

CHARACTERISTICS AND VARIABILITY OF THE ATMOSPHERIC WATER BALANCE IN THE AMAZON BASIN

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ABSTRACT

The water balance of the Amazon basin is of great importance, due to the presence of the world's largest hydrographic system. Hence, there is a concern that large-scale land use changes may change significantly the flow regimes of rivers within the region and the land-atmosphere exchange of moisture, as well as the moisture fluxes from the basin to other regions of South America. This paper describes a research effort to estimate the atmospheric water balance of the Amazon basin, as a whole and by regions, using the NCEP reanalysis, and the network of river and rainfall data in the region. Quantifications are made for the near-surface moisture input from the North Atlantic into the Northern Amazon, from the Northern Amazon into the southern part of the basin, and from the basin to adjacent regions outside the basin, such as central and Southern Brazil-Northern Argentina-Southern Brazil. Preliminary results indicate the presence of decadal variability in rainfall and moisture transport especially in the northern parts of the basin, the effects of ENSO, and a long-term trend that seems to be due to both natural and human induced climate variability.

INTRODUCTION

The atmospheric and terrestrial water cycles are important components of the global climate and terrestrial biospheric systems. Studies of water balance and water cycle are prominent issues on ongoing research, such as the GCIP-GEWEX in the Mississippi River basin and the Large Scale Atmosphere Biosphere Experiment in the Amazon basin LBA (Nobre et al. 1996). The Amazon basin contains half of the remaining tropical forest and remains as one of the major players in the regional and global energy and water balances. Variations on those balances either at interannual or long term are of special interest, since the Amazon region itself contains the world's largest hydrographic system, and it is one of the major centers of tropical convection than fuel the general circulation of the atmosphere. For instance, this hydrographic system is subject to interannual variability in tropical precipitation that ultimately translates into variations in downstream flow (Marengo 1992, Vorosmarty et al. 1996, Costa and Foley 1998)

It is clear that natural or human induced climate change can act to modify various aspects of surface hydrologic systems. For example, changes in land cover can significantly affect the surface water and energy balance through changes in net radiation, evapotranspiration, and runoff. On the other hand, the effects of biomass burning on the onset of the rainy season and the moisture transport in Amazonia are still being investigated.

Hence, there is a concern that large-scale land use and land cover changes may affect significantly the flow regimes of rivers within the region and the land-atmosphere exchange of moisture, as well as the hydrologic and atmospheric water budgets. Fluxes between the regional vegetation and the lower atmosphere control the inputs of water and energy to the atmosphere, and the dynamic characteristics of the planetary boundary layer. As such, it is reasonable to expect a significant impact on the region's climatology and hydrology in the wake of a large-scale land cover changes.

Furthermore, the question on to determine how the observed interannual and interdecadal variability of rainfall in the Amazon is related to changes in evapotranspiration, moisture convergence and runoff still remains. The answer will give insight into the extent that interannual variability is caused by changes in evapotranspiration versus remotely forced changes in circulation. In here, it may be more important not to assess the amount of local

evapotranspiration that falls as precipitation, but to understand how changes in evapotranspiration might ultimately affect precipitation..

Together with the NCEP/NCAR reanalysis from 1950 to 1998, and available long-term historical rainfall and river data in the basin, we address the Amazon hydrological cycle using the classic water budget approach. In addition, besides the interannual variability we focus more in interdecadal variations of the NCEP derived atmospheric water balance and moisture transport, for both northern and southern Amazonia and using rainfall indices from those regions as a mean to “validate” the moisture transport long-term variations.

BACKGROUND

Numerous studies using global climate models have reported possible effects of deforestation in the climate of Amazonia and adjacent regions. Reviews from several sensitivity experiments of Amazonian deforestation and their impacts can be found in Zeng (1999), Zeng and Neelin (1999), Marengo and Nobre (2000). In most of them, simulation of deforestation produces increase in surface air temperature, and significant decreases in evapotranspiration and precipitation, while less consensus is found on changes of runoff. Changes in latent heat can ultimately influence precipitation in two important ways. First, an increase in evapotranspiration adds moisture to the atmosphere which, if ‘recycled’, directly increases rainfall. Second, increased latent heating associated with this increased rainfall can drive an intensified circulation (e.g., the Hadley cell), resulting in changes to the moisture convergence from remote sources.

The lack of long-term and continuous sounding observations of the atmosphere, precipitation and evaporation data, and of measurements of river discharge along the Amazon and its main tributaries has forced many scientists to use indirect methods for determining the water balance for the region. Since the early 1980’s several studies have been devoted to studies of the water balance of the Amazon basin, using few observations from the sounding network in Brazilian Amazonia, rainfall and river from some individual stations, or from regional experiments carried out in the basin on the last 20 years (see reviews in Marengo et al. 2000).

Among these results, early studies by Salati and Marques (1984) have attempted to quantify the components of the water balance: Average precipitation was estimated as $11.9 \times 10^{12} \text{ m}^3 \text{ year}^{-1}$; discharge of the Amazon at Obidos was quantified as $5.5 \times 10^{12} \text{ m}^3 \text{ year}^{-1}$; and evapotranspiration was estimated by the Penman method as $6.4 \times 10^{12} \text{ m}^3 \text{ year}^{-1}$. The latter is in good agreement with the difference between precipitation and river discharge. The Amazon rivers drains an area of approximately $5.8 \times 10^6 \text{ km}^2$, with an average discharge of $5.5 \times 10^{12} \text{ m}^3 \text{ year}$, as indicated above.

The often inaccurate, irregularly spaced and often sparse observations are blended with model simulation to produce a globally consistent sequence of climatological fields. Major numerical simulation centers (NCEP, ECMWF, NASA/DAO) have carried out retrospective analysis (re-analyses) projects over the past few decades using a single model and data assimilation to represent climate evolution since the War World II. These worldwide gridded reanalyses have allowed assessments of the water vapor transport into Amazonia either long-term scales or for individual cases study (Matsuyama 1992, Rao et al. 1996, Costa and Foley 1998, Zeng 1999, Curtis and Hastenrath, 1999). Table 1 shows the estimates of the annual water balance across scales in the basin, from point measurements to basin-wide hydrological budgets. Most of them shows that the rate between evapotranspiration and precipitation varies from 40 to 75%.

The causes of interannual and decadal rainfall and moisture convergence variability the Amazon basin are still not completely understood, even though, as in many other regions of the world, the El Niño - Southern Oscillation (ENSO) seems to influence precipitation in the region (Marengo 1992, Rao et al. 1996, Nepstad et al. 1999, Zeng 1999). Some components of the interannual variability also may be also associated with variations in the strength of the observed surface easterlies over the tropical Atlantic (Marengo 1992). While this finding does reveal a connection between Atlantic trade winds and Amazon precipitation, it does not reveal cause and effect. For example, it is not obvious whether increased evaporation in the Amazon leads to more latent heat release, increasing the easterlies, or whether increased easterlies advect more water vapor into the basin, increasing precipitation. Archaeological evidence from the Amazon basin during the last 2000 years suggest a periodicity of approximately 500 years between episodes on intense and prolonged drought, possible associated with mega ENSO events (Meggers 1994).

Table 1. Annual water balance of the Amazon basin as deduced from previous studies (P=Precipitation, ET=Evapotranspiration, R=runoff, in mm/year).[From Marengo et al. 2000].

Study	P	ET	R
Baumgartner and Reichel (1975)	2170	1185	985
Villa Nova et al. (1976)	2005	1080	925
Marques et al. (1977)	2083	1000	1083
Marques et al. (1978)	2328	1261	1067
Jordan and Heuvelop (1983)	3684	1985	1759
Leopoldo et al. (1982)	2076	1676	400
Franken and Leopoldo (1984)	2510	1641	869
Shuttleworth et al. (1988a, b)	2636	1329	1317
Vorosmarty et al. (1989)	2260	1250	1010
Russell and Miller (1989)	2010	1620	380
Nizhizawa and Koike (1989)	2300	1451	849
Matsuyama (1992)	2153	1139	849
Marengo et al. (1994)	2888	1616	1272
Vorosmarty et al. (1996)	2301	1221	1080
Costa and Foley (1998)	2160	1360	1106
Oki (1999)	2076	1023	1053
Zeng (1999)	2044	1879	365

OBJECTIVES

The main objectives of this investigation can be summarized as:

- Assessment of the integrated atmospheric water vapor and moisture transport in the Amazon basin and a whole and in the northern and southern sub basins, using the NCEP/NCAR derived circulation and moisture fields.
- Validation of the NCEP/NCAR derived atmospheric water balance with observed rainfall and river observations in the Amazon region and its sub basins.
- Identification of interannual, and interdecadal variations in the atmospheric water vapor and moisture transport, and investigate the links to the Southern Oscillation and to decadal Atlantic/Pacific Ocean variability.
- Analysis of atmospheric water vapor and moisture transport in order to assess the effects of the observed “climate shift” of 1975-76 detected in the Pacific on the water cycle of the Amazon basin at decadal time scales.
- Investigate the role of local and remote forcing on the atmospheric moisture transport and water balance in the Amazon basin and the sub basin.

DATA AND METHODOLOGY

To estimate the atmospheric water vapor and moisture transport, we used the NCEP/NCAR reanalysis during the period 1950-98. Data was processed into monthly, seasonal and annual means, using the circulation, humidity from the 1000 hPa to the 300 hPa levels. More information on the NCEP/NCAR reanalyses and its statistics can be found in Kalnay et al. (1996). We are still confident that the NCEP/NCAR reanalysis captures most of the essential features of the large-scale circulation climatology. Precipitable water and atmospheric water transport were calculated as described in Rao et al. (1996) and Curtis and Hastenrath (1999). They showed that for tropical regions and the entire annual cycle the transient eddy transport is negligible, so that the total transport can be represented by the mean transport.

Studies by Trenberth and Guillemot (1995, 1998) have evaluated the precipitable water and moisture budgets from the NCEP, ECMWF and NASA/DAO and examined the differences between evaporation and precipitation. The moisture divergence in the NCEP/NCAR reanalyses exhibit major sources of errors in the tropical moisture budget. Moisture errors probably feed back and influence the divergent circulation through negative biases in latent heat and precipitation. They conclude that the reanalysis should be used with caution in climate and hydrological studies. Therefore, the need for a validation of these estimates of atmospheric moisture budget arises, and perhaps the best

way to assess this quantity is by an analysis of observed hydrological fields such integrated precipitation or river streamflow.

To examine rainfall in Amazonia and its variability in time, we used the September-August indices NAR (Northern Amazonian rainfall) and SAR (Southern Amazonian Rainfall) derived by Marengo (1992) and updated to include 1997-1998 by Marengo et al. (2000). For the compilation of NAR and SAR, stations were grouped according to their similarities in the annual cycle of precipitation. Departures from the long term mean for each year were divided by the standard deviation to normalized the time series. The average of all stations was calculated for each year yielding the respective normalized rainfall indices NAR and SAR. NAR is based on 78 stations distributed in northern, central and western Amazonia, while SAR was compiled from precipitation at 86 stations over the southern and southern and eastern Amazonia. From both NAR and SAR, a whole-Amazon rainfall index was also derived based on the areas average of NAR and SAR (regions indicated in Fig. 1). This new index (Integrated All-Amazon Rainfall index, ARI) implemented here represents a conjugation of different rainfall regimes in the entire Amazon basin, as represented by the 164 stations used to derive NAR and SAR (Marengo et al. 2000), and should be used in conjunction with NAR and SAR to better represent the variability in the basin and to capture the regional variations. River discharge represents the most accurate information about the terrestrial water cycle, however in large basins where the basin memory determines a large serial correlation or to backwater effects may be important, the representativity of these data for studies at interannual time scales may be jeopardized. After studies by and Meade et al. (1991) and Marengo et al. (1998) it was concluded that the river data from the Rio Negro at Manaus and the Amazon at Obidos were suitable for studies on climate variability, since they do not shows serial correlation. The Rio Negro at Manaus is available since 1903 to 1998, and the Obidos series from 1975 to 1998. Other river series available from 1931 to 1992 are for the Xingu River in Belomonte, which extends its basin to in southern Amazonia. These three river discharge series are used to complement the rainfall indices at regional and global Amazon scale.

PRELIMINARY RESULTS

The central and southern Amazonia exhibits the largest integrated moisture convergence, especially during summer. The Atlantic regions shows as the largest moisture source for Amazonia while the region is moisture source for other regions outside Amazonia. The northern portion of the basin, more sensitive to ENSO is source of moisture for the southern basin, less sensitive to ENSO and more dependent on local forcing.

On the long term, the integrated annual moisture flux divergence estimated by the NCEP reanalyses exhibits decadal time variations with periods of relative large and small moisture convergence and divergence. Given some uncertainties with the divergence derived from the reanalyses, it is a bit difficult to affirm that in fact, the integrated moisture flux divergence over the Amazon basin as a whole and over the northern and southern basins exhibit interdecadal fluctuations. The period extending from the late 1950's to the early 1970's is characterized by positive moisture flux convergence anomalies, while the rest of the record show negative flux convergence anomalies or anomalously increased moisture divergence. This tendency still holds for the whole and northern Amazonia, and in some degree for southern Amazonia.

The moisture flux divergence anomalies in southern Amazonia exhibit a period of positive anomalies in the middle 1980's which is not observed in northern Amazonia, while both regions show the positive moisture anomalies during the late 1950s- beginning of the 1970's. This later period is consistent with positive rainfall anomalies on that region as observed from the rainfall indices. There is some uncertainties in the interannual variability of moisture flux divergence/convergence as estimated by the reanalysis. Since even though the model produces increased divergence and thus less rainfall during the El Nino 1983 and 1987, the model also shows increased divergence during La Nina 1989, which is characterized by positive rainfall anomalies, especially in northern Amazonia. Further work is directed toward seasonal analysis of moisture transport, to identify the season where the best correlation between moisture transport and rainfall is found.

However, over it is important to indicate the presence of decadal time variations in rainfall and moisture transport in Amazonia. In addition, the South Atlantic and the South Pacific, the changes in the strength of the subtropical high and the associated surface wind are dynamically consistent with the distribution of local SST anomalies, suggesting the importance of atmospheric forcing in the decadal time scale, and this is supported by Venegas et al. (1998).

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