3. VARIABILITY OF AMERICAN MONSOON SYSTEMS (VAMOS) (G3)

3.1 SCIENTIFIC RATIONALE

The word monsoon is derived from an Arabian word referring to season: it was the term used by sailors to describe the seasonal reversal of the winds over the Arabian Sea. It is now applied to low latitude regions that experience pronounced changes in the low-level circulation and precipitation regimes that result from the seasonal cycle of heating associated with the reversal of the temperature gradient between continents and oceans.

3.1.1 The American monsoon systems

The Asian-Australian and American monsoon systems are the two dominant monsoon systems of the world. Viewed in a global context, these two systems constitute major components of the low-latitude atmospheric heating field and the seasonally-varying, zonally-averaged Hadley Circulation. During most of the year, the dominant feature of the low-latitude Hadley Circulation is a single direct cell which links the two hemispheres (descending motion in the winter hemisphere; ascending motion in the summer hemisphere). Similarly, the regional monsoonal components of the Hadley Circulation link the winter monsoon circulation of one hemisphere with its summer monsoon counterpart.

The configurations (size, shape and location) of the land masses and surrounding ocean features involved in the Asian-Australian and American monsoon systems have important differences:

- The distribution of land and ocean in the Asian-Australian sector is largely north-south oriented, with land (ocean) primarily to the north and ocean (land) primarily to the south in Asia and vice versa in Australia. Over the Americas, the orientation of the land masses is primarily north-south, with oceans to the east and west.
- The major mountain complex of southern Asia has an east-west orientation, while the major western continental mountain ranges over the Americas extend north and south for the entire length of both continents.
- The continents of the Americas are more similar in size than Asia and Australia, but exhibit different asymmetries. Most of the land mass of South America is at low latitudes, and in fact extends into the northern hemisphere, while North America resides in the middle and high latitudes.
- The Intertropical Convergence Zone (ITCZ) in the Asian-west Pacific sector executes a pronounced inter-hemispheric seasonal migration, while its counterpart in the eastern Pacific and eastern Atlantic executes a much smaller seasonal migration and remains north of the Equator (except for a weak secondary ITCZ that sometimes develops west of south America during the height of the warm season). Associated with this asymmetry is the great contrast between the relatively warm waters of the North Atlantic and Pacific and the colder waters of the South Atlantic and Pacific.

Turning to the individual continental scale features, the definition of a monsoon region has centred on the requirement of a reversal in the low-level flow and the steadiness of this flow (Fein and Stephens, 1987). One can also describe a three dimensional, continental scale "monsoon circulation system", which includes both an upward branch associated with the region of enhanced precipitation (e.g. the Indian "monsoon") and a downward branch associated with regions of suppressed precipitation (e.g. the compensating subsidence over the arid regions of the Middle East). The monsoon system perspective provides a useful framework for describing, understanding and modelling the annual cycle and interannual variability of the low and middle latitude continental precipitation and associated temperature regimes.

Fig. 3.1 shows the Northern Hemisphere wet season (June-July-August) and Southern Hemisphere wet season (December-January-February) rainfall. The continental monsoons and the oceanic ITCZs are clearly seen in this figure. During the Northern Hemisphere wet season, the northern branch of the Pacific ITCZ extends across much of the basin and merges with the continental monsoons of Mexico, central America and northern South America. In the Atlantic the ITCZ is at its most northern position and also merges with the monsoon over northern South America. During the Southern Hemisphere wet season, the ITCZ in both oceans weakens and the monsoon over Amazonia dominates and merges with the South Atlantic Convergence Zone (SACZ). In this context, the rainfall climatology of the low and middle latitude continental regions of the Americas is dominated by the eastern Pacific and western Atlantic ITCZs and the seasonal continental monsoons.

3.1.1.1 The monsoon system in the Northern Hemisphere

Climatologists and meteorologists have long referred to a "southwest monsoon" over Arizona and New Mexico, which begins in early July (Carleton, 1985, 1986, 1987; Adang and Gall, 1989; Hales, 1974). It is now apparent that this southwest monsoon is simply the northernmost portion of a more extensive region of heavy precipitation that first develops over southern Mexico and then spreads northward along the western slopes of the Sierra Madre Occidental (see Fig. 3.2).

The development phase of the North American monsoon system (May-June) is characterised by a decrease in synoptic-scale transient activity over northern Mexico and the U.S., as the mid-latitude storm track weakens and migrates 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. Early in the mature phase (July-August), a "monsoon high" becomes established in the upper-troposphere near the U.S.-Mexican border. This feature is analogous to the Tibetan High over Asia (Tang and Reiter, 1984; Carleton et al., 1990). The region of enhanced upper tropospheric divergence in the vicinity and to the south of the upper troposphere 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. There is some indication of increased divergence and precipitation in the vicinity of the "induced" trough over the eastern U.S. The decay phase of the system (September-October) is generally the reverse of the development phase, but proceeds at a slower pace. The ridge over the western U.S. weakens, as the monsoon high and Mexican monsoon precipitation retreat southward into the deep tropics.

The North American monsoon system, therefore, affects much of Mexico and the U.S. (Douglas et al., 1993). Major drought episodes in the midwestern U.S. are associated with what may be broadly characterised as an amplification of the upper tropospheric monsoon ridge. Associated changes in the lower troposphere include a weakening of the western end of the "Bermuda High" and the low-level jet over the Great Plains, which in turn is associated with a weakened inflow of moisture to the central U.S (McCorcle, 1988; Higgins et al., 1997a). A more or less reverse series of anomalies tends to develop during wet periods over the Midwest. Recent empirical studies provide evidence of a negative correlation between precipitation over the southwest U.S. monsoon region and over the northwestern U.S.-Mississippi Basin (Higgins et al., 1997b; Higgins et al., 1998a). The teleconnection may be one that develops over a time span of just a few days, with the arrival of a strong monsoon linked to atmospheric descent and drying over the Great Plains as a response to outflow from the monsoon (Higgins et al.,1998b). The primary mode of precipitation in July shows strong correlation with a mid-latitude circulation type termed the Pacific Transition Pattern. This suggests that mid-latitude circulation anomalies may play a part in the development of the monsoon system in Mexico.

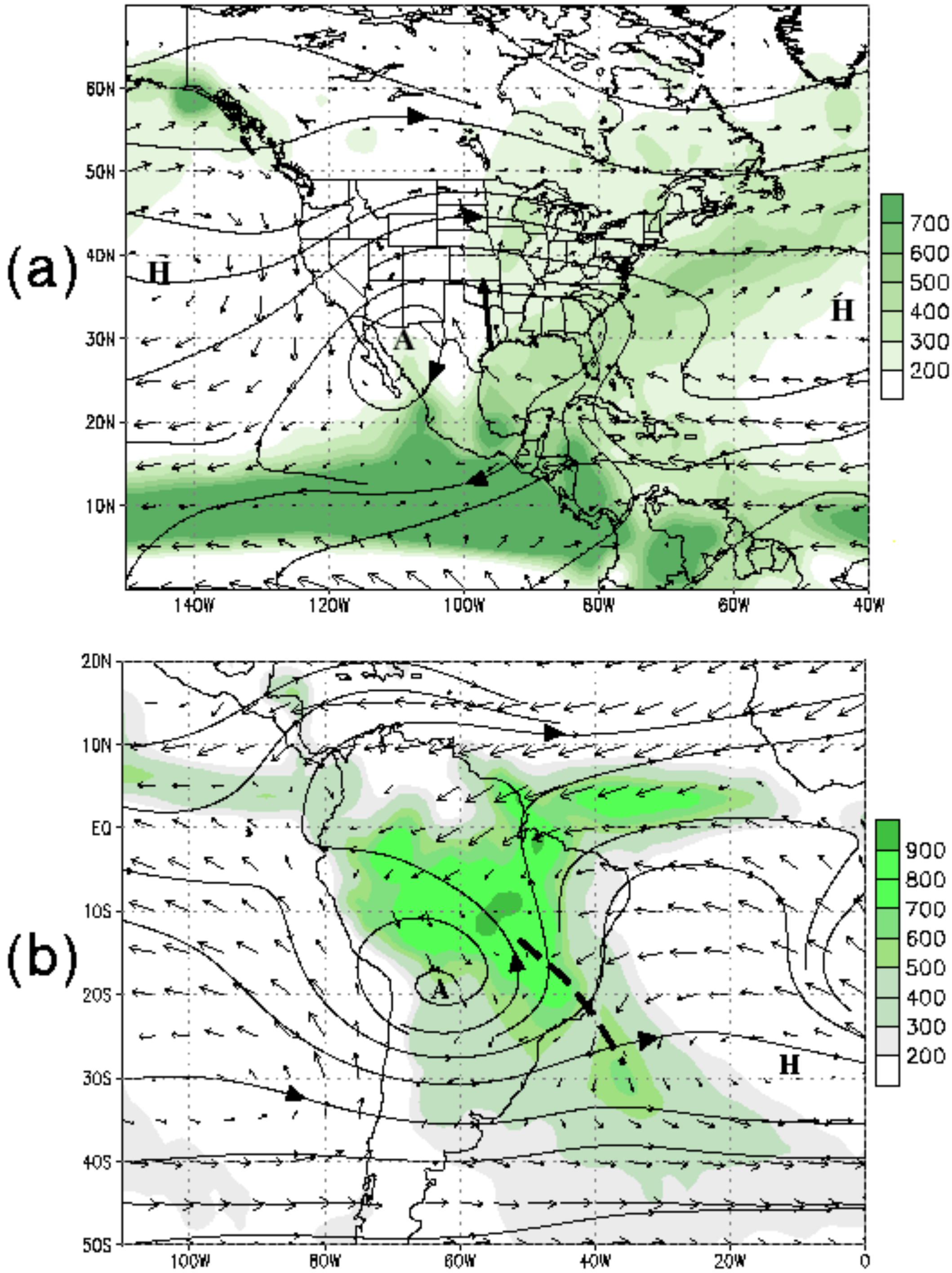

Fig. 3.1: Mean (1979-1995) 925 hPa vector wind and 200 hPa streamlines from the NCEP/NCAR reanalysis archive, and merged satellite estimates and station observations of precipitation (mm, shading): a) July-September. The position of the American North-Monsoon High is indicated by "A". The Bermuda and North Pacific subtropical high pressure centres are indicated by "H". The approximate location of the Great Plains low-level jet is indicated by the heavy solid line. b) December-February. The position of the Bolivian High is indicated by "A". The South Atlantic subtropical surface high pressure centre is indicated by "H". The approximate axis of the South Atlantic Convergence Zone is indicated by the heavy dashed line (courtesy of W. Higgins and M. Halpert (upper panel), resp. V. Kousky and M. Halpert (lower panel)).

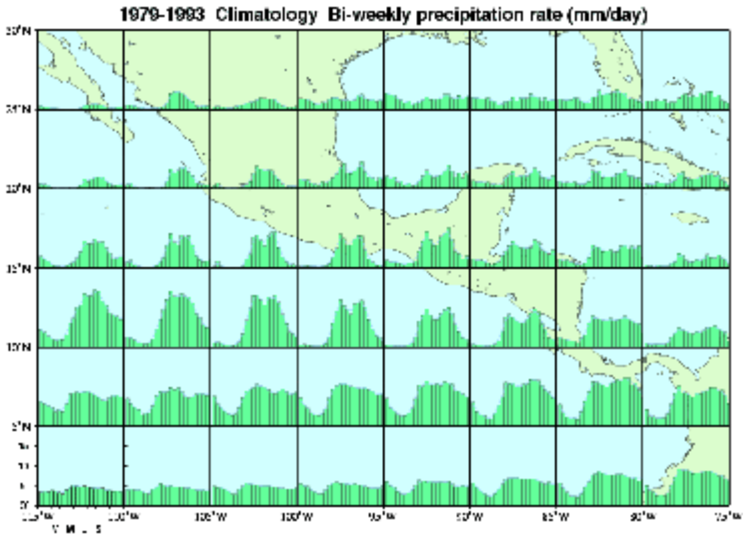

Fig. 3.2: Mean by-weekly precipitation (mm/day) during the period 1979-1993 in different regions of the Americas (Magaña et al., 1998).

The contribution of ocean processes to the interannual variability of rainfall over the Americas is discussed in Section 3.1.2. There is also evidence of links between tropical storm activity and the North American monsoon. The long rainfall record for Mexico City demonstrates that the summer monsoon was weak during the early 1900s and again in the late 1940s through the early 1960s, and was noticeably higher from the late 1920s to 1940 and again from the late 1960s to 1980. The eastern North Pacific had enhanced tropical storm activity in the 1920s, while the Gulf of Mexico was active in the 1930s (Díaz and Pulwarty, 1997). Thus, the wet 1920s and 1930s were associated with enhanced storm activity in one of the adjacent oceans. In contrast, the poor monsoon seasons of the 1940s were associated with reduced storm activity in the eastern North Pacific. This dry period extended into the 1950s when storm activity was greatly reduced in the Gulf of Mexico. The wet regimes of the late 1960s and 1970s were associated with a weakened Atlantic trade wind regime, decreased atmospheric stability and weak vertical shear. Tropical storm activity in the Gulf of Mexico and eastern North Pacific may not show strong year to year correlation, but decadal variability in storm activity between the two ocean regions appears to play an important part in the modulation of rainfall across much of Mexico.

The wintertime circulation over North America does not exhibit the pronounced reversal observed over portions of southern and eastern Asia. It does exhibit some similarities, however, such as the transient cold surges that spread southward east of the Rockies. These cold surges sometimes penetrate deep into the southern Gulf of Mexico and the Caribbean Sea, and trigger wind surges through low-altitude Mexican and Central American passes that affect SSTs in the eastern Pacific (DiMego et al., 1976; Schultz et al., 1997).

3.1.1.2 The monsoon system in the Southern Hemisphere

The characterisation of the seasonal cycle in the southern hemisphere as monsoonal in nature is more problematical. There is a seasonal shift in the inflow on the eastern side of the continent, which includes a distinct seasonal reversal in the cross equatorial flow, but the wind shifts are generally far from a complete reversal in the flow. Nevertheless, the elevated terrain of the Andes and the latent heating during the warm season give rise to an upper troposphere anticyclone ("the Bolivian High") that seems to be analogous to the Tibetan High. Furthermore, there is a marked seasonal cycle in the precipitation regime and associated continental-scale vertical motion field over the continent (Tanajura, 1996; Kousky and Ropelewski, 1997).

The development of the monsoon system in the southern hemisphere during the austral spring is characterised by a rapid southward shift of the region of intense convection from northwestern South America to the highland region of the central Andes (South American altiplano) and to the southern Amazon basin (Schwerdtfeger, 1976). In contrast to its counterpart in the northern hemisphere, transient synoptic systems at higher latitudes play an important role in modulating the southward shift in convection. Cold fronts that enter northern Argentina and southern Brazil are frequently accompanied by enhanced deep convection over the western and southern Amazonia (Kousky and Ferreira, 1981; Kousky, 1985) and by increased southward moisture flux from lower latitudes. It has been suggested that this moisture flux is enhanced by a strong low-level jet east of the Andes (Virji, 1981, 1982; Stensrud, 1996). The low-level jet over South America is not as well-documented as its counterpart over the Great Plains of North America. As the austral spring progresses, precipitation increases over the Brazilian altiplano and southeast Brazil, as the SACZ develops (Kousky, 1988). The Bolivian High becomes established near 15^{o}S, 65^{o}W, as the monsoon system achieves mature phase characteristics. Intraseasonal and interannual rainfall variability in the region of the South American altiplano is closely linked to changes in intensity and position of this high pressure system. To the east of the Bolivian High and off the east coast of Brazil there is an upper-level cold trough, where rainfall is very low (Kousky and Ropelewski, 1997). The decay phase of the monsoon begins in late summer as convection shifts gradually northward toward the equator. During 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 mid-latitudes begin to occur over the interior of subtropical South America.

Diagnostic studies of the diabatic heat source over the South American continent reveal a predominant role of the surface sensible heating in warming up the mid-troposphere over the central Andes during the pre-monsoon period. After the monsoon onset, strong latent heat release, accompanying deep convection over the subtropical highlands and the southern portion of the Amazon basin, maintains the thermal structure of the troposphere. The heating is largest in the mature phase, while the warm air spans the widest subtropical domain from the eastern south Pacific to the western south Atlantic.

Analysis of persistent wet and dry conditions over tropical and subtropical eastern South America during the austral summer reveals a dipole pattern of rainfall anomalies, with one centre over southeastern Brazil in the vicinity of the SACZ and another centre over southern Brazil, Uruguay and northeastern Argentina (Casarin and Kousky, 1986; Nogues-Paegle and Mo, 1996). This seesaw pattern, which reflects changes in the position and intensity of the SACZ on intraseasonal and interannual time scales, appears to be a regional component of a larger scale system. The southward extension and strengthening of the SACZ is associated with enhanced convection over the central and eastern tropical Pacific and dry conditions over the western Pacific and the maritime continent. Convection is simultaneously suppressed in the region of the SPCZ, over the Gulf of Mexico, and in the ITCZ over the north Atlantic (Grimm and Silva Dias, 1995a, b). In the opposite phase, there is a strong influx of moisture from the tropics into central Argentina and southern Brazil.

The contribution of ocean processes to the interannual variability of rainfall over the Americas is discussed in the following subsection. There is also evidence that inter-hemispheric teleconnections contribute to that variability. The North Atlantic Oscillation (NAO) is an example of such connections: blocking conditions over the North Atlantic are normally associated with negative rainfall anomalies over the eastern Amazonia and northeast Brazil (Namias, 1972).

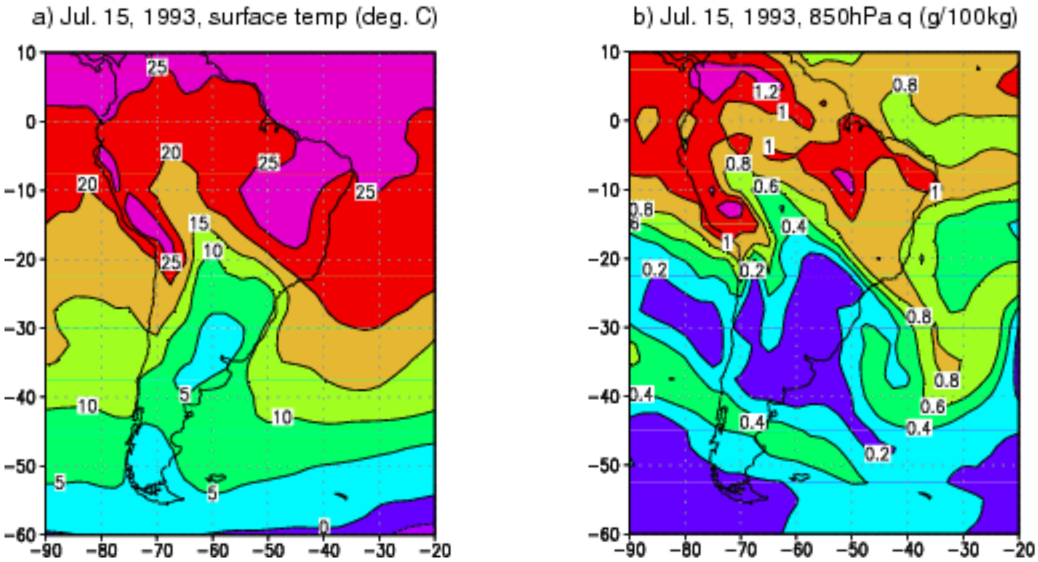

Fig. 3.3: Two features of a typical cold surge over South America during the Southern Hemisphere winter:

a) equatorward penetration of cold air at the surface (contour interval 5K),

b) decrease in specific humidity at 850hPa (contour interval 0.2 x 10-2g kg^{-1})

(courtesy of C. Vera).

Large-scale features, such as the ITCZ and SACZ, are frequently composed of organised mesoscale systems that are important in understanding the local climate and in weather forecasting. Some of these mesoscale systems are strongly tied to the local surface characteristics and are strongly modulated by the diurnal cycle. Satellite studies reveal the complexity of the diurnal variation of convection over the South American monsoon region (Kousky, 1980). There are clear indications of precipitation maxima associated with the inland penetration (sometimes up to several hundred kilometres) of convective activity initiated by the sea breeze along coastal sections of tropical South America. The large rivers and flooded areas in the equatorial region also provide the necessary forcing for the establishment of local circulation systems that can be clearly identified in satellite data and precipitation observations. The development and intensity of mesoscale convective systems, such as mesoscale convective complexes, squall lines and diurnal convection are strongly modulated by transient synoptic systems. At times, this scale interaction leads to excessive rainfall and flooding.

During the austral winter, precipitation is larger over northwestern South America north of the equator. The upper level subtropical jet stream is strongest at this time and is displaced equatorward over South America in agreement with the descending branch of a Hadley-type circulation over that area. Frontal systems move fast above regions of low specific humidity and high loss of heat by radiation, and are not associated with strong convective activity, but introduce cold surges, known as "friagens", in central and north Brazil (Fig. 3.3) (Parmenter, 1976; Hamilton and Tarifa, 1978; Fortune and Kousky, 1983; Marengo et al., 1997).

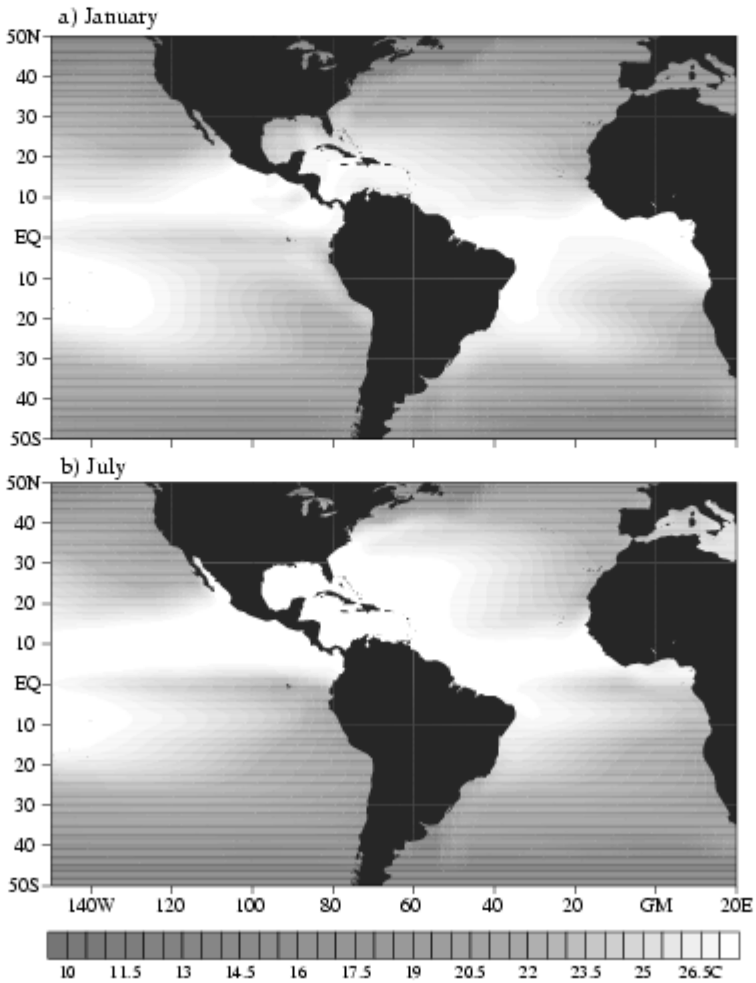

Fig. 3.4: Mean sea surface temperature distributions for a) January, and b) July. The northern hemisphere wet season shows a well defined "warm pool" extending from the eastern Pacific across central America and through the Caribbean Sea. In contrast, the southern hemisphere wet season shows warm pool temperatures weakening substantially and shifting southward. SST climatology for 1984-95 from Reynolds and Smith (1994) (courtesy of T. Mitchell).

3.1.2 The importance of ocean processes

For the American Monsoon System, the most important ocean-atmosphere-land interactions involve the eastern tropical Pacific and tropical Atlantic, as well as the Caribbean Sea and the Gulf of Mexico.

Fig. 3.4 shows the sea surface temperature field (SST) in the Northern and Southern Hemisphere wet seasons, respectively. During the northern hemisphere wet season there is a well defined "warm pool" that extends from the eastern Pacific across central America and through the Caribbean Sea. For the most part, the oceanic rainfall is coincident with the warmest SST, and the large-scale continental precipitation can be viewed as an extension of the ITCZs over the continents. In contrast, during the southern hemisphere wet season the warm pool temperatures weaken substantially and shift southward. Moreover, the direct connection between the continental precipitation and the oceanic ITCZs fades.

The eastern equatorial Pacific and Atlantic Oceans are characterised by cold tongue/ITCZ complexes with marked hemispheric asymmetry and strong seasonality. Southeasterly tradewinds drive equatorial and coastal upwelling, leading to cooler surface waters along and to the south of the equator. In contrast, north of the equator in the eastern Pacific and Atlantic, surface temperatures are warmer in the vicinity of the ITCZ. At comparable latitudes in the Southern Hemisphere, large-scale subsidence over cool surface waters leads to the formation of low level stratus decks and minimal precipitation (Mitchell and Wallace, 1992). The reasons for these inter-hemispheric asymmetries are not fully understood at present (Li and Philander, 1996; Philander et al., 1996).

The hemispheric asymmetries in the eastern Pacific and Atlantic Oceans are most marked near the coasts. In the eastern Pacific, for example, the coolest surface waters are found in the coastal upwelling regime off the west coast of South America, where the climate is of the "humid desert" type. North of the equator, on the other hand, the warmest waters in the ITCZ region are located off the west coast of Central America. This eastern Pacific "warm pool" develops in a region of convergent wind driven ocean currents, and is marked by extreme rainfall over both the ocean and neighbouring land mass. The intensity of these features decreases from east to west in and over the ocean, as upstream continental influences wane and as the trade winds become more zonally oriented. In the tropical Atlantic there is a deep warm pool along the coast of South America, with extensions into the Caribbean Sea and Gulf of Mexico. This warm pool, and the corresponding warm pool in the northeastern equatorial Pacific separated by the relatively narrow continental land mass of Central America, are noteworthy in that so little is known about the processes that contribute to their maintenance.

The wind driven oceanic circulation in the eastern equatorial Pacific and Atlantic is important in determining the patterns of SST variability (Wallace et al., 1989). Major zonal flows of the equatorial current system include the westward flowing North and South Equatorial Currents, between which flows the eastward North Equatorial Countercurrent north of the equator in the vicinity of the ITCZ. A meridional ridge/trough system in surface topography and thermocline depth delimits the latitudinal boundaries of these currents. The Equatorial Undercurrent flows eastward below the surface along the equator, providing a source for upwelled water from the thermocline. Superimposed on these zonal flows is a meridional circulation involving poleward Ekman divergence and upwelling near the equator, meridional convergence and downwelling at higher latitudes, and geostrophic inflow towards the equator from higher latitudes at thermocline depth.

Surface winds in the South Atlantic force a gyre-scale interior ocean circulation, which is closed along the western boundary by the strong, southward-flowing Brazil Current. The southwestern tropical Atlantic is also characterised by the SACZ (Casarin and Kousky, 1986; Kousky 1988; Kodama, 1992), which is in some ways analogous to the South Pacific Convergence Zone (SPCZ) in the southwestern Pacific. The SACZ is not as well documented and explored in terms of oceanographic consequences as its Pacific counterpart. It is unclear, for example, whether the

SACZ is associated with a South Equatorial Countercurrent in the south Atlantic to the same extent to which the SPCZ is associated with a similar current in the south Pacific.

The seasonally varying climate of the Americas is governed in part by pronounced seasonal variations in the surrounding tropical oceans. In boreal summer, for example, coastal and equatorial upwelling circulations intensify in response to intensified southeasterly trade winds, and the cold tongues of the equatorial eastern Pacific and Atlantic intensify and expand poleward. The ITCZ, and the warm surface waters underlying it, are displaced northward. The northern branch of the South Equatorial Current and the North Equatorial Countercurrent intensify in both the Atlantic and Pacific. Associated with these zonal current variations are changes in thermocline topography and meridional mass fluxes, which result in an increased heat flux from the Northern to Southern Hemisphere.

Boreal summer monsoon circulations also develop in the atmosphere with onshore flow of moisture laden air in Central America and in the southwest U.S. Convergence of this moisture flux over land leads to convection and marked increases in continental precipitation. In northeast Brazil on the other hand, boreal spring is the wet season, corresponding to the time when the equatorial oceans are warmest, and the ITCZ in the western Atlantic is at its southernmost position south of the equator. In the southwestern Atlantic, the SACZ is best developed in austral summer, whereas in austral winter, migratory cyclones and associated cold fronts coming from the Pacific affect this region.

The intensity of the American monsoon systems is significantly modulated on intraseasonal, interannual and decadal time scales. The impacts of El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific are global, with specific regional imprints on precipitation patterns over the Americas (Ropelewski and Halpert, 1987, 1989; Aceituno, 1988, 1989; Pisciottano et al., 1994). There is evidence that the monsoon in Mexico is modulated by ENSO (Cavazos and Hastenrath, 1990). Specifically, a wet equatorial central Pacific (warm ENSO) is associated with dryness along the Pacific coast of southern and western Mexico (Magaña and Quintanar, 1997). Several studies suggest that in late-spring/early-summer ENSO establishes a teleconnection pattern with an anomalous trough over North America, and the jet stream and storm track displaced southward of their average locations. (e.g., Kalnay et. al., 1990; Trenberth and Branstator, 1992; Trenberth and Guillemot, 1996; Bell and Janowiak, 1995; Janowiak, 1988). This results in increased frequency of storms and higher precipitation. Conversely, anomalously cold SSTs in the central equatorial Pacific are associated with a decreased frequency of storms and lower precipitation over North America. The modulation of monsoonal rainfall over South America SST variations in the tropical Atlantic is suggested by other studies (Namias, 1972; Hastenrath and Heller, 1977; Enfield, 1996). Through atmospheric teleconnections, ENSO events also affect the winds and therefore the oceanographic conditions in the Atlantic basin (Enfield and Mayer, 1997). In particular, the equatorial Atlantic is often characterised by unusually warm SSTs in the year following major ENSO warm events in the Pacific. Ocean-atmosphere interactions internal to the Atlantic are also an important source of interannual climate variability in that basin, in addition to that generated externally via teleconnections to the Pacific (Philander, 1986; Zebiak, 1993; Carton and Huang, 1994; Latif and Barnett, 1995).

Notable decadal time scale oceanic variations have also been reported in the Atlantic (Deser and Blackmon, 1993; Kushnir, 1994; Mehta and Delworth, 1995; Chang et al., 1997). Those variations include the so-called Atlantic dipole, which is characterised by inter-hemispheric variations in SST, surface winds and surface heat fluxes. The dipole influences the latitudinal position of the ITCZ and associated rainfall fields, and therefore has significant socio-economic impacts on countries bordering the region. The dipole also exhibits fluctuations on shorter seasonal and interannual time scales, which are important to describe and understand for the purposes of predicting short-term climate variability (Weiner and Soares, 1997). Decadal time scale variations have also been recently documented in the tropical Pacific (Trenberth and Hurrell, 1994; Graham, 1994; Deser et al., 1996). These low frequency variations manifest themselves in terms of SSTs with a spatial structure different from that associated with ENSO. Whether these variations represent a decadal modulation of the ENSO cycle, or arise from ocean-atmosphere interactions distinct from those associated with ENSO, is unknown at the present time. It is also unknown to what extent these decadal fluctuations are linked to decadal fluctuations in the North Pacific, and/or to anthropogenic climate change.

In addition to these long-term climate fluctuations, significant intraseasonal variations occur in the tropical Atlantic and Pacific which affect the detailed evolution of the seasonal cycle. Common to both basins are tropical instability waves with periods of about one month and horizontal scales of several hundred kilometres (Philander et al., 1985). These waves are important in regulating temperatures and large-scale current variations in the equatorial cold tongue regions through horizontal turbulent transports of heat and momentum. In the western Atlantic, ocean eddies are prominent in the strong western boundary current regime of the coast of South America, where they affect ocean circulation and heat transports. In the Pacific, intraseasonal (60-90 day) equatorial Kelvin waves forced by surface winds associated with the atmospheric Madden and Julian Oscillation (MJO) are a very pronounced mode of variability (Madden and Julian, 1994). Intraseasonal variations in SST, thermocline depth and ocean currents result from the passage of these waves along the equator, and poleward along the coasts of North, Central and South America. Enhancements of MJO and Kelvin wave energy at intraseasonal frequencies are, moreover, implicated in the development of ENSO warm events.

3.1.3 The importance of orography and land surface processes

Over the continents, the orography and coastal geometry have a profound role in modulating the continental monsoon circulations. For example, during the wet season in Mexico the rainfall along the western slopes of the Sierra Madre Occidental can exceed 65 cm, whereas less than 200 km directly to the west the wet season rainfall is over 40 cm less. This mesoscale structure is influenced by the complex surface characteristics from the gulf of California in the west to the Mexican highlands in the east. Over South America, the narrow Andes mountains strongly influence the character of the monsoon circulation. During the Southern Hemisphere wet season the western slopes of the Andes mountains are arid, but the eastern slopes exhibit a relative rainfall maximum. The surface characteristics of the Amazon basin also influence the local monsoon rainfall maxima at the southern edge of the basin and at the mouth of the Amazon River.

Land surface processes are particularly relevant to the American monsoonal circulations. Early warm season conditions, which are most likely related to global circulation, can provide the land surface with either an excess or a deficit of moisture relative to the long-term mean value. The hypothesis is that this anomaly influences subsequent moisture conditions, either locally or regionally, as larger-scale atmospheric circulation becomes less important and local convection (and perhaps moisture recycling) becomes dominant in the summer season (e.g. Rind, 1982; Mintz, 1984; Delworth and Manabe, 1989). Preliminary coupled terrestrial hydrologic-atmospheric modelling studies (Koster and Suarez, 1995) tend to support this hypothesis.

Dynamical processes controlled by the regional water and energy balance can influence water vapour flow and, in this way, contribute to the occurrence of extreme events. Land-surface processes also have substantial influence on elevated mixed layers, and on associated lids on atmospheric instability that act to determine the distribution of the regional precipitation in time and space (Benjamin and Carlson, 1986; Clark and Arritt, 1995). There is compelling evidence that meteorological prediction is sensitive to terrestrial hydrologic-atmospheric coupling processes, which argues for research aimed to identify the coupling processes that are most important for improved prediction, and the level of complexity that is worthwhile to include in sub-models describing those processes.

3.2 VAMOS: PROGRAMME DEFINITION

GOALS, one of the main streams of CLIVAR, deals with climate variability and predictability on seasonal-to-interannual time scales building upon the accomplishments and observing system of TOGA. GOALS, acting in collaboration with GEWEX, seeks to develop skilful prediction of global climate variability on seasonal-to-interannual time scales through exploitation of linkages with predictable variability of tropical heat sources and sinks associated with SST and other surface anomalies, or that predictability that may be inherent in the extratropical system. The overall strategy is to focus on the monsoon systems in order to capitalise on the known major heat sources that contribute to shape the global atmospheric circulation. The largest annually varying tropical heat source is associated with the switch from the Australian summer monsoon centred in January, to the Asian summer monsoon centred in July. The second largest monsoon occurs over the Americas as the large atmospheric heat source, associated with rainfall over the Amazon basin that peaks in January, migrates to the Northern Hemisphere in the northern summer. Two distinctive characteristics of the American monsoon system differ from the Asian-Australian monsoon system.

First, tropical SST anomalies are particularly influential on climate variability in the American sector. Hence, a study of the American monsoons will address the predictability of tropical SST to a greater extent than the other GOALS components. Second, complex orography and coastal geometry imprint a mesoscale signature upon the American monsoon systems that is strong enough to qualitatively influence its planetary-scale structure and behaviour. Hence, a study focused on American monsoons will emphasise multi-scale studies ranging from the planetary to the regional.

Because many countries are affected by these monsoons systems, it is advantageous to co-ordinate research programmes that address the outstanding scientific issues. Therefore CLIVAR has established two panels dealing with the different aspects of the Asian-Australian and the American monsoons: Asian-Australian Monsoon Panel and Variability of the American Monsoon Systems (VAMOS) Panel.

VAMOS is a component of CLIVAR GOALS with three major objectives:

1. to describe, understand, and model the mean and seasonal aspects of the American monsoon systems,
2. to investigate their predictability and to make predictions to a feasible extent, and
3. to prepare products in view of meeting societal needs.

VAMOS will focus on rainfall and the probability of occurrence of significant weather events such as tropical storms and temperature extremes. The term "monsoon system" encompasses not only the summer monsoon rainfall in the tropical Americas, but also the perturbations in the planetary, synoptic and mesoscale flow patterns that occur in association with it, including those in the winter hemisphere. The region of interest covers both the tropical and the extratropical Americas and surrounding oceans. Like the other regional components of CLIVAR, VAMOS will also foster the development of the observing, modelling and data management capabilities required for climate prediction.

A number of regional and national research projects, such as the Pan-American Climate Study (PACS), the GEWEX Continental Scale International Project (GCIP), the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) contribute to VAMOS. The Inter-American Institute for Global Change Research (IAI) provides important linkages to the societal impact of climate research within the Americas. Finally, the International Research Institute for Climate Prediction (IRI) provides a framework for VAMOS to carry out climate predictions and the assessment of predictability of the American monsoon systems. More detailed descriptions about the linkages to these programmes is provided in Section 3.8.

3.3 MODELLING AND PREDICTION

3.3.1 Atmospheric general circulation models (AGCMs)

Inference of causal relationships based on empirical evidence is often difficult because the anomalous surface wind field associated with the rainfall anomalies can induce SST anomalies of its own, and anomalous boundary conditions in a number of different regions are often interrelated by way of planetary-scale atmospheric teleconnections. In view of the complexity of these processes, AGCMs play key roles in establishing hypotheses on the atmospheric response to boundary forcing. Nevertheless, present AGCM simulations forced with climatological mean boundary conditions exhibit systematic biases in regions of the Americas and adjacent oceans. The models generally underestimate the wind stress in the equatorial belt, and the coverage of oceanic stratus clouds. These clouds play an important role in the energy balance of the PBL and the ocean mixed layer and are associated with the equatorial asymmetry of SST in the tropical Atlantic and eastern Pacific (Ma et al., 1996). Such well-defined biases 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.

VAMOS will encourage studies with AGCMs aimed at a better understanding of atmospheric sensitivity to anomalous boundary forcing. Results of several published AGCM studies suggest that tropical SST anomalies can influence warm season rainfall over the Americas (Moura and Shukla, 1981; Mechoso and Lyons, 1988; Mechoso et al., 1990; Díaz et al., 1998). AGCM experiments can explore the mechanisms by which monsoon rainfall anomalies over northeast Brazil are positively correlated with SST anomalies over the tropical South Atlantic and negatively correlated with SST anomalies over the tropical North Atlantic. Additional experiments may examine the hypothesis that SST 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. Such experiments are needed to understand, and ultimately to predict, the way in which 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.

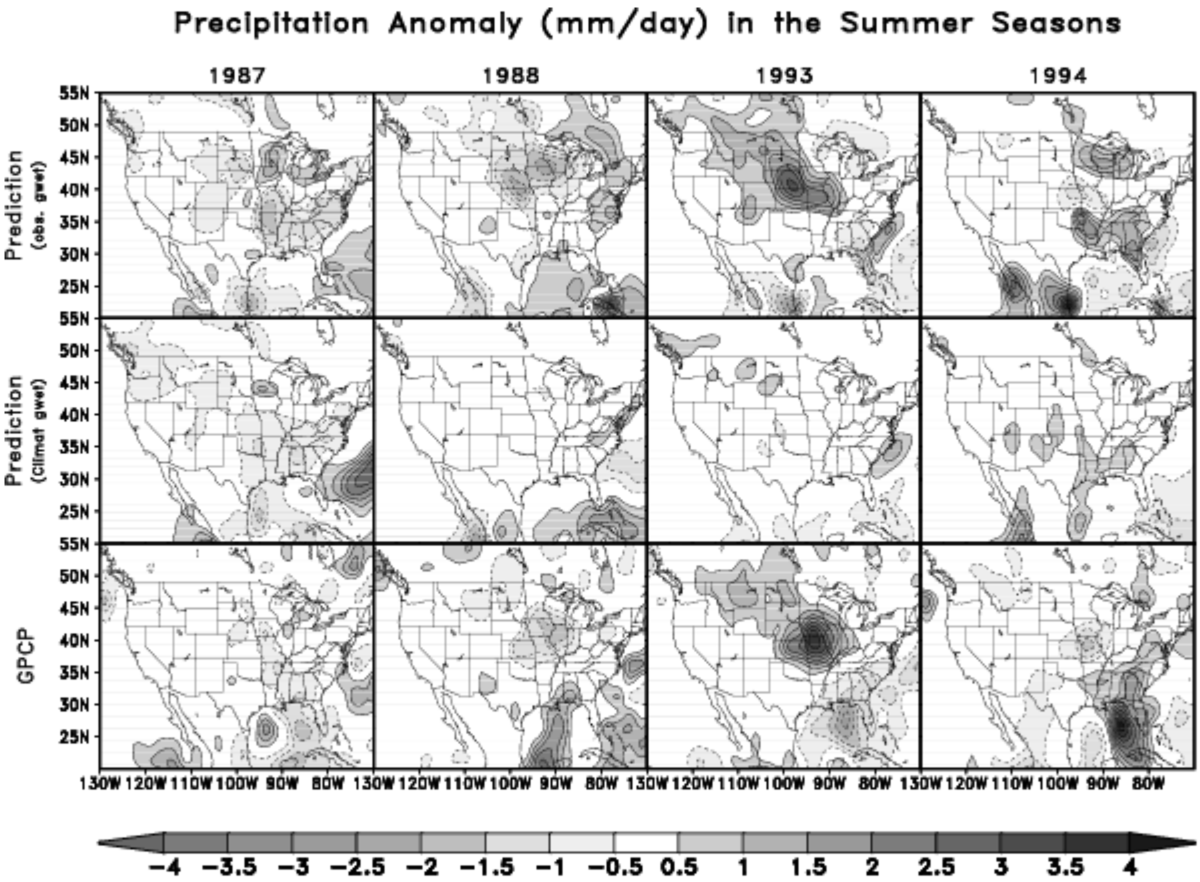

Fig. 3.5: Precipitation anomalies produced by AGCM forecasts for May-August 1987, 1988, 1993, and 1994. Soil wetness conditions were prescribed according to observational estimates for the corresponding periods (top row), or at climatological values for the northern summer season (middle row). In both forecasts, global sea-surface temperature anomalies for those years are included in the boundary forcing. The precipitation anomalies from the GPCP dataset are shown in the bottom row (courtesy of S. Schubert and M. J. Suarez).

AGCMs can also address the feedbacks involving land surface processes that can also play important roles in warm season rainfall over the Americas (Atlas et al., 1993, Betts et al., 1996). Fig. 3.5 shows results of controlled experiments using the Goddard Earth Observing System AGCM. Two ensemble forecasts were performed beginning in mid May of 1988, 1989, 1992, and 1993, and extending through the end of the following August. In the set of ensembles, soil wetness conditions were prescribed according to either observational estimates for the corresponding periods or at climatological values for the summer season. In both sets, the appropriate global SST anomalies were included in the boundary forcing. Fig. 3.5 also includes precipitation anomalies from the GPCP dataset.

Focusing on 1988 and 1993 summers that were quite anomalous over North America, Fig. 3.5 shows that when a realistic soil moisture anomaly is prescribed, the model reproduces precipitation anomalies similar to those observed; but when only climatological soil moisture is used, there is almost no anomalous precipitation over North America. These results are a dramatic demonstration of the importance of land surface processes in predicting summertime precipitation. In an actual forecast the soil moisture could not have been specified and the state of the entire hydrological system (land plus atmosphere) would have had to be predicted.

The principal issues to be addressed with AGCMs include:

- Are simulations by AGCMs realistically sensitive to slowly varying boundary forcing?
- What is the atmospheric response to SST anomalies in the Caribbean Sea and the Gulf of Mexico?
- In which way does the slowly evolving planetary-scale atmospheric response to boundary forcing modulate the more intermittent, higher-frequency synoptic and subsynoptic phenomena that are responsible for episodes of heavy rainfall and significant weather (e.g. flare-ups in the ITCZ and SACZ, migrating frontal systems, Atlantic and Caribbean hurricanes, and higher latitude blocking events associated with cold air outbreaks)?
- How can the simulations of the intensity of ITCZ rainfall and the diversity of convective heating profiles in the tropics be improved?
- How can the simulations of regional differences in the diurnal cycle of precipitation be improved?
- What vertical resolution is required for simulation of the different stratiform cloud regimes?
- Can AGCMs provide appropriate boundary (lateral) conditions to embedded mesoscale models?

3.3.2 Oceanic general circulation models (OGCMs)

OGCMs will address a number of important questions concerning the processes that contribute to SST variability in the tropical Pacific and Atlantic. The mechanisms that control the annual march of SST in the monsoon regime of the eastern tropical Pacific appear to be fundamentally different from those in the trade wind regime of the central Pacific, upon which much of the prior OGCM development effort has been focused. The lack of correspondence between fluctuations in SST and thermocline depth in the annual cycle of the eastern Pacific Ocean attests to the importance of other processes such as insolation and other surface fluxes, upwelling, horizontal advection and vertical mixing in the heat balance (Philander et al., 1987).

There are unresolved questions on the source of water upwelled in the equatorial cold tongue, the depth from which it originates, and the meridional extent of the upwelling cell. Also, it is unknown whether the upwelling water can be traced back to the surface in extratropical regions, as has been suggested in recent studies (Deser et al., 1996; Gu and Philander, 1997). As in the atmosphere, an issue that remains unresolved is the rectification of high-frequency forcing and internal instabilities into the low-frequency variability. 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. There also appears to be important smaller-scale regional variability that escapes the resolution of basin-scale OGCMs, but that may be significant for understanding the heat, mass, and momentum budgets over the eastern tropical Pacific. The region up to a few hundred kilometres of the Central American coast is generally very warm but can cool rapidly in response to winter northerlies blowing through gaps in the American cordillera.

The principal issues to be addressed with OGCMs include:

- What are, and how to model, the processes that contribute to the maintenance of the oceanic mixed layer in the presence of equatorial upwelling?
- What is the source of water upwelled in the equatorial cold tongue, the depth at which it originates, and the meridional extent of the upwelling cell?
- What is the relative importance of dynamical and thermodynamical processes associated with the seasonal variations of the meridional wind stress in the eastern tropical Pacific and Atlantic?

- What mechanisms control the seasonal cycle of SST in the monsoon regime of the eastern tropical Pacific and in the trade wind regime of the central Pacific?
- What role do tropical instability waves in and north of the cold tongue play in the transport of heat and momentum in the upper ocean?
- What is the role of small-scale regional variability in the heat, mass, and momentum budgets of coastal regions?

3.3.3 Coupled atmosphere-ocean-land GCMs (coupled GCMs)

Many of the challenges confronted in modelling the atmosphere, ocean and land surface are further heightened in a coupled context, as the interactions among the components can lead to strong internal feedbacks (Webster and Chou, 1980). A relevant case in point is the simulation of the coupled annual cycle in the eastern Pacific (Ma et al., 1994). The strong meridional gradients, and strong equatorially asymmetric character of the annual cycle evolution clearly involves coupling between land, atmosphere and ocean, and has proven a very difficult challenge for coupled models. At this time, many models are unable to simulate the evolution realistically, perhaps the most common errors being associated with the appearance of overlay warm waters and atmospheric convection to the south of the equator during the austral summer season (Mechoso et al., 1995). Such errors clearly impact the circulation over the Americas, and in particular, the simulation of the American monsoon systems. VAMOS will encourage studies that further elucidate the boundary layer, convective cloud interaction, and dynamical processes giving rise to seasonal-to-interannual variability in the American sector. It is only through improved understanding that better parameterisations and model simulations will be possible.

These issues to be addressed with coupled GCMs include:

- What mechanisms determine the variability of ENSO?
- Why do the simulated cold tongues in the equatorial Pacific and Atlantic Oceans tend to be so strong and persistent, to extend so far west, and to separate from continental coasts to the east?
- What are the atmospheric, oceanic, and coupled atmosphere-ocean processes that contribute to the existence of the persistent stratus clouds in the eastern Pacific and Atlantic Ocean?
- Why is it that coupled GCM simulations tend to show relatively warm water extending too far east in the subtropical southern Pacific and Atlantic Oceans?
- How strong are the connections between the variability of the coupled atmosphere-ocean system in the Pacific and Atlantic Oceans?
- What would be the impact on the precipitation forecasts over the Americas of extending operational forecasts of the coupled atmosphere-ocean system for the Pacific to include the Atlantic Ocean?

3.3.4 Mesoscale atmospheric models

The richly textured distribution of rainfall over the continents and oceanic convergence zones presents a challenge and an opportunity for regional analyses and predictions. Along the coasts and over the mountainous terrain of the Americas, the coarse-resolution rainfall simulated by GCMs cannot be compared directly with station data. GCM simulations are particularly poor in the summer, when mesoscale convective systems play a dominant role in organizing the precipitation (Horel et al., 1989; Rao et al., 1996).

VAMOS will focus attention on mesoscale processes that affect the distribution of continental-scale precipitation and its variability on seasonal-to- interannual time scales. Mesoscale processes have long been considered to have both deterministic and probabilistic components. Characteristics of the underlying surface on the mesoscale help to control the development and organisation of mesoscale circulations (Figueroa et al., 1995). Mesoscale resolution of such factors as the slope of the terrain, land-sea temperature contrasts, or variations in soil moisture and vegetation will be necessary in order to understand better the American monsoon systems. On the other hand, mesoscale instabilities (e.g. tropical storms or mesoscale convective systems) contribute a significant fraction of the total seasonal precipitation in many areas of the Americas, and their occurrence (or absence) can lead to large year-to-year variations in precipitation. Thus, VAMOS will evaluate the aggregate effect of such mesoscale instabilities on the climate of the American monsoon systems.

Mesoscale models are expected to contribute to VAMOS in several ways, including the analysis and simulation of the mesoscale aspects of the mean state and spatial and temporal variations of the American monsoon systems. There is a need to evaluate specific physical processes that affect important components of the American monsoon systems. For example, cool season surges through the mountain gaps of Central America are known to rapidly lower the sea surface temperature downwind of the gaps and modify regional oceanic currents. In addition, the low-level jet to the east of the Andes Mountains contributes to the meridional moisture transport from the Amazon Basin into the subtropical regions of South America and modulates convective outbreaks in those regions. There is also a need to perform sensitivity and predictability experiments in which a model with mesoscale resolution is nested within an AGCM or coupled atmosphere-ocean GCM. The nesting strategy employed may be one-way (i.e. the mesoscale structures in the interior domain do not affect the GCM solution in the outer domain) or two-way (i.e. the mesoscale structures in the interior domain may affect the global solution).

The mesoscale modelling strategies will most likely evolve over the duration of the VAMOS programme. To effectively employ mesoscale models, a number of fundamental model design issues must be addressed. These issues focus on how to improve mesoscale models for climate analysis and prediction and include:

- How do mesoscale physical processes, such as convection, differ as a function of latitude and how do these differences affect model parameterisations?
- What is the sensitivity of the mesoscale simulations to the details of the underlying surface: e.g. sea surface temperature gradients or terrain? How important is the specification of soil moisture to the initialisation of mesoscale simulations as a function of soil type and seasonally evolving vegetation?
- How well can the seasonally varying climate be simulated as a function of horizontal and vertical resolution?
- How dependent are mesoscale simulations on specific physical parameterisations, such as surface exchange, and how do these dependencies differ for the various components of the American monsoon systems?
- What is required to develop an integrated approach to air/land/sea interactions on the mesoscale?
- What are the most appropriate nesting strategies and what are the sensitivities to the nesting methodology?
- To what extent does the skill of the GCM or coupled GCM in which a mesoscale model is embedded control the skill of regional predictions?

3.3.5 Predictability

The quality of deterministic atmospheric forecasts depends heavily on the quality of the initial data. The initial data cannot be created with absolute accuracy because of errors in observational data, lack of coverage and problems with representativeness. Forecasts starting from two slightly different initial data which are equally likely to represent the true atmospheric state, will deviate from each other after a few days. On average such forecast pairs deviate from each other as randomly chosen atmospheric states after 10 to 15 days. From that one can deduct that deterministic forecasts of the weather beyond 12 days are presently hardly possible.

There is also an interest in forecasts of the mean (weekly, monthly, or seasonally averaged) state of the atmosphere but then with a longer lead time. Experiments have been shown that the boundary forcing (SSTs, snow, soil moisture) become important for such forecasts. There are areas, especially in the tropics, which show a high sensitivity of e.g. mean precipitation to the phase of ENSO. An atmospheric model could be used to predict atmospheric mean states for such areas, if the oceanic temperatures could be forecasted. The latter has successfully been achieved with statistical models but for larger lead times (more than 6 months) only forecasts with coupled ocean-atmosphere models have the chance of success. The forecast of the 1997-98 strong El Niño with a lead time of one year is an example of the potential skill of such forecasts with coupled models especially for the Americas. Comparisons between forecasts by different schemes may contribute to enhance progress in coupled modelling

Simulations-predictability issues arise in the context of regional scale models. At the present time, very little work has been done regarding sensitivity of mesoscale models to initial and boundary conditions. These studies are a necessary prerequisite to the prediction of regional scale climate over the Americas.

3.3.6 Prediction

At present, ENSO SST predictions are being done routinely with an array of coupled dynamical models, as well as statistical-dynamical and purely statistical models (Cane et al., 1986; Barnett et al., 1993; Penland and Magorian, 1993; Balmaseda et al., 1994; Ji et al., 1996). Nonetheless, dynamical climate prediction is in its infancy. For example, many systems do not utilise much of the observational information available, and are thus obviously limited. Almost none of the climate assimilation systems acknowledge atmosphere-ocean coupling, even though a coupled system is more natural and undoubtedly optimal for coupled models. Forecasting methodologies such as ensemble averaging, model output statistics (MOS) corrections and probability forecasting are only now beginning to be considered. And of course, aspects of climate other than ENSO remain by and large unexplored. Yet the achievements to date provide optimism for further improvements in climate forecasting and forecast products that will be of direct relevance to VAMOS. Given the proximity to the tropical Pacific, the gains made in ENSO prediction will undoubtedly benefit climate prediction over the Americas.

Another set of issues that are crucial to prediction of precipitation (and other variables) over the VAMOS region concerns the initialisation of land surface conditions. At this time, it is not known what the observational requirements are for regional climate prediction. Certainly improvements in present land surface models will be needed, especially at the regional scale. Progress in the representation of land-atmosphere interactions over the last two decades has been sufficient to motivate several operational modelling centres (e.g. the National Center for Environmental

Prediction, the European Centre for Medium Range Forecasting and the Japanese Meteorological Centre) to implement and benefit from modern-era, multi-layer soil-vegetation- atmosphere transfer schemes. Planetary, continental and regional atmospheric circulation patterns in such assimilation systems are constrained near truth by the assimilation of atmospheric observations. Nonetheless, the implementation of improved representation of terrestrial hydrologic-atmospheric interactions has undoubtedly improved the quality of the precipitation and low-level temperature analysis products provided by data assimilation systems. The sharp topography of the VAMOS region poses a particular challenge to prediction. At present, it is not known at what scale dynamical model predictions may become useful for the region. It will be necessary to evaluate continuously the state-of-the-art dynamical predictions against mixed statistical-dynamical (or even purely statistical) predictions. It would not be surprising if, at the regional scale, the latter actually prove superior in the short-term, given the complexities involved.

Methodological research akin to that for large-scale predictions is also necessary in the mesoscale domain for the Americas. Such research is essential to meet the objectives of VAMOS, and will be strongly encouraged by the programme.

3.4 SPECIAL OBSERVING NEEDS

3.4.1 Enhanced monitoring in the eastern tropical Pacific region

VAMOS will encourage the development of enhanced monitoring systems that will provide the observational basis for improvement of operational coupled ocean-atmosphere analysis and prediction systems for the eastern Pacific region, as well as for the tropical Atlantic. Monitoring is understood as continuous atmospheric and oceanic observations during a multi-year period.

Although the TAO array has improved the definition of the surface meteorological conditions and upper ocean thermal structure over the equatorial Pacific, the region to the east of the Line Islands (160^{o}W) remains among the most serious data gaps in the global observing system. Operational atmospheric analyses and forecasts of midtropospheric winds cannot be verified for lack of in situ observations, and even some aspects of the climatology are not very well established. A more accurate and detailed description of the annual march of the upper ocean temperature and salinity structure is needed off the west coast of the Americas. The TAO array covers only the equatorial zone, leaving seriously undersampled regions in the warm pool off the central American coast and the vast stratus decks to the south of the equatorial zone in the southeastern Pacific (see Fig. 3.6). Until these observational system gaps are filled through a combination of in situ and space-based observations, it is unlikely that the annual variation of the ITCZ-cold tongue complex can be analysed and forecast with the accuracy required for skilful predictions of seasonal-to-interannual variability of the American monsoon.

Concerning the eastern Pacific, several approaches are being considered to enhance monitoring of meteorological and oceanic conditions. For the atmosphere, the augmentation of the continental and island-based rawinsonde network, the use of ship-based soundings of opportunity, and sounding systems operated from manned and/or unmanned aircraft are promising. Extension of the TAO array along 95^{o}W from about 12^{o}S under the stratus deck, across the cold tongue, the equatorial front and into the warm pool to around 12^{o}N could provide valuable "synoptic" information on upper ocean temperature and salinity structure, as well as data to validate and constrain model-based analyses of the upper ocean heat and freshwater budgets in the ITCZ-cold tongue complex. Other approaches are being considered by the PIRATA programme for the tropical Atlantic.

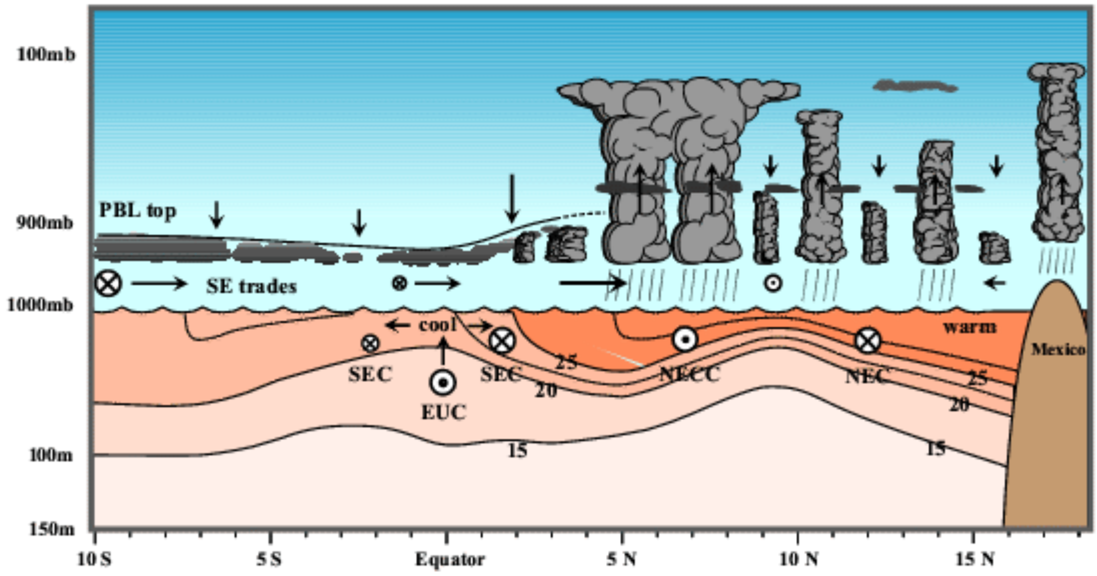

Fig. 3.6: Idealised cross section through the ITCZ/cold-tongue complex along 95^{o}W during July-September, showing features of the ocean-atmosphere stratification and current structure near the interface. SEC refers to the South Equatorial Current, NECC to the North Equatorial Countercurrent and EUC to the Equatorial Undercurrent. Ocean isotherms are in degrees Celsius. The deep convection between 5°N and 10°N indicates the location of the ITCZ. Encircled 'x' (dots) denote westward (eastward) flowing winds or currents (courtesy of S. K. Esbensen and W.S. Kessler).

3.4.2 Surface fluxes over the oceans

VAMOS will encourage the realisation of field studies that aim to provide improved description of surface fluxes over tropical oceans. Except for surface marine observations provided by the TAO moored buoy array, the tropical Pacific east of 160^{o}W remains among the most serious data gaps in the operational global observing system. Long records of research quality surface flux estimates that include radiative fluxes and rainfall are very limited over both the eastern Pacific and the Atlantic Oceans and must be augmented to support improvement and validation of boundary layer parameterisations in ocean-atmosphere climate models. Enhanced monitoring of the northeast Pacific warm-pool region, the equatorial cold tongue regime, the southeastern Pacific low cloud trade wind regime and the equatorial Atlantic using a combination of moored buoys and enhanced observing systems aboard ships of opportunity are promising approaches. International co-operation will be needed for effective implementation of these strategies.

3.4.3 Atmosphere-ocean interaction in the stratus deck region

The persistent stratus clouds off the Peru coast are believed to play an important role in accounting for the strong equatorial asymmetry in SST and surface wind in the eastern Pacific. Atmospheric and coupled GCMs have difficulty in simulating the extent and properties of these clouds and their interactions with the underlying SST field. The cloud deck is situated in cool air that flows equatorward around the east side of the subtropical anticyclone, and which maintains the atmospheric planetary boundary layer (PBL) in an unstable state as it encounters increasingly warmer waters. VAMOS will encourage projects that address the existence and variability of these cloud decks, and the way in which their presence affects the insolation and downward flux of infrared radiation at the air-sea interface. There is need to investigate the microstructure of the cloud deck and its variations with time, as well as its height, thickness, radiative properties and position relative the vertical structure of the PBL. It is also of interest to determine how deep into the ocean the influence of the cloud deck extends, and the evolution of the PBL structure as one follows air trajectories northwestward from the stratus deck into the relatively cloud-free equatorial cold tongue region. In addition, it is important to assess whether the temporal variations in the extent of the cloud deck are related to variations in the strength of the low-level flow around the subtropical anticyclone and/or to the subsidence aloft.

3.4.4 High resolution sea surface temperature

Higher spatial and temporal resolution SST data are required to study regional relationships between ocean boundary and American monsoon systems. The spatial resolution must be sufficient to resolve SST gradients in regions such as the Gulf of California. A 1^{o} long. by 1^{o} lat. COADS monthly SST data set is currently available for the period 1960 to 1993. VAMOS will require updates of these data through the life of the programme and, where the data are adequate, weekly analyses on this spatial scale. Specific requirements for higher spatial resolution weekly SST data will be developed to support studies utilizing nested regional numerical models. VAMOS anticipates these mesoscale modelling studies will require SST on spatial scales near 0.5^{o} long. by 0.5^{o} lat. for limited sub-domains of the VAMOS region. These higher resolution data will be required for time periods coinciding with model experiments.

3.4.5 Soil moisture

Over land areas, soil moisture is thought to play a role somewhat analogous to that of SST over the oceans (Delworth and Manabe, 1989; Koster and Suarez, 1995, 1996). VAMOS requires estimates of soil moisture in order to investigate these relationships, and will encourage work by the GEWEX programme aimed at providing the necessary observational estimates of soil moisture or some proxy for soil wetness. In principle, monthly, gridded, soil moisture would provide an untold wealth of insight into seasonal precipitation mechanisms over the Americas. Selected numerical and/or field studies require higher spatial and temporal resolution soil moisture data, e.g. weekly on 0.5^{o} long. by 0.5^{o} lat. analyses.

However, recognizing that gridded soil moisture estimates on these scales may not be attainable in the near future, some VAMOS requirements may be met through utilisation of a network of in situ soil moisture measurements. These requirements may be partially met over portions of North America by the soil moisture measurements taken as part of GCIP. VAMOS encourages similar observational programmes for Central and South America. In South America, VAMOS will look to the LBA programme to provide some of these data.

3.4.6 Precipitation

A major focus of VAMOS is understanding and prediction of seasonal precipitation. However, climate-scale phenomena do not generally respect the traditional calendar month boundaries. This is especially true for many aspects of the American monsoon systems including onsets, breaks and monsoon withdrawals. Thus, at a minimum, VAMOS requires the development of daily rainfall data sets over the Americas. This will require the integration of data from a variety of independent sources.

Recent numerical modelling experiments have highlighted the importance of properly capturing the diurnal cycle of evaporation and precipitation. The ability to correctly replicate the observed diurnal cycle is important in the context of climate model simulations. High quality hourly precipitation measurements are required for a better understanding, modelling and prediction of seasonal precipitation. The corresponding datasets are necessary both to validate regional numerical models that are run in a climate setting, and to provide a fuller understanding of the role of climate-scale variability in modulating the diurnal cycle of rainfall.

3.4.7 Vertical structure of the atmosphere

A more complete understanding of the evolution and variability of the American monsoon systems requires a full description of the atmospheric circulation associated with the events. While the major large-scale circulation features may be described using one of the GCM-based reanalyses (e.g. the NCEP/NCAR 40 year reanalysis), the study of regional features requires additional observations. For example, the global analyses are consistent with the notion that the flow is northerly along the eastern side of the Andes during the southern summer (Virji, 1981, 1982). The analyses also suggest the existence of a southward-flowing low-level jet from the Amazon basin into Argentina embedded in the large-scale northerly flow (Sugahara, et al., 1994: Stensrud, 1996). It is generally believed that the spatial structure and temporal variability of this jet are similar to that of its well-documented counterpart over the Great Plains of North America. These features are very important for convective developments. Mesoscale convective systems travelling eastward and forming over northern Argentina and southern Bolivia have been associated with a low-level warm and moist flow from the Amazon region (Guedes and Silva Días, 1985; Silva Días, 1989).

Studies have shown that approximately 30% of the southern summer days have a low-level jet east of the Andes at approximately 60^oW, 20^oS with an average speed of 13 m^{s-1} at about 1,500 m above sea level. In fact, the Andes seem to play a key role in the existence of this feature (Gandu and Geisler, 1992; Figueroa et al., 1995). The low-level jet appears to have marked diurnal oscillations in association with buoyancy oscillations above the elevated and heated Andes. The diurnal evolution of convective weather shows that summer showers tend to occur at night over most of Central Argentina (Paegle et al., 1982). The destabilising effects in the PBL of dynamical mechanisms, therefore, appear to be more important than the stabilizing effects of thermodynamical mechanisms during night-time. A marked diurnal cycle in the low-level flow east of the Andes has been simulated (Nicolini et al., 1987). In addition, the regions most favourable for the formation of convective systems are strongly correlated with those where the diurnal cycle has largest amplitudes (Machado and Guedes, 1996).

The available observational datasets are insufficient for study of the southern low-level jet in view of the subsynoptic scales involved and the sparseness of the South American observing system. Further data are needed to address several specific issues that require further clarification:

- What is the structure of the low-level jet east of the Andes?
- What are the mechanisms at work for its existence?

- What are the relationships between the jet and the mesoscale convection that contribute significantly to the total seasonal precipitation in southeastern South America?
- What is the relationship between the variability of the jet and that of the SACZ?
- What is the contribution of the moisture advected by the jet to the regional atmospheric hydrologic cycle?

Numerical models have difficulty with the extremely sharp topographic features of the Andes. Understanding the South American monsoon system requires more complete descriptions of the wind fields and atmospheric moisture transports and how they are influenced by these topographic features. Enhanced observations are required for the PBL and free atmosphere over the Southern Pacific, the west coast of South America, the Altiplano region, the lee of the Andes and across the continent into the SACZ. Enhanced observational periods with frequent soundings are necessary for model development and validation, as well as for empirical studies.

3.5 FIELD STUDIES

3.5.1 Atmospheric PBL structure above the cold tongue

Several field studies are required to assess whether it is possible to reconcile the observed vertical profile of wind speed and direction with existing models of PBL structure. The outcome will provide insights into how the models might be improved.

A field programme is under way funded by PACS to collect soundings in the PBL above the cold tongue region in the southerly regime in the far eastern Pacific. Another project is building a more comprehensive background climatology of the PBL structure over the cold tongue in the eastern equatorial Pacific to ascertain the degree to which the PBL reflects the local distribution of SST. Except for a few isolated field observations made during the Eastern Pacific Ocean Climate Studies (EPOCS), the vertical profile of the wind and thermodynamic variables in the southerly surface wind regime in the far eastern Pacific is virtually undocumented.

3.5.2 Structure and intensity of ITCZ rainfall

A PACS shipboard field study was carried out in summer of 1997 to test whether the hypothesis that the eastern Pacific clouds produce more rain than the western Pacific clouds but are not as deep is correct. It has generally been assumed that lower cloud-top temperatures are indicative of greater rainfall amounts. This ship-based study also examined the nature of the low-topped precipitating clouds over the eastern Pacific.

3.5.3 Air-sea fluxes in the cold tongue-ITCZ complex

A PACS field project aims to provide accurate measurements of the heat, momentum and fresh water fluxes in the eastern tropical Pacific. Of special interest is the relation of the vertical structure of the upper ocean and sea surface temperature to the local air-sea fluxes, and particularly, the role of the precipitation in governing SST. In this regard, two surface moorings will be set, one in the ITCZ (10^oN, 125^oW) and the other in the centre of the oceanic cold tongue (equator, 125^oW). Both moorings will make surface meteorological measurements, including wind velocity, air temperature, SST, incoming short-wave and long-wave radiation, relative humidity, barometric pressure, and precipitation. They will also make oceanic observations including temperature, salinity and horizontal velocity in the upper 200 m.

3.5.4 Vertical current profiles in the equatorial cold tongue

A PACS field investigation will deploy a surface mooring at 125^{o}W with a high vertical resolution (1 m) acoustic Doppler current profiler and several temperature and temperature/salinity recorders to sample both the velocity and density structure from a 2 m depth through the mixed layer and the upper portion of the thermocline. It is recognised that measurements at a single location will not be sufficient to resolve the modelling issues concerning the structure and dynamics of equatorial upwelling. In order to effectively address those issues in a field study, it will be necessary to deploy an array of moorings suitable for estimating the vertical profile of divergence and the relevant advection terms in the various budgets.

3.5.5 Tropical Rainfall Measuring Mission (TRMM)

In 1997 NASA/NASDA TRMM satellite was launched to map tropical precipitation. The eastern Pacific ITCZ presents a particular problem in this regard because of the sparsity of island-based stations in that region. The shipborne radar and precipitation measurements obtained over the tropical eastern Pacific Ocean provide valuable validation data for TRMM.

3.6 DIAGNOSTICS AND EMPIRICAL STUDIES

3.6.1 Diagnostic studies

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 cold tongue/ITCZ complexes and the stratus decks that could be addressed in diagnostic studies based on existing data sets.

VAMOS will encourage the realisation of statistical studies documenting relationships between anomalous boundary forcing and climate anomalies over the Americas, and diagnostic studies elucidating the physical and dynamical mechanisms through which these linkages occur. In this context, anomalous boundary forcing includes both SST 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. There is also need for descriptive and diagnostic studies of the tropical and extratropical storm tracks, ocean mixed layer, atmospheric PBL structure, and interfacial fluxes in the ITCZ-cold tongue complexes, based on existing marine surface observations and satellite data.

3.6.2 Empirical studies

It is becoming increasingly apparent that the ENSO phenomenon is subject to variability on decadal-to-century time scales. The warm polarity has become more prevalent since the mid-1970's and particularly since 1990 and the quasi biennial periodicity that characterised much of the previous 20 years has not been in evidence. Empirical studies are needed to clarify 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. VAMOS will encourage work on the processes that determine the evolution of the more subtle SST anomalies in the tropical Atlantic, and their impact on the atmospheric circulation.

Empirical studies that define and elucidate the fundamental characteristics of the regional distribution of continental precipitation are also needed. Terrain features over the Americas give 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 Rockies and Andes, episodic "gap winds" across central America and strong diurnal variations in rainfall patterns.

3.7 DATA SET DEVELOPMENT

The VAMOS Data Management will be based, as far as possible, on the principle of free and open access to data. Data access will be achieved through existing data centres, research institutions and universities to the fullest extent possible rather than through the establishment of one centralised data centre. To the extent possible, data management links will be established through a World Wide Web Home Page for VAMOS. The project will require assistance from the participants to co-ordinate a variety of data management activities. Specific tasks include further identification of existing VAMOS-related data, procedures for accessing them, and co-ordination of VAMOS-specific data needs for field studies.

3.7.1 Existing sources of data

An initial review of data sets of interest to VAMOS investigators reveal that some data are already available through existing institutions and distribution mechanisms. Some of these are listed in Table I (Section 3.10).

3.7.2 Historic data sets / data archaeology

While VAMOS will be able to take advantage of a number of existing data centre activities as well as the data sets discussed above, the programme will require a number of specific data sets. These will be more specifically defined in response to the detailed VAMOS science and implementation plans.

VAMOS will provide an opportunity to merge a number of data sets from several different data sources to provide a coherent description of the American monsoon systems to support diagnostic and empirical studies, model validation studies and prediction activities.

The development of historical daily precipitation and temperature data sets will be a key activity. The development of VAMOS daily precipitation and temperature data sets will build on current activities in PACS, GCIP, LBA, IAI and other regional and national activities.

A unique VAMOS data requirement arises from interest in the Intra-American Seas (IAS). The possible role of the IAS on regional precipitation will be one of the VAMOS research foci. This will require special efforts for improved historic SST, wind, and subsurface data in the Caribbean and Gulf of Mexico.

VAMOS will strongly encourage recovery of precipitation and surface temperature time series that are currently stowed away on non-digital formats in various non-conventional archives. This is especially applicable to data from South America where long term time series of good quality (sometimes going back to the turn of the century) exist in national records or private holdings in paper form. Examples are national and state agencies involved in the management of water resources and landowners. There is an urgent need to develop funding opportunities to rescue this valuable resource which might otherwise be lost due to the frailty of the records.

The private sector has recently engaged in active measurements efforts in some South America countries. As an example, one company has sold 800 automatic stations in Argentina only in the last 5 years. This figure should be compared with less of 100 sites currently available in the GTS. Policies need to be developed to access this important resource and make it available to the science community. A concern is the fact that many of the national weather services do not encourage the open exchange of data. This pressing issue, that threatens the integrity of key scientific data, needs to be addressed at the highest possible administrative levels.

3.7.3 The VAMOS data base

VAMOS will require development of a data base which will serve the needs of the diagnostics, empirical studies, modelling and prediction communities in VAMOS. The requirement to link with several data centres, research institutions and regional projects strongly suggests the development of a distributed data base structure linked through a VAMOS Home Page. While these links will not be able to service all of the VAMOS data needs, they will provide an efficient mechanism for providing information about data and for effecting data exchange. Distributed data bases have proven an effective means of servicing data needs without the requirement of a single large and costly data centre.

The distributed data base concept will allow VAMOS to interact efficiently with the Inter American Institute for Global Change Research (IAI), as well as with other regional centres such as CPTEC and regional projects such as GCIP and LBA.

3.8 LINKAGES

VAMOS will closely interact and co-operate with a number of national and regional projects as well as with other components of CLIVAR.

3.8.1 Within CLIVAR

Naturally, VAMOS has strong interactions with the other core projects of CLIVAR GOALS: G1 (ENSO: Extending and Improving the Predictions), G2 (Variability of the Asian-Australian Monsoon System) and G4 (African Climate Variability). Although VAMOS will focus mostly on seasonal-to-interannual climate variations, decadal climate variability might modulate and affect short-term climate variations of the American monsoons. Therefore, a co-ordination with research projects under the CLIVAR foci D2 (Tropical Atlantic Variability) and D4 (Pacific and Indian Ocean Decadal Climate Variability) is highly recommended.

3.8.2 Within WCRP

3.8.2.1 Global Energy and Water Cycle Experiment (GEWEX)

GEWEX emphasises the impact of weather systems on ground hydrology. Mesoscale modelling of continental precipitation in a climate context is an important element of the programme. The GEWEX Continental-scale International Programme (GCIP) focuses on North American rainfall and Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) on rainfall in the Amazon basin. A particularly important issue for GCIP is that the surface energy balance is known to affect the low-level jet over the great plains. Such coupling has been demonstrated by numerical modelling. This low-level jet is, in turn, a major factor in the regional moisture transport and moisture flux divergence in the Mississippi River region (Rasmusson, 1967).

(i) GEWEX Continental Scale International Project (GCIP)

The GEWEX Continental Scale International Project (GCIP) is a U.S.-led initiative being carried out in the Mississippi River Basin under the auspices of the WCRP's GEWEX programme. GCIP's mission is to demonstrate an ability to predict changes in water resources on seasonal, annual and interannual time scales within the framework of a global climate prediction system. GCIP has structured its programme around five objectives: 1) to determine and explain the annual, interannual and spatial variability of water and energy cycles in the Mississippi River Basin, 2) to develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins, 3) to develop and evaluate atmospheric, land and coupled data assimilation schemes that incorporate both remote and in-situ observations, 4) to provide access to GCIP in-situ, remote sensing and model data sets for use in GCIP and as benchmarks for model evaluation, and 5) to improve the utility of hydrologic predictions for water resources management up to seasonal and interannual time scales.

The second phase of GCIP is currently being planned based on needs to expand the geographical area for process studies to include the western U.S. A GCIP/PACS ad-hoc working group is developing a scientific prospectus focusing on the seasonal-to-interannual variability of warm season rainfall, surface air temperature, and the hydrologic cycle over North America. These improvements are needed to obtain more accurate water budget estimates and better information for model validation for both GCIP and VAMOS.

(ii) Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)

LBA is an international research programme aimed at creating the new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system. LBA is centred around two key questions that will be addressed through multi-disciplinary research, which will integrate studies in the physical, chemical, biological and human sciences: How does Amazonia currently function as a regional entity?, and how will changes in land use and climate affect the biological, chemical and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate?

In LBA, emphasis is given to observations and analysis which will increase the knowledge base for Amazonia in six general areas: physical climate, carbon storage and exchange, biogeochemistry, atmospheric chemistry, hydrology, and land use and land cover. The programme will help provide the basis for sustainable land use in Amazonia, using data and analysis to define the present state of the system and its response to observed perturbations, complemented by modelling to provide insight into possible changes in the future.

Meteorological and hydrological studies in the physical climate component will be conducted for nested spatial scales, from plots to the entire Amazonia, with emphasis on the understanding of the spatial and temporal variations of energy and water fluxes. Variations of climate and the responses of the Amazonian system to these variations, will be determined on daily to seasonal time scales. The data fields generated by a numerical weather prediction model will be stored and used in a four-dimensional data assimilation scheme as a primary tool to process the observational datasets.

VAMOS will contribute to co-ordinate the efforts of LBA and GCIP to encompass the largest hydrological basins in the Americas. This co-ordination will facilitate the unification of approaches across national boundaries. It will also facilitate the elaboration of the relative roles of soil moisture over land, and SSTs over oceans in determining precipitation and temperature patterns over a wide range of climate zones.

3.8.3 With other programmes

3.8.3.1 Pan-American Climate Study (PACS)

PACS is a U.S. project under the GOALS programme. Within the overall framework of CLIVAR, PACS can contribute to extend the scope and to improve the skill of operational seasonal-to-interannual climate prediction over the Americas, with emphasis on monsoons and extratropical summer rainfall and the coupling between them.

The scientific objectives of PACS are to promote a better understanding and more realistic simulation of (1) the boundary forcing of seasonal to interannual climate variations over the Americas, (2) the evolution of tropical SST anomalies in the tropical Pacific and Atlantic, (3) the seasonally varying mean climate over the Americas and adjacent ocean regions, (4) the time-dependent structure of the ITCZ/cold tongue complexes over the Atlantic and eastern Pacific, and (5) the relevant land surface processes over the Americas, including the effects of mesoscale orography and coastal geometry.

PACS sponsors dataset development, empirical studies, modelling and field activities. Dataset development is a decentralised effort designed to make global and American satellite and ground based datasets more accessible to the research community. Empirical studies, both statistical and diagnostic, address all five of the above objectives. Modelling includes atmospheric general circulation model (AGCM) simulations of the atmospheric response to boundary forcing, oceanic general circulation model (OGCM) simulations of the tropical oceans, coupled atmosphere-ocean general circulation model (coupled GCM) simulations focusing on the cold tongue-ITCZ complexes and the associated stratus decks and their interaction with the American monsoon systems, and simulation of the mesoscale structure of monsoon rainfall in a climate context. Field activities (exploratory measurements, enhanced monitoring, and process studies) contribute to the scientific objectives by providing improved datasets for initializing and verifying model simulations of the boundary forcing of rainfall anomalies over the Americas and the evolution of the tropical SST field, and promoting a better understanding and more realistic simulation of the structure of the ITCZ/cold tongue complex. PACS's field studies will focus on different regions of the American climate system in sequence. During the initial phase PACS will focus on atmosphere-ocean interaction in the tropical eastern Pacific, in association with the ENSO cycle and the climatological-mean annual march. During the second half of PACS the emphasis will gradually shift to the tropical Atlantic Ocean.

3.8.3.2 Pilot Research Moored Array in the Tropical Atlantic (PIRATA)

PIRATA is designed as the Atlantic counterpart of the TAO array in the tropical Pacific. In a three year (1997-2000) pilot project PIRATA aims 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 started with the deployment of two moorings in 1997. Deployment of up to 12 moorings is envisioned as part of a multinational effort involving Brazil, France, and the United States (see figure 6.6, page 203).

PIRATA is also being co-ordinated with the WOCE/ACCE programme scheduled for 1997-98, which will also be taking observations in the tropical Atlantic. VAMOS will provide PIRATA researchers with opportunities for enhanced co-operation with those working in the tropical Pacific under the sponsorship of PACS. It will facilitate the exchange of information with GCIP and LBA researchers on the information required from the tropical Atlantic for a better understanding of the moisture flux to the American monsoon systems.

3.8.3.3 Inter American Institute for Global Change Research (IAI)

In recognition of the importance of a regional approach to the study of global change, eleven countries of the Americas signed an agreement establishing the Inter American Institute for Global Change Research on May 13th, 1992, at Montevideo, Uruguay: Argentina, Bolivia, Brazil, Chile, Costa Rica, Dominican Republic, Mexico, Panama, Peru, United States, and Uruguay.

The IAI focuses on the 1) increased understanding of global change related phenomena and the societal implications of such phenomena, 2) increased overall scientific capacity of the region, 3) enhanced regional relationships, establishment of new institutional arrangements, and 4) promotion of the open exchange of scientific data and information generated by the Institute's research programmes, implementation of IAI Training and Education Programs.

The following research themes have been identified as initial priorities of the IAI: 1) tropical ecosystems and biogeochemical cycles, 2) impact of climate change on biodiversity, 3) ENSO and interannual climate variability, 4) ocean/atmosphere/land interactions in the inter tropical Americas, 5) comparative studies of oceanic, coastal and estuarine processes in the temperate zones, and 6) comparative studies of temperate terrestrial ecosystems and high latitude processes.

Although they are primarily concerned with the science of climate assessment and prediction on seasonal-to-interannual time scales, the regional programmes organised under the CLIVAR/GOALS contribute to a broader range of human endeavours. The participation of IAI is of special importance to VAMOS in view of the Institute's major thrust on the societal impacts of climate variability over the Americas. VAMOS will provide IAI researchers with opportunities for enhanced co-operation with other science programmes focusing on the American climate system, particularly with the large and regional scale modelling efforts developed in PACS and GCIP. It will also provide enhanced co-ordination of field activities in the American sector.

3.8.3.4 International Research Institute (IRI)

The International Research Institute for seasonal to interannual climate predictions was launched in 1996 by NOAA, and is developing toward a multi-national organisation focused on seasonal-to-interannual climate prediction, and the application of climate predictions to the benefit of societies. The goals of the IRI are 1) to continually develop dynamically and thermodynamically consistent coupled models of the global atmosphere, ocean, and land, 2) to serve as a basis for improved climate prediction, 3) to systematically explore the predictability of climate anomalies on time scales up to a few years, 4) to receive, analyse, and archive global atmospheric and oceanic data to improve the scope and accuracy of the forecasts, 5) to systematically produce useful climate forecasts on time scales of several months to several years on global space scales, and 6) to shape and augment these forecasts by incorporating additional physical, agricultural, economic and other appropriate data, to the explicit social and economic benefit of national societies.

Toward these goals, the IRI, acting in collaboration with both the climate and applications research communities, and the WMO network of meteorological and hydrologic centres, will foster activities in model and forecast system development, experimental forecasting, applications research, climate monitoring and dissemination, and targeted training. In addition, the IRI will establish selected regional applications pilot projects in which prototypical end-to-end systems are developed, evaluated, and refined, with continuing and active dialogue between climate researchers, technical experts, social scientists, and decision makers. The IRI programme of development and research will lead to improvements in ENSO-related predictions (and eventually more general climate predictions).

VAMOS will contribute to the efforts of IRI on assessing the predictability inherent in the tropical SST field and its impacts upon regional climate with the research programmes in PACS. It will also facilitate the focusing of the field and monitoring programmes in PACS and PIRATA, as well as GCIP and LBA, on the observational datasets that are more urgently needed for prediction improvements.

In terms of applications and human dimensions, the implementation VAMOS will consist of two stages. The first stage is the establishment of partnerships between physical scientists and social scientists. The second stage is the design and realisation of end-to-end problems. The IRI and VAMOS will need extensive climate and applications data base development for the Americas and adjacent oceanic regions. All programmes will benefit from co-ordinating the acquisition, technical support and distribution activities associated with this data base.

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3.10 Table 1: Preliminary list of data available for VAMOS research

Variable / source	Internet address
Precipitation	
Monthly precipitation data (NCDC)	http://www.ncdc.noaa.gov/ol/climate/climatedata.html
Legates and Willmott Climatology	http://dss.ucar.edu/datasets/ds236.0/
Daily global tropical cyclone positions (NCAR) Data	http://dss.ucar.edu/datasets/ds824.1/
GOES Precipitation Index (GPI) monthly-means	http://wesley.wwb.noaa.gov/ncep_data/index_sgi62_png.html
MSU - precipitation	http://www.cdc.noaa.gov/cdc/data.msu.html
GPCP	http://www.ncdc.noaa.gov/
OLR	
- Original data	http://wesley.wwb.noaa.gov/ncep_data/index_sgi62_png.html
- Complete fields (2.5^o x 2.5^o)	http://www.cdc.noaa.gov/cdc/data.interp_OLR.html
- Corrected for satellite drift	http://terra.msrc.sunysb.edu/data.html
MSU layer temperatures (Spencer and Christy)	http://www.cdc.noaa.gov/cdc/data.msu.html
Other Satellite Data	

SSM/I	http://www.ncdc.noaa.gov/ssmi/html/ssmi.html
ISCCP	http://isccp.giss.nasa.gov/isccp.html
HIRS (upper tropospheric water vapour)	http://www1.etl.noaa.gov/climsat/waterv/waterv.html
GEWEX / NASA Water Vapour Project	http://dss.ucar.edu/datasets/ds722.0/
Surface Observations	
Global Historic Climate Network (GHCN)	http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=ghcn.html
Climatic Research Unit (CRU) land surface temperature	http://www.cru.uea.ac.uk/cru/cru.htm
COADS sea surface observations	http://www.cdc.noaa.gov/coads/
1-degree latitude-longitude resolution	http://dss.ucar.edu/datasets/ds540.1/
SST analyses	
NCEP/NOAA	http://wesley.wwb.noaa.gov/ncep_data/index_sgi62_png.html
LDEO analyses	http://ingrid.ldgo.columbia.edu/descriptions/RSA_MOHSST5.html
FSU pseudo-stress analyses	http://www.coaps.fsu.edu/woce/
TOGA-TAO	http://www.pmel.noaa.gov/toga-tao/home.html
Reanalyses Data Sets	
NCEP/NCAR reanalysis	http://wesley.wwb.noaa.gov/reanalysis.html http://dss.ucar.edu/pub/reanalysis/ http://www.cdc.noaa.gov/cdc/reanalysis/
NASA reanalysis	http://dao.gsfc.nasa.gov/experiments/assim54A.html
ECMWF reanalysis	http://www.ecmwf.int/research/era/index.html http://dss.ucar.edu/pub/ec-reanalysis.html

VAMOS Related programme and Data Sources	
PIRATA	http://www.ifremer.fr/orstom/pirata/pirataus.html
Large Scale Biosphere- Atmosphere Experiment in Amazonia (LBA)	http://www.gewex.com/lambada.html http://lba.cptec.inpe.br/lba/indexi.html
Inter-American Institute for Global Change Research (IAI)	http://www.iai.int/
Global Energy and Water Cycle Experiment (GEWEX)	http://www.gewex.com/

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