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Monsoon in the Americas: Opportunities and Challenges

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Abstract
This article presents a comparative review of the North and South America Monsoon Systems and highlights the challenges and opportunities presented to those regions by the seasonal rains. Monsoon precipitation represents a major component of the water resources available to the southwestern US and to Brazil. Although each system shares classical features of the well-known southwest Indian monsoon, water use, agriculture, public safety, and energy policy in these two countries have been shaped by the unique regional complexities of monsoon rain across each region. A comparison between these two systems may offer perspective for ways by which these societies may adapt to current and future challenges, and take advantage of new opportunities.

1. *Introduction*

October 1993: A great pyramid rises 350 feet above the desert floor, one of the largest luxury hotels ever opened on the Las Vegas Strip, encircled by a man-made river and topped by the brightest beam of light in the world. August 1997: Eleven hikers exploring Lower Antelope Canyon near Page, Arizona, lose their lives when a wall of water 50 feet high tumbles down upon them under a clear blue sky. September 2003: A sugarcane plantation owner in Ituverava, São Paulo state, Brazil, rushes to harvest half his winter yield, bound for an ethanol fuel refinery, as the monsoon season begins – aware that the onset of the steady rains may destroy the remainder of his crop. June 2001: As a severe drought starves the reservoirs of hydroelectric power plants across Brazil, the government is forced to impose a rationing of electricity on its 170 million residents.

Ongoing drought in the southwestern US is altering the availability of water in an increasingly populated region already devoid of it. Sudden flash floods steal lives and livelihood leaving the dry ground unreplenished. In South America, water drives the energy economy. Hydroelectric power meets most energy needs. Ethanol production from sugarcane has freed Brazil from relying on foreign oil, taking that country closer than most to energy independence. Yet, deforestation and climate change conspire to alter the hydrology of the region.

Opportunity and challenge – both served up by the summer rains of the American monsoons.

Monsoon (from the Arabic *mausim*, meaning 'season') is a term that describes a continental-scale seasonal reversal of low-level wind direction, with a resulting shift in precipitation patterns. The monsoon is driven by seasonal changes in the temperature difference between land and surrounding oceans, a mechanism proposed over 300 years ago (Halley 1686). Geography sets the stage: the thermal contrast between a tropical or subtropical landmass and the adjacent warm ocean establishes the monsoon pattern (Ramage 1971).

The onset of monsoon rainfall during the warm season over land has a tremendous impact on countries in the tropical and subtropical regions where it occurs. Monsoon rains determine the livelihood of billions of people on Earth, who synchronize their societies to the seasonal shift in rainfall. Rains of the wet season transform dry, parched earth into fertile, life-giving soil, fill cisterns and reservoirs for drinking water, and ensure that the turbines of hydroelectric power plants continue to turn. Predicting whether next year's monsoon rains will be late or early, light or heavy, is knowledge critical to the management of agriculture, water availability, public safety, and energy production.

The best understood monsoon region on Earth is in India, due in part to the location of historical trade routes. Arab and Indian sailors have been tuned to the seasonal reversal in wind direction over the Arabian Sea for thousands of years (D'Souza 2008). In the 18th and 19th centuries, during the colonial period of Great Britain, the British East India Company maintained meteorological observations of the monsoon back to the late-1700s to optimize shipping trade routes to and from India. By the early 20th century, the general mechanism of the Indian monsoon was understood in terms of the seasonal reversal of the temperature difference between the continent and the surrounding oceans (Ramage 1971). Because of the low heat capacity of the land surface, the continent warms and surface pressure drops relative to the cooler oceans in summer. This pressure change pushes moist air northward into the continent, turned eastward by the Earth's rotation. By early June, this moist monsoon flow heralds the start of the rainy season as the warm air converges and ascends in the low pressure over the continent, leading to clouds and heavy rainfall. Monsoon rains advance northward as summer progresses, enhanced by forced ascent as the flow reaches the Himalayan foothills. In winter, this thermally direct circulation reverses as the land surface cools relative to the oceans. The winds flow southward off the continent, dried by sinking motion in the high pressure over land. The result is a well-defined summer monsoon season in South Asia, which typically runs from June to September. The rains do not fall continuously through the summer season – they are punctuated by extremes of flood and drought. In South Asia, more than 1 billion people manage their lives and livelihood by this seasonal rhythm of rainfall.

Monsoon climates occur in other parts of the world, notably in Australia (Manton and McBride 1992), West Africa (Janicot et al. 2008), and the Americas (e.g. Barros et al. 2002; Douglas et al. 1993; Zhou and Lau 1998). Of these, the North and South American Monsoon Systems (NAMS and SAMS respectively) are perhaps the least understood. Like the Indian monsoon, some tropical and subtropical land regions of the Americas experience a clear seasonality to precipitation, with a summertime maximum. However, the evolution of the NAMS and SAMS reveals distinctive characteristics that complicate the simple model of a seasonally reversing thermally direct circulation over land. Yet, as in South Asia and West Africa, the American monsoon's impact on agriculture, energy use, public safety and water resources are profound.

2. The North American Monsoon System

Like the Indian monsoon, the NAMS is the atmosphere's response to the seasonal migration of the sun's energy, and the reversal of the surface temperature gradient that follows this shift. By late June, intense summer heat dominates the arid mountains of northwestern Mexico, the deserts of southeastern California, across southern Utah and southwestern Colorado, to western New Mexico and Arizona (hereafter the monsoon region). Warming and expansion of the atmosphere lowers surface air pressure across this region. The low pressure draws moist air from the Eastern Pacific and the Gulf of Mexico into the

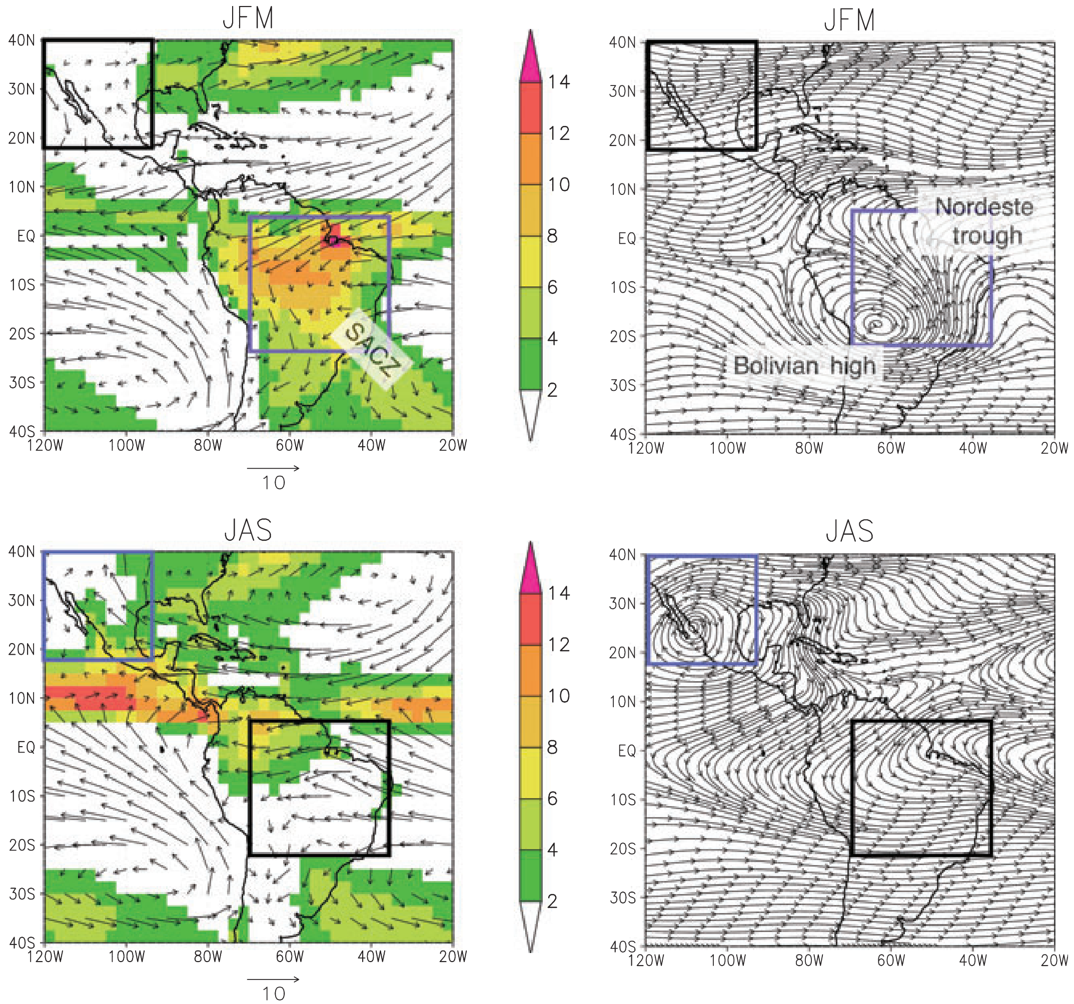

Fig. 1. NCEP (National Center for Environmental Protection) reanalysis wind composites and global precipitation climatology project precipitation for North and South America, including the SAMS and NAMS regions (boxed), averaged from 1979 to 2007 for January to March (top) and for July to September (bottom). Blue boxes indicate monsoon season in each hemisphere. Left column shows rainfall rate (mm/day) and 925 mb wind vectors (10 m/s reference vector is shown). Right column shows 200 mb streamlines.

continent. This circulation pattern sets the stage for thunderstorms to develop, as moist air is forced upward along mountainous regions to form deep, heavily raining clouds. As these thunderstorms become ubiquitous across the monsoon region, the collective outflow of air from their tops contribute to an upper-level anticyclone centered over northern Mexico, a hallmark atmospheric signature of the mature monsoon from July to September (Figure 1). Precipitation advances northward as the summer progresses, typically reaching southern Arizona by mid-July as the upper-level anticyclone moves northward (Douglas et al. 1993).

The NAMS has regional complexity that challenges a simple analogy with the classical monsoon system of South Asia. Recent studies of NAMS highlight interacting dynamical mechanisms that initiate, modulate, and maintain summer rainfall across the monsoon

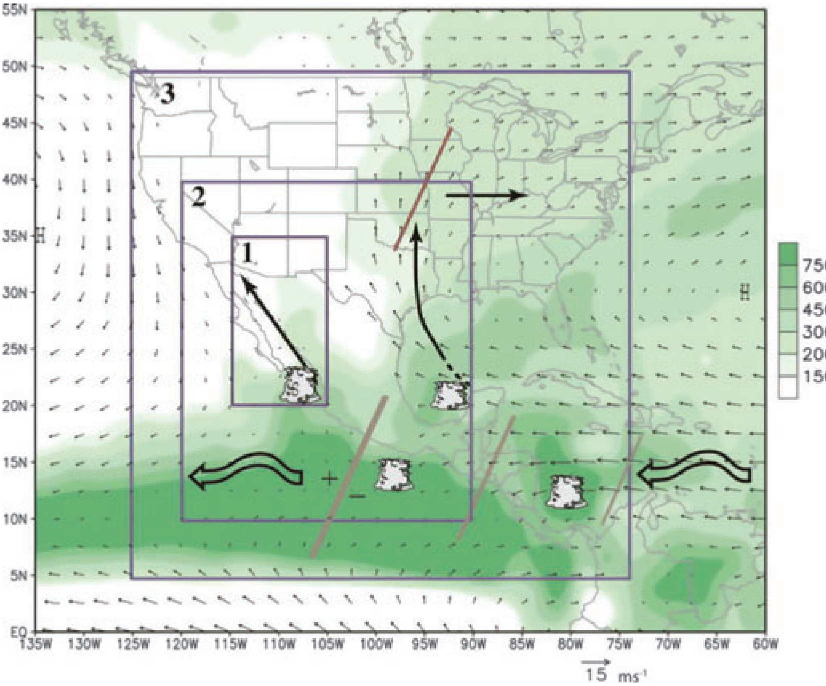

Fig. 2. Schematic of important NAMS atmospheric features. Short arrows show mean 925 h-Pa wind, green shade is precipitation (mm), averaged from July to September 1979–1995. Gulf of California low-level jet (long arrow at 110°W) supplies moisture into the NAMS (analogous to jet over the Great Plains, also shown). Rain systems and gulf surges are regulated by tropical easterly waves (wavy arrows) at 10–15°N. The mean location of troughs in easterly waves and mid-latitude upper level westerlies is shown as grey lines. Source: Adapted from Higgins and Gochis (2007).

region. In northern Mexico, thunderstorms may be triggered at the leading edge of surges in the low-level wind that travel northward along the Gulf of California. These 'gulf surges' transport moist air into the monsoon region and are associated with episodic heavy rainfall as the monsoon season sets in (Johnson et al. 2007). Waves in the tropical low-level easterly winds, which migrate northward to central Mexico during the monsoon season, organize thunderstorms into long-lived rain systems and energize them with injections of moist air (Adams and Comrie 1997). Although direct landfall of active tropical cyclones occurs in the southwestern coast of Mexico, they are very rare in the southwestern US with four events recorded during the past 100 years (Chenoweth and Landsea 2004). Nevertheless, by August and September, the moisture from remnant tropical cyclones may contribute to the seasonal precipitation totals in the northern NAMS region during some years (Adams and Comrie 1997). A recent study concludes that during the period 1992–2005, moisture from an average of about three decayed tropical cyclones per year reached as far north as the southwestern US, increasing rainfall totals at some locations by as much as 30% above average (Ritchie et al. 2008). Figure 2 summarizes the major atmospheric features of the NAMS.

North American Monsoon System rainfall is also influenced by global-scale circulation patterns with origins on the other side of the planet. The Indian Ocean is the genesis region for an equatorial eastward moving global scale wave of wind anomalies, known as the Madden-Julian Oscillation (MJO), which travels around the global tropics every

1–2 months. When the enhanced rainfall phase of the MJO reaches the Eastern Pacific, it can increase the likelihood of tropical cyclone formation near the Mexican west coast (Higgins and Shi 2001). Positive wind anomalies of the MJO are also associated with increased precipitation in the NAMS by triggering gulf surges (Lorenz and Hartmann 2006).

Surging demand of water in the southwestern US, spawned by increasing population and continued drought, require a better understanding of the mechanisms driving the NAMS. Recently, the most comprehensive field program ever undertaken to improve our understanding of the evolution and predictability of the NAMS was conducted in the monsoon region. The North American Monsoon Experiment (NAME)[1] took place from June to September 2004, with the participation of university scientists and students, federal agencies, and forecasters representing the research and operational communities of the USA and Mexico (Higgins and Gochis 2007). An unprecedented array of instruments were deployed, including an enhanced network of weather balloons across the region, several research ships, weather radars, vertical wind profilers, and surface meteorological stations (region 1 of Figure 2). The campaign established unprecedented cooperation in forecasting knowledge and infrastructure between the US National Weather Service and the *Servicio Meteorológico Nacional* of Mexico that continues to the present.

Several important findings from the NAME campaign have added to our understanding of how the monsoon functions. During NAME, scientists observed that terrain-induced thunderstorms along the Sierra Madre Occidental organize at times into large, long-lived rain systems. Daily solar heating of mountainous terrain sets the stage for the growth of afternoon rain clouds. Surges of tropical air northward in the Gulf of California prime the region with the moisture that fuels thunderstorms. Normally, these thunderstorms remain isolated, delivering intense rainfall for an hour or two. Such heavy rain bursts may result in flash flooding of narrow canyons many kilometers distant, as the fast moving floodwater has little time to percolate into the ground. But when traveling waves in tropical easterly winds stretch northward, their energy and moisture transforms isolated storms into widespread rain systems (an extreme and uncommon example is a hurricane). Under such conditions, mountain thunderstorms that pop up as the late morning sun heats the slopes of the Sierra Madre Occidental can merge together in the afternoon to form extensive precipitation systems. As these large rainmakers evolve through the night, widespread steady soaking rains may persist for many hours after the heavy isolated thunderstorms collapse (Lang et al. 2007). These mesoscale convective systems were found to produce the majority of the monsoon season rainfall, more so when tropical circulations extended northward.

One implication of this scenario is that when tropical circulations stir up the monsoon, the widespread saturating rains that result are more likely to penetrate into the dry surface, recharging aquifers for future use. Moreover, recent modeling work suggests that a significant portion of NAMS precipitation is recycled back into cloud systems to produce more rain (Dominguez et al. 2006). Such processes may be accounted for in hydrological and atmospheric model forecast simulations (Gochis et al. 2003), and are leading to marked improvements in short term to seasonal precipitation prediction and hydrological impacts.

3. NAMS: Water Storage and Flooding

In the monsoon region, there are marked differences in the summer and winter regimes of rainfall. The precipitation from frontal systems of the winter season chiefly replenishes

Fig. 3. The NAMS region. Shown are the Upper and Lower Colorado river basins, the dammed reservoirs of Lake Mead and Lake Powell, and regional topography.

snowpack in the high elevations, which melts gradually the following spring and summer. In contrast, the thunderstorms of the summer monsoon season deliver heavy rainfall at all elevations in short bursts, or in widespread soaking events when tropical circulations impinge northward. Winter snows deliver the bulk of precipitation in the northern monsoon region (Figure 3), near the headwaters of the Colorado River (Sheppard et al. 2002). Farther south, the summer monsoon supplies a larger fraction of the annual rain total.

This means that, compared with runoff from snowpack melt, monsoon rain plays a secondary role in replenishing the two main reservoirs that provide about 80% of the water storage capacity in the dry southwestern US: Lake Powell and Lake Mead. These reservoirs, formed from major dams along the Colorado River, are primarily maintained by discharge from the northern portion of the Colorado watershed (Figure 3) where snow melt dominates the water input. Lake Powell and Lake Mead typically reach their seasonal peak level by early July, whereas during the monsoon season of July, August and September, water levels actually decrease as runoff from snow melt tapers off (Tarboton 2007).

Monsoon rainfall has a more significant impact on the local hydrology of smaller streams and watersheds. Rain events during the summer monsoon generally take the form of heavy downpours from isolated thunderstorms, which produce highly localized rainfall. Though such storms do not contribute the majority of the annual rain total over the entire monsoon region, they spawn flooding events that can have severe local impacts. Flash flooding in narrow canyons causes loss of life each year across the southwest. This is the most significant hazard to recreational users of National Park Service and Bureau of Land Management lands during the summer season. Severe local flooding can lead to crop loss in agricultural regions. Erosion and resultant silt deposition, driven by local flooding, are important processes for base habitat of many native plant and animal species, as well as for the replenishment of soil nutrients in agricultural areas.

Crop loss and curtailed harvest stem from flood issues, rather than from lack of water. The Imperial Valley of southern California (north of Mexicali; Figure 3), the agricultural breadbasket of the desert southwest, was vulnerable to flooding from the Colorado River prior to the construction of a modern canal system, which today supplies year-round irrigation and flood control. Farmers stand to benefit from improved knowledge of the timing and severity of the summer monsoon by adjusting the timing of crop harvest (Grismer 2007). Winter vegetable imports to the USA from Mexico have increased dramatically since the implementation of the North American Free Trade Agreement in the early 1990s (Calvin and Barrios 1999). Production of winter vegetables to supply the US market is centered in the Mexican state of Sinaloa, on the southwest coast (Figure 3). Sinaloa's winter vegetable agriculture relies on irrigation, fed by reservoirs that are recharged by summer monsoon rainfall. Year-to-year variability in summer monsoon precipitation therefore directly impacts the winter vegetable market in the USA. The severe drought in the southwestern US and Mexico since the late-1990s may be in part a regional expression of anthropogenic climate change (Stahle et al. 2009), a conclusion that does not bode well for the agricultural future of the region.

4. *The South American Monsoon System*

In August, as the summer monsoon rains revive the arid southwestern US, the southern hemisphere winter season holds rainfall to a trickle in tropical South America. During that month, Earth's northern hemisphere is turned towards the sun, coaxing moist warm air and rainfall northward like the millions of songbirds that migrate with them. By December when summer arrives to South America, the amount of moisture available for rainmaking in the SAMS dwarfs that of the NAMS. The dry winters and rainy summers of northern, central, and southeastern Brazil result from a seasonal shift in wind patterns that have only recently been recognized as driven by a monsoon climate (Barros et al. 2002; Zhou and Lau 1998), but with unique features shared by no other monsoon region.

Unlike its North American counterpart, warm moist winds blow from the Atlantic Ocean westward across tropical South America all year round (Figure 1). Rather than a seasonal reversal of the prevailing wind direction, there is a strengthening of the northeasterly flow across the northeastern coastline of South America during the southern summer, as seen in Figure 1. This strong inflow of moist Atlantic air into the continent is guided southward by the Andes Mountains and helps fuel monsoon rainfall across tropical and subtropical South America. A unique ingredient to the SAMS is the presence of an extensive canopy of tropical rainforest. The Amazon rainforest contributes to making its own rain, by returning massive amounts of water to the air through evaporation and evapotranspiration. In fact, recycling of water within the Amazon rainforest accounts for some 50% of the rainfall that falls within the Amazon basin (Salati and Vose 1984). The amount of water vapor in the atmosphere available for conversion to rainfall is actually larger over the land (at 20°S) compared with the Atlantic Ocean, and twice that over the eastern Pacific Ocean (Berbery and Collini 2000).

Frontal systems that dominate winter rainfall in the higher latitudes extend their influence equatorward into the monsoon region during austral summer. During the monsoon season, cold fronts often slow to a halt across Brazil, extending from western Amazonia to southeastern Brazil. A low-level jet of northwesterly wind along these stationary fronts acts as a pipeline to carry moist air southeastward out of the forested tropics, modulating the structure of storm systems and setting the stage for monsoon rain across Brazil (Garreaud and Wallace 1998; Marengo et al. 2004; Rickenbach et al. 2002). Summer rainfall extends southeastward across tropical South America along this conduit of moist air, forming a feature called the South Atlantic Convergence Zone (SACZ; Figure 1) that extends into the southern Atlantic Ocean (Carvalho et al. 2004). During the monsoon season, the Nordeste (northeast) region of Brazil usually receives very small amounts of rainfall because the sinking air motion associated with the South Atlantic subtropical high-pressure system and the upper level Nordeste trough (Figure 1) inhibit cloud formation. In the higher latitudes, most rainfall is produced by the large mesoscale convective systems of the La Plata river basin of Argentina (Velasco and Fritsch 1987; Zipser et al. 2006). These rain systems form in association with middle latitude troughs in the upper level winds, and are often associated with extensive flooding during the spring season.

Summer warming of the land surface, and the monsoon cloud systems that follow, produce the upper-level wind patterns that are a hallmark feature of the SAMS. Like the anticyclone in the upper level winds of the NAMS, the circulation of the Bolivian High dominates the high altitude flow across central-west South America as the monsoon matures (Figure 1). This feature is driven mostly by latent heat released within summertime monsoon cloud systems in the SAMS (Silva Dias et al. 1983), with a small contribution from sensible heat transferred from the desert highlands of mountainous Bolivia (Lenters and Cook 1997). The upper level Nordeste trough over northeastern Brazil (Figure 1), in contrast, contributes to the suppression of rainfall in that region by producing sinking motion in the upper troposphere. This trough is also part of the atmosphere's dynamical response to the heating that forms the Bolivian High (Silva Dias et al. 1983), and is an example of the highly interconnected components of the SAMS.

Once the monsoon rains begin, the atmosphere modulates rainfall on timescales of 1–2 weeks during the wet season. In early 1999, the Tropical Rainfall Measuring Mission–Large-Scale Biosphere-Atmosphere (TRMM–LBA) and WET-season Atmospheric Mesoscale Campaign (WET-AMC), an international meteorological field experiment led by the USA and Brazil, was held in the western Brazilian state of Rondônia in part to investigate the mechanisms by which the atmosphere regulates rainfall during the monsoon. TRMM–LBA/WET-AMC shed light on the organization of rain systems during the wet season, and revealed important atmospheric controls on the intraseasonal variability of rainfall. During the 1999 wet season in the southwestern Amazon Basin, northwesterly low-level winds that interrupt the easterly flow every couple of weeks were

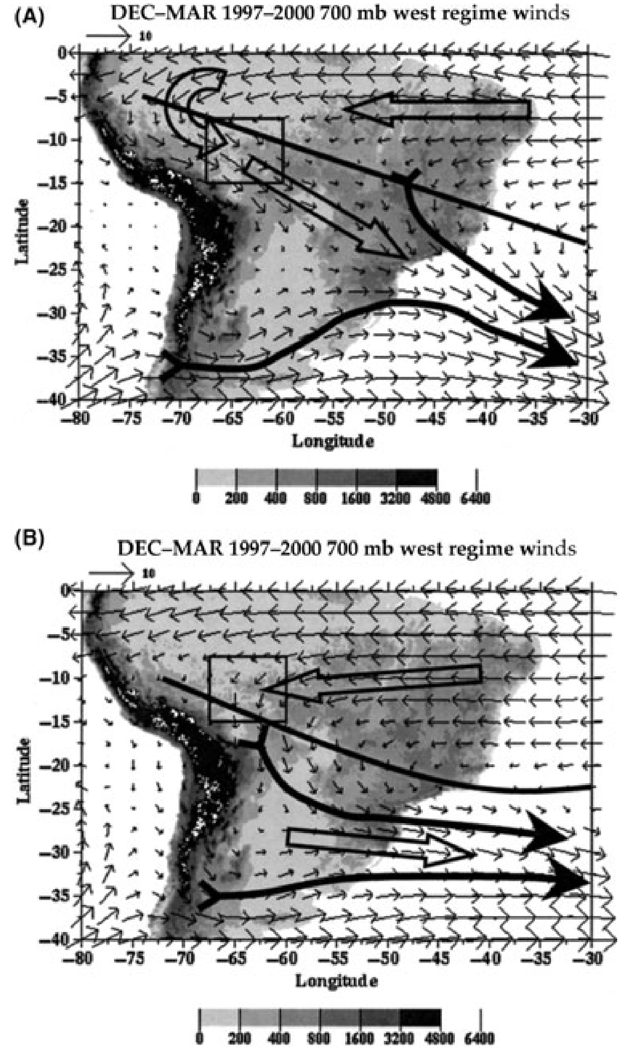

Fig. 4. Schematic of important SAMS atmospheric features. Shown are 3-year mean winds at 700 mb in the (a) westerly and (b) easterly wind regimes, and regional topography (meters). In the westerly regime, low-level winds (block arrow) bring tropical moisture to the southeast, feeding the SACZ (solid double arrows). These features are confined to the subtropics during the easterly regime. Box indicates Tropical Rainfall Measuring Mission–Large-Scale Biosphere-Atmosphere experiment region. Source: Adapted from Petersen et al. (2002).

shown to be associated with the establishment of the SACZ (Petersen et al. 2002; Rickenbach et al. 2002). Figure 4 shows a schematic of these features. The alternating wind regimes are associated with marked changes in the structure of precipitation systems within the monsoon season, somewhat analogous to active and break periods in the Indian and Asian monsoon. During the easterly wind (break) regime, convective systems were strengthened, with explosive afternoon growth associated with larger convective available potential energy and convective inhibition (Halverson et al. 2002). In contrast, precipitation systems in the northwesterly wind (active) regime were characterized by widespread, homogeneous weaker rainfall and fewer deep thunderstorms. A key feature of the northwesterly flow is the South American Low-Level Jet (SALLJ), which transports tropical moisture poleward to feed monsoon rainfall in subtropical South America (Herdies et al. 2002; Marengo et al. 2004). In fact, the SALLJ was the focus of a later field experiment (the SALLJ Experiment; Vera et al. 2006) to better understand the jet's crucial role in fueling rain systems in extratropical South America that can cause extensive flooding (Berbery and Barros 2002). This important moisture pipeline is established in part from the equatorward penetration of cold frontal systems. In this way, the periodic passage of frontal systems in the mid-latitudes plays an important role in modulating the monsoon rains in the Tropics and subtropics.

Remote influences from the other side of the world are also felt in the SAMS. For instance, every 1–2 months during the wet season, an MJO cycle emanating from the Indian Ocean brings bursts of precipitation and changes in wind patterns to the eastern Amazon Basin and SACZ regions (Carvalho et al. 2004). Every few years the shifts in sea surface temperatures and wind patterns in the Pacific Ocean known as the El Niño Southern Oscillation (Curtis 2008) bring changes to the amount of monsoon rainfall in South America. Strong El Niño events bring increased monsoon rainfall to coastal Peru and parts of Uruguay, Argentina and Southern Brazil and a decrease in monsoon rainfall in the Amazon Basin (Aceituno 1988; Grimm et al. 2000).

As a result of the unique atmospheric patterns of the South American monsoon, the summertime rainfall across the SAMS is abundant and has strong regional characteristics (Figure 1). This rain variability is reflected in the great contrasts in land surface type across the SAMS region – from the moist rainforests of western Amazonia, to the dry steppes of the Nordeste region, to the fertile grasslands of southeastern Brazil (Fu and Li 2004). The La Plata river basin (southern portion of Figure 5) contains the water resources to serve the agricultural and electricity needs of the most populated region in South America. Its location, centered in Argentina at the southern portion of the SAMS region, means that the regulation of river discharge (with the attending economic implications) is connected to the variability of the monsoon (Berbery and Barros 2002). In addition, the hydrology of the Amazon River system (northern portion of Figure 5), representing the largest flux of freshwater on Earth, is regulated entirely by the monsoon. In this regard, nature has provided unique opportunities for Brazil to harness the monsoon rains for economic advantage.

5. Energy from Water: Ethanol and Hydroelectric Power in the SAMS region

Brazil's energy and agricultural sector is strongly dependent upon the monsoon rains. In a country where more than 90% of the electricity comes from hydroelectric power and about 15% of the transportation fuel comes from sugarcane ethanol (Empresa de Pesquisa Energética 2008), the energy sector must pay close attention to the coming and going of the monsoon season.

Sugarcane production requires a tropical to subtropical climate with a well-defined dry season and over 1200 mm of rainfall during the wet season. Large portions of southeastern, central and northeastern Brazil fit this climatological requirement. Brazil has capitalized on this natural resource to become the world's largest producer and exporter of sugarcane and the ethanol fuel refined from it, particularly in the southeastern part of the country (Figure 5). Since the mid-1970s, Brazil has built a large national infrastructure to produce ethanol from sugarcane and to deliver it to tens of thousands of gas stations all over the country (Segall and Artz 2007). Vehicles in Brazil run on ethanol, gasoline, or any mixture of the two and represent about 90% of new automobiles in the country (Goldemberg 2008). The success of the Brazilian sugarcane ethanol industry is in large

Fig. 5. The SAMS region. Shown are the Amazon (northern) and La Plata (southern) river systems, location of major hydroelectric dams (blue triangles), and regional ethanol production from sugarcane. Green shaded regions from light to dark represent increasing ethanol production of between 0 and 100 million liters (lightest shade) and 2–11 billion liters (darkest shade) for the 2006–2007 growing season.

part because of the high energy content of the sugarcane plant and to the relative ease and low cost associated with ethanol refinement from sugarcane. The ratio of energy return to energy invested in ethanol production is around 8-to-10 for sugarcane. For comparison, that ratio is only about 1.5 for corn, making sugarcane a far more efficient choice when it comes to ethanol production. Moreover, a typical sugarcane field yields more than twice the amount of ethanol per hectare as a typical corn field.

Monsoon variability strongly affects not only crop yields, but also the timings of planting and harvesting of sugarcane in Brazil. Sugarcane is cultivated over a one to one-and-a-half year period and planting is planned to allow for harvesting during the dry season. The harvest of sugarcane is still mostly done by hand, in an arduous process that requires the fields to be burned prior to harvest (Bourne 2007). Burning not only makes it easier to cut the sugarcane stalks but also makes the fields safer for workers by removing sharp leaves and killing venomous snakes. The harvest of sugarcane is therefore most easily accomplished during the dry season when the fields burn easily and are more easily accessible to workers and machinery. In southeastern Brazil, the harvest of sugarcane usually begins after the end of the monsoon rains in April and lasts until about November, when the first strong, steady rains of the South American monsoon return. In Northeast Brazil sugarcane is also harvested during the dry season, which in that region usually lasts from September to March. Since sugarcane not harvested before monsoon onset is lost, there is a strong incentive for farmers to keep track of the monsoon rains to maximize productivity.

Today, sugarcane is Brazil's most important crop. sugarcane production in 2008 occupied about 7 million hectares of Brazilian farmland, primarily in southeastern Brazil (Figure 5), making it the largest sugarcane producing country in the world. The state of São Paulo in southeastern Brazil accounts for over 65% of the nation's total ethanol production of about 18 billion liters in 2007–2008 (UNICA, 2009).

Brazil's hydroelectric dams are the primary supply of electricity for the country. The abundant amount of monsoon rainfall feeds the largest watershed on Earth, the Amazon River basin and its tributary rivers. A large network of hydroelectric dams generates about 90% of the country's electrical power. This network includes the largest hydroelectric power plant in the world at the Itaipu Dam on the Paraná River in the La Plata river basin (Berbery and Barros 2002; Caetano de Souza 2008). Figure 5 shows five of Brazil's largest hydroelectric dams. Brazil is heavily dependent on hydroelectric power for its electricity; which in turn is regulated by rainfall. If there is a delay in the rainy season, or a decrease in the amount of rainfall in the area, electricity production drops (Alqueres and Praca 1991). Typically, power output of hydroelectric dams plummets during the dry season to roughly 10% of capacity.

6. Monsoon in the Americas: Current and Future Challenges

The NAMS and SAMS are opposite extremes of the global seasonal cycle of energy and water. Each region marks the end point of the sun's annual poleward migration, and receives the summer rains relied upon by millions of people on both sides of the equator. Though both monsoon climates share important features, the challenges and opportunities they present to the inhabitants of each region could not be more different. These point to the critical need to develop a clearer understanding of the workings of both monsoon systems.

The greatest contrast between the US Southwest and Brazil lies in the total rainfall delivered by the monsoon each year, which establishes fundamentally different energy-from-water paradigms for each country. A glance at Figure 1 makes clear that even temperate southeast Brazil receives four to five times as much summer rainfall as Arizona. This fact clearly places severe, but knowable, limits on population growth, energy use, and agricultural potential in the US Southwest. Water resources in the Colorado River basin are allocated well above the threshold required to maintain a healthy and sustainable river system (Jager and Smith 2008), in part because allocations were established in a relatively wet period (early 20th century) compared with historical norms. There is little potential to increase hydroelectric power generation beyond that provided by the massive Hoover and Glen Canyon dams. In the case of Glen Canyon Dam, the cost per kilowatt to generate power is about four times that of hydroelectric projects in the rainier eastern

Fig. 6. Lake Powell, several years into the current severe drought in the NAMS region. Upper panel shows the abandoned Hite Marina in 2005 (boat ramp visible on far left), 225 km (140 miles) north of Glen Canyon Dam. Hite Marina closed permanently in 2002 because of chronic low lake levels. At 'full pool' in 1999 the lake covered all vegetation in the canyon floor. Lower panel shows a recreational houseboat in 2007, when the lake was 29 m (95 feet) below the 1999 high water mark. Photographs by John Rickenbach.

states, with higher evaporative loss and greater irrigation requirements further reducing power production efficiency (Powell 2008). The current 10-year drought, combined with the legal requirement for the upper Colorado River basin to maintain a constant water supply for downstream states (notably California), has brought Lake Powell to dramatically low levels in recent years (Figure 6). The reduction in hydraulic pressure at Glen Canyon dam as a result of drought-induced water level decrease brought power generation down to one-third of capacity by 2007.

In Brazil on the other hand, expansion of hydroelectric power generation continues unabated because of the existence of major undammed river systems, ample precipitation for reservoir recharge, and less stringent water laws. For example, a series of dams is currently planned for the Xingu river basin (headwaters near Cuiaba; Figure 5), which includes major tributaries to the Amazon River. Although the resulting environmental consequences and displacement of indigenous people are unsolved issues, the untapped potential for power generation has been deemed crucial for Brazil's economic future by the Brazilian government (Fearnside 2006). On the ethanol front, the SAMS delivers ample rainfall to maintain and expand ethanol production from sugarcane. And yet, the climate of the Amazon region is vulnerable to changing land-use patterns. Deforestation leads to reduced evapotranspiration, a drier land surface, and more carbon release to the atmosphere, which accelerates the rate of deforestation in a positive feedback (Nobre et al. 1991).

A challenge for both societies lies in the ways each monsoon region responds to changing patterns of rainfall. The southwestern US is faced with a very narrow margin to adapt to even modest changes in an already limited resource. Currently, the region is faced with the driest decade in over 80 years (Piechota et al. 2004). If global climate change continues as projected, the best estimate given by climate models for the NAMS region is for continued decrease in rainfall through the 21st century (Bates et al. 2008). A warming trend and less rain both conspire to place severe pressure on the snowpack that supplies the water storage for the southwest. A projected decrease in summer rainfall suggests that the monsoon rains cannot make up the difference. In that scenario, current increasing water use trends are clearly not sustainable, a conclusion reached by a recent National Academy of Sciences report (NAS 2007). In the Amazon, deforestation continues unabated (Malhi et al. 2008). As the forest canopy itself provides moisture for monsoon rain, deforestation will probably lead to decreased precipitation. Whether these trends threaten the outlook for increased hydroelectric power production or expanded sugarcane yield are important unanswered questions. A clearer understanding of the American monsoon systems is needed for both societies to better adjust to inevitable challenges and to take advantage of new opportunities.

Short Biography

Dr Thomas Rickenbach is an Assistant Professor of Atmospheric Science in the Department of Geography at East Carolina University in Greenville, North Carolina. His research seeks to understand the feedbacks between tropical precipitation systems (such as thunderstorms and hurricanes) and regional climate in both the Tropics and higher latitudes. As a radar meteorologist, he has participated in field experiments to determine the structure and evolution of tropical cloud systems across the globe, including Australia, China, the equatorial Western Pacific Ocean, the USA, Brazil, and West Africa. Dr Rickenbach currently is studying the mechanisms for the onset of the monsoon season in tropical South America under the National Oceanic and Atmospheric Administration's Climate Prediction Program for the Americas. His research work has been published in the *Journal of Atmospheric Science, Journal of Geophysical Research, Monthly Weather Review, Journal of Climate, and the Bulletin of the American Meteorological Society*. Dr Rickenbach held a National Research Council Fellowship at the NASA Goddard Space Flight Center in Greenbelt, Maryland, and was a faculty member at the Joint Center for Earth System Technology at NASA GSFC and the University of Maryland, Baltimore County. He also taught in the Department of Meteorology at San Jose State University in San Jose, California. Dr Rickenbach received his BS degree in engineering at the University of California at Berkeley, and MS and PhD degrees in Atmospheric Science at Colorado State University in Ft Collins, Colorado.

Notes

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