Deconvolving Trends in North Atlantic Power Dissipation

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Abstract

Although considerable attention has been paid to basinwide trends in North Atlantic cyclone activity, to date, there has been little attempt to separately quantify trends in the east and west part of the Atlantic. In this paper, we show that the increase in North Atlantic cyclone activity has taken place almost entirely in the middle of the Atlantic Ocean, with no trend whatever in the western Atlantic. This lack of trend in the west Atlantic is consistent with the lack of trend in landfall statistics and provides a complete reconciliation of a problem outstanding in exchanges following Emanuel (2005a). The increase in observed activity in the middle of Atlantic Ocean may be due to improved observing practices (Landsea 2006, 2007) or to increased east Atlantic SST (Emanuel 2005), but the localization of the increase to the middle Atlantic is as distinct as any overall trend. We do not consider causation, but it is possible that increased eastern SSTs is causing hurricanes to form earlier and turn north earlier, mitigating landfall consequences.

Introduction

The present paper originates from a problem that was not resolved in an exchange arising out of Emanuel (2005a). Emanuel (2005a) reported that the power dissipation index (PDI, defined as the time integral of the cubed wind speed) had doubled in the Atlantic basin over the last 30 years. Comments by Landsea (2005) and Pielke (2005) noted respectively that there was no trend in PDI at landfall in the United States or in normalized economic losses, results at odds with the trend reported by Emanuel (2005a). In reply, Emanuel (2005b) acknowledged the lack of trend in these indices and made the rather unsatisfying hypothesis that the discrepancy could be due to simple randomness, while arguing that for the reality of the trend in Emanuel (2005a) on the basis that the Hurdat data set contained "about 100 times more data" than the landfall data set and that these results accordingly had "a signal-to-noise ratio that is ten times that of an index based on landfalling wind speeds."

This discrepancy is illustrated in Figure 1, showing PDI ("Power Dissipation Index" – the integral of wind speed cubed) in the top panel and landfall counts in the bottom panel. Emanuel (2005a) based its claim that PDI had doubled in the past 30 years on a comparison of recent values of smoothed PDI (the red curve shows the 1-4-6-4-1 smooth without end-point pinning as used in Emanuel 2005b) to values in the early 1970s. The low 2006 value is also shown by a bold red dot. By contrast, the number of U.S. landfall hurricanes (bottom) has no trend.

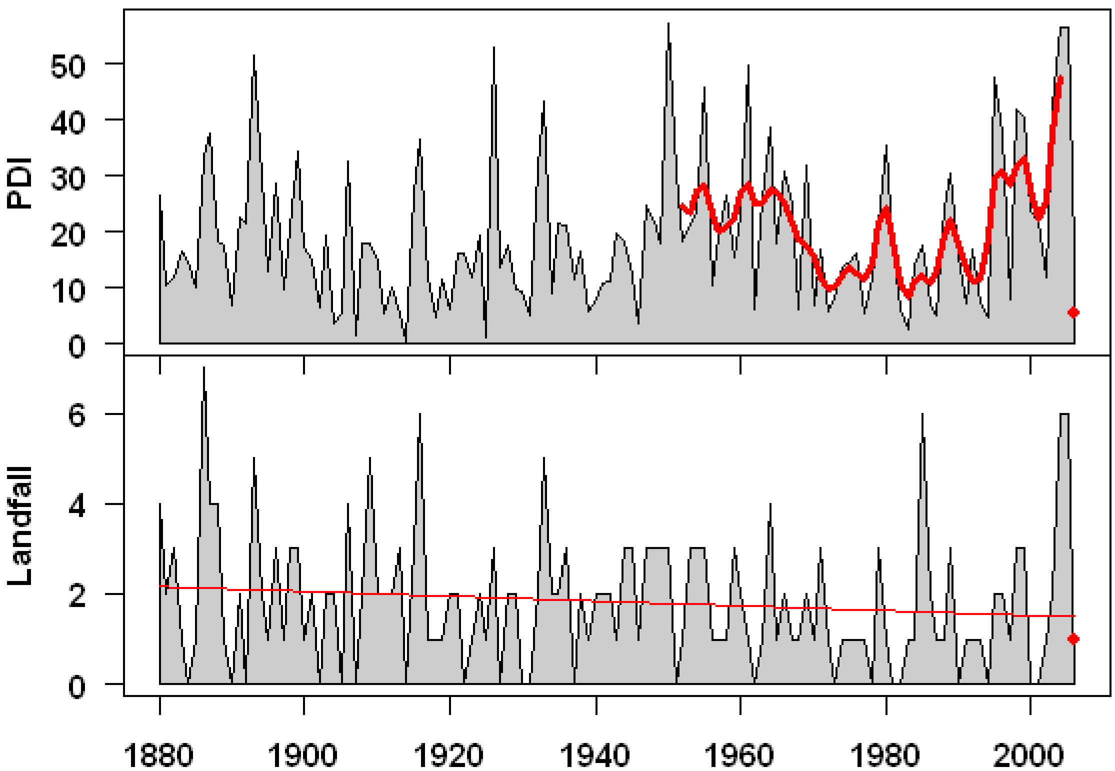

Figure 1. Top: Black – Total North Atlantic PDI with 1-4-6-4-1 smooth (red) as in Emanuel (2005) but without the pinned endpoints (according to Emanuel 2005b). 2006 value highlighted. Bottom - U.S. landfall hurricane count, together with 1900-2006 trend (adopting start from Landsea 2005).

Subsequent to Emanuel (2005), there has been some appreciation of the potential for changes in longitudinal distribution, but prior studies have failed to thoroughly quantify the changing longitudinal distribution (as done here). Landsea (2006, 2007) illustrated the difference in track locations between the busy 1933 and 2005 seasons, observing that the 1933 track records lacked the coverage of the 2005 season, suggesting that earlier measurements may have missed storms entirely. Pielke and McIntyre (AMS, January 2007) presented analysis showing that there had been pronounced eastward movement in the median reported storm (hurricane) track in the HURDAT data set, as shown in Figure xx, and presented an early version of the longitudinal analysis presented here, showing that the increase in hurricane-days and storm-days occurred in the easternmost quartile, while there was little trend in the westernmost quartile. In this presentation, we expand substantially on the earlier analysis, showing that the increase in activity can be localized in the mid-Atlantic.

Analysis

We analysed North Atlantic track data from the revised HURDAT data, (http://www.nhc.noaa.gov/tracks1851to2006_atl.txt) (downloaded in April 2007). For each recorded storm, the Hurdat database contains an estimate of latitude, longitude and wind speed (in knots) in 6-hour intervals. We adjusted wind speeds between 1944 and 1969 according to the Emanuel (submitted, 2007) implementation of the Landsea 1993 adjustment. This reduces wind speeds between 47 knots (24 m sec^{-1}) and 129 knots (65 m sec^{-1}), with a maximum reduction of about 14% at 82 knots (42 m sec^{-1}) – see Supplementary Figure 1. Landfall data was from http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512005-gt.txt, as downloaded in April 2007. "Storms" is used in this paper to denote cyclones with adjusted wind speeds exceeding 35 knots (hurricanes – 65 knots; category 3+ - 96 knots).

Figure 2 shows the pronounced eastward shift in median annual longitude of all measurements in the Hurdat dataset for 1880-2006, previously mentioned by Pielke and McIntyre (AMS Jan 2007). The median longitude of a recorded cyclone occurrence in the last part of the 20^{th} century is no less than 10 degrees further east relative to the first half of the century. Superimposed on this figure are the results of a breakpoints analysis using the strucchange package [Zeilis et al 2007, which implements methods due to Bau (1994, 1997) and Bau and Perron 1997], showing a breakpoint around 1960 with a very wide confidence interval.

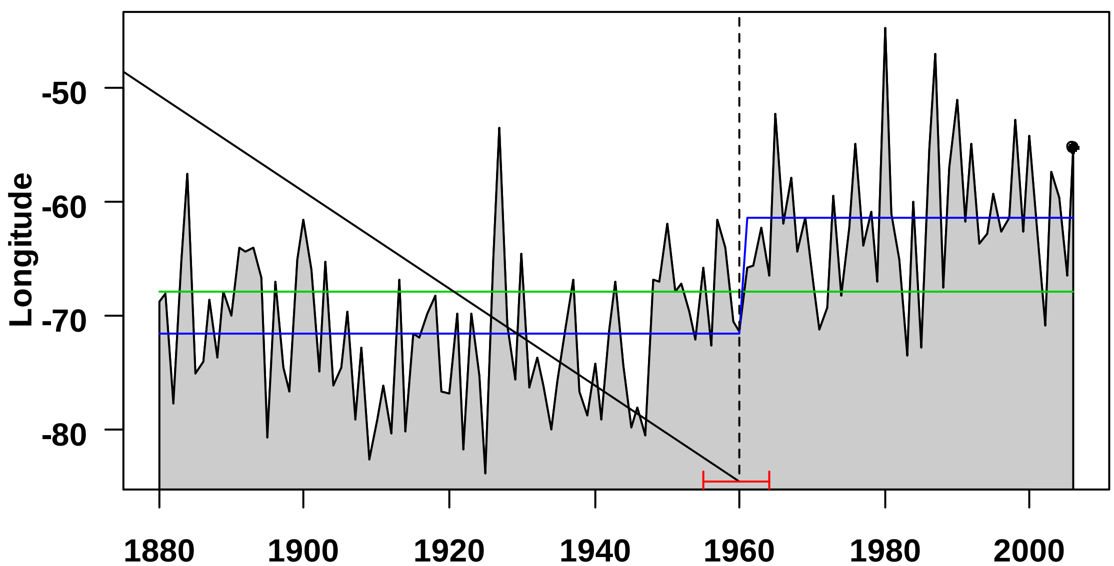

Figure 2. Median longitude of all storm measurements, showing mean (green) and breakpoint analysis (blue), confidence interval in red.

Storm, Hurricane and Category 3+ Days

Figure 3 shows a panel of 9 figures illustrating the changing distribution of storm, hurricane and category 3+ activity. In this figure, total storm-days (hurricane-days, category 3+-days) are shown for the period 1946-2006 (following the introduction of airborne reconnaissance) as compared to corresponding values for an equal-length period from 1880-1940. These show the changes at the lowest frequency within the HURDAT which extends only from 1850. Plots of trend coefficients yield similar results.

Out of the various possible indices of hurricane activity, we have preferred to use days for reasons discussed below. The top row shows contours for each of the two reference periods and the contour of the difference. The difference contour shows a remarkable decline in reported storm-days in the west Atlantic (especially the Gulf of Mexico) in the post-WW2 period, accompanied by a strong increase in storm-days in the northern mid-Atlantic with a lesser locus of increase in the south mid-Atlantic.

The middle panel shows the same contours for hurricane-days. The patterns are more or less similar – a decline in the Gulf of Mexico accompanied by an increase in the northern mid-Atlantic.

The bottom panel shows a quite different pattern of contours for category 3+days. Prior to WW2, there were relatively few category 3+ measurements; indeed, most such measurements occurred off the east coast of Florida. In this area, there was negligible increase in the post-WW2 period, but strong increases further to sea and off the Yucatan.

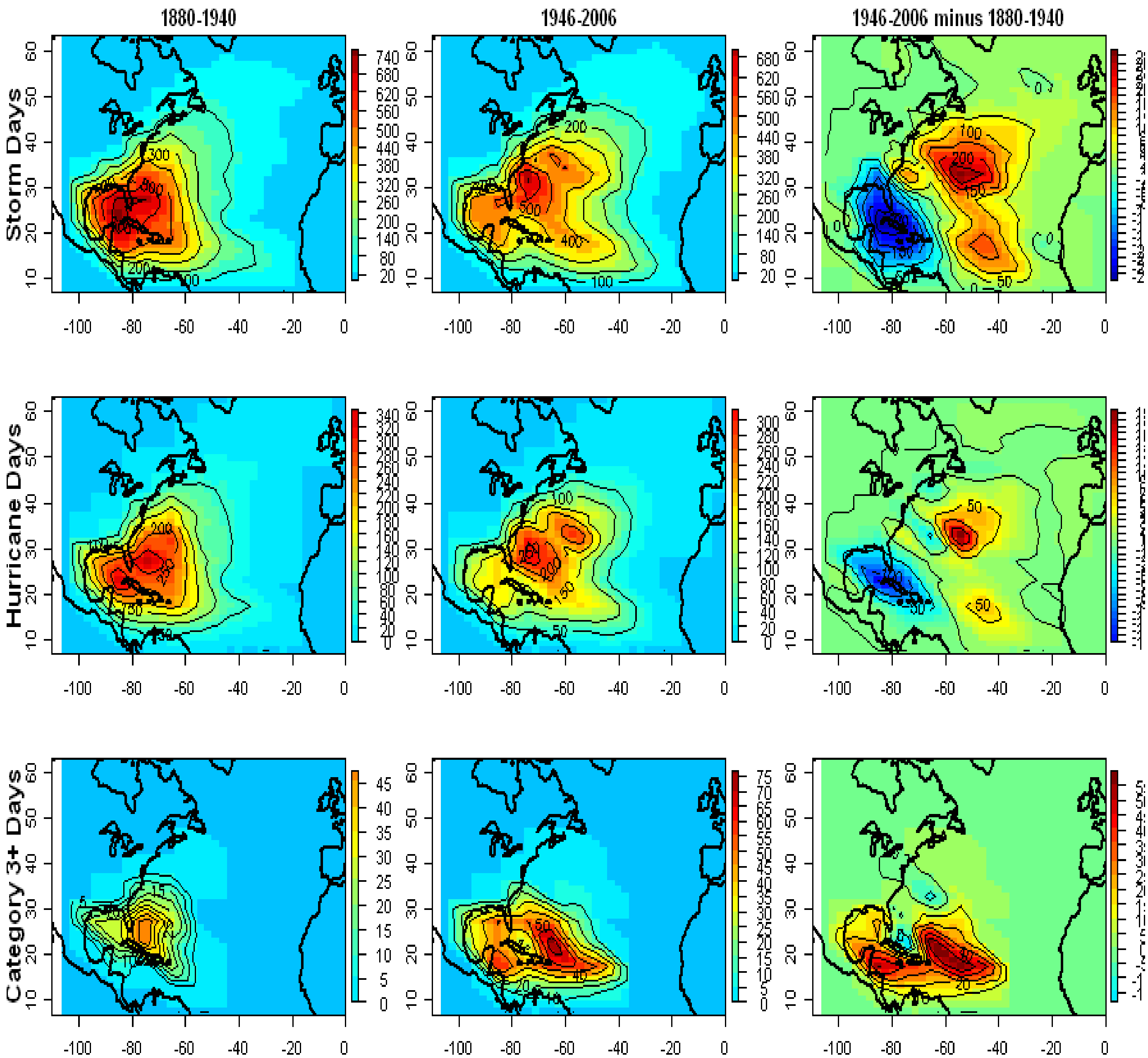

Figure 3. Contour Maps showing storm, hurricane and category 3+ days for 1880-1940, 1946-2006 and the difference. This highlights the increase in the central Atlantic and the decline in the Caribbean and Gulf of Mexico for storm days and hurricane days.

Figure 4 presents this information in a time series format. The median longitude of all HURDAT track measurements is 68W, with 55W being the east quartile and 80W being the west quartile. (See Supplementary Figure 2 for the location of the quartile lines on an Atlantic map.) All landfalls occur in the western third of the basin and most in the western quartile, while the two eastern quartiles are in the central or eastern Atlantic and are remote from land. Figure 4 has 12 panels: the three columns show storm, hurricane and category 3 days from left to right, while the rows show the four quartiles (from west to east) and the total basin. Once again, breakpoint analysis has been applied.

There are no trends or relevant upward breaks in the western half of the Atlantic. 1933 and 2005 both stand out as exceptional years, although the rank depends on the index. In the west half of the Atlantic, 1933 ranks ahead of 2005 in storm days and hurricane days, but the ranking is reversed for category 3+days.

The situation in the eastern quartile (the middle Atlantic and east) is very different. In this case, there is a pronounced increase in reported storm-days east of 55W, with breakpoints in 1947 and 1987. 1947 coincides with the introduction of aircraft reconnaissance, while there is no material change in measurement around 1987 (P. Klotzbach, pers. comm.) Somewhat contrary to some perceptions, there is a downward step at the beginning of the 20^{th} century, with measured late 19^{th} century activity being comparable to activity post WW2. Also somewhat surprisingly, there are no breakpoints in basinwide hurricane-days (bottom middle panel) or even basinwide category 3+ days (right middle panel), issues which will be discussed below.

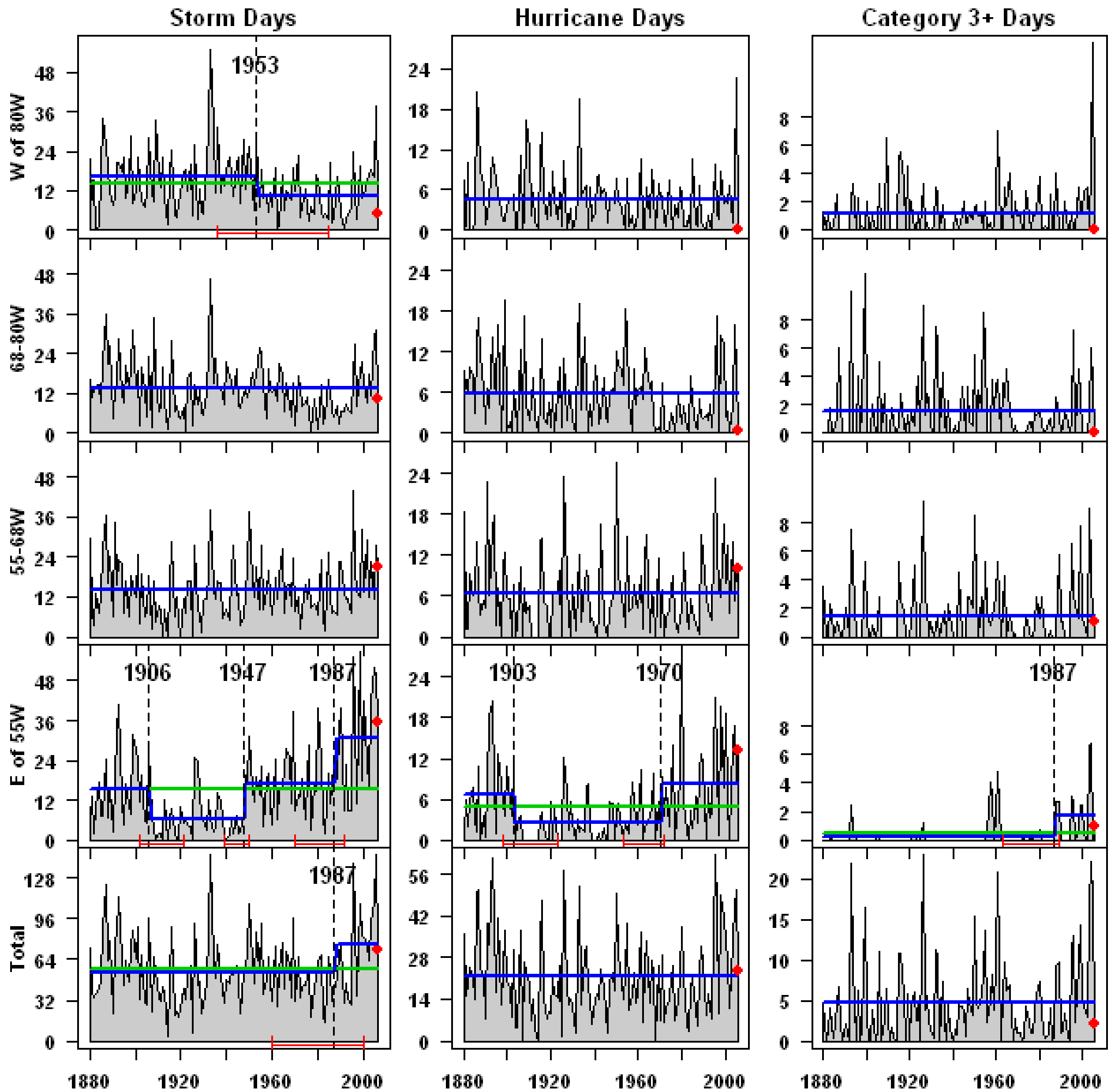

Figure 4. Days by category and quartile. Left panel – storm days; middle – hurricane days; right panel – category 3+ days. Top to bottom – by longitude quartile, east to west, and total. Breakpoint analysis is shown

Wind Speed Integrals

Figure 5 presents the same data, expressed this time as three different "wind speed integrals". ACE (Accumulated Cyclone Efficiency), used in Vimont and Kossin 2007, is the integral of the wind speed squared; PDI (Power Dissipation Index), used in Emanuel 2005a, is the integral of the wind speed cubed. For symmetry, we have also shown the simple integral of the wind speed. The bottom right panel shows the basinwide integral of wind speed cubed (PDI) used in Emanuel (2005a), together with the 1-4-6-4-1 smooth used in Emanuel (2005a) (also shown in Figure 1). The bottom middle panel shows the basinwide integral of wind speed squared (ACE) used in Vimont and Kossin 2007.

The appearance of most panels is strikingly similar to Figure 4, with some panels being virtually identical. The correlation of the Wind Speed Integral to storm-days exceeds 0.96 for all series and exceeds 0.98 in the far west; the correlation of ACE to hurricane-days exceeds 0.93 for all series; the correlation of PDI to category 3+ days exceeds 0.88 for all quartiles except the far west (where it is only 0.72). The higher the order of an integral, the greater the weighting of extreme wind speeds. Thus category 3+ measurements are emphasized by both category 3+ days and PDI and the similarity of the two series is hardly surprising. The weighting of non-hurricane storms is much greater in the calculation of storm days and the Wind Speed Integral, which likewise are linked. Hurricane-days and ACE are in between and similarly linked. The "day" metric can be viewed as a 0-power integral of wind speed above hurdle minimums, with each hurdle emphasizing the count of more and more extreme wind speeds

As noted the results are very similar to the day analysis. In the far west Atlantic, despite the very active 2005, no breakpoints (or trend) are observed for any of the integrals. On the other hand, there were substantial increases for all three integrals in the far eastern quartile (see fourth row), with several significant breakpoints. Two integrals (ACE, Wind Speed Integral) had breakpoints at the start of the 20^{th} century, with substantial declines in the first half of the 20^{th} century from late 19^{th} century levels. In 1946, both integrals had substantial increases, in which their levels returned to levels equivalent to the late 19^{th} century. The timing of the 1946 breakpoint coincides with the introduction of aircraft reconnaissance (a point made in a breakpoint analysis of category 3+ counts by Elsner et al 2000, 2004). No breakpoint is returned for PDI from this algorithm for the start of the 20^{th} century or after World War II, but the visual pattern is (unsurprisingly) similar to ACE. In 1987, a breakpoint is observed in 1987 for all three integrals.

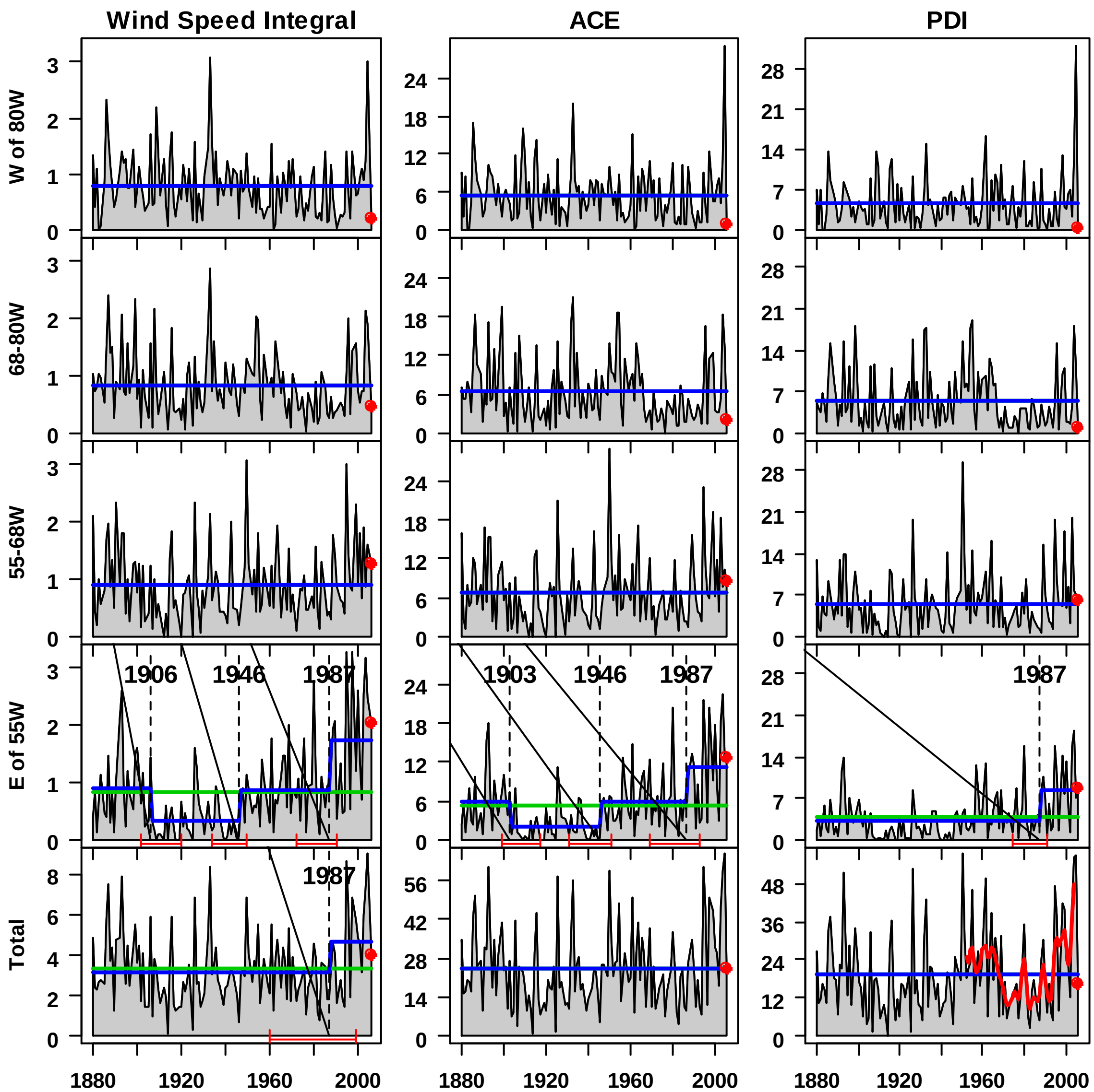

Figure 5. Three wind speed integrals. Left – integral of wind speed; middle – integral of wind speed squared (ACE); right panel – integral of wind speed cubed (PDI) . Top to bottom – by longitude quartile, east to west, and total. Breakpoint analysis is shown.

Figure 6 re-classifies the indices by latitude quartile (33.5N, 26.8N, 19.7N) instead of longiture quartile, providing a somewhat different perspective. In the two central quartiles (between 19.7N and 33.5N), there are no breakpoints for any category. There is a 1987 breakpoint for category 3+ days in the "far south" (south of 19.7N). North of 33.5N, there was a downward step at the end of the 19th century and upward step after World War II.

DISCUSSION

Over time, there have been changes in Hurdat definitions, with an increasing number of non-tropical cyclones being included in Hurdat (Simpson and Pelissier 1971). The most cited studies of basinwide activity (Emanuel 2005a; Webster et al 2005) do not separate out non-tropical cyclones in their calculation of total activity and, to be consistent, we followed their practice, but report on an analysis of the potential impact of changing non-tropical inclusions.

We also consider a broad range of indices of Atlantic hurricane activity. Many different indices have been used in recent articles, including PDI (Emanuel 2005a); ACE (Vimont and Kossin 2007); storm count (Holland and Webster 2007); storm, hurricane and category 3+ counts (Webster et al 2005); storm, hurricane and category 3+ days (Webster et al 2005). Each index emphasizes somewhat different aspects of cyclone activity, with PDI and ACE strongly weighting category 3+ activity, while storm counts and storm days are less dominated by intense hurricanes.

lack of trend in landfall indices is inherent in the Hurdat data as well, if the west Atlantic is isolated. In order to show this, we stratified all the measurements in the Hurdat database by longitudinal quartile (other subdivisions could have been used) and then calculated PDI (and other indices, such as storm-count and storm-days) for each quartile, as well as for the basin as a whole. By doing so, we obtained a more detailed statistical representation of the basin, observing sharp differences in indices for the east and west Atlantic.

There are a number of aspects to inhomogeneity in the data. Methods for detecting storms have changed over the years, with notable improvements in recent decades with the development of aircraft reconnaissance after World War II and satellite coverage in the 1960s and recently. Landsea 2007, summarizing earlier literature, observed that many cyclones may have been missed prior to modern surveillance, pointing to the notable gaps in east Atlantic storm observations in the active 1933 season. In reply, Trenberth (2007) pointed out the need to evaluate indices other than the simple count index discussed in Landsea 2007. This article provides such an evaluation.

In addition to the simple detection of storms, inhomogeneity in wind speed measurement was raised as long ago as Landsea 1993. Emanuel 2005a applied an interpretation of this methodology to reduce Hurdat windspeeds between 1946 and 1966; Landsea 2005 objected to the Emanuel 2005s adjustment. Emanuel 2007 varied the implementation a little (we apply this variation in our calculations.) Holland and Webster 2007 have argued that simple count indices are more reliable than indices that are more sensitive to changing methods of measuring wind speeds. While there is something to be said for this point, indices incorporating wind speeds (ACE, PDI) are embedded in recent literature and the issue cannot be avoided entirely.

Our impression, which we will justify below, is that there seems to be more homogeneity in the hurricane counts and hurricane-days (as compared to storm counts and days on one end and as compared to category 3+ counts and days on the other end.) With improved surveillance, more storms, especially in the east Atlantic, have become incorporated into the data base; and, recently, the proportion of category 3+ and, especially category 4+ measurements, has increased. In addition, inclusion criteria have varied over time and a conscious policy in the mid-1960s to include storms with more northerly origins is reported.

Complicating matters, all these changes have taken place in the context of a system with profound multidecadal variability and there is evidence that the scales of variability may extend longer than the period of relatively homogeneous satellite coverage or even aircraft reconnaissance (Goldenberg and Shapiro, 2001). In the west Atlantic, within the 20th century, 1933 is the most comparable season to 2005. It occurred prior to modern surveillance.

In the most recent prominent articles, the period of study is truncated on the basis of relatively homogeneous coverage (Emanuel et al 2005a begins in 1950 and benchmarks PDI doubling from the 1970s; Webster et al 2005 begins in 1970). In the analyses here, we have used the record back to 1880, the starting point of the GISS temperature record. Many indices are surprisingly high in the late 19th century. No one has suggested that the data prior to World War II **over-estimates** or over-detects hurricanes, although this is not impossible a priori and we prefer to keep this longer record in front of the reader, while discussing allowances that might be required in light of possibly incomplete earlier recording. We chose 1880 as a compromise between the earliest possible point (1851) and a desire to avoid a possible gross inhomogeneity between 1851 and 1880: there was a substantial increase in all indices from 1851 to 1880. This might be due to natural variability rather than inhomogeneity in detection. (We illustrate several series from 1850 in the Supplementary Information.) In any case, we utilize a much longer record than other recent studies.

Trends in the East and West Atlantic

Examination of a wide variety of indices of hurricane activity shows a consistent pattern:

- no trend in the western quartiles, despite a very active 2005 season;.
- pronounced changes in the east Atlantic with a downward step in many indices at the start of the 20th century, an upward step in the late 1940s and another step around 1987.

The lack of trend in the western quartiles in a broad range of hurricane indices, including PDI, offers a simple solution to the discrepancy between PDI and landfall statistics that initiated our inquiry. The lack of trend in landfall statistics is completely consistent with a corresponding lack of trend in PDI and other indices in the two western quartiles. This enables us to rule out the rather unsatisfying speculation of Emanuel (2005b) that the discrepancy might be merely random, resulting from the smaller size of the landfall dataset relative to the Hurdat dataset. The lack of trend in the landfall dataset is not random, but observable in the Hurdat dataset as well.

The lack of trend in the west Atlantic is not limited to the PDI metric used in Emanuel (2005b). The same lack of trend is observed in other metrics used in recent literature: ACE (Vimont and Kossin 2007) and storm counts and days, hurricane counts and days, category 3+ counts and days (Webster et al 2005).

Given that there is no trend in the west Atlantic, any overall increase necessarily requires that increases in the east Atlantic be large enough to account for the entire overall increase in activity, posing the question as to why there should be large increases in the east Atlantic without corresponding increases in the west Atlantic,

North and South

Theincreases in the far east Atlantic quartile in most indices, including storm count and PDI, is large enough to account for the entire basinwide increase.

In addition, Webster et al 2005 isolated a rather short period (30 years) which is much shorter than the potential period of multidecadal variability as estimated by Goldenberg and Shapiro (2001). When different periods are selected (e.g. 1880-2006), no “significant” trends can be observed in the Webster et al 2005 metrics even on a basinwide basis, let alone in the west Atlantic.

A 1930 Breakpoint?

Holland and Webster 2007 purported to identified 3 climate "regimes" in the Atlantic with breakpoints in 1930 and 1994, dates which they said did not correspond to any "known observing or analysis changes". They also referred to, but did not discuss, a possible 4th regime in the late 19th century. They asserted that there were approximately 50% increases in storm counts in 1930 and again in 1994.

The breakpoint algorithm used here is an excellent way of attempting a more formal test of the existence of these regimes. Our breakpoint analysis of the total storm counts series observed breakpoints in 1930 and 1987, each with very wide confidence intervals (see Figure 6, bottom left panel). The confidence interval for the 1930 breakpoint stretches from 1913 to 1951, a period which notably includes the introduction of aircraft reconnaissance in 1946-47. The confidence interval for the 1987 breakpoint includes the 1994 date proposed by Holland and Webster 2007.

However, in the over 80 series that we analyzed, we observed a 1930 breakpoint in only two other series: "Near East" quartile storm count (Figure 6 third row left) and far west quartile storm genesis (Figure 7 top row left). Accordingly, there is little evidence for 1930 as a basinwide regime change.

In the east Atlantic storm count and storm genesis series, there is a very distinct upward breakpoint in the late 1940s, coinciding with the introduction of aircraft reconnaissance. In the west Atlantic, there is a substantial multidecadal oscillation, with high values in the early 1930s, which give way to low values in the 1960s and 1970s. Our interpretation is that the apparent 1930 breakpoint in the basinwide storm count series conflates these two phenomena and that there is no basinwide regime change around 1930.

These results are not contradicted by any observation in Holland and Webster (AMS Workshop 2007), who asserted that "increases [in genesis count] have occurred in all regions except the western Caribbean and southern Gulf of Mexico, but the largest proportional increases have been in the eastern 1Atlantic." They divided the Atlantic basin into 4 quadrants with an east-west break more or less coinciding with our median (68N) and a north-south break at 22N. They then compared genesis counts between two 50-year periods (1906-1955 versus 1956-2005). Their analysis was based entirely on the difference in genesis counts between two 50-years periods. Their N-S division is split at 22N, which mixes a variety of different situations in the various quadrants. If the quadrants are divided at 31N (as in our Figure 9), the comparison in the northern quadrants is a comparison of de minimis amounts, which, in any event, primarily reflects a change in accounting policy in the 1960s. In the southwest basin, they did not observe any increase in genesis counts in the past 50 years, consistent with our findings, while they did observe an increase in genesis counts in the east Atlantic consistent with our findings as well.

The Late 19th Century

Holland and Webster (2007) reported a downward shift in storm count from the late 19th century (7-9 cyclones) to the early 20th century (6 cyclones), but did not include the prior regime (and its downward shift in their description of 20th century activity.)

Landsea (2007) also noted this higher recorded occurrence of cyclones in the late 19th century then in the early 20th century. He speculated that 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."

Many hurricane metrics are already at high levels in the late 19th century. Six years in the last quarter of the 19th century have more recorded hurricane-days than 2005. with high late 19th century counts even in the east Atlantic. If Landsea's speculation about late 19th century observational network is correct, then late 19th century hurricane activity will substantially outstrip recent activity, a result that raises many questions.

We observed an early 20th century downward breakpoint in many indices in the east Atlantic. The downward shift in many indices (e.g. storm days, storm count) was approximately equal to the upward shift in the late 1940s when aircraft reconnaissance was introduced and to the even later upward shift in east Atlantic hurricane-days in 1970 (presumably incorporating the effects of both aircraft reconnaissance and satellites.)

Contrary to the speculation of Landsea 2007 on late 19th century observation (and we refer here only to this issue), we believe that there are plausible reasons to think that late 19th century observations in the east Atlantic could have been more representative than observations in the 1930s. Hurricane observations prior to aircraft reconnaissance were observations of opportunity (or, more accurately, misadventure). In the 19th century, Atlantic merchant and fishing fleets were still substantially comprised of sailing vessels. Dobie (1914) reported that the sailing vessels in the Atlantic fleet in 1914 were still a majority, despite the invention of steam vessels many years earlier. There is an interaction between vessel type and shipping routes, which could easily introduce a bias in observations of misadventure. Steam vessels could follow great circle routes, while the trade winds were an important aspect of many 19th century sailing routes. Smaller vessels also required more trips to carry the same amount of cargo. Add in the disruptions in the first half 20th century economy occasioned by World War I and the Great Depression and, in our opinion, it is by no means obvious that the "observational network" in the trade wind zones in the late 19th century was less than the 1930s or other periods in the first half of the century. Accordingly, until a detailed analysis of actual sailing routes is carried out to establish the population of potential observers in this respective periods, we think that equal credence should be given to the possibility that 19th century observational network may not have been worse than the early 20th century network, and may have been better.

Periodization

Goldenberg and Shapiro 2001 observed that multidecadal variability in the Atlantic hurricane activity takes place on all scales.

Hurricane activity in the Atlantic was at low levels in the 1960s and 1970s, while activity in the 1930s (and the late 19th century) was at significantly higher levels than the 1960s and 1970s. Trend and breakpoint analysis over the 1880-2006 period, which includes periods of high hurricane activity, leads to very different results than analysis commencing in 1970 (Webster et al 2005 and the PDI doubling calculation in Emanuel 2005a).

Webster et al 2005 reported that the trend in Atlantic hurricane storm counts and storm days was "99% significant" over the period 1970-2004. However, for the period 1880-2006, our analysis found that there was no trend (also to 99% significance). The most plausible interpretation of this difference is that the period selected by Webster et al 2005, while selected on the basis of common satellite observation, inadvertently began at a low in the multidecadal oscillation and ended on a high. Under such circumstances, the methods of Webster et al 2005 are insufficient to permit them to distinguish a "trend" from variability present in the system.

Similarly in Emanuel 2005b, although the data is reported for the period 1950-2004, the article's most prominent claim (even in the article title) is that hurricane power dissipation has more than doubled in the past 30 years. As with Webster et al 2005, this comparison is benchmarked on decadal lows in the

1960s and 1970s. In our basinwide PDI series for 1880-2006, we did not observe any breakpoints or long-term trend, although a 1987 breakpoint was observed in the east Atlantic series.

1933

Landsea (2007) observed many similarities in the west Atlantic between the 1933 and 2005 seasons, while noting substantial differences in east Atlantic coverage. This is also readily observed in the various indices discussed here. In many indices (e.g. hurricane-days), 1933 levels were higher than 2005 levels in the west Atlantic, with the situation reversed in the east Atlantic, where 1933 values in the east Atlantic were very low. Although we believe that late 19th century observation may have been better than supposed in Landsea (2007), our analysis strongly supports the hypothesis that storm-days and hurricane-days are strongly under-reported in the east Atlantic in the 1930s.

However, this is not the only area of potential inhomogeneity.

A number of authorities (e,g, Webster et al 2005, Holland and Webster 2007) have emphasized that past estimates of wind speed include a substantial element of uncertainty additional to the uncertainty already present in count estimates (and have accordingly focused their attention on counts.) Despite this caveat, indices that are highly sensitive to wind speed estimates (ACE, PDI, count 3+ counts and days) continue to be used in the literature because of their physical significance. The ranking of the active 2005 season relative to the comparandum 1933 season is remarkably elevated in these indices that are most sensitive to possible inhomogeneity in extreme wind speed estimation. In the western basin, the differences between 1933 and 2005 can be isolated to a relatively small number of measurements in the most intense hurricanes, suggesting the desirability of detailed case analyses of the 5 most intense 1955 hurricanes to ascertain the confidence with which one can assert that Hurricane xx of 1933 did not reach category 4 status

A distinction has been drawn in the literature between “tropical” and “baroclinic” hurricanes [Hess and Elsner 1994; and Elsner 1996], with “tropical” hurricanes forming further to the east from African waves and/or the ITCZ. K and Elsner observed that, in “active” seasons, hurricanes tend to form further to the south and to the east, while in “inactive” seasons, hurricanes to form further north. K and E oberve that the median latitude of hurricanes in the quiet years 1992-1994 is to the north of the active years 1995-1996,. The analysis undertaken here is not inconsistent with such hypotheses. From a statistical point of view, one would expect to be able to discern “tropical” hurricanes within the 1933 season that is so similar to 2005 in other respects and to discern similar patterns of causation in 1933 as in 2005.

Secondly, this analysis shows the need for great caution in calculating trends on truncated series. Goldenberg and Shapiro (2001) noted that there is substantial multidecadal variability in Atlantic hurricane activity, extending over a longer period than the period of relatively homogeneous aircraft or satellite observation. While the Hurdat database prior to the late 1940s may be incomplete, nobody has suggested that it over-estimates past hurricane activity. By extending series earlier than starting points of 1950 (Emanuel 2005a) and especially 1970 (Webster et al 2005), some trends that seem “significant” within these short perspectives are not significant on a longer perspective, illustrating the need to cautiously consider all the available data prior to truncating the data set, regardless of how compelling the reasons for homogeneity may seem. When there are multiple layers of inhomogeneity, the data needs to be handled particularly carefully.

- [LAndsea – possible mention: 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.] The ranking of the active 2005 season relative to the active 1933 season is more pronounced in PDI and metrics that emphasize category 4+ wind speed measurements, and is reversed in some indices that do not weight extreme measurements so heavily (e.g. storm-days).

Like Elsner et al [2000, 2004], we believe that the evidence from breakpoint analysis of longitudinally stratified indices strongly supports evidence of technological inhomogeneity, especially with the introduction of aircraft reconnaissance in the late 1940s.

There is a further step increase in the east Atlantic that we date to 1987, somewhat earlier than proposed breakpoints of 1994. It is possible that some element of this pertains to changing satellite methodologies, but the greater part of the increase is almost certainly due to a real increase. There are real issues, as discussed above, with assessing whether activity in 2005 on a basinwide basis actually exceeded 1933 activity, but let's suppose that it did.

Indeed let's suppose that all the changes in this dataset are due to climatic factors and methodological changes made no contribution to the patterns. We are still left with the odd situation that no breakpoints or trends have occurred in the west Atlantic and the entire increase has occurred in the east Atlantic. If increased hurricane activity is due to climatic factors, a plausible hypothesis, then there is no reason not to suppose that the allocation of the increase is not also due to climatic factors.

If so, then matters seem to have been conveniently arranged so that the entire increase in activity has taken place in the eastern Atlantic remote from land. In the western Atlantic where landfall occurs, there has been no trend in any index of hurricane activity. 2005 was an extremely active year, but 1933 was comparable in many indices. If there had been a substantial trend or regime change in the western Atlantic, this would show up in many hurricane activities through distinct breakpoints such as are observed in the east Atlantic. These breakpoints are conspicuously absent in the west Atlantic. The occurrence of an unusual year in the west Atlantic (but with precedents in 1933 and 1886) has been conflated with a trend in the east Atlantic which itself is comprised to a considerable proportion of changing observation methodologies in these remote areas.

A 1987 Regime Change

We consistently observed a 1987 regime change in east Atlantic indices, resulting There is considerable evidence in many series for a regime change in the east Atlantic in 1987. This is earlier than the 1994 date used in Holland and Webster. The regime change was noted by many contemporary observers as the end of an exceptionally quiet multidecadal period.
To fully support this argument, detailed analysis of 19th and early 20th century shipping tracks is required and, to our knowledge, no such analysis has been undertaken to support this speculation.

Conclusion

The entire increase in Atlantic cyclone activity has taken place in the eastern part of the Atlantic, to the east of 63W; there was no trend in the western part of the basin. This lack of trend is completely consistent with a previously observed lack of trend in U.S. landfall hurricanes, all of which occur in the western part of the basin. It is possible to rule out a hypothesis of randomness as the basis for the discrepancy between lack of trend in landfall data and the seemingly significant trends in other overall basin indices of hurricane activity.

Breakpoint analysis of longitudinally stratified activity consistently shows a significant breakpoint in the late 1940s, which can be plausibly allocated to the introduction of aircraft reconnaissance. Other breakpoints are observed in the east Atlantic (and only the east Atlantic) at the start of the 20^{th} century (downward) and in 1987 (upward). The downward breakpoint at the start of the 20^{th} century may indicate that conversion of the Atlantic fleet from sail to steam may have resulted in first half 20^{th} century observations in the far east Atlantic being less complete than in the late 19^{th} century. This cannot be resolved on a priori reasoning.

In addition,///

Hurricane activity in the western NATL basin was historically low in the 1970-1994 period and decision makers should take care not to overlook these levels are likely to be frequently exceeded in the future whether due to global warming, randomness, natural causes, or some combination. Given the importance of landfalling storms to society, the research community should place even greater attention to the challenging and important scientific questions of tropical cyclone landfall climatology.

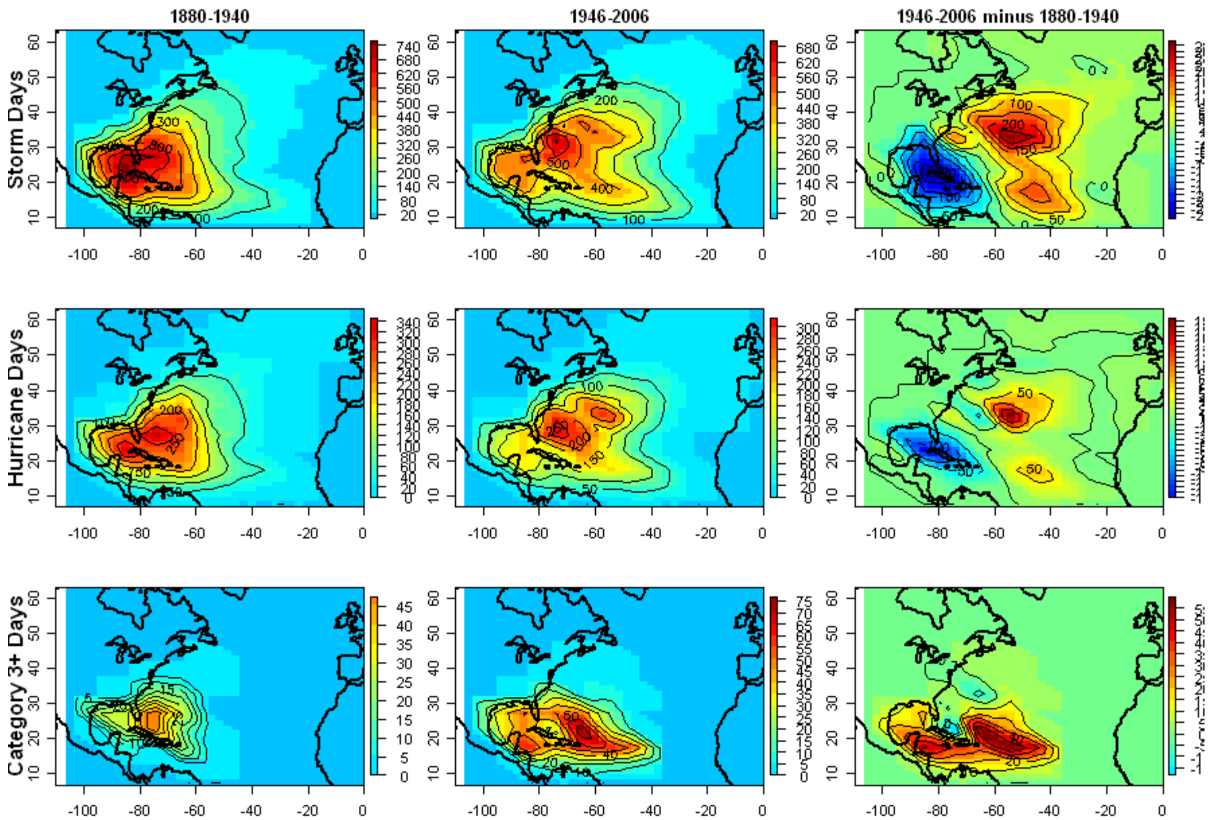

Figure 4. Contour Maps showing storm, hurricane and category 3+ days for 1880-1940, 1946-2006 and the difference. This highlights the increase in the central Atlantic and the decline in the Caribbean and Gulf of Mexico for storm days and hurricane days.

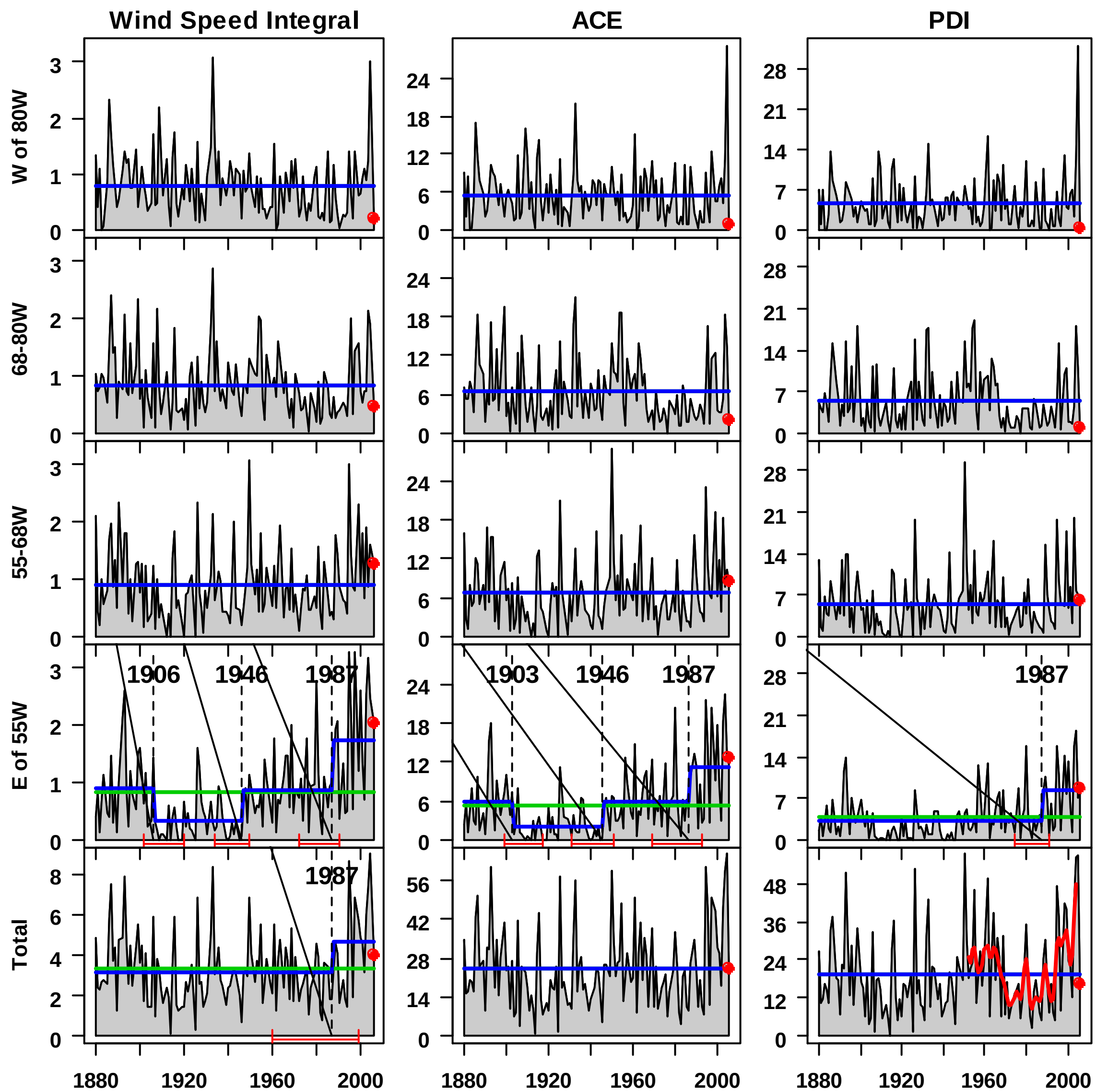

Figure 5. Three wind speed integrals. Left – integral of wind speed; middle – integral of wind speed squared (ACE); right panel – integral of wind speed cubed (PDI) . Top to bottom – by longitude quartile, east to west, and total. Breakpoint analysis is shown.

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SUPPLEMENTARY INFORMATION

There are many possible ways to measure hurricane activity, some placing more emphasis on intense hurricanes and some on all storms. Rather than advocating one index as pre-eminent, we present results for a comprehensive suite of indices and comment on the differences. Figures 4-7, 9 present the following indices for the four quartiles and the basin total:

- Three integrals of wind speed: the simple integral of wind speed (Wind Speed Integral), the integral of wind speed squared (Accumulated Cyclone Energy -ACE); the integral of wind speed cubed (Power Dissipation Index – PDI)
- storm, hurricane and category 3+ days
- storm, hurricane and category 3+ quartile counts by occurrence
- storm, hurricane and category 3 quartile counts by genesis
- storm, hurricane and category 3 quartile counts by maximum westward measurement

Figure 6 shows quartile counts by occurrence and Figure 7 shows quartile counts by genesis. All metrics are obviously closely related, but differ in details. For occurrence counts, a storm is counted if it occurs in a quartile, while genesis counts record only the quartile of genesis. In the occurrence count metric, a storm can occur in more than quartile; the basinwide total only counts each storm once and is identical to the basinwide total for genesis counts. Webster et al 2005 considered basinwide counts and days for A breakpoint analysis for the series shown here as category 3+ count was previously carried out by Elsner at al [2000, 2004] using a different algorithm. Elsner et al 2000 reported an upward break in 1943, a downward shift in 1965 and another upward shift in 1995, noting that that the exact years were estimates. They attributed the 1943 changepoint as "due in part" to improvements in observational techniques. Elsner et al 2004, using a different (MCMC) changepoint algorithm, identified changepoints in 1906, 1943 and 1995, noting that a "worthwhile" breakpoint model should be able to detect a changepoint in the mid-1940s, when aircraft reconnaissance was introduced.

Using a different algorithm, we observed a statistically significant breakpoint for category 3+ hurricanes in 1942, a date matching Elsner. The introduction of aircraft reconnaissance in 1947 is well within the confidence intervals of this calculation and is a plausible explanation for this breakpoint. The other changepoints reported by Elsner et al [2000,2004] were not determined to be significant according to the algorithm used here, although visually one can see level changes in the periods reported by Elsner et al [2000,2004].

the three categories shown here (see bottom rows).

The only upward break in any of the western quartiles is a slight upward step in west Atlantic storm genesis counts in 1930.

Non-Tropical Cyclones

Figure 8 shows a slightly different perspective by dividing the basin into 4 latitude quartiles (19.9N, 26.8N, 33.6N) quadrants: SE, SW, NE and NW, as opposed to the longitudinal stratification previously shown. The E-W division is at the median line and the N-S division is at 31N, varied slightly from the 22N line used in Holland and Webster (AMS Jan 2007).

There are a negligible number of storms in the Hurdat data base that originate north of 31N. There is a slight break in the mid-1960s. Previously virtually no storms were included in the data base originating north of 31N. Afterwards, about 1.7 storms per year are included. Simpson and Pelissier (1971) observed that inclusion criteria for the Hurdat data base had been modified to include some cold core storms. We have not attempted to segregate these northern origin storms as they form part of the data base used in Emanuel 2005a and Webster et al 2005.

In the two quadrants south of 31N, we compared genesis counts for the past 50 years to genesis counts for the prior 50 years, a coarse statistic used in Holland and Webster 2007b (AMS Workshop). In the western basin, there was no difference between the two periods, while there was a substantial increase in the east Atlantic, consistent with other analyses reported here.

Maximum Westward Reach

Figures 8 shows the quartile of maximum westward reach for each cyclone. The limit is defined for each wind speed minimum – thus the maximum westward reach at hurricane strength will generally differ from the maximum westward reach at storm strength, although the two indices are obviously highly correlated. The total basinwide counts match the counts in the earlier count series. These indices give a useful indication to how many storms or hurricanes might have been missed. Small breakpoints are observed in the 1960s in the eastern quartiles, due probably to satellite technology picking up storms that never came west. The total of the steps prior to 1986 amount to 3.2 storms per year, a number that is comparable to the estimate in Landsea 2007 of 2.2 “missed” storms per year, of which there would be approximately 1.7 “missed” hurricanes,

Median

As a result of all these various changes, the median longitude of an individual track observation in the Hurdat data set has moved eastwards by over 10 degrees from the first half of the century to the last half, a summary statistic that encapsulates many of the details discussed above. Indeed, it was the surprising change in this statistic that prompted the analysis presented here. A breakpoint is observed in 1960, which we interpret as reflecting the combination of the commencement of aircraft reconnaissance in the late 1940s and progressive implementation of satellite techniques commencing in the 1960s.

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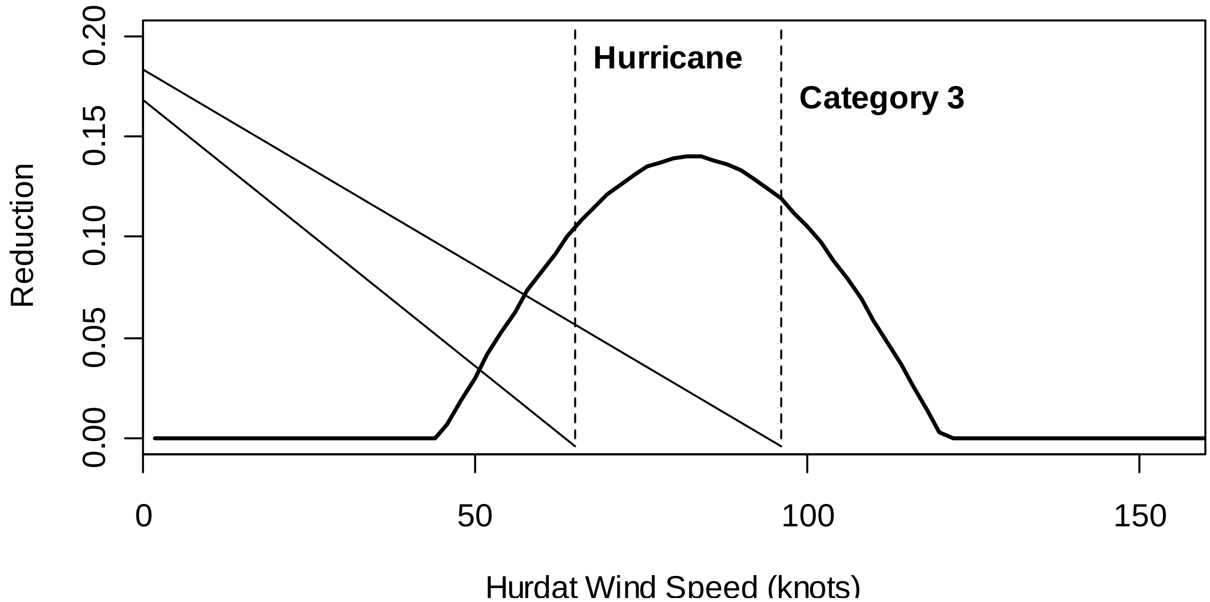
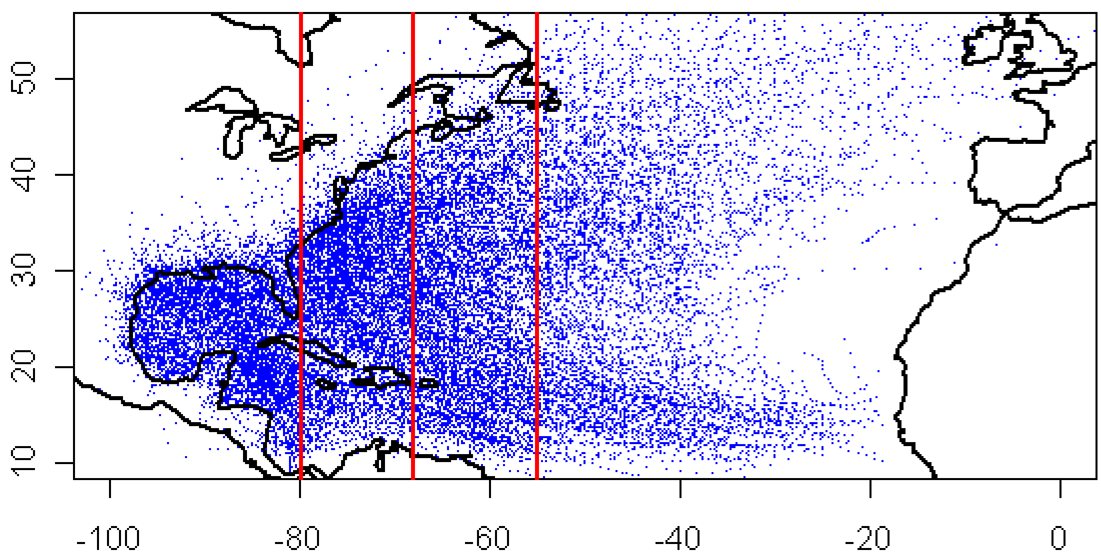
Figure 8 presents a cross-classification by latitude showing results for north-south, east-west quadrants partitioned at 68W and 31N. For quartile counts by occurrence, a cyclone can counted in more one than one quartile (the total being calculated separately to avoid double-counting in summation.) The genesis of a cyclone as a hurricane may occur in a different quartile than its genesis as a storm.



Supplementary Figure 1. Landsea 1993 wind speed adjustment as implemented in Emanuel 2007



Supplementary Figure 2. Longitude quartiles (79.9W, 68.1W, 55W). Each track measurement in the HURDAT database indicated by a dot.

In doing so, we are able to show that the entire increase in storm-days and hurricane-days has occurred in the central Atlantic between 60W and 35W, with a surprising proportion of the increase occurring north of 30N. This raises many attribution questions as to the degree to which the increase is related to climate as opposed to changes in detection, measurement and even definition. For category 3+ ("intense") hurricanes (96+ knots on the Saffir-Simpson scale), there is no trend and even a slight decline offshore Florida, but an increase in the central Atlantic east of 60W and in the "southern corridor" south of Cuba and towards the Yucatan. Again, there are many questions as to whether these changes relate to measurement or to climate.

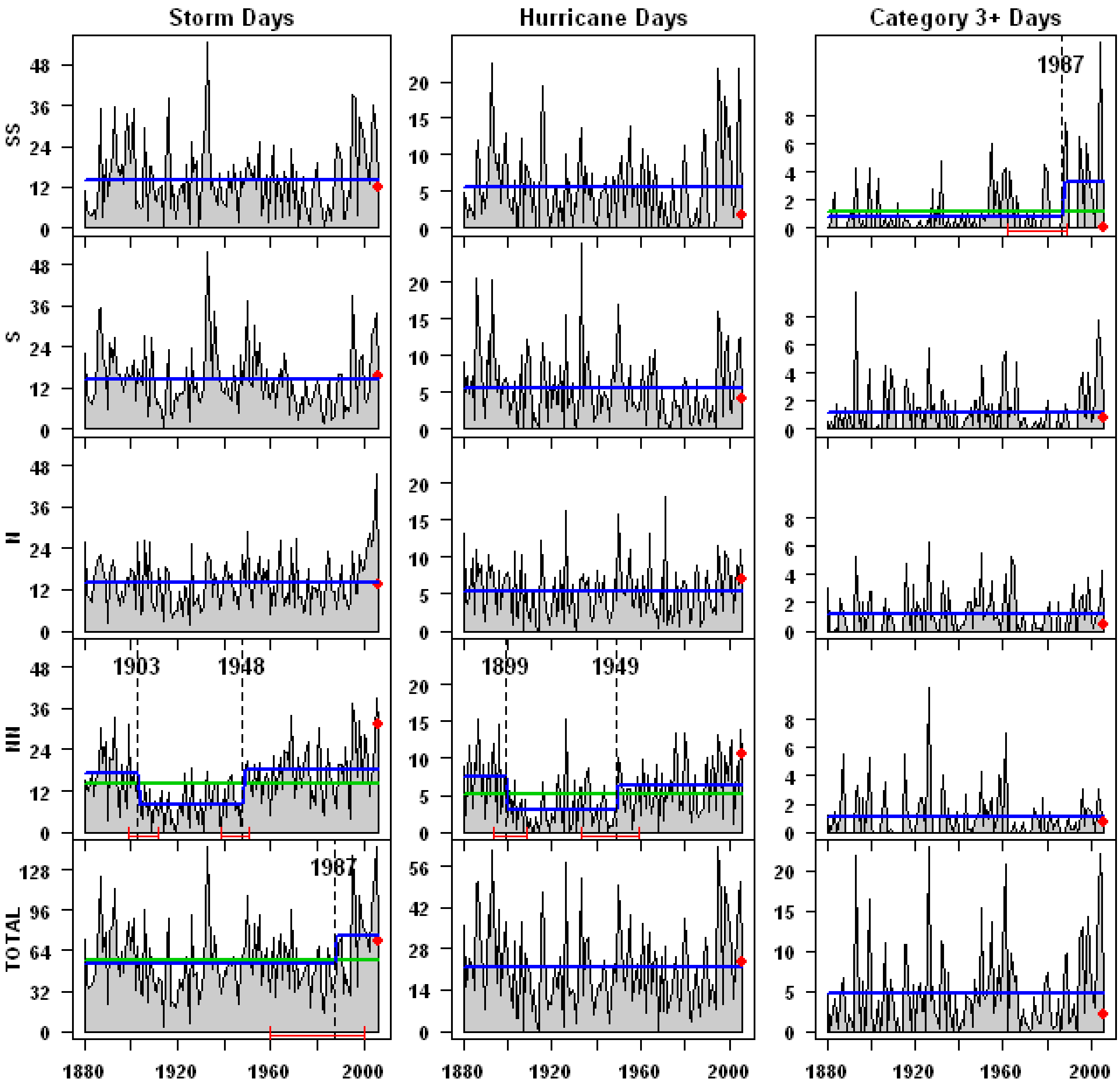


Figure 6. Days by category and latitudinal quartile. Left panel – storm days; middle – hurricane days; right panel – category 3+ days. Top to bottom – by latitude quartile, south to north, and total. Breakpoint analysis is shown

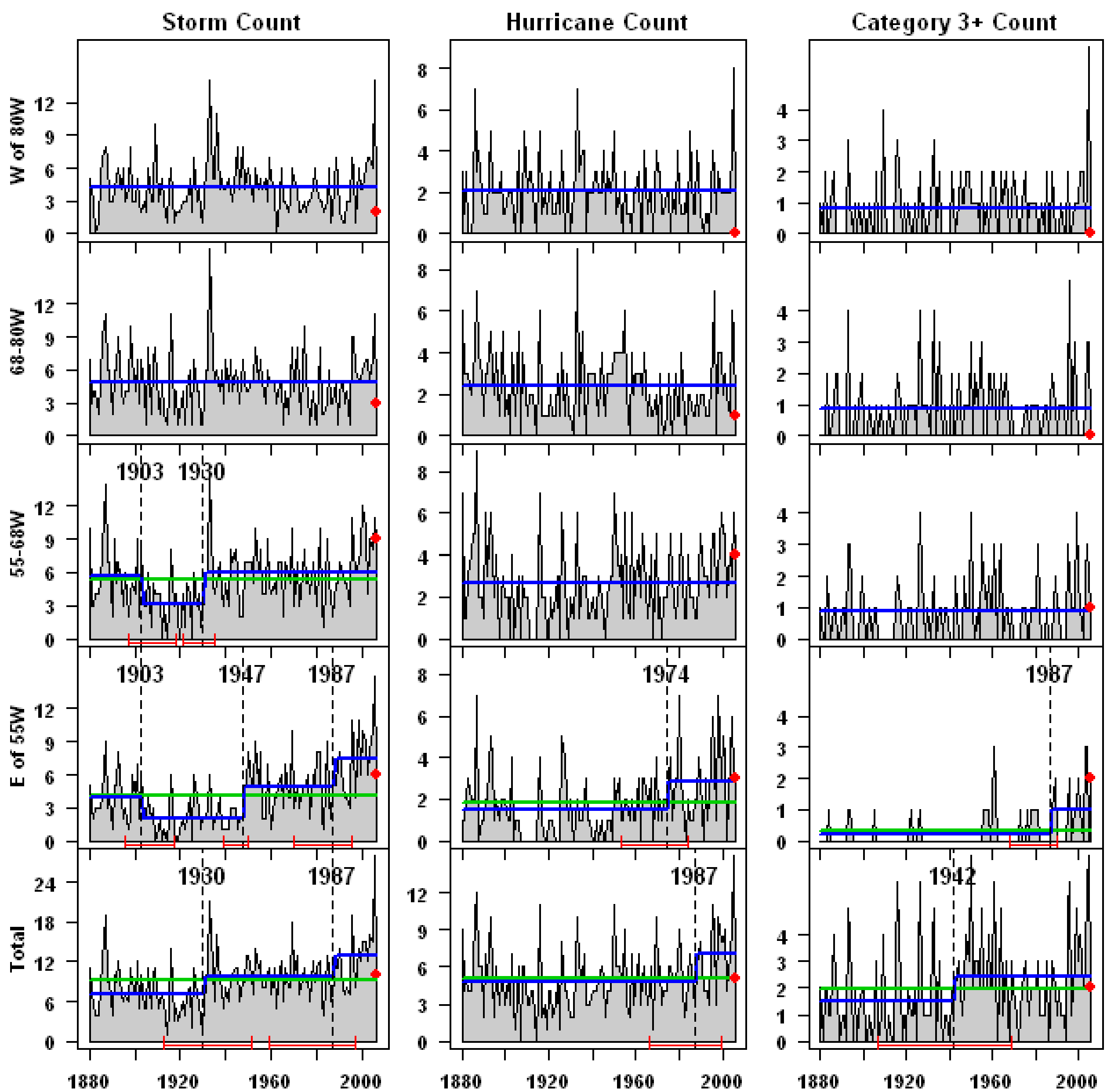


Figure 6. Quartile counts by occurrence. Left panel – storms; middle- hurricanes; right – category 3+ hurricanes. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown. 33.500 26.800 19.675

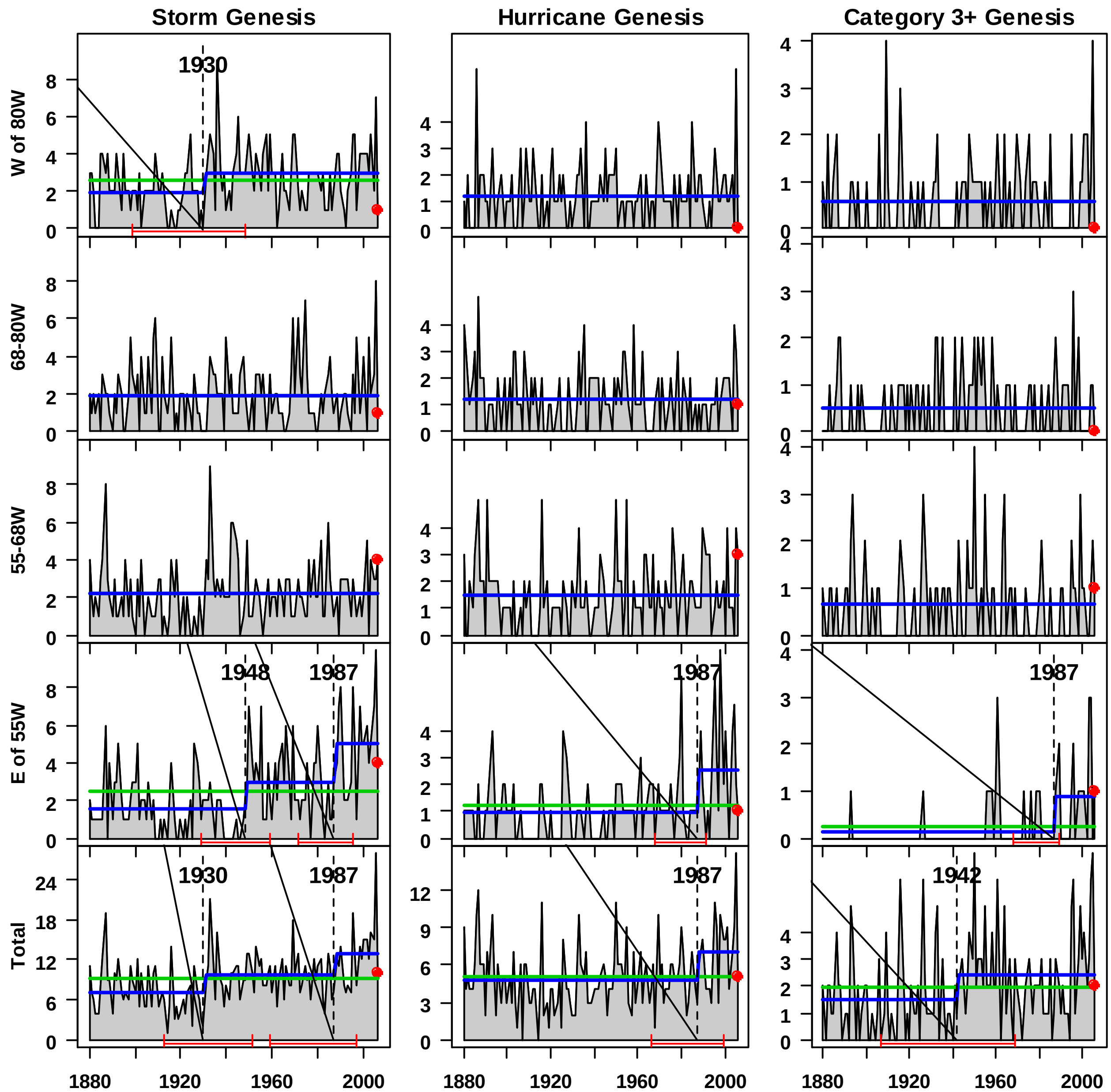


Figure 7. Quartile counts by genesis. . Left panel – storms; middle- hurricanes; right – category 3+ hurricanes.. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown.

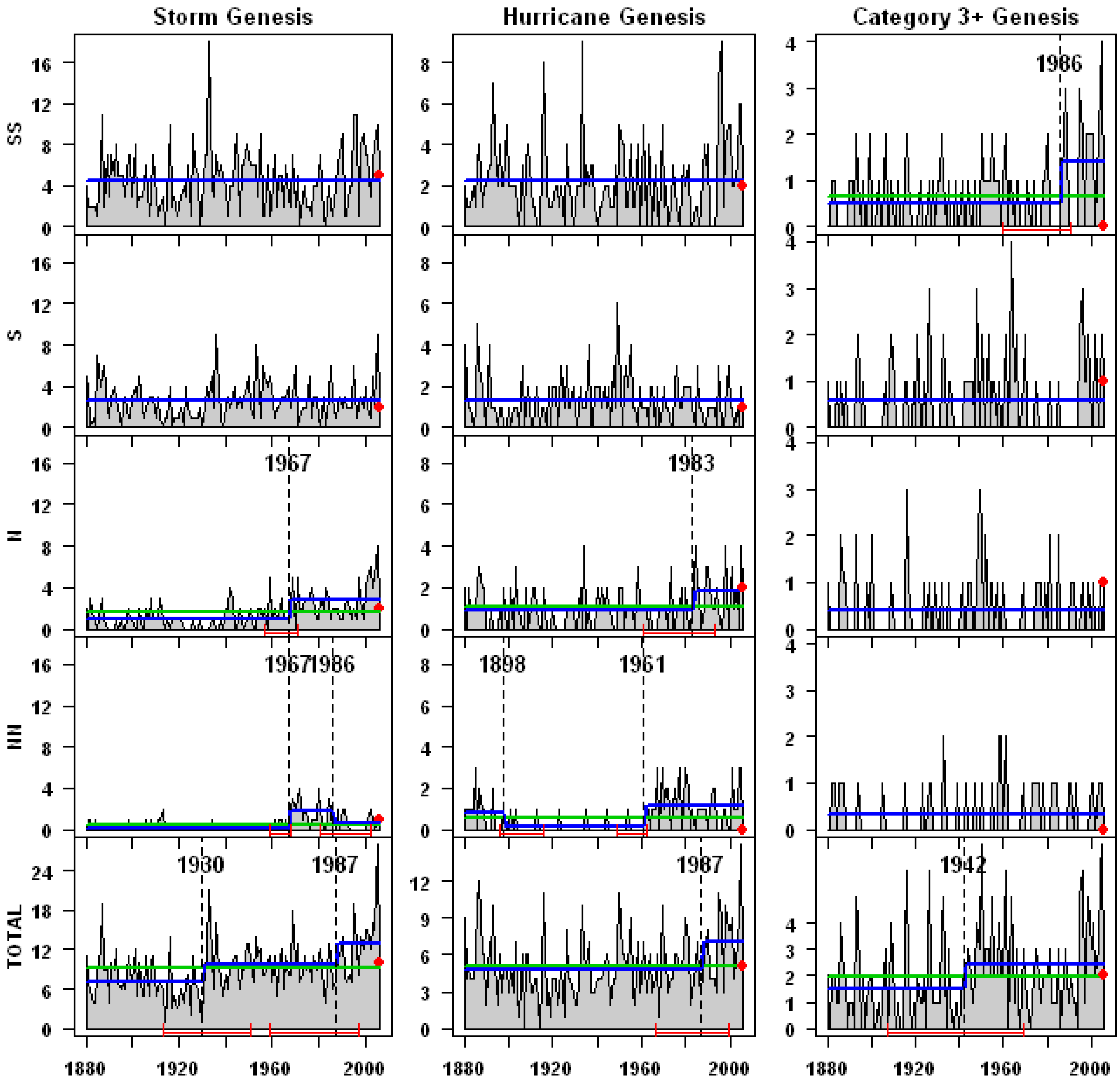


Figure 8. North-South distribution of genesis. 65.6 33.6 26.8 19.9 7.7

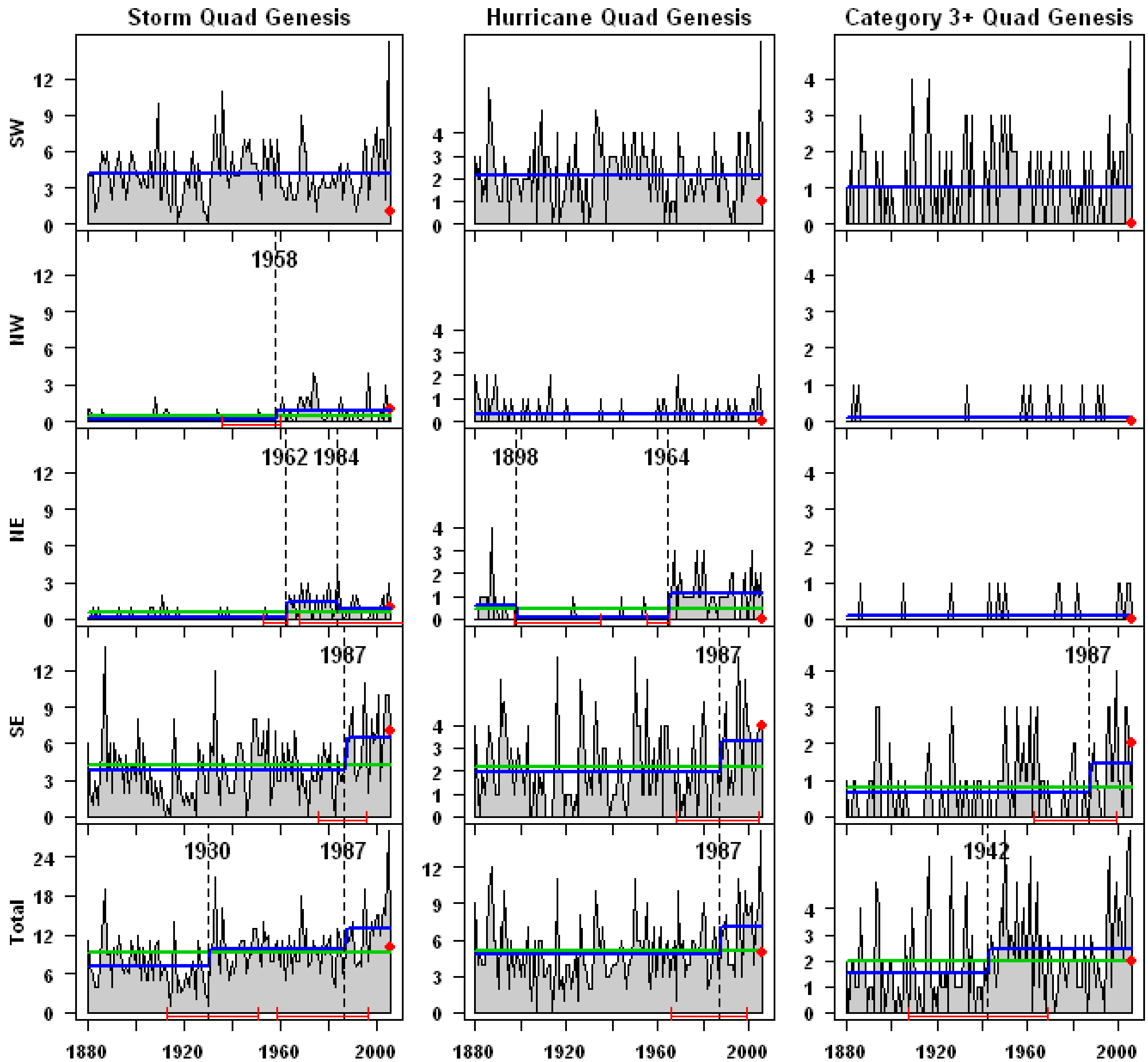


Figure 8. Quadrant counts by genesis. Left panel – storms; right panel – hurricanes. Top to bottom – by quadrant: southeast, northeast, southwest, northwest. Partitioned at 68W and 22N. Breakpoint analysis is shown. The storm genesis step is 0.8 per year in the NW quadrant and 0.9 per year in the NE quadrant.

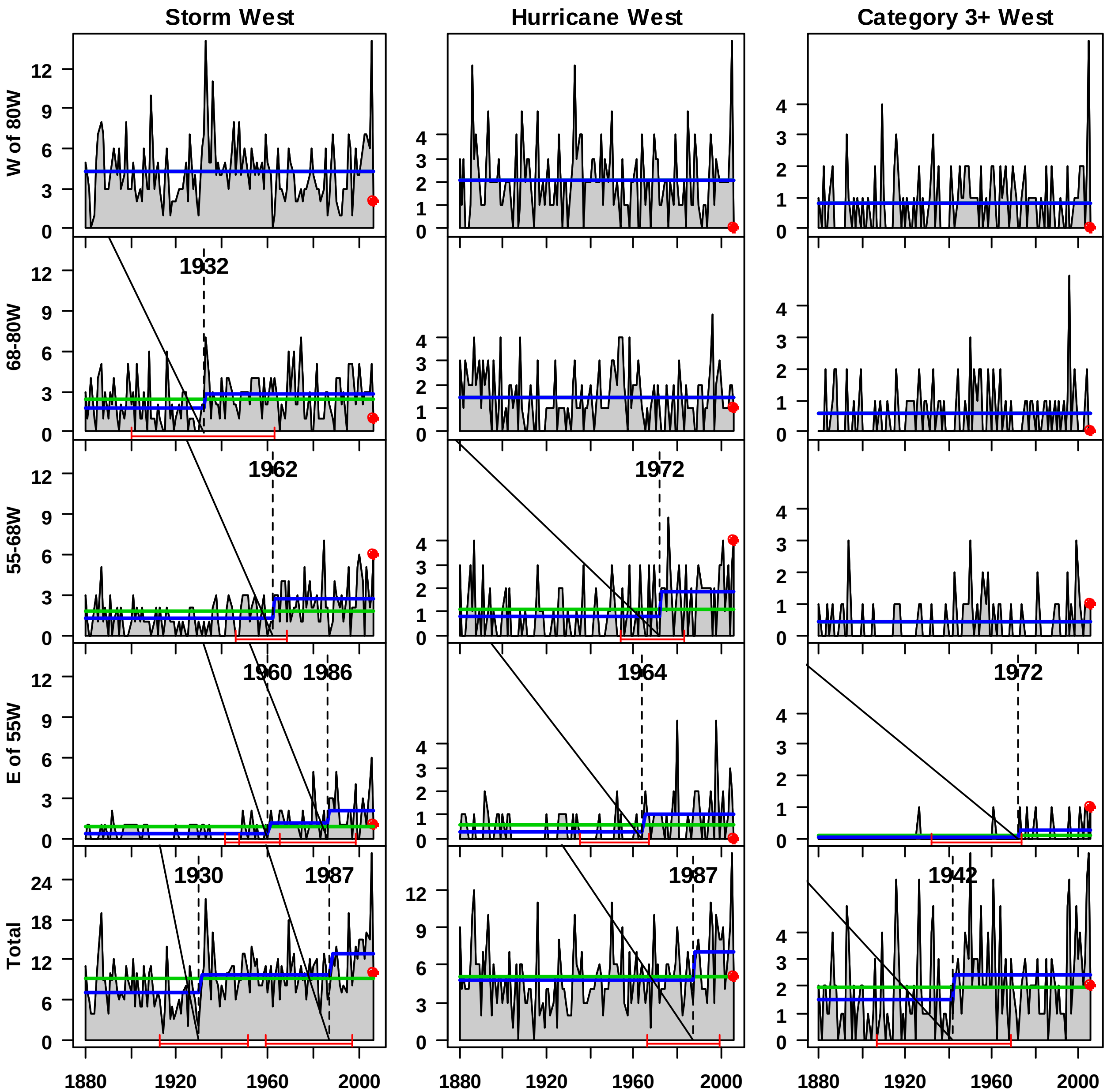


Figure 9. Quartile counts by maximum westward reach. . Left panel – storms; middle- hurricanes; right – category 3+ hurricanes. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown.