature; less detail is known about the other one.

The SAMS is characterized by intense precipitation over central Brazil and Bolivia, in a region that is linked to the Atlantic ITCZ to the northeast. The extension of the SAMS precipitation into the South Atlantic Convergence Zone (SACZ) to the southeast, mirrors the northeast extension of NAMS precipitation. In both cases, there is a substantial maritime component on the western flank of the subtropical Atlantic anticyclones. The upper-level anticyclone associated with the SAMS ("Bolivian High") establishes close to the Altiplano. The trade winds from the tropical Atlantic Ocean provide the moisture source for the SAMS. Moisture transport intensifies locally along the eastern scarp of the Andes, where the South American LLJ (SALLJ) develops with strongest winds over Bolivia. In contrast to NAMS, the SALLJ is present throughout the year and is not solely a warm season feature.

Figure 3 includes a sketch of the descending motion associated with the NAMS and SAMS. An integral and unifying aspect of both monsoon systems is the subsidence over the cool SSTs of the eastern Pacific. Here extensive stratocumulus decks provide a radiative heat sink to the tropical atmosphere that can balance the adiabatic warming due to the monsoonal descent. These stratocumulus decks arguably provide a direct coupling between both American monsoons and the Pacific Ocean. We return to this feature in section 5 of the paper. It has also been suggested that descent associated with SAMS occurs in the tropics across the equator, where it establishes links with the North Atlantic climate (e.g. Robertson et al. 2000).

3. Intraseasonal Variability

Precipitation during NAMS shows a relative minimum in the warm season along the Sierra Madre Oriental and the Caribbean. There does not seem to be such a feature in SAMS. The reasons for the NAMS feature are related to the seasonal displacements of the ITCZ in the eastern Pacific. SAMS interacts less directly with the tropical ITCZs.

During the warm season, tropical intraseasonal oscillations such as the Madden Julian Oscillation (MJO) modulate a number of different weather phenomena affecting both the NAMS and SAMS (e.g. tropical cyclones, tropical easterly waves, and Gulf of California surges). MJO-related impacts are linked to more regional meridional adjustments of the precipitation pattern over the eastern tropical Pacific.

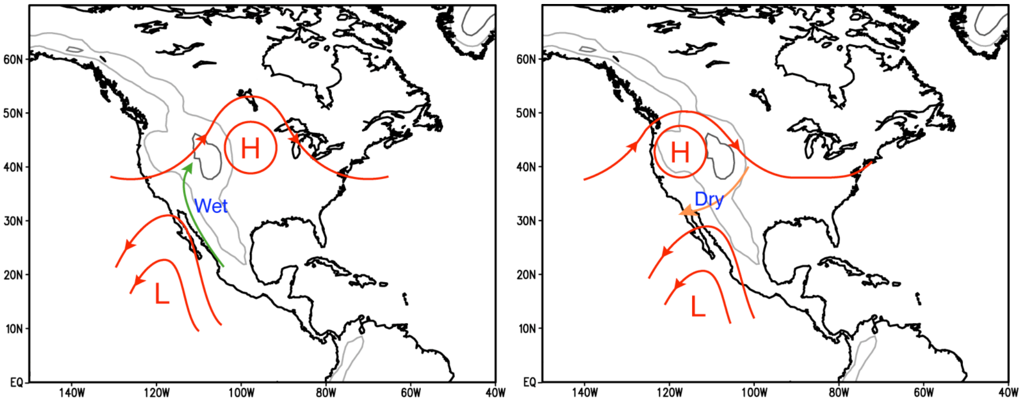

Figure 4. Schematic illustration of the circulation during a dry (left) and wet (dry) Gulf of California surge event for Arizona. (Courtesy Wayne Higgins)

Figure 4 is a schematic of the 700-hPa circulation for wet and dry moisture surges in Arizona, U.S. (AZ). Whether a surge is "wet" or "dry" depends on the relative location of the upper-level monsoon anticyclone at the time of the gulf surge. If the ridge axis is an eastward position, the situation is wetter-than-average in AZ and to the east, while if the ridge is towards the west then the situation is drier-than-average in the same location. Roughly one-half of gulf surges are not associated with enhanced precipitation in AZ.

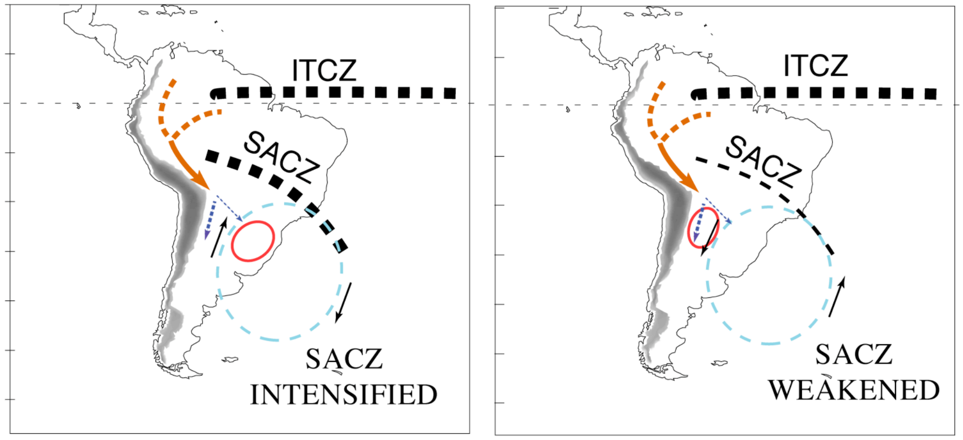

Figure 5. Opposite phases of the dominant mode of variability over South America during the warm season. Thick arrows indicate low level jets. The area bounded by a red circle is one in which enhancement of mesoscale convective systems is expected.

The intraseasonal (interannual and even intedecadal) variations of SAMS appear to be associated with a continental-scale eddy (Fig. 5). In the cyclonic phase of the eddy circulation, the SACZ intensifies with anomalous descent to the southwest and weakened low-level flow east of the Andes; the anticyclonic phase shows opposite characteristics.

The vertical velocity distribution associated with the mode is consistent with the reported dipole defined by persistent wet and dry anomalies over tropical and subtropical eastern South America during the austral summer, with one center over southeastern Brazil in the vicinity of the SACZ and another center over southern Brazil, Uruguay and northeastern Argentina. Consistent with this picture is the existence of different convection "regimes" in Amazonia as identified in recent field campaigns. An intense mode consisting of vertically developed convection is associated with an easterly wind regime, while a weaker, monsoon-type mode, is associated with a westerly wind regime (Herdies et al. 2002).

4. Interannual variability

The continental-scale pattern of NAMS interannual variability shows that anomalously wet (dry) summers in the southwest U.S. tend to be accompanied by similar conditions over the southeast U.S and by dry (wet) summers in the Great Plains of North America. The SAMS exhibits a similar type of behavior, with a dipolar relationship between precipitation over the SACZ and over southeastern South America. Warm seasons with an active SACZ tend to be accompanied by dry conditions in southeastern South America, and vice-versa, although ENSO effects modulate this tendency.

Some studies have reported that the intensity and extent of NAMS is correlated with SST anomalies in the Gulf of California. According to one of those studies, anomalously wet monsoon years in AZ are associated with significantly higher SSTs (>29°C) in the northern Gulf than dry years. The association of SST anomalies in the Atlantic and SAMS is somewhat less direct. Northeasterly and southeasterly trade winds advect moisture from the tropical Atlantic over the continent, but this moisture has to travel some distance before precipitating in the monsoon region. There is a suggestion that cold SST anomalies in the tropical North Atlantic are associated with stronger SAMS rains. On decadal timescales, there is evidence from river-flow records of a relationship between the North Atlantic and precipitation over the subtropical plains of South America.

ENSO can potentially exert an influence on the NAMS and SAMS through several pathways. Changes in the Walker and local Hadley circulations can modulate the monsoonal divergent circulations. The potential for this influence is greater for the SAMS due both to its being closer to the equator, as well as the seasonality of ENSO whose mature phase develops in the northern (southern) cold (warm) season. A second pathway of influence may be through ENSO's effect on eastern Pacific SSTs, both through changes in the region of warm SSTs off the west coast of Mexico (for NAMS) and stratus decks (especially for SAMS).

For both the NAMS and SAMS in the equatorial belt, El Niño and La Niña tend to be associated with anomalously dry and wet events, respectively. During El Niño the ITCZ shifts toward the equator, the Hadley circulation intensifies in the eastern Pacific, and there is a tendency for dry conditions over Mexico. The opposite conditions develop during La Niña. During the northern winter, there are significant and positive correlations between SST anomalies in the eastern equatorial Pacific and precipitation anomalies over the southwestern U.S. There is also evidence that northern winters characterized by wet (dry) conditions in the southwest are often followed by dry (wet) conditions in the same region (i.e., stronger and weaker NAMS, respectively). The out-of-phase relationship between precipitation in the southwestern/southeastern U.S. and the Great Plains of North America suggests that summer drought (flood) episodes in the latter region are (at least indirectly) related to anomalies the preceding winter. These associations between anomalies two seasons apart indicate the existence of mechanisms that provide a memory for the system. We return to this issue in section 6. For SAMS in the equatorial belt, a qualitatively similar and marginally significant El Niño-dry/La Niña-wet relationship has been suggested. The mechanism in this case seems to be associated with anomalies in the Walker circulation. During El Niño convection increases over the eastern tropical Pacific and subsidence increases over equatorial South America, which disfavors convection.

There is still another pathway for ENSO influence on the NAMS and SAMS. This involves the extratropics and the excitation of the Pacific North and South American Rossby wave trains or teleconnection patterns. For the SAMS, the influence is related to the subtropical eddy-circulation mentioned in section 3, which also involves the SACZ and anomalies of the opposite sense over the subtropical plains. Interannual and intraseasonal variability over subtropical South America can therefore be an expression of rectified modulation of intrinsic intraseasonal modes of atmospheric variability by remote forcing (Grimm et al. 2004).

Observational evidence indicates the springtime snowpack modulates the amplitude of the NAMS (Ropelewski et al. 2004). No similar relationship involving the snowpack has been proposed, to our knowledge, for the SAMS.

5. A discussion on the dynamics of the NAMS and SAMS

The distributions of continental masses, orography and SSTs combine to define the characteristics of the American monsoon systems. The dynamical balances that characterize NAMS and SAMS share key similarities at the continental scale, as well as some important differences. Over both North and South America, the summertime upper-level anticyclone/low-level heat low that characterizes a monsoon circulation is in spatial quadrature in longitude with ascent on the eastern side and subsidence on the western side (Chen 2003). This configuration of phase allows for a largely Sverdrup-type balance between the vorticity source associated with diabatically-forced continental-scale vertical motion, and advection of planetary vorticity. (The balance differs from that in the larger-scale Asian SW monsoon in a somewhat stronger contribution by zonal vorticity advection.) The low-level poleward motion associated with the Sverdrup balance feeds warm moist air into the convective regions in a positive feedback. The SAMS comprises convection over Amazonia and the SACZ; NAMS comprises convection in a region that emanates from the eastern Pacific ITCZ across Central America/Mexico and the Caribbean, and that extends northeastward along the eastern seaboard of North America in a way that resembles the SACZ. Thus, while NAMS is associated with convection over warm SSTs, i.e. the western hemisphere warm pool, the SAMS convection is largely over land. The latter difference is more formal than substantial since the Amazon is sometimes referred to as an “inland sea,” in connection with its atmospheric impact.

On their western flanks, both NAMS and SAMS are associated with subsidence over the cool waters of the eastern Pacific and their accompanying stratocumulus decks. Here, Sverdrup balance dictates equatorward winds and hence surface wind stresses that will lead to Ekman pumping of cool waters to the surface. The highest incidence of California stratocumulus clouds peaks in the warm season. However, the highest incidence of stratocumulus clouds off the coast of Perú-Ecuador occurs in the southern spring, indicating that the monsoon is not the only mechanism that determines their seasonal cycle. The upper-level anticyclones over North and South America develop at different distances from the equator. The low-level jet (LLJ) over the Gulf of California lies near 30N, while the South American LLJ is situated near 15S. Given the importance of the planetary-scale zonal temperature gradient in setting up the monsoonal divergent circulation, the distribution of SSTs in the eastern Pacific, with cold water off the California coast and warm water to the south, would appear to constrain NAMS to be situated further poleward than SAMS.

Baroclinic Rossby wave dynamics is largely responsible for setting up the planetary-scale features of the American monsoonal circulations presented above. Rossby waves generated by deep convection generate an area of subsidence westward and poleward of their source. The term “interactive Rodwell-Hoskins mechanism” (IRH) coined recently by J. D. Neelin and collaborators describes the way Rossby wave-induced subsidence to the west of monsoonal heating interacts with the convergence zone. The adjective “interactive” in IRH stresses that the spatial pattern of the monsoon heating itself is determined interactively with the subsidence regions. The subsidence itself interacts with the mid-latitude westerlies, with air parcels moving adiabatically and equatorward down the sloping isentropes and west-coast orography tending to localize the region of descent. An application of these arguments to NAMS and SAMS is consistent with Rossby wave descent over the eastern subtropical Pacific, where a persistent stratocumulus deck develops.

Returning to the issue of meridional extent of the American monsoons, the alignment of the continents could potentially allow both NAMS and SAMS to extend far poleward, and there is evidence that the SACZ and its North American counterpart on the eastern side of the continents extend into the midlatitudes in both cases. The monsoons extend poleward until the midlatitudes dynamical regime takes over, in which horizontal temperature advection by the westerlies is able to balance surface heat flux.

In addition to the planetary-scale wave dynamics discussed above, both American monsoon systems have smaller-scale features embedded within them, again with baroclinic Rossby wave dynamics. Within NAMS, there is an inverse relationship between precipitation in the core NAMS region/southeastern U.S. and that over the Great Plains of North America. Similarly, within SAMS the activity of the SACZ and precipitation over southeastern South America are inversely correlated. In both cases, to balance a stronger zone of regional convergence requires a regional strengthening of the upper-level anticyclone/low-level heat low structure that is then superposed on the planetary scale monsoon circulation. The associated scale interactions remain largely unexplored, but Fig. 4 presents an example of their importance.

6. Predictability

On intraseasonal time scales, accurate forecasts of MJO activity could be expected to lead significant improvements in the skill of warm season precipitation forecasts. The improvement for NAMS was suggested by Higgins et al. (2000), while that for SAMS results from the apparent MJO-type variability found in the SACZ (Nogués-Paegle et al. 2002). On seasonal to interannual time scales, the potential for prediction resides in the possible effects on the atmosphere of slowly-varying surface conditions, such as those in the oceans or land.

Predictability studies with global models generally indicate very modest levels of seasonal-mean precipitation skill over the NAMS and SAMS domains. Hindcast experiments have been carried out in both a two-tier context, in which the SST is predicted first, as well as in fully coupled GCMs. These predictions are made with ensembles of GCM runs, and expressed probabilistically, typically in terms of the ranked probability skill score (RPSS) of tercile-categorical predictions.

An evaluation has been made of IRI's real-time 1-month lead forecasts since their inception in 1997 (over the 1997-2001 interval; Goddard et al. 2003). Over this short period, the January-March seasonal-average precipitation predictions contain useful skill over the equatorial part of the SAMS domain, as well as over the subtropical plains, near 30S. The skill is very low at intermediate latitudes. Over the NAMS region during July-September, the IRI's real-time forecasts show some skill over northwest Mexico, but skill levels are generally lower than for the SAMS.

The reasons for the low hindcast skills, especially for the NAMS, can be attributed to the weak impact of ENSO described in section 4. The higher predictability in the north and south of the SAMS domain can also be attributed to ENSO; the spatial distribution of precipitation probabilities associated with ENSO show a similar pattern, for reasons discussed in section 4. However, the IRI seasonal forecasts do not use an initialization of land surface conditions, which may in certain situations lead to useful seasonal predictive skill.

Another reason for the low predictability of the American monsoon systems can be attributed to the importance discussed in section 4 of land atmosphere-land interactions. Increased surface heating by insolation increases towards the end of the dry season weaken the static stability of the overlying atmosphere and contribute to set up favorable conditions for the onset of the wet season. There are other contributors, however. On the one hand, regional soil conditions influence the intensity of surface warming. On the other hand, remote climate anomalies such as in SST influence conditions in the atmosphere. Since NAMS and SAMS regions appear to be marginally sensitive to oceanic anomalies, one could argue that regional variations in surface conditions are more important to the onset of the wet season than those in remote SST. It is well know that the successful simulation of land surface processes is one of the major current challenges for numerical modeling of climate variability.

7. Final Remarks and Recommendations for Future Research

Both the NAMS and SAMS comprise an upper-level anticyclone/low-level heat low structure; large-scale convergence zones with ascent to the east, and descent to the west over the ocean where stratocumulus clouds enhanced by subsidence and upwelling develop. The distribution of continental masses, orography and SSTs contribute to define the characteristics of the monsoon systems. A major difference between the NAMS and SAMS is that the former is farther away from the equator than the latter. The intraseasonal (interannual and even interdecadal) variations of the NAMS and SAMS appear to be associated with continental-scale modes in which stronger precipitation in the core monsoon regions is associated with drier conditions to the north and south, respectively. The relative roles of internal atmospheric dynamics remote forcing (particularly SST) local and regional land surface forcing in the development, maintenance and decay of NAMS and SAMS are a matter of current debate. Consistently with the marginal influence of slowly varying surface conditions reported so far, predictability of the NAMS and SAMS variations is low.

Despite progress in understanding, modeling and simulation the American monsoon systems, there is a number of outstanding issues some of which a selection is listed below.

- A better understanding is needed of the dynamical and thermal effects of the Bolivian Altiplano on the evolution of SAMS
- The role of land surface processes in the evolution of the American monsoon systems must be further explored. SAMS, in particular, evolves in a region where land surface conditions are rapidly changing due to deforestation.
- A better and more fundamental understanding is required of the SACZ and its possible counterpart over North America.
- The processes and mechanisms for the influence of the MJO on the variability of the American monsoon systems must be investigated further, including the possible impact on predictability.
- The interhemispheric effects of the American monsoons have not been fully explored.
- There are still many remaining issues on the interactions between the monsoons systems and the climate over the adjacent oceans. These include the links with the ITCZ variability and the subtropical highs.
- There is also a number of aspects to clarify in reference to the low-level jets, including the associated transports of water vapor and development of convective systems.
- A better knowledge of the intraseasonal variability of the monsoon systems is needed, in different time-scales as well as of the contribution of each time-scale and the interaction between them, in order to explore possible enhancements in mid-range predictability.

Internationally organized research on the American Monsoons has been accelerated in recent years by the WCRP/CLIVAR on the Variability of American Monsoon Systems (VAMOS). Specifically, VAMOS has encouraged the realization of the SALLJ experiment (SALLJEX) in 2003 and the North American Monsoon Experiment (NAME) in 2004. One major goal of VAMOS and its projects is to increase the prediction skill for warm season rainfall over the Americas. In order to achieve this goal it is necessary to improve the observing system over North and South America, particularly over the latter. In addition, prediction systems must be improved in many respects, including improved models able to produce a better simulation of the diurnal cycle and land surface processes. Last, but not least, multinational scientific collaboration and coordination have to be strengthened across the Americas.

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Figure Captions

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