2. Atmosphere-ocean Interactions

2.1 Science Background

It is generally understood that a substantial part of atmospheric predictability on seasonal and longer time scales is linked to the predictability of the oceans and, in particular, sea surface temperatures (SSTs). In addition to the important role of ENSO, there is growing evidence that SST anomalies in the Atlantic and Indo-Pacific sectors can have major impacts on weather and climate variability throughout the world (e.g., Fig. 2.1). Predictability on regional scales can be viewed as the result of often-complicated interactions between the SST-forced global-scale atmospheric variability and local climates. Such interactions with local climates involve land-surface feedbacks, weather and other short-term variability, as well as various climatologically important regional circulations such as low-level jets. Understanding predictability on regional scales therefore involves understanding the nature and source of the predictability in the oceans, and the physical processes by which that predictable signal is ultimately manifest on regional scales. Air-sea interactions are critical because most of the modes of variability (MJO, Monsoons, ENSO, upwelling) are fundamentally dependent on air-sea interaction processes.

The CPPA emphasis on precipitation prediction in the Americas leads to a scientific focus on air-sea interactions in the Eastern Pacific (EPac), the Intra-American Seas (IAS), and the tropical Atlantic. All three ocean regions behave quasi-coherently as part of the tropical sources of heat and moisture that interact with the surrounding land regions, to produce much of the potentially predictable signal over the Americas on intraseasonal to interannual time scales. The research approach is based on tightly focused process studies addressing specific problem areas for GCMs; the studies feature intensive field programs, enhanced monitoring, detailed research model simulations, global climate/regional model intercomparisons, predictability studies, and links with operational model improvement efforts. Compared to land, the oceans are data deserts, so measurements play an essential role.

While the need to address specific processes has led to regional foci for CPPA air-sea projects, e.g., the North American Monsoon Experiment (NAME) or the Eastern Pacific Investigation of Climate (EPIC), it is emphasized that the climate of the Americas must be viewed as an integrated system having both global and regional contexts. For example, from a global perspective, the eastern Pacific is heavily influenced by ENSO and thus depends on processes extending to the western Pacific and Indian Ocean. On regional scales, there are linkages between the various CPPA sub-areas: in boreal summer and fall the Western Hemisphere warm pool can affect subsidence in the southeast Pacific stratocumulus region; in turn, the latter region influences development of a southern hemisphere Inter-Tropical Convergence Zone (ITCZ), the equatorial cold tongue, and by extension the EPIC domain; moisture from the IAS region is transported into the Mexican monsoon domain, an anti-correlation exists between rainfall in the NAME region and rainfall over the Great Plains, etc.

In the remainder of this section we provide a general background on air-sea interaction issues relevant to short-term climate variability and predictability, discuss specific problems in improving predictions, and outline steps to implement an attack on these problems.

2.1.1 Eastern Pacific cold tongue, ITCZ, convection, Eastern Pacific boundary current region, cloud, SST interactions

The coupled climate system of the eastern Pacific consists of a complex interplay between the ocean, atmosphere, and cloud processes over a wide range of temporal and spatial scales. The complexity of this coupled system and the difficulty in properly representing all relevant physical processes has contributed to deficiencies in climate simulations of this region, thus hindering progress in prediction of intraseasonal-to-interannual variability of precipitation in the Americas.

Illustrative of the problems is the interaction between the eastern Pacific cold tongue and equatorial convection, schematically depicted in Fig. 2.2 (adapted from Raymond et al. 2004). Easterly and southeasterly trades contribute to equatorial upwelling and the eastern Pacific cold tongue. Additionally, there is an asymmetry in the SSTs between hemispheres (cooler water in the Southern Hemisphere (SH)) due to several factors: (1) the northwest-southeast orientation of the west coast of the Americas, leading to increased upwelling from the southeasterly trades in the SH; (2) strong winds and evaporative cooling in the southeasterly trades of the SH (Xie 1996); and (3) the reduction in solar radiation reaching the ocean surface in the SH due to more extensive stratocumulus decks (Philander et al. 1996). The equatorial cold tongue in turn stabilizes the marine boundary layer and modifies the southeasterly trade flow across it, decoupling the near-surface air from the low-level flow above and leading to a thin layer of light winds near the surface (Fig. 2.2, upper panel). High pressure over the cool water and higher SSTs to the north then accelerate the flow into ITCZ convection between 5 and 10°N (Wallace et al. 1989). Deep convection then feeds back to influence the large-scale circulation. Further complicating the situation, these phenomena and flow features vary on both seasonal and interannual (ENSO) time scales. Moreover, eastern Pacific convection itself varies over an extremely wide range of scales, from the diurnal cycle, to the several-day time scale of tropical easterly waves, to the weekly-to-monthly time scales of Kelvin waves and the MJO, and all the way up to seasonal, interannual, and ENSO time scales. The lower panel of Fig.2.2 shows the cloud field as determined by cloud radar in relation to the temperature structure in the upper ocean. Shallow clouds are seen south of the equator overlying the cool upper ocean, whereas deep convection is confined to the warm waters north of the equator. EPIC2001 observations reveal that the cold tongue is bounded by a frontal zone with exceedingly sharp temperature and salinity gradients, which represents a challenge for its proper representation in ocean models.

State-of-the-art global ocean-atmosphere models continue to suffer large biases in simulating tropical Pacific climate (Mechoso et al. 1995; Wang et al. 2005; Wittenburg et al. 2006; Large and Danabasoglu 2006). The equatorial cold tongue tends to be too cold, extends too far to the west, and displays a spurious warming toward the South American coast. Coupled general circulation models (GCMs) produce large warm biases of 3-4 C in subtropical SST in the Eastern Pacific boundary current region off South America partly associated with deficient coverage of low clouds (Fig. 2.3). This is apparently related to inadequate simulation of the radiative and other planetary boundary layer processes in the subsidence region (Mechoso et al. 1995). Recent model studies have indicated that stratus clouds (radiative fluxes) are only part of the problem; AGCM surface wind stresses, latent and sensible heat flux, and freshwater flux have large biases and do not provide realistic forcing for the ocean their, and ocean processes (e.g., eddy transports, response to the energetic spectral peak in buoyancy flux at the diurnal period, creation of very stable density gradients at the base of the ocean mixed layer by northward transport of intermediate waters underneath) also play critical roles.

The reduced meridional asymmetry in SST is associated with a so-called double ITCZ syndrome: too much rainfall south of the equator as the southern ITCZ persists too long during the warm season often at the expense of the northern ITCZ. In some models, the eastern Pacific ITCZ moves back and forth across the equator following the seasonal migration of the sun with only a weak preference for the Northern Hemisphere. In these models with reduced equatorial asymmetry in the mean climate, equatorial SST may be dominated by a semi-annual cycle instead an annual one as in observations.

These tropical biases limit the skill of coupled GCMs in simulating and predicting El Niño and the Southern Oscillation (ENSO), which is known to be sensitive to the mean state and strongly interactive with the seasonal cycle (Wallace et al. 1998; Neelin et al. 1998). Related to the biases in the mean cold tongue, many coupled GCMs simulate an ENSO with SST anomalies extending too far into the western Pacific and trapped too tightly on the equator. The latest NCEP Climate Forecast System (CFS) coupled GCM succeeded in reducing biases in the simulation of the cold tongue and its seasonal cycle (Wang et al. 2005), which indeed led to significant improvements in seasonal forecast (Saha et al. 2006). However, warm SST biases in the subtropical Southeast (SE) Pacific and too-weak meridional asymmetry in SST and ITCZ remain a problem in the CFS.

2.1.2 Intra-Americas Seas

The Intra-Americas Sea (IAS) is a climatic nexus for North and South America as well as for the tropical Pacific and Atlantic Oceans. It plays an important role in the climates of the Americas, hosting the second largest body of very warm (≥ 28.5°C) water on Earth: the Western Hemisphere warm pool (WHWP), comprised of the eastern North Pacific (ENP) and the Atlantic warm pool (AWP), the latter including the Caribbean Sea, Gulf of Mexico, and the western tropical North Atlantic (TNA). This large tropical diabatic heating center drives strong planetary-scale circulations in boreal summer. It influences rainfall and circulation in the associated far-field subsidence regions and it has a large interannual variability in its size (Wang et al. 2006). Easterly waves propagate from the tropical Atlantic through the IAS, maturing into destructive tropical cyclones (TCs). The IAS is an important pathway and moisture source for water vapor transport by the low-level jets for warm-season rainfall in North, Central and South America (Fig. 2.4)

(Helfand and Schubert 1995; Ruiz-Barradas and Nigam 2005; Mestas-Nuñez et al. 2006). Substantial changes to these pathways can lead to pronounced regional climate anomalies. For example, a temporary acceleration of the Caribbean trade flow in July is associated with the contemporaneous occurrence of a mid-summer drought (MSD) over Central America that is of key interest for agriculture (Magaña et al. 1999). The 1993 flood in the central United States was associated with a major enhancement of the low level flow of moisture from the Gulf of Mexico (Mo et al. 1997). On interannual and longer time scales, even subtle but sustained changes in the moisture inflow to the U.S. Great Plains from the Gulf of Mexico can contribute to severe drought conditions (Schubert et al. 2004). A full understanding of the processes that control the hydrological cycle and convective heating in the IAS region and their intricate relationships is therefore of broad interest for the Americas.

Current global AGCMs (e.g., the NCAR CAM 3.1) reproduce features associated with the IALLJ and North Atlantic subtropical high (NASH), and (in some) the midsummer drought in Central America (Magaña et al. 1999), but they have difficulty in correctly simulating the distribution and variability of overall rainfall intensity in the IAS region, and greatly overestimate rainfall south of about 10°N-15°N. 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 (Chen et al. 1999). The excessive rainfall in the IAS reproduced by models leads to an over-energized Hadley circulation (Nogues-Paegle et al. 1998), thus extending the influence of the rainfall error far afield. Nor do all AGCMs correctly reproduce the occurrence of the MSD during summer (Kiehl et al. 1998). The largest uncertainties in the moisture budget over the southeastern U.S. in current global reanalyses are related to their uncertainties in the representations of moisture flux by the low-level jets in the IAS region (Mo and Higgins 1996). Over the central and eastern United States, models do poorly in simulating the mean summer rainfall, reflecting deficiencies in the diurnal cycle, including the misrepresentation of cloud behavior and an overemphasis of local re-evaporation over the observed dominance of large scale controls such as the moisture convergence from the IAS, while also failing to reproduce the observed interannual changes in summer rainfall (Ruiz-Barradas and Nigam 2005). This suggests that our climate models must properly represent convective and boundary-layer processes over both ocean and land and reproduce both local climate processes and global climate modal variability, if they are to do well in the IAS region (An hypothesis to be tested? Same could be said for Asian monsoon region.). The IAS is, therefore, an ideal natural laboratory to test the overall fidelity of climate models.

2.2 Air-Sea Science Objectives and Priorities

In order to achieve the overarching goal of CPPA to improve seasonal-to-interannual forecasts over the Americas, we must identify and understand the physical processes that produce the relevant ocean variability and those that link the ocean variability to regional climate variability. We must, in particular, ensure that the our coupled climate models correctly capture the physical processes and phenomena that are critical for simulating these linkages including the basic structure and seasonal cycle of the ITCZ, Hadley Cell, Walker circulations, tropical/extratropical interactions, land-atmosphere interactions, monsoons, surface wind structure, clouds, oceanic warm pools, equatorial cold tongue, and upwelling. While minimizing model bias is a critical step, achieving reliable estimates of predictability and improved forecasts will also require that our new models realistically simulate the full spectrum of observed transient variability including the diurnal cycle, weather (including extreme events), low level jets, the MJO, mid-summer drought, oceanic eddies, Kelvin Waves, El Niño, as well as longer-term ocean-atmosphere variability.

Much has been learned about the dynamics of eastern Pacific ocean-atmosphere interaction but large uncertainties remain in a number of important physical processes and their parameterization in GCMs. CPPA aims to address the following scientific EPac issues.

Low cloud. Inadequate representation of low clouds in the SE Pacific appears to be an important source of tropical biases. These clouds display large spatio-temporal variations, changing from solid stratus off South America to much-reduced cloudiness, e.g., trade cumulus, toward the west. Leading AGCMs (including the GFS) simulate this climatological transition when SSTs are specified, but do not always correctly place the cloud regimes and tend to have an excessively shallow boundary layer (Bretherton et al. 2004). This generates sizeable surface flux errors compared to buoy and satellite observations. EPIC-2001 observations hint that drizzle and aerosol play a climatologically significant role in the cloud cover and albedo in this region (Bretherton et al 2004, Stevens et al. 2005 BAMS). Eastern equatorial Pacific low cloud variations during ENSO are also not reliably simulated. Some key scientific questions include: (1) What are the role of the space-time variability of both anthropogenic and natural aerosol in affecting stratocumulus drizzle processes and cloud structure, (2) What other processes are important for this cloud deck on diurnal to seasonal timescales, such as subsidence, cold advection and wave perturbations excited over South America and from the midlatitudes, and how does this cloud interact with convection over South America and the ITCZ?, (3) Are current turbulence and shallow cumulus parameterizations adequate to simulate the surface energy budget of the SE Pacific and its interaction with SST in coupled models?

[Following is the original text and some comments-CB]What causes this cloud regime transition [we basically understand this as associated with the natural evolution of the cloud structure as the boundary layer deepens in response to a reduced lower tropospheric stability, defined as the difference of free-tropospheric potential temperature and SST (Klein and Hartmann 1993; Wyant et al. 1997)], and what are the effects of SST variations? What roles do drizzle and aerosol play in cloud variations, which EPIC observations suggest is significant (Bretherton et al. 2004)?

Coastal upwelling. The southeasterly wind jet and the strong coastal upwelling (virtually to the equator) trigger the development of the meridional asymmetry of the Pacific climate. Farther offshore and east of 120°W, the southeast trades blow at large angles to SST isotherms, making surface Ekman advection less effective in spreading the cooling from the coast westward into the interior SE Pacific. Then what are the mechanisms for spreading the cooling? What role do ocean mesoscale eddies play, relative to the ocean's interaction with low cloud and other components of surface heat flux? Another issue with coastal upwelling is, how does it interact with the stratus deck nearshore, and how does this change when warmer water upwells during El Niño events? The coastal winds actually increase due to dissipation of stratus over land and nearshore combined with offshore SST anomalies. Is the SEPac subtropical high (and by extension the larger stratus region offshore) also changed by these interactions? Can the models replicate the observed behaviors?

The Southeastern Pacific boundary current regime. Outside the rather narrow region of coastal upwelling off the west coast of South America is a broad region of relatively slow Eastern boundary currents flowing to the northwest. The persistent stratus clouds span the region of coastal upwelling and extend out over the eastern boundary current regime, with the location of the annual maximum of the stratus clouds is some 500 to 800 km offshore. The oceanic boundary layer under the stratus in this region poses challenges in terms of understanding what controls its structure and thus SST. The surface fluxes add heat and remove freshwater. Mean advection rates in the upper ocean are low, a few cm/sec, and the residence time of this layer under the stratus is log. What keeps this layer cool? The prevailing southeast trades drive surface flow to the southwest, but over much of this offshore region the surface isotherms are parallel to the transport, and little cooling can be attributed to the coastal upwelling. There is removal of freshwater by evaporation in the strongly evaporative regime found offshore, What keeps the layer's salinity from climbing? The surface layer is warm, bounded on the bottom by cool, fresh Antarctic Intermediate Water (AAIW) moving to the northwest. The tradewinds are persistent in directrion but their magnitude fluctuates and these winds generate near-inertial oscillations in the surface layer. How much mixing (and thus cooling and freshening) is associated with these oscillations? NWP models do not replicate the variability in wind speed that leads to the generation of these near inertial oscillations; are NWP winds inadequate to be used to force a model ocean here? There is also a strong ocean response to the energetic diurnal spectral peak in surface buoyancy flux. To what extent does the non-linearity of the ocean surface layer rectify diurnal and near-inertial variability and lead to trends in the evolution of SST? Offshore advection of coastal water by westward propagating eddies is likely also to be a source of cooling, freshening,a nd nutrients. What role does eddy transport play in maintaining SST in this offshore region? To what extent do remote influences on the local surface winds or on the eddy generation and propagation modulate the SST under the stratus?

Equatorial upwelling and mixing. The surface current divergence, shoaling thermocline and strong vertical mixing are what maintains the equatorial cold tongue. What is the three-dimensional structure of the near-equatorial meridional circulation cells and how does it vary with winds? What determines the depth of penetration of wind-input momentum and what causes it to vary? How are surface heat fluxes transmitted into the upper thermocline and how is the thermal structure maintained in the presence of very strong upwelling?

Process interaction across scales. Meso- to synoptic-scale disturbances may contribute to basin-scale climate in important ways. Relatively well sampled, investigations of these phenomena can yield insights into important physical processes. What are the processes that allow and control exchanges across the sharp SST front north of the cold tongue? What role do ocean eddies, some excited by gap winds off Central America, play in the mixed layer heat budget in the eastern Pacific warm pool/band? What are the rectification effects of easterly waves on the warm pool and ITCZ? What causes pockets of open cells to form within the stratocumulus deck in the SE Pacific and how do they contribute to larger-scale variations in cloudiness and surface solar radiation?

Warm pool development. The large interannual anomalies in summer warm pool characteristics are related to winter forcing by climate modes such as ENSO and the NAO (Enfield et al. 2006). Ocean models are presently challenged by large uncertainties in the surface fluxes, by the complexity of the land-ocean-atmosphere interactions in the IAS region, and by the need to resolve important mesoscale processes such as current jets, coastal upwelling and eddy motions. To improve the predictability of summer rainfall, the MSD, and other climate features requires that the representation of the WHWP and its ocean-atmosphere interactions be improved in models.

Caribbean convection. We don't understand why Caribbean rainfall (away from orographic forcings) is less than in other tropical regions with equivalent warm sea surfaces. AGCMs utterly overestimate rainfall here (Biasutti et al 2006). There are two plausible reasons for this failure. One is that AGCMs cannot reproduce the distribution of convection related to land-sea contrast and topographic effects, and the resulting circulations (subsidence over the Caribbean Sea). The other is that parameterized convection in AGCMs is insufficiently sensitive to mid-tropospheric humidity (e. g. Derbyshire et al. 2004, QJRMS) and cannot be adequately suppressed in models by dry air in the lower-to-mid troposphere usually seen over the IAS. Understanding this process and correctly simulating it is of highest priority.

Mid-summer drought. Some AGCMs have simulated the MSD and mechanisms for it have been proposed (Magaña et al. 1999; Mapes et al. 2005) (Small et al. 2006). The Small et al. study showed that local SST is of secondary effect while changes in convection outside the MSD region are important via atmospheric wave adjustment. What are the relative contributions of the NASH, ITCZ, SST, IALLJ, land effects, and related local atmospheric circulations for the MSD and its interannual variability? While these mechanisms may all be at work, it is unclear which one(s) is (are) mainly responsible for the interannual variability of the MSD. The capability of coarse resolution AGCMs and high-resolution regional models to simulate and predict the MSD needs to be assessed against observations. *[I have made no change here. I believe that the research done to date on the MSD shows that it does not involve the factors cited for the Caribbean precip problem, except indirectly (the IALLJ).]*

Dynamics of low-level jets. The IALLJ (comprised of the Caribbean low-level jet and its northward branch in the Gulf of Mexico) plays a vital role in providing moisture to the surrounding land regions. How well AGCMs can reproduce the IALLJ and its moisture transport needs to be systematically documented. For prediction, it is essential to understand and reproduce in models the relationships between IALLJ strength and large-scale circulation factors such as ENSO, the NAO, Amazon convection, and the North Atlantic subtropical high (NASH), as well as surface forcing by large or small sizes of the AWP. The problem is that the structure and dynamics of the IALLJ remain unknown from observational point of view. Before the global reanalyses can be used to validate AGCM simulations, their depictions of the IALLJ have first to be corroborated by observations. There is, however, no aerological sounding history in the Caribbean core of the IALLJ. Observations of the IALLJ and its controlling factors are needed to advance our understanding and the capability to model the IALLJ and rainfall vitally depends on it.

Land-air-sea interaction. What are the roles of orography, coastal geometry, land-surface forcing, and land-ocean effects (runoff, upwelling) in modifying rainfall over the land and adjacent ocean, and how can the GCMs be made to properly reproduce them? Known AGCM problems include the coarse horizontal resolution of terrain, boundary layer parameterizations, cloud physics, diurnal cycle, and the re-evaporation of soil moisture. The diurnal cycle of convection in coastal environments represents a good example of an important land-air-sea interaction problem since so much of the precipitation in the Americas that is diurnally modulated occurs there (Garreaud and Wallace 1997).

Tropical cyclones. The primary factors affecting Atlantic TC frequency are ENSO and the AWP size, the former interannually and the latter both interannually and on the longer time scales of the Atlantic Multidecadal Oscillation (AMO) and anthropogenic forcing. With ENSO the mechanism appears to be upper level wind anomalies propagated eastward from west-central Pacific heating anomalies that alter the wind shear over the main development region (MDR) for TCs, usually during the boreal summer of ENSO onset years. With large warm pools, favorable surface heating extends farther eastward into the MDR where tropical depressions develop and mature, but also the tropospheric wind shear decreases due to wind changes at both high and low levels. Both factors favor the more frequent development of strong storms, but we don’t know the relative importance of these mechanisms or how they interact. We need to understand, and models need to emulate, the way in which the vertical shear and AWP size are linked. To accomplish this, the challenge is for models to simulate and capture the large scale forcing modes while simultaneously resolving and realistically simulating the TCs.

2.3 Air-Sea Implementation Strategies

Future forecasts on seasonal time scales will depend on successfully coupling a well-performing AGCM to an appropriate ocean model. The problem of predicting drought is a telling example of what we need to achieve. Recent studies employing long simulations with atmospheric general circulation models (AGCMs) forced with observed

SSTs (e.g., Schubert et al. 2004) (Hoerling and Kumar 2003) suggest that even subtle but sustained changes in the tropical SSTs can play an important role in forcing precipitation changes in the middle latitudes and particularly in the U.S. Great Plains and in the Southwest. There is evidence that the connections to ocean forcing can differ by region and season with, for example, the tropical Pacific SST (and perhaps the Indian Ocean) driving changes in the planetary scale waves and storm tracks during the cold season, while the impact of the Atlantic SSTs is primarily on the warm season low level circulation (e.g., trade winds, oceanic anticyclones, low level jets). The time scales involved range from intraseasonal to interannual (with ENSO playing an important role), or involve longer time scales where the SST anomalies are weaker yet through persistence and feedbacks with the land can lead to devastating long term drought conditions (e.g., Fig. 2 from Schubert et al. 2004) Despite the considerable progress that has been made in this area we are a long way from making reliable drought predictions. There is, even in the uncoupled framework, considerable uncertainty (model differences) in the response to SST forcing in the different basins that suggests very different estimates of the potential predictability of drought. Of course, true estimates of the predictability of drought will require fully coupled models that simulate realistic ocean variability and the associated teleconnections to regional climate.

2.3.1 IAS

The North American Monsoon Experiment (NAME), which took place in 2004-2005, is primarily concerned with the convective processes that link the ENP warm pool and ITCZ to the annual spring-summer migration of the monsoon rains from Central America northward along the western slopes of the Sierra Madre Oriental in northwestern Mexico, to the southern Rocky Mountains of the southwestern U.S. The IASCLIP program, as yet undeveloped, is the concept for a broader eastward extension of research into the AWP domain, to understand, simulate and predict, through data diagnostics, models and field campaigns, the seasonal and interannual behaviors of rainfall from the Caribbean to the central U.S. east of the Rockies, with emphasis on the transitions from boreal spring to summer and autumn. This involves the interplay of multiple factors, most of which covary with the size of the AWP: (1) the moisture budget above the AWP together with the variation of the Intra-Americas low-level jet (IALLJ) that transports moisture into and out of the region (Mestas-Nuñez et al. 2005; Mestas-Nuñez et al. 2006); (2) changes in the strength and latitude of the Intertropical Convergence Zone (ITCZ) in the Atlantic and eastern Pacific, and its embedded tropical waves; (3) the North Atlantic subtropical high (NASH) with its seasonal extension into the Caribbean and its interannual interaction with remote forcing by ENSO (Enfield et al. 2006), the North Atlantic Oscillation (NAO) (Czaja and Frankignoul 2002) and the Tropical Atlantic variability (TAV) (Chang et al. 1997); (4) Atlantic TCs whose number vary annually in response to ENSO (Gray 1984) and the AWP size (Wang et al. 2006); and (5) land-air-sea interactions, including the effects of topography (Magaña et al. 1999), land-ocean temperature differential, and soil moisture (Delworth and Manabe 1989) in modifying rainfall.

Because IAS research is in its infancy, the implementation should start with diagnostic and modeling studies designed to identify critical processes and to quantify the errors and biases of models in simulating and predicting rainfall in the region. These studies should be followed by numerical experiments to identify processes whose misrepresentations are responsible for the model errors and biases and to identify observations needed to improve our understanding of these processes and their representations in models. After that, a field campaign and/or long-term monitoring program can be designed to collect needed observations.

Phase I (2006 – 2009): Diagnostic and Modeling studies – Many issues 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 North American Regional Reanalysis (NARR) – based on the NCEP Eta model -- includes the IAS except for the southeastern corner of the IAS domain (Fig. 2.5). The obvious limitations of this product to the IAS studies are its undesirable boundary effect over the Caribbean and its lack of coverage over the southern part of the IAS region. A revised product can be made by extending the coverage of the NARR with its current boundaries moved farther south.

- Document common model deficiencies in simulating the key climate features (e.g., IALLJ, MSD, NASH, ITCZ) of the IAS region and identify critical elements in the models that are responsible for such deficiencies. Of known high priority are the model biases in precipitation and convection over the Caribbean.

- Document discrepancies in global reanalyses in the IAS region and identify possible sources for them. This can be done initially by comparing the reanalyses to conventional observations that already exist, such as sounding and raingauge data.

- Use existing observations and models to better understand the climate controls for summer moisture fluxes from the Caribbean into the U.S. Identify the critical processes for which field observations are needed to achieve a comprehensive understanding.

- Identify the in situ observations from the IAS region that are the most urgently needed for model validations and improvement of reanalyses.

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. Some of the needed observations are already evident.

- Our confidence in 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 suffer 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.

- One high priority for an IAS field campaign would be to take sounding observations in the core of the CALLJ from ship(s) and/or aircraft and from islands of the Lesser Antilles, and to increase the sounding frequencies at sites in the Yucatan, San Andres Island, and Corpus Christi to measure the structure and diurnal cycle of the IALLJ and its water vapor transport.

- It is desirable to obtain and analyze a comprehensive in situ observational data set that provides a full description of processes key to the MSD, such as its relation to the CALLJ and warm pool characteristics. Based on our current understanding, 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.

- 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 atmosphere and ocean. In coordination with NOAA hurricane research that usually focuses on the storms, additional measurements from land, ship and aircraft over the IAS would augment our ability 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

2.3.2 ITCZ, cold tongue and stratus deck

Diagnostic and modeling studies as well as field observations are necessary to advance research on air-sea interaction, and its roles in maintaining eastern Pacific climate and generating local and remote intraseasonal to interannual variability.

a. Diagnostic studies

The analysis and synthesis of existing data provide a better description of phenomena, new insights, and benchmarks for models to simulate. They also help form hypotheses to guide field observations and modeling studies. A non-exhaustive description of datasets useful for CPPA air-sea interaction studies follows.

Atmospheric reanalyses (from NCEP and ECMWF) These resources offer valuable information on large-scale structures of the atmosphere. Combined with satellite data, they are valuable for studying diurnal to interannual variations. They also provide forcing for single-column and regional models. Similarly, ocean reanalyses support studies of large-scale variability of the ocean.

Satellite data Microwave radiometers (TRMM Microwave Imager or TMI, SSM/I and AMSR) observe SST without cloud interference, surface wind speed, cloud water and liquid water paths, and precipitation over the ocean. TRMM also has a precipitation radar providing rainfall measurements over both the ocean and land. Geostationary and polar orbiting satellites provide observations of cloudiness, cloud top temperature and other microphysical properties of clouds. CloudSat and CALIPSO will provide the first quantitative estimate of large-scale distribution of drizzle in the SE Pacific stratocumulus region and unprecedented information on the vertical distribution of aerosol and cloud throughout the CPPA study area. QuikSCAT measures vector wind over the ocean surface. Satellite altimeters will be used to study ocean currents and eddies. Ocean color sensors on SeaWiFS and MODIS will be used to examine physical-biological interaction in upwelling zones.

Buoy data The Tropical Ocean-Atmosphere (TAO) array provides a long (>10 years) record of subsurface temperature (with currents and/or salinity at some sites), and surface meteorological observations over the equatorial Pacific from 8°S to 8°N. Under the stratus cloud deck at 85°W, 20°S, WHOI maintains a buoy since October 2000, collecting oceanographic (temperature, salinity and current) and surface meteorological data.

Atmospheric and oceanic soundings On cruises that service TAO and WHOI buoys, atmospheric sounding and oceanographic observations are conducted. The CTD and APDC data enable the construction of a climatology of equatorial band temperature, salinity and currents while atmospheric soundings (both by balloon and radar) shed light on the vertical structures of the atmospheric boundary layer and clouds.

b. Field studies

Field observations are necessary to fill critical gaps in understanding and parameterizing important physical processes. The **V**AMOS **O**cean-**C**loud-**A**tmosphere-**L**and **S**tudy (VOCALS) is part of the CLIVAR VAMOS (Variability of the American Monsoon Study) program. VOCALS aims at better understanding and modeling SE Pacific aerosol-cloud-drizzle feedbacks, the air-sea fluxes under the stratus clouds, the dynamics of the ocean surface layer in the eastern boundary current region off South America, including diurnal and near-inertial ocean response to surface forcing and the role of ocean eddies in moving cold water offshore, and the interaction of low cloud, SST, and the rugged terrain of western South America (http://www.joss.ucar.edu/vocals/). VOCALS plans to use aircraft and ships to sample boundary layer clouds, aerosol, and ocean eddies in the SE Pacific between the coastal zone and 1500 km offshore in October 2008.

The Pacific Upwelling and Mixing Physics (PUMP) experiment is a process study designed to improve our understanding of the complex of mechanisms connecting the thermocline to the surface in the equatorial Pacific cold tongue (http://www.pmel.noaa.gov/~kessler/clivar/pump.html). Its goal is to observe and understand the interaction of upwelling and mixing with each other and with the larger-scale equatorial current systems. PUMP's field component includes high-resolution moorings in the equatorial cold tongue and ship observations to quantify the upwelling and vertical mixing.

c. Modeling

Global coupled ocean-atmosphere models are valuable tools for seasonal climate prediction and projection of future climate. Reducing their biases in the tropical Pacific is an important objective of CPPA's air-sea interaction component. A hierarchy of models will be used.

SST is often used to evaluate the performance of coupled GCMs. More stringent tests are necessary to identify sources of model biases, including the examination of the vertical structure of currents and temperature in the ocean. Also important is an evaluation of individual components of surface heat flux and in particular, the balance between solar radiation and latent heat flux against observations. Vertical structures of the atmospheric boundary layer and clouds are another area that needs closer scrutiny, which offer more information about how low clouds are maintained in the model than simple cloudiness. In particular, global atmospheric GCMs and regional models often have difficulty handling transitions from the stratocumulus to cumulus regime (e.g., McCaa and Bretherton 2004; Wang et al. 2004). The interaction of low cloud with the ocean, both local and remote, also needs further studies.

The improved understanding from the diagnostic, field and modeling studies will lead to improved parameterizations of important subgrid processes and phenomena such as low cloud and vertical mixing in the equatorial upwelling. Single column models and large eddy simulations will be used to develop and test such parameterizations, forced and constrained by field observations.   In addition, detailed field observations can be compared with model output at the same location and time from short-range regional or global forecasts with systems such as the GFS/CFS. The GFDL and NCAR AGCMs also now can be run in such a forecast mode starting from a global reanalysis.

Regional models, forced on the sides by ocean/atmospheric (re)analysis, can capture the phases of weather disturbances in the atmosphere, as well as ocean equatorial waves and Tropical Instability Waves. They provide three-dimensional output in continuous time series that can be compared directly with field observations. This capability of a direct comparison with observations makes them an ideal testbed for parameterizations. Affording higher resolution than global models, regional models will also be used to study air-sea interaction in high gradient regions such as the equatorial/coastal upwelling zone and ITCZ.

2.3.3 Deliverables

- Produce a revised North American Regional Reanalysis (NARR);
- Produce an integrated dataset for each CPPA field program that can be used as a toolbox for model and parameterization development and assessment;
- Assessment of model deficiencies and observational requirements for IAS climate processes;
- Comprehensive in situ observational data sets for IAS region (2010-2011);
- Improved understanding of ITCZ, cold tongue, stratocumulus layer dynamics and coupling;

- Improvements to cumulus and cloud-topped boundary layer parameterizations

- Improved understanding of the Caribbean mid-summer drought (MSD);

- Predictive understanding and modeling of IAS-related summer rainfall in the U.S.;
- Identification of regional deficiencies (and causes) in global NWP reanalyses, GCMs, and satellite products;
- Measurably improved climate models that have significant summer predictability when initialized with data from the previous fall-winter;

- Measurable improvements in model simulations of eastern tropical Pacific and IAS climate and prediction of El Nino/Southern Oscillation and its influence on the Americas;

- A synthesis report to summarizing what has been from past CPPA Air-Sea Interaction projects;

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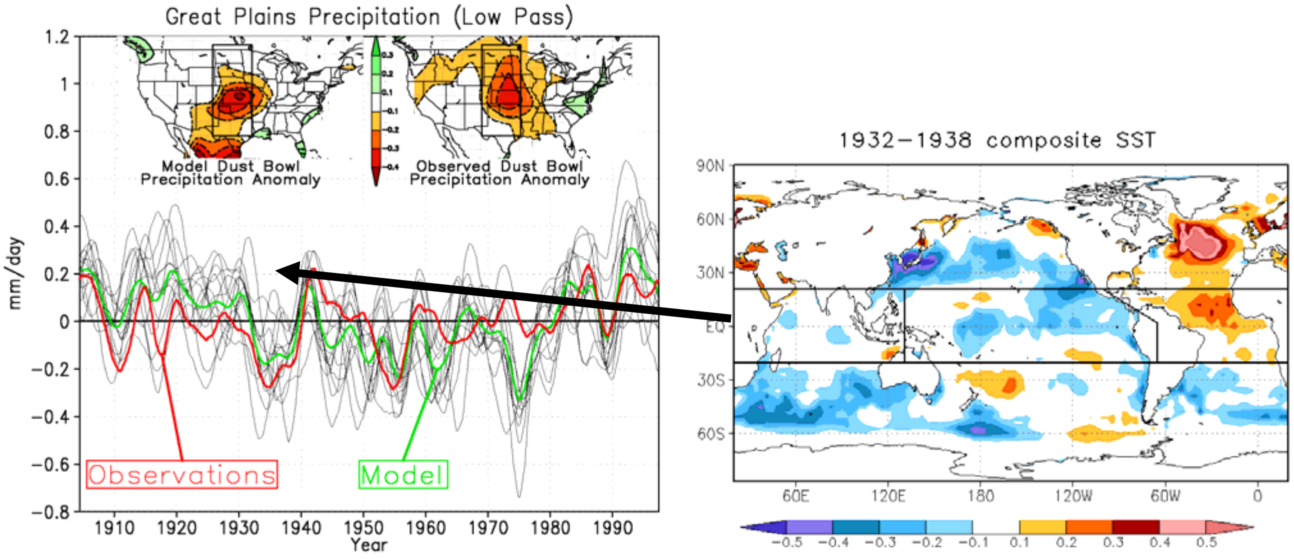


Figure 2.1. Left panel: Time series of precipitation anomalies averaged over the United States Great Plains region (30°-50°N, 95°-105°W, see box in insets). A filter is applied to remove time scales shorter than about 6 years. The thin black curves are the fourteen ensemble members of the AGCM runs forced with observed SSTs. The green solid curve is the ensemble mean. The red curve shows the observations. The maps show the simulated (left) and observed (right) precipitation anomalies averaged over the "Dust Bowl" period (1932-38). Units: mm/day. Right panel: The SST anomalies averaged over the Dust Bowl period (°C). From Schubert et al. 2004.

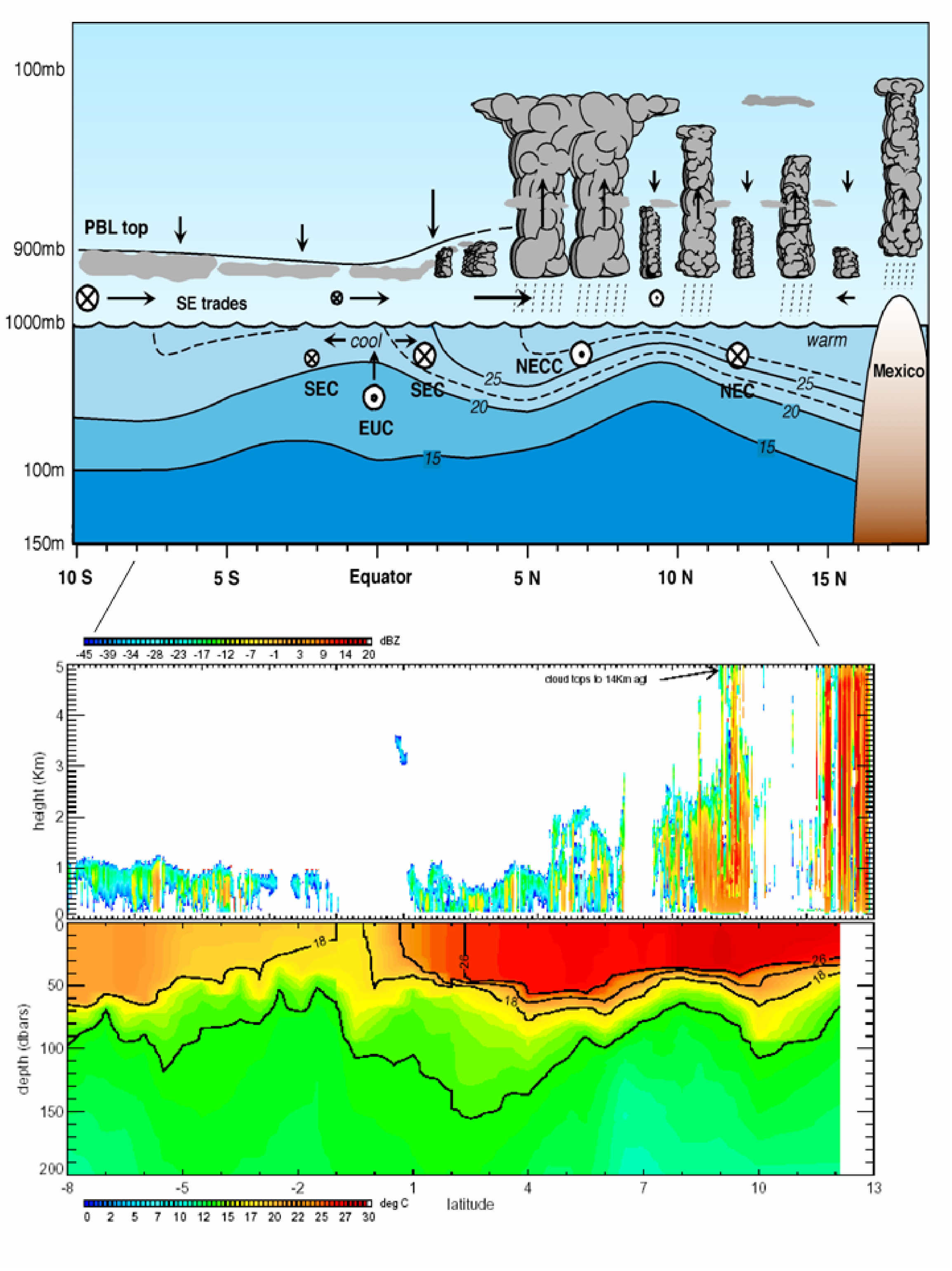


Figure 2.2. (upper) Idealized cross section through the ITCZ-cold tongue complex in the east Pacific showing the atmospheric meridional circulation, atmospheric boundary layer depth, and oceanic thermal structure. SEC refers to South Equatorial Current, NECC to the North Equatorial Countercurrent, and EUC to the Equatorial Undercurrent. The heavy cloud denotes the position of the ITCZ. Encircled x's (dots) denote westward (eastward) flowing winds or currents. (lower) North-south section of radar reflectivity field from cloud radar and upper-ocean temperature during EPIC2001.

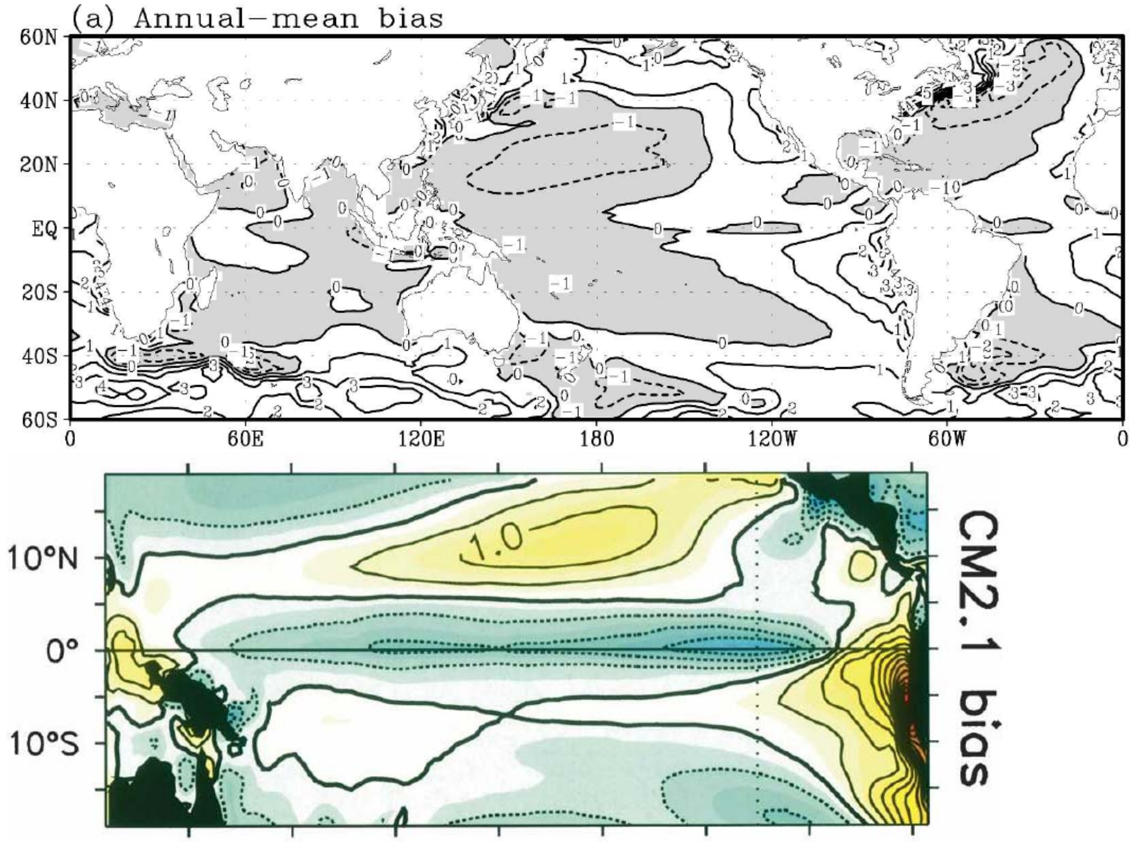


Figure 2.3. Annual-mean SST biases (°C) of the coupled simulations by the CFS (upper; Wang et al. 2005) and GFDL coupled GCM (lower; Wittenberg et al. 2006).

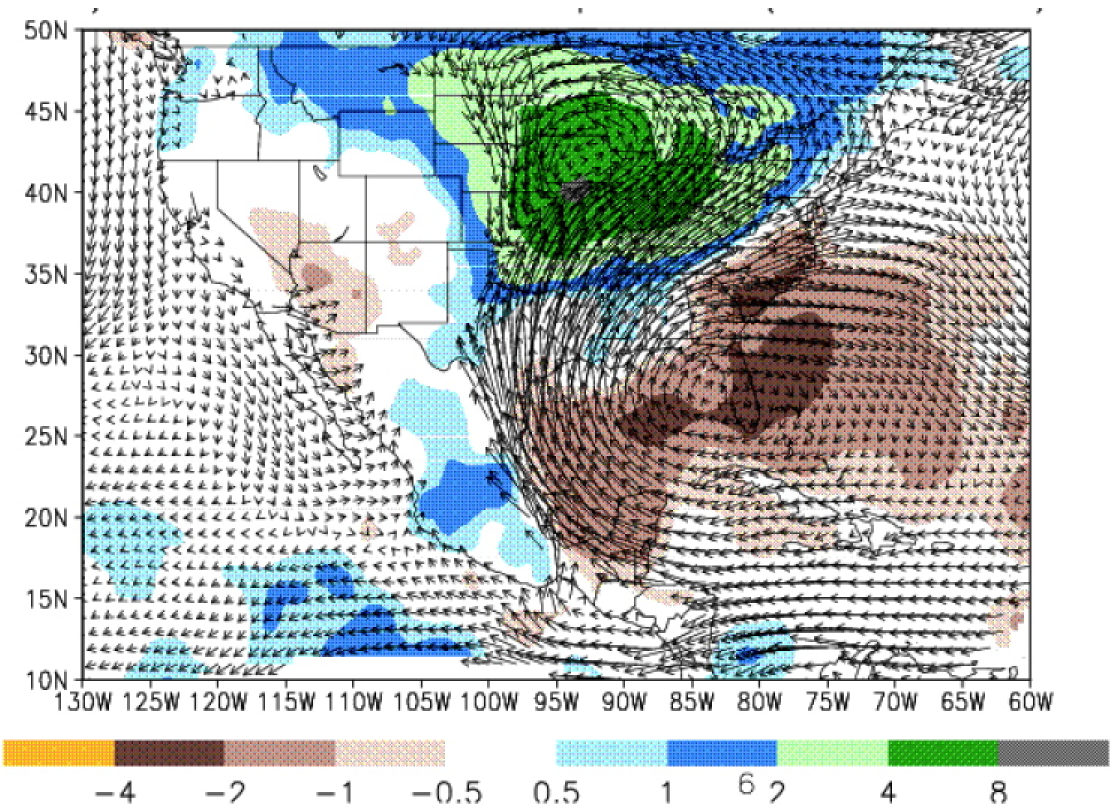


Figure 2.4 – Composite-averaged precipitation (colored, mm/day) and 925 hPa wind anomalies (m s^{-1}), for the positive phases of an index of the Caribbean low-level jet (CLLJ), based on the North American Regional Reanalysis (NARR) (provided by K. Mo).

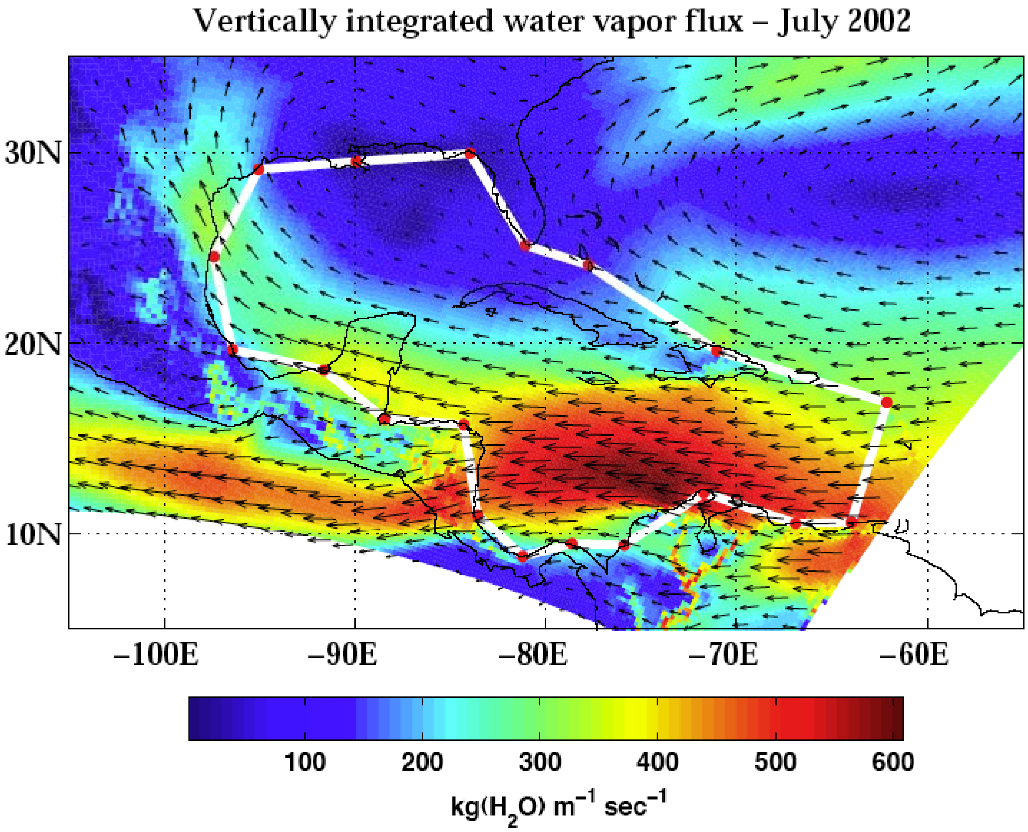
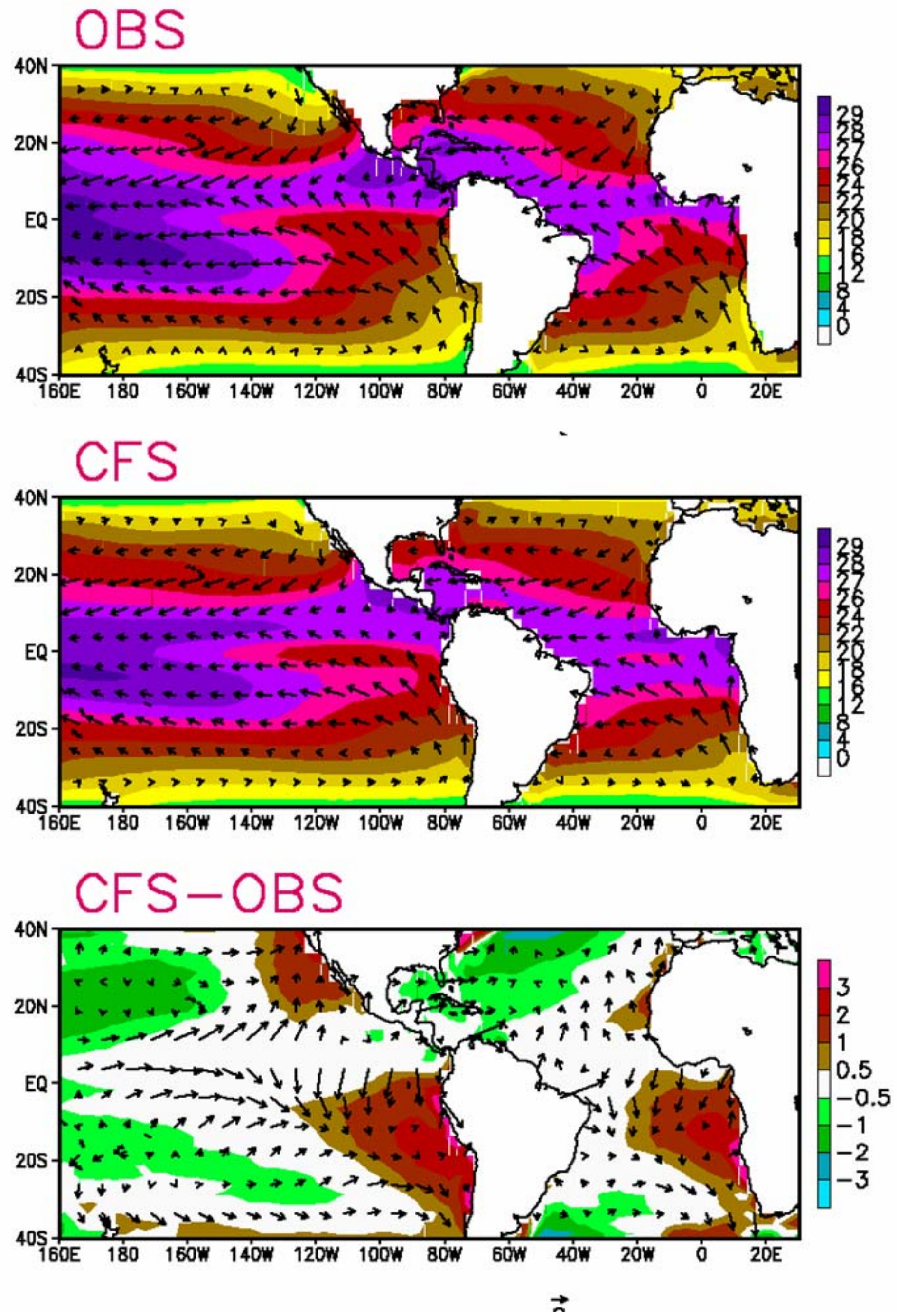


Figure 2.5. Vertically integrated water vapor flux for July 2002 used to illustrate the coverage of the IAS by the current NCEP Eta North American regional reanalysis. Stars mark the locations near the IAS coast at which sounding observations are available.


OBS
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EQ
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