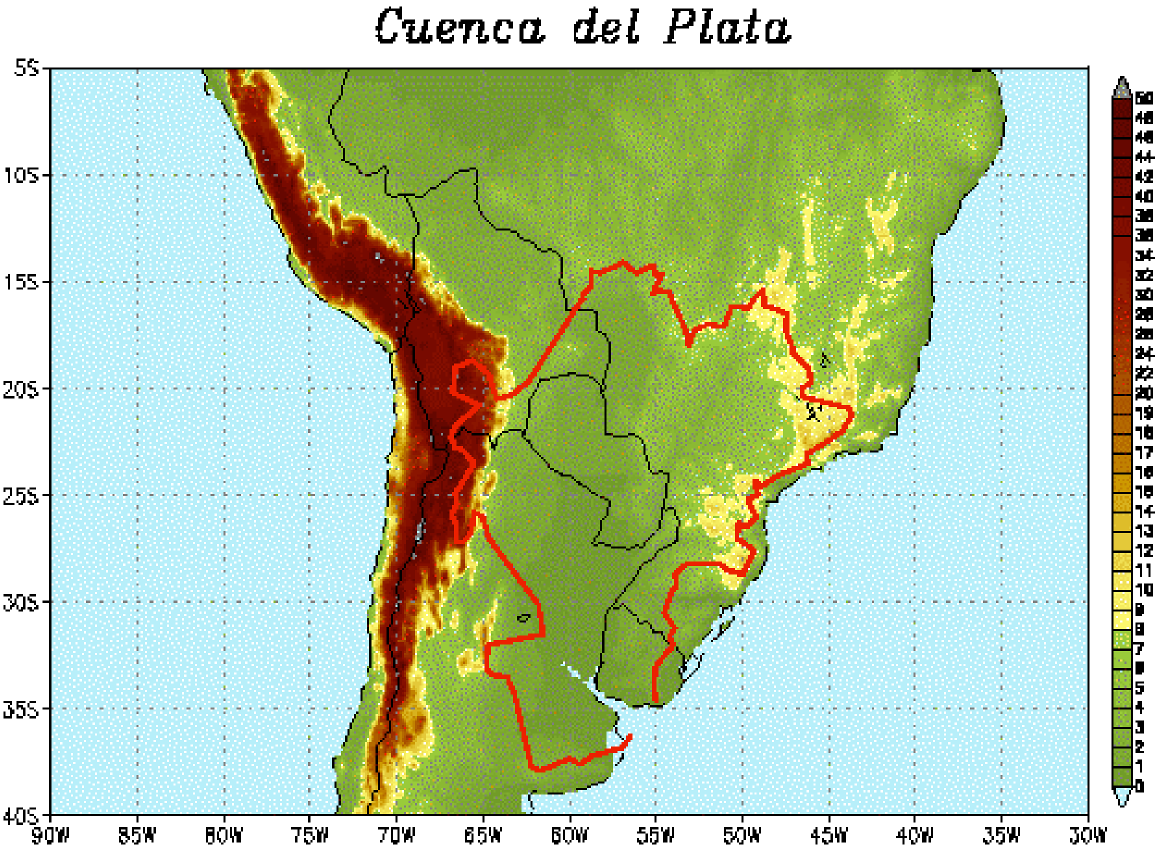
Climatology and Hydrology of the Plata Basin



A Document of VAMOS[1] Scientific Study Group on the Plata Basin

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Preface

A significant source of natural capital for the growing populations of Argentina, Brazil, Bolivia, Paraguay, and Uruguay, the Plata Basin generates 70% of the total Gross National Product of these countries and is critical to local economies as an agricultural center, natural waterway for transportation, and primary producer of hydroelectric energy. In view of the recent advances made in climate and hydrological forecasting, there is potential for improved decision-making in sectors such as water resource management and agriculture. In addition, the inhabitants of the Plata Basin, now nearly 60% of the total population of the five countries in the Basin, would greatly benefit by an early warning system to mitigate the impact of extreme events such as droughts and floods. Finally, there is need to address the significant environmental degradation that the Basin has experienced in the last decades as a result of land-use alteration and global climate change, and of the impacts of economic development.

Four countries in the Basin, Argentina, Brazil, Uruguay, and Paraguay, currently operate as an economic common market (MERCOSUR). This is a major effort toward a closer integration of their economies. Regional governments are using the framework of MERCOSUR to develop common socioeconomic policies. The scientific community is also starting to establish regional collaborative research activities in the framework of MERCOSUR. The present time, therefore, is especially auspicious for establishing an international program on the climatology and hydrology of the Plata Basin.

The WMO/WCRP CLIVAR panel on the Variability of American Monsoon Systems (VAMOS) has found general consensus on the region's readiness to embark on and support collaborative research on the Plata Basin's climate/hydrology. This readiness is primarily due to an enhanced awareness of the impact that climate variations can have on water resource management, energy production, agriculture and health. Improved prediction can potentially result in large economic and social benefits to the region.

The Panel at its annual meeting held in Montevideo, Uruguay, March 2001, appointed a VAMOS **Plata Basin Scientific Study Group (SSG).** *Members of the Plata Basin SSG are: Walter Baethgen (INIA, Uruguay), Vicente Barros (U. Buenos Aires, Argentina), E. Hugo Berbery (U. Maryland, USA), Robin Clarke (U. Federal Rio Grande do Sul, Brazil), Heidi Cullen (IRI, USA), Carlos Ereño (International CLIVAR Project Office), Benjamin Grassi (Universidad Nacional de Asunción, Paraguay), Dennis Lettenmaier (U. Washington, USA), C. Roberto Mechoso (Co-Chair,U. California, Los Angeles, USA), and Pedro Silva Dias (Co-Chair, U. Sao Paulo, Brazil). This document is intended to act as guidance for the design of a comprehensive program for the Basin.*

1. Introduction

The Plata Basin covers about 3.6 million km^2 (see Fig. 1). In terms of geographical extent, the basin is the fifth largest in the world and second only to the Amazon Basin in South America. The principal sub-basins are those of the Paraná, Paraguay and Uruguay Rivers. The Plata Basin covers parts of five countries, is home to about 50% of their combined population, and generates about 70% of their total GNP. Approximately 30% of the area belongs to Argentina, 7% to Bolivia, 46% to Brazil, 13% to Paraguay and 4% to Uruguay. The basin is important in different ways for the economies of those countries. Harvests and livestock are among the region's crucial resources, rivers are natural waterways, and surface transportation has greatly increased in recent years due to the integration of regional economies. Last, but not least, several hydroelectric plants provide most of the energy consumed. The countries in the basin have a history of international collaboration. Argentina and Uruguay built Salto Grande on the Uruguay River. Brazil and Paraguay built today’s largest power station in the world at Itaipú on the Paraná River. Argentina and Paraguay built Yacyretá, also a very large power station downstream from Itaipú.

1.1 Agriculture

The Plata Basin is one of the largest food producers (cereals, soybeans and livestock) in the world. The regional economy is largely based, directly or indirectly, on agriculture (crops and livestock). Argentinean provinces in the basin produce more than 90% of the country’s cereal and oil crop production, and grow more than 70% of the country's bovines. Brazilian states in the basin produce more than 30% of the country’s rice, soybeans, wheat, maize, and grow about 10% of the country’s bovines. Uruguay produces its entire cereal and oil crop and grows more than 80% of its livestock in the basin. Paraguay, whose economy largely depends directly or indirectly on agricultural production (90% of which corresponds to livestock), is entirely within the basin. This country’s production is about 10 Megatons (Mt), and is increasing due to new technologies and the expansion of productive areas.

Agricultural production in the southern region of the Plata Basin primarily develops on the highly fertile soils of the Pampas, an ecosystem in which native temperate and subtropical grasslands have been converted to croplands. Here, climate fluctuations on various time scales result in high variability of crop and animal-based production with the potential for negative consequences on food supply and on the economy at both regional and national levels. The Pampas extend over 75 million hectares, of which 26 million are cultivated. There has been a considerable increment of grain production in the last ten years due to the incorporation of updated technology and the revision of inadequate policies for the sector. The mean annual production of the Pampas is now more than 50 Mt, varying from 45 to more than 65 Mt in the best years.

Areas devoted to agriculture in Argentina have steadily increased during the last decade. Planted areas with grains and oil-seeds increased from 20 up to 26 million hectares. Changes are evidenced mainly in the Pampas, where land use strongly depends on economic conditions. (Cultivated lands increase in detriment of pastures during years with more favorable prices for grain crops compared with those for cattle). For example, the cultivated area in the province of Buenos Aires increased 40% between 1988 and 1993. Such changes in land use of the Pampas, which are shifting the boundary of the grain production frontier towards the marginal zones, require an intensification of production systems, higher input use, and result in increased risk of land degradation. This is of great concern; the organic soil content in some locations was reduced to 50 % of its value before agricultural practice at the beginning of the 20th century. For this reason and other economics aspects, direct seeding or minimum tilling is growing rapidly. At this point in time, there are more than 5M hectares under these types of tilling, and it is estimated that this number will more than double by the year 2010.

Agriculture in the Brazilian states of Rio Grande do Sul, Santa Catarina, and Paraná is based on land that was originally part of the Atlantic Forest (Mata Atlantica) and the Meridional Forests and Grasslands ecosystems. The Atlantic Forest ecosystem covers nearly the entire Brazilian coastline from the Northeast to the state of Rio Grande do Sul. More than 90% of this ecosystem has been gradually converted to agricultural uses since the early 1900's. Agricultural production in southern Brazil is highly mechanized. This has resulted in high crop productivity, but has brought serious environmental problems such as soil compaction and erosion, water contamination, and vegetation devastation. The northern region of the Plata Basin includes parts of the Cerrados ecosystem (a mixture of shrubs and pastures), which is characterized by low fertility soils that are also being gradually converted to annual crops (soybeans, wheat, maize, etc.).

1.2 Energy demand and hydropower generation

The largest hydropower plant in the world at the present time, Itaipú on the Paraná River, has been operating 18 generators (each of 700 MW) since 1982. Energy production in the year 2000 was 93.4 billion kWh (kilowatt-hours), which corresponds to about 95% of the energy used by Paraguay and 24% of that used by Brazil. Itaipú is one of many plants built between 1965 and 1985 on the upper Paraná (see map in Figure 1). These plants supply more than 50% of Brazil´s energy requirement, over 90% of which is obtained from hydropower. Still more plants are planned for the Iguazú and other tributaries of the Paraná (notably the Piquirí and Ivaí). The Uruguay River Basin also has a large hydropower potential, the total available energy being 16,500 MW, of which 6680 MW have so far been developed. Existing developments are on the Passo Fundo River, and at Salto Grande, on the international reach between Argentina and Uruguay. The latter country has built three hydropower stations on the Negro River. Among these, Gabriel Terra, built in 1945, was the first dam constructed on a flood plain and its reservoir was the largest in the world. The rivers of the Plata Basin also constitute the primary water supply for a densely populated area that includes Buenos Aires and São Paulo, the two largest cities in South America.

The growth in electricity demand has exceeded 5% in many of the countries of the Plata Basin, and there is a growing concern that construction of new power generation facilities will not keep pace with this demand. The heavy reliance on hydropower makes the basin's electricity supply vulnerable to drought and water shortages. In terms of water resources, the large hydroelectric power facilities built within the last 30 years have had a significant impact on the flow regime of the basin. The basin also is home to Guarany, one of the world's largest aquifers that extends 1.2 million km^2 in the Paraná basin with reserves estimated at 50,000 km^3.

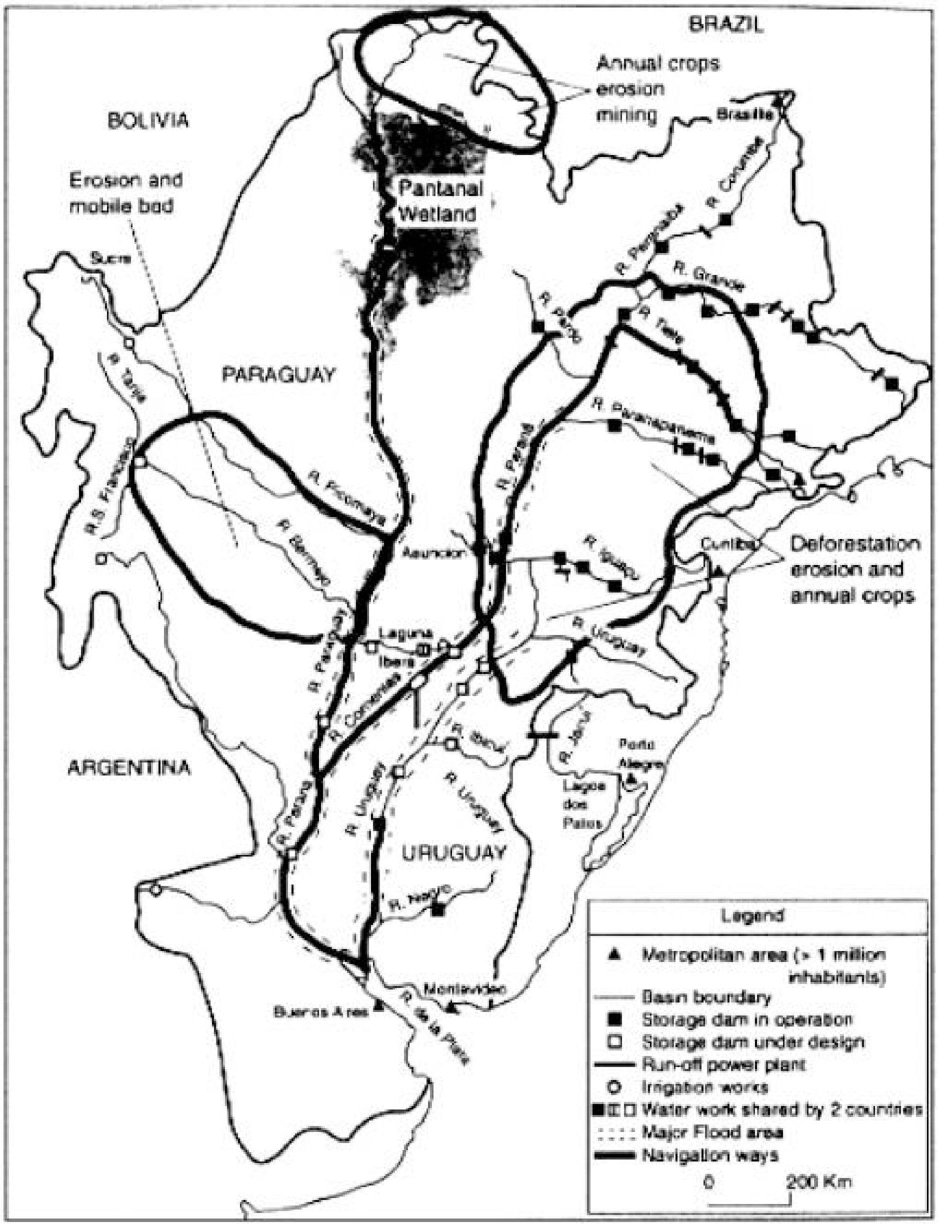

Figure 1. Water resource development in the la Plata Basin.

1.2.1
Privatization and integration

The recent restructuring of the power market within the MERCOSUR countries of Argentina, Brazil, Paraguay, and Uruguay has been designed to make hydropower projects more attractive for private investors. Currently, construction is ongoing to build Brazil's largest privatized hydropower project on the Uruguay River called Itá. This is one of the first large dam projects being promoted by the Inter-American Development Bank (IDB), as part of the IDB's new private sector funding initiative. Also part of this initiative is the plan for 16 dams in Brazil to be put up for bids by private companies. The predicted growth rate of electricity demand for

Southern Brazil, for example, is approximately 5.8% a year, mostly because of massive investment made in growing economic sectors such as the automotive and petrochemical industries. Deregulation is one strategy to meet increasing demand. The use of seasonal to interannual climate forecasts can also help to achieve higher efficiencies in order to better satisfy the increasing demand.

	Electricity production (BkWh)	% from hydropower (%)	Electricity generating capacity (GW)	% from hydropower (%)	Electricity Consumption (BkWh)
Argentina	75.2	48	21.8	42	75.6
Bolivia	2.6	54	.9	NA	NA
Brazil	316.9	91	62.4	87	336.2
Paraguay	50.3	99	7.3	99.4	1.5
Uruguay	5.7	95	2.2	70	5.9

Table 1. All numbers are from the Energy Information Administration http://www.eia.doe.gov/ and the CIA Factbook http://www.cia.gov/cia/publications/factbook/geos. Numbers reported are for 1998.

Growing demand for electricity throughout South America has helped to foster the interconnection of the region's various electricity grids. This trend is expected to continue as a result of further deregulation of the electricity sector and the relaxation of restrictions on international investment. Brazil's power sector is in the midst of a change from state to private control. According to the Brazilian Development Bank, five Brazilian power distributors underwent privatization during 1999. Argentina and Bolivia have also been attempting to boost productivity in the power sector by transferring assets from the state to the private sector. Since 1991, Argentina has aggressively pursued privatization. Brazil and Chile are the two most important export markets for Argentina, and these three governments are working towards integrating their electricity markets. In 1994, Bolivia passed a law allowing private firms to acquire 50% ownership of assets and the ability to obtain management control of generating facilities.

Brazil's small northern and larger southern electrical grids were joined in January 1999 into one grid that serves 98% of the country. Interconnection between the electric systems of Argentina and Uruguay has been in effect since 1974. A project valued at $230 million is underway to supply 1,000 MW of power to Brazil originating from Argentina. Electrosul of Brazil has an agreement with Uruguay for the purchase of 70 MW of energy, the project is estimated to cost $30 million. Four companies are currently exploring the potential of exporting electricity from Bolivia to Brazil's Matto Grosso

region. Due to its large generating potential, Bolivia is also currently analyzing several projects to export electricity to supply unmet demand in Brazil.

1.3 Transboundary Water Issues

The sustainable development of limited natural resources hinges upon effective dialogue between scientists, policy makers, resource managers, and end-users. The Plata Basin is a complex system, shaped by both natural processes and human demands, each having both spatial and temporal variability. Transboundary water issues have become a growing concern in South America, although this has only 5% of the world's population and 26% of the world's runoff. A sustainable development strategy for border areas must include: (a) diagnostic studies of each area, (b) environmental zoning proposals that define areas suitable for sustainable production as well as areas for environmental protection, (c) integrated programs that form part of an overall development strategy, and (d) national and binational investment projects formulated at the pre-feasibility and feasibility levels.

2. Mean Climatology of the Basin

2.1 Low-level circulation

The meridional wind field at 850 mb from ECMWF reanalyses shown in Fig. 2 illustrates the most relevant surface circulation features. Winds at that level are northerly over most of the basin with a maximum in the northwestern sector; northerlies are present throughout the year but are strongest during winter. The northeastern sector shows the signature of the South Atlantic Convergence Zone (SACZ), which has a well-defined annual cycle with strongest intensity during summer. Estimates of the annual cycle from other global analyses, while similar over the SACZ, can be very different east of the Andes. A similar broad description has been obtained for the moisture transport field over South America (Nogués-Paegle and Mo, 1997). We will return to this point later in this document.

The summer circulation over South America is dominated by a monsoon system (SAMS). Important geographical factors determining the monsoon evolution are the large land mass bisected by the equator, very high mountains to the west that effectively block air transport in the zonal direction, and surface cover that varies from tropical forests in Amazonia to high altitude deserts in the Bolivian Altiplano. Plentiful moisture supply from the Atlantic maintains a precipitation maximum over central Brazil. A major seasonal feature of the monsoonal circulation over South America is the Southern Atlantic Convergence Zone (SACZ), which extends southeastward along the northeastern boundary of the Plata Basin during the summer season. The SACZ is in several ways similar to the South Pacific Convergence Zone (SPCZ) that develops over the southwestern tropical Pacific. This document emphasizes the important role played by the SACZ on the variability of precipitation in the Plata Basin.

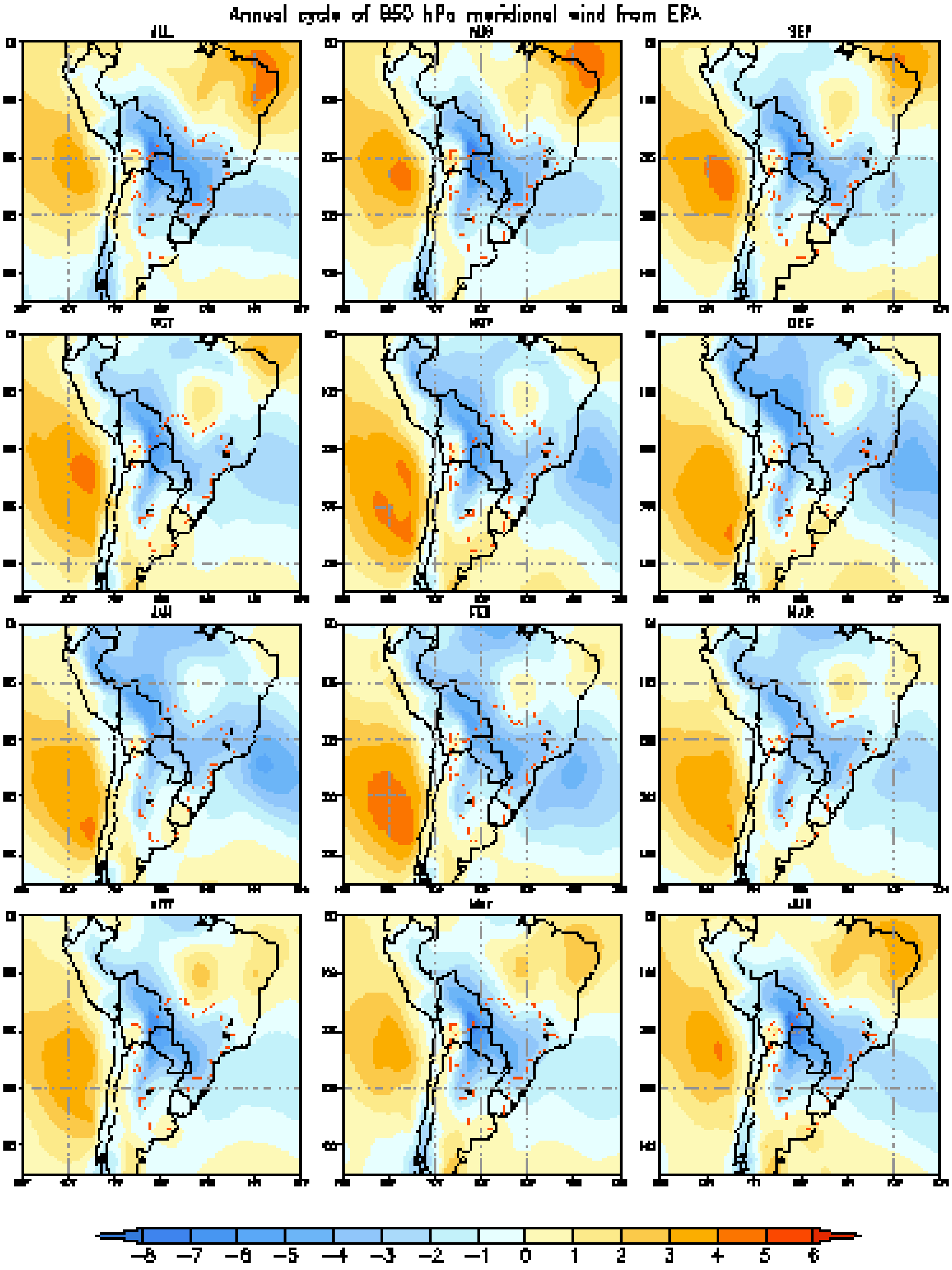

Figure 2.   Annual cycle of monthly-mean meridional wind (ms^{-1}) at the 850 hPa level from the ECMWF Reanalysis.

A northerly/northeasterly low-level jet east of the Andes (SALLJ) is an important mesoscale climatological feature of the Plata Basin (e.g.,Virji, 1981). To some extent, the SALLJ is the counterpart of the low-level jet that flows northwest over the Great Plains of the US (GPLLJ). The GPLLJ, however, develops primarily during the boreal warm season, while the SALLJ appears to be present most of the year (Nogues-Paegle and Berbery, 2000; see also http://www.met.utah.edu/jnpaegle/research/miami_report.html. Plans for a field experiment to obtain enhanced observations of the SALLJ are described in http://www.met.utah.edu/jnpaegle/research/ALLS.html).

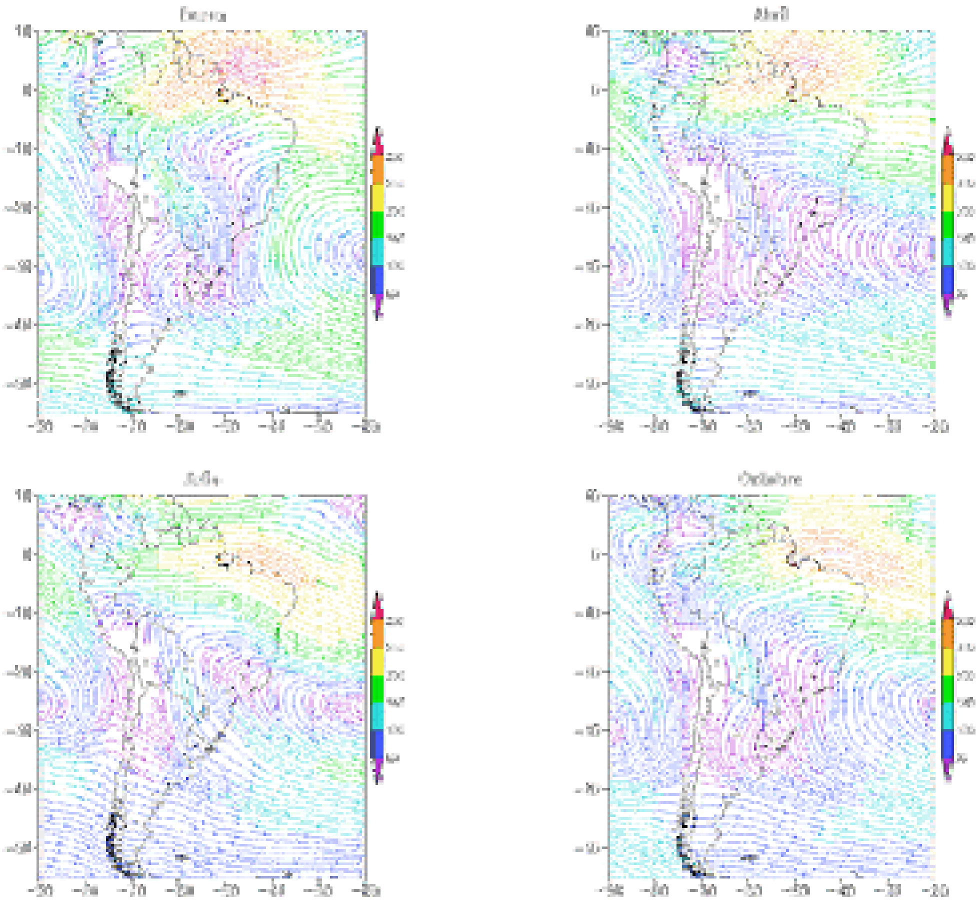

Figure 3. Mean monthly winds (m/s) at 850 hPa from NCEP/NCAR reanalysis 1958-1992.

Figure 3 gives a simplified view of the annual cycle of the low-level circulation over South America. In January, there is an important inflow from the tropical Atlantic coming from the Northern Hemisphere. This flow veers eastward over the tropical continent and then southward with a strong current along the eastern flank of the Andes Mountains. At 20°-25° S the wind is from the north all over the continent east of the Andes. This flow tends to divide in two branches towards the southwest and southeast. In April, the mean wind is somewhat similar to that in January, but the tropical easterlies in the Southern Hemisphere have a southern component. The northern component over subtropical South America is considerably weaker than in January. South of about 25° S the flow is primarily southward. In July, the low-level flow over most of the Plata Basin appears to be associated with the South Atlantic high. Most features of the summer flow are already present in October.

2.2 Moisture flux and sources

A complete understanding of the Plata Basin hydrology requires knowledge of the atmospheric component of the water cycle. This is, however, very limited at the present time due primarily to the lack of observational data since only about ten radiosondes are launched at different locations once a day. The small spatial scales of the SALLJ exacerbate the difficulties with the data scarcity.

Global analyses have been used to obtain preliminary descriptions of the moisture fluxes. Nogués-Paegle and Mo (1997) documented the moisture fluxes from the Tropics into Argentina, southern Brazil and northern Uruguay using NCEP/NCAR reanalyzes. Their results suggest that while the moisture source of the GPLLJ is a water mass (the Gulf of Mexico), the SALLJ has a continental moisture source.

Large discrepancies can be found, however, when attempting to compute moisture budgets on regional scales using global analyses from different operational centers (Wang and Paegle, 1996). Moreover, the use of more recent reanalysis products (Higgins et al., 1996) does not reduce these discrepancies. A possible reason is the inadequate temporal resolution of the reanalysis data set, which fails to capture the diurnal cycle. (Berbery and Rasmusson, 1999) The sampling frequency must be at least four times per day to obtain reliable estimates of the atmospheric water balance for the Mississippi sub-basins. There are indications that in the Plata Basin even 4 analyses per day may not be sufficient to resolve the complex nature of the diurnal cycle of moisture flux convergence (Berbery and Collini, 2000).

2.3 Precipitation

The annual mean total precipitation in the Plata Basin is about 1,100 mm, of which only about 20 % (23,000 $m^3 s^{-1}$) reaches the sea as surface water. The other 80 % is evaporated and infiltrated into the ground. It is apparent that any small percentage change in the evaporation and infiltration rate may lead to greater percentage changes in the runoff. Consequently due to changes in vegetation cover in most of the middle and upper Paraná, in the middle and lower Paraguay and in the upper Uruguay (see subsection 9.2) human activities in the last 50 years may have led to changes in runoff. Dams may also alter the evaporation, though probably at a lower rate.

Annual mean rainfall in the Plata Basin tends to decrease both from north to south and from east to west (Fig. 4). Corresponding amounts range from 1,800 mm in the maritime uplands along the Brazilian coast to 200 mm along the western boundary of the basin. Rainfall is large in the upper reaches of the Paraguay and Paraná River basins. The amplitude of the annual cycle in rainfall decreases from north to south (Fig. 5). The northern part of the basin has a well-defined annual cycle with maximum precipitation during summer (December-February). The central region (Northeast Argentina/Southern Brazil) has a more uniform seasonal distribution, with maxima during spring and autumn. Since the major rivers in the basin generally run from north to south, this rainfall regime contributes to the attenuation of the seasonal cycle downstream.

Around 20°-25°S, enhanced rainfall in summer is signature of the SACZ development, especially towards the east. In winter and spring, on the other hand, enhanced rainfall is signature of increased baroclinic activity. However, while the frequency of cyclogenesis is almost the same in those two seasons (Gan and Rao, 1991), the water vapor content of the atmosphere is higher and precipitation is larger in spring (Rao et al., 1996).

2.4 Temperature

The mean annual temperature in the basin ranges from around 15°C in the south to more than 25°C in the northwest. Most locations east of the Andes less than 800 km from the ocean have a mean annual temperature lower than 20°C. The higher altitudes in the eastern part of the Brazilian states of São Paulo, Paraná and Santa Catarina are substantially cooler than their surroundings.

In winter, monthly-mean temperatures have a clear north-south gradient. In July, for example, the mean temperature over the northwest part of the basin is more than 20°C, while that in the province of Buenos Aires is around 10°C cooler. In summer the gradient is more zonal reacting to the land ocean distribution. In January, the maximum mean temperatures are over 27.5°C in the Chaco and western Argentina, while they are less than 22.5°C in the coastal areas of southern Brazil, Uruguay and the province of Buenos Aires (Hoffmann, 1975).

3. Mean Hydrology of the Basin

3.1 Sub-basins

The hydrological behavior of the main rivers draining the Plata Basin is strongly influenced by basin topography - itself a product of geology and climate - and human activities (see Table 2). Topographic heights have strong meridional (the general direction of drainage) and zonal variations. The eastern boundary of the basin has a mean altitude of 1000 m, although the water divide can be as high as 1500 m in the east and as low as 200 m in the south. The western boundary includes the Andes Mountains, which reach altitudes between 1000 and 4000 m. There are, however, stretches in the northwest and southwest where altitudes reach only about 500 m and 300 m, respectively.

The Paraná River originates at the confluence of the Paranaiba and Grande Rivers in southeast Brazil (Fig. 1), and stretches of the river mark the boundary between Paraguay and Brazil, and Paraguay and Argentina. The Paraná flows mainly through the plains of Paraguay and Argentina before joining the Uruguay River at the head of the Plata River. The Paraná's main tributary is the Paraguay River, which originates in central Brazil. The poor natural drainage of the region through which the Paraguay flows has created the Pantanal, one of the world's largest wetlands with an area that can be as large as 140,000 km^2 (Fig. 1). The Pantanal's slope is 0.25 m km^{-1} in the east-west direction but only 0.01 m km^{-1} in the North-South direction. Such a very shallow slope produces a time lag in the flood peak between the north and south of the Pantanal of about four months.

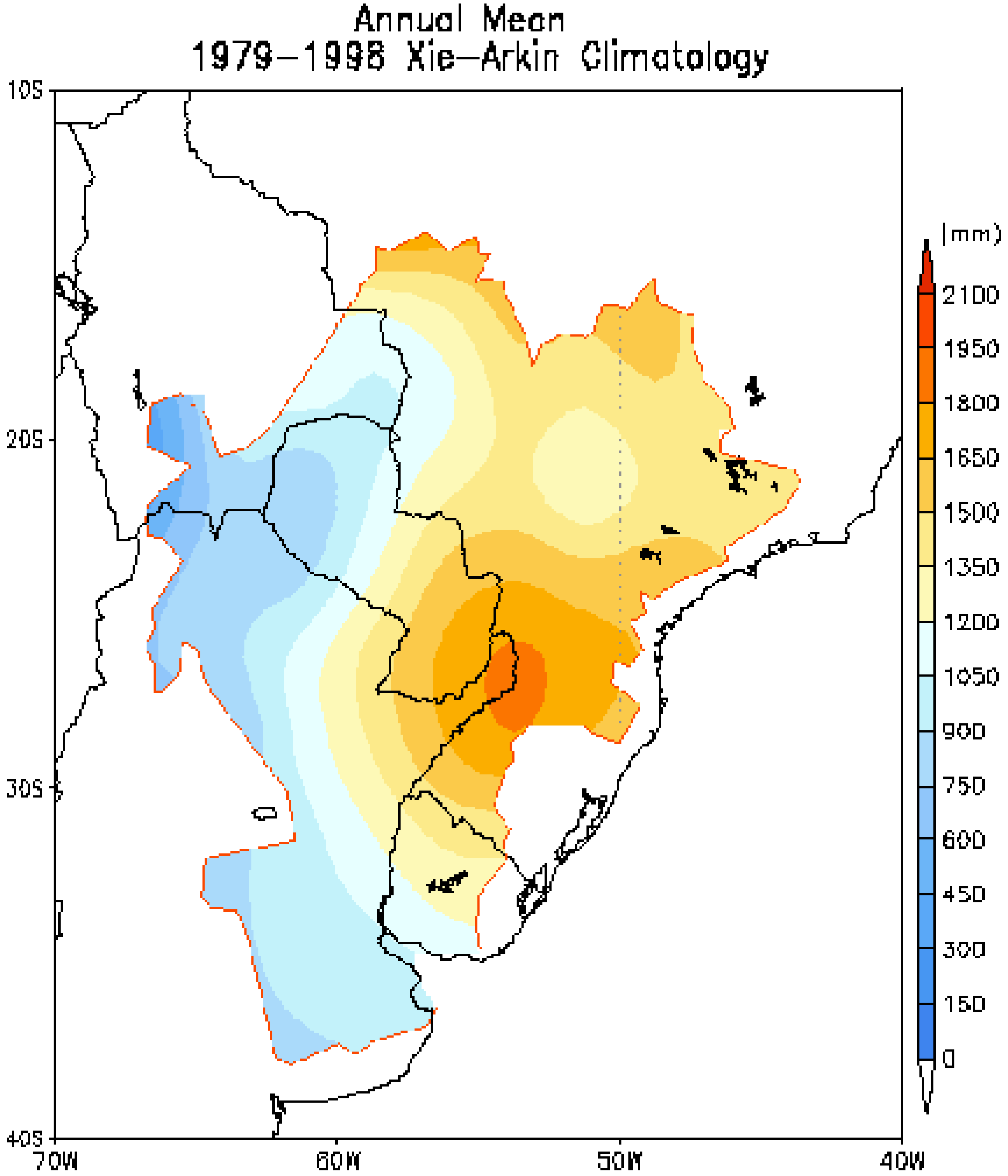

Figure 4. Annual-mean precipitation in the Plata Basin from Xie&Arkin.

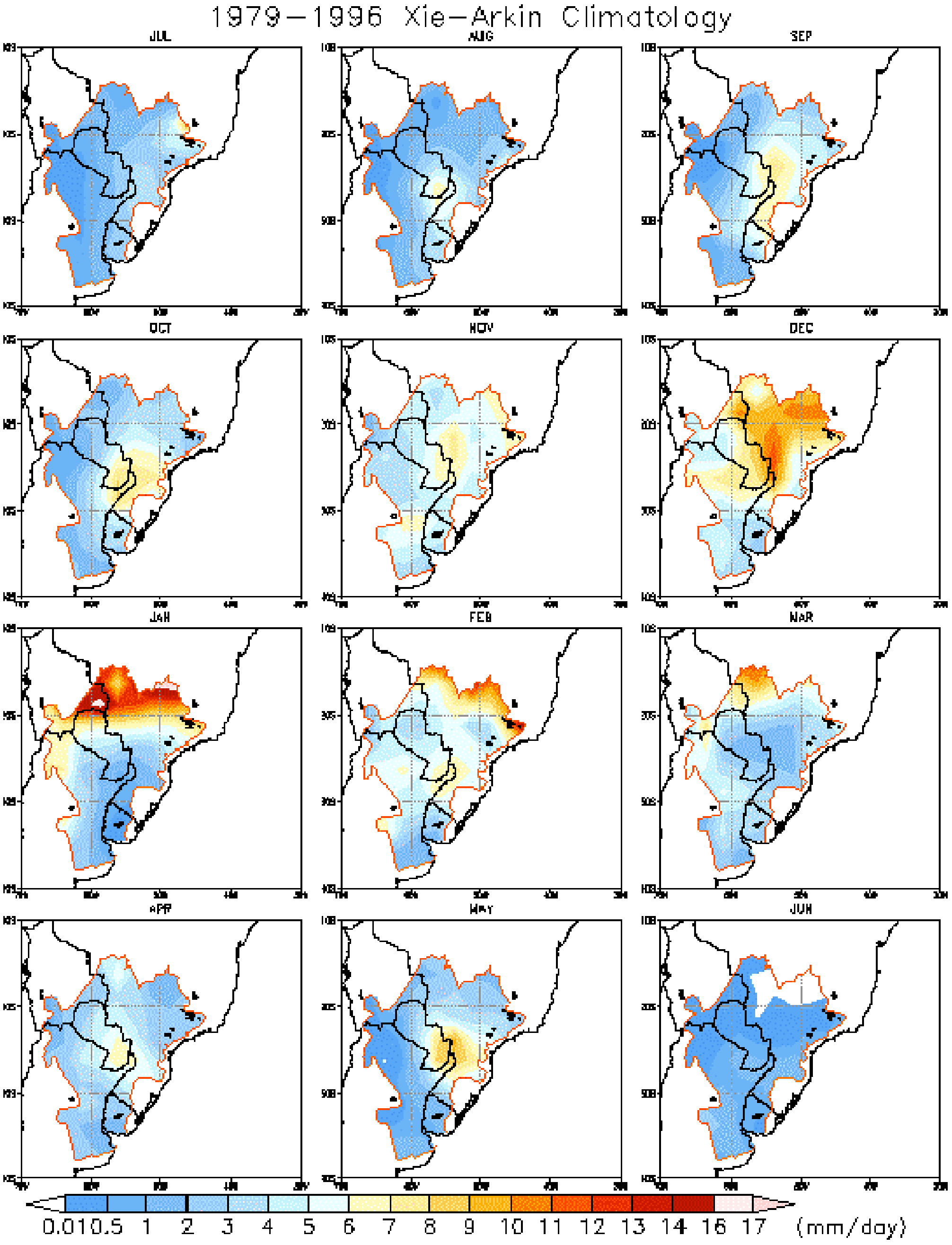

Figure 5. Monthly-mean precipitation in the Plata Basin from (Xie and Arkin, 1997).

Table 2 Selected characteristics of the three principal sub-basins.

Main River	Distance from upstream (km^2)	Basin area ($10^3 km^2$)	Annual-mean flow ($m^3 s^{-1}$)
Paraná River			
Junction of Paranaiba and Grande	1,200 (Paranaiba), 1,000 (Grande)	376	4,370
Junction with Paraguay	2,540	975	11,800
Mouth	3,780	1,510	17,700
Paraguay River			
At Cáceres	420	33.8	345
Final section	2,620	1,095	2,700
Uruguay River	1,600	365	5,500

The flow regime in the Paraguay River as a whole is strongly influenced by the Pantanal storage, one consequence being that annual peak water levels in the Upper Paraguay are correlated between one year and the next, regardless of rainfall conditions. Between the Pantanal and Corrientes in Argentina, where the Paraguay joins the Paraná, the mean slope is about 0.04 m km^{-1}.

The Uruguay River starts in the Serra do Mar and defines the boundary between the states of Santa Catarina and Rio Grande do Sul in Brazil. From there on it marks the boundary between Argentina and Brazil until its convergence with the Cuareim River, where it becomes the boundary between Argentina and Uruguay. The major tributary of the Uruguay River is the Negro River, which originates in Brazil and crosses Uruguay from the northeast to the west. The Negro's total length and the area of its basin are about 850 km and 71,200 km^2, respectively.

3.2 Hydrological regions

The Plata Basin is a combination of several regions with different hydrological characteristics. In the upper Paraná and Paraguay Basins, the rainy season occurs during summer. In the Uruguay Basin, on the other hand, high-flow season occurs during winter. Based on hydrological characteristics, the Plata Basin can be divided into six regions:

Upper Paraná. This region extends from the origins of the catchment to the confluence with the Iguazú River. The upper part has suffered significant change in soil cover characteristics, which has gone from 90% coverage to approximately 5% coverage in 50 years in some parts (Tucci et al., 1999).

Upper Paraguay. This region extends from the origins to the Apa River, on the border between Paraguay and Brazil, below El Pantanal.

Bermejo and Pilcomayo Rivers. The basins of these rivers are the largest producers of sediments.

Uruguay. This is a basin with significant changes in soil cover characteristics.

Middle and Lower Paraná and Paraguay. This region is characterized by wide floodplains, which remain flooded for long periods during large flood events but which make a small contribution to the total river discharge.

La Plata River. This is a shallow-water system significantly influenced by meteorological and astronomical tides. It may be separated into upper and lower parts.

As is to be expected in an area as large as the Plata Basin, the principal matters of hydrological concern vary considerably between sub-basin and from upper to lower reaches. In the Upper Paraná River, above the confluence with the Iguazú River, the principal factor is the use and operation of the huge hydropower production, and the change in land use from natural forest to arable cropping systems based on soybean production. In the lower courses of the Paraguay and Paraná Rivers, the principal matters of hydrological concern are navigation, and flood control. In the recent past, floods on those rivers have caused significant loss of life and damage to property.

Table 3. A comparison between the Plata and Mississippi River Basins.

	Mississippi	La Plata
Area	3.1 x 10^6 km^2	3.6 x 10^6 km^2
Minimum River Discharge	8,300 m^3s^{-1} (September)	18,300 m^3s^{-1} (September)
Maximum River Discharge	28,052 m^3s^{-1} (April)	23,700 m^3s^{-1} (March)
Historical Maximum Discharge	55,000 m^3s^{-1} (Spring)	72,000 m^3s^{-1} (Winter)
Timing of floods	Spring/Summer	All year/winter
Low-level Jet	Spring/Summer	All year
Monsoon Influence	Indirect	Direct

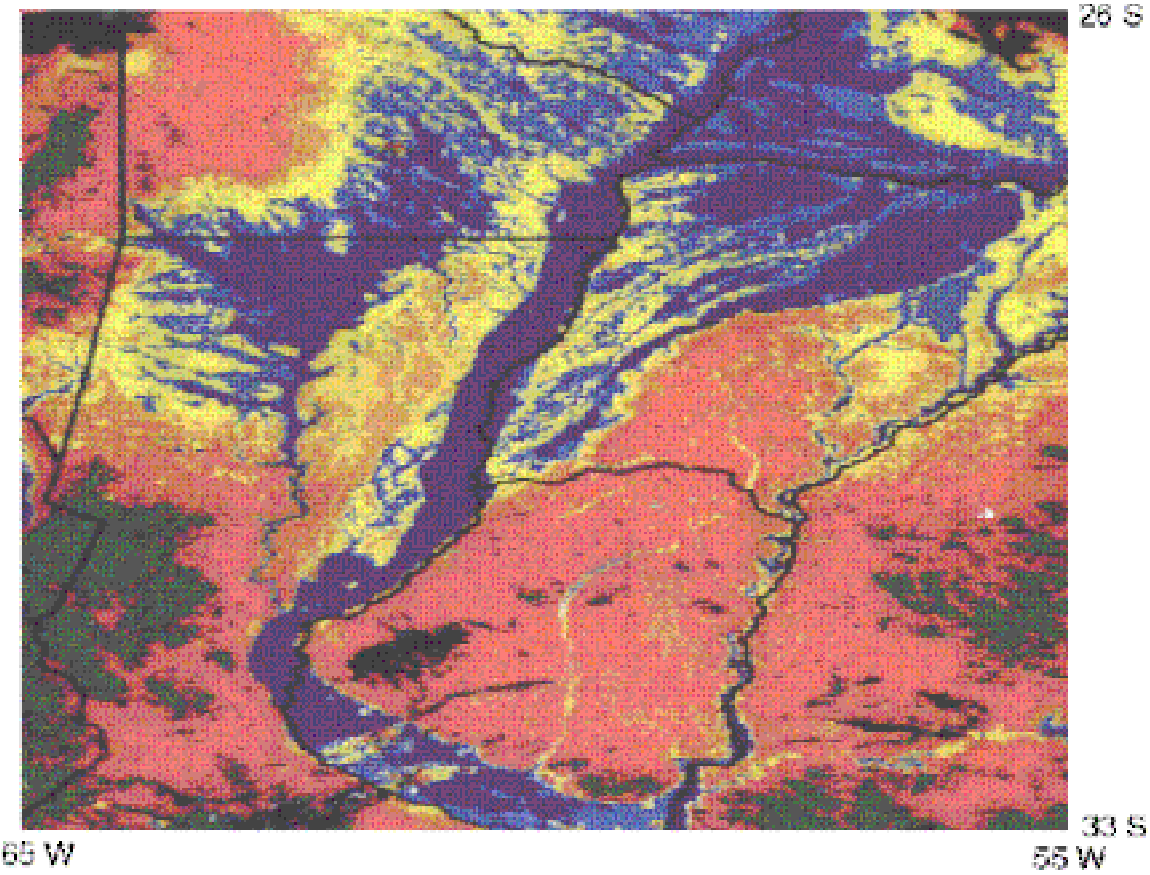

Figure 6. Satellite view of flooded areas during January 1998.

3.3 Temporal and spatial variability of hydrological conditions

The variability in soil moisture, soil cover and soil use can have important impacts on the water cycle. The flooded area of the Pantanal can increase from 10,000 km^2 during dry periods to more than 140,000 km^2 during flood periods with potential implications for atmosphere-land surface feedbacks. Another area of strong variability is on the Middle and Lower Paraná, which may have large areas flooded during several months in big floods (Fig. 6).

4. Variability of the Basin's Climate

4.1 Mesoscale variability and the diurnal cycle

The atmospheric water cycle of the Plata Basin is significantly influenced by mesoscale variabilities asociated with the SALLJ (Wang and Paegle, 1996; Berbery and Collini, 2000). The SALLJ has a diurnal cycle with a nighttime maximum that favors increased moisture flux convergence in the Plata Basin. This convergence, in turn, is associated with generalized nighttime ascent and precipitation. A second precipitation regime is found toward the eastern part of the basin, where largest values during daytime appear to be associated with a convectively unstable atmosphere, with convection being triggered by a sea breeze enhanced by the topography of southern Brazil.

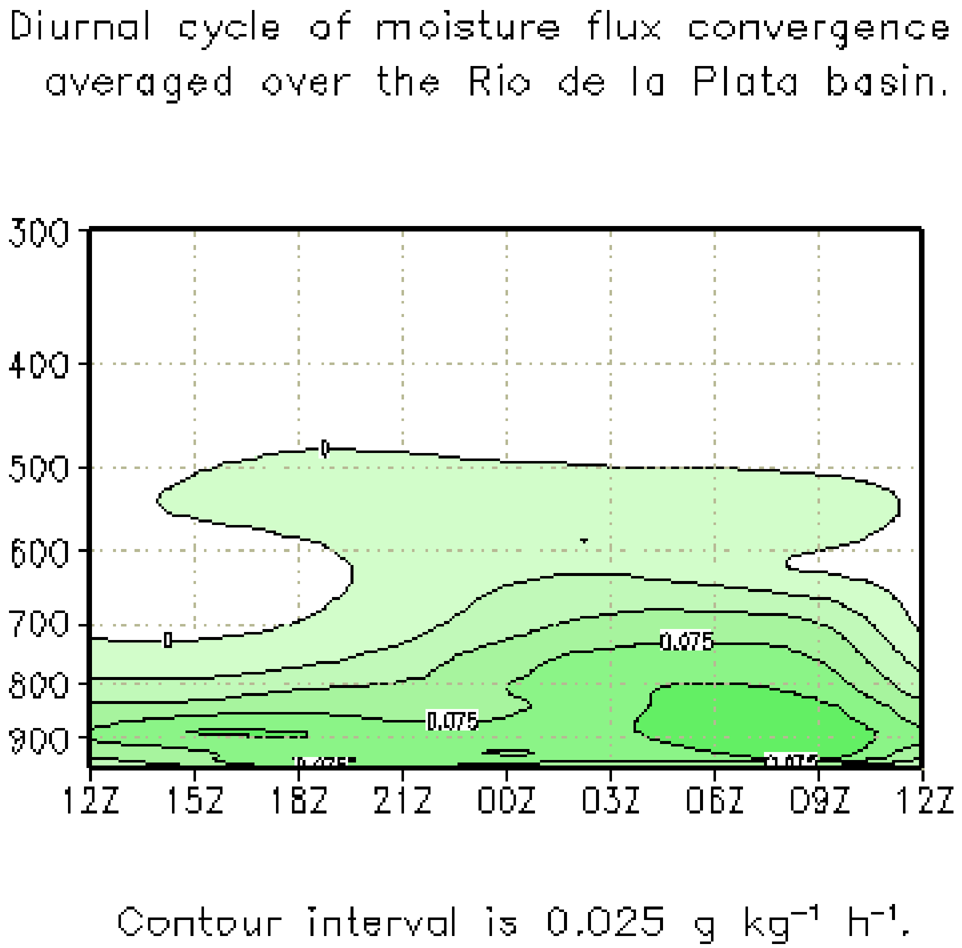

Figure 7. Diurnal cycle of moisture flux convergence over the Plata Basin during spring.

The diurnal cycle of moisture flux convergence for the entire basin is shown in Fig. 7 (Berbery and Collini, 2000). The afternoon maximum of convergence can be associated with the sea breeze/topographically forced diurnal regime on the eastern part of the region, while the nighttime maximum (between 6 and 9 UTC) is associated with SALLJ variations.

4.2 Synoptic scale variability

During the austral winter, the subtropical jet stream is strongest and closest to the equator and precipitation in the basin is primarily associated with extratropical cyclones. The south-western Atlantic Ocean just off the South American coast between 30° S and 45° S is one of the regions with the highest cyclogenetic activity in the Southern Hemisphere. Eastward traveling cyclonic systems that develop over the ocean can intensify after reaching the continent and follow trajectories along the coast. Sea surface temperature (SST) gradients can have a significant influence on the trajectories of these cyclones and their associated sensible and latent surface heat fluxes (Saraiva and Silva Dias, 1997). Frontal systems move rapidly over land regions of low specific humidity and high loss of heat by radiation, and are not generally associated with strong convective activity. Cold surges, known as "friagens" can reach as north as central and southern Brazil (Parameter, 1976; Hamilton and Tarifa, 1978; Fortune and Kousky, 1983; Marengo et al., 1998) and have large economic consequences.

Synoptic scales waves move across the basin. For cyclonic disturbances, the low-level perturbation intensifies at around 1,000 km east of the Andes mountains. Rainfall accumulated over cyclonic episodes amounts to more than 60% of the mean winter accumulated precipitation over central Argentina. This precipitation is associated with an increased contribution of moisture from the tropics along the eastern flank of the Andes Mountains, and positive anomalies of the atmospheric column water content (Vera et al., 2001).

4.3 Intraseasonal variability

Variability of the SACZ is of primary importance for precipitation variability in the Plata Basin during summer. Anomalies in rainfall over the SACZ tend to be out-of-phase with anomalies over adjacent regions to the south (e.g., Nogués-Paegle and Mo, 1997; Aceituno and Montecinos, 1997). Several studies agree that convection variability over South America is characterized by a dipole-type pattern with centers over the SACZ and the subtropical plains. Namely, when the SACZ is enhanced and associated precipitation/upward motion increase then subsidence increases and precipitation decreases to the south. Conversely, when the SACZ is weakened and associated precipitation/upward motion decrease, subsidence decreases and precipitation increases to the south. Such dipole-type variability is modulated by modes with different time scales.

It has been suggested that the Madden-Julian Oscillation (MJO) propagating along the tropics modulates the northward component of the dipole associated with SACZ variability (Nogués-Paegle and Mo, 1997). The southern component of the SACZ dipole is modulated by a higher frequency (22-28 day) mode that extends from the central Pacific eastward and southward from mid-latitudes before curving northeast towards South America. Convection variability in the SPCZ has been linked to that in the SACZ through southeastwardly propagating waves that curve toward the northeast over South America (Kiladis and Weickmann, 1992; Grimm and Silva-Dias, 1995; Liebmann et al., 1999).

4.4 Interannual variability

Several studies have found links between ENSO events in the equatorial Pacific Ocean and rainfall anomalies during late austral spring-early summer and late austral fall-early winter in extratropical South America. Here, there are significant negative correlations between rainfall and the Southern Oscillation Index (SOI) during October-November (Aceituno, 1988). Rainfall anomalies in northeastern Argentina, southeastern Brazil and Uruguay tend to be positive from November of El Niño years to February of the following years and negative from July to December of La Niña years (Ropelewski and Halpert, 1987,1989). In the same area but also in

Paraguay there is a positive and significant difference in spring precipitation between El Niño and La Niña (Kiladis and Diaz, 1989).

There are also detailed studies on the interannual response of the precipitation to the warm and cold phases of ENSO in some regions of the Plata Basin. Precipitation correlates significantly with ENSO indexes during the austral spring in the south of Brazil (Rao and Hada, 1990; Grimm et al., 1998) with similar signals during the winter. In Uruguay and southern Brazil rainfall tends to be higher than average in El Niño years, especially during November-January, and lower than average in years with a high index phase of the Southern Oscillation (HSOI years), especially in October-December (Pisciottano et al., 1994). In addition, rainfall anomalies tend to switch signs during January and February (late austral summer) after HSOI years, but not after El Niño years. These precipitation anomalies during ENSO events are associated with atmospheric circulation anomalies. Over most of southeastern South America in spring during warm (cold) ENSO events, the subtropical jet and cyclonic activity are enhanced (weakened). During most of the warm (cold) ENSO events, the Chaco low deepends (weakens) and the moisture advection from the north increases (Grimm et al., 2000).

The leading empirical orthogonal function (EOF) mode of both wind components in the upper troposphere over South America during summer from the NCEP reanalysis consists of a strong, anomalous, large-scale eddy circulation over the SACZ (Robertson and Mechoso, 2000). An anomalous cyclonic (anticyclonic) eddy was found to accompany an intensified (diffuse) SACZ, with anomalous descent (ascent) to the southwest. At low levels, an intensified (weakened) SACZ was found to be associated with a weak (strong) flows east of the Andes.

Interannual variability in the January-March period appears to be largely uncorrelated with ENSO, while it exhibits strong correlations with SSTs over the south west Atlantic (Robertson and Mechoso, 2000). However, similar SACZ circulation patterns also occur during the October–November period, at which time they are strongly teleconnected with ENSO (G. Cazes, A. W. Robertson and C. R. Mechoso, pers. comm. 2000). This marked seasonality in ENSO teleconnections is consistent with the findings of Pisciottano et al. (1994) who found the strongest ENSO influence on Uruguay rainfall to be in the spring. During the austral spring of El Niño years, the SACZ is weakened accompanied by enhanced ascent to the southwest and an intensified southward flow east of the Andes, consistent with positive rainfall anomalies over Uruguay.

During summer, increased (reduced) precipitation in southern Brazil, most of Uruguay and northeastern Argentina are likely to be associated with a weaker (stronger) SACZ, and with increased (reduced) rainfall further south in Argentina (Barros et al., 2000a). Barros et al., 2000 have also found meridional displacements of the SACZ to be important for precipitation, and that warm (cold) SST anomalies over the southwestern Atlantic (20°S - 40°S, west of 30°W) are likely to be accompanied by a southward (northward) shift of the SACZ. The precipitation field in southeastern South America is also affected in other seasons by SST anomalies in the neighboring Atlantic Ocean (Diaz et al., 1998; Barros et al 2000a).

4.5 Decadal variability and trends

Rainfall variability in most of southern South America has important interdecadal components. The strongest interdecadal variability in the annual cycle of precipitation occurs in regions of transition between precipitation regimes, especially in the Paraná River Basin (Rusticucci and Peñalba, 1997). In subtropical Argentina the annual precipitation also shows oscillations with periods from 7 to 10 years (Peñalba and Vargas, 1993; Minetti et al., 1982; Minetti and Vargas, 1983). On this time scale there is a close relationship between the temperature and precipitation regimes (Rusticucci and Peñalba, 1997). Precipitation trends in Argentina have been positive since 1916 and even increased after the late fifties (Castañeda and Barros, 1994). This behavior is consistent with a climatic jump around the 1960's, when the southern portion of South America experienced a significant warming (Vargas et al., 1995). Precipitation increased by up to 30% between 1956 and 1991 in several localities between 20° S and 35° S east of the Andes (Castañeda and Barros, 1994). In a large part of this region, most of the increase occurred during the 1960's, and it seems to have been associated with a reduction of the meridional gradient of surface temperature, which probably caused a southward shift of the regional circulation. Consistently, the leading principal component of annual precipitation correlates with the meridional gradient of temperature at interannual as well as interdecadal timescales (Barros and Doyle, 1996). Another strong precipitation increase was observed during late 1970s. This correlates with an increase in the subtropical temperature of the Southern Hemisphere and a decrease of the SOI (Barros and Doyle, 1996). The positive trend in precipitation during 1956-1991 has facilitated a southward extension of the agricultural frontier in Argentina increasing available lands by the 1960s in an amount that exceeds 100,000 km^2 (Barros et al, 2000b).

Trends in precipitation over the basin prior to the 1960s have also been detected. A linear trend has been reported in the monthly and annual rainfall in part of the province of Buenos Aires (Peñalba and Vargas, 1996). Decreased precipitation in subtropical Argentina tends to be associated with enhanced westerly flow in Patagonia (Schwerdtfeger and Vasino, 1954). The negative trend in the subtropical region in the period 1931-50 could be associated with a slowing of the westerlies over Patagonia. Significant negative correlations have been obtained between the westerly flow and rainfall in eastern Argentina (Díaz, 1959).

It has been suggested that when the zonal circulation is strong in the tropical Atlantic, the Hadley cell is weaker over the South American sector, which leads to a poleward displacement of the subtropical highs and to larger rainfall in the subtropical region (Pittock, 1980). These features are consistent with the notion that in a large region of subtropical South America east of the Andes, the periods of time in which systems are displaced anomalously far south tend to be associated with larger than average rainfall. The opposite occurs when the systems are displaced anomalously north. A near-cyclic 15-year component has been found in the leading mode of SACZ circulation anomalies (Robertson and Mechoso, 2000). This periodicity was corroborated from independent analyses of southwest Atlantic SSTs and river flows (see section 5.1).

5. Variability of the Basin’s Hydrology

5.1 River flow

Several studies have addressed the variability of river streamflow in the Plata Basin (e.g. Aceituno, 1988; Mechoso and Perez-Iribarren, 1992; Marengo, 1995; García and Vargas, 1998; Genta et al., 1998; García, 1999; Bischoff et al. 2000; Camilloni and Barros, 2000). The annual streamflow of the Negro, Paraguay, Paraná, and Uruguay Rivers during the period 1911-93 includes a nonlinear trend and a near-decadal component (Genta et al., 1998; Robertson and Mechoso, 1998). On the decadal time scale, high river runoff is associated with anomalously cool SSTs over the tropical North Atlantic, with the strong signal in the Paraguay and Paraná Rivers during summer. Interannual streamflow peaks with ENSO time scales were only found to be significant in the Negro and Uruguay Rivers in the southeast. Here, El Niño is associated with enhanced streamflow.

The interannual-to-decadal variability of the SACZ has an interdecadal 15-year component that is also present in river flow (Robertson and Mechoso, 2000). When the SACZ is intensified, the Paraná River in southern Brazil tend to swell while the Uruguay and Negro Rivers to the south tend to ebb. The interdecadal component was found to be much stronger in the north-south gradient of streamflow anomalies than in the streamflows themselves. The Paraná River is directly influenced by the SACZ. The Uruguay-Negro Rivers to the south are influenced in the opposite sense through the dipole in vertical motion, and possibly by accompanying variations in southward moisture transport by the SALLJ.

A 14–16-year interdecadal component in broad-scale SSTs and sea-level pressures over the South Atlantic has been documented by Venegas et al. (1998). A strengthening (weakening) of the subtropical anticyclone over the South Atlantic is found to accompany negative (positive) broad-scale underlying SST anomalies. This mode bears spatial and temporal similarities to that found by Robertson and Mechoso (2000), so that the latter may be the regional counterpart of basin-scale South Atlantic variability.

There is evidence of changes in the annual runoff cycle before and after 1983 (Camilloni and Barros, 2000). The maximum discharge changes from February (before 1880) to autumn (after 1983) in Corrientes and Posadas, together with an important increment in the mean annual discharge. These changes may be due to climate variability, river regulation by dams and/or runoff change because of changes in soil use. The climate signal is consistent with an increasing trend in the precipitation over the upper and middle Paraná basin during the fall season (Camilloni and Castañeda, 2000). River regulation by dams is a direct consequence of the annual cycle of precipitation and the overriding share of hydropower offer in the Brazilian energy matrix, which requires to save part of the waters for autumn and winter use.

5.2 Flood and drought

Flooding is of major concern in the Plata Basin. Most rivers have long and wide flood plains, which have been settled and cultivated. Over a considerable period of time (1950-73), annual floods were not extensive. This encouraged the belief that settlements could be built in locations that were subsequently shown to be at severe risk of flooding. The largest flood of the century occurred on the Paraná River in 1983 during a strong ENSO event. For a year and a half after the event, the Paraná flood level was above street level in parts of Santa Fé, Argentina (Tucci and

Clarke, 1998). In União da Vitória on the Iguazú River, the cost of the flood amounted to US$78 million. In the state of Santa Catarina the damages represented 8% of that state's gross product for the year. Losses for floods in Argentina during the 1983 and 1992 episodes exceeded US$1 billion each.

The four greatest peak discharges in the middle Paraná on record occurred during May to July, following the El Niño years of 1983, 1904, 1992 and 1998, when there were strong and positive SST anomalies in the Niño-3 region. Also, whenever SST in Niño-3 remains warmer during those months, there are large discharges on the middle Paraná, with a magnitude directly proportional to that of the of SST anomalies. In addition, for every El Niño event since 1976, SST anomalies in Niño-3 have been positive during the austral autumn of the following year, which suggests a phase change in the EN events. In this context, the probability of other event similar to 1983 is higher than what could be inferred from a simple recurrence analysis of the100 year record (Camilloni and Barros, 2000).

6. Selected Relevant Studies with Numerical Models

6.1 Atmospheric General Circulation Models (AGCMs)

Atmospheric general circulation models (AGCMs) refer to numerical models that simulate the evolution, maintenance and variations of the general circulation of the atmosphere. A comprehensive numerical model of the atmosphere can be used either as a AGCM or as an extended numerical weather prediction (NWP) model. The dependence of the solution on initial conditions is usually not emphasized in AGCM applications, as in climate simulations or climate predictions of the second kind, while it is crucially important in NWP applications, or climate predictions of the first kind.

AGCMs have been used to estimate regional moisture budgets. According to the moisture budgets by an AGCM in different regions of South America, by Lenters and Cook (1997), suggest that precipitation in the central Andes is primarily associated with orographic effects and large scale wind convergence. Over the SACZ, in contrast, evaporation, wind convergence and moisture advection make positive contributions to the balance, while orographic influences make a negative contribution and transients have a minimum impact. The AGCM simulations, however, do not capture the precipitation maximum in southern Brazil/northeastern Argentina, which corresponds to the SALLJ exit region. Experiments with and without orographic elevations using the same AGCM confirmed the important role played by the Andes in organizing the low-level convergence and precipitation in the region (Tanajura, 1996; Lenters and Cook, 1999).

6.2 Mesoscale models

It is apparent that simulations by AGCMs with relatively low-resolution cannot capture crucial local aspects of moisture fluxes and their convergence. This has motivated the use of ensembles of short-range forecasts performed with regional models to estimate moisture budgets in river basins. The consensus view is that such a procedure is the only one that can currently produce reliable results (Berbery and Rasmusson, 1999). The National Centers for Environmental Prediction (NCEP) Eta model (Mesinger et al., 1988) appears to be well suited to represent the sharp slopes of major mountain ranges. Even for a horizontal resolution of 80 km, the eta-model topography (with heights up to 5100 m) captures the massive block of the Andes mountains and the sharp slopes that in some regions become practically vertical walls. Other features, such as the Altiplano, the Brazilian Plateau, and the even smaller Guiana Highlands are also well captured.

The role of different processes participating in the moisture budget of the Plata Basin has been investigated by performing a series of forecasts using the Eta model with NCEP/NCAR reanalyses as initial and boundary conditions. (Berbery et al., 1996; Berbery and Collini, 2000). For the southern summer, the model successfully simulated the precipitation maxima over the SACZ, northeastern Argentina/Paraguay/southern Brazil, and southern Chile (see Fig. 8). The importance of the SALLJ in transporting moisture to higher latitudes is apparent in the upper panel of Fig. 9, which depicts the vertically integrated moisture flux as calculated in the model's computational grid. The exit region of the low-level jet coincides with a large area of moisture flux convergence collocated with the maximum in precipitation. Consistent with water balance concepts, the results suggest that moisture flux convergence related to the low-level jet is a key component in the processes that generate precipitation over northern Argentina, southern Brazil, and northern Uruguay (lower panel of Fig. 9).

6.3 Hydrological models

Hydrological models of river basins can be broadly divided into two types: (a) deterministic, and (b) statistical. Deterministic models seek to describe the relation between precipitation, evaporation and river-flow in physical terms. The river basin may be regarded as a single entity transforming mean precipitation, over the entire basin area, into runoff (a lumped model), or as a set of separate but inter-connected sub-basins which function in series or in parallel (a distributed model). In either case, the model consists of a set of hypothetical reservoirs with rules - often containing empirical constants – which determine how water is transferred between them and/or back to the atmosphere as evaporation losses. Water leaving the reservoirs may be routed along river channels to the exit point of the river basin; this routing procedure may involve empirical constants to give the appropriate delay before the output from a reservoir arrives at the basin outfall, or it may use simplified forms of the energy conservation equation. A deterministic model of any type contains parameters which must be estimated . Some parameters can be related to physically measurable quantitites, like soil depths. Others must be fitted by minimizing some measure of difference between modeled streamflow and observed streamflow, either heuristically or via formalized optimization procedures. Deterministic models are useful for making short-term predictions of river behavior (for example, flood routing) and also for giving qualitative estimates of how flow characteristics may change as a result of changes in soil cover. The latter application is limited by the fact that empirical constants fitted by optimization are those giving best fit to the observed (historic) record, and may not be appropriate where conditions of climate or soil cover have changed.

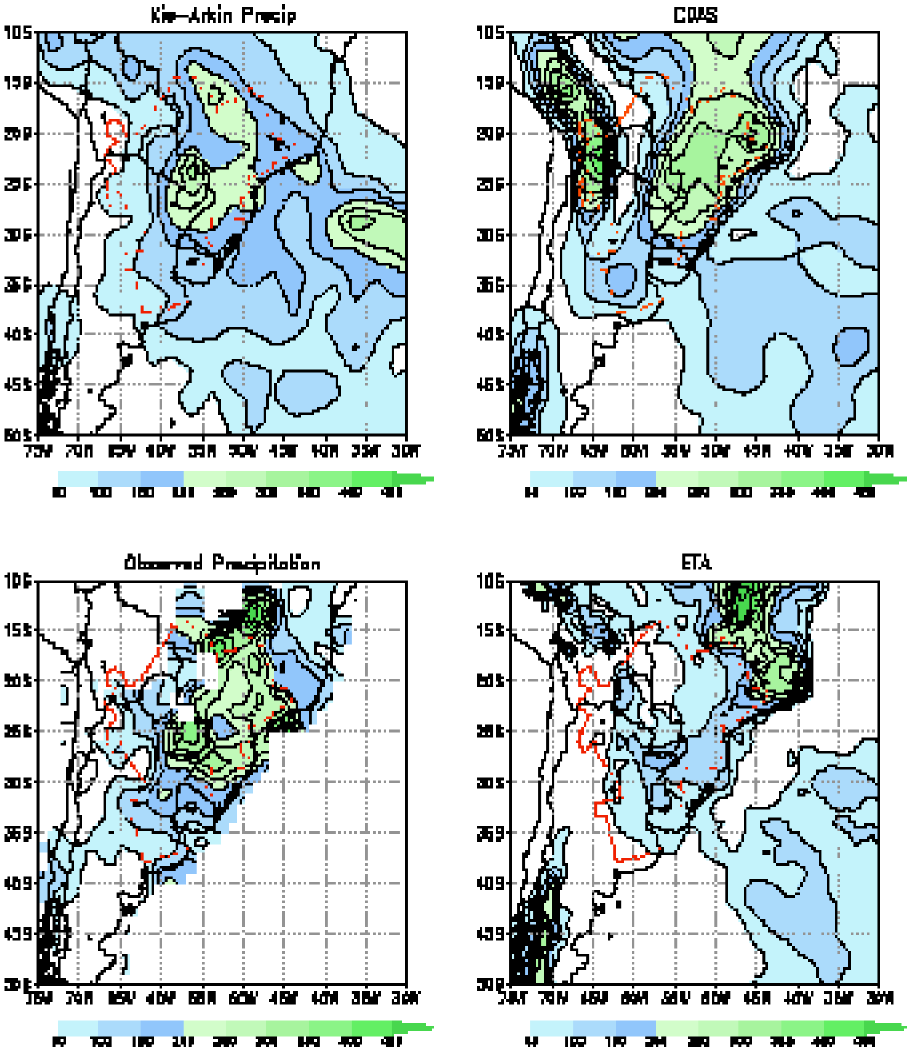

Figure 8. Eta model forecast precipitation and three observed estimates.

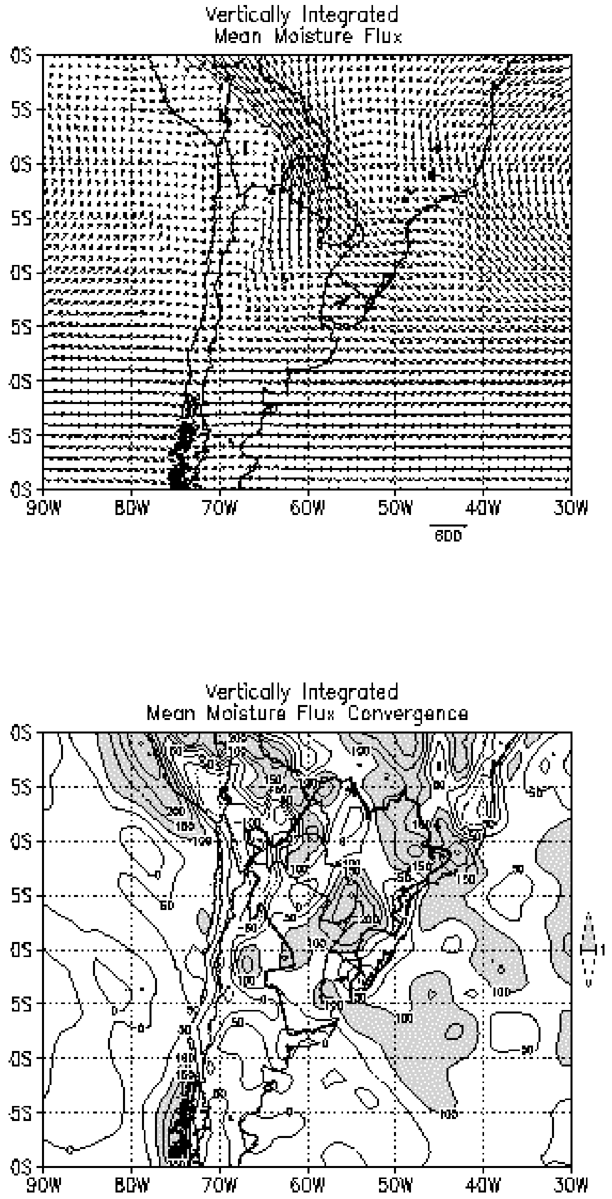

Figure 9. Vertical-mean moisture flux and its convergence simulated by the ETA model.

A deterministic model of the Plata Basin must be capable of describing (a) the flooding and subsequent drying out of large areas with relatively shallow gradients through processes of evaporation and infiltration; (b) the hydraulic interconnections between such areas. In such models, drainage basin behavior is represented by two kinds of elements: channels and cells. Channels are elements where flow is mainly concentrated and can be considered as one-dimensional (in the direction of channel flow). Water movement in channels is comparatively rapid, and dynamic effects are important. Less rapid flows occur across channel banks, to and from cells adjacent to the channels. Flow in cells can be in any direction, provided there is another cell, or a channel, into which the flow can pass. Flow in cells is considerably slower than in channels because of mild gradients and dense vegetation; the most important effect is storage, which increases or decreases water level, and these changes in their turn control water exchange between cells and channels. Cell behavior can be described by a combination of volume balance within the cell and simple hydraulic laws relating each cell to its adjacent cells, channels or boundaries. More recently, so-called macroscale hydrological models, which are designed to represent the hydrological as well as energy fluxes within large continental river basins, have been developed (see, e.g., Wood, 1991; Nijssen et al, 1997). In contrast to the “bottom up” approach traditionally used for implementation of hydrological models, in which models are implemented and tested for each of a number of tributary subcatchments, macroscale models start with the entire watershed, and subdivide, usually via a grid mesh and corresponding channel network.

Figure 10, for instance, shows the channel connectivity for the Variable Infiltration Capacity (VIC) model (Liang et al, 1994) for the Plata Basin at 1/2 degree spatial resolution, which is about the highest resolution justifiable given the spatial density of historic climate records. Models like VIC contain parameterizations of subgrid variability in soil and vegetation characteristics, as well as precipitation, temperature, and other model forcings. Macroscale hydrological models have been particularly useful for assessing the effects of historic and possible future changes in climate and vegetation (Matheussen et al., 2000; Nijssen et al, 2001a), as well as for use in seasonal to interannual climate forecasting, where models capable of representing the hydrology of large areas or watersheds are needed (e.g., Wood et al., 1997).

Statistical models of river basins do not incorporate knowledge of physical processes (although the parameters that they contain may sometimes be amenable to physical interpretation). The basic tools needed for the statistical modeling of streamflow are those of time-series analysis. The range of statistical models is very wide, and the following are but three examples: (i) auto-regressive moving-average (ARMA) models (univariate or multivariate) of streamflow sequences; (ii) ARMA models of streamflow incorporating precipitation as a causative variable; (iii) ARMA models driven by other causative variables, such as SSTs. Statistical models are typically used for short-term forecasting, although it is probable that the lead-time for forecasts would be lengthened if predictor variables (SSTs, possibly) were found which showed good correlation with streamflow. Perhaps the principal advantage of statistical models is that they provide measures of the uncertainty in forecasts.

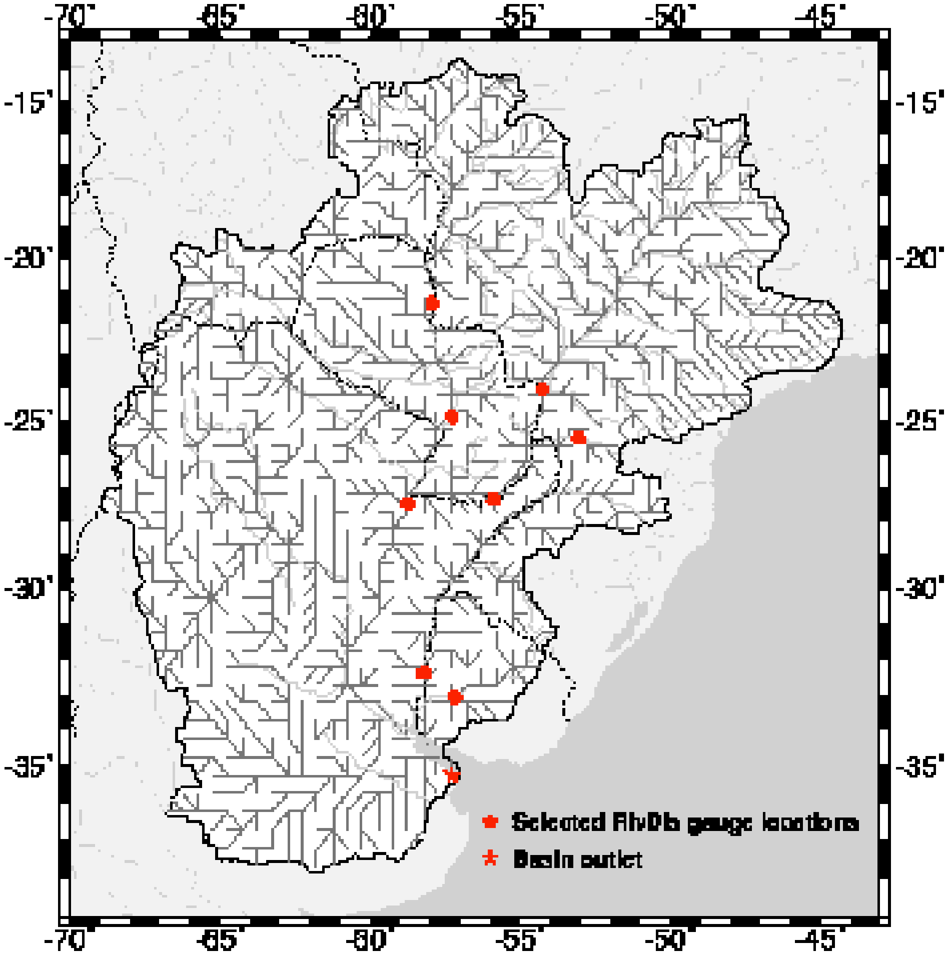

Figure 10. Channel connectivity for the Variable Infiltration Capacity (VIC) model

In recent years, statistical models for long-memory processes have been the subject of research, and the usefulness of such models for making streamflow predictions in the Plata Basin is a topic that needs to be explored. It would be reasonable (i) to explore whether long-memory models are appropriate for describing the flow characteristics of rivers in the Plata Basin; (ii) to explore how predictions given by such models compare with predictions given by models having a sound physical basis. A further point to be considered is that such models can provide measures of the uncertainty in predictions that result from their use. An important limitation of statistical models is that they require relatively long time series for estimation of parameters, and therefore may have difficulty representing the effects of changing climate.

6.4 Watershed models

Watershed models simulate the transformation of a series of daily rainfall inputs to the resulting streamflow hydrograph at the basin outlet. Due to the large area of the catchment rainfall-runoff modeling for the entire Plata Basin and its main sub-basins (Paraná, Paraguay, Uruguay, Bermejo and Pilcomayo) has only recently been attempted (Nijssen et al., 2001b). As part of a study of global rivers, Nijssen et al applied the VIC model to the Plata Basin at the very coarse spatial resolution of 2° longitude x 2° latitude, using the Global Precipitation Data Project (GPCP) and other global data sources as forcings, for the period 1979-93.

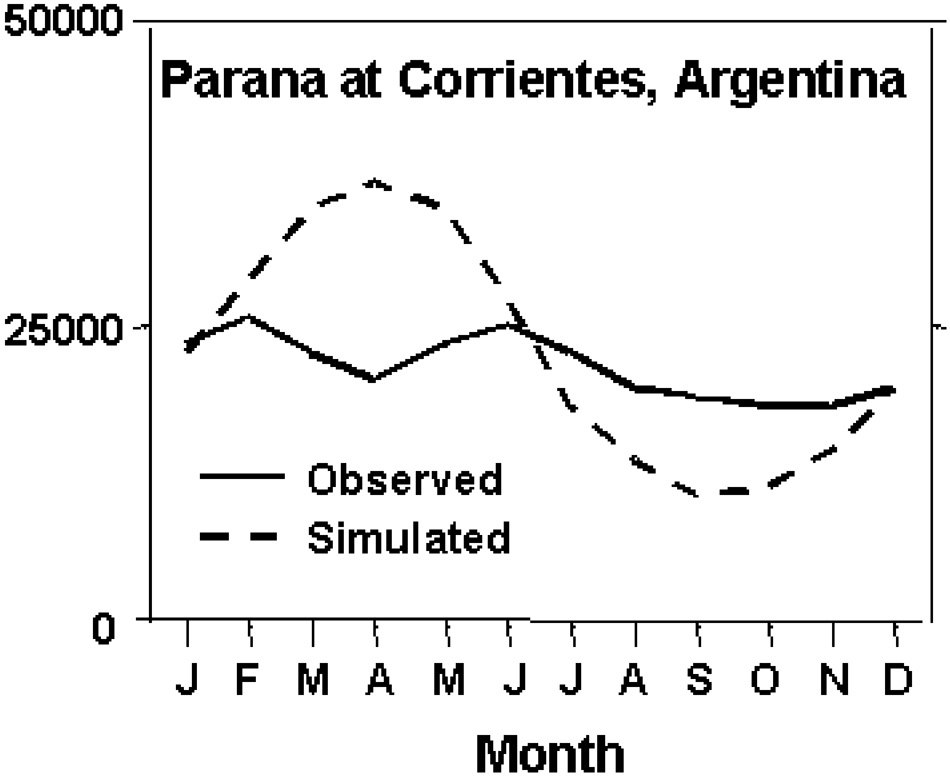

Figure 11. Mean monthly observed and simulated discharge (in m^3 s^{-1}) for the Parana River at Corrientes (Simulation period 1980-1993)

Figure 11 shows that although the annual mean runoff was reasonably well simulated, the model greatly overestimated the magnitude of the seasonal cycle of streamflow. The likely reason is the absence of a mechanism in the VIC model to represent the effects of surface storage in seasonal flood plains. A more recent version of the model includes explicit representation of the effects of storage in lakes and wetlands, and may resolve this problem. Another major obstacle to rainfall-runoff modeling in the Plata Basin is the lack of readily accessible historical rainfall data for the basin. Although much of this problem is traceable to the absence of long-term networks, some data are potentially available that have yet to be archived electronically, a problem that Platin may be able to resolve. In any event, most attempts at rainfall-runoff modeling have been confined to the smaller sub-basins, and large scale efforts have focused more on dynamic routing in the channel (see subsection 6.5).

Among the efforts at hydrological modeling at the sub-basin scale are application of the Hidro-Urfing model to the Laguna I and the Pereira Basins, two sub-basins of the Negro River catchment with a surface area of 13,945 km^2 and 11,354 km^2, respectively. Hidro-Urfing is a lumped conceptual-hydrological model based on the operational Sacramento catchment model developed by the U.S. National Weather Service and the California Department of Water Resources (Burnash et al. 1973, 1995) and the HBV model developed by the Swedish Meteorological and Hydrological Institute (Bergström 1976,1995). The model can be applied to large basins with small to gently undulating slopes. Daily rainfall and monthly-mean values of potential evapotranspiration are prescribed based on observational data. Calibration performed using precipitation and streamflow from observational data showed an acceptable agreement between computed and observed hydrographs for the major storms, both for the rising and the limbs (Genta et al. 1992; Silveira 1998, 2000). Other studies have been reported for tributaries of the Uruguay, Tietê and Iguazú Rivers, and for the Paraguay River and one of its tributaries (Tucci, 1991; Tucci and Damiani, 1994; Damiani, 1991).

IPH2 is a rainfall-runoff model developed at the Instituto de Pesquisas Hidráulicas (IPH). Like all hydrological models, its basis is the continuity equation. It works by regarding a drainage basin as a series of storage tanks, with rainfall entering at the top, and being split between what is passed back to the atmosphere as evaporation, and what emerges from the basin as runoff (streamflow). Depending on the number of tanks, and the number of parameters controlling the passage of water between them, the model can be made more complex or less so.The IPH2 Model was used to analyze the effects of climate change on the water resources of some Uruguay River tributaries. There have also been studies of the use of rainfall-runoff models on the Iguazú River to explore the effects of proposed hydro-electric schemes in a metropolitan region where urban growth is very rapid. The IPH2 Model was also used (Tucci, 1998) to study rainfall-runoff relationships for a set of tributaries of the Iguazú River near to Foz de Areia, the first large reservoir of the hydroelectric generating system on this river. The same model, together with a hydrodynamical model of channel flow, was used in a flood analysis of the metropolitan region of Curitiba, the capital of the Brazilian State of Paraná (Tucci, 1996).

TOPMODEL is a hydrological model that builds in aspects of basin topography (Beven and Kirkby, 1979). The use of TOPMODEL in a 59 km^2 basin of the Corumbataí River, which forms part of Tietê drainage basin draining to the Paraná River, was explored by Schuler et al. (2000). The authors concluded that the model showed good promise for future applications when adapted to local conditions.

The Water and Environment Institute of Argentina (INA) has applied watershed models to the lower part of the Iguazú basin. They obtained daily river flows by using the U.S. National

Weather Service River Forecast System (NWSRFS). This is a lumped input-output parameter model, which is the main tool for streamflow forecast in the US.

6.5 Hydrodynamical models

There are operative hydrodynamical models covering the major rivers of the Plata Basin: Plata itself, Paraná, and Uruguay.

From the hydrodynamical point of view the Plata River behaves as an estuary since water currents are basically controlled by the oceanic tides penetrating through its mouth. Though the tides amplitude is small (about 0,60 m between low and high tide), the very large river width (minimum 40 km) allows for a tidal prism important enough to dominate the flow regime despite the huge discharge received from the tributaries (average 22,000 $m^3 s^{-1}$). The base flow generated by this discharge is strong enough to avoid saline water penetration in the inner river, extending from its head to the upstream of the imaginary line Punta Piedras (Argentina) – Montevideo (Uruguay). The Plata's denomination as a river, instead of as an estuary, arises precisely from this freshwater character. The saline stratification can be detected in the outer region, though complete vertical mixing can occur for strong wind conditions.

The Plata River has been modeled as a shallow water body. Shallow-water models are good enough for engineering applications, mainly to provide boundary conditions for nested, local hydrodynamical models to be used in coastal engineering studies. At the present time, groups in Argentina, Uruguay and Brazil have development efforts on three-dimensional hydrodynamical models for the estuary and adjacent shelf waters.

The Plata River dynamics and its environment are strongly affected by the variability of its tributary rivers. Salinity structure and distribution and accompanying processes, like sedimentation and ecosystem metabolism, are modulated in such a way that provokes, among other effects, changes in mean sea level mainly in the northern coast. Fisheries in the area, which are a significant economic resource, are affected due to the sensitivity of commercial species to changes in the position of the saline front in the river which controls the spawning and fish recruitment.

Efforts to model the Paraná River have focused primarily in flood routing problems. One-dimensional models of different stretches of the river have been developed since the seventies for hydraulic engineering studies (Jaime and Menéndez, 1997). In addition, a model of the Paraná River Delta has been developed and is used in operational mode (Fontana, 1995).

The major concern with the Uruguay River in Argentina and Uruguay is flood routing. There have been several attempts to model the river with one-dimensional hydrodynamical models. The Comisión Técnica Mixta (CTM) in charge of the Salto Grande dam, has been operating a hydrodynamical model within an integrated monitoring/hydrological/hydrodynamical model system that assists in water management decisions. The model developed by DPHER for the Paraná Delta also includes the Uruguay River's stretch from the Salto Grande dam down to the rivers discharge in the Plata River. CARU (the bi-national commission that manages the Uruguay River) has another hydrodynamical model (based on MIKE 11) that is being operated by INA and DNH (Uruguay).

Flood behavior in the Paraguay River, particularly in areas subject to frequent seasonal flooding has been studied by Mascarenhas and Miguez (1994) using a hydrodynamical model, coupled with a cell model, to study; the authors used their model to describe the formation and passage downstream of floods originating within the Pantanal. In the Planalto region adjacent to the Pantanal, Colischonn et al. (2001) applied a distributed rainfall-runoff model, specifically developed for modeling large basins. The model was used on the basin of the Taquari River, a tributary of the Paraguay that joins it in the Pantanal. Its drainage area above this point is approximately 28 000 km^2. The distributed model has regular square cells of 100 km^2 which are sub-divided into blocks according to soil use and vegetation cover. Despite the limited rainfall records available, it was possible to model a flow sequence with reasonable precision, notably for monthly time intervals.

7. Predictability

7.1 Climate and weather prediction

Past experience in weather and seasonal climate prediction based on the Center for Ocean-Land-Atmosphere (COLA) model at CPTEC, Brazil, suggests that the regions with highest predictability in South America east of the Andes are northern Amazonia-Northeast Brazil and the extreme southern Brazil-northern Argentina. Central-southeast Brazil (where most of the Paraná Basin is located) predictability is relatively low. Here the transition between regimes of convection in Amazonia and the SACZ makes the ENSO signal less clear than in northeast Brazil. For this reason, local correlations between rainfall tend to be low. In addition, it is difficult to define a "peak of the rainy season" in this season. Similar results have been obtained with the CCM3, the ECHAM and NCEP models.

7.2 Hydrology

The predictability of hydrological parameters has also been studies using statistical techniques. A system for hydrometeorological forecasts in the seasonal-to-interannual range was developed by Liu et al. (1997) and Valdés et al. (1999). The key features of this system are: 1) multiple ENSO forecasts are integrated into one forecast, 2) each ENSO forecast is weighted according to its error covariance structure as a function of lead-time, and 3) both ENSO and seasonal hydrological forecasts are used to update the underlying persistence (markovian) stochastic process.

The system, which produced promising results for the stremflow anomalies of the Nare and Grande Rivers in Colombia, was applied to seasonal forecasts of the Paraná River at Corrientes (Valdés et al., 1999). Preliminary results show a weak negative correlation between runoff and the SOI (Aceituno, 1988). This relationship, furthermore, is clearer during low SOI episodes (García and Vargas, 1998; García, 1999). A sample of the results is given in Table 4. Valdés et al. (1999) also found a clear seasonality of forecasting skills. Similar results were obtained for the streamflows of the Paraná at Posadas and the Paraguay at Puerto Bermejo.

Table 4 RMSE (root-mean-square-error) reductions (in parenthesis) of seasonal streamflows for the Paraná River

Season Model	January - March	April - June	July - September	October - December
Climatology	5540.9	6768.19	5294.96	4940.44
Persistence	5413.5 (2%)	6464.96 (4.5%)	4160.42 (21%)	4307.00 (13%)
ENSO + Persistence	4576.60 (17%)	5800.52 (14%)	3905.17 (26%)	4024.82 (19%)

Interannual-to-decadal predictability of the Paraná River has been investigated by Robertson et al. (2001), based upon extracting near-cyclic components in summer-season streamflows at Corrientes over the period 1904-1997. These variations explain about 15% of the variance each for the near 9-year and 15-17 year cycles, compared to about 25% for ENSO. It was found that oscillatory components with periods of about 2-5, 8 and 17 years are accompanied by statistically significant changes in monthly streamflow. Autoregressive predictive models were then constructed for each component (Keppenne and Ghil, 1992). Cross-validated categorical hindcasts based on the 8-yr predicted component were found to yield some skill up to four years in advance for below-average flows; no skill is found for above-average flows. A prediction based upon the 8- and 17-yr oscillatory components, including data up to austral summer 1999, suggests increased probability of below-average flows until 2006.

The strongest discharges of the Paraná River during the fall and winter of the El Niño and SST anomalies in Niño-3 region have a Spearman rank correlation of 0.69 significant at the 95% level (Camilloni and Barros, 2000). This result together with those described in section 5b indicate that there is useful predictability from some months in advance.

Care is needed, however, with long-term predictions based on river flow. Although runoff integrates effects of climate change over a drainage basin, it is also affected by land-use change, and it is known (Bruijnzeel, 1996; Sahin and Hall, 1996) that deforestation – which has been widespread in some parts of the Plata Basin – often results in runoff increases. Moreover, annual runoff is not measured directly, but is estimated by means of a calibration curve (“rating curve”) from which river discharge is estimated, given daily observations of water level in the river (e.g., Mosley and McKerchar, 1993). Because of sediment deposition and/or erosion in river channels as a consequence of deforestation, the rating curve may change with time, and requires constant scrutiny and, if necessary, adjustment. Even without complications arising from land-use change, the uncertainty in the annual flow in the river Paraná at Corrientes has been estimated as roughly equal to the annual flow in the River Thames (Clarke et al., 2000). For the Amazon at Óbidos, the uncertainty in annual runoff is about equal to the annual flow in the Rhine.

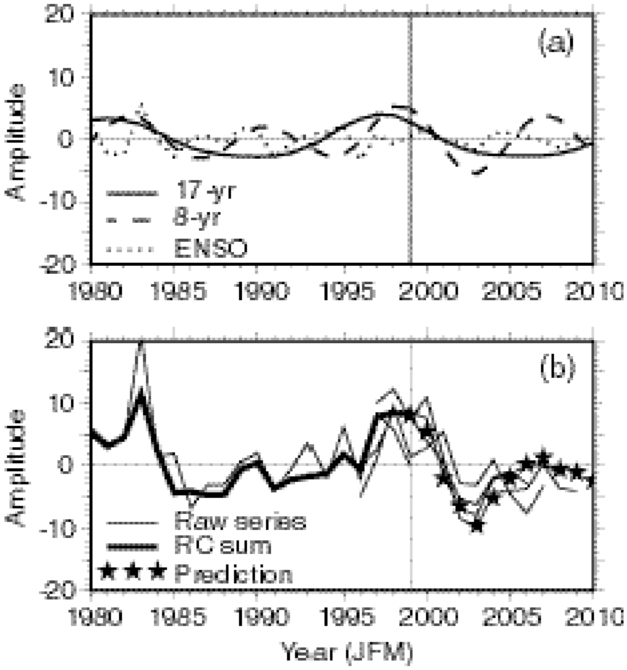

Figure 12. The RCs 1--2 and 3--4 computed over 1904—94, plotted 1980-99, together with their predictions made from 1999. (a) Individual RC sums and their predictions, and (b) combined sum (thick solid line) and prediction (stars), together with the raw January-March flow anomalies (thin line). The thin dotted curves in panel (b) show four predictions starting in1995, 1996, 1997 and 1998 respectively. Units: $10^3 m^3 s^{-1}$.

8. Sensitivity to Climate Change

Studies of climate change over particular regions of the world are particularly challenging. One possible strategy is to obtain different scenarios from the output of GCM simulations with current and doubled CO_2 concentrations (a word of caution is needed, since models still not consistent with each other and regional precipitation is not completely well simulated for present climate.) This approach was used to assess the impact of climate change on the Uruguay River Basin by Tucci and Damiani (1994). Specifically, they took the percentage increase of temperature and rainfall from simulations with the OS NASA Goddard Institute for Space Sciences (GISS), US NOAA Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO). These were transformed into streamflow anomalies by application of a watershed model.

Not unexpectedly, different model produced different results. The GISS scenario represents a reduction in the maximum and annual mean streamflow of 9%-14%, implying a reduction in energy generation of about 5%, although streamflow increases in February-March. GFDL's scenario represents an increase of 14%-33%, with the largest increase in October. This is interesting, since such an increase would be consistent with warmer SSTs in the tropical Pacific at a time of the year when connections with the climate in southeastern South America are strongest. The increase implies an increase in energy generation of 17%. The UKMO's scenario represents increases of 5%-21%. Minimum streamflows would decrease in all cases.

Tucci and Clarke (1998) examined important developments with potential environmental impacts on the Plata Basin: 1) installation of several hydropower reservoirs in the Upper Paraná River, in Brazil, from 1960-90; 2) deforestation in the Paraná, Uruguay and Paraguay basins from 1950-90; 3) introduction of intensive agricultural practice after 1970; 4) urban developments with change to flood regimes; and (5) navigation and conservation of the Upper Paraguay River. Flow increases since 1970 may have been caused by changes in vegetation cover or climate variations, which raises important questions on both water resource development and environmental conservation. Tucci et al. (1999) discussed water management and environmental issues taking account of climate patterns and the development of the five countries sharing the basin. They concluded that rainfall and land-use changes have both contributed to cause the flow increase, although there is not yet a clear answer as to the relative magnitudes of the two contributory causes.

Climate variability (both local and remote) can influence the water level, salinity and suspended sediment distribution in the Plata River. Water level rising and turbidity and salinity fronts displacements correlate with climate induced anomalies on tributary rivers flows. The (Paraná and Uruguay) river flows can have a distinct impact on the Plata River. The observation indicates that turbidity and salinity fronts displacements on the northern coast correlate with Uruguay River flow.

9. Environmental Issues

Understanding the interplay between the natural environment and human activity is critical for sustainable resource management in the Plata Basin. Two major environmental issues are soil erosion and deposition, and the Paraná–Paraguay waterway. The degradation of land by agriculture in northwestern Argentina in steepest terrain is generating increasing amounts of sediments that cause difficulties for the navigation in the lower Paraná River. The Paraná and its tributaries are increasingly polluted by industrial sources along their margins. Also, the increment of navigation as the Hydroway Project progresses may increase the risks of pollution by agro-chemicals.

Particularly in the Brazilian Planalto, there has been a dramatic increase since the 1970s in the area planted to annual crops such as soya. Intensive cultivation and the use of heavy machinery have resulted in greatly increased soil erosion and sediment transport to the Pantanal, whilst within this wetland the increase in cattle production disturbs soil that is then transported by water. Sediment is then deposited where the capacity for channel conveyance is reduced.

The Paraná-Paraguay Waterway Project (Hidrovia Paraguay-Paraná) is a 3,600 km long channel, running from Nueva Palmital near the coast of Argentina to a point upstream of Cáceres in Brazil. To increase the capacity for transport of agricultural and other products to and from the center of the sub-continent, works are planned that would deepen and straighten sections of the channel; the effects of such works on the Pantanal are therefore of major concern. Works to improve river conveyance are likely to decrease flooded areas, which may change the Pantanal from wetland to savannah, since the difference between rainfall and potential evaporation is negative. Two critical questions are therefore: will the proposed works modify flow conditions so as to reduce flow volumes entering the floodplain, and if so, by how much will it be reduced? What would be the effect on the flood-plain environment of a sequence of drought years?

Economic development in the basin can be seen as an outgrowth of the Treaty of the Plata Basin. Signed in 1969, the treaty created a mechanism for integrated development amongst the basin states and instituted the Intergovernmental Coordinating Committee of the Plata Basin Countries (CIC), a mechanism for the coordination of multinational initiatives. Unfortunately, population growth, increased urbanization, intensive agricultural practices, and growing energy demands, coupled with the economic crisis of the 1980's, has led to the unsustainable development of natural capital within the basin. The impacts associated with this development are 1) deforestation and the erosion of productive land, 2) silting of waterways and reservoirs, 3) soil and water pollution, 4) increased risk resulting from natural hazards (i.e., floods and droughts), and 5) loss of biodiversity (Tucci and Clarke, 1998). The following sections provide an overview of the major environmental issues at work in the basin and highlight points of intersection between socioeconomic and environmental processes.

9.1 Land–cover change, deforestation and agricultural production

Changes in land-cover, whether they are the result of environmental change or human activity, affect the volume, timing and quality of water available to catchment regions. These changes are the result of complex feedbacks between climate, hydrology, vegetation, and management. Ample evidence exists for land-cover change in the Upper Paraná, Paraguay and Uruguay River basins, with the most notable being a 28% increase in Paraná River flow since 1970. Tucci and Clarke (1998) note that this increase in river flow occurred after large areas of land had undergone deforestation and/or land-use change. The intensification of agricultural and industrial production led to a transition from coffee to soybeans and sugarcane in the Upper Paraná Basin. Soy, unlike coffee, is an annual crop and requires machine-intensive soil preparation. River flow increases also occurred in the Iguazú River Basin, a basin that has undergone little, if any, land-use change over the past several decades (García and Vargas, 1998).

Forested areas were cleared as result of the need for increased crops and pastures in both the Brazilian and Paraguayan drainage areas of the Paraguay River Basin. In response to demand for increased employment and revenue, the Government of Paraguay in the 1960's expanded agricultural production in the Paraguay and Paraná River Basins. Forested area, originally covering 45% of eastern Paraguay, decreased to 15% at the beginning of the 1990s (Bozzano and Weik, 1992). Tucci and Clarke (1998) report decreases in forested area in the Paraná Basin from 90% in 1952 down to 17% in 1985 and annual crops increased from 0% in 1963 to 58% in 1985. These large changes in hydrological regimes have had significant implications for water resources in both river basins and they raise a number of questions for understanding the links between land-use change and water resources, which are raised in Section 10.

9.2 Increased urbanization: Natural hazards and vulnerability

The population of the Plata Basin has grown from 61 million in 1968 to 116 million in 1994, with most people concentrated in small and intermediate cities lacking basic economic and social infrastructure. Population growth, in combination with expansion of the agricultural frontier and the implementation of large-scale energy projects, has led to increased vulnerability. It is anticipated that the most significant environmental problems confronting the Plata Basin countries in the future will come as a result of increased urbanization.

9.3 Critical regions for sustainable development

A number of distinct sub-regions of the Plata Basin face critical sustainable management problems (Cordeiro, 1999). They include: the Upper Paraguay, Pilcomayo, Bermejo River Basins, the Chaco region, and the Mirim Lagoon Basin. Here we briefly outline some critical environmental issues confronting the Upper Paraguay River Basin and, specifically, the region known as Pantanal (Wetland).

The Pantanal is the most extensive wetland ecosystem in the world, and home to a rich array of wildlife: more than 230 species of fishes, 80 species of mammals, 50 species of reptiles, and more than 650 classified species of aquatic birds. The Pantanal is famously flat, covers an area that can vary from about 10,000 to 140,000 km^2, and behaves like a reservoir retaining a significant portion of the total annual runoff.

The primary economy of the Pantanal has been driven by livestock production. In addition to this, manganese reserves are estimated at 100 million tons, iron ore reserves are estimated at 800 million tons. Areas of growth include copper, peat, lignite, gypsum, sapphires, amethysts, and topaz deposits. Minerals presently being exploited include gold, diamonds, limestone, marble, and clay. Since the mid-1970s, the traditional balance between agriculture and mining has been upset due to the expansion of the agricultural frontier in the upper sub-basin as mentioned in Section 9.2. The principal factors causing environmental problems in this sub-basin are soil erosion, caused mainly by production of soybeans and rice, and water pollution caused by the intensive use of agrochemicals and urban and industrial discharges. Soil erosion rates have been estimated at 300 tons km^{-2} $year^{-1}$ in the upper sub-basin and at 40 tons km^{-2} $year^{-1}$ in the lower basin. Overfishing and the dumping of hazardous chemicals, specifically large quantities of mercury used in gold mining, threaten fish populations. Associated with these existing problems are the potential impacts of ongoing development projects, including the Paraguay-Paraná Waterway Project.

10. Applications of Climate Forecasts: Case Studies

10.1 Application of Climate Forecasts to Water Resource Management: a case study of Itaipu

Hydropower facilities such as Itaipú, on the Paraná River are staffed by engineers whose primary goal is optimizing the problem of flood protection vs. energy generation. In the event of predictions of flood, reservoir managers must decide to what extent they will increase reservoir releases to safely accommodate incoming floodwaters. Inherent to this decision process are potential tradeoffs. An underestimation of flood volume leaves the reservoir system unable to fully regulate flow and results in water being discarded into spillways. This suboptimal choice incurs two types of losses: (i) environmental damage due to flooding, and (ii) financial loss due to decreased generating capacity. Financial losses can vary on the order of several million dollars per year. However, if reservoir operators overestimate the upcoming flood and draw their reservoir down too far, flood damage is avoided, resulting in another suboptimal choice with: (i) decreased hydropower output due to reduced hydraulic head on power turbines, and (ii) less water is available for other uses such as public water supply. For these reasons, reservoir operators have a clear need for inflow forecasting given the caveats inherent in forecast uncertainty.

Itaipu beat its own production record in 2000, generating a total of 93.4 million MWh, a 3.8% increase from 1999. This represents 84.4% of the station's theoretical maximum, allowing zero downtime. Engineers believe that even an increase in efficiency of only 2-3% resulting from the successful implementation of climate forecast information would provide a significant gain in power and water for irrigation and public use.

10.2 Application of Climate Forecasts to Agriculture: a case study in Uruguay

Crop and pasture production in Uruguay is characterized by technologically advanced producers managing relatively large areas with low to medium intensity against the background of high climatic variability. The lack of subsidies combined with low commodity prices requires producers to become increasingly efficient.

The impact of climate variability in Southeastern South America, which includes Uruguay, (see subsection 4.4) led to the establishment of pilot programs that bring together climate scientists, agronomists, crop modelers and farmer representatives. Supported by organizations such as NOAA (OGP), IRI, IAI and regional association of farmers, these groups participate in the Regional Climate Outlook Fora for South East South America. Uruguay hosted the first Forum in December 1997, and fora have been uninterruptedly organized in the region every 3-4 months. For the scientists involved these fora provide an excellent opportunity to interact, exchange results, discuss methodology, and obtain feedback from producers about the general approach, the methodologies used and additional information needs.

In 1999 the regional office of IFDC (International Fertilizer Development Center) in South East South America established collaborative activities with researchers from INIA (National Agricultural Research Institute, Uruguay) and NASA GISS to develop tools for optimizing the use of the climate outlooks (Baethgen and Magrin, 2000; Meinke et al., 2001). Activities include: (i) Identify crop or pasture systems that have a good signal of ENSO, i.e., where the underlying climatic fluctuations translate into associated fluctuations of production (e.g., Messina et al. 1999), (ii) Identify climate variables that explain a large proportion of the observed production variability (e.g., rainfall around flowering in maize, late frosts in wheat, soil water availability in rangelands), (iii) Use crop and pasture simulation models to explore management practices that can minimize losses or take advantage of favorable conditions associated with expected climate anomalies. Also, use the information to produce crop/pasture productivity forecasts, and (iv) Introduce these components in the Information and Decision Support Systems currently being developed for the region (Baethgen et al., 2000).

Short workshops are then conducted that include the climate scientists from the University of Uruguay, agricultural researchers (INIA and IFDC) and technical representatives of all the major farmer associations and government agricultural planners (Ministry of Agriculture and Fisheries). In these workshops, climate scientists present the outlook form the regional fora, as well as local experimental forecasts (which have higher spatial resolution) developed by the University climate research groups. The agronomists and modelers present results on the impact of climate variables on production under a range of different management scenarios ("what if" analyses). Finally, and most importantly, the technical representatives from the farmer associations critique the scientists work by providing feedback and suggesting alterations or modifications for the preliminary analyses conducted. The technical representatives will brief their associations on the final outcome. In addition, short documents for the press are prepared (newspapers, radio and TV). Finally, annual workshops for the press are planned, since that is still the major source of information for the farmers in this region. Similar activities are taking place in neighboring Argentina (G. Magrin, INTA, pers. comm. 1999) and in southern Brazil (G. Cunha, EMBRAPA, pers. comm., 2001) and the regional fora are playing an important role in facilitating cross-border collaboration.

The original program in Uruguay was developed in response to the considerable press coverage of ENSO-related climate variability, particularly after the 1997-98 El Niño event. Many people (often not scientists) with good access to the press were covering the subject and many forecasts were being disseminated, often contradicting each other. This resulted in much confusion and concern in the agricultural sector, since people could not tell which source was credible. The regional forum of December 1997 organized in Uruguay was extensively covered by the press and demonstrated to the agricultural sector of this region that there are scientifically sound approaches and people capable of conducting serious and useful work available.

This program in Uruguay is an excellent illustration of both the successes and the constraints for applying seasonal climate forecasts in the agricultural sector. On the one hand, policy makers have actually started to use information produced in the research program to respond to extreme events (testimonies from the Minister of Agriculture and Fisheries and from the National System for Emergencies in Uruguay can be found in http://www.inia.org.uy/disciplinas/agroclima/index.html, under "Testimonios"). On the other hand, farmers and other users are commonly finding difficult to effectively use the information of currently available seasonal climate forecasts to make better decisions and improve their planning. Thus, the program's research activities have increased the users awareness of the potential uses for climate outlooks but have also intensified the demand for better seasonal forecasts.

10.3 Application of Climate Forecasts to Urbanization: a case study in Buenos Aires

The application of climate forecasts to the management and solution of urban problems has had a limited impact in Argentina. Users in this country receive daily information on weather forecasts and, to a certain extent, on seasonal forecasts as well. However, such information is received with some skepticism, since forecasts are not perfect. At the same time, the Government has not implemented actions to include climatic and meteorological information in the context of a social communication process, which is broader and more complex than the simple distribution of climatological data. Finally, the collection and elaboration of basic climatological data is not a priority in the governmental agenda.

The difficulties emerging from the situation described above become evident in the analysis of the catastrophic floods produced in the last decades (1983 to present) in the fluvial littoral of the lower Plata Basin, where floods are the most important hazard among environmental risks. Such analysis has been performed for cities of intermediate size (Zárate and Campana in the province of Buenos Aires) and a large city (Buenos Aires) (Natenzon et. al., 2001)

Zárate and Campana have approximately 100.000 inhabitants each. Here, flood management was analyzed especially in the context of the early warning system (Gentile, 1999). Floods in these cities have three main causes: 1) overflows of the Paraná river, 2) *in situ* rains, and 3) effects of *"sudestadas."* (Sudestadas are hydro-meteorological situations in which persistent winds from the southeast produce the flood of the eastern coast of the Plata River.) The technical component of the Warning System (INA) proved to work properly. With the information of the situation in the upper basin, it is possible to forecast a flood approximately 30 days in advance.

The warning message reaches the cities through the offices of Civil Defense and the Argentinean Coastguard. The Civil Defense officer is responsible for disseminating the information to community organizations in flood prone neighborhoods, which in turn inform the affected neighbors. The Coastguard disseminates the warning to the population in the islands of the Delta. Despite this communication system, individuals get the first warning through the mass media, which inform of floods in the upper basin, rather than through the local communication channels. In case of floods due to local intense rains, there are meteorological warnings, but they have some deficiencies in the quality of information and in the anticipation timing.

Buenos Aires has about 3 million inhabitants. Here, the problem is more complex due to the difficulty to predict with precision the locations where rainstorms would cause the floods. Floods in Buenos Aires have two origins: intense rainstorms and *"sudestadas"*. Intense rainstorms cause the overflow of obsolete drainage systems (built at the beginning of the 20th century) without enough capacity to drain rains concentrated in a brief period of time. The *sudestada* prevents the streams that cross the city to discharge their waters in the Plata River (Barrenechea et. al., in press).

Intense rainstorms warnings are launched with very small anticipation, which hampers decision-making during emergencies. Accurate forecasts require a network of meteorological stations that provides a more complete coverage than that currently available. In the case of *sudestadas*, the tide gauge network of the Argentinean Navy Hydrographic Service-SHN allows an anticipation of about 12 to 24 hours. The combination of both situations -storms and sudestada- results in the maximum risk hypothesis, which may have serious impacts in spite of its low recurrence.

In any event, data collection is only an aspect of the problem. It would be desirable to include in the warning message some information of simple measures that population should follow before, during and after the potential flood so as to lower the impacts. The present warning system does not seem to be integrated; warning messages are generally very vague and do not include information on what people must do. Only in the current year –2001- the government of the city has started to broadcast frequent warnings during TV and radio programs advising individuals on actions to take in case of flood (Gentile, 2000; González, 2000).

In summary, information is scarce and a more sophisticated system of data collection should be implemented. But even in the present situation, all potential users do not employ the existing information in an integrated manner during the whole disaster cycle.

11. Motivation for an International Program on the Plata Basin

The review of climatology and hydrology of the Plata Basin presented in this document highlights the need for an international research program that targets three major topics of principal interest to countries in the basin:

- What climatological and hydrological factors determine the frequency of occurrence and spatial extent of floods and droughts?
- How predictable is the regional weather and climate variability and its impact on hydrological, agricultural and social systems of the basin?
- What are the impacts of global climate change and land use change on regional weather, climate, hydrology and agriculture? Can their impacts be predicted, at least in part?

To properly answer these questions a number of issues on the climatology and hydrology of the Plata Basin should be addressed.

1. To what degree is the basin climatology and hydrology affected by SST anomalies? Conversely, how do the larger scale precipitation and surface winds affect the nearby oceanic circulation? Does the SACZ play an active role, or is it merely responding passively to large-scale changes?
2. How is decadal variability in the tropical Atlantic SSTs linked to precipitation anomalies in the basin, particularly in the northern part (Upper Paraguay and Paraná, Upper Bermejo and Pilcomayo)?
3. What are the seasonal variations of the links between anomalies in SST and in climate over the basin?
4. What is the relative importance of local and remote sources of moisture in the basin? Of the water vapor that enters the basin and falls as precipitation, is any of it recycled within the la Plata basin itself? If so, how much, where from, and where does it fall?
5. Do soil processes play an important role in the basin? In particular, do the large variations in the flooded area of the Pantanal impact and one themselves influenced by the variations in region climatology? Does water evaporated from the Pantanal wetland fall as precipitation elsewhere within the Plata Basin? If so, how much is recycled, and where does it fall?
6. There are proposals to extend the navigable waterways of the Plata-Paraguay River system, by deepening and straightening parts of the channels. This is likely to accelerate drainage from the Pantanal, with consequent effects on the spatial extent of seasonal flooding. How would this affect evaporation from the Pantanal, and (see previous question) how would it affect precipitation elsewhere within the Plata Basin? Also, if the channel works are carried out, what would be the consequences for (a) flood frequency and magnitude, (b) duration and severity of drought, elsewhere within the basin?

7. If the spatial and temporal extent of flooded areas in the Patanal are changed as a consequence of channel works, what will be the consequences in terms of quantities of sediment removed by runoff? If the basin's sediment yield is increased, where will the transported sediment be deposited, and what will be the consequences for hydropower production, river navigation, and water supply?
8. What determines the near-cyclic variations in the major rivers of the Plata River Basin (Paraná, Paraguay, Uruguay, Negro)?
9. Can the links between near-cycles found in SST and streamflow variations be used to obtain useful probabilistic prediction of river behavior?
10. What are the climatological and hydrological characterization of droughts and floods in the Plata Basin both in time and space?
11. The change from native forest to annual high-value crops, such as soya, is likely to have (a) increased annual runoff; (b) affected the magnitudes and frequency of occurrence of floods and low flows in several parts of the basin, and the change in land-use accelerated after 1970. Can the effects of land-use change on annual runoff, flood flows, and low flow duration be separated, in the flow record, from the effects of climate variations?
12. What developments and improvements in hydrological models are required to better represent the relationships among model parameters and changes in soil use?
13. How predictable is the hydroclimatology variability in the Plata Basin?
14. What are the most limiting factors to adequately address these questions?

12. Relevance to the World Climate Research Programme (WCRP)

The scientific problems in the Plata Basin are highly relevant to WCRP/CLIVAR, which has an emphasis on ocean-atmosphere interactions. They are also highly relevant to WCRP/GEWEX, which ha s an emphasis on land-atmosphere interactions.

Within CLIVAR, the Plata Basin is of direct interest to VAMOS, which encourages study programs on a better understanding of the American monsoon systems and their variability. VAMOS also aims to a better understanding of the role of American monsoon systems in the global water cycle, improved observational datasets and improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources.

A particular important field program of VAMOS to be developed in the period 2002-2004 is the American Low-Level Jets (ALLS). The South American component of ALLS targets the low-level jet east of the Andes, which has been presented in this document a major contributor to moisture transports into the basin.

13. Outline of an Implementation Plan

Preliminary discussions on the needs to develop an implementation plan are under way. They are based on the fact that the basin is subject to strong teleconnections as well as strong local forcings, hence there is a potential for long range forecasting of runoff in the basin. This entails an improved ability to mitigate effects of floods and droughts, and/or more efficiently management water resources -- with attendant social benefits. An outline of an implementation plan can be based on four components.

13.1 Enhancement climate and hydrology monitoring

This component would include the planning of stream gauges as needed, and telemetering implementation of networks of hydrological instruments appropriate for monitoring and prediction in the long term. At the spatial scales for which a climate-based initiative would be relevant, a probable target would be 50-100 stream gauges. Relevant questions are where the existing ones are located and where the "holes" would be. Also, and quite likely more important, would be enhancement of the precipitation network both with gauges and radar. Additional augmentation of the surface meteorological network, including radiosondes, would also be an element. All of this requires an extensive review of the existing network.

13.2 Development of a data center in the region.

This component would be preceded with a data rescue effort. There almost certainly are surface climate data that are not readily available in electronic form, and that would be useful for model implementation (a key part of long-range ensemble hydrological forecasting has to do with correction for bias, which requires construction of the best possible retrospective data sets. In this way, model runs, forced with observations, can be compared with those forced with retrospective climate ensembles, and appropriate mappings made. In the U.S., archival surface station data goes back to 1950 in electronic form, and currently is being extended backward from there. The situation is not as favorable in the Plata Basin.

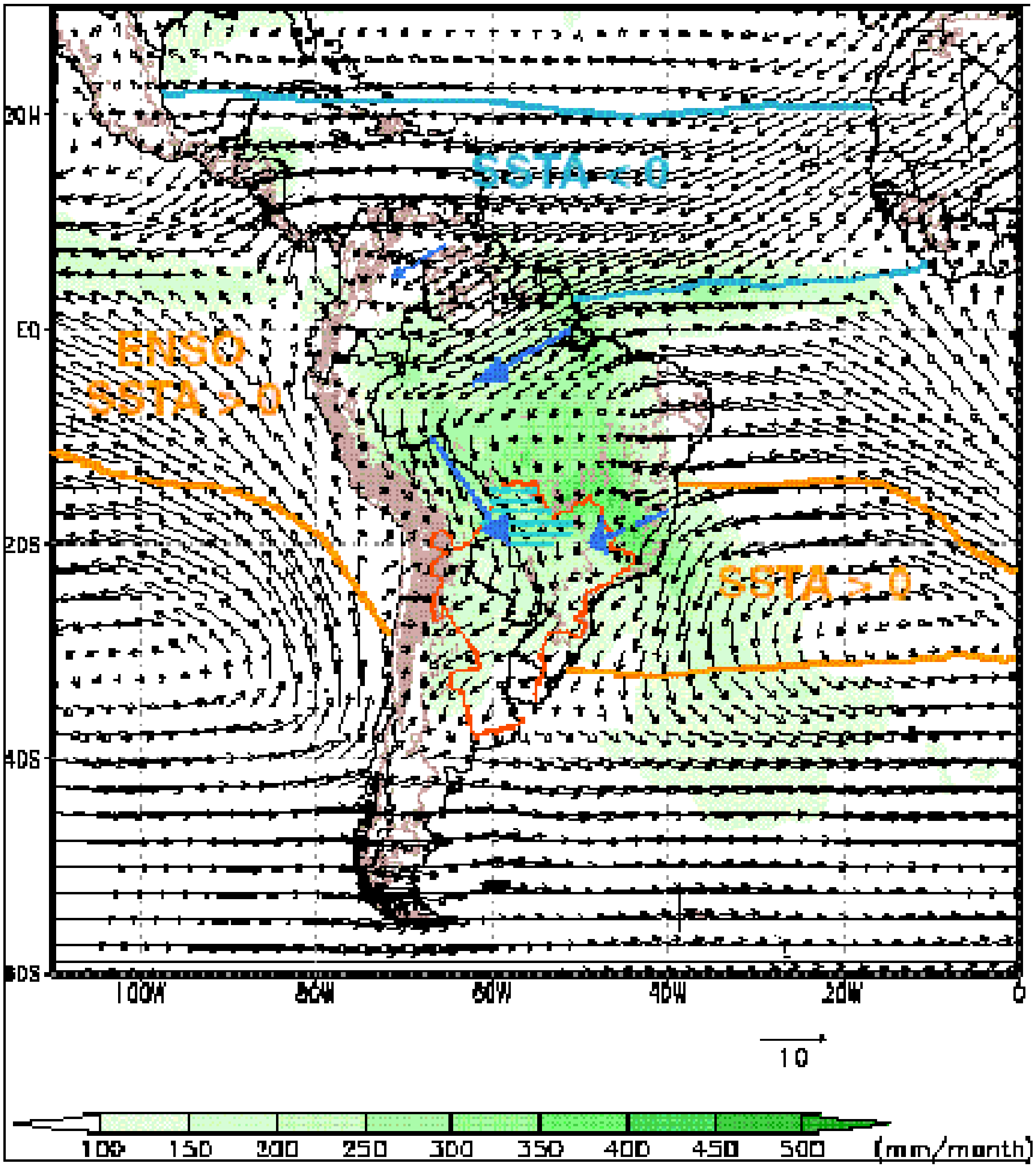

Figure 13. Links between climate variability in the Plata River Basin (area encircled by the red curve) and SST anomalies for the southern warm season (December-February). Green shading corresponds to precipitation (mm/month), black arrows to 925 hPa winds, thick blue arrows to maxima in vertically integrated moisture transport, and the blue hatched region to the Pantanal. The configuration of SST anomalies corresponds to enhanced precipitation in *the basin.*

13.3 Development of regional climate and hydrological prediction centers in the basin.

This component would aim to utilize the climate forecasting capability (to be implemented at an appropriate location within one or more of the participaing countries) to perform ensemble streamflow forecasts over the basin (and in particular, at selected gaged locations). Tasks would involve implementing a macroscale, presumably grid based (like VIC, NOAH, or similar) hydrological model, run to forecast time with observations, and subsequently out to (say 6 months to a year) ensemble climate forecasts. Because of the close link between the climate and hydrological foreasting, it makes sense to co-locate these activities, although that may not need to be explicitly stated. Key aspects of the forecast center would be (I) moderate to high resolution ensemble climate forecasts, presumably generated via nesting of a regional model within a global model, run with forecast SST in ensemble mode, (ii) real-time data acquisition, archiving, and handling system capable of extending a (gridded) surface forcing data set (precipitation, temperature, and other surface met variables) to real-time, (iii) a macroscale hydrological model, with interface to the ensemble climate forecasts, and run to forecast time with gridded observations, and (iv) surface data assimilation capability, e.g., for satellite observations, to improve hydrological forecast initial conditions.

13.4 Development of a system for information distribution

This component would produce a decision support system (DSS). The DSS would integrate climate and hydropower information with the ability to optimize operational strategies for agriculture, reservoir management, and drought/flooding control.

14. Summary

The current consensus is that climate variability in the Plata Basin is influenced by remote climate anomalies, such as SST variability in the Pacific and Atlantic Oceans. Positive precipitation anomalies correspond to warm events in the tropical Pacific. They also correspond to warm SST anomalies in the western South Atlantic, particularly during the southern spring. Furthermore, higher streamflow appears associated with cold SST anomalies in the north tropical Atlantic (see Fig. 10). The mechanisms at work for these connections are not clearly understood at present.

The current consensus, in addition, states that the major contribution to the moisture flux into the basin comes through a moisture corridor east of the Andes, at least during the monsoon season. There is also evidence that precipitation in the basin is inversely correlated with the intensity of the SACZ. Much work is requested to quantify these relationships.

The climatology and hydrology of the Plata Basin, therefore raises a number of important questions that address key aspects of those scientific disciplines. The answers to those questions have the potential for increased predictability of anomalies since it is becoming increasingly apparent that climatic variability ought to be considered for improvement of water resources management. In the Plata Basin, some of the flood protection works done along the Paraná River margin for cities partially located on the flood plain were designed after the 1992 flood. These proved to be inadequate during the 1998 ENSO event when a historical precipitation maximum of extraordinarly high intensity occurred on watersheds discharging on the Middle Paraná River. Then, the embankments built to avoid the flood produced by the Paraná River acted as a barrier to the discharge from these watersheds. The management of the Salto Grande dam was successful in 1998-1999, on the other hand, because climate information was taken into account.

Work will be required, however, to improve hydrological models to be used in support for water resources management at both the operational and strategic levels. Operational management demands short (days) to medium-term (seasonal) forecast. Strategic management, on the other hand, requires the evaluation of scenarios and knowledge of long-term (interseasonal to interdecadal) variability. At this level, the variability of climatological parameters needs to be considered.

One challenge to be addressed for the Plata Basin is the downscaling of precipitation produced by climate model forecasts to be used for prediction of water resources. Another is the identification of key variables that couple hydrological and atmospheric processes, e.g. precipitation and actual evapotranspiration. There is also strong interest in assessing the impact of deforestation in the Basin and other anthropic changes of runoff production mechanisms. From the hydrological viewpoint, it is important to evaluate hydrology of flat lands where vertical processes predominate, such as in the lower part of the Basin.

A better understanding of the climatology and hydrology of the Plata Basin will have many important benefits. Some will come from the more successful predictions of droughts and floods, which have significant direct and indirect effects on regional economies. The effects on agriculture generally imply the need to allocate funds for goods substitution, additional activities and, in some cases, compensations. The strategic planning at the economical level is strongly affected by such events, and improvement of forecast can be of great help. Flood events in particular have an impact on soil structure and conservation. Large amounts of soil disappear, transported by the rivers. This impact can be more important than the loss of the crop, since the time needed for soil recuperation is larger. These are all topics of great importance to the societies in one of the most populated and fertile regions of the Americas.

In view of the magnitude and extent of the problem, a research effort coordinated at the international level is required. The World Climate Research Programme (WCRP) through its CLIVAR and GEWEX components is ideally suited to provide scientific coordination.

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