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 trends in the east and west part of the Atlantic. We have stratified cyclone activity by longitude and calculated a cross-section of measures of activity in different parts of the basin. In the west Atlantic, despite the active 2005 season, there are no long-term trends in any metric. In contrast, in the east Atlantic (east of 55W), there have been increases in all relevant metrics, including storm counts and PDI. Indeed, the entire increase in basinwide activity has occurred in the eastern basin. Breakpoint analysis shows a significant break in the late 1940s in east Atlantic indices, which can be plausibly allocated to the introduction of aircraft reconnaissance. Another breakpoint occurs in 1987, some portion of which relates to satellite changes, but more to an actual increase in east Atlantic activity from relatively quiet prior periods.

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Introduction

The present paper arises out of an unresolved problem arising out of Emanuel (2005a), which reported that the power dissipation index (PDI, defined as the time integral of the cubed wind speed) doubled in the Atlantic basin over the period 1949-2004.

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 observed 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 reconciled by simple randomness. He observed that the Hurdat data set that he used contained “about 100 times more data” than the landfall data set and that his results accordingly had “a signal-to-noise ratio that is ten times that of an index based on landfalling wind speeds.”

In this paper, we reconcile these results by analyzing the longitudinal distribution of hurricane metrics using the identical dataset as Emanuel (2005a). We initially observed the changing longitudinal distribution by noticing that the median longitude of measurements in the Hurdat database had shifted approximately 10 degrees to the east over the century (www.climateaudit.org/p?=). While there has been increasing awareness of the increased proportion of storms and hurricanes from the east Atlantic in the hurricane record ( ), most of this discussion has been qualitative and, surprisingly, there has been little previous effort to develop quantitative indices that measure longitudinal stratification.

Our principal strategy in quantifying longitudinal stratification was to simply classify the Atlantic basin into four quartiles (defined using the population of all measurements exceeding 35 knots for the entire data set.) We then calculated a wide variety of indices for the 4 quartiles, yielding profound differences between behavior in the eastern and western parts of the basin, which then can illuminate somewhat stalemated debates on how much weight to place on older data in the Hurdat database. Our own preference is to show all the data from a variety of perspectives, rather than relying on any one metric as a pre-eminent measure of hurricane activity.

For each series presented here, we have used modern econometric methods to test for breakpoints. Previously, Elsner et al [2000, 2004] applied breakpoint analysis using their own algorithm to basinwide category 3+ counts. Our results for basinwide category 3+ counts are not incompatible with theirs, but we have substantially extended the analysis to nearly 100 series, each emphasizing a different aspect of hurricane activity.

The interpretation of changing hurricane indices is complicated by the simultaneous occurrence of pronounced multidecadal variability (Goldenberg and Shapiro 2001) with changing methods of both detecting hurricanes and measuring wind speed, and especially extreme wind speed. A wide variety of indices need to be considered at all times in order to tease a climatic interpretation from the data.

Analysis

Figure 1 shows the PDI and landfall data that require conciliation, shown here for the period 1880-2006[i]. Emanuel 2005a stated that PDI had doubled in the past 30 years, basing this claim on a version of the smoothed curve shown in the top panel of Figure 1. (Both smooths are based on 1-4-6-4-1 smooths, the version here illustrated without end-point pinning, a procedure used in Emanuel 2005a and withdrawn in Emanuel 2005b). PDI in 2006 was low. Two more years of normal or below-normal PDI would modify the visual impression substantially. The bottom panel of Figure 1 shows the number of U.S. landfall hurricanes, together with their 1880-2006 trend line which is flat.

In order to explain the seeming discrepancy, we analysed North Atlantic track data from the revised HURDAT data, (http://www.nhc.noaa.gov/tracks1851to2006_atl.txt) as 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. Wind speeds were adjusted according to the Emanuel (submitted, 2007) implementation of the Landsea 1993 adjustment, which 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 Figure 2. "Storms" denote cyclones with adjusted wind speeds exceeding 35 knots (hurricanes – 65 knots; category 3 - 96 knots). "Cyclone" is used to refer to the 3 categories collectively. Landfall data was from http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512005-gt.txt, as downloaded in April 2007.

We classified all measurements into longitudinal sectors according to . We show results here for data grouped into four quartiles (East - east of 55W; Near East - 55 to 68W; Near West - 68 to 80W and Far West - west of 80W.). We also examined groupings by 5 quintiles with equivalent results. All landfalls occur in the western third of the basin and most in the western quartile, while the eastern half, especially the southern portions, is relatively remote from land (see Figure 3).

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 8 presents a cross-classification by latitude showing results for north-south, east-west quadrants partitioned at 68W and 22N. 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.

In each case, we have illustrated the results of a breakpoints analysis using the strucchange package package [Zeilis et al 2007, which implements methods due to Bau (1994, 1997) and Bau and Perron 1997]. In the Supplementary Information, we provide the computer script by which these series and diagrams were prepared.

Wind Speed Integrals

Figure 4 shows the three wind speed integrals for four longitudinal quartiles and for the entire basin – format applied in the related figures. 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). The bottom middle panel shows the basinwide integral of wind speed squared (ACE) used in Vimont and Kossin 2007 (ACE). The pattern of activity differs markedly by longitude.

In the far west quartile, despite the very active 2005, no breakpoints (or trend) are observed for any of the integrals. The 1933 season, which Landsea (2007) illustrated as a comparandum for the active 2005 season, is particularly distinct in the Wind Speed Integral, where the 1933 season actually ranks ahead of the 2005 season in the two western quartiles. The respective ranking is not consistent across the indices, as the 2005 season has nearly double the PDI of the 1933 season. This difference can be isolated to the contributions from approximately 30 wind speed measurements from Rita, Katrina and especially Wilma, where xx measurements exceeding 120 knots are recorded in 2005 (none in 1933 although it was a busier season according to storm-days and hurricane-days).

In the Near West quartile (second row), low levels are observed in all three integrals in the 1950s and 1960s, the period used as a comparandum in the Emanuel 2005a doubling estimate. This also includes the period impacted by the Landsea 1993 adjustment to wind speeds (1946-1968), suggesting that the need for a detailed reconciliation of this adjustment prior to excessive weight being placed on interpretations relying on it.

Although there was no long-term trend in the west, there were significant breakpoints in the far eastern quartile. There was a distinct breakpoint in 1947 for the wind speed integral and ACE, coinciding with the introduction of aircraft reconnaissance (a point made in a breakpoint analysis of category 3+ counts by Elsner et al 2000, 2004 using a different algorithm). There is also a distinct downwards breakpoint at the start of the century, a point which appears to be inconsistent with comments in Landsea 2007 that observation in the late 19^{th} century was even sparser than in the early 20^{th} century. (See discussion below). For all three eastern quartile series, a breakpoint is assigned to 1987, rather than 1994-1995 as sometimes suggested, although the confidence intervals definitely do not preclude the later date.

For the basinwide Atlantic total ACE and PDI, rather surprisingly, no breakpoint is observed. A 1987 breakpoint is observed in all 3 series, in each case contributed by a corresponding increase in the eastern quartile. In the bottom right panel, the Emanuel 2005 smooth is shown for comparison. The apparent doubling in the total is a combination of two effects: the direct PDI increase in the eastern quartile contributes most of the effect, with a secondary contribution from the fact that PDI in the two central quartiles was below the long-term mean during the first part of the Emanuel 2005 study period of 1950-2004.

Storm, Hurricane and Category 3 Days and Quartile Counts

Figures 5 and 6 show closely related metrics, which have also appeared in recent literature. Figure 5 shows storm, hurricane and category 3 days for the four quartiles and the total basin, while Figure 6 shows quartile counts by occurrence (in this metric, a storm is counted if it occurs in a quartile). Basinwide counts and days for all three categories were used as a metric in Webster et al 2005, but only for the 1970-2004 period. (See bottom rows in Figure 5 and 6 for basinwide totals). Elsner et al [2000, 2004] also carried out a breakpoint analysis of the category 3+ count series (bottom right Figure 5) using a different algorithm.

For hurricane and category 3+ days, there are no breakpoints in the long-term series, while for hurricane and category 3+ counts, the only breakpoint occurs in 1946-47 at the time of the introduction of aircraft reconnaissance. The trends identified in Webster et al 2005 depend strongly on their selection of 1970 as a starting point. This starting point occurs at a low ebb of hurricane activity. If a longer period is used as a reference, the trend is no longer apparent.

The appearance of the day indices in most panels is strikingly similar to the Figure 3, with the appearance of many panels virtually identical. Correlations 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 (with a Durbin-Watson statistic below 1.5). The "day" metrics 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. Higher order integrals do something similar, with the higher power integrals emphasizing the more extreme wind speeds in the index.

The breakpoint analysis is almost identical in the two figures. In the western quartile, storm days in 1933 are distinctly higher than storm-days in 2005, but category 3+ days are dramatically higher in 2005.

The pattern in the eastern quartiles is also similar to the corresponding wind speed integrals. Storm-days show an upward step in 1947; the corresponding breakpoint for hurricane-days is estimated at 1956, but the confidence interval includes 1947. A 1987 breakpoint is observed for eastern quartile storm-days and category 3+-days. Somewhat surprisingly, no breakpoints are observed in basinwide hurricane-days or category 3+ days, although a 1987 breakpoint in storm-days is observed, ascribable to the eastern quartile increase.

For Figure 6 showing quartile counts by occurrence, again there is no trend in the western quartiles, although there is distinct pulse of category 3+ counts in the Near West quartile between 1946 and 1966. The patterns in the eastern basin are similar to the other indices: a downward step is noticeable at the start of the century, together with an upward breakpoint in the late 1940s and in 1987.

Breakpoints in the late 1940s are even more marked using this metric, as is the downward step at the start of the 20th century for storms and hurricanes in both eastern quartiles.

Elsner at al [2000, 2004] previously discussed breakpoints in basinwide category 3+ counts(bottom right panel Figure 6). 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 total category 3+ hurricanes in 1946, a date, which, if anything, is more compatible with known changes in observation technology. 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 elevated 2005 western quartile PDI is matched by an equally elevated count of category 3+ days. However, the difference between 2005 and 1933 levels in the western quartile is substantially reduced in hurricane count (and eliminated in the western half where 1933 activity in the near west quartile outstrips 2005 activity.)

The bottom left panel, showing basinwide storm counts, corresponds to the series studied in Holland and Webster 2007, where they purported to discern regimes commencing in 1930 and 1994 (See discussion below).

Quartile Counts by Genesis and Maximum Westward Reach

Figures 7, 8 and 9 show two related perspectives on storm tracks: a quartile genesis count is defined here as the first occurrence of a storm at hurdle wind speed; and quartile count by maximum westward reach is defined here as the quartile in which the maximum westerly longitude occurred at hurdle wind speed. The limit is defined for each wind speed minimum – thus the genesis or maximum westward reach at hurricane strength will generally differ from the genesis or maximum westward reach at storm strength, although the two indices are obviously highly correlated.

Breakpoints are observed in the late 1940s in the eastern quartiles for all categories, with another breakpoint in 1987 for storm and category 3+ counts. A slight breakpoint at 1930 occurs in the western quartile.

Figure 8 shows a slightly different perspective by dividing the basin into 4 quadrants: SE, SW, NE and NW, as opposed to the longitudinal stratification previously shown. The quadrants are chosen to match those of Holland and Webster (AMS Jan 2007) who observed that 1956-2005 storm genesis counts were higher in 3 of 4 quadrants than corresponding counts for 1906-2005. While this is true, considerable additional information can be extracted from the data. In both northern quartiles, there is a small but observable breakpoint in the 1960s, presumably corresponding to a reported change in policy to include additional northerly storms in the data base [,,,,]. In the southwest quadrant where Holland and Webster reported a 50-year to 50-year decline, the more notriceable result from a breakpoint analysis is the "pulse between 1930 and 1956, rather than a long-term decline.

Figure 9 gives what is probably the most relevant perspective for counting "missed" storms (although the simple count metric is only one element of the total perspective.) Somewhat surprisingly, there are no breakpoints in the 1940s. There are small breakpoints in the mid-1960s.

Median

As a result of all these various changes, the median longitude of an individual track observation has moved eastwards by over 10 degrees from the first half of the century to the last half. 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.

Discussion

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 20^{th} century, an upward step in the late 1940s and another upward 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 pattern is not random, but observable in the Hurdat dataset as well as the landfall dataset.

Any increase in basinwide Atlantic indices of hurricane activity derives almost entirely from increases in the east Atlantic. In contrast to the west Atlantic, significant breakpoints are observed in most east Atlantic indices. These increases are sufficient in some cases to result in an increase in the total index. For many indices of east Atlantic activity, a distinct breakpoint can be observed in the 1940s. This is consistent with the start of aircraft reconnaissance, an observation made by Elsner et all [2000,2004] in connection with basinwide category 3+ counts.

In addition to the 1947 breakpoint, there is a 1987 breakpoint for many east Atlantic indices. This is

Although there is no trend in western quartile hurricane activity, significant upward shifts in most metrics are observed in the far eastern quartile in the late 1940s and again in 1987. These increases are large enough in some indices to affect the overall total. For example, the overall increase in storm counts and storm days is contributed entirely by the increase in the far east quartile.

In addition, there is a noticeable decline in many indices at the start of the 20^{th} century in the far eastern quartile. Landsea (2007) acknowledged the higher recorded occurrence of cyclones in the late 19^{th} century occurred and 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.” While this may be the case, there are factors that may argue for better coverage in the late 19^{th} century than in the first part of the 20^{th} century. Hurricane observations in this period were observations of opportunity (or perhaps more accurately, misadventure). In the 19^{th} century, the 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 introduction of steam vessels many years earlier. There is an interaction between vessel type and location in the trade wind zones where hurricanes originate. Trade winds were an important part of 19th century sailing routes, while steam vessels could follow great circle routes. Since hurricane observations by ships were a matter of opportunity, or more precisely misadventure, it’s by no means a given that the “observational network” for hurricanes in the trade wind zones in the late 19^{th} century was less than in the first half of the 20^{th} century. At a minimum, if this assumption is to be relied on, it needs to be demonstrated from a detailed analysis of shipping traffic rather than merely asserted.

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.]

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.

In contrast to Landsea, both Mann and Emanuel (2006) and Holland and Webster (2007) have each argued that storm and hurricane counts in the Hurdat data base were sufficiently homogeneous to ground trend calculations back to the late nineteenth century and early 20th century respectively. The downward shift of many indices in the eastern basin at the start of the 20th century makes the selection of a 1905 start by Holland and Webster statistically inappropriate. Their hypothesized regime change in 1930 merely restores many indices to levels observed in the 19th century. More problematically, Holland and Webster 2007 asserted the existence of regimes without carrying out a breakpoint analysis. For nearly all indices examined here, there was no breakpoint in 1930. In addition, the pattern in the western Atlantic differed from that in the eastern Atlantic. While Holland and Webster did not carry out a breakpoint analysis, there is a 1930 breakpoint for the total series, but not in the quartiles and not for other indices. In our opinion, the perceived 1930 breakpoint in the total storm count series results from the conflation of two situations: the definite breakpoint in the 1940s, combined with an active early 1930s episode, resulting in mis-identification of a 1930 breakpoint (which has a very wide confidence interval).

Holland and Webster (AMS Workshop 2007) compared the genesis counts of Atlantic cyclones in 4 quadrants: east and west of approximately 70W and north and south of 22N. They reported that genesis counts for 1956-2005 were higher than for 1906-1955 for 3 of 4 quadrants, with the southwest quadrant in the western Caribbean and southern Gulf of Mexico being the exception. While this is correct, as noted above, the increase in the northern quadrants primarily occurs as a breakpoint in the 1960s, perhaps associated with changing definitions. Some portion of the decreased genesis count in the southwest quadrants can be traced to the increasing ability to identify hurricane sources further to the east. In such circumstances, there will be a greater inhomogeneity in the day metrics and the integrals than in the counts.

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.

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.

- 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).

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 20th century (downward) and in 1987 (upward). The downward breakpoint at the start of the 20th century may indicate that conversion of the Atlantic fleet from sail to steam may have resulted in first half 20th century observations in the far east Atlantic being less complete than in the late 19th 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.

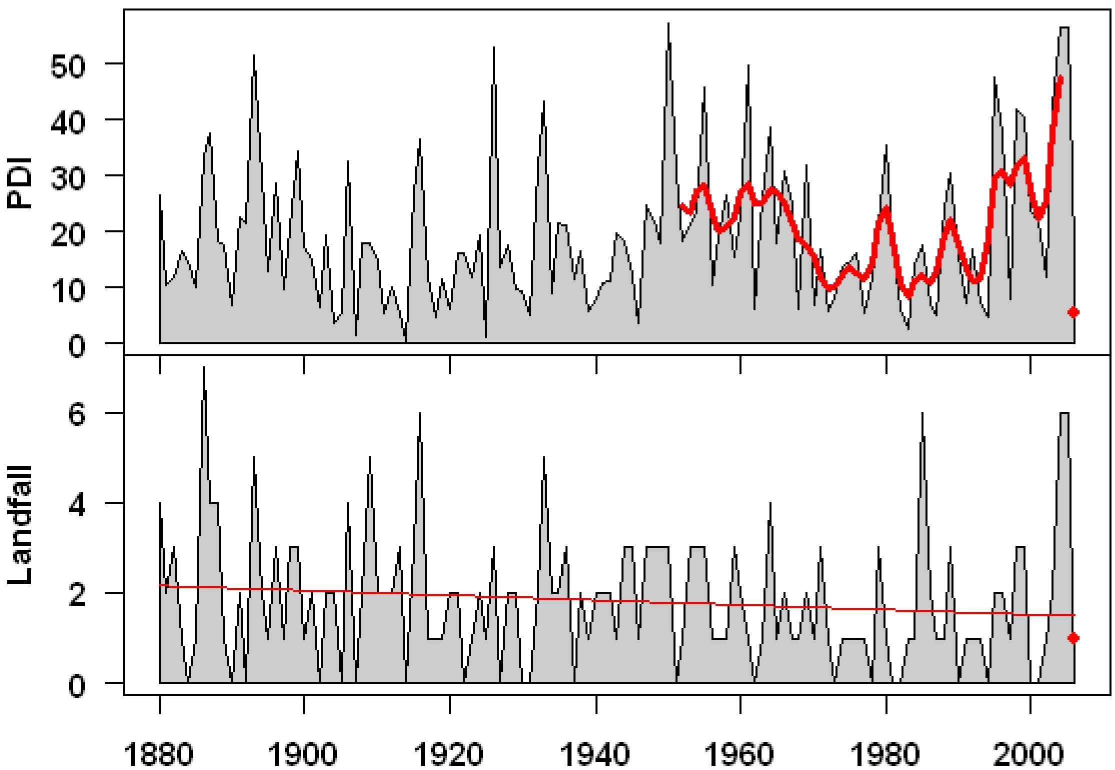

Figure 1. Top: Black – Total North Atlantic PDI with 1-4-6-4-1 smooth (red) as in Emanuel (2005) but without the pinned endpoints (according to Emanuel 2005b). 2006 value highlighted. Bottom - U.S. landfall hurricane count, together with 1900-2006 trend (adopting start from Landsea 2005). Strucc40.gif

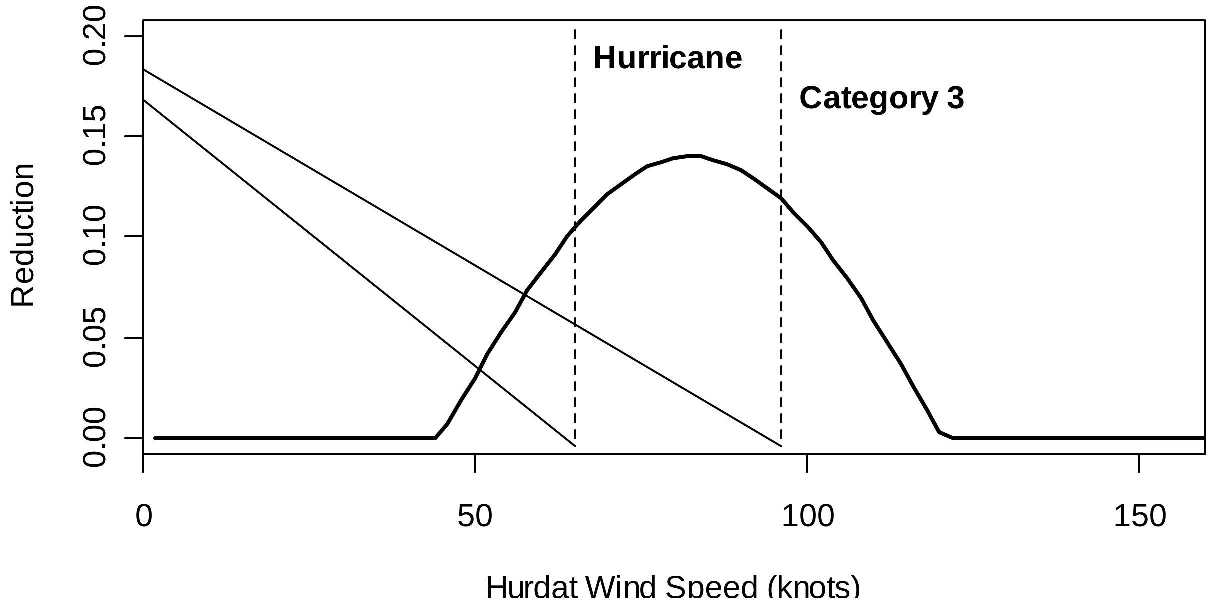

Figure 2. Landsea 1993 wind speed adjustment as implemented in Emanuel 2007

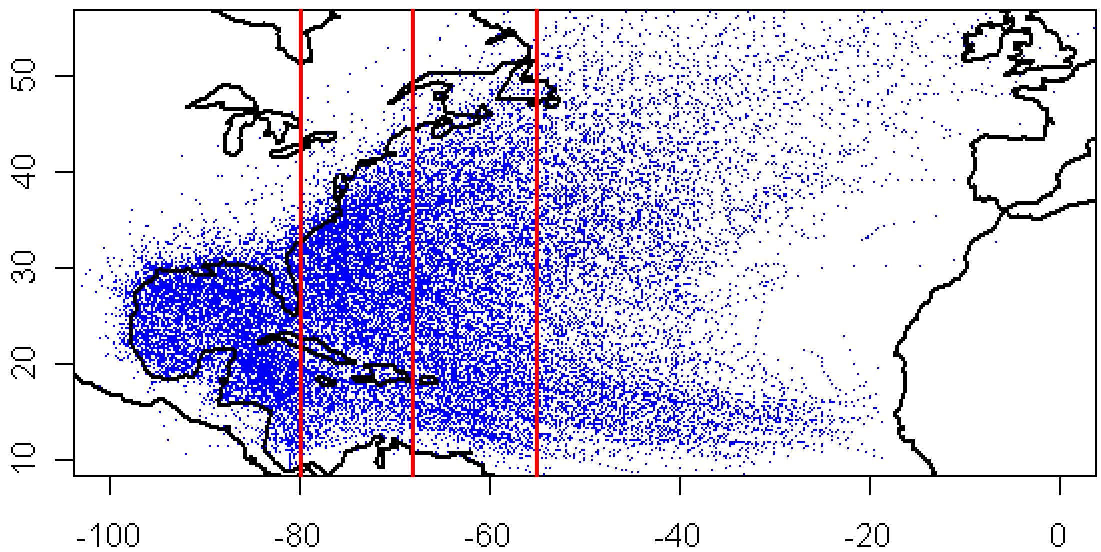

Figure 3. Longitude quartiles (79.9W, 68.1W, 55W). Each track measurement in the HURDAT database indicated by a dot.

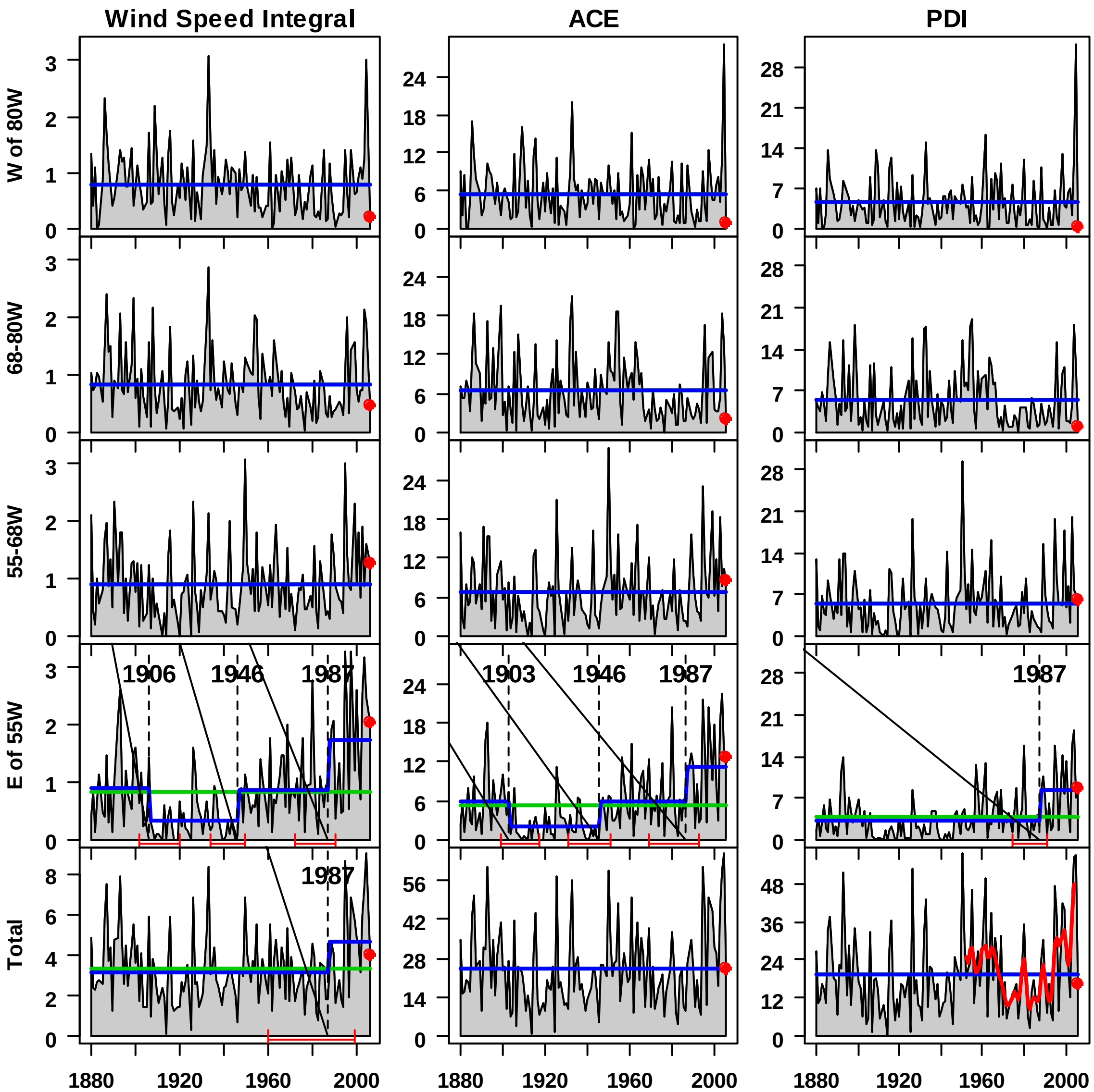

Figure 4. Three wind speed integrals. Left – integral of wind speed; middle – integral of wind speed squared (ACE); right panel – integral of wind speed cubed (PDI) . Top to bottom – by longitude quartile, east to west, and total. Breakpoint analysis is shown.

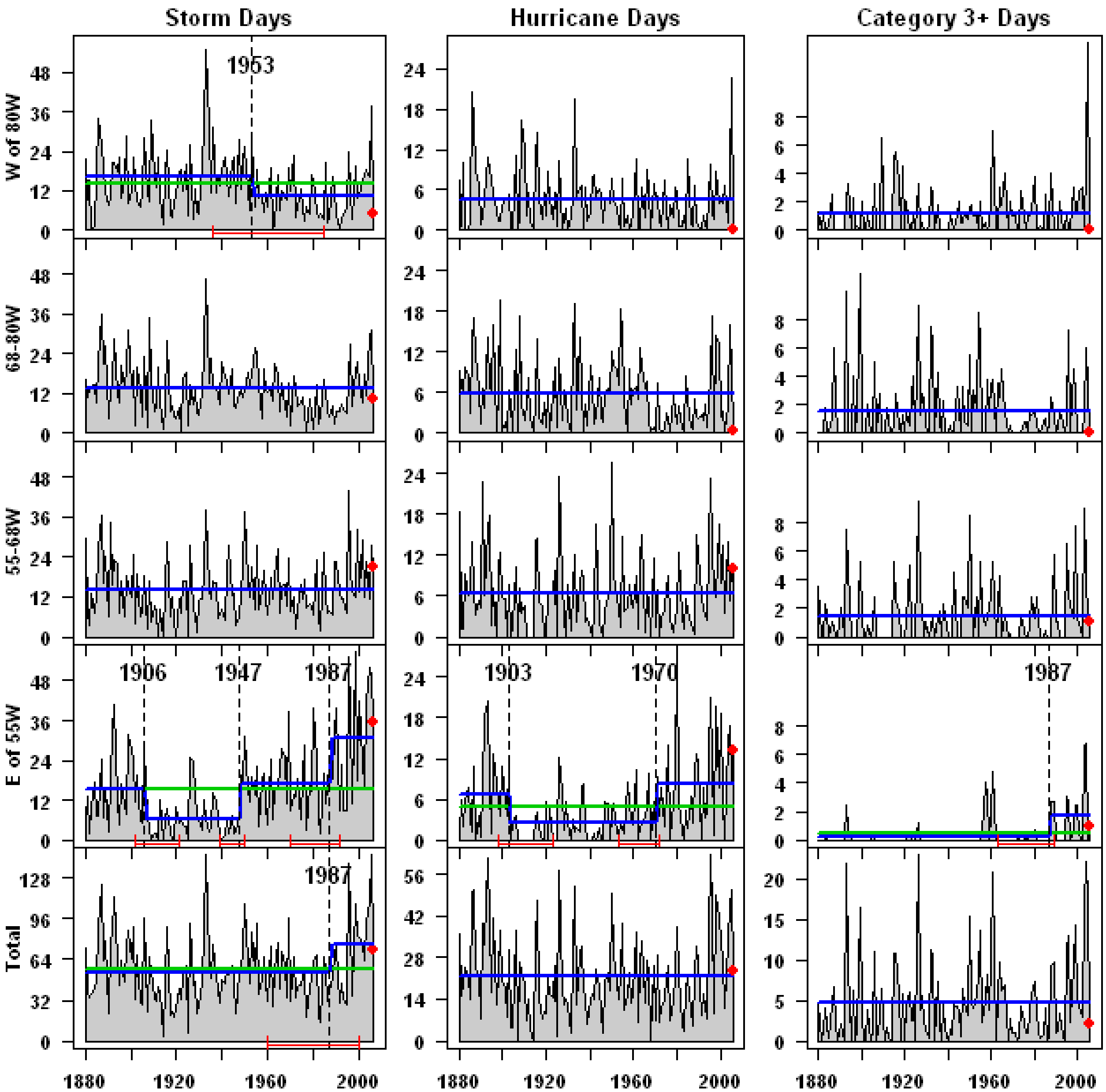

Figure 5. Quartile day count. Left panel – storm days; middle – hurricane days; right panel – category 3+ days. Top to bottom – by longitude quartile, east to west, and total. Breakpoint analysis is shown

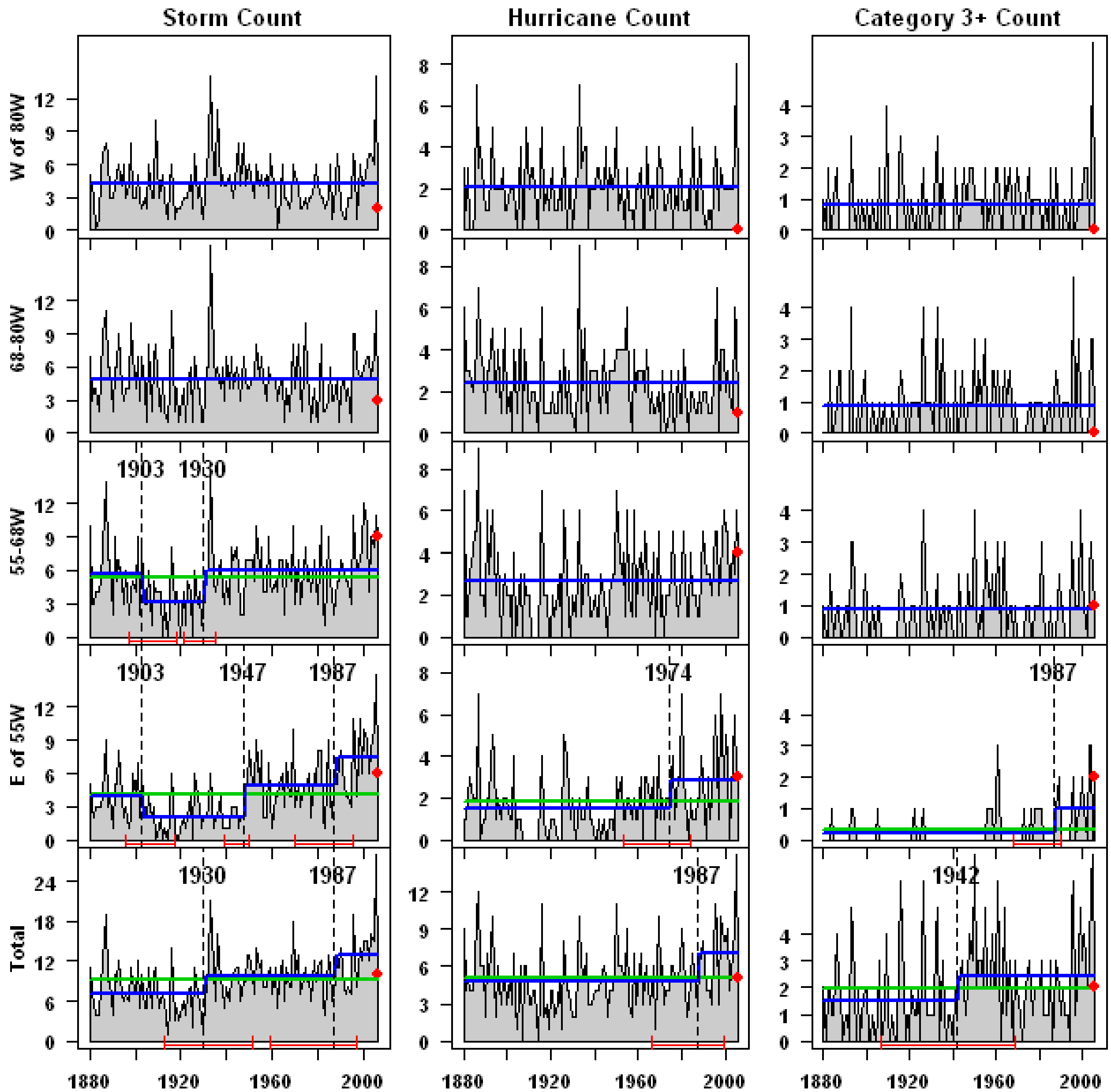

Figure 6. Quartile counts by occurrence. Left panel – storms; middle- hurricanes; right – category 3+ hurricanes. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown.

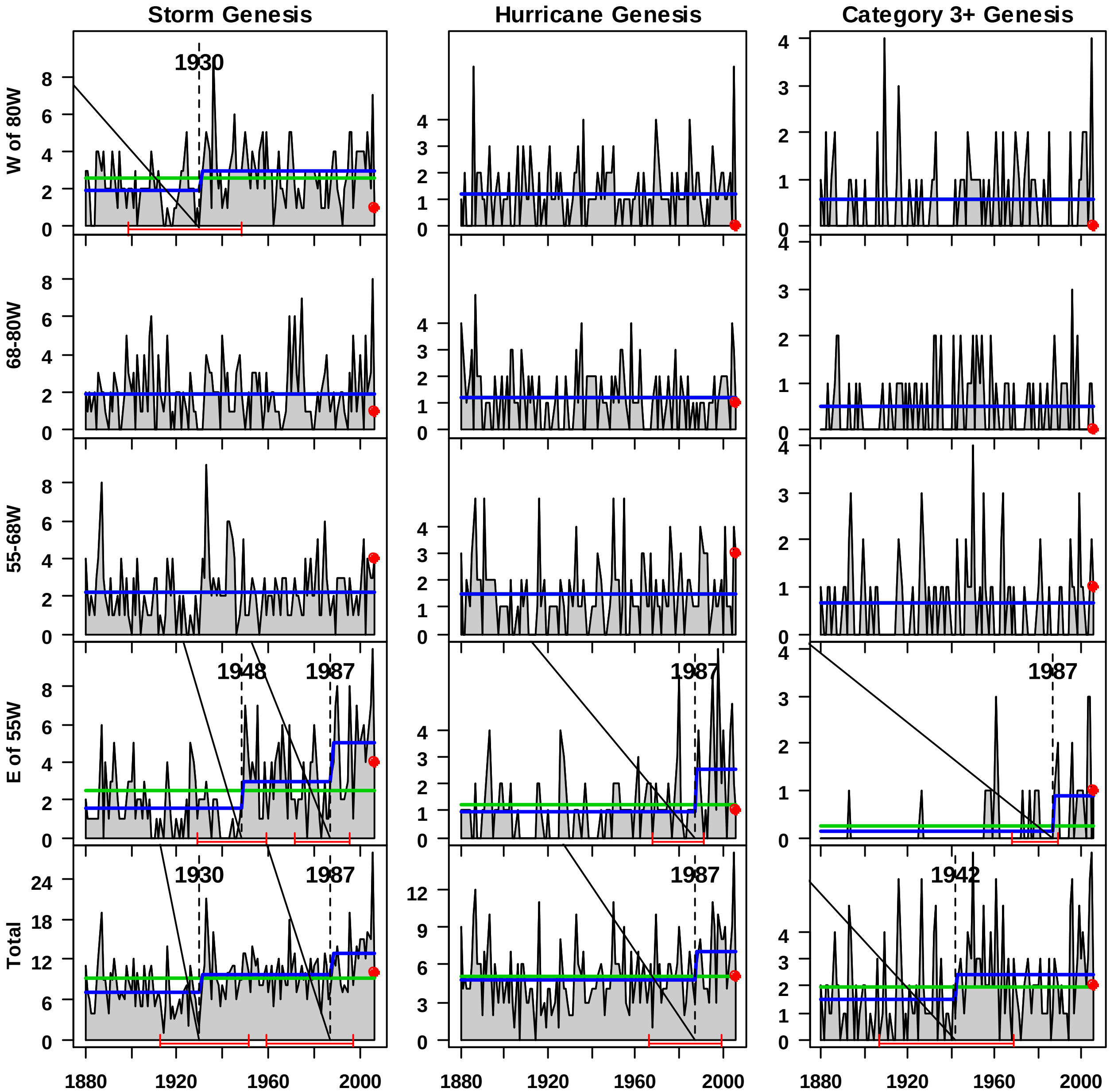

Figure 7. Quartile counts by genesis. . Left panel – storms; middle- hurricanes; right – category 3+ hurricanes.. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown.

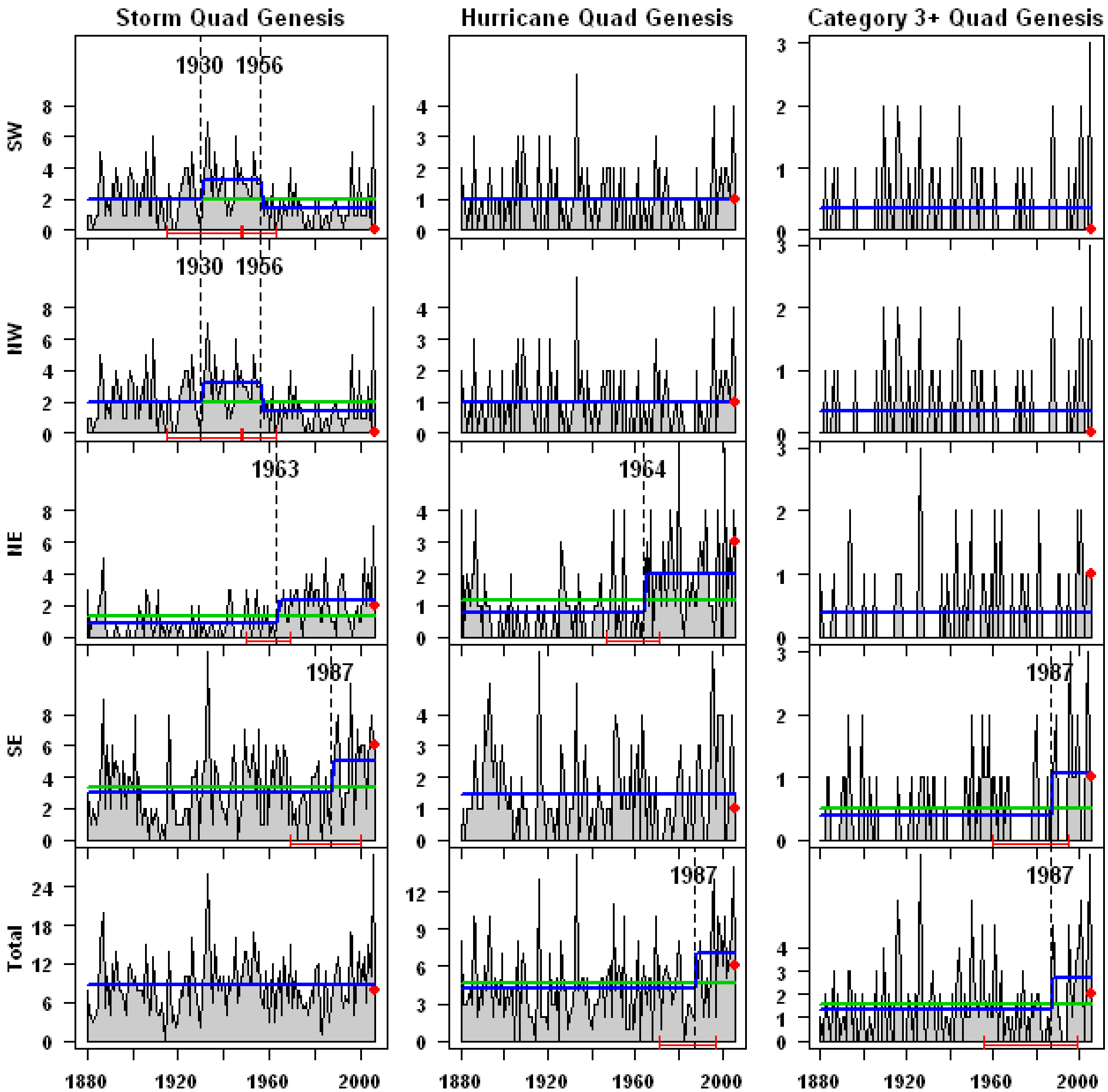

Figure 8. Quadrant counts by genesis. Left panel – storms; right panel – hurricanes. Top to bottom – by quadrant: southeast, northeast, southwest, northwest. Partitioned at 68W and 22N. Breakpoint analysis is shown.

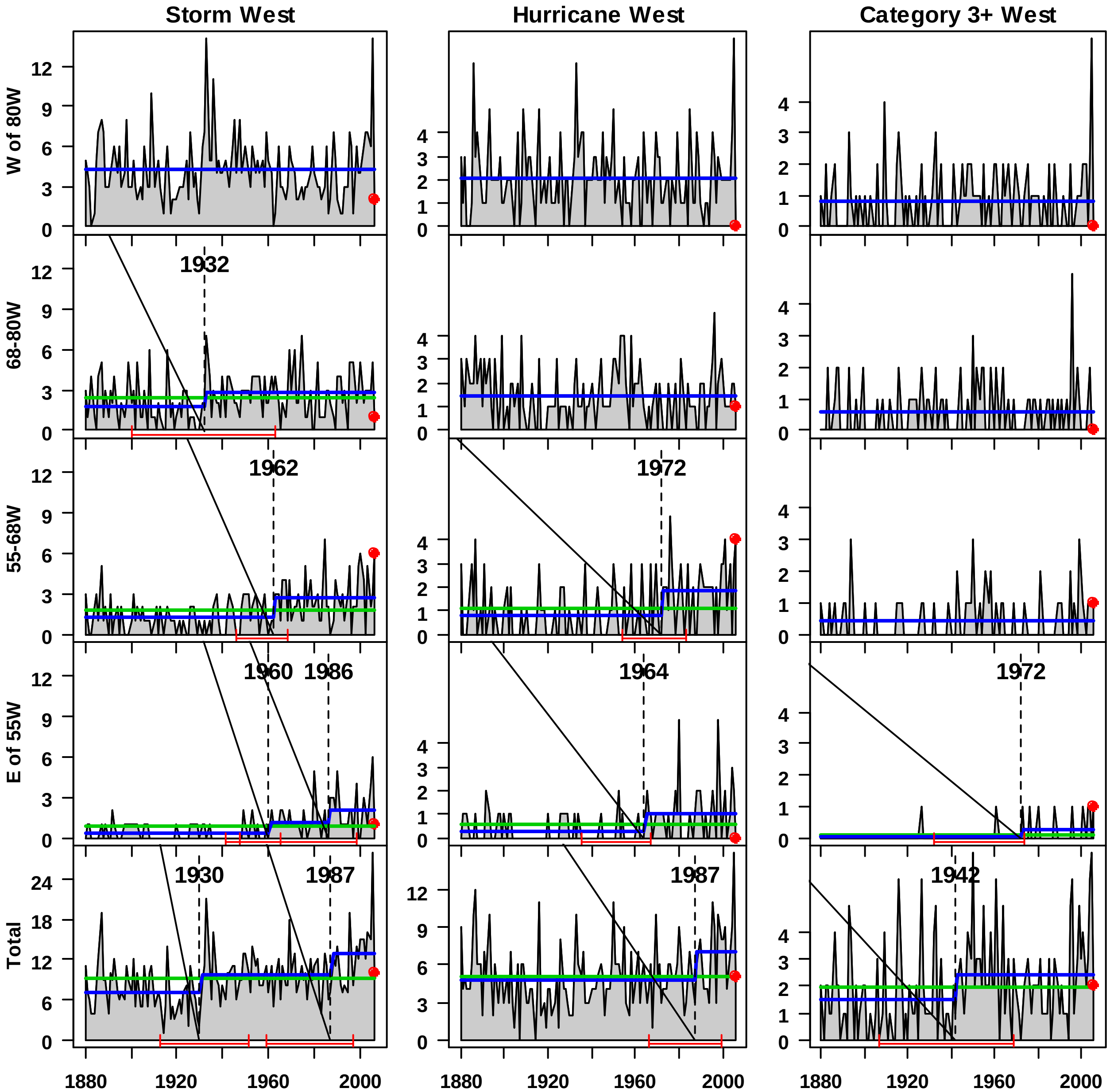

Figure 9. Quartile counts by maximum westward reach. . Left panel – storms; middle- hurricanes; right – category 3+ hurricanes. Top to bottom – by longitude quartile, east to west. Breakpoint analysis is shown.

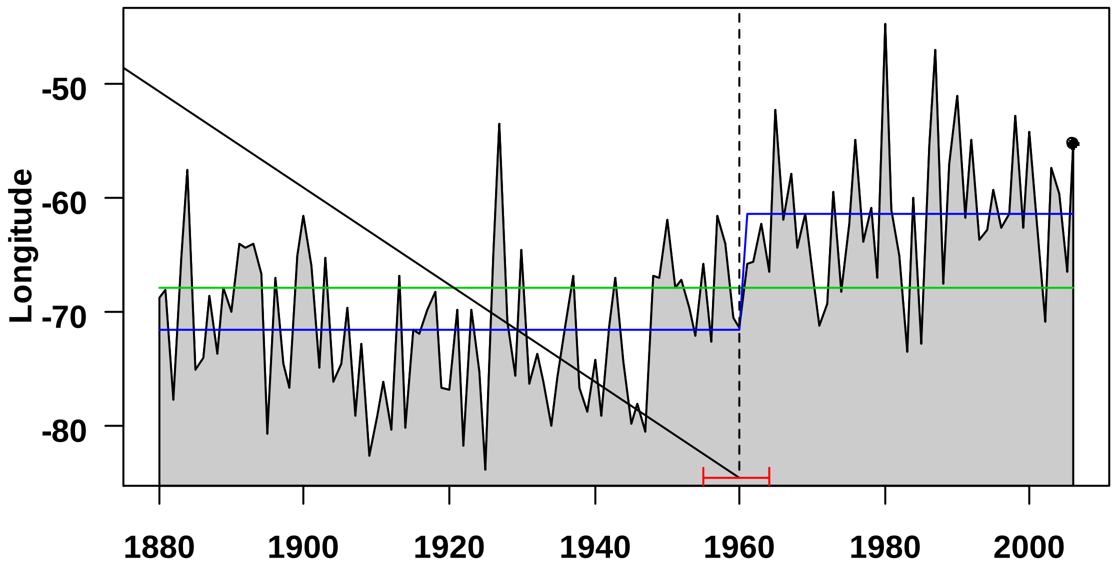

Figure 10. Median longitude of all storm measurements. Breakpoint in 1960.

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[i] This is a much longer interval than the 1950-2004 interval shown in Emanuel (2005b) or 1970-2004 shown in Webster et al 2005. We recognize that the methods for detecting and measuring cyclone activity were not homogeneous over the period. However by limiting analysis to shorter periods, relevant multidecadal variability is deleted, including the very active 1933 and 1886 seasons, which match 2005 in some metrics. We believe that it is better statistical practice to retain the longer record, while reminding readers of inhomogeneity as appropriate. We are unaware of any literature which argues that past cyclone activity **is over-estimated** in any of the metrics presented here. [However, the record from 1851-1880 seems too sparse to be helpful.]