

Exploring the climate problems of Brazil's Nordeste: a review

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Abstract This article reviews the exploration of the climate dynamics of Brazil's Nordeste in the course of a century. The drought-prone and semi-arid northern Nordeste of Brazil experiences a short rainy season around March–April, when the interhemispheric gradient of sea surface temperature (SST) in the tropical Atlantic is weakest and the Intertropical Convergence Zone (ITCZ) reaches its southernmost position in the course of the annual cycle. The recurrent Secas (droughts) have a severe socio-economic impact. During drought years, the interhemispheric SST gradient in the tropical Atlantic is steep and the ITCZ stays far North, while the waters of the eastern equatorial Pacific tend to be anomalously warm. Based on the extensive diagnostic exploration of the circulation mechanisms of interannual climate variability, empirical methods have been developed for the forecasting of the Nordeste rainy season. These have been applied in the real-time prediction of seasonal rainfall anomalies throughout the last decade of the 20th century.

Abbreviations

SST Sea Surface Temperature
ITCZ Intertropical Convergence Zone
SMR Stepwise Multiple Regression
MOS Model Output Statistics

1 Introduction

The Nordeste, which actually constitutes the easternmost corner of the continent (Fig. 1) is the region of earliest Portuguese colonization in the New World and has a long cultural tradition. The Northern Nordeste has a semi-arid climate with a short rainy season centered on March–April and large variations of rainfall from year to year. In its long history, the recurrent “Secas”, or droughts, have had severe human impact. The region has been

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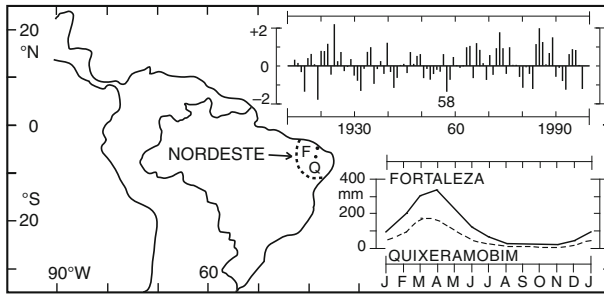


Fig. 1 Orientation map showing the Northern Nordeste of Brazil and the rainfall stations Fortaleza (F) and Quixeramobim (Q). Presented on the right are on top a 1912–1999 time series plot of rainfall in the Northern Nordeste (March–April–May–June, normalized departure, index from 27 raingauge stations; note the severe drought of 1958), and on bottom a diagram of the annual cycle of rainfall at Fortaleza and Quixeramobim

appropriately highlighted as a “problem climate” (Trewartha 1962). Indeed, a series of questions pose themselves: Why does the rainy season peak around March–April rather than conforming to the notion of July–August and January–February as the extremes of the annual cycle? Why do the rains fail in some years? How could one predict such climatic disasters? The famous Sir Gilbert Walker, not content with his daunting tasks of forecasting the Indian summer monsoon rainfall, devoted a meticulous paper to the Secas of Northeast Brazil, published in a prestigious German journal (Walker 1928). In hindsight it is obvious that Sir Gilbert did not have a clue. The pioneers of Brazilian meteorology pursued an interest in the climate of the Nordeste (Sampaio Ferraz 1925; Serra 1956), drawing attention to these issues. A recent book (Instituto Nacional de Meteorologia 2009) highlights the amazing development of meteorology in Brazil over the past hundred years. The essentials of circulation diagnostics and climate prediction for the Nordeste have been discussed in books and journal articles (Hastenrath 1985, pp. 293–300, 363–365; 1995, pp. 302–309, 385–386; 1990, 2000). In the present essay, Section 2 traces the history of human impact; Section 3 summarizes the progressive exploration in recent decades of the circulation mechanisms of the annual cycle; Section 4 discusses the interannual variability, and based on this Section 5 sketches the development of climate prediction methods and the operational real-time forecasting of the Nordeste rainy season; and reflections on this “problem climate” are expressed in the closing Section 6.

2 Human impact

A historical perspective of the human impact of the recurrent droughts is given in Carvalho (1973, pp. 95–103, 179–192), Goncalves de Souza (1979, pp 73–83, 305–307), SUDENE (1981, pp. 17–24), Hastenrath (1985, pp. 363–365), Davis (2001, pp. 79–90), and Aceituno et al. (2009), while a short review must suffice here.

Reports of Secas and their severe socio-economic consequences exist ever since the early century of Portuguese colonization. The Secas recurrently led to starvation and mass exodus. The refugees may initially have hoped to return home after the drought, but many stayed away forever. New settlements along rivers were founded by the “flagelados”. The Secas were responsible for the emigration of Nordestinos to distant regions of Brazil. They contributed to the labor force in the mines of Minas Gerais and the industrial hub of Sao Paulo, and they were instrumental in opening up the western extremity of the Amazon

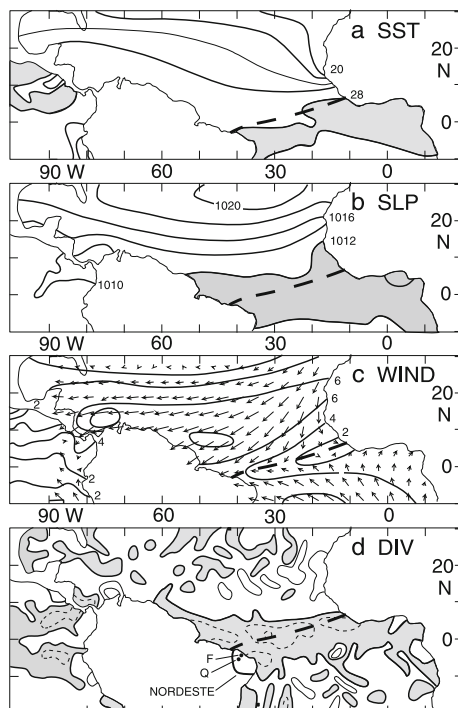
basin. Government initiatives to mitigate the effects of the droughts began in the 17th century. These included public work projects for the unemployed refugees, the construction of dams, plans for the exploitation of wind energy, and the development of alternative settlements.

3 Annual cycle

The short rainy season of Brazil's Nordeste is narrowly concentrated around March–April, as is illustrated in Fig. 1 for two long-term stations. The causes for this peculiar seasonality in rainfall could not well be appreciated without analyses of the large-scale circulation setting. The annual cycle of circulation in the tropical Atlantic sector has first been comprehensively documented in an atlas based on long-term ship observations (Hastenrath and Lamb 1977). A limited selection of maps is presented in Fig. 2. The map Fig. 2a of sea surface temperature (SST) shows a band of warmest surface waters across the tropical North Atlantic, contrasting with a cold water tongue immediately to the South of the Equator. A trough of lowest pressure (Fig. 2b) sits broadly over the warmest surface waters. Embedded in the high pressure trough is the confluence between the Northeast trades and the cross-equatorial airstream from the southern hemisphere (Fig. 2c). Somewhat to the South of the wind confluence extends a zone of largest convergence (Fig. 2d), the Intertropical Convergence Zone (ITCZ).

The SST maximum hydrostatically controls the low pressure trough, into which flow the airstreams from the two hemispheres, and thus the position of the ITCZ (Hastenrath and Druyan 1993; Hastenrath and Greischar 1993a). At the height of boreal summer, the

Fig. 2 Surface circulation over the tropical Atlantic and eastern Pacific, March 1958–97; (a) sea surface temperature, with isotherm spacing of 2°C and with area above 28°C shaded; (b) sea level pressure, with isobar spacing of 2 mb, and with area below 1012 mb shaded; (c) resultant wind direction and speed, with isotach spacing of 2 ms^{-1} ; confluence between airstreams is indicated by bold dashed line, repeated in panels a, b and d; (d) divergence with isoline spacing of $5 \times 10^{-6}\text{ s}^{-1}$, and convergence shaded; bold solid line encloses Northeast Brazil (Nordeste), and F and Q denote the stations Fortaleza and Quixeramobim



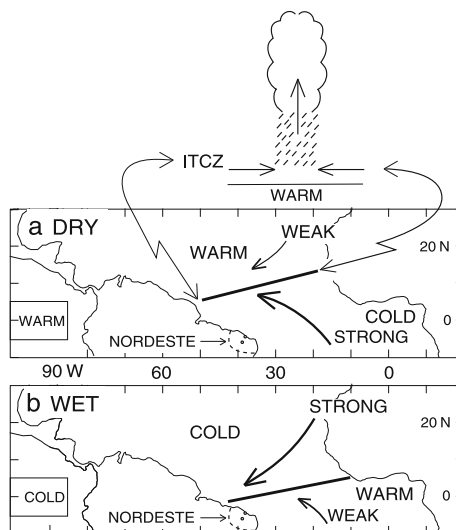
interhemispheric SST gradient is steep, the band of warmest surface waters is located far North, and along with that the near-equatorial low pressure trough and ITCZ. In the progression from boreal summer to winter, the interhemispheric SST gradient weakens, and the complex of SST maximum, low pressure trough, and ITCZ, shifts southward, reaching a southernmost position around March–April. After that, the waters of the tropical North Atlantic warm, the interhemispheric SST gradient steepens, and the complex of SST maximum, pressure trough and ITCZ migrate northward. The ITCZ is the major rainbearing system for the Nordeste and thus dictates the narrow concentration of the rainy season around March–April (Fig. 1, right side).

4 Interannual variability

The cartoon in Fig. 3 compacts the results from diagnostic research spread over two decades (Hastenrath and Heller 1977; Moura and Shukla 1981; Hastenrath et al. 1984; Hastenrath 1985, p., 293–300; Hastenrath and Druyan 1993; Hastenrath and Greischar 1993a,b). The maps of Figs. 3a and b illustrate the departures in the large-scale atmosphere-ocean setting characteristic of extremely DRY (Fig. 3a) and extremely WET (Fig. 3b) years in the Nordeste.

Thus, Fig. 3a indicates for the DRY years surface waters anomalously warm in the North and cold in the South, although what matters is the interhemispheric gradient of SST. As a consequence, the confluence between the airstreams from the two hemispheres sits far North, and along with that the rainbearing ITCZ. Fig. 3b for the Nordeste WET years shows departures broadly opposite to those in the DRY years, namely weakened interhemispheric SST gradient, more southerly ITCZ position, and cold Pacific waters. In context with the discussion in Section 3 it is noted that the circulation departure patterns characteristic of DRY and WET years broadly conform to the contrasts between the boreal summer dry season and late boreal winter rainy season in the course of the annual cycle; essential factors being the interhemispheric SST gradient and corresponding latitude position of the ITCZ.

Fig. 3 Schematic illustration of the characteristic circulation departures during (a) DRY and (b) WET years in Northern Northeast Brazil. During DRY as compared to WET years the interhemispheric SST gradient is enhanced, the Northeast tradewinds weaker, the cross-equatorial airstream from the Southern hemisphere stronger, and the enclosed wind confluence along with the ITCZ are displaced northward. Along with this the pre-season rainfall in the Nordeste is reduced, and the equatorial Pacific waters are anomalously warm



As indicated in Fig. 3a, the surface waters of the eastern equatorial Pacific tend to be anomalously warm during Nordeste drought years; the atmospheric circulation mechanisms leading from Pacific SST anomalies to those in the Atlantic have been progressively elucidated in a sequence of studies (Covey and Hastenrath 1978; Egger 1977; Horel and Wallace 1981; Hoskins and Karoly 1981; Nobre and Moura 1984; Curtis and Hastenrath 1995; Hastenrath 2000a,b; 2006; Kucharski et al. 2008). During El Niño years, an upper-tropospheric wave train extends from the equatorial eastern Pacific to the tropical North Atlantic, affecting the pattern of upper-tropospheric topography and divergence, and hence of vertical motion over the Atlantic. This leads to a weaker meridional pressure gradient on the equatorward flank of the North Atlantic subtropical high, weaker North Atlantic trade winds, an anomalously far northerly ITCZ position, conducive to Nordeste drought. Thus, this ENSO teleconnection leads into the known Atlantic circulation mechanisms of Nordeste drought.

Complementing these diagnostics of year to year variability, findings on variations on longer time scales are of interest (Chu 1984; Hastenrath 1985, pp. 314–315). Thus, in the rainfall of Northern Nordeste and in the circulation over the adjacent equatorial Atlantic a marked preference for variability around 13–14 years has been found, phase relationships between the rainfall and circulation variations being plausibly consistent. A concentration of spectral power in rainfall is further indicated around double that period, namely around 27–28 years. Such preferred time scales of variability are apparent in the time series plot in Fig. 1.

5 Climate prediction

The diagnostic research into the circulation mechanisms of interannual rainfall variability described in Section 4 forms the basis for the development of climate prediction methods. The characteristic departure patterns in the SST and surface wind fields discussed in Section 4 evolve gradually, and this offers the prospect of developing quantitative relationships to the subsequent rainfall conditions. The most pertinent predictors include pre-season rainfall in the Nordeste itself, the interhemispheric SST gradient and meridional wind component in the tropical Atlantic sector, and SST in the eastern equatorial Pacific. Expanding on the diagnostic insight into circulation mechanisms mentioned in Section 4, established statistical techniques were used to formulate quantitatively the relationships with the subsequent rainfall conditions. The proposition is to use information to the end of January to forecast the March to June rainfall. Techniques include stepwise multiple regression (SMR), linear discriminant analysis and neural networking. It is essential to keep a clear distinction between the dependent portion of the record (or training period) used for the method development, and the independent portion of record reserved for the verification of forecast performance. Such is the groundwork essential for the subsequent application of the forecasting method in real time.

The intrinsic feasibility of climate prediction for the Northern Nordeste was documented in the early 1980's, with particular attention to the severe drought of 1958 indicated in Fig. 1 (Hastenrath 1984; Hastenrath et al. 1984). However, a major practical challenge remained, namely to acquire the necessary input information in a timely manner. Thus, the observations through the end of January must be in hand by the first days of February, so that the prediction can be produced with useful lead time. It took the better part of a decade to overcome this logistic challenge. In tandem with this, methods were progressively improved (Hastenrath 1990; Hastenrath and Greischar 1993b). Then the time was ripe for

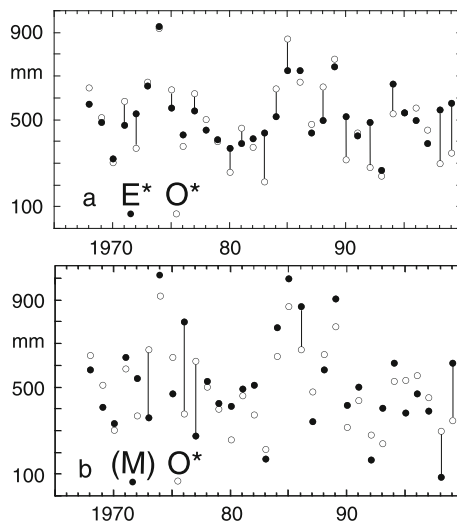
real-time application. A decade-long record of real-time forecasting bears out sustained performance (Ward and Folland 1991; Folland et al. 1993, 2001; Greischar and Hastenrath 2000; Moura and Hastenrath 2004; Hastenrath et al. 2009). The admirable motivation of local colleagues since the mid 1980's ensured the prompt transmission of pre-season rainfall measurements in the Nordeste—well before the era of fax and Email. While communication technology has advanced admirably since then, by the end of the millenium it proved no longer possible to obtain the necessary pre-season raingauge data in time. As a consequence, the operational real-time forecasting of the Nordeste rainy season, maintained for a decade at the University of Wisconsin, was discontinued.

Seasonal forecasting for Brazil's Nordeste has received increased attention in recent years (Nobre et al. 2001; Druyan et al. 2002; Misra et al. 2003; Sun et al. 2005, 2006; Leroy and Ceron 2007; Sun et al. 2007). A synergy of empirical and numerical modeling approaches is most desirable.

In our work at the University of Wisconsin, the period 1921–57 was the dependent portion of the record or “training period”, 1958–89 served as independent portion of the record or “verification period”, and the real-time forecasting continued to 2000 (although for that last year rain gauge measurements were no longer received for verification. Thus the years 1958–99 are available for verification of forecast performance.

A recent note (Hastenrath et al. 2009) compared the performance of numerical modeling and general-circulation-based empirical methods. The numerical model used was ECHAM4.5 (Roeckner et al. 1996). The years 1958–67 served for MOS (model output statistics) regression postprocessing. The empirical method used as input predictors to stepwise multiple regression (SMR) four indices, namely of pre-season rainfall, meridional SST gradient and meridional wind component in the tropical Atlantic, and SST in the eastern equatorial Pacific. Complementing this, an experiment was undertaken with pre-season rainfall as sole predictor. This is favored by the precursory ITCZ latitude position and then may (Paulo Nobre, pers. comm.) through local soil moistening and evapotranspiration processes favor the subsequent rainfall activity. Fig. 4 compares the predictions with the observed rainfall during 1969–99. Results are presented in part b for the numerical modeling and in part a for the empirical method with four predictors. Over the 32 year verification period the numerical modeling captures 49% of the variance as compared to 59% by the empirical method. As

Fig. 4 Time series plots of March–June precipitation indices in mm. **a** empirical predictions E^* dots, and gridded observations O^* open circles. **b** predictions from numerical modeling with regression MOS postprocessing (M) dots, and gridded observations O^* open circles



noted by a reviewer, for extreme dry and wet years Fig. 4 shows higher performance for the numerical modeling than the empirical method. Remarkably, the measurements of pre-season rainfall in the region itself used as sole predictor, can explain 35%. Consistent with these results for Brazil's Nordeste, a series of publications on tropical climate prediction conclude that numerical modeling does not surpass the performance of empirically based prediction (Barnston et al. 1994; 1999; Webster et al. 1998; Anderson et al. 1999; Bamzai and Shukla 1999; Cavalcanti et al. 2006; Lorenz 2007). Concerning expectations from downscaling in numerical modeling appreciation is in order for precision versus accuracy, an issue meriting further attention.

6 Concluding remarks

The recurrent Secas of Brazil's Nordeste, their severe human impact, and the possibility of their prediction, have long intrigued climatologists (Walker 1928; Sampaio Ferraz 1925; Serra 1956). Appropriately, Trewartha (1962, pp. 50–54) highlighted the Nordeste as a “problem climate”. Seasonal forecasting for the Nordeste in real time is an important task, to be tackled on the grounds of the known circulation diagnostics. The annual cycle of rainfall in the region is an elementary issue, but it can only be understood from the documentation of the annual cycle of circulation in the tropical Atlantic sector (Hastenrath and Lamb 1977). The departure patterns of the large-scale circulation during DRY as compared to WET years in the Nordeste are broadly in the sense of the contrast between the dry versus the rainy seasons in the annual cycle (Hastenrath and Heller 1977; Hastenrath and Greischar 1993a,b; Hastenrath and Druyan 1993). Such circulation anomalies evolve gradually, which offers the prospect for empirically-based climate prediction (Hastenrath et al. 1984). Essential is the diagnostic understanding of circulation mechanisms; statistical techniques merely serve to quantify the predictive relationships. The prediction efforts have been carried to successful real-time application over a decade (Greischar and Hastenrath 2000; Folland et al. 2001; Moura and Hastenrath 2004; Hastenrath et al. 2009). The precipitation departures depend prevalingly on the anomalous behavior of a single quasi-permanent circulation system, the Atlantic ITCZ. As a consequence, the interannual rainfall variability in this semi-arid region is large and the human impact severe. Fortunately, the known circulation mechanisms are favorable to seasonal forecasting for the northern Nordeste. For most other regions of the tropics the prospects are remote.

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