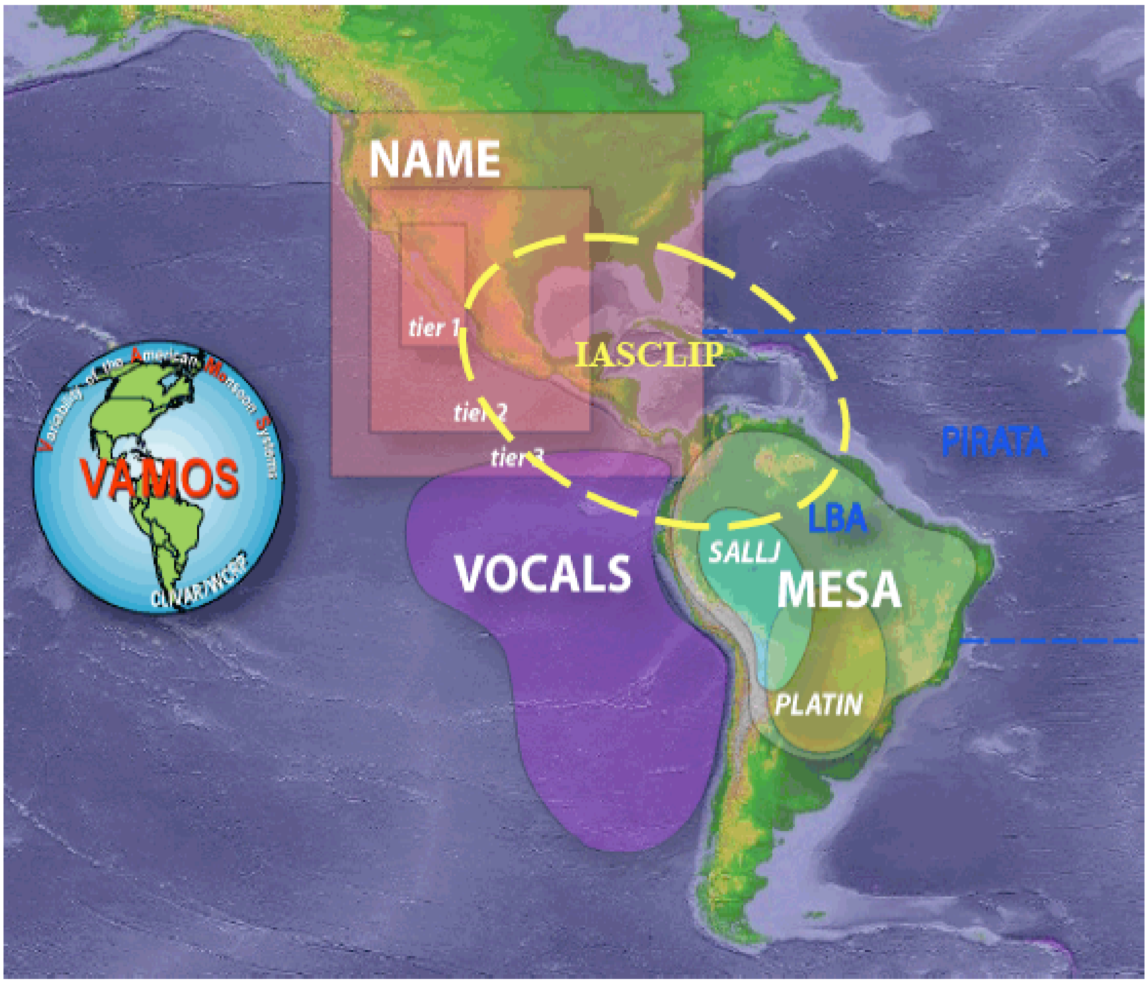
A Science and Implementation Plan for the

Intra Americas Study of Climate Processes (IASCLIP)

Prepared for the VAMOS Panel



April 2007 (draft)

Table of Contents

1. Introduction & Rationale

The Intra-Americas Sea (IAS) includes the Caribbean Sea and the Gulf of Mexico. In this prospectus, the IAS region is defined as a broad area covering the IAS itself, the adjacent lands, and the ocean off the west coast of Central America and northernmost South America (outlined by the dashed oval circle on the cover page). Understanding and predicting climate variability in the IAS region are important for a number of reasons.

The IAS region is vulnerable to climate variability and change (Gable et al 1990; Maul 1993). Many areas in the IAS region are heavily populated, especially along the coastal zones (Fig. 1). A potential sea-level rise associated with global warming would be a direct threat to many of the coastal communities (e.g., Lewsey et al. 2004). A gradual change in local climate has been observed since late 1950s, for example, in increases of the percent of days with very warm maximum or minimum temperatures, and extreme precipitation (e.g., Peterson et al. 2002). In boreal summer, the IAS region is often ravaged by tropical cyclones, with catastrophic loss of life and destruction of infrastructures and properties. The frequency and strength of these tropical cyclones vary strongly on interannual to interdecadal timescales (e.g., Goldenberg et al., 2001). Rainfall in the IAS region fluctuates with ENSO (e.g., Chen and Taylor 2002; Laing 2004; Malgrem et al. 1998), Atlantic multidecadal oscillations (AMOs), and the position of the ITCZ, which is related to the tropical Atlantic climate variability (TAV) east of the IAS, and also with the phase of the intraseasonal MJO. Severe anomalies in rainfall — both generalized and storm-related — can lead to damaging consequences in the economy, natural environment, and even social unrest in certain parts of the region. On an annual basis, much of the IAS region experiences a dry spell in mid- summer (July and August), which is known as the Mid Summer Drought (MSD) (section 2.1a). Management of agriculture, water resources, hydropower, and health related issues decisively depends on the timing, severity, and duration of the MSD (also known as *canicula* or *veranillo*). Dust from the Saharan Desert is also present in the Northern Atlantic and the Caribbean and it is suspected to influence the regional climate in IAS (Lau and Kim 2007).

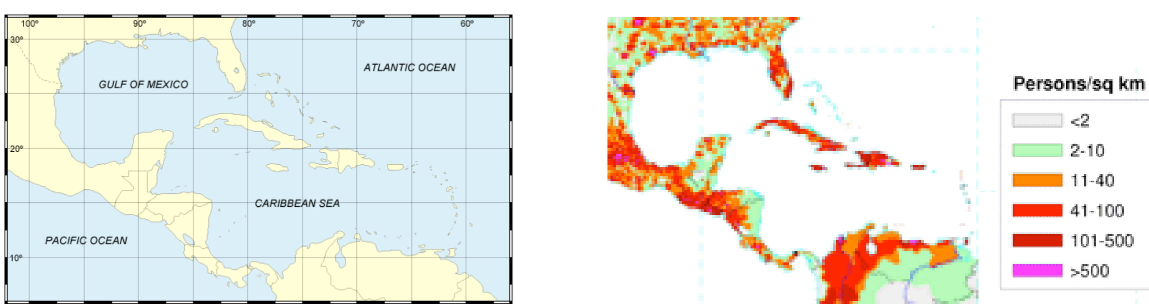


Fig. 1 The Intra-Americas Sea (IAS) region and its population density.

Past climate changes have left many footprints in the IAS region, as revealed by proxy records of temperature and precipitation based on ocean and lake sediment, and corals. Since 1700, significant interannual and interdecadal variability in the position of the Inter-Tropical Convergence Zone (ITCZ) has been identified at average periods near 3-7 (ENSO band), 9, 17 and 33 years (Linsley et al. 1994). Centered at 5,500 years ago, a development of arid conditions in the Caribbean region was synchronous with the onset of wetter conditions in the South American Altiplano, a possible consequence of a southward displacement of the ITCZ (Tedesco and Thunell 2003a). The Caribbean climate was relatively dry during the latter part of the Younger Dryas chronozone (10.5- 10 kyr BP) but changed to a wetter condition at the end of the last deglaciation (the early Holocene, approximately 10-7 kyr BP) accompanied by an increase in upwelling along the Venezuelan coast. This wetter climate persisted for nearly 4,000 years before the onset of another dry climate at approximately 3.2 kyr BP, which generally prevailed throughout the late Holocene (Hodell et al. 1991; Lin et al. 1997). In the southern Caribbean the thermocline/nutricline was shallow and the upwelling induced by the presence of the ITCZ was minor prior to 3.1 million years ago (Ma); After 3.1 Ma, the thermocline/ nutricline deepened, suggesting a shift of the mean position of the ITCZ among other factors (Kameo 2002). Correct interpretations and explanations of such proxy climate data from the IAS region will benefit from an improved understanding of the physical and dynamical processes in the current climate.

The IAS region is a nexus for North and South Americas as well as for the tropical Pacific and Atlantic Oceans. It plays an important role in the climates of the Americas and the Western Hemisphere. It hosts the second largest body of very warm (≥ 28.5°) water on Earth: the Western Hemisphere warm pool (WHWP) (Wang and Enfield 2001). Partially because of this, the IAS region also hosts the second largest diabatic heating center of the tropics, which drives strong planetary-scale circulations in boreal summer, second only to those in the western Pacific/Asian monsoon region. Easterly waves propagate from the tropical Atlantic through the IAS region, serving as embryos of tropical cyclones in both IAS and eastern Pacific. The Madden-Julian Oscillation, which is known to modulate cyclogenesis in the eastern Pacific, may also propagate into and through the IAS region to modulate cyclogenesis in the IAS and Atlantic. The IAS is a pathway and moisture source for water vapor transport by the low-level jets for warm-season rainfall in North, Central and South America.

Climate phenomena in the IAS region have substantial effects on the local geochemical system and ecosystems. The chemical composition of coastal water in the Caribbean Sea, for example, sensitively depends on rainfall and surface vegetation over land (Ceron et al. 2002). The position of the ITCZ and the associated strength of the trade wind determine the strength of upwelling along the southern coast of the Caribbean Sea and thereby influence the variability of the plankton population (Tedesco and Thunell 2003b) and organic carbon recycling crucial for the primary production (Muller-Karger et al 2001). Wind patterns in the Caribbean, especially in coastal zones, are important to spawning, larva transport, growth, and feeding behavior for many fishes and invertebrates (e.g., Clifton 1995; Sponaugle and Cowen 1996; Robertson et al. 1999; Criales et al 2002).

Current global climate models (GCM) have great difficulty in correctly simulating the distribution and variability of rainfall and winds in the IAS region. For example, Fig. 2 clearly shows that discrepancies between simulated and observed mean rainfall in the IAS region are particularly large in comparison to the rest of the tropics, which is very typical in global models (e.g., Chen et al. 1999). The excessive rainfall in the IAS reproduced by models leads to an overpredicted upper-tropospheric divergence in the region (Nogues-Paegle et al. 1998). Not all GCMs correctly reproduce the occurrence of the MSD during summer (Kiehl *et* al. 1998; Angeles *et al.* 2007). The largest uncertainties in the moisture budget over the southeastern US in current global model reanalyses are related to their uncertainties in the representations of moisture flux by the low-level jet in the IAS region (Mo and Higgins 1996).

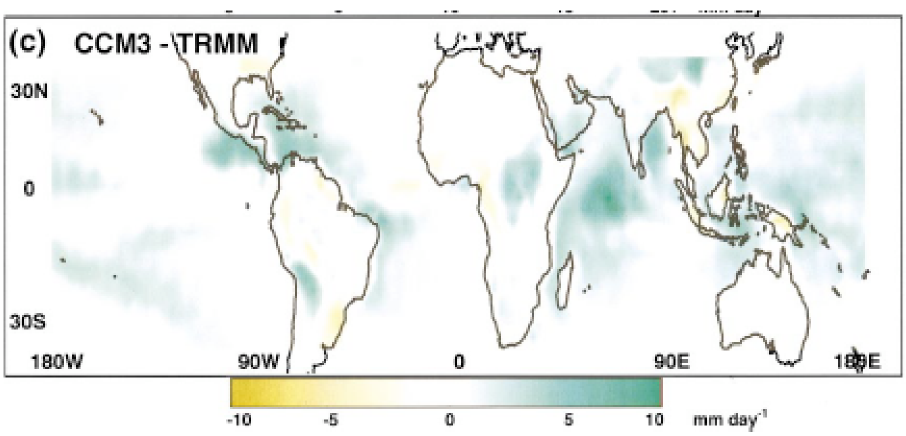


Fig. 2 The climatological mean difference (CCM3 - TRMM) in mm day^{-1}. (From Collier et al 2004)

The reasons for the poor simulation of rainfall in the IAS region include, among others, faulty global-scale background state, inadequate spatial resolution to resolve the details of the land-sea distribution and complex terrains, deficiencies in parameterizations of atmospheric convection and microphysics of warm clouds, boundary layer, and land surface conditions. The complexity of the diurnal cycle of rainfall over tropical mountains inside the IAS region (Poveda et al., 2005) highlights the complicated challenges for GCM and meso-scale models. Any improvement of GCM simulations of rainfall in the IAS region must be made as a part of collective efforts at improving GCM global performance. A better understanding of the physical processes crucial to the rainfall distribution and variability in the IAS region would contribute to such collective efforts that always benefit from regional emphases. The IAS region is an ideal natural laboratory for the study of physical and dynamical processes in tropical rainfall variability and its regional impacts. The IAS is semi-enclosed, surrounded by a variety of land configurations and surface conditions, including the Amazon tropical rainforest to the south, Sierra Madre Occidental (SMO) to the northwest, the US Great Plains to the north, and the Antilles island chain to the east. These make the region ideal for the study of land-air-sea interaction on various scales and with various local geometries. The IAS region is home to many weather and climate systems that are part of fundamental rain-making processes in the tropics and subtropics, such as low-level jets, easterly waves, the ITCZ, tropical cyclones, Saharan dust, and incursions of midlatitude Rossby waves and fronts ("nortes"), to name a few. These systems are subject to local influences of both ocean and land in the IAS region and remote influences from the Pacific and Atlantic Oceans. Since the pioneering program of GATE[1] until recently, most extensive climate-related research programs in the tropics have focused on air-sea interaction in open oceans (e.g., GATE, TOGA COARE, CEPEX, INDOEX, JASMINE, TEPPS, EPIC) or hydrological cycle over land (e.g., LBA). Very few have included both ocean and land and tackled the hydrological cycle in the context of land-air-sea interactions as part of their central research themes. A research program in the IAS region, with an emphasis on climate processes and hydrological cycle related to land-airsea interaction, will help fill the gap.

Many research activities and opportunities currently exist that are related to the IAS (Appendix A). Each focuses on a distinct aspect of the general climatic issues of the IAS and its surroundings. None of them directly addresses the processes and prediction of climate variability of rainfall specifically for the IAS region. A well design climate program concentrating on the problems of rainfall in the IAS and its adjacent regions will benefit from these existing activities and opportunities, and provide a direct linkage between them and issues of climate prediction for the IAS region.

The IAS region is a unique location in the world where so many countries are affected by the same set of climate phenomena. They share the same concerns of predicting climate variability, mitigating natural disasters and seizing opportunities resulting from climate variability. Many of the countries in the IAS region are limited in their capacity of all around climate research, yet can make unique and valuable contributions. International collaboration is pivotal to the success of any climate research program for the IAS region. By the same token, a successful climate research program for the IAS region would yield broad international benefits.

2. The Societal Concerns: Rainfall and Tropical Storms

As in many tropical regions in the world, rainfall is the most important climate variable to societies in the IAS and surrounding regions, as well as tropical storms. Being at the crossroads between North and South Americas, and between the Pacific and Atlantic Oceans, the variability in the IAS region is subject to influences from many directions. Among others, the north Atlantic subtropical high (NASH), the ITCZ, and the trade winds constantly affect the region. Hurricanes and tropical waves are active in the region in the summer months. Midlatitude weather systems penetrate into this region during boreal winter. All these atmospheric features interact with the Western Hemisphere warm pool (WHWP), topography, and landscapes. Remote influences (e.g., ENSO, NAO, TAV) may have direct impacts on winter rainfall but their main impacts on the summer rainy season and its tropical storms occur more indirectly, through their effects on the size and intensity of the WHWP. In this section, gross features of the annual and interannual variability of rainfall and tropical storms in the IAS and surrounding regions are reviewed. The following section (3) will describe the components of the IAS climate system as they relate to these concerns.

2.1 Rainfall variability

The variability of rainfall in the IAS and surrounding regions embraces a wide range of scales, from the diurnal cycle to multidecadal variations. The short-term (diurnal to subseasonal) variability offers an important venue for sampling the weather processes. Representing these processes well in prediction models is key to forecast the long-term (seasonal and interannual) variability of rainfall.

2.1a Seasonal cycle

In general terms, rain follows the sun with some delay across the equator, as moist convection is the main rain production mechanism. To be credible tools for prediction and research, climate models should successfully simulate the seasonal cycle. In the IAS region, the most prominent feature of the seasonal cycle in rainfall is its latitudinal migration. In austral summer (January – March), the major rain signals are confined south of 10°N, with the heaviest rain in the Amazon Basin over land and in the ITCZs over the oceans (Fig. 3a). To the north, rainfall in the southeast US is mainly concentrated within the storm track of winter synoptic-scale perturbations. In between, the majority of the IAS, including Central America, the Caribbean Islands, and the northern tip of South America, are in their driest season, often visited by cold surges from the north.

Through boreal spring (April – June), rainfall shifts northward from South America to Central America and extends along the western slopes of the Sierra Madre Occidental (SMO) to the Southwest US. Meanwhile, rainfall increases over the central US with many severe storms that cause flashflood and wind damages. In boreal summer, rainfall over the land of Central America and Mexico reaches its northern position, while a separated rain maximum develops over the Southeast of the US (Fig. 3b). Most of the IAS region is in the wettest season and most of South America (except the northern part) is dry. Notice that rainfall prefers land regions to the oceans within the IAS region. A southward migration of rainfall takes place in boreal fall, which brings the maximum rainfall back to the Amazon Basin in austral summer.

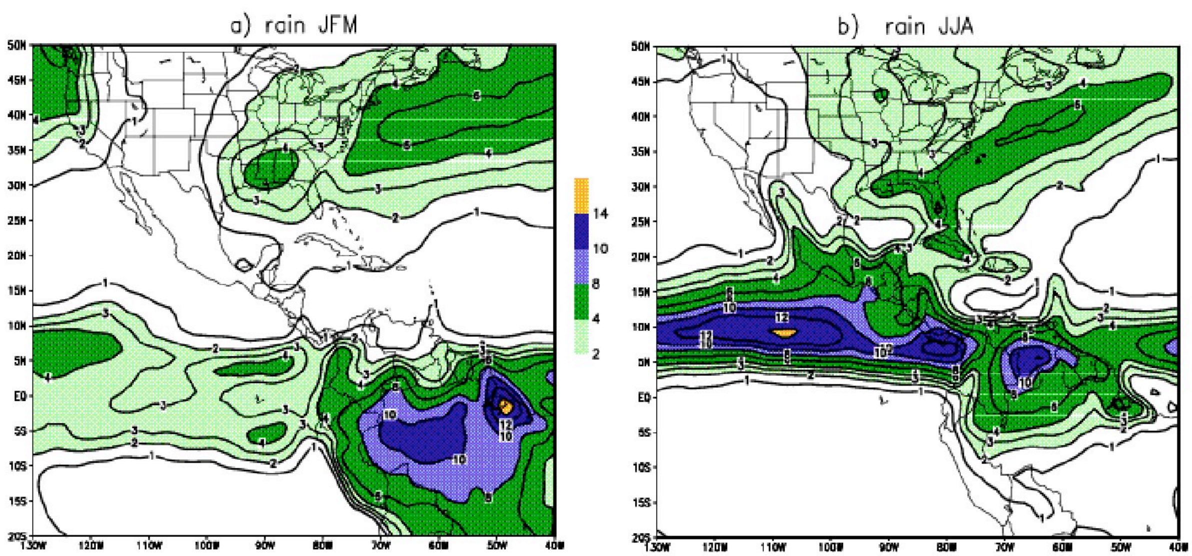


Fig. 3 Mean precipitation for (a) January- March (JFM) and (b) June-August (JJA) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm day^{-1}.

This meridional migration of rainfall comprises the major signals of the American Monsoons (Vera et al., 2006). The American monsoons, while smaller in scale and magnitude, share many common features with the classic monsoon systems in Asia and Africa. For example, a sudden onset of the monsoon separating the rainy from the dry seasons as part of the rainy region advances poleward; the subseasonal variability within a rainy season; the moisture supply by distinct low-level jets; and the interplay of surface conditions of land and the neighboring oceans, are common to all.

The South American monsoon peaks during November through late February (Nogués- Paegle et al. 2002). The onset of the wet season over South America starts in the equatorial Amazon and then spreads quickly to the east and southeast during austral spring (Horel et al. 1989). By late November, deep convection covers most of central South America from the equator to 20°S (Liebmann and Marengo 2001). At this time the eastern Amazon Basin, Northeast Brazil, and the areas immediately to the north enter into their dry seasons.

The North American monsoon is fully developed during July-early September (Higgins et al 2003). One characteristic of the North American monsoon is the northward advance of heavy rains along the western slopes of the SMO in boreal spring and summer (Douglas et al. 1993; Stensrud et al. 1995; Adams and Comrie 1997). It starts with the onset of the Mexican monsoon in May and June after the eastern North Pacific warm pool reaches its peak and continues until the rainy region reaches Arizona and New Mexico in July.

Investigations of the American monsoons have been promoted by two programs, the North American Monsoon Experiment (NAME, Higgins et al 2006) and Monsoon Experiment of South America (MESA, ref). More details of the American monsoons are given by Vera et al (2005).

Between the equator and Tropic of Cancer the monsoon exhibits a pronounced double peak structure in precipitation and diurnal temperature range in June and September. In between, precipitation over central and southern Mexico, the western coast of Central America, the central regions of Colombia, and the Caribbean maritime continent reaches a relative minimum. This temporary dry spell in July and August, namely, the Mid Summer Drought (MSD), Canícula, or Veranillo (Hastenrath 1967; Curtis 2002), is sufficiently regular as to appear in climatological averages (Fig. 4).

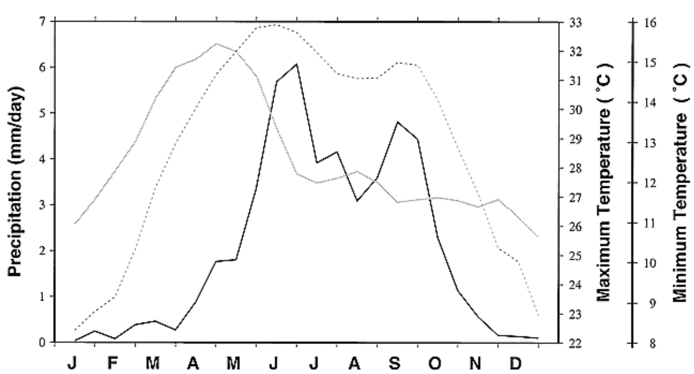


Fig. 4. Biweekly climatology of precipitation (black solid line), maximum temperature (gray solid line), and minimum temperature (dotted line) for Oaxaca, Mexico (17.8°N, 97.8°W). (From Magana et al. 1999)

This MSD is a marked feature of the seasonal cycle in the IAS region, bearing distinct features in comparison to the seasonal cycle at the same latitude in other part of the world (Magaña et al. 1999; Mapes et al. 2004). Associated with the MSD are a maximum of sea level pressure, a strong easterly CLLJ in the Caribbean region (Wang 2007), a strong vertical wind shear (Angeles *et al.* 2007), a minimum in tropical cyclogenesis in the Caribbean in July (Inoue et al 2002), and a peak in the Saharan Dust.

Easterly waves are responsible for the 10%-20% of dust concentration transport into the North Atlantic from North Africa (Jones et al., 2003). The dust particles originate in northern Africa and travel toward the NTA covering a wide latitudinal region from 5ºN to 30ºN. According to Rosenfeld et al. (2000), the dust by itself produces a rainfall reduction when the cloud is forming within desert dust layers. Saharan dust with large concentration of small size Cloud Condensation Nuclei (CCN) generates cloud formation with small droplets. Commonly, it has been believed the giant CCN (GCCN) causes a rainfall increase in convective clouds, enhancing the coalescence and collision, regardless of the distribution of small CCN. But they found that the coalescence-suppressing effect of very large concentration of small dust particles inhibits precipitation, even when GCCNs are present. Over the NTA, from June to August, an increase of aerosol optical thickness (AOT) causes a shallow cloud cover increase, a cloud droplet size decrease and the reduction/delay of the rainfall formation (Kaufman et al., 2005). Satellite images were used by Blanco et al. (2003) to analyze the African dust transport over the Mediterranean basin; those results demonstrated the existent of an annual Saharan dust cycle. It begins in spring, reaching its maximum concentration during the summer and decreasing appreciably during autumn and winter. An apparent correlation of variations of AOT with precipitation was recently observed while conducting routine measurements at the Arecibo Observatory (Comarazamy *et al.* 2006).

The MSD has many societal impacts to the IAS region. The MSD is directly related to the success or failure of agriculture. The relative reduction in precipitation during July and August may lead to fungus in maize crops. Technologies are being developed to reduce the fungus and to breed crops that are more resistant to the fungus. Water management in Mesoamerica also considers the role of the MSD in water levels in dams for hydropower generation. Heat waves related to the MSD may increase certain illnesses during the season. The cause for the MSD is not fully understood. It does not appear to be related to the Madden-Julian Oscillation (Madden and Julian 1971) that propagates eastward from the western Pacific. It is not a direct result of the seasonal migration of the ITCZ because its position never reaches latitudes higher than 15°N (section 3.3). Two possible mechanisms have been proposed. First, a local air-sea interaction process during the precipitation peak in June may result in a cooling of the sea surface of the warm pool because of a reduction of insolation due to increasing cloudiness. This surface cooling in July and August may lead to a substantial decrease in deep convective activity and hence the MSD (Magana et al 1999). The SST fluctuation alone, however, is not always sufficient to cause the MSD. Subsidence related to deep convective activity in other areas in the IAS may have to come into play (Magana and Ceatano 2004). Another possible mechanism is the northern Atlantic subtropical high (section 3.4), whose westward intrusion penetrating into the IAS region may suppress precipitation there (Mapes et al. 2004). A key to fully understanding the mechanism for the MSD would be to quantify the contributions from local air-sea interaction and overturning circulations vs. the Atlantic subtropical high.

2.1b Interannual variability

Being adjacent to the home of El Niño, the IAS region undergoes substantial interannual variability in its rainfall. Rainfall anomalies during boreal summer (June – September) associated with ENSO are shown in Fig. 5. During warm events, strong negative anomalies in rainfall are over land of Central America northward to central Mexico, and over the western Caribbean Sea (Fig. 5, left panel). The dry belt near 10 – 20°N is a sign of southward displacement of the ITCZ. Positive anomalies, generally weaker, are along the Caribbean coast of Central America, over Cuba, northern central South America, and the southeast of the US. During cold events of ENSO, rainfall over most of the IAS region is above normal, except off shore of Florida on both Gulf and Atlantic sides and over the Caribbean Sea along the Central American coast. However, only the anomalies over the Caribbean Sea and its southern and western coasts (negative during warm events and positive during cold events) are statistically significant (e.g., Ropelewski and Halpert 1987, 1989).

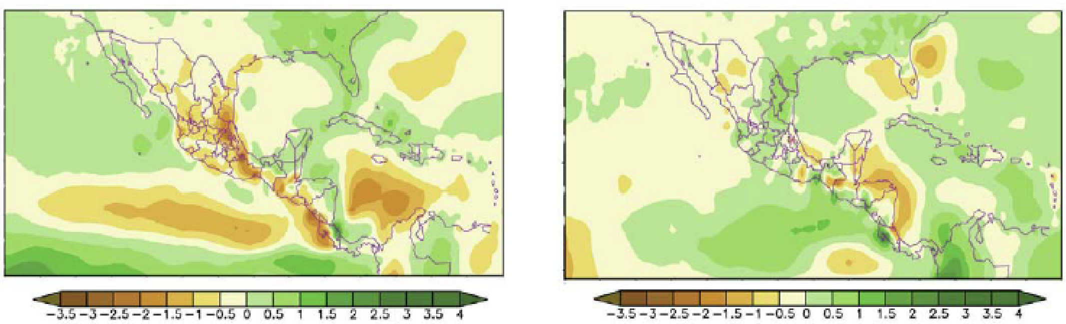


Fig. 5: Composite of precipitation anomalies (mm/day) during the summers (Jun-Jul-Aug-Sep) of (left panel) six El Niño onset years (1965,1972, 1982, 1986, 1991, 1997), and (right panel) La Niña years (1964, 1970, 1973, 1975, 1988, 1998). (From Magana 2000)

Influences of ENSO on rainfall in the IAS region is complicated by influences from SST anomalies in the tropical Atlantic Ocean; the Pacifc and Atlantic rainfall responses are comparable in magnitude but opposite in sign (Enfield 1996). Effects of the Western Hemisphere warm pool (WHWP) also interfere with or reinforce the ENSO influences, which will be discussed in section 3.1. A number of studies suggest that ENSO exerts its influence on the IAS region indirectly through the tropical Atlantic and the WHWP (Enfield and Alfaro 1999; Giannini et al. 2000; Chen and Taylor 2001; Taylor et al. 2002). Interaction between ENSO and the MSD has also been reported (Dias et al. 1994). In addition to the remote influences from the Pacific and Atlantic Oceans, rainfall in the IAS region is also closely related to a number of regional factors. They include the Western Hemisphere warm pool (section 3.1), the low-level jet (section 3.2), the ITCZ (section 3.3), the northern Atlantic subtropical high (section 3.4), and tropical cyclones and waves (section 2.2), to name a few. These factors serve to connect the remote influences to local responses and to land surface-atmosphere interactions. In the rest of this section, these factors are discussed.

An additional influencing signal in the the rainfall fluctuations caused by the Atlantic Ocean in the Caribbean region are reflected in the North Atlantic Oscillation (NAO), a dipole pattern of the north-south sea level pressure difference between Iceland in the North and approximately over the Azores Islands in the South (Pozo-Vázquez *et al.* 2001). A positive NAO affects the North Tropical Atlantic (NTA) basin by mean of anomaly strong trade winds, anomalous ocean-atmosphere heat fluxes and cooling of SSTs in the NTA, while negative NAO causes opposite effects. In addition, positive phases of NAO events during the wintertime generate a drier NTA summer, while negative phases of the NAO causes a wetter NTA spring (Giannini *et al.* 2001). A significant influence of the NAO in the eastern Caribbean has been reported by Malmgren *et al.* (1998).

2.2 Tropical cyclones (TCs) and easterly waves

Tropical cyclones (TCs), including hurricanes and their precursors, are the most damaging weather systems in the IAS region. While hurricane winds and storm surge are always dangerous and destructive, devastating hurricane damages in recent decades, especially loss of lives, are also caused by floods and landslides induced by hurricane rainfall. While TC track forecasting has improved in recent years, many challenges remain in predicting intensity of the winds and the rainfall distribution. Hurricane Mitch in 1998 is a case in point. About 10-12,000 lives perished because of flash floods and landslides caused by a meter of rain in the hills of Honduras and Nicaragua produced by Mitch, despite relatively small track errors and hurricane warnings posted for these countries.

During a hurricane season (June – November), the number of TCs formed in the IAS exhibits double peaks. The first peak is in June and July, and the second in October and November. The minimum of genesis during August coincides with the MSD (section 2.1a), a maximum of sea level pressure, and a strong easterly CLLJ. However, it is quite common during August and September to have TCs move into the IAS region from the east. Long-term variability of TCs in the IAS region is an unavoidable issue for the study of IAS climate. Hurricane activity fluctuates with known climate phenomena, such as ENSO (Gray 1984) and the Atlantic multidecadal oscillation (AMO – Goldenberg et al. 2001). During an ENSO warm event (El Niño), vertical shear in the zonal wind increases in the Atlantic sector due to the eastward shift of the convective center in the equatorial Pacific, likely resulting in an abnormally low number of TCs. The opposite would occur during a cold ENSO event (La Niña). On decadal timescales, there is a clear signature suggesting that the number of TCs in the IAS varies in tandem with the AMO (Fig. 6). The number IAS hurricane landfalls in years of AMO warm phase (positive SST anomalies in Fig. 6 is more than twice of that in years of AMO warm phase (Fig. 6). There also exists the question of how global warming may impact hurricane activity in the IAS. While the frequency of events is strongly dependent upon future ENSO states, current research (e.g., Knutson and Tuleya 2004) suggests relatively small (~5%) increases in wind speed and rainfall around the time of doubling in the amounts of greenhouse gases several decades from now. These possible changes are dwarfed by the large multidecadal swings in activity (Landsea et al. 1999).

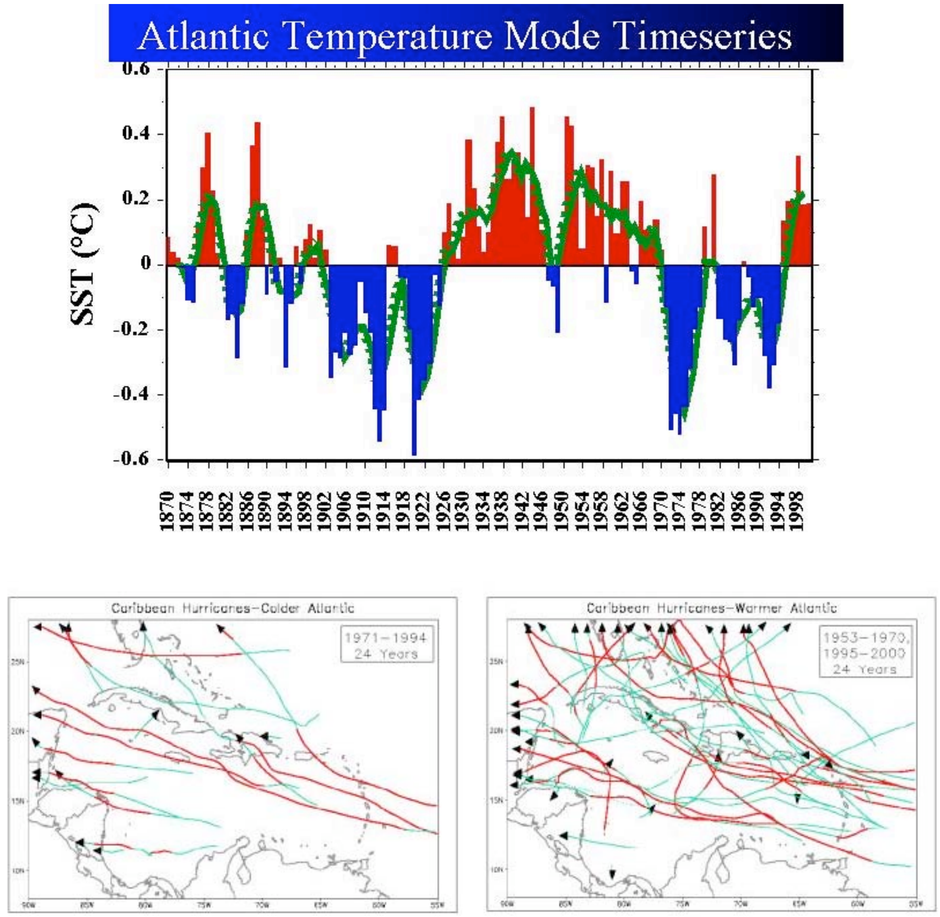


Fig. 6. Top: Smoothed (green) and unsmoothed (red/blue) versions of the detrended annual averages of Atlantic SST from the equator to 70°N. Bottom: Landfalling hurricane tracks in the IAS during years of cold (1971-1994, left) and warm (1953-1970 and 1995-2000, right) North Atlantic (AMO).

Recent NCAR CAM3.1 model experiments show that the AWP affects Atlantic hurricane activity through both the dynamical parameter of the tropospheric vertical wind shear and the thermodynamical parameter of the moist static instability of the troposphere (Wang and Lee 2007; Wang et al. 2007). Dynamically, the AWP-induced atmospheric circulation pattern is baroclinic (Gill 1980), with a cyclone in the lower troposphere and an anticyclone in the upper troposphere. This circulation structure reduces the lower tropospheric easterly and the upper tropospheric westerly flows, thus resulting in a reduction of the vertical wind shear that favors atmospheric convection. Thermodynamically, the AWP increases Convective Available Potential Energy (CAPE) due to the increased near-surface air temperature and water vapor content, providing the fuel for moist convection. More specifically, once the warm and moist surface air-parcel is lifted to the level of free convection, the air parcel gains greater buoyancy, thus we expect stronger and more frequent moist convection that favors hurricane development.

Many IAS TCs form from synoptic-scale disturbances often referred to as easterly waves (Pasch et al. 2004). Most of easterly waves, however, do not intensify into TCs but still are effective in rain production. Many of them form in the tropical Atlantic and propagate westward into the IAS region. Some form locally in the IAS. About 25 – 50% of mean signals in deep convective clouds in the IAS region are associated with the easterly waves (Gu and Zhang 2002), suggesting a similar or slightly less fractional contribution to total rainfall by them. The interannual and decadal variability of easterly waves in the IAS has only preliminarily been documented and studied (Thorncroft and Hodges 2001).

3. Large Scale and Regional Climate Components

3.1 Western Hemisphere Warm Pool (WHWP)

The Western Hemisphere Warm Pool (WHWP), extending over parts of the tropical northeastern Pacific (ENP), the Gulf of Mexico, the Caribbean Sea, and western part of the tropical North Atlantic (TNA), is the second largest body of warm water (SST > 28.5°C) in the world. Its size undergoes a substantial seasonal cycle (Fig. 7). It also varies on interannual timescales with extremes that rival the annual cycle (Wang and Enfield 2003). Although a large WHWP tends to develop following a warm event of ENSO, there is no systematic concurrence between the two. Only about half of identifiable ENSO warm events were followed by an anomalously large warm pool (Fig. 8).

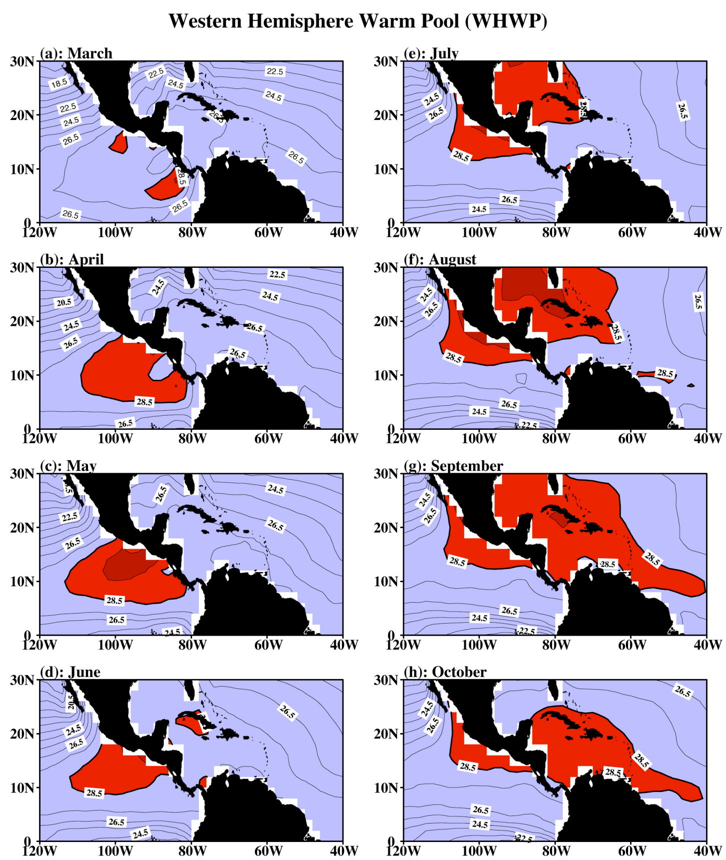


Fig. 7 Seasonal distributions of SST for the tropical WHWP: (a) Mar, (b) Apr, (c) May, (d) Jun, (e) Jul, (f) Aug, (g) Sep, and (h) Oct. The shading and dark contour represent water warmer than 28.5°C. (From Wang and Enfield 2003)

It has been shown that anomalies of the warm pool size are positively correlated with the warmth of the TNA region. The TNA and warm pool anomalies are believed to be a dominant influence on boreal summer climate in the northern tropics and subtropics of the Western Hemisphere (Wang et al. 2006). The WHWP is a birthplace of many tropical cyclones that cause loss of life and huge damages over the neighboring land areas. The number of Atlantic hurricanes varies with the size of the warm pool (Wang et al. 2006) as well as the tropical North Atlantic SST (Goldenberg et al. 2001). This relationship between hurricanes and the warm pool is due to less than normal vertical wind shear and an increase of the moist static instability which are both favorable to the development of hurricanes (Knaff 1997; Goldenberg et al. 2001; Wang and Lee 2007) or more than normal oceanic heat content that is favorable to the development of hurricanes (see section 3.5).

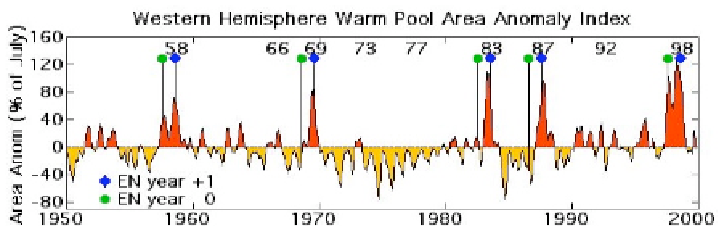


Fig. 8 Anomaly time series of the Americas warm pool area surrounded by the 28.5 °C isotherm. The series is expressed as a percentage of the climatological mean area for July. The July values of the five largest anomalies are indicated by the blue diamonds, and the July values of the prior years by green circles. Years of major ENSO warm events are also marked.

Partially because of the WHWP, the IAS region hosts the second largest tropical convection center in boreal summer. Associated with this convection center are large-scale circulations with their ascending branch rooted in the IAS region. These circulations are second only to those in the western Pacific and Asian summer monsoon region in the scale and intensity. Their descending branches reach as far as the southeastern Pacific, central South America, and the tropical eastern Atlantic (Fig. 9).

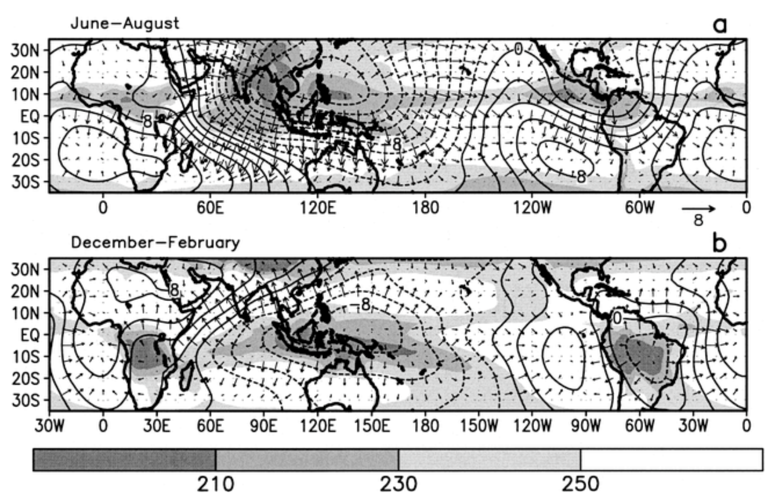


Fig. 9 1979–2000 climatological mean OLR (shaded, W m^{-2}), 200-hPa velocity potential (contours, interval is 2 x10^{6} m^{2} s^{-1}), and divergent wind vectors (m s^{-1}) for (a) JJA and (b) DJF. The divergent vector wind scale is located below (a). (From Chelliah and Bell, 2004)

The strength of the descending branches of these circulations can directly influence the cloud coverage and precipitation in these regions. Potential connections from the IAS convection center to marine stratus in the southeastern Pacific and precipitation in the Atlantic ITCZ are of particular interest to climate and its variability in South America.

Another important role the WHWP plays in the Western Hemisphere climate is its supply of water vapor to rainfall in South, Central, and North Americas. This will be discussed in section 3.2.

The Central America landmass divides the WHWP into two ocean regions: (1) the eastern North Pacific (ENP) warm pool and (2) the Atlantic warm pool (AWP). The ENP warm pool is highly correlated with ENSO since it is close to the ENSO region of maximum variance. If a warm pool 25% larger (smaller) than the climatological area is defined as a large (small) warm pool, observations after 1950 show that about two thirds of the overall AWPs (both large and small AWPs) appear unrelated to ENSO (Wang et al. 2006). In other words, the AWP does not highly depend on ENSO events.

Observations show that the AWP is correlated with rainfall anomalies in many places of the Western Hemisphere during the summer (Wang et a. 2006). Significant positive correlation is observed over the Caribbean, Mexico and Central America, and the southeast Pacific, while negative correlation is found over northwest US and Great Plains regions, and eastern South America. Locally, a large AWP is associated with a decrease in sea level pressure and an increase in atmospheric convection and cloudiness and thus an increased rainfall. Large (small) AWPs and warm (cold) TNA correspond to a weakening (strengthening) of the northward surface winds from the AWP to the Great Plains that disfavors (favors) moisture transport for rainfall over the Great Plains. On the other hand, large (small) AWPs and warm (cold) TNA strengthen (weaken) the summer regional Atlantic Hadley circulation that emanates from the warm pool region into the southeast Pacific, changing the subsidence over the southeast Pacific and thus the stratus cloud and drizzle there.

Not much is known quantitatively about the WHWP depth topography (or, consequently, its total heat content). There is a huge dichotomy between the northern Caribbean, where warm pool reaches nearly 100 m, and the southern reaches along the northern coast of South America, where upwelling maintains shallow warm pool depths. The contrast in heat potential of these two regions bears strongly on how hurricanes intensify en route to landfall, as occurred with Hurricane Wilma in the 2005 season. The open ocean waters of the northern Caribbean are generally oligotrophic and, thus, have a high degree of clarity, so short wave penetration (and, hence, heating) to substantial depths is likely. It is also a region of negative wind stress curl that favors downwelling, and where drifters tend to stagnate.

Air-sea heat exchanges in the warm pool are constantly modulated by various atmospheric systems, such as easterly waves, the ITCZ, tropical cyclones in boreal summer, and fronts in winter, in addition to the persistent trade wind and low-level jet. Significant air-sea moisture exchanges (especially evaporation in the eastern IAS and precipitation in the western IAS) affect the density stratification (and, thus, stability) of the upper water column and, hence, its dynamics. The upper ocean salinity structure of the warm pool is also influenced by the river discharge of several major rivers, a consequence of more indirect air-sea-land interactions (section 3.6). There is strong horizontal advection of the Gulf Stream System and oceanic mesoscale eddies are numerous and vigorous. Many of these processes are of synoptic or subseasonal timescales. But their cumulative effects on the mixed-layer dynamics and thermodynamics must be well simulated by models in order to reproduce and predict the seasonal to interannual variability of the size of the warm pool.

3.2 IntraAmericas Low-Level Jet (IALLJ) and water vapor budget

The trade wind plays an important role in modulating precipitation over the Caribbean region (Amador 1998, Amador and Magaña 1999). As the trade wind enters the Caribbean Sea, it intensifies and forms the IntraAmericas Low-Level Jet (IALLJ). The core of the low-level jet is at the level of 925 hPa. In austral summer, this low-level jet bifurcates into two branches (Fig. 10c). The central branch, also known as the Caribbean low-level jet (CLLJ), penetrates westward through the Caribbean Sea and Central America into the eastern Pacific. Strong surface wind associated with this low-level jet offshore of the Gulf of Papagayo may influence the Costa Rica dome dynamics during the boreal winter and spring.

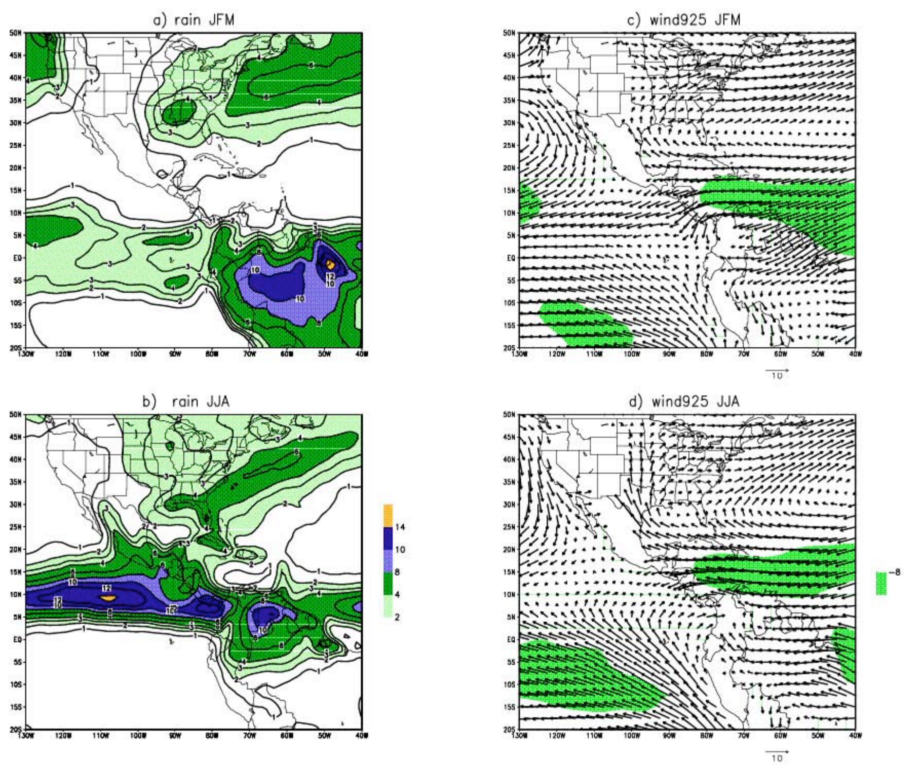


Fig. 10 Mean precipitation for January- March (JFM) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm/day, (b) same as (a), but for June-August (JJA), (c) Mean winds at 925 hPa for JFM averaged from 1997 to 2002 based on the CDAS (Kalnay et al. 1996). The unit vector is 10 m/sec. Areas where the zonal wind is greater than 8 m/sec are shaded, and (d) same as (c) but for JJA.

The southern branch goes into South America directly from the tropical Atlantic Ocean. There, it veers southward and connects with the South American low-level jet (SALLJ) along the eastern slope of the Andes. In boreal spring and summer, the central branch (CLLJ) is located near the same place as in austral summer, but it is now associated with the part of moisture transport that supplies moisture to the Great Plains. During these seasons, a northern branch splits from the central branch and veers toward the Gulf of Mexico, where it connects to the Great Plains Low-Level Jet (GPLLJ) (Fig. 10d). The strength of the southern branch peaks in February and the northern branch peaks in July. The strength of the central branch exhibits a semi-annual cycle with peaks in February and July. It also varies with ENSO phases. Weaker (stronger) than normal wind velocities at 925 hPa tend to occur at a warm (cold) ENSO phase during winter, and the opposite occurs during summer (Figs. 10 and 11; Amador et al., 2003).

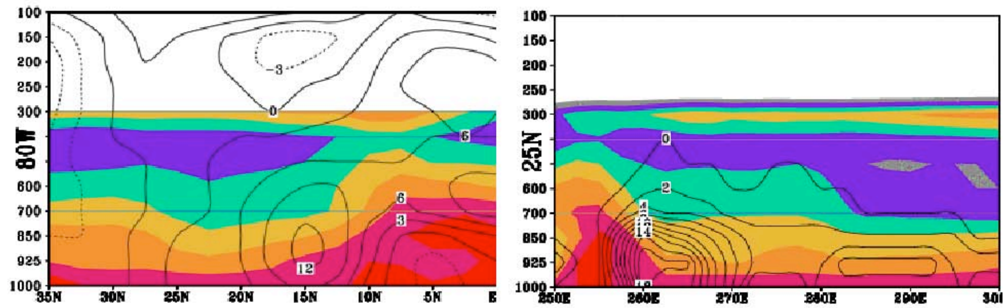


Fig. 11 Vertical-meridional cross-section of zonal wind (contours, m/sec) at 80˚W (left panel) and vertical-zonal cross-section of meridional wind (contours, m/sec) at 25˚N (Right panel) for July based on the NCEP/NCAR reanalysis.

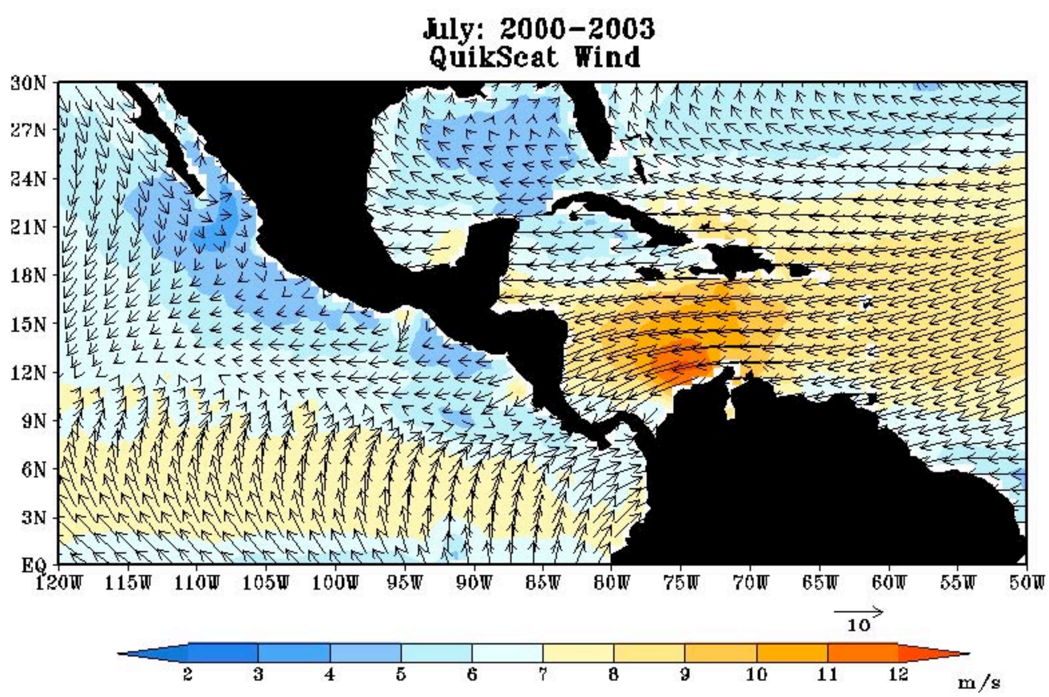


Fig. 12 July mean QuikScat winds (m s^{-1}) for the period 2000-2003 (from Amador et al., 2006).

The location and strength of the easterly winds influence the rainfall pattern over southern Mexico, Central America and the adjacent eastern Pacific (Fig. 10b). The peak of the CLLJ in July might be related to the MSD in part of Central America (Magaña et al. 1999; Magaña and Caetano 2005). Convective activity over the Caribbean might be reduced due to an increased low level vertical wind shear during summer (Amador et al., 2000). Cooling due to coastal upwelling induced by the CLLJ might contribute to the semi-aridicity of northern Venezuela and the Netherlands Antilles (Granger 1985). An important issue closely related to the moisture transport by the IALLJ is the water vapor budget (E-P) over the IAS. The fact that the IAS is a source of water vapor for the surrounding regions indicates that evaporation there exceeds precipitation (E>P). Evaporation can be substantially enhanced by the IALLJ, with its strong wind speed extending from its core at the 925 hPa level to the surface (Fig. 11). The signature of the IALLJ at the surface is well captured by satellite scatterometer wind data (Fig. 12). The variability of the moisture supply by the IAS would depend on both the variability of the IALLJ and the size of the warm pool (e.g., the fetch of surface wind of the IALLJ over the warm pool).

Observations show the CLLJ has both seasonal and interannual variability as well as longer timescale variations and that it relates to climate (Wang 2007). On seasonal timescale, the semi-annual strengthening of the easterly CLLJ results from the semi-annual variation of the meridional SST and SLP gradients that are due to the seasonal east-west excursion of the NASH. A positive ocean-atmosphere feedback may be operating for maintaining the easterly CLLJ. A meridional SST gradient in the Caribbean induces a meridional SLP gradient (Lindzen and Nigam 1987) that produces the easterly CLLJ. The easterly CLLJ in turn results in negative and positive wind stress curls to the north and south of the CLLJ core, respectively. The negative wind curl warms the northern Caribbean and the positive curl cools the southern Caribbean through oceanic Ekman dynamics, thus resulting in a further increase of the meridional SST gradient.

Interannually, the CLLJ anomalies vary with the Caribbean SLP anomalies that are connected to the variation of the NASH. In association with cold (warm) Caribbean SST anomalies, the atmosphere presents high (low) SLP anomalies near the Caribbean region that are consistent with the anomalously strong (weak) easterly CLLJ. The CLLJ is also remotely related to the SST anomalies in the Pacific and Atlantic, reflecting that these SST variations affect the NASH. During the winter, warm (cold) SST anomalies in the tropical Pacific correspond to a weak (strong) easterly CLLJ. However, this relationship is reversed during the summer. This is because the effects of ENSO on the NASH are opposite during the winter and summer. The CLLJ varies in phase with the North Atlantic Oscillation (NAO) since a strong (weak) NASH is associated with a strengthening (weakening) of both the CLLJ and the NAO. The CLLJ is positively correlated with the 925-hPa meridional wind anomalies (or the GPLLJ anomalies) from the ocean to the United States via the Gulf of Mexico. Thus, the CLLJ and the GPLLJ carry moisture from the ocean to the central United States, usually resulting in an opposite (or dipole) rainfall pattern in the tropical North Atlantic Ocean and Atlantic warm pool versus the central United States.

Consistent with this picture, Fig. 13 shows that reduced northward moisture flux across the gulf coast of the United States is correlated with decreased moisture flux convergence and less rainfall east of the Rocky Mountains (a), and with a warmer (larger) Atlantic warm pool and weaker CLLJ (b) (Mestas-Nuñez et al. 2007). These results are also consistent with the analysis of Ruiz-Barradas and Nigam (c, d) (2005).

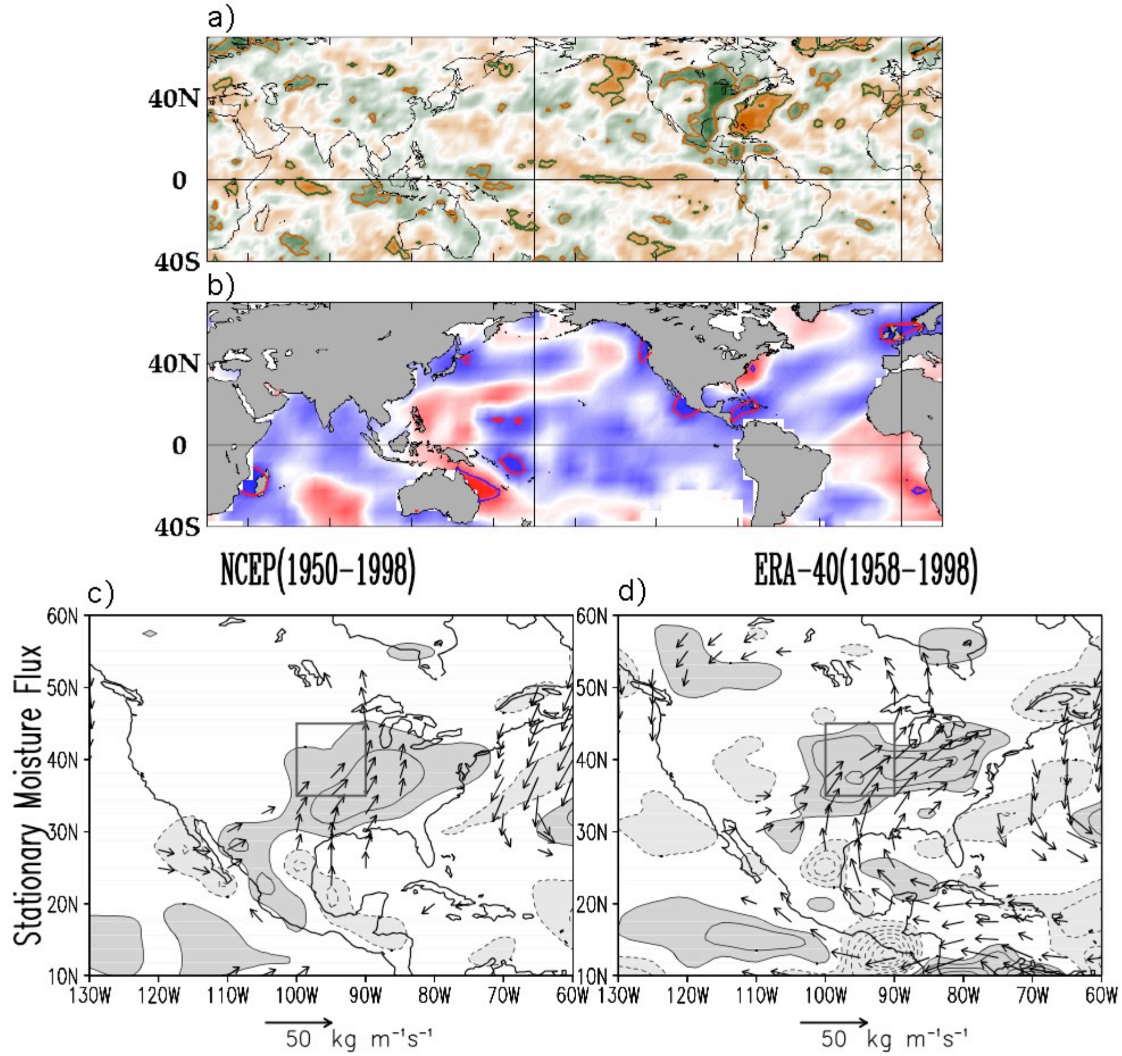


Fig. 13. Upper panels: Correlation of northward moisture flux across the Gulf of Mexico with CMAP precipitation (a) and sea surface temperature (b), from Mestas-Nuñez et al. (2007). Lower panels: Regression of NCEP reanalysis precipitation (c) and ERA reanalysis precipitation (d) on summer precipitation over the Great Plains (box area), from Ruiz-Barradas and Nigam (2005).

3.3 The Intertropical Convergence Zone (ITCZ)

In the Atlantic and eastern Pacific, the ITCZ is well defined as narrow bands of surface wind convergence and concentrated precipitation elongated zonally. This typical structure of a marine ITCZ is interrupted by the complex land-sea distribution and terrains in the IAS region. There, precipitation distribution in local warm seasons more or less follows the landmass. Nonetheless, precipitation in the IAS share common features with the marine ITCZ, and the two substantially influence each other. For example, westward-propagating synoptic-scale disturbances (e.g., easterly waves) contribute 10- 15% of total convection in the IAS region, as in the Pacific and Atlantic ITCZs (Gu and Zhang 2002). The annual migration of the strongest precipitation in the IAS region is in concert with those of the Atlantic and eastern Pacific ITCZs (Fig. 3; Hastenrath 2002), which is also concomitant with the development of mesoscale convective systems over the region seen from the TRMM satellite mission (see Fig. 7 of Poveda et al., 2006). In austral summer, when both Atlantic and Pacific ITCZs are at their southernmost positions, heavy rainfall over land in the region is confined to south of 10°N (Zhou and Lau 1998). At this time of the year, most of the land areas of the IAS region experience a dry season, except the southeast US where precipitation is concentrated underneath the winter storm tracks. During boreal spring (March – May), a double ITCZ exists in the eastern Pacific before the northern branch starts migrating northward (Zhang 2001). As both Atlantic and Pacific ITCZs migrate northward during boreal spring and summer, so does rainfall over land in the IAS region. Interactions between the ITCZ, the warm pool in the eastern Pacific, and the CLLJ to the east might be instrumental to the MSD in July (Magaña *et al* 1999; Magaña and Caetano 2005).

To a certain degree, anomalous latitudinal positions of the ITCZ manifest the influences of ENSO on precipitation in the IAS region. A southward shift of the Pacific ITCZ during El Niño results in an anomalously strong local meridional circulation and a reduction in seasonal mean rainfall over much of Mexico and the Caribbean (Higgins and Shi 2001; Hu and Feng 2002). To the opposite, a northward shift of the Pacific ITCZ during La Niña is accompanied with an increase in precipitation in those regions. On the Atlantic side, cold (warm) SST anomalies in the northern (southern) tropical Atlantic can modulate the location of the ITCZ and thus precipitation over northeast Brazil during austral summer (Nogues-Paegle and Mo 2002).

Understanding the variability and dynamics of the ITCZ is a global problem that should not and cannot be solved for the IAS region only. But the role of the ITCZ in IAS rainfall and effects of the IAS region on the ITCZ provide a unique scenario for the study of the ITCZ. Effects of land in the IAS region on the ITCZ, perhaps deviating sharply from any known ITCZ dynamics over the ocean and modulating the ITCZ over both the eastern Pacific and western Atlantic, provides an opportunity to advance our overall understanding of the ITCZ. How the distribution and variability of rainfall over land in the IAS region interact with the ITCZ over ocean, for example, is a subject that needs more research.

3.4 The North Atlantic subtropical high (NASH)

The North Atlantic subtropical high (NASH), also known as the Bermuda high, is a robust feature that directly affects the IAS region. The NASH is the most important factor in determining significant SST anomalies in the tropical North Atlantic (TNA) and in the IAS, and hence the size and the intensity of the AWP. The NASH determines the strength of the trade wind and its associated surface evaporation and coastal upwelling. The seasonal variability of the NASH is closely related to the seasonal cycle of precipitation in the IAS region. An anomalously strong NASH or an anomalously southward displacement of the NASH, when accompanied by a southward shift of the eastern Pacific ITCZ, would lead to a dry summer in the Caribbean (Giannini et al. 2000). A westward protrusion of the NASH contributes to the MSD (Mapes et al.

2004) and the CLLJ and CLLJ’s westward moisture transport (Wang and Lee 2007; Wang 2007). The NASH dominates most of the IAS region during the dry season of boreal winter. The position and strength of the NASH during summer are critical to the tracks of tropical cyclones in the region.

The NASH may fluctuate under a number of influences. The factor that produces the largest anomalies is the reduced meridional overturning circulation from the Amazon heat source into the NASH region when El Niño is at its peak during boreal winter. This produces a weaker NASH, a weak NE trade wind, and a rise in SST over the TNA region during the summer following the El Niño peak, which may lead to a large Atlantic warm pool. Conversely, the NCAR CAM3.1 ensemble runs show that the NASH is weakened if the AWP is large (Wang et al. 2007), suggesting a possible positive feedback between the two. A large AWP and a weakened NASH both favor increased rainfall in the Sahel and the Caribbean, and they also favor more frequent hurricanes.

The climatic importance of the NASH and its boreal summer IALLJ extension over the IAS is illustrated by Fig. 14, a composite based on strong occurrences of the IALLJ found in the NCEP North American Regional Reanalysis (NARR) (Mesinger et. al. 2004). The composite shows the enhanced rainfall pattern over the United States associated with strengthened IALLJ. It also shows negative rainfall anomalies covering the Gulf of Mexico and the Caribbean. The composite of 925 hPa wind anomalies indicates that the branch of moisture transport from the Caribbean through the Gulf of Mexico to the Great Plains strengthens. Over the Caribbean, strong zonal transport implies a strong CLLJ. The relationships between the CLLJ and rainfall over the Great Plains indicates that the conditions in the IAS are important to the floods and drought monitoring and prediction over the United States in summer.

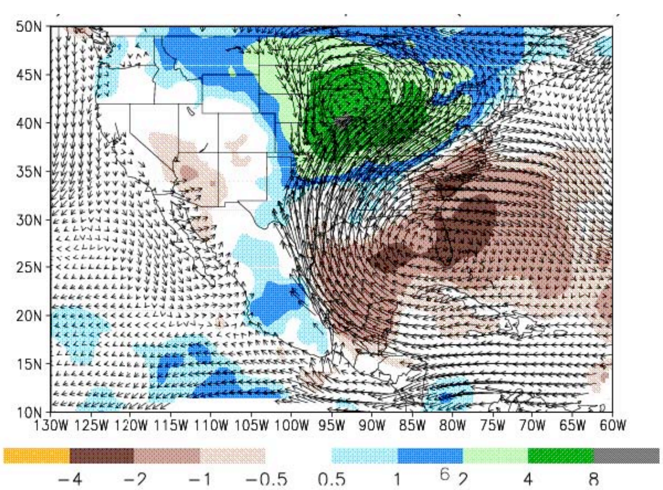


Fig. 14 Composite of precipitation (colored) and 925 hPa wind anomalies. The unit vector is ms-1.

Ocean-atmosphere variability within the Atlantic sector, mostly unrelated to ENSO, may also affect the NASH (Seager et al 2003). This includes the state of the NAO in the North Atlantic, especially during the boreal winter. A negative (positive) NAO pattern will typically lead to a weaker (stronger) NASH and correspondingly higher (lower) SSTs in the TNA region. Such anomalies, if they persist through the early calendar months of the year, will lead to anomalies of the summer warm pool and impact summer weather in the regions north of the equator. Another influence is tropical Atlantic variability (TAV), wherein, for example, a wind-evaporation-SST (WES) feedback can set in if the tropical South Atlantic is in a strong anomalous state. The resulting WES can induce an SST signal of the opposite polarity in the TNA region.

3.5 Climate response to the Atlantic warm pool

The ensemble runs of the NCAR community atmospheric model (CAM3.1) show that the AWP plays an important role in the summer climate of the Western Hemisphere (Wang and Lee 2007; Wang et al. 2007). The model control runs (CTRL) forced by climatological SSTs reproduce well the flows of moisture around the NASH and through the CLLJ into the central U.S. (Fig. 15).

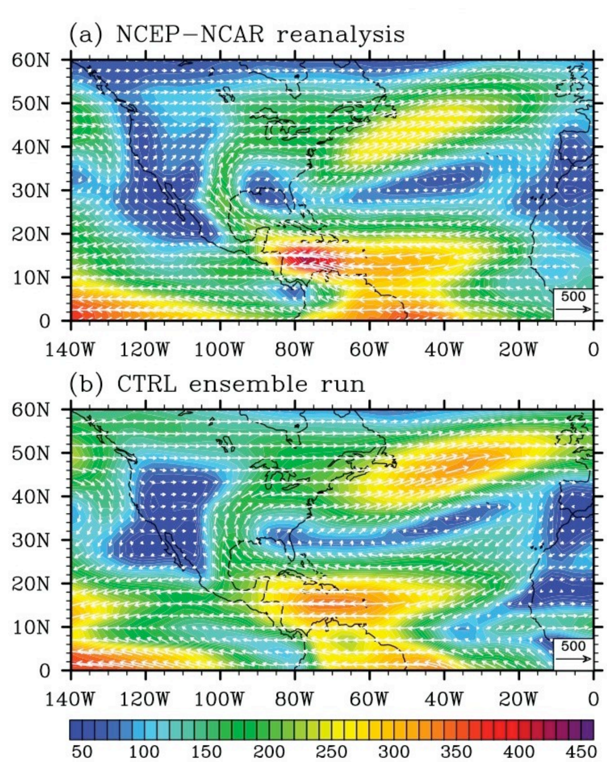


Fig. 15. The summer (JJA) vertically integrated moisture flux, calculated from (a) the NCEP-NCAR reanalysis and (b) the CTRL ensemble run. Arrows indicate the moisture flux vector and colors represent the amplitude of the moisture flux.

The impact of the normal warm pool on the model is found by running the model without the summertime increase in warm pool SST (ensemble, NO_AWP), then subtracting the NO_AWP model fields from those of the CTRL ensemble. The effect of the AWP is to weaken the summertime NASH, especially at its southwestern edge and it also strengthens the summertime continental low over the North American monsoon region. In response to these pressure changes, the easterly CLLJ and its westward moisture transport are weakened. The model experiments also show that the AWP weakens the southerly GPLLJ that reduces the northward moisture transport from the Gulf of Mexico to the United States east of the Rocky Mountains, resulting in a decrease of rainfall over the central United States in agreement with observations. Finally, the presence of the AWP during August-October induces a 5 m/sec decrease in the 200 hPa–850 hPa vertical shear over the IAS and western tropical North Atlantic (Fig. 16), as well as a large increase in convective available potential energy (CAPE), both important factors in hurricane development.

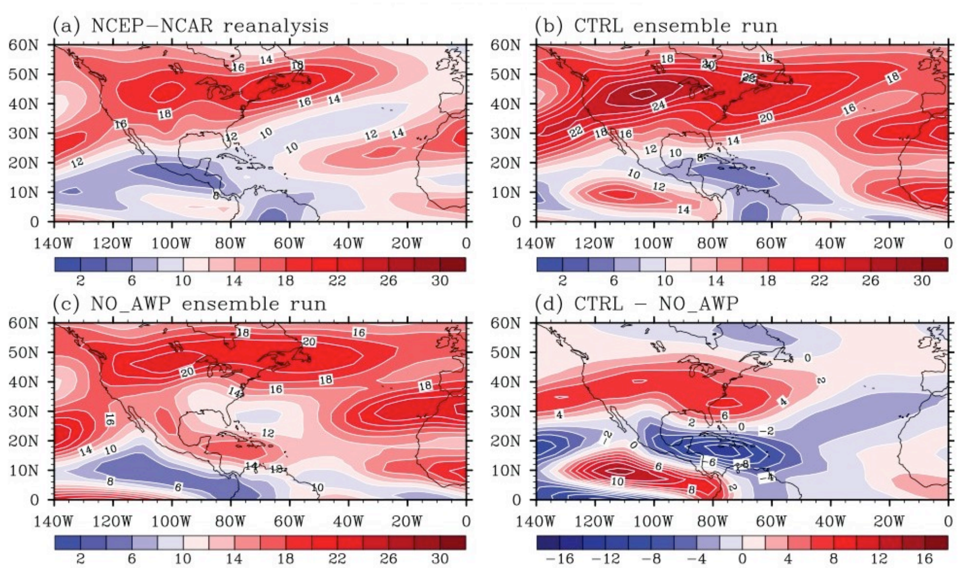


Fig. 16. The200 hPa minus 850 hPa vertical wind shear (m s^{-1}) during August-September-October (ASO) from (a) the NCEP-NCAR reanalysis, (b) the CTRL ensemble run, (c) the NO_AWP ensemble run, and (d) the difference between the CTRL and NO_AWP runs. From Wang et al. (2007).

Enfield et al. (2001) show that the Atlantic Multidecadal Oscillation (AMO) in North Atlantic SST is inversely correlated with rainfall over most regions of the United States and McCabe et al. (2004) show that the AMO was probably involved in past mega-droughts. As shown in Wang et al. (2006), the summer AWP area index also shows the signal of the AMO. Warm phases of the AMO are characterized by repeated large summer AWPs, the cumulative effects of which can amount to persistent drought during the growing season. Sutton and Hodson (2007) show that the climate response to the AMO SST anomalies is primarily forced by the tropical Atlantic SST anomalies. This seems to suggest that mechanism of the North Atlantic SST-related (or AMO-related) rainfall over North America may be operated through that of the AWP-induced change of the northward moisture transport. On interannual and longer timescales, even subtle but sustained changes in the moisture inflow to the United States Great Plains from the Gulf of Mexico can contribute to severe drought conditions, consistent with other studies (e.g., Schubert et al. 2004; Seager 2007).

3.6 Land-air-sea interactions

Land is without doubt an essential component of the climate system in the IAS region. It interacts with both atmosphere and ocean. Soil moisture, for example, has long been recognized to be very important to atmospheric variability, especially in the hydrological cycle (e.g., Delworth and Manabe 1989; Poveda et al 2001; Atlans et al 1993). In the IAS region, the onset of a wet season might be affected by the soil moisture content and surface latent heat flux during the seasonal transition, which are determined by rainfall in the preceding dry season (Fu and Li 2004). The topography of the region plays a major role in rainfall distribution and variability (Vargas and Trejos 1994; Poveda et al 2005). On many Caribbean islands, contrast between mean rainfall on the windward and leeward sides of mountains can be as large as a factor of 5 (e.g., Granger 1985). The vegetation in the region also plays a major role in the land-air interaction. The IAS for example has a large percentage of tropical cloud forests. These forests are unique among terrestrial ecosystems in their tight coupling to the atmospheric hydrologic cycle. This coupling is accomplished partly through regular cycles of inundation by orographic cloudbanks above 400m, and the moisture inputs from such cloud inundations are a significant fraction of regional annual rainfall (Bruijnzeel and Proctor 1993; Clark et al. 2000).

From a modeling perspective, changes in land surface temperature over the subtropical South America can modify precipitation not only locally but also remotely over the Caribbean Sea and Central America (Misra et al. 2002). The land effect in the IAS region cannot be fully understood without considering the adjacent oceans. The observed mean distribution of rainfall in the region can be viewed as a consequence of a competition between land and oceans. While moisture is more easily available locally over the ocean, lifting mechanisms are more vigorous over land through the effect of terrain and surface heating. The Caribbean Sea is a case in point, where mean rainfall amount is extremely low in comparison to that over the surrounding lands (Fig. 3). A poor representation of this competition might be a reason for the large errors in rainfall simulated by global models (e.g., Fig. 2). These errors can have directly effects on simulated water vapor budget of the region. Land surface temperature may also contribute to the horizontal pressure gradient in the region, which determines the strength of the low-level jet. Coastlines along the IAS are predominant both continental and in island where sea and land breezes contribute to the daily precipitation cycles and its contribution to the climatological mean.

Land-air-sea interactions in the IAS region might take place through modulation of SST by surface wind related to land convection. Satellite observations have shown that a strong convective event over the western Amazon during boreal spring induces significant change of surface winds and fluxes in the IAS and Northwestern tropical Atlantic during boreal spring (Fig. 17). Collectively, the strongest 20% of large-scale rainy events during boreal spring can leads to as much as 0.5°C cooling over Gulf of Mexico (Fig. 18, during the coolest season of the IAS). Such effect also has strong interannual variation, in part due to changes of rainfall and probably background atmospheric flow. This result suggests that the climate conditions, such as ocean surface winds and fluxes over IAS, cannot be adequately understood and presumably predicted without understanding their connection with convection over American continents. Strong rainy events in the western Amazon appear to enhance north and Northeasterly winds over tropical western Atlantic. The MSD might be another case in point (Magana et al 1999). Among others, land-air-sea interaction is the least understood process in the IAS region and perhaps also in other regions.

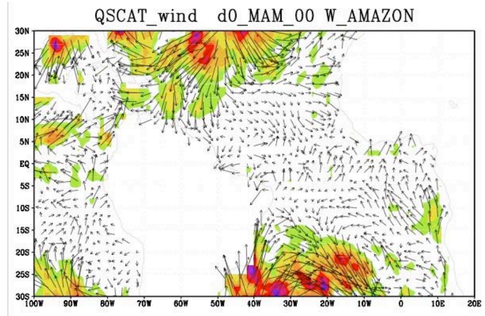


Fig. 17: Ocean surface wind anomalies one-day after peaks of Amazon rainfall (the red square) during boreal spring (MAM). The winds and rainfall are derived from QuikSCAT and TRMM observations.

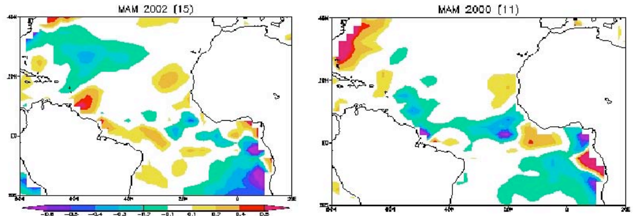


Fig. 18: SST anomalies induced by anomalous surface fluxes associated strongest 20% convective events during boreal spring (MAM) of (left) 2002 and (right) 2000 in the western Amazon. They are estimated by an ocean mixed layer model (Alexander 1992) with climatological mixed layer depths (Levitus and Boyer 1994). The SST anomalies are relative to the SSTs driven by climatological ocean surface fluxes for MAM. The scale of SST anomalies is indicated by color bar below a) in unit of ºC. Interannual variation is illustrated by the difference between a) and b).

Guided by the anticyclonic flow of the Bermuda High (NASH), most of moisture needed for the South America wet season rainfall comes from the tropical Atlantic, instead of the IAS. However, the northward reversal of the cross-equatorial flow in the Amazon appears to correlate to the strength and southwestern edge of the NASH and convection over the Antilles Island chain and the eastern Pacific part of the WHWP (Fig. 19).

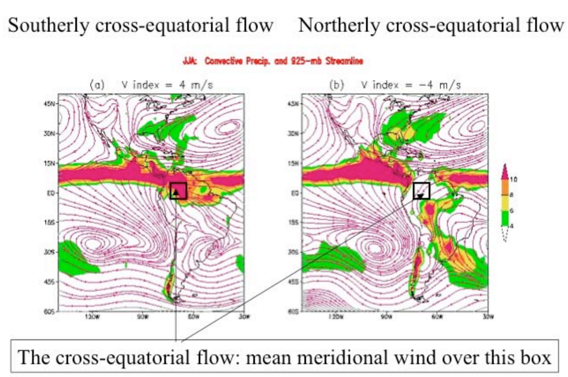


Fig. 19: Streamlines at 925 hPa and TRMM daily rainrate associated with (a) southerly (b) northerly cross-equatorial flow for boreal summer (JJA) based on the linear regression for one sigma of the cross-equatorial flow. Streamlines are derived from ECMWF reanalysis. The analysis period is 1979-1993.

The reversal of the cross-equatorial flow in the Amazon dominates the intraseasonal, seasonal and interannual variations of rainfall over tropical South America (Wang and Fu 2002). It also plays a central role in the onset of wet season of that region (Li and Fu 2004). Although the cause of the northerly reversal of the cross-equatorial flow is still a subject of research, the observed relation nevertheless suggests a possible connection between a stronger convection over the warm pool and an earlier northern reversal of the cross-equatorial flow in boreal spring. This can consequently cause an earlier northward withdrawal of rainfall from the Amazon to the Caribbean coast. This process could contribute to the observed anomalous rainfall dipole between the Caribbean and adjacent northwest South America and interior Amazon and northeast Brazil shown in Fig. 9.

3.7 Intraseasonal variability

In the IAS region, intraseasonal (30-90 day) variability (ISV) is mainly due to the Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972). The ISV in the IAS is much stronger in boreal summer than winter because in summer the warmer sea surface over the northern tropical eastern Pacific sets a favorable condition for the MJO to be enhanced there (Maloney and Kiehl 2002; Maloney and Esbensen 2003). Accompanying the significant MJO-related variability over the east Pacific, notable downstream effects occur in the Central America and IAS region. MJO related variability in the IAS region has been detected in OLR (*Magaña and Yanai* 1991), upper-level divergence (Mo 2000), low-level wind (*Cavazos et al*. 2002), rainfall (Barlow and Salstein 2006; Higgins and Shi 2001; Poveda et al 2005), and SST (Maloney and Esbensen 2007; Maloney et al. 2007). During an easterly phase of the MJO, trade winds are strengthened across the eastern Pacific and the Caribbean, and so are the Central American gap winds (e.g., the Tehuantepec and Papagayo jets) (Maloney and Esbensen 2007). Analysis of individual stations in Mexico and Central America shows that extreme rainfall events are strongly modulated by the phase of the MJO during July – September (Barlow and Salstein, 2006). The most significant effect of the MJO is perhaps the modulation of hurricanes in the IAS region. When MJO wind anomalies in the lower troposphere of the eastern Pacific are westerly, Gulf of Mexico and western Caribbean hurricane genesis is four times more likely than when the MJO winds are easterly (Maloney and Hartmann, 2000; Mo 2000; Arias and Poveda, 2006).

4. The IASCLIP Program

The North American Monsoon Experiment (NAME), centered on a process study (Tiers I and II) that took place in 2004-2005, is primarily concerned with the convective processes that link the ENP warm pool and overlying ITCZ to the annual spring-summer migration of the monsoon rains from Central America northward along the western slopes of the Sierra Madre Oriental in northwestern Mexico, to the southern Rocky Mountains of the southwestern U.S. This effort was embedded within a much larger region that included the IAS and the eastern United States, termed Tier III, for which no observational program was proposed although some special observations were made in Costa Rica and Belize in the summer of 2004 (Higgins et al, 2006). The IASCLIP program, as yet undeveloped, is the concept for a broader eastward extension of research into the Tier III and AWP domain, to understand, simulate and predict, through data diagnostics, models and field campaigns, the seasonal and interannual behaviors of rainfall and tropical storms from the Caribbean to the central U.S. east of the Rockies, with emphasis on the transitions from boreal spring to summer and autumn. This involves the interplay of multiple factors, most of which covary with the size of the AWP: (1) the moisture budget above the AWP together with the variation of the Intra-Americas low-level jet (IALLJ) that transports moisture into and out of the region (Mestas-Nuñez et al. 2005; Mestas-Nuñez et al. 2007; Wang et al. 2006); (2) changes in the strength and latitude of the Intertropical Convergence Zone (ITCZ) in the Atlantic and eastern Pacific, and its embedded tropical waves; (3) the North Atlantic subtropical high (NASH) with its seasonal extension into the Caribbean and its interannual interaction with remote forcing by ENSO (Enfield et al. 2006), the North Atlantic Oscillation (NAO) (Chang et al. 1997; Czaja and Frankignoul 2002) and the Tropical Atlantic variability (TAV) (Chang et al. 1997); (4) Atlantic TCs whose number vary annually in response to ENSO (Gray 1984) and the AWP size (Wang et al. 2006); (5) land-air-sea interactions, including the effects of topography (Magaña et al. 1999), land-ocean temperature differential, soil moisture (Delworth and Manabe 1989), vegetation (Lawton *et al*. 2001),; (6) and the roles of the aerosols in modifying rainfall.

The climate processes and hydrological cycle in the IAS region should be a focus of research for VAMOS for the following reasons:

(a) The climate variability in the IAS region is a manifestation of collective influences by several remote climate modes (ENSO, NAO, TAV, AMO). Accurate predictions of annual and interannual variability of the IAS critically depend on not only the prediction of those climate modes but also how they modulate the local processes. This poses an unusual challenge to climate study.

(b) The IAS region is a source of strong remote influences of climate variability in the Central, and North Americas and is host to the largest convective heating center of the hemisphere in boreal summer. A full understanding of the processes that control the hydrological cycle and convective heating in the IAS region and their intricate relationships is therefore of a broad interest for the Americas.

(c) Many, if not all, global climate models suffer from large errors in their simulations of precipitation in the IAS region. The complexity in the climate variability of the IAS is highlighted by remote vs. local climate controls, many types of precipitation systems, and complicated surface boundary conditions. Only if a climate model adequately represents convective and boundary-layer processes over both ocean and land and reproduces both local climate processes and global climate modal variability, can it do well in the IAS region. The IAS is, therefore, an ideal natural laboratory to test the overall fidelity of climate models.

The overall goal of the IASCLIP program is to promote, coordinate, and organize research activities that aim at improving our understanding of climate and hydrological processes in the IAS and improving our ability of representing these processes in global climate models. The IASCLIP program embraces two research themes, summarized from the discussions in section 3:

Theme 1. Mechanisms for the seasonal to interannual variability of rainfall in the IAS region.

The short-term (seasonal to interannual) climate variability of rainfall in the IAS region is controlled collectively and interactively by remote and local factors. “Remote controls” include ENSO, NAO, TAV, and AMO. “Local controls” are dominated by the WHWP (section 3.1) and NASH (section 3.4), and the IALLJ (section 3.2). Both remote and local factors must influence

IAS rainfall through modulating local precipitation processes, namely, the monsoons, trade wind and low-level jets (Section 3.2), ITCZ (section 3.3), TCs and easterly waves (section 2.2). These precipitation processes may interact with each other and feed back to the local climate controls. Contrasting effects of the ocean (moisture source, slow variability in surface temperature) and land (soil moisture, vegetation, topography, and a strong diurnal cycle of temperatures), and atmospheric composition (CCN, GCCN, and aerosols) on rainfall must play a vital role in realizing the remote and local influences on rainfall and in shaping the resulting seasonal and interannual variability of rainfall in the IAS into certain spatial distributions. It would be a challenge to assort and quantify the contributions of these processes to the short-term climate variability of rainfall in the IAS region.

Theme 2. Roles of the IAS region in the climate variability of Americas and the Western Hemisphere

Climate variability in Americas and the Western Hemisphere cannot be fully understood until the climate processes in the IAS region are. The IAS may influence remote areas through large-scale overturning circulations induced by convective heating from mesoscale convective systems in the IAS region and through water vapor transport by low-level jets from the IAS region. The physical processes that determine the variability of convective heating in the IAS region and the water vapor transports connect the IAS with climate variability in the remote areas and are therefore vital to the IASCLIP program. Central to these two research themes are several general scientific issues that are unique to the IAS region. These issues, to be discussed in the rest of this section, are all related to each other and none of them should be studied in isolation. Each issue, however, presents some unique challenges and serves as a research target for the IASCLIP program.

5. Relevant Science Issues

5.1 The Western Hemisphere warm pool (WHWP)

The WHWP is an essential factor for the climate of the IAS region and the Western Hemisphere because of its roles as a modulator of the ENSO effects on precipitation in the IAS region (section 3.1), as the summer convective heating center for the Western Hemisphere (section 3.1) and as a water vapor source and modulator of moisture transport (sections 2.1b and 3.2). Our understanding of these roles, however, remains qualitative and empirical. Notwithstanding the role of the warm pool in IAS climate suggested by the statistics, important questions remain to be addressed. First, mechanisms for the warm pool to influence local and remote precipitation, including the variability of local SST and the size of the warm pool, need to be identified. Second, mechanisms for the interannual variability of the warm pool need to be investigated. Relative effects of remote influences (e.g., ENSO, TAV, NAO) and local ones (the ITCZ, IALLJ, TCs and easterly waves) and the roles of oceanic processes (eddies, currents, upwelling) in comparison to surface energy exchanges with the atmosphere in the heat budget of the warm pool need to be quantified. Specific questions that need to be addressed include the following.

(a) What are the mechanisms by which the WHWP influences precipitation in the IAS region? – Based on a common notion that deep convection is more sensitive to small changes in SST where mean SST is high because of the Clausius-Clapeyron effect, precipitation would be sensitive to small anomalies in SST (< 0.5°C) in the IAS. But heaviest precipitation in the IAS region mainly occurs over land, except in the eastern Pacific and western Atlantic ITCZs (Fig. 3). The reason for the comparatively low rainfall over the Caribbean, compared with comparable warm water regions elsewhere, is not fully understood. Although it is thought that models generally overestimate the rainfall, the paucity of observations in the Caribbean makes it difficult to assess model performance. Possible effects of the WHWP on precipitation over land, in addition to its modulation of the water vapor transport (sections 3.1, 3.2), need to be explored.

(b) What are the mechanisms for the variability of the WHWP? – A recent observational diagnostic study (Enfield and Lee 2005) shows that the variability of the size of the WHWP is mainly due to fluctuations in surface heat fluxes controlled by the northeast trade wind in the Atlantic, whilst the trades are modulated by both ENSO and the NAO (Enfield et al. 2006). Ocean models are presently challenged by large uncertainties in the surface fluxes, by the complexity of the land-ocean-atmosphere interactions in the IAS region, and by the need to resolve important mesoscale processes such as current jets, coastal upwelling and eddy motions. To improve the predictability of summer rainfall, the MSD, and other climate features requires that the representation of the WHWP and its ocean-atmosphere interactions be improved in models. In addition to SST, mechanisms for the interannual variability in the upper-ocean heat content remain unknown, which is an important factor for TC intensification.

(c) How well can the WHWP be reproduced by ocean models? – This is a critical issue for coupled models to accurately predict the variability of the WHWP. This has been done by Lee et al. (2005) using a medium resolution version of the Miami HYCOM model and appropriate choices for surface fluxes and mixing algorithms. However, because of the complex coastal topography and associated upwelling in the IAS, it is likely that high-resolution models are required. To accurately reproduce the WHWP and its variability, it is essential to have the heat budget right for the upper ocean, which involves atmospheric forcing in surface wind (for latent and sensible heat fluxes, upwelling, and partially current thermal advection) and solar radiation flux (controlled primarily by clouds). The correct choice of surface fluxes for forcing such models has yet to be determined, although certain data sets do appear to be inappropriate (Enfield and Lee 2005).

(c) How does the warm pool influence hurricanes? – By forcing the NCAR CAM 3.1 AGCM with the summer SST (ASO) climatology and with warm pool SSTs replaced by winter values, Wang et al. (2007) have shown that the normal summer warm pool is responsible for a large decrease in tropospheric vertical shear. The same experiment also yields decreased moist static stability (Wang and Lee 2007), and both factors are important in the development of major hurricanes. Data diagnostics indicate that major hurricane activity and shear covary (in equivalent fashion) with warm pool size interannually (Wang et al. 2006) and multidecadally (Goldenberg et al. 2001). More model experimentation is needed to understand the role of

year-to-year fluctuations in the warm pool as they affect the dynamic and thermodynamic environment within which hurricanes mature.

5.2 Water vapor transport

An extremely important role of the IAS is to serve as a source of water vapor for precipitation in the IAS and surrounding regions (section 3.2). Water vapor transport from the IAS to the adjacent land areas is most efficient by the low-level jets (section 3.2). For improvement of precipitation prediction in the IAS and surrounding regions, the following questions need to be addressed to advance our knowledge of water vapor transport from this conceptual understanding.

(a) What are the structure and dynamics of the low-level jets in the IAS? – The IALLJ (comprised of the Caribbean low-level jet and its northward branch in the Gulf of Mexico) plays a vital role in providing moisture to the surrounding land regions. While many studies have been devoted to the GPLLJ and its role in precipitation in North America (section 3.2), few studies (Amador, 1998; Amador et al., 2003; Amador et al., 2006; Wang, 2007) have addressed the structure and dynamics of the IALLJ, so that many aspects of it remain unknown (e.g., origin, interaction with easterly waves, its role in the MSD). What are depicted by the global reanalysis (Fig. 11) have yet to be validated against *in situ* observations. Possible sources for errors and biases in the reanalysis products are the diurnal cycle of the CLLJ, which is not fully resolved by the global reanalysis, and the coarse spatial resolution and deficiency in boundary-layer parameterizations of the models that produce the global reanalysis. Notice from Fig. 7a that there are no in situ sounding observations near the core of the CLLJ. Many theories and hypotheses have been developed for the dynamics of the GPLLJ and SALLJ involving orography, midlatitude circulation, or strong diurnal cycle (e.g., Bonner 1968; Stensrud 1998; Byerle and Paegle 2003); very few are available for the low-latitude IALLJ. While the low-level jets are located at the western and southwestern edges of the NASH, the intensification of the wind might have to be explained in terms of other factors, such as low pressure systems in the IAS region created by local deep convection or land effects (section 3.6). Understanding the marine low-level jets has substantial global significance. In other monsoon regions (e.g., Asia and West Africa), marine low-level jets are also crucial to water vapor transport from ocean to land. Such water vapor transport by marine low-level jets is an important component of the global hydrological cycle.

The southernmost branch of the IntraAmericas Low-Level Jet (IALLJ), crosses over the Central American isthmus and become westerly winds over the tropical Pacific, thus enhancing the westerly Choco low-level Jet on the easternmost fringe of the tropical Pacific off Colombia (Poveda and Mesa, 2000; Poveda et al., 2006).

(b) What are the mechanisms for the interannual variability of water vapor transports? –In a model-based study of the impact of the warm pool, Wang et al. (2007) show that the presence of the summer warm pool is responsible for greater moisture over the IAS but a weaker NASH and IALLJ flows into the continental U.S. across 30°N and into the ENP across 75°W. Although the

NASH and the flow of the GPLLJ into the U.S. are weakened, the moisture transport is somewhat strengthened because of the increased specific humidity exiting northward from the Gulf of Mexico. In observations, however, large warm pools (warm IAS) are associated with reduced GPLLJ flow and *reduced* moisture transport together with less summer rainfall east of the Rockies (Wang et al. 2006), all consistent with Ruiz-Barradas and Nigam (2005). The physically inconsistent results for moisture transport are symptomatic of the counterplay between volume transport and moisture content of the air, and this represents a serious challenge for models to overcome. Also unexplored is whether the fractional contributions to water vapor transport from the IAS by evaporation from the IAS and the tropical Atlantic Ocean (Bosilovich and Schubert 2002) would vary interannually.

(c) How well do global and regional models reproduce the low-level jets? – Again, this issue has been addressed more for the GPLLJ but much less for the IALLJ. For prediction, it is essential to understand and reproduce in models the relationships between IALLJ strength and large-scale circulation factors such as ENSO, the NAO, Amazon convection, and the North Atlantic subtropical high (NASH), as well as surface forcing by large or small sizes of the AWP. On the positive side, observational studies now show that the boreal winter ENSO and NAO, and to a lesser extent, the Atlantic TAV, do influence the large interannual excursions in summer warm pool size, and by association, the NASH and the IALLJ (Enfield et al. 2006; Wang et al. 2006). An important charactersitic of the IALLJ is that it is stronger (weaker) than normal during warm (cold) ENSO phases during boreal summers (Amador et al. 2006). The key issue here is whether the characteristics and the controlling factors for the IALLJ are well represented by the models, an obvious requirement for predictability. Parameterizations and resolutions are concerns for the current global models and remote influences (through lateral boundaries) are issues for the regional models. If there are large errors and biases in model simulations, their causes (e.g., representations of local physical processes vs. remote influences) must be identified.

(d) Problems with reanalyses — Inevitably, reanalyses will be treated as data for the purpose of validating model behaviors, yet we know that the reanalyses themselves are uncertain in data-poor areas, such as the Caribbean. Before the global reanalyses can be used to validate AGCM simulations, their depictions of the IALLJ have first to be corroborated by observations. There is, however, no aerological sounding history in the Caribbean core of the IALLJ. Uncertainties in the IAS-integrated moisture transports in the NCAR/NCEP reanalysis have been assessed by Mestas-Nuñez et al. (2005). To further illustrate problems in the NCAR/NCEP reanalysis Fig. 20 is presented. Data from three stations near the Gulf of Mexico and continental USA (Monterrey, Corpus Christi and Lake Charles) were utilized to compare the annual cycle of the meridional wind and moisture flux associated with the GPLLJ entrance near 30°N, using soundings and NCEP/NCAR data at those sites. The results show evidence of a clear underestimation of reanalysis data when compared to observed data of nearly 60% of the low-level moisture flux at Lake Charles for the period May-September. Similarly, Corpus Christi and Monterrey present underestimations of that variable on the order of 9 and 20%, respectively. The implications of these results for diagnostic, modeling and process studies are evident. Since the selected region shows a reasonable time and spatial coverage of sounding data, contrary to what is the situation

in the central Caribbean and surrounding land areas, problems associated with global reanalyses in the latter regions are expected to be even more egregious.

(e) Linkages between the IAS and the Pacific -- The southernmost branch of the IntraAmericas Low-Level Jet (IALLJ), crosses over the Central American isthmus and become westerly winds over the tropical Pacific, thus enhancing the Choco low-level Jet over the easternmost fringe of the tropical Pacific off Colombia (Poveda and Mesa, 2000; Poveda et al., 2006).

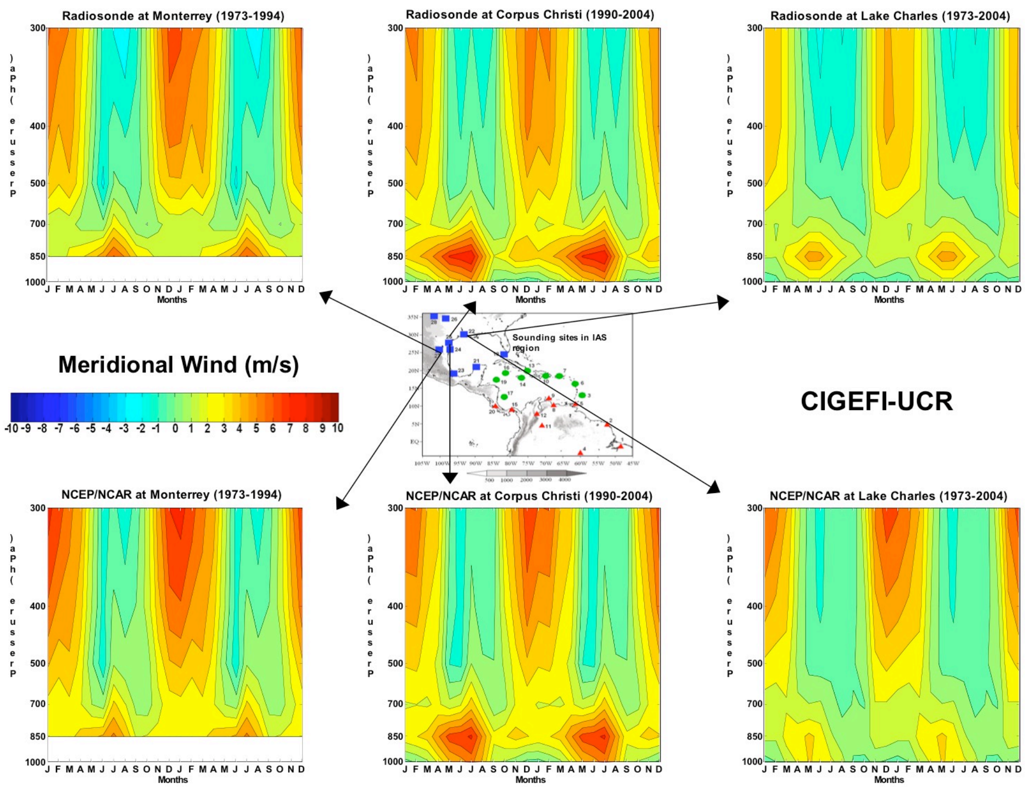


Fig. 20. Upper panels: Hovmuller diagrams of aerological observations at three stations near the entry to the Great Plains low-level jet (shown in the inset map). Lower panels: Hovmuller diagrams for the NCEP/NCAR reanalysis at grid locations near the sounding stations.

5.3 Land-air-sea interactions

River flows are very powerful indicators of diverse meteorological variables (albeit filtering high frequency variability); there Is a need to relate all these Issues with the annual and Interannual variability of weekly, monthly, seasonal, annual and interannual variability of river discharges (application In hydropower generation, very prominent in northern South America and all of Meso-America.)

The climate variability of the IAS region cannot be fully understood without considering land effects. The distribution of heaviest rainfall over land (Fig. 3) is testimony to the importance of land. But the exact role of land vs. ocean is not clear. In particular how land interacts with the ocean through the atmosphere (or directly via river discharge) on the annual and interannual timescales is unclear. The role of land in the IAS must be addressed if significant societal applications are to grow out of the research efforts. The following specific issues are applicable.

(a) How does land affect surface and low-level pressure distributions? – Pressure distributions are central to understanding the low-level jets. While the NASH plays an inevitable role in setting the pressure gradient at its southwestern and western edges for the IALLJ, the land distribution is likely to be crucial to the intensification of the trade wind when it enters the Caribbean Sea and subsequently exits into the Pacific or northward into North America. But it is unknown to what degree the land contribution to strengthening the pressure gradient is adiabatic (surface heating) or related to diabatic heating of convection over the northeastern part of the South America or the northern part of Central America. It is known that the diurnal cycle is crucially important to the GPLLJ (e.g., Stenrud 1998). But it is unclear whether the strong diurnal influence would extend from land to the ocean to affect the IALLJ.

(b) Why do many, if not most, GCMs misrepresent the spatial distribution of precipitation in the IAS region? – GCMs misplace the precipitation center over the ocean (Fig. 2) instead of over land as observed (Fig. 3) for several possible reasons. Models may do a poor job of representing the thermal properties of land surface (temperature, soil moisture, fluxes) and coarse resolution global models in general poorly resolve the effects caused by terrain. The SST data used in global models do not resolve fine structures due to coastal upwelling. Cumulus and boundary-layer parameterizations in models are inadequate (e.g., not equally capable over land and ocean). To identify and quantify the cause for the model errors in this regard can be a major contribution to overall model improvement. Known AGCM problems include the coarse horizontal resolution of terrain, boundary layer parameterizations, cloud physics, diurnal cycle, and the re-evaporation of soil moisture. The diurnal cycle of convection in coastal environments represents a good example of an important land-air-sea interaction problem since so much of the precipitation in the Americas that is diurnally modulated occurs there (Garreaud and Wallace 1997).

5.4 Mid-summer drought (MSD)

The MSD can be seen in climatologies from the eastern North Pacific to Florida and the eastern Caribbean, and it has great significance for subsistence agriculture throughout the Caribbean and Central America (Magaña et al. 1999). Understanding the mechanisms for the seasonal and interannual variability of the MSD is critical to its prediction. While simulating the MSD by global models may not be very difficult (Mapes et al. 2004), predicting its timing and intensity remains a challenge.

Some work has been done by Rauscher et al. (2006) to assess the ability of the IPCC (AR4) models to simulate the MSD. A comparison of the climate of the 20th century simulations (20c3m) with observations over the period 1961-1990 shows that nearly all models underestimate precipitation over southern Mexico and Central America; however, many of the global models do capture the MSD. Differences between projections for the A1B scenario (2061-2090) and the 20c3m (1961-1990) simulations show less precipitation in the future scenario with the change concentrated in the early part of the rainy season, concurrent with stronger trade wind flow over Central America. The reduction in precipitation is greatest in the higher-resolution models, suggesting that regional processes (e.g., topography that is not well-represented by GCMs) may play an important role in modulating future climate change in this region.

The MSD is not exclusively an IAS phenomenon and appears to be especially well-defined in the ENP. However, the Atlantic warm pool appears to have a strong impact on moisture convergence in the ENP (Wang et al. 2006b) so the MSD should be studied in the context of both regions. Some AGCMs have simulated the MSD and mechanisms for it have been proposed (Magaña et al. 1999; Magaña and Caetano 2005; Small et al. 2006). The roles of these mechanisms in the MSD and its interannual variability need to be further quantified. The Small et al. study showed that local SST is of secondary effect while changes in convection outside the MSD region are important via atmospheric wave adjustment. Angeles et al. suggests that increases in atmospheric particles further suppress precipitation in the region coinciding the peak of the Saharan dust with the MSD. What are the relative contributions of the NASH, ITCZ, SST, IALLJ, land and aerosol effects, and related local atmospheric circulations for the MSD and its interannual variability? While these mechanisms may all be at work, it is unclear which one(s) is (are) mainly responsible for the interannual variability of the MSD. The capability of coarse resolution AGCMs and high-resolution regional models to simulate and predict the MSD needs to be assessed against observations.

(a) What are the relative importance of NASH, ITCZ, SST, IALLJ, land effects, and related local atmospheric circulation in the MSD and its interannual variability? – While these mechanisms may all be at work, it is unclear which one(s) is (are) mainly responsible for the interannual variability of the MSD.

(b) What are the typical errors in global and regional models in their simulation and prediction of the MSD? - Magaña and Caetano (2004) suggested that high-resolution regional models are needed to predict the MSD. Mape et al. (2004) showed that some global models can simulate the MSD. The capability of these two types of models to simulate and predict the MSD needs to be quantified against observations.

5.5 Tropical cyclones

The primary factors affecting Atlantic TC frequency are ENSO and the AWP size, the former interannually and the latter both interannually and on the longer time scales of the Atlantic Multidecadal Oscillation (AMO) and anthropogenic forcing. With ENSO the mechanism appears to be upper level wind anomalies propagated eastward from west-central Pacific heating anomalies that alter the wind shear over the main development region (MDR) for TCs, usually during the boreal summer of ENSO onset years. With large warm pools, favorable surface heating extends farther eastward into the MDR where tropical depressions develop and mature, but also the tropospheric wind shear is observed to decrease due to wind changes at both high and low levels (Wang et al. 2006). Model experiments suggest that AWP anomalies alter the tropospheric circulation baroclinically through a Gill (1980) response to off-equatorial heating, which results in the corresponding shear anomalies (Wang et al. 2007). The same experiments indicate that the summer AWP is responsible for a greater moist static instability (Wang and Lee 2007). All of these factors favor the more frequent development of strong storms, but we don't know the relative importance of these mechanisms or how they interact. We need to understand,

and models need to emulate, the way in which the vertical shear tropospheric stability and AWP size are linked. To accomplish this, the challenge is for improved models to simulate and capture the large scale forcing modes while simultaneously resolving and realistically simulating the TCs.

Many questions on the long-term variability of TCs affecting the IAS region remain to be addressed. TCs that form in the Atlantic and propagate into the IAS region are influenced by both thermodynamics (SSTs, mid/low tropospheric moisture, moist static stability) and dynamics (tropospheric wind shear, vorticity of incipient disturbances). It is unknown which of these factors are the more important controls on the interannual to multidecadal variability of TCs, especially the 50-80 year variability that dramatically changes major hurricane activity and the associated risk to coastal populations. Changes between warm and cool phases of the multidecadal variability appear to be step functions rather than gradual transitions. We don't know why. It is unclear when the current warm episode, which began in 1995, would switch back to the cool phase. If the multidecadal swings of the 20th century were not natural (as per Delworth and Mann 2000; Gray et al. 2004; Knight et al. 2005), but primarily induced through anthropogenic aerosols (Mann and Emanuel 2006), then such a reversal may never occur. The magnitude of changes being induced upon TCs by anthropogenic warming today (Emanuel 2005) needs to be quantified but the artificial trends in the hurricane data base make detection through observations extremely difficult (Landsea et al. 2006). For impact of TCs on the IAS, it is unclear whether steering flow variability determines the likelihood of landfall or genesis location is the main factor. It remains a challenge to understand the mechanisms for longterm variability of TCs affecting the IAS region and to help predict such variability using long record of data in combination with processes studies.

Perhaps the most pressing challenge for TC research in the IAS context is the need to better understand and predict the sudden formation of TCs in the Caribbean and Gulf of Mexico. Unlike the so-called 'Cape Verde' storms that form in the tropical Atlantic and propogate into the IAS a week or more later, the storms that form in the IAS early and late in the season give little warning to coastal and island residents. Such storms have been known to make landfall as destructive hurricanes within only a few days of their formation.

5.6 The role of intraseasonal variability

Intraseasonal variability (ISV) in the Western Hemisphere is one of the least understood modulators of summer climate in the IAS region. ISV is better understood and well defined near the dateline, but rapidly loses definition toward the east and does not become clear again until one approaches Africa and the Indian Ocean. Yet, in almost every summer season there are palpable fluctuations in tropical storm activity on intraseasonal time scales that appear to correlate with large scale indices such as OLR and velocity potential at the top of the troposphere, and which, if understood and predictable, would greatly enhance intermediate timescale hurricane forecasts in the gap between synoptic predictions and seasonal outlooks.

5.7 Climate change issues

In principle, global warming considerations are beyond the purview of the CLIVAR monsoon programs such as VAMOS, which are mainly concerned with natural climate variability on time scales from diurnal to interannual. Yet, we know that knowledge and predictions predicated on the observations and analyses of 20th century variability will become increasingly irrelevant as the effects of anthropogenic warming begin to interact with the natural variability. AMIP and CMIP model ensembles are now available for evaluating and comparing the effects of natural and anthropogenically forced climate responses, such as the recent study by Rauscher et al. (2007) (Fig. 21). We also cannot expect CLIVAR programs charged with investigating global long-term climate change, detection and attribution to give the necessary priority to the anthropogenic impacts within a particular region, such as the IAS. Hence, it is not too early to think about conducting research into these issues.

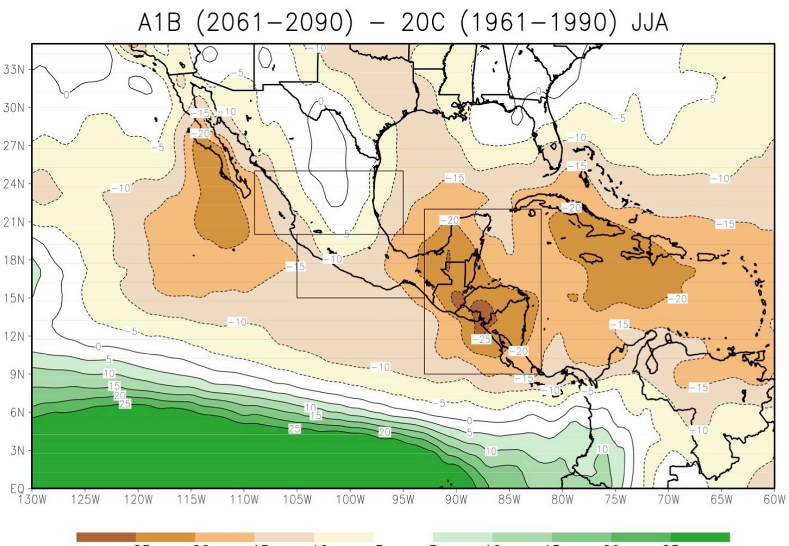


Fig. 21. Average JJA precipitation for the IPCC model ensemble average A1B(2061-2090)-20C(1961-1990) as a percentage of the 20C simulation. Positive (negative) values are in green (brown).

Nowhere is the need to understand climate change more urgent for the IAS than in the area of hurricane activity. There is an ongoing controversy as regards the comparative importance of greenhouse forcings and natural variability in modulating hurricane activity. The outcome of that debate will have potentially large consequences for changes over the next several decades (Enfield and Cid-Serrano 2007). Whereas natural, yearly to multidecadal variations in the warm pool may modify the shear and moist static stability that affect hurricane intensification, greenhouse forcing may force the troposphere more directly and in less predictable ways. For example, as the tropics become drier, there will be changes in the aerosol loadings over the tropical Atlantic that will inevitably impact hurricane activity, as apparently occurred during the inactive season of 2006 (Lau and Kim 2007). Factors such as these may unpredictably counteract the expected thermodynamic increase in hurricane intensity. This field, alone, will become an important area of research that will also bear on many of the other aspects of IAS climate.

The effects of rising sea surface temperatures in most coastal tropical regions will influence diurnal and seasonal hydrologic cycles in forested regions of the IAS. Because orographic cloud formation is determined by such processes as ocean evaporation and vertical atmospheric profiles of temperature and humidity, it is highly sensitive to climate change (Still et al. 1999; Pounds et al. 1999). Acceleration of the tropical hydrological cycle via enhanced ocean temperatures is expected to change these profiles, with concomitant impacts on lapse rates and freezing surfaces (Diaz and Graham 1996). Indeed, enhanced atmospheric warming with height (decreasing lapse rate) has been observed over the tropics (Gutzler 1992), and another analysis suggests an enhancement of the tropical hydrological cycle in recent decades (Flohn and Kapala 1989).

Climate model simulations of doubled CO_2 conditions also suggest an enhancement in the tropical ocean evaporation, with impacts on vertical profiles of temperature and humidity. Indeed there is already evidence at the well-studied cloud forest in Monteverde, Costa Rica, of a lift in cloud base height during the dry season. This has driven a drying trend, which has been linked to anuran extinctions, and is strongly correlated with tropical sea surface temperature variations (Pounds et al. 1999). In addition to climatic effects accompanying tropical ocean warming, lowland deforestation and consequent changes in the surface energy balance and evapotranspiration may also contribute to the cloud base rise and drying trend observed at Monteverde (Lawton et al. 2001). These authors show an effect on both convective and orographic cloud formation resulting from deforestation, such that these clouds have lower cloud water mixing ratios and higher cloud bases.

5.8 The interaction between clouds and aerosols

Fundamental questions relating aerosols and clouds to climate and precipitation need answers for the IAS.

a) What is the 4-D distribution of Cloud Condensation Nuclei (CCN) in the IAS, what are their sources, variability and what are their roles in clouds formation?

b) What is the variability of cloud heights and depths in the Caribbean as function of regional SSTs, and large scale forcings such as the ENSO, the NAO the Atlantic dipole and the Atlantic multi-decadal oscillation?

c) What is the relationship between aerosols and seasonal climate variation in the IAS ?

5.9 Societal impacts

Climate variability in the IAS region, as in many parts of the world, operates on several time scales, all of which can have a profound influence on society and economy of the region. However, a primary focus of the IASCLIP is on the seasonal to interannual rainfall variability during the boreal summer. The character of the early seasonal rainfall and mid-summer droughts and the impacts of this rainfall are different from that of the tropical-storm-dominated rainfall of the latter half of the season. The societal and economic effects of the rainfall season from its start through the MSD as well as the seasonal predictability of these rains needs to be examined more closely. There is no denying the heavy impact of the tropical storms in the areas along the storm tracks but there is little research on the character of the rainy seasons and impacts in IAS locations not directly influenced by tropical storms in a particular season. While there is seasonal predictability in the overall character of the hurricane season in the IAS there is no long range predictability on where, exactly, the storms will hit. Thus, except for the northern coast of South America, all parts of the IAS region must be prepared for excess rainfall associated with tropical storms the probability of a storm striking any specific location is still rather small, even in very active years. This leads to an extremely difficult problem in climate risk management. The IAS region has also experienced substantial changes in seasonal precipitation in the last few decades, with reductions in summer wet season rainfall not quite balanced by increases in winter dry season rainfall. In the last few decades, increasing Caribbean Basin SST appear to be reflected in amplified warming in mountain regions of Central America. These changes in climate profoundly affect water resources and ecosystem function in the region.

Each part of the rainfall season as well as variability on time scales from interannual through decades, not to mention climate change, represent unique challenges for the practical application of the knowledge expected to be gained in the IASCLIP. The first steps in process of providing relevant climate information require the identification of the specific problems, decision frameworks, and decision makers to develop effective climate risk management strategies. Although VAMOS is primarily concerned with the science issues, IASCLIP will form an umbrella under which organizations such as the IRI, IAI and World Bank can fund complementary efforts aimed at the human dimensions of IAS climate.

6. Implementation

To sufficiently address the issues raised in section 5, a combination of diagnosis of existing data, modeling, and process studies are needed. It is envisioned that the IASCLIP program would be conducted in three phases, with different emphases in each.

6.1 Phase I (2008 – 2011): Diagnostics and Modeling

Many issues raised here can at least partially be addressed by diagnoses of existing data and by numerical modeling and diagnoses. The second, observational phase must necessarily depend on the outcome of this phase aimed at identifying the most critical processes and the model deficiencies in replicating them. Model diagnoses should include both weather prediction and climate models as, increasingly, the distinction between the two has become blurred. In particular, the current extended weather forecast and seasonal prediction ensemble experiments can provide great sources of information. Also, individual modeling and predictability experiments, as well as new generation model experiments with regional climate models and cloud resolving models, should be encouraged. The NAMIP (NAME Model Intercomparison Project) should naturally extend into this. The recent model comparison project (CMIP3) related to IPCC AR4 provides a context of global climate change for the short-term regional climate variability. Diagnoses of these simulations for the 20th and 21st century climates can help us understand and interpret regional seasonal to interannual processes that must undergo changes in a changing climate to manifest regional impact of global warming.

6.1a Priority tasks

The ultimate outcomes of the first phase would be: (i) to explore the existing observational data (including in situ observations, satellite remote sensing, and data assimilation products) to document the fundamental climate features and their variability in the IAS region, (ii) to evaluate the current model capability of reproducing and predicting these fundamental climate features and their variability in the IAS region; (iii) to identify gaps in our observational descriptions of these features that may be filled by modeling activities, (v) to identify the need for new observations to address problems in our describing, understanding, simulating and predicting the short-term climate variability in the IAS region, and (vi) to develop innovative modeling approaches to study regional climate and climate variability in the IAS region. Particular Phase I tasks include but are not limited to:

1) Document the regional atmospheric and terrestrial water cycles, including their uncertainties. Investigation and intercomparison of regional water and energy balances will implicitly focus attention on the key circulation and hydroclimate features, including low-level jets and the challenging regional terrain and vegetation. Balance assessments will help gauge the circulation-hydroclimate consistency of reanalyses and model simulations, in a way that readily connects with land-surface hydroclimate (precipitation from raingauges and satellite data (e.g., TRMM), soil moisture, aerosols and clouds (e.g. AURA and CALIPSO), surface air temp, streamflow, drought indices, vegetation indices (e.g., NDVI, EVI). For example, diagnostic analysis of NARR data and the Global Soil Wetness Project 2 simulations will generate validation targets for water-cycle portrayals during seasonal and interannual variability over the IAS region.

2) Through intercomparison and validation against conventional observations, document uncertainties in global reanalyses in the IAS region and identify possible sources for the uncertainties. This task will help in determining whether unconstrained model integrations are faithfully reproducing critical characteristics of the IAS climate complex within acceptable limits.

3) Document common model deficiencies in simulating the key climate features (e.g., IALLJ, MSD, NASH, ITCZ, MJO, and diurnal cycles of rainfall) of the IAS region and identify critical elements in the models that are responsible for such deficiencies. One obvious task: Compare a subset of the global AMIP and CMIP control runs (CMIP3 multi-model archive) from the IPCC AR4 with each other and against observations. This is a matter of designing and proposing a series of diagnostic subprojects within the framework of the Program for Climate Model Diagnosis and Intercomparison (PCMDI, 2006). Studies similar to that of Rausch et al. (2006) for the MSD (section 5.7) should be extended to other aspects of IAS climate change, such as the NASH, the IALLJ and moisture transports.

4) Document model deficiencies in simulating oceanic variability of the IAS region. This will include the analyses of the ocean upper layer temperature, heat budget, and ocean circulation in the IAS. The diagnostic studies of the ocean component in the coupled models will allow us to assess how models simulate variability of the warm pool which plays an important role in

IAS's influences on climate and hurricanes. It will also provide a guideline for improving models and designing future field measurements in the IAS region.

5) Encourage and coordinate detailed analyses of output from existing efforts at experimental MJO prediction (http://www.cdc.noaa.gov/MJO/Forecasts/) and seasonal prediction (WCRP Task Force on Seasonal Prediction, TFSP), organized by The Working Group on Seasonal to Interannual Prediction (WGSIP) under CLIVAR, (http://wcrp.ipsl.jussieu.fr/SF_TFSP.html). If skills are useful, even under certain conditions, their societal applications (timescales depend on the precise application) will be explored. This involves making the forecast information available to local users and training on how to use the forecast information.

6) Encourage modeling innovations for simulation, prediction, and predictability studies of the IAS region. High-resolution RCMs, regional CRMs, nested tropical channel models, and nested GCMs may all provide new information unavailable from existing conventional models on important phenomena such as the IALLJ, boundary-layer structure, cloud microphysics, and moisture transport. The challenge of validating some of these high-resolution models would lead to investigations on new field experiments in this region.

7) Conduct diagnostic modeling for assessing the importance of the IAS region through its various forcing sources (e.g., warm warm pool and NASH, regional diabatic heating, orographic interaction) in generation of regional and hemispheric climate and climate variability patterns. This can provide important guidance for model assessment and subsequent observation gathering. Wang et al. (2007) is an example of one such study, but much more can be done.

8) Investigate the need and feasibility of producing a regional high-resolution reanalysis for the IAS region. The obvious limitations of the current NCEP North American Regional Reanalysis (NARR) for IAS studies are its lack of coverage over the southern part of the IAS region and the resulting undesirable boundary effects (Fig. 22).

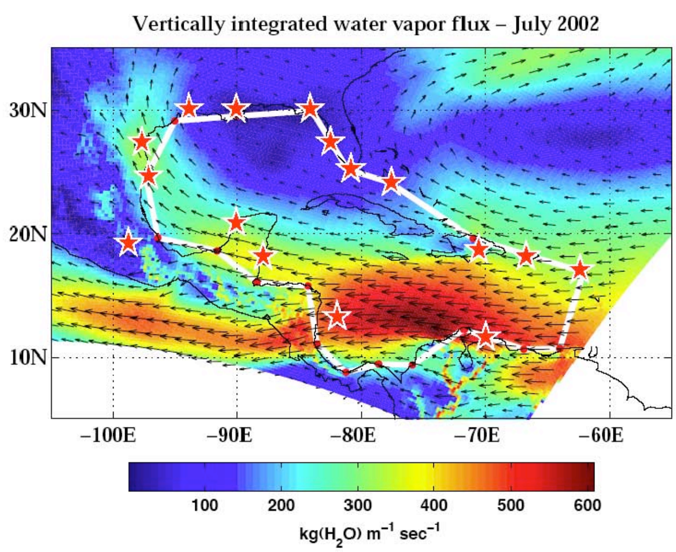


Fig. 22 Vertically integrated water vapor flux for July 2002 used to illustrate the coverage of the IAS by the current NCEP Eta North American regional reanalysis. Stars mark the locations near the IAS coast at which sounding observations are available.

With appropriate resources, the NARR can be improved by extending the coverage of the current Eta regional reanalysis with its current boundaries moved further south. We should also encourage WMO climate centers within the IAS region, some of which are already using models such as MM5 and WRF, to develop a regional reanalysis as part of an IASCLIP capacity building program (c.f. recommendation from VPM8 in Mexico City).

9) Identify the in situ observations from the IAS region that are the most urgently needed for model validations and improvement. This should be the culmination of collaborative efforts between modelers, diagnosticians, and experimentalists. Given the proximity to strong convective zones, the significance of in situ atmospheric observations over the narrow meso-American isthmus may be somewhat limited. But resolving the Caribbean and Choco low-level jets and moisture transports will be very important. It might be interesting to compare the COSMIC project (UCAR's Satellite Constellation observing system) temperature and humidity soundings with reanalysis and in-situ profiles. Of course COSMIC data are available only for the recent year, but their coverage over both land and ocean and the difficult regional terrain will be an asset. Land-surface data, on the other hand, are urgently needed to verify hydroclimate simulations and predictions, as also for 4D distributions of baseline aerosol sizes, and sources of seasonal variability. The new CALIPSO satellite includes an on-board multichannel Lidar which should be of great value in characterizing the optical thickness and size distribtions. However, ground based calibration will be needed before these data can be of use to the region.

6.1b Timetable for Phase I

2008: A workshop on IAS climate – The purposes of this workshop are (i) to summarize the current activities and most updated knowledge on IAS climate studies, (ii) to brainstorm current and potential PIs on the best way of organizing and coordinating research efforts on the issues discussed in this document, and (iii) to form working groups to target specific problems. The location and time of this workshop will be determined after the IAS SSC is officially approved by the VAMOS panel. One possibility is at the same location and time of the next VAMOS panel meeting. The following working groups are currently being considered:

WG A: Climate diagnostics, simulations, and prediction – This working group target tasks 6.1 – 6.4 using existing observations and model simulations.

WG B: Model development and experiments – The working group targets tasks 6.5 – 6.6 based on newly developed models, simulations, and new experiment designs. This is where the current NAMIP group may extend.

WG C: Data gaps – This working group targets tasks 6.7 and 6.8 to explore need and feasibility of a new regional reanalysis over the IAS region and new field campaign to solve the data gap problems emerged from the other tasks.

WG D: Climate impact – This working group will focus on whether and how the IASCLIP activities should be expanded from physical domain to human dimension and ecosystems. It will also investigate on the issue of regional capacity building. These issues are not well addressed in this current document.

These and possible other working groups will communicate closely with overlapping memberships. Each working group will report to the SSC.

2009: Working group meetings – Each working group will decide whether, where and when they will meet physically. Working group meeting can be associated with other national or international conferences/meeting as special sessions or organize their own workshops. A meeting will be held for the SSC members and working group leaders later in the year to review the programmatic progress and adjustment of the program plan.

2010: A second IAS climate workshop will be held. Its topics and scope (e.g., include nonphysical dimensions or not), location and time will be decided by the SSC meeting in 2009. The purpose of this workshop is to summarize the progress made and discuss weather a field campaign is needed. If it is deemed that a field campaign is needed, then a special scientific working group will be formed to be in charge of design and execute the campaign.

2011: Prepare for the field campaign if it is deemed necessary. Continue modeling and diagnostic analyses.

6.2 Phase II (2011 – 2012): Field Campaign

Although a truly meaningful discussion of observational needs must await the Phase I results, we can at least articulate several motivations for a field campaign in the IAS region to obtain in situ observations that are otherwise unavailable from the existing operational network.

• Our confidence of using reanalysis products as validations for model simulations must be built upon direct validations of the analysis products themselves against in situ observations. The utility of TRMM rainfall data for reanalysis verification can not be overstated. It is known that some reanalysis products suffer from large biases, especially in the moisture field and near the surface (e.g., Trenberth and Gillemot 2003), and that they ignore hurricane formation. *GP* This is especially so over ocean areas such as the Caribbean Sea, where few observations are routinely available. The first priority of an IAS field campaign would be to take sounding observations in the core of the CLLJ from ship(s) or aircraft and from islands of Lesser Antilles, and to increase sounding frequencies at the sites of Yucatan, *Isla San Andres*, and Corpus Christi to measure the vertical structure and diurnal cycle of the IALLJ and its water vapor transport. How much of this moisture transport crosses Central America and southern Mexico to converge over the ENP, and how much of that moisture then becomes a Pacific source for the NAMS? How much of that moisture becomes a Pacific source for the Choco low level jet? Some combination of soundings and satellites will be required to answer such questions.

• It is desirable to obtain a comprehensive in situ observational data set that provides a full description of processes key to the MSD not available from existing data. Based on our current understanding (sections 2 and 3), such a data set should include the CLLJ and its water vapor transport, air-sea fluxes, large-scale pressure distribution associated with the NASH, aerosols, convection and precipitation. The ECAC field campaign in 2001 (Magaña and Caetano 2004) provides piloting experience for this exercise.

- A full understanding of the regional air-land-sea interaction is essential to characterize the diurnal and intraseasonal hydrological cycles and determine possible impacts of rising SSTs and natural and antropogenic land surface modifications. This is more sensitive in regions where coastlines, vegetation and topography play major roles in rainfall as the case of Central America, Northern Coasts of South America and the Larger Antilles. This will lead to better understanding mountain clouds, and the roles of deforestation and urbanization in modulating surface temperatures and rainfall in relevant regions. This understanding will also aid in determining impacts of inland penetrating cyclones along the coasts. The works by Lawton et al. 2001 are good examples of determining impacts of low land deforestation in cloud formations and rainfall variations in Central America.

- Central to understanding the mechanisms for the interannual to interdecadal variability of TCs in the IAS (section 2.2) is the knowledge of the effects of the large scale environment, in both atmosphere and ocean. In coordination with NOAA hurricane research that usually focuses on the storms, additional measurements from land, ship and aircraft over the IAS would augment our ability to document and understand the role of the large-scale environment, including that of tropical easterly waves, and the MJO in TC genesis, intensification, and movement.

- Other needs for new in situ observations can be determined by modeling studies during Phase I. These could include, for example, the need for ocean moorings at one or more critical locations, if justified by discovered misbehaviors in the ocean GCMs needed for coupled model predictions.

6.3 Phase III (2012 – 2014: Consolidation

Traditionally, the last phase of a program that culminates in an observational study will end with post-field campaign data analysis and modeling. This of course will be true of IASCLIP as well. To that, however, we should add the need to develop applications of climate diagnostic tools as an outgrowth of improved model predictions, especially as regards the hydrologic cycle and the need to answer questions related to the impact of natural and anthropogenic climatic variations in the IAS region. Although this is an activity that can proceed through all phases of IASCLIP, it should become a primary focus for Phase III, and VAMOS should encourage the participation of funding agencies specifically concerned with the human dimensions of climate variability, such as the IRI, the IAI and the World Bank. A few specific examples may be outlined, with the understanding that they are not limited to Phase III:

- An evaluation of the ability of the current generation of seasonal climate forecast models to characterize the early part of the rainfall season (April to June) including the MSD, in the IAS region is also needed along with an effort to diagnose and improve the model outputs.

Diagnostics studies to examine whether forecast models replicate the rainfall mechanisms and the statistics of sub-seasonal rainfall is also required to provide tools for managing climate risk.

- An evaluation of the ability of the current generation of seasonal climate forecast models to characterize the July to October rainfall in the IAS region, exclusive of the areas directly influenced by tropical storms, is needed. Diagnostics studies to examine whether forecast models replicate the rainfall mechanisms and the statistics of sub-seasonal rainfall is also required to provide tools for managing climate risk on seasonal time scales.

- Applications of climate diagnostic tools related to the hydrologic cycle are needed to help answer questions related to the impact of natural and anthropogenic climatic variations in the IAS region.

- Tools for better management of climate related risks in areas of health (vector-borne diseases), water management, and agriculture need to be developed in collaboration with decision makers in the region. IASCLIP will build on efforts initiated in other programs e.g., the IAI Collaborative Research Networks and emerging IRI regional activities in agriculture and health, to develop climate risk management projects. This will require establishing collaborations not only with national and regional governmental bodies but also with NGOs and international organizations e.g., Pan-American Health Organization (PAHO), Consultative Group on International Agricultural Research (CGIAR), Global Water Partnership (GWP).

References

Adams, D.K., and A.C. Comrie, 1997: The North American monsoon. *Bull. Amer. Meteor. Soc.,* **78**, 2197-2213.

Amador, J. A., V. O. Magaña and J. B. Pérez, 2000. The low level jet and convective activity in the Caribbean. Preprints 24th Conference on Hurricanes and Tropical Meteorology, *American Meteorological Society*, **29,** 114-115.

Amador, J. A., J. R. Chacón, and S. Laporte, 2003. Climate and climate variability in the Arenal Basin of Costa Rica. In *Climate, Water and Trans-boundary Challenges in the Americas*. Ed. Henry Díaz and Barbara Morehouse. Kluwer Academic Publishers. Holland, pp. 317-349.

Amador, J. A., E. J. Alfaro, O. G. Lizano, and V. O. Magaña, 2006: Atmospheric forcing of the eastern tropical Pacific: A review. *Progress in Oceanography*, **69,** 101-142.

Amador J. A.,1998: A climatic feature of the tropical Americas: the trade wind easterly jet. *Topicos Meteorologicos y Oceanograficos*. **5**, (2),1-13.

Amador J. A., and V. Magaña 1999: Dynamics of the low level jet over the Caribbean Sea. The 23th Conference on hurricanes and tropical Meteorology. Dallas Tx, AMS 868-869.

Angeles, M., J. E. Gonzalez, P. Mulero, D. J. Erickson, III, and J. Hernandez-Figueroa, 2007: Assessment of PCM results for predictions of climate changes in the Caribbean. *International Journal of Climatology.* **27**, pp. 555-569.

Arias, P. A., and G. Poveda, 2007: The effects of the intraseasonal (40-50 day) oscillation on the hydro-climatology of northern Soutn America. In preparation.

Atlans, R., N. Wolfson, and J. Terry, 1993: The effect of SST and soil moisture anomalies on GL model simulation of the 1988 U.S. Summer drought. *J. Climate*, **6**, 2034-2048.

Barlow, M. and D. A. Salstein, 2006: Summertime influence of the Madden-Julian Oscillation on daily rainfall over Mexico and Central America. *Geophys. Res. Lett.*, **33,** doi:10.1029/2006GL027738.

Blanco, A., F. De Tomasi, E. Filippo, D. Manno, M. R. Perrone, et al., 2003: Characterization of African Dust Over Southern Italy. *Atmospheric Chemistry and Physics* **3**: 2147.

Bonner, W. D., 1968: Climatology of the low level jet. *Mon. Wea. Rev*., **96**, doi: 10.1175/1520-0493.

Bosilovich, M. G. and S. Schubert, 2002: Water Vapor Tracers as Diagnostics of the Regional Hydrologic Cycle. *Journal of Hydrometeorology*, **3,** 149-165.

Brubaker, K. L, P. A. Dirmeyer , A. Sudradjat, B. Levy and F. Bernal 2001: A 36-yr climatological description of the evaporative sources of warm season precipitation in the Mississippi river basin. *J. Hydromet.,* **2**, 537-557.

Bruijnzeel, L.A. and J. Proctor1995: *Tropical Montane Cloud Forests*. Eds Hamilton, L.S. Juvik, J.O. and Scatena, 38-78, Spring-Verlag, New York

Byerle, L.A., and J. Paegle, 2003: Modulation of the Great Plains low-level jet and moisture transports by orography and large-scale circulations. *J. Geophys. Res.,* **108**, doi:10.1029/2002JD003005.

Ceron, R.M.B., H.G. Padilla, R.D. Belmont, M.C.B. Torres, R.M. Garcia, A.P. Baez, 2002: Rainwater chemical composition at the end of the mid-summer drought in the Caribbean shore of the Yucatan Peninsula. *Atmospheric Environment* **36,** 2367-2374.

Chelliah, M, and G.D. Bell, 2004: Tropical Multidecadal and Interannual Climate Variability in the NCEP–NCAR Reanalysis. *Journal of Climate,* **17**, 1777–1803.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature*, **385,** 516-518.

Chen, A.A, and M.A. Taylor, 2002: Investigating the link between early season Caribbean rainfall and the El Nino plus 1 year. *International Journal Of Climatology*, **22**, 87-106.

Chen, J.M., C.T. Fong, F.J. Wang, C.H. Shiao, J.H. Chen, M.D. Cheng, 1999: Climate characteristics of the CWB Global Forecast System: Hydrological processes and atmospheric circulation. *Terrestrial Atmospheric And Oceanic Sciences* **10,** 737-762.

Clark,K.L., R.O. Lawton, and P.R. Butler, 2000: *Monteverde: Ecology and Coservation of a Tropical Could Forest* . Eds. Nadkarni, N.M. and Wheelwright, N.T., 15-38, Oxford University Press, New York.

Clifton KE, 1995: Growth And Reproduction For The Herbivorous Parrotfish Scarus- Iserti. *Marine Ecology-Progress Series* **116,** 39-46.

Collier, J. C., K.P. Bowman, and G.R. North, 2004: A Comparison of Tropical Precipitation Simulated by the Community Climate Model with That Measured by the Tropical Rainfall Measuring Mission Satellite. *J. Climate*, **17**, 3319–3333.

Comarazamy D., J.E. González, C.A. Tepley, S. Raizada, and V. Pandya The effects of atmospheric particle concentration on cloud microphysics over Arecibo, *J. Geophysical. Res.,* **111**, doi:10.1029/2005JD006243.

Criales MM, Yeung C, Amaya F, Lopez AC, Jones DL, Richards WJ, 2002: Larval supply of fishes, shrimps, and crabs into the nursery ground of the Cienaga Grande de Santa Marta, Colombian Caribbean. *Caribbean Journal Of Science* **38** (1- 2): 52-65.

Curtis S., 2002: Interannual variability of the bimodal distribution of summertime rainfall over Central America and tropical storm activity in the far-eastern Pacific. *Clim. Res.*, **22**, 141-146.

Czaja, A. and C. Frankignoul, 2002: Observed Impact of Atlantic SST Anomalies on the North Atlantic Oscillation. *J. Climate*, **15,** 606-623.

Delworth and Manabe, 1989: The influence of soil wetness on near-surface atmospheric variability. *J. Climate*, **2**, 1447-1462.

Diaz DP, Cordova QA, Grayeb BEP, 1994: Effect Of Enso On The Mid Summer Drought In Veracruz State, Mexico. *Atmosfera* **7**, 111-219.

Diaz, H.F., and Graham, N.E., 1996: Recent Changes in Tropical Freezing Heights and the Role of Surface Temperature. *Nature*, **383**, 152-155.

Dirmeyer, P.A., and K.L. Brubaker, 1999: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993. *J. Geophy. Res*., **104**, 19383-19397.

Douglas, M.W., R.A. Maddox, K. Howard, and S. Reyes, 1993: The Mexican monsoon. *J. Climate*, **6**, 1665-1667.

Enfield, D.B., 1996: Relationships of inter-American rainfall to tropical Atlantic and Pacific SST variability. *Geophysical Research Letters*, **23**, 3305-3308.

Enfield, D.B., and E.J. Alfaro, 1999: The dependence of Caribbean rainfall on the interaction of tropical Atlantic and Pacific Oceans. *Journal of Climate*, **12**, 2093- 2103.

Enfield, D.B., A.M. Mestas-Nunez, and P.J. Trimble, 2001: The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental US. *Geophys. Res. Lett.*, **28**, 2077-2080.

Enfield, D. B. and S.-k. Lee, 2005: The Heat Balance of the Western Hemisphere Warm Pool. *J. Climate*, **18,** 2662-2681.

Enfield, D. B., S.-K. Lee, and C. Wang, 2006: How are Large Western Hemisphere Warm Pools Formed? . *Prog. Oceanog.*, **70,** 346-365.

Flohn, H., and A. Kapala, 1989: Changes of Tropical Air-sea Interaction Processes over 30-year Period. *Nature*, **338**, 244-246.

Fu, R., and W. Li, 2004: Land surface on the transition from dry to wet season in Amazonia, *Theor. and Appl. Climatol*., **78**, 97-110.

Gable, F.J., M.M. Affs, J.H. Gentile, and D.G. Aubrey, 1990: Global climate issues in the costal wider Caribbean region. *Envir. Conservation*, **17**, 51-60.

Garreaud, R., and J.M. Wallace, 1997: The diurnal march of convective cloudiness over the Americas. Submitted to *Mon. Wea. Rev*., **125**, doi: 10.1175/1520-0493.

Giannini A, Kushnir Y, Cane MA, 2001: Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Climate*, **13**, 297-311.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez, and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, **293**:474- 479.

Granger, O. 1985: Caribbean Climates. *Progress in Physical Geography*, **9**, 16-43.

Gray, W. M., 1984: Atlantic seasonal hurricane frequency: Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, **112**, 1649-1668.

Gu, G. and C. Zhang, 2002: Cloud components of the ITCZ. *J. Geophy. Res.*, **107**, 4565, doi:10.1029/2002JD002089.

Gutzler, D.C. (1992). Climate Variability of Temperature and Humidity over Tropical Western Pacific. *Geophical Research Letters*, **19**, 1595-1598.

Hastenrath, S., 1967: Rainfall distribution and regime in Central America. *Arch. Meteor. Geophys. Bioklimatol.,* **15B,** 201–241.

Hastenrath, S., 2002: The Intertropical Convergence Zone of the eastern Pacific revisited. *International Journal Of Climatology* **22,** 347-356.

Helfand, H. M. and S. D. Schubert, 1995: Climatology of the simulated Great-Plains lowlevel jet and Its contribution to the continental moisture budget of the United-States. *J. Climate*, **8,** 784-806.

Higgins W.R., and W. Shi, 2001: Intercomparison of the principal modes of interannual and intraseasonal variability of the North American Monsoon System. *J. Climate*, **14**, 403-417.

Higgins W.R., W. Shi, E. Yarosh and R. Joyce 2000: Improved United States precipitation quality control system and analysis. NCEP/ Climate Prediction Center ATLAS No. 7. NCEP /NWS /NOAA. 47pp.

Higgins R. W., A. Douglas, A. Hahmann, E. H. Berbery , D. Gutzler, J. Shuttleworth, D. Stensrud, J. A. Amador, R. Carbone, M. Cortez, M. Douglas, R. Lobato, J. Meitin, C. Ropelewski, J. Schemm, S. Schubert, C. Zhang, 2003. Progress in Pan American CLIVAR Research: The North American Monsoon System. *Atmósfera*, **16**, 29-65.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak and K. C. Mo, 1997a: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. *J. Climate*, **10**, 481-507.

Higgins, W., J. A. Amador, A. Barros, E. H. Berbery, E. Caetano, R. Cifelli, R. Carbone, M. Cortez-Vazquez, A. Douglas, M. Douglas, G. Emmanuel, D. Gochis, D. Gutzler, R. Johnson, C. King, D. Lettenmaier, T. Lang, R. Lobato, R. Maddox, V. Magaña, J. Meitin, K. Mo, E. Pytlak, C. Ropelewski, S. Rutledge, J. Schemm, S. Schubert, F. Torres, A. White, C. Williams, A. Wood, R. Zamora, and C. Zhang, 2006. The North American Monsoon Experiment (NAME) 2004 Field Campaign. *Bulletin of the American Meteorological Society*, **87**, 79-94.

Higgins, R. W. and W. Shi, 2001: Intercomparison of the principal modes of interannual and intraseasonal variability of the North American monsoon system. *J. Climate*, **14,** 403-417.

Hodell, D.A, J.H. Curtis, G.A. Jones, A. Higueragundy, M. Brenner, M.W. Binford, K.T. Dorsey, 1991: Reconstruction of caribbean climate change over the past 10,500 years. *Nature* **352,** 790-793.

Horel, J.D., A.N. Hahmann, and J.E. Geisler, 1989: An investigation of the annual cycle of convective activity over the tropical Americas. *J. Climate***, 2**, 1388-1403.

Hu, Q. and S. Feng, 2001: Climatic Role of the Southerly Flow from the Gulf of Mexico in Interannual Variations in Summer Rainfall in the Central United States. *J. Climate*, **14**, 3156-3170.

------------- and -------------, 2002: Interannual rainfall variations in the North American summer monsoon region: 1900-98 *J. Climate*, **15**, 1189-1202.

Inatsu, M., H. Mukougawa, and S. P. Xie, 2000: Formation of subtropical westerly jet core in an idealized GCM without mountains. *Geophys. Res. Lett*., **27**, 529-532.

Inatsu, M., H. Mukougawa, and S. P. Xie, 2002: Stationary eddy response to surface boundary forcing: Idealized GCM experiments. *J. Atmos. Sci*., **59**, 1898-1915.

Inoue, M., I.C. Handoh, G.R. Bigg, 2002: Bimodal distribution of tropical cyclogenesis in the Caribbean: Characteristics and environmental factors. *Journal Of Climate* **15** (20): 2897-2905.

Kalnay E., and co-authors 1996: The NMC/NCAR CDAS/Reanalysis Project. *Bull. Amer. Meteor .Soc*. **77**, 437-471.

Kameo, K., 2002: Late Pliocene Caribbean surface water dynamics and climatic changes based on calcareous nannofossil records. *Palaeogeography Palaeoclimatology Palaeoecology*. **179,** 211-226.

Kaufman, Y. J., and T. Nakajima, 1993: Effect of Amazon smoke on cloud microphysics and albedo-analysis from satellite imagery, *J. Applied Meteor.,* **32***,* 729–744.

Khain, A., M. Ovtchinnikov, M. Pinsky, A. Pokrovsky, and H. Krugliak, 2000: Notes on the state-of-the-art numerical modeling of cloud microphysics, *Atmospheric Research,* **55**, 159-224.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson and P. J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate,* **11**, 1131-1149.

Knaff, J.A., 1997: Implications of Summertime Sea Level Pressure Anomalies in the Tropical Atlantic Region; *Journal of Climate*. 10, 789–804.

Knutson, T.R., and R. E. Tuleya. 2004: Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization. *Journal of Climate*: Vol. 17, No. 18, pp. 3477–3495.

Laing, A.G., 2004: Cases of heavy precipitation and flash floods in the Caribbean during El Nino winters. *Journal Of Hydrometeorology*, **5**, 577-594.

Landsea, C.W., Pielke, Jr., R.A., Mestas-Nuñez, A.M., Knaff, J.A., 1999: Atlantic basin hurricanes: Indices of climatic changes, *Climatic Change*, **42**, 89-129

Lawton, R.O., U.S. Nair, R.A. Pielke, and R.M. Welch, 2001: Climatic Impact of Tropical Lowland Deforestation on Nearby Montane Cloud Forests. *Science*, **294**, 584-587.

Lee, S.-K., D. B. Enfield, and C. Wang, 2005: OGCM sensitivity experiments on the annual cycle of Western Hemisphere Warm Pool. *J. Geophys. Res.*, **110,** doi:10.1029/2004JC002640.

Lewsey, C., G. Cid, E. Kruse, 2004: Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy*, **28**, 393-409.

Liebmann, B., and J. A. Marengo, 2001: The Seasonality and Interannual Variability of Rainfall in the Brazilian Amazon Basin. *J. Climate*, **14**, 4308-4318.

Lin HL, Peterson LC, Overpeck JT, Trumbore SE, Murray DW, 1997: Late Quaternary climate change from delta O-18 records of multiple species of planktonic foraminifera: High-resolution records from the anoxic Cariaco Basin, Venezuela. *Paleoceanography* **12**, 415-427.

Linsley, B.K., R.B. Dunbar, G.M. Wellington, and D.A. Mucciarone, 1994: A Coral- Based Reconstruction Of Intertropical Convergence Zone Variability Over Central- America. *Journal of Geophysical Research-Oceans* **99,** 9977-9994.

Liu, Y., D. L. Zhang, and M. K. Yau, 1997: A multiscale numerical study of hurricane Andrews (1992) Part I: Explicit simulation and verification, *Mon. Wea. Rev.,* **125***,* 1065-1092.

Madden, R. A., and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci*., **28**, 702-708.

Magaña, V., 2000: Interannual Climate Variability in the Mexico, Central America, and Carribean Region. CLIVAR *Exchanges*, **16**, 1-2.

Magaña, V., J. Amador and S. Medina, 1999: The midsummer drought over Mexico and Central America. *J. Climate* **12**,1577-1588.

Magaña, V., and E. Ceatano, 2004: Temporal Evolution Of Summer Convective Activity Over The Americas Warm Pools. *Geophysical Research Letters*, submitted.

Maloney, E. D. and S. K. Esbensen, 2007: Satellite and Buoy Observations of Boreal Summer Intraseasonal Variability in the Tropical Northeast Pacific *Monthly Weather Review*, **135,** 3-19.

Mapes, B.E., P. Liu, and N. Buenning, 2005: Indian monsoon onset and Americas midsummer drought: out-of-equilibrium responses to smooth seasonal forcing. *J. Climate*, submitted.

Maul, G.A., 1993: Climate Change in the Intra-Americas Sea. United Nations Environmental Program, pp 389.

Mesinger, F., and co-authors 2004: North American regional reanslysis. Proceedings of the AMS annual meeting Seattle, Wa. Jan 2004.

Mestas-Nunez, A.M., and D.B. Enfield, 1999: Rotated global modes of non-ENSO sea surface temperature variability. *Journal of Climate*, **12**, 2734-2746.

Mestas-Nuñez, A. M., C. Zhang, and D. B. Enfield, 2005: Uncertainties in estimating moisture fluxes in the Intra-Americas Sea. *J. Hydromet*., **6,** 696-709.

Mestas-Nuñez, A. M., D. B. Enfield, and C. Zhang, 2007: Water vapor fluxes over the Intra-Americas Sea: Seasonal and interannual variability and associations with rainfall. *J. Climate*, **20,** in press.

Misra V., P.A. Dirmeyer, and B.P. Kirtman, 2002: A comparative study of two land surface schemes in regional climate integrations over South America. *Journal Of Geophysical Research-Atmospheres,* **107** (D20): Art. No. 8080

Mo, K. C., and E. H. Berbery 2004: The low level jets and the summer precipitation regimes over North America. *J. Geophy Res*. doi: 10.1029/2003JD004106.

Mo, K.C., and R.W. Higgins, 1996: Large-scale atmospheric water vapor transport as evaluated from the NCEP/NCAR and the NASA/DOA reanalyses. *J. Climate*, **9**, 1531- 1545.

Mo, K.C., J. N. Paegle, and R. W. Higgins, 1997: Atmospheric processes associated with summer floods and droughts in the central United States. *J. Climate*, **10**, 3028-3046.

Muller-Karger F, Varela R, Thunell R, Scranton M, Bohrer R, Taylor G, Capelo J, Astor Y, Tappa E, Ho TY, Walsh JJ, 2001: Annual cycle of primary production in the Cariaco Basin: Response to upwelling and implications for vertical export. *Journal Of Geophysical Research-Oceans* **106**, 4527-4542.

Negri , A. J., R. F. Alder, E. J. Nelkin and G. J. Hoffmann 1994: Regional rainfall climatologies derived from Special Sensor Microwave Imager (SSM/I) data, *Bull. Am Meteorol. Soc*., **75**, 1165-1182.

Nigam, S., and A. Ruiz-Barradas, 2006: Seasonal hydroclimate variability over North America in global and regional reanalysis and AMIP simulations: Varied representation. *J. Climate*, **19**, 815-837

Nogués-Paegle, J., and, coauthors, 2002: Progress in Pan American CLIVAR Research: Understanding the South American Monsoon. *Meteorologica*, **27**, 3-30.

Nogués-Paegle, J., and K. Mo, 2002: Linkages between Summer Rainfall Variability over South America and Sea Surface Temperature Anomalies. *J. Climate*. **15**, 1389–1407.

Nogués-Paegle, J., and K. Mo, and Paegle J, 1998: Predictability of the NCEP–NCAR Reanalysis Model during Austral Summer. *Monthly Weather Review* **126**, 3135-3152.

Pasch, R.J., M.B. Lawrence, L.A. Avila, J.L. Beven, J.L. Franklin and S.R. Stewart. 2004: Atlantic Hurricane Season of 2002. *Monthly Weather Review*: **132**, 1829–1859.

Paegle, J., K.C. Mo, and J.N. Paegle, 1996: Dependence of simulated precipitation on surface evaporation during the 1993 United States summer floods. *Mon. Wea. Rev*., **124**, 345-361.

Peterson, T.C., M.A. Taylor, R. Demeritte, D.L. Duncombe, S. Burton, F. Thompson, A. Porter, M. Mercedes, E. Villegas, R.S. Fils, A.K. Tank, A. Martis, R. Warner, A. Joyette, W. Mills, L. Alexander, B. Gleason, 2002: Recent changes in climate extremes in the Caribbean region. *Journal Of Geophysical Research Atmospheres* **107** (D21): Art. No. 4601.

Pounds, J.A., M.P.L. Fodgen, and J. H. Campbell, 1999: Biological Response to Climate Change on a Tropical Mountain. *Nature* **398**, 611-615.

Poveda, G., and O. J. Mesa, 2000: On the existence of Lloró (the rainiest locality on Earth): Enhanced ocean-atmosphere-land interaction by a low-level jet". *Geophysical Research Letters*, Vol. 27, No. 11, 1675-1678.

Poveda, G., A. Jaramillo, M.M. Gil, N. Quiceno, N., and R. Mantilla, 2001: Seasonality in ENSO-related precipitation, river discharges, soil moisture, and vegetation index in Colombia. *Water Resources Research*, **37**, 2169– 2178.

Poveda, G., O. J. Mesa, L. F. Salazar, P. A Arias, H. A. Moreno, S. C. Vieira, P. A. Agudelo, V. G. Toro, and J. F. Alvarez, 2005: The Diurnal Cycle of Precipitation in the Tropical Andes of Colombia, *Mon. Wea. Rev*., **133**, 228-240.

Poveda, G., et al., 2005: Diurnal cycle of precipitation in the tropical Andes of Colombia. *Monthly Weather Review*, **133,** 228-240.

Poveda et al., 2006: Modern climate variability in northern South America and southern Mesoamerica. *Palaeogeography, Palaeoclimatology, & Palaeoecology*, **234**, 3-27.

Pozo-Vázquez, D., M. J. Esteban-Parra, F. S. Rodrigo, Y. Castro-Díez, 2001: A Study of NAO Variability and its Possible non-linear Influences on European Surface Temperature. *Climate Dynamics* **17**: 701.

Rasmusson, E. M., 1967: Atmospheric water vapor transport and the water balance of North America: Part I. Characteristics of the water vapor flux field. *Mon. Wea. Rev.*, **95,** 403-426.

——, 1968: Atmospheric water vapor transport and the water balance of North America: Part II. Large-scale water balance investigations. *Mon. Wea. Rev.*, **96,** 720-734.

——, 1971: A study of the hydrology of eastern North America using atmospheric vapor flux data. *Mon. Wea. Rev.*, **99,** 119-135.

Rauscher, S.A., F. Giorgi, N.S. Diffenbaugh, and A. Seth, 2007: Changes in 21st century summer rainfall over southern Mexico and Central America in the IPCC AR4 simulations. Presubmission manuscript.

Robertson DR, Swearer SE, Kaufmann K, Brothers EB, 1999: Settlement vs. environmental dynamics in a pelagic-spawning reef fish at Caribbean Panama. ***Ecological Monographs* 69,** 195-218.

Ropelewski, C.F.; and M.S. Halpert. 1987. Global and regional scale precipitation patterns associated with the El Niño–Southern Oscillation. Monthly Weather Review 115:1606–1626.

Ropelewski, C.F. and M.S. Halpert, 1989. Precipitation patterns associated with high index phase of Southern Oscillation, *J. Climate*, **2**, 268-284.

Ropelewski C. F. And E. S. Yarosh, 1998: The observed mean Annual cycle of moisture budgets over the central United States (1973-1992). *J. Climate*, **11**, 2180-2190.

Salati, E., Vose P.B., Amazon basin, a system in equilibrium. *Science*, **225**, 129-138.

Rosenfeld D., R. Yinon, L. Ronen, 2000: Desert Supressing Precipitation: A possible desertification feedback loop. *PNAS* **98**, 5975.

Ruiz-Barradas, A. and S. Nigam, 2005: Warm Season Rainfall Variability over the U.S. Great Plains in Observations, NCEP and ERA-40 Reanalyses, and NCAR and NASA Atmospheric Model Simulations. *J. Climate*, **18,** 1808-1830.

Schmitz, J. T., and S. L. Mullen 1996: water vapor transport associated with the summertime North American monsoon as depicted by ECMWF analyses. *J. Climate*, **9**, 1621-1634.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister, 2004b: On the cause of the 1930s Dust Bowl. *Science*, **303**, 1855-1859.

Seager, R., 2007: The turn of the century North American drought: Global context, dynamics and past analogues. *J. Climate*, submitted.

Seager, R., R. Murtugudde, N. Naik, A. Clement, N. Gordon, and J. Miller, 2003: Air-sea interaction and the seasonal cycle of the subtropical anticyclones. *J. Climate*, **16**, 1948-1966.

Small, R.J.O., S.P. de Szoeke, and S.-P. Xie, 2006: The Central American mid-summer drought: regional aspects and large scale forcing. *J. Climate*, in press.

Spencer, P.L., and D.J. Stensrud, 1998: Simulating flash flood events: Importance of the subgrid representation of convection. *Mon. Wea. Rev*, **126**, 2884–2912.

Sponaugle S and Cowen RK, 1996: Nearshore patterns of coral reef fish larval supply to Barbados, West Indies. *Marine Ecology-Progress* Series 133 (1-3): 13-28.

Stensrud, D.J., R.L. Gall, S.L. Mullen, and K.W. Howard, 1995: Model climatology of the Mexican monsoon, *J. Climate*, **8**, 1775-1794.

Still, C.J., P.N. Foster, and S.H. Schneider, 1999: Simulating the Effects of Climate Change on Tropical Montane Cloud Forests. *Nature*, **398**, 608-610.

Sudradjat, A., K.L. Brubaker, P.A. Dirmeyer, 2003: Interannual variability of surface evaporative moisture sources of warm-season precipitation in the Mississippi River basin. *Journal Of Geophysical Research-Atmospheres* **108** Art. No. 8612.

Sutton, R. T., and D. L. R. Hodson, 2007: Climate response to basin-scale warming and cooling of the North Atlantic Ocean. *J. Climate*, **20**, 891-907.

Taylor MA, Enfield DB, Chen AA, 2002: Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal Of Geophysical Research Oceans.* **107** Art. No. 3127

Tedesco, K., and R. Thunell, 2003a: High resolution tropical climate record for the last 6,000 years. *Geophysical Research Letters* **30**, Art. No. 1891.

Tedesco, K., and R. Thunell, 2003b: Seasonal and interannual variations in planktonic foraminiferal flux and assemblage composition in the Cariaco Basin, Venezuela. *Journal Of Foraminiferal Research* **33,** 192-210.

Thorncroft, C., and K. Hodges. 2001: African Easterly Wave Variability and Its Relationship to Atlantic Tropical Cyclone Activity. *Journal of Climate*: **14**, 1166–1179.

Trenberth, K.E., and C.J. Guillemot, 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. *J. Climate*, **9**, 1288-1298.

Vargas, AB, and VFS Trejos, 1994: Changes In The General-Circulation And Its Influence On Precipitation Trends In Central-America - Costa-Rica. *Ambio* **23** (1): 87-90.

Vera, C., W. Higgins, J. Amador, T. Ambrizzi, R. Garreaud, D. Gochis, D. Guztler, D. Lettenmaier, J. Marengo, C. R. Mechoso, J. Nogues-Paegle, P.L. Silva Dias, and C. Zhang, 2005: Toward a unified view of the American monsoon systems. *Journal of Climate*, **19**, 4977-5000.

Wang, C. and D. B. Enfield, 2001: The Tropical Western Hemisphere warm pool. *Geophys. Res. Lett.*, **28,** 1635-1638.

Wang, C. and D. B. Enfield, 2003: A further study of the tropical Western Hemisphere warm pool. *J. Climate*, **16,** 1476-1493.

Wang, C., D. B. Enfield, S.-K. Lee, and C. Landsea, 2006: Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic hurricanes. *J. Climate*, **19,** 3011-3028.

Wang, C. and S.-K. Lee, 2007: Atlantic warm pool, Caribbean low-level jet, and their potential impact on Atlantic hurricanes. *Geophys. Res. Lett.*, **34,** doi:10.1029/2006GL028579.

Wang, C., 2007: Variability of the Caribbean low-level jet and its relations to climate. *Clim. Dyn.*, **28**, in press.

Wang, C., S.-K. Lee, and D. B. Enfield, 2007: Impact of the Atlantic Warm Pool on the Summer Climate of the Western Hemisphere. *J. Climate*, **20,** in press.

Wang, Y., 2002: An explicit simulation of tropical cyclones with a triply nested movable mesh primitive equation model: TCM3. Part II: Model refinements and sensitivity to cloud microphysics parameterization, *Mon. Wea. Rev.,* **130***,* 3022-3036.

Wright, R.M., 2001: Wind energy development in the Caribbean. *Renewable Energy* **24** (3-4): 439-444 Sp. Iss.

Wu, Y.H., and S. Raman, 1998, The summertime Great Plains low level jet and the effect of its origin on moisture transport. *Boundary Layer Meteor.*, **88**, 445-466.

Yarosh, E. S., C. F. Ropelewski, and K. E. Mitchell, 1996: Comparisons of humidity observations and Eta model analyses and forecasts for water balance studies. *J. Geophys. Res.,* **101,** 23289–23298.

Zhang, C., 2001: Double ITCZs. *J. Geophy. Res.*, **106**, 11,785-11,792.

Zhou, J. and W. K.–M. Lau, 1998: Does a monsoon climate exist over South America. *J. Climate*, **11**, 1020-1040.

Appendix A: Other activities related to the IAS

A1 Inter-America Institute (IAI) for Global Chang Research (www.iai.int) – The IAI is an intergovernmental organization supported by 19 countries in the Americas dedicated to develop the capacity of understanding the integrated impact of present and future global change on regional and continental environments in the Americas and to promote collaborative research and informed action at all levels. The research foci of the IAI are (i) Understanding Climate Change and Variability in the Americas, (ii) Comparative Studies of Ecosystem, Biodiversity, Land Use and Cover, and Water Resources in the Americas, (iii) Understanding Global Change Modulations of the Composition of the Atmosphere, Oceans and Fresh Waters, and (iv) Understanding the Human Dimensions and Policy Implications of Global Change, Climate Variability and Land Use. The IAI supports research grants, training, and scientific workshop. There are many overlapping research interests between the IAI and IASCLIP. The IASCLIP can enhance some of the ongoing research of the IAI. The IAI provide multidisciplinary relevance for the IASCLIP.

A2 Intra-Americas Sea Initiative (IASI) (www.iasinitiative.org) – The IASI is an international, multi-institutional effort to improve our understanding of the connectivity and societal impacts of climate variability, oceanography, geology, and ecology in the Intra-Americas Sea and adjacent regions. Its specific objectives are: (i) improve regional observation and modeling systems, and increase their accessibility to the wider community; (ii) facilitate interactions and information exchange among the scientific community, relevant agencies, and end users (resource managers, educators, NGOs, activists, developers); and (iii) participate in capacity-building in countries of the Intra- Americas Sea (IAS). Through a website, the IASI provide information of research, education/training, workshops/meetings, and other activities related to the IAS. The IASI is now mainly an initiative of ocean science. It provides IASCLIP background for its oceanic component. The IASCLIP would be a natural expansion of the IASI to include atmospheric and hydrological sciences.

A3 The Caribbean Community Climate Change Centre (CCCCC) (www.caribbeanclimate.org) - The main goal of the CCCCC is to improve the ability of people living in the Caribbean communities from climate change related phenomena to adopt more sustainable lifestyles. Its specific objective is to improve the knowledge of communities at risk associated with climate change in order to adapt to the problems because of climate change. Its focus includes collaborative iniatives and joint-programme development. The CCCC can serve as an agent for the IASCLIP to communicate with the Caribbean communities and governments to earn logistical and moral support for the IASCLIP.

A4 Water Center for the Humid Tropics of Latin America and the Caribbean ("Centro del Agua del Trópico Húmedo para América Latina y el Caribe") (CATHALAC) (www.cathalac.org) – CATHALAC was established to serve as administrative focal point in the Latin America and the Caribbean region for training, research and technology transfer in the field of water resources and the environment. It has eight areas of interest: (a) Air-Sea-Land Interactions; (b)

Hydrological Process Studies; (c) Small Island; (d) Integrated Urban Water Management; (e) Water Quality Control; (f) Water Resources Assessment, Management and Conservation; (g) Hydrology and Public Health; and (f) Knowledge, Information and Technology Transfer. CATHALAC has built an extensive network of research institutes, universities, governmental authorities, and donors that form the basic prerequisite for regional cooperation and coordinated research. The Center promotes, participates, and coordinates the elaboration of proposals for extensive regional projects. CATHALAC and IASCLIP share many mutual research interests in local hydrological cycle. CATHALAC provide a link between the hydrological research of the IASCLIP to societal impacts of in the IAS region. The IASCLIP research will enhance the understanding of the hydrological process studies of CATHALAC.

A5 The SouthEast Atlantic Coastal Ocean Observing System (SEACOOS) (www.seacoos.org) – The SEACOOS is one of the coastal component of the Integrated Ocean Observing System (IOOS), whose objective is to collect and disseminate data and data products to serve the critical and expanding needs of environmental protection, public health, industry, education, research, and recreation. The SEACOOS initiative is an eleven-institution collaboration to develop a regional coastal ocean observing system for the southeast (NC, SC, GA, FL) United States. It includes observing, modeling, and data management. Near real-time observations of SST and surface wind are available from stations in part of the Gulf costal zone (Fig. A1). Oceanic observations needed for the IASCLIP can be supplemented by the existing observing system of the SEACOOS *A6 The Global Ocean Data Assimilation Experiment* (GODAE, www.bom.gov.au/bmrc/ocean/GODAE) - GODAE is a global system of observations, communications, modeling and assimilation designed to deliver regular, comprehensive information on the state of the oceans. Within GODAE, special efforts are made by many international research groups to focus on data assimilation and prediction of the IAS using high-resolution ocean models. Table A1 gives examples of ocean models used in such efforts. These modeling efforts can benefit tremendously the research on the mechanisms for the variability of the WHWP. They can also be integrated into the coupled modeling components of the IASCLIP.

A7 Gulf drilling – There numerous drilling platforms operated by oil industries in the Gulf of Mexico (Fig. A2). The drilling operations require forecasts of surface winds and ocean currents, particularly those related to tropical cyclones. Meteorology measurements are taken from some of these platforms. There might be potential collaborative partnerships among the industries, research institutes, and government to expand the meteorology measurements from these platforms to benefit both research and forecast.

A8 The Atlantic Marine ITCZ Climate Process Study (AMI-PROS) – The AMI-PROS is a research program under development to improve our understanding of the processes key to the short-term climate variability of the Atlantic marine ITCZ. It initial emphasis is the eastern Atlantic ITCZ, with an intension of field experiment in 2006 and 2007. The western Atlantic ITCZ is also a research subject of the AMI-PROS, which naturally overlap with IASCLIP's interest in the same subject.

A9 VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS, www.ofps.ucar.edu/vocals) - The overall goal of VOCALS is to develop and promote scientific activities leading to an improved understanding and model simulation of southeastern Pacific stratus decks. As indicated by Fig. 3.1b, deep convective heating is a potential remote factor for cloud variability in the southeastern Pacific region. The diagnostic and modeling efforts from the two programs are naturally connected, at least from a large-scale perspective.

A10 The North American Monsoon Experiment (NAME, www.ofps.ucar.edu/name*) and the Monsoon Experiment of South America (MESA,* www.ofps.ucar.edu/mesa*)* – Obviously, there are many common issues between these two existing research programs and the proposed IASCLIP. The water vapor transport from the IAS, for example, is a critical process for the monsoons in both North and South America. The IASCLIP program, however, intends to address a set of problems that currently are not the focuses of either NAME or MESA. The three programs are therefore complimentary and mutually beneficial. Particularly, the IASCLIP can be viewed as a natural extension of NAME from its current focus on Tier 1 domain, namely, the core region of the North American monsoon in Baja California, Sierra Madre Occidental, and Southwest of the US, to its Tier 3 domain, which includes partially the IAS (see the cover page). This extension would also forge a connection between NAME and MESA.

Appendix B: Acronyms

AMI-PROS: The Atlantic Marine ITCZ Climate Process Study
AWP: Atlantic Warm Pool
CLLJ: Caribbean low-level jet
CATHALAC: Centro del Agua del Trópico Húmedo para América Latina y el Caribe
(Water Center for the Humid Tropics of Latin America and the Caribbean)
CCCCC: The Caribbean Community Climate Change Centre
CEPEX: Central Pacific Experiment
ECAC: Experimento Climático en las Albercas de Agua Caliente de las Américas (The Climate Experiment over the Americas Warm Pools)
ENSO: El Nino and Southern Oscillation
EPIC - Eastern Pacific Investigation of Climate
GATE: Global Atmosphere Tropical Experiment
GCM: general circulation model
GPLLJ: Great Plain Low-Level Jet
IAI: Inter-America Institute
IALLJ: IntraAmerican low-level jet
IAS: IntraAmericas Sea
IASCLIP: IntraAmericas Study of Climate Process
IASI: Intra-Americas Sea Initiative
INDOEX: Indian Ocean Experiment
IOOS: Integrated Ocean Observing System
IRI: International Research Institute for Climate and Society
ITCZ: intratropical convergence zone
JASMINE: Joint Air Sea Monsoon Interaction Experiment
LBA: Large Scale Biosphere-Atmosphere Experiment in Amazonia
MDO: multidecadal oscillations (of the Atlantic)
MESA: Monsoon Experiment of South America
MSD: Mid Summer Drought
NAME: North American Monsoon Experiment
NASH: north Atlantic subtropical high
SEACOOS: The SouthEast Atlantic Coastal Ocean Observing System
SMO: Sierra Madre Occidental
SST: sea surface temperature
TAV: tropical Atlantic variability
TC: tropical cyclone
TEPPS – Tropical Eastern Pacific Pilot Study
TNA: tropical North Atlantic
TOGA COARE: Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment
TRMM: tropical rainfall measurement mission
VAMOS: Variability of American Monsoon Systems
WHWP: Western Hemisphere warm pool