SEASONAL INFLUENCES UPON AND LONG-TERM TRENDS IN THE LENGTH OF THE

ATLANTIC HURRICANE SEASON

by

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ABSTRACT
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Atlantic tropical cyclone (TC) seasons vary yearly in length with some seasons

significantly shorter or longer than normal. Kossin (2008) suggested that from 1980 to

2007, the Atlantic TC season increased in length; however, their study only considered a

subset of the Atlantic basin south of 30°N and east of 75°W. It is uncertain whether this

trend holds over the entire Atlantic basin or continues into the present. It is also unclear

as to whether meaningful sub-seasonal variability in the environmental factors

necessary for TC formation exists between early- and late-starting and -ending seasons.

Quantile regression is used to evaluate long-term trends in Atlantic TC season length. No

statistically-significant trend in Atlantic TC season length exists for the years 1979 to

2013 independent of the subset of the basin considered. No trend in Atlantic TC season

length between 1979 and 2007 – the period studied by Kossin (2008) – exists when

considering the entire Atlantic basin. Linear regression, as applied to June and

November monthly-mean reanalysis data, is used to examine sub-seasonal

environmental variability between early- and late-starting and -ending TC seasons.

Early-starting and late-ending seasons are associated with environmental conditions that promote an increased likelihood of TC development along the preferred genesis pathways for such events.

While confidence in these results is relatively high, they only explain a small portion of the total variation in Atlantic TC season length. More research is needed to understand how variability on all scales influences season length and the predictability of Atlantic TC season length.

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1. Introduction

Every year, multiple meteorological organizations, research groups, and private firms release predictions of the number of tropical storms, hurricanes, and major hurricanes they expect to form that year, particularly within the North Atlantic basin. Other attributes of tropical cyclone (TC) activity, however, such as when the first TC will form or how long the season will last, are typically not forecasted. Officially, the Atlantic TC season begins on 1 June and ends on 30 November. Over 97% of TC activity within the Atlantic basin occurs between these two dates (HRD 2015). However, as assessed utilizing the National Hurricane Center "best track" database (Jarvinen et al. 1984), the average first TC formation for the period 1979-2013 occurred on 25 June and the average last TC formation occurred on 5 November. The question thus remains: what causes some seasons to be significantly shorter or longer than average?

It is worthwhile to consider whether there could be a relationship between the period over which the conditions necessary for TC development are present at one of more locations and the length of the TC season. Gray (1968, 1979) identified six necessary but not sufficient criteria for TC development: sea surface temperatures (SSTs) greater than or equal to 26.5°C, abundant lower- to mid-tropospheric relative humidity, conditional instability through a deep tropospheric layer, large lower tropospheric cyclonic relative vorticity, low vertical wind shear of the horizontal winds (roughly less than 10 m s^{-1} between the surface and tropopause), and displacement by at least 5° latitude poleward from the equator. These six conditions may be condensed (e.g., as done by Frank 1987 and others) into four: sufficiently large cyclone vertical

vorticity, weak vertical wind shear of the horizontal winds, SSTs greater than or equal to 26°C, and abundant lower- to middle-tropospheric relative humidity. The SST criterion may alternatively be expressed in terms of upper oceanic heat content and/or potential intensity, the latter of which is influenced by both SST and outflow-layer temperatures (e.g., Emanuel 1986). Likewise, the relative humidity and vertical wind shear criteria may alternatively be represented by ventilation, which reflects the extent to which environmental, middle-tropospheric low entropy air may be imported into the circulation of a TC or predecessor disturbance (e.g., Tang and Emanuel 2012, Tang and Camargo 2014).

Subsequent investigators (e.g., Bruyere et al. 2012, Camargo et al. 2007, Emanuel 2010, Emanuel and Nolan 2004, McGauley et al. 2011, Schumacher et al. 2009, Tang and Camargo 2014, and Tippett et al. 2010) have utilized these criteria to develop, apply, and evaluate genesis potential indices. Such indices are designed to highlight whether conditions favorable for TC development exist in observations or climate model outputs at one or more locations and times. For example, utilizing eight model outputs from the fifth Coupled Model Intercomparison Project (CMIP5), RCP8.5 experiment, Tang and Camargo (2014) utilized the ventilation index of Tang and Emanuel (2012) to estimate potential future changes in TC season length in the Atlantic basin and across the globe. In the context of these genesis potential indices, greater lower to middle-tropospheric moisture content, higher upper oceanic heat content and/or potential intensity, lower vertical wind shear, and sufficiently large cyclonic vertical vorticity indicate a greater potential for tropical cyclogenesis (e.g., McGauley and Nolan 2011).

Presumably, TC seasons that begin earlier and/or end later than normal are characterized by the presence of these necessary ingredients for TC formation at times when they are not typically present. The inverse is presumably true for seasons that begin later and/or end earlier than normal. In this work, we seek to examine whether this is true, particularly in the context of the genesis pathways that early- and late-season north Atlantic TCs typically follow (McTaggart-Cowan et al. 2008, 2013).

In addition to understanding the synoptic- to climate-scale factors that control the length of an individual TC season, it is worthwhile to consider whether the length of the Atlantic TC season has increased or decreased in recent decades. Focusing on an extended North Atlantic main development region (MDR) south of 30°N and east of 75°W, Kossin (2008) utilized quantile regression to identify changes in the annual distribution of Atlantic TC formation dates. Their findings (Kossin 2008, their Fig 4) suggest that the Atlantic TC season has increased in length by ten or more days per decade since 1950, reflective of both earlier starts and later ends to the season. However, it should be noted that the degree of uncertainty in these results is high given that the trends in both season start and end dates are significantly different than zero only to 80-90% confidence. This was attributed, albeit also with low confidence, to warmer May SSTs across the extended MDR, with an increase of the area-averaged SST by 1°C corresponding to as much as a twenty day shift in the start and/or end of the season. Though quantile regression is relatively insensitive to *individual* outliers, whether this result is due to several abnormally long TC seasons during the early-to-mid-2000s (e.g., 2003, 2005, and 2007) or represents a robust trend remains unclear. In

addition, whether this trend holds in whole or in part for the entire Atlantic basin also remains uncertain. This is particularly important given that many of the earliest and latest forming storms undergo genesis outside of the MDR with non-tropical (i.e., baroclinic) origins (McTaggart-Cowan et al. 2008, 2013).

Our research thus has two goals: 1) to evaluate whether the trends in TC season start and end dates found by Kossin (2008) hold when the period of record is extended to the present and the set of TCs considered is extended to the entire basin and 2) to evaluate how the synoptic- to planetary-scale distributions of proxies for the necessary conditions for tropical cyclogenesis vary between early- and late- starting and ending Atlantic TC seasons, particularly in light of the different genesis pathways followed by early- and late-season TCs. The remainder of this work is structured as follows. Section two outlines the data utilized and methodology followed in this study. Section three presents results regarding long-term trends in Atlantic TC season length for the period 1979-2013. Section four presents results regarding the synoptic- to planetary-scale conditions that characterize early and late starting and ending Atlantic TC seasons. A summary of the key findings of the work and a discussion of their implications is presented in section five.

2. Data and Methodology

In this study, we consider all Atlantic TC formations – including subtropical cyclones but excluding tropical depressions – contained within the National Hurricane Center "best track" database (Jarvinen et al. 1984) for the 35 year period between 1979

and 2013. This encompasses a total of 433 TC events. The year 1979 is chosen as the start of our analysis period for several reasons. First, this is the first year for which ERA-Interim reanalysis data (Dee et al. 2011), the use of which is described below, are available. Second, as one goal of this work is to examine whether the TC season length trends between 1980 and 2007 identified by Kossin (2008) continue into the present, we desire that the start of our period of record closely match that of Kossin (2008). We note that the sensitivity to a starting year of 1979 versus 1980 in the results to be presented is negligible (not shown). Furthermore, as routine geostationary satellite surveillance of TCs began in the mid-1960s (e.g., Neumann et al. 1999), it is unlikely that TCs were systematically missed over part or all of the period of record considered herein (e.g., Landsea 2007). Landsea (2007) also notes that advances in observational and analysis capabilities appear to be contributing to one additional Atlantic TC event per year since 2002, with many of their cited examples occurring at start or end of the TC season. While it is possible that this could influence both the results presented herein as well as those of Kossin (2008), no attempt is made to account for this possible change in classification practices.

To evaluate whether the trends in season start and end dates found by Kossin (2008) hold when the period of record is extended to the present and the entire basin is considered, we apply the method of quantile regression. In contrast to linear (or least squares) regression, which provides a method by which the nature of an assumed linear relationship between the means of grouped data can be evaluated, quantile (or percentile) regression (Koenker and Bassett 1978, Koenker and Hallock 2001) provides a

method for evaluating the nature of an assumed linear relationship for conditional

quantile functions. One common application of quantile regression is median

regression, though quantile regression need not be limited exclusively to the median (or

50th percentile) of a data set. Quantile regression has been applied in the atmospheric

sciences to examine long-term trends in Atlantic TC season length (Kossin 2008) and the

intensity of the most intense Atlantic basin TCs (Elsner et al. 2008). Quantile regression

considers the topology of the full dataset of TC events, rather than just the first and last

TCs for each season, thereby increasing the degrees of freedom of the statistical

analysis; furthermore, unlike linear regression, it is relatively insensitive to individual

outliers within the data (Kossin 2008).

Herein, quantile regression is first utilized to replicate the findings of Kossin

(2008), considering only TCs that formed within their extended MDR between 1980 and

2007. Quantiles between the 5th and 95th percentile, every 5%, are considered. This

analysis is then replicated for the period beginning 1979; as noted in the Introduction,

the results are found to be insensitive to this difference in start year. Next, to evaluate

whether the trends in season length identified by Kossin (2008) hold when the period of

record is extended to the present, the analysis is repeated with an ending year of 2013.

Subsequently, to evaluate whether the trends in season length identified by Kossin

(2008) hold when the set of TCs is extended to the full Atlantic basin, the analysis is

repeated for the periods of 1979 to 2007 and 1979 to 2013 when considering all Atlantic

basin TCs. Finally, the sensitivity in how changing the end of the period of record by one

year at a time is examined by repeating the analysis, over both Kossin (2008)'s extended

MDR and the full basin, for end years between 2002 and 2013. The 90th percentile

confidence interval is computed for each analysis utilizing bootstrapping with 200

surrogates.

To assess how the synoptic- to planetary-scale distributions of the necessary

conditions for TC formation vary between early- and late- starting and ending Atlantic

TC seasons, linear regression is utilized. The 10%, 25%, 75%, and 90% formation date for

each Atlantic TC season is first identified. These values are then linearly regressed

against SST, 850 hPa relative vorticity, 600 hPa relative humidity, 500 hPa geopotential

height, and 850-300 hPa vertical wind shear magnitude. Monthly mean SST data are

obtained from the NOAA Extended Reconstructed Sea Surface Temperature dataset,

version 3b, on a 2° latitude x 2° longitude grid (Smith et al. 2008). It should be noted

that this dataset differs slightly from that described by Smith et al. (2008) in that

satellite-derived SST data are not used in its composition so as to remove a cold SST bias

introduced by non-clear sky satellite SST retrievals. All atmospheric fields are obtained

from the ERA-Interim (Dee et al. 2011) reanalysis on an approximate 0.7° latitude x 0.7°

longitude grid. Sensitivity in the results to be presented to the choice of SST or

atmospheric reanalysis dataset is expected to be small but is not explicitly examined.

The results are insensitive to one isobaric level (50 hPa) shifts in the isobaric level(s)

over which atmospheric fields are considered (not shown).

Herein, linear regression takes the form:

$$\frac{\partial J}{\partial x} = \frac{\text{cov}(\mathbf{J}, \mathbf{x})}{\text{var}(\mathbf{x})} \tag{1}$$

This notation follows that of Torn and Hakim (2008), where the left-hand side of (1) represents the slope of the linear regression line between **J**, here defined as the nth percentile date, and **x**, here defined as the relevant oceanic or atmospheric field. Note that in (1), the long-term (1979 to 2013) means for each field are removed from both **J** and **x**. Thus, (1) enables the identification in changes in the nth percentile date as a function of changes in a given forcing. In (1), cov refers to the covariance between **J** and **x**, while var refers to the variance of **x**. In the analyses to follow (Section 4), the right-hand side of (1) is multiplied by the standard deviation of **x**, such that a one standard deviation change in **x** is responsible for a N day change in the nth percentile date. A student's t test is utilized to test whether the slope of the linear regression between **J** and **x** is non-zero to 90%, 95%, and 99% confidence.

Four sets of linear regression analyses between monthly mean values of each field and nth percentile formation date are conducted: (1) June monthly mean to 10th percentile formation date, (2) June and July monthly means to 25th percentile formation date, (3) October and November monthly means to 75th percentile formation date, and (4) November monthly mean to 90th percentile formation date. The results are found to be qualitatively similar between linear regressions conducted against the 10th and 25th percentile formation dates and between linear regressions conducted against the 75th and 90th percentile formation dates (not shown). Consequently, the results presented in Section 4 consider only linear regression computed between June monthly mean fields and the 10th percentile formation date and between November monthly mean fields and the 90th percentile formation date. Positive (negative) values of (1) thus indicate

that the start – as measured by the 10th percentile formation date – or end – as measured by the 90th percentile formation date – of the TC season becomes later (earlier) as a given oceanic or atmospheric field increases in value.

3. Results – Quantile Regression

Over the period 1979-2007, when considering only TCs that formed within the extended MDR of Kossin (2008), the Atlantic TC season increased in length by approximately 1.5 days per year, as primarily associated with a later end to the season (Fig. 1a). This trend is not statistically-significant to greater than 90% confidence, however. These results are nearly identical to those obtained for the period 1980-2007 considered by Kossin (2008, their Fig. 4c), with subtle differences resulting from the inclusion of 1979 and subtropical cyclone formations within our analysis.

We next sought to examine sensitivity in this result to the choice of end year. For the periods 1979-2001 and 1979-2002, no statistically-significant trend in season length can be identified (Figs. 1f,g). There is some indication of a broadening of the peak of the season – here defined as formation events occurring between the 25th and 75th percentiles – but this result is also not statistically-significant to greater than 90% confidence. Introducing subsequent seasons into the analysis (Figs. 1b-e), particularly the active 2005 season (Beven et al. 2008), results in the gradual development of the trend identified over the period 1979-2007 (Fig. 1a). This trend primarily results from five seasons (2001, 2003, 2004, 2005, and 2007) with season end dates – here represented by the 95th percentile TC formation date so as to increase the degrees of

freedom of the analysis – two to seven weeks later than the 1979-2013 average (Table 1).

Extending the end of the analysis through 2013 results in the elimination of the non-statistically-significant trend in season length identified for the period 1979-2007 (Fig. 1h). The below-average 2009 season (Berg and Avila 2011) contributes particularly strongly to the elimination of this trend (not shown), as manifest by a season end date approximately two-and-a-half weeks earlier than the long-term average (Table 2). This implies that the trend identified by Kossin (2008) is a function of the several abnormally-long TC seasons seen during the early-to-mid-2000s. It should also be noted that extending the analysis through 2013 decreases uncertainty in the results, as manifest by a narrower 90% confidence interval at both the start and end of the season.

When considering TC formation events across the entire Atlantic basin, no statistically-significant trend in season length is identified for the period 1979-2007 (Fig. 2a). For the periods 1979-2001 and 1979-2002, a non-statistically-significant trend towards seasons that are shorter by one day per year is identified (not shown). The comparatively longer seasons of 2003 through 2007 (Table 3) act to eliminate this trend but, unlike for the Kossin (2008) extended MDR, are insufficient so as to result in an identifiable trend toward longer seasons. Furthermore, no statistically-significant trend in season length is identified for the period 1979-2013 (Fig. 2b). The uncertainty in this result is somewhat less than that for the case when only TC formation events within the Kossin (2008) extended MDR are considered (c.f. Figs. 1h and 2b). Consequently, it is argued that the trend toward longer Atlantic TC seasons identified by Kossin (2008) is

not indicative of a robust long-term trend but is primarily the result of both the set of TC

formation events considered and end date of the analysis. Fluctuations in season length

therefore appear to be primarily controlled by interannual variability in the necessary

conditions for TC formation, particularly early and late in the season.

4. Results – Linear Regression

a. Early-starting seasons

Tropical cyclones that form before the 10th percentile date for each season

preferentially do so in the Gulf of Mexico, northwestern Caribbean Sea, and near the

southeastern United States coastline (Fig. 3). Note that the TCs within this composite

that form in the MDR are almost exclusively associated with later-starting Atlantic TC

seasons. The preferred genesis pathway for TCs that form in the preferred regions for

early-season development is weak tropical transition, as evaluated utilizing the genesis

pathway classification database of McTaggart-Cowan et al. (2013). For reference,

tropical transition (TT; Davis and Bosart 2003, 2004) occurs in environments in which

organized deep, moist convection upshear of an extratropical cyclone, through the

horizontal and vertical redistribution of potential vorticity, acts to weaken initially strong

vertical wind shear atop the surface low. If the cyclone is located over sufficiently warm

waters (SST $\geq$ 26°C) for a sufficiently long period of time ($\geq$ 24 h) and is of sufficient

intensity so as to foster wind-induced surface heat exchange (e.g., Emanuel 1987), an

initially cold-core extratropical cyclone may transform into a warm-cored TC.

In the preferred genesis locations for early-season Atlantic TCs, June monthly-mean SST is between 24-28°C (Fig. 4a), 600 hPa relative humidity is between 40-60% (Fig. 4c), 850 hPa relative vorticity is approximately zero (Fig. 4b), and the 850-300 hPa vertical wind shear magnitude is less than 10 m s^{-1} (Fig. 4e). Thus, in the June monthly mean, the SST and deep-layer vertical wind shear criteria for tropical cyclogenesis generally are met, whereas the precursor disturbance and middle tropospheric relative humidity criteria for tropical cyclogenesis generally are not met. Earlier-starting Atlantic TC seasons are associated with statistically-significant (to ≥ 90% confidence, as assessed utilizing a student's *t* test) increases in June monthly-mean 600 hPa relative humidity off of the coast of Florida (Fig. 4c) and June monthly-mean cyclonic 850 hPa relative vorticity in the eastern Gulf of Mexico (Fig. 4b). One standard deviation increases in 600 hPa relative humidity (7.5%; Fig. 5c) or 850 hPa relative vorticity (0.5 x 10^{-5} s^{-1}; Fig. 5b) are each associated with a six to nine day earlier start to the Atlantic TC season relative to its mean.

Further, earlier-starting Atlantic TC seasons are associated with a statistically-significant amplification of the June monthly-mean 500 hPa trough across eastern North America (Fig. 4d). A one standard deviation reduction in 500 hPa geopotential height (20 m; Fig. 5d) is associated with a six to nine day earlier start to the Atlantic TC season relative to its mean. We hypothesize that, in earlier-starting Atlantic TC seasons, a deeper mean 500 hPa trough across eastern North America results in an elevated likelihood that a given lower tropospheric frontal zone, along which TT may occur, will not dissipate until it reaches the regions in which early-season TC formation

preferentially occurs. We further hypothesize that, in earlier-starting Atlantic TC seasons, a deeper mean 500 hPa trough across eastern North America results in elevated middle tropospheric relative humidity as manifest through stronger quasi-geostrophic forcing for middle tropospheric ascent. Thus, though tropical cyclogenesis occurs on sub-synoptic to synoptic time scales, there exist statistically-significant sub-seasonal-scale conditions that promote an elevated or suppressed likelihood of early-season Atlantic TC formation.

The 10th percentile Atlantic TC formation date is also associated with statistically-significant linear correlations to non-local synoptic- to planetary-scale variability (Fig. 4). This is particularly evident in the subtropical and mid-latitude Southern Hemisphere and from the eastern Atlantic Ocean to eastern Asia in the mid-latitude Northern Hemisphere. It is unclear, however, as to whether the relationship between this variability, in whole or in part, and the 10th percentile Atlantic TC formation date is causal or merely associative in nature. The cause of this variability is also uncertain. The atmospheric and oceanic variability highlighted by Fig. 4 does not closely resemble that associated with any predominant planetary-scale modes of climatic variability known to the authors. Therefore, further research is necessary to identify what is responsible for the synoptic- to planetary-scale variability associated with early-starting Atlantic TC seasons.

b. Late-ending seasons

Tropical cyclones that form after the 90th percentile formation date for each season preferentially do so in in the western Caribbean Sea and subtropical western Atlantic

(Fig. 6). Late-season TCs that form in the subtropical western north Atlantic almost exclusively are the result of tropical transition, whereas TCs that form in the western Caribbean Sea either result from tropical transition or are of non-baroclinic origins. In the preferred genesis locations for late-season Atlantic TCs, November monthly-mean SST is between 24-28°C (Fig. 7a), 600 hPa relative humidity is between 30-60% (Fig. 7c), 850 hPa relative vorticity is approximately zero (Fig. 7b), and the 850-300 hPa vertical wind shear magnitude is between 10-20 m s^{-1} (Fig. 7e). Thus, in the November monthly mean, SST generally is sufficiently warm, deep-layer vertical wind shear is marginally favorable, and both middle tropospheric relative humidity and lower tropospheric relative vorticity are insufficiently large so as to promote tropical cyclogenesis.

To first order, late-ending Atlantic TC seasons occur during cool-phase El Niño-Southern Oscillation (ENSO; e.g., Bjerknes 1969 and subsequent works) events. This is manifest by a strengthened Walker circulation, as reflected in both November monthly-mean SST (Fig. 7a) and 600 hPa relative humidity (Fig. 7c) fields across the equatorial Pacific. A one standard deviation decrease in SST (1-2°C; Fig. 8a) and reduction in 600 hPa relative humidity (7.5-12.5%; Fig. 8c) in the eastern equatorial Pacific is associated with a six to nine day extension of the Atlantic TC season relative to its mean. For reference, note that the 90th percentile formation date exhibits a marginally statistically-significant (to 90% confidence; not shown) inverse linear correlation with the November mean value of the Oceanic Niño Index (L'Heureux et al. 2013). Coherent modes of variability in the subtropics and middle latitudes of the Northern and Southern Hemispheres that are associated with early-/late-ending Atlantic TC seasons (Fig. 7)

presumably stem in part from ENSO's influence upon the global circulation in boreal fall (e.g., Horel and Wallace 1981).

Focusing upon the Northern Hemisphere, late-ending Atlantic TC seasons are associated with a strengthened and westward-shifted lower tropospheric subtropical anticyclone in the eastern north Pacific. This is reflected in both November monthly-mean SST (Fig. 7a) and 850 hPa relative vorticity (Fig. 7b) fields. A one standard deviation reduction in 850 hPa relative vorticity (0.6×10^{-5} s^{-1}; Fig. 8b) north-northeast of Hawaii, with a corresponding one standard deviation increase (decrease) in SST (0.5°C; Fig. 8a) to the west (east), is associated with a three to six day extension of the Atlantic TC season relative to its mean. It is unclear, however, as to whether the relationship between this variability and the 90th percentile Atlantic TC formation date is causal or merely associative – e.g., through a common linkage to ENSO – in nature.

In closer proximity to where late-season Atlantic TCs form, late-ending Atlantic TC seasons are associated with an eastward shift and amplification of the November monthly-mean 500 hPa trough across eastern North America (Fig. 7d). A one standard deviation (30-40 m; Fig. 8d) increase (decrease) in 500 hPa geopotential height across the central United States (western north Atlantic) is associated with a three to nine day extension of the Atlantic TC season relative to its mean. Downstream, late-ending Atlantic TC seasons are associated with an amplification of the November monthly-mean 500 hPa ridge across Greenland (Fig. 7d). A one standard deviation increase in 500 hPa geopotential height near Greenland (70-80 m; Fig. 8d) is associated with a three to six day extension of the Atlantic TC season relative to its mean. Like-natured variability

in November monthly-mean 850 hPa relative vorticity (Fig. 7b) and 850-300 hPa vertical wind shear magnitude (Fig. 7e) accompany the above-described modulation in the longwave pattern during late-ending Atlantic TC seasons.

Finally, late-ending Atlantic TC seasons are associated with reduced 500 hPa geopotential height, increased 600 hPa relative humidity, and increased 850 hPa relative vorticity across the northwestern Caribbean Sea (Figs. 7b-d). A one standard deviation increase in 600 hPa relative humidity (7.5-10%; Fig. 8bc), reduction in 500 hPa geopotential height (10 m; Fig. 8d), and increase in 850 hPa relative vorticity (0.4 x 10^{-5} s^{-1}; Fig. 8b) is associated with a three to six day extension of the Atlantic TC season relative to its mean.

The modulation of the November monthly-mean atmospheric pattern across the Atlantic Ocean during late-ending Atlantic TC seasons is consistent with an increased frequency of slow-moving extratropical cyclones across the subtropical western Atlantic. Given sufficiently warm SSTs, this is consistent with an increased likelihood of late-season TT occurrence in the subtropical western Atlantic so long as deep, moist convection associated with a given extratropical cyclone is able to locally reduce the 850-300 hPa vertical wind shear on meso- to synoptic time scales (e.g., Davis and Bosart 2003, 2004). We hypothesize that the modulation of the November monthly-mean atmospheric pattern across the Atlantic Ocean during late-ending Atlantic TC seasons also promotes an elevated likelihood that a given lower tropospheric frontal zone will not dissipate until after reaching the western Caribbean Sea, thereby increasing the likelihood of a weak late-season TT event in that portion of the basin. What results in an

increased likelihood of non-baroclinic TC formation in the western Caribbean Sea late in the Atlantic TC season, however, is uncertain from this analysis.

5. **Conclusions**

The length of the Atlantic TC season varies from year to year with some seasons significantly shorter or longer than the average. Kossin (2008) suggested that the duration of the year over which TCs formed within an extended main development region of the Atlantic basin has increased over the course of the last several decades. Herein, we first determined whether this trend holds over the full Atlantic basin as well as when the period of record is extended to the present. Subsequently, we examined the monthly-mean synoptic- to planetary-scale conditions associated with early and late starting and ending Atlantic TC seasons.

Quantile regression was applied to National Hurricane Center "best track" data (Jarvinen et al. 1984) for the 35 year period between 1979 and 2013 to first replicate and subsequently expand upon Kossin's (2008) research. Extending the end of the analysis through 2013 resulted in the elimination of the trend toward longer Atlantic TC seasons identified by Kossin (2008). This trend appears to be a function of several abnormally-long Atlantic TC seasons during the early-to-mid-2000s. Why these particular seasons were considerably longer than normal is unclear, however, and the question was left for future study. Furthermore, when TC formation events across the entire Atlantic basin were considered, no statistically-significant trend in season length was identified for any time period considered between 1979-2007 and 1979-2013.

Variations in season length therefore appear to be primarily controlled by interannual variability in the necessary conditions for TC formation, particularly early and late in the Atlantic TC season.

Utilizing linear regression applied to June and November monthly-mean reanalysis data, synoptic- to planetary-scale variability associated with early and late starting and ending Atlantic TC seasons was identified. Earlier starting Atlantic TC seasons are associated with a deeper June monthly-mean 500 hPa trough across eastern North America. We hypothesize that this promotes a greater likelihood that lower tropospheric fronts – along which TT may take place given otherwise favorable environmental conditions – will not dissipate until they intrude upon the regions in which most early-season Atlantic TCs form. There also appear to be statistically-significant correlations between the 10th percentile Atlantic TC formation date and non-local synoptic- to planetary-scale variability. However, the true extent of the linear relationships and the cause(s) of the variability are uncertain and worthy of future study. Late-ending Atlantic TC seasons primarily occur during cool-phase ENSO (e.g., La Niña) events. A later end to the Atlantic TC season is associated with an eastward-shift and amplification in the November monthly-mean 500 hPa trough across eastern North America and the presence of above-normal 500 hPa heights near Greenland. It is this modulation of the atmospheric pattern that is hypothesized to increase the likelihood of both late-season TT events across the subtropical Atlantic and baroclinically-influenced tropical cyclogenesis across the western Caribbean Sea.

These results, while associated with statistically-significant (to ≥90% confidence) linear relationships, only explain a small portion of the total variation in Atlantic TC season length. For instance, in order for TCs to form, environmental conditions must locally be favorable on shorter time scales of several hours to a few days. Thus, while the results elucidate variability in the large-scale conditions necessary to support TC formation that is associated with early-starting and late-ending Atlantic TC seasons, knowledge of variability on smaller spatiotemporal scales is necessary to more completely quantify variability in Atlantic TC season length. Furthermore, there may also be other modes of sub-seasonal to climatic modes of variability that influence Atlantic TC season length that are not indicated by the analyses presented in this work, though we note that no statistically-significant relationship between Atlantic TC season length and TC count exists (not shown). Regardless, the results may be useful, particularly from a preparation standpoint, to people and financial interests located in coastal regions near the preferred locations for early- and late-season Atlantic TC formation.

The results presented in this manuscript motivate a number of future studies aimed both at better understanding past, present, and future variability in TC season length and at quantifying the large-scale conditions (and the predictability thereof) that promote early-starting and late-ending TC seasons. For instance, how well do monthly-mean anomalies from individual Atlantic TC seasons project upon the linear regression analyses presented herein? What results in multiple successive short or long Atlantic TC seasons, such as was observed in the early 2000s? Case studies of both early- and late-starting and -ending seasons may provide insight toward addressing these questions.

Furthermore, the methods utilized in this study can be readily adapted to understand long-term trends in season length and large-scale variability contributing to early-starting and/or late-ending seasons in other oceanic basins that feature well-defined TC seasons. These methods may also be readily adapted to subsets of cyclones – e.g., only TCs with maximum sustained surface winds of ≥ 33 m s^{-1} – for any basin in which TCs occur. Finally, given appropriate downscaling and statistical sampling methods, these methods may be applied to climate model outputs to evaluate potential future changes in both TC season length and early- and late-season genesis pathways under a wide range of emissions scenarios.

The results presented herein also motivate an investigation into the predictability – or lack thereof – of the large-scale conditions that promote early-starting and late-ending tropical cyclone seasons, whether in the Atlantic basin or elsewhere. In other words, are early- and/or late-season tropical cyclone formation events primarily driven by synoptic-scale variability, which projects to some extent onto the monthly-mean fields considered in this study, or by climate-scale variability that is inherently more slowly-evolving (and thus more predictable) than that on the synoptic-scale? For the Atlantic basin, apart from an inverse linear relationship between the 90th percentile formation date and the November ENSO state, no statistically-significant linear relationships are identified between the 10th and 90th percentile formation dates and individual modes of climate variability (not shown). This argues against dominant climate-scale controls. However, it is possible that such relationships may exist if combinations of multiple modes of climate variability are considered. Further

investigation is planned to address the intrinsic predictability of comparatively short and
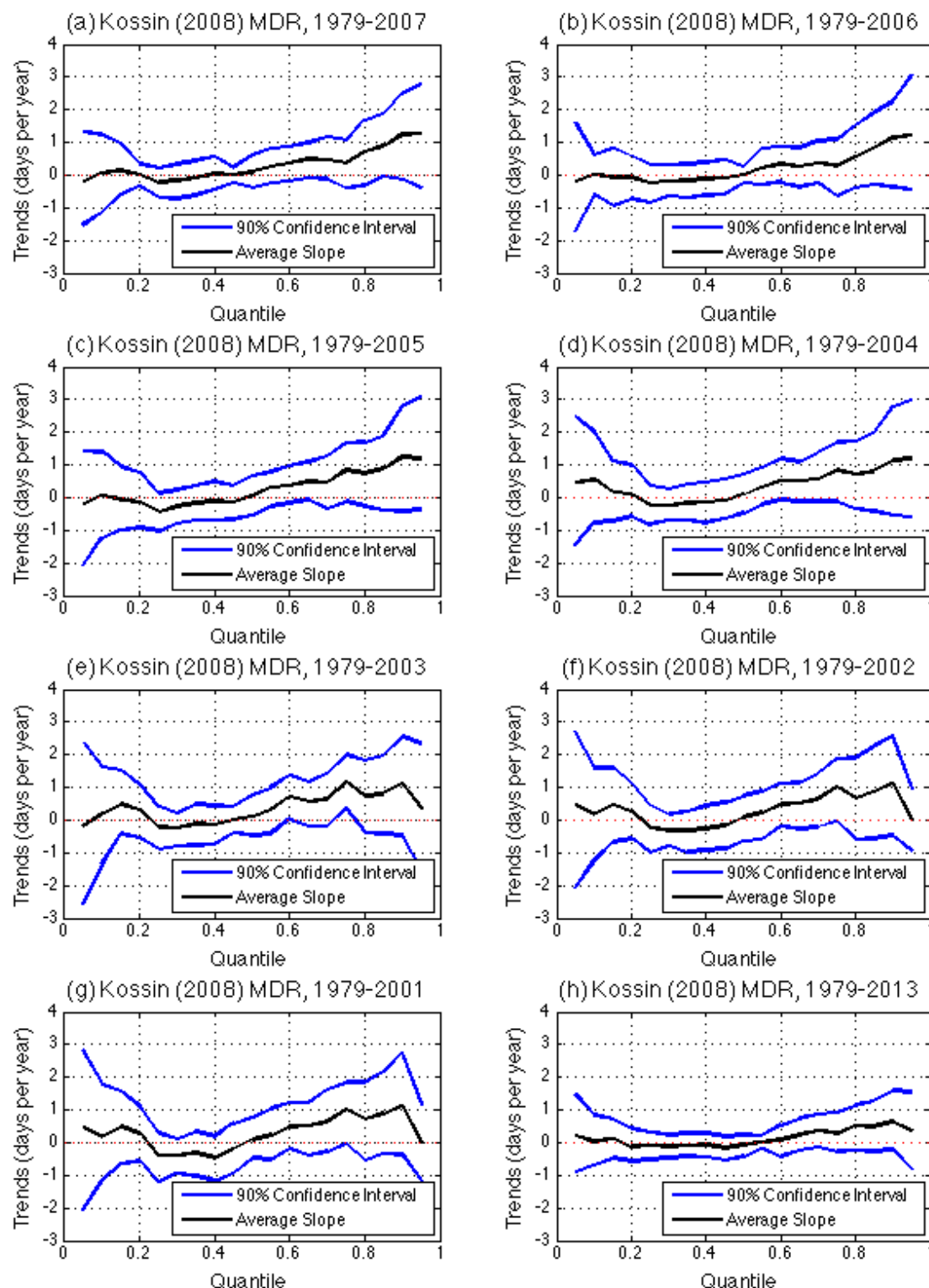
long Atlantic TC seasons.

Figure 1. Trends in tropical cyclone formation dates in the region south of 30°N and east of 75°W used by Kossin (2008), at the 0.05-0.95 quantiles. Trends are based on the periods (a) 1979-2007, (b) 1979-2006, (c) 1979-2005, (d) 1979-2004, (e) 1979-2003, (f) 1979-2002, (g) 1979-2001, and (h) 1979-2013. Blue line indicates 90% confidence interval.
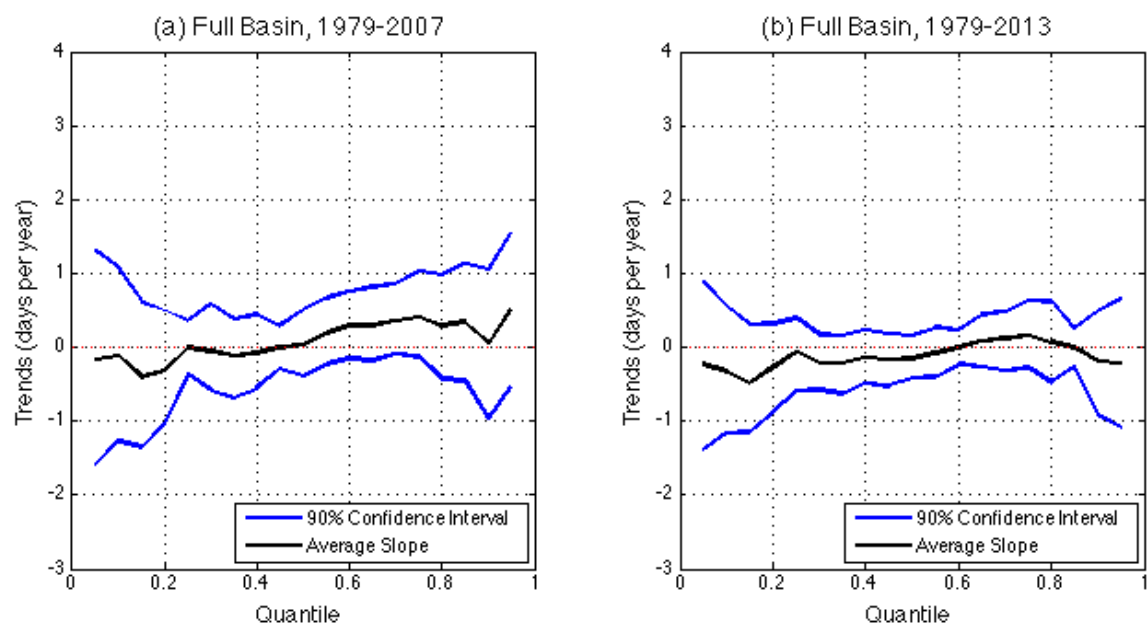
Figure 2. Trends in tropical cyclone formation dates for the full Atlantic basin, at the 0.05-0.95 quantiles. Trends are based on the periods (a) 1979-2007 and (b) 1979-2013. Blue line indicates 90% confidence interval.
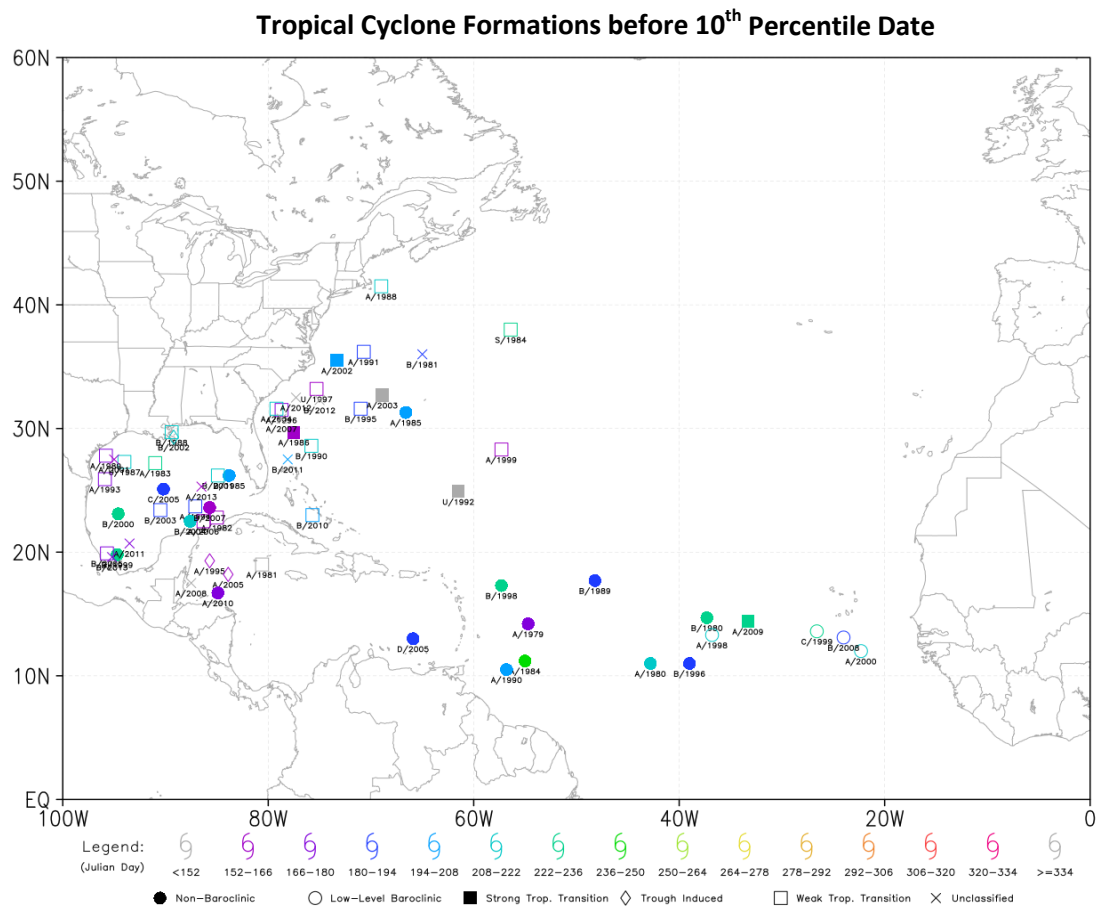
Figure 3. Tropical cyclone (TC) genesis location for storms forming before the 10th percentile date for each season. Colors indicate Julian date of formation. Symbol indicates genesis pathway as determined by McTaggart-Cowan et al. (2013). Label by each TC indicates the first letter of the storm's name followed by the year of formation.
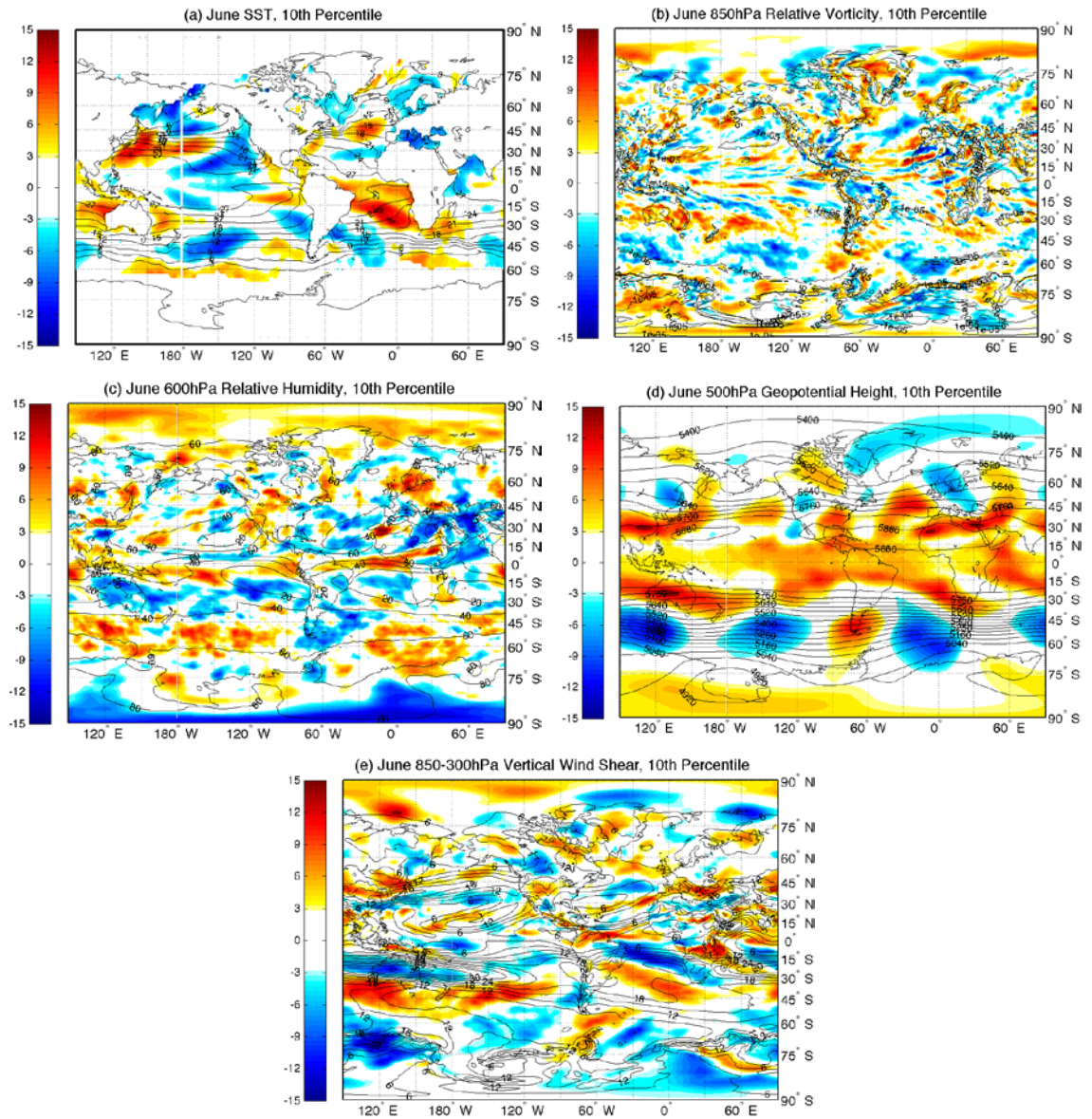
Figure 4. Linear regression (colored shading) of the 10th percentile formation date for each Atlantic TC season against June monthly-mean (a) SST (°C), (b) 850hPa relative vorticity (x10^{-5} s^{-1}), (c) 600hPa relative humidity (%), (d) 500hPa geopotential height (m), and (e) 850-300hPa vertical wind shear magnitude (m s^{-1}). Blue shading indicates a shift towards an earlier start date while red shading indicates a shift towards a later start date with a one standard deviation increase in the stated variable. Relative vorticity values are opposite in the southern hemisphere. Contours show composite (1979-2013) June monthly-mean values for each variable.
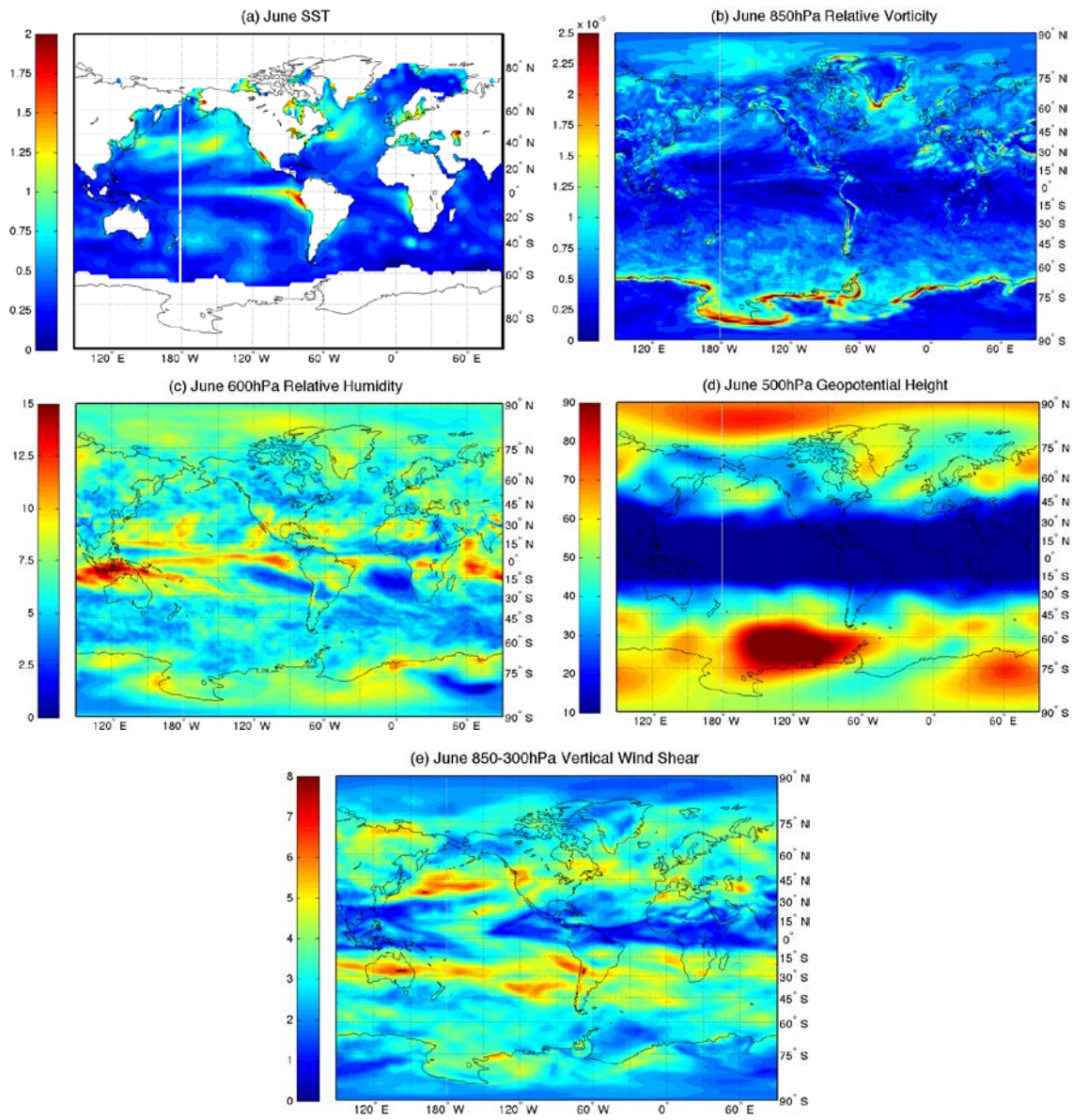
Figure 5. Standard deviations in June monthly-mean (a) SST (°C), (b) 850hPa relative vorticity (x10⁻⁵ s⁻¹), (c) 600hPa relative humidity (%), (d) 500hPa geopotential height (m), and (e) 850-300hPa vertical wind shear magnitude (m s⁻¹) between 1979-2013.

Figure 6. Tropical cyclone (TC) genesis location for storms forming after the 90th percentile date for each season. Colors indicate Julian date of formation. Symbol indicates genesis pathway as determined by McTaggart-Cowan et al. (2013). Label by each TC indicates the first letter of the storm's name followed by the year of formation.

Figure 7. Linear regression (colored shading) of the 90th percentile formation date for each Atlantic TC season against November monthly-mean (a) SST (°C), (b) 850hPa relative vorticity (x10^{-5} s^{-1}), (c) 600hPa relative humidity (%), (d) 500hPa geopotential height (m), and (e) 850-300hPa vertical wind shear magnitude (m s^{-1}). Blue shading indicates a shift towards an earlier end date while red shading indicates a shift towards a later end date with a one standard deviation increase in the stated variable. Relative vorticity values are opposite in the southern hemisphere. Contours show composite (1979-2013) November monthly-mean values for each variable.

Figure 8. Standard deviations in monthly-mean November (a) SST (°C), (b) 850hPa relative vorticity (x10^{-5} s^{-1}), (c) 600hPa relative humidity (%), (d) 500hPa geopotential height (m), and (e) 850-300hPa vertical wind shear magnitude (m s^{-1}) between 1979-2013.
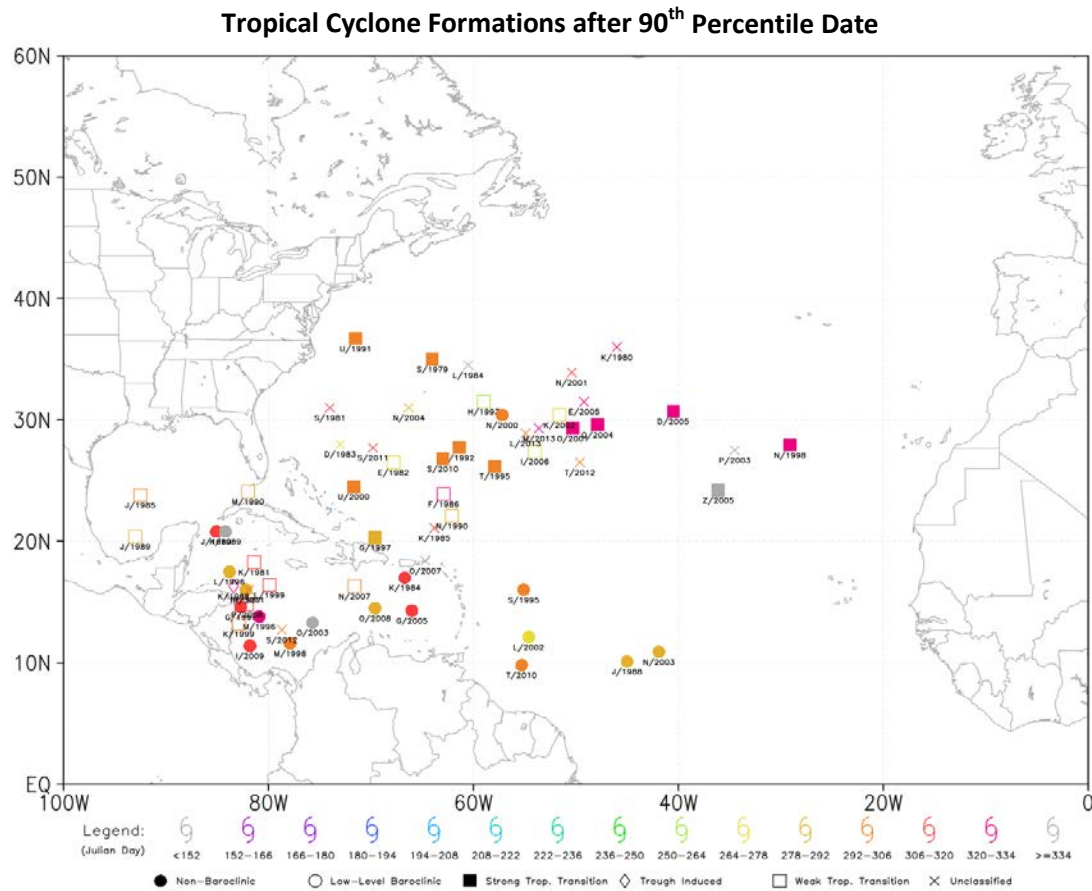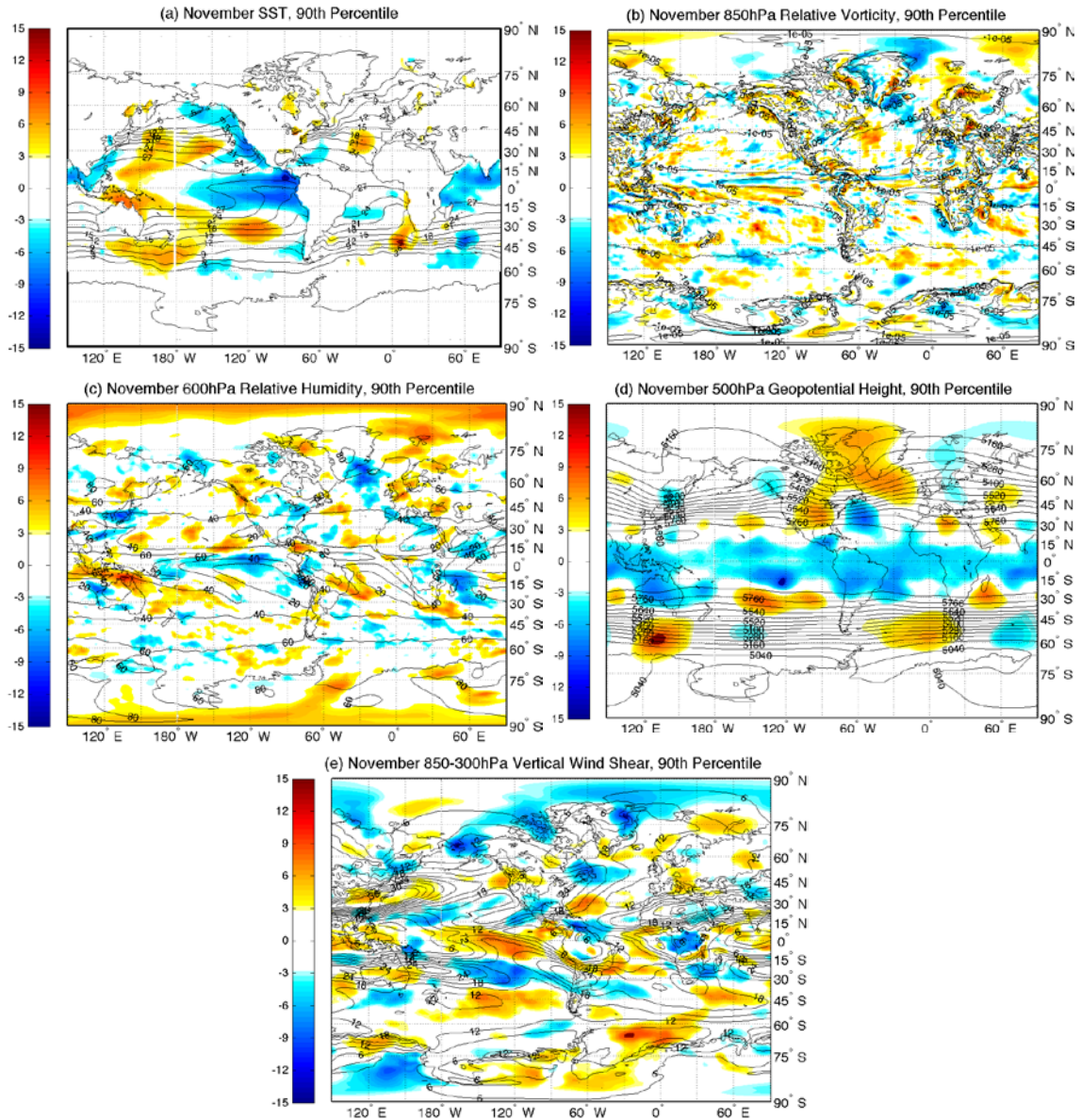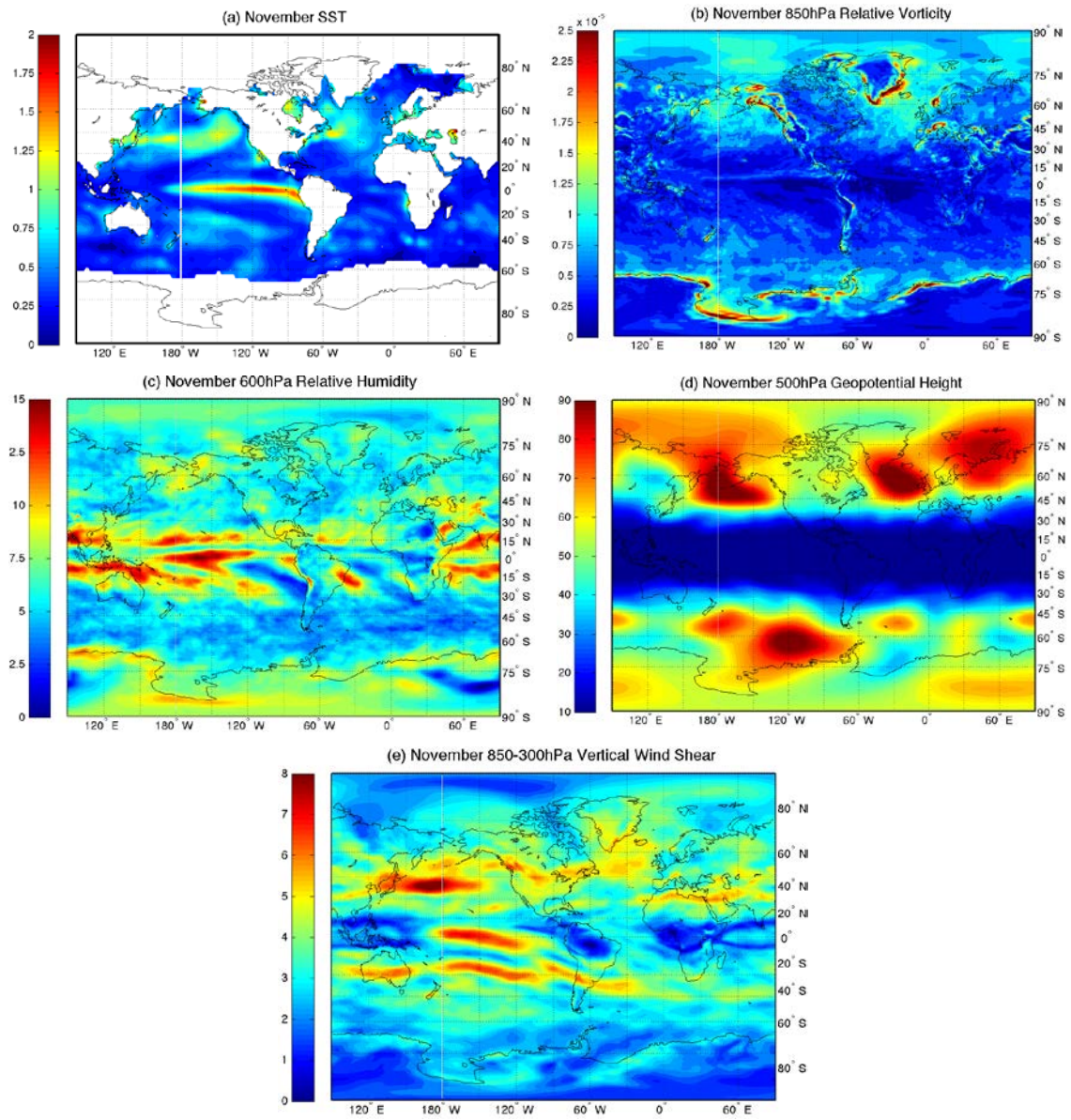
Season	5th Percentile Formation Date	95th Percentile Formation Date
2001	August 19	November 14
2002	August 30	September 22
2003	July 26	November 18
2004	August 11	October 31
2005	July 9	December 5
2006	August 8	September 24
2007	August 19	November 28
1979-2013 average	August 7	October 16

Table 1: 5th and 95th percentile TC formation dates for TCs forming within the extended MDR of Kossin (2008) for the years 2001-2007. For reference, the 1979-2013 average 5th and 95th percentile TC formation dates are provided in the bottom row.

Season	5th Percentile Formation Date	95th Percentile Formation Date
2008	July 19	October 12
2009	August 12	September 29
2010	August 13	October 29
2011	August 7	October 21
2012	August 2	October 16
2013	July 14	November 8
1979-2013 average	August 7	October 16

Table 2: As in Table 1, except for 2008-2013.

Season	5th Percentile Formation Date	95th Percentile Formation Date
2001	July 16	November 10
2002	July 27	September 22
2003	June 8	October 29
2004	August 6	October 24
2005	June 30	November 20
2006	June 28	September 22
2007	May 25	November 10
1979-2013 average	July 10	October 24

Table 3: As in Table 1, except for TCs forming within the full Atlantic basin.

REFERENCES

Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163-172.

Berg, R. J., and L. A. Avila, 2011: Atlantic hurricane season of 2009. *Mon. Wea. Rev.*, **139**, 1049-1069

Beven, J. L. II, and coauthors, 2008: Atlantic hurricane season of 2005. *Mon. Wea. Rev.*, **136**, 1109-1173.

Bruyère, C. L., G. J. Holland, and E. Towler, 2012: Investigating the use of a genesis potential index for tropical cyclones in the north Atlantic basin. *J. Climate*, **25**, 8611–8626.

Camargo, S. J., K. A. Emanuel, and A. H. Sobel, 2007: Use of a genesis potential index to Diagnose ENSO effects on tropical cyclone genesis. *J. Climate*, **20**, 4819–4834.

Davis, C. A., and L. F. Bosart, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.*, **131**, 2730-2747.

Davis, C. A., and L. F. Bosart, 2004: The TT problem: forecasting the tropical transition of cyclones. *Bull. Amer. Meteor. Soc.*, **85**, 1657-1662.

Dee, D. P., and coauthors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553-597.

Elsner, J. B., J. P. Kossin, and T. H. Jagger, 2008: The increasing intensity of the strongest tropical cyclones. *Nature*, **455**, 92-95.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: steady-

state maintenance. *J. Atmos. Sci.*, **43**, 585-605.

Emanuel, K. A., 1987: An air-sea interaction model of intraseasonal oscillations in the tropics. *J. Atmos. Sci.*, **44**, 2324-2340.

Emanuel, K. A., 2010: Tropical cyclone activity downscaled from NOAA-CIRES reanalysis, 1908– 1958. *J. Adv. Model. Earth Syst.*, **2** (1), doi:10.3894/JAMES.2010.2.1.

Emanuel, K. A., and D. S. Nolan, 2004: Tropical cyclone activity and global climate. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 240–241.

Frank, W. M., 1987: "Tropical cyclone formation." Chapter 3, *A Global View of Tropical Cyclones*, Office of Naval Research, Arlington, Virginia, 53-90.

Gray, W. M., 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the Tropical Oceans*, D. B. Shaw, Ed., Royal Meteorological Society, 155–218.

Horel, J. D., and J. M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813-829.

Hurricane Research Division (HRD), cited 2015: "Tropical Cyclone FAQ: When is hurricane season?" [Available online at http://www.aoml.noaa.gov/hrd/tcfaq/G1.html].

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1984: A tropical cyclone data tape for the North Atlantic Basin, 1886-1983: Contents, limitations, and uses. *NOAA Technical Memorandum NWS NHC 22*, Coral Gables, Florida, 21 pp.

Koenker, R., and G. Bassett, 1978: Regression quantiles. *Econometrica*, **46**, 33-50.

Koenker, R., and K. F. Halloch, 2001: Quantile regression. *J. Econ. Perspect.*, **15**, 143-156.

Kossin, J. P., 2008: Is the North Atlantic hurricane season getting longer? *Geophys. Res. Lett.*, **35**, L23705.

L'Heureux, M. L., D. C. Collins, and Z.-Z. Hu, 2013: Linear trends in sea surface temperature of the tropical Pacific Ocean and implications for the El Niño-Southern Oscillation. *Clim Dyn.*, **40**, 1223-1236.

Landsea, C. W., 2007: Counting Atlantic tropical cyclones back to 1900. *Eos, Trans. Amer. Geophys. Union*, **88**, 197-203.

McGauley, M. G., and D. S. Nolan, 2011: Measuring environmental favorability for tropical cyclogenesis by statistical analysis of threshold parameters. *J. Climate*, **24**, 5968–5997.

McTaggart-Cowan, R., G. D. Deane, L. F. Bosart, C. A. Davis, and T. J. Galarneau, Jr., 2008: Climatology of tropical cyclogenesis in the North Atlantic (1948-2004). *Mon. Wea. Rev.*, **136**, 1284-1304.

McTaggart-Cowan, R., T. J. Galarneau, Jr., L. F. Bosart, R. W. Moore, and O. Martius, 2013: A global climatology of baroclinically influenced tropical cyclogenesis. *Mon. Wea. Rev.*, **141**, 1963-1989.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and G. R. Hammer, 1999: Tropical cyclones of the North Atlantic Ocean, 1871-1998. *Historical Climatology Series 6-2*, 206 pp.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2008: Improvements to

NOAA's historical merged land-ocean surface temperature analysis (1880-2006). *J. Climate*, **21**, 2283-2296.

Tang, B., and K. Emanuel, 2012: A ventilation index for tropical cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 1901-1912.

Tang, B., and S. J. Camargo, 2014: Environmental control of tropical cyclones in CMIP5: A ventilation perspective, *J. Adv. Model. Earth Syst.*, **6**, 115-128.

Tippett, M. K., S. J. Camargo, and A. H. Sobel, 2011: A Poisson regression index for tropical cyclone genesis and the role of large-scale vorticity in genesis. *J. Climate*, **24**, 2335–2357

Torn, R. D., and G. J. Hakim, 2008: Ensemble-based sensitivity analysis. *Mon. Wea. Rev.*, **136**, 663-677.