US CLIVAR Pan American Research:

A Science Prospectus and Implementation Plan

Executive summary

The Tropical Ocean-Global Atmosphere (TOGA) program (1985-1995) demonstrated the feasibility of operational seasonal-to-interannual climate prediction of equatorial Pacific sea surface temperature anomalies based on numerical models of the physics of the tropical ocean-atmosphere system, and it clarified the planetary-scale atmospheric response associated with the sea surface temperature anomalies. The Pan American component of the U.S. CLIVAR program has evolved from the Pan American Climate Studies (PACS) Program and both are built on the heritage of the TOGA program.

U.S. CLIVAR seeks to extend the scope and improve the skill of operational climate prediction over the Americas on seasonal and longer time scales. The three specific objectives of US CLIVAR Pan American research are:

1. Promote a better understanding of and more realistic simulation of
   - the response of planetary-scale atmospheric circulation and precipitation patterns to potentially predictable surface boundary conditions such as sea surface temperature, soil moisture, and vegetation.
   - the coupling between ocean and land processes.
   - the seasonally varying climatological mean state of the ocean, atmosphere, and land surface.
   - the effects of land surface processes and orography on the variability of seasonal rainfall patterns.

2. Determine the predictability of warm season precipitation anomalies over the Americas on seasonal and longer time scales.

3. Advance the development of the climate observing and prediction system for seasonal and longer time scales.

The atmospheric circulation, in isolation, is not predictable beyond a week or two. Hence, prospects for improved climate prediction on seasonal and longer time scales depend on the ability to exploit the relationships between the planetary-scale atmospheric circulation and the slowly evolving and potentially predictable boundary forcing, i.e., the fields of sea surface temperature, vegetation, and soil moisture, in which the season-to-season “memory” of the ocean-atmosphere-land system resides. For this reason, the evolution of the boundary forcing of the atmosphere is important. Regional rainfall anomalies over the Americas are largely a reflection of the intensification or weakening, or translations of
the climatological-mean rainfall features, i.e., the monsoons, the oceanic ITCZs, and the
tropical and extratropical cyclone tracks. An understanding of these climatological-mean
features and their seasonal evolution is a prerequisite for the interpretation and prediction
of the anomalies. As part of this task, new observations are needed of the ocean mixed
layer and the overlying atmosphere in eastern tropical Pacific and Atlantic Oceans to
improve our understanding of the cold-tongue/ITCZ complexes, the subtropical
stratocumulus decks and the Pan American warm pool region and the role that these
phenomena play in coupling the ocean, atmosphere and land in the Pan American region.
The distribution of rainfall over the Americas is shaped not only by sea surface
temperature patterns but also by land surface processes, particularly during the warm
season, when vegetation and soil moisture are highly influential. Orography and coastal
geometry mediate these effects and leave a distinctive mesoscale imprint on the rainfall
patterns. These issues will be addressed in collaboration with the Global Energy and
Water Experiment (GEWEX) and its regional programs. CLIVAR will supply the
coupled climate modeling expertise, with emphasis on the processes that couple climate
variability over the oceans to that over the land. GEWEX will supply the hydrological
expertise and emphasize the processes that couple the land surface to the overlying
atmosphere.

The climate processes addressed by US CLIVAR Pan American research are the same as
those involved in assessing the effects of anthropogenic climate change. Anthropogenic
changes in atmospheric gases and particulate composition modify the global energy
balance. The practical consequences for humans depend on how the climate system
responds on regional scales to such global energy balance changes. Any regional
response is likely to be tied to natural regional climate variations and its modeling cannot
be credible unless the significant natural climate variations are understood and included
in the models addressing anthropogenic changes. Hence, US CLIVAR research will
increase the accuracy and credibility of regional projections of future anthropogenic
climate change over the American continents.

U.S. CLIVAR Pan American research encompasses a broad range of activities, including
empirical studies, dataset development, modeling, climate monitoring, and more
intensive, limited-term field experiments. In order to make the best use of resources,
major field studies that require extensive national planning will focus on different regions
of the Pan-American climate system in sequence.

This scientific prospectus and implementation plan provides the motivation and scientific
basis for U.S. CLIVAR Pan American research and describes how that research that will
be carried out in pursuit of its specific objectives. Section 1 gives a scientific description
of phenomena in the ocean-atmosphere-land system that are likely to be of importance
for understanding and predicting climate variations over the Americas on time scales of a
season and longer. The climate and weather variations over the Americas that provide the
practical and scientific motivation for PACS are discussed in Section 2, while Sections 3-5
describe the empirical studies, dataset development, and modeling that will be
conducted under its auspices, respectively. Section 6 describes the strategy for field
studies envisioned as part of U.S. CLIVAR, including pilot projects and activities already
underway and those likely to be proposed for the 2000-2010 time frame. Section 8
discusses linkages with GEWEX and its regional programs and NASA’s earth observing
missions. Section 8 also describes the anticipated linkages with emerging national and
international programs. Program management is described in Section 9.

1. SCIENTIFIC BACKGROUND FOR PAN AMERICAN REGIONAL
CLIMATE

1.1 What determines the annual mean climate?

The rainfall climatology of the Pan American region is dominated by ITCZs and the
continental monsoons. The tropical Atlantic and eastern Pacific tradewind regions are
noted for fair weather and a large excess of evaporation over precipitation, while narrow
ITCZs which separate the regions are marked by heavy and persistent rainfall. The
positions and intensities of the ITCZs are sensitive to the underlying land surface and the
sea-surface temperature distribution. Rainfall over the tropical and subtropical Americas
and the adjacent oceans is dominated by seasonally dependent monsoonal circulations,
which produce widespread rain and upper-level anticyclones in the summer hemisphere.
The northeasterly and southeasterly tradewind belts, that occupy most of the tropics and
subtropics, border the major monsoonal rain areas. However, seasonal reversals of
surface winds are less pronounced within the Pan American domain than they are in the
Australasian sector of the tropics. The prevalent upper-tropospheric westerlies over the
equatorial eastern Pacific allows for a higher degree of interaction between the Northern
and Southern Hemisphere circulations than occurs elsewhere in the tropics. Figure 1
shows the distribution of annual mean rainfall over the tropics based on two different sets
of measurements. The continental monsoons and the oceanic ITCZs are clearly evident in
both, but the oceanic ITCZs are more prominent in the microwave imagery (top panel),
which is more sensitive to low-level rain systems. Both plots show the contrasting
structure of the ITCZ-dominated Pan American domain and the monsoon-dominated
Australasian region. The annual mean climate over the Pan American domain is marked
by strong equatorial asymmetries which cannot be explained on the basis of simple
considerations of sun-earth geometry. The heavy and persistent rainfall associated with
the ITCZ is centered, not on the equator, but at 5-10°N, as indicated in Fig. 2. Stratiform
cloud decks, indicated by the gray-blue shading, are of greater extent in the Southern
Hemisphere, and act to cool the underlying ocean by shielding it from incoming solar
radiation.

The highest sea surface temperatures are observed, not along the equator, but to the north,
where a broad latitudinal belt of high sea surface temperature extends from the Pacific
coast of southern Mexico, eastward across the Caribbean Sea, into the Atlantic. The
highest temperatures off southern Mexico (Figs. 3 and 4) occur with relatively light
surface currents and mean wind speeds. In contrast to the western Pacific, however, both
the surface currents and winds are strong over the warm ocean areas in the Caribbean and
Atlantic. The narrower latitudinal bands of high sea surface temperatures close to the
equator in the eastern Pacific and Atlantic oceans, between 5-10°N, are more or less
coincident with the annual mean position of the ITCZ, as shown in Fig. 3. They coincide
with the eastward-flowing North Equatorial Countercurrent (Fig. 4), which is linked to
the strong meridional gradient of wind stress across the ITCZ. The easterly surface winds
along the equator drive the westward-flowing South Equatorial Current, which is
deflected toward the right in the Northern Hemisphere and toward the left in the Southern
Hemisphere by the Coriolis force. The induced equatorial upwelling of large volumes of
cold, nutrient-rich water is responsible for the pronounced “equatorial cold tongues”;
indicated by the bluish shading in Figs. 3 and 4, and for the equatorial maximum in
chlorophyll concentrations revealed by the Coastal Zone Color Scanner imagery in Fig. 5.

The size, shape, and location of the North and South American land masses contribute to
the asymmetry of the Pan American climate. Figure 6 shows the North and South
American typography. The major western continental mountain ranges over the Americas
extend from northwest to southeast for the entire length of both continents. As can be
seen in Figs. 2 and 3, the winds along the Pacific coast are largely parallel to shore of
South America and are very weak along the North American shore. The southeasterly
tradewinds approximately parallel the South American coastline, while the northeasterly
tradewinds in the tropical Pacific are roughly perpendicular to the west coasts of Mexico
and Central America. The tradewinds in the Gulf of Mexico and the Caribbean Sea are
considerably weakened by the Mexican and Central American Sierra Madre mountain
ranges as boundary layer air crosses over the land to the Pacific. On the eastern slopes of
the Rocky Mountains and the Andes, the annual mean near-surface flow is poleward and
tends to either parallel the mountain range or move down the slope. The location of most
of South America to the east of North America and at low latitudes extending into the
Northern Hemisphere contributes to the north-south asymmetry. The character of the
South American continent, with the Andes cordillera to the west and a land mass that
extends from the Northern Hemisphere equatorial region to the high latitudes of the
Southern Hemisphere, creates distinctive climate patterns in the overlying atmosphere.
Unlike North America, which lies mostly in midlatitudes, South America is a tropical
continent that ends to the south in a narrow conical shape. The lowlands of the continent
assume an approximate "T" shape with the west-to-east Amazon basin in the tropics and
the north-to-south La Plata basin perpendicular to it and extending poleward to about
40°S. This is different from North America, where the main river basins extend
equatorward from middle latitudes. The central Andes are closed to tropical moisture and
dry conditions prevail there. This situation is similar to conditions over North America
and an analogy can be drawn between the North American Great Plains and the
subtropical plains of South America.

The land surface also influences the climatic mean state and variability by interacting not
only with winds through terrain but also with the atmospheric boundary layer and hence
moist convection through its controls of sensible and latent heat flux. Figure 7 shows the
annual mean distribution of soil moisture, snow cover, and vegetation. Large values of
soil moisture and the vegetation index are found over tropical South and Central
America, and over the subtropical regions of the southeastern United States and South
America. These features of the land surface that alter the surface and water balances are
slowly varying and potentially predictable. Although the sea surface temperature is warm
and moisture readily available in the Pan American warm pool region, the precipitation appears to be greater over tropical South America than over the warm water.

The strong equatorial asymmetry in the mean climate evidently is a manifestation of coupled ocean-atmosphere-land interactions, perhaps even more intricate than those involved in ENSO. Many questions remain. Does the ITCZ in the Atlantic and Pacific oceans result from the underlying belt of warm sea surface temperature or is warm water a response to the ITCZ? Neither view is adequate as the ITCZ and the underlying warm water along with the surface winds, ocean currents, oceanic upwelling, stratus cloud decks, and deep atmospheric convection are all elements of a response to the land-sea geometry. Both circulations in the meridional and the zonal plane are important. To what extent does the large equatorial asymmetry in the annual mean climate derive from oceanic processes related to the northwest-southeast orientation of the west coasts of South America and Africa or from atmospheric planetary waves induced by the differences in orography and the land-sea distribution in the Northern and Southern hemispheres or from the superimposed seasonal march? And to what extent do land surface processes contribute to the annual mean patterns?

1.2 What determines the seasonal march?

The march of the seasons over the Americas contains some of the classical textbook elements that are easily quantified in global atmospheric models. Warm season maxima in rainfall occur in both hemispheres, over Columbia/Central America, and over Southern Brazil/Paraguay, with accompanying surface lows and upper-level anticyclones over the elevated terrain of northwestern Mexico and the central Andes (Fig. 8). During the Northern Hemisphere warm season, the ITCZ bands in the Pacific and the Atlantic merge with the continental monsoons of Central America and northern South America. During the Southern Hemisphere warm season, the ITCZ bands weaken to the north of the equator and the monsoon over Amazonia dominates and merges with the South Atlantic Convergence Zone (SACZ). Rainfall in the upper reaches of the Amazon is year-round. Also relatively well understood and simulated are the rainy winters of US Pacific Northwest and southern Chile.

The North American monsoon system develops in May-June as synoptic-scale transient activity decreases over northern Mexico and the US, and midlatitude storms weaken and their tracks migrate poleward. Heavy rainfall starts over southern Mexico and quickly spreads northward along the western slopes of the Sierra Madre Occidental into Arizona and New Mexico by early July. In July-August, a “monsoon high” becomes established in the upper troposphere near the US-Mexican border (see Fig. 8). This feature is analogous to the Tibetan anticyclone over Asia. The region of enhanced upper-tropospheric divergence in the vicinity and to the south of the upper-tropospheric high coincides with enhanced upper-tropospheric easterlies or weaker westerlies and enhanced Mexican monsoon rainfall. In contrast, the flow is more convergent and rainfall diminishes in the increasingly anticyclonic westerly flow to the north and east of the
monsoon high. Upper-level divergence and precipitation apparently increase in the vicinity of the “induced” trough over the eastern US. The system decays in September-October, but generally at a slower pace than during development. The ridge over the western US weakens, as the monsoon high and Mexican monsoon precipitation retreat southward into the deep tropics.

The monsoon system develops in the Southern Hemisphere during the austral spring with a rapid southward shift of the region of intense convection from northwestern South America to the highland region of the central Andes (Altiplano) and to the southern Amazon basin. Transient synoptic systems at higher latitudes, in contrast to the Northern Hemisphere monsoon, modulate the southward shift in convection. In particular, cold fronts enter northern Argentina and southern Brazil, frequently accompanied by enhanced deep convection over the western and southern Amazonia and by increased southward moisture flux from lower latitudes. A strong low-level jet that occurs to the east of the Andes, which is not as well documented as its counterpart over the Great Plains of North America, can enhance this moisture flux. As the austral spring progresses, and the SACZ develops, precipitation increases over the Brazilian altiplano and southeast Brazil, and the anticyclone over the central Andes becomes established. The monsoon decays in late summer as convection shifts gradually northward toward the equator. By April and May, the low-level southward flow of moisture from the western Amazonia weakens, as more frequent incursions of drier and cooler air from the midlatitudes begin to occur over the interior of subtropical South America. The narrow midlatitude section of the continent is exposed to strong westerly flow and seasonal variations that are not as pronounced as those over North America at the same latitudes.

The temperature and humidity patterns of the lower troposphere are closely related to the climatological precipitation patterns. These patterns are determined over land by both the advection of air from the ocean, depending on near surface winds and sea surface temperature, and on the seasonally and diurnally varying fluxes of water vapor and energy between the land and atmosphere. The water vapor and energy fluxes over the Andes have an observable effect on midtropospheric temperature during the pre-monsoon period and may affect subsequent evolution of the monsoon. Surface sensible heating warms the midtroposphere over the central Andes during the pre-monsoon period and after the monsoon onset. Strong latent heat release accompanies the deep convection over the subtropical highlands and the southern portion of the Amazon basin, changing the thermal structure of the troposphere, with this warm air eventually covering a large area, from the eastern south Pacific to the western south Atlantic.

The seasonal march also contains some surprises such as the large differences between the March-April versus the September-October climates over the tropical oceans adjacent to the Americas (Fig. 9), a single March-May rainy season in Northeast Brazil and coastal Ecuador, and, in general, the much less pronounced rainy season during the March-May period in the eastern Amazon than in the western Amazon. A double peak structure (wet-dry-wet) in the seasonal march of precipitation is found over the west coasts of Mexico and Central America (Fig. 10). This dry period along the west coast of Mexico and Central America is called the midsummer drought. The variation in climatological
precipitation is accompanied by a double peak structure in the diurnal temperature range (i.e., small-large-small) equatorward of the Tropic of Cancer. The physical and dynamical mechanisms responsible for the climatological midsummer drought are not well understood.

At the time of heaviest rainfall in the equatorial belt, March-April, a double ITCZ, symmetric about the equator, is often observed in the eastern Pacific, and the Atlantic ITCZ is on the equator. In contrast, September-October is the time of strongest equatorial asymmetry, the strongest northward cross equatorial flow, the northernmost position of the ITCZ, and the maximum extent of the Southern Hemisphere stratus cloud decks. Related to this annual march in the atmosphere is a strong modulation in the intensity of the equatorial cold tongues (Fig. 11). For example, the water temperatures near the Galapagos Islands range from 22°C in September to near 27°C in March. These sea-surface temperature changes are remarkably regular from year to year in both the eastern Pacific and the Atlantic, even in the presence of El Niño, as demonstrated in Fig. 12.

Why should such an oscillation exist at all? Why is the annual cycle be so much stronger than the semiannual cycle in the equatorial belt? How is the seasonal march of rainfall, temperature, wind, and ocean currents in the ITCZ/cold tongue complex linked to the American and west African monsoons? The oceanic seasonal march near the equator does not follow any simple model for the oceanic response to atmospheric forcing: cold sea surface temperatures are present typically nine months of the year, with the warming confined to a period of less than three months ending in March; the usual westward surface current reverses from April through June even though the wind continues to blow from the east; and the eastward flow in the subsurface equatorial undercurrent is a maximum in May-June, following the period of weakest surface easterly wind stress. It is notable that the maximum sea surface temperature in March precedes the onset of the period of eastward flow, which advects warm water eastward. The notion that a reduction in easterly wind stress leads to reduced upwelling and so to a deeper thermocline and warmer sea surface temperature does not appear to be applicable to the seasonal march: the seasonal variations in thermocline depth and sea surface temperature (Fig. 13) do not exhibit the well-defined inverse relation characteristic of the ENSO cycle. The processes responsible for the sea-surface temperature variations in the seasonal march and the ENSO cycle may be quite different.

Over the tropical eastern Pacific and Atlantic the seasonal march is more pronounced and more regular from year to year in the meridional wind stress than in the zonal wind stress because the former is more directly tied to the seasonal march of the monsoon convection over Central America and West Africa. Seasonal variations in the meridional wind stress influence the seasonal march in surface temperatures on or near the equator in several ways: wind speed affects the net sensible and latent heat flux at the air-sea interface and the amount of wind-induced mixing and entrainment in the mixed layer; wind stress curl can induce upwelling or downwelling; meridional stress can force meridional flow and change the rate of upwelling and the meridional temperature advection, etc. What is the relative importance of these processes in the seasonal march of sea surface temperature? How does the modulation of the strength of the cold tongues contribute to the absence of a rainy season at the time of the September equinox over much of equatorial South
America? Does the seasonal march in the latitude of the ITCZs contribute to the greater
southward displacement of the jet stream over the United States in springtime than in
autumn, and to the consequent heavier rainfall and a higher frequency of occurrence of
severe thunderstorms to the east of the Rockies in springtime? North-south thermal
contrasts and the related circulation cells in the atmosphere and ocean may be
instrumental in producing the distinctive features of the seasonal march in the Pan
American region and they may account for some of the interannual variability as well.

Another intriguing feature of the seasonal march over the Americas is the abrupt onset of
the summer monsoon over much of northwestern Mexico and the southwestern United
States in early July, as reflected in the frequency of occurrence of deep convective
clouds (Fig. 14). Rainfall simultaneously decreases over the northern Rockies, the US
Great Plains, and parts of the Caribbean and Central America, and sea level pressure over
Mexico abruptly rises (Fig. 15). The increased pressure gradient across Central America
is accompanied by a freshening of the northeast trades at some locations. The reversal of
the surface winds over the Gulf of California from northwesterly to southeasterly is
accompanied by an abrupt increase in low-level moisture. The magnitude, abruptness,
and year-to-year regularity of this shift in rainfall and associated circulation patterns are
quite remarkable, considering the small changes in solar heating from June to July.

How do land surface processes contribute to the seasonal march of Pan American
climate? Soil moisture, snow cover, and vegetation control the exchange of energy
between land and atmosphere and the partitioning between latent and sensible heat.
Figure 16 shows the soil moisture and vegetation at the equinoxes. At lower elevations,
soil moisture is typically larger in spring than in fall, and decreases as the summer
progresses. On the other hand, biological activity associated with vegetation typically
peaks in summer and then declines in most regions as winter approaches. Snow cover
advances and retreats rapidly from polar regions to middle latitudes over Canada and
most of the United States during Northern Hemisphere fall and spring (Fig. 17).
Representing the effects of these land “memory” processes in coupled ocean-atmosphere-
land climate models is a major challenge.

1.3 What determines anomalies over North America?

Wintertime climate anomalies over North America are better understood than summer.
The North American climate is affected on seasonal and longer time scales by complex
interactions between the Pacific and Atlantic oceans, the North American landmass, and
the atmosphere. The El Niño/Southern Oscillation phenomenon (Section 1.6) exerts a
strong influence on US precipitation and surface temperature. The record El Niño event
of 1997/98 brought extreme rainfall and flooding to California in February 1998, features
that were successfully predicted by atmospheric general circulation models with
prescribed sea surface temperature taken from the coupled ocean-atmosphere model
output one to two seasons in advance.

The linkages between tropical sea surface temperature anomalies and extratropical
climate anomalies are not as pronounced during summer as during winter. The
extraordinarily wet and humid 1983 summer in southern California and Arizona may have been an aftermath of the 1982-1983 ENSO warm episode. During this summer, an unusual number of Pacific hurricanes tracked northward into the Gulf of California. The abrupt resurgence of the eastern equatorial Pacific cold tongue in early 1988, while sea surface temperatures to the north of the ITCZ remained above normal, might have served to draw the ITCZ northward, inducing an extratropical response and possibly contributing to the drought over the central United States during April and May of that year. The latter event is one of several episodes in which patterns of precipitation anomalies have been simulated, with some degree of success, in forecast integrations out to a season in advance with prescribed tropical sea surface temperature anomalies.

The North American monsoon system, which affects much of the Mexico and southwestern United States, draws moisture from both the Pacific and the Gulf of Mexico. The time of onset and strength of the upper-level monsoon ridge over the southwestern US during summer may influence major drought and flood episodes in the midwestern US. The climatological onset of summer rains over northern Mexico and Arizona around July 1 coincides with a decrease of rainfall over the Great Plains and an increase on the east coast (Fig. 18). The midwestern floods in July 1993 coincided with a delayed onset of the monsoon rains in Arizona. Interannual fluctuations in the onset date of the monsoon in the southwestern United States appear to be correlated with fluctuations in the intensity of summer rainfall in this region such that early monsoons tend to be very wet and late monsoons tend to be somewhat dry. Wet (dry) monsoons in the Southwest often follow winters characterized by dry (wet) conditions in the Southwest and wet (dry) conditions in the Pacific Northwest. Interannual variability of the summer monsoon in the American Southwest also appears to be modulated by decadal climate fluctuations in the North Pacific.

The low-level jet over the Great Plains, which transports moisture from the Gulf of Mexico, is linked to the strength of the “Bermuda High”, which is possibly influenced by the Atlantic sea surface temperature. Little has been established empirically regarding associations between Atlantic sea surface temperature and North American climate. Anomalous soil moisture or snow cover early in the warm season, related to conditions during the previous winter, may influence subsequent hydrological and biological conditions through much of the growing season.

1.4 What determines anomalies over South America?

Climate anomalies over South America are regional manifestations of hemispheric scale climate variations. Summer rains are largest over the tropical continent and extend into the Atlantic Ocean in a northwest to southeast band (SACZ). Climate anomalies often appear as modulations of this convection band over tropical and subtropical latitudes. Persistent wet and dry conditions over tropical and subtropical eastern South America during summer appear as a dipole pattern of rainfall anomalies, with one center over southeastern Brazil in the vicinity of the SACZ and another center over southern Brazil, Uruguay, and northeastern Argentina. This seesaw pattern reflects changes in the position and intensity of the SACZ on intraseasonal and interannual time scales. Enhancement of
the SACZ coincides with suppression of convection over the Inter-American Seas (Gulf of Mexico and the Caribbean Sea) and the ITCZ over the north Atlantic.

An example of how hemispheric scale climate anomalies influence the South American continent may be seen in the long-term trends over the mid and high latitudes of the Southern Hemisphere. A reduction of sea-level pressure over Antarctica and increased pressure over the three midlatitude ocean basins has been documented in decadal time scales. This trend influences the Atlantic moisture flux into South America, consistent with precipitation increases observed over southern South America during the last three decades. There is also evidence of inter-hemispheric teleconnections between the North Atlantic and South America. For example, the positive phase of the North Atlantic Oscillation (NAO), which is associated with warm surface temperature over North America, is correlated with increased precipitation over northern and central South America in summer.

The distinctive shape of the South American land mass may determine some aspects of the climate anomalies. Unlike North America, which lies mostly in midlatitudes, South America is a tropical continent with a narrow conical extension to the south and the steep Andes cordillera to the west. Linkages have been established between rainy afternoon episodes in the central Andes with a weakened low-level jet on the eastern slopes resulting in tropical moisture flux reaching the central Andes highlands. There is also evidence from modeling and data assimilation studies that the enhancement of South American tropical convection may be coupled to descending motion over the stratus deck off the west coast of South America. Low-level flow east of the Andes is weakened with enhanced tropical convection as a geostrophic response to the low-level low pressure center that develops under the SACZ. The opposite phase of this seesaw pattern exhibits a weakened SACZ, strong low-level northerly flow east of the Andes, and a resulting influx of moisture from the tropics into the subtropical plains of southern Brazil and central Argentina. The central Andes are then closed to tropical moisture and dry conditions prevail. This situation is similar to conditions over North America and an analogy can be drawn between the North-American Great Plains and the subtropical plains of South America. Both regions have mountains to the west that are dry when the plains are wet and vice-versa.

1.5 Role of the land surface

The land surface consists of the soil, vegetation and surface water and ice in many forms. Soil and vegetation are altered by their interactions with the atmosphere and by the activity of humans and other organisms. Vegetation regulates fluxes of water from the soil and the distribution and application of solar radiation, thus altering surface temperature. It responds not only to moisture availability, but to the availability of light, nutrients, and atmospheric stresses (heat, cold, aridity). Humans alter the landscape through agriculture and land-use practices. Hence, the land component of the climate system involves not only geophysics but biology, chemistry, and sociology, with these latter factors increasing in importance on longer time scales.
Because of the rapid exchange of water between the soil and the atmosphere, the sum of the water in soil and in the atmosphere changes more slowly than either of these water reservoirs individually, hence imposing a long-term memory on the coupled land-atmosphere system. Land surface memory depends on how soil stores water, and how vegetation moves it into the atmosphere, and how precipitation transports it back to the land surface. Increased evapotranspiration from wetter soil moistens the lower atmosphere and increases latent heat content and moist static energy, all of which can contribute to increased rainfall locally and downwind. Dry soil conditions have the opposite effect. The US drought of 1988 provides an example of remotely forced circulation anomalies amplified by local land-atmosphere feedbacks. The extent and severity of the drought depended on both ocean temperature anomalies and soil moisture anomalies. Soil moisture conditions that were upstream of the 1993 floods over the central US similarly influenced the outcome.

Water losses to the ocean and overlying atmosphere weaken land-atmosphere feedbacks most during the cold season. However, winter snowpack stores surface water seasonally and may modify North American summer precipitation and the response of the monsoon system to ENSO, resulting in a seasonal variation in the association between El Niño fluctuations and precipitation over the southwestern US. Abundant spring snow may lead to deficient summer rain, and sparse snow to heavier rain.

Seasonal green-up or leaf-out, with increases in leaf and vegetation cover and decreases in albedo, is rapidly initiated by the onset of the warm season (at higher latitudes) or the wet season (at lower latitudes). It can have noticeable impact on observable quantities such as near surface air temperature. The magnitude of the changes in land surface parameters during the seasonal green-up is generally much larger and more rapid than those associated with land use or land cover change. Proper observational or dynamic representation could help improve predictability during transitional seasons.

Vegetation responds to interannual variations in climate, and becomes a source of further climate variations through land-atmosphere feedbacks. Figure 19 shows that monthly anomalies of leaf area index (LAI) are most significant over the Great Plains (particularly toward the south), over the region of the North American monsoon, the Caribbean coast of South America, the Nordeste, from the Pampas to Patagonia, and along the western slopes of the Andes. Tropical forests change little except for trends associated with deforestation. Large swings in land surface characteristics can occur in regions of sparse vegetation and correspondingly impact evapotranspiration, providing long-term system memory. An example of this is when one or more significant wet seasons in a semi-arid region increases biomass productivity, and the added biomass provides fuel for fires (and a strong source of aerosols) in a subsequent dry year.

Land use and land cover change accrue over decades to centuries. Anthropogenic land use changes during the last century have been so widespread over North America that there is little land outside high latitudes that retains its natural vegetation cover. The rate of land use change in Central and South America is accelerating, especially in tropical forests and savannas where logging, ranching, and farming are altering the landscape.
These changes are likely supplemented by land cover changes occurring in response to anthropogenic climate change. Recent assessments by the USGCRP suggest a mixed but wide-ranging set of climate changes that will invoke responses in both the natural distribution of biota and human land use practices.

Linkage of the land surface to the atmospheric hydrological cycle promotes feedbacks involving radiation that may exacerbate anomalies, e.g., positive anomaly in shortwave radiation (perhaps due to reduced cloud cover) may increase surface temperatures and the Bowen ratio, hence decreasing humidity in the boundary layer and further suppressing cloudiness. Aerosols from dust, the smoke of natural and manmade fires, urban pollution, and natural forest emitters can alter the local and regional radiation balance and atmospheric chemistry in ways that are only beginning to be understood. Such effects may either enhance or diminish climate perturbations.

1.6 El Nino/Southern Oscillation

The aspects of the ENSO phenomenon relevant to the Pan American region are the processes that control the sea surface temperature and rainfall in the equatorial cold tongue/ITCZ region, the influence of ENSO upon precipitation over the Americas, interactions between the seasonal march and the ENSO cycle, the effect of mean equatorial asymmetries on ENSO, the relation between warm episodes in the equatorial waveguide and El Niño events along the Ecuador and Peru coasts, teleconnections between ENSO and the Atlantic sector, and ENSO-like behavior in the Atlantic. Many of the more predictable regional climate anomalies associated with ENSO occur over the Americas, as summarized in Fig. 20. Most of these features can be explained on the basis of teleconnection patterns in the geopotential height and wind fields induced by differences in the distribution of deep convection over the Pacific sector during the warm and cold phases of the ENSO cycle.

The typical pattern of sea-surface temperature anomalies associated with the ENSO cycle is shown in Fig. 21, together with the corresponding pattern of rainfall anomalies over the tropical Atlantic and Pacific. During warm episodes rainfall tends to be enhanced within the region of positive sea-surface temperature anomalies, particularly along the outer margins of the equatorial dry zone (Figs. 1 and 2), and suppressed over much of the surrounding region. The enhancement or suppression of rainfall tends to be most pronounced during the rainy season, as illustrated in Fig. 22. The ITCZ migrates southward toward the equator every year during the warm season (February-April), but penetrates deep into the equatorial zone only during warm episodes of the ENSO cycle.

The distribution of anomalous rainfall during a typical warm episode of the ENSO cycle is repeated in Fig. 23, this time superimposed upon the corresponding anomalies in mean tropospheric temperature (a surrogate for the upper-tropospheric geopotential height field). The temperature pattern, which can be viewed as the planetary-scale response to the anomalies in the rainfall distribution, is characterized by a remarkable degree of equatorial symmetry. The pair of strong positive centers near 15° latitude, just east of the dateline, corresponds to the anticyclonic gyres in published studies based on the 200-mb wind field. The tight ‘packing’ of the contours on the poleward flanks of these gyres is
indicative of an enhanced meridional temperature gradient and a strengthening of the
westerlies at the jet stream level, which favors an increased incidence of winter storms
downstream over the southeastern United States (the green patch in Fig. 20). These and
other extratropical features such as the positive temperature anomalies over Canada (Figs.
20 and 23) were first noted by Sir Gilbert Walker over 60 years ago and they have been
observed to recur during most of the warm episodes that have been recorded since that
time.

The present generation of coupled models of the ENSO cycle has had success in
predicting, out to several seasons in advance, the changes in amplitude and polarity of the
typical (or “canonical” as it is sometimes called) pattern of sea surface temperature
anomalies. In the simplest models, forecasts of an index of this pattern are then used as a
basis for predicting the amplitude and polarity of the anomalous rainfall and circulation
patterns in Figs. 20 and 23. Just as ENSO distorts the seasonal march in many areas of
the world, rendering “forecasts” based on climatology erroneous, so the departures from
the canonical ENSO cycle that give each individual warm or cold episode its own
peculiar character constitute a major source of error in current prediction models based
on the canonical ENSO cycle. For example, the scientific community was caught off
guard by the onset of the exceptionally strong 1982-1983 warm episode, which was
preceded by a somewhat different sequence of events than any ENSO observed during
the previous three decades. Indeed, there are times when anomalous ocean temperatures
and winds in the equatorial Pacific bear so little resemblance to the “canonical” ENSO
pattern that it is not even clear whether to classify them as “warm” or “cold.” Sea-surface
temperature anomalies in the tropical Atlantic tend to be rather weak; i.e., on the order of
tenths of °C, as opposed to values in excess of 1°C in the eastern Pacific. Within the
Atlantic equatorial waveguide (near the node in the dipole pattern in Fig. 24) there is
evidence of the signature of local ocean-atmosphere coupling analogous to that which
occurs in association with ENSO, but the amplitudes are smaller. Less is known about the
generation and maintenance of sea-surface temperature anomalies off the equator.

The wintertime geopotential height field and sea-surface temperature anomalies over the
Caribbean and the tropical North Atlantic are linked to Pacific/North American (PNA)
pattern. Evidently, when the PNA pattern is in positive polarity with a ridge over the
Rockies, sea-level pressure tends to be above normal over the Sargasso Sea and the Gulf
of Mexico, enhancing the pressure gradient that drives the tradewinds in this sector,
leading to stronger surface winds and cooling of the sea surface. The North Atlantic
tradewinds and the underlying sea surface temperature also exhibit interannual variability
that appears to be independent of ENSO and possibly linked to extratropical circulation
anomalies over the North Atlantic sector. The persistence of sea-surface temperature
anomalies and their potential for feedback to the atmosphere in subsequent seasons
depends upon the depth to which they extend. Little is known about the subsurface
structure of the off-equatorial ocean temperature anomalies in the tropical Atlantic.

ENSO also affects the climate of southeastern South America, including northeastern
Argentina, Uruguay and southern Brazil. Precipitation anomalies are consistently positive
from the November of an ENSO warm event through February of the following year, and
negative from July through December of a cold event year. There is some evidence that the ENSO connection between southeastern South America and the tropical Pacific is established through a wave train that extends from the tropical Pacific to South America. This wave train is called the Pacific-South American pattern, by analogy to the PNA teleconnection pattern over North America. The PSA has an equivalent barotropic structure and it is excited by atmospheric convection over the tropical Pacific. The PSA is modulated by seasonal changes in the basic state flow which undergoes quasi-biennial changes not seen in the Northern Hemisphere.

1.7 ITCZ/cold tongue complexes

With the exception of a few isolated regions of highly localized orographic forcing, the eastern Pacific ITCZ is responsible for the heaviest annual mean rainfall observed anywhere on Earth. The ITCZ appears as a continuous band of precipitation and surface convergence in monthly averaged maps, but is in fact made up of transient mesoscale and synoptic scale weather disturbances that obscure the ITCZ structure at an instant in time. Much of the rain falls from clouds whose tops do not show up as cold in infrared imagery as those associated with convection over and near the tropical land masses or over the “warm pool” region of the western Pacific. This is reminiscent of one of the major findings of the Global Atmospheric Research Program’s (GARP) Global Atlantic Tropical Experiment (GATE) twenty-five years ago. Vertical profiles of vertical velocity and latent heat release in synoptic-scale disturbances in the Atlantic ITCZ region reach peak values 2-3 km above sea level, as compared to 5-10 km in disturbances over the “warm pool” region of the tropical western Pacific (Fig. 25). Strong boundary-layer convergence evidently plays a critical role in organizing and maintaining the shallow but persistent convection in the ITCZs. Operational numerical weather prediction models and climate models have had difficulty in simulating the intensity of the ITCZ rainfall and the diversity of the convective heating profiles observed in different parts of the tropics. Existing model parameterizations of radiative transfer in clouds, cloud microphysics, and convection will need to be reconsidered in light of this problem.

In the season of coldest temperatures, the equatorial cold tongue is characterized by pronounced divergence in the surface wind field just north of the equator and weaker convergence in a band just south of the equator (Fig. 26). The ITCZ to the north of the equator appears as an intense and narrow band extending from near the coast of Central America to the central Pacific. The position and intensity of the divergent and convergent bands associated with the ITCZ/cold tongue complex are not simulated well in current operational prediction models. The reasons for these discrepancies are not well understood. The difficulty may be systematic errors in the simulated convective and radiative heating profiles or the inability of the models to properly simulate the mesoscale and synoptic scale weather disturbances that form the time-averaged ITCZ. In addition, the equatorial atmospheric boundary layer in the Atlantic and eastern Pacific, north of the equator, is characterized by strong and persistent backing of the wind with height from southerly at the surface to easterly at the top of the planetary boundary layer. Present difficulties in simulating the surface wind stress patterns over the eastern Pacific may be
due in part to the inability of climate models to simulate the complex vertical structure of
the atmospheric boundary layer in the cross-equatorial ITCZ inflow.

Throughout the colder part of the year there are vigorous tropical instability waves in the
ocean along the SST front to the north of the cold tongue (clearly visible in the satellite
imagery shown in Fig. 27) that appear to transport significant amounts of heat and
momentum in the upper ocean. In the extreme eastern Pacific the northern edge of the
equatorial cold tongue is often abrupt. Immediately to the north of this “equatorial front”
is a region of strong air mass modification, where northward-moving air that has just
crossed the equatorial cold tongue flows over much warmer surface waters. This
transition is marked by an abrupt increase in surface wind speed and a decrease in
relative humidity, as the boundary layer becomes unstable, and drier, faster-moving air is
mixed downward toward the surface. Stratocumulus clouds form, analogous to those that
develop when continental air flows over the Gulf Stream during wintertime. The
distortions of the sea surface temperature front by tropical instability waves (Fig. 26) can
produce distinct signatures in the stratocumulus cloud patterns and surface wind fields.

1.8 Stratus cloud decks

Oceanic boundary layer cloud decks are extensive to the west of Peru and Chile in the
Pacific, to the west of Angola in the Atlantic (Figs. 2 and 9), and off California and in the
vicinity of the Azores. These cloud decks are highly reflective of solar radiation, and
hence produce both local and global cooling. The stratocumulus and cumulus rising into
stratus, which make up these decks, are capped by strong inversions at heights between
500 and 1500m. The stratus cloud decks are observed in regions of large-scale subsidence
and their variability is governed by the interplay among radiative transfer, boundary-layer
turbulence, surface fluxes, cloud microphysics, and the thermodynamic conditions just
above the inversion. They exhibit weekly, annual, and interannual variability in response
to changes in sea surface temperature, winds, and the temperature of the overlying air.
They also have a pronounced diurnal rhythm of nighttime thickening and daytime
thinning due to the interplay between strong longwave cooling at cloud top and solar
heating within the clouds. This diurnal variability is enhanced along the eastern edges of
the cloud decks where land-sea differences affect the dynamics and thermodynamics of
the boundary layer. Stratus decks are particularly variable along their western edge,
where they transition from stratiform to tradewind cumulus as air flows equatorward in
the trades. These transition zones have a potential for positive feedbacks between cloud
amount and the underlying sea surface temperature: an increase in cloud amount tends to
cool the ocean and a cooler ocean leads to a shallower boundary layer and more
stratiform clouds, and a larger fractional cloud amount. Drizzle is often observed in
marine stratocumulus clouds and can have a substantial impact on the dynamics and
macroscopic characteristics of the clouds. The sensitivity of the drizzle processes to CCN
aerosol characteristics couples these aerosols to the stability and extent of the stratus
decks.
1.9 Subseasonal climate variability

US CLIVAR research is also concerned with frequency of occurrence of significant weather events such as hurricanes, flood, and drought over the course of a season. Subseasonal tropical rainfall variability is organized both on the smaller scales of local weather phenomena such as severe storms and sea breeze circulations as well as on the larger scales of intraseasonal phenomena. Intraseasonal fluctuations are clearly evident in the tropical planetary-scale sea-level pressure, wind, and precipitation fields.

Over the Pacific, the most prominent intraseasonal fluctuations are associated with the 30-60 day “Madden-Julian Oscillation” (MJO) that affects the atmospheric circulation throughout the global tropics and subtropics, and in particular, the wintertime jet stream and atmospheric circulation features over the north and south Pacific oceans and over western North America and southern South America. The MJO modulates storminess and temperatures over North and South America and hurricane activity in both the Pacific and Atlantic basins. It is characterized by an eastward progression of large regions of enhanced and suppressed tropical rainfall, usually first evident over the western Indian Ocean, and propagating over the very warm ocean waters of the western and central tropical Pacific. It generally becomes very nondescript as it moves over the cooler ocean waters of the eastern Pacific but reappears over the tropical Atlantic and Indian oceans.

Distinct patterns of lower-level and upper-level atmospheric circulation anomalies are associated with the MJO. Madden-Julian Oscillation activity varies from year to year, with long periods of strong activity followed by periods in which the oscillation is weak or absent. Strong MJO activity is often observed during weak La Niña years or during ENSO-neutral years, while weak or absent MJO activity is typically associated with strong El Niño episodes.

The MJO impacts the wintertime atmospheric circulation over the North Pacific and western North America. It contributes to blocking activity (i.e., atmospheric circulation features that persist near the same location for several days or more) over the high latitudes of the North Pacific. The strongest impacts of intraseasonal variability on the US occur during the winter months over the western states that receives the bulk of its annual precipitation at this time. Storms are often accompanied by persistent atmospheric circulation features and last for several days or more. Of particular concern are extreme precipitation events linked to flooding. Extreme precipitation events can occur at all phases of the ENSO cycle, but the largest fraction of these events occur during La Niña episodes and during ENSO-neutral winters.

During La Niña episodes much of the Pacific Northwest experiences increased storminess and precipitation, and more overall days with measurable precipitation. The risk of flooding in this region is greater during the weak La Niñas due to an increase in extreme precipitation events in the weaker episodes. In the tropical Pacific, winters with neutral-to-moderate cold episodes, are often characterized by enhanced 30-60 day MJO activity, and is a stronger linkage between the MJO events and extreme west coast precipitation events (Fig. 28). A recent example is the winter of 1996/97, which featured
heavy flooding in California and in the Pacific Northwest (estimated damage costs of $2-3 billion at the time of the event) and a very active MJO.

During the Northern Hemisphere summer months low-frequency variability in the tropics is dominated by interannual variations associated with ENSO and by intraseasonal variations such as the MJO. The MJO can have a significant impact on regions that experience rainy seasons both during winter and summer seasons. For example, during the Northern Hemisphere summer season the MJO-related effects on the Indian summer monsoon are well documented. MJO-related effects on the North American summer monsoon also occur, though they are weaker. However, the relative influences of ENSO and the MJO on the summer precipitation regime of North America are not well understood. Statistical relationships between these modes and the frequency of occurrence of various kinds of significant weather events (e.g. floods, droughts, heat waves) are needed to obtain detailed information on the climatic signatures of these modes.

MJO-related impacts on the North American summer precipitation patterns are strongly linked to north-south adjustments of the precipitation pattern in the eastern tropical Pacific. A strong relationship between the leading mode of intraseasonal variability of the North American monsoon system, the MJO, and the points of origin of tropical cyclones is also present. Although tropical cyclones occur throughout the Northern Hemisphere warm season (typically May-November) in both the Pacific and the Atlantic basins, in any given year there are periods of enhanced and suppressed activity within the season. There is evidence that the MJO modulates this activity (particularly for the strongest storms) by providing a large-scale environment that is favorable or unfavorable for development (Fig. 29). The strongest tropical cyclones tend to develop when the MJO favors enhanced precipitation. As the MJO progresses eastward, the favored region for tropical cyclone activity also shifts eastward from the western Pacific to the eastern Pacific and finally to the Atlantic basin. While this relationship appears robust, the MJO is one of many factors that contribute to the development of tropical cyclones. For example, it is well known that sea surface temperatures must be sufficiently warm and vertical wind shear must be sufficiently weak for tropical disturbances to form and persist.

Over South America, circulation anomalies occur with 40-48 and 20-25 day periods during the austral summer. This modulation appears as a dipole of strong and weak convection as discussed in section 1.4. The longest period is related to the MJO. The 200 hPa streamfunction exhibits a wave number 1 structure in the tropics and a wave train propagating downstream from the convective area in the tropical Pacific. The development of the SACZ-dipole pattern is also affected by the 20-25 day mode, which features meridional propagation of convection over South America from midlatitudes to the tropics. A wave train is found in the 200 hPa streamfunction extending from the central Pacific eastward to about 60°S and curving toward the northeast over South America.
When the SACZ is enhanced, these two modes become meridionally aligned over the continent and extend into the Inter-American seas and the North Atlantic. This in turn may have an impact on (wintertime) precipitation over North America. Improvement of summer rainfall simulation over tropical South America may therefore lead to improved prediction for the Northern Hemisphere. This is substantiated by evaluation of forecasts produced by the NCEP reanalysis model that shows that erroneous simulation of convection over tropical South America produces a southward shift of the subtropical jet over North America.

Over southwestern North America, mesoscale models have simulated many of the observed features of the North American monsoon, including southerly low-level flow over the Gulf of California, the diurnal cycle of convection, and a low-level jet that develops over the northern end of the Gulf of California. One particularly important mesoscale feature that the models reproduce is a “gulf surge”, a low-level, northward surge of moist tropical air that often travels the entire length of the Gulf of California. Common characteristics of these disturbances include changes in surface weather (a rise in dewpoint temperature, a decrease in the diurnal temperature range, a windshift with an increased southerly wind component, and increased cloudiness and precipitation). Gulf surges appear to promote increased convective activity in northwestern Mexico and the southwestern US, and are related to the passage of Tropical Easterly Waves (TEWs) across western Mexico. One aspect of the connection between gulf surges and TEWs that has not been explored is the extent to which they might influence the interannual variability in the onset and intensity of the summer monsoon in this region. Sustained and enhanced in situ and satellite observations are required to examine the structure of the TEWs and Gulf of California surge events, their frequency of occurrence, and the temporal evolution of the moisture transport.

Wintertime cold air outbreaks along the eastern slopes of the Rockies often generate pressure surges that penetrate deep into Central America, creating strong pressure differences across the mountain ranges that form the Continental Divide. During such periods, strong to gale force winds blow across three pronounced gaps in the mountains: one across the Isthmus of Tehuantepec in southern Mexico, one across Lake Nicaragua, and one across Panama near the Canal Zone. Downstream of these gaps, tongues of strong winds extend 100 km or more into the Pacific, where they give rise to a succession of long-lived mesoscale eddies in the ocean circulation. The signature of the gap winds is also evident in the Coastal Zone Color Scanner imagery shown in Fig. 5 and in monthly mean wind fields (Fig. 30).

A remarkable amount of mesoscale structure is evident in the rainfall climatology (Fig. 14). The relationship of these features to the orography and to the coastal geometry becomes even more obvious when diurnal variations are taken into account (Fig. 31). These structures are obviously related to terrain, but in a manner that involves processes much more complex than orographically induced ascent and subsidence.
2. PRACTICAL AND SCIENTIFIC MOTIVATION FOR PAN AMERICAN CLIMATE RESEARCH

US CLIVAR promotes an improved understanding of the processes that control the distribution of rainfall over the Americas and applies that knowledge to improve the models used for climate prediction on seasonal and longer time scales. More accurate and detailed information concerning the statistical probabilities of various rainfall scenarios are required for planning of such activities as agriculture and providing water resources. The focus of Pan American research is regional, rather than global, because large-scale sea surface temperature variations are more clearly defined and most strongly coupled to variations in continental rainfall in the tropical Atlantic and eastern Pacific oceans. It is continental, as opposed to national, because seasonal rainfall anomalies over the United States can only be understood in the context of the broader, continental scale pattern in which they are embedded.

The climate processes addressed by US CLIVAR Pan American research are the same as those involved in assessing the effects of anthropogenic climate change. Anthropogenic changes in atmospheric gases and particulate composition modify the global energy balance. The practical consequences for humans depend on how the climate system responds on regional scales to such global energy balance changes. Any regional response is likely to be tied to natural regional climate variations and its modeling cannot be credible unless the significant natural climate variations are understood and included in the models addressing anthropogenic changes. Hence, US CLIVAR research will increase the accuracy and credibility of regional projections of future anthropogenic climate change over the American continents.

Until recently social and economic systems have usually been caught off guard by large seasonal climate anomalies and suffered losses or were unable to capitalize on favorable conditions. Better understanding of the sources of climate variability gained through focused research over the past decades has lead to the development of routine seasonal climate prediction systems at several national and international centers in the Pan American Region such as the U.S. National Centers for Environmental Prediction (NCEP) and the International Research Institute for Climate Prediction (IRI).

Figure 32 shows a selection of time series illustrating the large year-to-year variability of seasonal-mean rainfall. Features visible in these plots include the anomalous summer of 1993, marked by disastrous floods in the central US and drought in the southeast, and the summers of 1988 and 1991 in which the farmers in the central US suffered major drought-related crop losses. Longer time scale features such as the legendary “dust bowl” epoch in the central US in the 1930’s are also evident. In semiarid regions, such as parts of Arizona and northeast Brazil, the interannual variability tends to be even larger in relation to the seasonal mean rainfall, rendering agriculture a high-risk venture.

Following the success of TOGA, government agencies in Peru (Lagos and Buizer 1992) and Brazil have been incorporating El Niño predictions into their agricultural planning. The El Niño/ Southern Oscillation (ENSO) phenomenon is the major source and best
understood aspect of interannual global climate variability. Benefits of the forecasts are illustrated by Table 1, which shows grain production for a number of recent years in the state of Ceara in northeast Brazil and corresponding rainfall totals over the state, both expressed as percentages of normal. The moderately severe drought conditions that prevailed in 1987 drastically reduced grain production that year but similar drought conditions in 1992, after the advent of climate prediction, only slightly reduced agricultural production, and even the much more severe drought of the following year had a less adverse impact on grain production than the 1987 drought.

Major ENSO warm events, such as the 1982/83 and 1997/98 events, present the best opportunity for assessing the range of impacts to be expected from climate variability. The impacts of coherent climate variability during major ENSO events stand out against the background of normal weather variability. A wide range of social and economic sectors were impacted by the 1997/98 El Niño (Fig. 33). These sectors included: agriculture; energy; water resources; health; ecosystems; tourism; social systems. Regionally they were focused in the global tropics/subtropics and in midlatitudes in the Americas. Seasonal forecasts for temperature and rainfall were available for the U.S. and some use of these was made for disaster mitigation and economic benefit. Mitigation actions were also taken in other countries with great success. A number of institutions make routine forecasts with lead times of using statistical and dynamical tools for sea surface temperature (SST) variations in the tropical Pacific. NCEP and the IRI also make routine seasonal temperature and rainfall forecasts for continental areas.

Empirical studies have identified a number of significant relationships between tropical sea surface temperature anomalies and concurrent or subsequent rainfall anomalies over the Americas (Figs. 24 and 34). Rainfall on the coastal plain of Ecuador and northern Peru is positively correlated with sea surface temperature in the equatorial Pacific. The same distinctive “El Niño signature” is apparent, with varying degrees of strength, in several of the other correlation maps. Tropical Atlantic sea surface temperature signatures are also apparent in several of the patterns: particularly the one for February-May rainfall in northeast Brazil.

Significant spatial correlations do not alone constitute proof that sea surface temperature anomalies influence rainfall; inference of causality on the basis of empirical evidence alone is fraught with ambiguity. However, they suggest modeling experiments required to establish causality. The effects of ENSO on rainfall in Ecuador, as well as in more remote regions such as the southeastern United States have in fact, been verified by numerous experiments with atmospheric general circulation models (AGCMs), and the dynamical mechanisms that give rise to the remote response are reasonably well understood. Sea surface temperature anomalies in the tropical Atlantic have likewise been shown to influence northeast Brazil rainfall. The extratropical response to tropical sea surface temperature anomalies is strongest during the cold season. Hence, most AGCM investigations have been based on wintertime conditions.

Equatorial sea surface temperature anomalies associated with ENSO may influence warm season rainfall over the Americas. Still the correlation pattern for summer rainfall over
the US Great Plains in Fig. 34 remains difficult to interpret. Are the North Pacific
features in the sea surface temperature correlation pattern by the same atmospheric
circulation anomalies that are responsible for the rainfall anomalies? Is the hint of an
ENSO signature in the pattern indicative of a causal relationship? The answers to such
questions must take into account the positive or negative feedbacks by the land surface in
modulating the response. In addition, anomalies in soil moisture, vegetation
characteristics, or changes in land use and land cover can act alone to alter climate. The
soil moisture feedback to precipitation anomalies is generally positive, and it can
potentially enhance the extremes. The vegetation feedbacks may help to shift marginal
zones from one climate regime to another. Such a bipolar mode may operate in sub-
Saharan Africa, and large swings in climate may be the norm for western North America
as well.

Statistics of significant weather events may be predictable a season or more in advance.
The ENSO cycle may exert a far-reaching influence on summertime climate in the Pan
American domain through its control of hurricane frequency and in the partitioning of the
storms between the Caribbean/Gulf of Mexico and the eastern Pacific. Figure 35 shows
the position of the Atlantic storms on the last day that they exhibited hurricane force
winds for two sets of years, classified on the basis of an index of equatorial Pacific sea
surface temperature. More than twice as many storms enter the Gulf of Mexico and make
landfall along its coastline during the cold years as during the warm years. Figure 36
shows analogous warm versus cold year composites, but for hurricane and tropical storm
days. Warm years of the ENSO cycle are characterized by more Pacific storm days in
general, and more of the storms reach northwestern Mexico and Hawaii before they
dissipate.

3. EMPIRICAL STUDIES

Observational studies of the interactions between the tropical ocean and the global
atmosphere conducted during the late 1960s and 1970s laid the groundwork for the
advances in numerical prediction of ENSO and its impacts on global climate that took
place during TOGA. They demonstrated the linkage between tropical sea surface
temperature anomalies and regional climate anomalies in the extratropics, and they
revealed and illuminated the essential ocean-atmosphere feedback mechanisms that give
rise to the ENSO cycle. The knowledge gained from these investigations shaped the
atmospheric and oceanic GCM experiments during TOGA and stimulated the
development of a new generation of coupled models capable of simulating what are
believed to be the essential aspects of the ENSO cycle. Pan American CLIVAR research
focuses more attention on the role of land processes in the coupled ocean-atmosphere-
land system. Empirical studies will contribute to all of the Pan American scientific
objectives.
3.1 Atmospheric response to boundary conditions

The ENSO cycle modulates rainfall over much of the United States. Cold season linkages over the southern states are firmly established. The strength and dependability of possible warm season linkages is not yet well known. Hence, US CLIVAR needs (a) statistical studies documenting relationships between anomalous boundary forcing and climate anomalies over the Americas and (b) diagnostic studies elucidating the physical and dynamical mechanisms through which these linkages occur. Anomalous boundary forcing includes both sea surface temperature and land surface processes, and climate anomalies refer not only to mean temperature and rainfall, but also to the frequency of droughts, floods, and severe thunderstorm outbreaks, and to the tropical and extra-tropical storm tracks. The relationships of interest are likely to be seasonally dependent, and some of them may be nonlinear.

Inference of causal relationships based on empirical evidence is often difficult because the anomalous surface wind field associated with the rainfall anomalies may induce sea surface temperature anomalies of its own, and anomalous boundary conditions in a number of different regions are often interrelated by way of planetary-scale atmospheric teleconnections. For this reason, empirical studies of the atmospheric response to anomalous boundary forcing need to be complemented by a program of experimentation with atmospheric general circulation models described in section 5.1.

3.2 Coupling between land and ocean

Empirical studies are needed to explore the mechanisms that link the oceanic climate variability to that over land in the Pan American region. Of particular interest is answering the question of whether land surface processes play a passive role in seasonal-to-decadal climate variability, merely responding to a signal that is largely determined externally by coupled ocean-atmosphere interaction, or whether land surface processes can play an active role in determining such climatic features as seasonal precipitation patterns over land. Continued efforts to build a climate observing system over land, especially in Latin America, will be essential to support empirical and modeling studies addressing these problems.

3.3 Seasonally varying mean climate

The synoptic climatology of rainfall and significant weather events over the Americas is still in need of further elaboration, particularly for the warm season. There are indications of inverse relationships between monsoonal rainfall and rainfall in adjacent regions that warrant further exploration. There remain outstanding questions concerning the mechanisms of the annual march in the ITCZ/cold tongue complexes and the stratus decks that could be addressed in diagnostic studies based on existing datasets.

3.4 Regional distribution of continental precipitation

Topography over the Americas gives rise to a number of distinctive local features in the synoptic climatology such as low-level jets with moist, poleward flow to the east of the
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Rockies and Andes, episodic “gap winds” across central America, and strong diurnal
variations in rainfall patterns. Empirical studies that define and elucidate the fundamental
characteristics of these features will complement the mesoscale modeling effort in US
CLIVAR described in Section 5.2.

3.5 Evolution of tropical sea surface temperature anomalies

It is becoming increasingly apparent that the ENSO phenomenon is subject to variability
on decadal-to-centennial time scales. The warm polarity has become more prevalent since
the mid-1970s and particularly since 1990, and the biennial periodicity that characterized
much of the previous 20 years has not been in evidence. Whether these long-term
changes should be viewed as deterministic fluctuations in the coupled climate system, or
whether they are merely a reflection of sampling variability associated with the ENSO
cycle has yet to be determined. Empirical studies are needed to clarify the nature of this
long-term variability and to determine whether it is potentially predictable or at least
subject to real-time assessment. Less is known about the processes that determine the
evolution of the more subtle sea surface temperature anomalies in the tropical Atlantic,
but there is evidence of organization on a space scale comparable to the width of the
basin and on time scales longer than the characteristic thermal damping time of the mixed
layer. Descriptive and diagnostic studies of the ocean mixed layer, the atmospheric
planetary boundary-layer structure, and the interfacial fluxes in the ITCZ/cold tongue
complexes, based on existing marine surface observations and satellite data, will provide
a large-scale context for the Eastern Pacific field studies described in Section 6.
Empirical studies will also provide guidance for the design of Atlantic and South
American field studies focusing on the mechanisms of large-scale atmosphere-ocean-land
coupling that may be proposed during the CLIVAR period, as discussed in Section 6.4.

4. DATA SET DEVELOPMENT AND MANAGEMENT

Pan American investigators have at their disposal a much larger array of observational
and model-generated datasets than was available during TOGA. Relevant satellite-based
datasets include radiative fluxes, precipitation estimates, cloud parameters, layer-
averaged temperature and humidity, wind stress over the oceans, sea level, ocean color,
and properties of vegetation. The satellite measurements, in combination with the
ongoing components of the in situ global observing system put into place during GARP
and TOGA and datasets derived from US CLIVAR and GEWEX field programs, provide
unprecedented opportunities for innovative investigations in pursuit of the Pan American
scientific objectives. The UCAR Joint Office for Science Support (JOSS) provides
NOAA's Pan American Climate Studies Program with limited data set development and
management support with online data access for some of the PACS data sets.
US CLIVAR does not fund a major data management activity of its own: it relies heavily
upon a number of ongoing data management efforts funded by the mission agencies. As a
part of their routine operations, weather prediction centers perform the management,
quality control, synthesis, and gridding of many of the atmospheric datasets needed by
Pan American investigators. Reanalysis projects currently in progress at the National
Centers for Environmental Prediction (NCEP) and the European Centre for Medium-
Range Weather Forecasts (ECMWF) will substantially upgrade historical datasets derived from these analyses, especially for model-generated fields such as precipitation rates. An analogous ocean data assimilation system established at NCEP under the auspices of TOGA produces gridded oceanographic datasets. The Global Precipitation Climatology Project provides precipitation estimates based on infrared and microwave satellite data, rain gauge measurements, and model outputs. Monthly mean precipitation estimates for the period 1986-2000 are being produced on a 2.5° latitude-longitude resolution grid.

The International Satellite Cloud Climatology Project (ISCCP) provides cloud amount, top temperature and pressure, optical thickness, and water path for cirrus, deep convective, middle, and low clouds on a 30-km grid with 3-hour and monthly time resolution for 1983-91. A reanalysis of this data with improved cloud detection and an ice-phase microphysical model in the retrieval algorithm is scheduled to be completed by 2000. A limited amount of pixel resolution data is available for the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE), the First ISCCP Regional Experiment (FIRE), and the Atlantic Stratocumulus Transition Experiment (ASTEX) field programs. Radiative flux profiles generated in the retrieval algorithm are being routinely archived. ISCCP is scheduled to continue through the year 2000.

NASA has developed and flown on the Terra satellite a new generation of instruments for getting measurement of land properties. These measurements should be available for climate model improvement by 2001. Previous observations have been developed into useful datasets over land by the International Satellite Land Surface Climatology Project (ISLSCP). Their previously developed data have been widely used in the land surface schemes of operational and research models. Other monitoring products that are satellite based include the NOAA/NESDIS precipitation and precipitable water and soil wetness index products, with high-resolution GOES satellite estimates of rainfall over South America.

The Global Soil Wetness Project (GSWP) is producing retrospective multi-model estimates of soil moisture and surface fluxes over the globe. The NASA Land Data Assimilation System (LDAS) is similar to GSWP, but is a higher-resolution operational product, a version of which will eventually be coupled to the NASA DAO atmospheric data assimilation system. LDAS is operational over the United States, and is expanding to cover all of North America and eventually the globe.

Many of the datasets needed by Pan American investigators are already available through existing data distribution centers. The NOAA National Climate Data Center offers monthly and seasonal data for precipitation and other variables, from a variety of sources and in a number of different formats. The National Center for Atmospheric Research (NCAR) data library maintains an extensive collection of use to Pan American researchers, including precipitation datasets, gridded atmospheric analyses, selected oceanographic data, and more specialized datasets such as daily global tropical cyclone positions. The NOAA Pacific Marine Environmental Laboratory (PMEL) offers data from the TAO array, in near real time. The NOAA Atlantic Oceanographic and
Meteorological Laboratory (AOML) provides data from the volunteer observing
ship/expendable bathythermograph temperature (VOS/XBT) program and temperature
and current data from the tropical and global drifting buoy array. It will also provide sea-
surface salinity observations and analysis products as they become available.

NOAA’s NCEP provides global atmospheric reanalysis data on CD-ROMs and the
NOAA Climate Diagnostics Center (CDC) in a self-describing common data form
(netCDF) format. The Climate Diagnostics Center is also archiving monthly mean data
from the NCEP ocean model and, more recently, weekly means that include surface
fluxes generated by the coupled model. Ocean reanalysis products will be added to this
archive as they become available.

US CLIVAR is supporting the assembly of additional daily and monthly precipitation
records for Mexican stations, the preparation of 1° latitude-longitude resolution monthly
sea surface temperature data for the tropical and extratropical Pacific and Atlantic basins
based on the Comprehensive Ocean-Atmosphere Data Set (COADS), and the extension
of ISCCP-type convective cloud data back to the early 1970s. Data from US CLIVAR-
sponsored field studies described in Section 6 will be available to the scientific
community soon after the field observation phase. The data that do not require extensive
post-processing should be available in real or near-real time and the more intensively
processed datasets should generally be available within a year of the time that the
observations are taken.

5. MODELING

Numerical modeling in US CLIVAR Pan American research addresses the overall goal of
extending the scope and improving the skill of operational climate prediction over the
Americas on time scales of a season and longer. A broad-based program of
experimentation with a hierarchy of models will contribute to the pursuit of all three Pan
American scientific objectives. Simulation of boundary forced rainfall anomalies and the
frequency of occurrence of significant weather events over the Americas addresses the
potential predictability of the atmosphere, given perfect knowledge of the boundary
conditions, while the simulation of quantities such as sea surface temperature, soil
moisture, snow cover and vegetation addresses the predictability of the boundary
conditions. Improved representation of coupling between atmosphere and land surface
processes developed by GEWEX investigators will be required for understanding and
simulating modes of climate variability that depend significantly on land surface
"memory". Simulation of the seasonally varying mean precipitation and other aspects of
climate over the Americas and the adjacent oceans as an initial value problem with
coupled GCMs provides an incisive test of current understanding of the coupled ocean-
atmosphere-land system, as reflected in the design of the models. Of particular
importance is the simulation of the structure of the ITCZ/cold tongue complex and the
monsoonal precipitation patterns over the land, which play a central role in the coupling
between the tropical atmosphere, the ocean and land surface processes on seasonal and
longer time scales.
US CLIVAR will emphasize the use of fully coupled ocean-atmosphere-land models to study the role of land surface processes in climate variability. A limited amount of high resolution modeling will be required for the understanding and synthesis of observations from the field studies described in Section 6. The challenge of simulating phenomena that determine the regional distribution of precipitation over the Americas, such as the low-level jets over the continents, the mesoscale convective systems that form the highly persistent ITCZ, the equatorial cold tongues with their shallow oceanic mixed layers, and the marine boundary layer cloud decks in the eastern Pacific, provides a major stimulus for the development of high resolution global climate models that exploit increasingly powerful supercomputers. Understanding Pan American climate phenomena in the context of the atmospheric and oceanic general circulation and simulating them realistically will require major advances in the understanding of large-scale ocean-atmosphere-land interaction and state-of-the-art climate modeling.

5.1 Atmospheric general circulation models (AGCMs)

AGCM simulations can provide insights into the physical mechanisms responsible for the remote linkages between anomalous conditions at the earth's surface and the regional climate variations. These investigations have traditionally compared simulations with different prescribed sea surface temperatures, often as motivated by empirical correlations. The observed correlation pattern in Fig. 24 indicates that monsoon rainfall anomalies over northeast Brazil are positively correlated with sea surface temperature anomalies over the tropical South Atlantic and negatively correlated with sea surface temperature anomalies over the tropical North Atlantic. AGCM simulations with sea surface temperature anomalies prescribed in accordance with this pattern yield rainfall anomalies of the observed sign, relative to the “control run” with climatological mean sea surface temperature. The consistency between the model simulations and the observations supports the inference that the sea surface temperature anomalies cause the anomalous rainfall. In a similar manner, AGCM experiments can examine the hypothesis that sea surface temperature anomalies associated with El Niño are capable of inducing rainfall anomalies over northeast Brazil and other regions of the Americas, independently of the anomalies in the Atlantic.

AGCMs also provide a powerful tool for exploring the relative contributions of oceanic and land processes to the determination of the seasonal cycle of precipitation. In particular, modifications of the prescribed seasonality of the sea surface temperatures or of the seasonal cycle of solar heating or of other model parameters can be used. Initial studies suggest that precipitation in the eastern Amazon is more controlled by oceanic conditions while the western Amazon is controlled is more influenced by the seasonality of land solar heating. The AGCM experiments, together with detailed observations of regional weather phenomena show how the slowly evolving planetary-scale atmospheric response to boundary forcing modulates the more intermittent, higher frequency synoptic and subsynoptic phenomena that are responsible for the individual episodes of heavy rainfall and significant weather, e.g., flareups in the ITCZ and the SACZ, migrating
frontal systems, and higher latitude blocking events associated with wintertime cold air
outbreaks. Although deterministic prediction of phenomena such as these is not feasible
on seasonal and longer time scales, AGCM simulations with realistic models can
potentially provide more accurate and detailed information concerning their frequency or
likelihood of occurrence than empirical evidence alone.

AGCM simulations forced with climatological-mean boundary conditions exhibit
systematic biases in regions of interest to US CLIVAR, e.g., an underestimation of wind
stress in the equatorial belt. Increasing the horizontal resolution may alleviate this
problem by increasing the poleward eddy momentum flux and it may, at the same time,
provide a better representation of topographic effects on the low level flow. The Andes,
for example, may help determine the prevailing along-shore surface winds off Peru and
the associated oceanic upwelling in that region. Models also underestimate the coverage
of oceanic stratus clouds, hence their reflection of solar energy and the consequences for
the atmospheric planetary boundary layer (PBL) and the ocean mixed layer believed to be
responsible for much of the equatorial asymmetry of sea surface temperature in the
tropical Atlantic and eastern Pacific. These well-defined biases within the Pan American
region serve to highlight basic deficiencies in the atmospheric models that need to be
corrected in order to pave the way for the development of realistic coupled models.

5.2 Mesoscale atmospheric models

Mesoscale processes affect the distribution of continental-scale precipitation and its
variability on seasonal and longer time scales. Along the coasts and over the mountainous
terrain of the Americas, the simulated rainfall in the AGCMs and coupled GCMs cannot
be compared directly with the station data because the weather systems and the
topographic features (see Fig. 6) responsible for the observed rainfall patterns have length
scales almost an order of magnitude smaller than those resolved by the GCM grids
currently in use. The AGCM and coupled GCM simulations are particularly poor in
summer, when mesoscale convective systems organize the precipitation over the
Americas and in the ITCZs over the eastern Pacific and western Atlantic oceans.

Many aspects of the detailed distribution of rainfall over the Americas and in the oceanic
ITCZs can be understood without resolving mesoscale processes over the entire globe.
High-resolution regional models have demonstrated a useful capability to "downscale"
the coarse resolution information from global climate models to provide more accurate
and detailed descriptions of regional precipitation. However, much work remains to
determine the most appropriate numerical methods and modeling strategies. Furthermore,
advances in supercomputing technology may make it feasible to resolve mesoscale
processes over the globe during the next ten years, making it unnecessary to deal with the
practical problems of variable spatial resolution. In the meantime, a number of technical
issues remain for the use of mesoscale models in climate research. What horizontal and
vertical resolutions are required for a nested model to adequately simulate seasonal and
interannual variations in summertime rainfall? How sensitive are the simulations to the
techniques employed to nest the mesoscale models in global models? Very little has yet
been done to apply variable resolution methods developed in other disciplines that would
allow a global model to increase its resolution where it is needed, or other approaches
such as a “window model”, in which the large-scale flow is simulated directly at a lower
resolution, while the selected region is examined at higher resolution through the use of a
perturbation model that has essentially the same physics and model dynamical structure.

Modeling strategies will evolve over the CLIVAR period as the scientific objectives of
the program are advanced. Initially, the emphasis is being placed on modeling the
seasonally varying mean climate over the tropical Americas and adjacent oceans,
including phenomena such as sea breezes and mountain-valley winds, examining how
mesoscale features influence the planetary and synoptic scale climatology of the Pan
American domain and how they influence the thermodynamic and dynamical structure of
the ocean mixed layer in the ITCZ/cold tongue region. These studies should pave the way
for addressing the influence of the slowly varying planetary-scale interannual
fluctuations, such as the ENSO phenomenon, upon the mesoscale circulation and
precipitation patterns, and the frequency and distribution of significant weather events.
These studies will likely first consider the tropical portion of the Pan American domain,
where the impacts are most direct, and expand to address summer conditions in the
extratropics.

5.3 Modeling the Effects of the Land Surface

Modeling the role of the land surface, as a lower boundary condition for atmospheric
models, requires theoretical and observational exploration of the processes involved,
modeling sensitivity studies to determine the relative importance of different processes,
and numerically implementation of the improved understanding. Analogous to efforts to
represent the effects of clouds in climate models, the energy and water conservation
requirements of the land boundary conditions were first introduced with very simple
schemes. More complex schemes are now included in most operational forecast and data
assimilation systems. An explicit representation of vegetation and its role in the
hydrological cycle has been introduced, along with more detailed treatments of soil
moisture, snow, runoff, and river routing. With application of prescribed atmospheric
forcing, land may respond in a rather deterministic fashion, but when coupled to AGCMs,
the feedbacks can result in non-linear responses to perturbations that are quite different
than what one finds integrating either model separately. Enhanced or reduced sensitivities
can result; multiple equilibria may be attained.

The physical parameters that a land scheme determines are the net radiation absorbed by
the surface, how that energy is partitioned between latent and sensible heat, conductive
heat storage, and what is the difference in temperature between the surface and the near-
surface air required for net radiation to be balanced by these other fluxes. Vegetation is a
major determinant of all these factors. Also significant is the vertical movement of water
and heat within the soil column. In the present generation of land surface schemes,
observational data on the horizontal distribution of vegetation types, properties, and soil
characteristics are used as model parameters. Vegetation characteristics affect basic
properties such as albedo and roughness length. Soil properties affect the partitioning of
rainfall between runoff and infiltration, as well as the radiative, thermal, and water
holding capacities of the land. Improvements in such information, either from
observations or as interactive components of the model, should allow for more realistic
simulations of climate and its variability.

5.4 Ocean General Circulation Models (OGCMs)

The processes that determine the annual march of sea surface temperature in the eastern
equatorial Pacific Ocean are only partly known, yet this is a crucial facet of the
climatology in the Pan American domain, particularly with respect to the annual march of
the ITCZ and the northwestward shift of the American monsoon from equatorial South
America to Central America and Mexico in boreal summer. Although the annual march is
largely a reflection of coupled air-sea interactions, there remain a number of important
questions concerning the processes that contribute to sea surface temperature variability
in this region that could be addressed in the context of OGCM experiments in which the
ocean is forced by specified atmospheric fluxes. As the important components of the
ocean response become better understood, improvement of coupled models will be
expedited.

The mechanisms that control the annual march of sea surface temperature in the monsoon
regime of the eastern tropical Pacific appear to be fundamentally different from those in
the tradewind regime of the central Pacific, upon which much of the prior OGCM
development effort has been focused. In the central Pacific, where interannual variability
associated with El Niño is dominant over the seasonal cycle, the forcing is mainly in the
form of zonal wind variations. Further east, where the meridional winds are strong, the
seasonal cycle is the dominant signal. The sea surface temperature variations associated
with that cycle differ significantly from those associated with El Niño in not being
correlated with vertical movements of the thermocline. This attests to the importance, on
annual time scales, of other processes such as insolation and other surface fluxes,
upwelling, horizontal advection, and vertical mixing in the heat balance. Vertical mixing
influences sea surface temperature not only by entraining cold water into the upper layer,
but also by changing the mixed layer depth over which the surface heat and momentum
fluxes are distributed. The depth of the thermocline is a parameter that strongly
influences these various processes and hence sea surface temperatures. Valuable
information about the nature of this influence should be available from observational and
modeling studies of the seasonal cycle during different phases of the ENSO, with which
is associated large changes in the depth of the thermocline.

Ocean models have been able to simulate some aspects of annual variability in the eastern
equatorial Pacific, particularly features with large zonal scale such as the basin-wide
pressure gradients and zonal currents, yet they have had trouble simulating the annual
cycle of sea surface temperature in the eastern Pacific without resorting to
parameterizations that to some extent predetermine the result through either relaxation
terms or particular specifications of the heat fluxes. It is unclear to what extent these
unsatisfactory results are due to incomplete model physics or insufficiently well-observed
surface forcing functions. Efforts to improve these models have often focused on
parameterization of mixed layer physics, upwelling, and entrainment. One of the major motivations for the field studies described in the next section is the need for improved estimates of the surface fluxes for testing the various OGCM parameterizations.

As in the atmosphere, an issue that remains unresolved is the rectification of high-frequency forcing and internal instabilities into the low-frequency variability. Such forcing includes the equatorial intraseasonal waves, and instabilities that are prominent particularly north of the equator at periods near 20-30 days; both of these signals are modulated by the annual cycle and by ENSO. Model results suggest that the vertical velocity field can fluctuate rapidly in connection with these and other phenomena. Since mixing is an irreversible process, the net effect of high-frequency signals on the annual cycle might be quite different than would be deduced from low frequency averages alone.

Smaller-scale regional variability escapes the resolution of basin-scale OGCMs but may be significant for understanding the heat, mass, and momentum budgets over the eastern tropical Pacific. The region up to a few hundred kilometers off the Central American coast is generally very warm but can cool rapidly in response to winter northerlies blowing through gaps in the American cordillera. South of the equator, the annual coastal upwelling signal has been cited as important for the development of much larger-scale phenomena, but the processes by which the narrow coastal features might influence the larger scale have not yet been clearly elucidated. Present basin-scale OGCMs handle these near-coastal signals poorly.

The question of closure of the equatorial and tropical current systems in the east Pacific remains obscure. The fate of water flowing eastward in the North Equatorial Countercurrent and Equatorial Undercurrent is not known. To date, these current systems have been largely understood as a feature of the dynamics of the broad central Pacific, far from boundaries, where the zonal scales are very long. Similarly, the source of water upwelled in the equatorial cold tongue, the depth from which it originates, and the meridional extent of the upwelling cell have not yet been established, and it is not known whether the upwelling water can be traced back to the surface in extratropical regions, as has been suggested from theory. These and other questions about the closure of the current systems in the east speak to the most fundamental aspects of the ocean circulation in the Pan American region; they will become tractable as the community develops confidence in the performance of OGCMs in the tropical eastern Pacific.

5.5 Coupled ocean-atmosphere GCMs

Improved prediction of sea surface temperature anomalies and their effects on climate will require the development of coupled GCMs capable of simulating the seasonally varying climate accurately, since it is the mean climate that determines the linear stability and nonlinear dynamical properties of the coupled system. Coupled models tend to be more sensitive to small perturbations and to display more complex behavior than their AGCM and OGCM components. The Pan American domain, with its strong ocean-atmosphere-land interactions, provides an attractive test bed for these models. Working correctly, coupled models become the tools needed for predicting seasonal-to-interannual climate variability and for the longer term response to anthropogenic forcing.
The success of some coupled GCMs in predicting the initiation and termination of the 1997-98 El Niño indicates that they can potentially predict not only the anomalous sea surface temperature patterns in the tropical Pacific but their teleconnections to other tropical regions and the extratropics. Despite these successes, however, coupled models share some troublesome systematic errors. The simulated equatorial Pacific cold tongue generally extends too far west and tends to be too strong and too narrow. The largest biases in sea surface temperature occur along the eastern and western ends of the Pacific basin: simulated sea surface temperature is not cold enough in the east and not warm enough in the west. The models also tend to underestimate the strong equatorial rainfall anomalies in the mean climate of the eastern Pacific: sea surface temperature and rainfall are too high south of the equator. The climatological mean annual march, which strongly influences the characteristics of the ENSO cycle, also tends to be unrealistic: the ITCZ migrates across the equator rather than remaining in the Northern Hemisphere throughout nearly the entire year as observed. A pervasive problem in many of the coupled GCMs is that the western Pacific warm pool extends too far east along 10°S. This feature, combined with the tendency for the cold tongue to extend too far west along the equator, renders simulated meridional gradients too strong and zonal gradients too weak south of the equator. The excessively high sea surface temperatures in the eastern Pacific south of the equator appear to be a consequence of the lack of stratiform cloudiness that allows an excessive amount of insolation to reach the ocean surface. Many of these deficiencies relate are manifested during the "southerly regime" described in more detail in Section 6.

Coupled models will provide the ultimate test of any theory of why the cold-tongue/ITCZ complexes exist, why they tend to be asymmetric about the equator, and why they exhibit a strong annual cycle. These models will be the focal point for investigating the stratus decks and their role in global climate. Since they simulate feedbacks not represented in the AGCMs, they provide the most reliable indication of the global response to local boundary forcing.

Improved prediction of sea surface temperature anomalies in the Pan American region is a prerequisite for successful prediction of rainfall on seasonal and longer time scales over the Americas. Sea surface temperature anomalies in the tropical Pacific are currently predicted operationally out to several seasons in advance using simple coupled ocean-atmosphere models, in which the mean state and climatological-mean seasonal cycle are prescribed. The evolution of the complete tropical Pacific system is also predicted operationally using coupled GCMs. The model predictions have shown considerable skill; nevertheless, the prolonged warm episode over the tropical Pacific during the early 1990s was not successfully predicted. At present there is no definitive explanation of this phenomenon. Apparently sea surface temperature in the tropical Pacific varies, not only in response to the ENSO cycle, but also in response to processes operative on longer time scales. The El Niño event of 1997-98 was more intense than other well-documented events of the past. For many months peaking in December 1997, SSTs recorded values that in locations of the tropical Pacific were more than 5°C warmer than average. Climate prediction models demonstrated only limited ability to predict ENSO. Neither the onset
nor the amplitude of the event was well predicted by most models, and the success in predicting the evolution (growth, decay) of the event once it had begun was mixed. In general, the more comprehensive (primitive-equation) coupled models gave better and more skillful results. To promote a better understanding and improved simulation of the evolution of the SST anomalies, it will be necessary to consider the coupling between the atmosphere and ocean over a wide spectrum of time scales, ranging from a season to decades. Sensitivity studies with coupled GCMs may also be used to explore mechanisms determining the seasonal cycle of sea surface temperatures and their controls on precipitation. For example, the annual cycle of solar heating can be turned off over various regions in the model to modify sea surface temperatures and/or land processes and hence the seasonality of precipitation patterns. Coupled GCMs are the principal tool to be used in support of those studies. The improved understanding of the physical processes responsible for the variability of the tropical oceans and the improved ability to predict them with coupled GCMs will be directly relevant to the methodologies used in operational prediction centers.

A number of important technical issues in the design of coupled models have yet to be resolved. Experiments have been conducted to explore how a change in the resolution of one component of the coupled system affects the results. If the OGCM has high (finer than 1° latitude-longitude) horizontal resolution that can capture the equatorially trapped waves that transmit the signal of the wind forcing across the Pacific basin, then a realistic ENSO cycle can be reproduced in the coupled model. If the resolution of the OGCM is degraded to the point where it fails to capture those modes, other processes dominate the evolution of sea surface temperature in the equatorial waveguide and the simulation of the ENSO cycle is unrealistic. The effect of AGCM resolution on the performance of the coupled system is relatively unexplored. Coupled GCMs in which the AGCM has high horizontal resolution tend to produce a realistic annual cycle in sea surface temperature in the eastern equatorial Pacific but a very weak ENSO cycle. If the AGCM has a substantially coarser horizontal resolution than the OGCM (as is the case for most models), the simulation of the feedbacks between the atmosphere and the ocean is compromised to some extent because the AGCM is incapable of responding to the fine structure in the sea surface temperature field such as the equatorial cold tongues and narrow coastal upwelling zones. Resolving this problem requires a better understanding of the connection between the seasonal and interannual variability.

6. FIELD STUDIES

The framework for Pan American CLIVAR field studies is built on three major initiatives: EPIC (Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System), NAME (North American Monsoon Experiment) and MESA (Monsoon Experiment South America). Through enhanced climate monitoring and intensive observational campaigns, EPIC seeks a better understanding and more realistic simulation of the cold-tongue/ITCZ complex in the eastern Pacific and the processes that are responsible for the structure and variability of the extensive boundary-layer cloud decks in the southeastern Pacific. The results of EPIC are expected to improve the
performance of coupled ocean-atmosphere models over the eastern Pacific and result in improved short-term climate analysis and prediction systems for the Americas. NAME, a major national process study, supports Pan American CLIVAR scientific objectives by better defining the structure and dynamics of the monsoon in the data sparse regions of the southwestern United States and northwestern Mexico through intensive field campaigns, and will synthesize these observations to validate and improve simulations of the North American monsoon variability using coupled ocean-atmosphere-land models. MESA seeks to describe and understand several key components of the seasonally varying climate over South America that have yet to be adequately observed, including the low-level jet on the eastern slopes of the Andes and the interaction of the monsoon over the Andean highlands with circulation over the southeastern Pacific. In addition, enhanced climate monitoring, as part of MESA, will support empirical and modeling studies of ocean-atmosphere-land interactions involving the Amazon basin and southeastern South America.

EPIC is primarily a CLIVAR initiative, while NAME and MESA are joint initiatives of CLIVAR and GEWEX. The NAME and MESA field programs are also major components of the international CLIVAR VAMOS program which is being developed by VAMOS scientists and agencies in both North and South America. Elements of the US EPIC initiative are included in VAMOS implementation plans for NAME and MESA.

6.1 EPIC (Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System)

EPIC is a process study to improve the description and understanding of the cold-tongue/ITCZ (CTIC) and boundary-layer cloud deck regions. It focuses on investigating the key physical processes that must be parameterized for successful CTIC and stratus deck simulation with dynamical ocean-atmosphere models. EPIC pilot studies funded by the NOAA PACS program have already been conducted in the equatorial Pacific at 125°W, where the prevailing September-October surface winds are easterly. EPIC is presently studying the ocean-atmosphere coupling in the monsoonal regime further to the east, where southerly surface winds prevail at the equator in September-October, while maintaining interest in the eastern central Pacific and the oceanographic processes associated with the western part of the cold tongue. EPIC investigators are also studying air-sea interaction in the stratus deck region off the coasts of Peru and Chile. US EPIC efforts are a contribution to the international CLIVAR VAMOS program and are a focus of US CLIVAR Pacific and Pan American climate research.

The scientific objectives of EPIC are:

1. To observe and understand the ocean-atmosphere processes responsible for the structure and evolution of the large-scale heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex, and to
2. observe and understand the dynamical, radiative, and microphysical properties of the extensive boundary-layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime, their interactions with the ocean below, and the evolution of the upper ocean under the stratus decks.
To accomplish these objectives, enhanced monitoring and empirical studies are being conducted by the NOAA PACS program during 1999-2004 that carry on some elements from the pilot studies, initiate new elements, and provide the spatial and temporal context for EPIC. An intensive observational study called EPIC 2001 will take place in the 2000-2003 time frame, consisting of a CTIC component and an exploratory stratus deck component. An intensive observational program in the southeastern Pacific stratus deck regime is anticipated if the exploratory observations of the stratus decks and the underlying ocean during EPIC 2001 reveal significant discrepancies between models and observations. Such a project would be closely coordinated with VAMOS investigators in South America. Data analysis and modeling in which results from the enhanced climate monitoring and intensive observations are synthesized would be used for coupled model validation and improvement.

6.1.1 Pilot field studies

EPIC field studies already underway have focused primarily on the ITCZ/cold tongue complex in the eastern Pacific, which dominates the interannual variability of the coupled climate system, and the stratus cloud deck off the coast of Peru. Within the eastern Pacific cold tongue region there exist two rather different regimes that prevail within different ranges of longitude that will be labeled as “the easterly regime” and “the southerly regime” on the basis of the direction of the prevailing winds along the equator as illustrated in Fig. 37. The dividing line, near 110°W, corresponds to the ridge in the equatorial sea-level pressure profile.

Westward of 110°W, the zonal pressure gradient along the equator drives easterly surface winds that comprise the lower branch of the Walker Circulation. The easterlies induce a distinctive, equatorially symmetric upwelling signature in the sea surface temperature pattern: a reflection of surface Ekman divergence, partially balanced by an opposing geostrophic convergence due to the eastward-directed pressure gradient force that sets up in response to these winds. The divergence represents the upper branch of a pair of wind-driven circulation cells in the meridional plane, symmetric about the equator, whose convergent, lower branch is at the depth of the thermocline and the core of the Equatorial Undercurrent. The strongest and most coherent sea surface temperature fluctuations that occur in association with the ENSO cycle lie within this easterly regime. Seasonal variations are also observed, but they are weaker than those in the southerly regime farther to the east. Eastward of 110°W the strong equatorial asymmetry in the American coastline induces northward cross-equatorial flow in the atmospheric planetary boundary layer, whose curvature is in cyclostrophic balance with the zonal sea-level pressure gradient along the equator. The cold tongue, centered near 1°S, cannot be interpreted as an equatorial upwelling signature induced by westerly wind stress, since the zonal wind at these longitudes is quite weak. It may simply be the surface signature of the ridge in the thermocline above the equatorial undercurrent, rendered visible in the sea surface temperature pattern by wind-driven entrainment. Alternatively, it could be a manifestation of upwelling to the south of the equator induced by the southerly surface
winds, or it might be the signature of the plume of the cold water upwelled along the
coast of Peru.

The observed distribution of rainfall and cloud types, together with the prevailing cross-
equatorial southerly surface winds, depicted schematically in Fig. 38, suggests that this
southerly regime is characterized by a thermally direct time-mean meridional circulation.
Subsidence and extensive stratiform cloudiness prevail to the south of the equator where
sea surface temperature is remarkably cold considering the latitude, and ascent and deep
convection occur over the warm pool to the north. Much of the meridional contrast in sea
surface temperature is concentrated in a rather strong “equatorial front” which usually
lies near 2°N, and most of the rainfall is concentrated in the ITCZ, which migrates
seasonally between 6° and 12°N.

The equatorial asymmetries of wind, rain, and temperature are strongest during the boreal
summer and early autumn, when the ITCZ at these longitudes is particularly broad and
active and merges with the monsoonal precipitation over Central America. The southern
limit of the rain area, characterized by strong low-level southerly inflow, appears to be an
integral part of the ITCZ, whereas the northern limit appears to be related to the land-sea
geometry that determines the outline of the monsoonal rainfall. The extent of the stratus
cloud deck west of the Peru coast is also greatest during the boreal late summer and early
autumn and the northward flow across the equator is strongest.

The northward cross-equatorial flow, which is believed to be quite shallow, exhibits
strong diffluence as it crosses the equatorial cold tongue, and it is subject to strong air
mass modification as it passes over the warmer waters to the north of the equatorial front.
Stratocumulus cloud streets aligned with the flow, analogous to those that develop in
polar air masses advected over the Gulf Stream, are often observed downstream of the
front. The front and the atmospheric features associated with it migrate northward and
southward with the passage of westward-propagating 20-day period 1000-km wavelength
tropical instability waves whose signature is clearly evident in the sea surface
temperature image shown in Fig. 27.

The degree to which this seasonally varying meridional circulation and the associated
clouds and rainfall influences the sea surface temperature distribution and the structure of
temperature and salinity in the ocean mixed layer in the vicinity of the equatorial cold
tongue is not known. It has been suggested that the strengthening of this northward flow
around May of each year that occurs in association with the northward migration of the
monsoonal rain area over the Americas might be responsible for the pronounced
strengthening of the cold tongue at this time, but ocean models, at least as presently
formulated, exhibit only a weak response to this seasonally dependent forcing.

Sea surface temperature and mixed-layer structure within the southerly regime are
determined by a subtle interplay between a number of competing processes which may be
affected, to varying degrees, by the meridional circulation: northwestward advection of
cold water that has upwelled along the South American coast, the input of solar energy
which may be highly sensitive to the fractional coverage of stratus clouds, local wind-
driven upwelling and entrainment, and southward transport of heat by the tropical instability waves. Coupled ocean-atmosphere models fail to capture the strength of this southerly regime.

6.1.2 Expanded monitoring of the tropical eastern Pacific

EPIC enhanced ocean and atmosphere monitoring in the southerly regime of the tropical eastern Pacific builds upon the TOGA observing system, a collection of sparse in-situ observations from research and voluntary observing ships and island stations anchored by the TAO array of moored buoys. In the cold tongue / ITCZ complex, monitoring will be focussed along 95 °W, the easternmost Tropical Atmosphere Ocean (TAO) line. In the stratus deck region, monitoring is centered at 85°W, 18°S. The EPIC enhanced monitoring period is nominally 1999-2004. It is expected that these data will lead to improved climatologies of this region, and will set the context for more intensive field activities as described in 6.1.3.

Atmospheric monitoring

With nearly 70 buoys arranged along 10 lines, the TAO array forms the basic observing framework for monitoring surface wind, temperature, relative humidity, and subsurface ocean temperature in the tropical Pacific. As part of EPIC enhanced monitoring, the eastern-most TAO line at 95°W has been enhanced with additional moorings at 3.5°N, 10°N, and 12°N, and with additional sensors, including shortwave and longwave radiometers, rain gauges, barometric pressure, thermistors, conductivity sensors, and current meters. Daily averages of nearly all quantities are telemetered to Pacific Marine Environmental Laboratory via Service Argos and are made available within one day at PMEL maintained ftp databases. High-resolution data will be made available in delay mode via PMEL and via national archives.

These enhancements will enable the determination of the net surface heat, moisture, and momentum flux at the 10 sites along 95°W. With the southernmost site at 8°S, 95°W and the northernmost site at 12°N, 95°W, the picket fence extends from the stratus deck region, through the cold tongue, and north of the ITCZ monsoon trough. Surface heat flux products currently available for this region show discrepancies in both phase and magnitude of the seasonal climatologies. At 0°-110°W, the seasonal climatologies can vary by as much 80 W m⁻², although for most products the differences are closer to 20-40 W m⁻². For climate prediction, flux estimates must be accurate to 10 W m⁻². Ultimately, determination of the optimal flux product will be made based on comparisons with direct measurements, and based on which product succeeds best in closing the heat budgets.

The long time series of flux measurements from buoys will provide a benchmark by which products can be measured. These enhancements will help elucidate the nature of the surface meteorological variability, and the degree and means by which the ocean and atmosphere are coupled in the southerly regime of the eastern tropical Pacific. The ITCZ/cold tongue system is clearly coupled on seasonal and longer time scales. However, even on weekly timescales, TAO wind and sea surface temperature show tight correlation
patterns. Recent QuikSCAT scatterometer wind stress and sea surface temperature measurements indicate that coupling occurs on tropical instability wave time- and space-scales. In situ time series from the buoys will help diagnose the mechanism by which the coupling occurs.

The persistent stratus clouds off the Peruvian coast are believed to play an important role in accounting for the strong equatorial asymmetry in sea surface temperature and surface winds in the eastern Pacific. Atmospheric and coupled GCMs have difficulty simulating the extent and properties of these clouds and their interactions with the underlying sea surface temperature field. Thus, a well-instrumented air-sea interaction buoy will be deployed at 18°S, 85°W in the persistent stratus cloud deck region west of Peru and Chile for three years. The site was chosen because it is representative of the stratus region and was occupied by a NOAA NDBC buoy from 1985-1995, which will provide some historical context. The mooring will provide, with good vertical and temporal resolution, upper ocean velocity, temperature, and salinity profiles, and will collect a complete set of surface meteorological time series, allowing computation of the air-sea fluxes of momentum, heat, and freshwater. Surface meteorological data will be telemetered, enabling near real-time analysis and data assimilation.

Computation of the sensible and latent heat fluxes from buoy data will rely on a bulk algorithm. The COARE algorithm was developed for the western Pacific warm pool. In order to have the required 10 W m⁻² accuracy, the bulk algorithm must be validated, and possibly tuned, for the stratocumulus conditions of the eastern Pacific southerly regime. While marine stratocumulus clouds have been extensively studied in the past, almost no data exists on clouds or air-sea fluxes in this region. Thus, cloud and marine boundary layer measurements will be made aboard the TAO tender (NOAA ship Ka'imimoana or NOAA ship Ron Brown) which services the 95°W and 110°W TAO lines every 6 months. The instrument package consists of a cloud ceilometer, an S-band cloud/precipitation Doppler radar, a water vapor/liquid microwave radiometer, and an automated air-sea flux package including a sonic anemometer, a pair of pyranometers, a pair of pyrgeometers, slow air temperature and humidity sensors, and a ship-motion package to make the necessary corrections to calculate directly the co-variances for turbulent fluxes. This set of instruments will allow computation of low cloud statistics (integrated liquid water content, cloud base height, and fraction) and the complete surface energy budget of the oceanic and atmospheric boundary layers. The cloud statistics will help improve cloud models and satellite retrieval methods. When combined with measurements of downward longwave and shortwave radiative fluxes, the cloud measurements will allow computation of cloud IR and visible optical thicknesses plus the surface cloud radiative forcing, a key diagnostic variable in climate models.

The TAO tender will also be used to launch radiosondes to monitor the tropospheric structure; in particular, the atmospheric boundary layer (ABL) along 95°W and 110°W on 6-month intervals. These observations will be used to examine the ABL and its relationships to the underlying sea surface temperature and the background, large-scale atmospheric flow. Higher temporal resolution will be provided at island stations. However, at present the operational upper-air sounding network is extremely sparse. At
As with the atmospheric monitoring, the TAO array forms the basic framework of ocean monitoring. Standard ocean TAO measurements include sea surface temperature and
subsurface temperature at 10 depths with 20 m to 200 m vertical resolution. This vertical
resolution, however, is not sufficient for monitoring variability within the mixed layer,
the site of active ocean-atmospheric interactions. Thus as part of the EPIC enhanced
monitoring program, the 10 enhanced 95°W TAO moorings (at 8°S, 5°S, 2°S, 0°, 2°N,
3.5°N, 5°N, 8°N, 10°N, and 12°N) have additional sensors to monitor the upper ocean
temperature, salinity, and surface currents. These TAO ocean measurements together
with the surface heat, moisture, and momentum flux enhancements form a
complementary coupled ocean-atmosphere observing system for the ITCZ/cold tongue
complex in the southerly regime of the eastern tropical Pacific. Although zonal gradients
and thus the effects of zonal advection are not well resolved, the local response to the
surface wind and buoyancy forcing can be evaluated at each of the ten 95°W mooring.
Understanding the relationship between the meridional gradients in the surface forcing
and sea surface temperature is a major objective of this study. The Pan American region
is characterized by large meridional gradients not only in the heating and sea surface
temperature fields, but also in the rainfall and salinity fields. Conductivity Temperature
Depth (CTD) measurements taken from the TAO tender along 95°W show surface
salinity as low as 33.5 psu near 5-8°N associated with the ITCZ, while south of 5°S, the
surface salinity is higher than 35 psu. Salinity is an important variable not only because it
is a rough indicator of rainfall patterns, but because it affects the buoyancy of the water
column. Thus salinity can affect sea surface temperature through its influence on vertical
mixing, penetrative radiation, and dynamic height (and thus ocean currents and
advection). It is expected that the freshwater influence within the ITCZ plays an
important role in maintaining the warm sea surface temperatures despite the shallow
thermocline in the region.

In the stratus region, the air-sea interaction buoy at 18°S, 85°W will monitor the upper
temperature, salinity, and current profile with high temporal and vertical resolution.
Ocean measurements also will include a floating sea surface temperature sensor at 5 cm
depth. These data will be used to analyze the temporal evolution of the surface forcing
and upper ocean structure on time scales from minutes to seasonal, and possible feedback
mechanisms that link that evolution of the atmospheric and oceanic boundary layers in
the stratus region. Understanding and properly parameterizing the coupling mechanism
in the stratus region is crucial for simulating the observed climatic asymmetries in the
Pan American region.

Circulation in the Pan American region is fully three-dimensional with strong upwelling
near the equator and relatively shallow zonal currents associated with the Equatorial
Undercurrent, South Equatorial Current, the North Equatorial Countercurrent and the
North Equatorial Current, all of which are in some way affected by the nearby continental
boundaries. Understanding the three-dimensional circulation is critical for determining
the inter-hemispheric transfers and the pathways of water as they enter and exit the
equatorial current system. At present, this complex oceanic circulation is not adequately
monitored. As part of the ENSO observing system, the horizontal currents have been
monitored at 0° 110°W by an Acoustic Doppler Current Profiler (ADCP) and/or current
meters since 1980, providing one of the longest time series of currents available. The
enhanced moorings along 95°W also have a very sparse array of current meters.
However, with only 1-2 current meters per mooring, this array does not adequately resolve the vertical shear. ARGO floats and surface drifters will be relied upon to provide information on the large-scale circulation patterns. Shipboard ADCP measurements from the TAO tender provide excellent meridional resolution of the current structure, but only every 6 months. Large-scale geostrophic current fields can also be computed from dynamic height estimates from TAO moorings, CTDs, and XBTs, and from TOPEX satellite sea level height measurements. However, none of these monitoring systems is able to measure the equatorial upwelling that is crucial for understanding the dynamics and variability of the cold tongue. Likewise, while the large-scale current structures may be resolved, the rich variability and interactions associated with the large horizontal and vertical shears between the currents structures are not well resolved. Feasibility studies based on historical data, and numerical and theoretical models may lead to an improved strategy for monitoring the critical components of this three-dimensional ocean circulation.

6.1.3 EPIC 2001

In addition to the expanded monitoring discussed in the previous section, Pan American CLIVAR investigators will conduct a short-term field study, called EPIC 2001, which is designed to improve understanding and modeling of seasonal-to-decadal climate variability within the eastern tropical Pacific. The experiment consists of four components, focusing on (a) ITCZ/warm-pool phenomena, (b) cross-equatorial inflow into the ITCZ, (c) upper ocean structure and mixing in the ITCZ/warm-pool, and (d) an exploratory study of boundary-layer cloud properties in the southeasterly tradewind regime. Each component will be coordinated to share resources and create a dataset with added value. The field phase, involving intensive shipboard atmospheric and oceanic boundary-layer measurements and aircraft surveys, is presently scheduled for a 6-week period in August-October 2001. Taking advantage of the enhanced monitoring already in place along 95°W, the fieldwork for the first three components will be focused along 95°W, particularly near 10°N.

6.2 North American Monsoon Experiment (NAME)

During 2000-2010, the Pan American field studies will emphasize the American monsoons. A specific process study of interest to US CLIVAR is the North American Monsoon Experiment (NAME), an internationally coordinated effort aimed at determining the sources and limits of predictability of warm season precipitation over North America, with emphasis on time scales ranging from seasonal-to-interannual. The US NAME is a major process study of US CLIVAR.

The principal objectives of NAME are:
1. a better understanding of the key components of the North American monsoon system and its variability.
2. a better understanding of the role of this system in the global water cycle.
3. improved observational datasets.
4. improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources.

Achieving these objectives will require improved empirical and modeling studies of the monsoon system and its variability, sustained observations of the atmosphere, ocean and land and enhanced observations over portions of the core monsoon region, combination of the observations and numerical models through data assimilation, and coupled model runs with various combinations of the relevant boundary forcing parameters.

NAME will link CLIVAR-led programs, which have an emphasis on ocean-atmosphere interactions and GEWEX-led programs, which have an emphasis on land-atmosphere interactions and ground hydrology, in order to determine the relative importance of the coupled interactions between the ocean, land, and atmosphere as they relate to the monsoon. NAME will integrate the work of GEWEX/GAPP, which continues and expands GCIP efforts with a NOAA PACS/GCIP research initiative on the seasonal-to-interannual variability of warm season precipitation. In addition, NAME will also make a major contribution to CLIVAR/VAMOS, which is coordinating international field programs and dataset development efforts as well as empirical and modeling research on the American monsoons. Other anticipated benefits of NAME include: joint international experience in the exploitation of in situ data and new satellite sensors measuring atmospheric, surface, and hydrological parameters over the Americas; joint international experience in assessing the capabilities and limitations of assimilated data products for capturing these parameters; advancements in coupled model development over land and ocean areas; advancements in the development of the climate observing system; and the production of consistent datasets over North America that can act as test beds for the validation of numerical model products and remote sensing data.

The NAME objectives will be addressed by a mix of diagnostic, modeling, and prediction studies together with enhanced observations. This research activity will necessarily be diverse because it seeks to answer scientific questions relating to several different coupled processes and phenomena. A multi-scale (tiered) approach to the analytic, diagnostic, and model development activities of NAME is recommended (Fig. 40). NAME will include focused activities in the core monsoon region, on the regional-scale and on the continental-scale, which for convenience are referred to as Tier I, Tier II, and Tier III respectively. Each tier has a specific research focus aimed at improving warm-season precipitation prediction, and activities related to each tier will proceed concurrently.

Tier I focuses on key aspects of the low-level circulation and precipitation patterns in the core monsoon region. The goal of activities in this region is improved monitoring and modeling of the coupling between the sea breeze/land breeze and mountain/valley circulations. This coupling is intimately related to the diurnal cycle of moisture and convection in the core monsoon region, so a better understanding of it is viewed as a fundamental step towards improved warm season precipitation prediction. Some principal scientific questions are: How is the coupling between the sea breeze/land breeze and mountain/valley circulations along the Gulf of California related to the diurnal cycle of
moisture and convection? What role does the Gulf of California low-level jet play in the
summer precipitation and hydrology of southwestern North America? What are the
dominant sources of precipitable moisture for monsoon precipitation over southwestern
North America? What are the relative roles of local variations in sea surface temperature
and land-surface parameters (topography, soil moisture, and vegetation cover) in
modulating warm season precipitation in this region? What are the effects of aerosol
loading from dust, smoke, and anthropogenic emissions on precipitation in the core
monsoon region?

Tier II focuses on regional-scale features over southwestern North America and the warm
pool region to the southwest of Mexico. The goal of activities in this region is an
improved description and understanding of intraseasonal aspects of the monsoon. A field
study focusing on intraseasonal variability might address the following questions: How
important are interactions between Tropical Easterly Waves (TEWs) and Gulf of
California moisture surges in the prediction of monsoon precipitation? What is the nature
of the relationship between the Madden-Julian Oscillation (MJO), tropical cyclone
activity, and monsoon precipitation? What portion of the skill of summer precipitation
forecasts, in addition to that already harvested from ENSO, will arise from an ability to
forecast MJO activity over a season? What is the physical setting for the bimodal
distribution (i.e., wet-dry-wet) in warm season precipitation over Mexico and Central
America and what factors influence its interannual variability?

Tier III focuses on aspects of the continental-scale monsoon circulation. Here the goal is
an improved description and understanding of spatial/temporal linkages between warm
season precipitation, circulation parameters and the dominant boundary forcing
parameters. A field study focusing on the continental-scale monsoon might address the
following questions: How is the evolution of the warm season precipitation regime over
North America related to the seasonal evolution of the boundary conditions? What are
the interrelationships between year-to-year variations in the boundary conditions, the
atmospheric circulation, and the continental hydrologic regime? What are the links, if
any, between the strength of the summer monsoon in southwestern North America and
summertime precipitation over the central United States? What are the relationships
between the statistical frequency and magnitude of extreme events (e.g., floods, droughts,
hurricanes) and climate variability on intraseasonal-to-interannual time scales?

Elements of the field study would include special soundings (rawinsondes, pilot
balloons), improvements to the raingauge network (both simple and digital recording
raingauges), transects from the Gulf of California to the Sierra Madre Occidental (wind,
surface temperature, sea-level pressure from automated weather stations), research
aircraft flights, and other ground-based elements (e.g., 915 MHz wind profilers, radars).
The overall philosophy for observing-system enhancements will be to augment pre-
existing routine observing systems over the region of interest with special observations
that will adequately describe the features of interest. Regional mesoscale models and
regional data assimilation systems will be used to guide enhanced monitoring activities.
These studies will be carried out in tandem with land surface model experiments and land
data assimilation experiments, and will benefit from multi-year regional reanalyses and retrospective soil moisture analyses.

The enhanced monitoring activities should operate for at least 4 summer months (June-September) to coincide with the peak monsoon season. During this period there would be a number of Intensive Observing Periods (IOPs), each lasting from 2-5 days, in order to describe some aspects of the regional low-level circulation in greater detail than can be provided by twice-daily soundings. The timing of the enhanced monitoring activities would be coordinated with other field studies such as EPIC, ALLS, and CEOP.

6.3 Monsoon Experiment South America (MESA)

The South American monsoon system exhibits similarities and differences from its North American counterpart as briefly discussed in section 1.4. Similar overall objectives as those described for NAME above have guided the development of MESA. The two experiments are internationally coordinated efforts to improve prediction of warm-season precipitation over South and North America and have been coordinated under the auspices of VAMOS/International CLIVAR. The principal objectives are 1) a better understanding of the key components of the American monsoon systems and their variability, 2) a better understanding of the role of those systems in the global water cycle, 3) improved observational datasets, and 4) improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources. MESA benefits from recent field experiments (such as LBA and campaigns over the Altiplano) that have started to shed some light on land-atmosphere interactions in South America. MESA is designed using a two-stage approach, in which each stage has its own scientific objectives and is preparatory of the next (Fig. 41).

MESA’s Stage 1 comprises the component of the American Low-Level Jets (ALLS) program that focuses on the moisture corridor between the Andes and the Brazilian Altiplano. The main objective of this component is to better understand the role of moisture transports, their variability, and links to remote and local climate anomalies of the South American low-level jet (SALLJ). Scientists from Argentina, Brazil, Chile, and the US have developed a field program on SALLJ under the auspices of VAMOS.

Scientists from Bolivia and Paraguay are expected to participate in the campaign, which is planned for 2002-2005. Stage 1 also comprises VEPIC, a field program along the Chilean coast that is an extension of EPIC. Peruvian scientists will also be involved in VEPIC, which is tentatively scheduled for 2002-2004.

Stage 2 will be a study of the hydroclimatolgy of the La Plata River Basin (PLATIN). Here the goal is an improved description and understanding of spatial / temporal linkages between precipitation and streamflow. Scientists from Argentina, Brazil, Uruguay and the US have prepared a document preparatory to a field campaign. The current tentative date for PLATIN is 2005-2010.

These stages have been motivated by a recognition of the unique character of the South American climate and its linkages to the nearby oceans (South Pacific and both North and South Atlantic). The disparity between North and South America regarding 1) density of conventional observing systems and 2) number of past field experiments available to
address the above stated objectives. This has resulted in a stronger dependence on numerical products and satellite data for studies related to the climate of South America than for similar studies over North America. MESA stage 1 is currently planned to precede NAME Tier I in an effort to decrease this dependence and to address the scientific challenge posed by the regional climate over South America.

7. THE PAN AMERICAN OBSERVING SYSTEM

US CLIVAR will promote the establishment of an integrated network of climate observations of the coupled land-atmosphere-ocean system in the Pan American region, built on existing operational networks and the legacy of the TOGA program in the Pacific Ocean. Figure 42 shows elements of the current surface and upper-air components of the existing climate observing system. In general, the climate observing system is less dense over Latin America than it is over the US, and large areas of South America are without upper-air soundings. The TAO and PIRATA mooring arrays in the tropical eastern Pacific and Atlantic Oceans provide unprecedented coverage of upper-ocean temperature, salinity and surface meteorological data, but vast areas of the tropical and southern Pacific and Atlantic Oceans are virtually without routine upper air soundings.

Through its Pacific, Pan American and Atlantic observational activities, US CLIVAR will begin a number of enhanced monitoring activities that will promote the development of a permanent climate observing system. The ARGO system of upper-ocean profiling floats will provide unprecedented coverage of upper ocean temperature and salinity over large areas of the Pacific and Atlantic Oceans during the CLIVAR period. A network of research quality air-sea interaction buoys will provide information on upper-ocean conditions and air-sea exchanges of heat, water and momentum in key climatic regimes over the Pan American domain. The NOAA PACS SONET project provides seed money for upper-air sounding equipment and training in Latin American. VAMOS investigators are planning an array of moored upper-ocean buoys extending the full length of the west coast of South America. NASA and international research satellite missions providing improved global coverage of sea surface temperature, wind stress, sea level, precipitation and other climatic parameters may become operational during the CLIVAR period. A legacy of US CLIVAR will be the further development and integration of these disparate data sources to produce a climate data set that is capable of describing the coupled ocean-atmosphere-land system.

8. RELATIONSHIP OF US CLIVAR TO OTHER PAN AMERICAN CLIMATE RESEARCH EFFORTS

US CLIVAR and GEWEX are complementary programs in the Pan American region that both emphasize continental precipitation. US CLIVAR emphasizes the planetary-scale context and the variability of the weather systems that produce rain, on seasonal and longer time scales while GEWEX emphasizes land-atmosphere interaction on intraseasonal-to-interannual time scales. Mesoscale modeling of continental precipitation in a climate context is a common element of both programs. The GEWEX projects of GCIP focus on North American rainfall and the Brazil/NASA led LBA
A NOAA hydrometeorology program focuses on rainfall in the Amazon basin. A NOAA PACS/GCIP research initiative focuses on the seasonal-to-interannual variability of warm season rainfall, surface air temperature, and the hydrologic cycle over North America. United States CLIVAR and GEWEX will bring together the respective strengths and areas of expertise of their participating scientists. There will be cooperation through complimentary projects such as the CLIVAR Seasonal-to-Interannual Modeling and Prediction project (SIMAP), the GEWEX Land Atmosphere System Study (GLASS), and through the ISLSCP and the GSWP.

CLIVAR is going forward with the formulation of plans for an international research project focused on VAMOS. It is anticipated that US CLIVAR Pan American research will make a major contribution to VAMOS, and that US CLIVAR will benefit from international coordination and planning of field programs and dataset development, and from the development of new empirical and modeling research on the American monsoons by scientists in North, Central, and South America. US CLIVAR will coordinate its eastern Pacific field studies with the Scripps-Lamont CORC, which has begun enhanced ocean monitoring in the eastern tropical Pacific for 5 years beginning in 1998. It is anticipated that Pan American research activities of US CLIVAR will contribute to the development of a CLIVAR Pacific BECS, focusing on the processes that couple tropical, subtropical, and subarctic wind-driven gyres on seasonal-to-decadal time scales, including the decadal modulation of ENSO.

NASA is sponsoring a number of research satellite missions of importance to US CLIVAR. TRMM launched its first satellite in November 1997 to map tropical precipitation. The satellite orbits between 35°N and 35°S at an altitude of 350 km. The low inclination and altitude maximizes coverage and resolution in the tropics. A 2-cm wavelength radar and passive microwave radiometers with frequencies ranging from 10 to 85 GHz measure the rainfall. These remote measurements must be validated by ground-based rain measurements. The eastern Pacific ITCZ presents a particular problem in this regard because of the sparse island stations in that region. The shipborne radar and other precipitation measurements obtained during US CLIVAR process studies over the tropical eastern Pacific Ocean will provide valuable validation data for TRMM. In addition, wind stress measurements from the NASA QuikSCAT, sea surface temperature from the TRMM microwave instrument, and sea level from TOPEX and its follow-ons, are providing data of unprecedented quality for air-sea interaction research.

A pilot-scale moored measurement program is being designed as the centerpiece of PIRATA. The purpose of PIRATA is to provide time series data of surface fluxes, surface temperature and salinity, and upper ocean heat and salt content to examine processes by which the ocean and atmosphere interact in key regions of the tropical Atlantic. The field phase of PIRATA began in 1997 and is scheduled to last for three years. Deployment of up to 14 moorings is part of a multinational effort involving Brazil, France, and the United States. PIRATA will contribute to planning for a CLIVAR BECS on Atlantic climate variability.
9. PROGRAM MANAGEMENT

The US CLIVAR Pan American Implementation Panel provides advice to the US CLIVAR Scientific Steering Committee (SSC) regarding the design and implementation of US CLIVAR research activities in the Pan American region and provides liaison with the international CLIVAR VAMOS program. The Pan American panel also establishes subgroups, as necessary, for detailed planning with regard to specific program elements such as monitoring, process studies, dataset development, and modeling. The US CLIVAR program is jointly administered by an interagency group made up of program managers from the participating agencies. Proposals for Pan American research are solicited as part of a US CLIVAR program announcement issued once a year. The program announcement is developed by the US CLIVAR SSC and its implementation panels in consultation with the agency program managers. Proposals are reviewed for scientific merit and relevance to US CLIVAR objectives. Proposals from NOAA and NASA investigators are considered in competition with proposals from external investigators. The program managers jointly determine those proposals to be supported from the results of the mail reviews and advice from the US CLIVAR SSC and its implementation panels.

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NOTES ON ILLUSTRATIONS

Figure 1. The rainfall estimates in the upper panel are a hybrid of two different datasets. Over the oceans they are based on the MSU carried aboard the Television Infrared Operational Satellites (TIROS) for the period 1979-1991. The method for inferring rainfall from MSU measurements is described in Spencer (1993). Over land, they are based on a compilation of historical rain gauge data by Legates and Willmott (1990). The GPI is described in Arkin and Meisner (1987), and based on 1986-1993.

Figure 2. Surface winds are based on an analysis of the COADS (Woodruff et al. 1987, 1993) performed by Sadler et al. (1987). They represent averages for the period 1900-1979. Rainfall estimates are as in the upper panel of the previous figure. The outline for the stratus cloud decks corresponds to the 0.3 contour in an albedo map derived from 4 years of visible satellite imagery. Only surface winds in excess of 3 m/s are plotted, and annual precipitation totals in excess of 2 m are shaded.

Figure 3. Surface winds and sea-surface temperature climatologies are from Sadler et al. (1987) as in the previous figure. The shading varies from blue to red for cold to warm sea surface temperatures, with gray indicating temperatures near 27°C. The wind plotting convention is as in the previous figure.

Figure 4. As in Fig. 3, but arrows denote surface currents based on the Richardson (1989) climatology of the historical record of ship drift measurements.

Figure 5. Courtesy of G. Feldman, NASA.

Figure 7. Circulation data taken from the NCEP/NCAR reanalysis archive. Precipitation estimates are based on merged satellite and station observations. North American panel courtesy of W. Higgins and M. Halpert; South American panel courtesy of V. Kousky and M. Halpert.

Figure 12. After Mitchell and Wallace (1992), based on observations from the COADS for 1946-1985.

Figure 13. Based on data from the TOGA-TAO array (McPhaden and McCarty, 1992). The climatology for 140°W is based on observations for July 1983 to December 1991 and for 110°W from March 1980-June 1982 and July 1983-December 1991. The period of large anomalies during the 1982-1983 ENSO event, July 1982-June 1983, were not included in the climatology to prevent large biases due to this single event. Red shading for temperatures greater than 24°C, with increases in color intensity for each 1°C increase in temperature. Blue contours for temperatures less than and equal to 22°C; contour interval 2°C.

Figure 14. Derived from high-resolution infrared images from geostationary satellites, 8 per day. Courtesy of K. Howard, NOAA NSSL.

Figure 15. Surface wind changes based on the COADS; sea-level pressure based on the ECMWF operational analyses; and rainfall as in the upper panel of Fig. 1. The surface wind and sea-level pressure climatologies are based on data for 1946-1979 and 1980-1989, respectively. Only vector wind changes with magnitudes in excess of 1 m/s are plotted. Pressure changes in increments of 0.6 mb are contoured, and precipitation changes in excess of 5 cm in magnitude are shaded. The sea-level pressure analysis over land is consistent with an analysis of historical airport pressure records (not shown).


Figure 21. Regression of sea surface temperature and MSU precipitation on an index of eastern equatorial Pacific (6°N-6°S, 180-80°W) sea surface temperature. The analysis is based on data for 1982-1991 and 1979-1991 for the sea surface temperature and precipitation fields, respectively. The sea surface temperature analyses are from NOAA NCEP. Temperature contour interval 0.2°C per 1 standard deviation of the index, with negative (zero) contours dashed (thickened). Shading for precipitation anomalies greater than 1 cm per 1 standard deviation of the index. Precipitation anomalies range from -4 to +10 cm per 1 standard deviation of the index.
Figure 24. The precipitation time series is the average of 6 stations in northeast Brazil (including Fortaleza and Quixeramobim), and the sea surface temperature is from the COADS. The analysis is based on data for 1946-1985.

Figure 25. After Thompson et al. (1979).

Figure 26. The NSCAT wind vectors are the simple average over one degree bins and one month. The divergence is calculated from the averaged wind vectors and then zonally smoothed along each latitude with a Loess smoother having a half span of 10 degrees. Courtesy of D. Chelton, Oregon State University.

Figure 27. Observations taken by the NOAA-7 Advanced Very High Resolution Radiometer (AVHRR). Courtesy of Gene Feldman, NASA.

Figure 30. 10-m vector winds are from the European Remote Sensing Satellite (ERS-1) and the sea surface temperature analysis is from NOAA’s NCEP. The ERS-1 winds are plotted with a 1° resolution. Sea surface temperatures range from nearly 29°C in regions of reddest shading to below 27°C along 5°N.

Figure 31. Based on high-resolution infrared images from geostationary satellites, 8 per day. Courtesy of K. Howard, NOAA NSSL.

Figure 32. US series obtained from the National Climate Data Center Climate Division dataset, and Brazil and Ecuador time series from the NCAR World Monthly Surface Station Climatology.

Figure 34. Precipitation time series as in Fig. 39. Sea surface temperature for 1950-1991 from Smith et al. (1996) and for 1992 from Reynolds and Smith (1994).

Figure 37. Sea level pressure and surface wind from Sadler et al. (1987). Rainfall as in Fig. 1.

GLOSSARY OF ACRONYMS

ALLS: American Low-level Jets
AGCM: Atmospheric Global Circulation Model
ASTEX: Atlantic Stratocumulus Transition Experiment
ATLAS: Automated Temperature Line Acquisition System
AVHRR: Advanced Very High Resolution Radiometer
BECS: Basinwide Extended Climate Studies
CDF: common data format
CIRES: Cooperative Institute for Research in Environmental Sciences
CLIVAR: Climate Variability and Predictability
COADS: Comprehensive Ocean-Atmosphere Data Set
COARE: Coupled Ocean-Atmosphere Response Experiment
CORC: Consortium for the Ocean’s Role in Climate
CTD: conductivity temperature depth
ECMWF: European Centre for Medium-Range Weather Forecasts
ENSO: El Niño/Southern Oscillation
EPOCS: Equatorial Pacific Ocean Climate Studies
EUC: equatorial undercurrent
FIRE: First ISCCP Regional Experiment
GARP: Global Atmospheric Research Program
GATE: GARP Atlantic Tropical Experiment
GCIP: GEWEX Continental-scale International Project
GCM: Global Circulation Model
GEWEX: Global Energy and Water Experiment
GOALS: Global Ocean-Atmosphere-Land System
GPI: GOES Precipitation Index
IMET: Improved Meteorological Instrument
ISCCP: International Satellite Cloud Climatology Project
ITCZ: intertropical convergence zone
LBA: Large-Scale Biosphere-Atmosphere Experiment in Amazonia
MSU: microwave sounding unit
NASA: National Aeronautics and Space Administration
NCAR: National Center for Atmospheric Research
NCEP: National Centers for Environmental Prediction
NECC: north equatorial countercurrent
NOAA: National Oceanic and Atmospheric Administration
NSCAT: NASA scatterometer
NSSL: National Severe Storms Laboratory
OAR: Office of Oceanic and Atmospheric Research
OGCM: Ocean Global Circulation Model
OGP: Office of Global Programs
PACS: Pan American Climate Studies
PBL: planetary boundary layer
PIRATA: Pilot Research Moored Array in the Tropical Atlantic
PMEL: Pacific Marine Environmental Laboratory
PNA: Pacific North American
SEC: south equatorial current
SONET: sounding network
SWG: Science Working Group
TAO: Tropical Atmosphere-Ocean
TIROS: Television Infrared Operational Satellite
TOGA: Tropical Ocean-Global Atmosphere
TRMM: Tropical Rainfall Measurement Mission
USF/ADCP: University of South Florida Acoustic Doppler Current Profiler
VAMOS: Variability of the American Monsoon Systems
VOS: volunteer observing ship
WCRP: World Climate Research Programme
XBT: expendable bathythermograph
Figure 1. Annual mean precipitation over the tropics, as inferred from different data sources. The upper panel is based on the microwave sounding unit over the ocean and a land climatology compiled from station data. The lower panel shows the Geostationary Operational Environmental Satellite precipitation index (GPI) inferred from high-resolution imagery of outgoing longwave radiation. The bands of heavy precipitation over the tropical Pacific and Atlantic are the oceanic ITCZs. Quantitative estimates of precipitation in meters per year can be inferred from the color bar at the bottom.
Figure 2. Climatological annual mean conditions over the PACS region. Vectors denote surface winds, orange-yellow shading denotes precipitation, and gray-blue shading denotes stratus cloud decks. Over both the Atlantic and Pacific, the ITCZ is located well to the north of the equator, and southeasterly trades extend across the equator. The stratus cloud decks are more extensive in the Southern Hemisphere.
Figure 3. As in Fig. 2, but shading denotes annual mean sea surface temperature. The warmest (reddest) waters are observed, not on the equator, but in the Northern Hemisphere near the latitude of the ITCZ.
**Figure 4.** As in Fig. 3, but arrows denote surface currents. The eastward arrows at the latitude of the ITCZ correspond to the North Equatorial Countercurrent and the longer westward arrows along and just to the south of the equator correspond to the South Equatorial Current.
Figure 5. Annual mean chlorophyll concentrations based on Coastal Zone Color Scanner imagery. The color scale has been adjusted to enhance the weak gradients in the vicinity of the equator. The enhanced concentrations along the equator in both oceans are signatures of upwelling. Concentrations are also enhanced beneath the ITCZ, in the region of coastal upwelling along the Peruvian coast and downstream (on the Pacific side) of the gaps in the mountain ranges of Central America.
Figure 6. Topography of North and South America at approximately 5\degree \textprime \ (shading interval 200 m) resolution and at the typical 2\degree latitude-longitude resolution of an atmospheric general circulation model that is used in climate simulations.
Figure 7. Annual mean distribution of soil moisture and vegetation over North and South America. Annual mean soil moisture (blues), fpar vegetation (greens), and snow (white).
Figure 8. Mean (1979-1995) warm season precipitation (mm, shading) and circulation at 925 hPa (vector winds) and 200 hPa (streamlines): a) July-September. The position of upper level monsoon anticyclone over the southwestern United States and northwestern Mexico is indicated by an "A". The subtropical surface high pressure centers over Bermuda and North Pacific are indicated by "H". The approximate location of the Great Plains low-level jet is indicated by a heavy solid arrow. b) December-February. The position of the upper level monsoon high over Bolivia is indicated by an "A". The South Atlantic subtropical surface high pressure center is indicated by an "H". The approximate axis of the South Atlantic Convergence Zone (ACZ) is indicated by the heavy dashed line.
Figure 9. As in Fig. 2, but for the March-April mean (upper panel) and September-October mean conditions (lower panel). Note the double ITCZ configuration in the Pacific, symmetric about the equator in March-April, in contrast to the prominent single ITCZ near 10°N in September. A strongly contrasting structure is also observed in the Atlantic sector, with the ITCZ displaced farther north in September-October. Rainfall rates in excess of 20 cm per month are colored orange-yellow.
Figure 10. Time-latitude sections of the mean (1961-1990) annual cycle of (a) precipitation, (b) maximum surface temperature, (c) minimum surface temperature, and (d) diurnal temperature range (i.e. the difference between [b] and [c]). Data are averaged zonally over west coast land points at each latitude.
Figure 11. As in Fig. 3 but for the March-April mean (upper panel) and September-October mean conditions (lower panel). The warm pool to the north of the equator is present year round. The largest seasonal contrasts are observed along the southern flank of the equatorial cold tongue. September-October is the time of strongest meridional temperature contrast across the equator.
Figure 12. Scatter plot of monthly mean sea surface temperature (°C) in the equatorial cold tongue regions of the Atlantic and Pacific for individual years/months, grouped by calendar month. The dots for each calendar month are staggered along the x axis to make them more visible, and the calendar year is repeated. Note the high degree of reproducibility of the seasonal march, particularly in the Atlantic, where El Niño exerts only a modest influence.
Figure 13. Depth-time sections of climatological mean temperature (°C) on the equator at 110°W (upper panel) and 140°W (lower panel) showing how the seasonal march tends to be much stronger near the surface than near the thermocline.
Figure 14. Frequency of occurrence of clouds with tops colder than -38°C as revealed by high-resolution satellite imagery for the years 1990-93. (top) June, (middle) July, (bottom) the difference of July minus June. In most years, the northward shift of the rainfall in northwestern Mexico and Arizona occurs rather abruptly around July 1. Despite this shift, the same distinctive signature of the orography and coastal geometry is evident during both months over much of Central America.
Figure 15. July minus June differences in surface winds (arrows), sea-level pressure (contours: gold denotes pressure increases; zero contour thickened), and rainfall (shading: red denotes increases and blue decreases). The freshening of the trades over much of Central America is related to the rise in sea-level pressure over Mexico. The prevailing northwesterly winds along the west coast of Mexico weaken, allowing surges of moist southerly flow to penetrate into the Gulf of California. The linkage between month-to-month changes in the continental monsoon and the ITCZ appears to be stronger in the microwave sounding unit imagery and rain gauge data shown here than in the infrared imagery shown in the previous figure.
Figure 16. March-April and September-October soil moisture (blues) and vegetation (greens).
October, November, December snow cover

April, May, June snow cover

Figure 17.
Figure 18. July minus June precipitation (1.5cm/month shading intervals).
Figure 19. Interannual variability of vegetation (LAI).
Figure 20. Summary of the major large-scale climate anomalies associated with the warm phase of the ENSO cycle during the Northern Hemisphere winter.
Figure 21. Sea surface temperature anomalies (contour interval 0.2°C) and ocean rainfall anomalies during a typical warm episode of the ENSO cycle. Enhanced rainfall, indicated by the red shading, is observed over the region of above-normal sea surface temperature, and reduced rainfall, indicated by the blue shading, is observed throughout much of the surrounding region and over the tropical Atlantic adjacent to Northeast Brazil.
Figure 22. Time-latitude sections of the core of the heavy rainfall associated with the Pacific ITCZ, averaged over longitudes 180-110°W. Estimated rainfall amounts range from 20 cm per month for the orange up to ~50 cm per month for the yellow. Each year the ITCZ is closest to the equator from February through April. The rainy seasons of 1983 and 1987 fell within warm episodes of the ENSO cycle.
Figure 23. Anomalous rainfall observed during a typical warm episode of the ENSO cycle (colored shading, repeated from Fig. 21) shown with the corresponding pattern of anomalies in mean tropospheric temperature (contours: gold positive and green negative). The pair of temperature extrema straddling the equator in the eastern Pacific are warm anomalies, which correspond to anomalous anticyclonic gyres in the upper-tropospheric flow. These disturbances in the upper-level flow are responsible for the wide-ranging impacts of ENSO upon the climate of the Americas.
**Figure 24.** Correlation between average February through May precipitation in northeast Brazil and sea surface temperature. Red (blue) shading indicates regions in which above-normal sea surface temperatures tend to be observed in conjunction with the above (below) normal rainfall in northeast Brazil. The strongest correlations are on the order of 0.7. Northeast Brazil rainfall tends to be more strongly correlated with Atlantic sea surface temperatures than with Pacific sea surface temperatures.
Figure 25. Contrasting vertical mass flux profiles in disturbed regions of the ITCZ in the eastern Atlantic and the "warm core" region of the western Pacific. In the ITCZ the low-level convergence (indicated by the large negative vertical derivative) is concentrated within the lowest 1.5 km, whereas in the western Pacific it is much weaker and extends all the way up to 5 km.
Figure 26. NASA scatterometer (NSCAT) 10-m vector wind averaged for November 1996 (vectors) and the corresponding divergence field. Red and blue denote convergence and divergence, respectively. Shading units in increments of $10^{-5}$ s$^{-1}$. 
Figure 27. Sea surface temperature based on high-resolution satellite imagery during a two-week period in July 1984, a time when the equatorial Pacific was relatively cold. The reddish color represents temperatures in excess of 27°C, which often correspond to the threshold for tropical convection to be able to occur. The colder waters of the equatorial cold tongue are rendered in shades of blue. The sharp northern edge of the cold tongue is distorted by westward-propagating tropical instability waves which originate in the ocean, but produce a distinct signature in the fields of cloudiness and wind speed.
Figure 28. Typical wintertime weather anomalies preceding heavy precipitation events over the northwestern U.S.
Figure 29. Composited evolution of 200 hPa velocity potential anomalies ($10^6 \text{ m}^2 \text{ s}^{-1}$) and points of origin of weather systems that developed into hurricanes or typhoons (o).
Figure 30. Surface wind and sea temperature averaged for December 1992. Shading over land indicates elevations in excess of 500 m. Strong offshore flow downstream of the gaps in the mountain ranges, with monthly mean wind speeds as high as 10 m s\(^{-1}\), gives rise to local sea surface temperature minima, indicated by the lighter red shading in the figure and enhanced chlorophyll concentrations (Fig. 5).
Figure 31. Frequency of deep convection as indicated by the occurrence of clouds with tops colder than -38°C at two different times of day during July. Around 5 AM local time (top) the highlands are cloud free and the offshore waters experience the highest frequency of convective clouds, whereas around 5 PM local time (middle), convection tends to be concentrated over the high terrain and the compensating subsidence tends to keep offshore waters relatively cloud free. The difference between 5 PM minus 5 AM (bottom panel) shows even more clearly the complex influences of the mountain ranges and the shape of the coastline. It is interesting to note how at ~5 PM, the continental monsoon and the ITCZ are well separated, but at ~5 AM they appear to be nearly merged.
Figure 32. Time series of warm season rainfall over selected regions: U.S. Great Plains; southeast U.S.; Arizona; Ceara, Brazil; and Guayaquil, Ecuador. Average months as indicated.
Figure 33. Nature of global El Niño impacts during 1997-1998.
Figure 34. Simultaneous linear correlations between seasonal-mean rainfall in the indicated region (yellow dot) and Pacific and Atlantic sea surface temperature anomalies. Averaging months and periods of record as indicated.
Figure 35. Hurricane positions on the last day that they exhibit hurricane-force winds during the (a) 25 warmest and (b) 25 coldest years in terms of sea surface temperature in the equatorial cold tongue region (6°N-6°S, 180-90°W) based on the period of record 1886-1992.
Figure 36. Daily hurricane and tropical cyclone positions during the (a) 10 warmest and (b) 10 coldest years in terms of sea surface temperature in the equatorial cold tongue regions based on the period of record (1949-1992).
Figure 37. Equatorial wind regimes as defined in the text, superimposed upon the average September-October climatology. Surface vector wind, rainfall, and stratus cloud sources and plotting conventions as in Fig. 2. The contours indicate sea-level pressure (contour interval 1 mb). The heavy line depicts the "ridge line" in the sea-level pressure field, i.e., the highest pressure at each latitude.
Figure 38. Idealized cross section through the ITCZ/cold tongue complex in the monsoonal regime showing the atmospheric meridional circulation and planetary boundary-layer depth and the oceanic thermal structure. SEC refers to the South Equatorial Current, NECC to the North Equatorial Countercurrent, and EUC to the Equatorial Undercurrent. The heavy cloud denotes the position of the ITCZ. Encircled x's (dots) denote westward (eastward) flowing winds or currents.
Figure 39. Upper-air sounding stations with enhanced monitoring for PACS.
Figure 40. Schematic figure illustrating the implementation plan for the North American Monsoon Experiment (NAME). Analytic, diagnostic, and model development activities will be organized using a multiscale approach. NAME includes specific research objectives addressing mesoscale (Tier I), regional scale (Tier II), and continental scale (Tier III) phenomena.
Figure 41. Implementation plan for MESA (Monsoon Experiment South America). MESA will have two stages conducted in sequence: (a) Stage 1 focuses on describing and understanding the role of the South American low-level jet in climate variability and on elements of EPIC, and (b) Stage 2, a study of the hydroclimatolgy of the La Plata river basin (PLATIN). SALLJ: South American Low-Level Jet, VEPIC: VAMOS Eastern Pacific Investigation of Climate, LBA: Large Scale Biosphere-Atmosphere in Amazonia, PIRATA: Pilot Research Moored Array in the Tropical Atlantic, OSEPA: Ocean Southeast Pacific Array.
Figure 42. The Pan American climate observing system.
Wintertime Predictability for U.S. Surface Air Temperature (left) and Precipitation (right) (JFM 1958–1998)

El Nino Southern Oscillation (ENSO)

ENSO+Pacific Decadal Oscillation (PDO)

ENSO+PDO+Arctic Oscillation (AO)
Mexican Sounding and Automated Surface Observation Networks

- Red dots — radiosonde sites
- Green squares — automatic weather stations
- Black crosshair — daily precipitation/hydrology observations
  (from regional centers in Hermosillo and Culiacan)