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Counting Atlantic Tropical Cyclones Back to 1900

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Climate variability and any resulting change in the characteristics of tropical cyclones (tropical storms, subtropical storms, and hurricanes) have become topics of great interest and research within the past 2 years [*International Workshop on Tropical Cyclones*, 2006]. An emerging focus is how the frequency of tropical cyclones has changed over time and whether any changes could be linked to anthropogenic global warming.

The Atlantic is the one tropical cyclone basin that has quantitative records back to the mid-nineteenth century for the whole basin (i.e., North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) [*Jarvinen et al.*, 1984; *Landsea et al.*, 2004]. *Mann and Emanuel* [2006] used this data set to find a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period of 1871–2005. Likewise, *Holland and Webster* [2007] analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both papers linked these changes directly to anthropogenic greenhouse warming. However, both analyses, with no indication of uncertainty or error bars, presumed that tropical cyclone counts are complete or nearly complete for the entire basin going back in time for at least a century. This article will show that this presumption is not reasonable and that improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones.

Reanalysis of Historical Tropical Cyclone Counts

Mann and Emanuel [2006, p. 238] stated that "although wind estimates prior to the 1940s are problematic, detection of the existence of tropical cyclones is less so, because without aircraft and satellites to warn them off, ships often encountered storms at sea, at least peripherally." *Holland and Webster* [2007] likewise make similar arguments.

Their assumptions disregarded the recommendations of the original database documentation [*Jarvinen et al.*, 1984] and database extension and reanalysis documentation [*Landsea et al.*, 2004] that tropical cyclones were missed before the mid-twentieth century. In particular, *Landsea et al.* [2004] estimated an undercount bias of zero to six tropical cyclones per year between 1851 and 1885 and zero to four per year between 1886 and 1910. These undercounts roughly take into account the typical size of tropical cyclones, the density of shipping tracks over the Atlantic basin, and the amount of populated coastline. As one goes back further in time, the numbers of ships and shipping lanes decreases and fewer people live in the tropical and subtropical coastal regions. These factors make it increasingly likely that some tropical cyclones would not be counted the farther back in time examined.

Consider the two most active Atlantic hurricane seasons on record (Figure 1): 1933, with 21 tropical cyclones, and 2005, with 28. On the basis of just those cyclones that struck land, 1933 had more impacts (19) than 2005 (17). The difference in frequency between these two years is that there are many more tracks present over the open Atlantic Ocean in 2005 than there were in 1933. Is this evidence of a significant undercount in the historical records?

Here a simple analysis demonstrates the existence of a sizable bias in historical tropical cyclone counts. Figure 2a shows the time series of tropical cyclones going back to 1900, with both multidecadal variations [*Goldenberg et al.*, 2001] and a long-term trend being readily apparent. The data are stratified to indicate which tropical cyclones struck land and which stayed over the open ocean. The former are determined by their center either crossing a coastline or passing within 111 kilometers (60 nautical miles) of a landmass (either island or mainland) as a tropical cyclone.

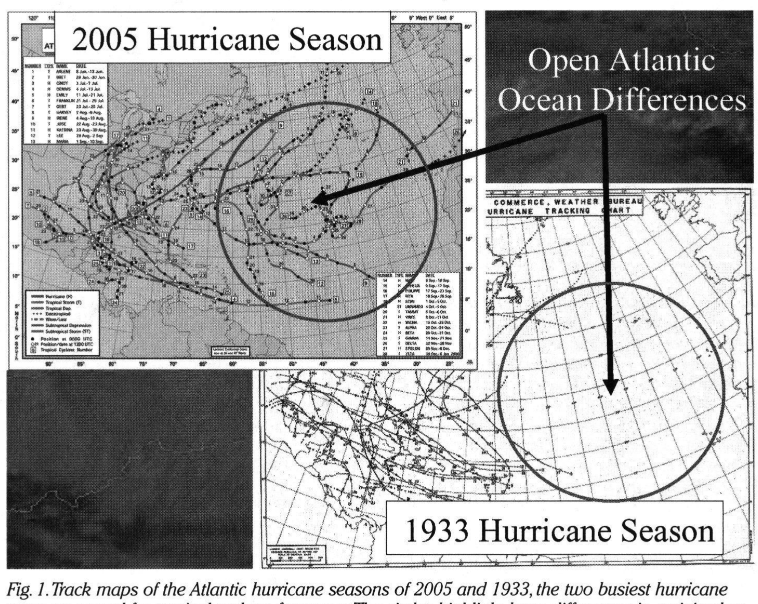

Fig. 1. Track maps of the Atlantic hurricane seasons of 2005 and 1933, the two busiest hurricane years on record for tropical cyclone frequency. The circles highlight large differences in activity that occurred over the open Atlantic Ocean. Original color image appears at the back of this volume.

By C. W. Landsea

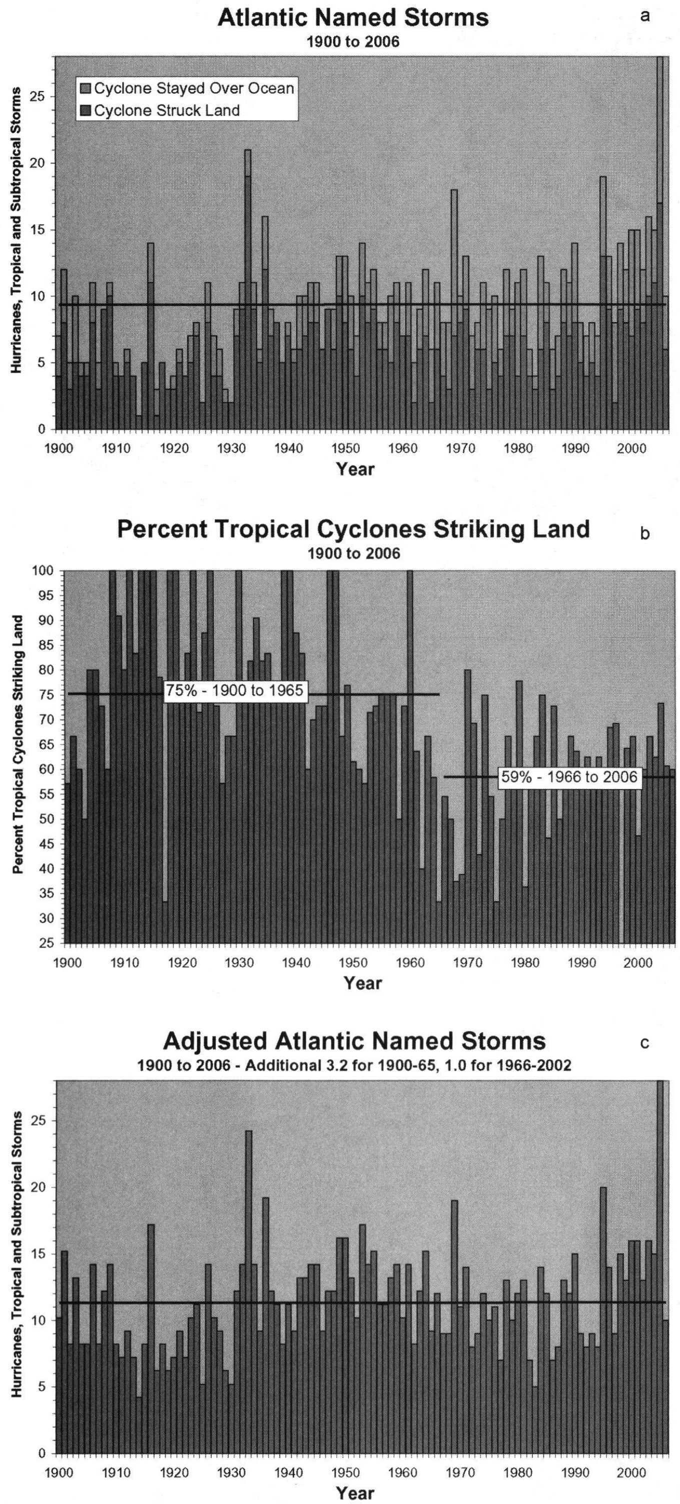

Fig. 2. (a) The 1900–2006 record of number of tropical cyclones in the Atlantic basin, stratified by those that struck land (e.g., as a tropical storm, subtropical storm, or hurricane) versus those that stayed over the open ocean. The solid line is the 1900–2006 long-term mean of 9.2 per year. (b) Percentage of all reported tropical storms, subtropical storms, and hurricanes that struck land. (c) A bias-corrected time series of tropical storms, subtropical storms, and hurricanes to take into account undercounts before the advent of geostationary satellite imagery in 1966 and new technology available since about 2002. The adjusted 1900–2006 long-term mean is 11.5 per year. Original color image appears at the back of this volume.

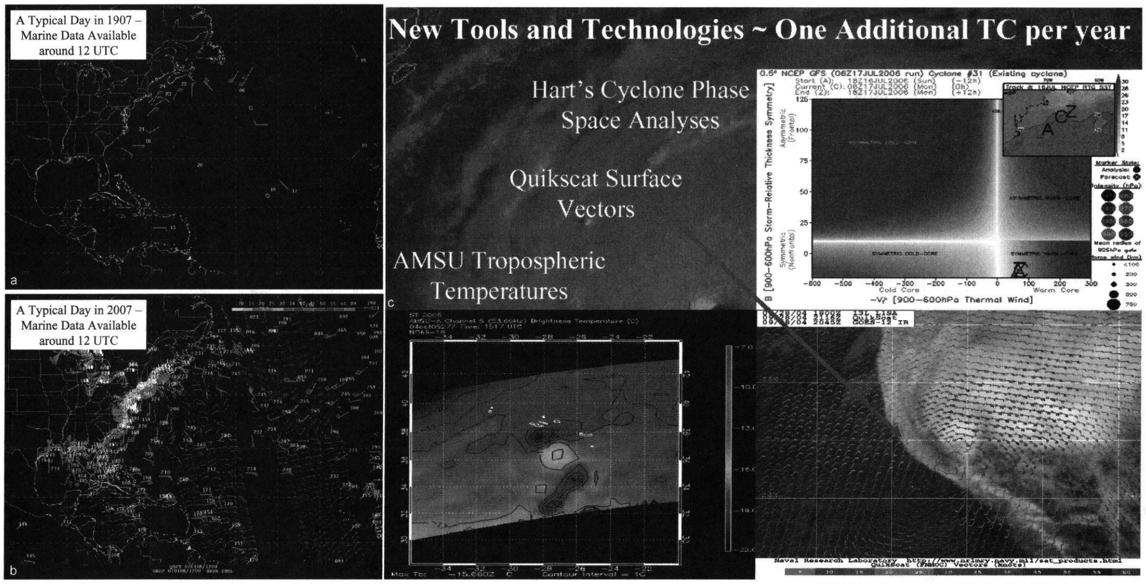

*Fig. 3. (a) Surface marine observations available in the Atlantic basin around 1200 UTC for a typical day in 1907. These observations were based entirely on ship measurements. (b) Same as Figure 3a but for a typical day in 2007. These data include moored and drifting buoys, Quikscat, as well as ship observations. (c) Depiction of new monitoring and analysis technologies (advanced microwave sounding unit tropospheric temperatures [*Brueske and Velden, *2003], Quikscat [*Atlas et al., *2001], and the cyclone phase space analyses [*Hart, *2003]) that have increased Atlantic tropical cyclone counts by about one additional system per year. Original color image appears at the back of this volume.*

The year 1900 is chosen as the first in this analysis. It is at about that time that a sufficient number of people lived along the coastline, such that if even a weak tropical storm struck it would likely have been detected and recorded. However, this beginning date of 1900 of having recorded all tropical cyclones that have struck land may be somewhat optimistic, especially for short-lived, relatively weak tropical storms. Consider the detection difficulties of a 1-day tropical cyclone such as Gert, which struck Mexico in 2005 in a sparsely population region of the coast and produced no observed surface tropical storm force winds, caused minimal impact, and was only identified as being a tropical cyclone via satellite imagery and aircraft reconnaissance. Therefore, conclusions from this paper on the number of 'missed' tropical cyclones are likely conservative.

The linear correlation coefficient between the frequency of all tropical storms and those that struck land is a very high 0.87 for 1900–2006. This value might be somewhat surprising given that some years can be quite active yet places such as the continental United States can be relatively untouched (such as what occurred in 2000 and 2001) or seasons that are quiet can have large U.S. impacts (such as 1992 with Hurricane Andrew). The likely reason for such a strong association between the frequency of all tropical cyclones and those that strike land is that taking into consideration all landmasses (i.e., Mexico, Central America, the Caribbean islands, Bermuda, Canada, and the Azores) in addition to the continental United States makes it much more likely that overall busy years will have many landfalls and quiet seasons generally will have fewer tropical cyclone strikes on land.

However, differentiating between the frequency of tropical cyclones that struck land versus those that remained over the open ocean shows that more of the latter were observed in recent decades compared with earlier in the twentieth century (Figure 2a). Figure 2b shows the tropical cyclone data expressed as an annual percentage that make landfall. In the era since geostationary satellite imagery began, in 1966 [*Neumann et al.*, 1999], the average is 59%. While sizable interannual variations are present, this value of slightly more than half is quite stable across the four decades of satellite coverage including periods of both active hurricane seasons (62% from 1995 onward) and a quiet hurricane regime (59% from 1971 to 1994). This value is even steady within the active era between seasons with numerous U.S. landfalling cyclones in 2004 and 2005 (65%) and relative lack of strikes in the United States between 1995 and 2003 (60%). Again, it is likely that the inclusion of tropical cyclones to make landfall in any landmass—in addition to those that just hit the continental United States—minimizes the long-term variability of the percent that strike land caused by genesis location and steering pattern changes.

However, data from the first 66 years, shown in Figure 2b, have a quite different long-term character, with an average of 75% of tropical cyclones striking land. While there were no years with more than 80% striking land from 1966 onward, there were 15 years between 1900 and 1965 in which all (100%) recorded tropical cyclones struck land that season. This difference in the long-term percentage of tropical cyclones that struck land (75% from 1900–1965 versus 59% from 1966–2006) indicates a large bias toward underreporting of tropical cyclones that remained over the open Atlantic Ocean. Even though aircraft reconnaissance began in 1944, this covered only about one half of the Atlantic basin, as systems east of 55°W were generally not monitored or observed with this type of observational platform. Thus aircraft reconnaissance should not have been expected to provide complete monitoring of all tropical cyclone activity in the Atlantic.

'Missed' Cyclones

Assuming that a similar long-term average of about 59% of tropical cyclones actually struck land during 1900–1965, this increases the record by 2.2 additional tropical cyclones per year for this earlier era. Such a broad-brush approach assumes that the amount of shipping remained constant throughout the first two thirds of the twentieth century, which it certainly has not. This technique could, and should, be refined in the future to take into account shipping density variations over time and how this would be manifested in observations of tropical cyclone frequency, duration, and intensity.

The frequency of 'missed' tropical cyclones in the nineteenth century would likely be substantially larger because of the even sparser coverage from shipping tracks and fewer coastal regions being inhabited. It is to be noted that the late nineteenth century was generally an active period with more recorded tropical cyclones than in the first 25 years of the twentieth century [*Neumann et al.*, 1999; *Landsea et al.*, 2004; *Mann and Emanuel*, 2006], despite fewer observations being available for detecting both coastal and ocean-only tropical cyclones.

The concept that numerous tropical cyclones were missed in the presatellite era should not be surprising given the typical tropical cyclone duration (~1 week), the mesoscale nature of the high winds in a tropical cyclone, and the relative sparse ship-based observations available over the entire North Atlantic Ocean. Figures 3a and 3b demonstrate the vast difference in surface marine observations available today versus those available a century ago.

Moreover, new tools and data sources that have become available just in the past few years are already producing another artificial increase in tropical cyclone frequency (Figure 3c). Quikscat [*Atlas et al.*, 2001], the advanced microwave sounding unit [*Brueske and Velden*, 2003], and the cyclone phase space analyses [*Hart*, 2003] are the primary reasons that the U.S. National Weather Service's National Hurricane Center recognized that Ana of 2003, Otto of 2004, the unnamed subtropical storm of 2005, and the unnamed tropical storm of 2006 (see respective tropical cyclone reports online at http://www.nhc.noaa.gov/pastall.shtml) were tropical cyclones and thus included in the Atlantic tropical cyclone database. These systems would have been considered extratropical cyclones previously and thus not counted as tropical cyclones before the start of the 21st century.

Inclusion of 3.2 additional tropical cyclones per year within 1900–1965 and 1.0 per year from 1966 to 2002 is shown in Figure 2c. Apparent in the adjusted tropical cyclone frequency record are the multidecadal quiet and active periods (quiet up to 1925, active from 1926 to 1970, quiet from 1971 to 1994, and active from 1995 onward) associated with the Atlantic multidecadal oscillation [*Goldenberg et al.*, 2001]. A reanalysis of the trends with the inclusion of these additional tropical cyclones leads to an insignificant trend for both the periods between quiet eras and active eras. This is consistent with the findings of *Solow and Moore* [2002], who did a similar calculation using the U.S. landfalling record.

While efforts are under way to reanalyze the Atlantic hurricane database, which has led to some previously unrecognized tropical cyclones being added into the observational record (averaging 0.9 new tropical cyclones per year between 1886 and 1914 [*Landsea et al.*, 2004]), such efforts will not be able to recover observations of open-ocean tropical cyclones that were just never taken. Researchers cannot assume that the Atlantic tropical cyclone database presents a complete depiction of frequency of events before the advent of satellite imagery in the mid-1960s. Moreover, newly available advanced tools and techniques are also contributing toward monitoring about one additional Atlantic tropical cyclone per year since 2002. Thus large, long-term 'trends' in tropical cyclone frequency are primarily manifestations of increased monitoring capabilities and likely not related to any real change in the climate in which they develop. Obviously, better monitoring in recent decades will also increase our ability to accurately measure tropical cyclone intensity and duration, though these are beyond the scope of this article.

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Author Information

Christopher W. Landsea, NOAA National Weather Service, National Hurricane Center, Miami, Florida; E-mail: Chris.Landsea@noaa.gov

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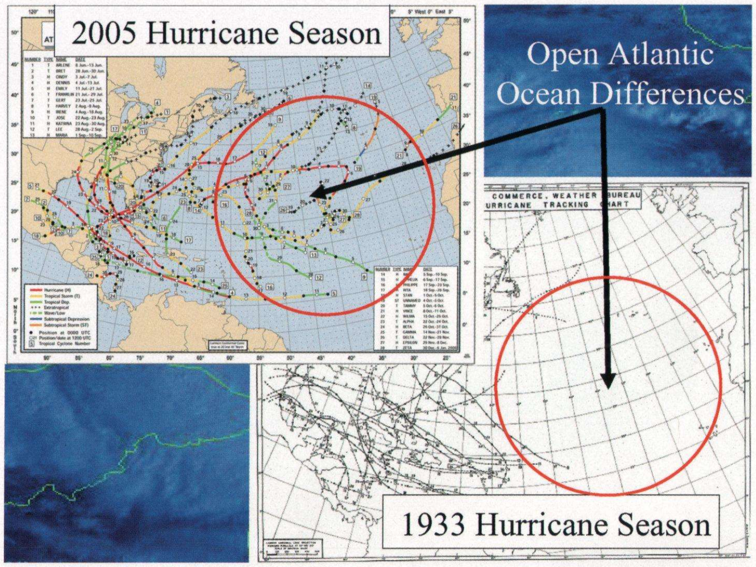

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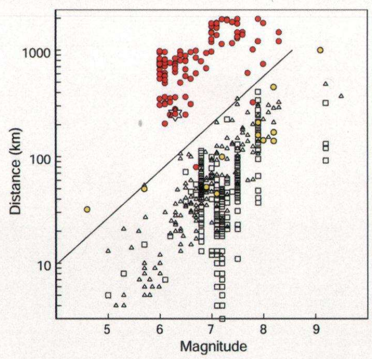
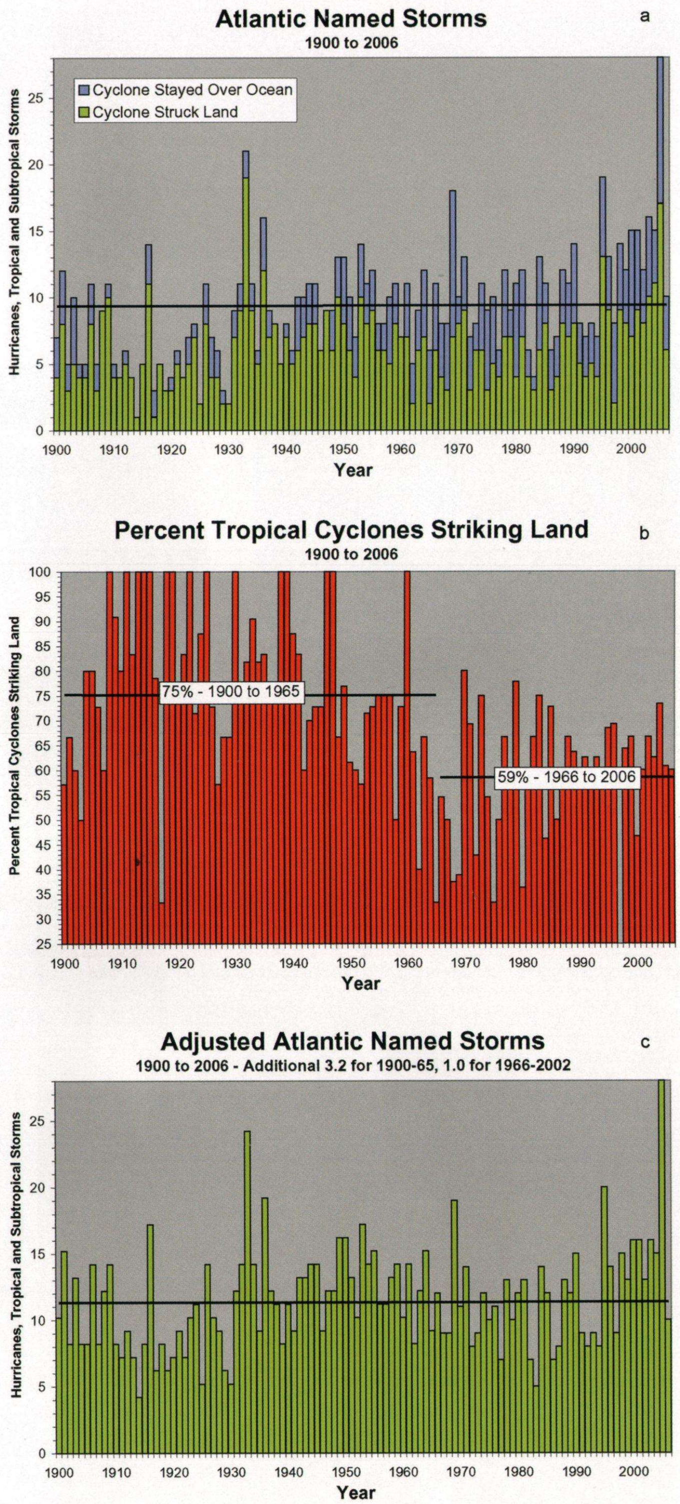


Fig. 1. Distance between the earthquake epicenter and hydrologic response as a function of earthquake magnitude. Increases in stream discharge, shallow liquefaction, and eruption of mud volcanoes are shown with open squares, triangles, and yellow circles respectively; data are from compilations and references presented by Montgomery and Manga *[2003] and* Wang et al. *[2005, 2006], with mud volcano data compiled by* Manga and Brodsky *[2006] and from Table 1 of* Mellors et al. *[2007]. The red circles show the distance between regional earthquakes and the location of the Lusi volcano. The star represents the distance between the Lusi mud volcano and the earthquake 2 days prior to the eruption. Earthquake locations and properties are obtained from the U.S. Geological Survey's National Earthquake Information Center catalog (http://neic.usgs.gov/neis/epic/epic.html).*



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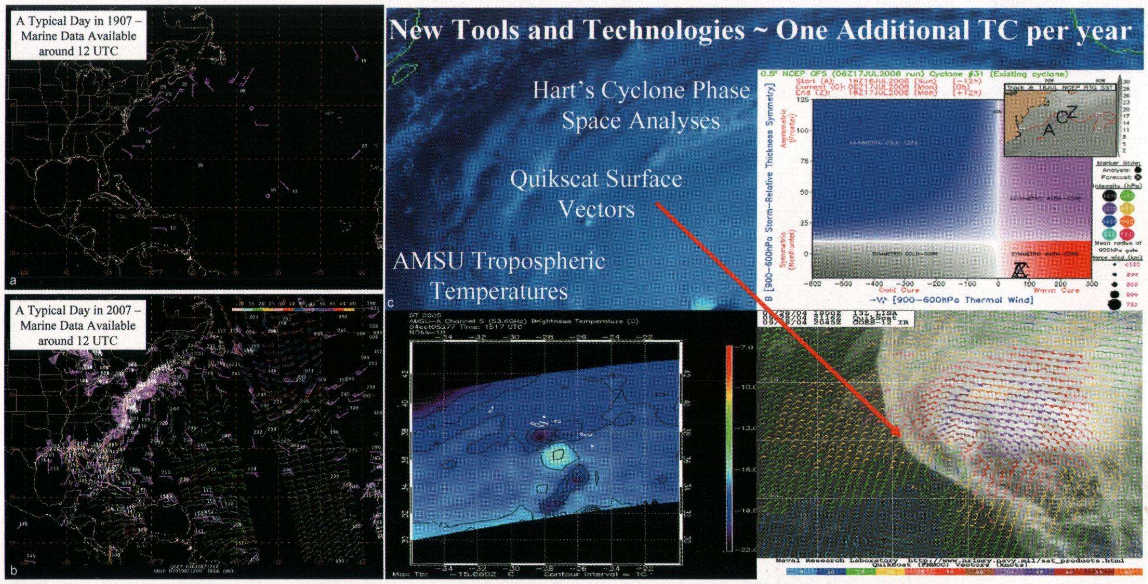

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