SCIENCE PLAN
International Pacific Research Center

Contents

1. Introduction

The International Pacific Research Center (IPRC) was established in 1997 within the School of Ocean and Earth Science and Technology (SOEST) of the University of Hawaii. IPRC performs research on climate variability and change with a focus on the Asia-Pacific region. As of 2010 the IPRC had 9 tenure-track faculty members and nearly 50 additional research scientists and scientific support staff. Extramural research funding has been received at a level of roughly $7 million per year. Conceived under the "U.S.-Japan Common Agenda for Cooperation in Global Perspective" IPRC represents a unique institutional collaboration between the US and Japan. The overall governance of the IPRC is in the hands of an international committee with members appointed by the relevant Japanese and US Federal agencies and the University of Hawaii.

This document presents the key scientific questions for the IPRC and describes the activities that IPRC researchers will conduct to address these questions. The focus is on issues for which substantial effort and progress are anticipated in the next five years, although activities in many areas described here can be expected to continue beyond that horizon. Also, given the size and scope of the IPRC, *this document does not attempt to describe all ongoing and planned activities, but rather is designed to discuss what IPRC scientists regard as the most important issues to be addressed and the planned activities expected to have the most consequential outcomes*. More detailed descriptions of planned activities including anticipated milestones and time lines can be found in extensive proposal documents for IPRC's externally funded projects.

Chapter 2 presents an overview of IPRC's plans in the form of a statement of IPRC's officially endorsed *mission*, a broader *vision* of the significance, scope and focus of IPRC's activities, and then a *brief statement of the particular role* of the IPRC in the global climate science community. Chapter 3 is the core of the plan, and presents the science issues and activities in some detail. Chapter 4 describes the contribution of IPRC's Asia-Pacific Data-Research Center in support of IPRC research activities. Chapter 5 describes the connections with broader concerns in the community and how the proposed research as described in this plan relate to IPRC's agreements with its principal supporting agencies, JAMSTEC, NOAA and NASA.

2. IPRC's Mission, Vision and Role in the Research Community

Mission

IPRC's mission is:

To provide an international research environment dedicated to improving mankind's understanding of the nature and predictability of climate variations and change in the Asia-Pacific region, and to developing innovative ways to utilize knowledge gained for the benefit of society.

Vision

Asia and the Pacific region are home to over half the world's people, all of whom are affected by variations in the climate system on a range of timescales from intraseasonal to centennial and longer. IPRC researchers conduct modeling and diagnostic studies to document these variations and understand their causes, whether the causes are purely natural or have an anthropogenic component. Through advances in basic research IPRC supports the ultimate practical goal of improving environmental prediction for the Asia-Pacific region. One focus of IPRC investigations is understanding key phenomena rooted in the tropics such as the El Niño-Southern Oscillation of the ocean-atmosphere system, monsoon circulations, interannual variability in the Indian Ocean region, intraseasonal oscillations of the tropical atmosphere, and tropical cyclones. Other examples of important issues for IPRC study include the nature of decadal variability in the extratropical North Pacific Ocean, the dynamics of the very strong Kuroshio and Oyashio ocean currents in the western North Pacific and the role of marginal seas in the climate system. Concerns about human induced climate change are addressed through modeling studies of past climate and through assessment of model predictions for future trends in climate. IPRC's strength in modeling and diagnosing climate variability on various timescales fosters a particular interest in understanding how longer period climate trends may affect higher-frequency variability, including the occurrence of extreme events.

IPRC research leverages the strengths of close partners and collaborators to allow leading edge studies of some of the most important and timely issues in climate science. In particular, such collaborations allow IPRC researchers access to the state-of-the-art technology in terms of computational facilities and observational systems. There have been major advances in spaceborne, remote-sensing instrumentation during the past decade, which revolutionized our ability to observe the Earth's climate system, and that progress is continuing. At the same time, ocean-atmospheric modeling has advanced to the point where global models have spatial resolutions that approach those of satellite observations, enabling them to take full advantage of the high resolution of satellite data, both as forcing fields for model simulations and for validation. IPRC researchers are carrying out research activities that utilize these new resources, seeking to discover new phenomena, understand their underlying dynamics, and determine their role in the climate system. Results of these studies contribute to the validation and improvement of state-of-the-art, global climate models, such as those now being used to predict global climate change.

The amount of observational data and model-based products available for climate studies has increased tremendously in the past decade, and will continue to expand as the Earth's climate observing system is fully implemented. Through its Asia-Pacific Data-Research Center (APDRC), the IPRC operates and continually improves a web-based, data-server system that makes data resources readily accessible and usable by IPRC researchers, the international climate community, policy makers, and the general public. The APDRC also undertakes data-intensive research activities that both advance knowledge and lead to improvements in data preparation and data products.

From its advent as a US/Japan partnership, the IPRC has sought to foster close ties with the international climate research community. IPRC research contributes directly to the goals of prominent international climate programs. These programs include: the Climate Variability and Predictability (CLIVAR), Global Energy and Water Experiment (GEWEX), and the Stratospheric Processes and their Role in Climate (SPARC) programs of the World Climate Research Program (WCRP); the Global Earth Observation System of Systems (GEOSS); and the Intergovernmental Panel on Climate Change (IPCC).

In partnership with UH/SOEST, IPRC makes an important contribution to the international climate research enterprise through training of students and young scientists.

IPRC's Particular Role in the Climate Research Community

By virtue of its international institutional foundations, its location, its assembled expertise, and its scientific focus, the IPRC plays a uniquely valuable role in the climate research community. The JAMSTEC-UH institutional arrangements encourage, and provide stable support for, the Japan-US collaboration that is at the core of IPRC's activities. IPRC's location in the mid-Pacific significantly facilitates the practical aspects of collaborating with Japan and other Asian nations. The IPRC has assembled an international group of faculty and researchers with outstanding expertise in aspects of the meteorology and oceanography of the Asia-Pacific region. These scientists represent the largest concentration of such experts at any US university, and IPRC's explicit scientific focus on the Asian-Pacific region is also unique for a US institution. The IPRC draws on the expertise of our UH SOEST colleagues who also generally have a Pacific focus to their research interests and expertise. The multicultural nature of society in Hawaii, the international background of the IPRC faculty, and the particular IPRC science focus all combine to make the IPRC an ideal institution for younger scientists from Asia to be exposed to, and develop lasting connections with, the US research community. In an ever more globalized scientific community, the IPRC is a leader in establishing deep and long-lasting US-Asia research collaborations focusing on issues with practical importance for the people of the entire Asia-Pacific region.

3. Science Questions, Planned Activities, and Expected Outcomes

This chapter describes the individual areas that will be investigated by IPRC researchers. The presentation for each of the areas consists of a brief review of the background and hypotheses to be tested, a crystallization of the main aims in terms of a number of science questions, an overview of the strategy for answering the questions, and a final brief summary of the anticipated outcomes for the proposed work including new insights and new capabilities (e.g. in terms of modeling and prediction). Given the breadth of some of the scientific questions posed, IPRC's contributions, even including those of our direct collaborators, may represent only a fraction of the community effort for a given research issue. The descriptions try where possible to identify the specific strengths of IPRC in addressing particular aspects of these questions.

The individual areas are grouped into larger subject categories: *Indo-Pacific Climate*, *Regional and Small-Scale Climate Processes and Phenomena*, *Asian and Global Monsoon Systems*, and *Paleoclimate*. This grouping provides some overall "vertical" structure to the IPRC plans, but in practice many individual science questions will span more than one subject category. More generally, there are many "horizontal" linkages across the areas and categories that will affect the implementation of the activities in this plan. For example, modeling and diagnostic tools developed for one set of issues may be applied profitably to the activities in other areas. Also, while the division into subject categories adopted here is based to a considerable extent on the space and time scales of the phenomena studied, many of the most exciting issues in climate science involve strong coupling among phenomena with widely disparate space and time scales.

Some fundamental concerns connect IPRC efforts across many of the individual subject areas described in this chapter. Notably many issues and activities in individual sections in this chapter are related to attribution and prediction of long-term climate change. Indeed, it is striking to see how many of the individual research areas have at least some applicability to climate change concerns. A number of individual research areas also have relevance for seasonal forecasting. Chapter 5 below highlights IPRC's plans related to these cross-cutting concerns.

3.1 Large-Scale Indo-Pacific Climate

The large-scale climate of the Indo-Pacific region involves the ocean circulation, the coupling of the ocean and atmosphere, the natural climate variability, and the emerging impact on these of anthropogenic climate change. The studies described here can be summarized as investigating the role of the ocean in the climate system and are designed to increase fundamental understanding of the ocean circulation, air-sea interaction, climate modes and climate change. A theme running through many of the issues considered is the impact of processes at mesoscales on the large-scale climate variations. These concerns are timely as novel opportunities are now afforded by developments in remotely sensed observations from satellites, in situ observing systems, and high resolution modeling. This unprecedented data stream calls for exploration of new climate phenomena that span wavenumber-frequency space that were previously inaccessible. A further key motivation is the increasing signal of anthropogenic climate change and its interaction with natural climate modes. To take advantage of these scientific opportunities, we outline activities that include the processing and synthesis of data from state-of-the-art observing systems, and applying a hierarchy of models ranging from highly simplified mechanistic systems to high-resolution, comprehensive, global general circulation models.

3.1a Ocean Circulation

3.1a_1 Near-surface circulation: tropical countercurrents

While many aspects of the near surface circulation are of potential interest, our focus will be on countercurrents in the subtropical oceans whose existence defies Sverdrup theory, the dynamics of ocean jets such as the Kuroshio and its extension, and ocean salinity.

Background

A remarkable aspect of the upper-ocean circulation in the tropical and subtropical South Indian Ocean (SIO) is the presence of near-surface, eastward flow across the basin, primary examples being the SIO Countercurrent (SICC; Palastanga et al., 2007; Siedler et al., 2006) and the Eastern Gyral Current (EGC; Meyers et al., 1995), the latter located in the region near the entrance of the Indonesian throughflow (ITF). These flows have been detected in observations, although details about their precise location, intensity, and variability (both in space and time) are still being explored. While the flows also been successfully simulated in numerical models, their basic dynamics remain unclear. The jets flow counter to the circulations predicted by both Ekman and Sverdrup theory. Thus, these flows represent a fundamental gap in our first-order understanding of the large-scale mean flow in the SIO.

These surface currents are likely part of deeper baroclinic circulation. Assuming geostrophy and neglecting bottom effects, any deviation from the Sverdrup circulation must vanish on vertical integration; therefore, the surface eastward flow must be accompanied by an anomalous deep westward flow. Hydrographic observations and deep-float trajectories seem to agree with this picture, but the evidence is not conclusive because of the sparseness of available data.

Science Hypotheses

The validity of each of the following hypotheses will be investigated.

- The high-pressure ridge and the broad eastward flow south of the pressure maximum are forced by the eastern inflow boundary conditions of the ITF and its advection of low-density water across the basin.

- Rainfall in the latitude band of the ridge contributes to the ridge in sea surface height.

- The eastward flow is enhanced by negative buoyancy fluxes (both cooling and evaporation) in the southern part of the SIO, increasing the across-basin meridional density gradient there.

- The Eastern Gyre (EG) is a distinct feature of the mean circulation in the SIO that circulates around a separated region of the high-pressure ridge, and the EGC is the eastward-flowing branch of the EG. The EG is separated from the rest of the ridge due to external forcing by winds and buoyancy flux, the damping of higher-order Rossby waves, or both.

- The SICC is the surface expression of a baroclinic (surface-eastward, subsurface-westward) pair of currents, generated by the radiation of Rossby waves from the southwestern tip of Australia along Rossby-wave characteristics that flow northward as well as westward because of the background Sverdrup circulation.

- The SICC is an arrested front, formed where characteristics overlap.

- The ITF forces the SICC by intensifying of the Rossby-wave signal emanating from the southwest tip of Australia.

- Convection and/or subduction southwest or south of Australia strengthen the SICC.

- Subtropical Ekman convergence or buoyancy flux contributes to, but is not the primary cause, of the SICC.

Strategy

An improved, three-dimensional climatological flow field will be constructed down to 1000 m depths. A recent, high-quality climatology called Hydrobase2 will be used together with data from Argo floats and WOCE lines, to estimate geostrophic flows and to study water mass composition. Absolute velocity products derived from surface or deep floats will be used as a reference for these geostrophic calculations. Satellite winds will be used to compute the Ekman component of the ocean circulation and to force the models. These analyses will be compared with global and regional numerical models to investigate the dynamics of the near-surface flows in the SIO.

Expected Outcomes

An improved picture of the mean, three-dimensional structure of the upper Southern Indian Ocean will be obtained, which will lead to better understanding of the dynamics of the near-surface eastward (and subsurface westward) currents. If the surface and subsurface branches of the baroclinic circulation are connected through subduction or convection as hypothesized above, this current system forms part of the meridional overturning circulation involving the ITF. This likely has implications for the heat transport of the overturning circulation, and thereby on the global climate.

3.1a_2 Subsurface circulation and its role in regional climate and climate change

Background

The upper and lower thermocline circulation plays a special role in climate, since it provides the source waters for the surface circulation, and is the region where thermal anomalies and tracers such as carbon are sequestered for time scales of decades or longer. Recent charting of the ocean's surface by multi-sensor satellite missions have resulted in a dramatic improvement of the description and understanding of the upper layer dynamics. Unlike the upper ocean, which is subject to direct wind forcing, the forcing of mean subthermocline flow involves diapycnal mass flux and eddy stress across the thermocline.

Major progress in observing the circulation of the deeper ocean is expected through the Argo program (http://www.argo.ucsd.edu/), a global array of several thousand autonomous profiling floats that provides an unprecedented number of hydrographic observations. The processing of Argo data started as a decentralized activity in dozens of national efforts but is gradually developing into a well-coordinated international system. IPRC possesses the resources and skills in the processing of Argo observations, and is therefore well-positioned to study the intermediate-depth circulation of the Indo-Pacific Ocean.

In a steady flow without propagating baroclinic Rossby waves, large-scale wind-driven currents should be concentrated in the mixed layer and should extend all the way to the western boundary. In reality, the vertical structure and zonal extent of such a flow is affected strongly by eddies through lateral and vertical momentum transfer (horizontal Reynolds stress and inviscid form stress, respectively). Modeling studies have therefore investigated how diapycnal upwelling and eddy stress drive subthermocline zonal jets, including the Equatorial Subsurface Countercurrents known as the Tsuchiya Jets. For example, the Hawaiian Lee Countercurrent (HLCC), a branch of a zonal recirculation driven by localized wind curl associated with the Hawaiian Islands, is surprisingly deep in an eddy-resolving model simulation (Sasaki and Nonaka, 2006), suggesting that eddy stress spreads its momentum vertically. Its zonal extent appears limited by energy sinks due to the generation of eddies (Yu et al., 2003). Air-sea interaction may play a role in altering the horizontal structure of the oceanic recirculation.

Interactions with the wind stress curl are important for currents such as the HLCC and help the current system extend far westward and may be responsible for small-scale atmospheric features (Xie et al,. 2001). At thermocline domes, diapycnal upwelling may also interact with eddy forcing in driving subthermocline ocean (Furue et al., 2009). Variations in winds and surface buoyancy flux may lead to variations in deep currents. Such variations will propagate along characteristics of baroclinic Rossby waves. In a coarse-resolution model (Furue et al., 2009) the Costa Rica Dome surface and subthermocline recirculation gyres are associated with the upwelling dome generated by wind curl at the Papagayo mountain gap (Kessler, 2002; Xie et al., 2005). Similar dynamics may be important in other thermocline domes such as the ones in the tropical Atlantic.

Interaction between the upper and subthermocline oceans through eddy stress must be ubiquitous and may account for some of the deep zonal jets discovered recently (Treguier, 2003; Nakano and Hasumi, 2005; Maximenko, et al. 2005). In such a case, topographic features may restrict or regulate eddy-driven deep flows. Studies of these recirculations and eddy effects have been limited to theoretical discussions in idealized contexts and to the deep recirculation gyres associated with the Gulf Stream and the Kuroshio. The recent availability of global eddy-resolving simulations and high-resolution observations allows us to explore those dynamics in other areas and in more realistic contexts.

Science Questions

- What are the horizontal and vertical structures of the intermediate (100-2000 meters) depth circulations?

- Do deeper currents correlate with geostrophic currents at the surface? Is the vertical structure adequately described by baroclinic or equivalent barotropic modes?

- How does the vertical structure depend on horizontal scale?

- Are deeper currents consistent with results of high-resolution models such as OFES?

- What governs the dynamical balance, what are the roles of diapycnal and eddy driven fluxes? What terms dominate the potential vorticity budget, and what ageostrophic terms generate potential vorticity?

- How do intermediate currents interact with bottom topography?

- How do baroclinicity and barotropization coexist and how well are they presented by the existing theories?

- How deep does the subduction induced by the Ekman pumping extend?

Strategy

A combination of data processing, analysis and modeling will be employed. Argo data, now scattered among many Data Assembly Centers (DAC), will be aggregated in conjunction with the APDRC to provide near real-time in situ and gridded data in user-friendly formats to IPRC and other scientists. Variables will include temperature (in situ and potential), salinity, spiciness, density (in situ and potential) and its vertical gradient, dynamic height relative to 1000m and absolute dynamic depth referenced to the concurrent altimeter-monitored sea level, mixed layer and barrier layer depths, current velocities at the sea surface and at the parking level of each float (Yoshinari et al., 2005; Lebedev et al., 2007). Subsurface data will be interpolated onto standard levels and sigma-theta surfaces and aggregated to compute ensemble averages, seasonal, annual, monthly means and near-real time 10-daily maps.

The APDRC product will be compared with other data and models. The interannual and higher-frequency variability in subsurface ocean observed with the Argo float array and satellites, and simulated with high-resolution will be documented. The geographic distribution of modal vertical structure and its dependence on horizontal scale will be determined. Horizontal divergences/convergences of currents at 1000m depth will be compared with the Ekman pumping/suction to evaluate the baroclinic response of ocean to low-frequency local wind forcing. Results of eddy-resolving models such as OFES will be analyzed to identify regions where eddy stress or upwelling drives deep currents, and eddy form stress and Reynolds stress will be computed for those regions. These stress fields may be used to drive an extended Sverdrup model (e.g. the turbulent Sverdrup balance; Rhines and Holland, 1979, Holland and Rhines, 1980, Furue et al., 2009) to confirm that those stresses indeed explain the structure (zonal extent and vertical structure, in particular) of the deep currents. Correlations between deep currents, eddy stresses, and surface fluxes (winds and buoyancy flux) will be explored and their dynamics will be investigated. Dynamical hypotheses gained from these analyses will be tested using layer models and idealized regional models. Mechanisms of eddy generation will also be investigated using these simpler models.

Expected Outcomes

The processed Argo data will be a major product and will be distributed to the community via the APDRC. We expect to obtain insight into the dynamics and three-dimensional structure of subthermocline currents driven by eddy forcing or diapycnal upwelling. This improved understanding will inform the study of tracer distributions in the thermocline, and the role of subsurface currents in variations of surface climate. Both the data analyses and the model simulations will be of use in validation of the ocean salinity from Aquarius.

3.1a_3 Decadal variations of ocean jets

Background

The Kuroshio Extension plays a major part in the North Pacific Ocean decadal variability (Schneider and Cornuelle, 2005). The current explanation for low frequency variability of the Kuroshio Extension relies on long, linear, first baroclinic Rossby waves in a background state of stratified ocean at rest. Such dynamics can successfully explain the timing of decadal anomalies in the Kuroshio Extension in response to prior Central North Pacific variations of the wind stress curl (Qiu et al., 2005). However, this model fails in reproducing the sharp meridional structrre of the response that is focused on the existing fronts in the northwestern Pacific (Nonaka et al., 2006, Taguchi et al., 2007). To model ocean-to-atmosphere coupling, it is essential to properly resolve these fronts (Nonaka and Xie, 2003; Minobe et al,. 2008), and account for the dynamics underlying their low frequency variations. A number of hypotheses have been advanced to account for the sharp gradients in the response to large scale forcing. The meridional dependence of the Rossby wave speed leads to the development of meridional gradients (Qiu, 2003), but does not select a specific latitude for the response. Instead, theories have to rely on the interaction of the wind forced signals with the mean circulation structures in the western Pacific. The hypotheses governing this sharp response naturally all deal with the potential vorticity of the North Western Pacific, and either ascribe the sharpness of the response to upstream interaction with the coast of Japan, to interaction with the recirculation gyres, or to the background potential vorticity field of the Kuroshio Extension.

Hypotheses

We will investigate whether the meridional structure of the decadal shifts in the Kuroshio Extension results from any of:

- Interactions of the wind-forced signals with the recirculation gyres (Taguchi et al., 2007)

- Upstream generation of high potential vorticity at the coast of Japan and subsequent offshore advection (Nakano et al., 2008)

- The modulation of Rossby waves by a background potential vorticity field due to the Kuroshio Extension jet (Killworth and Blundell, 2003, Cushman-Roisan et al., 1993).

Strategy

Potential vorticity budgets in high resolution simulations with models such as OFES or integrations of regional model will be computed. This analysis will be interpreted in light of results from more idealized models. Connecting simulations with high resolution general circulation models to simpler models, typically with only a few vertical layers, is critical to testing our understanding.

Expected Outcomes

Understanding the physics of the ocean fronts is essential to realistic modeling of the air-sea coupling in the extratropics.. The adjustment of the ocean in the presence of jets is also a much needed expansion of the widely-used Sverdrup approximation, and will be useful in exploring adjustments in other ocean regions.

3.1a_4 Ocean salinity

Background

Scientific progress on salinity variation and its role in climate change, particularly in terms of global cycling of water (Schmitt et al., 2008), has been limited because conventional salinity sampling is too sparse to give a global view of salinity variability. The Aquarius/SAC-D satellite is scheduled to be launched in 2010, and is designed to measure sea-surface salinity (SSS) globally for 3 years with resolutions of up to 100km, and an accuracy of 0.1-0.2 psu for monthly mean values (Lagerloef et al., 2008). Like all satellite-retrieved data, Aquarius SSS needs to be validated. Satellite SSS errors due to sea roughness (and therefore wind speed and wave height) and low sea-surface temperature (SST) are of particular concern. This is in line with earlier experience of IPRC scientists who have worked to validate satellite-derived sea-surface wind and precipitation. Aquarius will provide an unprecedented view of surface salinity with extensive observations of phenomena on small scales. Observations indicate dominant variance at decadal scales in the tropical Atlantic (e.g. Grodsky et al., 2006) and in the subtropical Atlantic and Pacific (Gordon and Giulivi, 2008). The variations seen in the extratropics in coarse resolution models are well reproduced by stochastic models (Hall and Manabe, 1997). However, the salinity variations in these models project poorly onto standing modes such as empirical orthogonal functions (Mignot and Frankignoul, 2003). The lack of negative feedbacks of surface salinity with the atmosphere renders ocean mixing and advection by gyres and swift boundary currents as the only processes limiting low frequency variance (Spall, 1993), with a concomitant regional scale of the patterns. The salinity patterns and their underlying fresh water budgets expected to be seen from the 100 km Aquarius resolution are unknown.

Science Questions

- What is the expected accuracy of monthly-mean SSS maps of Aquarius?

- How large is the difference between SSS observed by satellite and 5-m salinity measured by Argo floats and what accounts for the difference?

- What new features will be revealed from Aquarius swath data and monthly maps?

- How well can we close the global freshwater budget?

- What are the patterns of salinity variability?

- What processes determine these patterns?

Strategy

We will use the Argo profiles to obtain monthly maps of surface-mixed-layer (SML) depth, undoubtedly with many bins with no data. Such maps will help identify regions with shallow SML, where Aquarius SSS may differ significantly from bulk SSS. Aquarius swath data will be used to discover fine SSS structures that could only be revealed occasionally by historical towed and ship-pumped data with high spatial resolution. Observations of such fine structure will help our understanding of lateral mixing. Argo profiles of salinity will be sorted according to their complexity into two groups. The group with salinity homogenized by vertical mixing will be used to calibrate satellite data. Profiles with strong subsurface salinity will be isolated to study regional dynamics. A one-dimensional model of the mixed layer will be used to reproduce the observed complexity of Argo profiles and to understand factors and mechanisms controlling this complexity. Quality-controlled salinity and temperature data, both in situ and interpolated on a regular grid, will be made available to the research community via APDRC servers.

Patterns of SSS simulated by high resolution ocean and coupled models, will be analyzed and the underlying processes and scales (Delcroix et al. 2005) determined. To close the freshwater budget, we need evaporation, precipitation, and river runoff (also referred to as freshwater discharge). Satellite-based, merged precipitation products (such as CMAP and GPCP) are close to the (unknown) true field with errors of about 10%, much better than anticipated. Since the freshwater discharge (into the ocean) is hard to obtain on a monthly base, a relaxation scheme is used by ocean models to constrain model surface salinity along the coastline. There are many evaporation products, which can differ by more than 10%. How can we decide which product is closer to the (unknown) truth? Recent publications by Tim Liu (Xie, et al. 2008; Liu and Xie, 2008) have shown two different approaches to obtain the net fresh water flux: one through estimating evaporation, and the other through the divergence of moisture advection that gives the net fresh water flux. We intend to use monthly-mean Aquarius data, after validating them using Argo data, to constrain other model forcing fields and to take advantage of model-calculated evaporation to cross-validate existing evaporation products.

Expected Outcomes

The project will produce monthly maps of SML depth from Argo data, and use them to determine where Aquarius-derived SSS can be used as bulk SSS. The results will also provide a new estimate for the global freshwater budget as well as a description of the modes and scales of salinity variations expected from Aquarius.

3.1b Air-Sea Interaction

Background

Ocean-atmosphere interaction and feedback are of fundamental importance for understanding and modeling the climate and its variability. The atmospheric response to SST or surface heat-flux anomalies lies at the heart of understanding the ocean's role in climate. Since the ocean performs a significant fraction of the poleward heat transport, this response must be important for the coupled state, at least at low frequencies such as decadal. Most of the published work, however, suggests that the response of the extratropical atmosphere to the ocean is weak and/or difficult to detect (see Kushnir et al., 2002). Recent satellite observations, however, show a strong and ubiquitous response of the atmospheric boundary layer to SST variations associated with oceanic mesoscale activity (Nonaka and Xie, 2003; Chelton et al., 2004), hinting at an ocean-to-atmosphere feedback. The underlying hypothesis relies on increased vertical mixing in the atmosphere in response to warm anomalies of SST together with the adjustment of the atmospheric pressure (Small et al., 2008). On the planetary scale, observational studies suggest that variations in the Kuroshio Extension feed back to the central Pacific atmosphere (Qiu et al., 2007),while recent model analysis indicate a strong feedback of the atmosphere to ocean induced changes of the surface heat budget (Kwon and Deser, 2007). Idealized GCM experiments indicate that the extratropical storm tracks respond strongly to SST anomalies, resulting in changes in near-surface baroclinicity (Inatsu et al., 2002). Similarly experiments with idealized models show a strong sensitivity of the storm tracks to the sharpness of the oceanic SST gradients (Nakamura et al., 2008). Observational and modeling studies suggest that SST fronts in the Southern Ocean affect the formation and variability of atmospheric storm tracks (Nakamura and Shimpo, 2004; Inatsu and Hoskins, 2005). The effects of coastal orography on the atmosphere also affords an opportunity to study ocean-atmosphere interaction processes.

Science Questions

- What are the mechanisms responsible for variability of ocean currents and SST fronts on timescales from seasonal to interdecadal?

- How does the atmosphere respond to the presence and variability of an SST front? Is there observational evidence for deep atmospheric response to extratropical SST above the atmospheric boundary layer? What is the role of storm tracks in this response?

- What maintains the Baiyu rain band - a vitally important climatic phenomenon in East Asia - and its eastward extension?

Strategy

Scale interaction can be now investigated using high resolution observations, and high resolution modeling. Our collaborations with JAMSTEC allow access to advanced ocean-atmospheric models at the highest possible resolution. NASA satellites provide high-resolution observations ideal for studying air-sea interaction near sharp ocean fronts and triggered by coastal orography. Fluxes that couple the ocean and atmosphere in both the tropics and extratropics will be diagnosed. The response of the extratropical storm track to ocean heat transport convergence and SST will be determined from model simulations and available observations. Satellite observations of surface fluxes including precipitation will be particularly interesting. The interaction between the atmospheric and oceanic boundary layers, in particular the air-sea heat fluxes in the Kuroshio and the Kuroshio Extension will be explored in regional ocean and coupled models.

3.1c Climate Modes and Predictability

While great progress has been made in understanding the processes driving large-scale interannual climate variations, many issues remain to be investigated. For example, in the coming years the global warming signal and decadal natural variability are expected to be of comparable size raising the question of the interaction of these signals. IPRC will pursue projects to understand the role of atmosphere-ocean interaction in large-scale interannual climate variability in both the tropics and extratropics.

3.1c_1 Tropical modes

In the tropics, ocean-atmosphere interaction organizes climate variability into modes with well-defined space-time structures. As an example, the El Niño/Southern Oscillation (ENSO) is the dominant mode of variability with global influence. Understanding and modeling the coupled mode has progressed to such a degree that ENSO predictions with some degree of skill up to 6-12 months are routine nowadays. While there is a general understanding that ENSO arises from Pacific Ocean-atmosphere interaction, each El Niño is unique in its evolution (onset and decay) and spatial pattern. It is unclear what causes these deviations from the canonical ENSO. Far from simply being a slave to ENSO, the tropical Indian Ocean has been found to be more dynamical than previously thought. Indeed the tropical Indian Ocean interacts with the atmosphere to form its own mode of interannual variability, the Indian Ocean Dipole (IOD), and also acts to modify ENSO. Bjerknes feedback within the tropical Indian Ocean is key to the IOD (Saji et al., 1999) while the El Niño-induced tropical Indian Ocean warming plays a role of capacitor to prolong ENSO influences on the East Asian and Northwest Pacific summer monsoons (Xie et al., 2009). There also is evidence that ocean-atmosphere interaction in the tropical Indian Ocean affects the growth and decay of ENSO (Annamalai et al., 2005; Kug et al., 2006).

Science Questions

- What causes non-canonical development of ENSO? How do non-canonical aspects of ENSO affect tropical regions outside the equatorial Pacific?

- How does the tropical Indian Ocean respond to ENSO? What are the important ocean-atmospheric processes for tropical Indian Ocean variability, by internal feedback, or in response to ENSO, or both?

- How does inter-basin interaction between the Pacific and Indian Ocean affect the evolution and spatial pattern of ENSO-related anomalies?

Tropical SST variability is not fully explained by a few well-established modes such as ENSO and the IOD. There is evidence that non-modal SST changes cause prolonged droughts and floods in the midlatitudes via atmospheric teleconnection (Schubert et al., 2004; Hoerling and Kumar, 2003; Deser et al., 2004). For example, Meehl and Hu (2007) examine a very long PCM control integration and compare the structure and dynamics of multidecadal mega drought-causing SST anomalies with those of higher frequency modes of variability.

- What are the mechanisms responsible for non-modal SST variability in the tropics, that can have important and far-reaching climate effects? Does air-sea interaction play a role? How predictable is such SST variability?

In summer there is an atmospheric mode of variability over East Asia and the Northwest Pacific, referred to as the Pacific-Japan (PJ) mode (Nitta, 1987). The associated rainfall anomalies have important effects on this densely populated region. PJ variability is tied to ENSO, not concurrently but two seasons in advance (Wang et al., 2003; Kosaka and Nakamura, 2006). The dynamics responsible for this ENSO-PJ relationship is not well understood.

- Is the PJ pattern a mode of the moist atmosphere resulting from interaction with the mean flow and convection-circulation feedback?

- How do SST anomalies excite the PJ pattern? What is relative importance of SST forcing from the SST in the tropical Indian Ocean, and the western and equatorial Pacific?

- How predictable is the PJ pattern and the associated rainfall?

3.1c_2 Extratropical modes

Background

The significance of coupling of the ocean and atmosphere outside of the tropics is a long standing problem. Recent work has shown that such coupling can be vigorous in the atmospheric boundary layer, and that this interaction involves mesoscales including those associated with fronts (Xie, 2004; Small et al., 2008). The degree to which this coupling extends beyond the boundary layer into the free atmosphere, and whether this leads to significant perturbations on interannual and decadal time scale remains unclear. The climatological signature of the narrow Gulf Stream due to convergences in the boundary layer extends all the way to the free atmosphere (Minobe et al., 2008). However, the degree to which the extratropical ocean to atmosphere coupling remains significant for interannual and decadal anomalies remains unclear. Recent analysis of coupled models show a strong imprint of the ocean-induced perturbations in the Kuroshio Extension region (Kwon et al., 2007), the generality of this result remains unknown. Furthermore, the variety of modes considered in this context has increased in recent years. In the Pacific, the discussion was largely confined to issues related to ENSO and the Pacific Decadal Oscillation. Recently, new modes have been added to this mix, such as the North Pacific Gyre Oscillation (Di Lorenzo et al., 2008). This expanding range of climate modes identified as being of interest calls for a renewed effort in investigating their interaction and possible coupling.

Science Questions

- What is the role of mesoscale and frontal processes in forming modes of climate variability?

- How do natural climate modes interact with the forced climate signal?

- Are the ever-expanding group of identified climate modes independent, or are they part of a larger interactive pattern?

- How will the processes forming the climate mode change under global warming?

- How does frontal air-sea interaction affect the large-scale climate modes?

- Do coarse-resolution climate models capture the essential physics of the climate modes?

Strategy

Our research strategy is to analyze in situ and satellite observations and assimilated data products to improve the description of ocean-atmosphere phenomena and processes, and to conduct diagnostic and modeling studies to investigate physical mechanisms involved. The models to be used include stand-alone ocean/atmosphere and fully coupled models, both regional and global. The improved physical understanding will also help define requirements for new observing systems for climate monitoring. This effort will synthesize results from the other subsections of this section such as those dealing with ocean circulation and frontal scale air-sea interaction, as well as aspects of small-scale oceanography discussed in Section 3.2 below.

Expected Outcomes

We expect to improve the description, understanding, and simulation of oceanic, atmospheric, and coupled processes, and the resultant modes of climate variability.

3.1d The Role of the Oceans in Climate Change

Anthropogenic increase in greenhouse gas (GHG) concentrations is projected to cause the interface between the ocean-atmosphere to warm. In fact, robust warming trends and their effects on physical and biological environments have begun to be detected, most notably over the tropical Indian Ocean where sea surface temperature (SST) has risen steadily for the past five decades, and the signal there is now far above the noise level of natural variability (Du and Xie, 2008). The rates of change in temperature, precipitation and other physical parameters, and their spatial patterns are determined by complex interactions of the ocean, atmosphere, land and ice/snow. This subsection focuses on the role of ocean-atmosphere interaction in global warming, an important element of global warming dynamics.

3.1d_1 Surface climate feedback

Background

The ocean's role in regulating atmospheric warming is quite evident. Historical hydrographic observations show that the ocean is absorbing much of anthropogenic radiative heating (Levitus et al., 2005), which would otherwise cause a greater warming in the atmosphere (Meehl et al., 2005). In many climate model simulations, surface warming over the subpolar North Atlantic and Southern Ocean is much weaker than elsewhere because of deep/bottom water formation in those regions (Manabe et al., 1991). Despite the importance of ocean regulation of surface temperature, traditional climate feedback analysis is based on radiative balance at the top of the atmosphere and does not explicitly consider the ocean. We propose to study mechanisms controlling oceanic warming.

Surface evaporation is the major means for the ocean to balance radiative forcing. Recent analyses of IPCC AR4 model simulations at IPRC (Du and Xie, 2008) show that surface atmospheric stability and relative humidity increase in response to anthropogenic GHG forcing and that these increases act to reduce surface evaporation, acting as positive feedback for SST warming. The evaporation effects of surface stability and relative humidity changes also explain why in climate models, precipitation increases at a much slower rate than surface temperature (Richter and Xie, 2009), a discrepancy with important consequences to tropical atmospheric circulation (Held and Soden, 2006). We will develop a climate feedback analysis method based on the ocean mixed layer heat budget that will enable us to identify explicitly ocean-atmospheric processes important for ocean surface warming.

Science Questions

- What controls heat exchange between the ocean and atmosphere in response to anthropogenic GHG forcing? How does the ocean regulate atmospheric warming?

- What are important ocean-atmospheric processes for SST warming?

- What controls surface evaporation? What causes changes in surface stability and relative humidity?

3.1d_2 Formation of geographical patterns of climate change

Background

The geographical patterns of mean climate and climate variability have long been a subject of investigation. SST variations are especially important for climate distribution. The development of the equatorial cold tongue in the Pacific causes the east-west contrast between lush Indonesia and the barren Pacific coast of Peru. Interannual waxing and waning of the cold tongue associated with ENSO produces climate anomalies around the world. The geographical variations of the mean climate will change in response to global warming. Indeed models generally predict that surface warming be largest in polar regions and smallest over the deep-water formation region of the North Atlantic.

Observed climate anomalies reflect both natural variability and forced climate change, and the forced component is expected to increase in relative importance over the next century. It is thus important to know the patterns of climate change (e.g. SST and precipitation) and their mechanisms for the purpose of detection, attribution and seasonal prediction. Ocean changes and their interaction with the atmosphere are likely crucial for climate change pattern formation.

Science Questions

- What geographical patterns of mean climate change are likely to emerge in the next century? Do they resemble modes of natural variability?

- What shapes these patterns? What role does ocean-atmosphere interaction play?

- Does relative importance of various ocean-atmospheric feedbacks vary among models? Does this variation explain the diversity in spatial patterns of forced climate change simulated in the models?

3.1d_3 Changes in temporal variability

Background

Modes of interannual climate variability are important sources of seasonal predictability. Under anthropogenic GHG forcing, both the mean state and modes of variability are likely to change, which will affect seasonal prediction.

Ocean-atmospheric modes of particular interest in this context include ENSO, IOD, and tropical Indian Ocean capacitor effect. Model studies suggest that global warming-induced wind change in the equatorial Indian Ocean is likely easterly, leading to shoaling of the thermocline in the east (Vecchi and Soden, 2007; Du and Xie, 2008) and possibly favoring the development of the IOD. Predicted ENSO changes in response to global warming are found to vary greatly among current models (e.g., Meehl et al., 2006). Unfortunately strong air-sea feedback makes it difficult isolate the cause of differences in the model response in this regard. This illustrates the need to go beyond superficial intercomparison and study in detail the myriad of mechanisms that may be important in the model simulations.

Science Questions

- How do major modes of climate variability change, in variance, spatial pattern, period and seasonality?

- How well can we explain such changes in terms of changes in mean state such as the enhanced stratification in the upper ocean?

Strategy

Iteration of diagnostic, experimental, and observational approaches will be employed to shed light on global warming dynamics with an emphasis on understanding the role of air-sea interaction. The instrumental record too short to distinguish aspects of climate change from natural variability, so the focus will be on diagnostic studies using the IPCC AR4-5 database. The extent to which the models are consistent will be determined, and the causes of differences studied. For a given phenomenon, a variety of mechanisms are likely to operate and their relative importance may vary and cause differences in model response to GHG forcing. We will not know the relative importance of these mechanisms in the real system for some time, but it is important to identify these mechanisms and study how they work. In this regard, we will determine if a given mechanism is represented particularly well in a subset of models. We will conduct experiments using a hierarchy of models (including fully coupled GCMs) to isolate and study particular processes and mechanisms. Wherever possible, we will compare mechanisms and patterns of variability in models with observations.

In some cases when climate change signal is particularly strong or the natural variability noise is low, we may find a match between model results and observations. The secular warming trend in tropical Indian Ocean SST provides a particularly promising case. Many models predict a thermocline shoaling in the east equatorial Indian Ocean (Vecchi and Soden, 2007), but sea surface height observations - from the brief satellite altimetry record and the sparse network of coastal tide gauges - suggest an opposite trend (Church et al., 2004; Trenary and Han, 2008).

The CMIP5 multi-model output database for the IPCC AR5 will become available in 2010 or 2011. Compared to CMIP3/AR4, CMIP5 includes some new experiments. The IPRC is well positioned to contribute to the analysis of the decadal prediction experiments, given its expertise in ocean circulation and decadal variability. It will also include runs by earth system models (ESM), enabling studies of chemical-physical feedback involving aerosols and GHG cycle.

Expected Outcomes

This research will lead to improved understanding of the role of the ocean in global warming dynamics. Going beyond conventional statistical model intercomparisons, our improved understanding will provide the basis for reducing uncertainties in model projections of future climate. The results of our studies will have important implications for seasonal prediction since the observed anomalies (included in the initial conditions for prediction models) will increasingly include climate change signals. Our results will shed light on mechanisms for climate change on regional scales.

3.2 Regional and Small-Scale Climate Processes and Phenomena

The overall goals of this section are to describe issues and research strategies to (i) advance our understanding of the climate state and its variability in specific regions within the Asia-Pacific domain, (ii) determine the synoptic and climatic effects of small and regional-scale oceanic, atmospheric and land surface processes, and (iii) to improve the representation of such processes in regional and global climate models. Many of the highest-impact atmospheric phenomena are extreme mesoscale events such as tropical cyclones and localized intense rainfall incidents. The study of extreme mesoscale events and the synoptic and climate controls over such events is largely included in this section.

The questions and activities are collected into several subsections. The first two subsections describe a number of issues that relate to two specific geographical areas of interest: the Maritime Continent region (3.2a), and the Hawaiian Islands (3.2b). Then a number of subsections deal with some more generic issues related to observation, diagnosis and modeling of small to meso-scale processes. The following three subsections collect issues related mainly to atmospheric processes, specifically: the diurnal cycle (3.2c), tropical cyclones (3.2d), and microphysical effects on cloud processes (3.2e). Then a final subsection (3.2f) discusses a number of issues related to small scale ocean processes, including scale interactions in the equatorial thermocline, mesoscale and submesoscale physical processes in the upper ocean and their role in the marine ecosystem, and the dynamics and impact of multiple-jets in the ocean.

3.2a The Maritime Continent over the Indo-Western Pacific Warm Pool

Background

The Maritime Continent (MC) of the Indo-western Pacific Ocean is a special region where both land-sea contrast and meso-scale mountains are critical in shaping the space-time dependence of atmospheric convection, including its pronounced diurnal cycle (Neale and Slingo, 2003; Zhou and Wang, 2006; Wang et al., 2007). Convection over the MC and surrounding oceans provides tremendous internal atmospheric heating that drives not only the tropical circulation but also has strong influence on the global scale. Convection over the MC displays large variability on diurnal and intraseasonal-to-interannual timescales. Recently observational and modeling studies demonstrate the possible topographic effects of the MC on both propagation and initiation of the Madden-Julian Oscillation (MJO) through modulation of deep convection and the adjustment of large-scale equatorial waves (Hsu et al., 2006; Neale and Slingo, 2007). The complex land-sea contrast and orography of the MC make the regional and local circulations very complicated, contributing to the rich fine scale-structure of the diurnal precipitation cycle, not only locally, but also over extensive ocean regions. The MC is also in the path of the seasonal transition of convection between the Asian and Australian summer monsoons. The transition from the Northern to Southern Hemisphere monsoon is relatively smooth, but the return of strong convection to the Northern Hemisphere is characterized by an abrupt onset of the Asian summer monsoon. This transition across the MC may be a key factor in the interannual variability of both monsoons.

The islands and mountains of the MC also affect the ocean by introducing regions of narrow, intense wind curl, which can generate ocean currents and eddies. Because of the long effective memory in the ocean circulation, island influences on ocean currents and eddies can be quite persistent. Islands in the MC region may modulate the diurnal variability in sea surface temperature (SST) through the land-sea breeze and the cloud/precipitation diurnal cycle. The SST in turn may have considerable feedback to the local/regional circulations and convection. This local/regional air-sea interaction could play an important role in determining the mean climate and longer term larger-scale climate variability. Island effects on eddies could also play an important role in enhancing ocean biological activity by upwelling nutrients into the euphotic zone (e.g., Seki et al., 2001).

While land-sea contrast and orography are considered important for local, regional and global climates, they are poorly represented in most of global ocean-atmosphere models (Neale and Slingo, 2003). This may largely limit the capability of these models in reproducing the mean climate and climate variability as well as the use the models in the assessment of possible future climate change. The multi-scale interactions in the atmosphere and ocean as well as their coupled processes in the MC region are yet to be understood.

Scientific Questions

- How do the land-sea contrast and orography regulate local/regional atmospheric circulations, and convection and its diurnal cycle in the MC region?

- What are the dominant modes of short-term and long-term climate variation over the MC and what is their contribution to the large-scale climate variability, in particular the MJO?

- Does the air-sea interaction in the marginal seas matter to local/regional circulation and climate variability in the region?

- How can the small-scale effects of the land-sea contrast be incorporated in conventional GCMs through parameterization?

- What are the anticipated effects of global warming on the circulation over the MC?

Strategy

Both satellite observations and the results from the global cloud-resolving model (NICAM) simulations are being analyzed by IPRC scientists to document the diurnal cycle of clouds and precipitation. The NICAM simulations provide high temporal and spatial resolution of the three-dimensional dynamical and thermodynamic fields and thus are critical to investigating the physical processes, in particular those associated with mesoscale organization of convection, in the region. The regional cloud-resolving model developed at IPRC (iRCRM, Wang, 2007) is also a useful tool for sensitivity experiments to help isolate different physical processes. The IPRC regional atmospheric model (iRAM, Wang et al., 2003; 2004a,b; 2007) with high resolution will be used to perform sensitivity experiments to understand how the land-sea contrast and mountains over the MC affect the large-scale circulations and variability in the region. Finally, results from both the regional and global cloud-resolving models will be analyzed to develop a parameterization of island effects for coarse-resolution models.

The potential effect of a realistic representation of the MC islands on both the regional and global climates will be evaluated through sensitivity experiments using the NICAM with either removal of orography over the MC or removal of the whole land areas over the MC. The potential importance of air-sea interaction in the region will be examined using the IPRC regional coupled model (iROAM, Xie et al., 2007). The iROAM has been updated with the MOM2 ocean component being replaced by HYCOM, and this version is now running on the local IPRC clusters.

Expected Outcomes

We expect to obtain a better understanding of mesoscale climate processes in the MC region and the importance of air-sea interaction in shaping the local/regional circulations and convection and of the role of mesoscale processes in the mean climate and variability on diurnal and intraseasonal-to-interannual timescales. The new parameterization scheme that may be developed has potential to improve the representation of the subgrid scale orography and small islands over the MC in relatively coarse GCMs and thus improve the simulation of mean climate and climate variability.

3.2b Regional and Local-Scale Atmospheric Circulation in the Hawaiian Region

Background

Hawaii's dominant industries - first agriculture and now tourism - have been crucially linked to the generally favorable prevailing weather. The extensive and economically critical coastal zones in Hawaii are particularly vulnerable both to extreme individual weather events such tropical cyclones and also to the effects of gradual environmental change. Hawaii's available water resources are completely dependent on local weather, further increasing Hawaii's sensitivity to environmental variations. Improving our understanding of the processes involved in controlling the weather and climate around Hawaii is thus a natural priority for the State and for the State's premier climate research center, the IPRC. Interest in Hawaii climate issues on seasonal to centennial scales has been fostered by NOAA through programs such as the Integrated Data and Environmental Applications (IDEA) Center, the Pacific Regional Integrated Science and Assessment (RISA), the Pacific Climate Information Service (PaCIS) and the Pacific Risk Management Ohana (PRiMO). Modeling and prediction of local-scale atmospheric circulation for the Hawaii region are also important aspects of the new Hawaii Ocean Observing System (HiOOS) project supported by the University of Hawaii and NOAA.

A particular challenge in providing useful weather data and forecasts, as well as long term climate projections, for Hawaii is the very prominent small-scale variability of meteorological fields associated with the topography. The global models providing the basic daily and seasonal forecasts are run with horizontal spatial resolution of the order of 50 km. The available global gridded reanalyses of observations are also produced with horizontal resolution no finer than 100 km. Even the meteorological surface station network in Hawaii is relatively sparse, given the typical sharp gradients in meteorological fields. The NWS Honolulu Forecast Office (HFO) also produces experimental high-resolution short-term forecasts from a limited-area forecast model. These forecasts are produced at 4 km resolution (1 km on Oahu), but are limited to 48 hours.

A large fraction of the rain that falls over the Hawaiian Islands results from orographic uplift of large scale flow. Thus there is some expectation that the local rainfall may be related statistically to the regional-scale flow patterns, and that such connections may apply on a range of timescales from daily to seasonal (Lyons, 1982; Chu and Chen, 2005).

Global warming can be expected to have quite significant effects on the weather with consequences for the natural and human environments. The tall and steep topography of the islands leads to distributions of flora and fauna that in many cases are strongly stratified by altitude.

Changes in the prevailing temperature and rainfall patterns may cause the habitat zones for various species to shift upward. Such shifts can cause significant problems for some species. For example many Hawaiian bird species now survive only at higher elevations where temperatures are too cool for mosquitoes, which carry avian diseases such as malaria. As the climate warms mosquitoes can be expected to expand their altitude range and possibly threaten the habitat for the bird species. Issues of habitat in Hawaii are particularly consequential as the state, with less than 1% of the land area of the US, is home to about 1/3 of the recognized endangered species in the nation (Mehrhoff, 1998).

The population of Hawaii is already stressing the available freshwater resources for urban consumption and agricultural use (Mink and Bauer, 1998). An ability to forecast rainfall on seasonal timescales could be valuable for planning water usage for the agricultural sector. Planning for sustainable development over the next century will require an assessment of the effects of anticipated global climate changes in Hawaii - particularly projections of how the mean rainfall, and rainfall variability may change. Extreme short-period rainfall events are of particular interest as Hawaii is subject to frequent and damaging flash floods.

Scientific Questions

- How closely are local rainfall rates over the islands connected with the large-scale circulation patterns on daily and seasonal timescales? How well can statistical downscaling approaches account for interannual seasonal variations in rainfall. Can statistical approaches be used to generate useful local forecasts from fairly coarse resolution numerical forecasts?

- How well can current global and regional climate models simulate the synoptic meteorology of the Hawaiian islands region? At how fine a resolution must global models be run to simulate both reasonable synoptic variability and rainfall variations over the islands?

- How well can nested regional models, when forced with realistic boundary conditions, account for the Hawaii climatology of wind, temperature and rainfall, including the diurnal and seasonal cycles. How well can such models account for the interannual and intraseasonal variations in atmospheric fields and the space and time variability, including the diurnal cycle, on local scales?

- How do we anticipate that the atmospheric behavior, including the climatology of extreme events such as intense rainfalls and extended drought, will change in response to large scale global warming? How robust are predictions of such responses to the details of the global coupled atmosphere-ocean models used, and to the statistical or model-based downscaling techniques employed?

Strategy

Statistical approaches will be used to relate regional-scale circulation patters to the rainfall on the Islands. Some preliminary work along these lines has already been completed (Timm and Diaz, 2009). The expectation is that similar techniques for downscaling can be applied to observations, numerical forecast fields and climate model simulations. In terms of numerical forecasts the NOAA Historical Reforecast project has made available a 30 year archive of daily ensemble 15-day forecasts (Hamill et al., 2006). As noted by Hamill et al., these numerical results are being used to find the best statistical downscaling for forecasts of local fields (e.g. station rainfall) in various regions, but so far no application to Hawaii and the Pacific Islands has been attempted.

These dynamical-statistical approaches will be supplemented by more direct high-resolution numerical modelling. IPRC scientists will conduct numerical climate change projection experiments using nested regional atmospheric models with high resolution over Hawaii. These experiments will consist of model integrations representing current (or late 20th century) conditions and then perturbed runs for conditions anticipated for a global warming climate in the mid and late 21st centuries. The SSTs and lateral boundary conditions will be taken from lower resolution coupled atmosphere/ocean global model integrations (such as those archived for CMIP3). In the short term the WRF community model will be used as the basis for this work, taking advantage of its efficient multiple nesting capabilities. However, aspects of the WRF cloud and convection physics will be changed to those used with some success in the IPRC regional model. A key validation for such a model will be its ability to reproduce the detailed geographical and seasonal variations of rainfall over the Hawaiian islands. In the longer term nested coupled ocean-atmosphere model could be applied to the same types of experiments.

Expected Outcomes

The research to be performed in this area should result in an enhanced high-resolution modeling capability for weather and climate over the Hawaiian Islands. Improved procedures for statistical downscaling of large-scale fields to local scales should be developed along with an assessment of how well such techniques work in scaling gridded observational analyses, short-term forecasts and seasonal forecasts. The research will also yield high resolution projections for the response of climate in Hawaii to projected changes in the global climate.

3.2c Diurnal Cycle of Clouds and Precipitation

Background

The diurnal cycle of clouds and precipitation (DCCP) is fundamental to weather and climate variability, particularly in the tropics. The DCCP affects mean climate since diurnal cloud-sun correlation rectifies into the mean radiation balance. An inaccurate treatment of the diurnal cycle degrades climate simulation or prediction (Randall et al., 1991; Yang and Slingo, 2001; Hall et al., 2003). The DCCP can also affect variability on a wide range of time scales, the partitioning of precipitation between the land and ocean and between convective and stratiform components (Randall et al., 1991; Betts and Jakob 2002; Neale and Slingo, 2003; Wang et al., 2007). The phase and amplitude of the diurnal cycle of solar radiative forcing can have substantial impacts on interannual variability, e.g., summer flooding in the central United States (Segal et al., 2002).

At most land locations, the maximum in convective rainfall occurs in later afternoon with high cloudiness lagging by a few hours into early evening, while the minimum convective rainfall occurs in the early morning. This generalized view can be significantly modified by particular dynamical features (e.g., low level jets or waves), by local orography, and by the initiation, propagation, and decay of mesoscale convective systems (Yang and Slingo, 2001; Mapes et al., 2003; Mori et al., 2004; Zhou and Wang, 2006). Accurate representation of the interaction among the various elements of the atmosphere-surface system is crucial for simulating the correct amplitude and phase of the DCCP. Simulation of the DCCP provides a key test of many aspects of the physical parameterizations in a model, from radiative transfer and surface exchanges through to boundary layer processes, clouds and precipitation (Lin et al., 2000; Yang and Slingo, 2001; Betts and Jakob, 2002a).

Although current state-of-the-art atmospheric general circulation models (AGCMs) or other large-scale or mesoscale atmospheric models can simulate the DCCP to some degree, the simulations typical have considerable deficiencies. In comparison with observations, it appears that most models produce a too early precipitation maximum and too large amplitude over land but too small amplitude over ocean. Some studies have investigated the causes of the discrepancies and tried to improve the simulation of the DCCP (Yang and Slingo 2001; Betts and Jakob 2002a,b; Wang et al., 2007). However, progress has been rather slow mainly due to the lack of our understanding of the complex physical processes that drive the DCCP. Further, the problem is particularly challenging since the DCCP has strong regional dependency and operates and interacts on local, regional, as well as continental and larger scales.

Scientific Questions

The overall objective here is to improve the simulation of the DCCP and the warm season hydrological cycle in regional and global climate models through improved physical understanding of the DCCP and improvements of physical parameterizations in numerical models. We will address the following scientific questions:

- What are the key physical processes that determine the phase and amplitude of the DCCP in the tropics?

- What are the major causes of the deficiencies in the DCCP simulated in climate models and how can we improve the model physics to achieve the realistic simulation of the DCCP?

- How does the diurnal cycle contribute to the long-term mean climate and longer-term climate variability?

Strategy

To address the scientific questions above, we will first examine the observed features of the DCCP in the tropics based on advanced satellite products and work to understand them using the output from the global cloud-resolving model (NICAM) simulations and the IPRC regional cloud-resolving model (iRCRM, Wang, 2007). The NICAM simulations provide high temporal and spatial resolution three-dimensional dynamical and thermodynamic fields and thus are useful for analyzing the physical processes involved in the DCCP. The iRCRM will be used to perform sensitivity experiments to help isolate different physical processes and their relative importance in determining the phase and amplitude of the DCCP. The IPRC regional atmospheric model (iRAM, Wang et al., 2003; 2004a,b; 2007) with high resolution will be used to perform sensitivity experiments to identify the major discrepancies in phase and amplitude of the tropical DCCP between observations and the model in simulation with a focus on the summer Asian monsoon and Maritime Continent region. Finally, the iRAM will be used as a test bed for the improvement of model physical parameterizations. The improved parameterizations will be further tested in global AGCMs, such as the ECHAM5 (which uses the same convective parameterization scheme as that used in iRAM). The effect of the diurnal cycle on both long-term mean climate and longer-term variability will be investigated using both iRAM and other AGCMs and CGCMs through sensitivity experiments that exclude the diurnal forcing in the model.

Expected Outcomes

We expect to get a better understanding of the key physical processes that determine the phase and amplitude of the DCCP in the tropics and achieve improved simulation of the DCCP in atmospheric models by modifying the existing physical parameterizations through or the development of new parameterizations. We also expect to determine how more accurate representation of the DCCP may improve the simulated mean climate and variability, in particular in the tropics.

3.2d Tropical Cyclones

Background

Tropical cyclones (TCs) are rapidly rotating, warm-cored, atmospheric vortices and are among the most destructive natural hazards in the world. An intense TC is often featured with a calm, precipitation-free eye surrounded by a nearly closed eyewall, and distinct spiral rainbands further outside. TCs mainly develop over warm waters in the tropical or subtropical oceans. The formation and structure and intensity changes of TCs involve complex multi-scale interactions that are not yet completely understood. As a result, our ability to predict the genesis, motion, structure, and intensity change of a TC is very limited. Recent concerns about the possible impact of global warming on the activities of TCs have renewed questions about what determines the TC intensity and what factors affect the TC frequency over different ocean basins.

Several key factors are believed to critically impact TC intensity, including the internal dynamics and such external forcings as the vertical shear of the environment and the deep layer mean environmental flow (Wang and Wu, 2004). For a given thermodynamic structure of the atmosphere and the ocean there exists a theoretical upper bound of TC intensity, namely the maximum potential intensity (MPI; Emanuel, 1988; Holland, 1997). However, recent observational and numerical studies indicate that in some cases a TC can attain an intensity that is higher than its thermodynamic MPI, indicating that the current MPI theories may miss some important processes that affect the TC intensity (Persing and Montgomery, 2003; Montgomery et al., 2007; Bryan and Rotunno, 2008). On the other hand, some studies have devoted to what factors may limit the TC intensity given favorable thermodynamic conditions (Emanuel, 2000; Zeng et al., 2007, 2008). Both vertical shear and the translational speed are found to generally suppress TC intensity. The concentric eyewall cycle generally terminates the intensification processes of a TC and is a result of either the internal dynamics (Terwey and Montgomery, 2008) or external forcing (Nong and Emanuel, 2003; Kuo et al., 2004; 2008).

In addition, little is known about the processes that control TC size. This may represent the biggest uncertainty in our understanding and prediction of TC structure. Given the importance of the size of a TC in determining its large-scale momentum, heat, and moisture transport, recent studies have started paying attention to this issue (Wang, 2008 a,b; Maclay et al., 2008). .

Scientific Questions

- What determines the MPI of a TC, and what limits the TC intensity given the favorable thermodynamic environmental conditions?

- How do aerosols affect TC genesis, structure and intensity?

- What determines the size of TCs?

- How will anticipated large-scale global warming affect TC genesis locations, TC tracks, and TC intensity?

- How do TCs contribute to the mean climate and climate variability though meridional transports of heat, moisture, and momentum in the atmosphere and through inducing heat transport in the ocean?

Strategy

To address the above scientific questions, we will conduct data analysis and perform numerical experiments using NICAM, iRCRM and TCM4 to understand the dynamical processes that impact TC structure and intensity changes, and to understand scale interactions in TC genesis, including the large-scale control and the role of air-sea interaction physics. TCM4 is a quadruply nested movable mesh, nonhydrostatic, fully compressible, cloud resolving model suitable for the study of TC dynamics and physics (Wang 2007, 2008a,b). Observational data analysis will help to identify the large-scale control of TC genesis, and structure and intensity changes. The detailed physical and dynamical processes will be studied with numerical experiments using TCM4 and other high-resolution models. The two-moments cloud microphysics scheme now implemented into iRAM will be implemented into TCM4 to study the possible effect of aerosols on TC genesis, structure, and intensity. The interaction between TCs and climate will be investigated using the iRAM and iROAM as well as the NICAM. High resolution GCMs will be used to understand how TCs affect global general circulation and climate variability in the middle and high latitudes. Both CGCMs and iROAM will be used to evaluate the impact of global warming on the activities of TCs in the central and western Pacific, and the Indian Ocean.

Expected Outcomes

We expect to obtain improved understanding of not only the large-scale control of TC genesis, structure, and intensity, but also the feedback of TCs on the large-scale environment. In particular, the details of both internal dynamics and external forcing in determining the TC intensity and structure will be revealed. The possible effect of TCs on mean climate and climate variability will be clarified and, in turn, the global climate change on TC activities will be evaluated with the focus on frequency, track, and structure and intensity responses to global warming due to the increase of greenhouse gases. Conceptual models of multi-scale interactions involved in TC genesis, structure and intensity changes will be developed. Results will be used for improving our capability of predicting TC activities on both seasonal and interannual time scales.

3.2e Aerosol and Microphysical Effects on Cloud Simulation in Climate Models

Background

The effect of aerosol on clouds and precipitation has emerged as one of the key issues in understanding and forecasting climate change. Natural and anthropogenic aerosols can affect the optical properties of clouds and the extent of cloud cover, which in turn strongly affect the radiative balance of the Earth. The recent IPCC AR4 provided estimates of the global-mean values for various climate forcings from pre-industrial times to 2005, along with their uncertainties. The climate forcing from the increased long-lived greenhouse gas concentrations was found to be 2.7 W-m^{-2} with uncertainty of about 10%. The global radiative forcing associated with the indirect effect of anthropogenic tropospheric aerosols on cloud brightness was estimated to be between -0.3 and -1.8 W-m^{-2}, i.e. the uncertainty from aerosol effects is of the same magnitude as the total forcing from the greenhouse gas increases. The difficulty in determining effects of aerosol-cloud interactions is the greatest uncertainty in attributing the climate changes observed over the last 150 years to natural and anthropogenic causes, and so is the single greatest source of uncertainty in using the observed record to evaluate (or calibrate) models that are used to forecast future global warming trends. The key role of aerosols in climate change research is recognized by the US Global Change Research Program Climate/ Change Science Program (CCSP) Strategic Plan in which the very first science question is "What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?"

The treatment of the subgrid-scale cloud dynamics and microphysics in current GCMs is generally extremely simplified. While GCMs can do a reasonable job in simulating the climatological mean precipitation rates, current GCMs generally have important deficiencies in the simulation of more detailed aspects of cloud and precipitation behavior. Even mean cloud radiative forcing is generally poorly simulated in GCMs for many regions of the world. Notably the strong negative radiative forcing associated with extensive regions of oceanic stratocumulus is difficult for GCMs to simulate accurately. The issue of how climate feedbacks and global climate sensitivity in GCMs may depend on assumptions concerning microphysical cloud and precipitation processes remains a source of great uncertainty for climate projections.

The IPRC has had considerable success in modeling clouds in a limited-area climate model applied to various regions within the full Asia-Pacific sector (Wang et al., 2004a,b). This work has employed subgrid-scale convective parameterizations similar to those in global models, but has avoided the extremely crude cloud parameterizations typical of current global GCMs, in favor of an explicit grid-scale treatment of microphysics. This provides a basis for a more detailed assessment of aerosol and cloud microphysical effects on cloud properties described here.

Scientific Questions

- How sensitive are model predictions of cloud and precipitation properties in the Asia-Pacific region to treatments of the cloud microphysics?

- Can model treatments of the microphysics be usefully constrained by available satellite and field experiment data?

- How does the simulation of the diurnal cycle of tropical rainfall and cloud depend on the treatment of cloud microphysics?

- How does the treatment of cloud microphysics affect the simulated cloud climate feedbacks in response to large-scale climate forcing?

Strategy

The original cloud microphysical scheme in the IPRC regional atmospheric model has been replaced with a more sophisticated scheme which includes as prognostic variables two moments of the size distributions for cloud water droplets and ice crystals (Phillips et al., 2003, 2007). This new version of iRAM will be applied initially to simulation of the eastern tropical and subtropical Pacific region. This is a notably challenging area for model simulation of even the mean cloud fields, but one in which the IPRC regional model has had some degree of success (Wang et al., 2004a,b). The VOCALS field campaign planned for late 2008 off the west coast of South America will provide a key source of data for comparison with these simulations (Wood and Mechoso, 2008). The VOCALS experimental results represent a particularly useful test bed for the IPRC modeling efforts as the geographical area of interest has extensive low cloud decks and relatively well-defined localized sources of pollution. Beyond comparisons with data from these existing or planned field experiments, the IPRC modeling results can be compared with satellite observations such as those from the MOPITT instrument on the Terra satellite, and other ongoing or planned satellite observations of cloud properties.

The simulation of the diurnal cycle of tropical rainfall represents another test of the cloud treatments within climate models. With several years of TRMM satellite data supplementing ground-based observations, there is now a rather extensive observational basis for detailed comparisons with model simulations (Takayabu, 2002; Zhou and Wang, 2006; Yamamoto et al., 2008). Current global GCMs typically do a rather poor job in capturing the observed diurnal rainfall cycle (Yang and Slingo, 2001; Lee et al., 2007). The IPRC regional climate model has already been applied to investigations of the diurnal rainfall cycle in particular tropical regions, and the sensitivity of the diurnal simulation to the assumptions employed in the convective parameterizations has been studied (Wang et al., 2007). However, given the short timescales involved, the diurnal rainfall simulation may be significantly affected by the cloud microphysical treatments as well. With the enhanced microphysical modeling capability, the IPRC model can be used to investigate the sensitivity of the simulated diurnal rainfall cycle to the details of the microphysical treatments and can assess how strongly the rainfall observations can constrain the microphysical as well as dynamical subgrid scale parameterizations.

The IPRC regional model nested within global GCM output has been applied in studies of the regional response to global warming (e.g. Stowasser et al., 2007, 2008). The development of the version with enhanced microphysics will allow a broader range of climate change issues to be addressed using the IPRC regional model. The model will be run with aerosol concentrations derived from a coupled chemistry-dynamics low-resolution global model. Comparisons of results for present day and projected late-21st century aerosol concentrations will allow assessment of anthropogenic effects of anthropogenic emissions on future regional climates. As noted in subsection 3.2d we also plan to implement the enhanced microphysics scheme into the nested non-hydrostatic model, TCM4, to study the possible effect of aerosols on tropical cyclone genesis, structure, and intensity. In the longer term the IPRC regional model will be extended to include a coupled treatment of transport and chemistry of aerosol species.

Expected Outcomes

These activities will lead to an improved modeling capability of cloud properties in the IPRC regional models. In addition these activities will result in a significantly improved understanding of how important the various details of these treatments are to simulations of cloud climate forcing and cloud climate feedbacks, and how well the details of the cloud treatments can be constrained by observations. These insights can aid in the formulation of the next generation of high-resolution global models that will be used for climate change attribution and projection.

3.2f Small Scale Ocean Processes

There is a growing appreciation that small scales in the ocean can have a profound effect on the larger scale dynamics and fluxes in the ocean. This appreciation has come from a combination of recent observational, theoretical and numerical modeling studies together with an acknowledgement of deficiencies in present day global models. Advances have been made through application of high-resolution satellite data and high resolution numerical models. Perhaps most notable is the progress made in identifying and understanding of the role of submesoscale features (scales of order 1km) in the dynamics and thermodynamics of the near surface ocean. Submescale features can also have a major impact on the functioning of the marine ecosystem through their impact on the supply of nutrients to the euphotic zone. Increased vertical resolution in both observations and models has revealed small vertical scale features in tracers and velocity that have a large lateral extent. Such features are particularly evident in the equatorial thermocline and are likely to contribute significantly to both the vertical and lateral mixing of ocean properties. On a somewhat larger scale, satellite altimetry and high resolution models show the presence of zonally coherent jet-like features in the velocity field with a meridional scale O(100km). In certain regions these features dominate the flow. The presence of these jet-like features will likely impact the energy and enstrophy cascades of the flow and the dispersion of tracers.

Although it has been demonstrated in some cases that the impact of small-scale ocean processes is large, in general it is unclear to what extent these processes need to be taken into account in global models used in climate research or forecast. Assessing their importance requires carefully designed analysis and numerical experimentation. The major goals of the research undertaken at the IPRC include:

- A determination of the underlying physics

- A quantification of the impact on broader scales

- An establishment of the role of smaller scale processes in the dynamics of the coupled ocean/atmosphere system

The following describes three specific areas of research.

3.2f_1 Scale interactions in the equatorial thermocline

A number of studies have shown that the amplitude and time evolution of ENSO events are very sensitive to the ocean state. The ocean state in models is very dependent on the imposed lateral and vertical mixing, and yet mixing remains poorly understood. The extraordinary wealth of spatial scales in the equatorial thermocline coupled with the high temporal variability raises a number of intriguing and important questions relating to how scale interactions affect lateral and vertical mixing in the thermocline, and how the mixing feeds back to larger scales. A reason to believe that the parameterization of mixing used in ocean models at present may be inadequate comes from the observation of small vertical scale (SVS) structures with large lateral extent that are found in both the velocity and tracer fields. These SVS structures appear to influence, or perhaps even dominate, the mixing. A combination of theoretical and idealized studies, the explicit representation of SVS structures in basin scale models, the testing of their impact in coupled ocean/atmosphere GCMs, and in situ observations will be used to address the following questions

- What controls the mixing in the equatorial thermocline?

- How are the lateral and vertical scales of dominant features selected?

- What role do SVS structures play in lateral and vertical mixing?

- How do different mixing regimes impact on the basin scale dynamics?

- How are ENSO dynamics affected by the mixing produced by SVS structures?

- What are the feedbacks among the different scales?

3.2f_2 Meso- and submesoscale physics in the upper ocean and their impact on the marine ecosystem

Meso- and submesoscale features in the ocean can have a significant impact on the dynamics and thermodynamics of the upper ocean, affecting the interaction of the ocean and atmosphere, the restratification of the near-surface ocean, and the exchange between the surface and deeper waters through processes such as the instability of mixed layer fronts, strain-driven frontogenesis and nonlinear Ekman pumping. Small scale features in the atmosphere such as the wind jets associated with gaps in topography or island chains, the vorticity field associated with easterly waves, and the atmospheric response to oceanic mesoscale features, have been found to induce a significant response in the ocean at the meso- and submesoscale. The ocean response to small scale features found in high resolution atmospheric models has yet to be fully explored.

Meso- and submesoscale motions can influence the marine ecosystem in two ways; through the injection of nutrients into the euphotic zone, and the lateral stirring and mixing of reacting components of the system. Lagrangian descriptors of the flow can be used to determine the relationship between the two. As well as impacting primary production, the submesoscale creates a very different world for the microbial activity than that found in coarsely resolved models, and will affect the role and functioning of the microbes in the ecosystem, an aspect that has yet to be considered.

With regard to the physics, work at the IPRC will focus on the combined effects of meso- and submesoscale ocean dynamics, small scale atmospheric forcing and changes to the system. Idealized studies using high resolution ocean-only and coupled regional models will be conducted as well as a number of case studies. Planned and future high resolution basin and global simulations will also be utilized. The flow around the Hawaiian Islands is ideal in providing a case study with a mix of coherent vortices, strong stretching events, and variable and focused winds. With regard to the biology, the work will be directed towards elucidating the impact of meso- and submesoscale dynamics on the marine ecosystem down to the microbial community and will be done in strong collaboration with the NSF funded Center for Microbial Oceanography Research and Education (CMORE). Questions that will be addressed include

- How does the presence of submesoscale features influence the response of the upper ocean to changing atmospheric conditions?

- Is it possible to quantify the contributions from different physical processes on the rates of exchange between the surface and deep-ocean?

- How is the ocean response affected by the spatial and temporal characteristics of atmospheric disturbances?

- How important are ocean/atmosphere interactions on the oceanic mesoscale and smaller?

- How does the presence of submesoscale features influence the response of the marine ecosystem to changing environmental conditions?

- How does the presence of submesoscale features affect the functioning of the marine ecosystem down to the microbial activity?

3.2f_3 The dynamics and impact of multiple-jets in the ocean

Analysis of the mean ocean dynamic topography, based on combination of satellite and drifter observations (Niiler et al., 2003; Maximenko and Niiler, 2006) revealed a banded pattern of nearly zonal, alternating zonal geostrophic currents (Maximenko and Niiler, 2005; Maximenko et al., 2008). Ubiquitous in nature (Galperin et al., 2004; Nakano and Hasumi, 2005; Richards et al., 2006), this newly discovered phenomenon challenges our understanding of the ocean circulation. These anisotropic current features can be observed in surface geostrophic currents and are found in high resolution model simulations. In the model simulations the near-zonal persistent jets are found as well in the deep ocean. The term "multiple-jets" is used rather loosely to describe these features. The jets have a large zonal coherency, have multiple cores in the meridional direction and a meridional scale of O(100km). Their presence raises numerous questions as to their formation mechanism and their impact on ocean dynamics and tracer transport. In certain regions, such as the North Pacific and the ACC, a working hypothesis for the presence of these jets is that they are formed through an eddy-mean flow interaction involving the inhibition of the meridional transport of PV by sharpening PV gradients (the so-called "Phillips" effect). Results from high resolution models, combined with more idealized experiments, allow a detailed analysis of the dynamics of jets. Initial experiments on the dispersion of particles show as expected a greater dispersion rate in the zonal direction compared to that in the meridional direction, but the results also give an indication of "anomalous" dispersion at long times together with an influence by Rossby waves. Questions to be addressed include:

- What are the balances of momentum, energy and potential vorticity associated with the jets?

- How important is the larger scale heterogeneity of the flow and bottom topography?

- What are the Lagrangian coherent structures in the flow?

- How do these relate to the dispersion characteristics?

- How does a mix of jets and Rossby waves influence the dispersion of tracers?

3.3 The Asian and Global Monsoon Systems

The monsoon system involves complex atmosphere-ocean-land-ice interactions. In the past two decades monsoon science has progressed dramatically, yet our knowledge and understanding of monsoon climate variability and change remain limited. Most state-of-the-art coupled atmosphere-ocean-land climate models still have great difficulty in simulating the mean state and variability at intraseasonal-to-interannual and longer time scales. At the same time, society has increasing demands for accurate monsoon prediction, which is important for protecting lives and property, ensuring sustained economic development, and adapting to anticipated climate change.

The overall goal of the research outlined in this section is to study the variability, predictability, and past and future long-term changes of the Asian-Australian monsoon and the global monsoon system. The monsoon research outlined in the original IPRC Science Plan focussed on diagnostic and modeling studies to determine the nature and mechanisms of monsoon variability. Many basic questions remain open and the current plan includes investigations of these questions. However, in the decade since the original Science Plan was written considerable progress has been made on basic understanding and model development. So the current plan has a larger effort devoted to improving and assessing practical extended-range prediction systems for monsoon variability. Also, while the principal focus of IPRC's efforts remains on monsoons in the Asia-Pacific region, the new plan proposes to use the insights gained in studying the Asian-Australian monsoon system to help understand issues concerning global monsoon circulations.

The various scientific issues to be addressed are organized in subsections as follows. First some basic questions related primarily to the dynamics and modeling of the monsoon intraseasonal oscillation are discussed in subsection 3.3a. Some issues connected with the practical question of model initialization for forecasts of the monsoon intraseasonal oscillation are addressed in subsection 3.3b. The effects of land-ocean-atmosphere processes on monsoon circulations are considered in subsection 3.3c. The response of the monsoon circulations to anthropogenic forcing, including changes in atmospheric greenhouse gas and aerosol concentrations, is considered in subsection 3.3d. Issues related to the interactions among synoptic-scale variability, the intraseasonal oscillation, and lower-frequency variability in the monsoon climate system are discussed in subsection 3.3e.

3.3a Dynamics and Modeling of the Intraseasonal Oscillation

Background

The recurrent tropical Intraseasonal Oscillation (ISO) with a period of 10-90-day offers an opportunity to extend weather forecasts beyond two weeks and thus bridge the gap between medium-range weather forecasts and seasonal climate prediction (Waliser, 2005). Under the ISO label we include both the eastward propagating Madden-Julian Oscillation (MJO, Madden and Julian, 1971) dominant in boreal winter, and the northeastward propagating Boreal Summer Intraseasonal Oscillation (BSISO) dominant in boreal summer. The ISO is particularly active in the Indo-western Pacific warm-pool and may impact Asia and North America through northeastward propagation and tropical-extratropical teleconnections (Yasunari, 1979; Li and Wang, 1994; Jiang et al., 2004; Wang et al., 2006; Pan and Li, 2007; Ding and Wang, 2007). On its way eastward and northward, the ISO spawns frequent occurrences of tropical cyclones over the Indian Ocean, and over the northwestern Pacific, northeast Pacific, and Atlantic Oceans (Maloney and

Hartmann, 2000a, b; Bessafi and Wheeler, 2006; Fu et al., 2007). The intraseasonal variability in the western Pacific region also regulates the onset and termination of El Niño (Lengaigne et al., 2004). Although the wide impacts of the ISO on weather and climate variability in the tropics and extra-tropics have been well recognized, our understanding of the dynamics of, as well as our simulation capability for, the ISO remain very limited. This limitation significantly impedes the progress of seamless prediction of monsoon/climate systems and weakens our confidence in the projection of extreme events related to future monsoon/climate changes.

Most contemporary general circulation models (GCMs) still have various problems in reasonably simulating the ISO. A few global models (e.g., ECHAM GCM and super-parameterized CAM) do show comparatively good simulations of the ISO (Fu et al., 2003; Lin et al., 2008; Sperber and Annamalai, 2008; Kim et al. 2009; Benedict and Randall 2009), but are still afflicted by various weaknesses (Fu et al., 2006; Lin et al., 2006; Stan et al., 2010). The exact reasons that separate the good and bad models remain elusive, although many studies have suggested that the model problems mainly lie in the inadequate representations of moist convection (Tokioka et al., 1988; Wang and Schlesinger, 1999; Maloney and Hartmann, 2001; Zhang and Mu, 2005; Neale et al., 2008) and atmosphere-ocean coupling (e.g., Fu et al., 2003; Fu and Wang, 2004a).

To ensure steady progress in advancing our knowledge and simulations of the ISO, much more effort is needed in at least the following three areas: (i) better understanding of the dynamics of the ISO, including its initiation, propagation, and interactions with the Maritime Continent; (ii) validating model simulations of the ISO with advanced datasets from satellite retrievals, reanalysis, and in situ observations; and (iii) improving the sub-grid parameterizations for global models. The ISO can be initiated from the circumnavigation of a pre-existing ISO (Sperber et al., 1997; Matthews, 2008), extratropical disturbances (Hsu et al., 1990; Pan and Li, 2007; Ray et al., 2009), and local processes including air-sea interactions (Wang and Xie, 1998; Fu and Wang, 2004b; Stephens et al., 2004; Jiang and Li, 2005; Wang et al., 2005; Li et al., 2008). Various mechanisms, such as frictional CISK (Wang, 1988, Li and Zhou, 2009), stratiform rain (Fu and Wang, 2009), air-sea coupling (Fu et al., 2003), and wind-evaporation feedback (Sobel et al., 2009), have been suggested as mechanisms that help to maintain the ISO. Major physical processes that lead the ISO to propagate eastward and northward include boundary-layer convergence (Wang and Li, 1994), low-level moistening (Fu et al., 2008a), vertical shear (Jiang et al., 2004), air-sea coupling (Fu and Wang, 2004a), and zonal advection (Maloney et al., 2010). As briefly reviewed here, efforts in past years have tried to advance our understanding of the ISO, however, the pathway that guarantees a realistic simulation of the ISO is still elusive.

Scientific Issues and Questions

Initiation and Propagation of the ISO: The initiation of the ISO over western Indian Ocean is the least predictable aspect of the life-cycle of the ISO. The physical processes leading to different types of ISO initiations (Matthews, 2008) are still elusive due to the lack of quality data with high spatial and temporal resolution. The extended-range forecasting skill for the ISO is largely determined by the capability of models in reproducing the propagating directions and speed of the observed ISO. Further effort is needed to better understand the processes controlling ISO propagation in order to help guide the improvement of models.

Multi-scale Interactions over the Maritime Continent: The Maritime Continent is a well-known barrier as global models have difficulty in propagating the simulated ISO from the tropical Indian Ocean to the western Pacific Ocean (e.g., Vitart et al., 2007), which significantly shortens the intraseasonal forecasting skill. This model weakness is due to our lack of knowledge concerning the multi-scale interactions over the Maritime Continent and how to include these complex interactions into models.

Effects of Organized Mesoscale Convective Systems (MCS): The MCS play an important role in the upscale organization of convection during the development and mature phase of the ISO. The effects of such mesoscale systems have been misrepresented in current global models, which has resulted in underestimated boundary-layer cooling/dryness and lower-troposphere moistening at the peak phase of the ISO (Fu et al., 2006). Better representation of MCS is expected to increase the fraction of stratiform rain, which is demonstrated to be critical to sustain a robust ISO in global models (e.g., Fu and Wang, 2009).

Heating profiles and energetics of the ISO: The interaction between convective heating and large-scale circulation has been recognized as the key process maintaining the ISO (Wang, 2005). The heating profiles associated with the lifecycle of ISO contain important information concerning the mechanisms governing the ISO (Tokioka et al., 1988; Cho and Pendlebury, 1997; Mapes, 2000; Lin et al., 2004). Due to the limited 3-D observations over the main ISO activity region (the Indo-western Pacific warm-pool), our knowledge of the heating profiles and energy transformations at different stages of ISO is very limited.

Effects of Air-Sea Interactions: In earlier work we have demonstrated that air-sea coupling plays an important role to enhance both eastward and northward propagation of the ISO (Fu et al., 2003; Fu and Wang, 2004) and acts to improve the potential predictability (Fu et al., 2007) and practical prediction skill (Fu et al., 2008) for the ISO. However, we still don't know whether high-frequency atmospheric forcing can generate significant intraseasonal SST anomalies through nonlinear ocean processes and whether high-frequency SST variability (e.g., caused by the diurnal cycle or mesoscale ocean eddies) can significantly impact the evolution of atmospheric intraseasonal variability.

The following are specific questions to be addressed:

- What initiates the ISO convection in the western Indian Ocean and what processes determine the propagation directions and speeds of the ISO?

- Why can some ISO events propagate across the Maritime Continent and others are stopped? What are the key processes leading the ISO across the Maritime Continent and misrepresented in current global models?

- What controls the evolution of the organized mesoscale convective systems? How will the organized MCS impact the ISO? How can the effects of the organized MCS be represented in global models?

- What is the 3-D evolution of atmospheric heating during the life cycles of the ISO? How will the interactions between atmospheric heating and large-scale dynamics determine the evolution of the ISO?

- How can high-frequency SST variability (e.g., diurnal cycle) and ocean mesoscale eddies impact the evolution of the ISO? Could high-frequency atmospheric forcing of the ocean be rectified into a significant intraseasonal SST signal?

Strategy

The planned international field campaigns (CINDY, DYNAMO, and AMIE) over the tropical Indian Ocean and Western Pacific Ocean in late 2011 and early 2012 will offer accurate in situ observations with high spatial and temporal resolutions. Ultra-high resolution (~ 2 km) reanalysis datasets constrained with these observations will also be produced. In combination with similar datasets developed during TWP-ICE, TOGA COARE, and GATE field campaigns along with satellite retrievals (e.g., AIRS, TRMM, QuikSCAT, AMSR-E and CloudSat), latest generation reanalyses (e.g., NCEP/CFSR, NASA/MERRA, and ERA Interim), ocean observations (e.g, ARGO floaters and buoys), and available NICAM outputs, we will diagnose the processes determining the initiation and propagation of the ISO, the multi-scale interactions over the Maritime Continent, the mass/heat/momentum budgets of the organized mesoscale convective systems (Leary and Houze, 1980), the heating profiles (Yanai and Johnson, 1993) and energetics (Mu and Zhang, 2006) at different stages of the ISO lifecycle, as well as the rectification of the high-frequency atmospheric/oceanic processes on the ISO through air-sea interactions.

The information and knowledge gained from these diagnostic studies will be used to form new hypotheses and validate and refine sub-grid parameterization schemes for global models (Donner, 1993; Gray, 2000). Numerical experiments with NICAM and conventional global/regional models will be carried out to test the newly formed hypotheses on the initiation and propagation of the ISO, its interactions with the Maritime Continent, the roles of the organized MCS, heating profiles, and high-frequency air-sea interaction at different stages of the ISO lifecycle.

Expected Outcomes

The proposed diagnostic and modeling studies will advance our understanding on the initiation, maintenance, and propagation of the ISO and provide valuable information to validate and refine sub-grid parameterization and evaluate the NICAM along with those models participating in current and planned model intercomparison projects (e.g., CLIVAR AAMP, Year of Tropical Convection and Asian Monsoon Year).

3.3b Predictability and Prediction of the Monsoon Intraseasonal Oscillation and Seasonal Anomalies

Background

The Intraseasonal Oscillation (ISO) is a fundamental building block of Asian-Australian summer monsoon (Wang, 2006). The associated rainy and inactive phases of the monsoon ISO strongly modulate the occurrence of extreme events (e.g., droughts, floods, and TC genesis), which have tremendous social and economic effects (e.g., on agriculture, water management, and disaster prevention) throughout the Asian-Australian monsoon region, particularly in Southeast Asia. A capability of forecasting the monsoon intraseasonal oscillation beyond two weeks is extremely desirable and would provide great benefits for the inhabitants of this area. A better understanding of the impacts of initial conditions on the skill of monsoon rainfall predictions and the development of improved initialization methods are important steps towards this gaol.

Due to the incomplete coverage of global observation systems and unavoidable errors in observations and data analysis, any initial condition used for the weather/climate forecasts can only be an approximation of the real atmospheric state. Ensemble forecasts have been proven to be a pragmatic way to reduce forecast errors due to the uncertainties in the initial conditions (Leith, 1974; Lewis, 2005). In order to improve the efficiency of ensemble forecasts and to provide reliable ensemble spreads, different ensemble generation techniques, such as the breeding vector method (Toth and Kalnay, 1997; Liess et al., 2005), singular vector method (Palmer, 2000), and ensemble Kalman filter (Hamill, 2006) have been tested and applied (Buizza et al., 2005). In addition to perturbations of the initial conditions, ensemble methods based on perturbations of model parameters may also be able to improve forecasts (Buizza et al., 1999).

Since the pioneering work of Lorenz (1963), it has become well accepted that, due to the chaotic nature of Earth's atmosphere, the forecast skill of day-to-day weather is limited by the growth of unavoidable small errors in the initial conditions. Useful deterministic weather forecasts can be made only for lead times of a week or two at the most. On the other hand, seasonal forecasts are primarily determined by the surface boundary conditions over the ocean, land, and ice in atmospheric-only models, or by the slow coupled dynamics and initial memory of anomalous conditions in atmosphere-ocean coupled models. For an intraseasonal prediction for lead times between synoptic and seasonal, the prediction may be sensitive to both atmospheric initial conditions and surface boundary conditions (Waliser et al., 2003; Reichler and Roads, 2005; Fu et al., 2007). The recent study of Fu et al. (2008b) further indicated that in order to allow the underlying SST anomaly to extend the ISO predictability, atmospheric initial conditions need to be fairly accurate. If the initial atmospheric conditions are not consistent with the underlying intraseasonal SST anomalies, the coupling will not act to extend the predictability of ISO. This indicates not only the need of coupled ocean-atmosphere models but also the importance of proper initialization of this system in order to improve the forecasting of the ISO.

Scientific Issues and Questions

In many previous ISO forecast studies, the initial atmospheric conditions were taken from either NCEP or ECMWF reanalyses, or from global data analysis systems at various NWP centers (e.g., Hendon et al., 2000; Jones et al., 2000; Seo et al., 2005, Vitart et al., 2007, Woolnough et al., 2007; Fu et al., 2008a). Thus, ISO forecasting has been basically treated as an extension of short-term weather forecasting. The experimental forecasts conducted by Krishnamurti et al. (1992), however, used a special procedure to generate atmospheric initial conditions by retaining only time-mean and 30-50-day variability (Webster and Hoyas, 2004). Whether the exclusion of the weather activity in the initial condition helps or harms ISO forecasting is still an open issue. Retaining the weather activity may make ISO forecasts less skillful if the weather plays a similar role as the fast waves in the forecast of quasi-geostrophic motion. Theoretical studies have established that the interaction of the equatorial planetary waves with "residual heating" (the heating remaining from mesoscale and synoptic scale motion) is the "backbone" of the eastward propagating intraseasonal disturbances (e.g., Wang, 1988). On the other hand, studies have indicated that the upscale cascade of energy and momentum from mesoscale to planetary scale is important for maintaining large-scale disturbances, such as the ISO (Mapes and Houze, 1995; Houze et al., 2000; Moncrieff and Klinker, 1997).

The in situ observations are sparse over the Indo-Pacific warm-pool where the atmospheric/oceanic variations associated with the ISO are strongest (Wang and Rui, 1990). Thus the analysis and reanalysis products in this region depend strongly on the accuracy of the physics of the assimilation model. This can obviously lead to significant uncertainties/errors in the initial state used for ISO forecasting (e.g. Fu et al., 2006). Most contemporary global models underestimate ISO variability (Lin et al., 2006) which suggests that the amplitude of intraseasonal variations in current analysis and reanalysis datasets may also be underestimated. This has been shown to be the case for NCEP reanalysis (Shinoda et al., 1999).

Our understanding of the role of the initial conditions in ISO prediction remains incomplete, despite the results of the preliminary studies mentioned above. Our future research will address the following set of questions and is expected to contribute to progress on this important issue.

- To what degree do current reanalysis datasets capture the observed convective activity associated with intraseasonal variability? What are the spatial and temporal distributions of the intraseasonal biases in these reanalysis datasets?

- How will the inclusion of weather activity in the initial conditions influence the ISO forecasting skill?

- How will the ISO strength in the initial conditions impact the forecast? How can one correct the biases of reanalyses in representing the ISO in the real world? Are there other ways (e.g., rainfall assimilation) to generate better initial conditions for ISO forecasting?

- How will different ensemble generation methods affect ISO forecasting?

- Can better ISO forecasts improve the prediction of TC genesis?

Strategy

Both satellite observations and in situ observations will be used to quantify the intraseasonal biases of the NCEP/CFSRR, NASA/MERRA and ECMWF ERA Interim reanalyses (e.g., Fu et al., 2006) and to document the regional/ temporal distributions of these biases. This effort will be used to improve the representation of the ISO in current reanalysis datasets. The original and improved reanalysis data will be used to initialize UH Hybrid Coupled Model (UHHCM, Fu et al., 2002). The impacts of different initial ISO intensities on the forecast will then be assessed. In order to develop a better initialization for ISO forecasting, two avenues will be explored: 1) develop a method (e.g., MME) to combine several available reanalysis datasets (e.g., NCEP, ECMWF, CFSRR, and MERRA) into a consolidated reanalysis; 2) take advantage of high-quality precipitation observations and develop a physical initialization package for UHHCM (Krishnamurti et al.,1991, Treadon, 1996).

In order to assess the impacts of including weather activity in the initial conditions, filtering strategies (including spatial smoothing) will be used to separate the intraseasonal component from the high-frequency weather component. The impact can be estimated by comparing forecasts made with the inclusion and exclusion of the weather component in the initial conditions. Other sensitivity experiments with UHHCM can also be conducted to test the impacts of different ensemble generation methods. The forecast ISO fields will be used along with the TC genesis potential index (Emanuel, 2008) to make a forecast of TC occurrence, and this will be validated with available TC observations.

We will also assess the predictability of the seasonal anomalies of the monsoon precipitation and run-off, using multi-physics global and regional climate models (including vegetation and hydrological models) ensemble experiments. For the regional models, output from global coupled models will be used as driving fields in targeted land regions (e.g., Yellow River basin, Indo-

China). The sensitivity of the model solutions to various components of the large-scale forcing and land-surface feedback will be examined. The seasonal predictability study fits nicely with IPRC's participation in the Climate Prediction and its Application to Society (CliPAS) project. CliPAS is supported by the Pacific Economic Cooperation (APEC) Climate Center (APCC). The key objective of CliPAS is to develop a well-validated Multi-Model Ensemble (MME) prediction system and to study the predictability of the seasonal and sub-seasonal climate variations. CliPAS is a coordinated research community consisting of 12 institutions and it involves a large group of climate scientists from United States, South Korea, Japan, China, and Australia.

Expected Outcomes

This project is expected to advance our understanding of the monsoon ISO predictability and to lead to some new strategies for initializing ocean-atmosphere coupled model forecasts that will improve prediction of the ISO, seasonal anomalies and their modulated extreme events (e.g., TC).

3.3c Effect of Land-Atmosphere-Ocean Interactions on the Mean State and Variability of the Monsoon

Background

The monsoon spectrum peaks at the diurnal, synoptic, intraseasonal, interannual and interdecadal timescales (Li, 2010). Previous studies indicated that the atmosphere-ocean interactions in the warm ocean play an important role in regulating the monsoon interannual (Li et al., 2001; Li and Zhang, 2002; Wang et al., 2003; Li et al., 2006; Wu et al., 2009, 2010ab) and intraseasonal (Fu et al., 2003) variability. So far it is not clear how the atmosphere-land interaction and the change of land surface conditions (such as vegetation type and soil moisture) may affect the monsoon mean climate and variability. It has been shown that the preceding winter-spring snow cover or snow depth may exert a marked impact on the summer monsoon (e.g., Vernekar et al. 1995; Bamzai and Marx, 2000; Zhang et al., 2004). The overall objective is to determine the relative role of the atmosphere-land and atmosphere-ocean interactions in regulating the monsoon climate variability and in modulating the monsoon-ENSO and the monsoon-IOD teleconnection patterns.

There are many processes that determine the mean seasonal evolution and interannual variability of the Asian Summer Monsoon (ASM). Despite recent improvements in physical parameterizations in numerical models, simulating the monsoon annual cycle and its variations at intraseasonal (< 3 months) to interannual (> one year) time scales remains among the most difficult challenges facing the modeling community (e.g., Sperber and Palmer, 1996; Annamalai et al., 2007). While it is known that the spatial and temporal variations in sea surface temperature (SST) exert profound influence on the ASM, understanding the role played by land-surface processes (snow cover, soil moisture, vegetation, surface roughness, etc.) in determining the ASM annual cycle and its spectrum of variability needs sustained research efforts including observational diagnostic studies and systematic exploration with fully coupled models.

During the month of May and early June, a prominent feature over the Asian region is the gradual development of the quasi-stationary monsoon trough (a region of low-pressure whose axis runs through Pakistan, central India, the Bay of Bengal, and the South China Sea). In late July and early August, the trough extends well into the tropical western Pacific. It is observed that maximum rainfall occurs to the south of the trough where maximum convergence and Ekman pumping takes place. The fixed geographical location of the ASM implies that other effects such as those due to orography and land/sea thermal contrasts must also be important ingredients in driving the monsoon circulation (Hoskins and Rodwell, 1995). To what degree do the land-surface processes determine the location and intensity of the monsoon trough, particularly in May and early June? Do the land-surface processes determine the poleward extension of the land-locked monsoon convection? None of the coupled models that participated in the IPCC AR4/CMIP3 intercomparison is able to capture the correct location and intensity of the monsoon trough (Annamalai et al., 2007). In particular, in all the models considered the simulated annual cycle of the monsoon precipitation is weaker than observed over the south Asian region, but stronger over plains of India and China (Annamalai et al., 2007).

As regards to the onset of the ASM in late May, observational studies suggest that the sensible heat flux over Tibet during spring and early summer is instrumental in creating the meridional reversal in upper tropospheric temperature that subsequently triggers the onset of the ASM (Yanai et al., 1992). On the other hand, the northern Indian Ocean is the warmest of all the tropical oceans in boreal spring, and modeling studies indicate that the northward extent of SST may be important in the monsoon annual cycle (Fennessy and Shukla, 1994, unpublished). What are the relative roles of the annual cycle in SST over the tropical Indian Ocean and the elevated heat source over Tibet in the formation of the monsoon trough, and so in the onset of the monsoon?

Modeling studies identified the Indian monsoon region as one of the major hot spots where soil moisture variations can have significant impact on monsoon variations (e.g., Fennessy and Shukla, 1999; Yasunari, 2006). The studies of Vernekar et al. (1995), and Bamzai and Marx (2000) highlighted the effect of previous winter-spring Eurasian snow cover on the summer monsoon circulation. The conclusion of these studies is that remote responses from the snow-mass anomalies include significant changes in the sensible-heat flux, latent-heat flux and sea level pressure, leading to changes in summer precipitation over the land mass of the Indian subcontinent. In sharp contrast, Robock et al. (2004) note that in their study the snow-albedo feedback is always operating, but the snow cover effect on soil moisture by itself does not control the monsoon. Anomalous snow cover impacts on temperature were not prolonged by soil moisture feedbacks because of its short time memory, and Robock et al. found no obvious relationship between soil moisture and the monsoon. Douville et al. (2002) also found that changes in soil moisture did not have a clear and homogenous response over the Indian monsoon region. In an earlier study, Sud and Smith (1985) determined that the monsoon is significantly weakened when surface albedo is increased or surface roughness is decreased. Suffice it to say that there is no consensus among earlier modeling studies in quantifying the effect of land-surface processes on the mean monsoon.

At intraseasonal time scales, while Webster (1983) found that soil moisture variations strongly impacted the poleward migration of convection, Ferranti et al. (1997) concluded that interactive land-atmosphere processes modified only the variance but not the northward movement of rainfall – again revealing inconsistencies among model solutions. Recent observations show that the land-surface temperature over south Asia varies significantly on intraseasonal time scales. Specifically, during a monsoon break the warming of the land-surface increases the land-sea contrast and results in an intensification of the large scale meridional temperature gradient. The possible role of such modulation of the temperature gradient in promoting the poleward migration of convection, and thus helping to induce the next monsoon active phase, is not understood. In addition, once a break is initiated, the reduction in precipitation and soil moisture can alter the albedo and the nature of the land-atmosphere feedbacks, possibly leading to extended duration of monsoon breaks. In a particular season, a prolonged monsoon break can significantly alter the seasonal-mean rainfall, and therefore it is imperative to understand the role of land surface processes on monsoon intraseasonal variations. Further, the role of soil moisture (and other land surface processes) in the genesis of low pressure monsoon synoptic systems over the land regions during July/August, and on the development of extreme rainfall events is not known.

Scientific Questions

- How important are the land-surface processes in determining the location (poleward extent) and intensity of the quasi-stationary monsoon trough, and the annual cycle of the monsoon? In the current coupled climate models, what land-surface processes (such as surface roughness) lead to unusually high seasonal mean rainfall over the plains of India and China?

- What is the relative significance of SST annual cycle over the tropical Indian Ocean versus the elevated heat source over Tibet in the formation of the monsoon trough, and in the onset of the monsoon?

- What is the structure of the northward-propagating monsoon intraseasonal mode over the land and what is difference from the northward propagating mode over the ocean? Do land-atmosphere feedbacks impact synoptic systems that form over the land, extended active/break monsoon epochs, northward propagation of intraseasonal convective rainbands, and extreme rainfall events?

- Does a more realistic representation of land-surface processes in climate models lead to a better prediction of the monsoon?

Strategy

The lack of consensus among past studies can be attributed at least partly to our lack of understanding of the land-atmosphere interactions over the monsoon domain. Understanding has been limited primarily due to dearth of quality soil moisture observations and to the significant systematic errors in climate models. The land-atmosphere physical processes are linked by means of complex feedback mechanisms involving heat fluxes, precipitation and convection. The models to be used include both global and regional climate models. Our focus will be on the change of land surface conditions over South and East Asia and Maritime Continent regions. We plan to compare and synthesize results obtained by multi-model runs at IPRC and JAMSTEC. The integration length ranges from one season to multiple years. The model output will be validated against satellite and in situ observations. We will investigate the structure and evolution of the dominant monsoon modes on various temporal and spatial scales and reveal physical mechanisms behind the observations and GCM simulations. In particular, we will compare outputs from high-resolution GCMs (e.g., NICAM, MRI 20-km simulation, SINTEX-F T319 simulation) with available observations, to investigate the intraseasonal, interannual and interdecadal variability of the monsoon in the Indo-Pacific regions.

Most earlier modeling studies were performed with atmospheric general circulation models with some prognostic treatment of land processes, but with prescribed SSTs. Since the ASM is a coupled ocean-atmosphere-land interaction system, a fully coupled model is needed to advance our understanding. The availability of coordinated enhanced in situ observations (as part of GEWEX – Global Energy and Water Cycle Experiment) along the Himalayas and Tibetan Plateau, together with the availability of a coupled ocean-atmosphere-land model that has realistic representation of mean monsoon and its spectrum of variability (the latest version of the GFDL coupled model, CM2.1), offers a unique opportunity for systematic evaluation of the role of land-surface processes in the monsoon. Although systematic model errors still exist in CM2.1, it is by far the best model for monsoon studies (documented in a series of publications: Annamalai et al. 2007; Sperber and Annamalai, 2008; Stowasser et al., 2008). Moreover the CM2.1 model code is easily accessible. The observations from GEWEX will provide an opportunity to validate the model simulations, and to investigate any improvements in prediction that may be obtained with better soil moisture initialization. Applying the expertise at IPRC in modeling and diagnostics, along with expertise on land and hydrological processes at JAMSTEC, the active role of land-surface processes on all aspects of the monsoon will be examined in detail.

The role of land surface treatment in monsoon seasonal prediction is a focus of IPRC's participation in the Climate Prediction and its Application to Society (CliPAS) project (see 3.3b, above). Within CliPAS, IPRC scientists focus on the monsoon rainfall prediction and predictability over land, and are exploring methods for improving both the land component of coupled models and the initialization of land-surface variables.

Expected Outcomes

We expect the results of our research will fill the key gaps in our knowledge of the role of land surface processes and atmosphere-ocean processes on the monsoon prediction and predictability. The systematic evaluation with a fully coupled model will allow us to quantify the role of land-atmosphere interactions on the monsoon variability.

3.3d Recent and Future Changes of the Monsoon, Tropical Cyclone and Mean Circulation

Background

The seasonal mean rainfall associated with the Asian Summer Monsoon (ASM) is a critical factor in the economies of the world's most populous countries. Given their anticipated population rise, countries influenced by the ASM will surely face increased stress in the near future, which will seriously impact the stability of their social, economic, and political infrastructures. The expected stress of population growth may be exacerbated depending on how the typical mean seasonal rainfall and the variability associated with the ASM responds to global warming. Thus, there is great interest in determining how the monsoon will respond to expected anthropogenic effects such as increases in greenhouse gas and aerosol concentrations. We are interested in changes in the mean monsoon as well as changes in the climatology of: extended monsoon breaks (breaks that last for more than seven days), the occurrence of strong rain-bearing systems such as monsoon depressions, the frequency of severe droughts and floods, and the clustering of drought/ and flood events.

Modeling studies that examined the ASM response in experiments where the present-day concentrations of greenhouse gases were doubled (Meehl and Washington, 1993; Mahfouf et al., 1994; Kitoh et al., 1997; Hu et al. 2000; May, 2002) produced quite different results depending on the model employed. The response of a model to climate forcing may depend on the basic state the model simulates in the control mode (Sperber and Palmer, 1996; Annamalai and Liu, 2005; Turner et al., 2005). We have chosen to concentrate of analysis of experiments performed with those coupled ocean-atmosphere models that demonstrate the best success in simulating the current monsoon climate. Unfortunately, even the most successful of current models have systematic errors that will add uncertainty to any future projections.

Recent modeling studies examining the effect of both greenhouse gases and aerosols on the monsoon have produced conflicting results (e.g., Ramanathan et al., 2005; Lau et al., 2006; Meehl et al., 2008). While the effect of greenhouse gases and sulfate aerosols is generally agreed to increase the monsoon precipitation, Ramanathan et al. (2005) find that black carbon aerosols have the opposite effect on monsoon rainfall, and in particular their results suggest that droughts over the Indian subcontinent may become more frequent in the next decades. In contrast, Lau et al. (2006) indicate that the direct heating associated with carbon aerosol should lead to a strengthened monsoon circulation.

Stowasser et al. (2008) investigated the mechanisms responsible for the increase in the time-mean ASM precipitation in the $4xCO_2$ runs compared to the twentieth century (20c3m) integrations of the GFDL_CM2.1 coupled model. Despite a significant increase in the land-sea thermal contrast over the Indian longitudes in boreal spring and summer, the monsoon onset is delayed in the $4xCO_2$ runs. The seasonal mean rainfall, however, increased significantly over India and the western Pacific region, while the rainfall decreased over the equatorial Indian Ocean. Despite an increase in rainfall over continental India, in the $4xCO_2$ runs there is a reduction in the cross-equatorial low-level monsoon flow. Analysis of the model integrations revealed that changes in precipitation over the equatorial Indian Ocean force regional circulations that, in turn, favor enhanced precipitation over India. While greenhouse gas forcing results in substantial warming of the land surface, it is the regional changes in the air-sea interaction processes over the tropical Indian Ocean that are instrumental in causing the precipitation increase over the monsoon region.

The working hypothesis adopted in previous studies (Chung et al., 2002; Ramanathan et al., 2005) is that the surface cooling due to black carbon aerosols increases the atmospheric stability, reduces evaporation, and subsequently monsoon rainfall. In addition, aerosols nucleate cloud drops that then reduce the precipitation efficiency. Since maximum black carbon aerosol concentrations are observed over the Indian-subcontinent and Northern Indian Ocean region during November through April, the overall effect of the aerosols on the ocean surface cooling is hypothesized to linger into early parts of July (primarily due to the thermal inertia of the ocean). This then reduces the seasonal rainfall associated with the ASM. Our ongoing research indicates that even without black carbon aerosol forcing, the ASM shows a declining trend in CM2.1 20th century simulations, with the trend most pronounced in the last 40-50 years (1950-2000).

Studies that directly evaluated future changes in WNP TC tracks have yielded diverse results. For example, Bengtsson et al. (2007) used the ECHAM5 global climate model with T213 resolution (about 60-km grid size) forced by the projected future sea surface temperature (SST) of the SRES A1B scenario and reported that TC track density will decrease in the overall region of the WNP except for the eastern WNP. On the other hand, Stowasser et al. (2007) used a regional model (horizontal resolution of 0.5 degrees) driven by lateral boundary conditions produced by outputs of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 2 (CCSM2) under an extremely strong (6 x CO2) forcing and reported that the warming leads to significantly more TCs in the South China Sea, but little change in TC occurrence in other areas compared to the present-day experiment. Yokoi and Takayabu (2009) investigated future changes in TC genesis frequency (TGF) over the WNP using CMIP3 (World Climate Research Programme's Coupled Model Inter-comparison Project phase 3) models with medium resolution (T63–T106). Similar to the results obtained by McDonald et al. (2005), the authors reported that the prevailing genesis region in the WNP shows significant southeastward shift. Given that the future changes projected by these numerical studies are contradictory to the observed trends in the last 40 years during which the global mean air temperature had increased by about 0.5 C (e.g., Wu and Wang 2004), it is difficult to determine whether the present-day trend is due to anthropogenic influences or due in part to long-term natural variability. Taking into account the results of both numerical and observational studies, the overall pattern of future change in TC tracks over the WNP remains uncertain.

Our recent high-resolution (T319) modeling study shows a distinctive change of TC frequency in the western and central Pacific under the global warming A1B scenario. Such a change is related to the change of the tropical mean circulation and convection over the Maritime Continent and western North Pacific monsoon regions. Various studies have reported a weakening of the trade wind and a central Pacific warming pattern in the future warming climate. How the tropical coupled SST-precipitation-wind patterns set up under global warming conditions is still not clear.

Scientific Questions

- At decadal and longer time scales, to what extent do increases in greenhouse gas, aerosol (sulfate and black carbon) and dust concentrations influence the time-mean state of the ASM and tropical Indian Ocean? How do these climate forcings affect the probability of occurrence of extreme events over the ASM domain?

- What is the effect of winter-spring time black carbon aerosol on the Eurasian snow cover albedo? How does this then affect Tibetan Plateau heat fluxes, and the ASM circulation? Does this snow albedo effect linger through the entire ASM season?

- What causes the change of the tropical mean circulation and tropical cyclones under the global warming? Does a uniform SST warming lead to the similar trade wind and TC changes? What mechanisms are responsible for the formation of the coupled SST-precipitation-wind patterns simulated in the future warming scenarios?

- How does an improvement in the basic state climatology simulated by a coupled model affect the sensitivity to climate perturbations?

Strategy

A number of activities are planned. First, detailed diagnostics will be carried out with all available observations/reanalyses products to understand the recent changes in the ASM and tropical Indian Ocean climate systems, and various hypotheses will be framed. Second, hypotheses will be tested by diagnosing long integrations from coupled models that showed reasonable skill in simulating the mean monsoon precipitation and ENSO-monsoon association. Third, a suite of idealized and realistic coupled model runs will be performed to assess the relative and combined role of greenhouse gases and aerosols. Fourth, the sensitivity of the coupled model results to horizontal resolution will be tested.

To understand how the monsoon and mean circulation respond to anthropogenic forcing such as increases in greenhouse gas and aerosol concentrations, we propose to analyze the IPCC AR4/AR5, SINTEX-F T319 and T106 simulations and other model outputs in the present and future climate with emphasis on monsoon hydrological cycles related to 1) Asian-Australian monsoon onset and seasonal march, 2) monsoon subseasonal variabilities, 3) monsoon-ENSO relationship and the monsoon-Indian Ocean dipole relationship, 4) Tibet Plateau/East Asia climate and long-term trends, 5) extreme events, and 6) changes of humidity, cloud and rainfall structures associated with diurnal cycles and synoptic-scale disturbances. We will document the monsoon extreme events and variability on intraseasonal-to-interannual timescales, with a particular focus on extended monsoon breaks, the occurrence of strong rain-bearing systems such as monsoon depressions, the change of frequency of tropical cyclones and severe droughts/floods, and the clustering of drought and flood events. Research activities include the diagnosis of the trend of the monsoon rainfall and SST/circulation over and tropical and higher latitude oceans. Hypotheses related to the cause of the global warming SST and rainfall patterns will be tested. A suite of idealized and realistic coupled model runs will be performed to assess the relative and combined role of greenhouse gases and aerosol.

We will assess possible future changes in TC tracks and TC genesis frequency over the WNP and globe under various emission scenarios, by analyzing the 20-km-mesh MRI/JMA-AGCM and ECHAM5 T319 simulations based on 25-year and 20-year integrations of the present day and future climate. The MRI model experiment design will use the multi-model projected future changes in AR4 first then use AR5 results.

Expected Outcome

The proposed research will elucidate the reason for the large uncertainties in current climate models projections of monsoon rainfall at decadal to longer time scales and reveal the cause of the monsoon and mean flow changes under global warming. In particular we will improve the understanding the air-sea interaction processes over the tropical Indian Ocean, and their role in monsoon circulation at all time scales.

3.3e Feedback of High-Frequency Perturbations to Lower-Frequency Climate Variations in the Tropics

Background

Prediction of extreme climate and weather is challenging due to the rich spectrum of atmospheric and oceanic motions involved and the complicated interactions among different temporal and spatial scales. Many previous studies have demonstrated close relationships among the tropical synoptic-scale (typically 3-8-day) variability (SSV), the atmospheric Intraseasonal Oscillation (ISO, 20-70-day) and the El Niño-Southern Oscillation (ENSO). We aim to study the physical mechanisms through which SSV feeds back to ISO, and how the SSV and ISO act to modulate ENSO.

We hypothesize that SSV may impact the ISO through the following three processes. First, SSV may influence the ISO through the nonlinear rectification of the surface latent heat flux. Although the synoptic-scale zonal or meridional wind averaged over an ISO period is typically very small, the wind speed associated with SSV has a significant projection into the intraseasonal (20-70-day) band due to the nonlinear dependence of the wind speed on zonal and meridional wind components. Our analysis indicates that SSV is greatly enhanced (weakened) during the active (break) phase of the ISO (Zhou and Li, 2008). The increased wind speed during the active ISO phase may further enhance the surface latent heat flux and thus strengthen ISO convection through the pre-conditioning of surface moisture in the region. This implies a positive SSV-to-ISO feedback through nonlinear rectification of surface latent heat fluxes. Secondly, SSV may influence ISO through internal atmospheric dynamics such as eddy momentum transport. Thirdly, SSV may impact ISO through induced intraseasonal SST changes. Robust intraseasonal SST signals were observed in the tropical Pacific and Indian Oceans during the TOGA/ COARE and JASMINE/BOBMEX field experiments (e.g., Hendon and Glick, 1997, Lau and Sui, 1997, Jones et al., 1998, Shinoda et al., 1998, Shinoda and Hendon, 1998, Han et al., 2001 Sengupta et al., 2001, Vecchi and Harrison, 2002). So far, it is not clear what fraction of the intraseasonal SST variation is attributable to atmospheric SSV forcing, through either the nonlinear rectification of surface wind stress/heat flux or ocean nonlinear advection processes.

Observations show that significant high frequency (< 90 days, hereafter HF) atmospheric activity such as the MJO and westerly wind burst (WWB) precede or occur during the onset of El Niño events (Luther et al., 1983; Luther and Harrison, 1984; Lukas et al., 1984; Harrison and Luther, 1990; Delcroix et al., 1993; McPhaden et al., 1998; Matthews and Kiladis, 1999; Vecchi and Harrison, 2000; Kessler 2001; Zhang and Gottschalck, 2002; Yu et al. 2003; McPhaden, 2004). This finding has motivated numerous studies that have investigated the role of the HF atmospheric variabilities in triggering low-frequency (LF) ENSO events. For example, studies by Keen (1982), Lukas (1988) and Reneging et al. (2004) suggested that the westerlies associated with MJO/WWB may shift the warm pool eastward, triggering ocean Kelvin wave pulses that propagate into the eastern equatorial Pacific and affect the SST anomaly there. Linear model results by Rustling and On-line (2000), Bloodstone and Hendon (2005) and Suavely-Gary ate al. (2005) showed that the LF tail of MJO may indeed trigger an El Niño event. Moreover, the MJO and WWB may have a significant impact on ENSO predictability (e.g., Kessler et al., 1995; Kleeman and Moore, 1997; Moore and Kleeman, 1999; Perigaud and Cassou, 2000; Zhang et al., 2001; Zhang and Gottschalck, 2002; McPhaden, 2004).

While affected by HF atmospheric disturbances, ENSO also exerts a large-scale control on the MJO/WWB activity (Liebmann et al., 1994, Maloney and Hartmann, 1998, Tziperman and Yu, 2007). This two-way interaction implies that HF atmospheric variability may be regarded as a multiplicative (rather than additive) noise in the LF ENSO dynamics (Perez et al., 2005; Jin et al., 2007).

An open question is how ENSO modulates HF atmospheric variability (including the ISO and SSV). We hypothesize that ENSO may affect the HF atmospheric variability through the change of the background horizontal and vertical shear. For example, during El Niño, low-level westerly and upper-level easterly anomalies lead to the increased background easterly shear and low-level cyclonic shear in western North Pacific, which may favor the growth of the HF low-level Rossby wave perturbations (Wang and Xie, 1996), characterized by twin cyclonic (or anticyclonic) gyres off the equator and zonal wind variations on the equator (Matsuno, 1966, Gill, 1980). The Ekman-pumping induced moisture convergence in the planetary boundary layer may further magnify the HF Rossby wave perturbations through convection-circulation feedback. Given the asymmetry in the background condition between El Niño and La Niña, it is anticipated that the HF atmospheric variability will behave asymmetrically and depend on the phase of ENSO.

Strategy and Science Questions

The strategy is to combine the observational analysis with the numerical model experiments. A new eddy kinetic energy diagnosis tool will be developed to separate the effect of the ISO and the lower-frequency background flow. We will focus on examining upscale feedbacks in the tropics, with a special focus on the SSV feedback to ISO and the ISO feedback to ENSO. Various nonlinear rectification mechanisms will be tested. They include the nonlinear rectification of the surface latent heat flux, apparent heat and moisture sources, and eddy momentum transport. The numerical models to be used include coupled and uncoupled atmospheric and oceanic models. An anomaly atmospheric GCM will be used for studying the effect of the LF background flow on the HF wind variability.

The following are specific scientific questions to be addressed:

- How and through what processes does the ISO modulate the 3D structure and evolution of SSV? How does SSV feed back to the ISO through the nonlinear rectification of intraseasonal surface latent heat fluxes? What is the role of the synoptic eddy momentum transfer in modulating the ISO? To what extent is the intraseasonal SST variability induced by the atmospheric SSV forcing?

- How and through what process does ENSO modulate MJO and SSV activity? What are the relative roles of the nonlinear rectification of surface wind stress/heat flux versus internal ocean nonlinear processes in changing the equatorial SST and how sensitive is the SST change to the model subgrid-scale mixing parameterization?

Expected Outcomes

The research activities will advance our current understanding of multi-scale interactions in the tropics. Revealing the dynamics of upscale feedbacks including SSV feedback to ISO and ISO feedback to ENSO will not only advance our understanding of the mechanisms for ISO and ENSO, but also improve our seasonal and subseasonal prediction capability. Successful forecasts of the ENSO-state dependent MJO may offer an avenue for bridging the gap between medium-range weather forecasting and short-term climate prediction.

3.4 Paleoclimate

The climate of the past may hold important clues to understanding its future evolution. Recent discoveries on past ice-sheet instabilities have prompted a surge of activities to monitor, understand and predict the response of the Greenland and Antarctic ice-sheets to greenhouse warming. A partial rapid meltdown of these ice-sheets would lead to a global sea-level rise of several meters with catastrophic effects for low-lying countries and islands in the Pacific. Moreover, meltwater from the disintegrating Greenland ice-sheet could trigger a substantial weakening of the Atlantic Meridional Overturning Circulation (AMOC), with climate-effects that would be felt worldwide: relative cooling of the Northern Hemisphere, weakened Indian summer monsoon, increased El Niño variability and reduced upwelling and marine productivity in the major southeastern basin upwelling regions.

Assessing the sensitivity of the major ice-sheets and the ocean's thermohaline and wind-driven circulation to perturbations, such as an increase in CO_2 concentrations, requires an understanding of their past behavior. Paleo-data have provided a unique means to decipher important aspects of abrupt climate change. With the discovery of Heinrich and Dansgaard-Oeschger events in the late 1980's and early 1990's evidence emerged that under glacial conditions the climate system is capable of generating spontaneous rapid transitions from one state to another. What caused such abrupt transitions remains elusive. Possible threshold behavior has been suggested for the

AMOC, ice-sheets and the carbon cycle. Moreover, on millennial to orbital timescales these climate components seem to interact with each other vigorously. The nature of these interactions has not been explored satisfactorily.

The main goals of the paleo-climate research group at the IPRC are

- to assess the stability of the major ice-sheets using paleo-climate data and coupled ice-sheet climate models

- to identify the climate and biogeochemical impacts of reorganizations of the AMOC

- to elucidate the mechanisms that drive glacial cycles and millennial-scale glacial climate variability

- to develop a better understanding of climate-carbon cycle interactions under past and future climate conditions

- to quantify ENSO's sensitivity to past and future climate change using paleo-proxy archives from the Pacific and state-of-the art forced climate models

One key lesson that can be learned from the paleo-climate history is that long-term climate variations, while often generated in particular regions, have far-reaching effects on climate elsewhere. Understanding fundamental dynamics of past climate variability hence requires a global perspective that encapsulates oceanic and atmospheric teleconnections.

3.4a Ice-sheet Ocean Interactions

The ice-sheets play a major role in the climate system. Their response to orbital forcing is a of the key driver of glacial-interglacial cycles. Their internal instability mechanisms seem to play a major role in generating millennial-scale variability such as Heinrich events. Simulating and understanding the underlying dynamics provides a new challenge for earth system modeling. Ice-sheets influence the climate system via changes in albedo, topography, hydrology and sea level. The climate system itself provides the major forcing for the waxing and waning of ice sheets through fluxes of heat and fresh water. By coupling an existing climate-carbon cycle model with an existing ice-sheet model, IPRC will develop a powerful tool to study climate-ice-sheet interations and the mechanisms for glacial-interglacial climate change.

Using this new tool the following questions will be addressed:

- What triggered glacial terminations?

- How did ice-sheets respond to the occasional shutdowns of the AMOC?

- How do ice-sheets respond to orbital forcing?

- How stable is the Antarctic ice-sheet with respect to future greenhouse warming?

- What processes triggered meltwater pulses during the last glacial termination?

- What effects did changes in ice-sheet orography have on North Pacific climate?

3.4b Carbon cycle-climate interactions

Ice cores from Antarctica reveal that atmospheric greenhouse gas concentrations co-varied with temperatures throughout the last 700,000 years. While a substantial amount of the recorded glacial-interglacial climate variability can be attributed to greenhouse gas forcing, the origin of glacial cycles in CO_2 and methane still remains elusive. Dozens of hypotheses have been proposed during the last decade to explain the origin of glacial-interglacial CO_2 changes. None of them alone seems to explain the full magnitude of these variations. Earth system models of intermediate complexity will be used to elucidate the fundamental driving mechanisms of global carbon cycle variability on millennial to orbital timescales.

The following questions shall be addressed:

- What mechanisms are responsible for glacial-interglacial cycles in CO_2?

- How does the carbon cycle respond to orbital forcing?

- What ocean/climate conditions are favorable for releasing massive amounts of carbon?

- What led to the ^{14}C drop of about 190 permil during the Mystery Interval (~ 17ka B.P.)?

- How stable was the lysocline during the late Pleistocene?

- What role did the North Pacific play in the deglacial atmospheric CO_2 increase?

- What triggered the carbon release during the PETM?

- How did the PETM carbon release affect climate and the ocean circulation?

- Were PETM climate conditions in the Pacific and Indian Ocean favorable for generating hypercanes?

3.4c Abrupt Climate Change

The possibility of abrupt climate change continues to represent one of the greatest societal threats of greenhouse warming. There are a variety of mechanisms for abrupt climate change that can often be traced back to the bifurcation structure of the underlying dynamical equations. Typically emphasized over the past decade has been the possible abrupt cessation of the AMOC due to increased high-latitude freshwater flux from melting glaciers and ice sheets. There is currently some debate over the likelihood of such a scenario. Paleo-data may hold important clues to the mechanisms that led to meltwater pulses and ice-sheet instabilities during previous climate episodes.

As documented in ice-cores, certain massive climate transitions during the last glacial period, such as the Bølling- Ållerød, occurred within about 10-20 years. It is still unclear what mechanism were involved in these rapid warming events and whether similar mechanisms may operate under future greenhouse warming conditions.

There are other possible sources within the climate system for abrupt climate change that have received less attention, and yet may represent an equal or even greater threat: among them is the potential methane release from destabilizing methane hydrates. Potentially abrupt vegetation changes may occur in semi-arid regions, as greenhouse gasses continue to increase. As exemplified by the termination of the African Humid Period (~ 5-6 ka B.P), such transitions are often the result of positive climate-vegetation feedbacks.

The following questions will be addressed:

- What triggered the Bølling- Ållerød, 14,600 years ago?

- Under what conditions can Dansgaard-Oeschger events occur?

- What is the underlying mechanism for Dansgaard-Oeschger events?

- What role do ice-sheet instabilities play in generating abrupt climate change?

- What is the origin of millennial-scale variability in the North Pacific?

- Can anthropogenic greenhouse warming destabilize methane hydrates?

- How fast can the Greenland and Antarctic ice-sheets disintegrate?

- Can ENSO respond abruptly to external forcing?

3.4d The Sensitivity of ENSO to Past and Future Climate Change

Current generation global coupled general circulation models (GCMs) however, show little consensus with regard to the projected future behavior of ENSO. While some state-of-the-art coupled GCMs simulate an intensification of ENSO variability under CO_2 doubling conditions, other models show no significant change or even a weakening of ENSO activity. Partly, this large uncertainty can be attributed to the simulated differences in the background states, partly to the different regimes in which ENSO operates in the climate control simulations. One possibility to constrain the sensitivity of ENSO to climate change is to study the past history of ENSO using proxy-based climate reconstructions as well as numerical models.

Paleo proxies, documentary research and instrumental data, all capture variations in ENSO behavior over the past centuries and throughout the Holocene. Much of this variability appears to be internal to the earth's climate system, but there is evidence from intermediate coupled models and coupled general circulation models that orbital variations have been responsible for systematic changes in ENSO statistics throughout the Holocene. Such changes can occur quite abruptly, on timescales that are much shorter than the orbital forcing timescale. Recently, volcanic aerosol forcing as well as changes in the solar irradiance have also been suggested as potential drivers for low-frequency changes of ENSO. Separating externally forced signals in tropical Pacific climate reconstructions and model simulations from those that are generated by internal instabilities is a fundamental problem that will be addressed. IPRC scientists will further elucidate the physical mechanisms responsible for the sensitivity of tropical Pacific climate under paleo and future greenhouse warming conditions.

The following questions will be addressed by conducting a suite of climate sensitivity experiments using state-of-the art coupled GCMs as well as intermediate coupled models:

- What is the range of internally generated ENSO variability on decadal and centennial timescales in comparison with the externally-induced low-frequency modulation of ENSO?

- What are the mechanisms that produce internally generated and externally-induced long-term changes in ENSO?

- How does ENSO respond to the radiative forcing induced by strong volcanic eruptions?

- Can changes in solar irradiance modulate ENSO activity?

- In what ways does orbital forcing influence ENSO variability?

- What is the effect of orbital forcing on tropical instraseasonal variability?

- How stable were ENSO teleconnections during the Late Pleistocene?

- What are optimal paleo-proxy locations to reconstruct ENSO variability?

- What is the degree of consistency between different paleo-ENSO reconstructions during the last millennium?

4. Asia-Pacific Data-Research Center (APDRC)

The amount of observational data and model-based products that are available to study Asia-Pacific climate has increased dramatically in the last decade, owing to the successful outcomes of recent international observational programs and to advances in satellite technology and modeling capability. Despite their availability, however, data and products are often underutilized by researchers and the broader user community, largely a consequence of the difficulty in finding data and their lack of easy accessibility. Thus, a primary motivation for the APDRC is to increase the ease and efficiency by which users can find and access data. Toward this end, the APDRC Mission is:

To increase understanding of climate variability in the Asia-Pacific region: by developing the computational, data management, and networking infrastructure necessary to make data resources readily accessible and usable by researchers and other users; and by undertaking data-intensive research activities that will both advance knowledge and lead to improvements in data preparation and data products.

The linkage of research activities with data management in one center is novel, and it has led to increased data usage, to improvements in data products, and hence to more rapid scientific progress. It is hoped and expected that the APDRC will develop into a powerful research resource, not just for IPRC scientists, but for the international climate community as well. In addition to the obvious scientific benefits of such an international resource, the collection and distribution of data between the IPRC and other countries in the Asia-Pacific region (and elsewhere) will provide a means for strengthening international collaboration.

Activities within the APDRC are divided into three thrusts. They are outlined in the following subsections.

<u>A. Operate and Continue Development of the Web-based, Integrated Data Server System</u>

The goals of this thrust are to provide: web-based browsing and viewing capabilities for both gridded and non-gridded (in situ) data sets and products; easy access for down-loading data in their original formats and in user-friendly and assimilation-friendly formats, including the handling of metadata and quality flags; and easy access to desktop tools for powerful display and analysis of data and products on the client's computer.

To implement these goals, the APDRC staff has closely coordinated its development activities with: the evolving plans of the National Virtual Ocean Data System (NVODS), which was considered a central element for the planning and implementation of the Global Ocean Observing System (GOOS) by its sponsor, the National Oceanographic Partnership Program (NOPP); and, currently, with the Data Management and Communication (DMAC) requirements of the Integrated Ocean Observing System (Hankin, et al., 2004). In addition, APDRC activities have taken place in collaboration with national (PMEL, GFDL, NODC, etc.) and international partners (Australia, Japan, India, etc.) on the implementation of a distributed and linked climate data server network. In particular, the project has collaborated (and will continue to collaborate) closely with PMEL scientists on technical aspects of server development, taking advantage of their substantial expertise. The project will also collaborate closely with Japan on server infrastructure development and on data and product management and distribution.

The server management team maintains all the APDRC server hardware and software. The group installs and makes upgrades to all the server software, and ensures that programs are up-to-date. The group also oversees the day-to-day operation of the server machines and provides upgrades to these machines. The server management group will be aware of new advances in technology, including both hardware and software, in order to provide future direction and recommendations for the APDRC computing infrastructure. The group also interacts with the IPRC computing facility to provide technical support to users.

Activities within this APDRC objective include:

- Operation and maintenance of multiple, integrated web-based servers;

- Ongoing server upgrade and development; and

- Partnership with other data sites on sister-server interoperability.

B. Provide a Global Data Base and Data Management for Climate Data and Products

The overarching goal of this objective is to provide the required data-management and metadata infrastructure for easy usability of data and products. The data management group within the APDRC identifies important datasets from each of three sub-disciplines: oceanographic data, atmospheric data and air-sea flux data. IPRC scientists identify data and products that may be useful for climate research efforts (but not necessarily maintained on local machines). This information is passed to the data management group who will acquire, or link to, the data. In addition, the group provides data updates when needed, documentation, and, where possible, quality control of the data sets. As part of their thematic research activities, members of the IPRC compile research results that utilize and evaluate data and products. As a result, they can recommend additional "value-added" products, to be undertaken by the APDRC product development efforts, which make the original data more useful to clients.

Activities within the second APDRC objective include:

- Acquisition and preparation of data and products for the local archive;

- Establishment of linkages to remote products and necessary metadata;

- Documentation and cataloguing of local and remote data and products; and

- Maintenance and enhancement of the web interface and multiple web pages for public outreach.

C. Develop and Serve New Climate Related Products for Research and Applications Users

The overarching goal of this thrust is to implement the second part of the APDRC Mission "by undertaking data-intensive research activities that will both advance knowledge and lead to improvements in data preparation and data products."

The intent is to link, whenever possible, IPRC research with the development of new climate-related products for research and applications users. Typically, researchers focus on the publication of new research results. In some cases, though, these new results can result in a useful climate product, such as an index or a regularly updated atmospheric or oceanographic analysis, and this APDRC thrust will encourage the development of such legacy products. A recent example is the new Argo float product entitled, "Velocity data assessed from trajectories of Argo floats at parking level and at the sea surface" released in 2006 as a Technical Report and Database (Yoshinari et al., 2006).

An important part of this thrust is to enhance national and international activities to meet critical regional needs for ocean, climate and ecosystem information for applications users, particularly those in the Asia-Pacific region. Specifically, activities support GEOSS through the Integrated Ocean Observing System (IOOS) and the regional Hawaii organization HiOOS, the Global Ocean Data Assimilation Experiment (GODAE), and the Pacific Climate Information Service (PaCIS). Regional modeling efforts within the APDRC will particularly contribute to these programs.

Activities within the third APDRC objective include:

- Development of integrated data products in support of NOAA activities including HiOOS;

- Encourage activities within the IPRC research areas that result in the development of climate products;

- Undertake value-added activities that produce enhanced data products;

- Carry out GODAE Product Server activities for a broad range of research and applications users, focusing on satellite and model-derived products;

- Implementation of high-resolution regional models, which allow the downscaling of operational models, for the Pacific Islands regions with initial focus on the Hawaii region;

- Data rescue and historic data quality control activities.

5. Connections with Broader Concerns

The division into subject categories adopted in Chapter 3 is based largely on the space and time scales of the phenomena under investigation. Of course, the climate-related issues facing society (and that ultimately drive IPRC research) do not necessarily fall conveniently into these categories. Sections 5.1 and 5.2 of this chapter will show briefly how the proposed research at IPRC will help address some important societal concerns by improving capability in projecting long term climate trends (5.1) and in making shorter-term climate predictions (5.2).

This Science Plan has been written to provide a fairly broad and unified overview of the IPRC science issues and activities. So detailed descriptions of time lines, personnel and other resources required have not been covered and are left for the detailed proposals and agreements with individual agencies. Sections 5.3-5.5 show how the present science plan connects with some of the imperatives of our principal supporting agencies. Section 5.3 discusses research related to Hawaii and Pacific islands that is a key focus for NOAA. Section 5.4 shows the connections between the Science Plan and the research proposed in the JAMSTEC-IPRC initiative (JII). Section 5.5 discusses the NASA focus for IPRC research plans.

5.1 Climate Change Focus

Public and governmental interest in climate science has increased enormously in recent years. There is a broad consensus now that the climate system is undergoing significant change, that even larger changes may be expected over the next century, and that such changes are largely driven by human activities. There is naturally a great demand for projections of how the climate system will evolve under various scenarios of future human activity. Decisions on mitigation and adaptation strategies require confident and reasonably detailed climate projections.

Nearly all our planned research activities at IPRC have some relevance to climate change issues and IPRC anticipates making a substantial contribution to the basic science underlying climate prediction for the next century. A key issue is understanding and modeling the feedbacks in the system that control the radiative response to global climate forcing and hence determine the global-mean climate sensitivity. IPRC scientists have conducted some of the most detailed analyses of cloud feedbacks as simulated in coupled global ocean-atmosphere models and this work will be extended to IPCC AR5 simulations when they become available (Section 3.3e). The IPRC regional atmospheric model with upgraded treatments of cloud microphysics will being applied to evaluate climate feedbacks in the tropics and subtropics (Section 3.3e).

While the feedbacks controlling the global radiative response will determine the overall temperature sensitivity of climate, there remain other uncertainties in the projected regional and local responses to large-scale climate forcing. IPRC research includes studies of the role of ocean circulation in the formation of geographical patterns of global warming (Sections 3.1a_2, 3.1d_1) and in the response of the main modes of interannual variability in response to global climate forcing (Section 3.1d_3). Section 3.3d discusses IPRC plans to investigate Asian summer monsoon response to climate forcing, including regional-scale forcings caused by air pollution. At a more local scale IPRC will conduct research aimed at producing reliable climate projections for specific areas including the islands that compose the Maritime Continent (Section 3.2a) and Hawaii (Section 3.2b). One of the most important aspects of climate change for many locations in the Asia-Pacific region is the expected effects on tropical cyclone climatology. IPRC has conducted modeling work on global warming effects on climate change and proposes to extend and improve this work (Section 3.2d).

The paleoclimate research plans described in Section 3.4 are designed to answer important questions about the history of the earth's climate during the Quaternary. Improved understanding of the mechanisms that produced variations in the past can provide important guidance for modeling future climate changes. More specifically the work proposed to investigate fluctuations in the Atlantic meridional overturning circulation (3.4a, 3.4c), and the low frequency modulation of the ENSO cycles in the tropical Pacific (3.4d), may have rather direct application to understanding and modeling climate evolution over the next century.

5.2 Subseasonal to Seasonal Forecast Focus

The term "extended range weather forecasting" has come to apply to forecasts with lead times beyond about 5-7 days. For the ~90 day lead-time seasonal forecasts it is likely that little predictability comes from the atmospheric initial conditions, and what skill there is must depend on properly representing the processes leading to slow variations in the boundary conditions provided by the ocean, sea ice and land surface (and possibly also the slowly varying aspects of the stratospheric circulation). On the subseasonal (say 10-30 day) time scale, the situation is less clear - almost certainly atmosphere-ocean-land interaction will have some effect, but there may also be some potential predictability from internal atmospheric dynamical processes.

The IPRC's interest in large-scale air-sea coupling, monsoon dynamics, tropical intraseasonal variations, and tropical convection have positioned it well to contribute to efforts improving extended range forecasting with lead times from of order a week to several seasons. The seasonal forecasting problem is addressed in this Science Plan through proposed work on the dynamics and predictability of large-scale coupled atmosphere-ocean modes (Section 3.1c), through studies of the role of land surface processes on Asian summer monsoon circulations (3.3c), and through studies designed to understand the low-frequency effects of intraseasonal atmospheric variations in the tropics (3.3e). In collaboration with its US and international partners, the IPRC will continue to participate in the Climate Prediction and its Application to Society (CliPAS) project, which aims directly to develop a well-validated multi-model ensemble prediction system (3.3c). for seasonal forecasts.

The field of subseasonal forecasting has recently experienced something of a renaissance over the possibility that large-scale organized tropical convection, such as that driving the familiar Madden-Julian Oscillation (MJO), may be somewhat predictable on extended lead times, even considering only purely atmospheric aspects of the phenomenon. The Year of Tropical Convection (YOTC) program was started in 2008 as an unprecedented joint effort of the World Climate Research Program (WCRP) and the World Weather Research Program (WWRP) to conduct coordinated observing, modeling and forecasting of organized tropical convection, and assess the prospects for improving subseasonal weather forecasts. IPRC's research plans fit in well with the WCRP/WWRP/YOTC aims. The work proposed in Section 3.3b focuses specifically on the predictability if tropical intraseasonal variations and the optimal construction of initial conditions for practical subseasonal forecasts. In addition the work on the basic dynamics of intraseasonal oscillations (Section 3.3a), Maritime Continent meteorology (3.2a), and tropical diurnal rainfall variability (3.2c) will all contribute useful background to understanding the subseasonal predictability of tropical convection. Finally, some preliminary IPRC-JAMSTEC work has suggested that the large-scale circulation associated with the MJO may be a strong determinant of when and where some tropical cyclones form. The implications for producing skillful extended range forecasts of tropical cyclones (at least in some regions of the tropics) will be investigated further (3.2d).

5.3 NOAA Focus - Hawaii and Pacific Island Issues

The islands in the Pacific Ocean encompassed by Polynesia, Micronesia and Melanesia are spread over an enormous region and represent a unique physical and human environment. The inhabited islands range from the large, heavily-populated and topographically prominent main Hawaiian Islands to small atolls such as those that make up the nation of Tuvalu. The IPRC is the premier climate modeling and diagnostics research institution located within this region and so has a natural focus on the issues relating to the Pacific island environment. This is a specific focus as well for IPRC's funding from NOAA, and connects IPRC to NOAA programs such as the Pacific Regional Integrated Science and Assessment (RISA), and the Pacific Climate Information Service (PaCIS). NOAA specifically supports the work of the Asia-Pacific Data-Research Center (APDRC) in both its service and research roles (described above in Chapter 4).

Interannual variability in the entire low-latitude Pacific region is dominated by the ENSO variations which greatly affect rainfall and sea-level for the Pacific islands. Much of IPRC work relates to understanding and predicting the ENSO variations, including work related directly to seasonal forecasting of rainfall for Pacific islands (Sections 3.1c_1, 3.1c_2). Tropical cyclones are extremely dangerous hazards for Pacific island communities. IPRC's research plans include application of high resolution global and regional atmospheric models to study of the dynamics and predictability of tropical cyclones (Section 3.2d). Long-term climate change issues relevant for the Pacific islands in IPRC's plans include proposed work on formation of large-scale patterns of SST and rainfall changes (Sections 3.1d_1, 3.1d_2), work on downscaling climate projections of rainfall for Hawaii (Section 3.2b), and work on global warming effects on tropical cyclone climatology (Section 3.2d).

5.4 JAMSTEC-IPRC Initiative

Since April 2007, IPRC-JAMSTEC collaborative research has been devoted to science issues and activities described in the "JAMSTEC-IPRC Initiative" (JII) document. The present Science Plan has been written to provide the reader with a fairly broad and unified overview of the IPRC science issues and activities. So detailed descriptions of time lines, personnel and other resources required have not been covered and are left for the detailed proposals and agreements with individual agencies. However, given the central role of the JAMSTEC partnership for IPRC, it is of interest to show how the more detailed JII activity descriptions are reflected in the present overall IPRC Science Plan.

The JII summarizes activities in seven specific "JII-Themes":

1) Model development, diagnosis, and applications
2) Atmospheric composition
3) Climate variability and predictability
4) Ecosystem dynamics
5) Hydrological cycle and monsoons
6) Paleoclimate dynamics

7) Data management, data serving, and product development

The JII-Theme 1 activities are reflected in various parts of Sections 3.2 and 3.3 of the Science Plan. JII-Theme 2 activities appear in Subsection 3.2e of the Science Plan. JII-Theme 3 activities are largely found in Sections 3.1 and 3.3. JII-Theme 4 activities are included in Subsection 3.2f of the Science Plan. JII-Theme 5 issues and activities map into Section 3.3. JII-Theme 6 activities are included in Section 3.4 of the Science Plan. The activities in JII-Theme 7 are conducted on the IPRC side within the APDRC and so are reflected in the description of APDRC plans in Chapter 4 of the present Science Plan. A diagram showing some of the connections between the present Science Plan sections and the JII Themes is shown in the Appendix.

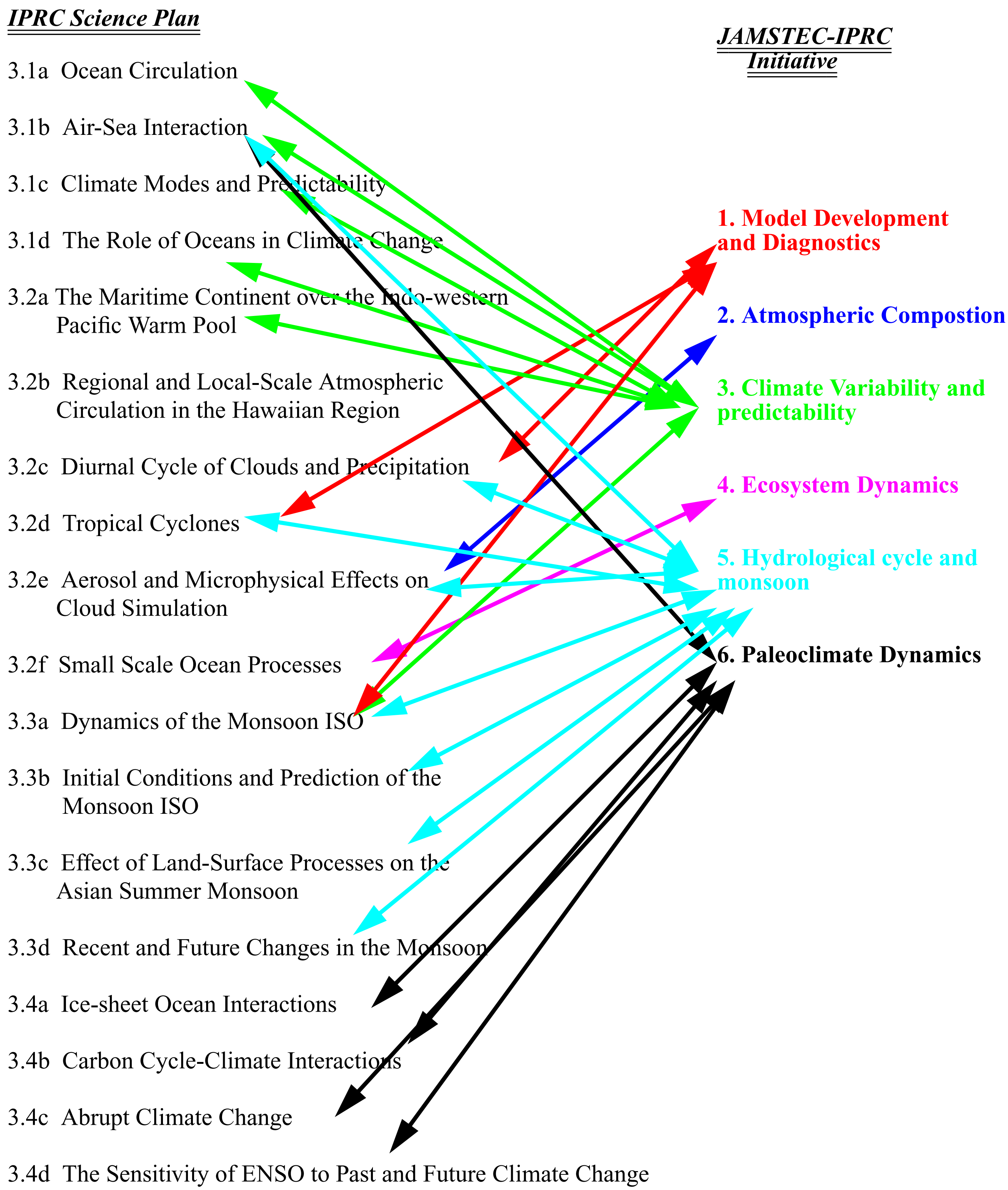
5.5 Relation to NASA Proposal and NASA Priorities

The NASA Earth Science Enterprise has as its science goals to "observe, understand and model the Earth system to learn how it is changing, and the consequences for life on Earth." These goals clearly fit with IPRC's interests and capabilities. NASA has funded IPRC for over a decade, most recently through a grant for 2007-2012 "Data Intensive Research and Modeling at the International Pacific Research Center". NASA's earth science mandate is broad, but the core is a focus on developing and applying space-borne, remote-sensing earth science observations. Over the last decade IPRC has had strong research programs involving application of satellite data to uncover new phenomena and to study the relevant physical mechanisms using complementary in situ measurements and modeling efforts. IPRC's interest and expertise in high resolution atmospheric and oceanic modeling has provided a particular IPRC has made particular strides in applying the measurements from NASA's Tropical Rain Measuring Mission (TRMM), Ocean Vector Wind, and Ocean Topography Programs, all of which have provided long continuous records of key climate observations. These extensive observations will be analyzed further, but IPRC scientist will also aggressively pursue application of the more recent generation of NASA satellite observations. Results from the A-Train satellites including CloudSat are providing unprecedented views of the cloud fields and this creates important opportunities for evaluating model performance. In the near future IPRC will be among the first to analyze Aquarius ocean surface salinity, and results from the Global Precipitation Mission. Almost every project described in Sections 3.1-3.3 in this plan involve application of satellite data for diagnosis of phenomena and mechanisms, for model evaluation, and/or for providing realistic forcing fields for numerical simulation models.

The 2007-2012 NASA proposal grouped the proposed research tasks under 4 main (but overlapping) Themes: Multiscale Interaction (Theme 1), Climate Processes and Variability (Theme 2), Numerical Modeling (Theme 3), and Data Assimilation (Theme 4). The connections between the IPRC NASA Themes and the present Science Plan sections are shown in a diagram in the Appendix.

Appendix Connections With Research in the JII and IPRC's 2007-2012 NASA Proposal

The following pages show a graphical representation of the connections between the research outlined in Chapter 3 of this Science Plan and the main science areas in the IPRC proposals to JAMSTEC (the JII Themes) and NASA (the Themes used to organize the research in the 2007-2012 proposal).


IPRC Science Plan
3.1a Ocean Circulation
3.1b Air-Sea Interaction
3.1c Climate Modes and Predictability
3.1d The Role of Oceans in Climate Change
3.2a The Maritime Continent over the Indo-western Pacific Warm Pool
3.2b Regional and Local-Scale Atmospheric Circulation in the Hawaiian Region
3.2c Diurnal Cycle of Clouds and Precipitation
3.2d Tropical Cyclones
3.2e Aerosol and Microphysical Effects on Cloud Simulation
3.2f Small Scale Ocean Processes
3.3a Dynamics of the Monsoon ISO
3.3b Initial Conditions and Prediction of the Monsoon ISO
3.3c Effect of Land-Surface Processes on the Asian Summer Monsoon
3.3d Recent and Future Changes in the Monsoon
3.4a Ice-sheet Ocean Interactions
3.4b Carbon Cycle-Climate Interactions
3.4c Abrupt Climate Change
3.4d The Sensitivity of ENSO to Past and Future Climate Change
JAMSTEC-IPRC Initiative
1. Model Development and Diagnostics
2. Atmospheric Compostion
3. Climate Variability and predictability
4. Ecosystem Dynamics
5. Hydrological cycle and monsoon
6. Paleoclimate Dynamics


IPRC Science Plan
NASA Proposal
3.1a Ocean Circulation
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3.4b Carbon Cycle-Climate Interactions
3.4c Abrupt Climate Change
3.4d The Sensitivity of ENSO to Past and Future Climate Change
Theme 1: Multiscale Interactions
Theme 2: Climate Processes and Variability
Theme 3: Modeling
Theme 4: Data Assimilation

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