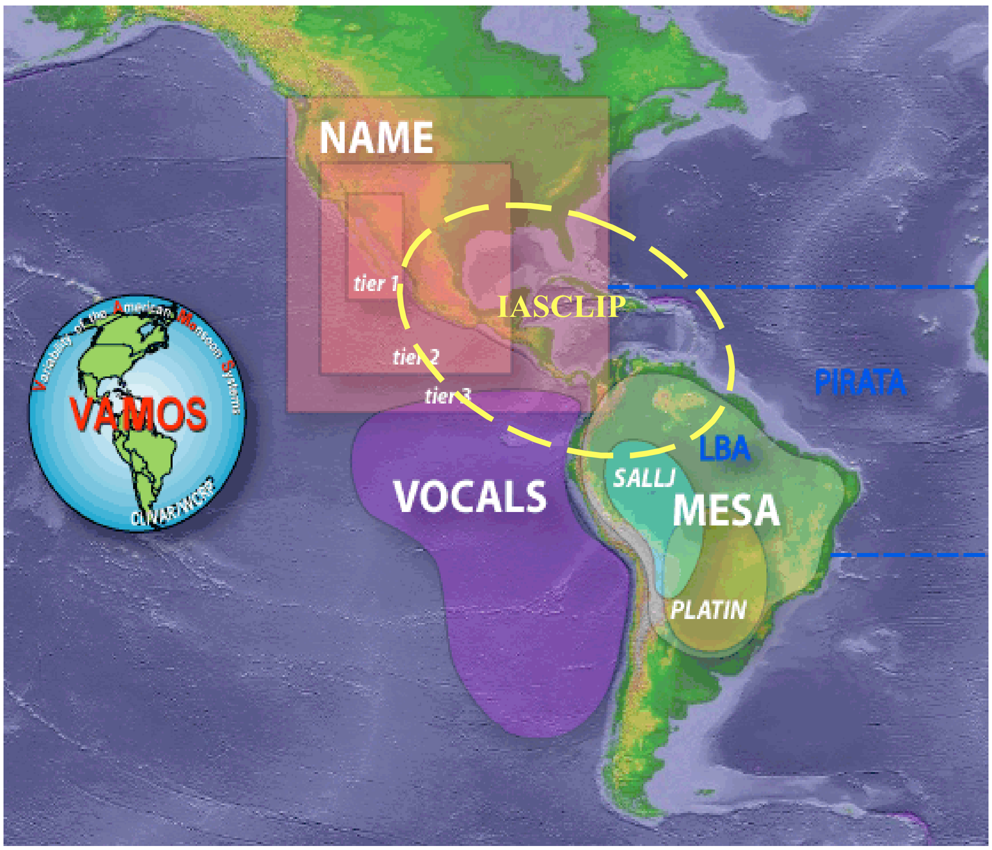
A Prospectus for
An Intra-Americas Study of Climate Processes
(IASCLIP)

Prepared for the VAMOS Panel



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Preface

This prospectus outlines the need for a research program to study physical and dynamical processes underlying rainfall variability and prediction in the Intra-Americas Sea (IAS) region and its surroundings. It covers a broad range of scientific issues. The main purpose of this prospectus is to solicit feedbacks from the VAMOS panel and research community for further development of a science plan, in which research priorities and foci will be identified. Constructive criticisms and suggestions on this prospectus, issues raised here, and the future of climate research for the IAS region are sincerely welcome.

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1. Rationale

The intraAmericas Sea (IAS) includes the Caribbean Sea and the Gulf of Mexico. In this prospectus, the IAS region is defined as a broad area covering the IAS itself, the adjacent lands, and the ocean off the west coast of Central America (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 (Gable et al 1990; Maul 1993). Many areas in the IAS region are heavily populated, especially along the coastal zones (Fig. 1). A potential sea-level rise associated with global warming would be a direct threat to many of the coastal communities (e.g., Lewsey et al. 2004). A gradual change in local climate has been observed since late 1950s, for example, in increases of the percent of days with very warm maximum or minimum temperatures, and extreme precipitation (e.g., Peterson et al. 2002). In boreal summer, the IAS region is often ravaged by tropical cyclones, with catastrophic loss of life and destruction of infrastructures and propertes. The frequency and strength of these tropical cyclones vary strongly on interannual to interdecadal timescales. Rainfall in the IAS region fluctuates with ENSO (e.g., Chen and Taylor 2002; Laing 2004), Atlantic multidecadal oscillations (MDOs), and the position of the ITCZ, which is related to the tropical Atlantic climate variability (TAV) east of the IAS. Severe anomalies in rainfall — both generalized and storm-related — can lead to damaging consequences in the economy, natural environment, and even social stability 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 2.3). Management of agriculture, water resources, and health related issues decisively depends on the timing, severity, and duration of the MSD (also known as *canicula* or *veranillo*).

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 the a shift of the mean position of the ITCZ among other factors (Kameo 2002). Correct interpretations and explanations of such proxy climate data from the IAS region will benefit from an improved understanding of the physical and dynamical processes in the current climate.

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

Climate phenomena in the IAS region have substantial effects on the local geochemical system and ecosystem. 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). 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).

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, boundary layer, and land surface conditions. 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 understand 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 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, and incursions of midlatitude Rossby waves and fronts, 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 form 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. Background and scientific issues I: Local variability

As in many other regions in the world, rainfall is the most important climate variable to societies in the IAS and surrounding regions. Being at the crossroads between North and South Americas, and between the Pacific and Atlantic Oceans, the variability

[1] Global Atmospheric Tropical Experiment

of rainfall 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 certain 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) on IAS precipitation are mediated by modulations of these basic climatological features. In this section, gross features of the annual and interannual variability of rainfall in the IAS and surrounding regions are reviewed, followed by discussions of their main climate controls.

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 across the equator, as moist convection is the main rain production mechanisms. 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.

This meridional migration of rainfall comprises the major signals of the American Monsoons. 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 May and June after the eastern North Pacific warm pool reaches its peak development 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 2005) and Monsoon Experiment of South America (MESA, ref). More details of the American monsoons are given by Vera et al (2005).

Between the equator and Tropic of Cancer the monsoon exhibits a pronounced double peak structure in precipitation and diurnal temperature range in June and September. In between, precipitation over central and southern Mexico, the western coast of Central America, and the Caribbean maritime continent reaches a relative minimum. This temporary dry spell in July and August, namely, the Mid Summer Drought (MSD), Canícula, or Veranillo (Hastenrath 1967; Curtis 2002), is sufficiently regular as to appear in climatological averages (Fig. 4). This MSD is a marked feature of the seasonal cycle in the IAS region, bearing distinct features in comparison to the seasonal cycle at the same latitude in other part of the world (Magaña et al. 1999; Mapes et al. 2004). Associated with the MSD is a significant increase in temperature and a minimum in tropical cyclogenesis in the Caribbean in July (Inoue et al 2002).

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. Heat waves related to the MSD may increase certain illnesses during the season.

The cause for the MSD is not fully understood. It does not appear to be related to the Madden-Julian Oscillation (Madden and Julian 1971) that propagates eastward from the western Pacific. It is not a direct result of the seasonal migration of the ITCZ because its position never reaches latitudes higher than 15˚N (section 2.4). 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 2.5), whose westward intrusion penetrating into the IAS region may suppress precipitation there (Mapes et al. 2004). A key to fully understanding the mechanism for the MSD would be to quantify the contributions from local air-sea interaction and overturning circulations vs. the Atlantic subtropical high.

2.1b Interannual variability

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

Influences of ENSO on rainfall in the IAS region is complicated by influences from SST anomalies in the tropical Atlantic Ocean; the Pacifc and Atlatnic 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 2.2. 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 2.2), the low-level jet (section 2.3), the ITCZ (section 2.4), the northern Atlantic subtropical high (section 2.5), and tropical cyclones and waves (section 2.6), to name a few. These factors serve to connect the remote influences to local responses. In the rest of this section, these factors are discussed.

2.2 Western Hemisphere Warm Pool (WHWP)

The Western Hemisphere Warm Pool (WHWP), also known as the Americas Warm Pool (AWP), extending over parts of the tropical northeastern Pacific (ENP), the Gulf of

Mexico, the Caribbean Sea, and western part of the tropical North Atlantic (TNA), is the second largest body of warm water (SST > 28.5˚C) in the world. Its size undergoes a substantial seasonal cycle (Fig. 6). Its 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. 7). It has been hypothesized 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.

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 hurricanes each year in the IAS region varies with the size of the warm pool (Wang and Enfield 2003) as well as the tropical North Atlantic SST (Goldenberg et al. 2001). This relationship between the IAS hurricanes and the WHWP might come indirectly from less than normal vertical shear which is unfavorable to the development of hurricanes (Knaff 1997; Goldenberg et al. 2001) or directly from more than normal oceanic heat content that is favorable to the development of hurricanes (see section 2.6).

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

Varying semi-independently of ENSO, the WHWP modulates the influences of ENSO on rainfall in the IAS region. The SST difference between the tropical eastern Pacific and western Atlantic forms a zonal gradient that varies independently with ENSO and TAV, respectively, and is closely related to the rainfall variability in the Caribbean region (Enfield and Alfaro 1999; Taylor et al., 2002). Because only half of the warm events were followed by very large warm pools (Fig. 7), ENSO influences on IAS rainfall can be grouped into those with and without anomalously large sizes of the warm pool. Composites of rainfall anomaly for these two groups show similar patterns with opposite signs (Fig. 8). This indicates that the ENSO influences on IAS rainfall (during the summer following peak ENSO anomalies) cannot be fully understood without the knowledge of the behavior of the warm pool. In other words, even if ENSO forecast was perfect, the predictability of summer rainfall in the IAS region sensitively depends on our ability to predict the size of the warm pool following the peak of El Niño events.

The interannual variability of the WHWP semi-independent of ENSO (Fig. 7) suggests that local processes must be as important as remote influences of ENSO. Those processes include tropical Atlantic variability (TAV) and the low-latitude forcing of the North Atlantic Oscillation (NAO), whose correlation with ENSO is insignificant. Both of these bear on the question of why large WHWPs do not invariably follow peak El Niño anomalies in the Pacific (Enfield et al. 2004). Those mechanisms are, however, not well understood.

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. The open ocean waters of the northern Caribbean are generally oligotrophic and, thus, have a high degree of clarity, so short wave penetration (and, hence, heating) to substantial depths is likely. It is also a region of negative wind stress curl that favors downwelling, and where drifters tend to stagnate.

Air-sea heat exchanges in the warm pool are constantly modulated by various atmospheric systems, such as easterly waves, the ITCZ, tropical cyclones in boreal summer, and fronts in winter, in addition to the persistent trade wind and low-level jet. Significant air-sea moisture exchanges (especially evaporation in the eastern IAS and precipitation in the western IAS) affect the density stratification (and, thus, stability) of the upper water column and, hence, its dynamics. The upper ocean salinity structure of the warm pool is also influenced by the river discharge of several major rivers, a consequence of more indirect air-sea-land interactions (section 2.9). 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.

Notwithstanding the role of the warm pool in IAS climate suggested by the statistics, important questions remain to be addressed. First, mechanisms for the warm pool, including the variability of local SST and the size of the warm pool, to influence local and remote precipitation need to be identified. Second, mechanisms for the interannual variability of the warm pool need to be investigated. Relative effects of remote influences (e.g., ENSO, TAV, NAO) and local ones (the ITCZ, IALLJ, TCs and easterly waves) and the roles of oceanic processes (eddies, currents, upwelling) in comparison to surface energy exchanges with the atmosphere in the heat budget of the warm pool need to be quantified.

2.3 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. 9c). The central branch, also known as the Caribbean low-level jet (CALLJ), penetrates westward through the Caribbean Sea and Central America into the eastern Pacific. Strong surface wind associated with this low-level jet offshore the Gulf of Papagayo may influence the Costa Rica dome dynamics. 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 (CALLJ) is located near the same place as in austral summer, but it is now associated with the part of moisture transport that supplies moisture to the Great Plains. During these seasons, a northern branch splits from the central branch and veers toward the Gulf of Mexico, where it connects the Great Plain Low-Level Jet (GPLLJ) (Fig. 9d). 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) The location and strength of the easterly winds influence the rainfall pattern over southern Mexico, Central America and the adjacent eastern Pacific (Fig. 9b). The peak of the CALLJ 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 CALLJ might contribute to the semi-aridicity of northern Venezuela and the Netherlands Antilles (Granger 1985). Water vapor transport from the IAS into South and North Americas will be discussed more in section 3.2.

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 (section 3.2) 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. 10). The signature of the IALLJ at the surface is well captured by satellite scatterometer wind data (Fig. 11). 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).

2.4 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). 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 CALLJ to the east might be instrumental to the MSD in July (Magaña *et al* 1999; Magaña and Caetano 2005).

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

Understanding the variability and its 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 of advance of 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.

2.5 Northern Atlantic subtropical high (NASH)

The Northern Atlantic subtropical high (NASH), also known as the Bermuda high, is a robust feature that affects directly 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 amplitude of the WHWP. 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 in precipitation in the IAS region. An anomalously strong NASH or an anomalously southward displacement of the NASH, when accompanied by a southward shift of the eastern Pacific ITCZ, would lead to a dry summer in the Caribbean (Giannini et al. 2000). A westward protrusion of the NASH contributes to the MSD (Mapes et al. 2004). The NASH dominates most of the IAS region during the dry season of boreal winter. The position and strength of the NASH are critical to the tracks of tropical cyclones in the region. The strength of the IALLJ and its moisture transport are also likely to be related to the NASH, with the CALLJ alone its southwest edge and the GPLLJ along its west edge.

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 weak NASH, a weak NE trade wind, and a rise in SST over the TNA region during the summer following El Niño peak, which might lead to a large Americas warm pool. This favors increase rainfall in the Sahel and the Caribbean and surrounding land regions, and it also favors more frequent hurricanes. The fact that the northern Pacific high also has a midsummer spike that associated with suggests that they might be connected through planetary waves 1-3 that propagate from the east Atlantic and Africa. If so, the NASH would be a part of the inter-basin interaction.

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

2.6 Tropical cyclones (TCs) and easterly waves

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

During a hurricane season (June – November), the number of TCs formed in the IAS exhibits double peaks. The first peak is in June and July, and the second in October and November. The minimum of genesis during August coincides with the MSD (section 2.1). However, it is quite common during August and September to have TCs move into the IAS region from the east. Long-term variability of TCs in the IAS region is an unavoidable issue for the study of IAS climate. Hurricane activity fluctuates with known climate phenomena, such as ENSO (Gray 1984) and the Atlantic multidecadal oscillation (MDO – Goldenberg et al. 2001). During an ENSO warm event (El Nino), 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 Nina). On decadal timescales, there is a clear signature suggesting that the number of TCs in the IAS vary in tandem with the MDO (Figs. 12 and 13). The number IAS hurricane landfall in years of warm Atlantic (positive SST anomalies in Fig. 13) is more than twice of that in years of cold Atlantic (Fig. 14). 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 windspeed and rainfall around the time of doubling in the amounts of greenhouse gases several decades from now. These possible changes are dwarfed by these large multidecadal swings in activity (Landsea et al. 1999).

While Pacific and Atlantic SST might be useful indices for forecasting interannual and decadal variability of TC number in the IAS, the mechanisms connecting the SST and TC variability are not clear but likely are linked to tropospheric circulation changes as well as alterations in the thermodynamic stratification (Goldenberg et al. 2001, Chelliah and Bell 2004). Such mechanisms must be understood in the context of TC formation, intensification, and motion.

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).

2.7 Land-air-sea interaction

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; Atlans et al 1993). In the IAS region, the onset of a wet season might be affect 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). Another example is the topographic effect. Rainfall distribution and variability highly depend on the orientation of the winds with respect to local terrains (Vargas and Trejos 1994). 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). 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. In many coastal regions, sea breezes and land breezes are crucial to daily precipitation and its contribution to the 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. 15). 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. 16, during the coolest season of the IAS). Such effect also has strong interannual variation, in part due to changes of rainfall and probably background atmospheric flow. This result suggests that the climate conditions, such as ocean surface winds and fluxes over IAS, cannot be adequately understood and presumably predicted without understanding their connection with convection over American continents. Strong rainy events in the western Amazon appear to enhance north and Northeasterly winds over tropical western Atlantic. The MSD might be another case in point (Magana et al 1999). Among others, land-air-sea interaction is the least understood process in the IAS region and perhaps also in other regions.

Guided by anticyclonic flow of Bermuda Hight (NASH), most of moisture needed for South America wet season rainfall comes from the tropical Atlantic, instead of IAS. However, the northward reversal of the cross-equatorial flow in Amazon appears to correlate to the strength and southwestern edge of the Bermuda High (NASH) and convection over the Antilles Island chair and the eastern Pacific part of IAS warm pool (Fig. 17). 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 IAS warm pool and an earlier northern reversal of the cross-equatorial flow in boreal spring. This can consequently cause an earlier northward withdraw of rainfall from Amazon to the coast of Caribbean Sea. 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. 8.

3. Background and scientific issues I: Broad influences

The IAS region plays an important role in the climate of Americas and the western Hemisphere for two reasons: Its convective heating center is the largest in the western Hemisphere in boreal summer and its supplies moisture to precipitation in both South and North Americas.

3.1 Convective heating center

Partially because of the WHWP, the IAS region hosts the second largest convection center in boreal summer in the entire tropics. 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. The IAS convective center and its associated large-scale circulation are among the dominant climate features in the western Hemisphere. Upper-level divergent flows of the circulations reach as far as the southeastern Pacific, central South America, and the tropical eastern Atlantic (Fig. 18), implying descending motions in these regions. 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 this part of the world, particularly South America. Correlation between an WHWP index and precipitation (Fig. 19), for example, suggests broad influences from the IAS region to the rest of the tropical western Hemisphere.

3.2 Moisture source

Water vapor transported by the IALLJ from the IAS into South and North Americas is vital to precipitation there. In austral summer, its southern branch of the IALLJ supplies moisture to rainfall associated with the South American monsoon (Fig. 9a). In boreal summer, the northern branch of the IALLJ, together with the GPLLJ, contributes to the moisture transport that supplies moisture to rainfall in the central United States (Fig. 9b; Yarosh et al. 1996; Ropelewski and Yarosh 1998). The strength of the CALLJ and GPLLJ and rainfall over the central United States reaches their maxim in June-July (Mo and Berbery 2004). Almost one-third of all the moisture that enters the continental US is transported by the GPLLJ (Helfand and Schubert 1995).

The WHWP plays important roles in rainfall in regions surrounding the IAS for possibly various reasons. One is the possible modulation of the moisture budget above an anomalous WHWP, thus affecting the export of moisture into the Central American and North American land regions in the boreal summer. Based on limited sounding observations, it has long been suspected that the IAS serves as a source of water vapor for rainfall in North, Central, and South Americas (Hastenrath 1966; Rasmusson 1967, 1968, 1971). Brubaker et al (2001) used a back trajectory algorithm to trace the surface evaporative sources of observed rainfall over the Mississippi Valley. In addition to the local contribution, they found that 20% of warm season precipitation is contributed by evaporation over the Gulf of Mexico and Caribbean Sea. This was further confirmed using the long-record global model reanalysis data (Mestas-Nuñez et al. 2005). Net export of moisture from the IAS means evaporation (E) is greater than precipitation (P) within the IAS ($E-P > 0$). As discussed in section 2.3, moisture is exported from the IAS mainly by the IntraAmerican low-level jet (IALLJ), which enters into the Caribbean Sea as part of the trade wind and splits into three branches into South, Central and North Americas respectively. The core of the low-level jet is normally at the 925 hPa level but strong wind extends to the surface (section 2.3). The low-level jet is, therefore, not only a conveyer belt for moisture, but also a moisture collector that modulates surface evaporation and the moisture content it carries. The warm pool comes into play because, the larger the warm pool is, the greater fetch of the low-level jet would be in contact with warmer sea surface and the more efficiently surface evaporation would be enhanced.

Moisture transport from the IAS into the central US in boreal summer varies on interannual timescales independently of the ENSO (Hu and Feng 2001). Stronger CALLJ/GPLLJ and their associated moisture transport lead to positive rainfall anomalies over the central United States (Mo et al. 1997), which is associated with the negative rainfall anomalies along the Gulf Coast and East Coast (Higgins et al. 1997). This interannual variability of moisture transport is often related to extreme rainfall events in the central US (Paegle et al. 1996; Trenberth and Guillemot 1996; Mo et al. 1997). For example, the source of moisture from the IAS increased enormously during the peak (July) of the 1993 flood over the US while local evaporation provided moisture for only 33% of precipitation. In comparison, during the peak (June) of the 1998 drought, the local evaporation provided moisture for 41% of precipitation (Dirmeyer and Brubaker 1999). The moisture transport from the IAS plays a more important role than local evaporation in the interannual variability of precipitation over the Mississippi River basin (Sudradjat et al 2003). The interactions of the low-level jet with synoptic-scale flow could have led to severe weather events (tornadoes, gust winds, large hails and heavy rain) over the central US during June 13-19 and 20-26, 1993 (Wu and Raman 1998). The importance of the moisture transport by the low-level jet is further underlined by the finding that the largest discrepancies in rainfall estimate over US during spring and summer between the NCEP and NASA global reanalyses are directly related to the differences in their low-level jets (Mo and Higgins 1996).

A composite of precipitation based on the NCEP Eta regional reanalysis (Mesinger et. al. 2004) shows the enhanced rainfall pattern over the United associated with strengthened IALLJ (Fig. 20). 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 CALLJ. The association between the IALLJ and precipitation over the Great Plains can also be established by the composite of precipitation anomalies based on the magnitude of the CALLJ, which can be measured by a CALLJ index defined as the mean zonal wind at 925 hPa averaged over the area (12.5-17˚N, 70-80˚W). The signal over North America is strongest about 4 days after the CALLJ index is over 1.2 standard deviations. The relationships between the CALLJ 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.

4. The IASCLIP Program

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, MDO). 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 (section 2). This posts an unusual challenge to the climate study.

(b) The IAS region is a source of strong remote influences of climate variability in the western Hemisphere through its role as a source of moisture for precipitation in South, Central, and North Americas and as a host of the largest convective heating center of the hemisphere in boreal summer. A fully understanding of the processes that control the hydrological cycle and convective heating in the IAS region and their intricate relationships is therefore of a broad interest for the Americas.

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

The overall goal of this IASCLIP program is to promote, coordinate, and organize research activities that aim at improving our understanding of climate and hydrological processes in the IAS and improving our ability of representing these processes in global climate models. The IASCLIP program embraces two research themes, summarized from the discussions in section 2:

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

The short-term climate variability of rainfall in the IAS region is controlled collectively and interactively by remote and local factors. "Remote controls" include ENSO, NAO, TAV, and MDO. "Local controls" are dominated by the WHWP (section 2.2) and NASH (section 2.5). Both remote and local factors must influence IAS rainfall through modulating local precipitation processes, namely, the monsoons, trade wind and low-level jets (Section 2.3), ITCZ (section 2.4), TCs and easterly waves (section 2.6). These precipitation processes may interact with each other and feed back to the local climate controls. Contrasting effects of the ocean (moisture source, slow variability in surface temperature) and land (soil moisture, vegetation, topography, fast variability in surface temperature) on rainfall must play a vital role in realizing the remote and local influences on rainfall and in shaping the resulting seasonal and interannual variability of rainfall in the IAS into certain spatial distributions. It would be a challenge to assort and quantify the contributions of these processes to the short-term climate variability of rainfall in the IAS region.

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

Climate variability in Americas and the western Hemisphere cannot be fully understood until the climate processes in the IAS region are. The IAS may influence remote areas through large-scale overturning circulations induced by convective heating in the IAS region and through water vapor transport by low-level jets from the IAS region. The physical processes that determine the variability of convective heating in the IAS region and water vapor transport and connect this two with climate variability in the remote areas are therefore vital to the IASCLIP program.

Central to these two research themes are several general scientific issues that are unique to the IAS region. These issues, to be discussed in the rest of this section, are all related to each other and none of them should be studied in isolation. Each issue, however, presents some unique challenges and serves as a research target for the IASCLIP program.

4.1 WHWP

The WHWP is an essential factor for the climate of the IAS region and the western Hemisphere because of its roles in modulating the ENSO effects on precipitation in the IAS region (section 2.2), convective heating in the IAS (section 3.1) and water vapor source and transport (sections 2.3 and 3.2). Our understanding of these roles, however, remains qualitative and empirical. The following questions need to be addressed to

(a) What are the mechanisms for the WHWP to influence precipitation in the IAS region? – Based on a comment notion that deep convection is more sensitive to small changes in SST where mean SST is high because of the Clausius-Clapeyron effect, precipitation would be sensitive to small anomalies in SST (< 0.5˚C) in the IAS. But heaviest precipitation in the IAS region mainly occurs over land, except in the eastern Pacific and western Atlantic ITCZs (Fig. 3). Possible effects of the WHWP on precipitation over land, in addition to its modulation of the water vapor transport (section 4.2), need to be explored.

(b) What are the mechanisms for the variability of the WHWP? – A recent observational diagnostic study (Enfield et al. 2005) relates the interannual variability of the size of the WHWP is mainly due to fluctuations in surface heat fluxes controlled by the northeast trade wind in the Atlantic; the trades are modulated by both ENSO and NAO. This empirical result needs to be confirmed by quantifying the heat budget of the upper ocean. In addition to SST, mechanisms for the interannual variability in the upper-ocean heat content remain unknown, which is an important factor for TC intensification (section 4.5).

(c) *How well can the WHWP be reproduced by ocean models?* – This is a critical issue for coupled models to accurately predict the variability of the WHWP. Because of the complex coastal lines and associated upwelling in the IAS, it is likely that high-resolution models are required (Appendix A6). To accurately reproduce the WHWP and its variability, it is essential to have the heat budget right for the upper ocean, which involves atmospheric forcing in surface wind (for latent and sensible heat fluxes, upwelling, and partially current thermal advection) and solar radiation flux (controlled primarily by clouds). It should be identified which of the atmospheric forcing simulated SST and upper-ocean heat content is the most sensitive to.

4.2 Water vapor transport

An extremely important role of the IAS is to serve as a source of water vapor for precipitation in the region and adjacent regions (section 3.2). Water vapor transport from the IAS to the adjacent land areas is most efficient by the low-level jets (section 2.3). 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?* – While many studies have devoted to the GPLLJ and its role in precipitation in North America (section 3.2), the structure and dynamics of the IALLJ remains unknown. What depicted by the global reanalysis (Fig. 10) have yet to be validated again in situ observations. Possible sources for errors and biases in the reanalysis products are the diurnal cycle of the CALLJ, which is not fully resolved by the global reanalysis, and the coarse spatial resolution and deficiency in boundary-layer parameterizations of the models that produce the global reanalysis. Notice from Fig. 6a that there is not in situ sounding observation near the core of the CALLJ. Many theories and hypothesis have been developed for the dynamics of the GPLLJ and SALLJ involving orography, midlatitude circulation, or strong diurnal cycle (e.g., Bonner 1968; Stenrud 1998; Byerle and Paegle 2003); very few, if any at all, available for the IALLJ. While the low-level jets are located at the western and southwestern edges of the NASH, the intensification of the wind might have to be explained in terms of other factors, such as low pressure systems in the IAS region created by local deep convection or land effects (section 4.3). 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.

(b) *What are the mechanisms for the interannual variability of the water vapor transport?* – It is conceivable that the strength of the IALLJ is the primary control for the water vapor transport from the IAS. How much each of its factors (i.e., the NASH, local convection and land effects) contributes to the interannual variability of the IAJJL needs to be quantified. It is unclear whether the interannual variability of the IALLJ is random or modulcated by known climate modes, such as ENSO, NAO, and TAV. In addition, water vapor sources (surface evaporation) must also come into play to modulate the amount of water vapor being transported. Also unexplored is whether the fractional contributions to water vapor transport from the IAS by evaporation from the IAS and the tropical Atlantic Ocean (Bosilovich and Schubert 2002) would vary interannually.

(c) *How well do global and regional models reproduce the low-level jets?* – Again, this issue has been addressed more for the GPLLJ but much less for the IALLJ. The key issue here is whether the controlling factors for the low-level jets are well represented by the models. Parameterization and resolutions are concerns for the current global models and remote influences (through lateral boundaries) are for the regional models. If there are large errors and biases in model simulations, their causes (e.g., representations of local physical processes vs. remote influences) must be identified.

4.3 Land-air-sea interaction

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 a testament of the importance of land. But the exact role of land vs. ocean is not clear. Especially, how land interacts with the ocean through the atmosphere (or directly via river discharge) on the annual and interannual timescales is unclear. The role of land in the IAS can be addressed

(a) *How does land affect surface and low-level pressure distributions?* – Pressure distributions are central to understand 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. But it is unknown to what degree the land contribution to strengthening the pressure gradient is adiabatic (surface heating) or related to diabatic heating of convection over the northeastern part of the South America or the northern part of Central America. It is known that the diurnal cycle is crucially important to the GPLLJ (e.g., Stenrud 1998). But it is unclear whether the strong diurnal influence would extend from land to the ocean to affect the IALLJ.

(b) *Why do many, if not most, GCMs misrepresent the spatial distribution of precipitation in the IAS region?* – GCMs misplace the precipitation center over the ocean (Fig. 2) instead of over land as observed (Fig. 3) for several possible reasons. The thermal properties of land surface (temperature, soil moisture, fluxes) might be poorly represented by models. The physical properties (terrains) are poorly resolved by coarse resolution global models. The SST data used in global models do not resolve fine structures due to coastal upwelling. Cumulus and boundary-layer parameterizations in models are inadequate (e.g., not equally capable over land and ocea). To identify and quantify the cause for the model errors in this regard can be a major contribution to overall model improvement.

4.4 MSD

Understanding the mechanisms for the seasonal and interannual variability of the MSD is critical to its prediction. While simulating the MSD by global models may not be very difficult (Mapes et al. 2004), predicting its timing and intensity remains a challenge. Several possible mechanisms for the MSD have been proposed and tested (e.g., Magaña *et* al. 1999; Mapes et al. 2004; Magaña and Caetano 2005). Their roles in the MSD and its interannual variability need to be further quantified.

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

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

4.5 TC

Many questions on long-term variability of TCs affecting the IAS region remain need to be addressed. TCs that form in the Atlantic and propagate into the IAS region are influenced by both thermodynamics (SSTs, mid/low tropospheric moisture, moist static stability) and dynamics (tropospheric wind shear, vorticity of incipient disturbances). It is unknown which of these factors are the more important controls on the interannual to multidecadal variability of TCs, especially the 50-80 year variability that dramatically changes major hurricane activity. Changes between warm and cool phase of the multidecadal variability appear to be step functions rather than gradual transitions. We don't why. It is unclear when the current warm episode, which began in 1995, would switch back to the cool phase. The magnitude changes being induced upon TCs by anthropogenic warming today needs to be quantified. For impact of TCs on the IAS, it is unclear whether steering flow variability determines the likelihood of landfall or genesis location is the main factor. It remains a challenge to understand the mechanisms for long-term variability of TCs affecting the IAS region and to help predict such variability using long record of data in combination of processes studies.

5. Implementation

If endorsed by the VAMOS panel, a science working group (SWG) should be formed, whose immediate task would be completing a science document and implementation plan for the IASCLIP program in 2005. Meanwhile, the SWG should seek endorsement and support from national, international, and private funding agencies. Partnerships with other activities in the IAS, especially with national modeling centers, should also be sought. The SWG will also be responsible for organizing workshops and meeting to forge collaborations among IASCLIP scientists, forming a science team to design the process studies, working with UCAR JOSS on the logistics for the process studies, and establishing a data policy for the program.

To sufficiently address the issues raised in section 4, a combination of diagnosis of existing data, modeling, and process studies are needed. It is envisioned that the IASCLIP program would be conducted in three phases, with different emphases in each.

Phase I (2006 – 2009): Diagnostic and Modeling – Many issues raised in this prospectus can at least partially be addressed by diagnoses of existing data and by numerical modeling. These efforts should be able to better assort problems that need to be addressed with new observations and how process studies should be conducted to maximum the benefit. Particular tasks include but are not limited to:

- Produce a regional high-resolution reanalysis for the IAS region. The current NCEP Eta regional reanalysis for North America includes the IAS but in the southeastern corner of its domain (Fig. 21). The obvious limitations of this product to the IAS studies are its undesirable boundary effect and its lack of coverage over the southern part of the IAS region. This new product can be made by extending the coverage of the current Eta regional reanalysis with its current boundaries moved further south.

- Document common model deficiencies in simulating the key climate features (e.g., IALLJ, MSD, NASH, ITCZ) of the IAS region and to identify critical elements in the models that are responsible for such deficiencies.
- Document uncertainties in global reanalysis (their discrepancies) in the IAS region and identify possible sources for the uncertainties.
- Identify the in situ observations from the IAS region that are the most urgently needed for model validations and improvement.

Phase II (2010 – 2011): Field Campaign – There are several reasons for the need for a field campaign in the IAS region to obtain in situ observations that are otherwise unavailable from the existing operational network.

- Our confidence of using reanalysis products as validations for model simulations must be built upon direct validations of the analysis products themselves against in situ observations. It is known some reanalysis products suffers from large biases, especially in the moisture field and near the surface (e.g., Trenberth and Gillemot 2003). This is especially so over ocean, such as the Caribbean Sea, where no observations are routinely available. The first priority of an IAS field campaign would be taking sounding observations in the core of the CALLJ from ship(s) or aircraft and from islands of Lesser Antilles, and to increase sounding frequencies at the sites of Yucatan, *Isla del San Andre*, and Corpus Christi to measure the structure and diurnal cycle of the IALLJ and its water vapor transport.
- It is desirable to obtain a comprehensive in situ observational data set that provides a full description of processes key to the MSD not available from existing data. Based on our current understanding (sections 2.1 and 4.4), such a data set should include the CALLJ and its water vapor transport, air-sea fluxes, large-scale pressure distribution associated with the NASH, convection and precipitation. The ECAC field campaign in 2001 (Magaña and Caetano 2004) provides piloting experience for this exercise.
- Central to understanding the mechanisms for the interannual to interdecadal variability of TCs in the IAS (section 2.6) is the knowledge of the effects of the large-scale environment, in both atmoshere and ocean. In cooridnation with NOAA huricane research that usually focuses on the storms, additional measurements from land, ship and aircraft over the IAS would augment our ability of documenting and understanding the role of the large-scale environment in TC genesis, intensification, and movement.
- Other needs for new in situ observations can be determined by modeling studies during Phase I.

Phase III (2012 – 2014): Post-Field Campaign Data Analysis and Modeling

Appendix A Other Activities related to the IAS

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

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

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

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

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

A5 The SouthEast Atlantic Coastal Ocean Observing System (SEACOOS) (www.seacoos.org) – The SEACOOS is one of the coastal component of the Integrated Ocean Observing System (IOOS), whose objective is to collect and disseminate data and data products to serve the critical and expanding needs of environmental protection, public health, industry, education, research, and recreation. The SEACOOS initiative is an eleven-institution collaboration to develop a regional coastal ocean observing system for the southeast (NC, SC, GA, FL) United States. It includes observing, modeling, and data management. Near real-time observations of SST and surface wind are available from stations in part of the Gulf costal zone (Fig. A1). Oceanic observations needed for the IASCLIP can be supplemented by the existing observing system of the SEACOOS.

A6 The Global Ocean Data Assimilation Experiment (GODAE, www.bom.gov.au/bmrc/ocean/GODAE) - GODAE is a global system of observations, communications, modeling and assimilation designed to deliver regular, comprehensive information on the state of the oceans. Within GODAE, special efforts are made by many international research groups to focus on data assimilation and prediction of the IAS using high-resolution ocean models. Table A1 gives examples of ocean models used in such efforts. These modeling efforts can benefit tremendously the research on the mechanisms for the variability of the WHWP. They can also be integrated into the coupled modeling components of the IASCLIP.

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

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

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

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

Apeendix B Acronyms

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

References

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

Amador, J. A., V. O. Magaña and J. B. Pérez, 2000. The low level jet and convective activity in the Caribbean. Preprints 24th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, 29 May-2 June, 114-115.

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

Amador, J. A. E. J., Alfaro, O. G. Lizano, and V. O. Magaña, 2004. *Atmospheric forcing of the eastern tropical Pacific: A review*. Submitted to *Progress in Oceanography, November* 2004. *Progress in Oceanography Special Issue: Review of Eastern Tropical Pacific Oceanography (P. Fiedler and M. Lavin, Guest Editors.)*

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

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

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

Bosilovich, M.G., and S.D. Schubert, 2002: Water vapor tracers as diagnostics of the regional hydrologic cycle. J. Hydrometeor, **3**, 149-165.

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

Ceron, R.M.B., H.G. Padilla, R.D. Belmont, M.C.B. Torres, R.M. Garcia, A.P. Baez, 2002: Rainwater chemical composition at the end of the mid-summer drought in the Caribbean shore of the Yucatan Peninsula. ATMOSPHERIC ENVIRONMENT 36 (14): 2367-2374.

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

Chen, A.A, and M.A. Taylor, 2002: Investigating the link between early season Caribbean rainfall and the El Nino plus 1 year. INTERNATIONAL JOURNAL OF CLIMATOLOGY, 22, 87-106.

Chen, J.M., C.T. Fong, F.J. Wang, C.H. Shiao, J.H. Chen, M.D. Cheng, 1999: Climate characteristics of the CWB Global Forecast System: Hydrological processes and atmospheric circulation. TERRESTRIAL ATMOSPHERIC AND OCEANIC SCIENCES 10 (4): 737-762.

Clifton KE, 1995: Growth And Reproduction For The Herbivorous Parrotfish Scarus-Iserti. Marine Ecology-Progress Series 116 (1-3): 39-46.

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

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

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

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

Diaz DP, Cordova QA, Grayeb BEP, 1994: Effect Of Enso On The Mid Summer Drought In Veracruz State, Mexico. ATMOSFERA 7 (4): 111-219.

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

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

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

Enfield, D.B., and E.J. Alfaro, 1999: The dependence of Caribbean rainfall on the interaction of tropical Atlantic and Pacific Oceans. Journal of Climate, 12(7):2093-2103.

Enfield, D.B., S.-K. Lee, and C. Wang, 2004: How are Large Western Hemisphere Warm Pools Formed? J. Climate, submitted.

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

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

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

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

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

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

Gu, G. and C. Zhang, 2002: Cloud components of the ITCZ. J. Geophy. Res., *J. Geophy. Res.*, 107(D21), 4565, doi:10.1029/2002JD002089.

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

Hastenrath, S., 2002: The Intertropical Convergence Zone of the eastern Pacific revisited. INTERNATIONAL JOURNAL OF CLIMATOLOGY 22 (3): 347-356.

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

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

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

Higgins R. W., A. Douglas, A. Hahmann, E. H. Berbery , D. Gutzler, J. Shuttleworth, D. Stensrud, J. A. Amador, R. Carbone, M. Cortez, M. Douglas, R. Lobato, J. Meitin, C. Ropelewski, J. Schemm, S. Schubert, C. Zhang, 2003. Progress in Pan American CLIVAR Research: The North American Monsoon System. Atmósfera, 16(1), 29-65.

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

Hodell, D.A, J.H. Curtis, G.A. Jones, A. Higueragundy, M. Brenner, M.W. Binford, K.T. Dorsey, 1991: Reconstruction of caribbean climate change over the past 10,500 years. NATURE 352 (6338): 790-793.

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

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

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

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

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

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

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

Kameo, K., 2002: Late Pliocene Caribbean surface water dynamics and climatic changes based on calcareous nannofossil records. PALAEOGEOGRAPHY PALAEOCLIMATOLOGY PALAEOECOLOGY. 179 (3-4): 211-226.

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

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

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

Laing, A.G., 2004: Cases of heavy precipitation and flash floods in the Caribbean during El Nino winters. JOURNAL OF HYDROMETEOROLOGY, 5, 577-594.

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

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

Liebmann, B., and J. A. Marengo, 2001: The Seasonality and Interannual Variability of Rainfall in the Brazilian Amazon Basin. *J. Climate*, **14**, 4308-4318.
Lin HL, Peterson LC, Overpeck JT, Trumbore SE, Murray DW, 1997: Late Quaternary climate change from delta O-18 records of multiple species of planktonic foraminifera: High-resolution records from the anoxic Cariaco Basin, Venezuela. PALEOCEANOGRAPHY 12 (3): 415-427.
Linsley, B.K., R.B. Dunbar, G.M. Wellington, and D.A. Mucciarone, 1994: A Coral-Based Reconstruction Of Intertropical Convergence Zone Variability Over Central-America. Journal of Geophysical Research-Oceans 99 (C5): 9977-9994.
Madden, R. A., and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702-708.
Magaña, V., 2000: Interannual Climate Variability in the Mexico, Central America, and Carribean Region. CLIVAR Exchange, 16, 1-2.
Magaña, V., J. Amador and S. Medina, 1999: The midsummer drought over Mexico and Central America. J. Climate 12,1577-1588.
Magaña, V., and E. Ceatano, 2004: TEMPORAL EVOLUTION OF SUMMER CONVECTIVE ACTIVITY OVER THE AMERICAS WARM POOLS. *Geophysical Research Letters*, submitted.
Mapes, B.E., N. Buenning, I.-S. Kang, G. N. Kiladis, D. M. Schultz, K.M. Weickmann, 2005: Strides, steps and stumbles in the march of the seasons. Bull. Amer. Met. Soc., in press.
Mapes, B.E., P. Liu, and N. Buenning, 2005: Indian monsoon onset and Americas midsummer drought: out-of-equilibrium responses to smooth seasonal forcing. J. Climate, submitted.
Maul, G.A., 1993: Climate Change in the Intra-Americas Sea. United Nations Environmental Program, pp 389.
Mesinger, F., and co-authors 2004: North American regional reanslysis. Proceedings of the AMS annual meeting Seattle, Wa. Jan 2004.
Mestas-Nunez, A.M., and D.B. Enfield, 1999: Rotated global modes of non-ENSO sea surface temperature variability. Journal of Climate, 12(9):2734-2746.
Mestas-Nuñez, A.M., C. Zhang, D.B. Enfield, 2005: Uncertainties in Estimating Moisture Fluxes over the Intra-Americas Sea. J. Hydrometeorol, submitted.
Misra V., P.A. Dirmeyer, and B.P. Kirtman, 2002: A comparative study of two land surface schemes in regional climate integrations over South America. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 107 (D20): Art. No. 8080
Mo, K. C., and E. H. Berbery 2004: The low level jets and the summer precipitation regimes over North America. J. Geophy Res. doi: 10.1029/2003JD004106.
Mo, K.C., and R.W. Higgins, 1996: Large-scale atmospheric water vapor transport as evaluated from the NCEP/NCAR and the NASA/DOA reanalyses. J. Climate, 9, 1531-1545.
Mo, K.C., J. N. Paegle, and R. W. Higgins, 1997: Atmospheric processes associated with summer floods and droughts in the central United States. J. Climate, 10, 3028-3046.
Muller-Karger F, Varela R, Thunell R, Scranton M, Bohrer R, Taylor G, Capelo J, Astor Y, Tappa E, Ho TY, Walsh JJ, 2001: Annual cycle of primary production in the Cariaco Basin: Response to upwelling and implications for vertical export. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS 106 (C3): 4527-4542.

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

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

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

Nogués-Paegle, J., and K. Mo, and Paegle J, 1998: Predictability of the NCEP–NCAR Reanalysis Model during Austral Summer. MONTHLY WEATHER REVIEW 126 (12): 3135-3152.

Pasch, R.J., M.B. Lawrence, L.A. Avila, J.L. Beven, J.L. Franklin and S.R. Stewart. 2004: Atlantic Hurricane Season of 2002. *Monthly Weather Review*: Vol. 132, No. 7, pp. 1829–1859.

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

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

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

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

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

Robertson DR, Swearer SE, Kaufmann K, Brothers EB, 1999: Settlement vs. environmental dynamics in a pelagic-spawning reef fish at Caribbean Panama. ECOLOGICAL MONOGRAPHS 69 (2): 195-218.

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

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

Ropelewski and Yarosh 1998

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

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

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

Sponaugle S and Cowen RK, 1996: Nearshore patterns of coral reef fish larval supply to Barbados, West Indies. MARINE ECOLOGY-PROGRESS SERIES 133 (1-3): 13-

28.
Stensrud, D.J., R.L. Gall, S.L. Mullen, and K.W. Howard, 1995: Model climatology of the Mexican monsoon, *J. Climate*, **8**, 1775-1794.
Sudradjat, A., K.L. Brubaker, P.A. Dirmeyer, 2003: Interannual variability of surface evaporative moisture sources of warm-season precipitation in the Mississippi River basin. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 108 (D16): Art. No. 8612.
Taylor MA, Enfield DB, Chen AA, 2002: Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS. 107 (C9): Art. No. 3127 SEP
Tedesco, K., and R. Thunell, 2003a: High resolution tropical climate record for the last 6,000 years. GEOPHYSICAL RESEARCH LETTERS 30 (17): Art. No. 1891.
Tedesco, K., and R. Thunell, 2003b: Seasonal and interannual variations in planktonic foraminiferal flux and assemblage composition in the Cariaco Basin, Venezuela. JOURNAL OF FORAMINIFERAL RESEARCH 33 (3): 192-210.
Thorncroft, C., and K. Hodges. 2001: African Easterly Wave Variability and Its Relationship to Atlantic Tropical Cyclone Activity. *Journal of Climate*: Vol. 14, No. 6, pp. 1166–1179.
Trenberth, K.E., and C.J. Guillemot, 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. J. Climate, 9, 1288-1298.
Vargas, AB, and VFS Trejos, 1994: Changes In The General-Circulation And Its Influence On Precipitation Trends In Central-America - Costa-Rica. Ambio 23 (1): 87-90.
Vera, C., W. Higgins, J. Amador, T. Ambrizzi, R. Garreaud, D. Gochis, D. Guztler, D. Lettenmaier, J. Marengo, C. R. Mechoso, J. Nogues-Paegle, and C. Zhang, 2005: A Unified View of the American Monsoon Systems. Journal of Climate, submitted.
Wang, C. and D. B. Enfield, 2001: The Tropical Western Hemisphere warm pool. Geophys. Res. Lett., **28,** 1635-1638.
Wang, C. and D. B. Enfield, 2003: A further study of the tropical Western Hemisphere warm pool. J. Climate, **16,** 1476-1493.
Wright, R.M., 2001: Wind energy development in the Caribbean. RENEWABLE ENERGY 24 (3-4): 439-444 Sp. Iss.
Wu, Y.H., and S. Raman, 1998, The summertime Great Plains low level jet and the effect of its origin on moisture transport. Boundary Layer Meteor., 88, 445-466.
Yarosh et al. 1996;
Zhang, C., 2001: Double ITCZs. J. Geophy. Res., 106, 11,785-11,792.
Zhou, J. and W. K.–M. Lau, 1998: Does a monsoon climate exist over South America. *J. Climate*, **11**, 1020-1040.

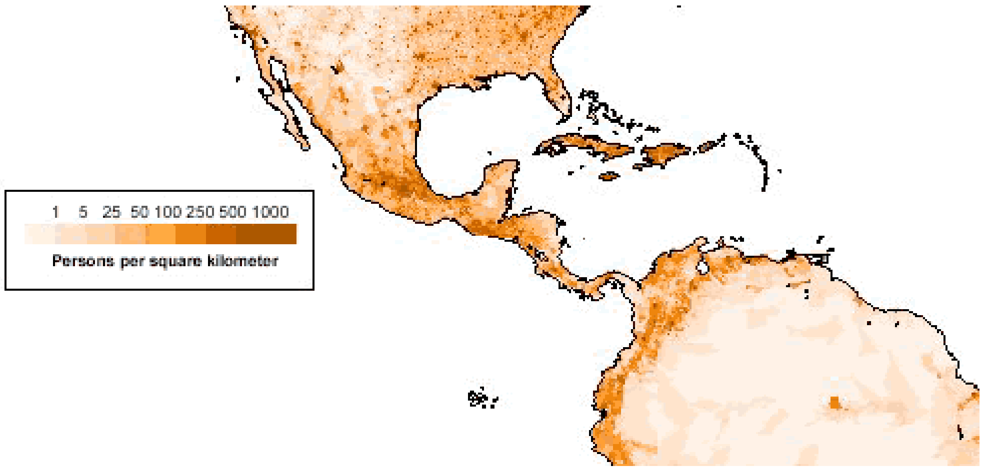

Figure 1 Population density of the areas surrounding the IAS (Courtesy of Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI), and World Resources Institute (WRI). 2000. Available at http://sedac.ciesin.columbia.edu/plue/gpw.

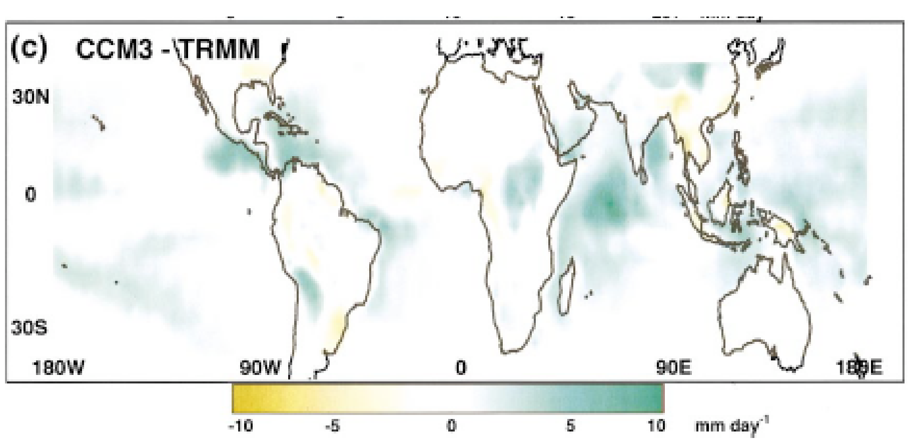

Figure 2 The climatological mean difference (CCM3 - TRMM) in mm day^{-1}. (From Collier et al 2004)

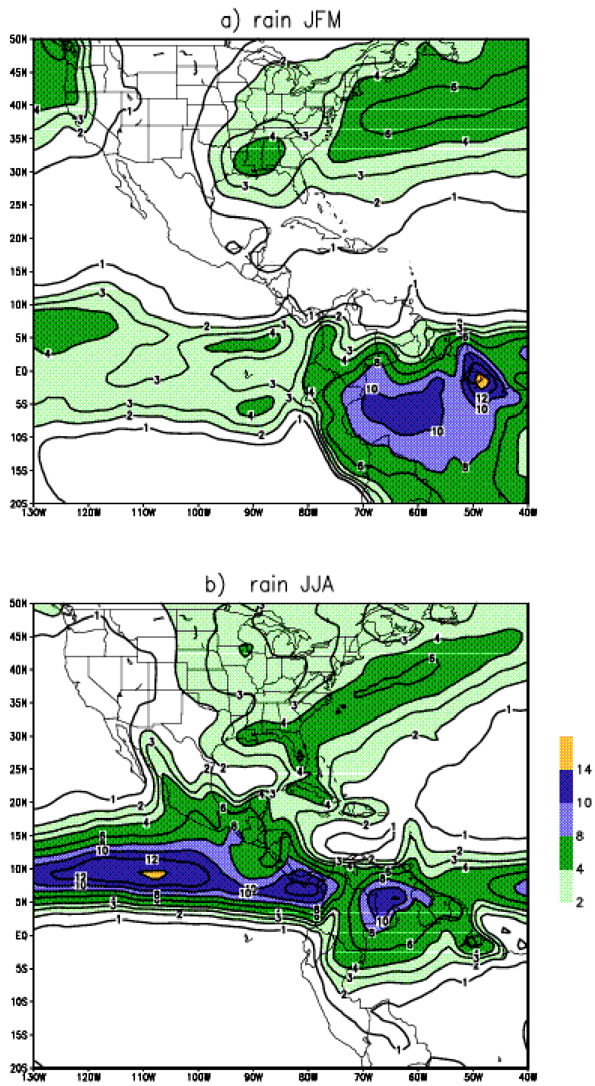

Figure3 Mean precipitation for (a) January- March (JFM) and (b) June-August (JJA) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm day^{-1}.

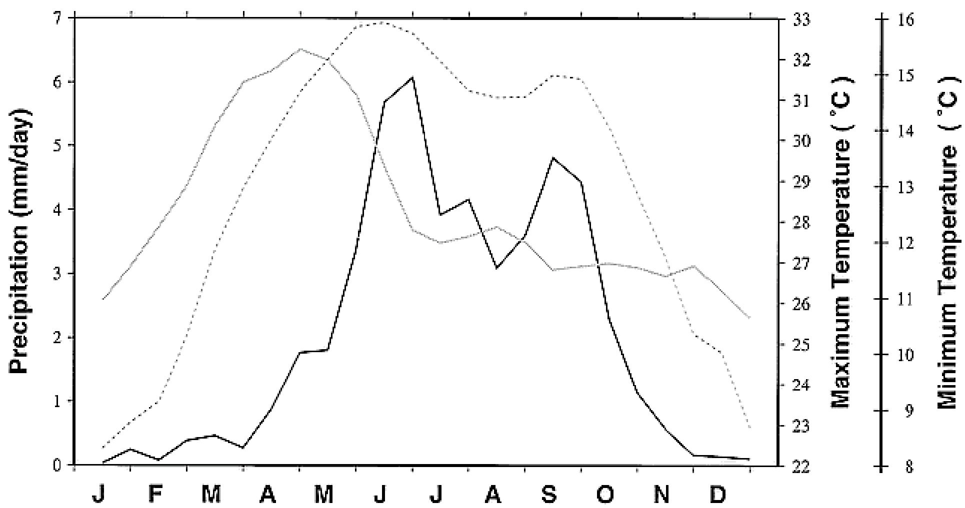

Figure 4. Biweekly climatology of precipitation (black solid line), maximum temperature (gray solid line), and minimum temperature (dotted line) for Oaxaca, Mexico (17.8˚N, 97.8˚W). (From Magana et al. 1999)

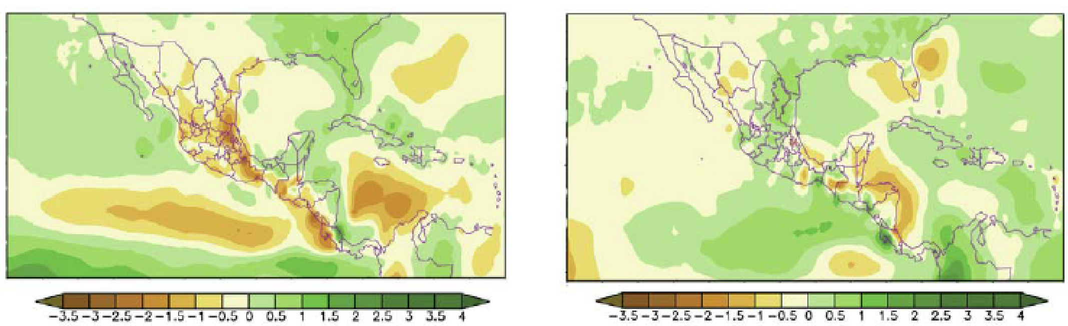

Figure 5 Composite of precipitation anomalies (mm/day) during the summers (Jun-Jul-Aug-Sep) of (left panel) six El Niño onset years (1965,1972, 1982, 1986, 1991, 1997), and (right panel) La Niña years (1964, 1970, 1973, 1975, 1988, 1998). (From Magana 2000)

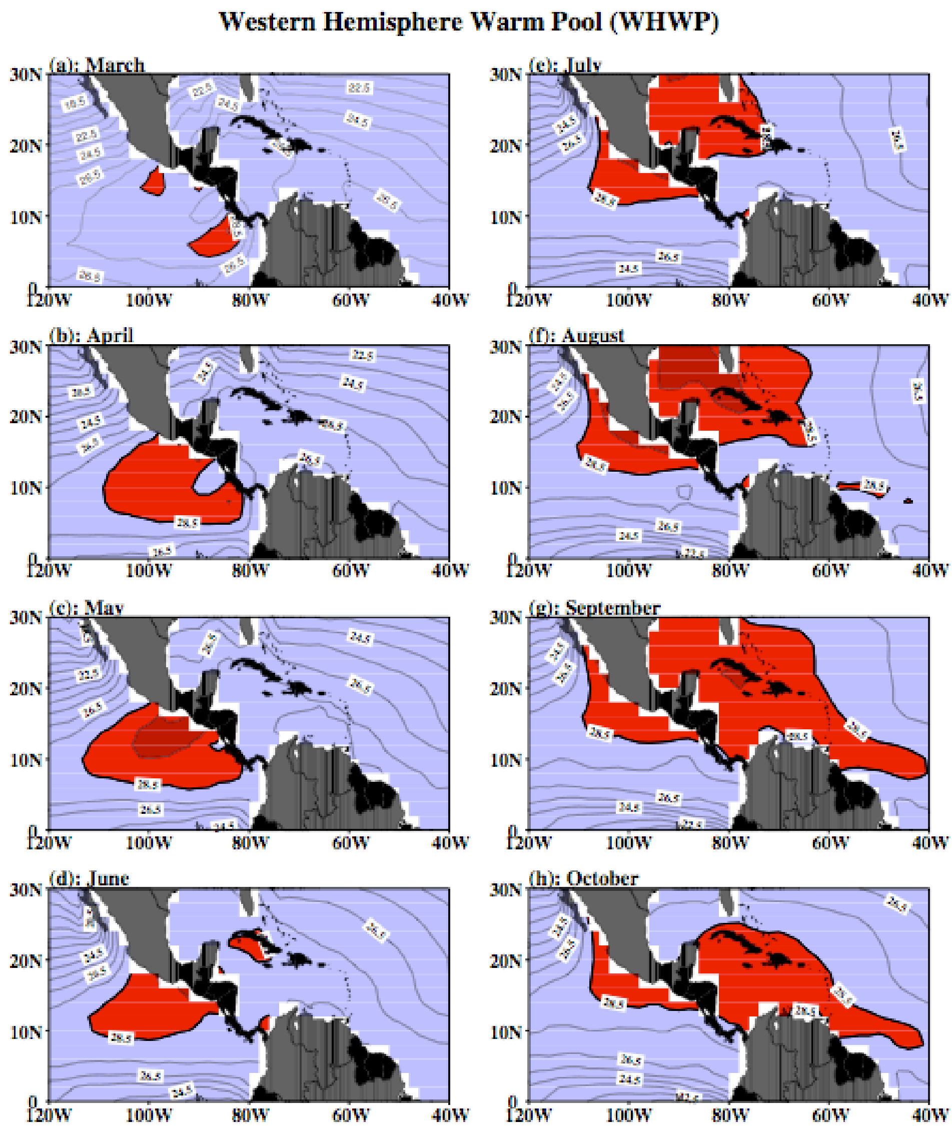

Figure 6 Seasonal distributions of SST for the tropical WHWP: (a) Mar, (b) Apr, (c) May, (d) Jun, (e) Jul, (f) Aug, (g) Sep, and (h) Oct. The red shading and dark contour represent water warmer than 28.5°C. (From Wang and Enfield 2003)

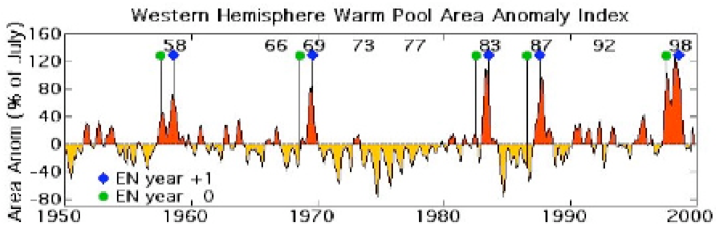

Figure 7 Anomaly time series of the Americas warm pool area surrounded by the 28.5 °C isotherm. The series is expressed as a percentage of the climatological mean area for July. The July values of the five largest anomalies are indicated by the blue diamonds, and the July values of the prior years by green circles. Years of major ENSO warm events are also marked.

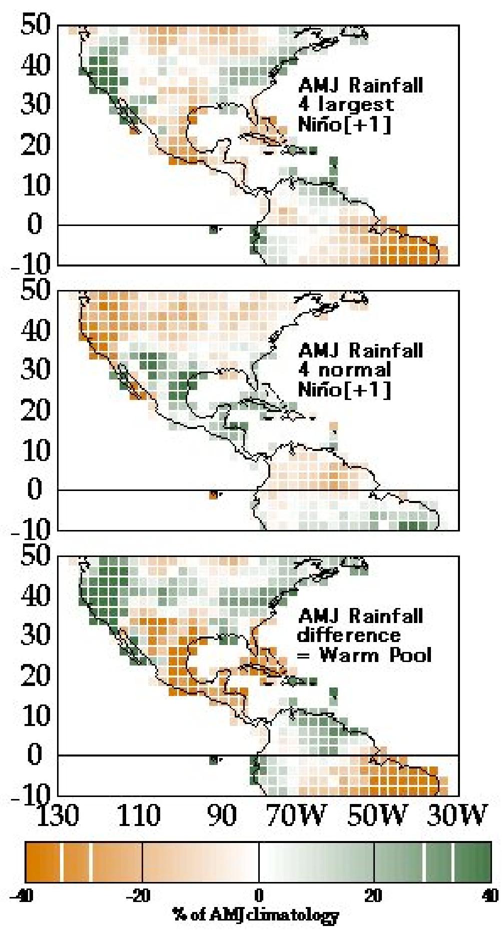

Figure 8. Top: Composite of averaged rainfall for the early summer (April-May-June; AMJ) period of four large warm pools following recognized El Niño events. Middle: Same, but for four summers following warm events without large warm pools. Bottom: The middle map subtracted from the top map. White lines in the color bar indicate significance levels. (From Enfield and Wang 2002)

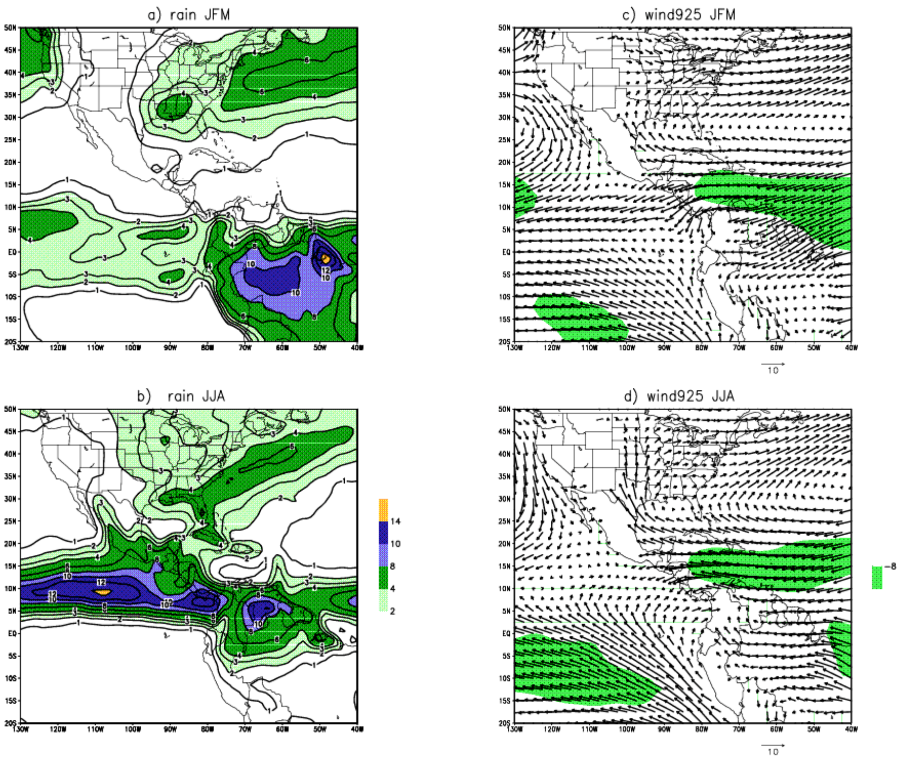

Figure 9 Mean precipitation for January- March (JFM) averaged from 1997-2002. Data were taken from 1-degree resolution precipitation data set from satellite estimates (Negri et al. 1994). Contour interval 1 mm day^{-1}, (b) same as (a), but for June-August (JJA), (c) Mean winds at 925 hPa for JFM averaged from 1997 to 2002 based on the CDAS (Kalnay et al. 1996). The unit vector is 10 m s^{-1}. Areas where the zonal wind is greater than 8 m s^{-1} are shaded, and (d) same as (c) but for JJA.

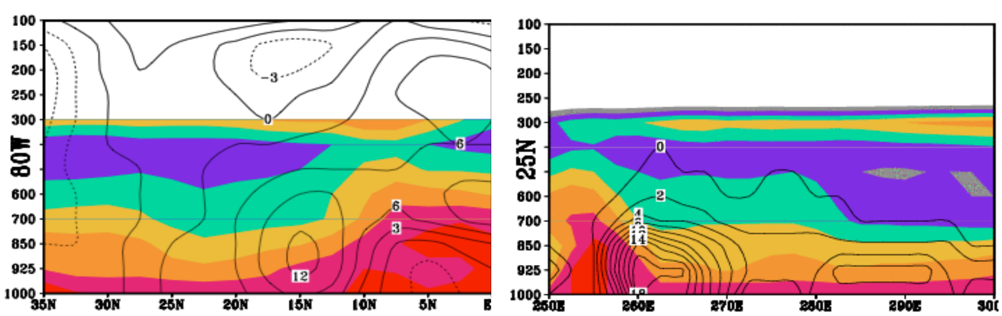

Figure 10 Vertical-meridional cross-section of zonal wind (contours, m s^{-1}) at 80°W (left panel) and vertical-zonal cross-section of meridional wind (contours, m s^{-1}) at 25°N (Right panel) for July based on the NCEP/NCAR reanalysis.

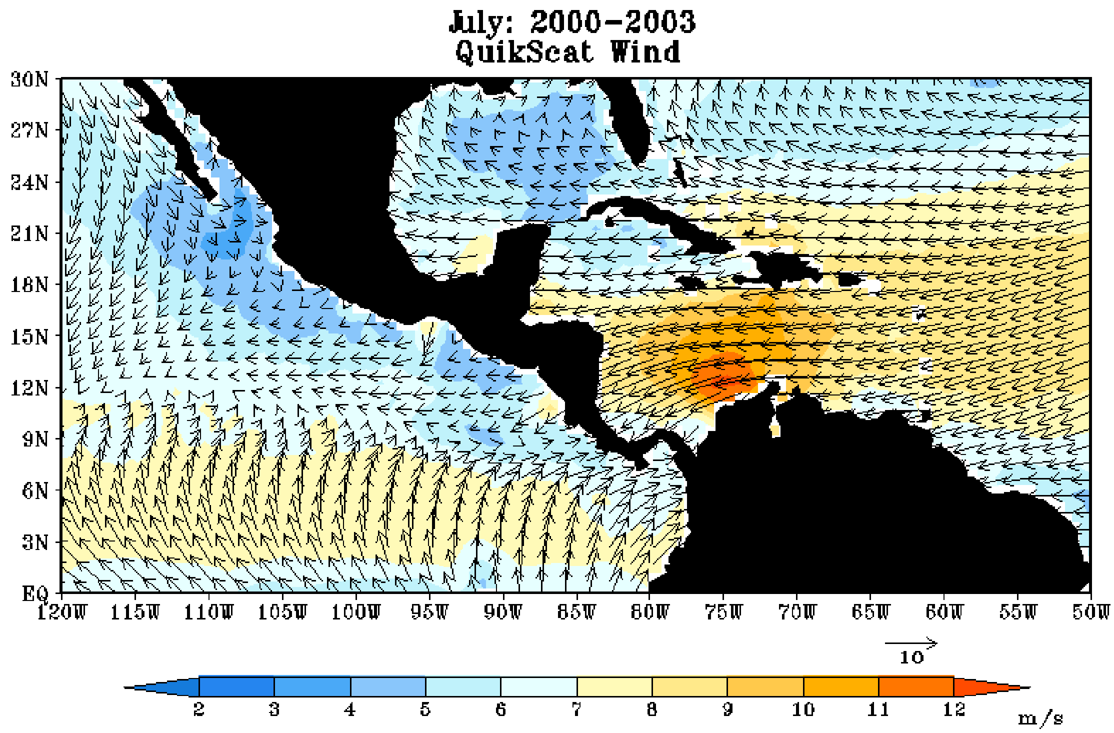

Fig. 11 July mean QuikScat winds (m s^{-1}) for the period 2000-2003 (from Amador et al., 2004).

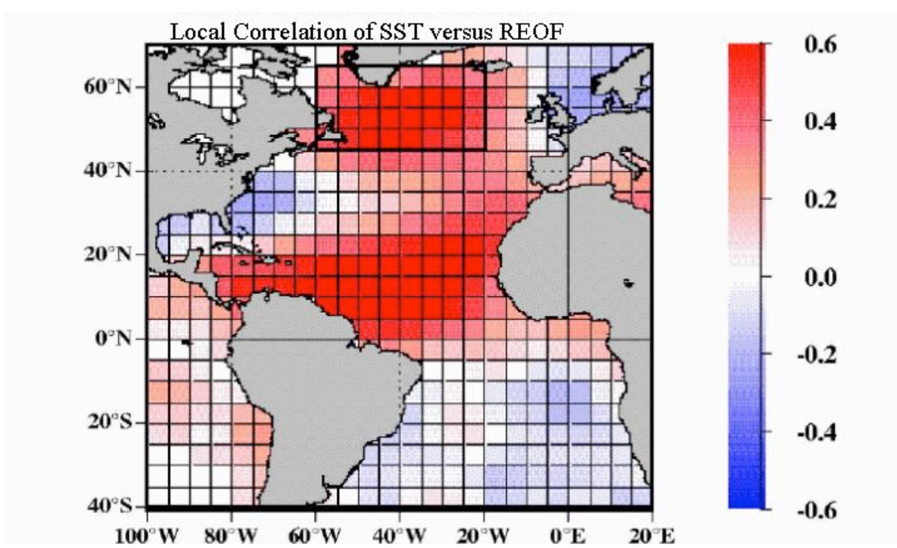

Figure 12 Spatial pattern in SST of the Atlantic multidecadal Oscillation (MDO). (From Mestas-Nunez and Enfield 1999).

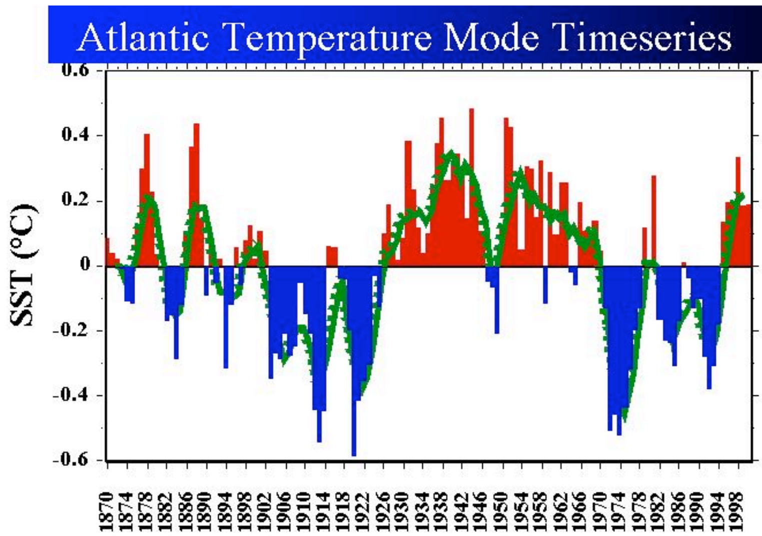

Figure 13 SST time series (averaged over the northern Atlantic box in Fig. 2.6a) associated with the MDO. (From Goldernburg et al. 2001).

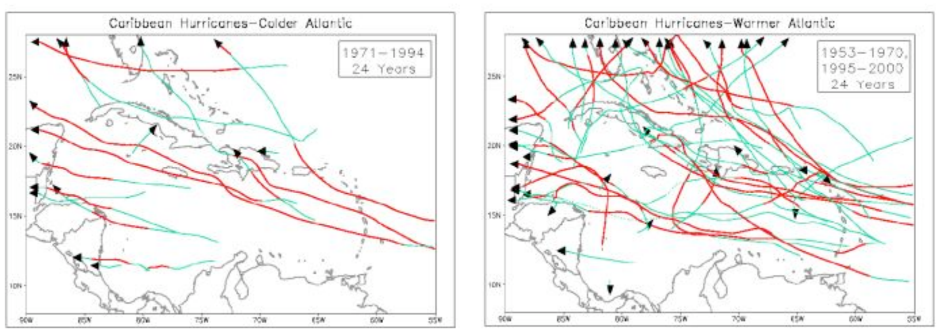

Figure 14 Landfall hurricane tracks in the IAS during years of cold (1971-1994, left) and warm (1953-1970 and 1995-2000, right) Atlantic.

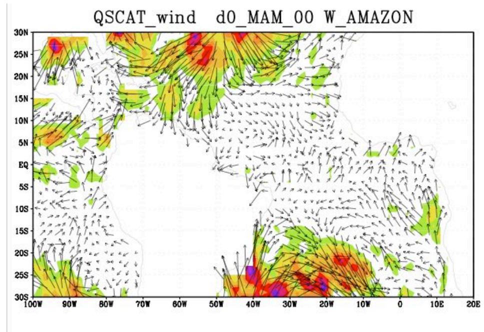

Figure 15: Ocean surface wind anomalies one-day after peaks of Amazon rainfall (the red square) during boreal spring (MAM). The winds and rainfall are derived from QuikSCAT and TRMM observations.

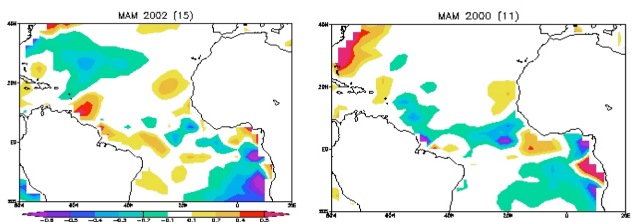

Figure 16: SST anomalies induced by anomalous surface fluxes associated strongest 20% convective events during boreal spring (MAM) of (left) 2002 and (right) 2000 in the western Amazon. They are estimated by an ocean mixed layer model (Alexander 1992) with climatological mixed layer depths (Levitus and 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 °C. Interannual variation is illustrated by the difference between a) and b).

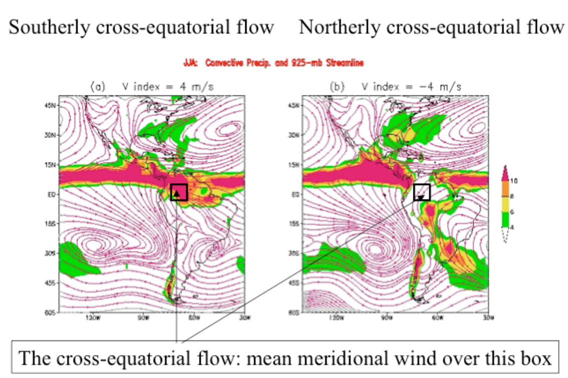

Figure 17: Streamlines at 925 hPa and TRMM daily rainrate associated with (a) southerly (b) northerly cross-equatorial flow for boreal summer (JJA) based on the linear regression for one sigma of the cross-equatorial flow. Streamlines are derived from ECMWF reanalysis. The analysis period is 1979-1993.

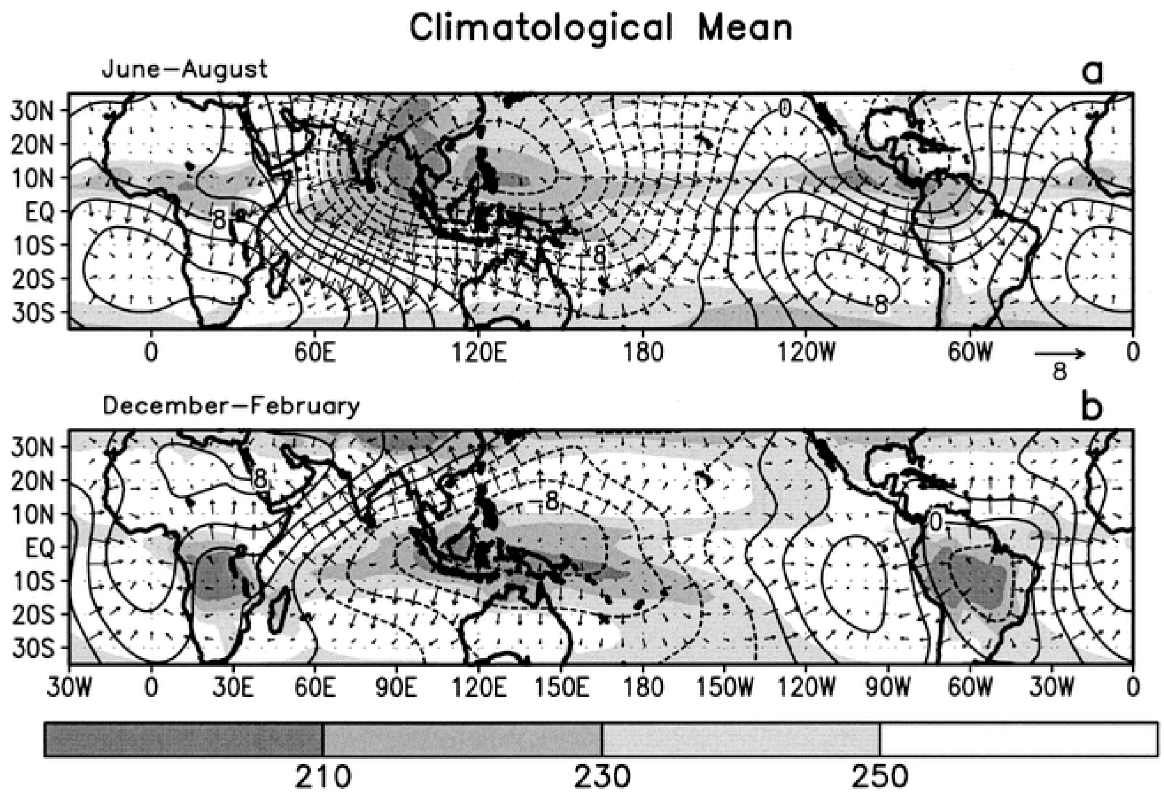

Figure 18 Climatological mean OLR (shaded, W m^{-2}), 200-hPa velocity potential (contours, interval is 2 $x10^6$ m^2 s^{-1}), and divergent wind vectors (m s^{-1}) for (a) JJA and (b) DJF, 1979–2000. The divergent vector wind scale is located below (a). (From Chelliah and Bell, 2004)

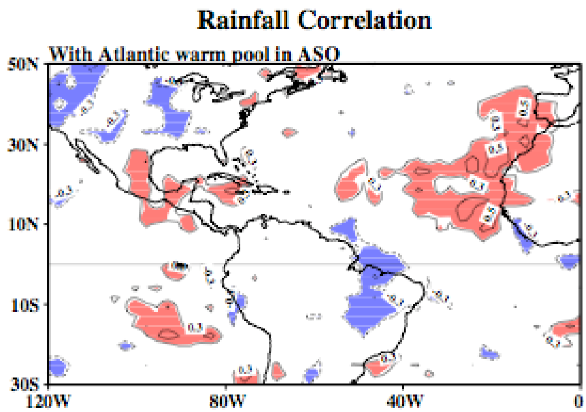

Figure 19 Correlation between a WHWP index and precipitation during August - October.

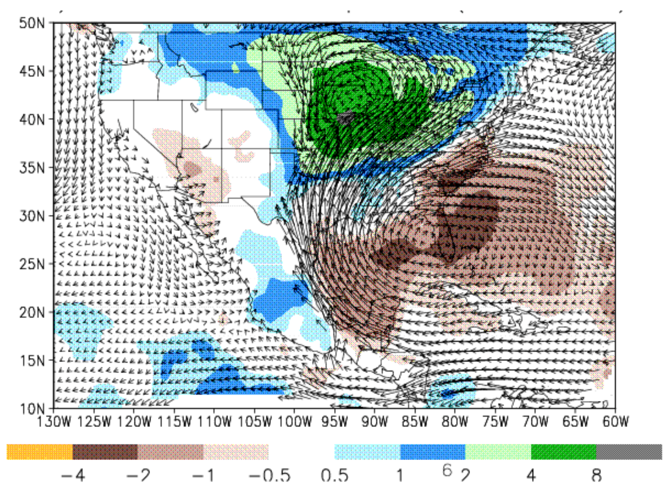

Figure 20 Composite of precipitation (colored) and 925 hPa wind anomalies. The unit vector is ms^{-1}.

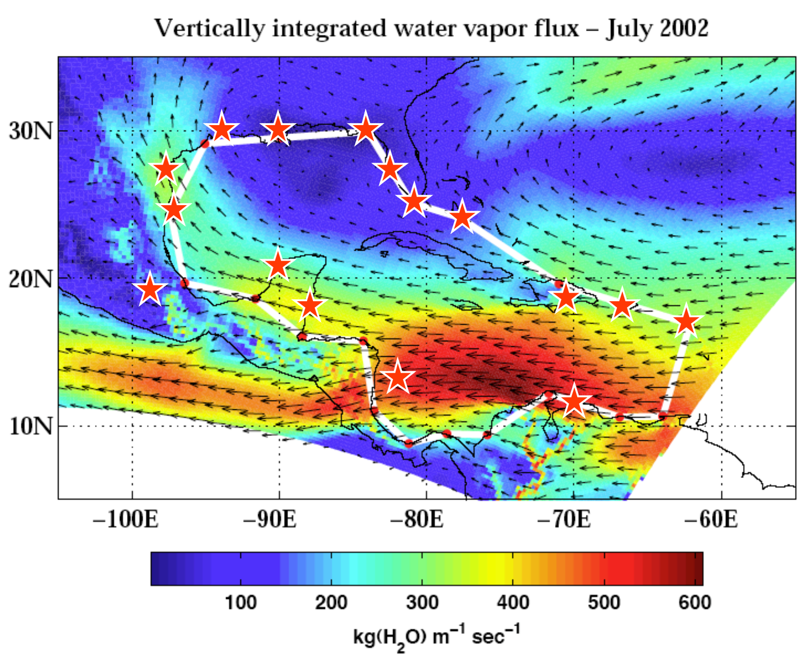

Figure 21 Vertically integrated water vapor flux for July 2002 used to illustrate the coverage of the IAS by the current NCEP Eta North American regional reanalysis. Stars mark the locations near the IAS coast at which sounding observations are available.

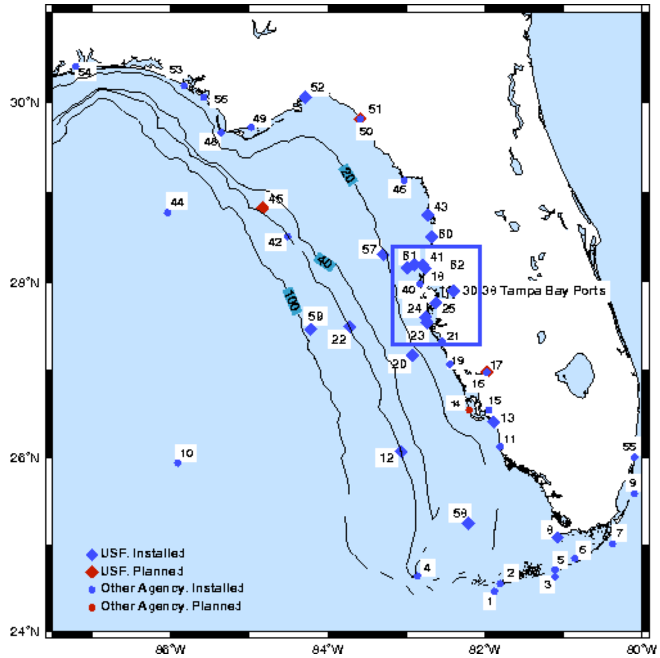

Figure A1 West Florida Shelf Observing Stations of the SEACOOS.

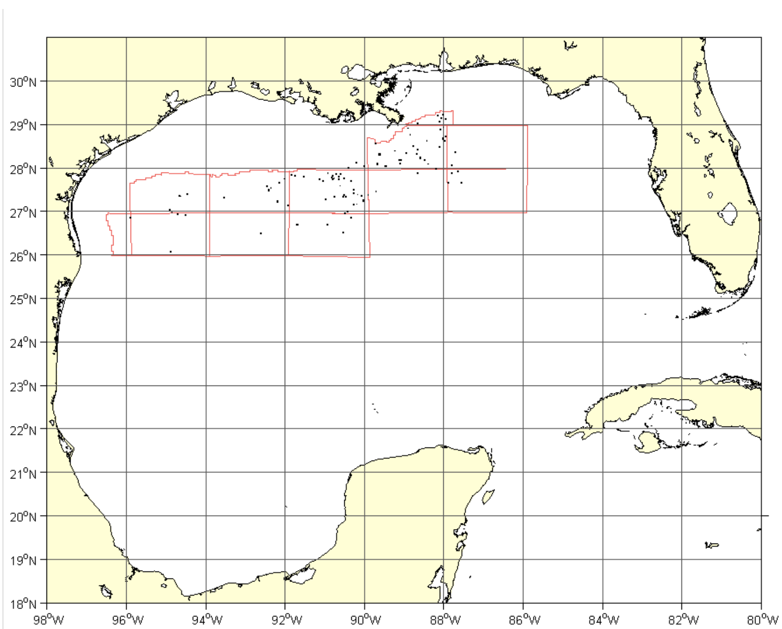

Figure A2 Locations of current drilling platforms in the Gulf of Mexico.

Table A1 Information on Ocean Models of the IAS

Model	Horizontal domain (grid resolution)	Vertical Grid (layers)	Data Assim.(DA), Hindcast (H), Forecast (F)	References (web links)
HYCOM-IAS	NATL (1/12˚) IAS nested (1/24˚)	Hybrid-isopycnic, z & sigma (15)	NATL: DA, H, F	Romanou et al. (2004) (HYCOM: hycom.rsmas.miami.edu)
NCOM-IAS	GOM & CS (1/24˚)	Hybrid-sigma & z (41)	DA, F	Morey et al. (2003) Zavala-Hidalgo et al.(2003) (www7320.nrlssc.navy.mil /IASNFS_WWW/)
CANDIE-CS	CS (19km) West CS nested (6km) MBRS nested (3km)	z-level (31)	DA	Sheng and Tang (2003, 2004) (CANDIE: www.phys.ocean.dal.ca/programs/CANDIE/)
POM-WCS	West CS, curvilinear grid (3-8 km)	Sigma (16)	DA, H	Thattai (2003) (POM: www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/)
POM-PROFS	West NATL, curvilinear grid (5-20km)	Sigma (25)	DA, H	Oey et al. (2003) Ezer et al. (2003) (www.aos.princeton.edu/WWWPUBLIC/PROFS/)
OPA-AGRIF	NATL (1/3˚) CS nested (1/9˚) MBRS nested (1/27˚)	z-level (34)	OPA: H Nested: Spin-up stage	Candela et al. (2003) (OPA: www.lodyc.jussieu.fr/opa/)
ROMS-CS	NATL (10km) GOM-CS nested	s-coord. (30)	DA	Haidvogel et al (2000) (ROMS: marine.rutgers.edu/po/)

(Note that regional models of the GOM only, such as CUPOM and MOM, as well as global high-resolution models such as NLOM and POP are not listed here).

Acronyms: CANDIE- Canadian version of DieCAST; CS- Caribbean Sea; IAS- Intra-American Seas; CUPOM- Colorado University version of POM; GOM- Gulf of Mexico; HYCOM- Hybrid Coordinate Ocean Model; MBRS- Meso-American Barrier Reef System; MOM- Modular Ocean Model; NATL- North Atlantic; NCOM- Navy Coastal Ocean Model; NLOM- Navy Layered Ocean Model; OPA- Ocean Parallellise general circulation model; POM- Princeton Ocean Model; POP- Parallel Ocean Model; PROFS- Princeton Regional Ocean Forecast System; ROMS- Regional Ocean Modeling System.