# The effect of Atlantic sea surface temperature dipole mode on hurricanes: Implications for the 2004 Atlantic hurricane season

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[1] Results from this study indicate that the dipole mode of tropical Atlantic Ocean sea surface temperature (SST) anomalies is correlated with the overall activity of hurricanes as well as with the annual hurricane landfall frequency along the southeast coast of the United States. The tropical Atlantic SST dipole mode could affect hurricanes in at least three ways: 1) modulating the weather in West Saharan Africa; 2) influencing the local SST and hence the atmosphere-ocean environment in the hurricane main development region; 3) coupling with the tropical and subtropical atmospheric circulation that control the steering of hurricanes. The warm tropical North Atlantic and cool tropical South Atlantic waters are likely one of the main causes for Florida's hurricane havoc in 2004.
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## 1. Introduction

[2] By September 26, 2004, four hurricanes made landfall in Florida in less than six weeks, making 2004 the busiest hurricane season for Floridians. The active 2004 Atlantic hurricane season was not a surprise in view of the recent increase of Atlantic hurricane activity at decadal and multi-decadal scales [*Goldenberg et al.*, 2001; *Xie et al.*, 2000, 2002]. In fact, predictions of above normal hurricane activity for 2004 were issued well in advance by the National Hurricane Center of the National Oceanic and Atmospheric Administration (NOAA) (http://www.nhc.noaa.gov). What's unusual about the 2004 Atlantic hurricane season is the rare coupling between the large number of hurricanes formed in the tropical Atlantic Ocean and the presence of a persistent westward steering current associated with a stable subtropical high pressure system over the northwest subtropical Atlantic Ocean in August and September. Historically, El Niño or the lack of it was often blamed for the interannual variations of Atlantic hurricane activity [*Gray*, 1984], which is, however, unlikely this time. During the summer (June–September) of 2004, the sea surface temperature (SST) anomalies in the tropical Atlantic Ocean exhibited a well-defined dipole structure, with positive (negative) anomalies north (south) of the equator (Figure 1a). This cross-equatorial SST gradient persisted throughout summer 2004. Our study indicates that this Atlantic SST dipole mode (DM) [*Servain*, 1991] could have played an important role in creating Florida's 2004 hurricane havoc.


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## 2. Effects of Atlantic SST Dipole Mode

[3] The DM, representing the first empirical orthogonal function of the Atlantic SST, is a dominant climatic signal in the region (see *Marshall et al.* [2001] for an in-depth review). It is characterized by opposite SST anomalies between the tropical North and South Atlantic Oceans. Previous studies on the effects of Atlantic SST DM concerned mainly decadal climatic variability [*Chang et al.*, 1997]. Our study indicates that both the annual Atlantic hurricane numbers and the annual hurricane landfall strikes in Florida and the Caribbean islands are strongly correlated with the Atlantic SST DM (Figure 1b). Both correlations (R = +0.5 and +0.4, respectively) are significant at the 99% confidence level. A warm tropical North Atlantic Ocean, coupled with a cool tropical South Atlantic (the positive phase of the DM) leads to an active Atlantic hurricane season and brings an above normal number of hurricanes to Florida and the Caribbean islands, and vice versa. Composite hurricane tracks (Figure 2) associated with the positive phase (solid) and the negative phase (dashed) of the Atlantic SST DM clearly indicate a preference of more westward tracks when the DM is in positive phase as in the summer of 2004, than in the negative phase. Notice also that the origins of the hurricane tracks during the positive phase of the SST DM are generally clustered to the south of the storm tracks during the negative phase of the SST DM. Thus, hurricanes formed at relatively low latitudes during the positive phase of the SST DM are more likely to make landfall in the Caribbean and the southern coast of continental United States, such as Florida.

[4] Atlantic SST DM could influence the Atlantic hurricane activity and landfall in three ways (Figure 3). First, the positive (negative) phase of the DM usually corresponds to wet (dry) climatic conditions in West Saharan Africa [*Lamb*, 1978; *Folland et al.*, 1986]. Above normal rainfall in West Sahel signals stronger easterly waves, which favor above normal Atlantic hurricane activity [*Gray et al.*, 1993]. Secondly, the warm tropical North Atlantic water during the positive phase of the DM provides an ideal environment for tropical cyclogenesis through its influence on moist static stability [*Malkus and Riehl*, 1960], as well as an inverse relationship with local sea-level pressure and vertical wind shear [*Gray*, 1984; *Shapiro*, 1982; *Knaff*, 1997]. Indeed, SSTs in the hurricane "main development region or MDR" from 10° to 20°N between Africa and the Americas [*Goldenberg and Shapiro*, 1996] contribute, with a large percentage of variance, to the number of hurricanes generated within the MDR [*Saunders and Harris*, 1997]. Finally, the Atlantic SST DM affects the subtropical surface pressure, which, in turn, plays an important role in the North Atlantic Oscillation (NAO) [*Marshall et al.*, 2001, and

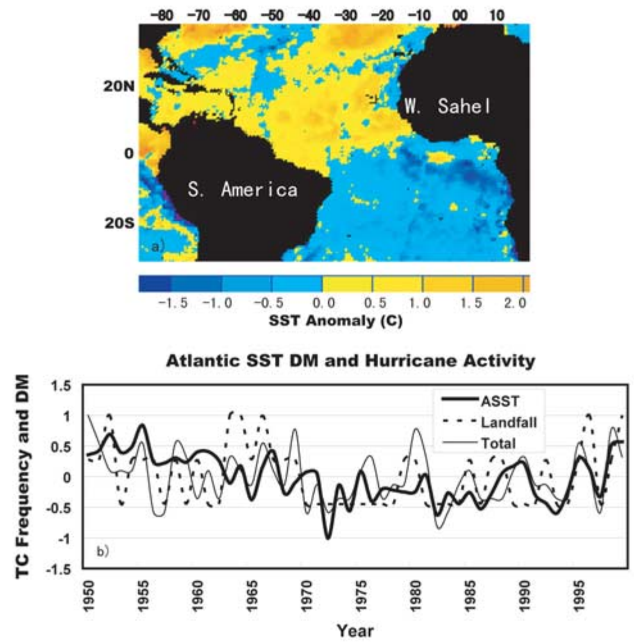


**Figure 1.** Atlantic SST dipole mode (DM) and hurricane landfall frequency. (a) Atlantic sea surface temperature (SST) anomalies (°C) at the start of the 2004 Atlantic hurricane season (6/1/2004) (http://www.osdpd.noaa.gov/PSB/EPS/SST/climo.html). (b) Time series of DM (thick solid) computed as the amplitude of the 1st EOF of Atlantic SST; normalized anomalies of annual hurricane landfall frequency along the coast of Florida and the Caribbean islands (dashed); and annual Atlantic hurricane frequency (thin solid). Landfall is defined as the contact of storm eyewall with coastline and only includes Atlantic hurricanes. Normalized anomaly is the anomaly (actual-mean) divided by the absolute value of the maximum anomaly.

references therein]. NAO is one of the oldest known climatic weather patterns depicting the pressure differences between the Azores and Iceland. The positive NAO phase corresponds to higher (lower) surface pressure in the subtropical Azores High (Icelandic low), whereas the negative NAO phase depicts the opposite. The May and June averaged NAO index is correlated with North Atlantic hurricane tracks of the following hurricane season [*Elsner*, 2003]. Negative NAO phases are correlated with weaker Azores High and straight-moving hurricane tracks that tend to cross the Caribbean islands and the U.S. southeast coast.

## 3. Discussion and Conclusions

[5] Other studies suggested that the effect of North Atlantic SST on the variability of Atlantic hurricanes is small at inter-annual time scale [*Shapiro and Goldenberg*, 1998], but large at multi-decadal scale [*Goldenberg et al.*, 2001]. In fact, the multi-decadal warming of SST in the MDR and the associated climatic conditions that started around 1995 were the primary basis for NOAA to predict an active 2004 hurricane season. Whether or not Atlantic SST DM is also an important factor modulating the inter-annual variability of Atlantic hurricanes, as shown in this study, needs further confirmation.

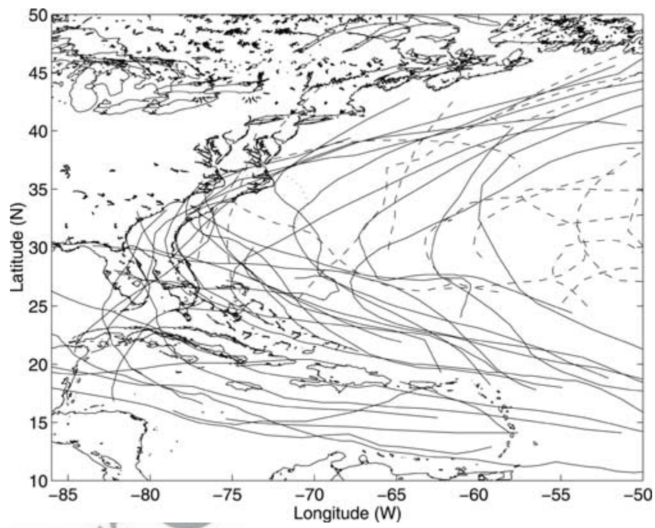


**Figure 2.** The composite hurricane tracks during negative and positive Atlantic SST DM. Dashed and solid tracks correspond to negative and positive DM years, respectively. More hurricanes move toward the southeast United States during positive DM, increasing the chance of hurricane landfall in the Caribbean islands and the U.S. southeast coast. In contrary, Atlantic hurricanes are more likely to take more northward curving tracks during negative DM, reducing the chance of hurricane strikes in the Caribbean islands and U.S. Southeast coast.

[6] It is evident that the Atlantic SST DM in the summer of 2004 is associated with an active Atlantic hurricane season, and the majority of the storms moved westward, leading to a record number of hurricanes striking Florida and the Caribbean islands. All of these occurred when a weak warm event is developing in the tropical Pacific, which, if affected the 2004 Atlantic hurricane activity at all, was supposed to suppress it [*Gray*, 1984]. Thus, the active 2004 hurricane season was clearly not a result of the El Niño, but likely the consequence of the coupled atmo-

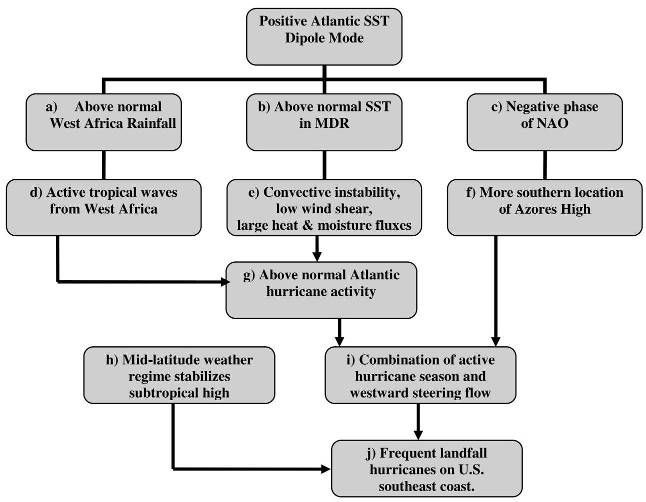


**Figure 3.** Schematic summary of the positive phase of the Atlantic SST DM and its effects on Atlantic hurricane activity and hurricane landfall frequency from the Caribbean islands to the U.S. southeast coast.

sphere-ocean response to the Atlantic SST DM. Historical relationships between the Atlantic SST DM and landfalling hurricanes in Florida and Caribbean islands seem to support this conclusion.

[7] The Atlantic SST DM was in a positive phase throughout summer 2004. The average July–September 2004 SST difference between tropical North Atlantic (0–20°N) and tropical South Atlantic (0–20°S) was 0.3°C. The average NAO index for May and June, 2004 (the two months when NAO was shown to be correlated with Atlantic hurricane tracks) [*Elsner*, 2003] computed by NOAA Climate Prediction Center (CPC) was −1.05, which signals a favorable condition for straight westward moving North Atlantic hurricane tracks [*Elsner*, 2003]. During the summer (June–September) of 2004, preliminary NOAA CPC reports (W. Thiaw, personal communication, 2004) indicated that slightly above or near normal rainfall occurred in West Saharan Africa. These observed climatic conditions in summer 2004 are in keeping with those that favor more frequent landfall hurricanes along the southeast U.S. coast (Figure 3).

[8] In addition to the Atlantic SST DM and the associated coupled atmosphere-ocean processes in the tropical Atlantic region, there were likely other climatic factors that contributed to the creation of the spatial and temporal characteristics of the 2004 Atlantic hurricanes and tracks. For example, extra-tropical processes, such as blocking patterns, might have also played a role in the creation of the persistent subtropical circulation pattern favorable for the westward steering of hurricanes in August and September 2004. A stable mid-latitude circulation pattern to the north of the Northwest Atlantic subtropical high could stabilize the subtropical high pressure system and consequently allow multiple hurricanes to follow similar tracks. Validating such hypothesis requires further analyses that are beyond the scope of this study.

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