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Climate Prediction Program for the Americas (CPPA): Science Plan and Implementation Strategies

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With Contributions from the CPPA Core Project Leads

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1. OVERVIEW OF THE CLIMATE PREDICTION PROGRAM FOR THE AMERICAS (CPPA)

1.1 What is CPPA?

The Climate Prediction Program for the Americas (CPPA) is an integrated competitive research program to improve operational intraseasonal to interannual climate and hydrologic predictions and their applications within the NOAA Climate Program. To support this mission, CPPA has four scientific objectives:

1) To improve the predictive understanding and numerical simulation of oceanic, atmospheric and land-surface processes, including the ability to quantify uncertainties;
2) To quantify the sources and limits of predictability of climate variations on intra-seasonal to interannual (ISI) time scales, and the role of longer term climate change as it affects ISI predictability;
3) To advance the scientific basis for NOAA's operational climate forecasts, monitoring, and analysis systems; and
4) To develop climate-based hydrologic forecasting capabilities for decision support and water resource applications.

The CPPA program integrates NOAA's contributions to the former GEWEX Americas Prediction Project (GAPP) and CLIVAR Pan American Climate Studies (PACS), to bring together the PACS legacy in coupled ocean-atmospheric processes and large-scale modeling and the GAPP legacy in land-atmosphere interactions and regional modeling. This integration provides a more holistic approach to develop the scientific basis for improved climate and hydrologic predictions for decision support and water resources applications through improved understanding of the predictability of the coupled atmosphere, land, ocean system as a whole, and advanced modeling of land-ocean-atmosphere interactions.

1.2 Scientific Rationale

1.2.1 Background

Climate predictability, an inherent property of the climate system, exhibits significant variability at multiple space and time scales. At the intraseasonal to interannual time scale, atmosphere, land, ocean, and their interactions all play an important role in defining climate predictability. To advance the strategies and scientific approaches for skilful prediction, it is fundamentally important to understand how different processes play a role in providing or limiting climate predictability.

Through the legacy of PACS and GAPP, much has been learned about different sources of climate predictability, and progress has been made in improving climate prediction skill. In PACS, coupled atmosphere-ocean models were used to understand the limits of climate predictability that exploits the memory of ocean processes. The ENSO cycle is the principal source of seasonal-to-interannual (SI) predictability in the Pan American region, so understanding ocean-atmosphere coupling processes through observations and modeling in the eastern tropical Pacific was an important focus of PACS. Major weaknesses in global coupled atmosphere-ocean models that limit ENSO prediction skill have been identified and targeted for improvement, leading to the initiation of community-wide research that addresses the prominent tropical biases commonly found in global models. However ENSO provides predictability mainly for the cold season, so PACS also included major support for studies of the North and South American monsoon systems in the warm season, including the North American Monsoon Experiment (NAME) and the Monsoon Experiment in South America (MESA). These process studies combine observations, diagnostic analysis, and modeling to improve predictability of warm season precipitation.

As a complement to the PACS focus on atmosphere-ocean coupling, GAPP investigated the role of land memory provided by soil moisture, snow, and vegetation. GAPP supported some of the first studies to establish the role of land-atmosphere interactions on climate predictability in the North American region. This motivated improvements in land surface modeling and development of the North American Land Data Assimilation System (N-LDAS) to reduce errors in the stores of soil moisture and energy for more accurate atmospheric reanalysis and forecast. The program also had a strong focus on orographic processes, including cold season hydrometeorology and monsoon-related warm season precipitation in the western cordilleras. GAPP-supported research on convective processes in complex terrain was an important component of NAME.

Working in tandem, GAPP PIs and the NOAA Core Project teams (described in Chapter 5) accelerated the implementation of GAPP research within the operational framework of NOAA’s climatic and hydrologic forecast systems. GAPP-supported research demonstrated the feasibility of end-to-end seasonal hydrologic prediction and the use of probabilistic hydrologic forecasts in water resources decision-making.

1.2.2 Science objectives and components

Building upon the strengths and successes of PACS and GAPP, CPPA integrates their separate foci into a single program to develop a unified view of the atmosphere-land-ocean system, emphasizing the relative role of each component and their interactions on climate predictability in the Americas. The ultimate goals of CPPA are to better quantify the limits of climate predictability; to improve understanding and modeling of atmosphere, land, ocean processes and their feedbacks; and to improve operational climate and hydrologic forecasting to support decision-making. CPPA also expands the interest beyond the SI time scale of PACS and GAPP to include the intraseasonal time scale (two weeks to one month), which has important implications for probabilistic prediction of extreme events. The intraseasonal time scale has been the weakest link in providing temporally seamless prediction products for decision support and water resources applications.

The CPPA plan also recognizes that long-term climate change and SI prediction are now closely coupled problems. Many of the same processes that limit SI prediction skill, and therefore are targets of CPPA research, also limit confidence in our ability to assess the climatic response to increasing greenhouse gases. Conversely, we now recognize that the changing climatic basic state now presents a crucial limitation on SI predictability: the climate is now significantly different from the post-World War II period studied extensively by researchers to characterize SI variability. Therefore CPPA research is tightly linked to the longer time scale global climate change that is the focus of the US Climate Change Science Program.

The overall science components that support the science objectives are shown in Figure 1.1, which also outlines the organization of this Science Plan. The science components include quantifying the limits of climate predictability across the Americas, improve understanding and modeling of land-atmosphere and ocean-atmosphere interaction processes, improve NOAA's operational climate prediction, monitoring, and analysis system, and improve climate-based hydrologic forecasting and water resources applications. Each of these components is described in more detail in chapters 2 to 6 of this document.

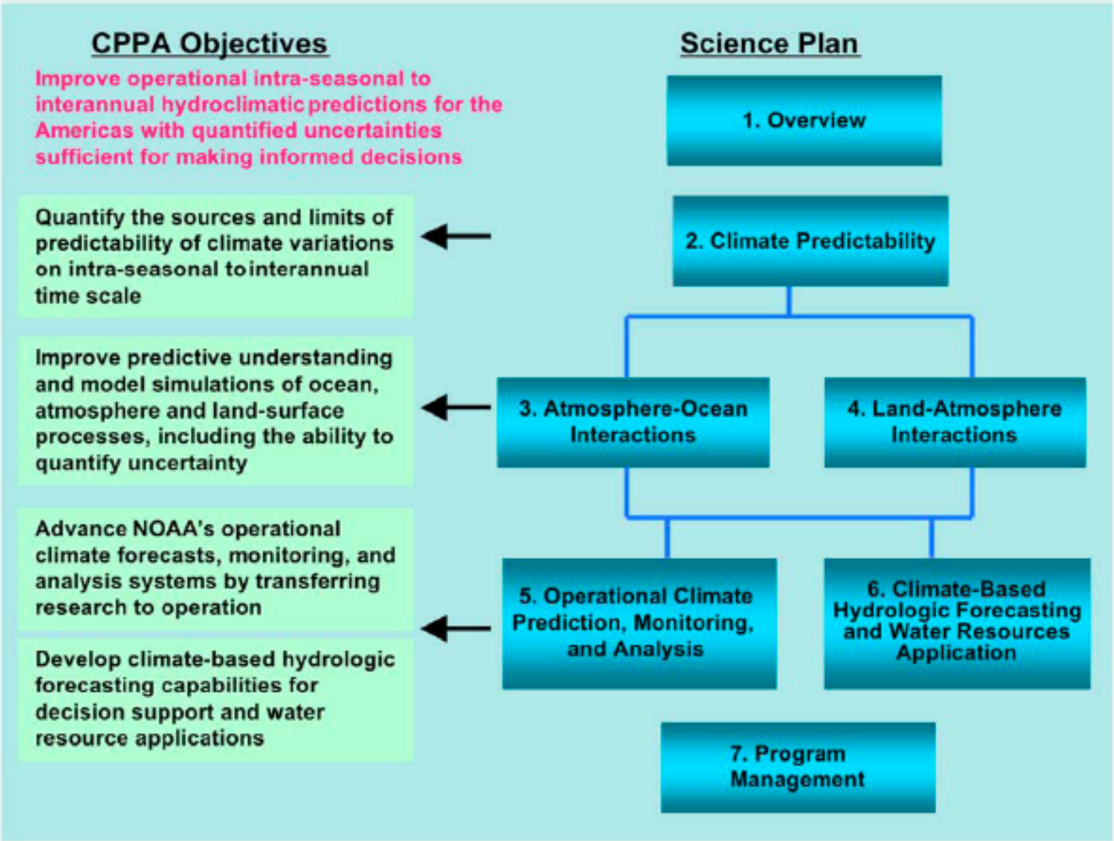


Figure 1.1 A summary of the CPPA science objectives and components and their linkages. The numbers in each box indicate chapters of this Science Plan.

1.2.3 Overarching science themes

Recognizing that ENSO and the American Monsoon Systems (AMS) are dominant sources of climate variability and predictability for cold season and warm season precipitation respectively in the Americas, CPPA will continue to support research initiated by PACS and GAPP to advance the understanding and prediction of the ENSO cycle and the North and South American monsoon systems. Besides ENSO and the monsoon systems, recent research has provided insights on other climate components and linkages that should be explored to enhance prediction skill over the Americas. One such component is the western Hemisphere warm pool or the Intra-Americas Sea (IAS), which forces a major diabatic heating center that drives planetary-scale circulations in boreal summer and provides predominant source of summer moisture for the U.S. CPPA will support research to quantify the predictability and improve the prediction of these large-scale climate systems.

- For ENSO, research will emphasize processes in the Eastern Pacific such as low clouds, coastal upwelling, the Southeast Pacific boundary current regime, and equatorial upwelling and mixing that are not well understood, as well as address predictability of the "non-canonical" aspects of ENSO that constitute a major source of error in current prediction models.
- For the North and South American monsoon, CPPA will support the continued implementation of NAME and MESA to accomplish the designed objectives and deliverables, to investigate mechanisms that link the oceanic climate variability to that over land in the Pan American region, and explore a unified approach in understanding the North and South American monsoon that constitute the two extremes of the annual cycle over the Americas, and possible linkages between the two systems.
- For the IAS, CPPA will support research that aims at understanding and modeling the warm pool development, convection in the Eastern Pacific and the Caribbean Sea, air-sea-land interaction processes, and the effects of these processes on climatological features such as the mid-summer drought, low-level jets onto the continents, and fluctuations in the numbers and tracks of tropical cyclones that are observed in that region.

To improve prediction skill that meets societal needs, predictability of large-scale systems such as ENSO, AMS, and IAS must be linked to predictable signals that manifest on regional scales with high societal impacts. CPPA has identified three regional-scale hydroclimatic components that are critical testbeds for demonstrating improvements in climate/hydrologic prediction skill:

- Both ENSO and the monsoon systems exert large influences on the hydroclimate of the western cordilleras. To provide climate prediction useful for decision support requires improved understanding and modeling of hydroclimatic processes over complex terrain. Following the pioneering research of GAPP, CPPA will continue to support hydroclimate predictions in the mountains, with a focus on addressing data gaps in the mountains, and building an integrated regional-scale climate system model for the mountain regions that will lead to improved long-range precipitation forecasts and better understanding of how the water and energy balance respond to environmental changes.

- Recent droughts in the western U.S. have exposed the vulnerability of the society and our lack of ability to monitor and predict droughts. CPPA will make significant contributions to advancing the techniques to monitor drought, and to improve the understanding of the role of the atmosphere, land, and ocean, and their coupling on the initiation, persistence and demise of droughts. These will advance the scientific basis for drought predictions needed by the National Integrated Drought Information System (NIDIS).
- Climate extremes are often devastating and costly to society. The western U.S. is prone to severe winter storms that lead to flooding and wind damages, and hurricanes can cause severe damages in the Southeast. CPPA will support research to understand and exploit the relationships between various modes of tropical variability and extreme events to improve their predictions at the ISI time scale. This priority also supports the GEWEX goal to advance the scientific understanding of extreme events. Examples of climate extremes that will be investigated by CPPA include the relationships between the Madden Julian Oscillation (MJO) and heavy precipitation in the West Coast, and linkages between MJO and Tropical Easterly Waves (TEW) on the development of tropical cyclones in the warm season.

In summary, CPPA has identified six key large-scale and regional-scale climate components that are highly relevant to climate and hydrologic prediction at the intraseasonal to interannual time scale, with significant implications for decision-making support and resource management for the Americas. They include:

- American monsoon systems
- ENSO-based predictability in the Americas
- Hydroclimatic prediction in mountainous regions
- The western hemispheric warm pool
- American droughts
- Modes of large-scale variability and the predictability of extreme events

These components constitute the overarching science themes and are schematically summarized in Figure 1.2 and discussed in Chapter 2. Advancement in understanding, modeling, and predicting these key climate components depends critically on progress in the science components, namely air-sea and land-atmosphere interactions (Chapter 3 and Chapter 4). Integrating research from these components will collectively advance climate and hydrologic predictions for the Americas and enable their use in decision-making and water resources management (Chapter 5 and Chapter 6).

1.3 Implementation Strategies

To make significant progress towards the CPPA science goals, research will be undertaken on observations, modeling, analysis, and integrating these approaches to address the science questions identified for each of the six overarching science themes shown in Figure 1.2. In addition, CPPA recognizes and supports the need for transition from research to operations, so synthesis projects will be supported to synthesize the scientific results and technological advances developed by PIs into strategies that can be implemented, and demonstration projects will be developed to apply operational and/or experimental climate and hydrologic forecasts to assess their value and explore better approaches to incorporate new science into operational forecasts.

While each science element may employ and emphasize a different mix of approaches detailed in the following chapters, an overview of the implementation strategies is outlined below.

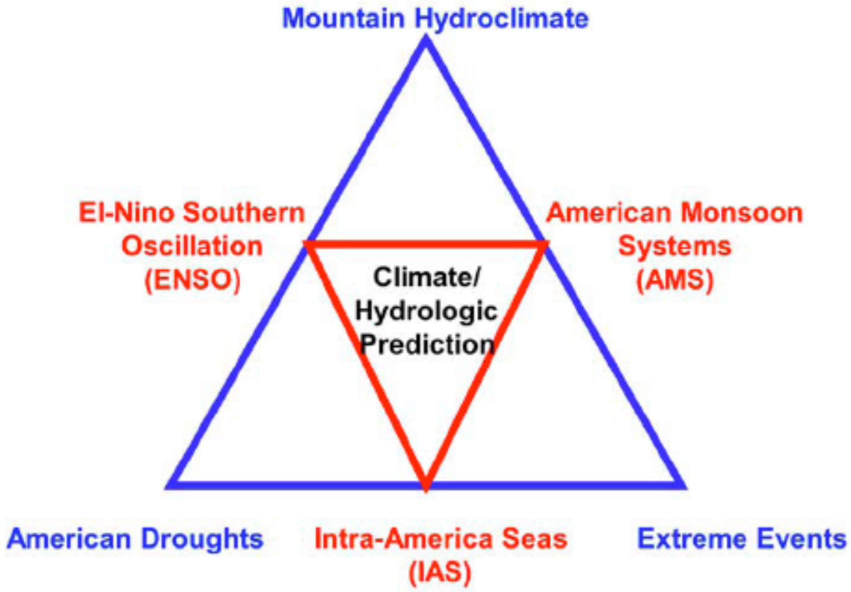


Figure 1.2 A schematic of the overarching science themes covered by CPPA. Shown in red are the three key large-scale climate systems (ENSO, AMS, and IAS) that significantly contribute to intraseasonal to interannual predictability in the Americas, and in blue are the three key regional climatic aspects (mountain hydroclimate, American droughts, and extreme events) that constitute important testbeds for demonstrating improved prediction skill to meet societal needs.

1.3.1 Observations and data development

CPPA will jointly support field projects with other funding agencies to obtain critical measurements needed to advance the scientific understanding of the six CPPA climate components in Figure 1.2. CPPA will support the development and maintenance of datasets including multi-platform measurements obtained from field projects, long-term observational datasets (e.g., streamflow data), model input and output data (e.g., outputs from model reforecasts and model intercomparison projects), model assimilated data products (e.g., atmospheric reanalysis and assimilated land data), and synthesis of multiple datasets to support analysis and modeling tasks. To address CPPA's mission, both large-scale and regional-scale (high resolution) datasets are important. Innovative and integrative use of multiple CPPA datasets will be emphasized.

1.3.2 Process analysis and modeling

CPPA will support analysis and modeling studies to improve understanding of key climate processes and quantify the relative roles of land, atmosphere, and ocean on the limits of climate predictability. To improve prediction skill, CPPA will support efforts to diagnose model errors, and develop and evaluate models. Relevant to CPPA's objectives are global and regional climate (or earth system) models, global and regional land and ocean models, hydrologic prediction models and analysis tools. CPPA also encourages coordinated numerical experiments and analyses such as intercomparison of model simulations and forecasts, and comparison of observation- and model-based estimates of land-atmosphere and ocean-atmosphere feedbacks (e.g., coupling strength), and projects that synthesize across analysis or modeling studies to develop or assess different strategies or approaches for improved models.

1.3.3 Transition to operations

To enable transition from research to operations, CPPA will support the following research or activities:

- Development of an infrastructure and strategy that allows individual PIs or groups to demonstrate the readiness of their approach in NOAA's operational climate forecast system.
- Research to improve models/techniques used in NOAA's operational climate forecast system, particularly to enhance accuracy and spatial specificity needed by users of the forecasts. Examples include improved dynamical downscaling models, land, and ocean models, and land data assimilation system to improve initialization of model forecasts.
- Integrated investigations such as intercomparison of hydrologic prediction models, and projects that demonstrate and assess end-to-end hydrologic forecasting techniques and assess the propagation of uncertainties through the system.
- Development of collaborative linkages between CPPA PIs and the National Weather Service (NWS) Office of Hydrologic Development (OHD) with the operational hydrologic forecasting community (e.g., NWS River Forecast Centers (RFCs)) and water resources applications (e.g., NOAA Regional Integrated Science and Assessment (RISA) Program).

1.4 Programmatic Context and Linkages

The NOAA climate program has been responsive to the increasing demands (especially at the local and regional level) for more focused products and a broader suite of climate information services. In particular, the NOAA climate program strategy recognizes that the demand for climate information requires a source of reliable, accessible, and relevant information. In order to build an effective climate service, which could provide the information demands for a broad array of users, the following elements are required:

- Understand the past and current state of the climate;
- Advance predictive understanding and skill about the future state of the climate;
- Develop climate information services.

Consistent with the elements required for the strategy above, the NOAA Climate Goal reorganized in 2007 from 5 programs (Climate Observation and Analysis; Climate Forcing; Climate Predictions and Projections; Climate and Ecosystems; and Regional Decision Support) to 3 programs (Climate Observation and Monitoring; Climate Research and Modeling; Climate Service Development). The CPPA program, formerly included in the "Climate Predictions and Projections" program, is now in the "Climate Research and Modeling" program of the restructured NOAA Climate Goal. The objectives of the "Climate Research and Modeling" Program are to provide: 1) climate forecasts for multiple time-scales to enable regional and national managers to better plan for the impacts of climate variability; and 2) climate assessments and projections to support policy decisions with objective and accurate climate change information. CPPA will contribute to the NOAA Climate Goal through its focus on regional impact of large-scale circulations over the Americas, its thrust on improving operational climate prediction on intra-seasonal to interannual time scales, its moisture budget emphasis, and its hydrologic applications.

NOAA recognizes that the framework for delivering climate services must:

- Produce and provide past, present and future climate information at regional to global scales with adequate skill, coverage and variables to respond to demands;
- Embody partnerships across national and local levels;
- Consolidate and integrate strong climate information interfaces for users within and external to NOAA;
- Integrate climate activities across the agency from an 'end-to-end' perspective; and
- Develop climate information services for applications in National Weather Service (NWS), National Marine Fisheries Service (NMFS), National Ocean Service (NOS), Arctic, and atmospheric composition.

Climate variability and change profoundly influence the health, prosperity, and well-being of the people of the United States as well as all other nations of the world, with vital global economic and security implications. In the United States this has led to substantial new demands for climate information and a compelling need for an improved capability to plan for and adapt to climate variability and change. To address this challenge the Nation requires a dedicated climate service to consolidate the efforts of the country's climate data, analysis, modeling, prediction and information enterprises. This service would ensure that advances in climate science (such as the contributions of the CPPA program) are effectively communicated to meet the rising tide of requirements for climate information.

NOAA stands ready to provide the coordination and leadership necessary for the development of a National Climate Service (NCS). NOAA's distinctive observational assets, monitoring, assessment and prediction capacity, service delivery capabilities, and interest in engaging the range of federal assets outside of NOAA, make it an ideal agency to begin establishing the NCS. Important parts of the infrastructure and institutional capabilities required for a NCS currently exist.

The CPPA program will contribute to a National Climate Service in many important ways by advancing NOAA's operational climate forecasts, monitoring, and analysis systems, and by developing climate-based hydrologic forecasting capabilities for decision support and water resource applications throughout the Americas.

1.4.1 Linkage to international programs

- The World Climate Research Programme (WCRP) aims to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine the extent to which climate can be predicted and the extent of human influence on climate. The WCRP encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface, which together constitute the Earth's physical climate system. WCRP provides the international framework for scientific cooperation in the study of global change through the Earth System Science Partnership. The CPPA research contributes to WCRP mainly though its contributions to CLIVAR and GEWEX. The integration of GEWEX and CLIVAR components within CPPA fits very well with Coordinated Observation and prediction of the Earth System (COPES) that is WCRP's new strategic framework for 2005-2015.
    - Global Energy and Water Cycle Experiment (GEWEX) is the sole program with a major focus on land surface processes within WCRP. CPPA contributes to GEWEX through GAPP as one of the GEWEX Continental-Scale Experiments (CSEs) and a member of the GEWEX Hydrometeorology Panel (GHP). GHP gives guidance to CPPA and others to achieve demonstrable skill in predicting changes in water resources and soil moisture as an integral part of the climate system up to seasonal and annual time scales. CPPA will provide leadership for GHP predictability studies, transferability strategies and will contribute to GEWEX's Water Resources Applications Project (WRAP).
    - Climate Variability and Predictability (CLIVAR) is an international program investigating climate variability and predictability on time-scales from months to decades and the response of the climate system to anthropogenic forcing. CLIVAR focuses on the role of the coupled ocean and atmosphere within the overall climate system, with emphasis on variability, especially within the oceans, on seasonal to centennial time scales. The ocean and large-scale components of the CPPA program contribute to CLIVAR. In particular, the CLIVAR VAMOS (Variability of American Monsoon Systems) program has a regional purview similar to CPPA, and many CPPA scientists have been very active participants in VAMOS program efforts. VAMOS provides an excellent vehicle for leveraging CPPA funding and activities on an international scale.

  - Climate and Cryosphere (CliC) aims to assess and quantify the impacts of climatic variability and change on components of the cryosphere and their consequences for the climate system, and determine the stability of the global cryosphere. Beyond its bipolar focus, the purview of CliC will also include relevant cold season regions processes elsewhere, such as permafrost and ephemeral snow cover over the North American region.
  - Year of Tropical Convection (YOTC; 2008-2011) is a joint WCRP-THORPEX research activity whose intent is to exploit the vast amounts of existing and emerging observations and high-resolution model analysis to advance basic knowledge, diagnosis, modeling, parameterization, and prediction of multi-scale tropical convection and two-way interaction between the tropics and extra-tropics with emphasis on the intersection between weather and climate.

- International Geosphere-Biosphere Programme (IGBP): The Vision of IGBP is to provide scientific knowledge to improve the sustainability of the living Earth. IGBP studies the interactions between biological, chemical and physical processes and human systems IGBP collaborates with other programmes to develop and impart the understanding necessary to respond to global change.

- United Nations Educational Science and Culture Organization/Hydrology for Environment, Life and Policy (UNESCO/HELP) is a joint project developed under the guidance of UNESCO and is endorsed by a number of agencies including WMO and the IGBP. HELP is a proactive program aimed at preparing appropriate strategies to respond to climate variability and thereby provide better advice for the development of water policy. It is believed that the implementation of HELP basins will advance the goals of CPPA in the area of water resources applications.

1.4.2 Linkage to national programs

- U.S. Climate Change Science Program (CCSP): CPPA is expected to make major contributions to the CCSP mainly through its contributions to the Climate Variability and Change component and the Global Water Cycle component.

- US CLIVAR: The national manifestation of the International CLIVAR program has identified improved predictive capability as the main objective to leave as its legacy. US CLIVAR supports three implementation panels and several ad hoc working groups to guide and implement coordinated U.S. research on climate variability. Its panels are organized to address broad functional goals of (i) predictability/prediction; (ii) process and model improvement, and (iii) phenomena/observations/synthesis. These panels develop and coordinate research plans and activities, provide input to agency programs, and assess achievement using measurable performance metrics. CPPA research activities involve all three panels and the CPPA Science Panel consists of members from all three US CLIVAR panels. US CLIVAR provides a mechanism for communication and collaboration between CPPA and other agencies.

- NASA: CPPA interacts with NASA in several activities, such as the 2004 NAME field campaign, the associated 2004 field campaign in soil moisture (SMEX2004), and

GAME (the Global Model Evaluation and Climate Process Team). Previously, the NASA Terrestrial Hydrology Program and NOAA jointly sponsored the GEWEX Americas Prediction Project (GAPP), and GAPP is part of CPPA. In 2007, NASA and NOAA co-sponsored the North American Mountain Hydroclimate Workshop to identify research priorities in mountain hydroclimate and water resources and potential field projects to support the research. NASA and NOAA CPPA are active members of the US CCSP Global Water Cycle Interagency Working group.

- NOAA Regional Support Program: This program is parallel to Prediction and Projections Program under NOAA Climate Program. The Regional Support program is to increase availability of climate products and services to enhance public and private sector decision-making. CPPA works very closely with this program on water resource application issues and to interact with stakeholders.

- NSF: CPPA interacts with NSF by jointly supporting relevant projects. In the past, joint projects include the East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC 2001), the South American Low Level Jet Experiment (SALLJEX), the North American Monsoon Experiment (NAME 2004), and the Climate Process Team.

- DOE's Atmospheric Radiation Program (ARM) is intended to improve understanding of the transfer of radiation through the atmosphere. A central ARM component is the ARM Climate Research Facility (ACRF), which is a national user facility that provides a unique asset for the study of global change. The fixed and mobile ACRF sites provide surface radiation flux data, cloud measurements, and boundary layer soundings, in addition to other ground based and remote sensing measurements at multiple observing locations. Enhanced observations are collected during Intensive Observation Periods (IOP) of a few weeks, several times during each year.

- Strategic Plans. NOAA Research is framed within the NOAA Strategic Plan. The current plan ("Research in NOAA: Toward Understanding and Predicting Earth's Environment- A Five-Year Plan: Fiscal years 2008 – 2012" November 2007) is developed around NOAA's Mission Goals, one of which is Climate (Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond). A more narrow scope is presented in the NWS Office of Hydrologic Development Strategic Plan, which has as a focus the development of techniques for improving hydrologic forecasting in all time scales from minutes to seasons.

2. CLIMATE PREDICTABILITY ON INTRASEASONAL TO INTERANNUAL TIME SCALES

2.1 Science Background

The predictability of climate on intraseasonal to interannual time scales involves a complicated interplay between the various components of the atmosphere-land-ocean system. The importance and relative roles of each subsystem in contributing to predictability can vary depending on geographical location, season, and time scale. The various subsystems and interactions that operate to produce signals that are potentially predictable beyond weather time scales are represented in Figure 2.1. According to this schematic, *ocean-atmosphere coupling*, especially associated with the ENSO cycle, provides some of the strongest atmospheric forcing on seasonal and longer time scales. *Land-ocean coupling* contributes to a strong diurnal cycle in some coastal regions and is a critical element of the monsoons and their predictability on seasonal time scales. *Land-atmosphere interactions* are crucial to providing potential predictability during the warm season, with soil moisture and snow (accumulated during the preceding cold season) playing a key role. Ultimately, the predictability that is of relevance to the society depends on how these climate subsystems interact with the *atmospheric dynamics*, i.e., a rich spectrum of atmospheric modes of variability including such phenomena as the Madden-Julian Oscillation, the Pacific North American pattern, annular modes, various orographically-forced systems, land-atmosphere processes, and extreme weather and hydrologic events.

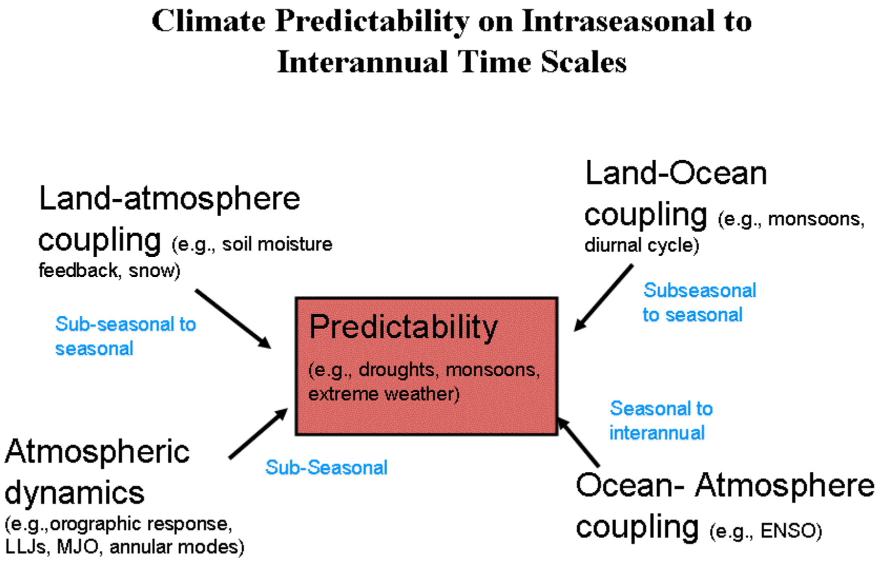


Figure 2.1 The various subsystems and interactions that operate to produce signals that are potentially predictable beyond weather time scales.

CPPA seeks to improve our understanding of coupled land-ocean-atmosphere processes that can contribute to the predictability of the hydroclimate of the Americas, and to develop the means to transfer this knowledge to improve and utilize climate predictions. To achieve this, the following overarching theme is presented:

***To develop and demonstrate an improved capability to make reliable monthly to seasonal predictions of precipitation and other hydrologic variables through improved understanding and representation of ocean- and land-related processes in climate prediction models.*”**

To make measurable progress on this broad goal, the science plan for CPPA is organized into four focus areas that present significant opportunities for substantial improvement in prediction skill in the next few years. These four focus areas are listed here and justified in more detail in this section. A summary of the CPPA implementation strategy to address these areas follows, and subsequent chapters then provide elaboration on the different aspects of CPPA implementation.

- Identifying the sources and limits of warm season predictability based on improved understanding of the American monsoon systems, in particular, the effect of remote influences on hydrometeorological integrators such as winter snow pack, soil moisture and the Western Hemisphere warm pool (WHWP);
- Improving seasonal predictability of remote influences (ENSO, NAO, Amazon convection, etc.) of inter-American climate anomalies through (a) identification of the impacts of the lower frequency modes on the predictability of the seasonal distribution of daily precipitation; (b) characterization of inter-event variability; (c) better prediction of orographic precipitation in regions affected by these climate patterns; and (d) research on modulation of the ENSO cycle and its teleconnections by climatic forcing outside the tropical Pacific;
- Identification and examination of processes related to drought and other climate extremes across the seasonal cycle;
- Understanding the effects of predictable seasonal and subseasonal climate anomalies on extreme weather events.

2.1.1 The monsoon system

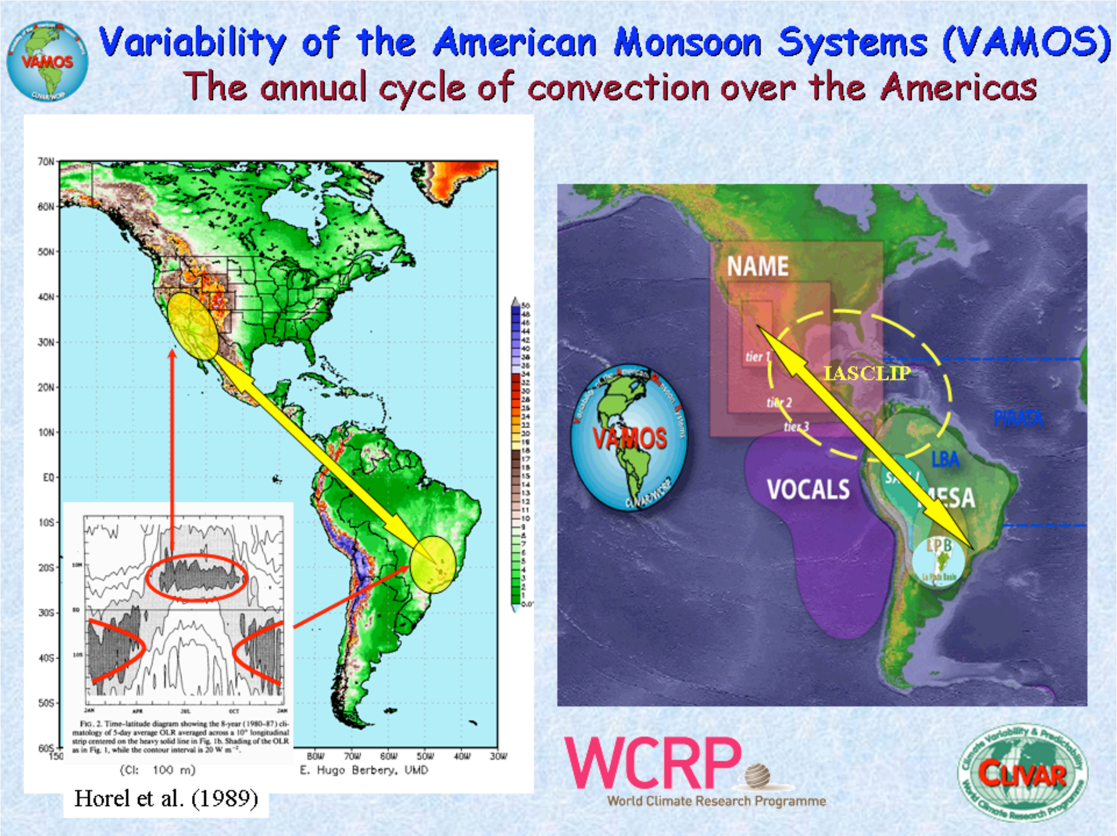
The Monsoon systems are a useful framework for describing, diagnosing and predicting warm season climate controls and the nature and causes of year-to-year precipitation variability. Understanding the major elements of the monsoon regimes and their variability, within the context of the evolving land surface-atmosphere-ocean annual cycle, is fundamental for improving warm season precipitation prediction across the Americas. CPPA research on the monsoon systems will build on the previous success of CLIVAR’s Variability of the American Monsoon Systems (VAMOS) Panel to implement science components for the separate American continents: NAME, the North American Monsoon Experiment, and MESA, the Monsoon Experiment of South America. The recently added VAMOS science component “Intra Americas Study of Climate Processes (IASCLIP)” will favor an integrated approach towards the studies of the Americas, as the natural link between the North and South American Monsoons. IASCLIP will also link the research on the IAS convection center to marine stratus in the southeastern Pacific, where the VAMOS Ocean-Atmosphere-Land Study (VOCALS) will soon have its field campaign.

The NAME region represents a unique challenge for climate modeling and data assimilation. It is a region marked by complex terrain and characterized by a wide range of phenomena including a strong diurnal cycle and the associated land-sea breezes, low level moisture surges, low level jets, tropical easterly waves, intense monsoonal circulations, intraseasonal variability, and continental-scale variations that link the different components of the monsoon. NAMS exhibits large-scale coherence in the form of several known phenomena that have an important impact on intraseasonal to decadal time scales. The El Niño/Southern Oscillation (ENSO) is the best understood of these phenomena, but previous research on the NAMS has also identified several others, including the Madden-Julian Oscillation (MJO) and the Pacific Decadal Oscillation (PDO) , the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). However, the relative influences of these phenomena on the warm season precipitation regime over North America are not well understood. Conversely, the large-scale convective heating associated with the monsoon affects circulation elsewhere, as shown by the relationship between the strength of deep convection and the amplitude and location of the summer subtropical anticyclones in the Pacific and Atlantic. Intraseasonal and interannual fluctuations of monsoon rainfall in the core monsoon region are often out-of-phase with summer rainfall across the central United States; at present the mechanisms for this feature remain unclear.

Prospects for improved prediction on seasonal-to-interannual time scales hinge on the inherent predictability of the system, and our ability to quantify the initial states and forecast the evolution of the surface forcing variables (e.g. SST and soil moisture). In the NAME Tier 3 region, circulation anomalies are influenced by SSTs in the tropical Pacific associated with ENSO, as well as in the North Pacific and the tropical and North Atlantic. SSTs in the tropical North Atlantic and eastern Pacific influence tropical cyclone development, which in turn influence the frequency and intensity of moisture surges, mesoscale-convective systems and complexes, and the attendant rainfall. SSTs in the Gulf of California and the Intra-Americas Sea also play a role in modulating the low level circulations and moisture transports associated with the monsoon. In the IAS region in summer, the Western Hemisphere warm pool is overlain by mean easterly winds on the southern limb of the North Atlantic Subtropical High. These winds sweep Atlantic moisture and tropical storms westward through the Caribbean, and northward into the United States. Flow also crosses Central America into the eastern North Pacific, contributing to the moisture source for the North American summer monsoon (e.g., Rasmusson et al. 1967; Helfand and Schubert 1995; Higgins et al. 1997; Mo and Berbery 2004). In addition to SST influences, the land surface has many memory mechanisms beyond soil moisture, especially over the western US. Snow extends surface moisture memory across winter and spring. Vegetation in semi-arid regions, which shows pronounced seasonal and interannual variability, acts as an atmospheric boundary condition that affects momentum transfer, radiation, heat, and moisture fluxes.

As with NAME, the South American Monsoon System is modulated by SSTs and soil moisture. Although significant advances in the understanding of ENSO effects have been made, a number of related issues and their importance in the South America climate remain to be investigated. Likewise, the soil moisture effects during the development stage are now better understood (Fu et al. 1999; Betts and Viterbo 2005; Collini et al. 2008), but the impacts of using consistent surface conditions in model simulations still need to be demonstrated. In the same way that the North American Monsoon affects the continental scale hydroclimate and therefore the hydrology of large basins, the monsoon precipitation in South America plays an important role on drought and flood in the La Plata Basin where monsoon rainfall occurs at its headwaters.

The schematic diagram in Figure 2.2 shows the evolution of the annual cycle of precipitation (left) and how it relates to the VAMOS science components (right). In this framework it can be considered that the North and South American monsoons constitute the two extremes of the annual cycle over the Americas. This unified approach, placing the monsoons in the context of the annual cycle, seems a better approach for predictability analysis.



Variability of the American Monsoon Systems (VAMOS)

The annual cycle of convection over the Americas

FIG. 2. Time-latitude diagram showing the 8-year (1980-87) climatology of 5-day average OLR averaged across a 10° longitudinal strip centered on the heavy solid line in Fig. 1b. Shading of the OLR as in Fig. 1, while the contour interval is 20 W m^{-2}.

(CI: 100 m)

E. Hugo Berbery, UMD

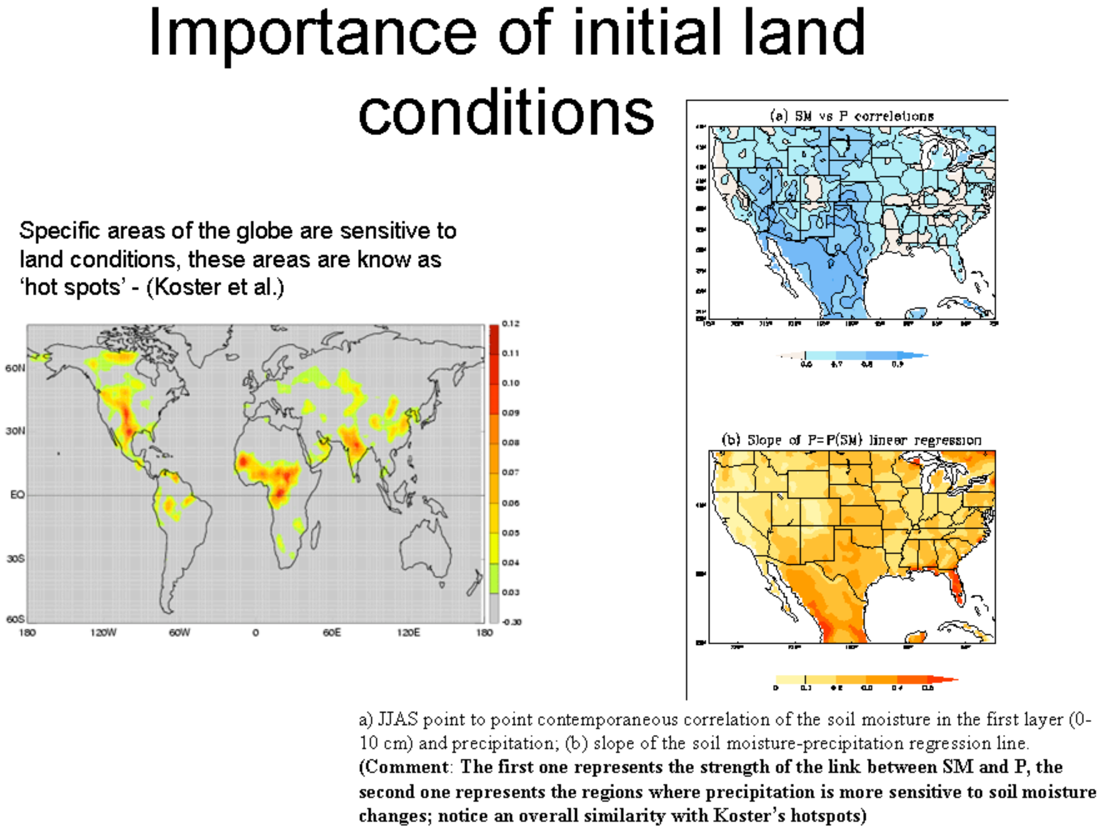
Horel et al. (1989)

Figure 2.2 A Schematic diagram showing the evolution of the annual cycle of precipitation (left) and how it relates to the VAMOS science components (right).

The relative importance of land and ocean influences on precipitation over the Americas changes with the seasons. The influence of the land surface is strongest during the warm season, when the continents are warmer than the surrounding oceans and surface evaporation is large and varies across terrain and vegetative cover. It should be noted that the influence of SST anomalies on cold season precipitation can indirectly affect warm season rainfall, since they play a role in determining the initial springtime soil moisture conditions and vegetative cover, as well as the late spring warm pool anomaly, which in turn can feed back upon the warm season climate through their influence on moisture transports and surface air temperature and evaporation.

Individual warm season precipitation events occur in association with the synoptic, diurnal, and mesoscale atmospheric circulation systems. The number and/or intensity of these events over a month or season can vary substantially from year to year. Part of this time averaged variability in the North American Monsoon domain appears to be a response to subtle variations in the distribution of tropical SSTs, but the continental response to these tropical anomalies is much less robust in summer than in winter. There is also persuasive evidence that variations in land surface conditions, particularly soil moisture and vegetation, can also play a significant role in warm season precipitation variability over mid-latitude continental-scale areas. Because these land surface anomalies are themselves largely determined by fluctuations of precipitation, it has been suggested (Betts et al. 1996; Koster et al., 2000, 2004; Betts and Viterbo 2005; Luo et al. 2007) that there are important feedbacks between the atmosphere and land surface that can be either positive (in which case climate anomalies are self-sustaining) or negative (self suppressing). The left panel of Figure 2.3 presents the areas that exhibit sensitivity of precipitation predictions to land conditions (Koster et al. 2004). These are regions where land-atmosphere feedbacks may be largest, thus adding useful information for prediction of the hydroclimate. Although the existence of hot spots with significant soil moisture memory effects has been questioned as model dependent, several diagnostics with multiple observational datasets have verified that certain regions may act as such “hot spots”. For example, Dirmeyer et al. (2008) largely corroborate the hot spots regions based on a large number of land surface models driven by observations, rather than free running GCMs discussed in Koster et al. Likewise, Luo et al. (2007) also show evidence from the NARR data that those regions have larger correlations and sensitivity linking land and atmospheric variables (right panels of Figure 2.3). Progress in the diagnosis of these feedback pathways will require significant advances in the quality of observations and modeling in the American Monsoons domain.

Recent research in land-memory processes suggests that seasonal predictions conditioned on land-memory states have lower variability and therefore higher predictability than unconditioned seasonal predictions. Similar progress has been made in understanding how remote climate patterns (ENSO, NAO, etc.) can set up late spring anomalies in the size and intensity of the WHWP, which in turn affects summer pressure patterns and moisture transports into the central United States. Understanding the strength of these relationships for different geographical regions and seasons, and their robustness over time and models remains a challenge that needs to be addressed.


Importance of initial land conditions

Specific areas of the globe are sensitive to land conditions, these areas are know as ‘hot spots’ - (Koster et al.)

(a) SM vs P correlations

(b) Slope of P=P(SM) linear regression

a) JJAS point to point contemporaneous correlation of the soil moisture in the first layer (0-10 cm) and precipitation; (b) slope of the soil moisture-precipitation regression line. **(Comment: The first one represents the strength of the link between SM and P, the second one represents the regions where precipitation is more sensitive to soil moisture changes; notice an overall similarity with Koster’s hotspots)**

Figure 2.3 Examples showing the importance of initial land conditions to predicting precipitation. Left panel: Specific areas or ‘hot spots’ that exhibit sensitivity to land conditions (Koster et al. 2004). Right panels: Contemporaneous correlation between soil moisture and precipitation (top) and the slope of the soil moisture-precipitation regression line (bottom) (Luo et al. 2007).

2.1.2 ENSO and cold season prediction

Many of the more predictable regional climate anomalies associated with ENSO occur over the Americas (Figure 2.4a). Most of those features can be explained on the basis of teleconnection patterns in the geopotential height and wind fields induced by differences in the distribution of deep convection over the tropical Pacific sector during the warm and cold phases of the ENSO cycle. Figure 2.4b shows for example, a schematic view of the distribution of anomalous tropical rainfall and the corresponding anomalies of the upper-tropospheric geopotential height field during a typical warm episode of the ENSO cycle for the northern winter. The pair of positive centers in the response near 15° latitude, just east of the dateline, have a strong degree of equatorial symmetry, despite some asymmetry in the heating anomaly. To the north, the implied enhanced meridional temperature gradient and strengthening of the westerlies at the jet stream level, favors an increased incidence of winter storms downstream over the southeastern and southwestern United States, and a corresponding decrease of winter precipitation over the Pacific

Northwest. Moreover, the atmospheric response to the Pacific heating anomaly frequently includes a reduction in the strength of the NE trades and evaporation in the Atlantic during winter and spring leading to late spring anomalies in the size and intensity of the Atlantic warm pool.

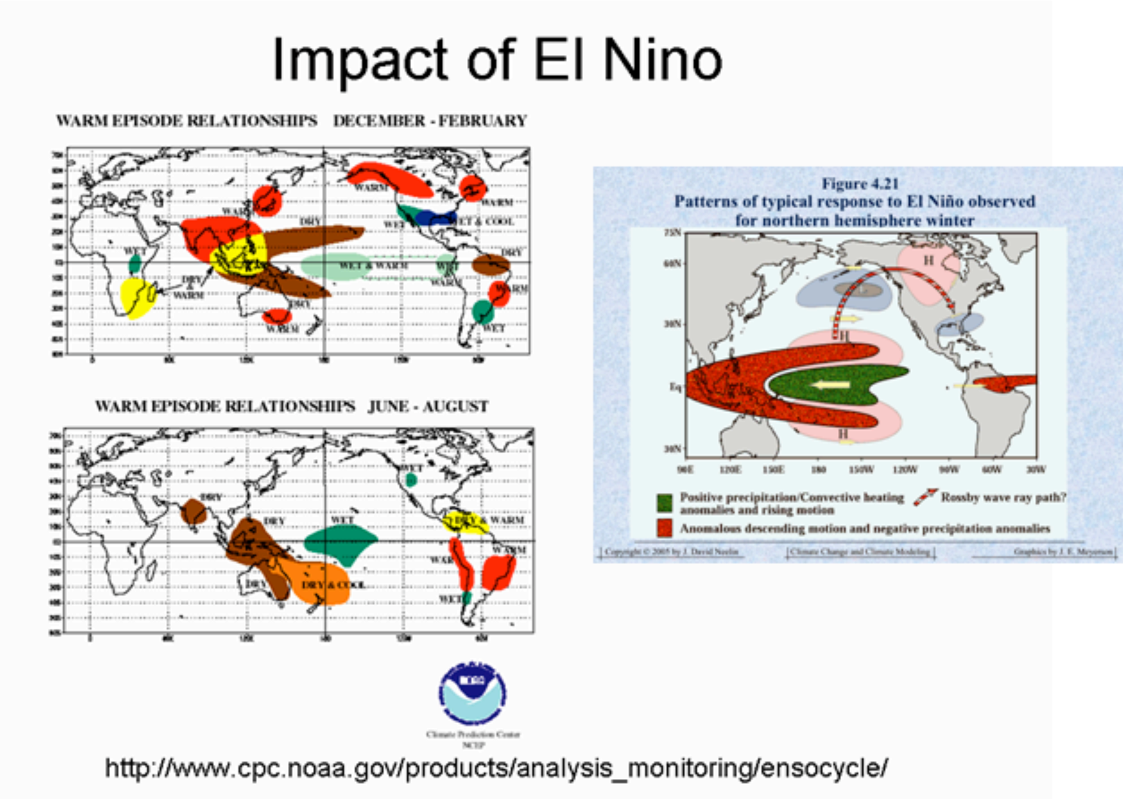


Figure 2.4 (a) Global effects of ENSO (left); (b) North American effects of ENSO (right) (Source: David Neelin).

The current status (success and limits) of ENSO prediction can be summarized as follows:

- Both statistical and dynamical models can produce useful tropical SSTA forecasts for the peak phase of ENSO (in boreal winter and spring) up to two seasons in advance;
- A consensus forecast (i.e. an ensemble across prediction systems) is remarkably skillful, whereas an ensemble of realizations of a single prediction system improves the skill only marginally;
- The periods of retrospective forecasting are too short to fully capture the effects on ENSO variability of multi-decadal fluctuations, and long-term climate change, or to distinguish between the skill scores of various prediction systems and the resulting low signal-to-noise ratio in multi-model ensembles presently limits the effectiveness of forecasts;

- Models predict the sign of extreme events well, but too often predict warm or cold events when the observations call for normal conditions.
- Consistency among forecasts initialized one month apart is not a good *a priori* measure of forecast skill.

The present generation of coupled models of the ENSO cycle has had success in predicting, out to several seasons in advance, the changes in amplitude and polarity of the typical (or "canonical" as it is sometimes called) pattern of SST anomalies. In the simplest models, forecasts of an index of this pattern are then used as a basis for predicting the amplitude and polarity of anomalous rainfall and circulation patterns. Just as ENSO distorts the seasonal cycle in many areas of the world to render climatology-based "forecasts" erroneous, departures from the canonical ENSO cycle that give each individual warm or cold episode its own peculiar character constitute a major source of error in current prediction models based on the canonical ENSO cycle. For example, the scientific community was caught off guard by the onset of the exceptionally strong 1982-1983 warm episode, which was preceded by a somewhat different sequence of events than any ENSO observed during the previous three decades. Indeed, there are times when anomalous ocean temperatures and winds in the equatorial Pacific bear so little resemblance to the "canonical" ENSO pattern that it is not even clear whether to classify them as "warm" or "cold." Other climate patterns, such as the NAO, can reinforce or interfere with the ENSO influence on phenomena such as the WHWP.

For these reasons the present reliance on empirical relationships and canonical anomaly patterns inherently limits ENSO-related prediction skill. Numerical climate prediction must be improved to address this limitation, just as empirical weather prediction methods were supplanted by numerical prediction models several decades ago.

Therefore, a critical test of the usefulness of the next generation of coupled climate models is the extent to which these non-canonical (and, in a changing climate, possibly nonstationary) aspects of ENSO and the associated teleconnection patterns can be simulated and predicted. In this way, improvement of SI prediction skill -- the overarching goal of CPPA -- will directly serve to reduce uncertainties in long-term climate change projections (Palmer et al. 2008). Using SI prediction as a testbed for climate change has the huge advantage of allowing validation of model quality on a shorter time scale than is possible for climate change research.

CPPA strategies for improvements in ENSO-related process study and prediction are discussed in more detail in Chapter 3 and Chapter 5.

2.1.3 Hydroclimatological prediction during the cold season

Western North America is marked by pronounced topographic variations across the region. Realizing the regional scale climate predictability in this region, where the ENSO signal is strong in the cold season, depends crucially on our understanding of the dynamic and thermodynamic effects of orography and its interactions with large-scale circulation anomalies. Two distinctively different regional climate regimes of the western U.S., both strongly affected by orography, are of particular interest. They are the maritime climate of the Pacific Northwest and Northern California and the semi-arid climate of the Southwest, both of which depend on cold season snowpack in the mountainous areas for a large fraction of their water supplies. Improved understanding and modeling of the hydrometeorology related to orography is critical to improved predictions and successful use of short-term to seasonal climate forecasts for managing water resources in these regions.

Major gaps remain in our understanding of the natural evolution of clouds and precipitation in mountainous terrain, especially at horizontal scales less than 100 km. Most measurements of air motions over complex orography (Neff, 1990) lack the spatial resolution to identify small-scale features like gravity waves, barrier jets, cold air pools, convergence zones, channel and blocked flows.

There remains a need for careful comparisons of different modeling approaches including regional climate models, simple dynamical models and/or subgrid parameterizations (e..g, Rhea 1978; Alpert 1986; Barros and Lettenmaier 1993, 1994; Leung and Ghan 1995, 1998), and statistical models (e.g., Chua and Bras 1982; Daly et al. 1994; Hutchinson 1995; Widmann et al. 2002) of orographic effects. Because existing networks of measurements do not adequately resolve precipitation in regions of complex terrain, statistical methods and regional reanalyses are useful for providing more accurate estimates of water budgets in mountainous river basins and evaluating orographic precipitation models.

2.1.4 Western hemisphere warm pool and warm season prediction

The Intra Americas Sea includes the Caribbean Sea and the Gulf of Mexico. The IAS region is defined as a broad area covering the IAS itself, the western tropical North Atlantic, the adjacent lands, and the ocean off the west coast of Central America. The region is vulnerable to climate variability and change, with footprints clearly found in corals, sediments, and tree rings. Current GCMs have great difficulty in simulating the distribution and variability of rainfall and winds in the IAS region. Most models overestimate the warm season pricipitation in the Caribbean region overlain by the Intra-Americas Low-Level Jet (IALLJ) and these errors cascade to the moisture transports into the eastern North Pacific and the central United States.

Relevant scientific issues for the IAS are rainfall variability, the Western Hemisphere Warm Pool (WHWP), the IALLJ, the Inter-Tropical Convergence Zone (ITCZ), North Atlantic Subtropical High, tropospheric environment for tropical cyclones (TCs), and Land-Air-Sea Interaction. Recent diagnostic research involving data and forced AGCM experiments reveal a large-scale atmospheric response to WHWP anomalies that involve contemporaneous summer anomalies in all of these climate factors (Wang et al. 2006, 2008). The IAS region plays an important role in the climate of the Americas for two reasons: its convective heating center is the largest in the Western Hemisphere in the boreal summer and it supplies moisture for precipitation in both South and North Americas. Chapter 3 expands on the science aspects related to IAS that should be addressed in the future.

2.1.5 Droughts

Drought, especially prolonged multi-year drought, has tremendous societal and economic impacts on the United States, and many other countries throughout the world. Estimates of the costs of drought to the United States alone range from \$6-\$8 billion annually, with major droughts costing substantially more (e.g., \$62B in 1988).

Modeling work has now attributed the major North American droughts of the last century and a half to global circulation anomalies forced by SSTs, with the tropical oceans playing an important, and probably dominant, role. Hong and Kalnay (2002) found that the 1998 Oklahoma-Texas drought was originated by SST anomalies, but once it was established, the dry soil anomalies helped maintain the pattern for several months, before the mechanism was overwhelmed by synoptic scale disturbances in the autumn. Schubert et al. (2004) also report that the 1930s Dust Bowl was caused by anomalous tropical SSTs and that land-atmosphere interactions increased its severity. A successful drought prediction will require several steps: 1) a successful SST prediction, 2) a successful simulation of the global circulation response to the SST anomalies and 3) a proper simulation of the land-atmosphere interaction that relates precipitation anomaly and drought. On seasonal and interannual time scales, our ability to predict the SSTs associated with ENSO has improved considerably over the last two decades, but further work is required to better understand and quantify the physical processes linking ENSO to regional drought and to bring other climate patterns and time scales (e.g., AMO) into the mix.. There is also a need to quantify the predictability of drought associated with such influences, and to examine the role of other ocean basins. For multiyear droughts, it appears that the observed precipitation reduction averaged over the drought can be simulated by climate models forced by only the small change in mean SSTs during the drought interval (e.g. the 1930s) and that knowledge of variability at the shorter time scale such as the detailed ENSO evolution during the drought period may not be required. Certain combinations of multi-ocean anomalies, such as a cool Pacific and warm North Atlantic, appear to accentuate the tendency for North American drought (McCabe et al. 2004). Anecdotally, just such a combination of SST anomalies may explain the severe southeast drought of 2007 (Hoerling, Mitchell, personal comms.). Such forecasts of long-term changes in SSTs using coupled models, if successful, could be used to assess the likelihood of a drought persisting over the next few years as a result of a persisting La Nina-like state.

Drought prediction – or drought hindcasts – requires land-atmosphere and ocean reanalyses to initialize and validate the models. However, significant errors in the atmospheric moisture budgets of current atmospheric reanalyses make them of limited use for validating models and hindcasts. It still needs to be determined where the problems lie and whether improved models, improved observations or improved data assimilation are the answer. For example, deficiencies in ocean and atmospheric reanalyses such as the North American Regional Reanalysis (NARR) and the Simple Ocean Data Assimilation (SODA) may be partially traceable to the very poor monitoring by upper air soundings above, and of ocean circulation and thermal structure in the Intra-Americas Sea region.

Climate prediction models are most skillful at the large spatial and temporal scales, but they have typically been less effective in producing information on smaller scales, such as extreme events, that are the highest priority for the users of climate forecasts. There is thus a need to assess and improve downscaling methods that can fill the gaps in providing climate predictions and extreme event probabilities at the regional scale.

Currently the online U.S. and North American Drought Monitors are the main vehicles for communicating to users past and current status of drought. These have been successful and popular, partly because of their simplicity, but could be improved by providing more quantitative information, expanding to specialized maps for different users, and establishing a drought early warning system. The latter will require soil moisture estimates either from direct measurements or from land data assimilation systems (LDAS). LDAS is currently in an experimental stage and efforts must be accelerated to develop accurate systems that have been validated against historical records. Drought monitoring is currently constrained by a lack of high spatial resolution soil moisture measurements (satellite data have insufficient vertical depth) and poor knowledge of snowpack, which is a major source of soil moisture in spring and summer for many regions. Drought monitoring needs to be integrated with real-time attribution studies to assess the causes of a drought and the probability of its continuation or termination.

2.1.6 Modes of variability and extreme events

Drought, hurricanes, storm surge, heat waves, tornadoes, cold-air outbreaks, and other extreme events have important societal impacts on the Americas. For example, droughts and various water resource issues are of paramount importance in the western U.S. The future of hurricane activity along the North American coasts has important implications for future development of coastal (structures, levees) and offshore (e.g., oil platform) infrastructure. Information on future changes in other climate extremes is needed for society to make informed decisions on how to invest in critical infrastructure in risk-prone, rapidly developing areas and to modernize water systems, dams, runways, roads and bridges.

To begin to address these issues, CPPA will explore predictability and develop a predictive capacity where possible across intraseasonal-to-interannual time scales, focusing on high-impact climate extremes. The challenge will be in understanding the underlying cause and predictability of high impact climate extremes, ensuring that climate models are capable of resolving them, and developing a prediction infrastructure to operationally produce outlooks of high impact climate extremes across these timescales.

CPPA will focus its activities on intraseasonal, seasonal, annual, and interannual, time scales. On these time scales, the predictability of climate extremes, such as active and inactive hurricane seasons, is determined by low-frequency phenomena such as the Madden-Julian Oscillation, the North Atlantic Oscillation, and El Niño. These physical modes of the climate system provide a physical basis for seeking to develop useful predictive capabilities. For example, the MJO and El Niño have been noted to influence hurricane activity in the Atlantic, and possibly the northeast Pacific, as well as wintertime weather patterns over the midlatitudes. Predictions based on these modes of low-frequency variability represent an initial value problem, requiring integration of key observations of the initial state for a successful outcome. A crucial research issue is to determine where useful predictability may be present and when it is exploitable through statistical and dynamical models.

Tropical rainfall exhibits strong variability on sub-seasonal time scales. These fluctuations often go through an entire cycle in a month or two, and so are referred to as "intraseasonal oscillations". Four other terms that are often used interchangeably to refer to intraseasonal oscillations are "Madden-Julian Oscillation" or "MJO", "30-60 day oscillation", and "30-60 day wave" (hereafter MJO is used).

The MJO is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall, observed mainly over the Indian Ocean and Pacific Ocean. The anomalous rainfall is usually first evident over the western Indian Ocean, and remains evident as it propagates over the very warm ocean waters of the western and central tropical Pacific. This pattern of tropical rainfall generally becomes nondescript as it moves over the cooler ocean waters of the eastern Pacific but reappears over the tropical Atlantic and Indian Ocean. There are distinct patterns of lower-level and upper-level atmospheric circulation anomalies that accompany the MJO-related pattern of tropical rainfall. These circulation features, however, extend around the globe and are not confined to only the eastern hemisphere.

The MJO affects the wintertime jet streams and atmospheric circulation features in the subtropics and mid-latitudes of both hemispheres and, as a consequence, has an important influence on the patterns of storminess over the Americas. The MJO is also a contributor to blocking activity (i.e. atmospheric circulation features that persist near the same location for several days or more) over the high latitudes of both hemispheres that influence weather patterns over the Americas.

The strongest impacts of intraseasonal variability on the U.S. occur during the winter months over the western U.S. During winter, this region receives the bulk of its annual precipitation. Storms in this region can last for several days or more and are often accompanied by persistent atmospheric circulation features linked to MJO activity. Of particular concern are the extreme precipitation events which lead to flooding. During the NH summer the MJO has a modulating effect on hurricane activity in both the Pacific and Atlantic basins. MJO-related effects on the North American summer monsoon also occur, though they are relatively weak. Thus, it is very important to monitor and predict MJO activity, since this activity has profound implications for short-term climate variability and extreme weather events through the year.

There is strong year-to-year variability in MJO activity, with long periods of strong activity followed by periods in which the oscillation is weak or absent. This interannual variability of the MJO is partly linked to the ENSO cycle. Strong MJO activity is often observed during weak La Niña years or during ENSO-neutral years, while weak or absent MJO activity is typically associated with strong El Niño episodes.

According to Gottschalck and Higgins (2007), the MJO has documented relationships with numerous phenomena, including the ENSO cycle, tropical cyclone activity in all of the ocean basins, and the monsoon systems in both hemispheres (including the American

Monsoon Systems). The MJO often produces distinct periods of anomalous precipitation over near equatorial and subtropical regions of the Americas, Africa, and the Maritime Continent. The relationships noted above often result in short-term (week 1-3) weather hazards and/or benefits that can have far reaching socioeconomic impacts.

Dynamical models generally do not predict the MJO well, partly because of the inherent difficulties that still remain regarding the correct mathematical treatment of tropical convective (rainfall) processes. However, due to its slowly evolving nature, accurate prediction of the MJO is fundamentally related to our ability to monitor the feature and to assess its relative position and strength.

The annular Arctic Oscillation (AO) and the Antarctic Oscillation (AAO) are the leading modes of circulation variability of the Northern Hemisphere and Southern Hemisphere high latitudes, respectively. They are defined as the monthly-mean tropospheric pattern of variability, but their influence extends beyond this. Both modes have connections to extreme weather events and long-term climate trends in the Americas, and have important connections to the stratosphere.

Both the AO and the North Atlantic Oscillation or NAO (which can be viewed as the projection of the annular AO onto the North Atlantic sector) exert a strong influence on wintertime climate, not only over the Euro-Atlantic half of the hemisphere, but also over the Pacific and North American half as well. The AO (NAO) affects not only the mean conditions, but also the day-to-day variability, modulating the intensity of mid-latitude storms and the frequency of occurrence of high-latitude blocking and cold air outbreaks throughout the hemisphere. The recent trend in the AO toward its high-index polarity with stronger subpolar westerlies has tended to reduce the severity of winter weather over most middle- and high-latitude Northern Hemisphere continental regions. While the influence of the AO on these features has been studied rather extensively, additional work is required to determine to what extent the AAO influences day-to-day variability in the Southern Hemisphere, including over South America.

Observations show that large variations in the strength of the stratospheric circulation, appearing first above 50 kilometers, descend to the lowermost stratosphere and are followed by anomalous tropospheric weather regimes. These stratospheric events also precede shifts in the probability distributions of extreme values of the AO (and NAO), the location of storm tracks, and the local likelihood of mid-latitude storms. Observations suggest that these stratospheric harbingers may be used as a predictor of tropospheric weather regimes.

2.2 Science Objectives and Priorities

Predictability of the American monsoons

Recent exploratory diagnostic research on seasonal prediction of warm season precipitation has shown that the skill of land surface-based prediction is not stationary in time. Such nonstationarity has limited operational utility of empirical forecast techniques. On the other hand, research using dynamical models is often limited to sensitivity studies rather than true prediction. More research is needed to determine model fidelity in predicting warm season precipitation.

Cold season hydroclimate predictability

Topographic influences are particularly relevant for the cold season in regions such as the northwestern U.S. Research will focus on improving the ENSO-related prediction skill of hydroclimatic anomalies across the Americas, including downscaling of large-scale seasonal predictions for hydrologic predictions over basins with complex terrain.

Drought predictability on multi-season time scales

CPPA research will identify ocean-atmosphere circulation regimes and land-atmosphere interactions that are associated with the initiation, intensification, and demise of persistent droughts. The research will be carried out in close coordination with the development of NIDIS, a new operational drought monitoring and information dissemination system.

Subseasonal and extreme weather forecasts

There are indications that intraseasonal variability can contribute to higher frequency variability and particularly to extreme weather forecasts. CPPA will seek to gain understanding of intraseasonal-to-seasonal mechanisms that can enhance shorter term predictions, with a focus on winter and summer extreme events.

2.3 Implementation Strategies

2.3.1 The American monsoons predictability

Empirical and modeling studies are needed to explore the mechanisms that link the oceanic climate variability to that over land in the Pan American region. Recent research has provided evidence that land memory may be relevant in regions where SSTs have weak or no effects. However, feedbacks involving the ocean and atmosphere may introduce stochastic or chaotic behavior into the climate and land system’s overlay.

Accurate representation of land surface effects in climate models will be required to study the subtle mechanisms such as land heating and orographic effects that couple climate variability over the ocean and land during the warm season. Models must also replicate key features of the diurnal cycle (e.g., timing of the convective maximum) in order to achieve precision at longer timescales.

The physical parameters determined by land surface schemes are the net radiation absorbed by the surface, the partition between latent and sensible heat, conductive heat storage, and the radiative temperatures of the land surface and boundary-layer air that are required for energy balance. Vegetation is a major factor in the surface energy and water balance. Also significant is the vertical movement of water and heat within the soil column. In the present generation of land surface schemes, observational data on the horizontal distribution of vegetation types, properties, and soil characteristics are used as model parameters. Vegetation characteristics affect basic properties such as albedo and roughness length. Soil properties affect the partitioning of rainfall between runoff and infiltration, as well as the radiative, thermal, and water-holding capacities of the land.

Parameterizations of the energy and water conservation requirements of the land surface were first introduced with very simple schemes, analogous to early efforts to represent the effects of clouds in climate models. More complex schemes are now included in most operational forecast and data assimilation systems. An explicit representation of vegetation and its role in the hydrological cycle has been introduced, along with more detailed treatments of soil moisture, snow, runoff, and river routing.

Improvements in the representation of air-sea-land interaction processes will also be required for understanding and simulation of the mechanisms that are relevant for the climate of the Americas. NAME, VOCALS, IASCLIP, and PLATEX (the proposed field campaign of LPB) should thus be of most relevance for improvements of model parameterizations.

2.3.2 Cold season predictability

Snow and ice cover provide a memory of the frozen precipitation; they influence the surface radiative transfer, and dictate future melt-water availability. One significant development in recent years is the routine provision of snow-cover data products by the National Operational Hydrologic Remote Sensing Center and National Snow and Ice Data Center (http://www.nsidc.colorado.edu). Research supported by GAPP and its predecessor program within GEWEX, GCIP, showed that improved model parameterizations for snow and frozen ground, and sub-grid snow distribution improve the simulation of regional and global climate.

Given the present standing of snow/ice land memory research, the evolving priorities for related studies in the CPPA program will be:

- Research to quantify the role of snow (spatial extent and duration) in seasonal prediction of subsequent climate anomalies and hydrologic variables such as streamflow. Potential studies include statistical analyses based on CPPA-supported hydrologic data sets, sensitivity studies of simulated climate and hydrology to the amount and extent of frozen precipitation at timescales up to seasonal, using observations to prescribe regional snow/ice cover in prediction models; and evaluating improvements in prediction skill and usefulness to water management that results from the use of LDAS-like products for model initializations. Initial CPPA foci will include studies on the NAME region, and the role of snow on the North American monsoon strength and persistence; and the potential relationship between springtime snow extent and summer temperatures and precipitation across the Americas.
- Development of improved snow/ice cover sub-models in LDAS, with emphasis on vegetation-covered areas, and comparing them against existing or new observations at both plot and regional scale.

2.3.3 Drought predictability

Atmospheric response to boundary conditions

The ENSO cycle modulates rainfall over much of the United States, especially for the cold season and southern states. The strength and dependability of possible warm-season links are not yet well known. However, winter anomalies of ENSO and/or the NAO that persist into the boreal spring typically influence the subsequent character of the WHWP and can thus affect the summer climate indirectly through the atmospheric characteristics associated with the warm pool, such as moisture transports and the tropical cyclone environment. Hence, CPPA is interested in supporting (a) statistical studies that document the relationships between anomalous boundary forcing and climate anomalies over the Americas and (b) diagnostic studies that elucidate the physical and dynamical mechanisms through which these links occur. Anomalous boundary forcing includes both sea surface temperature and land surface processes, and climate anomalies refer not only to mean temperature and rainfall but also to the frequency of droughts, floods, and severe thunderstorm outbreaks and to tropical and extratropical storm tracks.

Empirical studies, complemented by numerical experimentation, will examine the complex interactions between SSTs and land processes, and how they influence rainfall anomalies and the surface wind systems. AGCMs will be needed to explore the relative contributions of oceanic and land processes to seasonal precipitation anomalies. For example, initial studies suggest that precipitation in the eastern Amazon is more controlled by oceanic conditions while the western Amazon is more influenced by the seasonality of land solar heating. Both can force anomalies in the North Atlantic Subtropical High, and NE trades via the regional Hadley circulation and thus influence the development of warm pool anomalies by the boreal summer. AGCM experiments, together with detailed observations of regional weather phenomena can show how the slowly evolving planetary-scale atmospheric response to boundary forcing modulates the more intermittent, higher frequency synoptic and sub-synoptic phenomena that are responsible for the individual episodes of heavy rainfall and significant weather during both winter and summer. Although deterministic prediction of phenomena such as these is not feasible on seasonal and longer time scales, realistic models can potentially provide more accurate and detailed information concerning their frequency or likelihood of occurrence than empirical evidence alone.

AGCM simulations can also provide insights into the physical mechanisms responsible for the remote links between anomalous conditions at Earth's surface and regional climate variations. These investigations have traditionally compared simulations where the model is forced with different prescribed sea surface temperatures, the distribution of which is often motivated by empirical studies.

Soil-moisture memory

Previous NOAA funded research programs, such as GCIP and GAPP, have created a legacy in understanding soil-moisture related land memory that will benefit and guide the research to be undertaken in CPPA. In modeling studies, GCIP demonstrated conclusively that regional soil moisture status can change the rate at which water vapor is converted to precipitation and particularly, how it contributed to the persistent heavy rain and subsequent flooding in the Mississippi River basin in 1993. For drought prediction, a more relevant question is whether land-atmosphere coupling extends the predictability of drought beyond the direct effects of soil moisture persistence. That is, anomalously low soil moisture anomaly will likely persist even with normal future precipitation, can land-atmosphere feedbacks extend drought predictability beyond soil moisture persistence?

In general, research in soil moisture-related land-memory processes is still limited by the comparative scarcity of soil-moisture data. It was this lack of relevant, regional scale observations of soil moisture that motivated the Land Data Assimilation System (LDAS) initiative. The LDAS methodology will continue to be applied in the context of CPPA. Although LDAS is a promising tool, important differences remain among products produced by different modeling systems even when they are initialized with the same set of observations. Notwithstanding the progress that has been made towards providing model-calculated soil-moisture fields using LDAS, the basic requirement for soil-moisture observations over extensive land areas remains. Given the scarcity and poor representativeness of point measurements, the prospect of providing remotely sensed, area average soil moisture is a tempting option. CPPA will maintain its interest in new developments in remote sensing of soil moisture. CPPA's focus will be on investigating how remotely sensed data could best be used to improve prediction of climate and hydrologic variables at timescales from days to seasonal and to assess their usefulness for water resources management.

Currently, limitations in exploiting soil moisture memory to improve climate/ hydrometeorological predictions are (a) the poor quantitative precipitation forecasts (QPF) in coupled hydrologic models, and (b) the parameterization of crucial processes that are part of the surface water and energy budgets in the assimilation systems. Even if observations of precipitation are available to improve the specification of initial soil moisture state, shortcomings in the simulation of rainfall in predictive runs can rapidly degrade the quality of the simulation and subsequent evolution of the moisture store. The desire to improve simulation and prediction of the moisture available at the land surface therefore puts an emphasis on the need for research to improve the representation of atmospheric processes that generate precipitation. This need is particularly acute for understanding the influence of topography on precipitation. CPPA will therefore support development of improved precipitation data sets, gridded for optimum utility in high resolution modeling studies and for monitoring hydroclimatic variability.

Recognizing the current status and needs for research in soil-moisture land memory, the initial priorities within the CPPA program will include:

- Research to quantify the role of land-atmosphere coupling on predictability of drought. This includes process studies that identify the pathways that link land, atmosphere, and precipitation at different time scales, and coupled land-atmosphere model experiments with different land surface initializations to quantify the influence of land-atmosphere feedbacks on drought predictability beyond soil moisture persistence.

- Research to quantify the role of soil moisture in seasonal predictability. CPPA is interested in diagnostic/analysis based on CPPA-supported hydrologic data sets, modeling studies using RCM and GCM models, and testing whether LDAS-like model initializations result in improved prediction relevant to water management. Initial CPPA foci will include studies on the NAME region, and the role of soil moisture and snow on the North American monsoon strength and persistence; the relationship between springtime soil moisture and summer precipitation across the Americas; and the role of soil moisture from LDAS-like systems on precipitation prediction.

- Research in support of a soil moisture remote sensing mission to improve the initialization of predictive models, with emphasis on how remotely sensed observations could best be used to improve prediction of climate and hydrologic variables at timescales from days up to seasonal.
- Improvement of observations of precipitation in regions of the Americas where data are sparse (like over the mountainous regions of the western United States and the subtropical regions affected by the monsoons) to support model development and evaluation, and to improve regional LDAS for phenomenon-specific (e.g. monsoon) predictability studies.
- Research leading to improved understanding and more skillful modeling of precipitation processes in the atmosphere and their interaction with topography with special emphasis on warm-season convective processes relevant to soil-moisture memory studies.

Vegetation and land cover memory

Over the last decade, there has been major progress in understanding and modeling the influence and importance of vegetation on surface exchanges of energy, water, and carbon. GCIP research demonstrated that including improved representation of vegetation, even in a simple form, can result in a significant improvement in the predictive capability of seasonal prediction models. Just as important, GCIP research also fostered an important new capability to estimate, from field data, the values of several parameters required in more complete models of vegetation response. There were also some early studies using coupled models capable of representing the seasonal evolution of vegetation and the impact of climate on the vigor and amount of vegetation. The latter is a precursor for vegetation memory studies under CPPA.

Investigations can be carried out on the effect of interannual variability in vegetation (e.g. time of leaf-out) on interannual climate variability, through multi-member ensemble integrations with regional, coupled hydrologic-atmospheric models, with and without interactive vegetation. Ultimately, such investigations will help determine whether including interactive vegetation improves the simulation of climate variables in the Americas, and the relative roles of various land-memory processes in climate variability and prediction. Such integrations could also investigate whether including interactive vegetation modifies the relative sensitivity of the models to changes in sea surface temperatures versus land memory processes in general.

The initial focus is to better understand whether improved representation of seasonal dynamics and inter-annual variability of vegetation will lead to better seasonal climate and hydrologic predictions. Such studies will contribute to an understanding of the role of vegetation in seasonal climate phenomena, such as the monsoon systems of the Americas, and predictability of droughts.

- Investigation of the mean seasonal cycle and predictability of its variability.

  Implementation activities within this element include both modeling and statistical analysis of seasonal and interannual variability of precipitation (both liquid and solid) and snowpack in orographic regions of the CPPA domain with a goal of better understanding the remote and local controls, in addition to ENSO, that are important for cold season precipitation and streamflow. The goals are to better quantify the fraction of explained variance of such controls for both precipitation and streamflow, to understand the spatial and time scales of the remote/local controls and response, and to quantify their potential lead times in prognostic applications. There is a need to diagnose the seasonal cycle and its interannual variability for precipitation and snowpack, including exploring relationships in terms of dynamical atmospheric metrics, as well as hydrologically relevant measures such as atmospheric moisture flux convergence and streamflow. A related implementation objective for CPPA is to understand the mechanisms by which climate anomalies persist across the seasonal cycle, a key question with regard to drought-related prediction. Understanding how these relationships are captured by global and regional climate forecasts is important for developing models and application strategies.

- Apply climate and hydrologic models in seasonal climate forecasting for basins with complex terrain. The implementation activity for this element needs to build upon the activities described above; especially those that evaluate model complexity and scale with respect to orographic precipitation and snowmelt. The implementation activities need to (i) evaluate whether more complex model parameterizations and increased spatial resolutions lead to improved skill, especially when applied to simulating the water budgets of major river basins in the western U.S. affected by orography and (ii) assess seasonal climate forecast skill through studies that will apply climate and hydrology models in river basins with complex orography and examine the impacts on water management. These studies will be done by applying a suite of climate models and precipitation downscaling methods to explore ways to improve seasonal predictions of precipitation anomalies through ensemble approaches and characterization of forecast uncertainty.

2.3.4 Predicting high-impact climate extremes on intraseasonal-to-interannual timescales

CPPA will promote studies that link weather and climate. The international community has come to a consensus on outstanding issues in weather-climate research and development, reflected in an upcoming World Meteorological Organization (WMO) white paper (Brunet et al. 2008). The white paper outlines four areas that deserve special attention:

- Seamless weather-climate prediction with ensemble prediction systems. An international sharing of weather-climate ensemble predictions will allow development of multi-model products that are more skillful than any one national center can achieve on its own. Additionally, participating centers can also collaborate by sharing reforecast data sets and experimental, high-resolution simulations.

- The multi-scale organization of tropical convection and its two-way interaction with the global circulation. Current forecast models are notably poor in predicting many of the major modes of tropical variability, including the Madden-Julian Oscillation (MJO). The MJO can force Rossby waves that interact with the extratropical features, and several studies have suggested that improved representation of the modes of tropical variability will improve extratropical weather-climate forecasts.

- Data assimilation for coupled models as a prediction and validation tool.

  The white paper argues for two elements, the first of which is known as "IESA" or Integrated Earth System Analysis. Under IESA, the data assimilation is unified for the land, ocean, atmosphere, and cryosphere. This coupled assimilation may be able to reduce inconsistencies among analyses of different components of the Earth system, resulting in improved initializations for weather and climate forecasts. The second element is the testing of climate models as if they were weather-prediction models, with repeated assimilation/short-term forecast cycles. Model biases may be more evident and easier to diagnose in short-term forecasts than long-lead climate forecasts.

- Sub-seasonal and seasonal predictions for social and economic development. Interaction with social scientists can aid in the R&D of weather-climate products that are most directly relevant to users, especially in developing countries.

CPPA will contribute to elements of the weather-climate linkage problem that focus on product development and model diagnosis using next-generation reanalyses and reforecasts. NOAA has invested resources into ensemble forecast systems for medium-range forecasts (1 day – 2 weeks) and for climate forecasts (> 1 month). It has no system specifically configured for weather-climate leads of 1 week – 1 month. It is feasible to extend or complement existing development efforts to produce operational ensemble forecast systems with companion reforecast data sets to extract the signal from noise due to chaos and model error. Tailored suites of products can be developed for fire weather, drought, severe weather, and hot and cold spells, and transferred to operations if determined to be useful.

A key to making progress on these difficult climate predictability issues is increasing the available computing resources for both advanced models and in some cases for large ensembles of hindcasts, forecasts or reforecasts. The number of ensembles will need to be large enough to rigorously address signal to noise issues for the problem being addressed. The practical utility of predictions of high impact climate extremes will be heavily dependent on users developing a sense of trust, which can be enhanced based on careful hindcast studies that assess the likely reliability and skill of potential forecasts in a controlled setting. For example, enhanced computing may enable increasingly realistic simulations of hurricane behavior and perhaps useful predictions of hurricane activity levels for the next one or two seasons--and such skill can be partially anticipated in advance using hindcasts for previous seasons.

Improved predictions of extreme events are a challenge for current AGCMs. Progress can be made by developing nested regional models with improved convective schemes, and implementing downscaling methods. One area of particular promise is the strong relationship between the AGCM response to anomalous warm pools -- including the anomalies of vertical wind shear and CAPE as they affect TC activity (Wang et al. 2008) -- and the recent improvements in TC activity simulation using models at NOAA-GFDL (Knutson et al. 2007).

Development of higher resolution coupled climate models will also be useful for more reliable El Niño predictions, and will increase our confidence in predictions in crucial regions of the tropical Pacific and Atlantic that are believed to have a large influence on droughts in the continental U.S. and on Atlantic hurricane activity. Higher resolution climate model simulations of the Southwest U.S. should enhance our ability to simulate precipitation associated with the North American monsoon as well as precipitation variability for regions with high mountains and complex topography. Higher resolution models may also be useful for simulating and possibly predicting Madden-Julian Oscillation behavior in a much more realistic way than is possible with current climate models.

Advances in modeling efforts should be complemented by development of statistical schemes that can extract the usable signal in climate extremes from the unpredictable random signal and provide useful probabilistic forecasts of climate extremes. Advances in assimilation and initialization techniques will also be crucial to the success of initial value-dependent dynamical model forecasts. Careful integration with improved observations will greatly assist modelers in their efforts to improve representations of key physical processes in the models, which could lead to a reduction of model biases and ultimately to enhanced model reliability and skill.

2.4 Deliverables

- Development of land surface data sets, updated in real time, with resolution and quality sufficient for use in seasonal-to-interannual prediction efforts
- Improvement of regional and ocean reanalyses such as the NARR and SODA through improved monitoring and model improvements
- Development of precipitation data sets, updated in real time and discriminating rain from snow, with resolution and quality sufficient to validate hydrologic prediction and support streamflow forecasting efforts
- Improved predictive understanding and simulation of the roles of SST forcing and atmosphere-land surface interactions in the initiation, maintenance, and demise of drought and pluvial conditions throughout the Americas

- Diagnosis and predictive understanding of inter-event variability of ENSO extrema throughout the seasonal cycle
- Portable versions of operational models and basic support to be made available to the community, for evaluations and improvements.

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3. ATMOSPHERE-OCEAN INTERACTIONS

3.1 Science Background

As discussed in Chapters 1 and 2, 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 (see discussions in Section 2). 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 requires understanding the nature and source of the predictability in the oceans, and the physical processes by which that predictable signal ultimately manifests on regional scales. Air-sea interactions are critical because most of the modes of variability (monsoons, ENSO, convection, 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. Land-air-sea interaction plays an important role in shaping the mean state and seasonal cycle over these regions, most notably in the northward displacement of the ITCZ (Philander et al. 1996). State-of-the-art coupled ocean-atmosphere GCMs suffer large biases over the tropical Pacific and Atlantic, limiting their ability to simulate and predict ENSO and other modes of variability. The EPac is a region of complex SST and cloud system variability (e.g., equatorial cold tongue, deep convection, stratocumulus cloud decks), all of which impact climate predictability. The IAS is an important source of moisture for warm-season rainfall over the US and both the EPac and IAS are important for hurricane development. Yet much is still not known about air-sea interactions in these regions and their influence on the climate system of the Americas. A central theme of air-sea interaction research is the development and implementation of focused process studies addressing specific problem areas for GCMs: the studies feature intensive field programs, enhanced monitoring, detailed research model simulations, global/regional climate 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 on shorter time scales by the MJO and thus depends on processes extending to the western Pacific and Indian Oceans.

On the inter-American regional scale, the bi-hemispheric monsoon system is an interlocking set of seasonal relationships, with 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 large areas of the continent, an anti-correlation exists between rainfall in the NAME region and rainfall over the Great Plains, etc. Finally, the Amazon convection during the boreal winter and early spring affects subsidence over the North Atlantic subtropical high (NASH), and thus, the NE trades and tropical North Atlantic SST anomalies in late spring and early summer.

ENSO's effect on cold-season precipitation over North America is well established, and it is now possible to predict ENSO two to three seasons ahead with empirical and dynamical models. The challenge is the prediction of deviations in space and time from a canonical ENSO, which makes each El Niño and its regional influences unique (see Sec. 2.1.2). Conceivably a realistic mean state is important for models to simulate non-canonical developments of ENSO. Recent model studies indicate that long-lasting droughts over the US are forced by SST anomalies but the physical mechanisms for this oceanic influence are not understood (see Sec. 2.1.5). Thus the need for improved climate prediction calls for improved understanding and modeling of ocean-atmospheric processes and interactions over the eastern Pacific, the IAS and the Atlantic.

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.

Although the focus in this chapter is on ocean-atmosphere interactions, it is important to note that these cannot be considered in isolation from land processes. Thus, for example, precipitation anomalies over the Midwest during boreal spring, associated with moisture transport from the IAS, can affect soil moisture there in a way that can carry over to summer and either accentuate or ameliorate the possibilities that summer anomalies will produce a severe drought.

3.1.1 Air-sea interactions in the Eastern Pacific

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 ITCZ convection, schematically depicted in Figure 3.1 (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 (Figure 3.1, 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 and hurricanes, 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 MJO and ENSO, in particular, are important sources of predictability on intraseasonal and interannual timescales, respectively. The lower panel of Figure 3.1 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. The 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; de Szeoke and Xie 2008). 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 Southeast (SE) Pacific off South America partly associated with deficient coverage of low clouds (Figure 3.2). This is apparently related to inadequate simulation of the radiative and other planetary boundary layer processes in the subsidence region (Philander et al. 1996). Recent model studies have indicated that stratus clouds and their associate 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, and ocean processes also play critical roles (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).

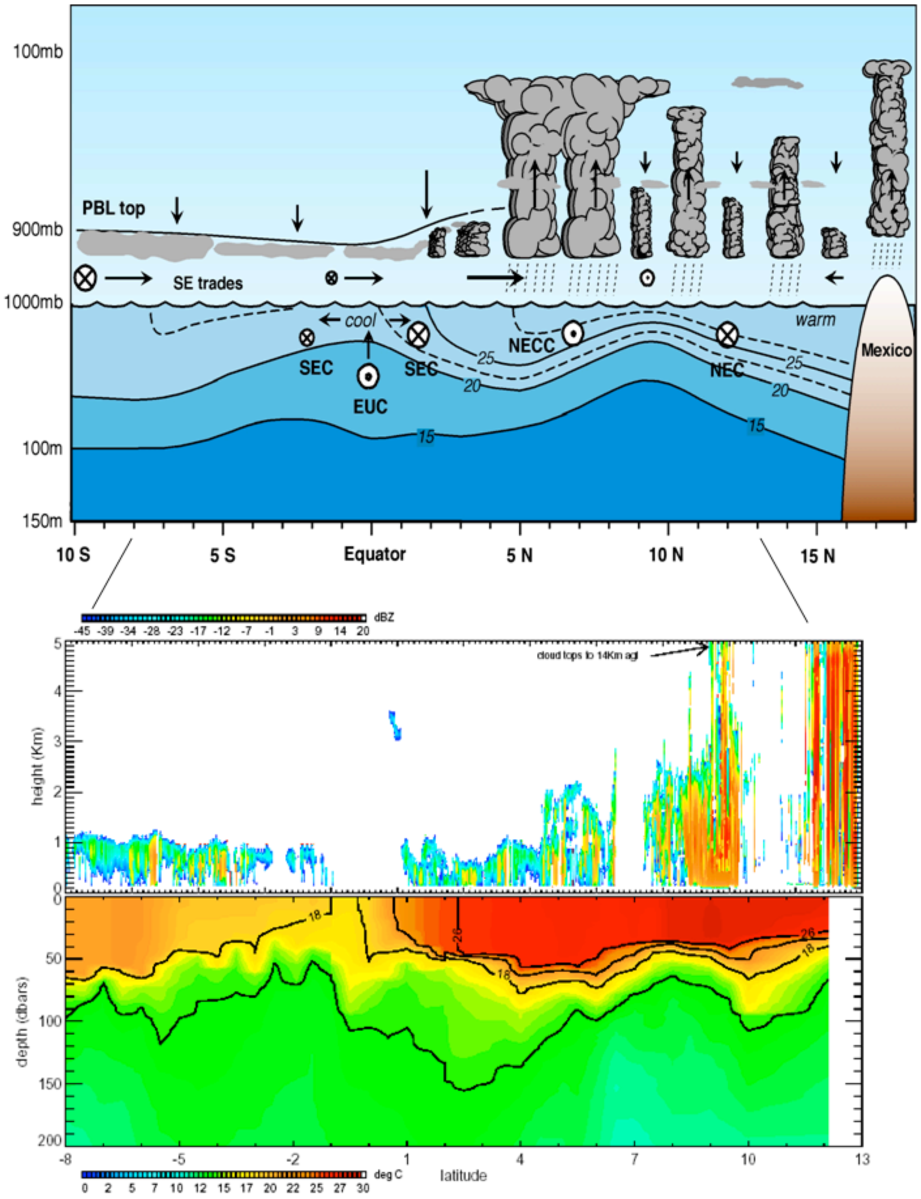

Figure 3.1. (Upper) Idealized cross section through the ITCZ-cold tongue complex in the east Pacific showing the atmospheric meridional circulation, atmospheric boundary layer depth, and oceanic thermal structure. SEC refers to South Equatorial Current, NECC to the North Equatorial Countercurrent, and 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.

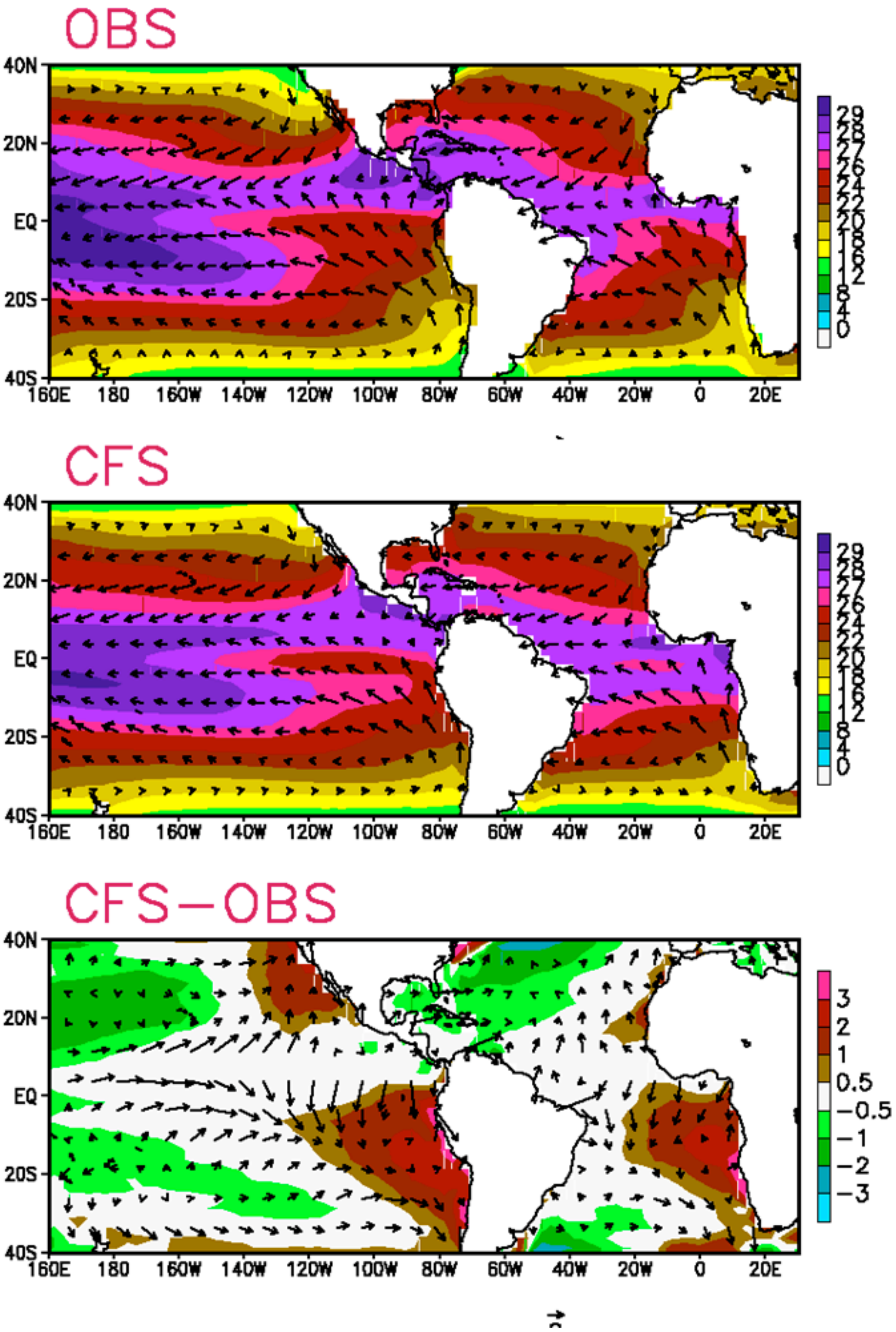

Figure 3.2. Annual-mean SST biases (°C) of the coupled simulations by the CFS (Wang et al. 2005).

The reduced meridional asymmetry in SST in models 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. These GCM shortcomings are related to deficiencies in SST gradient-trade wind feedback (or Bjerknes feedback), SST-surface latent heat flux feedback (e.g., wind-evaporation-SST feedback), and SST-surface shortwave flux feedback (Lin 2007). 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, simulated 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 the 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. Some produce spurious ENSO peaking in July instead of December. 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.

Similar problems plague the coupled models in the Atlantic basin (Richter and Xie 2008). Warm biases exist in the stratocumulus zone off southern Africa, thermocline slopes along the equator are wrong or even reversed, and meridional eddy heat fluxes into the equatorial zone are misrepresented due to inadequate horizontal resolution in OGCMs.

3.1.2 Air-sea interactions in the Intra-Americas Seas

The Western Hemisphere warm pool (WHWP), comprised of warm water regions in the IAS, western tropical Atlantic and eastern North Pacific (ENP), is a climatic nexus for North and South America as well as for the tropical Pacific and Atlantic Oceans (discussed in Sec. 2.1d). This large tropical diabatic heating center drives strong hemispheric-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. 2003). Although the ENP and Atlantic portions of the WHWP interact with each other and jointly affect the large-scale circulation and climate of the Western Hemisphere, they tend to play different roles vis-à-vis the regional climates. The ENP warm pool acts primarily through ENSO in the boreal winter and affects the summer monsoon development in the western United States. The Atlantic warm pool (AWP) including the IAS, being the predominant source of summer moisture for the United States east of the Rocky Mountains, is associated with summer rainfall fluctuations in the Caribbean and eastern United States, and has a large influence on Atlantic basin hurricanes (Wang et al. 2006a, Mestas-Nuñez et al. 2007). The latter indications from observations are consistent with the response of the NCAR Community atmospheric model (CAM 3.1) to the AWP (Wang et al. 2007, 2008).

Easterly waves propagate from the tropical Atlantic and encounter favorable conditions for convective growth as they transit through the IAS, often 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 (Figure 3.3) (Helfand and Schubert 1995; Ruiz-Barradas and Nigam 2005; Mestas-Nuñez et al. 2007). 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), or rainfall hiatus, 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) and this occurred with flooding in spring 2008 as well. On interannual and longer time scales, even subtle but sustained deficits 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). Since 1950, springtime anomalies of Midwest rainfall and tornado activity are consistently related to moisture flux departures from normal across the gulf coast. Whether such events are related to warm pool developments, as in summer, or to other remote forcing, is not known. We also need to understand what leads to persistence of such departures for a season or more and how this affects droughts and flooding through the exacerbating effects of soil moisture anomalies. A full understanding of the processes that control the hydrologic 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 observed features associated with the Intra-America Low-Level Jet (IALLJ) and 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 the 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 produced by the models leads to an over-energized Hadley circulation (Nogues-Paegle et al. 1998), thus extending the influence of the rainfall error far afield. In addition, not all AGCMs correctly reproduce the occurrence of the MSD (Kiehl et al. 1998).

Over the central and eastern United States, improvements in regional mesoscale models, their data assimilation systems and representation of the surface conditions have led to a reduction of the residual of the water balance (e.g., Berbery et al. 2003; Mesinger 2006). Arguably, future local improvements may come from the correct representation of precipitation processes, their triggering mechanisms and evaporation at the surface, rather than on the representation of the low-level jets and their diurnal variations, which at current mesoscale model resolutions are well represented. However, errors in the model convection can lead to an imbalance in the water budget over the IAS and in turn affect the moisture transports out of the IAS into the surrounding land areas. Betts et al. (2006) have shown that some state-of-the-art global reanalyses like NCEP-DOE and ERA-40 have also notably improved with respect to their first versions. Major changes in the atmospheric circulation patterns, with the associated differences in surface temperature, humidity, precipitation, cloud fields and incoming surface SW and LW radiation fluxes are captured by both reanalyses and the ISLSCP-II data sets.

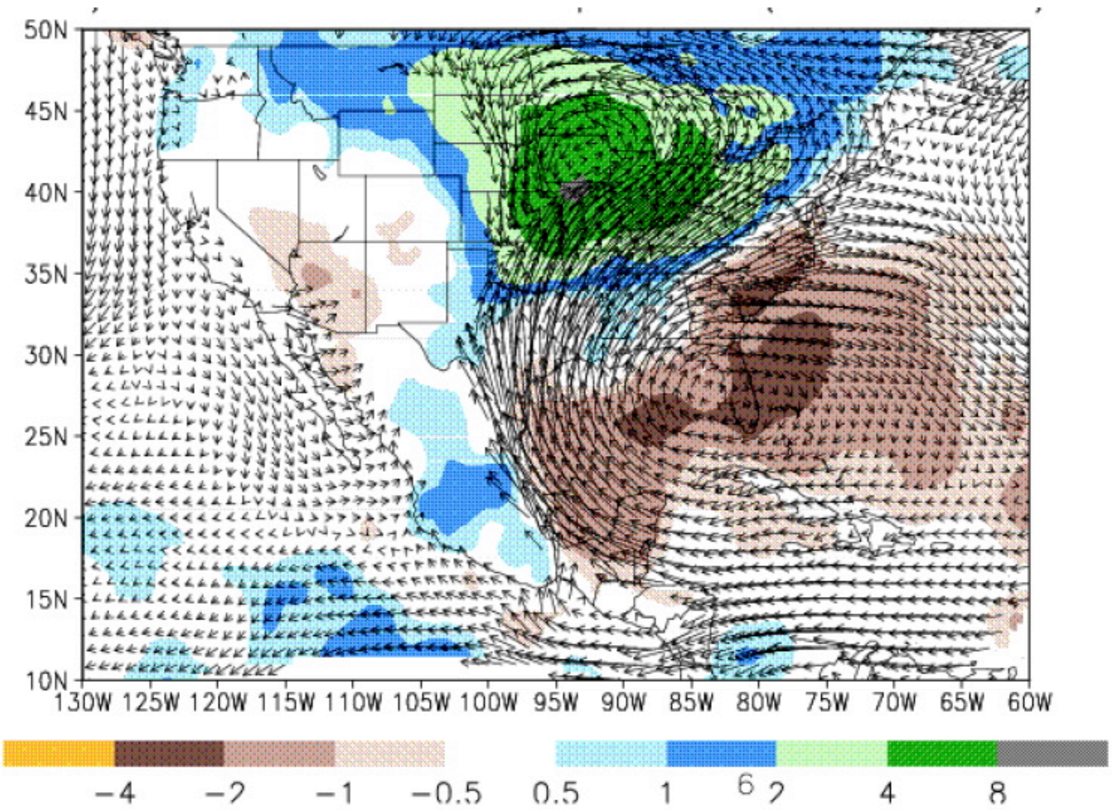

Figure 3.3 Composite-averaged precipitation (colored, mm/day) and 925 hPa wind anomalies (m s^{-1}), for the positive phases of an index of the Caribbean low-level jet (CLLJ), based on the North American Regional Reanalysis (NARR) (provided by K. Mo).

Unlike regional mesoscale models and current global reanalyses, global models do poorly in simulating the mean summer rainfall. This reflects deficiencies in simulating the diurnal cycle, 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. Models also fail to reproduce the observed interannual changes in summer rainfall (Ruiz-Barradas and Nigam 2005). This suggests that climate models must properly represent convective and boundary layer processes over both ocean and land and reproduce both local climate processes and modes of global climate variability, if they are to do well in the IAS region. The IAS is, therefore, an ideal natural laboratory to test the overall fidelity of climate models.

3.2 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 coupled climate models correctly capture the physical processes and phenomena that are critical to simulating these linkages, which include 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 the models to 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, El Niño, as well as longer-term ocean-atmosphere variability.

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

3.2.1. Eastern Pacific

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. Most leading AGCMs (including the GFS) can simulate this climatological transition when SSTs are specified, but they do not always correctly place the cloud regimes and tend to simulate an excessively shallow boundary layer (Bretherton et al. 2004). This generates sizeable surface flux errors compared to buoy and satellite observations. Observations from the PACS-supported EPIC-2001 field campaign 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). Variations of low clouds in the Eastern equatorial Pacific 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 (Kollias et al. 2004), (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 (Garreaud and Munoz 2004) and from the midlatitudes, and how does this cloud deck interact with convection over South America and the ITCZ, (3) what causes pockets of open cells to form within the stratocumulus deck in the SE Pacific (Wood et al. 2008) and how do they contribute to larger-scale variations in cloudiness and surface solar radiation, (4) 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?

Coastal upwelling. The southeasterly wind jet (Munoz and Garreaud 2005) and the strong coastal upwelling (virtually to the equator) trigger the development of the meridional asymmetry of the Pacific climate. An issue with coastal upwelling is, how does it interact with the stratus deck near shore, and how does this interaction change when warmer water upwells during El Niño events? During El Nino, the coastal winds actually increase due to dissipation of stratus over land and near shore combined with offshore SST anomalies. Is the SE Pacific subtropical high (and by extension the larger stratus region offshore) also changed by these interactions? Can the models replicate the observed behaviors*?*

Southeast 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. The oceanic boundary layer under the stratus in this region poses challenges in terms of understanding what controls its structure and thus SST (Colbo and Weller 2007). The surface fluxes add heat and remove freshwater. Mean advection rates in the upper ocean are low, a few cm s^{-1}, and the residence time of this layer under the stratus is long. What keeps this layer cool besides stratus clouds? The prevailing southeast trades drive surface flow to the southwest, but over much of this offshore region the surface isotherms are parallel to the Ekman 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 trade winds are persistent in direction 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? 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, and 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 maintain 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? What are the processes that allow and control exchanges across the sharp SST front north of the cold tongue? What are the physical mechanisms for the interaction of the seasonal cycle and ENSO and for the latter's phase locking?

The difficulty in simulating the equatorial Atlantic circulation and thermal structure with coupled models makes a case for integrating land processes with ocean-atmosphere interactions. For example, model biases in the diabatic heating over the Amazon region and equatorial Africa are responsible for a westerly low-level wind bias over the equatorial Atlantic (Chang et al. 2007; Richter and Xie 2008). The underestimation of Amazon heating is also likely to produce too little subsidence over the Caribbean where convective rain is too plentiful in the models. Clearly, the convective heating over the Amazon creates a huge challenge for modelers, but also a great opportunity to improve predictability in the Western Hemisphere.

3.2.2. Western Hemisphere Warm Pool

Warm pool development. 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. Upwelling along the southern boundary of the Caribbean is strong during most of the year and the advection of upwelled water northward impacts the state of the Atlantic warm pool during the warm season. In order for OGCMs to get the warm pool heat budget correct they must properly represent the upwelling for 'perfect winds' and the coupled models must replicate the Caribbean low-level jet acceptably well. One of the known model biases is a too-weak Amazon convection, which can influence warm pool development through Hadley-induced subsidence over the NASH and introduces a westerly bias in the low-level wind over the equatorial Atlantic (Figure 3.4; Deser et al. 2006; Chang et al. 2007, 2008; Richter and Xie 2008).

Eastern Pacific convection. The seasonal and interannual variability of the ITCZ is strongly regulated by SST over the eastern Pacific warm pool. This coupling is particularly strong on the south edge of the warm pool while it is less clear what controls the convection on the northeastern part of the warm pool off Central America and Mexico. The Central American landmass, via gap winds and the resultant thermocline structure, has clear imprints on the eastern Pacific ITCZ (Xie et al. 2005). Recent studies indicate that ocean eddies and Rossby waves have significant impacts on atmospheric convection (Hashizume et al. 2001; Wijesekera et al. 2005; Farrar and Weller 2006). High-frequency wind variability associated with easterly waves and the MJO is important for sea surface evaporation and warm pool SST (Raymond et al. 2006; Maloney and Esbensen 2007). The vertical velocity and latent heating display bottom-heavy structures over the eastern Pacific warm pool, in contrast to the top-heavy ones over the warm Pacific (Thompson et al. 1979; Back and Bretherton 2006). Given that eastern Pacific convection initiates atmospheric teleconnection to North America, it is important to study the interaction of the ITCZ and ocean processes, both locally over the eastern Pacific warm pool and remotely via the Hadley/Walker circulation.

Caribbean convection. While the Caribbean Sea is as warm as the eastern Pacific warm pool in boreal summer, convection is much weaker in the former than the latter region. We do not 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 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). Another is that parameterized convection in AGCMs is insufficiently sensitive to mid-tropospheric humidity (e.g. Derbyshire et al. 2004) and cannot be adequately suppressed in models by dry air in the lower-to-mid troposphere usually seen over the IAS. A related problem, in some models, is the way precipitation occurs. For example, in NCAR CAM3, the presence of convective available potential energy (CAPE) in the model troposphere unrealistically causes precipitation until all the CAPE is exhausted, with no mechanism for mixing from drier adjacent environments. Understanding these processes and correctly simulating them is of highest priority because it carries over to the water budget above the IAS and the moisture transports into land areas. Caribbean precipitation is just one of the known deficiencies of convective parameterizations that must affect model success throughout the WHWP and surrounding regions. The contrast with eastern Pacific convection offers a valuable focus for studying WHWP-atmosphere interaction.

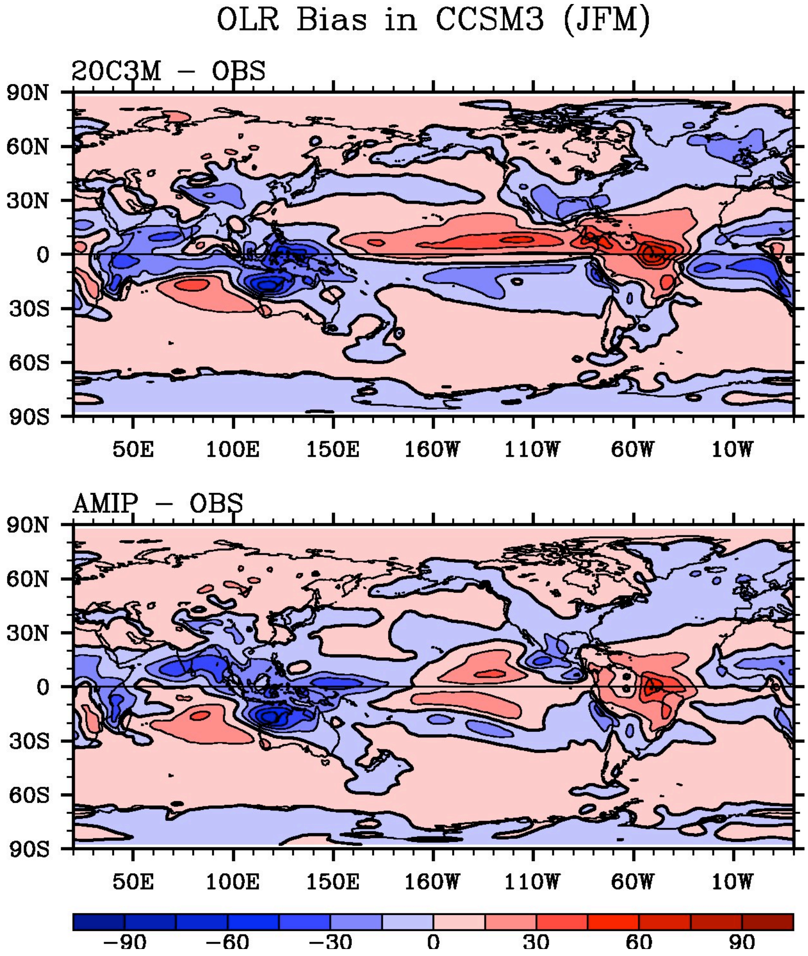

Figure 3.4. The outgoing longwave radiative flux (OLR) bias of two CCSM3 runs, 20C3M and AMIP, for boreal winter (JFM) are shown in the upper and lower panel, respectively. The NCEP-NCAR reanalysis dataset is used for the subtracted observations. Positive (negative) values imply a deficient (excessive) deep tropical convection. Units are W m^{-2} (courtesy S.-K. Lee).

Mid-summer drought. The MSD can be seen in climatologies from the eastern North Pacific to Florida and the eastern Caribbean, and it has great significance for subsistence agriculture throughout the Caribbean and Central America (Magaña et al. 1999). The MSD is not exclusively an IAS phenomenon and appears to be especially well defined in the ENP. It also occurs over southern China during the Asian summer monsoon (Ding and Sikka 2006). However, the Atlantic warm pool appears to have a strong impact on moisture convergence in the ENP (Wang et al. 2006b) so the MSD should be studied in the context of both WHWP regions. Some AGCMs have simulated the MSD and mechanisms for it have been proposed (Magaña et al. 1999; Mapes et al. 2005; Small et al. 2007). 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.

<u>Dynamics of low-level jets.</u> 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 (Figure 3.5). 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 NASH, as well as surface forcing by large or small sizes of the AWP. Unfortunately, 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.

<u>Land-air-sea interaction.</u> 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. Another common problem is the tendency for models to have deficient convection in the Amazon basin, which affects subsidence over the North Atlantic and Caribbean and winds over the equatorial Atlantic (Figure 3.4). 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).

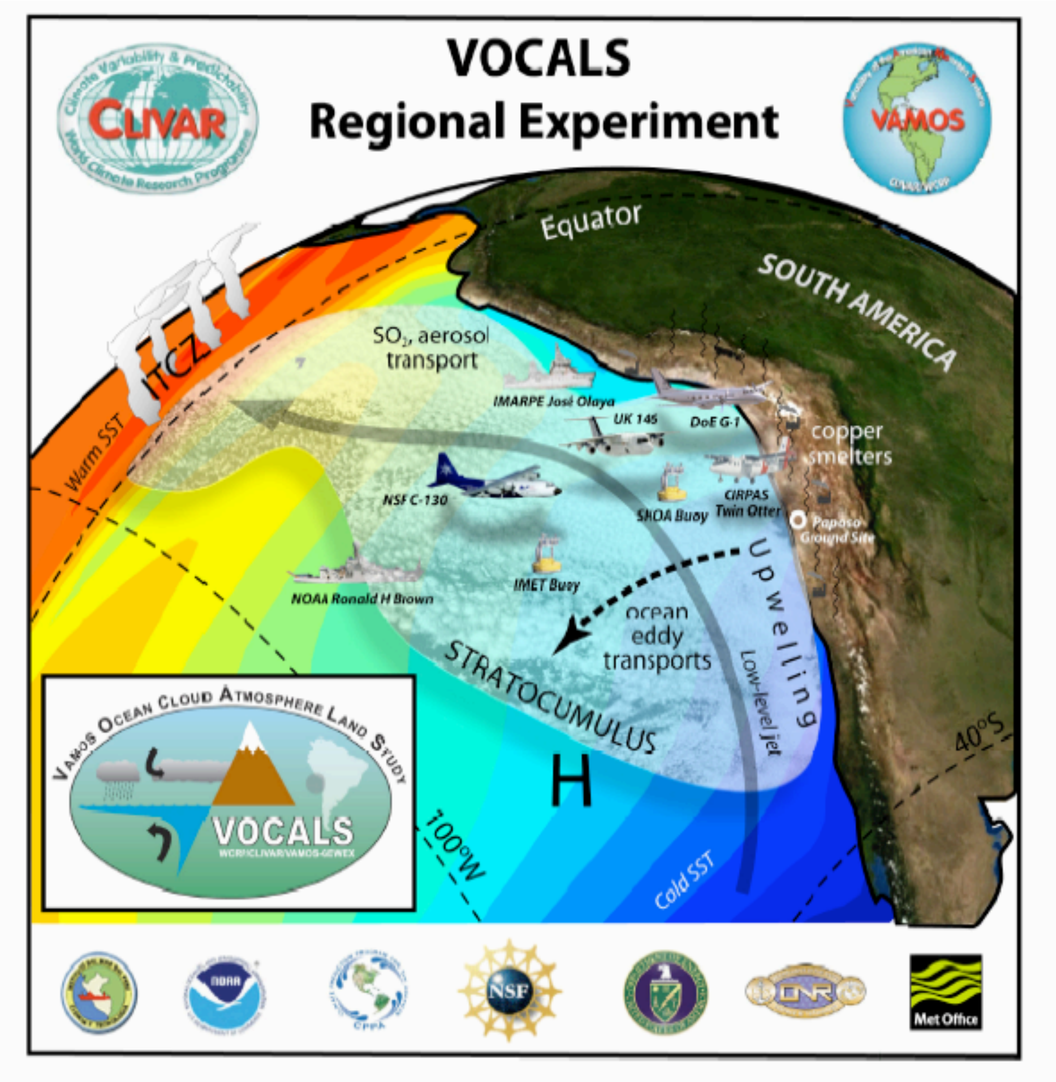

Figure 3.5. Schematic showing the principal components of the VOCALS-REX regional field program planned for October-November 2008.

Tropical cyclones. 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. Tropical cyclone activity is in the IAS region is also modulated by the MJO (Maloney and Hartmann 2000). 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, while CAPE increases. These factors all 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. A third strong influence on TCs is the outbreaks of the Saharan air layer (SAL) during the hurricane season. Only about a decade of good measurements of the SAL is available to assess how well models replicate SAL outbreaks, which discourage storm development.

3.3 Air-Sea Implementation Strategies

3.3.1 ITCZ, cold tongue and stratus deck

Most of the air-sea interactions studies in this region are organized in the **V**AMOS **O**cean-**C**loud-**A**tmosphere-**L**and **S**tudy (VOCALS), which 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.eol.ucar.edu/projects/vocals/). The VOCALS strategy is based on a close coordination of observations, analysis, and modeling. The observations include both long term monitoring and an intensive field program (VOCALS-REX – see below)

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 brief 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 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^{o}S to 8^{o}N. Under the stratus cloud deck at 85^{o}W, 20^{o}S, WHOI maintains a buoy since October 2000, collecting oceanographic (temperature, salinity and current) and surface meteorological data (Cronin et al., 2002; Colbo and Weller 2007). In 2006 surface meteorological sensors were added to the SHOA/DART buoy at 85^{o}W, 20^{o}S. In the tropical Atlantic, the PIRATA mooring array provides valuable data with TAO-style moorings from 20S to 20N. The U.S. National Data Buoy Center (NDBC) maintains four buoys in the central Caribbean with surface meteorological and ocean wave measurements, and numerous buoys in the Gulf of Mexico.

Atmospheric and oceanic soundings On cruises that service TAO and WHOI buoys, atmospheric sounding and oceanographic observations are conducted (Kollias et al. 2004; Fairall et al., 2008; Wood et al. 2008). 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

Section 3.3.1a describes panoply of routine/monitoring observations that provide a long term data base for air-sea interaction studies. However, intensive field observations are also necessary to fill critical gaps in understanding and parameterizing important physical processes. For this VOCALS has developed plans for a region experiment (REX) 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-November 2008 (Figure 3.5). Details of the field program and coordination with modeling efforts are contained on the VOCALS website cited above.

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. Mostly these modeling activities are organized under VOCALS. More complete details can be found in the VOCALS Modeling Plan1, but we summarize the range of activities below.

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

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1 Available at *www.eol.ucar.edu/projects/vocals/documentation/VOCALS_Modeling_0906.pdf*

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 needs further study.

A principal goal of VOCALS is to improve model simulations of key climate processes using the southeast Pacific (SEP) as a test-bed, particularly in coupled models that are used for climate change projection and ENSO forecasting. VOCALS-Mod, therefore, provides the context for VOCALS and will directly benefit from the observations collected in the field campaign. The principal objectives of VOCALS-Mod are (1) improving the understanding and simulation of diurnal, seasonal, inter-annual, and inter-decadal variability in the SEP; (2) improving the understanding and simulation of oceanic budgets of heat, salinity, and nutrients in the SEP and their feedbacks on the regional climate; (3) developing the capability for simulation of cloud optical properties (coverage, thickness, and droplet size) and the effect on these properties of aerosols emitted in the region; (4) elucidating the interactions between the SEP climate and remote climates. VOCALS-Mod will provide modeling support for VOCALS-REx through real-time forecasts and data assimilation. The research methodology in VOCALS-Mod will be organized into several themes:

- Downscaling to the VOCALS-REx study region: Global reanalysis data will be used as forcings for RAMs and ROMs, the output of which will provide invaluable regional context in which to interpret VOCALS-REx field data. The model data will be compared directly with VOCALS-REx and VOCALS extended observations (e.g. mesoscale ocean eddies, satellite and ship-observed clouds), and will be used to force LES models and SCMs to better understand physical and chemical processes and improve their representation in large-scale models.

- Ocean mesoscale eddy structure and transports: High resolution ROMs will be used in conjunction with the VOCALS-REx oceanographic mesoscale survey and satellite data to determine the horizontal and vertical eddy structure, eddy heat/freshwater/biota transports from the coastal upwelling region to the remote SEP, and interactions between the eddies, the mixed layer and the deeper ocean. The ability of ROMs to accurately resolve the eddy structure will be critically tested using VOCALS-REx data.

- Aerosol-cloud-drizzle-ocean interactions: Data collected by VOCALS-REx will be used to constrain and refine parameterizations of aerosol scavenging, cloud fraction and cloud microphysical processes used in participating AGCMs and RAMs, building on results from the EPIC stratocumulus cruise (Bretherton et al. 2004). LES models will be used to investigate the physical processes involved in the formation and maintenance of pockets of open cells (POCs).

- Diagnostic studies of the regional climate system: RAMs, ROMs and ROAMs will be used to investigate the coupling between the atmosphere, ocean and land in the SEP region including feedbacks between SST and clouds, the strong diurnal cycle, orographically and thermally patterned wind forcing, and mesoscale eddy modulation of the boundary layer depth and cloud cover, and interactions between coastal upwelling, the coastal jet, and cloud cover.

- Development of a Multi-Scale Simulation and Prediction (MUSSIP) System: VOCALS-Mod will investigate one possible approach to a Multi-Scale Simulation and Prediction (MUSSIP) system. This will be based on a RAM coupled to an eddy-resolving ROM embedded within a global climate model or forced by reanalysis data. The focus will be on the eastern tropical Pacific and adjacent areas of the South American continent, from approximately 5°N-30°S, and 65-90°W. The MUSSIP approach is predicated on the importance of climate interactions across scales, i.e., that global changes are manifested in their regional details by downscaling effects (e.g., wind and cloud patterns adjacent to the Andes and coastal upwelling zone) and that global changes themselves occur through important upscaling effects of the regional climate (e.g., teleconnection consequences for precipitation changes throughout the tropics due to Southeast Pacific SST changes).

The VOCALS modeling vision is based on the concept of a multiscale hierarchy of models. This is motivated by the multiscale nature of processes in the SEP and fits well with the multiscale hierarchy of VOCALS observations, including REx, extended in-situ and satellite data. To implement this vision, VOCALS-Mod will coordinate activities carried out at operational centers (NCEP), research laboratories (NCAR, GFDL) and universities, with the goal of using VOCALS observational datasets both to evaluate model performance and to inform physical parameterization development. Use of the operational modeling systems will provide insight into the time evolution of errors and their dependency on the analysis employed for initialization; use of research modeling systems will facilitate the realization of hypothesis-testing experiments. The collaborations established will make available the hierarchy of numerical models needed to address the broad range of space and time scales of processes in the VOCALS region.

A VOCALS model assessment project has started (VOCA). The first stage (PreVOCA) of this is currently taking place prior to VOCALS-REx and aims to critically assess the ability of global and regional atmospheric, oceanic, and chemical transport models to simulate and predict synoptically-varying clouds, meteorology, ocean circulation and aerosols in the southeast Pacific (SEP) subtropical stratocumulus regime for a month in the southern spring season. All participating models must be run in some form of weather forecast mode. Currently, thirteen modeling centers worldwide, including the major US centers, have performed and submitted model runs. These simulations will be tested using data from cruises, the IMET buoy, satellites, and from VOCALS-REx itself.

VOCALS-Mod participants will participate in organized modeling activities, such as the community-wide “Correcting Tropical Biases Workshops”, the GCSS/WGNE Pacific Cross-section Intercomparison (GPCI) project, and the GEWEX Cloud System Study (GCSS).

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.

3.3.2 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 (Intra-Americas Study of Climate Processes) program, recently approved by the VAMOS panel (March 2008), 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 as needed, 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. The IASCLIP Science and Implementation Plan is available at ftp.aoml.noaa.gov/phod/pub/enfield/Visitor_temp. IASCLIP research 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 (Figure 3.6; Mestas-Nuñez et al. 2005; Mestas-Nuñez et al. 2007; Wang et al. 2006b); (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. 2006a); 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. Eventually, a field campaign and/or long-term monitoring program may be justified to collect observations needed for the improvement of model performance.

Phase I (2008 – 2011): Diagnostic and Modeling studies – Many issues can at least partially be addressed by diagnoses of existing data and by numerical modeling. These efforts should better assort problems that may 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:

- 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 soundings 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.

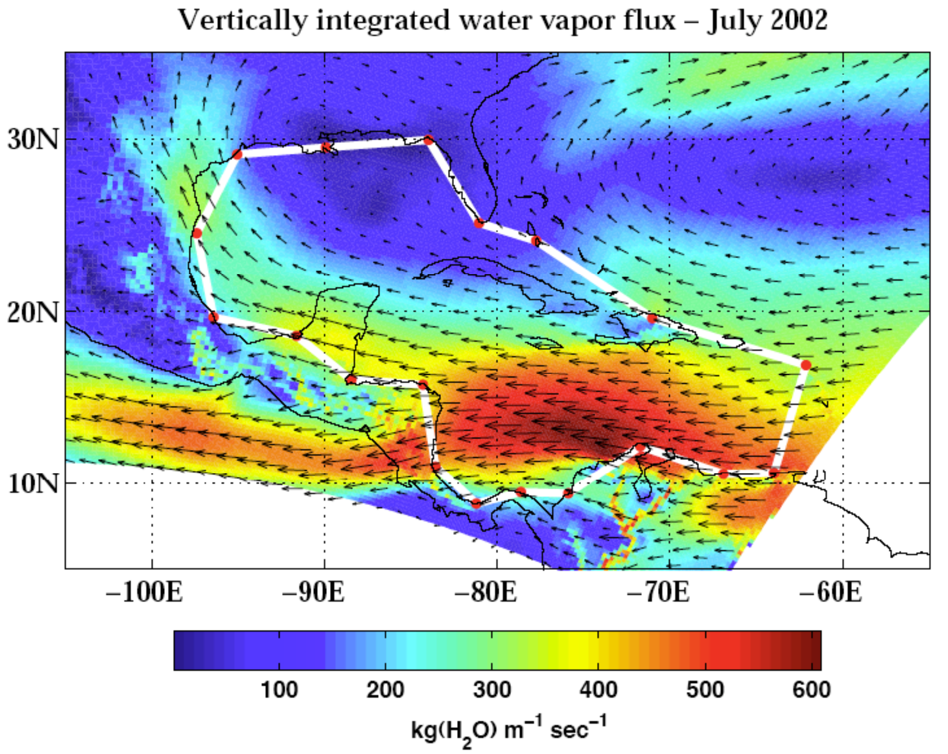

Figure 3.6. Vertically integrated water vapor flux for July 2002 used to illustrate the coverage of the IAS by the current NCEP Eta North American regional reanalysis. Stars mark the locations near the IAS coast at which sounding observations are available.

Phase II (2011 - 2012): Field Campaign – It is premature at this stage of our knowledge of the IAS to prejudge what a possible field campaign would look like. Assuming success in the Phase I activities of model assessments, a field campaign could be launched early in the next decade. However, it is certainly possible to anticipate a number of characteristics that an observational strategy would have:

- The woefully inadequate ocean monitoring in the IAS region would be expanded during an extended observation period (EOP) of 2-3 years, by deploying surface drifters, XBTs and even shallow Argo floats. Assuming the proven value of this, most of these expansions would become part of a permanent legacy of IASCLIP.
- Atmospheric profiling would be improved, at least during the EOP, by supplying radiosonde expendables for more frequent soundings by regional meteorological services, and by deploying semi-autonomous stations at strategically located small islands.
- An embedded, intensive observation period (IOP) would feature expanded ocean and atmosphere observations spanning from mid-spring to late summer with oceanographic cruises (helped by partners in Colombia and/or Mexico) and with aircraft overflights synergistically coordinated with NOAA's Hurricane Research Division, who share many of the IASCLIP objectives related to tropical cyclones.
- To the extent possible, observations will be expanded by supplementing the existing systems. An example is the opportunity to deploy additional sensors on and below the NDBC platforms already moored in the Caribbean.

3.4 Deliverables

Short term

- Produce and maintain a central data archive structure at NCAR/EOL either housing or linking to observations and model output for each CPPA field program. CPPA investigators will be expected to submit to this archive (the contents of which will be made publically available within a few years of execution);
- Produce one or more integrated datasets for each CPPA field program that can be used as a toolbox for model and parameterization development and assessment. These are synthesis and value-added products that are distinct from the central archive;
- Produce a preliminary multi-model intercomparison for the VOCALS region to provide guidance and context for the VOCALS-REX field program;
- Develop metrics for assessing model deficiencies (e.g., MJO and tropical biases), and develop observational requirements for eastern Pacific and IAS climate processes;
- A synthesis report summarizing what has been accomplished from past CPPA Air-Sea Interaction projects;

Longer term

- Comprehensive in situ observational data sets for eastern Pacific and IAS region;
- Improvements in global, NARR and ocean (e.g., SODA) reanalyses through assessments and improved monitoring;
- Improved understanding of cold tongue, stratocumulus layer dynamics, ITCZ convection, WHWP, and their coupling;
- Improvements to cumulus and cloud-topped boundary layer parameterizations
- Predictive understanding and modeling of summer rainfall in the U.S.;
- 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;
- Recommendations for optimal global climate observing systems

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4. LAND-ATMOSPHERE INTERACTIONS

4.1 Science Background

The Climate Prediction Program for the Americas (CPPA) vision is to improve operational intraseasonal to interannual climate prediction and hydrologic applications. It is recognized that the land surface and the atmosphere are a tightly coupled system that evolve together on both diurnal and seasonal time scales (Betts, 2000). Previous research has provided guidance on which aspects of the coupled land-atmosphere system and geographical regions (e.g., Koster et al. 2004) are most likely to be associated with predictability. Therefore, this chapter identifies the science rationale and implementation tasks required to: (1) improve the understanding and model simulation of coupled land-atmosphere processes through observation, data analysis, and modeling studies; (2) determine the influence of land-atmosphere processes on intra-seasonal to interannual climate predictability; and (3) use this knowledge to advance operational climate forecasts, monitoring, and analysis systems.

There are four aspects of the land-atmosphere interaction which possess “memory like” characteristics, in the sense that, at any point in time, the then current land-surface energy and water exchanges that influence the overlying atmosphere are themselves, in part, determined by the history or the climate to which the land-surface has itself been exposed in preceding months. These land-memory mechanisms include: (i) the storage of water near the surface as soil moisture (ii) its storage on the surface as snow and ice, (iii) nature and seasonal progression of growing vegetation, and (iv) the influence of topography on atmospheric processes. Both water storages affect the surface interactions with the overlying atmosphere and the amount of water leaving as runoff in streams or to ground water. The nature and seasonal progression of growing vegetation also represents a land memory, because the nature and growth status of plants partly reflect past climate but controls current surface energy, moisture, and momentum exchanges. In addition, topography, although not a land memory in the sense just described, has a well-recognized and persistent (remembered) influence on precipitation and hydrologic flows and, during the cold season, can determine whether precipitation falls in liquid or solid form, and therefore the accumulation and melt of snowpack on the ground, which in turn has an impact on the energy budget at the surface.

Recent research in land-memory processes suggest that seasonal predictions conditioned on land-memory states have lower variability and therefore higher predictability than unconditioned seasonal predictions. Understanding the strength of these relationships for different geographical regions and seasons, and their robustness over time and models remains a challenge that needs to be addressed.

To address the CPPA vision, it is necessary to identify, adequately understand, and capably model those land-atmosphere features, phenomena, and processes that can contribute to intra-seasonal to interannual predictions of climate and hydrologic variables. CPPA will address this goal in a study area that includes the North and South American continents. This extended study area provides an opportunity to investigate hydrometeorological interactions in more extreme environments than were sampled under the pervious GCIP or GAPP programs, and to make more explicit connections to large-scale atmospheric and ocean processes.

4.2 Science Objectives and Priorities

4.2.1 Topographic influences

Subscale variability of topography has a marked influence on atmospheric processes including atmospheric circulation, cloud, and precipitation, and a strong control on surface hydrological flows. The interaction between atmospheric and hydrologic processes and topography necessarily involves questions of both temporal and spatial scale, as well as identification of significant, controlling topographic parameters, such as elevation, slope, and aspect. Such topographic parameters can be readily derived from digital elevation models at various spatial scales in the CPPA study area. On the other hand, precipitation data in mountainous areas are often poorly sampled by ground stations and poorly measured by radar. This factor places significant demands on analysis techniques and underlies the need for additional, strategically placed, ground stations.

On modeling of orographic precipitation, significant challenges remain in simulating both cold season and warm season orographic precipitation. These challenges are partly due to the difficulty in representing scale interactions (e.g., the influence of large-scale circulation on regional precipitation, and the influence of local condensation and microphysical processes on upstream flow stability), and inadequate model representation of processes such as microphysics and embedded convection in mesoscale clouds. For warm season precipitation, in particular, key issues associated with the initiation and life-cycle of convection over the North American Cordillera and the eastward propagation of organized convection are not well understood and have not been properly represented by existing parameterizations. Although higher spatial resolution is considered desirable, physics parameterizations are resolution dependent, and the appropriate scale for modeling and analysis has not been well defined.

In addition to direct effects of orographic forcing on precipitation, also fundamental to CPPA are the indirect and remote effects of the North American Cordillera. Indirect effects include the orographic influences on the initiation of convection and heat-generated mesoscale circulations in mountainous terrain. Remote (far-field) effects involve traveling mesoscale systems (Carbone et al. 2002) not represented by existing (single-column) parameterizations. These research issues can be addressed using a hierarchical modeling approach based on (parameterized) regional-scale and (explicit) cloud-resolving models (Liu et al. 1999, 2000a, 2000b) that stem from oceanic convection studies (Grabowski et al. 1998; Wu et al. 1999). These models provide statistically meaningful results that contribute to the development of both GCMs and statistical models.

Besides dynamical models, statistical models of the influence of topography on precipitation are also useful for downscaling precipitation patterns for hydrologic modeling. Statistical analysis of the interaction of precipitation with topographic parameters involves calibrating appropriate, single-point statistical models to the observed temporal variability (Hutchinson, 1991a, 1995a). Such models can conveniently separate long-term average precipitation patterns from anomaly patterns. These separate components can have different spatial scales and different topographic dependencies. This approach can be advantageous when using observations to calibrate topographic dependencies to support the spatial interpolation and statistical simulation of precipitation patterns. It can also help to identify key statistical parameters associated with longer-term change and predictability.

On modeling of surface/subsurface and vegetation processes, much progress has been made with one-dimensional models to simulate hydrological and ecological processes, but challenges remain in translating skill from point modeling to correctly capturing the simultaneous spatial distribution of multiple variables such as snow and streamflow in regions of complex terrain. When hydrologic models capable of describing the horizontal movement of water are coupled to regional models, the resulting coupled models can represent the hydrologic response of catchments to topography. Testing the performance of such coupled hydrometeorological models is a priority for CPPA. A useful testbed for studying the role of orography and land surface states on hydrologic prediction and evaluating hydrometeorological models is to investigate the atmospheric and hydrologic processes during flooding associated with the Atmospheric River (AR) (e.g., Ralph et al. 2006). Because of the links between AR and the Madden-Julian Oscillation, this has important implications to atmospheric and hydrologic predictions at the intraseasonal time scale.

Among the questions relating to predictability, issues associated with topography that will be addressed under CPPA are the following:

- Is it possible to define a robust statistical relationship between topography and precipitation? Specifically, how sensitive are the parameters in such a statistical relationship to geographical location and interannual variability, and are the parameters in such a statistical relationship different for liquid and frozen precipitation?
- Can coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography?
- How does the influence of topography on precipitation, including its influence on whether precipitation falls in liquid or solid form, the displacement of precipitation by upstream blocking, and the formation of mesoscale convective systems, modify the magnitude and timing of hydrologic flows in watersheds of differing spatial scale?
- What are the impacts of the complex terrain and land surface states on flooding during extreme events such as that associated with the AR with potential predictability at the intraseasonal time scale?

4.2.2 Snow, ice and frozen soil

Snow processes are important in climate and weather prediction models because of snow's high albedo and low thermal conductivity, and its considerable spatial and temporal variability. The controls exerted by snow and ice on energy and water exchanges between the atmosphere and the underlying soil are therefore markedly different than corresponding controls on other surfaces. In addition, the timing of snowmelt and the subsequent fate of melted water play an extremely important role in the hydrological response of catchments.

Several studies have investigated the development and validation of snow submodels in climate models (e.g., Loth et al., 1993; Lynch-Steiglitz, 1994; Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000). These stand-alone model evaluations are encouraging but reveal that there are significant observational problems when validating snow/ice models. There are, for instance, challenges in accurately specifying the model forcing data. Measuring snowfall is difficult, especially in windy conditions.

It is also difficult to specify a threshold temperature to characterize when precipitation falls as snow rather than rain, and although it is difficult to measure downward long-wave radiation, it is important to do so because this component is the dominant wintertime radiation flux (Yang et al., 1997). There has been a general lack of measurements of snow temperature and density, and snow water equivalent and snow depth are often sampled infrequently, which makes model validation difficult, especially during the (often rapid) snow ablation period.

Yang (2000)) reviewed the snow/ice models used in weather forecasting, climate research, watershed modeling, and process studies. There are numerous snow/ice models, but the models that were used in the Schlosser et al. (2000) intercomparison study show substantial mutual disagreement because there is currently limited understanding of many important snow/ice processes. Poorly understood processes include the time-evolution of snow albedo, the representation of patchy snow/ice cover, sublimation, snowmelt and re-freezing, the retention and transport of melt water, and, not least, the mutual interaction between the snow/ice processes and the soil and vegetation processes within a comprehensive land-atmosphere model (Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000).

When coupled to climate models, snow/ice models do seem to be able to capture the broad features of the seasonal snow regime such as seasonal variations in the snow line. However, a convincing explanation of the still significant discrepancies in simulations of snow cover remains illusive because of the complex feedbacks between precipitation, air temperature, radiation, topography, vegetation, and snow. In the case of global models, for instance, the reasons for the frequent delays in modeled snowmelt at high latitudes in Eurasia and North America are not known (Yang et al., 1999), and similar unexplained weaknesses are also observed in regional climate model simulations for areas such as the Pacific Northwest U.S. (Leung and Ghan, 1999; Leung and Qian 2003).

Thus, there are many difficult challenges remaining in the development of adequate representations of snow accumulation and snowmelt processes before predictive coupled hydrologic-atmospheric models can be expected to successfully reproduce the observed relationship between spring snow pack and subsequent summer rainfall in the southwest U.S. (Gutzler and Preston, 1997). By investigating the development of both uncoupled and coupled snow/ice models in regions with and without strong topography and by studying the potential climate predictability associated with the snow/ice memory in the

North America context at catchment to regional length scales and at time scales up to seasonal, CPPA may meet this requirement.

Although there have been many studies of the effect of liquid soil moisture on climate, the effect of frozen soils on land surface processes and the climate system has received little attention. However, approximately 60% of the exposed land surface in the Northern Hemisphere experiences seasonal freezing and thawing (Zhang et al., 2000) which often lasts several months and may reach depths of 2 to 3 m, while about 24% of northern hemisphere continents are classified as permafrost regions (Zhang, et al., 1999). Because of the latent heat of fusion, freezing and thawing wet soil involves a very substantial uptake or release of energy, so soils that freeze and thaw have, in effect, a large heat capacity. Freeze-thaw cycles influence the thermal and hydrological properties of the soil and this attribute has a significant impact on surface energy and moisture balances (Kineshita, 1982; Williams and Smith, 1989; Yershov, 1998) and, hence, on the climate system. Freezing soil increases its thermal conductivity and hence the soil heat flux, but it reduces its hydraulic conductivity and infiltration, thus increasing runoff, although near surface soil moisture may still increase due to restricted deep drainage. The existence of a thin frozen layer at the surface essentially decouples the moisture exchange between the land surface and the atmosphere. Soil freeze/thaw has a great impact on the onset of plant growth in the spring, on the regional carbon cycle and ecosystems and on the infiltration rates of spring snowmelt.

Among the land-atmosphere predictability questions associated with snow and ice cover that will be addressed under CPPA are the following:

- Can snow/ice submodels adequately represent the observed seasonal evolution of snow cover at catchment and regional scales and can they correctly simulate the effect of snowmelt on the hydrological response of catchments?
- Can regional climate models adequately reproduce observed relationships between snow/ice cover and regional climate?
- Can coupled regional hydrometeorological models that include snow/ice submodels adequately reproduce the observed seasonal evolution of snow cover and snow water equivalent at catchment and regional scales and the associated hydrological response of catchments?
- How can the timing, duration, areal extent, and depth of seasonally frozen and thawed soils best be observed?

4.2.3 Soil moisture

Hydrologic states that have long memory, such as soil moisture, may serve to integrate past atmospheric forcing and enhance prediction skills for regional climates. Fennessey and Shukla (1999), Atlas et al. (1993), Bounoua and Krishnamurti (1993a,b), Xue and Shukla (1993), and Oglesby (1991) presented examples of numerical experiments, based on general circulation models that indicate the sensitivity of climate simulation to initialization of surface soil moisture. Early studies by Delworth and Manabe (1993) showed that the presence of an interactive soil-moisture reservoir acts to increase the variance and add memory to near-surface atmospheric variables such as humidity, while Milly and Dunne (1994) identified and analyzed shifts in the atmospheric general circulation and hydrologic cycle in response to soil water storage capacity. Koster and Suarez (1996, 1999) introduced statistical measures to distinguish between inherent climate variability and variability due to the presence of land memory in the form of soil moisture.

On weather and storm event time scales, there is also evidence that initial soil conditions can reinforce the development of precipitating weather systems. At the regional scale, soil-moisture availability has substantial influence on elevated mixed layers and on associated "lids" on atmospheric instability that act to focus the release of convective instability and hence determine the distribution of the regional precipitation in time and space (Benjamin and Carlson, 1986; Clark and Arritt, 1995). Such coupling was clearly demonstrated by numerical modeling (Paegle et al., 1996; Beljaars et al., 1996; Betts et al., 1996; Liu and Avissar, 1999a,b). These mechanisms are believed to have played a significant role in the Mississippi River floods in 1993. Castelli and Rodriguez-Iturbe (1993) showed that growth of baroclinic instability could be enhanced by anomalies in surface fluxes. Using numerical mesoscale atmospheric models, Chang and Wetzel (1991) and Fast and McCorcle (1991) showed that the evolution of summertime weather systems in the Midwestern U.S. is critically dependent on so-called "dryline" conditions where sharp gradients in soil moisture are present.

Thus, it is apparent that, in certain conditions, land memory in the form of the soil-moisture store, perhaps reinforced by positive feedback mechanisms such as recycling of precipitation, has significant effects on atmospheric variability and predictability and can lead to greater persistence of weather and climate anomalies. Delineation of the conditions under which soil-moisture state is important to the evolution of weather and climate, coupled with ways of estimating the initial soil-moisture state based on in situ and satellite observations and the realistic simulation of the subsequent evolution of that soil-moisture state in predictive models, should allow the extension of atmospheric forecast skills.

Among the land-atmosphere predictability questions associated with soil moisture that will be addressed under CPPA are the following:

- Can the land surface models used in climate prediction models adequately represent the observed seasonal evolution of soil moisture and hydrologic response at catchment to continental scales?
- Does the use of off-line calculations of soil moisture improve predictions of seasonal climate and hydrologic responses?
- Are there ways of estimating the initial soil-moisture climate model state based on in situ and satellite observations, and does the use of such initialization methods improve the ability of these models to predict climate and hydrologic responses?

4.2.4 Vegetation and land cover dynamics

Vegetation plays a major role in determining the surface energy partition and the removal of moisture from the soil by transpiration. Representation of the vegetation's response to atmospheric and hydrologic influences is currently weak in models used to generate monthly to seasonal predictions of precipitation and hydrologic variables.

There has been substantial progress in representing heterogeneous vegetation by specifying area average parameters on two fronts, one being essentially empirical and the other theoretical. The empirical approach (e.g., Mason, 1988; Blyth, et al., 1993; Noilhan and Lacarrere, 1995; Arain et al., 1996, 1997) is to create a coupled surface-atmosphere model, and to postulate and test hypothetical rules (often called "aggregation rules" see Shuttleworth, 1991) that give parameters applicable at larger scales by combining the parameters that control surface exchanges for small plots of uniform land cover. The theoretical approach (e.g. L'Homme, 1992; McNaughton, 1994; Raupach, 1995; and Raupach and Finnigan, 1995, 1997) is to adopt the equations that are accepted as reasonable descriptions of land-atmosphere exchanges for small plots of uniform land cover and to assume that such equations can also be used to describe the area-average behavior of heterogeneous cover, and to derive theoretical equations that link the parameters required at large scales with those that apply for individual small plots.

Most meteorological models either prescribe a seasonal evolution in vegetation parameters or assume that they are constant. Assimilating satellite observations is one way to provide a more realistic representation of current vegetation status in model simulations, and there is now great opportunity to develop this approach with data from the recently launched Earth Observing System. However, when using this approach, care is needed to avoid creating inconsistencies between the space-time distribution of soil moisture and the assimilated vegetation biomass growth pattern.

Incorporating dynamic vegetation into a land-surface model is a relatively new development, but research in this area has already provided important insights. Claussen (1995), for instance, used an interactively coupled global atmosphere-biome model to assess the dynamics of deserts and drought in the Sahel. He found that the comparison of atmospheric states associated with these equilibria corroborates Charney's (1975) hypothesis that deserts may, in part, be self-inducing through albedo enhancement. Ji (1995) developed a climate-vegetation interaction model to simulate the seasonal variations of biomass, carbon dioxide, energy, and water fluxes for temperate forest ecosystems in northeastern China. Foley et al. (1998) directly coupled the GENESIS GCM and IBIS Dynamic Global Vegetation Model through a common treatment of land-surface and ecophysiological processes. They found that the atmospheric portion of the model correctly simulates the basic zonal distribution of temperature and precipitation (albeit with several important regional biases) and that the biogeographic vegetation model was able to capture the general placement of forests and grasslands reasonably well.

Among the predictability questions associated with seasonally changing vegetation cover that will be addressed under CPPA are as follows.

- How can the representation of the dynamic biophysical properties of vegetation and heterogeneous land cover be improved and validated in predictive models?

- Do currently available vegetation dynamics sub-models realistically simulate the seasonal cycle of vegetation growth and senescence?
- Does the use of dynamic vegetation models improve the prediction of climate?
- How does dynamic vegetation in coupled land-atmosphere modeling influence the predicted precipitation, and how does it influence the relative importance with respect to predictability of precipitation arising from sea surface temperature anomalies and land-memory processes?

4.3 Implementation Strategies

4.3.1 Soil-moisture memory

Research into soil moisture-related land-memory processes remains inhibited by the comparative scarcity of soil-moisture data. It was this lack of relevant, regional scale observations of soil moisture that stimulated the Land Data Assimilation System (LDAS) (Mitchell et al., 2004). That successful LDAS methodology will be adopted and applied in the context of CPPA. Given the scarcity and poor representativeness of point measurements of soil-moisture, the prospect of providing remotely sensed, area average observations are essential. Here, CPPA's focus is to investigate how such remotely sensed observations could best be used to improve prediction of climate and hydrologic variables, and what the likely improvement in predictability would be and their usefulness for water resources.

Currently, the primary limitation on exploiting soil moisture memory to improve climate/hydrometeorological predictions is the poor quantitative precipitation forecasts (QPF) in coupled hydrologic models. Even if observations of precipitation are available to improve the definition of initial soil moisture status, shortcomings in the simulation of rainfall in predictive runs can rapidly degrade the quality of the simulation subsequent evolution of the moisture store. The desire to improve simulation and prediction of the moisture available at the land surface therefore puts emphasis on the need for research to improve the representation of those atmospheric processes that generate precipitation.

Recognizing the current status and needs for research in soil-moisture land memory, and its influence on atmospheric processes, the initial priorities for research in this area within the CPPA program will therefore include:

- Research to quantify the role of soil moisture in seasonal predictability studies. There is a range of potential studies that potentially include statistical analyses, modeling studies using RCM and GCM models, and testing whether LDAS-like model initializations result in improved prediction. It is necessary to determine whether improved predictions are useful on water management spatial and temporal scales.
- Research in support of a soil moisture remote sensing observations, to improve the initiation of predictive models, with emphasis on how such remotely sensed observations could best be used to improve prediction of

climate and hydrologic variables at timescales from days up to seasonal, and on what the likely improvement in predictability would be.

- Improve observations of precipitation in regions of the Americas where data are sparse, as the basis for improving models' representation of precipitation processes and to improve the performance of regional LDAS in the context of phenomena-specific (e.g. monsoon) predictability studies. Here there is a need to expand LDAS studies to include the entire CPPA study area.
- Subsequently, research leading to improved understanding and more capable modeling of precipitation processes in the atmosphere and their interaction with topography with (in the context of soil-moisture memory studies) special emphasis on warm-season convective processes.

4.3.2 Snow memory

Snow and ice cover "remembers" frozen precipitation, influences current surface radiation transfer, and dictates future melt-water availability. Recent research showed that improved model parameterizations for snow and frozen ground, and for sub-grid snow distribution snow improves the modeled regional and global climate. Given the present standing of snow/ice land memory research, the evolving priorities for related studies in the CPPA program will be:

- Research to quantify the role of snow extent in seasonal predictability studies. There is a range of potential studies that potentially include statistical analyses based on hydrologic data sets, sensitivity studies of the modeled climate and hydrologic variables to the amount and extent of frozen precipitation at timescales up to seasonal, using observations to prescribe regional snow/ice cover in the models; and testing whether LDAS-like model initializations result in improved prediction. It is necessary to determine whether improved predictions are useful on water management spatial and temporal scales.
- The development of improved snow/ice cover sub-models in LDAS, with emphasis on vegetation-covered areas, and testing these relative to existing or new observations at both plot and regional scale.

4.3.3 Vegetation memory

Over the last decade, there has been major progress in understanding and modeling the influence and importance of vegetation on surface exchanges of energy, water, and carbon. Because land surface models with interactive vegetation, i.e., models that simulates the growth and die-back of vegetation, are comparatively recent, stand-alone testing, intercomparison, and, if required calibration against observations at selected sites are required. The next step is to test the ability of two-dimensional arrays interactive vegetation models, when forced with spatially distributed climate data, and validate their ability to reproduce the regional patterns of vegetation growth and senescence observed by satellite sensors. Given these results, investigations can be carried out on the effect of inter-annual variability in vegetation (e.g. time of leaf-out) on inter-annual climate variability, through multi-member ensemble integrations with regional, coupled hydrologic-atmospheric models, with and without interactive vegetation. Ultimately, such investigations will help determine whether including interactive vegetation improves the simulation of climate variables, and the relative roles of various land-memory processes in climate variability and prediction. Such integrations could also investigate whether including interactive vegetation modifies the relative sensitivity of the models to changes in sea surface temperatures versus land memory processes in general. Thus, given the still emerging status of land-atmosphere models with interactive vegetation, the evolving priorities for vegetation memory studies will be:

- More in-depth evaluation of vegetation models forced with observed meteorology and comparison with in-situ and remotely sensed data
- Sensitivity studies of the modeled climate need to be conducted to investigate the contribution of inter-annual vegetation variability on climate variability and the significance of vegetation ‘memory’ on model predictions. The initial focus is to better understand whether improved representation of seasonal dynamics and inter-annual variability in vegetation will lead to better seasonal climate and hydrologic predictions. Such studies will contribute to an understanding of the role of vegetation in seasonal climate phenomena, such as the North American Monsoon System.

4.3.4 Topographic influences

Implementation activities that focus on the linkages between atmospheric and surface hydrometeorological processes and how these linkages address the CPPA prediction goal would include studies and analyses that:

- Quantify the sensitivity of runoff generation to evapotranspiration, particularly changes that would be associated with lengthening of the snow-free season.
- Investigate how the effects of topography on precipitation (including amount and phase) modify the magnitude and timing of hydrological flows in watersheds of differing spatial scales.
- Determine the extent to which seasonal soil moisture carry-over (from the end of the summer season through the following winter) and soil freeze/thaw state affects runoff generation during winter storms and spring snowmelt. These analyses and related data sets, in combination with mesoscale reconstruction of precipitation and associated hydrologic model forcings, would support studies focused on evaluation of hydrologic model parameterizations and hydrologic model predictions from mountainous regions.
- Investigate the impacts of topography and the land surface states on flooding during heavy precipitation events such as that associated with the Atmospheric River that have implications to atmospheric and hydrologic predictions at the intraseasonal time scale.

- Carry out hydrometeorological model experiments to evaluate whether coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography.
- Advance the understanding of the large-scale water balance and its variability in mountainous terrain through improved measurements and modeling.
- Apply climate and hydrologic models in seasonal climate forecasting for basins with complex terrain.

4.3.5 Coordinated Enhanced Observation Period (CEOP)

The Coordinated Energy and water cycle Observations Project (CEOP; 2008) is a merger of the previous World Climate Research Project (WCRP) Global Energy and Water-cycle Experiment (GEWEX) Hydrometeorology Panel (GHP) and the 'Coordinated Enhanced Observing Period' ('CEOP', Lawford et al. 2006), which was an element of WCRP initiated by GEWEX. This natural merger between GHP and 'CEOP' now better coordinates similar international activities being undertaken by both groups.

Many of the former GEWEX Continental Experiments (CSEs) have evolved to more complete Regional Hydroclimate Projects (RHPs) and even beyond in that more than GEWEX efforts are now needed to solve regional problems involving a climate prediction focus (CLImate VARiations; CLIVAR) and a biological focus (International Geosphere Biosphere Program, IGBP). Many regions now have an anthropogenic climate focus.

In addition to the RHPs, the new CEOP includes groups focused on regional studies in cold regions, high elevations, monsoon, and semi-arid regions. These international groups provide an international context for the climates associated with the CPPA region.

The science of CEOP continues to provide a traditional focus on Water and Energy budgets, which will extend the efforts to understand average conditions to conditions during the 'CEOP' time period of 2003-2004 to present and a GHP effort to understand average conditions during an earlier period. This extension will have a special focus on extremes during the 'CEOP' period. Additional crosscutting science efforts will examine the effects of aerosols and how water isotopes might be better utilized.

CEOP also adds explicit global, regional, land surface modeling activities as part of its international activities. All of these modeling groups are looking at an ensemble of models in many different regions focused on the many CEOP reference sites including the CPPA related sites over the Americas.

CEOP Data Management has now successfully implemented a data policy allowing the sharing of in situ reference site data, model output data, and satellite data and set up archival centers of this data at the National Center for Atmospheric Research (NCAR) and the Max Planck Institute (MPI). During CEOP, satellite data will come on line at the University of Tokyo (UT) and then along with the other data be moved to a central data archive where it can be accessed and distributed to interested users. By the end of CEOP in 2012, there will be a functioning CEOP data center that will have been used by all of the CEOP science groups. It should be noted that this CEOP data is already open to outside groups. CEOP data management is also in the process of developing links to a number of associated groups, such as the Global Runoff Data Centre and Global Precipitation Climatology Centre.

In short, CEOP is now the focal point for WCRP/GEWEX Global Hydrometeorological Research and as such will provide the international setting for CPPA-related coupled land atmosphere research.

4.3.6 Remote sensing activities

Breakthrough advances in techniques to observe continental and regional precipitation, surface soil-moisture, snow, surface soil freezing and thawing, surface inundation, river flow, and total terrestrial water-storage changes, combined with better estimates of evaporation, now provide the basis for a concerted integrated CPPA remote sensing research effort. Satellite data sets provide a valuable extension to conventional in-situ ground-based observations. To answer the CPPA science questions, vertical water fluxes (i.e. precipitation and evaporation), the amount of land water storage (i.e. soil moisture, inland water bodies, etc), and lateral land water fluxes (i.e. river flow) must be integrated and interpreted. CPPA remote sensing data must be: (a) Spatially and temporally rectified to allow intercomparison and quality evaluation of disparate model and observation data, (b) Physically rectified or constrained using four dimensional data assimilation and modeling techniques, and (c) used to interconnect the products of disparate research teams.

4.3.7 Coupled land-atmosphere assimilation

Most current data assimilation efforts utilize separate, uncoupled (i.e. inconsistent) atmosphere, ocean and land modeling systems. The uncoupled approach fails to maximize information extracted from the growing suite of remote sensing measurements. Analysis errors are often the sum of large compensating errors in individual processes, including precipitation, and surface and atmospheric fluxes. While truly coupled assimilations will be needed eventually to improve coupled predictions, the current separate land-ocean-atmosphere data assimilation methodology provide a better process description due to inadequate understanding of feedbacks between the complex subsystems. For example, current uncoupled Land Data Assimilation Systems (LDAS) use observed precipitation and solar radiation as forcings (not truly coupled assimilation), to avoid cloud and precipitation errors that are characteristic of coupled systems. It is precisely these fluxes or energy and mass exchanges that are at the heart of Earth system feedbacks and which, at present, are so uncertain in coupled models. To achieve the goal of fully coupled atmosphere-land data assimilation systems that should produce the best and most physically consistent estimates of the energy and water cycle, CPPA will need advanced coupled process models with improved feedback processes, better observations, and comprehensive methods for coupled assimilation.

The elements of this effort are as follows:

- Identify and obtain all relevant observations of precipitation, snow, soil moisture, upper atmosphere humidity, evaporation, and other components of the energy and water cycle, implement an integrated system.
- Develop methods to assimilate measurable components of the land-atmosphere system, including precipitation, cloudiness, radiation, evaporation, temperature, humidity, vegetation, soil moisture, groundwater, cryosphere, etc.
- Develop coupled land- atmosphere data assimilation systems that achieve internally consistent, accurate and unbiased coupled state estimates.

4.4 Deliverables

- Quantify the influence of land states on the seasonal prediction skill of precipitation and temperature within the CPPA domain.
- Quantify the sensitivity of seasonal climate predictions to land states, including soil moisture, snow, orography and vegetation.
- Provide a reanalysis of the atmospheric and land surface states using state-of-the-science numerical modeling and data assimilation systems.
- Develop and test procedures to coupled assimilate new data products (e.g. satellite data sets) and off-line model outputs (e.g., from LDAS systems) to provide improved weather and seasonal forecasts.

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5. OPERATIONAL CLIMATE PREDICTION, MONITORING AND ANALYSIS

5.1 Scientific Background

This chapter addresses the third objective of the CPPA program: improving actual prediction skill (the validation of actual forecasts, an operational objective), not just predictability (the theoretical prospects for making better prediction, a research objective). In order to improve operational prediction skill, we must consider all three earth system components of ocean, atmosphere, and land through coupled global and regional models and empirical techniques. This chapter emphasizes the implementation of improvements to NOAA's operational large-scale SI prediction products. Chapter 6 will focus more specifically on prediction of the land surface and its hydrologic variables (streamflow, snowpack, soil moisture, primarily with uncoupled and high resolution hydrologic models) and the decision-support component for improving the management of water resources based on the hydrological predictions.

5.1.1 Three overarching approaches to SI prediction

For the purposes of this chapter, it is useful to group operational SI prediction techniques into one of the following three overarching approaches:

- **Dynamical Approach:** Apply real-time dynamical models (with hindcasts/reanalyses)
- **Empirical Approach**: Statistical techniques (and their associated historical databases)
- **Hybrid Approach:** Techniques that combine the dynamical and empirical approaches

As a point of clarification, an empirical approach for SI prediction may utilize reanalysis fields, current analyses, and dynamic model SI hindcasts produced by the dynamical approach, provided that the empirical technique does not require a real-time dynamic model forecast. If the prediction technique applies both empirical/statistical tools and also requires a real-time dynamic model SI forecast, then the technique will be regarded as a hybrid technique. One example of a hybrid technique is one that requires the dynamical SST forecast for the Nino 3.4 Pacific region from one or more GCMs with coupled ocean model, but then applies statistical methods to the dynamical Nino 3.4 SST prediction (and possibly its hindcasts) to derive an SI prediction of precipitation and near-surface air temperature over the continental U.S. (CONUS).

As cited in Chapter 2, both statistical/empirical approaches and dynamical model approaches produce useful SI predictions of tropical Pacific SST for the peak phase of ENSO up to two seasons in advance. The recent book by Van den Dool (2007) provides an excellent overview of various empirical techniques used for seasonal climate prediction. The dynamical SI approach at NCEP, using the global ocean-atmosphere-land Coupled Forecast System (CFS) developed in NCEP's Environmental Modeling Center (EMC), is presented by Saha et al. (2006). Other global coupled dynamical seasonal prediction systems have also been developed and are routinely applied at NASA and ECMWF, and elsewhere.

Up until the past few years, the SI climate prediction skill of empirical techniques exceeded that provided by dynamical models, but that situation has changed recently for tropical Pacific SST. Furthermore, there is increasing concern that rapid climate change may diminish the future applicability of empirical prediction schemes derived from analysis of 20th Century climate variability.

Figure 5.1 from Saha et al. (2006) illustrates that the third-generation (CFS03) NCEP global ocean-atmosphere-land Coupled Forecast System (CFS) that was implemented in NCEP operations in August 2004 produces SI predictions of Nino 3.4 SST having more skill than the competing empirical techniques used operationally at NCEP's Climate Prediction Center (CPC). At present, for SI prediction of precipitation and near-surface air temperature over continental landmasses, the skill of empirical techniques and skill of dynamical models are roughly competitive with each other. Thus hybrid techniques that utilize predictions from both Approaches 1 and 2 above are appealing.

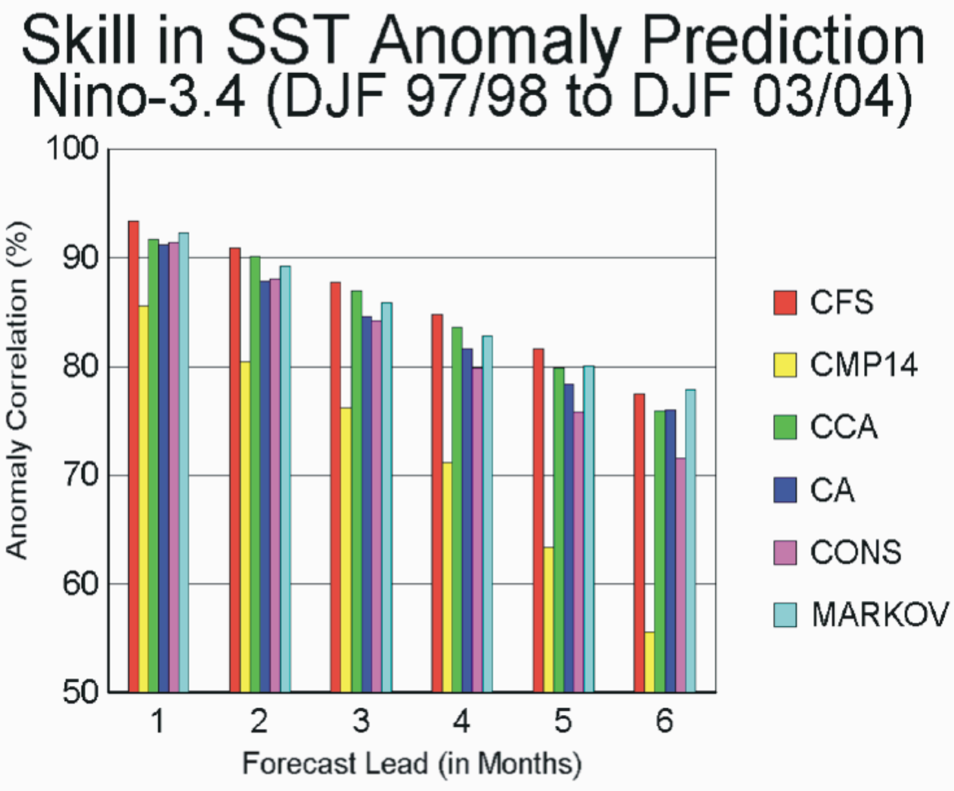

Figure 5.1 Forecast anomaly correlation for NINO3.4 SST for DJF season over the period 1997/1998 to 2003/2004. CFS: current NCEP coupled Climate Forecast System; CMP14: previous NCEP coupled climate forecast system; CCA: Canonical Correlation Analysis (statistical); CA: Constructed Analog (statistical); MARKOV: Markov technique (statistical).

Moreover, dynamical SI predictions based on current models are often characterized by substantial bias and a lack of sufficient spatial resolution for regional applications. Thus another important role of many hybrid SI techniques is to bias-correct and spatially downscale the dynamical predictions. Such bias correction and downscaling are critically needed for the water resource applications of SI predictions described in Chapter 6. Sections 5.2 and 5.3 below further address the CPPA objectives, priorities and strategies for downscaling in operational SI prediction.

5.1.2 Objective criteria for operational implementation of an SI prediction approach

The scientific challenge for operational SI climate prediction is how to objectively decide when operational implementation is warranted for an SI prediction approach that has shown promise in the research community. For a given approach to achieve operational status, it should satisfy the following five operational prediction criteria:

- A priori demonstration of the prediction skill of the approach with respect to a benchmark (e.g. climatology or an already existing operational SI prediction approach) over a sufficiently long historical hindcast period (two or more decades) for a reasonably large region (e.g. CONUS, or South America, etc) for one or more reasonably useful variables (e.g. SST, precipitation, air temperature, snowpack) for reasonably long lead times (e.g. at least intraseasonal of 3-6 weeks, but preferably 1-6 months or longer);
- Existence and availability of a sufficiently long historical database of the inputs required by the approach from which (a) the hindcast skill can be effectively demonstrated and (b) the approach is objectively reproducible by other scientists. The first criterion requires this criterion;
- Definition for the approach of a quantifiable prediction skill metric, which is reproducible over two or more decades;
- Establish that the required input databases for the approach are dependably available in real-time for operational use;
- Confirm the computational feasibility of the approach (does the operational prediction agency have the computational resources to apply the approach in a usefully timely fashion).

It is paramount to further illustrate the first three criteria above. As strongly emphasized in Saha et al. (2006), the new CFS dynamical SI prediction suite (CF03) at NCEP cited earlier in Section 5.1.1 includes a set of fully coupled CFS retrospective hindcasts covering a 24-year period (1981–2004), with 15 CFS forecast members per calendar month out to nine months into the future. This CFS hindcast archive provides a wealth of information for researchers to study interactive atmosphere–land–ocean processes. Moreover, these 24 years of fully coupled CFS hindcasts are of pillar importance to the proper application of operational CFS seasonal forecasts. These hindcasts provide the essential a priori estimate of model skill that is critical for CPC forecasters in determining the utility of the real-time dynamical forecast in the operational framework. Figure 5.2 provides an example of what CPC forecasters refer to as the operational CFS "skill mask", or skill map. The example in Figure 5.2 is the spatial map of the correlation with observed precipitation of CFS ensemble mean seasonal forecast of 3-month total precipitation over CONUS. The skill map in Figure 5.2 was created from the 24-year CFS hindcast archive. An extensive set of such CFS skill maps over the global domain for SST, precipitation, 2-meter air temperature, 500 hPa height and 700 hPa height (and CONUS domain for precipitation and air temperature) are available at: http://www.cpc.ncep.noaa.gov/products/people/wwang/cfs_skills/.

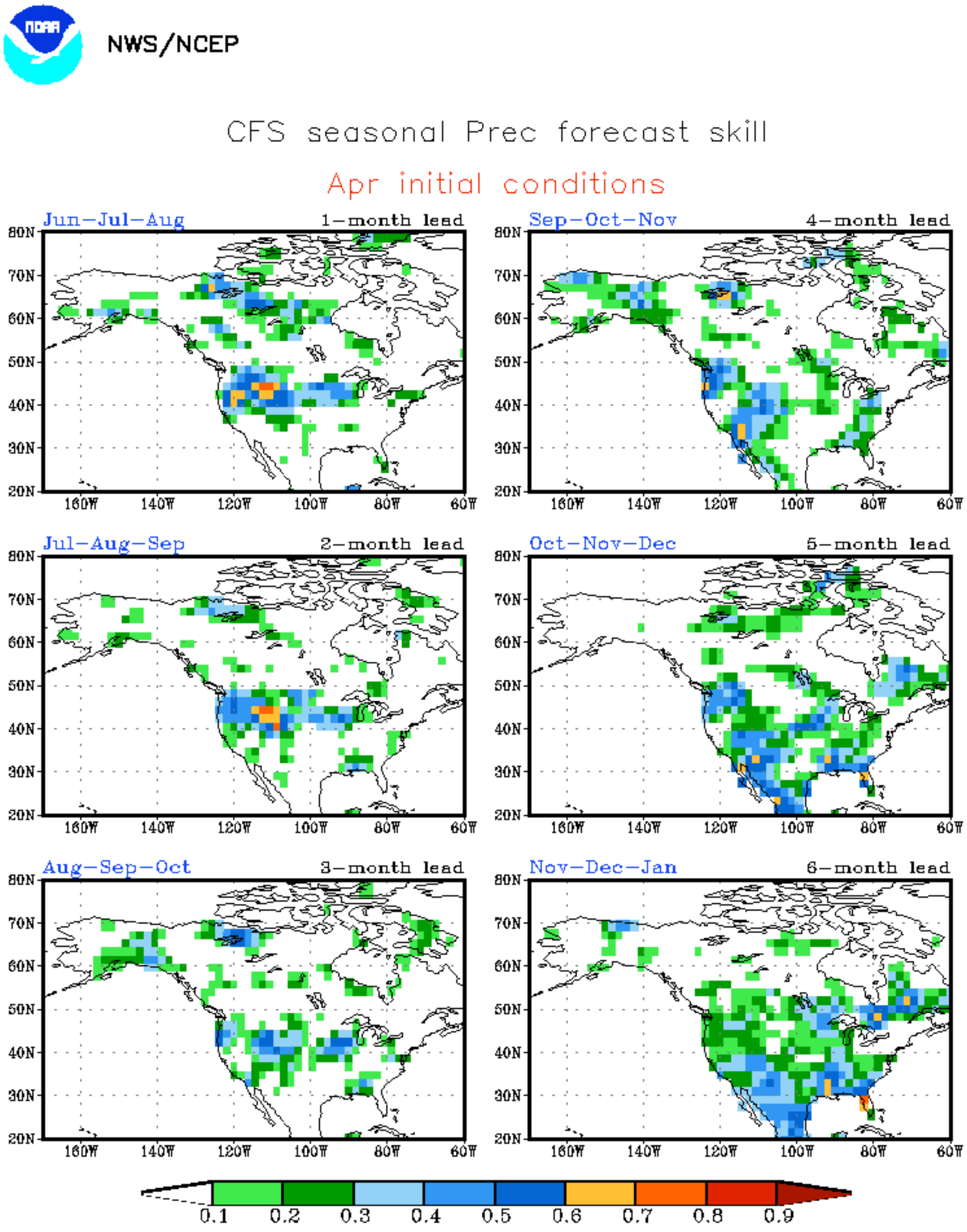

Figure 5.2 Spatial map of correlation (range 0-1) between CFS predictions and verifying analysis of 3-month precipitation totals over the 22-year CFS hindcast period of 1982-2003 for the ensemble mean of 15 CFS forecast members initialized during the period 11 April and 03 May for each year of the 1982-2003 hindcast period.

Many of the present and future viable approaches for SI prediction embrace the prediction of an anomaly or departure from climatology. Hence most approaches for SI prediction require and depend heavily on companion components for analysis/monitoring and reanalysis that provide the requisite historical database from which to derive both a suitable observed climatology and to derive observed anomalies from the climatology. Therefore, the above five criteria apply also to the required analysis/reanalysis components. In the analysis/reanalysis context, the term "prediction skill" in the above criteria can be replaced by "a stable/reliable measure of current condition". If the skill measure for a given prediction approach requires the analysis/reanalysis of a verification quantity whose historical time series is not stable or reliable, then the approach is very likely not a candidate for operational use.

The five criteria above for a candidate SI prediction approach to qualify for use in routine real-time operational practice are formidable criteria for any PI in the research community to meet. Consequently, these necessary but demanding criteria contribute substantially to the huge challenge of transitioning promising research into operational practice. The pillar theme of the next sub-section is to describe several explicit mechanisms and pathways available to CPPA PIs to greatly foster successful transition of SI prediction research into NOAA operational practice.

5.2 Scientific Objectives and Priorities

In Chapters 2-4, the respective sections on science objectives and priorities emphasized priority research needs, such as physical process studies via observations and models of ocean-atmosphere interaction, land-atmosphere interaction, ocean data assimilation or land data assimilation. In contrast, here in Chapter 5, the present section on science objectives and priorities emphasizes the priority needs and requirements to facilitate the **transition** of science and research to operational practice. This focus is consistent with the third CPPA objective given in Chapter 1: to advance operational climate forecasts, monitoring and analysis systems. Given that CPPA is a program in the NOAA Climate Program Office, the latter objective is especially aimed at improving NOAA operational climate forecasts and monitoring at NCEP, via EMC dynamical climate models for SI prediction or CPC empirical and hybrid approaches for SI prediction.

In the setting of this mandate to transition research to operations (hereafter denoted RTO), the objectives for CPPA are to provide defined pathways, infrastructure, support mechanisms and operational collaborators for RTO to CPPA investigators in the research community. The CPPA plan here offers to focus on the following such RTO mechanisms:

1 - CPPA Synthesis Teams

2 - NOAA CPPA Core Project

3 - NOAA Climate Test Bed (CTB)

4 - NOAA Hydrological Test Bed (HTB)

This section presents RTO mechanism 1-3 above, including the NOAA Climate Test Bed (CTB) at NCEP. Collectively, mechanisms 1-3 provide a path for CPPA research on large-scale predictability, derived from the synthesis of air-sea interaction research (Chapters 2 and 3) and land-atmosphere interaction research (Chapters 2 and 4) to be tested and integrated into the operational dynamical prediction environment at NCEP. The implementation strategy to accomplish this is described in section 5.3. RTO mechanism 4, the NOAA Hydrological Test Bed (HTB, located at the NWS Office of Hydrologic Development), is introduced briefly below and then presented more fully in Chapter 6.

In CPPA annual Announcements of Opportunity (AOs), annual CPPA PIs meetings and other CPPA forums, CPPA will seek and sponsor CPPA PIs offering suitable proposals to form CPPA Synthesis Teams. Such Synthesis Teams will work with currently funded CPPA PIs working in related CPPA research endeavors to identify methods, algorithms, physical parameterizations, models or modeling approaches and data sets that they collectively judge to be sufficiently demonstrated, mature, and sustainable to comprise strong RTO candidates for SI prediction. The teams will produce data sets, model codes and scripts and reports based on prior or presently funded CPPA grants to facilitate the transition of CPPA research findings into model improvement and NWS operations and give recommendations for future research directions. The teams will play a coordinating role in CPPA working groups to bring PIs in the area(s) together. The teams should work with the CPPA Core Project, Climate Testbed, and/or Hydrology Testbed to implement RTO activities. CPPA seeks teams in areas of 1) air-sea interaction, 2) land-atmosphere interaction and 3) hydrologic forecasting and water resource applications, consistent with the scientific priorities described in Chapters 2-4.

CPPA and its GEWEX-related predecessor programs (GAPP and GCIP) have and will continue to fund the CPPA Core Project, with two components in NOAA's National Weather Service (NWS): one component in EMC of NCEP and one component in the NWS Office of Hydrology (OHD). The objective of the CPPA Core Project is to provide EMC and OHD focal points and collaborators to CPPA Synthesis Teams and CPPA PIs for the purpose carrying out CPPA transition of research to operations. The Core Project PIs and their group members will be the mechanism by which external CPPA PIs interface with the NOAA CTB and HTB Test Beds. The Core Project PIs will host regular scheduled teleconferences with CPPA external PIs to coordinate and accelerate CPPA RTO.

The NOAA Climate Program Office (CPO) and EMC and CPC of NCEP have recently initiated a new and far reaching RTO mechanism at NCEP called the NOAA Climate Test Bed (CTB). The objective of the CTB is to accelerate the transition of research advancements into improved NOAA operational climate forecasts, products and applications. The Climate Test Bed provides an NCEP operational testing environment on NCEP computational platforms to support short-term competitive applied research and development projects that will result in a direct influence on operational methodologies, and/or new guidance products or techniques leading to improved quality and applicability of operational SI climate predictions. The CTB computer platform at NCEP can mimic operational computing power and leverage operational NCEP data streams, including operational and retrospective global and regional reanalysis of the atmosphere, ocean and land, and dynamical climate model (CFS) forecasts and hindcasts spanning two or more decades. Scientists from the research community, including CPPA, are sought to carry out competitive CTB projects jointly with EMC and CPC members via proposals to CTB AOs. CTB proposals require an external PI and an internal (EMC or CPC) Co-I. The CTB AOs seek projects that have been previously developed and demonstrated externally via other programs (such as CPPA) and that have been identified by the internal NCEP co-I as having clear potential to be implemented operationally at NCEP in the 3-4 year time frame. Projects that have a longer development time scale (4-7 years) should be supported by programs other than CTB, such as CPPA AOs and AOs of other CPO programs. More details on the CTB, including recently updated Science Plans for key CTB science priorities (CFS Improvements; Multi-Model Ensembles; Climate Forecast Products) are provided at http://www.cpc.ncep.noaa.gov/products/ctb/.

Over the past several years the CTB has supported a number of projects aimed at accelerating improvements in NCEP's Climate Forecast System. More recently, the CTB has explored the feasibility of either acquiring or executing seasonal hindcasts from other global coupled atmosphere-ocean-land dynamical models besides the NCEP CFS, such as the global coupled model of GFDL, NASA/GMAO and NCAR, or from international centers. This will allow CTB-funded external PIs to explore multi-model approaches and multi-model applications to SI climate prediction.

The CTB will interact with the CPPA Core Project component of NWS/OHD and the Hydrological Test Bed (HTB) therein. The HTB will accelerate the implementation of operational hydrometeorological products and services, including enhancing and extending forecast skill for high-impact weather, especially precipitation, by facilitating interactions among researchers and operational forecasters. The CTB will collaborate with the HTB in several areas, especially improved warm season precipitation forecasts, use of ensemble model output and forecaster generation of probabilistic products, and improved operational monitoring and prediction of weather–climate linkages. With advancements in land surface modeling, the hydrometeorological community has also made considerable progress in streamflow prediction, drought monitoring, and anticipating extreme events. The CTB will endeavor to use the CFS and MME forecasts to enhance hydrometeorological applications.

The CTB AOs will especially seek proposals that address top CPC SI prediction priorities. The CPC priorities (not in prioritized order) are improvement of:

1 - MME seasonal prediction skill

2 - CFS seasonal prediction skill

3 - Atmospheric, oceanic, and land reanalysis (multi-decadal), globally and the Americas

4 - Downscaling, via hierarchy of techniques down to 5 km scale

5 - Physically based and verifiable drought outlooks for the NIDIS

6 - Warm season predictions of precipitation over the Americas (outlook tools, skill measures)

7 - Economic benefits via application of climate prediction products

8 - Measures of seasonal prediction skill

9 - Understanding of sub-seasonal predictability (MJO, AO, NAO, PNA)

10 - Understanding of decadal trends and their physical causes

11 - Prediction of atmospheric response under weak or neutral ENSO

12 - Breadth of climatologies (extreme events, mesoscale events, PDFs of weather events)

The operational implementation strategy and support infrastructure presented in the next section substantially address CPC priority areas 1-6 above.

5.3 Implementation Strategy

5.3.1 End-to-end SI prediction infrastructure for the NOAA Climate Test Bed (CTB)

This section presents an infrastructure and strategy that allows a PI or group of collaborating PIs to demonstrate the five criteria given in Section 5.1.2 for operational SI-prediction feasibility. The infrastructure and strategy recommended below heavily utilizes the concepts of test beds, data assimilation/reanalysis, hindcasts, and intercomparisons with a clear benchmark. The benchmark is often an already existing operational approach, or in absence of that, the prediction offered by climatology. The proposed infrastructure is to be first exercised in multi-year hindcast and reanalysis mode over two or more decades in a test bed environment, and then secondly transitioned into operations for those approaches whose hindcast results warrant operational practice (that is, satisfy the five criteria in Section 5.1.2).

The infrastructure advocated by CPPA for the end-to-end seasonal prediction system is depicted in Figure 5.3. This figure is an extension of the well known ‘Shukla Downscaling Staircase’ presented by J. Shukla at the Joint PACS/GCIP Workshop in September 1997, and also presented in Figure 3-7 of Hornberger (2001). The seasonal prediction/predictability infrastructure in Figure 5.3 is composed of free-running prediction models and 4-D data assimilation systems (4DDA) ingesting in-situ and satellite observations into assimilating "background" models. The models in the prediction and companion 4DDA components of Figure 5.3 are frequently and ideally the same model. For both the prediction and data assimilation capabilities, the comprehensive infrastructure of Figure 5.3 supports the execution of the following necessary attributes:

- Ocean, land, atmosphere
- Global and regional,
- Coupled and uncoupled
- Retrospective and real-time
- Downscaling

The uncoupled modeling attribute cited above is envisioned mainly for application in the hydrologic prediction and water-resource management applications presented in Chapter 6.

The key extension added in Figure 5.3 with respect to the traditional depiction of the 'Shukla staircase' is the companion suite of ocean, land, and atmosphere data assimilation components to initialize the ocean, land and atmospheric states of the prediction models and to provide the analysis products required for monitoring climate. Thus Fig. 5.3 provides the conceptual framework for integrating and transitioning CPPA's ocean-atmosphere and land-atmosphere interaction research (as outlined in previous chapters) into the operational prediction environment.

To interpret the figure, one starts with the upper left corner and the chain of downscaling models proceeds counterclockwise. Circles represent data assimilation systems. The layers of boxes represent a set of ensemble of model predictions, which could be multiple members of either a single model or multi-models. The diamonds represent ensembles of model output fields.

The first modeling suite in the upper left (denoted OAL-GCM) is a coupled global ocean/atmosphere/land general circulation model. This OAL-GCM and the three global data assimilation systems (atmosphere, ocean, land) pointing to it represent the cornerstone of the entire infrastructure. The OAL-GCM suite is often referred to as a "Tier 1" system, because it is fully coupled without applying flux corrections in the ocean-atmosphere or land-atmosphere interactions. The global atmospheric and ocean prediction components of Figure 5.3, including their companion global atmospheric and ocean data assimilation components, are already in place at several operational and research centers.

The second modeling suite in the lower left of Figure 5.3 (denoted AL-GCM) is a coupled global atmosphere/land general circulation model (possibly at higher resolution then the OAL-GCM). The AL-GCM suite has no coupled ocean component, but rather uses time-dependent SST fields (often after bias correction) externally provided by either the OAL-GCM suite of the upper left or by empirically predicted SST fields. Such an AL-GCM suite is often referred to as a "Tier 2" suite, since it requires SST predictions from a 2nd separate prediction suite. The third modeling suite in the lower right is a high resolution, imbedded, coupled atmosphere/land regional climate model (RCM), using the same externally provided SST fields (again either dynamically predicted or empirically predicted) as would be provided to an AL-GCM. The fourth modeling suite in the upper right is a high-resolution, uncoupled, land-only macroscale hydrology model (MHM), such as those discussed in Chapter 6.

Figure 5.3 is to be regarded as a **test bed** infrastructure for the CTB. Aside from the cornerstone suite of the OAL-GCM system in the upper left quadrant, none of the other three quadrants would be implemented operationally unless their seasonal SI climate predictions (either alone or in weighted combination with the OAL-GCM climate predictions) exceeded the SI prediction skill of the OAL-GCM benchmark suite over multi-decade hindcasts tests for the predicted variable and region of interest (this is an example of meeting the first criterion in Section 5.1.2). For example, the RCM component (lower right quadrant of Figure 5.3) would be transitioned to actual operations as a dynamical downscaling component only if the RCMs demonstrate in hindcast mode useful additional skill over and above the parent GCMs (especially empirically downscaled and bias-corrected GCMs).

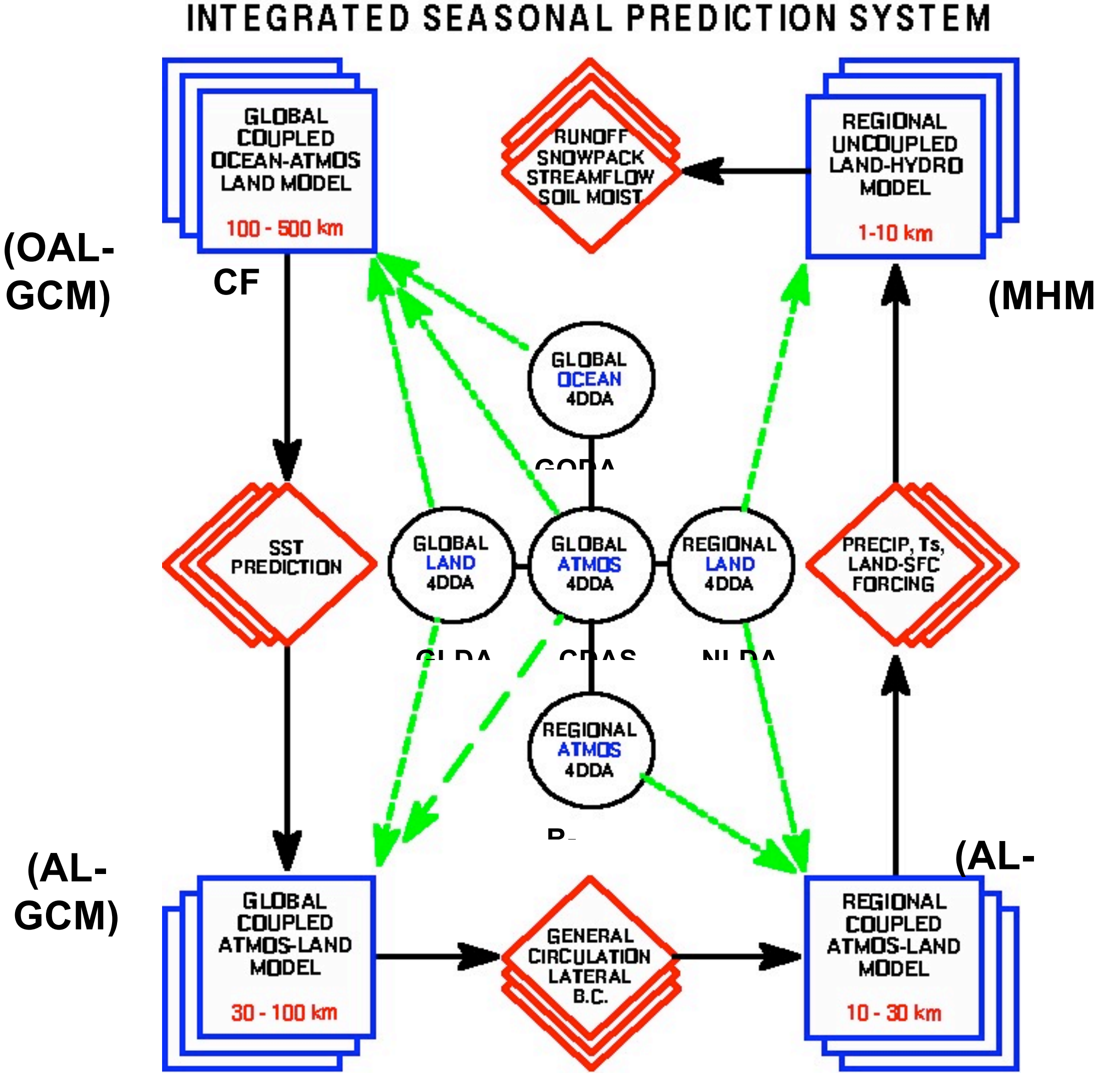

Figure 5.3 Multi-scale end-to-end seasonal prediction system with downscaling.

The four modeling suites in Figure 5.3 (OAL-GCM, AL-GCM, RCM, and MHM) need not all be in place at a given institution for that institution to contribute model or assimilation research and demonstrations in support of Figure 5.3's demonstration capabilities. In the U.S. for example, it is likely that the real-time and hindcast OAL-GCM system with its companion global ocean, global atmosphere, and global land 4DDA systems -- will be in place at only a handful of institutions (e.g. NCEP, GFDL and NASA). However, the global SST predictions and global atmospheric predictions provided from the OAL-GCM component of these latter institutions can be provided to a host of collaborating institutions to drive their own experiments, research and demonstrations in the remaining components of Figure 5.3.

The pathfinder research already accomplished by PIs of (a) CPPA and its predecessor programs (GAPP, PACS, GCIP) and (b) sister programs in the NOAA Climate Program Office and NASA Terrestrial Hydrology Program, have provided NCEP with pilot components of all the non-operational (non-CFS) components in the end-to-end infrastructure of Figure 5.3. Hence any or all components of Figure 5.3 can be made available to the NOAA Climate Test Bed and its sponsored PIs by the NCEP CPPA Core Project.

Ideally, as emphasized in Section 5.2, the components of Figure 5.3 should be executed in a multi-year hindcast mode. *A hindcast attribute to Figure 5.3 can serve the dual purposes of (a) a system for a priori demonstration of prediction skill to justify transition to operations <u>and</u> (b) as a powerful testbed to carry out ocean-memory or land-memory predictability studies, ocean-atmosphere or land-atmosphere coupling studies and related physical process studies, as described in the prior Chapters 2-4.*

5.3.2 Implementation strategy for transitioning ocean-atmosphere and land-atmosphere interactions research

Presently at NCEP, the operational OAL-GCM suite is the CFS (Saha et al., 2006). As such, the CFS currently provides the principal operational platform on which to carry out RTO activities derived from CPPA-supported research on large-scale ocean-atmosphere interactions, as described in chapters 2 and 3. NCEP scientists will use the CFS to participate in CPPA model-based research, such as ongoing exercises aimed at improving simulations of warm season precipitation and investigating the predictability of drought from global SST anomalies. The CTB provides a mechanism for non-NCEP investigators to carry out such research using the CFS as well.

Land-atmosphere interaction research in CPPA seeks to improve land and hydrology models, land data assimilation, and land-atmosphere coupling. Global and regional land data assimilation has been greatly advanced by international and national GEWEX initiatives, such as the LDAS activities of CPPA and its GAPP and GCIP predecessors, as well as the GSWP activities of the GLASS-ISLSCP components of GEWEX.

In the setting of Figure 5.3, and using the deliverables from Chapter 2 and Chapter 4, CPPA scientists will execute studies to demonstrate the degree of improvement in SI prediction skill from the following:

- Improvements to the initial land states of the land components of Figure 5.3 via global and regional land data assimilation (LDAS)
- Improvements to the physical realism of land models, land processes and land-atmosphere coupling
- Dynamical downscaling by coupled Regional Climate Models (RCMs)
- Downscaling by uncoupled Macroscale Hydrological Models (MHMs).

We emphasize that these studies will be carried out in the context of predicting the large-scale circulation anomalies simulated by global prediction models forced by ocean-atmosphere interaction processes. The goal will be to assess the combined effects of improvements in ocean-atmosphere and land-atmosphere interaction for SI prediction skill.

The implementation strategies for MHMs will be presented in Chapter 6. Here we present implementation strategies for LDAS, improved physics in land models, and downscaling by RCMs.

Land Data Assimilation Systems (LDAS)

An LDAS is the crucial land component that will provide the initial conditions of land states of soil moisture, soil temperature, snow pack and vegetation state for the integrated seasonal prediction system of Figure 5.3. The heart of each LDAS will be the land surface model (LSM) that generates the physical background states into which land-surface observations and forcing will be assimilated. The application of the coupled LDAS approach in the NCEP North American Regional Reanalysis or NARR (Mesinger et al., 2006), via the Noah LSM and precipitation assimilation incorporated into NARR by the CPPA Core Project, provides a clear demonstration of the benefits of using LDAS in regional data assimilation.

A hallmark of the GEWEX component of CPPA (i.e. GAPP and its GCIP predecessor) is the development and demonstration of both global and regional land data assimilation systems, both coupled and uncoupled. The North American Land Data Assimilation System (NLDAS) project (Mitchell et al., 2004) is one example. The GCIP-3 special issue of JGR includes ten papers (see Table 1 Mitchell et al., 2004) with extensive results and validations of four land models in the NLDAS setting, both real-time and retrospective, via the simultaneous application of a wide host of new GAPP products and deliverables. Hence the benchmark pilot system for the regional LDAS component of Figure 5.1 has been delivered by the GAPP predecessor of CPPA.

Simultaneously, the GLDAS initiative (Rodell et al., 2004) and the Land Information System (LIS) initiative (Kumar et al., 2006) spearheaded by NASA/GSFC/HSB is making rapid progress in developing and demonstrating a real-time and retrospective uncoupled GLDAS, as well working hand-in-hand with the CPPA Core Project at NCEP to transition the uncoupled GLDAS/LIS to the Climate Test Bed of NCEP. The joint NLDAS and GLDAS thrusts of NASA and NCEP have been formally included in the new NCEP-NASA-DOD Joint Center for Satellite Data Assimilation (JCSDA), which will provide external PIs access to the NLDAS and GLDAS infrastructure for research purposes. The CPPA Core Project at NCEP will utilize the JCSDA infrastructure as a platform to transition CPPA-sponsored LDAS research and development into NCEP seasonal prediction operations.

A key thrust of LDAS initiatives is the development of algorithms for the assimilation of satellite-derived land-state information (soil moisture, vegetation state, snow pack, land surface skin temperature) (Rodell and Houser, 2004; Reichle et al., 2008). This effort will include the development of adjoint models and Kalman Filter (KF) models needed by variational assimilation methods. In this context, new forward radiative models for land surface emissivity are being developed by JCSDA-sponsored PIs to transform LDAS land states and surface characteristics into the satellite radiance channels (e.g. microwave bands) measured by the growing number of satellite instruments in the EOS era.

Improved Land Surface Models and Land-Atmosphere Coupling

The physical process studies, land-atmosphere interaction studies and water and energy budget studies spurred by the initiatives and deliverables of Chapters 2 and 4 will yield improved land surface models (LSMs). CPPA land-arena PIs will provide improved land physics, such as adding new capabilities to simulate groundwater, dynamic vegetation, multi-layer vegetation canopies (with two-stream radiative-transfer treatments), and sub-grid redistribution of snow cover, as well as providing new MODIS-based global data bases of land surface characteristics (e.g. surface albedo, leaf area index). The LSM improvements that emerge from these studies can be first tested efficiently in the uncoupled LDAS components of Figure 5.3 and then tested in the coupled GCM and RCM components. The existing LDAS systems employed by CPPA investigators today are already configured to execute multiple LSMs in parallel. Such parallel LSM executions can in turn yield still further improvements in the LSMs via multi-model intercomparisons and validation.

Regional Climate Models (RCMs)

Over the past 5-10 years, through the grants program of the NOAA Climate Program Office (CPO), including CPPA and its predecessor programs, a number of independent investigations of various applications of RCMs have been carried out, such as Anderson et al. (2003) and Gutzler et al. (2005). These and other RCM investigations have spanned the following three broad configurations or modes:

1 - RCM **simulation** mode:

-- driven by atmospheric and SST analyses

2 - RCM **semi-prognostic** mode:

-- driven by atmospheric predictions and SST analyses

3 - RCM **fully-prognostic** mode:

-- driven by atmospheric and SST predictions

The past success of RCMs in simulation and semi-prognostic modes comes from the ability of their higher resolution to better resolve: 1) the influence of orography, especially the role of regional elevated heat sources as central forcing mechanisms for monsoon circulations; 2) the diurnal cycle, especially the low-level nocturnal jets prominent, for example, in south central U.S. 3) summer season nocturnal precipitation maxima associated with these nocturnal jets; 4) SST gradients in nearby coastal ocean areas; 5) mesoscale convective complexes, which play a dominant role in summer precipitation anomalies; and 6) winter snow cover and snowmelt, especially in high orography areas.

While there is a plethora of RCM simulation mode studies (Hong and Leetma, 1999; Takle et al., 1999; Gutzler et al., 2005; to name but a few of many), and a growing body of semi-prognostic RCM studies (Fennessy and Shukla, 2000; Leung and Ghan, 1999), fully prognostic RCM studies are sparse, though some are emerging (Kim et al., 2000).

To explore the utility and value of fully-prognostic RCMs in operational seasonal to interannual climate prediction, CPPA is sponsoring a wider assessment and demonstration of fully-prognostic RCM executions as part of its FY08 call. Each participating RCM will include a regional atmospheric model coupled to a regional land model, with or without coupling to a regional ocean model driven by a global coupled model. The specific goal is to involve multiple RCM groups to execute multiple RCMs in fully prognostic mode from global seasonal predictions in hindcast mode spanning multiple years across more than two decades. Such fully prognostic RCM seasonal forecasts will be comprised of several members from each participating RCM over a period of 27 years (1982-2008) or longer.

The atmospheric and SST forecasts for these fully prognostic RCM seasonal predictions will be provided initially by the current NCEP Climate Forecast System (CFS; see Saha et al. 2006), then the next version of the CFS system that will be available in 2009/2010 and finally the next version of the NASA coupled model that will also be available in the 2009/2010 time frame. Key differences between the current CFS and the next version of CFS, and their companion global reanalyses, are presented below in Section 5.3.c. The coupled global forecasts and regional forecasts will be distributed to CPPA and other researchers via a public server. The initial emphasis of this effort will be on winter season forecasts, because large-scale prediction skill is greatest during this season.

The following dual benchmarks will be used for determining the "value added" of the fully-predictive multi-RCM seasonal predictions over and above those of the driving global model: 1) comparison to the empirically or statistically downscaled and bias-corrected global predictions of the parent CFS and NASA global models that provided the predicted lateral boundary conditions and 2) comparison to empirical seasonal prediction tools, such as ENSO compositing, Optimal Climate Normals (OCN), or CCA (Canonical Correlation Analysis).

Other benchmarks will be established in the course of the experiment. Of special interest will be determining the added value of an RCM ensemble to a global ensemble. The long RCM hindcast set is critical for quantifying the RCMs' ability to capture realistic interannual variability and to cast the RCM predictions more skillfully in terms of anomalies from each RCM's own climatology. Moreover, the long 27-year RCM hindcasts are needed to compute CONUS skill maps of the RCMs and compare them with those of the CFS and NASA global models.

5.3.3 Application and assessment of climate forecast system reanalysis and reforecast

At the time of this writing (early 2008), EMC of NCEP is about to begin a 2-year production period to produce its next-generation global reanalysis and its companion next-generation coupled Climate Forecast System (CFS), including a new CFS reforecast database. Together, this new global reanalysis and new CFS reforecast of NCEP are referred to as the CFS Reanalysis and Reforecast (CFSRR) project. The CFSRR will provide NCEP's next-generation of the components of the upper left section of Figure 5.3 -- namely, the next-generation coupled OAL-GCM as well as the three supporting global 4DDA systems for atmosphere, ocean, and land. More details are provided below.

The global reanalysis of CFSRR will span 1979-2009 and will additionally include a real-time extension known as the Climate Data Assimilation System (CDAS) of CFSRR. Hallmark **features of the new CFSRR global reanalysis,** compared to the previous NCEP/DOE Global Reanalysis 2 (R-2) of Kanamitsu et al. (2002) used by the current CFS, include the following:

1 - much higher spatial resolution (T382 spectral horizontal resolution and 64 vertical levels) than the previous NCEP Global Reanalysis 2 -- R-2 (which was T62 spectral resolution and 28 vertical levels),

2 - uses the NCEP operational Global Atmospheric Data assimilation System (GDAS) as of late 2007 (the older R-2 used the operational GDAS as of late 1999), including assimilation of satellite radiances from historical satellites,

3 - uses the NCEP 3D Global Ocean Data Assimilation System (GODAS), with the GFDL MOM4 ocean model (the older R-2 had no coupled ocean model and no ocean data assimilation system),

4 - uses the NCEP 3D Global Land Data Assimilation System (GLDAS) (the older R-2 had no GLDAS component),

5 - uses the observed atmospheric CO2 trend in the radiation physics (the older R-2 used a temporally constant CO2 concentration).

The CFS reforecast of the CFSRR will span 1982-2009. Hallmark **features of the new CFS coupled O-A-L global model**, compared to the current CFS, include the following:

1 - spatial resolution of T126 spectral horizontal resolution and 64 vertical levels (current CFS: T62 spectral resolution and 64 vertical levels),

2 - uses the May 2008 operational GFS as the atmospheric model component (current CFS: February 2003 version of the GFS). Compared to the February 2003 version, the May 2008 version a) replaces the sigma vertical coordinate with a hybrid vertical coordinate (sigma-pressure), b) adds a sub-grid scale parameterization of mountain blocking, c) uses reduced vertical diffusion, d) applies an upgraded longwave radiation scheme,

3 - uses the new GFDL MOM-4 ocean model at 0.25-0.50 degree horizontal resolution and 40 vertical levels (current CFS: GFDL MOM-3 ocean model at 0.33-1.0 degree horizontal resolution and 40 vertical levels),

4 - uses the new Noah land model with four soil layers (current CFS: uses the old OSU land model and two soil layers),

5 - uses a dynamic sea-ice model with fractional ice cover and variable ice depth (current CFS: does not include a dynamic sea-ice model),

6 - uses the observed atmospheric CO2 trend (current CFS: had temporally constant

CO2)

It is important to emphasize here that the GLDAS component and Noah LSM components of the new CFSRR were deliverables of the GAPP and GCIP predecessors of CPPA.

The CFSRR project will produce 28 years (1982-2009) of CFS ensemble seasonal reforecasts. For each month of these 28 years, approximately 28 members of CFS 1-year forecasts will be produced, which altogether will yield a new CFS hindcast database of about 9400 CFS members. From this new database, new CFS skill masks for precipitation and surface air temperature will be created, similar to that illustrated in Figure 5.2 from the previous generation of CFS. Additionally, the CFS will be executed in real-time to produce for each successive month an operational ensemble of CFS seasonal forecasts out to one year.

EMC is expecting to take about two years to execute the reanalysis and reforecast components of CFSRR (roughly one year for the reanalysis and one-year for the reforecast), with the reanalysis targeted for completion around the middle of 2009 and the reforecast targeted for completion around the middle of 2010.

The CFSRR project will provide the new-generation cornerstone for the upper left section of Figure 5.3. As such, the products of the reanalysis and reforecast of CFSRR will provide a rich database for future investigations by CPPA and CTB PIs. One example is the creation of new and higher resolution global energy and water budgets from the new reanalysis, intercomparison with those derived from other relatively new global reanalysis from other centers, and assessment of any temporal trends in these budgets and possible linkages of these trends to the CO2 trend (i.e., whether the hydrological cycle is accelerating). Another example is a new-generation of diagnostic monsoon studies for the various monsoon regions of the world. A third example is using the new CFSRR reforecasts to drive the downscaling studies represented by the lower left, lower right, and upper right of Figure 5.3. Another critical path of study would be diagnostic investigations and verification of the physical processes in the CFS reforecasts, resulting in recommendations for future improvements to CFS physics (atmosphere, ocean, land, sea ice). Similarly, the CFS reforecasts could be examined for trends in the forecasts of extreme events and the possible relationship of these extreme events to the increase in atmospheric CO2.

5.4 Deliverables

The initiatives and methodologies described in this chapter will endeavor to provide the short term and long term deliverables listed below.

Short term

In accordance with the Regional Climate Model sub-section of Section 5.3.2 above, over the next few years, by summer 2011, CPPA will deliver the following "synthesis product" quantifying the performance of several RCMs executed in fully predictive mode for winter season forecasts, as follows:

- Execution and assessment of a multi-model RCM winter hindcast experiment for 27 winter seasons (1982-2008) with RCMs executed in fully predictive mode driven by NCEP CFS seasonal forecasts and NASA global model seasonal forecasts. Comparison of the SI seasonal prediction skill of the fully predictive RCMs with the SI prediction skill of the parent global model forecasts, especially comparisons of precipitation and near-surface air temperature over CONUS.

Longer term

- Land Data Assimilation Systems (LDAS) on both the North American domain (NLDAS) and the global domain (GLDAS) that can execute in both hindcast mode and real-time operational mode with multiple land models in parallel. Additionally, CPPA will deliver NLDAS and GLDAS infrastructures, and their required input databases, that can be utilized by either the NOAA CTB or executed at the home institutions of individual CPPA-sponsored PIs. The CPPA Core Project at NCEP, along with its NASA collaborators, will provide a central role in the provision, support, execution and validation of the NLDAS and GLDAS, as well as in land-memory predictability studies to demonstrate the value of initial land states from LDAS on the seasonal predictability of GCMs and RCMs.
- Improved land surface models (LSMs), wherein improvements are demonstrated within a hierarchy of settings that begin with single flux stations, and then extend to regional and global uncoupled domains in the NLDAS and GLDAS, and finally extend to regional and global coupled domains in RCMs and GCMs at seasonal prediction time scales. Three areas of focus will be additions of or improvements to the treatment of 1) groundwater, 2) dynamic vegetation cover and 3) multi-layer snowpack with subgrid redistribution of snow.
- Further fundamental understanding of the role of the ocean in climate predictability over the Americas on seasonal to interannual timescales during the current period of rapid climate change;
- Quantify the predictability of key ocean/atmosphere processes that influence hydrologic forecasting for water resources management in the Americas;
- Quantify connections between the leading patterns of climate variability (e.g. ENSO, PDO, AO) and weather extremes in the Americas;
- Assess current levels of SI predictability as well as the sources and limitations of forecast uncertainty in the Americas;
- Quantify the relative influences of ocean/atmosphere and land/atmosphere processes on simulations and predictions of seasonal climate in the Americas
- Reduce major systematic errors and biases in fully coupled (ocean-land-atmosphere) climate models that affect climate predictability in the Americas;
- Assess the predictability and prediction skill of drought in the Americas on seasonal-to-interannual time scales, in terms of both remote oceanic forcing and land-surface feedback mechanisms

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6. CLIMATE-BASED HYDROLOGIC FORECASTING AND WATER RESOURCES APPLICATIONS

6.1 Introduction

Improvements in seasonal climate prediction obtained by CPPA have the potential to improve forecasts in a diverse range of river basins throughout the Americas. The challenge is to translate information from seasonal climate forecasts and land surface moisture states into streamflow forecasts, including their associated probabilities. This research challenge is significant because it involves integrating many sources of uncertain information and accounting for how hydrological processes behave in response to this information (Schaake et al., 2007).

Uncertainties in streamflow forecasts are easily understood if we consider the details of the forecasting process. Forecasts of streamflow are produced by forcing a hydrologic model with historical station data to estimate land surface moisture states at the start of the forecast period (e.g., snowpack and soil moisture), and then forcing the hydrologic model with local-scale climate forecasts for several months into the future. Uncertainties in streamflow forecasts therefore stem from uncertainties in climate forecasts, uncertainties in basin initial conditions, and uncertainties in the hydrologic model itself, including model structure and parameters.

6.2 Research Priorities

The overall goal of CPPA hydrology research is to quantify and reduce uncertainties in hydrologic forecasts for a diverse range of river basins in the Americas. CPPA will support research to estimate streamflow forecasts, as well as to assess uncertainties in climate forecasts, uncertainties in basin initial conditions, and uncertainties in the hydrologic model itself. An important component of uncertainty analysis is predictability studies, and CPPA will also support research on hydrologic predictability that can identify areas for forecast improvements that can be addressed in future years of the CPPA program.

6.2.1 Uncertainties in climate forecasts

Persistent anomalies in the state of the land and ocean can significantly influence variability in precipitation and temperature across the globe, and the potential predictability of precipitation and temperature is quite high for many regions in the Americas (Mantua et al., 2003). The research challenge for streamflow prediction is to produce accurate and reliable *local-scale* quantitative forecasts of precipitation and temperature. Potential research topics for CPPA include the development of quantitative forecasts, statistical methods for post-processing of climate model output, the search for location-specific predictive indices, and the development of methods to merge forecasts with different lead times and to combine different types of forecast information. Retrospective analysis of climate predictions will be critical to develop techniques that produce statistically meaningful prediction intervals. The overarching requirements for all methods include the need to preserve the observed space-time correlation structure in precipitation and temperature patterns, proper treatment of the intermittent and skewed character of daily precipitation distributions, and accounting for the heteroscedastic space-time scale-dependent nature of forecast errors.

NCEP's initiative for the Climate Forecast System Reanalysis and Reforecast (CFSRR; see chapter 5) will be a valuable dataset for CPPA investigators. The CFSRR involves a global reanlysis for the period 1979-2009 (T382 spectral resolution, 64 vertical levels, assimilation of satellite radiances, GFDL MOM-4 coupled ocean model with assimilation, trends in atmospheric CO2). The CFS reforecast is for the period 1982-2009 (T126 spectral resolution, 64 vertical levels, GFDL MOM-4 ocean model, Noah land-surface model, dynamic sea ice model, and trends in atmospheric CO2). The CFS reforecast will produce ensemble forecasts (28 ensemble members) for a lead-time of one year, with ensemble forecasts generated once per month. At the time of writing (May 2008), the CFS global reanalysis is expected to be completed by early 2009, and the CFS reforecast is expected to be completed by early 2010. CPPA investigators are encouraged to use the reanalysis and reforecast datasets to develop and test seasonal hydrological forecast methods.

6.2.2 Uncertainties in basin initial states

Uncertainties in basin initial states largely stem from uncertainties in historical model forcing data (Clark and Slater, 2006). This is especially true for spatially distributed hydrologic models, where, in many basins, it is necessary to interpolate/extrapolate meteorological station data over large distances. CPPA will support research to develop Ensemble Quantitative Precipitation Estimation (EQPE) techniques, including multi-sensor EQPE techniques that account for uncertainties associated with use of rain gages, radars, satellites, etc in precipitation estimation over a wide range of space and time scales. Example research questions may include assessment of the hydrologic impact of uncertainties in model forcing data in different regions and assessment of the extent to which additional observations and new observing technologies result in more accurate hydroclimate predictions.

A key research area for CPPA is to reduce uncertainty in basin initial states through land data assimilation techniques (see also Chapter 4). The role of data assimilation in hydrological ensemble prediction is to process all available observations to produce the best possible probabilistic estimates of initial hydrological conditions. The weight given to observations (which determine the size of the model state update) depends on estimates of the relative errors in models and observations as well as estimates of the covariance between model states and the model equivalent of the observations. Key priorities for CPPA are to develop methods that produce reliable error estimates (both for the model and for in situ and satellite observations) and to develop methods to effectively propagate information across space and among variables. A challenge for CPPA is to develop data assimilation techniques to use all of the available data and especially to process potential new satellite observations. This will provide improved hydrologic ensemble prediction, especially in data sparse areas. As with other areas, important considerations in hydrologic data assimilation research are ensuring that new methods are flexible enough to handle non-Gaussian and space-time interdependent hydrologic variables.

6.2.3 Uncertainties in the hydrologic model

Model uncertainties stem from uncertainties in the choice of model parameters and weaknesses in model structure. Model parameters define the characteristics of the basin/region and include attributes such as topography, land cover/land use and soil properties.. Model structure describes the model, including the model architecture, e.g., the number and arrangement of soil layers, and the methods used to estimate hydrologic fluxes, e.g., the functions used to compute percolation, interflow, baseflow, and surface runoff (Clark et al., 2008).

Uncertainties in model structure and model parameters are normally treated separately. Parameter uncertainty is typically quantified by combining model output from multiple simulations of streamflow produced using a finite number of equally plausible parameter sets (Beven and Freer, 2001; Vrugt et al., 2003). Structural uncertainty is typically quantified by combining output from multiple models (Butts et al., 2004; Georgakakos et al., 2004; Vrugt and Robinson, 2006). Separate treatment of uncertainties in model parameters and structure is understandable given that model structure is normally defined as part of model development and model parameters are specific to each model, and are defined when the model is applied to a specific location.

CPPA will support development of methods that explicitly quantify all sources of uncertainty in the modeling process as well as methods to post-process hydrologic ensemble forecasts to produce reliable probabilistic forecasts. Example science questions include: How can uncertainties in hydrological models, model parameters and hydrological initial conditions be represented in hydrological ensemble prediction? Can we attribute and quantify the sources of uncertainty? How do we generate consistent ensembles that reflect the total uncertainty of the system, including space-time correlations, and the uncertainty that comes from hydrologic initial states, parameters, and model structure? How can we quantify structural uncertainty in cases when we have only a small number of model structures? How can we quantify hydrologic uncertainty in ungauged basins? How can we post-process hydrologic ensemble forecasts to fix multi-scale bias and spread problems, produce reliable probabilistic forecasts and possibly improve forecast skill? An important consideration for all science questions will be accounting for the interactions between the different types of model errors.

Quantifying uncertainty is only one aspect of the modeling problem and opportunities also exist to assess the extent to which incorporation of improved process understanding in hydrologic models results in more accurate hydroclimate predictions. For example, the hydrologic models used by the National Weather Service River Forecast Centers do not explicitly model the storage and fluxes of water in the vegetation canopy, and it will be interesting to assess if incorporating vegetation processes can improve simulations of streamflow. A key consideration with all model complexity studies is determining the complexity of the model that can be supported by the available data, and, as such, data witholding experiments in highly instrumented catchments are needed to determine the appropriate model structures for operational streamflow forecasting applications.

6.2.4 Predictability

Quantifying uncertainty provides insights into hydrologic predictability. By quantifying regional variations in hydrologic uncertainty, CPPA research will unravel the key factors that govern the ability to predict streamflow in different regions across the Americas. Example science questions may include: What is the relative role of weather and climate forecasts versus initial basin states in affecting the skill of hydrologic forecasts? What is the relative significance of hydrologic model uncertainty in gauged and ungauged basins? This research is needed to address how best to represent relevant hydrologic processes in distributed models over a range of spatial scales, to develop strategies for estimation of hydrologic model parameters (including regionalization and parameter transferability), and to understand the importance of hydrologic processes in coupled land-atmosphere modeling. In short, research on quantifying hydrologic uncertainties is necessary to identify areas where we can improve hydrologic predictions in future years of the CPPA program.

6.2.5 Anthropogenic considerations

Streamflow in most U.S. rivers depends not only on natural hydrologic processes but on anthropogenic factors such as upstream diversions, reservoir regulation irrigation return flow and land use change as well. The effect of such anthropogenic factors must be considered as part of the ensemble streamflow prediction process. Such factors may serve to increase uncertainty in streamflow forecasts because the full effect of anthropogenic factors may be unknown.

6.3 Implementation

To effectively achieve the CPPA science objective related improved hydrologic predictions, there are three implementation priorities. First, CPPA needs to effectively utilize research across its program — in quantitative precipitation and temperature forecasts in scales usable by hydrologic models, model development, orographic precipitation research, land memory research, and so forth — to develop and evaluate end-to-end prediction systems for seasonal hydrologic forecasting and water resources management. Secondly, CPPA should support the development of collaborative activities with appropriate state and federal agencies, as well as the academic and private sector that have interests in CPPA forecast products. CPPA is particularly interested in continuing collaboration with the NWS Office of Hydrologic Development and the NWS River Forecast Centers, with a focus on seasonal forecasting of streamflow, snow pack and soil moisture. Five NWS/OHD-led initiatives are of particular interest to CPPA research: the Advanced Hydrologic Prediction Service (AHPS), the Experimental Ensemble Forecasting System (XEFS), the Hydrologic Ensemble Experiment (HEPEX), the Community Hydrologic Prediction System (CHPS), and the Hydrology testbed. Thirdly, CPPA should build on the strong and successful linkages with water users that have been developed as part of the NOAA Regional Integrated Sciences and Assessments (RISA) program.

6.3.1 Fostering integrated CPPA activities

Previous GAPP and GCIP research on water resources has focused on individual projects and case studies addressing one or more components of hydrologic prediction, without the benefit of integration or collaboration amongst GCIP/GAPP investigators. Notable exceptions were the North American Land Data Assimilation System (NLDAS) activities and the Water and Energy Budget Study (WEBS), the latter which successfully analyzed the budgets of the Mississippi River basin. For CPPA to realize its scientific goals, a more structured approach for transferring research results across the program will be required.

CPPA will encourage implementation activities that promote such an integrated project approach. For example, CPPA research into land memory processes, orographic precipitation, and seasonal climate prediction has significant implications for activities in hydrologic prediction and predictability. Land surface memory accounts for a significant portion of predictability of hydrologic processes over seasonal to interannual time scales. In particular, the persistence of dry soil moisture states leads to significant skill in low flow (drought) forecasting. In contrast, skill in high flow (flood) forecasting for seasonal predictions requires climate predictability (e.g., predicting the occurrence of anomalous precipitation). Integrated investigations linking with CPPA land memory research and seasonal climate prediction are needed to understand their relative roles on hydrologic predictability, and assess predictability for water resources applications as a function of lead time, spatial scale, and geographic location. Hydrologic model intercomparsions are also needed to assess how alternate model formulations affect predictability. This work will help in understanding the spatial variations in hydrologic predictability over the CPPA domain, and target regions and water resources applications where predictability could provide information and value to water resources management.

Many areas of hydrologic prediction and predictability would benefit from an integrated approach. For instance, land surface memory associated with soil moisture states suggests that there may be significant opportunities for improving drought forecasting over seasonal to interannual times scales. GAPP research can address issues of prediction and predictability of low flow and drought through integrated activities that include model development (e.g. better formulation and calibration of baseflow hydrologic processes), seasonal prediction of precipitation (including both orographically dominated GAPP regions and monsoon-dominated regions), and water resources applications. Retrospective studies are also needed to understand seasonal and interannual variations in baseflow, their predictability based on climate forcings, and their modulation by the land surface.

CPPA will encourage activities that not only build across its program elements (science and applications), but also between CPPA investigators and related non-CPPA applications-oriented programs. Some additional examples of integrated activities are provided in the next three sections.

6.3.2 Community efforts in forecast technologies (HEPEX)

The Hydrological Ensemble Prediction Experiment (HEPEX) provides opportunities for community development of ensemble forecast technologies. HEPEX is a relatively new initiative designed to bring the international hydrological community together with the meteorological community to demonstrate how to produce reliable "engineering quality" hydrological ensemble forecasts that can be used with confidence to assist the water resources sector to make decisions. Representatives of operational hydrological services and operational water resources agencies are participating in HEPEX to define and execute the project. HEPEX will address critical science problems in ensemble hydrologic prediction through a series of Test bed demonstration projects. HEPEX does not have a dedicated source of funding, and its activities will be carried out by scientists that already have appropriate funding or who might seek funding for their efforts. CPPA will provide funding for investigators interested in participating in HEPEX intercomparison experiments.

6.3.3 Collaborative linkages with the operational forecasting community

Operational forecasts of river conditions provide vital information for flood warning, water management, navigation, recreation, and environmental management. Several federal and local agencies are involved in hydrologic forecasting to various degrees for operational decision-making. However, NWS is the only agency whose river forecasting activity covers the entire United States, and it is their responsibility for issuing river forecasts and flood warnings to the public. Many federal and local water agencies directly rely on NWS river forecasts to meet their operational forecasting needs. By continuing a strong collaboration in streamflow forecasting research with the NWS Office of Hydrologic Development (OHD) and the NWS River Forecast Centers (RFCs), CPPA would have a broad impact on the water resources community.

The Advanced Hydrologic Prediction Service (AHPS) initiative of NWS offers unique opportunities for CPPA to demonstrate accomplishments towards its broad water resources related goals. CPPA welcomes collaborative efforts with the NWS hydrology program that could demonstrate the potential of CPPA research to meet AHPS science infusion requirements. In a manner similar to its current arrangement with NCEP, CPPA will continue developing parallel research and operational pathways with the NWS/OHD and RFCs. The research pathway will involve targeted hydrologic research conducted primarily by scientists in the academic and government research laboratory community. The operational pathway would be conducted within NWS/OH and its RFCs and would deal primarily with the implementation of improved long-range hydrologic forecasting capability developed through CPPA.

6.3.4 The Community Hydrologic Prediction System (CHPS)

CHPS is being developed by OHD to provide a common research, development, and operational environment for hydrologic systems development, including the development of new hydrologic models, and new ensemble and data assimilation techniques. It is scheduled to be field deployed in 2011. CPPA should fund projects that seek to use CHPS, since that will provide a more expedited transition of research to operations.

6.3.5 The Experimental Ensemble Forecasting System (XEFS)

This umbrella initiative is coordinating all ensemble, data assimilation and verification work being done at OHD, and correspond to one of HEPEX testbeds.

6.3.6 The Hydrology Testbed

The Hydrology testbed received initial funding from CPPA through the OHD component of the Core project. Although a final science plan is yet to be developed, its goals are similar to NCEP's Climate Testbed, although it will cover all forecasting time scales ranging from minutes (flash floods and debris flows) to days (river main stem floods) and months (droughts). OHD collaborative research will be funneled through the testbed.

6.3.7 Collaborative linkages in water resources applications

Facilitating the transfer of improved seasonal predictions into water management operations is a challenge for CPPA. Forging relationships with water managers often takes time and two-way interaction to reach a common understanding of the role and value of forecasts in decision-making. However, examples of established relationships exist within the NOAA/OGP Regional Integrated Sciences and Assessments (RISA) Program. Explicit in the RISA program is the partnership between the scientific community and the users (decision-makers or "stakeholders") of scientific knowledge. Many RISA projects focus on the role of climate variability and water resources decision-making. Where appropriate, CPPA implementation activities should build on the strong and successful linkages to water users developed through the RISA program centers. By combining the season prediction capabilities demonstrated by CPPA, with the regional and local knowledge on user decision-making developed at the RISA centers, both programs would more effectively implement their applications research for the benefit of interested users. For successful CPPA/RISA partnerships, the NOAA National Climate Transition Program many also provide opportunities for transitioning research applications to operations. In addition to the RISAs, other programs with non-NOAA main funding serve similar purposes.

6.4 Deliverables

In its first few years, implementation of proposed CPPA research activities will:

- Establish collaborative activities with the NWS Office of Hydrologic Development and River Forecast Centers to improve seasonal hydrologic forecasting techniques; and
- Establish collaborative linkages with selected water management partners to demonstrate utility of seasonal predictions for water resources management.

Over the long-term, CPPA research in hydrology and water resources will:

- Develop improved models and techniques for making quantitative probabilistic hydrologic forecasts that integrate with CPPA research in land memory process, orographic process, remote sensing, and climate predictions; and

- Demonstrate end-to-end hydroclimatic forecasting technologies at seasonal climate time scales.

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7. PROGRAM MANAGEMENT

7.1 CPPA Management Structure

The CPPA program management structure includes the program manager(s) from the NOAA Climate Program Office, the CPPA Science Panel, and CPPA working groups.

Program managers are responsible for the overall implementation of the CPPA Program. The implementation by NOAA program managers is based on the science and implementation priorities identified by the CPPA Science Panel in the CPPA Science and Implementation Plan, which are consistent with the priorities of NOAA Climate mission goals.

CPPA Science Panel develops the CPPA Science Plan and provides scientific guidance for CPPA management. The membership and the Terms of Reference for the Science Panel are attached as an appendix.

CPPA Core Projects assist in transition and infusion of research resulting from the CPPA funded projects into NCEP and OHD and River Forecast Centers operations. The current Core Project leads are Ken Mitchell (NCEP) and Pedro Restrepo (OHD).

CPPA working groups For CPPA to realize its scientific goals and to demonstrate its contributions to the NOAA Climate Program, a structured approach for transferring research results across the program elements will be required. This will be done through the establishment of working groups within CPPA. Each funded PI can elect to join one or more of the working groups. Each working group elects a chair or co-chairs to coordinate its activities. The working groups will report to the CPPA Science Panel and CPPA program managers. There are currently seven working groups on:

- Intra-America Seas (IAS)
- Land Data Assimilation System-Drought (LDAS-Drought)
- Multi-RCM Ensemble Downscaling (MRED)
- North American Monsoon Experiment (NAME)
- VAMOS Ocean-Cloud-Land Study (VOCALS)
- US CLIVAR Drought
- US CLIVAR MJO

7.2 Data Management

7.2.1 Introduction

To accomplish CPPA goals and major science objectives requires the development of a comprehensive and accessible database for the study areas and the establishment of an evolving program of model development that will permit observations and analyses to be extended spatially within North America or applied globally with new observations.

These data sets will consist primarily of relevant operational data from existing in situ, remote sensing, and model output sources and will also include special (surface, upper air, and satellite) meteorological and hydrological observations with increased spatial and temporal resolution. Some retrospective data sets (in addition to the data sets previously collected for the GEWEX Continental-scale International Project [GCIP] and the GEWEX Americas Prediction Project [GAPP]) may be necessary for the development of hypotheses and evaluation of models. While CPPA researchers may produce individual unique data sets for hydrological and atmospheric studies during the course of the project (and include them in the CPPA archive), most of the data of interest will be collected routinely from operational sources and available through established data centers. CPPA will take advantage of the groundwork and infrastructure accomplished by GCIP/GAPP that relied upon and enhanced existing operational/research meteorological and hydrological networks (i.e. upgraded facilities such as doppler radars, wind profilers, automatic weather stations, and soil moisture measurements). CPPA will also collaborate (and link archives) with other related programs and field projects. NCAR's Earth Observing Laboratory (EOL) will coordinate the data management for CPPA.

The EOL coordination activities fall into three major areas: (1) determine the data requirements of the CPPA scientific community and develop them into a comprehensive CPPA Data Management Plan through input received from the CPPA Science Panel, CPPA investigators, and other tools such as the data questionnaire; (2) collection of real-time data for preliminary data analysis; and (3) establishment of a coordinated distributed archive system and providing data access/support of both research and operational data sets for the CPPA investigators and the global scientific community. To accomplish these goals, EOL will also be responsible for the establishment and maintenance of the CPPA Data Management Portal. These web pages provide "one-stop" access to all distributed CPPA data sets, documentation, on-line field catalog products, collaborating project data archives, and other relevant data links. EOL will make arrangements to ensure that "orphan" data sets (i.e. smaller regional and local networks) will be archived and made available through the CPPA archive. The EOL may also quality control and reformat selected operational data sets (e.g. atmospheric soundings or surface data) prior to access by the community as well as prepare special products or composited data sets. Oversight of the CPPA data management tasks will come from the CPPA Science Panel, as well as coordination with the individual investigators, and other participating groups.

EOL will also provide and maintain data management support for various CPPA related field projects such as the North American Monsoon Experiment (NAME) [http://www.eol.ucar.edu/projects/name], VAMOS Ocean-Cloud-Land Study (VOCALS) [http://www.eol.ucar.edu/projects/vocals], and possible future field projects such as the La Plata Basin Regional Hydroclimate Project (LPB) [http://www.eol.ucar.edu/projects/lpb/] and the proposed Western U.S. Mountain Hydroclimate Field Project.

7.2.2 Data policy

The basis for the CPPA data policy is the World Meteorological Organization (WMO) Resolution 40 on the policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities. This resolution was adopted by the XII WMO Congress during June 1995 in recognition of the requirement for the global exchange of all types of environmental data and the basic responsibility of WMO Members and their national Meteorological Services in support of safety, security and economic benefits of their countries to adopt the following policy on the international exchange of meteorological and related data and products:

"As a fundamental principle of the World Meteorological Organization (WMO), and in consonance with the expanding requirements for its scientific and technical expertise, the WMO commits itself to broadening and enhancing the free and unrestricted international exchange of meteorological and related data and products."

In general, users will have free and open access to all the CPPA data, subject to procedures in place at the various CPPA Data Archive Centers (CDACs).

7.2.3 Data management strategy

The first step in organizing the CPPA data management support is to determine what data are required from the various scientific components of the program. In addition to the data described in this plan, EOL has developed and distributed a data questionnaire to survey the CPPA participants to document this information. This questionnaire information with input from other data sources, CPPA investigators, and sample data sets will be used to obtain detailed information regarding the various data sets (e.g. data format, data set size, data frequency and resolution, real-time operational requirements, etc.). This will assist the EOL (and the collaborating Data Archive Centers) in handling and processing the data as well as identifying and developing any format converters necessary. The PIs (and data sources) that will be submitting data to the archive will be requested to adequately document data sets in accordance with standard international metadata standards agreed upon by CPPA and summarized in the Data Management Plan.

The EOL will have the primary responsibility to develop the CPPA Data Management Plan. This document will contain details of the strategic and tactical data management implementation such as: (1) describing data policies and protocol, data compilation (including special data sets) and attribution; (2) providing details of the CPPA data archive system and data submission/access; (3) identifying the sources of observations from existing and planned networks; and (4) providing details and assisting in developing integrated data sets from existing observational systems and operational model output. The EOL will also collaborate on data management with other CPPA related programs such as the VAMOS, MESA, and other related regional projects.

7.2.4 Data archive and access

The CPPA will take advantage of the capabilities at existing VDACs to implement a distributed data management system. EOL will provide “one-stop” single-point access (Portal) using the web for search and order of CPPA data from the various CDACs operated by different nationalities/agencies with the capability to transfer data sets electronically from the respective CDAC to the user. Access to the data will be provided through a Data Management web page (http://www.eol.ucar.edu/projects/cppa/dm/) and also linked from the CPPA "Home" page. These Data Management pages will contain general information on the data archive and on-going activities in CPPA (i.e. documents, reports), data submission instructions and guidelines, links to related programs and projects, and direct data access via the various CDACs.

EOL will be responsible for the long-term data stewardship of CPPA data and metadata. This includes ensuring that "orphan" datasets are properly collected and archived, verifying that data at the various CDACs will be archived and available in the long-term, and that all supporting information (e.g. field catalog) are included in the archive.

7.3 CPPA Synthesis Products

All funded investigators have a responsibility to contribute to CPPA synthesis products. The working groups will take leadership in developing and producing these products. CPPA Synthesis Products will be developed to address specific CPPA scientific questions that, when answered, will help achieve the CPPA objectives described in Chapters 1 - 6. The current products (middle column), working group (right column) responsible for their compilation, and time horizon (left column) for their completion are as follows:

CPPA Objective: To quantify the sources and limits of predictability of climate variations on intra-seasonal to interannual time scales

5 - 8 years	Quantify the relative contribution of the atmosphere, land, and ocean to climate predictability in the Americas for the cold and warm seasons	CP, AS, LA
5 – 8 years	Develop and test procedures for improved regional analysis of the atmosphere, land, and ocean for predictability study	CP, AS, LA
3 years	Recommendations for optimal global climate observing systems	CP, AS, LA

CPPA Objective: To improve the predictive understanding and numerical simulation of oceanic, atmospheric and land-surface processes, including the ability to quantify uncertainties

5 years	A synthesis report on the accomplishments of CPPA field study and modeling projects (EPIC, NAME, VOCALS, IASCLIP)	CP, AS, LA
5 – 8 years	Assess and document model improvements in simulating the eastern tropical Pacific and IAS climate in journal paper(s)	AS
5 – 8 years	Assess and document model improvements in representing land memory processes, including soil moisture, snow/ice, vegetation, and atmospheric response to land forcing such as topography and	LA

	vegetation in journal paper(s)	
5 – 8 years	Identify model improvements and simulation techniques that can be transitioned to operations	AS, LA

CPPA Objective: To advance NOAA's operational climate forecasts, monitoring, and analysis systems

3 - 5 years	Implement model improvements to operational climate forecast system	AS, LA
5 - 8 years	Assess and update climate forecast skill of the operational forecast system	AS, LA
5 years	Assess the impacts of downscaling on regional climate prediction skill	AS, LA

CPPA Objective: To develop climate-based hydrologic forecasting capabilities for decision support and water resource applications

5 years	Develop a hydrologic forecasting system that integrates advances in land modeling and climate forecasts, monitoring and measurements	WR, LA
2-4 years	Coordinate a demonstration of end-to-end hydroclimatic forecasting for selected river basins with participation from CPPA investigators and selected water management partners	WR

APPENDIX: CPPA SCIENCE PANEL

Membership

Ruby Leung (Chair, DOE/Pacific Northwest National Laboratory)
Hugo Berbery (University of Maryland)
Martyn Clark (University of Colorado)
David Enfield (NOAA/AOML)
Chris Fairall (NOAA/ETL)
Dave Gutzler (University of New Mexico)
Wayne Higgins (NOAA/NCEP/CPC)
Paul Houser (IGES/Center for Research on Environment and Water)
Richard Johnson (Colorado State University)
John Roads (Scripps Institution of Oceanography)
Siegfried Schubert (NASA/GSFC)
Eric Wood (Princeton University)
Shang-Ping Xie (University of Hawaii at Manoa)

Terms of References

- To develop a CPPA Science Plan and Implementation Strategies document based on the CPPA objectives and synthesis of the existing PACS and GAPP plans
- To review and prioritize CPPA research and identify research gaps
- To develop a structure that coordinates CPPA research activities, and to synthesize research outcomes
- To coordinate with relevant national and international programs to communicate and integrate CPPA objectives and results
- To develop suitable milestones to promote funding opportunities