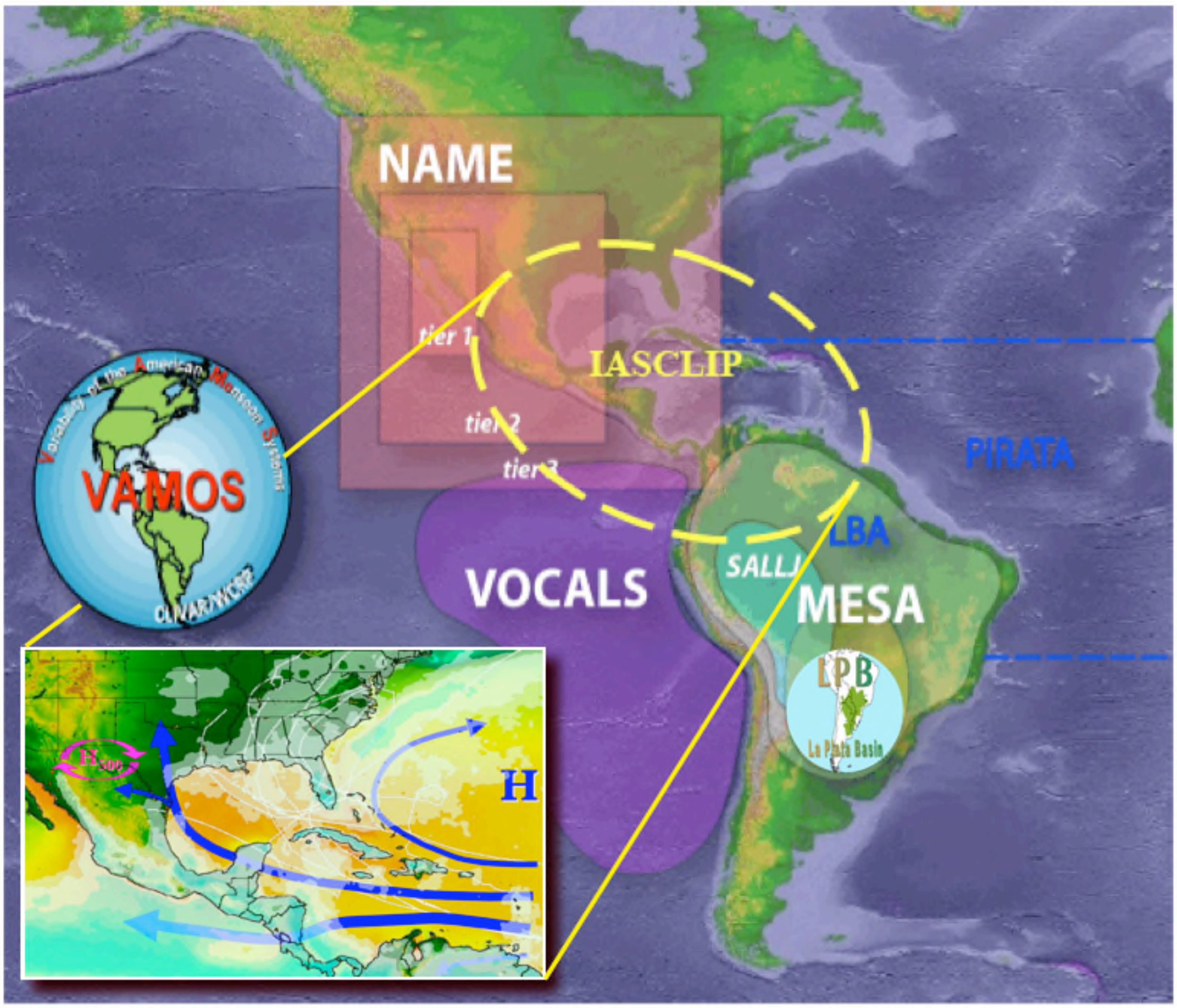
A Science and Implementation Plan for the

Intra Americas Study of Climate Processes (IASCLIP)

Prepared for the VAMOS Panel



March 2008 (revised)

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Executive Summary

The Intra-Americas Seas CLImate Program (IASCLIP) is proposed for 2009-2014, as a new component of CLIVAR VAMOS. The overarching goal is to estimate and exploit potential predictability of warm-season weather and climate in the region, mainly on intraseasonal to interannual time scales, based on improved understanding and modeling of relevant physical and dynamical processes. IASCLIP will also seek to link research to societal applications in the region.

In the IAS region in summer, the Western Hemisphere warm pool (WHWP) is overlain by mean easterly winds on the southern limb of the North Atlantic Subtropical High (NASH). These winds sweep Atlantic moisture and tropical storms westward through the Caribbean, and northward into the United States. Flow also crosses Central America into the eastern North Pacific, contributing to the moisture source for the North American summer monsoon. Three main science issues (section 5) are identified as targets for IASCLIP: (i) What are the sources and predictability of summertime anomalies in the WHWP? (ii) What are the structure and dynamics of the regional atmospheric circulation and low-level jets? How does this flow depend on and interact with boundary conditions such as the WHWP, land heating, and topography to modulate precipitation and storms? (iii) Within this climate setting, how can predictions of important weather phenomena such as tropical cyclogenesis events within the region be improved?

After a comprehensive review of literature on IAS climate and its variability, this document outlines scientific challenges and offers a plan to address them. The plan will be executed by several working groups, each focusing on specific tasks. The three components of IASCLIP execution are:

1. **Diagnostics and modeling efforts.** These will continue throughout IASCLIP. The present state of model-based (regional and global) simulation and prediction will be assessed against observations. Experimentation will highlight key phenomena, isolate their roots in physical processes, and detect weaknesses in model parameterizations. Observational comparisons will invariably run up against a lack of data on key aspects, especially vertical structure and cloudy and turbulent processes.

2. **An observational campaign.** This will respond to the shortcomings above. A 2-year (nominal 2011-2012) Extended Observing Period (EOP) is expected, with a first summer of experimental forecasting and trial deployments used to guide Intensive Observing Periods (IOPs) in the second year. Enhanced monitoring (e.g. buoys, enhanced soundings, and subsetting and archiving of satellite and other data streams) will span the whole EOP, putting the IOP in context.

3. **Applications and capacity building.** This work will attempt to link the tangible outcomes of the scientific research components above to end users of climate products.

The time line for IASCLIP activities has three Phases. In Phase I, component 1 (with some international collaboration and capacity building aspects) will ramp up. The EOP will mark the beginning of Phase II. In Phase III, field data integration and assimilation activities will increasingly consolidate results from components 1 and 2, translating these into meaningful gains in understanding and prediction capability, which component 3 will link to societal interests.

Plan contributors

Eric Alfaro	University of Costa Rica
Jorge Amador	University of Costa Rica
Ernesto Hugo Berbery	University of Maryland
Tony Busalacchi	University of Maryland
Michael Douglas	NOAA/NSSL
David Enfield	NOAA/AOML
Luis Miguel Farfan	CICESE (Mexico)
Rong Fu	Georgia Tech
David Gochis	UCAR
Lisa Goddard	IRI
Jorge Gonzalez	Santa Clara University
David Gutzler	University of New Mexico
Kris Karnauskas	University of Maryland
Christopher Landsea	NOAA/NHC
Ben Kirtman	University of Miami
Victor Magana	National Autonomous University of Mexico
Brian Mapes	University of Miami
Kingtse Mo	NOAA/CPC
Chris Mooers	University of Miami
Ernesto Muñoz	NOAA/AOML
Sumant Nigam	University of Maryland
Ramon Perez	Institute of Meteorology
Germán Poveda	Universidad Nacional de Colombia
Celeste Saulo	University of Buenos Aires
Siegfried Schubert	NASA/GSFC
Michael Taylor	University of the West Indies
Chunzai Wang	NOAA/AOML
Chidong Zhang	University of Miami
Paquita Zuidema	University of Miami

1. Introduction & Rationale

The Intra-Americas Sea (IAS) includes the Caribbean Sea and the Gulf of Mexico. In this document, 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 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 Madden-Julian Oscillation or MJO (Maloney and Hartmann 2000). 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 (Prospero and Lamb 2003) and it is suspected to influence the regional climate in IAS (Lau and Kim 2007).

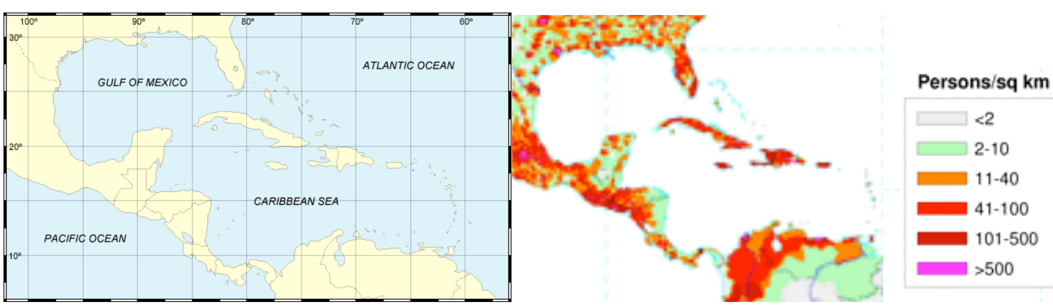

Fig. 1 The Intra-Americas Sea (IAS) region and its population density.

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 climatic 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 MJO (Madden and Julian 1971), 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 (Mo 2000). 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 Americas.

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).

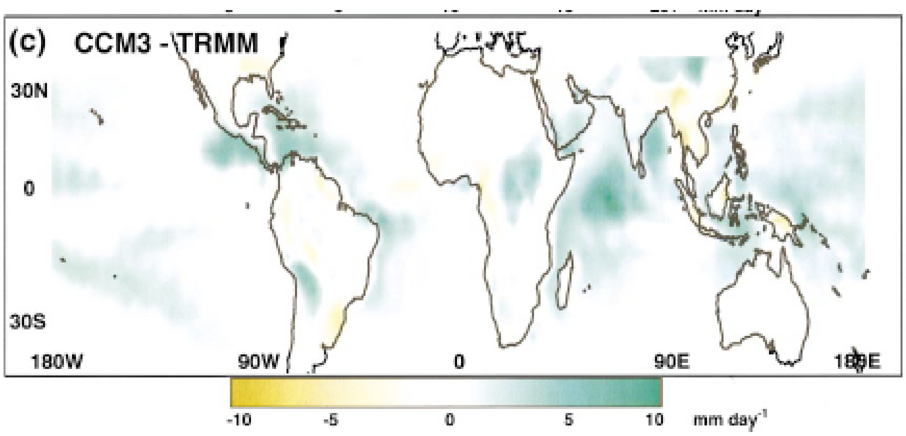

Fig. 2 The climatological mean difference (CCM3 - TRMM) in mm day^{-1}. (From Collier et al 2004)

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-air-sea 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.

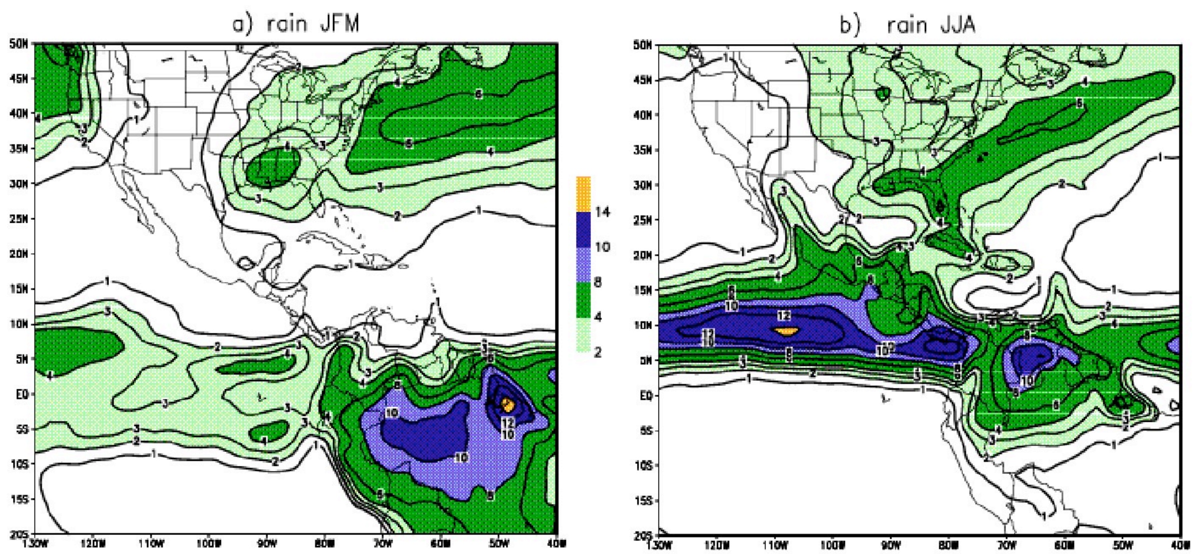

Fig. 3 Mean precipitation for (a) January- March (JFM) and (b) June-August (JJA) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm day^{-1}.

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[1]). More details of the American monsoons are given by Vera et al (2006).

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 reaches a relative minimum over central and southern Mexico, the western coast of Central America, the central regions of Colombia, and the Caribbean maritime continent. 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).

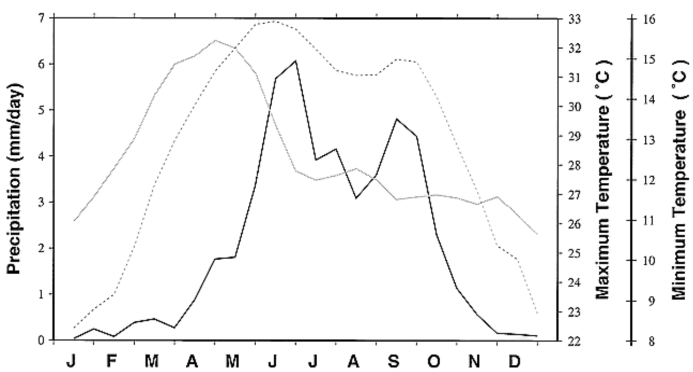

Fig. 4. Biweekly climatology of precipitation (black solid line), maximum temperature (gray solid line), and minimum temperature (dotted line) for Oaxaca, Mexico (17.8˚N, 97.8˚W). (From Magana et al. 1999)

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. 2005). Associated with the MSD are a maximum of sea level pressure, a strong easterly Caribbean Low-Level Jet (CLLJ) in the Caribbean region (Wang 2007; Muñoz et al. 2008), 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 Saharan dust (Prospero and Lamb 2003).

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 Northern Tropical Atlantic (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.

[1] http://www.clivar.org/organization/vamos/VPM10_presentations/MESA_Progress-Plans.pdf

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 MJO 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 increases during the MSD as part of a semiannual pressure cycle and may suppress precipitation there (Mapes et al. 2005, Wang 2007). 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 Pacific 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 and an acceleration of the easterly CLLJ across the isthmus into the Pacific where sea level pressure is anomalously low. 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 Pacific cold events of ENSO, rainfall over most of the IAS region is above normal, except over Florida and 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).

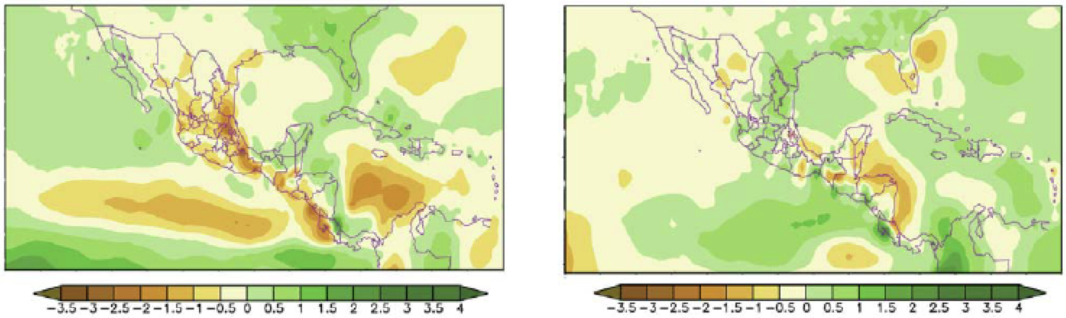

Fig. 5: Composite of precipitation anomalies (mm/day) during the summers (Jun-Jul-Aug-Sep) of (left panel) six El Niño onset years (1965,1972, 1982, 1986, 1991, 1997), and (right panel) La Niña years (1964, 1970, 1973, 1975, 1988, 1998). (From Magana 2000)

Influences of ENSO on rainfall in the IAS region is complicated by influences from SST anomalies in the tropical Atlantic Ocean; the Pacific 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. These factors are discussed in detail in section 3.

An additional influencing signal in 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; Visbeck et al. 2001). A positive NAO affects the NTA basin by mean of anomalously strong trade winds, increased ocean-to-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 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, with the loss of lives, are also caused by floods and landslides induced by hurricane rainfall, especially where hilly regions have been denuded of vegetaion. While TC track forecasting has improved in recent years, many challenges remain in predicting wind intensity and rainfall distributions. Hurricane Mitch in 1998 is a case in point. About 10 to 12 thousand 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.

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).

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. These storms present a particular challenge to understand and predict because they typically spring up from mesoscale cloud clusters with little or no warning. 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 see TCs that generate off Africa propagate into the IAS region from the east. Hurricanes Gilbert (1988) and Wilma (2005) are notable examples and such storms are often the most intense of the season. Long-term variability of TC activity 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 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).

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.

On interdecadal 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) is more than twice of that in years of AMO warm phase (Fig. 6). However, 80% of large (small) WHWPs occur during warm (cool) phases of the

AMO, whilst observations and models agree that large (small) WHWPs are associated with favorable (unfavorable) tropospheric conditions for hurricane development (Wang et al. 2006, 2007). Hence, studies of how the WHWP relates to TC activity can shed valuable light on the multidecadal storm regimes.

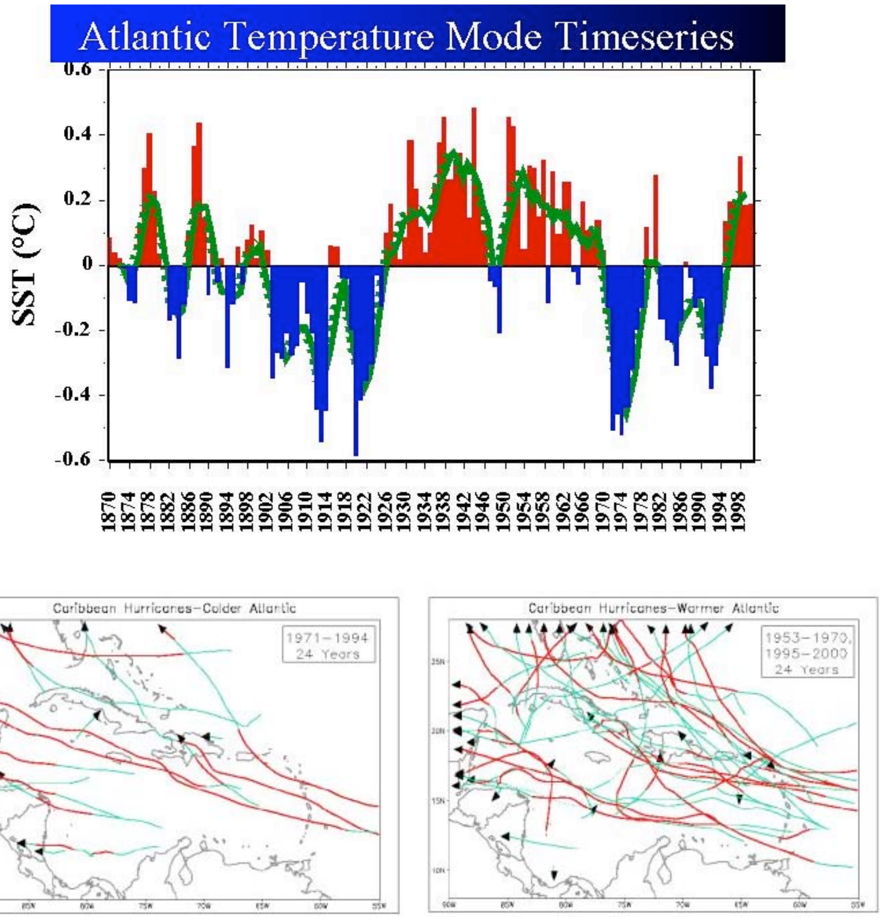

Fig. 6. Top: Smoothed (green) and unsmoothed (red/blue) versions of the detrended annual averages of Atlantic SST from the equator to 70°N. Bottom: Landfalling hurricane tracks in the IAS during years of cold (1971-1994, left) and warm (1953-1970 and 1995-2000, right) North Atlantic (AMO).

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). In spite of indications that increasing absolute ocean temperatures will increase the maximum potential intensity of hurricanes (Emanuel 2005), the IPCC multi-model projections suggest that the environment for hurricanes (shear and CAPE) will become more hostile for hurricane development by 2100 AD (Vecchi and Soden 2007). Since the WHWP must necessarily grow with increasing temperature, these relationships run counter to our expectations based on 20th century observations at interannual to multidecadal timescales. Clearly, much research is needed to effectively anticipate TC activity in the coming decades.

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 eastern North 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).

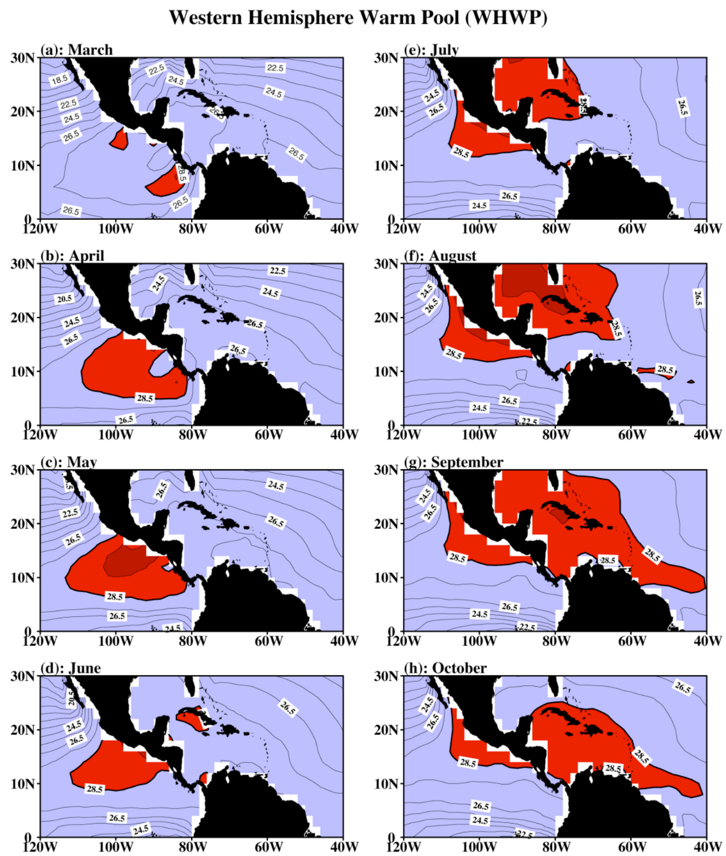

Fig. 7 Seasonal distributions of SST for the tropical WHWP: (a) Mar, (b) Apr, (c) May, (d) Jun, (e) Jul, (f) Aug, (g) Sep, and (h) Oct. The shading and dark contour represent water warmer than 28.5°C. (From Wang and Enfield 2003)

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).

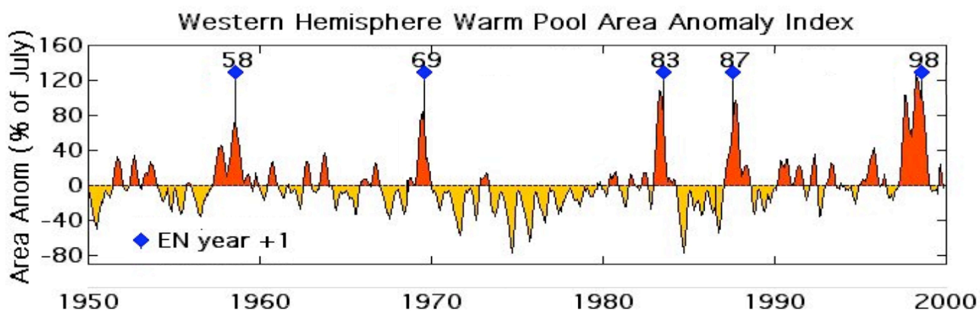

Fig. 8 Anomaly time series of the WHWP area surrounded by the 28.5 °C isotherm. The series is expressed as a percentage of the climatological mean area for July. The July values of the five largest anomalies are indicated by the blue diamonds, and the July values of the prior years by green circles.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

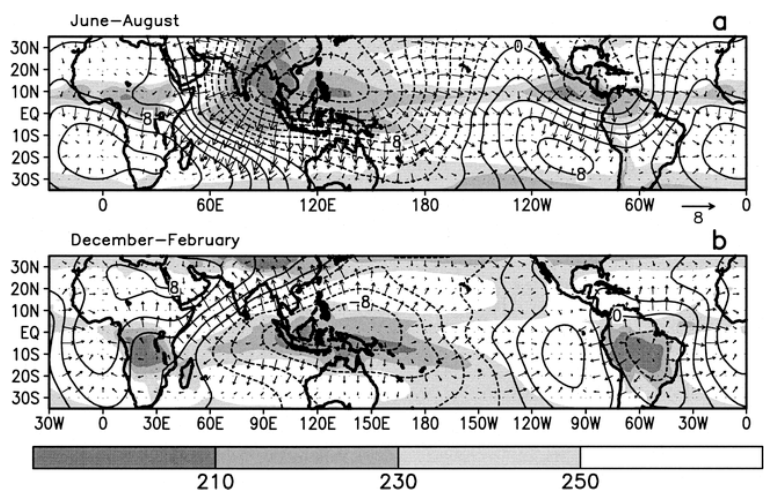

Fig. 9 1979–2000 climatological mean outgoing longwave radiatin (OLR, shaded, W m^{-2}), 200-hPa velocity potential (contours, interval is 2 $x10^6$ m^2 s^{-1}), and divergent wind vectors (m s^{-1}) for (a) JJA and (b) DJF. The divergent vector wind scale is located below (a). (From Chelliah and Bell,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

Another important role of the WHWP 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: the eastern North Pacific (ENP) warm pool and 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 is 25% larger (smaller) than its climatological area it 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 the 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 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,..

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 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.

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 water vapor transport that supplies moisture to the Great Plains (Fig. 6; Muñoz et al. 2008). 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).

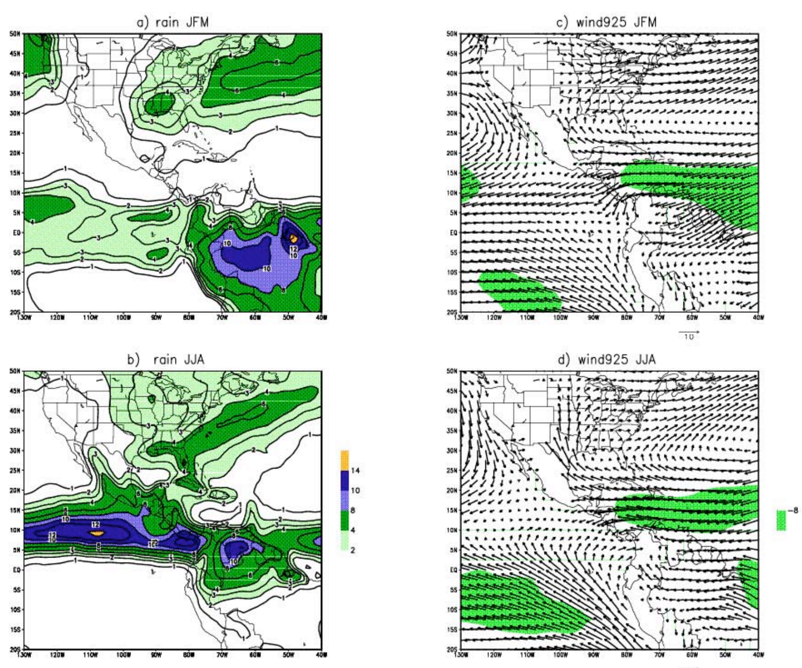

Fig. 10 Mean precipitation for January- March (JFM) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm/day, (b) same as (a), but for June-August (JJA), (c) Mean winds at 925 hPa for JFM averaged 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.

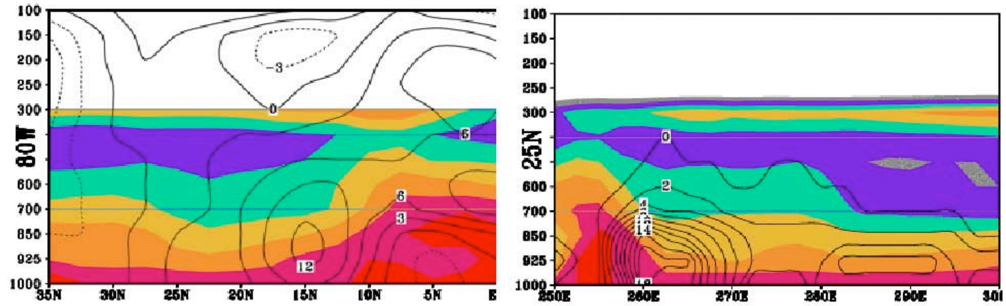

Fig. 11 Vertical-meridional cross-section of zonal wind (contours, m/sec) at 80˚W (left panel) and vertical-zonal cross-section of meridional wind (contours, m/sec) at 25˚N (Right panel) for July based on the NCEP/NCAR reanalysis.

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).

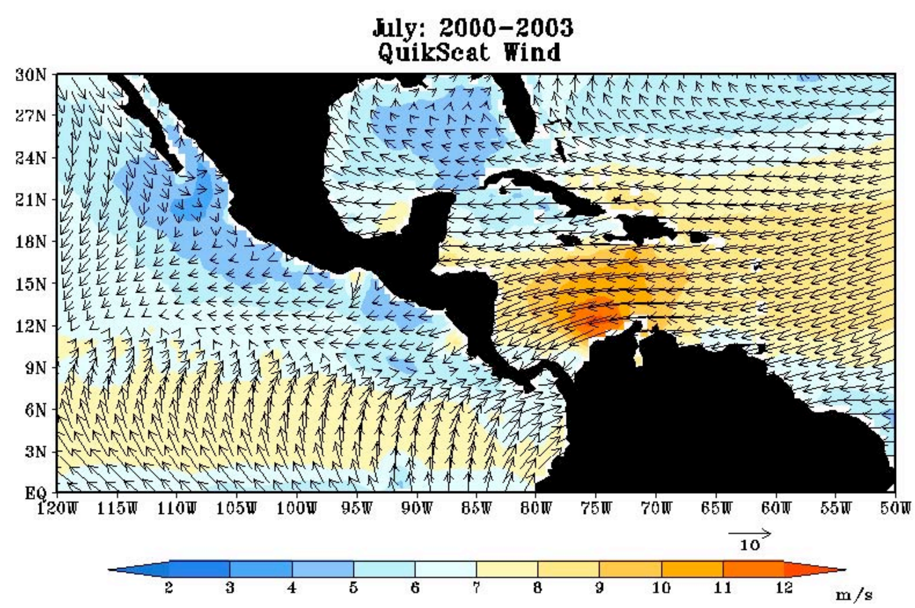

Fig. 12 July mean QuikScat winds (m s^{-1}) for the period 2000-2003 (from Amador et al., 2006).

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 sea level pressure (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. Also, the vertical structure of air temperature across the Caribbean has a southward temperature gradient with a stronger thermal wind at the lower levels nearby the coastal mountains of northern South America (Muñoz et al. 2008).

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 (Wang, 2007; Muñoz et al. 2008; White et al. 2008). 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. In fact, the SST anomalies in the Niño3.4 region seem to influence the July CLLJ anomalies with a few months lead time, which in consideration of the strong persistence of CLLJ monthly anomalies during summer may provide a source of predictability for the IALLJ (Muñoz et al. 2008). 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 (Wang, 2007). 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 (2005) (Figs. 13c, d).

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).

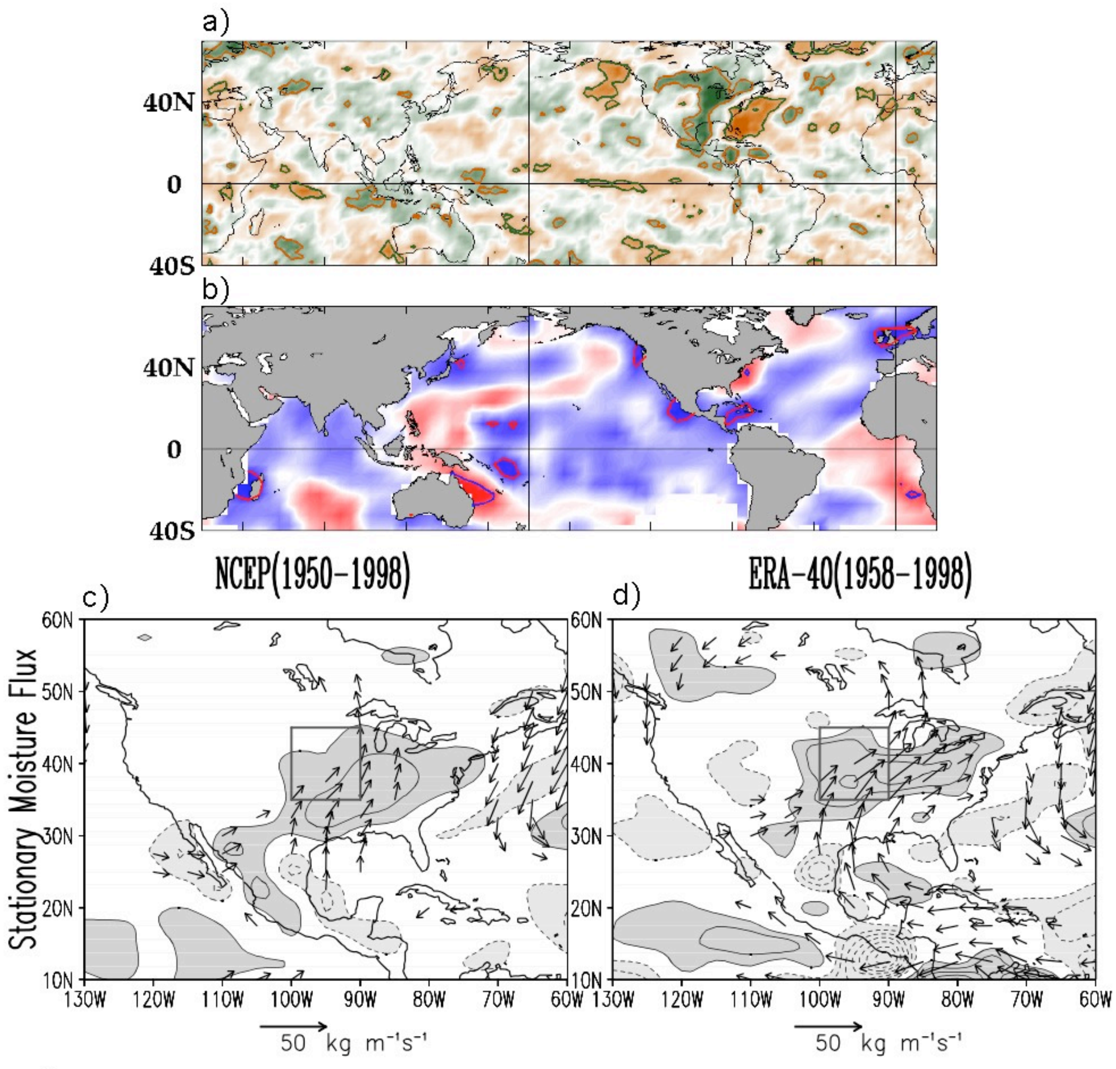

Fig. 13. Upper panels: Correlation of northward moisture flux across the Gulf of Mexico with CMAP precipitation (a) and sea surface temperature (b), from Mestas-Nuñez et al. (2007). Lower panels: Regression of NCEP reanalysis precipitation (c) and ERA reanalysis precipitation (d) on summer precipitation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

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. 2005) and the CLLJ and CLLJ's westward moisture transport (Wang and Lee 2007; Wang 2007; Muñoz et al. 2008). 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 northeast 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 in 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.

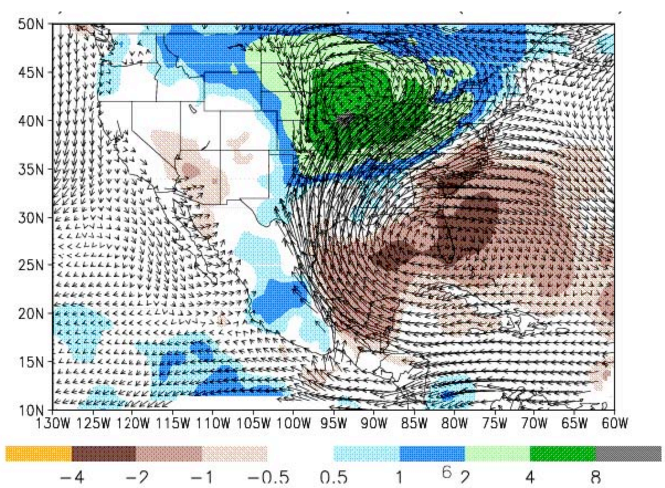

Fig. 14 Composite of precipitation (colored) and 925 hPa wind anomalies. The unit vector is ms-1.

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, especially during the boreal winter. A negative (positive) NAO pattern typically leads 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, would 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 (Tanimoto and Xie 1999). 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 (AWP)

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). 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.

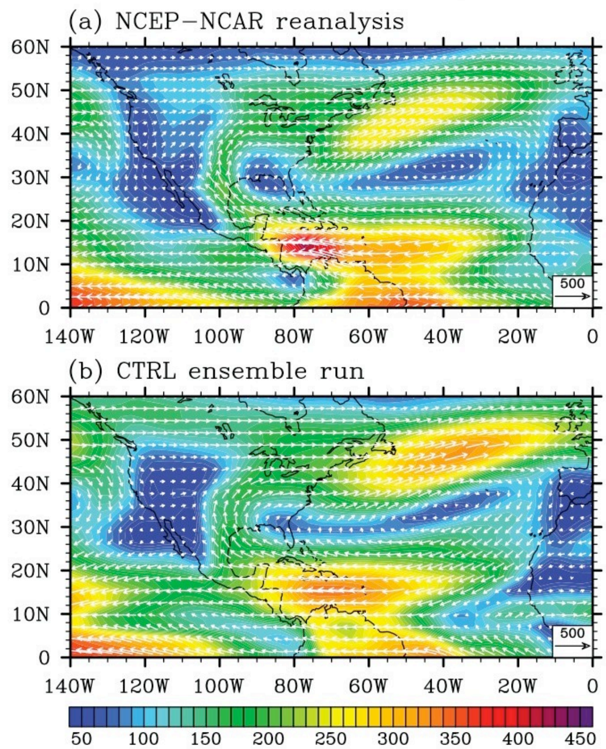

Fig. 15. The summer (JJA) vertically integrated moisture flux, calculated from (a) the NCEP-NCAR reanalysis and (b) the CTRL ensemble run. Arrows indicate the moisture flux vector and colors represent the amplitude of the moisture flux.

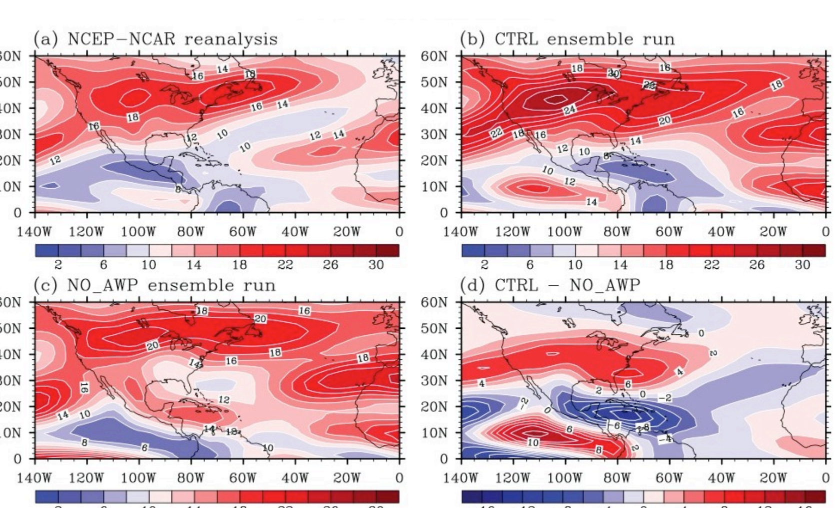

Fig. 16. The200 hPa minus 850 hPa vertical wind shear (m s^{-1}) during August-September-October (ASO) from (a) the NCEP-NCAR reanalysis, (b) the CTRL ensemble run, (c) the NO_AWP ensemble run, and (d) the difference between the CTRL and NO_AWP runs. From Wang et al. (2007).

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) showed 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 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 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, due in part to changes of rainfall and probably background atmospheric flow. This result suggests that the climate conditions, such as ocean surface winds and fluxes over the 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.

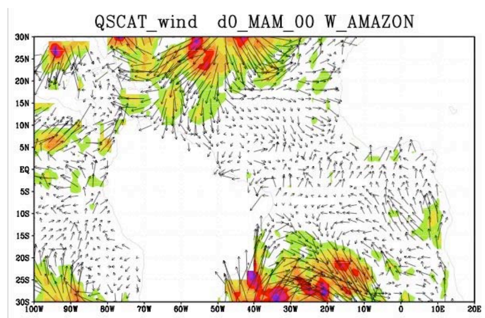

Fig. 17: Ocean surface wind anomalies one-day after peaks of Amazon rainfall (the red square) during boreal spring (MAM). The winds and rainfall are derived from QuikSCAT and TRMM observations.

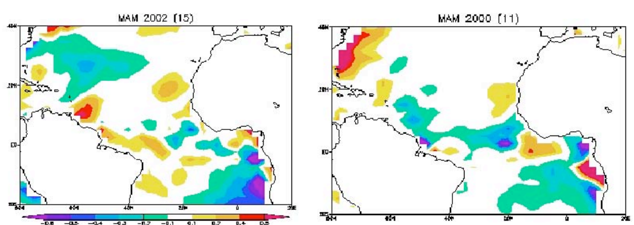

Fig. 18: SST anomalies induced by anomalous surface fluxes associated strongest 20% convective events during boreal spring (MAM) of (left) 2002 and (right) 2000 in the western Amazon. They are estimated by an ocean mixed layer model (Alexander 1992) with climatological mixed layer depths (Levitus and 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 NASH, most of moisture needed for 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).

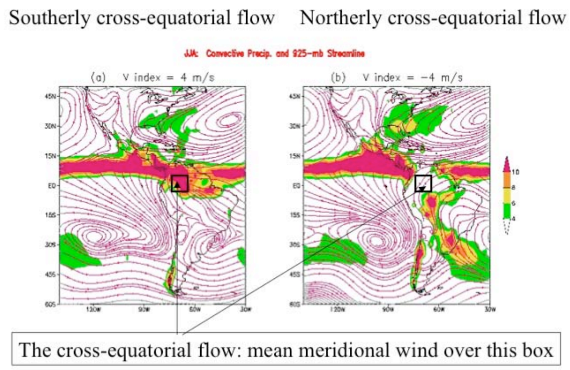

Fig. 19: Streamlines at 925 hPa and TRMM daily rainrate associated with (a) southerly (b) northerly cross-equatorial flow for boreal summer (JJA) based on the linear regression for one sigma of the cross-equatorial flow. Streamlines are derived from ECMWF reanalysis. The analysis period is 1979-1993.

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 MJO, (Madden and Julian 1971). 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 outgoing longwave radiation (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 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 region, improving our ability of representing these processes in global climate models and predicting them on subseasonal to interannual timescales, and facilitating applications of climate forecast products in the IAS region. The IASCLIP program embraces two research themes, summarized from the discussions in section 3:

The North American Monsoon Experiment (NAME, Higgins et al, 2006), 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. The IASCLIP program, proposed as a component of VAMOS, extends the NAME emphasis eastward into the Tier III and AWP domain. It strives to understand, simulate and predict, through data diagnostics, models and field campaigns, the subseasonal to 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 co-vary 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 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 and Caribbean 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), and (6) possible 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) ENSO research has led to improved predictions of climate mostly during boreal winter but improved boreal summer predictions have remained elusive and this is the season in which much of the U.S. gets hurricanes and most of its rainfall, and in which the IAS region has its rainy season on which agriculture and other activities are critically dependent. The most attractive paradigm for improving this situation is to understand and predict how the AWP integrates strong remote forcing during winter and spring to produce SST anomalies that then feed back on the atmosphere in summer.

(c) 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.

(d) 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.

5. Key Science Issues

We elect to present the science issues through a cascade from the largest to the smallest scales. At the largest, hemispheric scale (5.1) the Western Hemisphere warm pool is the organizing concept for an ocean region that integrates the forcing effects of remote climate variability in winter and subsequently unleashes impacts on the atmosphere over the IAS and surrounding land areas during the season of maximum heating. At this scale we are most concerned with issues that affect predictability, that is, the ability of coupled ocean-atmosphere models and forced ocean models to replicate the processes by which warm pool anomalies mature in the winter and early spring and persist into the summer. At the intermediate scale of the IAS (5.2) we shift our emphasis to the Intra-Americas Low-Level Jet (IALLJ) -- comprised of the Caribbean low-level jet and its northward branch in the Gulf of Mexico -- and its warm season response to large scale oceanic and atsmospheric anomalies. The IALLJ is primarily responsible for the delivery of tropical moisture to the surrounding populated land regions. Finally, at the smallest scale (5.3) we encounter the complicating effects of land heating and orography as the moisture exported by the IALLJ enters or crosses surrounding land masses. At the largest scale, remote influences are foremost, while at the smallest scale we are increasingly concerned with the local modulating effects of an inhomogeneous ocean and land boundary condition.

5.1 The Western Hemisphere warm pool (WHWP)

The WHWP is an essential link in the climate of the IAS region and the Western Hemisphere because of its roles as a season-shifting modulator of remote climate effects (section 3.1), as the summer convective heating center for the Western Hemisphere (section 3.1), as a water vapor source and as a modulator of moisture transports (sections 2.1b and 3.2). What emerges from recent research is that the WHWP acts much like a time-delay climate capacitor that can integrate persistent atmospheric forcing in the cold season by the likes of ENSO and the NAO, resulting in a mature warm pool anomaly by late spring and persisting into the summer months, whence it can force the atmosphere during the period of maximum heating. The very nature of this process holds out promise for potential predictability of summer impacts on rainfall and tropical cyclones, provided that models can be made to reproduce these processes. Most of the warm season climate characteristics we are concerned with – convective instability and rainfall, the low-level jets and moisture transports, the mid-summer drought (MSD), ITCZ and tropical cyclones (TCs) – are likely related to the forcing effects of the summer warm pool anomalies.

Our understanding of these roles, however, remains qualitative and empirical. Notwithstanding the role of the warm pool in IAS climate suggested by statistics and model experiments, 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 and its predictability 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 for the variability of the WHWP?* – This question goes to the crux of predictability on the seasonal to interannual time scale. Preliminary research (Enfield and Lee 2005) suggests that the variability of the WHWP responds significantly to fluctuations in surface heat fluxes controlled by variable cloudiness and the northeast trade winds in the Atlantic, whilst the trades are in turn modulated by both ENSO and the NAO during the winter and early spring (Enfield et al. 2006). To improve the predictability of summer rainfall and TCs, the MSD, and other climate features requires that our understanding of these processes be improved and that ocean models and their coupled counterparts be made to properly replicate them and reproduce the observed inter-seasonal evolution of the warm pool. Ocean models are presently challenged by large uncertainties in the surface fluxes and mixing representations, by the complexity of the land-ocean-atmosphere interactions in the IAS region, and by the need to resolve important mesoscale processes such as ocean current jets, coastal upwelling and eddy motions. In addition to SST, mechanisms for the interannual variability in the upper-ocean vertical structure and heat content remain unknown, which is an important factor for TC intensification.

(b) *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. Recent studies based on observations and models confirm this (Wang et al. 2006, 2007). But the 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. This characteristic is apparently not properly simulated by many models. Although the paucity of ocean- and surface-based observations in the Caribbean makes exact assessment difficult. One hypothesis is that as the IALLJ accelerates into the Caribbean from the tropical North Atlantic, strong lateral divergence and subsidence discourage rainfall across the Caribbean until the jet again decelerates as it approaches the coast of Central America (White et al. 2007; Muñoz et al. 2008). Possible effects of the WHWP on precipitation over land, in addition to its modulation of the water vapor transports (sections 3.1, 3.2), need to be explored. Outside the Atlantic IAS, questions persist about how warm pool-engendered moisture transports affect rainfall where the IALLJ exits into eastern North America and across Central America into the eastern North Pacific. Most vexing is the fact than when the warm pool heating is greater, the IALLJ weakens but the moisture content of the exported air is greater, hence it is not clear how the moisture flux (q•**V**) is affected in the aggregate. Recent studies (Wang et al. 2006, 2007) suggest that the moisture export decreases but we don't know whether this conflictive relationship is predictable.

(c) How does the warm pool influence hurricanes? – Data diagnostics indicate that major hurricane activity and shear co-vary with warm pool size interannually (Wang et al. 2006) and multidecadally (Goldenberg et al. 2001). By forcing the NCAR CAM 3.1 AGCM with the summer SST climatology and with warm pool SSTs replaced by winter values, Wang et al. (2007) have shown that the normal summer warm pool is likely responsible for a significant decrease in tropospheric vertical shear and increase in instability (Wang and Lee 2007), two factors important in the development of major hurricanes. It appears likely that the shear relationship can be explained as part of the Gill (1980) response to atmospheric heating over the warm pool anomalies. The existence of physically comprehensible relationships in observations and models, together with the prospect of predicting Atlantic SST anomalies (section 5.1-a) gives us some hope that significant progress can be made to improve the seasonal outlooks for TCs. Moreover, we have seen recent progress in meeting the challenge of combining the climate predictability of low-resolution global models with the accuracy of high resolution regional models that resolve tropical cyclones (e.g., Knutson et al. 2007).

Many unanswered questions remain about the possible thermal impact of the tropical Atlantic on TCs. The Tropical Upper Troposphere Trough (TUTT) usually positioned north and east of the IAS was strongly developed during the enigmatic 2007 hurricane season; it interacted with transient extratropical troughs to produce frequent and strong southwesterly wind shear which may explain why most TCs refused to develop into major hurricanes. The evidence suggests that when the TNA is cool (small warm pool) the TUTT is stronger (Knaff 1997). How tightly is the TUTT connected to TNA warmth and the AWP size, or is this a quasi-independent influence on vertical shear? What relation, if any, exists between tropical Atlantic thermal conditions and the frequency and intensity of outbreaks of the Saharan air layer (SAL), which discourages convective development? For impact of TCs on the IAS, it is unclear whether steering flow variability determines the likelihood of landfall or whether genesis location is the main factor. How tightly is the NASH connected to TNA thermal anomalies and does the NASH have a predictable effect on the relative frequency of storms that make landfall (storm track patterns)? 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.

Many questions about the long timescale variability of TCs affecting the IAS region remain to be addressed. Is it true -- as suggested by the fact that 80% of large/small warm pools occur during warm/cool phases of the AMO – that these warm pool mechanisms are responsible for the AMO-TC relationship of Goldenberg et al. (2001)? TCs that form in the Atlantic and propagate into the IAS region are influenced by both thermodynamics (SSTs, mid/low tropospheric moisture) and dynamics (tropospheric wind shear, vorticity of incipient disturbances, and subsidence). It is uncertain 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, may 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). 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.

(d) *Climate change issues* -- We fear that knowledge and predictions predicated solely on the observations and analyses of 20th century variability may become increasingly compromised for parts of the climate system as the effects of anthropogenic warming begin to interact with natural variability. As an example of this, the IPCC multi-model ensemble projects a 24% weakening of the Atlantic meridional overturning circulation (AMOC) during the 21st century, accompanied by a slower warming of the North Atlantic than elsewhere in the global tropics (Fig. 21).

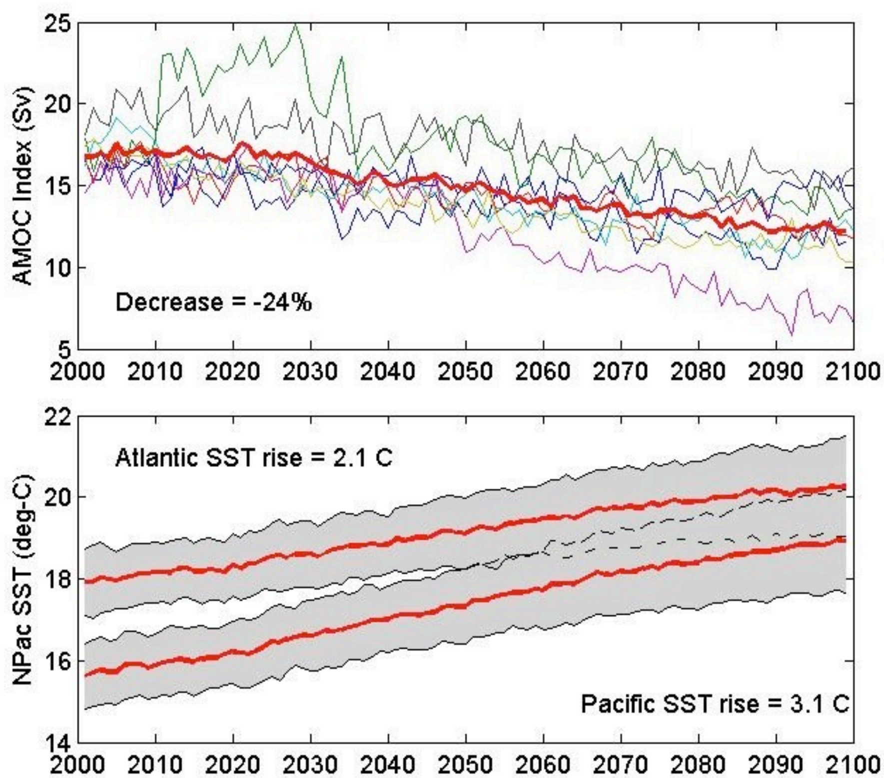

Fig. 21. Upper: 21st century projections of the streamline-based index of the Atlantic meridional overturning circulation (AMOC) for eight selected IPCC models in the AR4-WG1 report. Red curve is the ensemble average. Lower: Ensemble-averaged annual SSTs for the North Atlantic (upper curve, red) and Indo-Pacific (lower curve, red). Gray fill is ± one standard deviation; overlapping spreads are indicated by dashed lines. (Enfield et al. 2008)

The models also project that the vertical wind shear and humidity in the tropical Atlantic will become more hostile for hurricane development (Vecchi and Soden 2007), exactly opposite to our current expectation for naturally warming SSTs based on 20th century data. Similar difficulties apply to rainfall in the IAS, projected to become significantly drier in the decades to come in spite of warmer SSTs. As argued by Latif et al.(2007), differential heating of one region with respect to the global tropical background can make that region look cool to the atmosphere even if not judged cool by normal standards. 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. It therefore behooves us to include these conflictive relationships in our research menu for the large scale milieu of the IAS.

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 made 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 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 and the annual pressure cycle, and its role in the MSD). IALLJ features 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 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, a full explanation for the intensification of the wind might lie with other factors, such as low pressure systems in the IAS region created by local deep convection or land effects (section 3.6). Or, because much of the IALLJ lies equatorward of 20°N, is it best attributed to the annual cycle and anomalies of pressure changes between the tropical Atlantic and east Pacific (White et al. 2007)? 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. Correct modeling of the IALLJ is probably necessary in order to correctly simulate and predict the effects of divergence and subsidence on Caribbean precipitation.

(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 air 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.

5.3 Land-air-sea interactions

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. In the following subsections we address topics that are related to the (a) thermal effects and (b) dynamical effects of *land-air-sea interactions.* We also include consideration of tropical cyclones in the context of the IAS region (c).

(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 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) *Mid-summer drought (MSD)* – Understanding the large-scale and land-interactive mechanisms for the seasonal and interannual variability of the MSD is critical to its prediction. Magana et al. (1999) have shown that the MSD has its greatest amplitude along the west coast of Central America and diminished amplitude along the Caribbean coast, and that the period of reduced rainfall in July-August coincides with the annual maximum of the strength of the IALLJ. The most straightforward explanation for these observations is that when the IALLJ is stronger, the frequency of easterly winds impinging on the Caribbean coast increases, causing more orographic uplift and rainfall, while the frequency of southwesterly monsoonal flows on the Pacific side decrease in favor of easterlies crossing the isthmus into the downslope Pacific coastal region (enhanced dry conditions). However, the MSD is still detectable on the Caribbean side and it can be seen in climatology as far as Cuba, Florida and the eastern Caribbean. Therefore, some large-scale mechanism must underly the IAS-scale occurrence of the MSD while the easterly-westerly hypothesis best explains how it is spatially modulated across Central America. Large-scale mechanisms could include the climatology and anomalies of the NASH, the semiannual sea level pressure variation and their relation to the IALLJ (Wang 2008; Muñoz et al 2008), as well as their associated patterns of divergence and subsidence. Although we have treated the MSD separately from the overall questions about rainfall (5.1-b), the two must be inextricably related; the same processes mentioned here are also candidates for explaining the variation in strength of the rainy season and its spatial variation, although the relative importance of large-scale and land-interactive processes may differ.

The MSD is not exclusively an IAS phenomenon and appears to be especially well-defined in the eastern North Pacific. However, the Atlantic warm pool appears to have a strong impact on moisture convergence in the ENP (Wang et al. 2006) so the MSD should be studied in the context of both regions. Many AGCM simulations show an MSD, so it appears to be a somewhat robust aspect of global seasonality (Mapes et al. 2005, Rauscher et al. 2008).Various mechanisms have been proposed (Magaña et al. 1999; Magaña and Caetano 2005; Small et al. 2006); these need to be further explored and quantified. The Small et al. study showed that local SST changes are a secondary effect, and heatings outside the MSD region impact the MSD. Angeles et al. (2007) 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.

(c) Tropical cyclones -- 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 propagate 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. Tropical waves can traverse the entire Atlantic with little development, only to explosively amplify into a large mesoscale complex upon entering the Caribbean and then quickly mature into a severe hurricane. Can this be simply attributed to the higher SSTs in the Caribbean, and if so, why do these developments usually not occur preferentially during the warmest part of the season (August-September)? What are the possible influences of land masses in the region, such as the South American continent? Or is it attributable to the climatological frequency of dust incursions into the IAS?

Intraseasonal variability (ISV) is one of the least understood modulators of tropical cyclones in the IAS region. ISV is better understood and well defined as the MJO 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.

(d) Complications due to anthropogenic warming -- 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.

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 include three main components conducted in three phases, with different emphases in each.

6.1 Program components

(a) Component I: Diagnostics and modeling

Some overall modeling goals of IASCLIP are

(i) To provide quantitative model based estimates of the limit of predictability in the IAS region (i.e., current measures of skill for real operational prediction systems and theoretical limits of predictability based on signal-to-noise ratios along with other measures).

(ii) To provide comprehensive understanding of the physical processes underpinning this predictability. The IASCLIP modeling activity will examine the predictability associated with information in the initial state of the climate system and with the interactions and couplings among the various elements of the IAS climate system (i.e., WHWP, NASH, IALLJ). The modeling strategy fully acknowledges the importance of remote forcing (i.e., ENSO, TAV, NAO, SAMS, NAMS) and the role that the IAS region has in global climate variability.

(iii) To improve model processes that are critical to IAS predictability. These "process-level" issues will require both fundamental improvements to the physical parameterizations, and improvements to how we model the interactions between the local processes and regional and larger scale variability in regional and global models.

Prospects for improved prediction on seasonal-to-interannual time scales hinge on the inherent predictability of the system, and our ability to quantify the initial states and forecast the evolution of the surface forcing variables (e.g. SST and land state including soil moisture). In addition to understanding the role of remote SST forcing throughout the Pacific and Atlantic Oceans, we must understand the nature and role of nearby SST anomalies such as those that form in the Gulf of California, the Gulf of Mexico, the IAS, the south eastern Pacific, tropical Atlantic and the South Atlantic, just to name a few. The land surface has an important role in the flow of the region, via both thermal effects („such as surface temperature, dependent on possibly-predictable soil moisture) and mechanical effects (i.e. orographic and frictional). Dust and smoke from land sources may also have a significant influence on the climate of the Americas. IASCLIP seeks to understand these processes through numerical experimentation, diagnostic studies and hypothesis testing.

The IASCLIP modeling strategy outlined in the following also recognizes three distinct, but related roles that observations play in model development and assessment. These are (1) to guide model development by providing constraints on model simulations at the process level (e.g. convection, land/atmosphere and ocean/atmosphere interactions); (2) to help assess the veracity of model simulations of the various key regional phenomena (e.g. low level jets, land/sea breezes, mid-summer drought, tropical storms), and the linkages to regional and larger-scale climate variability; and (3) to provide initial and boundary conditions, and verification data for model predictions.

The modeling strategy also recognizes the importance of fostering research in global coupled ocean-land-atmosphere modeling and regional climate modeling. The modeling strategy is a multi-scale approach in which local processes are embedded in, and are fully coupled with, larger scale dynamics. The relatively poor simulation of some aspects of the low level jets, planetary boundary layer processes, clouds and ocean mixing are all problems that necessarily require a regional multi-scale focus but also are critical issues for improving global model simulations and predictions.

The IASCLIP modeling strategy spans all aspects of IASCLIP: not only initially, but also as an integral part of the field campaign (section 6.1b) and in the ultimate consolidation of the program's goals.

The main tasks of the modeling activities are:

(i) **Quantifying Predictability:** Assessing the fidelity of current global and regional models in simulating and predicting IAS climate variability on time scales from intra-seasonal to inter-annual. Retrospective predictions and simulation experiments from the DEMETER project, NCEP CFS, SMIP and CMIP and from the newly initialed WCRP Coupled Historical Forecast Project (CHFP) will be evaluated in terms of how well they predict and simulate variability in the IAS regional hydrometeorology and variations in the WHWP. For example, can models predict the interannual variability of IAS SSTs from remote forcings, and then the resulting inter-annual variability in the GPLLJ and moisture transport over North America? Do models simulate the interannual variability in the IALLJ and its relationship to the MSD? Can we determine model pathologies that may lie behind discrepancies, and do they involve key processes within the IAS region that an appropriate field campaign could illuminate?

(ii) **Mechanisms for Predictability:** Numerical experiments will use both global and regional simulations to diagnose and understand the basic mechanisms for predictability. For example, what role does the local land state play (both mechanical and thermodynamic) in the variation of temperature and rainfall? What is the role of SST anomalies in the IAS, larger WHWP, and beyond? What causes these SST anomalies? What is the role of remote forcing? What is the role of the low level jets in hydrological variations over land? How does the atmosphere resolve the opposing effects of humidity and wind speed in moisture fluxes, and how does this affect the predictability of moisture transports? How does the variability over the continents and ocean interact? How do coupled atmosphere-ocean processes influence local climate?

(iii) **Improving Model Physical Processes:** IASCLIP modeling community participation in the design (if deemed necessary) of a field campaign. Here the strategy is that data assimilation activities (see discussion below) based on existing data and that activities based on (i) and (ii) will guide the design of the IASCLIP field campaign. Then after Phase II (the field campaign), an update to the assimilation datasets will be produced, This provides strong linkages between Phases I and II assuring better observations and scientific understanding to serve model improvements.

A major tactic of IASCLIP modeling work will be to use data assimilation.

Data assimilation activities enhance the value and extend the impact of IAS region observations, to address issues on space and time scales that are most relevant to the IAS community. In addition, data assimilation provides an important framework for quantifying the value of observations, and for assessing and understanding model deficiencies.

A key goal is the creation of the best possible research quality assimilated data sets for studying the IAS region and its interactions with the larger-scale environment. This effort may rely on both regional and global systems. The former have the potential to provide higher resolution and more complete depictions of the various phenomena such as Gulf surges, low level jets, convective zones and tropical easterly waves, while the latter provide information (at a somewhat lower resolution) about linkages between the Americas and global-scale variability and the role of remote boundary forcing. Additionally, we anticipate that off-line land data assimilation systems and simplified 1-dimensional land/atmosphere and ocean/atmosphere data assimilation systems may provide invaluable "controlled" environments for addressing issues of land-atmosphere and ocean-atmosphere interactions and model errors.

Specific examples of data sets to be generated include a series of assimilations for the IAS region covering the EOP both with and without various components of observations. If observations are found to improve forecasts or simulations, recommendations will be made to continue such data collection. Comparisons should ideally be performed among multiple models, in both free running and assimilation mode. Different assimilation schemes should also be compared. Naturally, efforts should also take advantage of existing operational and special analysis products.

Data assimilation provides a powerful way of learning about model errors. As a step in coupled model development, it is sometimes assumed that a model forced (via data insertion) to remain close to the observed state will produce more realistic fluxes (e.g. radiation, latent and sensible) compared with the same model run in simulation mode. If parameterizations are given the "right" input during an assimilation, yet still produce the wrong outputs, it may indicate the sources of errors more specifcally.In other words, ata assimilation provides a mechanism for diagnosing errors early, before they have a chance to compromise the entire model state. For example, analysis increments or short term errors obtained during an assimilation can provide valuable information about model deficiencies.

This approach to addressing model errors relies on having assimilation systems attached to the models of interest. Although this currently limits the analysis to special (mainly numerical weather prediction) models, projects such as the Data Assimilation Research Testbed (DART) and developments using the Earth System Modeling Framework (ESMF) will steadily expand these capabilities to a wider range of climate models.

In summary, the specific goals to be addressed through data assimilation are to assess the impact of the IAS observations, better understand the nature of model errors, and to obtain a better understanding and improved simulation of the full range of phenomena comprising IAS regional climate variability within the context of the global climate.

(b) Component II: Field campaign

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

(i) The need for field research about IASCLIP science questions

The overarching need for field work is to fill in critical weaknesses of operational data streams (including remote sensing and model-based analyses). These weaknesses may be 'critical' scientifically, e.g. in order to distinguish or assess the relative roles of several mechanisms; or 'critical' to impacts, e.g. to understand how large-scale climate variations are expressed in a complex geographical setting; or 'critical' for correcting identified model pathologies.

Weaknesses of operational data include lack of trustworthy vertical structure information in key locations; unresolved or uncalibrated depictions of phenomena near complex geography; inaccuracy of measured fields and fluxes; and lack of microphysical (including aerosol and chemistry) characterization and profiles. Based on the review of science issues in section 5, we can anticipate a few examples of science objectives that can only be met in the field:

Ocean examples:

- Quantify the flux components, at both the air-sea interface and Warm Pool base, that govern SST anomalies in this region, to inform upper ocean parameterization efforts. This might involve intensive ship observations for short periods, extended by buoy deployments, and further by remote sensing calibrated using these field observations.
- Using such an extended time record, explore the importance of winter-spring forcing conditions vs. summer conditions (wet season with its more local feedbacks) in governing SST patterns going into the summer and hurricane season.

Atmosphere:

- Establish profiles of wind and humidity in the LLJs, in order to discover the relative roles of these two variables – which are thought to be oppositely impacted by interannual WHWP SST anomalies for example – in governing variations in their product (moisture flux). This might be done with special observations at sea (like shipborne upsondes, dropsondes, aerosondes, or driftsondes launched from eastern Caribbean islands), and/or with enhanced soundings at existing sites (like Yucatan, Isla San Andres, and Corpus Christi).
- Sample enough convective weather situations (e.g. with satellite data, soundings, aircraft, and surface-based remote sensing tools like radar) to tease apart relative roles of the local "ingredients" regulating development of clouds and rain (inversions, dryness at various levels, dust in the dry layers, etc.). Shipborne radars such as used during EPIC, can reveal much about the convective processes, structures and levels that can give clues as to the nature of Caribbean convection, why it is atypical for the tropics and why models tend to get it wrong.
- Examine how these ingredients vary across phases of large-scale weather and climate signals (e.g. synoptically, throughout the season, in 2 years), to understand how these macro-signals get expressed in terms of clouds and rain and how these processes can be appropriately parameterized for coarse models. For example, how does the convective environment change as an easterly wave enters the Caribbean and a mesoscale cloud cluster explosively develops, and does this provide clues as to why tropical cyclones develop abruptly in the Caribbean at certain times of the rainy season as opposed to others?

Land:

- Document the thermodynamic structure of the PBL over lands in the region , and how it contrasts with the structure of the adjacent or incident marine atmosphere.
- Explore the short and long-term variations of this land-sea contrast and dependence on landscape and vegetation conditions, to improve understanding of net radiation – PBL – cloud – rain – soil moisture feedbacks and how to parameterize these well.
- Document the effects of landscape parameters such as deforestation, urbanization, and orography in channeling wind, generating mountain clouds, and modulating surface

temperatures and rainfall in regions of interest. Improved understanding of these issues will also aid in determining impacts of inland penetrating cyclones along the coasts.

The above and other ideas will of course have to be suitably refined into testable hypotheses during Phase I, in order to propose field work in more detail.

Data integration is too important to leave unmentioned. Part and parcel of a modern field campaign has to be an explicit plan to ensure that the data are collected carefully, archived properly, and used well. The separate data collections arising from the above activities must be assembled into final quality controlled datasets, meaningful analyses, assimilated products and forecast assessments that address the larger scientific goals of the program.

(ii) Anticipated EOP and IOP structure of a proposed 2-year field campaign

The IASCLIP field campaign is envisioned to cover a two-year Extended Observing Period (EOP, 2011-1012), which is simply the bare minimum for sampling interannual climate differences. It may become desirable to continue some observations as "monitoring," or transition them to operations, but such considerations would be premature here. The NAME program successfully demonstrated this two-year strategy, using 2003 forecast studies that refined tools and sampling strategies, and calibrated expectations of the broader community, before the main NAME 2004 campaign.

The first EOP year (Year One) will be devoted to a largely "virtual" field campaign, in which remote sensing products, model-based analyses and forecasts, and operational data are assembled and examined with the hungry eyes that field research engenders. Trial deployments of observation technologies can be conducted under this Year One umbrella of context, and autonomous monitoring systems (e.g. buoys) can be set out, in order to cover at least two warm seasons.

Monitoring efforts will include looking for signs of persistent atmospheric forcing during the critical winter-spring period, when summer’s SST anomalies may be forged. Experimental forecasts will also be shaken down during this year, and the performance of models, including the success of forecasts, will be assessed through attribution analysis of events and comparison against observations. This effort will inform and fine-tune the needs of the coordinated field campaigns during the IOP year.

In Year Two, proposed Intensive Obvserving Periods (IOPs) will involve many more observing platforms, limited logistically to shorter intervals. In light of the complex seasonality in the region, it seems desirable to consider multiple IOPs spaced throughout the season.

Early work could capture the springtime preconditioning of SST anomalies and perhaps the early rains (which begin climatologically in mid-May). Mid-summer (July-August) observations could examine the MSD phenomenon, African dust (whose arrival in Florida peaks in July, and for which field work may be planned in these same years under other auspices), and linkages to the NAM onset as will be watched by members of the NAME community. In the fall season, when tropical waves and cyclones tap the warm pool's stored energy, IASCLIP research may be able to fruitfully align with and extend existing hurricane research activities, e.g. by also studying "upstream" systems or the scientifically (as well as operationally) important case of nondevelopers. These 3 IOPs would address questions of how SST anomalies arise; how LLJs and the humidity they transport are shaped and how they vary; how the nature of convection varies through the season; and how clouds and precipitation participate in larger disturbances in hurricane season, among others. Intraseasonal variability will invariably be sampled, albeit in unplanned ways. IASCLIP should plan to enhance the resources of the Aircraft Operations Center in Tampa to do research flights early (July) and late (October) in the hurricane season in coordination with AOML's Hurricane Research Division's operational flight plans. These are times when aircraft demands are less and they match with the Caribbean cyclogenesis periods of interest to IASCLIP.

A multi-IOP approach is also desirable logistically, since down time for instrument maintenance and personnel rest or changeout tends to improve the quality of the resulting data sets.

(iii) Anticipated equipment deployments

The IASCLIP EOP and embedded IOPs could use to full advantage all the observational tools available today, including:

- upsondes – ranging from simple enhancements at operational sites, to special Integrated Sounding System (ISS) deployments with detailed ancillary observations like surface fluxes and meteorology, wind profiling, etc.

- buoys – including enhancements to operational networks, and special deployments for extra precision, difficult variables, air-sea flux measurements, buoy-based rainfall measurements and perhaps automated profiling capabilities.

- aircraft -- ranging from traditional crewed flights sampling in and around important events too rare to await at a point, to remotely piloted drones, to driftsondes which could drop E-W curtains of soundings across the Caribbean while drifting on the deep easterlies.

- watercraft -- from ship cruises for full ocean-interface-atmosphere profiling (often needed anyway for buoy tending), to new autonomous ocean sampling technologies.

- remote sensing – in addition to sensors implied in the above, numerous satellites will observe the region in many ways. Some may be looking for calibration-validation partnerships, offering mutual benefits to IASCLIP.

- Enhanced drifting buoy deployments – a new kind of drifting buoy developed at AOML measures thermal structure through and below the ocean mixed layer. They also return valuable information relative to the air-sea interactions in the vicinity of tropical cyclones.

It is impossible to offer more specifics at this stage, as actual deployments will need to be proposed by a community of PIs, based on specific hypotheses, articulated testably, and prioritized in the face of resource constraints by duly charged steering bodies. Nonetheless, it seems clear that scientific progress on understanding and learning to predict these phenomena will require some field component. Recent experience suggests the above as a reasonable sketch of a model for field activities that has a good chance of succeeding at advancing the goals of IASCLIP.

(c) Component III: Application and capacity building

One ultimate legacy of IASCLIP should be schemes for society to benefit from climate predictions and projections. This may be achieved through (i) technology transfer for various Institutions in the Caribbean and Mesoamerican regions; (ii) development of tailor-made products for end users along with decision support schemes that consider risk management practices and (iii) integrated models that allow stakeholders to evaluate the importance of climate information in their planning activities. Here, end users include all sectors of the society, ranging from government, industry, educational institutes, down to individual citizens. While improvement in climate information will be done mainly at few operational and research centers in the IAS and neighboring regions, the strengthening of end users' ability to interpret and apply climate diagnoses and prognoses should be carried out throughout the IAS region as broadly as possible. The link between atmospheric scientists and users requires a good communication strategy.

Climate outreach and capacity building will have to be accomplished with support from a broad IASCLIP community. This IASCLIP community includes, in addition to scientists who participate in IASCLIP research activities, people from various sectors of the societies, such as scientists who work on fields relevant but outside IASCLIP, national and local government, industries, foundations and charity organizations, and education institutes. By forming such an "IASCLIP alliance", the efforts of scientific exploration and application can be maximized. The work of the alliance can advance in the sequence required for more difficult tasks to build on the success of earlier, more reachable ones, as follows.

• The contribution from IASCLIP to improvement of models and associated climate products will mainly be made through its components of data diagnostic and modeling (section 6.1a) and field campaign (section 6.1b). However, IASCLIP will consider the development of sector specific climate information that will serve in the decision making process, including identification of climate information for specific needs, development of decision making schemes based on risk assessment and management, and tools to estimate the socio-economic benefits of a climate information culture in the region.

• The IAS region consists of many countries whose sizes and economies would not allow the implementation of sophisticated climate models locally, despite the importance of climate prediction and projection to them. Even within countries with climate research and operation capability, gaping gaps still exist between operations and applications. One mission of IASCLIP should be to help bridge the gaps and make climate products of significant benefit to end users in the region. A number of previous studies on the use of climate information in the region may serve as guidelines on the type of climate information most needed in every region and on means of collaboration at the regional level.

• Capacity building will be a major effort of bridging this gap. Improved model products and climate prediction resources, in general, will be made available to key operational and research centers in the IAS and IASCLIP researchers will work with designated WMO training centers to help train new scientists and meteorologists from the region with the knowledge required to use them. Breaching the gap between IASCLIP researchers and end users must be leveraged through organizations that have the mission and experience of climate outreach. This will gradually come about as a new generation of climate-knowledgeable people with local knowledge and contacts can apply the improved resources in collaboration with appropriate international agencies such as the InterAmerican Institute for Global Change Research (IAI) and the Lamont-based International Research Institute for Climate and Society (IRI).

Model improvement and applications

IASCLIP will first engage with climate-oriented operational (or quasi-operational) centers and research institutes with the capacity of producing climate predictions specifically tailored for the IAS region. Such climate prediction can be made directly from high-resolution climate models or indirectly through down-scaling from coarse resolution climate models by high-resolution regional models. High resolution is an essential element because it is key for a better definition of terrain-modulated rainfall and its hydrological applications. Models should include evaluation schemes that reassure end-users about the information provided so as to have more impact on their planning.

Applications of such high-resolution climate products will meet three main challenges. (i) make these products available directly to the scientists, forecasters and public sector managers (water, energy, emergency management, etc.) spread over the IAS region. (ii) make these products in forms that can be directly plugged into algorithms for specific applications, and (iii) train the local product distributors to fully appreciate the emergency management of the climate products and their nuances. These challenges will have to be met by both infrastructure and human capacity building.

Human capacity

Several steps need to be taken toward building an IASCLIP Alliance. (i) Identify the broad IASCLIP community. This would start from interested scientists from the IAS region. They will contact other interested parties in the region. (ii) The IASCLIP Alliance will be organized mainly through communications via emails and electronic newsletters. Workshops and special sessions at major international conferences can be considered to convene alliance members on specific issues. (iii) If deemed necessary and productive, leaders from the IASCLIP Alliance can be selected to form a capacity building advisory committee. This committee is needed only when capacity building activities grow into a scope and complexity that are beyond the expertise of IAS SSC members.

The IASCLIP Alliance will help identify specific tasks for capacity building. It is anticipated that the following tasks are beneficial and feasible:

— Professional training. IASCLIP should help regional professionals to better recognize the potential and limitations of available climate prediction products and practices, facilitate experimental research tools (e.g., statistical and numerical models) for regional and local applications, and provide guidance to modify available tools or design their own (e.g., statistical models). This can be done through regional summer schools and workshops organized by competent regional and international entities with the participation of IASCLIP scientists as appropriate. Another way is to coordinate with regional Climate Research Networks (CRNs) organized and funded under the auspices of the IAI. A third is to channel improvements in climate products and their interpretation through the Regional Climate Outlook Forums (RCOFs) that include participation of the IRI. In several countries, the inertia of traditional forecasting practices at hydrometeorological centers makes the adoption of more modern methods difficult. IASCLIP should look for ways to evangelize newer methods such as assessing the forecast performance produced by alternative approaches.

— Scholar and student exchange. Many of the IAS countries presently lack professionals with the knowledge required to make use of improved products and predictions and communicate appropriately derived information to the competent authorities and end users for whom they have contacts. However, a number of educational entities around the IAS have been designated by the World Meteorological Organization (WMO) as Regional Meteorological Training Centers (RMTCs). By working through and collaborating with organizations such as IAI, IRI and WMO-CLIPS, IASCLIP and its researchers can work with the RMTCs to add targeted climate courses to their curricula and to graduate professionals who have done climate-oriented thesis research. Mechanisms to achieve this can include the organization of summer climate institutes at the host institutions wherein certain IASCLIP researchers can teach climate courses and establish rapport with local professors and students, in some cases becoming *in absentia* members of thesis committees. Another mechanism is to procure financing for students to intern for short periods at IASCLIP research institutions to do hands-on research as part of their degree work and form useful alliances with IASCLIP researchers. This should help to further bridge the technology gaps during their subsequent careers. Once graduated, these professionals can receive further hands-on experience by working at appropriate operational sites, such as the NOAA-NCEP Tropical Desk. This would give the opportunity to professionals of the WMO Regions III and IV (South America and Caribbean) to work at the Hydrometeorological Prediction Center for a period of about three months, first learning and eventually developing forecasts for the IAS region.

— Information sharing. Workshops can be organized for regional and local professionals who work in the area of climate prediction and applications to exchange information and experience, and for research and operation scientists to get feedback from end users of their products and to provide guidance on how their products can be most effectively used. The regional hydrometeorological centers have long worked with various sectors whose stakeholders value climate information but they have generally not offered decision support tools. Therefore, IASCLIP should focus, not only on producing better climate predictions, but also on the development of sector specific decision making tools that help stakeholders to assess the economic value of better climate information. There is a long history of efforts aimed at making use of climate information, but most such experiments have failed because stakeholders had not been appropriately engaged in the process. Consequently, IASCLIP from the very beginning should consider the incorporation of stakeholders as part of the capacity building process in order to make them participants in the design of decision support tools.

— Technical support for infrastructure building and improvement. IASCLIP should actively involve stakeholders in every country to design a Climate Information System that better fits the needs and capabilities of the region. The World Meteorological Organization (WMO) has been actively promoting the improvement of operational activities in the climate area in various countries of the region. Therefore, it is necessary to evaluate the impact of such WMO efforts in order to modify practices in the capacity building process that IASCLIP is interested in.

It is unlikely that IASCLIP will have the financial strength for major infrastructure building in the IAS region. What IASCLIP can contribute to this aspect is to identify, through its scientific investigations (Components I and II), essential elements that are currently lacking at local facilities but which, if reconfigured, can potentially yield high benefit to the society in terms of contributions to climate prediction and applications of its products. IASCLIP can play an active role in engaging regional government agencies, industries, and international organizations to promote and facilitate improvement and establishment of such facilities.

6.2 Timetable

Phase I (2009 – 2011)

Phase I will mainly focus on diagnostics and modeling activities (IASCLIP Component I, section 6.1a), to evaluate the need of a field campaign, to prepare for such a field campaign if deemed necessary (section 6.1b), and to initiate coordination and collaboration among regional participants of the program to assess the scope of capacity building IASCLIP may contribute (section 6.1c). Some specific milestones are listed below:

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 (see 6.3b) to target specific problems. The location and time of this workshop has been scheduled for March 24, immediately preceding the 11th VAMOS panel meeting in Miami.

– Coordination of existing research activities relevant to IASCLIP.

– Coordinating IASCLIP proposals to NOAA CPPA AO for 2009. It is anticipated that the NOAA CPPA AO for 2009 would explicitly include languages that encourage proposals targeting the climate issues related to the IAS. Although there will not be specific fund set aside for IASCLIP and proposals on IAS issues will be competing equally with other proposals, it may be beneficial to communicate with potential PIs and NOAA CPPA program managers about priorities in the context of the IASCLIP to avoid redundancies and to maximize the payoff of limited resources.

2009:

– Working group and SSC meetings. Working groups organized along topical lines (see below) will decide whether, where and when they will meet physically or virtually. Working group meetings 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 Science Steering Committee (SSC) members and working group leaders later in the year to review the programmatic progress and adjustment of the program plan. Working group leaders can explore the option of conducting teleconferences in which Powerpoint presentations with solicited contributions are discussed in several stages.

– Initiating the IASCLIP Alliance. Information will be collected for people who are outside the climate research and operation fields but might be interested in IASCLIP and willing to join the IASCLIP Alliance (section 6.1c). Scientists from various countries are encouraged to initiate dialogues with people from different societal sectors of their regions. Initial contact will also be made to international organizations (e.g., the UN, WMO, World Bank, IAI, etc.) that may be part of the IASCLIP Alliance.

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 the need for a field campaign, what its priorities should be, and how its plan should be updated from the one outlined in this document. If it is deemed that a field campaign is needed, then a special scientific working group will be formed to be in charge of updating its design and execute the campaign. Other working groups will be asked to submit their recommendations to that group.

– An IASCLIP Alliance conference, if deemed necessary.

– Preparation for the field campaign if it is deemed necessary. Continue modeling and diagnostic analyses.

Phase II (2011 – 2012): Field Campaign

2011:

– Year One field campaign — Extended Observational Period (EOP).

2012:

– Year Two field campaign — Intensive Observational Periods (IOPs)

Activities related to Components I and III will continue throughout Phase II. Planning and debriefing meeting for the field campaign will be held as needed. A third IAS climate workshop, possibly in conjunction with an IASCLIP Alliance conference is anticipated in 2012.

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. A few specific examples may be outlined, with the understanding that they are not limited to Phase III:

- Application schemes should be developed to transfer useful information from model forecasts, including quantified uncertainties, to end users. Users also need trusted evaluation of the ability of the forecast models, specific to important forecast aspects. For example, total early-season rainfall (April to June) may be critical to agriculture, while flood hazards may depend on, subseasonal rainfall variability

- 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).

Near the end of Phase III, another IAS climate workshop and IASCLIP Alliance conference are necessary to review the progress and objective achievement of the program.

A Multi-Phase activity: Experimental predictions

One useful endeavor would be an experimental forecast activity that is continually improved as hypotheses are tested against outcomes. This activity would include a web-based suite of data-based analyses updated monthly and a small ensemble of models similarly updated and designed to integrate from initial conditions throughout the critical winter-spring period leading up to summer. During Phase I this activity would be strictly experimental, designed to test the limits of existing data and models when stressed by exploratory attempts at prediction of summer ocean and hydrometeorological conditions. Each month from January to June the product suite updates and new model integrations can be discussed by all interested parties via teleconference, including a subsequent redaction of an updated outlook. This will reveal the weaknesses in initial working hypotheses and indicate areas where data diagnostics and models fall short of needs and require targeted field studies in Phase II. During the first year of an expanded observation period (EOP), this activity will become more intense and lead to refinements of planning for an intensive observational period (IOP) in the second year of Phase II. The activity would of course continue into Phase III but would then include the consolidation of field results and model enhancements built upon an improved understanding of processes. The realistic testing of ideas and models throughout IASCLIP should make the eventual adoption of evolved methods and models at operational centers faster and more likely. The evolved toolbox and model approaches will provide a basis for outreach-oriented organizations (IRI, IAI, World Bank) to build upon and for technology transfer to subregions within the IAS (Central America, Anglophone islands, etc.).

6.3 Project structure

(a) Science Steering Committee (SSC)

IASCLIP research will be overseen and directed by a Science Steering Committee (SSC). The SSC is charged with developing and leading cooperative international research to achieve the science objectives of IASCLIP. Its members will represent education, research and operation institutes from various countries of the IAS region. The SSC membership will be approved by the International CLIVAR VAMOS panel and CLIVAR SSG.

The Terms of Reference for the IASCLIP SSC are:

- continue develop and finalize the IASCLIP Science and Implementation Plan
- take the responsibility for the scientific integrity of the program and the execution of its plan
- organize annual plenary workshops in conjunction with VAMOS panel meetings.
- facilitate the coordination and collaboration between IASCLIP working groups
- work with governments and funding agencies to promote funding opportunities for the IASCLIP activities
- communicate with relevant national and international programs for integrating the scientific results and their relevance to societies
- pursue the forming of the IASCLIP Alliance
- monitoring IASCLIP progress, synthesize its results, and report them to the VAMOS panel and funding agencies

Each IASCLIP SSC member will normally serve a term of three years. Exceptions of serving two consecutive terms are allowed with good reasons. After its first three years, 1/3 of its members will rotate out every year.

(b) Working Groups

The purpose of forming Working Groups (WG) is to facilitate collaborations and information exchanges among scientists who are interested in the IASCLIP research and are willing to contribute to the program, and to better track the progress of the program. WG will be formed on volunteer basis, including all who are willing to participate. Leaders of the WG will be initially appointed by the SSC and then rotate within each group as seen fit by the group members. WG leaders communicate informally with the SSC regularly and report to SSC formally once a year. The following WG are suggested:

WG A: Climate diagnostics, simulations, and prediction – This working group will target part of the program component I using existing observations and model simulations. The multi-phase experimental predictions will be the centerpiece for this WG.

WG B: Model development and experiments – The working group will focus on newly developed models, simulations, and new experiment designs, also part of program component I. The susccessful NAMAP and NAMAP2 activities in the NAME program may serve as a useful model for this group's plans.

WG C: Data gaps – This working group will explore the need and feasibility of solving the data gap problems emerging from the other tasks. A possible field campaign will be a main issue of this WG.

WG D: Climate impact – This working group will focus on how the IASCLIP activities should be expanded from physical domain to human dimension and ecosystems. It will include both regional applications of climate forecast and capacity building.

The final formation of the WGs will be decided at the first IASCLIP workshop in March 2008.

(c) Project Office

An IASCLIP Project Office will be established at the UCAR Joint Office for Science Support (JOSS). The role of the Project Office will be same as in other research programs: (i) provide the requisite infrastructure for the design and implementation of the IASCLIP field campaign, (ii) manage the IASCLIP program field operations (including relevant communications) for the accomplishment of the program scientific objectives; (iii) provide scientific data management services to IASCLIP, including data collection, field catalogs of imagery and reports,and final data archiving and dissemination; and (iv) provide specialized logistics support for the implementation of IASCLIP, including administrative and fiscal support, workshop/conference/educational and specific training coordination and implementation.

6.4 Data Policy

The IASCLIP data policy is based on the NAME data policy. The following data protocol and management issues will be discussed by the IASCLIP Science Steering Committee. This data policy will hold for all IASCLIP participants.

(1) Data Categories

In order to set up data release guidelines which balance the interests of both data users and data providers, NAME data are divided into three categories:

Category 1: Standard data. (e.g. operational rawinsondes, surface standard meteorology, satellite data)

Category 2: Enhanced or Experimental data. (e.g. data acquired from IASCLIP field campaign, including but not limited to ships, aircraft, buoys and networks of rawinsondes, raingauges, pibal balloons, radars, wind profilers, enhanced surface meteorological and hydrological measurement including surface fluxes, soil moisture, stream flow, and vegetation)

Category 3: Modeling data.(e.g., numerical simulations and experiments specifically performed for the IASCLIP program)

Data of Category 2 are further divided into two groups: Preliminary data and final data. Preliminary data are those without or with limited quality control, which are for "quick look" by IASCLIP investigators (e.g., for use in experimental predictions) and are not intended for public use. Final data are those after ultimate quality control and are for public use.

(2) Data Release and Dissemination

a. Release of Data in Compliance with WMO Resolution 40 (CG-XII) and WMO Resolution 25 (CG-XIII)

IASCLIP is an international project, initiated by VAMOS/CLIVAR/WCRP, whose co-sponsor is WMO. It is thus appropriate that any policy for release and dissemination of IASCLIP data should principally comply with the WMO policy, practice and guidelines for the exchange of meteorological, hydrological, and related data and products; that is, *free and unrestricted exchange of essential data and products*.

The no-restriction principle shall in particular mean that no financial implications are involved for the IASCLIP data exchange. IASCLIP data files available through one of the IASCLIP Data Archives (NDA) shall be offered free of charge to the data users.

b. No Commercial Use or Exploitation

All IASCLIP data shall be delivered to users only for scientific studies designed to meet IASCLIP objectives. Commercial use and exploitation by either the data users or the NDA is prohibited, unless specific permission has been obtained from the IASCLIP investigators concerned in writing.

c. No Data Transfer to Third Parties

During the initial data analysis period (15 months after the data were collected), no data may be provided to a third party (journal articles, presentations, research proposals, other investigators) without the consent of the investigator who collected the data. This initial analysis period is designed to provide an opportunity to adequately quality control the combined data set.

Unrestricted copying of the original data by multiple, independent users may lead to errors in the data and loss of identity of its IASCLIP-NDA origin and is strictly prohibited. The NDA will offer IASCLIP data files to potential data users through electronic means, (e.g. the Internet) or other designated media (e.g. CD ROMs).

d. Timing for Release of IASCLIP Data from NDA

All investigators participating in NAME must agree to promptly submit their processed data to the NDA to facilitate intercomparison of results, quality control checks and inter-calibrations, and an integrated interpretation of the combined data set. The turn-around period is **6 months** after the field experiment for Category 1 and preliminary Category 2 data and **15 months** at maximum for final Category 2 data. No requirement for release of the Category 3 data (but see 2.5 below). The NDA will release to the science community all archived Category 1 data 6 months after the field experiment and all final Category 2 data 15 months after the field experiment.

e. Data exchanges among IASCLIP investigators

All data shall be promptly provided to other IASCLIP investigators upon request. A list of IASCLIP investigators will be maintained by the IASCLIP Science Steering Committee, which will include the principle investigators who directly participate in the field experiment or provide modeling/diagnostic guidance in the planning of IASCLIP activities.

In special cases, a non-IASCLIP data user may establish direct contact to an IASCLIP data provider in order to agree on exceptions (i.e. shortenings of the turn-around period) to these rules for specific data or data periods. These communications shall be performed with co-ordination of the NDA.

f. Publications using IASCLIP data

All data will be considered public domain 15 months following the end of the IASCLIP field experiment and any use of the data in publications will include either acknowledgment or co-authorship at the discretion of the investigator who collected the data.

Data users of IASCLIP data are encouraged to establish direct contact with PIs and IASCLIP investigators for the purpose of complete interpretation and analysis of data for publication purposes. This is in particular recommended for Category 2 data.

g. IASCLIP Publication Library

Whenever IASCLIP E data distributed by NDA are being used for publication of scientific results, the author(s) shall sent a copy of the respective publication, preferably in electronic form, to the IASCLIP Project Office in order to build up an IASCLIP publication library. The Project Office will maintain this library and will make it public, for example via the IASCLIP website, for a continuous monitoring of the IASCLIP data applications and IASCLIP achievements in general.

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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 International Research Institute for Climate and Society (IRI) (www.iri.columbia.edu) - The IRI was established as a cooperative agreement between NOAA's Climate Program Office and Columbia University. It is part of The Earth Institute at Columbia University, and is located at the Lamont Campus. The IRI conducts climate research oriented toward producing climate predictions in the service of societal applications worldwide. In the Caribbean and Central American region the IRI has cooperated with local and regional agencies in promulgating climate predictions and applications in the region, e.g., at Regional Climate Outlook Forums (RCOFs).

A4 The Caribbean Institute for Meteorology and Hydrology (CIMH) (www.cimh.edu.bb) - The CIMH is an amalgamation of the Caribbean Meteorological Institute (established in 1967) and the Caribbean Operational Hydrological Institute (in 1997), Located at Husbands, St. James, Barbados and funded by 16 member country governments of the English speaking Caribbean for training, research, data collection and storage, instrument repair maintenance and calibration. CIMH professionals also teach the BSc in Meteorology at the Cave Hill Campus.

A5 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.

A6 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.

A7 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.

A8 Gulf drilling – There numerous drilling platforms operated by oil industries in the Gulf of Mexico. 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.

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

AGCM: Atmospheric general circulation model
AOT: Aerosol optical thickness
AOML: Atlantic Oceanic and Meteorological Laboratory
AMO: Atlantic Multidecadal Oscillation
AMOC: Atlantic Meridional Overturning Circulation
AWP: Atlantic Warm Pool
CAM3.1: Community Atlmospheric Model version 3.1
CLLJ: Caribbean low-level jet
CAPE: Convective Available Potential Energy
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
CCN: Cloud condensation nuclei
CEPEX: Central Pacific Experiment
CGIAR: Consultative Group on International Agricultural Research
CLIVAR: CLImate VARiations Program
CHFP: Coupled Historical Forecast Project
CPPA: Climate Prediction Program for the Americas
CRN:Climate Research Network
ENP: Eastern North Pacific
ENSO: El Nino and Southern Oscillation
EOP: Extended observational period
EPIC - Eastern Pacific Investigation of Climate
GATE: Global Atmosphere Tropical Experiment
GCCN: Giant cloud condensation nuclei
GCM: general circulation model
GPLLJ: Great Plain Low-Level Jet
GWP: Global Water Partnership
IAI: Inter-America Institute
IALLJ: IntraAmerican low-level jet
IAS: IntraAmericas Sea
IASCLIP: IntraAmericas Study of Climate Processes
IASI: Intra-Americas Sea Initiative
INDOEX: Indian Ocean Experiment
IOOS: Integrated Ocean Observing System
IOP Intensive observational period
IPCC: Intergovernmental Panel on Climate Change
IRI: International Research Institute for Climate and Society
ISV: Intraseasonal variability
ITCZ: intratropical convergence zone
JASMINE: Joint Air Sea Monsoon Interaction Experiment
LBA: Large Scale Biosphere-Atmosphere Experiment in Amazonia
MJO: Madden-Julian Oscillation
MESA: Monsoon Experiment of South America
MSD: Mid Summer Drought
NAM: North American Monsoon
NAME: North American Monsoon Experiment
NAMIP: North American Monsoon Intercomparison Project
NAMS: North American Monsoon System

NAO: North Atlantic Oscillation
NASH: north Atlantic subtropical high
NCAR: National Center for Atmospheric Research
NCEP: National Centers for Environmental Prediction
OLR: Outgoing Longwave Radiation
RMTC: Regional Meteorological Training Center
SAMS: South American Monsoon System
SALLJ: South American Low-level Jet
SEACOOS: The SouthEast Atlantic Coastal Ocean Observing System
SMO: Sierra Madre Occidental
SSC: Science Steering Committee
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
TUTT: Tropical Upper Troposphere Trough
VAMOS: Variability of American Monsoon Systems
WCRP: World Climate Research Programme
WG: Working group
WHWP: Western Hemisphere warm pool
WMO: World Meteorological Organization