Tropical Atlantic Latent Heat Flux,

Convection over Northeastern Brazil and PIRATA network

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Abstract

This work aims at studying the relationship between tropical Atlantic latent heat flux and convective cloud coverage over the Northeast of Brazil (NEB) during the four months of the main rainy season (February to May) in this region. The correlation with the anomalies of these data is investigated, without lag and with one-month lag (the heat flux in advance). In both cases, a significant positive correlation appears in the Northern Western Tropical Atlantic, and a significant negative correlation is obtained for a limited area off eastern NEB. These two correlation patterns are linked to anomalies in the trade wind intensity and in the meridional position of the inter-tropical convergence zone (ITCZ), that respectively relate to the latent heat flux anomalies and NEB convective coverage anomalies. The patterns obtained here show that the Northern Tropical Atlantic has a predominant influence on NEB, and that the key-region of the Southern Tropical Atlantic is only located around the NEB eastern coast. The impact of the Atlantic heat fluxes on the NEB convection is somewhat different of the classical meridional dipole related to the SST variability. The analysis of the horizontal moisture flux shows that during flood years an additional meridional inflow balances the eastward loss, and the upward velocity reinforced over NEB contributes to intensify NEB convection. The positive correlation pattern indicates that the location of the northern branch of the PIRATA (Pilot Research moored Array in the Tropical Atlantic) moorings is pertinent to monitor the ocean-atmosphere interface parameters. The negative correlation pattern off NEB provides new argumentation in the design of the possible extension of the PIRATA array towards the Brazilian coast. Complementary results at one-month lag and the real-time availability of the PIRATA data confirm the potentiality of NEB forecasting.

Key Words: *Tropical Atlantic, Heat Fluxes, Convective Systems, PIRATA*

Introduction

The northern Northeast of Brazil (nNEB) precipitation regime, with its main rainy season from February to May (Strang, 1972), is the predominant rainfall regime in the Northeast of Brazil (NEB) semi-arid region (Kousky, 1979). February-May (hereafter FMAM) is the period of the year when the Intertropical Convergence Zone (ITCZ) attains its southernmost position, reaching the NEB (Hastenrath and Heller, 1977). The high rainfall interanual variability shows normal years intercalated with drought and flood years, and has consequent economic and social impacts. Several studies have related this interanual variability to ocean parameters such as sea surface temperature (SST). Correlation studies (Hastenrath and Heller, 1977; Moura and Shukla, 1981) between SST anomalies and rainfall anomalies over NEB highlighted a dipole-like pattern straddling the ITCZ. Negative (positive) SST anomalies in the southern Tropical Atlantic and positive (negative) anomalies in the northern Tropical Atlantic are associated with drought (humid) years. Chung (1982) linked SST, wind and precipitation in NEB, showing that stronger than normal trade winds in the South Atlantic take place in the months preceding the FMAM rainy season during drought years. Hastenrath and Heller (1977) associated anomalously drought years with a weakening of the equatorward part of the North Atlantic subtropical high, an equatorward expansion of the South Atlantic subtropical high and an anomalous northward position of the ITCZ. They obtained opposite patterns for abundant rainy seasons.

Droughts and floods in the NEB are also related with the phases of El Niño Southern Oscillation (ENSO). During a warm ENSO episode (El Niño event), the Walker cell migrates eastward causing anomalous subsiding motions over the Amazonia, NEB and Tropical Atlantic, thus reducing the precipitation. On the other hand, during a cold ENSO episode (La Niña) the vertical motion is increased over those regions, with more rainfall. Significant links between ENSO events and the precipitation in the NEB region are found in numerical modeling experiments and observation (Harzallah et al.; 1996; Roucou et al., 1996). Those authors also have showed that the anomalies in the SST field in the Tropical Atlantic change the Hadley cell in such a way to cause anomalous subsidence in dryer than normal years and accelerated vertical motion in years with an excess of rainfall over the NEB.

Fluxes at the ocean-atmosphere interface – latent and sensible heat fluxes, and momentum flux – are essential parameters for ocean-atmosphere interaction studies. In a sensitivity study, Wang (1996) showed that the latent heat flux is the most significant of the three fluxes just mentioned, when considering the structure and the internal dynamics of intense convective systems. Works done in the context of the TOGA-COARE project (Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment) in the Pacific have shown the influence of heat fluxes on convection, which are directly linked to precipitation. These fluxes act significantly in the atmosphere carrying humidity and heat necessary for the development of convection and precipitation (Rotunno and Emanuel 1987, Tao 1991). On the other hand, atmospheric conditions such as wind, cloud coverage and precipitation affect ocean surface parameters by altering the fluxes (Webster and Lukas, 1992).

This preliminary work aims at studying the relationship between observations of the Tropical Atlantic latent heat flux and the convective systems over NEB. The convective cloud coverage data used here are available on a 2.5° horizontal grid. This limited us to a better definition of the NEB. We defined this region between 10°S and the northern coast, and between 45°W and the eastern coast (see maps in Figure 1).

In order to measure variables of the ocean-atmosphere interaction in the Tropical Atlantic, an observational network has been set up, the Pilot Research moored Array in the Tropical Atlantic (PIRATA) (Servain et al., 1998). The locations of the moorings (See Figure 1) have been chosen to monitor the two main modes of the Tropical Atlantic variability – the meridional mode and the equatorial mode (Servain et al., 2000). Here we will also investigate whether the locations of the moorings are adequate for the study of the relationships between heat fluxes and NEB convection.

This work is based on a correlation study between anomalies of latent heat flux and convective cloud coverage. We try to answer the following questions: What is the impact of the Tropical Atlantic heat fluxes on NEB convection? What is the relative importance of the strong latent heat fluxes on both sides of the ITCZ? Could the link between latent heat flux and NEB convection lead to potential forecast applications?

The data used in this study, their climatologies during the FMAM season and the methods of calculations are presented in Section 1. In Section 2, we present correlation of the tropical Atlantic latent heat flux anomalies with the NEB convective cloud coverage anomalies during the rainy season without lag and with one-month lag (the heat flux in advance). Section 3 is a discussion of these results, before the conclusion in Section 4.

1. Data and Methods:

We decided to base this preliminary study on observation data. This criterion restricted the data choice and the period of study. After a comparison study between three latent heat flux data sets (Durand et al., 2002), we chose the da Silva latent heat flux data set (da Silva, 1994), based on in-situ observations. These data are monthly available from 1945 to 1995 on a 1° global grid.

Here, positive heat fluxes mean a heat transfer from the ocean towards the atmosphere. Therefore in the correlation study (section 2), when we mention positive (negative) flux anomalies that means a positive (negative) energy transfer into the atmosphere.

Machado et al. (2004) justified the use of the convective cloud cover to define the rainy season. They obtained a good relationship between precipitation and convective cloud cover at a monthly scale. The use of cloud coverage data gives a simple and objective approach, and the spatial cover avoids extrapolations that may be spurious in case of few raingauge measurements. The convective cloud coverage data are derived from satellite observations and processed by the ISSCP project (International Satellite Cloud Climatology Project; Schiffer and Rossow, 1985). In order to describe only the clouds with convective activity, we used the cloud coverage with cloud top pressure smaller than 310 hPa. The data are available on a 2.5° grid, every 3 hours, from 1983 to 1994. The heat flux data temporal resolution is monthly, so we calculated monthly means of the convective cloud coverage. Taking in account the temporal limitations of both data sets, we have at our disposal a ten-year data period, from 1984 to 1993. We defined the NEB region as the area localized between 45°W and 35°W and between 10°S and 2.5°S (i.e.11 grid points). We averaged the monthly convective cloud coverage of these 11 grid points, and defined a NEB convective cloud coverage index as the normalized anomalies (anomalies divided by the standard deviation) of this monthly series.

For the discussion and the interpretation of the results we used also data from the monthly NCEP reanalysis (Kalnay et al., 1996): the wind field, the vertical velocity and the specific humidity (between 1000 hPa and 300 hPa). The low level wind data is used to define the ITCZ position as the quasi-zonal line where the meridional component is zero. We calculated the horizontal moisture flux as the horizontal wind multiplied by the specific humidity.

Figure 1 shows the FMAM climatology of (a) the latent heat flux and (b) the convective cloud coverage. The FMAM climatology of the NCEP 925 hPa level wind field, and the FMAM climatological position of the ITCZ, are also represented.

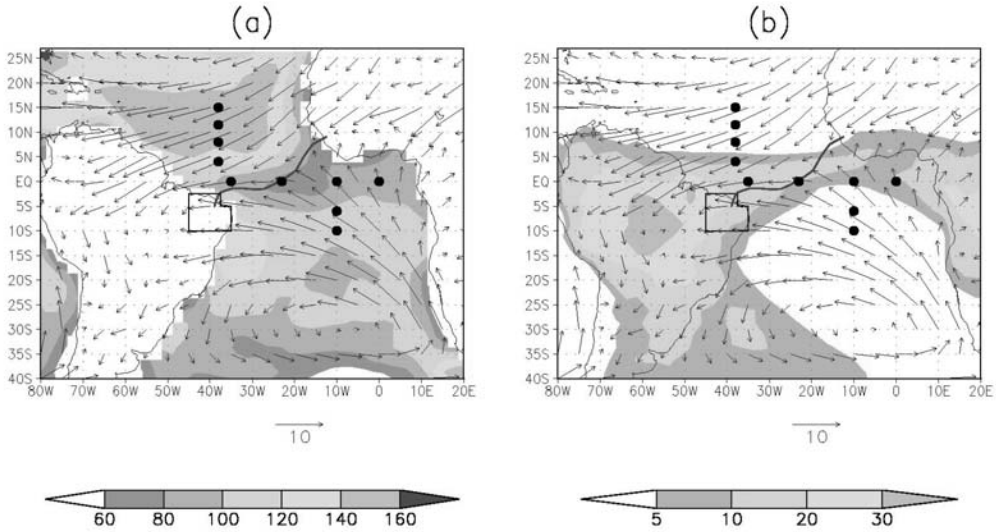

Figure 1: FMAM climatology of (a) the da Silva latent heat flux (W/m^2) and (b) the convective cloud coverage (%). The FMAM climatology of the wind field at 925 hPa is also plotted. The black polygon delimits NEB, and the full black circles indicate the position of the PIRATA buoys. The red line is the climatological position of the ITCZ during FMAM months.

The latent heat flux FMAM climatology (Fig. 1a) shows large values on both sides of the ITCZ. Over the ocean, the ITCZ (i.e., the region of maximum convection) is also the region of low-level wind confluence. On both sides of the ITCZ, trade winds are strong and the relatively weak cloud coverage allows a large amount of solar radiation to reach the surface. However, given the total cloud coverage climatology (not represented here), the regions of maximum latent heat fluxes do not coincide exactly with the regions of minimum cloud coverage. This suggests that wind is the most important parameter that modulates the flux intensity.

The FMAM climatology of convective cloud coverage (Fig. 1b) shows a large convective cloud coverage maximum (mean values between 20 and 30 % of the total surface) spreading over the Amazonia and the nNEB. Over the ocean, convective cloud coverage values are smaller, but the ITCZ appears clearly as the region of maximum convection over the tropical Atlantic. Values up to 20% are observed between 7°S and 5°N on the western part of the Atlantic and between the equator and 5°N on the eastern part.

2. Results

In order to analyze the relationships between the latent heat flux and the convective cloud coverage, we calculated the correlation with their monthly anomalies. The two data sets are characterized by strong seasonal cycles, which contribute to a large portion of their correlation, hiding the signal of the correlation based on the non-seasonal variability. Calculating the correlation with normalized anomalies (monthly value minus monthly climatology, divided by the standard deviation of the month) eliminates the contribution of the seasonal cycle. Two kinds of correlation are calculated, one with a time series without lag and the other with one-month lag. Hereafter, when speaking of one-month lag correlation, it means that the heat flux is in advance with respect to the convective parameter. For the in-phase correlation, both the heat flux and convective time series are made of individual February to May monthly values from each year of 1984-1993 (i.e. 40 values). For the one-month lag correlation, the convective time series is made again of February to May values, while the heat flux time series is now made of January to April values. The significance of the correlation is estimated with the Student T-test. With series of 40 values, correlation larger than 0.31 in absolute value are 95%-significant.

Figure 2 shows maps of correlation, (a) in phase, and (b) with one-month lag, between the latent heat flux anomalies of the whole tropical Atlantic Ocean, and the convective cloud coverage anomalies over NEB during the rainy season. In these maps only the 95%-significant correlation values are colored.

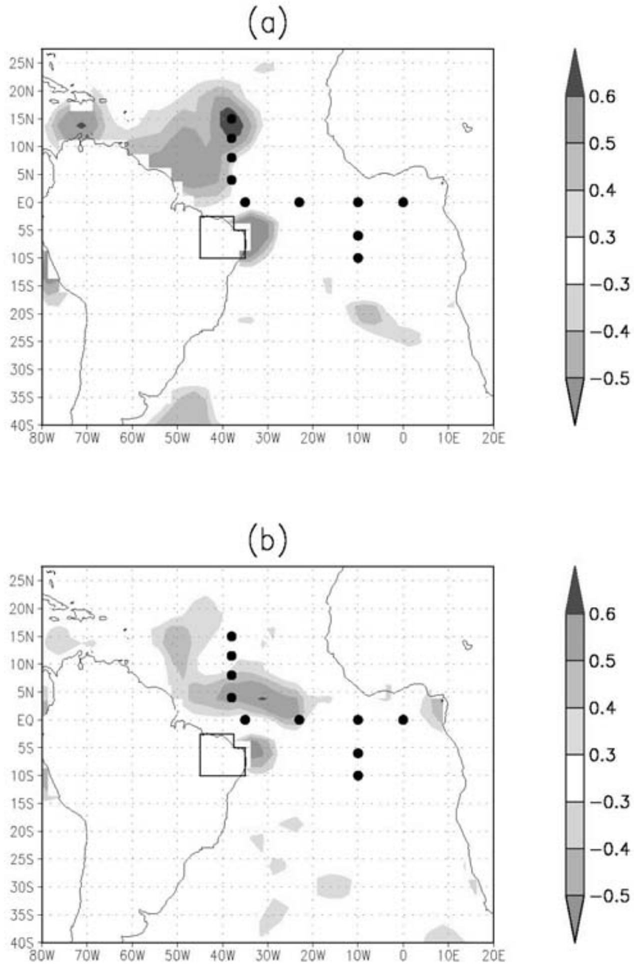

Figure 2: (a) Correlation of the monthly mean anomalous values of NEB convective cloud coverage with the Tropical Atlantic latent heat flux for FMAM during the 1984-1993 period; (b) The same as (a) with the NEB convective cloud cover in the months FMAM and the Tropical Atlantic heat flux in the months JFMA (one month lag). The black polygon delimits NEB, and the full black circles indicate the position of the PIRATA buoys.

These maps help to determine which regions of the tropical Atlantic are linked (with regard to the surface latent heat flux) to the NEB convective coverage variability. The correlation in phase (Fig. 2a) shows a strong signal of positive correlation in the northwestern tropical Atlantic with a maximum (greater than 0.6) in the vicinity of 15°N-38°W where a PIRATA mooring is located. The correlation decreases when approaching the northern coast of South America. Off the NEB, in the region between 2°S and 12°S, and between the Brazilian coast and 30°W, there is a large negative correlation area up to -0.5 near the coast. Those positive and negative correlation areas outline a meridional dipole-like pattern, although quite different from the already known SST-dipole pattern (e.g. Servain, 1991). Here the northern part is larger than the southern, and the southern part does not spread over the entire Southern basin, but is confined near the eastern NEB coast.

With one-month lag (Fig. 2b), a large positive correlation area is also observed in the Northwestern Tropical Atlantic. Globally one-month lag correlation is weaker than in-phase correlation, except in the region between 40°W and 30°W and along 5°N, where the maximum of one-month lag correlation is located, reaching values between 0.5 and 0.6. The one-month lag correlation maximum is located near the northern coast of South America, contrarily to what is observed for the in-phase correlation where the maximum occurs at the vicinity of 15°N. The same way as in the case without lag, latent heat flux anomalies off NEB are negatively correlated with convection over the NEB. It is interesting to enhance the fact that the one-month lag correlation pattern is quite coherent with the in-phase pattern.

3. Discussion

In the ten years we have studied, five are characterized by a positive anomaly of the NEB convective coverage (1984, 1985, 1986, 1988 and 1989), hereafter named "flood years", and the other five (1987, 1990, 1991, 1992, 1993), - hereafter named "drought years" -, present a negative anomaly. During the FMAM main rainy season, precipitation is mainly due to the convective activity of the ITCZ, reaching NEB in this season. See on Figure 3 the average position of the ITCZ during the five flood (drought) years represented by a blue (red) line.

The composite anomalies of the NCEP surface wind field (not shown here) for rainy (drought) years show stronger (weaker) trade winds in the northern hemisphere, and weaker (stronger) trade winds in the southern hemisphere. This anomaly in the wind field is associated with an abnormal southward (northward) displacement of the ITCZ (See Figure 3 for a representation of the ITCZ average position during flood years and drought years). This is coherent with the results obtained by Hastenrath and Heller (1977), showing that during abnormally rainy (drought) years over NEB, the ITCZ is southward (northward) of its average position. During the years of positive (negative) convective coverage anomaly, stronger (weaker) trade winds in the northern hemisphere imply a positive (negative) latent heat flux anomaly in this region, and weaker (stronger) southern trade winds will induce a negative (positive) latent heat flux anomaly off NEB eastern coast. This explains at once the positive correlation pattern in the western northern Tropical Atlantic, and the negative correlation pattern off NEB (Figure 2).

To understand better the mechanisms that feed convection over NEB, and how convection increase during flood years, we calculated the horizontal moisture flux from NCEP data (as horizontal wind multiplicated by the specific humidity). We plotted the bias between flood years and drought years, for the FMAM months, at the 1000 hPa level (Figure 3). Hereafter when we speak of bias, it means the bias between FMAM of flood years and FMAM of drought years of the considered variable. Hereafter we make an analysis based on flood years, and comment the phenomena associated with them. For drought years we obtain opposite patterns. Figure 3 represents the bias of the horizontal moisture at the 1000 hPa level, and a blue (red) line also indicates the ITCZ average position during the FMAM months for the flood (drought) years.

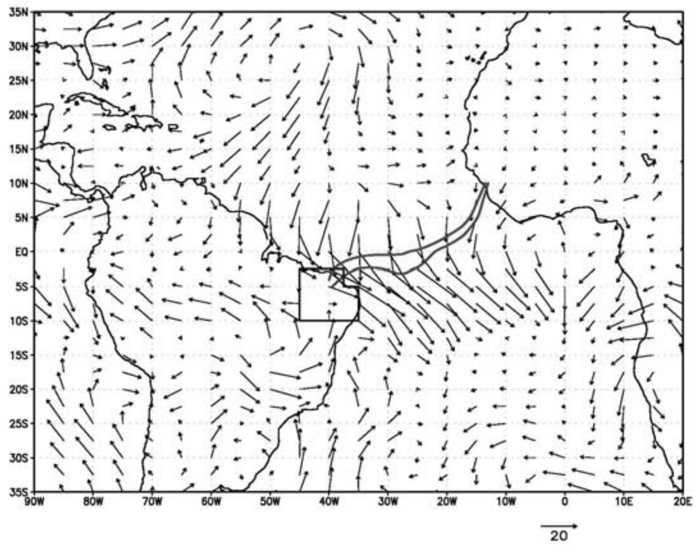

*Figure 3: Bias of the FMAM 1000 hPa horizontal moisture flux (*1000 g/kg.m/s) between flood years and drought years. The blue (red) line indicates the average ITCZ position for FMAM of the five flood (drought) years. The black polygon delimits the region defining NEB.*

The horizontal moisture flux bias is coherent with the surface wind anomalies described previously. Figure 3 shows clearly the intensification of the North Atlantic Subtropical High, the southward displacement of the ITCZ, the intensification of the northern trade winds and the decreasing of southern trade winds, characteristics of flood years.

It is important to underline the fact that zonal flux is positive when it is eastward, and meridional flux is positive when it is northward. The horizontal moisture flux FMAM climatology (not shown here) shows that the westward moisture flux from the ocean is the main contribution to NEB. But the bias (figure 3) shows clearly that flood years are characterized by an eastward anomaly. In these years, the additional moisture necessary to feed NEB convection, seems coming from the meridional contribution: the southward bias near NEB northern coast between 10°N and the equator, and the northward bias south of NEB, increase the meridional moisture contribution during flood years. Thus the total NEB moisture amount is larger and can feed convection.

To confirm this explanation, we extracted vertical profiles between 1000 hPa and 300 hPa of the zonal moisture flux (averaged between 10°S and the equator) and of the meridional moisture flux (averaged between 45°W and 35°W), and plotted the bias between FMAM of flood years and of drought years of these two variables (Figure 4a and 4b respectively). These figures also represent the vertical velocity profiles (with the same spatial averages). Negative values of the vertical velocity bias indicate an upward bias.

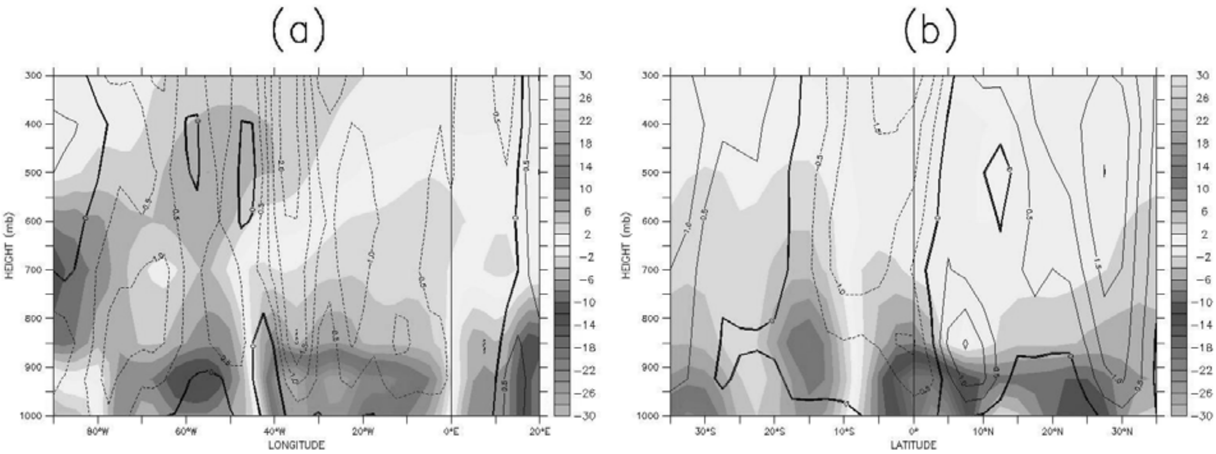

Figure 4: Bias between flood years and drought years (a) of the FMAM zonal moisture flux (10^{-3} g/kg.m/s) averaged between 10°S and the equator, and (b) of the FMAM meridional moisture flux (10^{-3} g/kg.m/s) averaged between 45°W and 35°W. In both cases the black contours represent the vertical velocity omega (10^{-2} Pa/s). Contour interval is 0.5, and negative contours (upward bias) are dashed.

In the region between 43°W and 2°W, the bias of zonal moisture flux is positive (Figure 4a), showing a reduced zonal moisture contribution during flood years, as observed before. The bias is more intense in low levels (from 1000 hPa to 850 hPa level). Negative zonal flux bias, west of

45°W indicates an enhanced westward zonal flux in the west of NEB. Flood years are also characterized with a reinforced ascending motion between 40° and 30°W, with maximum values above 35°W, which is the eastern part of NEB.

During flood years, the meridional moisture flux (Figure 4b) is characterized by an intensification of the southward flux between 10°N and 5°S and of the northward flux, south of 10°S. Again these biases are larger in low levels (from surface to 850 hPa for the southward contribution, and from surface to 700 hPa for the northward one). These flux biases are associated with enhanced ascending motion in the region centered on 0°N-5°S, corresponding to the southward displacement of the ITCZ in flood years.

These profiles show that although the westward moisture contribution in NEB is smaller during flood years, this loss is balanced by an additional meridional moisture contribution from both north and south. This larger total NEB moisture amount, associated with the increased ascending motion, allows a more intense convective activity and more precipitation.

The average wind field from the northern western tropical Atlantic (see Figure 1) – and consequently the mean horizontal humidity flux from this region – does not feed convection over the NEB directly, but rather over regions in the northwest of the NEB. Thus, the positive correlation between the northern tropical Atlantic and NEB convection anomalies (Figure 2) is not a causal relationship, but results of the fact that the heat flux anomalies and the NEB convection anomalies are linked to the same atmospheric modification.

The negative correlation pattern obtained in the vicinity of NEB eastern coast (Figure 2) is unexpected at first sight: less latent heat in NEB vicinity can appear in contradiction with more convection and rain in NEB. In fact, flood years are characterized by a modification of the atmospheric circulation, reinforcing northern trade winds, and decreasing southern trade winds. Thus the latent heat flux off NEB and the westward moisture flux into NEB are reduced. But the intensified meridional moisture flux contributes to increase NEB moisture amount. This, associated with an increased upward motion, contributes to sustain a more intensive convective activity.

The different correlation patterns obtained in this study highlight the fact that the relation between heat flux and convective activity is complex, not linear and is not of the same type in the whole Atlantic basin. The lag correlation study has to be investigated further, it could lead to interesting forecast applications, considering the oceanic and atmospheric surface data provided by the PIRATA buoys located in the areas of large correlation, particularly the 4 buoys located at 38°W, between 4°N and 15°N: the buoys at 15°N and 12°N are in the area of positive in phase correlation, and the two other at 8°N and 4°N are in the area of positive one month lag correlation. Moreover, a great advantage of PIRATA data is their availability in real time, which is very interesting for forecast applications.

4. Conclusion

The main results of this correlation study between the normalized anomalies of the tropical Atlantic latent heat flux and the convective coverage anomalies over NEB during its rainy season (FMAM) are a large positive correlation in the northern tropical Atlantic, where the western branch of the PIRATA moorings is located, and a large negative correlation in a limited area off NEB.

The positive correlation pattern is not the result of a causal relationship between latent heat flux anomalies in northern tropical Atlantic and convection anomalies over NEB. It is due to anomalies in the atmospheric circulation that in turn drive anomalies of the latent heat flux and NEB convection. The analysis of the horizontal moisture flux showed that the additional humidity present in NEB region during flood years do not come from a westward inflow, but from a southward additional contribution. Those results show the relevance of the PIRATA moorings along 38°W, and the pertinence of the data of these buoys for studies of the convection over NEB.

Flood years are also characterized by an increased ascendant motion over NEB, which helps convective activity.

The negative correlation between latent heat flux off NEB and convective cloud coverage over NEB has also its origin in the modification of the atmospheric circulation. An abnormally southward (northward) position of the ITCZ induces larger (smaller) convective coverage over NEB (the “dipole effect”), and weaker (stronger) trade winds off NEB, which means negative (positive) heat fluxes anomalies off NEB and, thus, a negative correlation.

What is brand new here from the previous studies is the choice of observation-based data of the coupled latent heat flux/convective cloud coverage to investigate the impact of the tropical Atlantic on NEB. This allows to obtain new correlation patterns, compared to the already known SST dipole. Although our results are coherent with previous works on the relationship between the tropical Atlantic and precipitation over NEB, they give new elements, potentially useful for forecasting experiments of the NEB climate. Indeed, while the importance of the variability of the latent heat flux in the western Northern Atlantic is confirmed, the weight of the Southern tropical Atlantic is limited to the oceanic region immediately off the NEB. When considering the impact of heat fluxes, the rest of the Southern tropical Atlantic does not seem to have a strong influence on NEB. Of course, we have not analyzed the precipitation during the period from April to August, the main rainy season on the eastern NEB coast, and future investigation is necessary. These results must be taken in consideration for the design of any future SW Extension of the PIRATA array, close to the Brazilian coast.

It is still necessary to investigate why the in-phase correlation between NEB convection anomalies and the heat flux anomalies in northern Tropical Atlantic is more intense towards the north, while the one-month lag correlation is more intense towards NEB. The PIRATA data from the buoys along 38°W could give useful information about that question, and their positions are really pertinent to be used in forecasting experiments.

In further works it is planned to use a longer time series of convective coverage data with a better temporal resolution allowing a weekly analysis. It would be interesting to calculate one-week or two-week lag correlations. This temporal scale is more adequate for the horizontal transport of humidity from the tropical Atlantic to NEB.

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References

Chung J. C., 1982: Correlation between the tropical Atlantic trade winds and precipitation in Northeastern Brazil. *J. of Climatology*, 2, 35-46.

da Silva, A. M., C. C. Young, and S. Levitus, 1994: Algorithms and Procedures. Vol.1, *Atlas of Surface Marine Data*, NOAA Atlas Series, 74 pp.

Durand, B., H. Laurent, L. A. T. Machado, J. Servain, 2002: Relações entre os fluxos de calor na superfície do Atlântico Tropical e a cobertura de nuvens. *Anais do XII Congresso Brasileiro de Meteorologia.*

Harzallah, A., J. O. R. Aragão, and R. Sadourny, 1996: Interannual rainfall variability in Northeast Brazil: observation and model simulation. *Int. J. Climatol.*, 16, 861-878.

Hastenrath, S. and L. Heller, 1977: Dynamics of climatic hazards in Northeast Brazil. *Quart. J. Roy. Meteor. Soc.*, 103, 77-92.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chellah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A Leetmaa, R. Reynolds, Roy Jenne, and Dennis Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, 77, 437-471.

Kousky, V. E., 1979: Frontal Influences on Northeast Brazil. *Month. Weath. Rev*., 107, 1140-1153.

Machado, L. A. T., H. Laurent, N. Dessay, I. Miranda, 2004, *in press*: Seasonal and diurnal variability of convection over the Amazonia : A comparison of different vegetation types and large scale forcing. *Theoretical And Applied Climatology*, DOI 10.1007/s00704-004-0044-9, n. in press, 2004.

Moura, A. D. and J. Shukla, 1981: On the dynamics of droughts in Northeast Brazil: observations, theory and numerical experiments with a general circulation model. *J. Atmos. Sci*., 38, 2653-2675.

Rotunno, R., and K. A. Emmanuel, 1987: An air-sea interaction theory for tropical cyclones*. J. Atmos. Sci*., 44, 542-561.

Roucou, P., J. O. R. Aragão, A. Harzallah, B. Fontaine, and S. Janicot, 1996: Vertical motion changes related to Northeast Brazil rainfall variability: a GCM simulation. *Int. J. Climatol*., 16, 879-891.

Schiffer, R. A. e Rossow, W. B., 1985: ISCCP global radiance data set: A new resource for climate research, *Bull. Amer. Meteor. Soc.*, 66, 1498-1505.

Servain, J., 1991: Simple Climatic Indices for the Tropical Atlantic Ocean and Some Applications. *Jour. Of Geophys. Res*., 96, 15,137-15,146.

Servain, J., A. J. Busalacchi, M. J. McPhaden, A. D. Moura, G. Reverdin, M. Viana, S. E. Zebiak, 1998: A Pilot Moored Array in the Tropical Atlantic (PIRATA). *Bull. Amer. Meteor. Soc.*, 79, 2019-2031.

Servain, J., I. Wainer, L. H. Ayina, and H. Roquet, 2000: Relationship between the simulated climatic variability modes of the tropical Atlantic*, Int. J. Climatol*., 20, 939-953.

Strang, D. M. G. D., 1972: Climatological analysis of rainfall normals in Northeast Brazil – IAE-MO2/72 (available from C.T.A., São José dos Campos, SP, Brazil).

Tao, W. K., and J. Simpson, 1991: Numerical simulation of a subtropical squall line over Taiwan Strait. *Mon. Wea. Rev*., 119, 2699-2723.

Wang, Y., W.-K. Tao, J. Simpson, 1996: The Impact of Ocean Surface Fluxes on a TOGA COARE Convective System. *Monthly Weather Review*,124, 2753-2763.

Webster, J., and R. Lukas, 1992: TOGA COARE: The Coupled Ocean-Atmosphere Response Experiment. *Bull. Amer. Meteor. Soc*., 73, 1377-1416.