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INTER-DECADAL SHIFTS IN INTENSE EXTRATROPICAL CYCLONES IN THE NORTHERN HEMISPHERN

by

Timm Uhlmann

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Mathematics

at

The University of Wisconsin-Milwaukee

May 2016

ABSTRACT

INTER-DECADAL SHIFTS IN INTENSE EXTRATROPICAL CYCLONES IN THE NORTHERN HEMISPHERN

by

Timm Uhlmann

The University of Wisconsin-Milwaukee, 2016
Under the Supervision of Professor Kyle Swanson

Cyclones, both tropical and extratropical, have a large socioeconomic impact during any given year. Understanding the formation and evolution of these cyclones in the current climate therefore becomes imperative to minimize loss to property and life. Previous work by Kossin et al (2014) showed a significant poleward migration for the most intense tropical cyclones from 1982 to 2009. This sparks the interest in whether extratropical cyclones exhibit a similar trend within a changing climate. Data used stems from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Analysis for an analogous time period from 1980-2015. Tracking and identification of cyclones is performed using the 850-mb level relative vorticity field with procedures similar to that used by Hodges (1995, 1996, 1999) and then limited to 30 degrees North latitude and higher. A statistically significant shift in the most intense cyclones, defined separately for minimal central pressure and vorticity maxima, from the Pacific Oceanic basin to the Atlantic Oceanic basin is found.

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Introduction

Cyclones, both tropical and extratropical cause a large amount of socioeconomic impact during any given year. In Europe, winter time extratropical storms pose the second highest cause of insurance loss due to natural disasters, behind only tropical cyclones (Swiss Re, 2000). European storm Kyrill, which impacted Western, Central, and Eastern Europe in 2007 brought over 1 billion dollars in damage after intensifying over the northern Atlantic (Fink et al 2009).

With considerable impact comes the need to understand the formation and evolution of both types of cyclones, along with their role in a changing climate, in order to minimize loss of life and property and further the overall understanding involved in forecasting these events. In a previous study by Bengtsson et al (2006) on extratropical cyclones in a warming climate, an ensemble of three 30-yr integrations of the Max Planck Institute (MPI) coupled atmosphere–ocean model (OM; ECHAM OM) was used to compare storm tracks for the period 2070–99 with the control period 1960–89. They found that there was a general poleward shift in cyclone tracks during this period with little to no intensification. This is in agreement with other previous studies that utilized similar Lagrangian techniques studies such as Yin (2005) and Fischer-Bruns et al. (2005). Within this paper, intensification will be a reference to either the depth of the pressure field as estimated by the mean sea level pressure (MSLP) or the magnitude of the relative vorticity field at the 850 millibar level. This is in contrast to fields such as wind speed and precipitation, which are arguably equally important, particularly from the perspective of the public.

A study by Kossin et al. (2014), they found a poleward shift for the most intense tropical cyclones for both hemispheres in both the Atlantic and Pacific Ocean basins using the past 30 years of data spanning from 1982 to 2009. This observed shift in tracks for tropical cyclones begets the question of whether similar trends can be found in the movement of extratropical cyclones. Following these ties further then leads to other possible trend changes such as along with the general trends of other factors such as precipitation, location, etc. As is well documented, extratropical cyclones grow primarily from baroclinic instability and receive the majority of their energy from the conversion of potential energy, with relatively smaller contributions from latent heat release, (when compared to tropical systems). This potential energy is primarily derived from a difference in temperature, which is at its peak in the winter months, which is why most studies, including this one, focus on this time frame.

Studies on the change in extratropical cyclones in a changing climate include one conducted by Bengtsson et al (2009). Their analysis studied the general life cycles of extratropical cyclones and their overall structures by comparing the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis with a high resolution version of the ECHAM5 global climate model. They found that there was a general poleward shift between the model runs in regards to mid latitude cyclones, including comparisons to a previous paper. In terms of intensity as defined by central pressure, they found cyclones became a few mb deeper for the southern hemisphere during the winter months June, July, and August (JJA). Additionally, overall cyclone high wind speed increased slightly (~1m/s) during the winter months of the northern hemisphere and overall precipitation totals increased with the warming climate. Additionally, their work along with others showed an overall decrease in the number of most intense cyclones (Bengtsson et al 2006, Meehl et al 2007, Catto et al 2011). This has been thought to occur due to an uneven increase in surface heating, where the poles receiving more than areas further equator-ward, thus decreasing the overall temperature gradient and baroclinic instability.

The goal of this paper is to further investigate the overall structures of the extratropical cyclones utilizing storm tracking algorithms similar to those used by Hodges (1995,1996,1999). Additionally, the overall latitude change in extratropical cyclones will be revisited including a change in longitude associated with the oceanic basins of the Atlantic and the Pacific, as these provide the source for the most intense storms.

Methodology

Data

Utilized in this study was data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Reanalysis, which contains real time data starting in 1979. For analysis of the extratropical system, only the winter months of December-February (DJF) are considered through 2015, as these provide the timeframe for the most intense storms. The initial data is imported and the Southern Hemisphere discarded in order to focus the overall study upon the Northern Hemisphere. Coordinates for all parameter fields were then compressed and centered upon the Northern Hemisphere with the North Pole as the center with a uniform 360x360 grid to form the polar map.

Feature Tracking & Identification

Historically, the choice of field for tracking cyclones varies but the traditional field for extratropical cyclones has been mean sea level pressure (MSLP) as utilized by Hodges (1995). However, some more recent studies have also utilized the 850-mb vorticity field to implement tracking of cyclones including Hodges (1996) and by Ayrault and Joly (2000). Advantages in tracking via the vorticity field have been found as it does a better job representing more prominent maximal features. Comparison between MSLP and vorticity has shown to produce similar results otherwise, although vorticity can be found to be generally better at describing smaller scale systems (Hoskins and Hodges 2002). This same study by Hoskins and Hodges (2002) also found that tracking via negative pressure anomalies generally created tracks more sensitive to overall more slow moving systems as opposed to positive vorticity anomalies at the 850-hPa level. Since this paper is primarily interested in the changes within the maxima of both pressure, vorticity, etc., tracking via the 850-mb vorticity is performed.

In general for feature tracking, the features in question must be identified for each given time step and then linked together to make a coherent picture of the evolution of that feature with time. Since tracking in this case is done via the 850-hPa vorticity, local maxima are tracked through time to identify the overall storm paths. A copy of the code used by Hodges (1995, 1996, 1999) was obtained, but due to the lengthy nature of the algorithms in Fortran, the essence of the method has been ported over to Matlab. Matlab was determined to be a better choice as the built in functions allowed for a drastic shortening and simplification of the overall code.

To identify the cyclones and track them, the following procedure was used:

1. For any given time step, contours were drawn around all regions with vorticity values exceeding $5x10^{-5}$.
2. Contours are then used to generate polygons and their corresponding (x,y) coordinate pairs along the $5x10^{-5}$ contours.
3. Local maxima are then identified within these contours and are considered to be the center of the cyclone.
4. Perimeter squared over area calculations are performed for all identified polygons corresponding to cyclones. A perfect circle will yield the result of 4 π from this calculation as shown in Equation 1.

$$\frac{P^2}{A} = \frac{(2\pi r)^2}{\pi r^2} = 4\pi \qquad (1)$$

where P is the perimeter, A is the area, and r represent the radius of a hypothetical circle.

5. The perimeter over area squared is then normalized by the perfect circle remainder and compared to the arbitrary value of 4. All cyclones identified for the time step exceeding this value are discarded.

The perimeter squared over area calculation is necessary to exclude filaments and other smaller scale disturbances that are present in the vorticity field that could contaminate the data. The normalization using the factor of 4π uses the assumption that any given cyclone is approximately circular in shape.

Next, each time step must be associated with the next to create a contiguous set of storm tracks. There are multiple available techniques for doing this and one of the simpler methods is the nearest neighbor approach (Blender et al. 1997). This approach functions optimally for relatively smaller number of tracked features, but as the overall number of possible storms increases so too does the problem of storm association as outlined in Fig. 1.

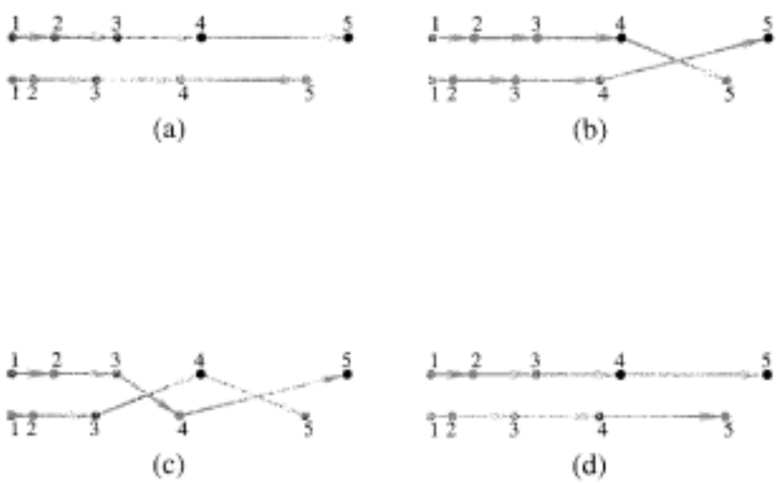

FIG 1. Taken from Hodges (1999), "Importance of feature point ordering on nearest neighbor searches: (a) result of nearest neighbor search for a particular feature-point indexing, (b) same as (a) except indexing at frame 4 swapped, (c) same as (b) except indexing swapped at frame 3, (d) result of cost function optimization using either (b) or (c) as initialization."

Since this study is deals with a large volume of possible cyclones for any given time step, this method was not considered to be efficient. Instead, the general tracking procedure used was that outlined by Hodges (1995,1996, 1999) which optimizes the overall track identification utilizing the minimization of a cost function. This cost function attempts to minimize the change in distance as we all as changes in the maxima of the observed feature, as outlined in Eq 2.

$$Max\ Consideration\ Value = \frac{1}{Degrees}\sqrt{(x_{t+1}-x_t)^2+(y_{t+1}-y_t)^2}+\frac{\left|\xi_{max}^{t+1}-\xi_{max}^{t}\right|}{\xi_{thresh}} \qquad (2)$$

where x and y are the coordinates of the vorticity maximums for the current and next time step, degrees is the maximum distance to search, in degrees, that we will consider, ξ_{max}^{t} is the vorticity maximum value found within a given contour, ξ_{thresh} is the initial contour threshold defined towards the beginning of the process as $5x10^{-5}s^{-1}$, and the maximum consideration value being the tracking algorithm constraint utilized to keep the search within approximately ten grid points. Utilizing this function, all the identified cyclones are labeled and paired with any corresponding cyclones from the previous time step. Any unidentified storms are then labeled as a new storm. The final step for the identification and tracking process then loops through to accumulate all the possible storms by their track number to get a cohesive set of track information across the year.

Once all the storms have been identified, the next calculation performed is the removal of all storms with maximum vorticity latitude locations originating further south than 30 degrees latitude. This is similar to the paper by Bengtsson et al (2009) in which all storms with origin under 25 degrees north are excluded for extratropical analysis. This is to eliminate any influence that tropical cyclones might have upon the extratropical analysis, including the possibility of a tropical cyclone migrating poleward and transitioning over to extratropical cyclone. That said, there is currently no measure in place to account for systems that started in the tropics but didn't reach identification criteria and/or their peak until they were well within the extratropics. However, given the relatively high latitude limit imposed upon the definition of extratropics, this effect was considered to be minimal. After this is done, all storm tracks that do not last longer than 96 hours, are removed. This further limits storms considered to those that are sufficiently developed to last for four days as well as acting as an additional filter for anomalously identified storms caused by brief anomalies in vorticity.

Extratropical Cyclone General Structure

The analysis conducted for the general structure of extratropical cyclones will initially consider the structure of the extratropical cyclone in general, before moving on to the top 100 most intense storms for the entire period. Most intense storms have been defined separately as either the minima in MSLP or maxima in vorticity for the top 50 or 100 cyclones for each given time period. This separation sets up two separate cyclone analyses. It should be further noted that storms defined by either definition do not necessarily coincide as maxima in relative vorticity will tend to be further south following the conservation of absolute vorticity.

Pressure

Pressure for this section is assumed to mean the MSLP. Pressure trends for all storms found in the analysis shows an initial value around 1008 mb two days ahead of the minima in pressure with a gradual deepening towards the time of the minima, and the greatest rate of intensification around 6-12 hours prior. Following the time of minimum, the overall rate of occlusion is less than the rate of intensification, ending the 48-hour period around 1006 mb, with the primary discrepancy being the deepening and filling in the 6 hours surrounding the minimum, as identified in Fig 2.

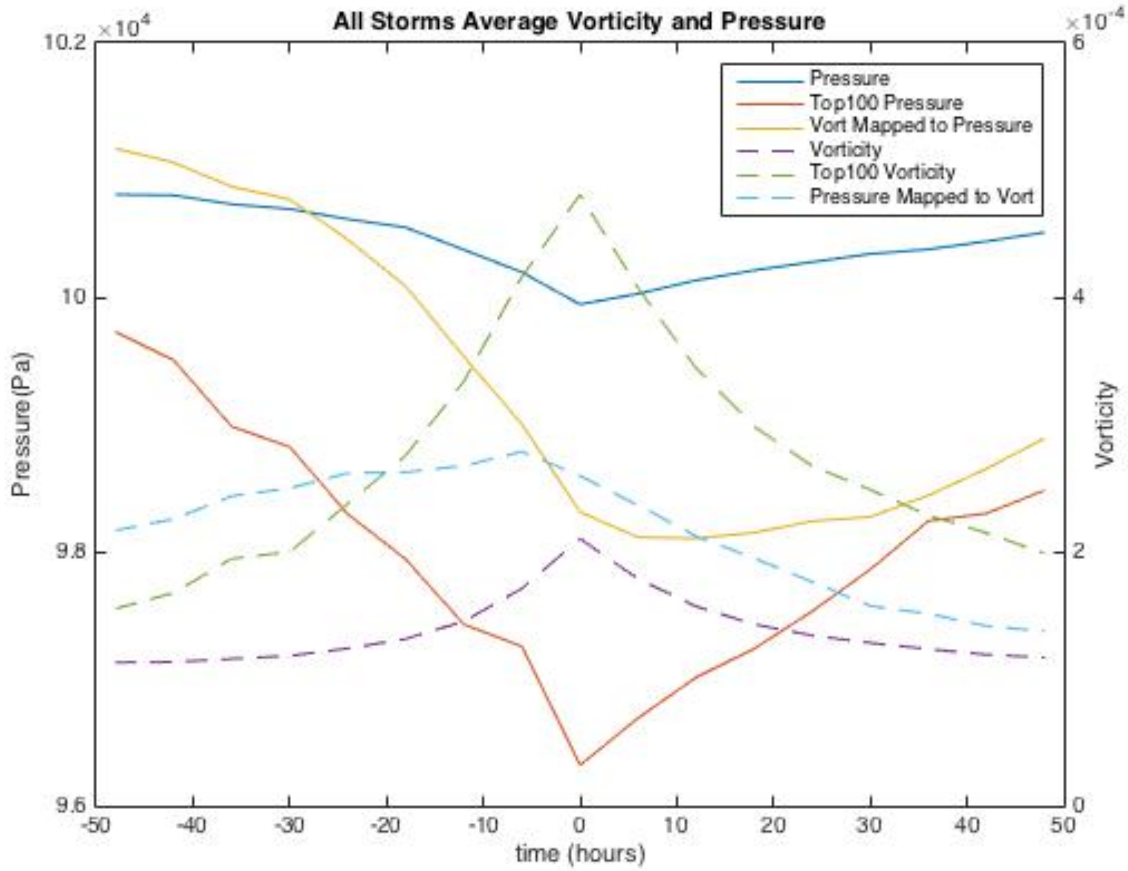

FIG 2. Shown is the comparison of mean sea level pressure (solid lines) and vorticity (dashed lines) centered around the time of peak intensity. Pressure lines are those of all storms (blue), average of top 100 most intense by pressure (red), and the average pressure corresponding to the top 100 vorticity centered cyclones (yellow). Similarly, vorticity is mapped by average of all cyclones (purple), most intense (green), and vorticity corresponding to the pressure centered storms (light blue).

Analysis then continues into the pressure trends of the top 100 most intense storms, as identified by pressure, and shows an expected overall deepening in values. Setting them apart from the overall trends, the most intense cyclones show a much stronger deepening rate leading into the the time of minimal pressure. Similar to the average, the top 100 most intense storms follow a similar structure in the overall pressure rise rate following the time of the minima, implying these systems can be expected to last significantly longer as the pressure gradually rises.

Perhaps the most interesting is the third pressure trend shown in Fig 2 show the trend of pressure along the most intense storms identified by their vorticity value. Of particular note is the fact that the initial pressure readings exceed that of the average cyclone by a few millibars before rapidly deepening as the vorticity value begins to increase, eventually exceeding the average storm at around 24-30 hours before the minima. Additionally, there is a notable offset in the peak time of the maximum vorticity when compared to the minimum in pressure of approximately 6-12 hours. Previous work conducted by Temperton (1973) suggests that this could be in part predicted as the scale of extratropical cyclones is great enough that the mass field will adjust to the wind field during geostrophic adjustment. Following the time of the minimal pressure, the occlusion of the cyclone is significantly slower than average, with an average increase of just 1-2 millibars in the 24 hour period following the minima, quickly closely the gap in pressure towards the top 100 deepest pressure cyclones.

Vorticity

The vorticity values exhibit a similar set of interesting behaviors. The average cyclone intensifies by only a small margin relative to the most intense cyclones, ranging from the initial average around $1.35\text{x}10^{-4}$ s^{-1} to $1.65\text{x}10^{-4}s^{-1}$. The top 100 most intense storms, as defined by the central vorticity, instead exhibit a significant increase in vorticity after a comparable start to the average cyclone, rapidly intensifying in the 24-30 hour window preceding the maximum value to $4.81\text{x}10^{-4}$ s^{-1}. This is a substantial increase from the average cyclone and is notably reflected in the corresponding, but slightly delayed, strong deepening rate of the MSLP corresponding to the most intense vorticity cyclones.

Similar to the pressure being mapped to the most intense vorticity cyclones, the corresponding vorticities were mapped to the deepest MSLP cyclones for comparison. The overall vorticity values were around 60-80% higher than the average cyclone, including being initially higher than the highest vorticity cyclones. Again a shift of approximately 6-12 hours is exhibited with the peak vorticity value being achieved before the pressure value. Following the time of the peak for these cyclones, the rate of decay is greater than the initial rate of intensification leading up to the cyclone's end. Overall, the general increase and persistence of the vorticity values during the deepest MSLP storms suggests that although vorticity plays a part in the eventual deepening of an extratropical cyclone, a slow and persistent vorticity field is necessary for the deepest extratropical cyclones.

Latitude

One possible explanation considered for the discrepancy in the trends of pressure and vorticity sorted storms is the discrepancy in latitude. As shown in Fig 3, the average latitude of the most intense storms sorted by vorticity is significantly further south at times of peak intensity than those sorted by pressure. Assuming the conservation of absolute vorticity, the plotted relative vorticity at 850 mb would be expected to be higher at lower latitudes as the Earth vorticity component of absolute vorticity increases. Performing the calculation between the two latitudes for relative vorticity yields a result on the order of 10^{-5}, which is a full order of magnitude below the observed difference. The implication is that the discrepancy in vorticity between the two sets of storms cannot be wholly explained by a shift in latitude.

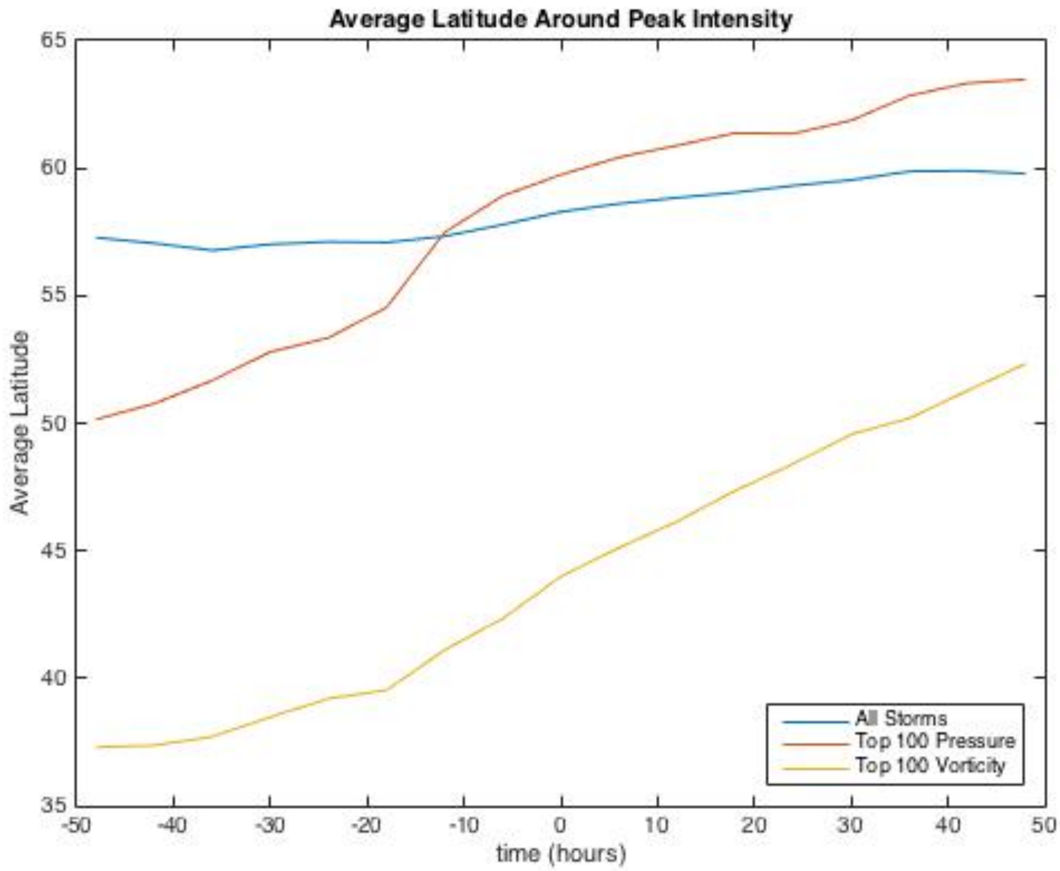

FIG 3. Shown are the average latitude trends for all storms(blue), top 100 intense storms as identified by pressure (red), and top 100 storms as identified by vorticity (yellow).

Precipitation

Precipitation wise the average has its expected value well below that of the most intense storms using either classification. That said, there is a significant increase in the overall precipitation for storms identified by the vorticity maxima as opposed to pressure minima. This may again be a result of the fact that the storms identified by their vorticity maxima are up to ten degrees further south which will place them into warmer environments with significantly more available moisture.

The most intense storms exhibit markedly different structures, with those using MSLP containing a distinctly asymmetrical pattern compared to the much more symmetrical vorticity centered storms. For the most intense vorticity related storms, the swift collapse of the precipitation formation is likely due to the similar decay in the primary lifting mechanism leading to occlusion behind the values of peak intensity. For the storms related to pressure, this is not as clear as the lowered vorticity values associated with these storms would indicate a possibly a larger system with lesser gradients, thus allowing precipitation formation to remain more widespread and consistent through the lifecycle of the storm.

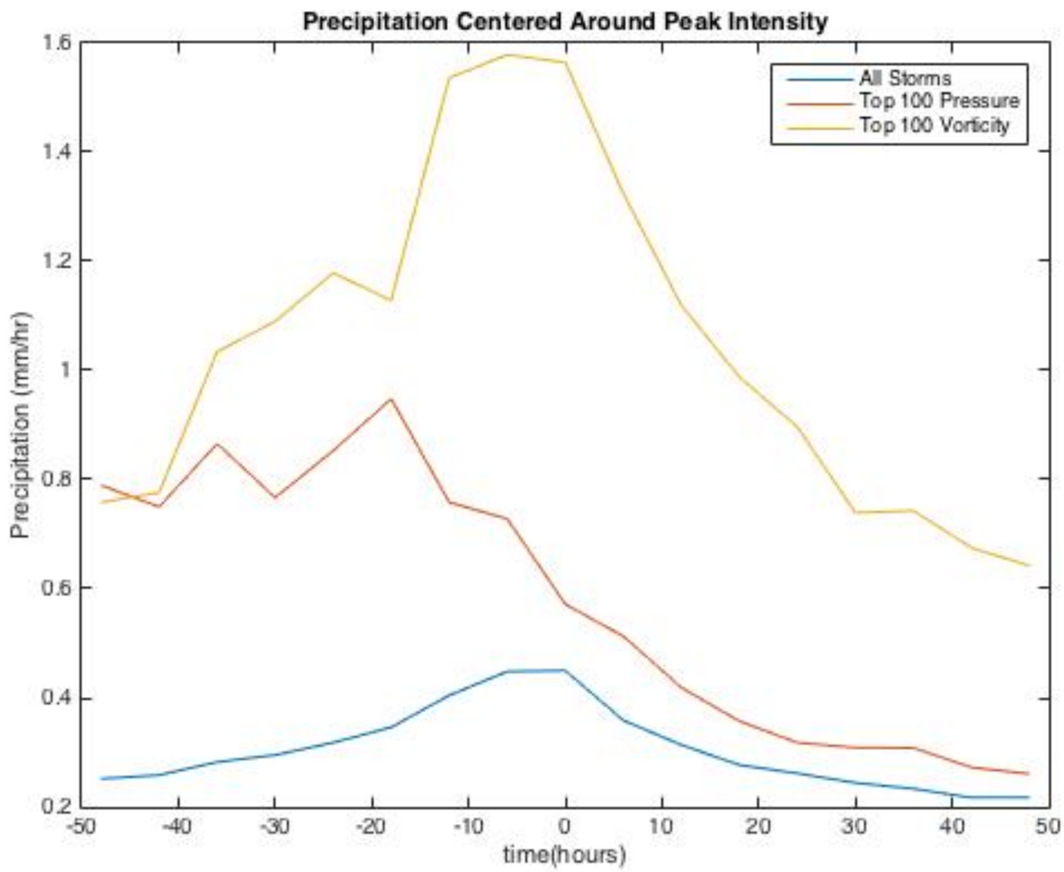

FIG 4. Area averaged precipitation in mm/hr around peak intensity as averaged around all storms (blue), top 100 pressure centered (red), and top 100 vorticity centered (yellow).

The analysis of these variables agrees thus far with previous research for the ERA-Interim Reanalysis as conducted by Bengtsson et al (2009) who conducted a similar analysis on the structure of extratropical cyclones using the 50 most intense storms, as defined by vorticity values, and defining extratropical storms as those with latitudes greater than 25 degrees. Their results are summarized in Fig 5.

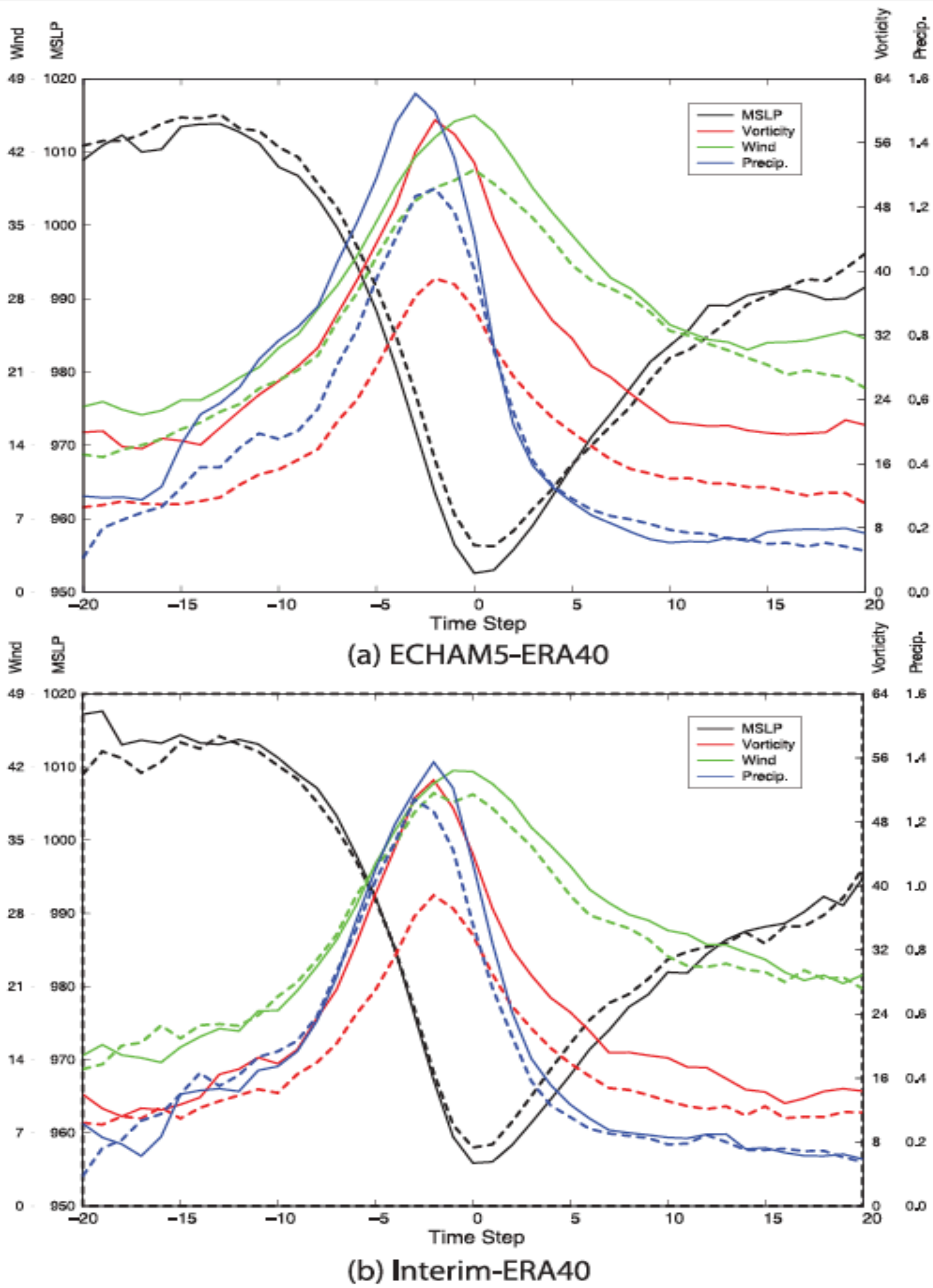

FIG 5 Taken from Bengtsson et al (2009): "(a) Life cycle composites of the 100 most intense storms, identified in T42 j850, for the NH DJF for T213 ECHAM5 in 20C (solid line) and ERA-40 (1979–2002) (dashed line); (b) life cycle composites of the identically same 50 most intense storms in the Interim reanalysis (solid line) and ERA-40 (dashed line). Parameters shown are MSLP (hPa; black), j850 (1025 s21; red), 925-hPa winds (m s21; green), and area-averaged total precipitation (mm h21;blue)."

Trends in 5-year Intervals

The preliminary analysis of extratropical cyclones explores the effects of sorting via minima in MSLP and maxima in vorticity. From this point we will address the evolution of extratropical cyclones with time in sets of 5 years starting in 1980 and ending in 2015. Each set of five years results in approximately 250-300 identified storms which are then further sorted into the top 50 most intense storms, representing the top ~20%, once again identified separately by both pressure and vorticity.

Pressure and Vorticity Trends

The top 50 average across each five-year period yields result very similar to the general structure found for extratropical cyclones with a rapid deepening and filling in the six hours to either side of the minima. Pressure minima for these cyclones are approximately 10 mb weaker than the average for the top 100 storms, but this is to be expected due to the averaging in general. For the top 50 storms, the time period of 2000-2005 shows the highest minimal pressures while the 2010-2015 period exhibits the lowest as shown in Fig. 6. The difference between the two can not be considered statistically significant however.

The average vorticity trends are also similar in structure with a near symmetrical rate of intensification and diminishment around the time of peak vorticity with the greatest rates in the 12-18 hours around the peak as provided by Fig. 7. The three most intense storms identified are in the five year periods of 1980-1985, 1995-2000, and 2010-2015, with differences overall too small to be considered statistically significant. These result do not support the conclusion that the most intense storms are getting more intense as time progresses.

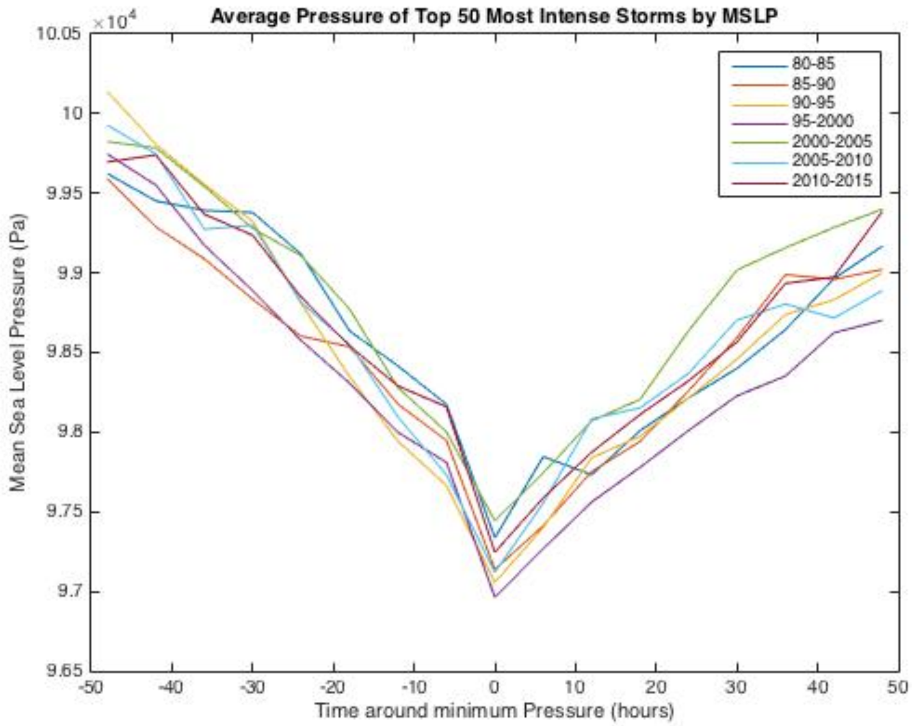

FIG 6. Average MSLP around the time of peak intensity, defined by pressure, for the top 50 storms of each 5 year period.

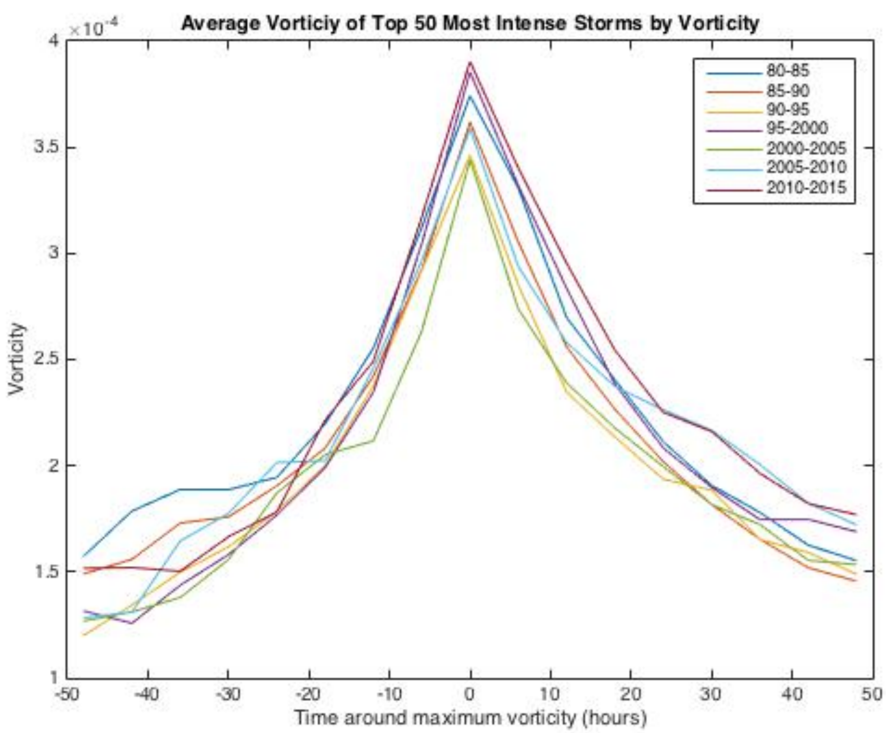

FIG 7 Average 850-mb relative vorticity values around the time of peak intensity as defined by vorticity for the top 50 most intense storm of each 5 year period.

Cross Referenced Vorticity & Pressure

The most intense vorticity and MSLP storms were also cross referenced by mapping the vorticity to the most intense MSLP defined storms and the MSLP values to the most intense vorticity defined storms. For pressure intense storms, the greatest rate of change in vorticity comes after the time of the peak with a rapid de-intensification of the central vorticity maximum as the storm's energy begins to diminish. Interestingly, unlike the previous averaged analysis, not all of the peaks in vorticity coincide as they range between 0-12 hours, implying that the time of the peak vorticity could be a few hours closer to the time of minimum MSLP. The rate of decay for the storms is similar however, while the initial rate of intensification varies considerably more.

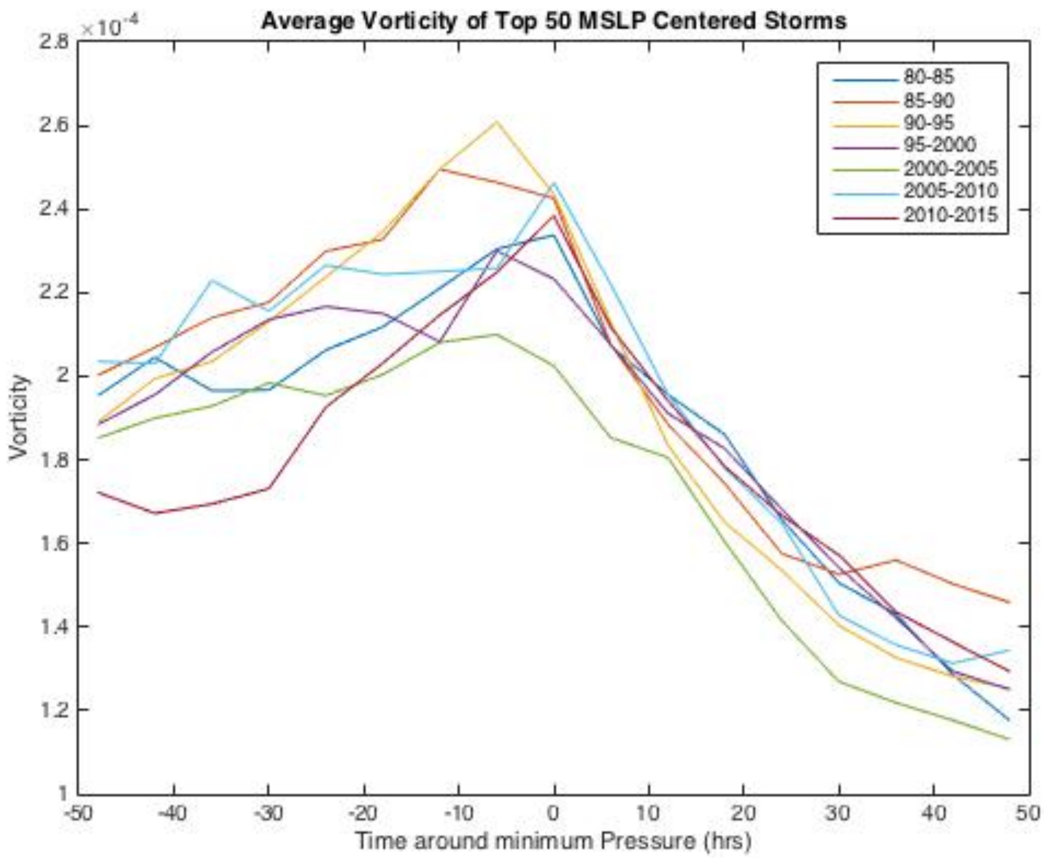

FIG 8. Average 5 year 850-mb vorticity trends for the top 50 most intense storms, defined by pressure, for each 5-year period.

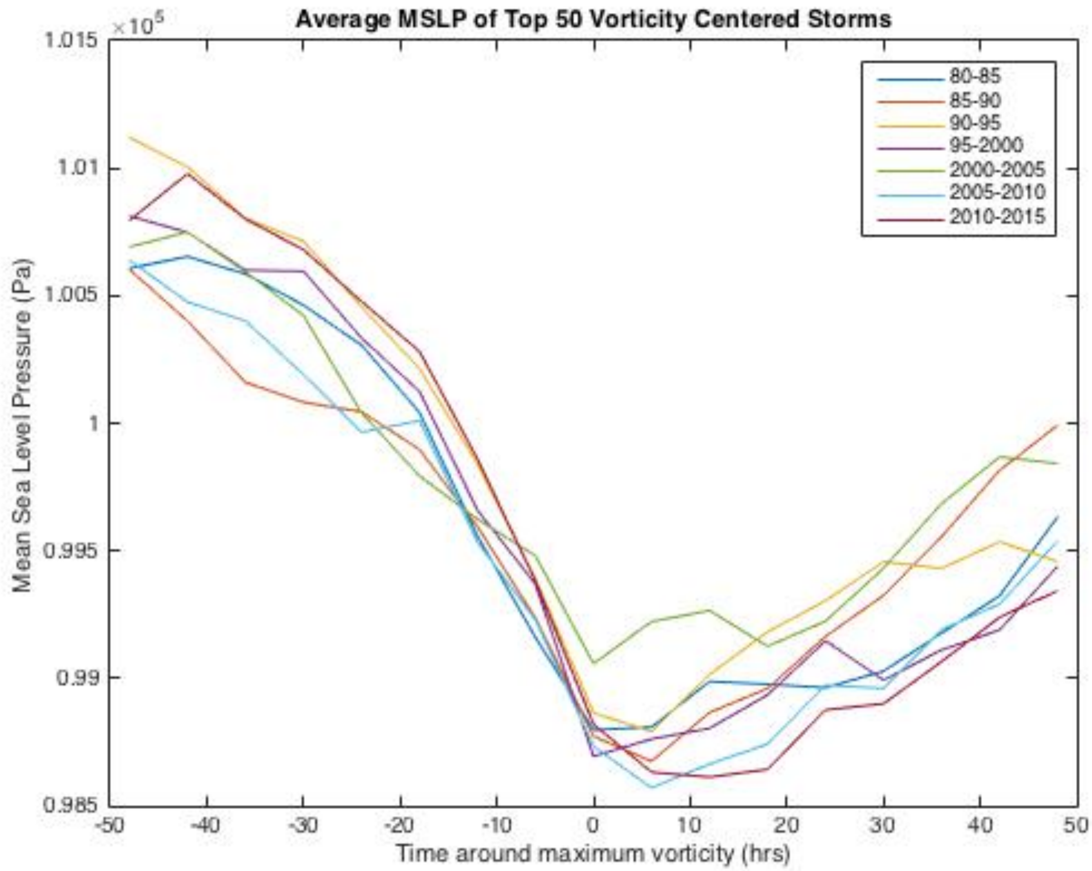

FIG 9. Average 5-year MSLP trends for the top 50 most intense storms, defined by vorticity, for each 5-year period.

Similarly, for the overall pressure trends associated with the times of maximal vorticity, the rate of most rapid deepening occurs in the 18 hours before the time of the minimal pressure followed by a time of relative uncertainty as not all 5 year averages hit their minimal pressure at the same time. The offset is as great as six to twelve hours. The average rate of deepening for the 18 hours leading up to the vorticity maximum corresponds to a drop of 0.47 mb/hr with a standard deviation of .09 mb/hr. The timing of the peaks shown with these trends likewise exhibit no uniformity as a number of 5 year averages hit their minima up to 6-12 hours after the vorticity maximum, but a few, namely the 2000-2005 and 2010-2015 trends are closer to time zero, coinciding with the time of maximal vorticity. Pinpointing the exact timing and correlation between the two is not possible with the given dataset however, due to the 6-hour time step. Following the time of the minimum, the filling of the low pressure system is uncertain for for a period behind the time of the minimum as not all of the peaks coincide, but if the last eighteen hours of the 48-hour period are considered, the fill rate is approximately 0.17 mb/hr with a standard deviation of 0.07 mb/hr.

Neither trend supports the conclusion that storms are getting more intense in terms of vorticity nor in terms of pressure over the time period of the data set. However, it does show that there is a decent amount of variability in the correlation between the two parameters for extratropical cyclones on the order of approximately a day (24 hours).

Latitude Trends

Extratropical cyclones have been suggested to be moving poleward in previous research (Bengtsson et al 2009), similar to the poleward shift of tropical cyclones as a result of the expanding tropical zone with a warming climate (Bengtsson et al 2006, Yin 2005, Fischer-Bruns et al 2005). Although the analysis of storm tracks based upon latitude is beyond the scope of this paper, the average latitude around both the time of pressure maxima and vorticity minima are calculated and shown in Figs 10 and 11 respectively.

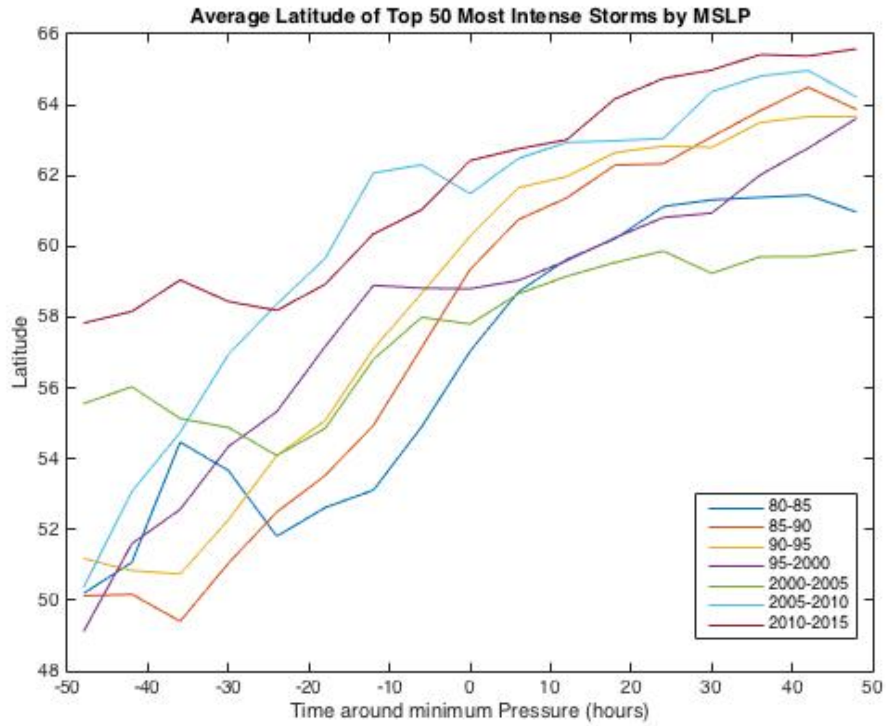

FIG 10. Average latitude of the top 50 most intense storms as defined by MSLP for each 5 year period.

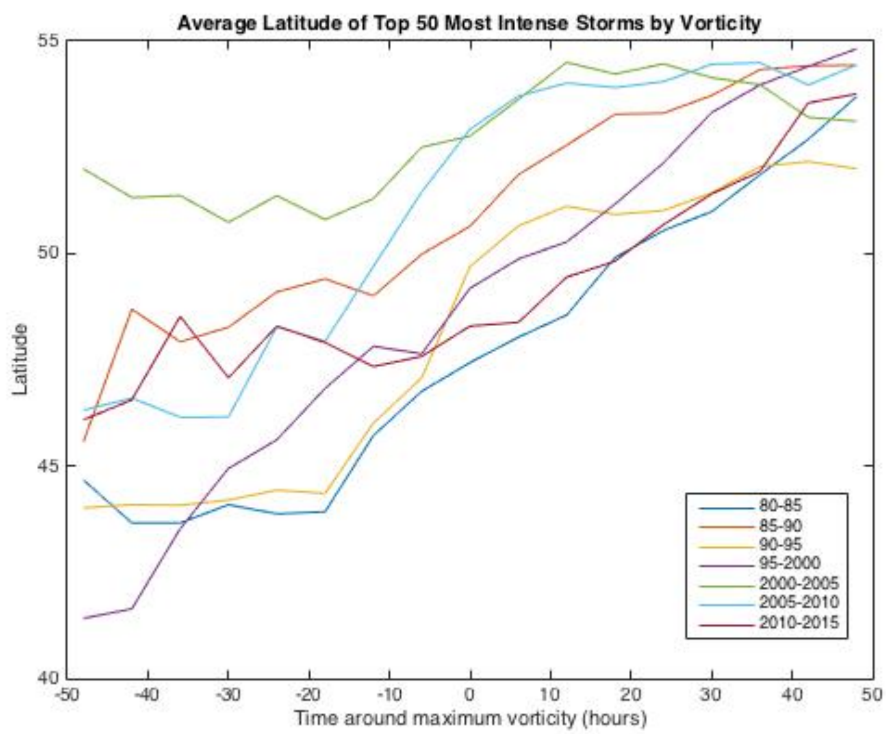

FIG 11. Average latitude of the top 50 most intense storms, as defined by vorticity, for each 5-year period.

Of note in this analysis is that for the storms based upon pressure, the average storms from the past ten years (2010-2015) are in the upper latitudes starting around 24 hours before the time of the peak intensity, although the difference compared to the next two storms is only that of a degree. That said, the time period of 2000-2005 starts at a relatively high latitude, but concludes the 48 hour period at the lowest overall latitude in the data set. Therefore, although all the storms do travel further north during their lifetime, it is not possible to conclude that the average latitude increases, e.g. a poleward shift is occurring, for northern hemispheric storms based upon pressure.

For the storms based upon vorticity, the trend is even more convoluted as the latitude has no consistent pattern with each given 5-year average. A general increase in latitude is present over the life cycle of the storms, but as shown by the 2000-2005 period, there is a great variability in the overall track. Therefore, it is once again not possible to conclude that the most intense storms defined by vorticity maxima are shifting northwards either.

Precipitation Trends

Precipitation trends on the 5-year time scale average have also been computed to take note if the more recent years have had more precipitation in the most intense cyclones. In terms of pressure, the average extratropical cyclone has a great deal of variability with very few trends until the minimum in pressure is reached at which point there is a consistently rapid diminishment in the overall amounts of rainfall.

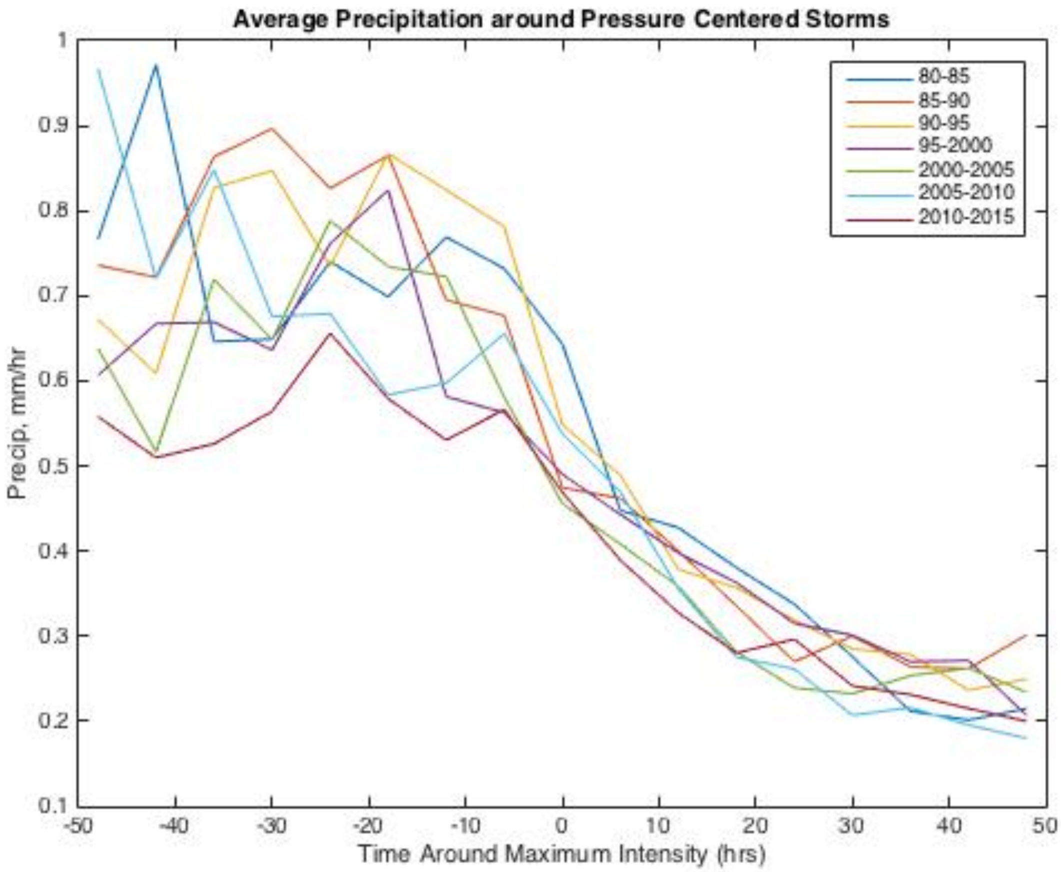

FIG 12. The average area average precipitation for each 5-year period for the top 50 most intense pressure defined storms.

Vorticity centered storms are more consistent in the overall structure through the time periods of the data and exhibit a more consistent increase and decrease in average rainfall around the time of maxima for each 5-year period. Once again, no consistent difference has been located.

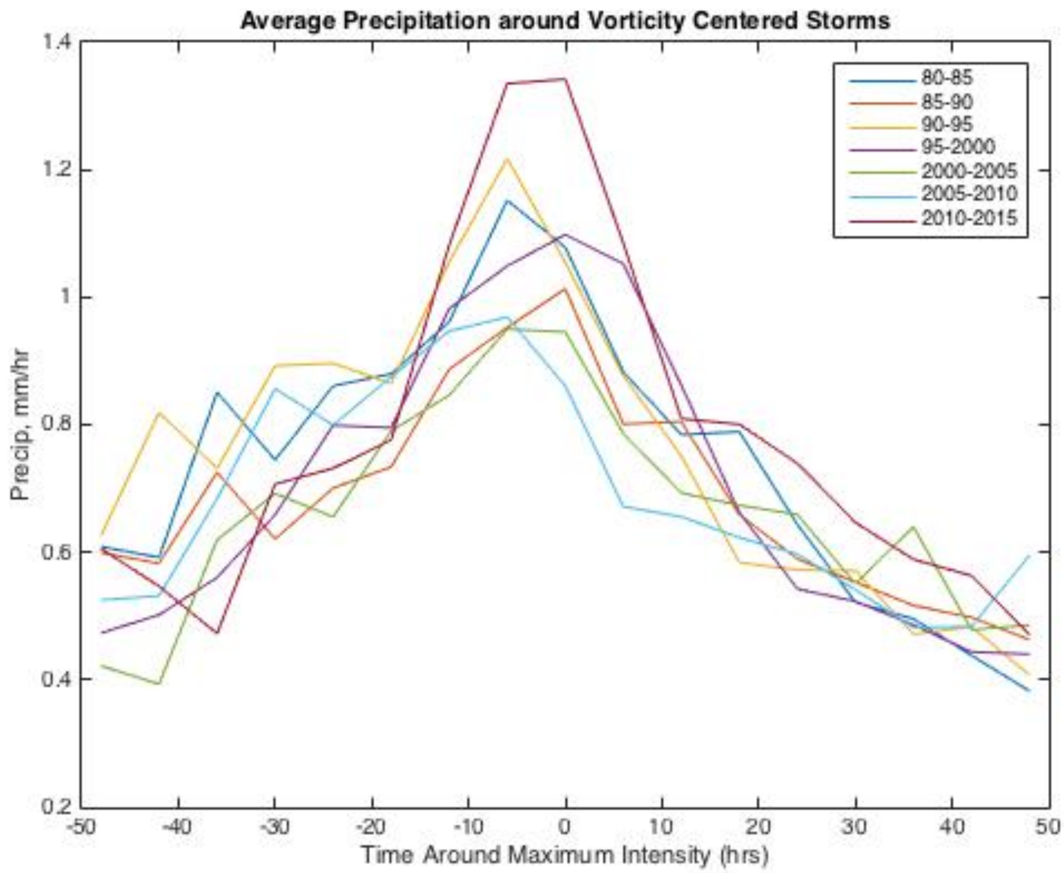

FIG 13. Area averaged precipitation for the top 50 most intense storms, defined by vorticity, for each 5-year period.

Tracks

The overall tracks of all extratropical cyclones need to be considered as well. Of note is the relatively higher concentration of extratropical cyclones over both the Pacific oceanic basin and the Atlantic basin towards northern Europe. The implication of these locations is that the majority of the most intense storms occur over the oceans, agreeing with previous results for the most intense extratropical cyclones (e.g. Bengtsson et al 2005).

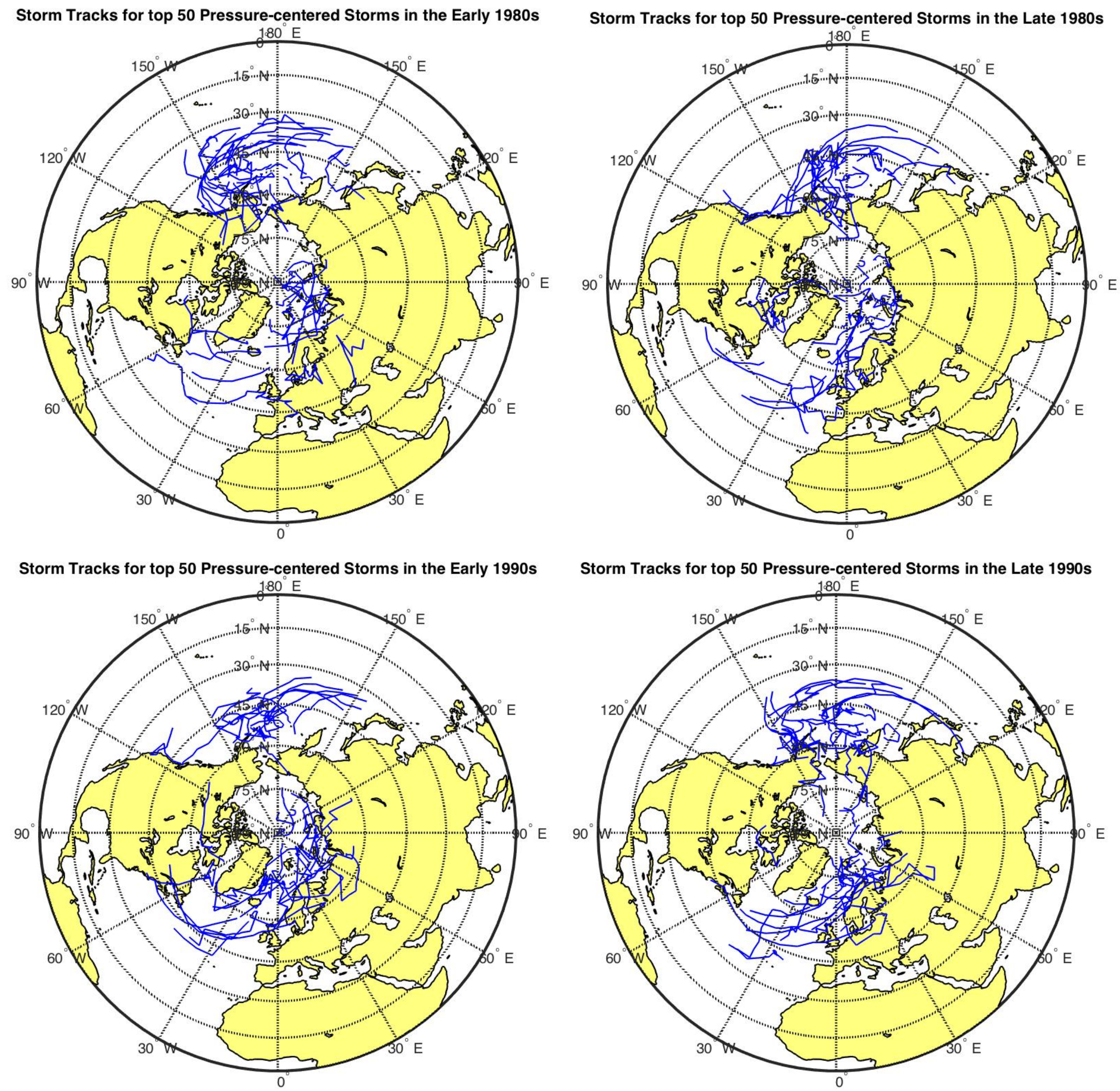

FIG 14. The track images of the top 50 most intense winter cyclones identified by MSLP plotted in the Northern Hemisphere around the North Pole, by 5 year periods with 1980-1985(top left), 1985-1990 (top right), 1990-1995 (bottom left), and 1995-2000(bottom right).

The most significant change over the course of time is the apparent shift of the most intense cyclones from the Pacific oceanic basin over to the Atlantic oceanic basin. The images containing the tracks show a trend of most intense storms tracks, for both MSLP and vorticity values, shifting away from the Pacific and towards the Atlantic. In order to investigate this further, bar graphs of the number of storms in each basin were created to show the evolution of the overall number of storms over time. From these, an apparent shift towards the Atlantic appears for the trend in the vorticity identified cyclones while remaining relatively unpronounced in the pressure cyclones.

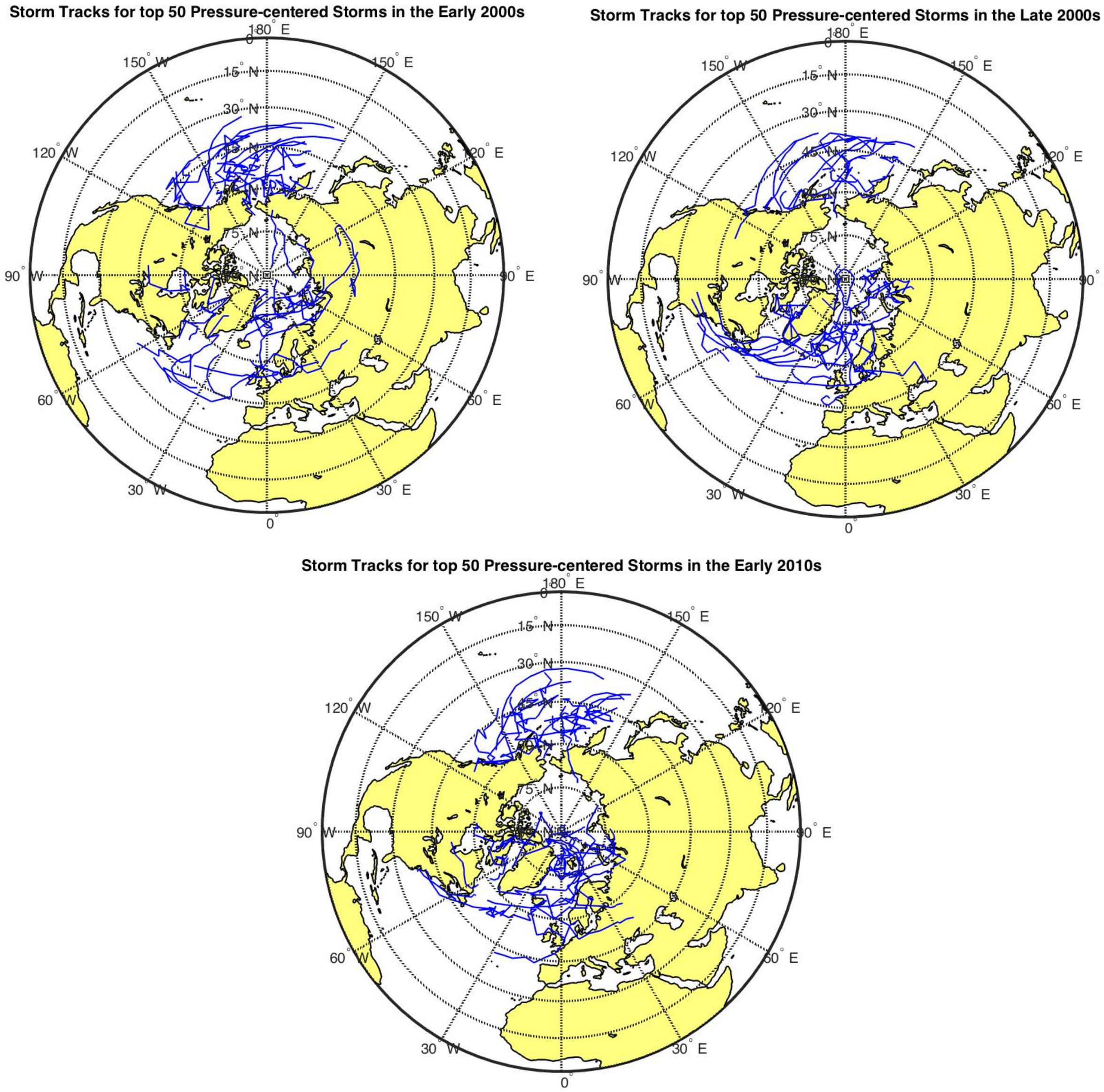

FIG 15. The track images of the top 50 most intense winter cyclones identified by MSLP plotted in the Northern Hemisphere around the North Pole, by 5 year periods with 2000-2005 (top left), 2005-2010 (top right), and 2010-2015 (bottom).

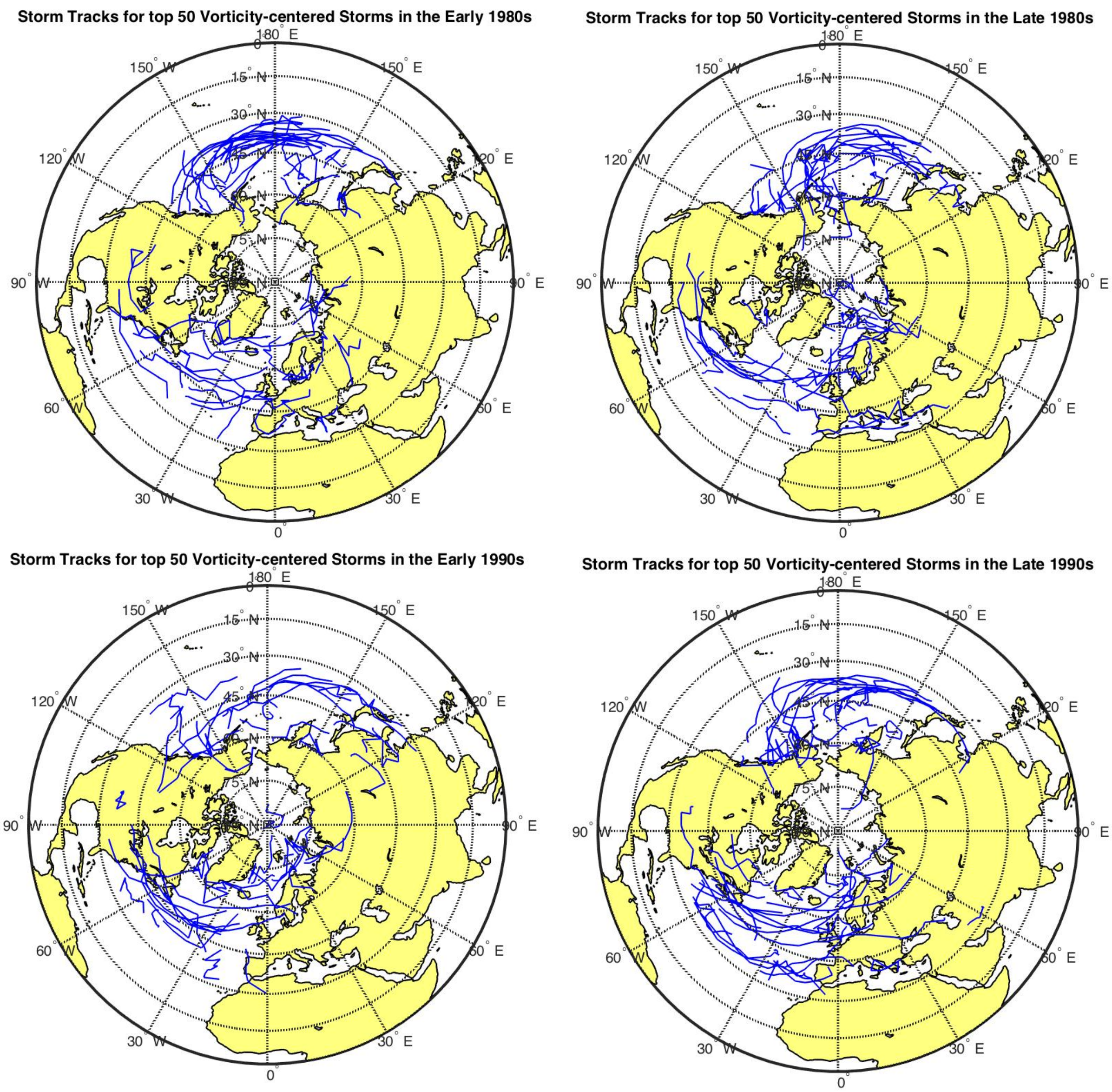

FIG 16. The track images of the top 50 most intense winter cyclones identified by vorticity plotted in the Northern Hemisphere around the North Pole, by 5 year periods with 1980-1985(top left), 1985-1990 (top right), 1990-1995 (bottom left), and 1995-2000(bottom right).

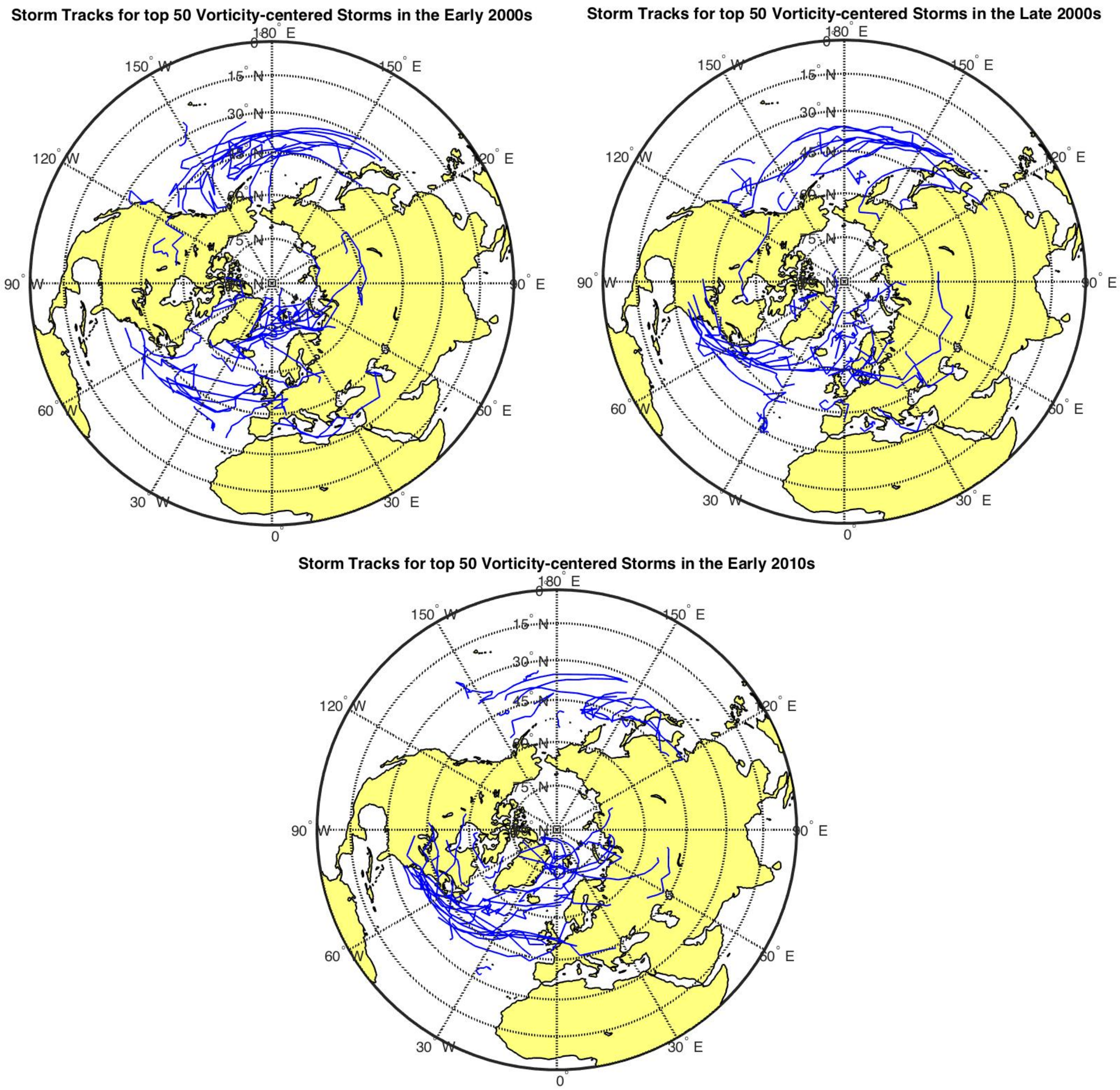

FIG 17. The track images of the top 50 most intense winter cyclones identified by vorticity plotted in the Northern Hemisphere around the North Pole, by 5 year periods with 2000-2005 (top left), 2005-2010 (top right), and 2010-2015 (bottom).

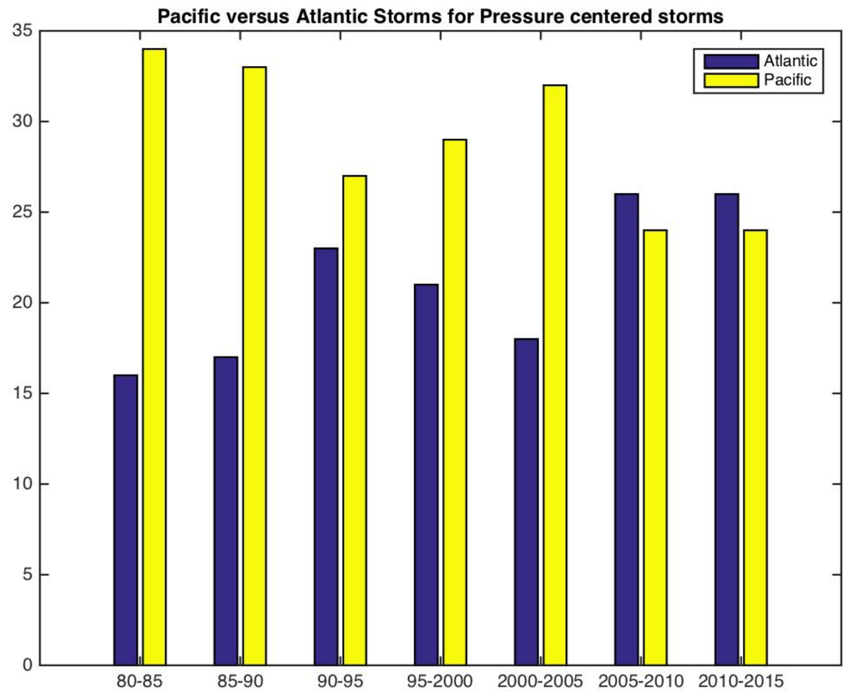

FIG 18 Bar graph showing the total number of Atlantic and Pacific basin storms out of the top 50 most intense, defined by pressure, for each 5-year period.

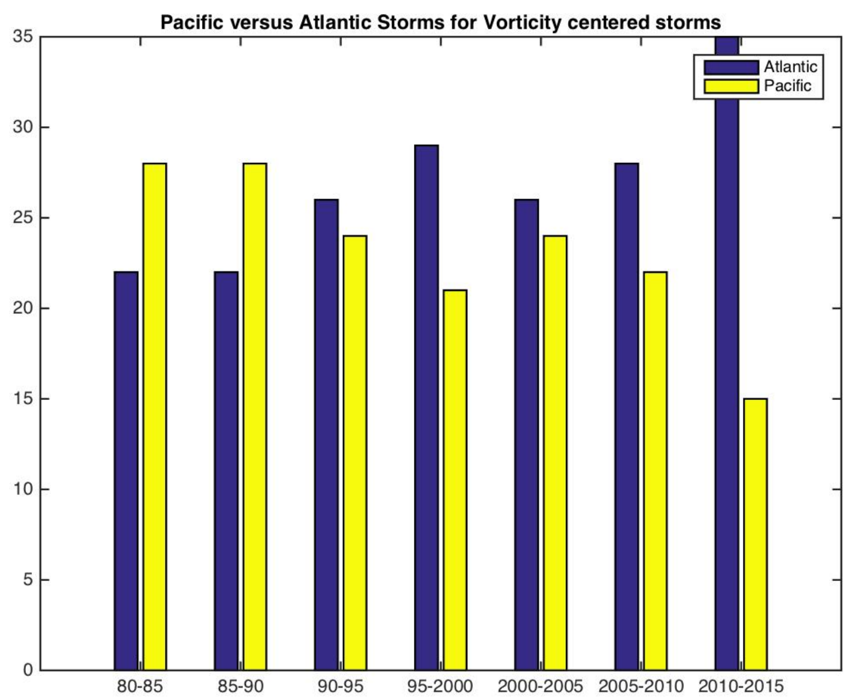

FIG 19 Bar graph showing the total number of Atlantic and Pacific basin storms out of the top 50 most intense storms, defined by vorticity, for each 5-year period.

To test the statistical significance of this shift, the bootstrap method was performed. The pool of 200 storms formed from the top 50 from the sets in the 80s and 90s was used for this test as this twenty-year period is considered to form the base for the analysis. From this base, 10,000 sample cases of 50 random storms were selected to form the basis, as shown in Table 1.

TABLE 1 The number of observed storms for both the Pacific and Atlantic basin are shown for each given five-year period along with the 95% confidence intervals from the bootstrap test for 10,000 samples of 50 random storms chosen from the collective pool. Thresholds at or exceeding the upper limit(green) or lower limit (red) are highlighted.

5-Year Data	Pressure		Vorticity		Bootstrap Results		
Years	Atlantic	Pacific	Atlantic	Pacific		Atlantic	Pacific
1980-1985	16	34	22	28	Pressure		
1985-1990	17	33	20	30	Upper Bound	32	32
1990-1995	23	27	25	25	Lower Bound	18	18
1995-2000	21	29	26	24	Vorticity		
2000-2005	20	30	26	24	Upper Bound	33	30
2005-2010	26	24	28	22	Lower Bound	20	17
2010-2015	26	24	35	15			

The first two sets of five-year periods under the most intense MSLP storms, representing the 80s, both exceed the 95% confidence intervals with an abnormally large number of storms identified for the Pacific basin. This trend then disappears into the 90s and beyond as the number of storms begins to favor the Atlantic. While this does not necessarily prove a shift from Pacific to Atlantic, it does show that the 80s were particularly active over the mid-latitudes in the Pacific. Further backing this story are the cyclones identified by vorticity. These storms sit comfortably within the 95% interval throughout most of the period until the last and most recent five years where they get to the upper bounds. Since these do not necessarily represent the same set of storms as those identified by MSLP, as covered previously in this paper, this secondary trend lends further credit to the idea that storms are becoming more focused in the Atlantic over the Pacific.

Decadal Track Comparison

In order to further aid in identifying a climatic signal however, the investigation in the overall basins was expanded to the decadal scale for the 80s, 90s, and the most recent years of 2005-2015. The given data spans a period of 35 years, thus the winters of 2000-2005 were excluded in order to capture the decade of 2005-2015, but these were not found to significantly impact the results.

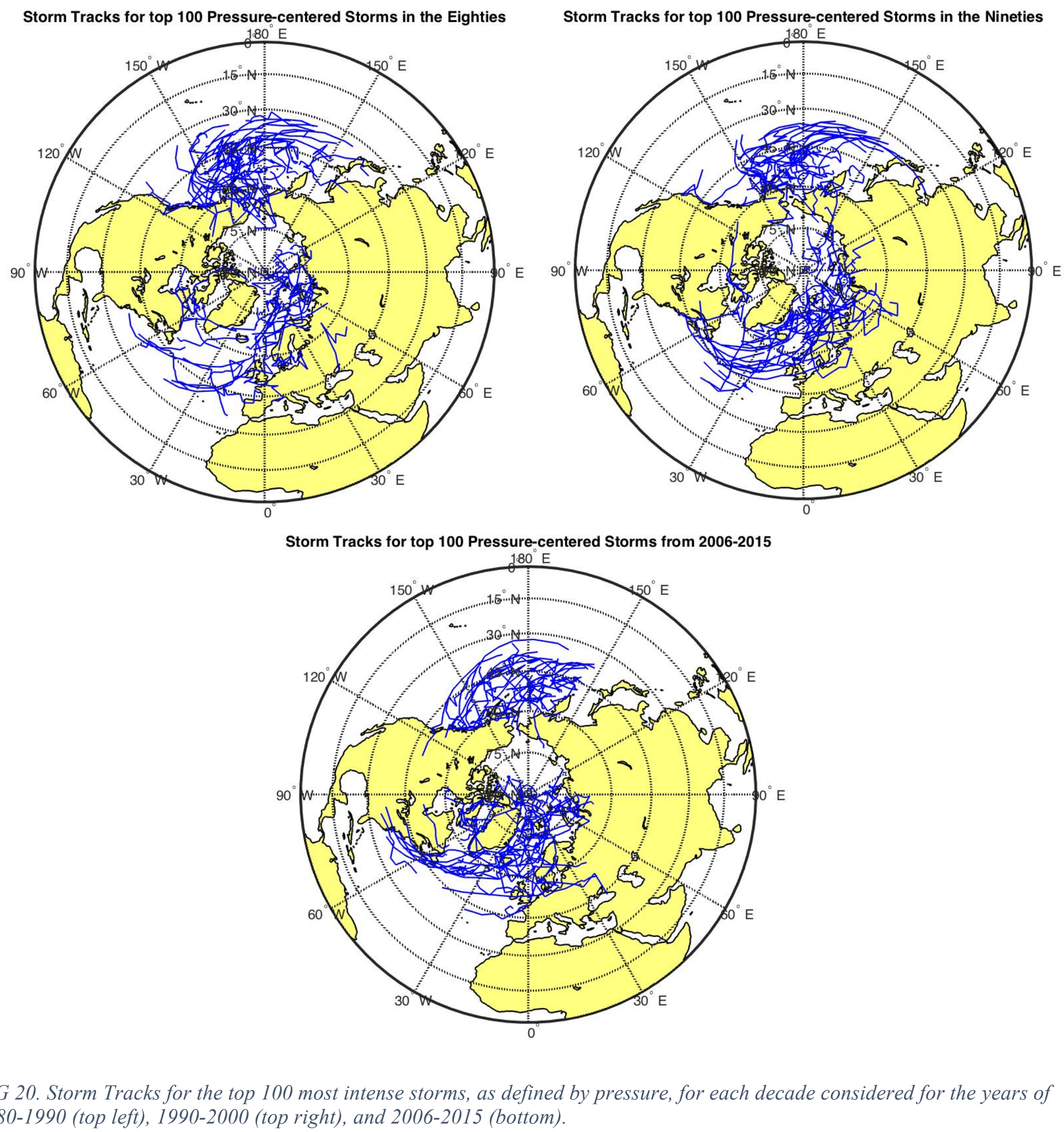

FIG 20. Storm Tracks for the top 100 most intense storms, as defined by pressure, for each decade considered for the years of 1980-1990 (top left), 1990-2000 (top right), and 2006-2015 (bottom).

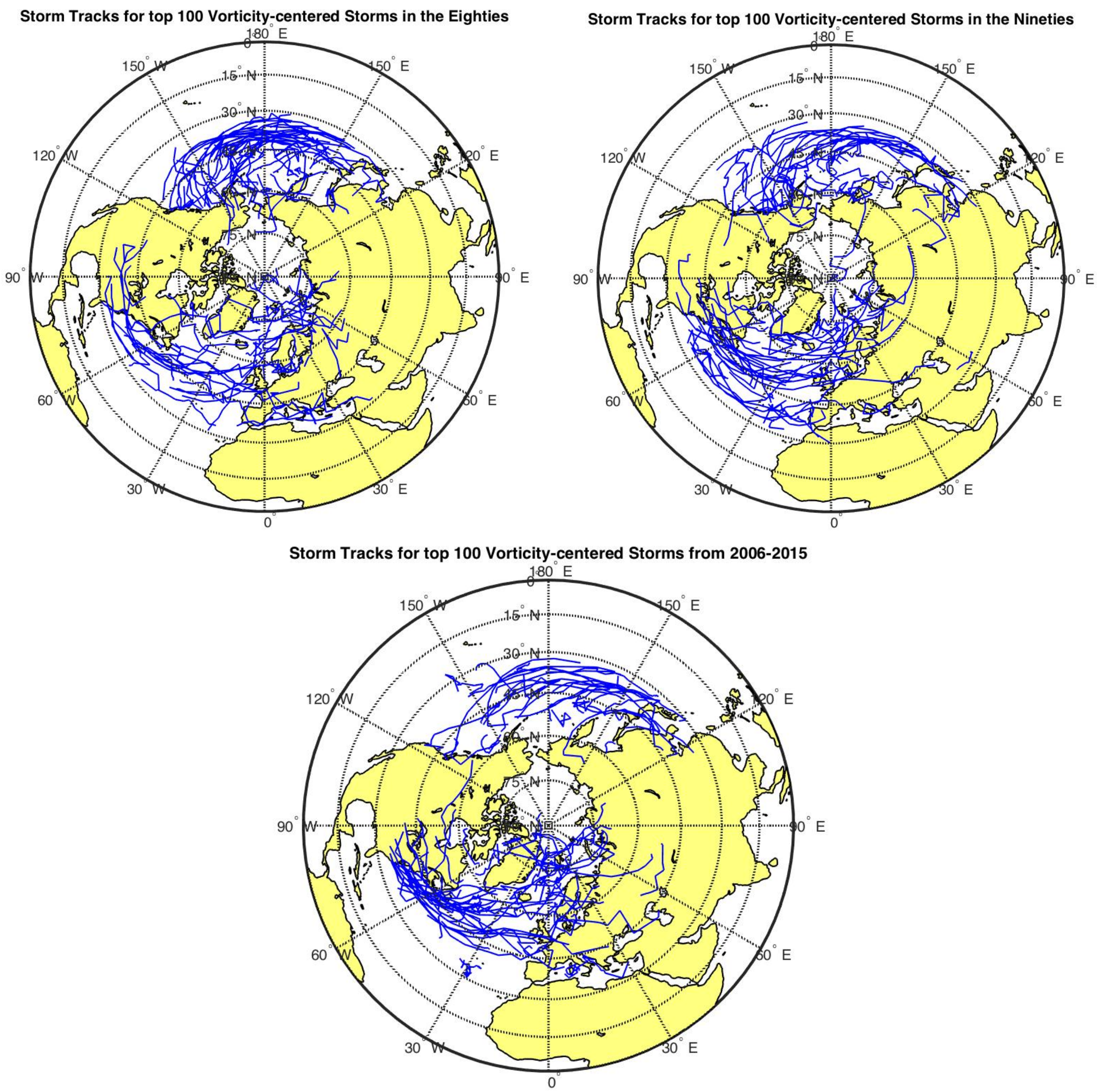

FIG 21. Storm Tracks for the top 100 most intense storms, as defined by vorticity, for each decade considered for the years of 1980-1990 (top left), 1990-2000 (top right), and 2006-2015 (bottom).

Similar to the five-year period, both tracks and their densities are particularly heavy and widespread during the 80s but make a shift towards the Atlantic region by the 2000s. Unlike the trend observed for the 5-year periods, the rise in Atlantic systems coupled with the decrease in the Pacific systems becomes drastically more pronounced. Similar to the 5-year analysis however, the vorticity trend still shows a more significant increase in the number of Atlantic cyclones by the last decade. The pressure trend suggests more of a decrease of Pacific cyclones in the first decade.

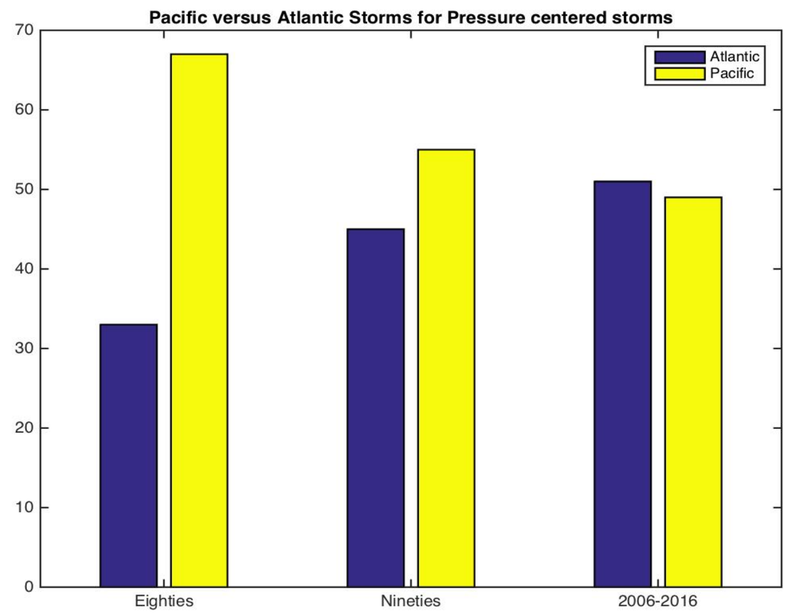

FIG 22 Bar Graph showing the total number of Atlantic and Pacific basin storms out of the top 100 most intense storms, as defined by MSLP.

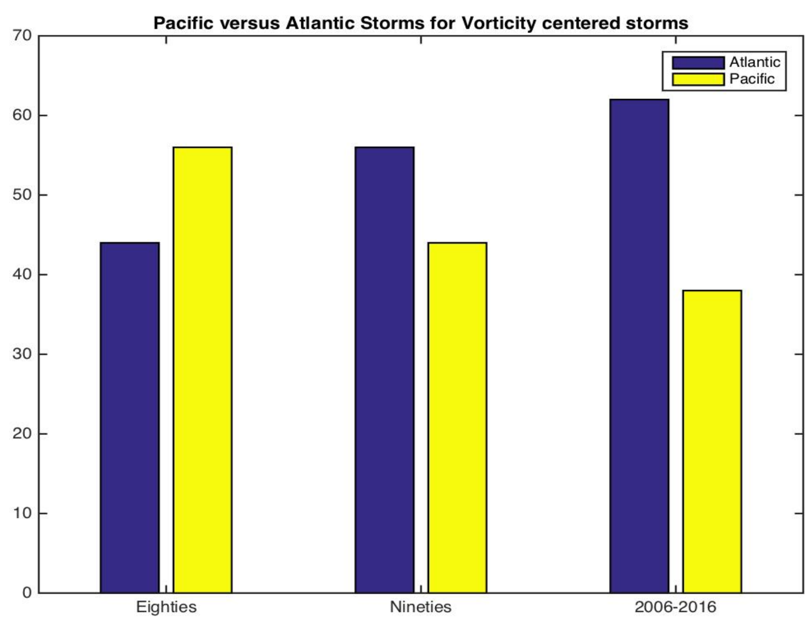

FIG 23. Bar Graph showing the total number of Atlantic and Pacific basin storms out of the top 100 most intense storms, as defined by vorticity.

Bootstrap testing performed upon the decadal analysis yields somewhat similar results to that suggested by a purely quantitative analysis. Namely, a significantly large number of pressure intense storms in the 1980s decreasing over time to fall within the normal range of data, and a significant increase in vorticity based cyclones for the Atlantic. Together with the previous 5-year analysis conducted upon the data suggest a shift for the most intense storms from the Pacific basin over towards the Atlantic for intensity based upon both pressure and vorticity as shown in Table 2.

TABLE 2. The number of observed storms per decade is recorded for the Atlantic and Pacific basin utilizing the most 100 intense storms as defined by both vorticity and pressure. The 95% confidence intervals of the 10,000 samples of 100 storms via bootstrap testing are shown with those values exceeding the upper bound(red) and lower bound(green) highlighted.

Decadal Data	Pressure		Vorticity	
Years	Atlantic	Pacific	Atlantic	Pacific
1980-1990	33	67	42	58
1990-2000	45	55	52	48
2005-2015	51	49	62	38
	Pressure		Vorticity	
Bootstrap	Atlantic	Pacific	Atlantic	Pacific
Upper Bound	61	59	62	57
Lower Bound	41	39	43	38

A large part of the variability in the intense storms over the two ocean basins may be tied into the over oscillations exhibited in the sea-surface temperature anomalies (SSTA) over the past century. In work conducted by Mestas-Nuñez and Enfield (2010), it was found that multiple non-ENSO (El Nino Southern Oscillation) modes exist for both the North Pacific and North Atlantic. Their results showed an oscillation period on the order of 15-40 years for the North Atlantic which directly impact the overall oscillations of the North Atlantic. Specifically, positive SSTA in the southern Pacific and negative SSTA for the northern Pacific were shown through the 1980s, effectively enhancing atmospheric baroclinicity and perhaps explaining in part the observed larger number of intense cyclones present in the basin during this period. Similarly, a shift in the northern Atlantic mode had been shown, which compared to previous research cited in their paper, with the initial shift in the 1960s. A secondary shift in the anomalies for the northern Atlantic has also been suggested to occur in the mid 1990s around the time of 1995 (Kerr 1997), similar to the observed timing of increase in the number of Atlantic cyclones.

Conclusions

The general nature of the extratropical cyclone has been shown to involve a gradual deepening towards the time of pressure minima. This deepening is at its greatest 6-12 prior, with the greatest rates exhibited by the the storms corresponding to maximal vorticity values while the overall deepest storms maintained a more consistent measure of vorticity. Precipitation structure between the most intense pressure and vorticity storms also varied with the vorticity related storms exhibiting a more symmetrical structure and rapid decay following the maximum in vorticity as the lifting mechanism decays and the system occludes. Pressure related storms were more asymmetric around their peak with a more gradual decay towards the end of the storm and greatly diminished precipitation over the entire considered 4 day period around the peak.

No significant trends were found in precipitation or changes in overall intensity for either pressure or vorticity for the time period as tracked by 5-year averages. Additionally, although no significant shifts in extratropical cyclone paths were detected in the poleward direction.

For decadal trends, an abnormally large number of the most intense MSLP DJF cyclones have been found to be based within the Pacific during the 80s by bootstrap testing. This holds true considering 5 year periods of 1980-1985 and 1985-1990 and considering the decade as a whole. In terms of vorticity intense storms, a significant increase in Atlantic activity has been found towards the end of our analysis by both the 5-year analysis for the time of 2010-2015 and by considering the last decade spanning from 2005-2015. Although the top pressure and vorticity intense storms do not necessarily happen to be the same storms, this suggests a migration of the most intense storms towards the Atlantic basin. This does not provide insight on the overall number of intense storms in either basin however. Possible explanations put forth include the shift in the Atlantic inter-decadal mode for the SSTAs occurring in the mid 1990s. Future work would focus upon a larger data set extending towards the other marked shift in the Atlantic mode noted in previous research to occur in the 1960s (Mestas-Nuñez and Enfield 2010).

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