Decline in Florida Hurricanes Linked to Surface Warming

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Abstract

The recent increase in Atlantic hurricane activity does not signify an increased threat of a strike to the United States. In fact, there has been a significant decline in the number of hurricanes affecting Florida since the middle 20th century. Here we show that Florida's decline results from fewer hurricanes passing through the Bahamas and the western Caribbean Sea en route to eastern Florida. The decline is statistically linked to rising surface air temperatures in an area centered over the Greater Antilles. The warming reduces deep atmospheric convection leading to circulation patterns that are unfavorable for tropical cyclone genesis and tracks across the northern Caribbean. Improving risk assessment of future hurricane strikes in this highly developed coastal region has the potential for reducing societal vulnerability through greater preparedness and insurance mechanisms.

1. Introduction

Florida gets hit by more hurricanes than elsewhere in the United States (Elsner and Kara 1999). Two of the three category 5 hurricanes (Simpson 1974) to hit the United States did so in Florida. The warm waters along the Bahamas and Greater Antilles provide an abundant energy source for hurricanes en route to Florida (Maloney and Hartmann 2000). Century-long records of U.S. hurricane activity reveal interannual variability related to El Niño-Southern oscillation (ENSO) and the North Atlantic oscillation (NAO), but no long-term trends (Elsner et al. 2001). Long-term trends in regional coastal hurricane activity have yet to be examined systematically.

However, Elsner et al. (2004) find a significant decline in hurricanes over Florida since the middle 20th century. In fact, since 1966 only 3 hurricanes (David, Andrew, and Erin) have directly hit Florida's east coast, which is remarkable given the recent significant upswing in overall Atlantic hurricane activity (Elsner et al. 2000; Goldenberg et al. 2001; Elsner et al. 2004). Here we show that Florida's decline is due to fewer hurricanes passing through the Bahamas and the western Caribbean Sea. Surface-air temperature increases appear to reduce the threat of hurricanes over eastern Florida. The warming inhibits deep atmospheric convection over the Greater Antilles leading to circulation patterns that are unfavorable for tropical cyclone genesis and tracks across the northern Caribbean.

2. Fewer eastern Florida hurricanes

First we identify a reduction in the rate of hurricanes across eastern Florida and show that the decline is unrelated to the NAO or ENSO. Counts of Florida hurricanes are taken from the U.S. National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS)/Tropical Prediction Center (Jarvinen et al. 1984). An eastern Florida hurricane is a tropical cyclone that makes a direct landfall between Key Largo and the Georgia state border at hurricane intensity (maximum sustained near-surface wind speeds $\geq$33 m s^{-1}). Counts are plotted in Fig. 1 for hurricanes and major hurricanes (maximum sustained near-surface wind speeds ≥ 50 m s^{-1}) affecting the coast since 1900. More than three times as many hurricanes and more than four times as many major hurricanes struck eastern Florida before 1952 than after. The choice of 1952 as a change-point year is statistically justified in Elsner et al. 2004).

The role of ENSO and the NAO in modulating regional hurricane activity is well-established (Goldenberg and Shapiro 1996; Jagger et al. 2001). Using a Poisson regression model (Solow and Moore 2000), here we determine that there is still a significant (p-value < 0.017) decline in hurricane activity over eastern Florida after accounting for the effects of NAO and ENSO. The Poisson regression includes an indictor variable set to a value of 1 for years prior 1952 and 0 after. Values for the NAO are calculated from sea level pressures at Gibraltar and at a station over southwest Iceland (Jones et al. 1997). Values are averaged over the pre- and early-hurricane season months of May and June as a compromise between signal strength and timing relative to the hurricane season. Equatorial fluctuations in sea-surface temperature (SST) over the Pacific Ocean (6°N–6°S, 180°–90°W) averaged from August through October are used as an index for the ENSO (Deser and Wallace 1990). Results are not sensitive to the precise specification of the change point year. Next we consider whether the reduction in hurricane activity along Florida's east coast might be related to regional-scale changes rather than those associated with changes in ENSO or the NAO.

3. Regional trends

We examine regional changes using NCEP-NCAR Reanalysis (NNR) data (Kalnay et al. 1996; Kistler et al. 2000) over the domain of box 2 (25°–17.5°N, 85°–67°W) shown in Fig. 1. The area includes Cuba, Hispaniola, and Jamaica; and data are available from 1948–2002. The NNR is a statistical combination of 6-hour forecasts and observations. Surface observations of temperature, moisture, and wind over land are not used in the reanalysis (Kalnay and Cai 2003). However, atmospheric vertical soundings of wind and temperature (rawinsondes and satellite soundings) strongly influence the NNR, and surface temperatures are estimated from atmospheric values.

A long-term warming trend in August–October averaged surface-air temperatures over the Greater Antilles is seen in Fig. 2. The trend explains 33% of the annual variability amounting to 0.087 ± 0.017 K decade^{-1} (p-value < 0.0001). The rate of warming is similar to hemispheric estimates during the second half of the 20th century. Precipitation rates show a decreasing trend of $-3.73 \pm 0.73 \times 10^{-6}$ kg m^{-2} s^{-1} decade^{-1} (p-value < 0.0001) explaining 31% of the inter-annual variability. The decline in precipitation rates in this region is consistent with recent rainfall deficits and droughts over nearby Puerto Rico (Stallard 2000; Malmgren et al. 1998). In contrast, we find no long-term trend in vertical shear of the zonal (east-west) wind or sea-surface temperature (SST), both of which are related to the amount of basin-wide hurricane activity (DeMaria et al. 2001; Shapiro and Goldenberg 1998). Instead we suggest that warming along the archipelago contributes to fewer hurricanes over Florida through an increase in convective stability due to lower near-surface relative humidity. With greater convective stability, the atmosphere produces less deep convection leading to circulation anomalies that are opposed to tropical cyclogenesis.

To examine this conjecture, we first show a significant relationship between surface air temperatures and southeast Florida hurricanes. We model the annual counts of southeast Florida hurricanes and major hurricanes (maximum sustained winds exceeding 50 m s^{-1}) since 1948 using temperature as a predictor. After accounting for the yearly trend, temperature is a significant predictor of southeast Florida hurricane (p-value $= 0.069$) and major hurricane (p-value $= 0.031$) activity. The relationship can can be seen graphically in Fig. 3. During the 27 years of negative temperature anomalies (below the long-term trend), there were 8 eastern Florida hurricanes, 4 of which were major. This compares with only 1 hurricane and no major hurricanes during the 28 years of positive temperature anomalies. Thus higher temperatures over the Greater Antilles are statistically linked to fewer hurricanes over Florida.

4. Hypothesis

An explanation for this relationship centers on regional atmospheric changes associated with drying near the surface. As the tropical atmosphere is conditionally unstable [unstable with respect to moist (relative humidity = 100%) vertical motions, but stable with respect to dry vertical motions], drying leads to greater overall stability and less thunderstorm activity (deep convection). Indeed, low-level (925 hPa) values of relative humidity show a significant relationship to seasonal-averaged values of large-scale vertical motion 200 hPa levels (Fig. 3c). With drier air aloft widespread deep convection is diminished (vertical motion values are less negative).

With less atmospheric convection over the region to the southeast of Florida, the large-scale circulation pattern becomes less conducive to tropical storm development and intensification. We compute an index of horizontal shear (HSI) over box 2 using zonal wind speeds averaged in boxes 1 and 3. The HSI is computed as $(u1_{200} - u3_{200}) - (u1_{850} - u3_{850})$ and measures the degree to which the large-scale atmospheric flow is conducive to tropical cyclogenesis. Positive values indicate anticyclone rotation above cyclonic rotation (favorable for hurricanes). Decreasing values of HSI indicate a trend toward a less favorable tropical cyclone environment to the southeast of Florida. Values of HSI were relatively large during the late 1940s and early 1950s, but have decreased since.

Besides the decreasing trend in HSI values, thickness between two pressure levels explains a significant portion of the inter-annual variability of HSI. Higher pressures above lower pressures (greater thickness) leads to anticyclonic shear above cyclonic shear. The trend and the thickness relationship are removed from the HSI using linear regression before considering the relationship with surface-air temperatures. The regression of surface-air temperature residuals on HSI residuals indicates a significant negative relationship amounting to -7.16 ± 1.848 m s^{-1} K^{-1} that explains 22% of the inter-annual variation (p-value = 0.0003). Thus surface warming is linked to large-scale circulation changes detrimental to tropical cyclone formation and intensification. Moreover, these same circulation changes may be important in routing hurricanes away from

Florida. Note that Hurricane Andrew (1992), the last major hurricane to hit eastern Florida, tracked north of box 2.

5. Summary and Discussion

A decline in eastern Florida hurricane activity since the mid 20th century is documented. A Poisson regression model gives a 40% reduction in the interannual rate after accounting for the effects of the NAO and ENSO. The decline is consistent with results from Jamaica which show an unprecedented decline in late 20th century tropical cyclone activity from records that extend back to the 18th century (Chenoweth 2003). A statistically significant link between local surface warming in limiting deep-convection and creating a large-scale environment that is less conducive to tropical cyclones is demonstrated. The response (eastern Florida hurricane counts) is modeled as a change point while the forcing (surface air temperatures) is modeled as linear consistent with threshold behavior in dissipative, non-equilibrium systems.

Local influences from urbanization and land-use changes could be responsible for increases in surface air temperature over the Florida peninsula and Greater Antilles, especially during the day (Marshall et al. 2004). The additional warmth throughout the lower troposphere (not shown) leads to greater static stability and less large-scale ascent and deep convection along the archipelago. Less convection leads to drying aloft and large-scale circulation anomalies, both of which inhibit tropical cyclones. In contrast, over the open ocean, where the air has a continuous supply of moisture the link between surface warming and atmospheric drying is not evident. A similar mechanism might explain the 20-year decline in tropical cyclone activity over the Australian region (Nicholls et al. 1998). The physical hypothesis can be more precisely examined with the aid of a mesoscale atmospheric model. However, the statistically significant link between eastern Florida hurricanes and regional temperatures is new and important regardless of whether our hypothesis about it cause is correct.

Alternatively, changes in the large-scale environment could lead to fewer tropical cyclones. It is argued that above normal sea-level pressures (SLP) are associated with increased subsidence and a reduction in middle level moisture leading to radiative cooling and increased vertical shear (Knaff 1997). Although we find significant SLP rises, they are associated with middle level warming rather than cooling. Moreover, we find no significant relationship between SLP and vertical shear over box 2. It appears that increasing SLP results from flow anomalies forced by surface warming. Our results support the idea of local forcing as important in modulating environmental conditions conducive to tropical-cyclone genesis (Inoue 2002; Handoh and Bigg 2000).

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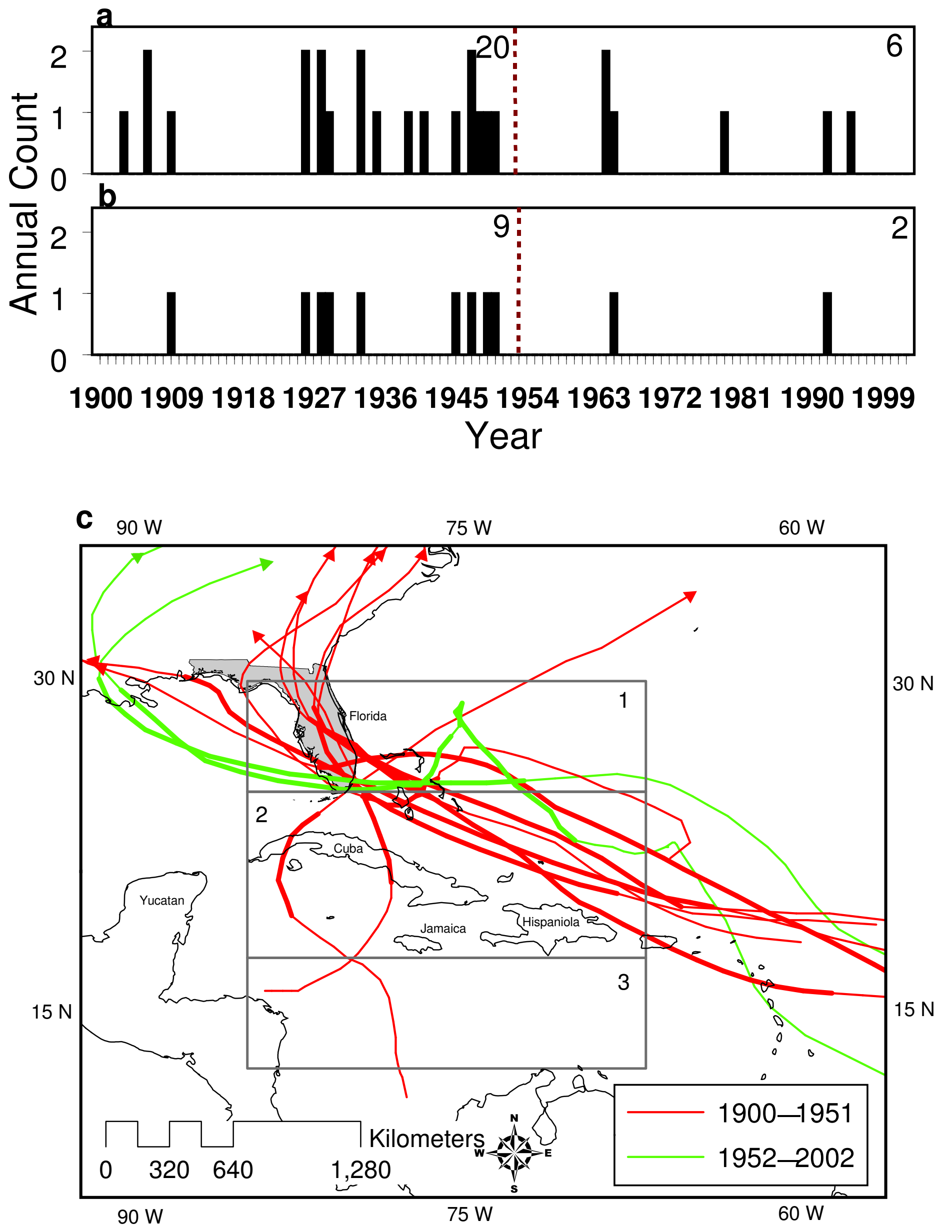

Figure 1: Annual counts and tracks of eastern Florida hurricanes (1900–2002). (a) Annual count of eastern Florida hurricanes and (b) major hurricanes (maximum wind speeds $\geq$ 50 m s^{-1}). Numbers refer to total counts before and after (inclusive) 1952. The choice of 1952 as the change-point year is statistically justified in Elsner et al. (2004). (c) Tracks of the 11 eastern Florida major hurricanes since 1900. Dark tracks are hurricanes before 1952. Thick lines indicate hurricane at major hurricane intensity. Florida is shaded. The numbered boxes are the areas over which the NCEP-NCAR reanalysis data are averaged.

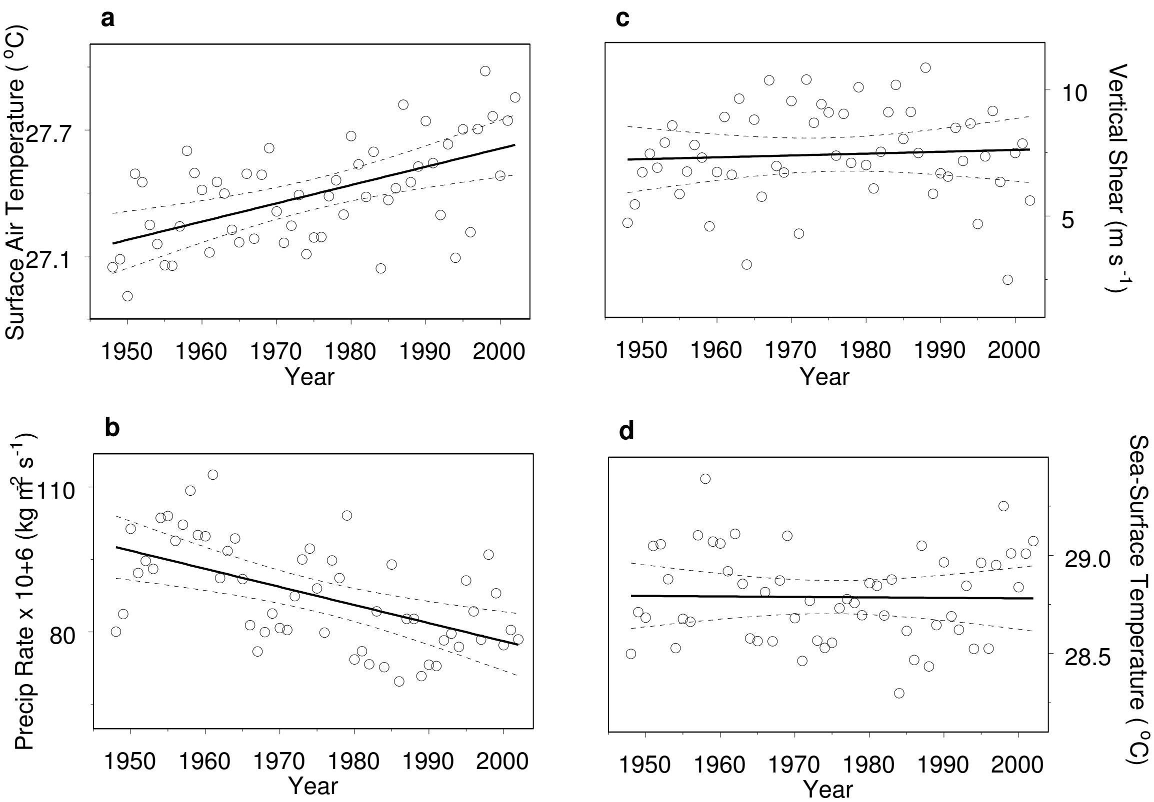

Figure 2: Time trends in conditions over the Greater Antilles. August through October (hurricane season) average daily values in box 2 (see Fig. 1) from the NCAR-NCEP reanalysis data. (a) Surface-air temperature (b) Precipitation rate (c) Vertical shear of the zonal wind (west to east) (d) Sea-surface temperature. Solid line is best-fit linear regression and the dashed lines are the simultaneous 99% confidence bounds. There is a significant increasing trend in surface-air temperature and a significant decreasing trend in precipitation rate during the second half of the 20th century. Vertical shear and sea-surface temperatures are not trending.

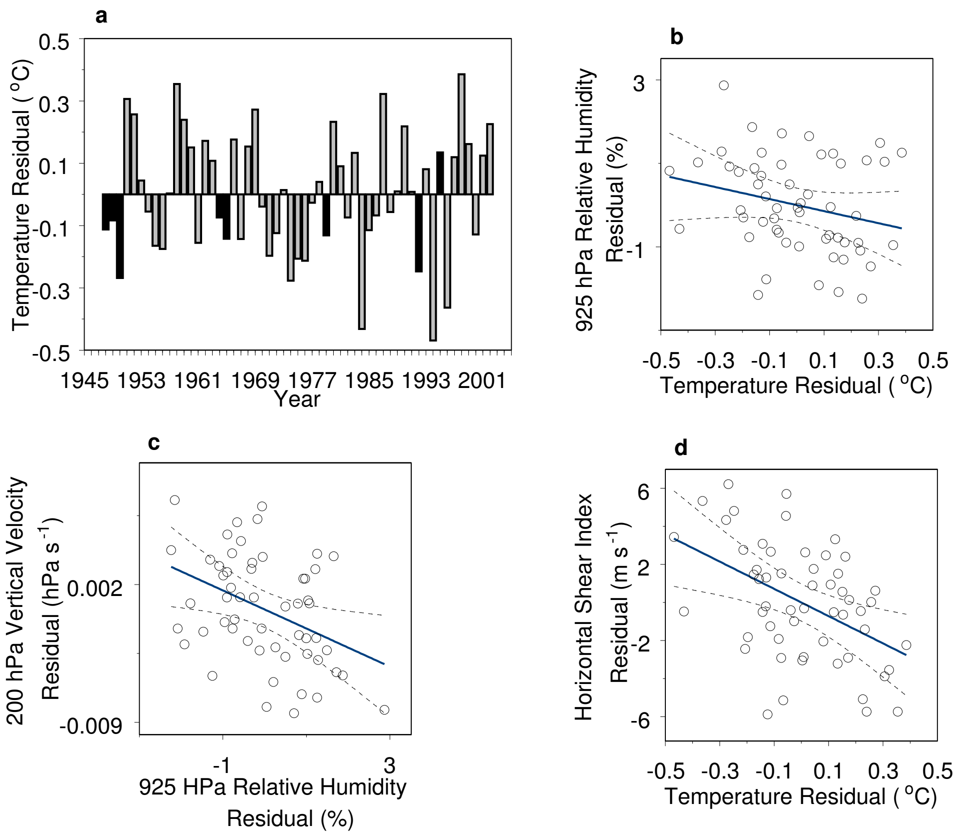

Figure 3: Regional relationships. (a) Surface-air temperature residuals from a linear regression model of temperature on year. Black bars indicate years in which eastern Florida received a direct hurricane hit. (b) Regression of the 925 hPa relative humidity residuals on surface-air temperature residuals. (c) Regression of the 200 hPa vertical motion residuals on the 925 hPa relative humidity residuals. (d) Regression of the horizontal shear index (HSI) residuals on surface-air temperature residuals. The solid line is a best-fit linear regression and the dashed lines are the simultaneous 99% confidence bounds.