Climate Change Impact on Tropical Cyclones

Rather than asking if climate change, anthropogenic and/or cyclical global warming, is occurring, it is perhaps best to review the available historical data, take note of trends over the past few decades, and gain an understanding of how certain economic threats, tropical cyclones in particular, are changing over time. The second step is to determine if the results of the review are generally in line with the scientific community with regard to the anticipated impacts of climate change.

Tropical Cyclones

According to a climate change/global warming literature review, the main takeaways in terms of tropical cyclone activity are the following:

- Increase in tropical cyclone intensity.
- Decrease in activity in the Atlantic basin.
- Increase in the rate of intensification.
- Increase in the amount of precipitation.
- Increase in the size of storms.
- Decrease in movement speed.
- Increase in storm surge.
- Poleward shift of development location.
- Poleward shift of the maximum wind location.

There is some disagreement with regard to *global* activity increases/decreases.

Our review of tropical cyclone activity for the Western Pacific, Eastern Pacific, and Atlantic basin concur with the above statements of:

- Increase in intensity
- Decrease of activity in the Atlantic basin.

Tropical Cyclone Data

Data for this analysis were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) version 4, (Knapp et al, 2010), which includes distance to land in kilometers. Every effort was made to filter the cyclones by proximity to land with their greatest recorded wind speed at landfall. The period of record for the Atlantic (AL) is 1851 through 2018, 1884 to 2018 for the West Pacific (WPAC), and 1949-2018 for the East Pacific (EPAC). With regard to Japan landfall occurrences, the WPAC data are limited to south of 30N up until 1911. Between 1911 and 1932, several years have no data north of 30N. Given these quirks and the unrated intensities, the majority of the WPAC basin review covers 1945 through 2018. Due to observation issues, basin counts are a complex issue, and perhaps analyses should be limited to the satellite era; 1971 - current (Fett, 1964; Dvorak, 1975; Velden and Hawkins, 2010). As such, **climatological trends are difficult to ascertain throughout the bulk of the available data.** Yet, proximity to land and landfall may prove more representative due to a variety of observational sources (Raga, 2012).

The following climate indices were reviewed in relation to activity in all the basins for the time allowed by the historical extent of the climate index dataset: North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), El Niño-Southern Oscillation (ENSO) Region 3.4 SSTA, QBO, Sunspot count both monthly and annually, North Pacific Index (NPI), Pacific Decadal Oscillation (PDO), Pacific Meridional Mode (PMM).

Atlantic Tropical Cyclones

The Atlantic (AL) tropical cyclone basin extends from the Gulf of Mexico to western Africa. It includes the Caribbean Islands, Bahamas, Windward Islands, and the US coast from Texas to Maine.

AL DISCUSSION/TRENDS: When looking at the AL basin, data was used from 1851 to 2018 with an understanding that data prior to 1971 may not be as robust as data post that year. Limitations in observations prior to 1971 do lower the confidence in long-term climate trends. Notable trends in our data analysis include a noticeable positive trend in tropical storm final counts for the basin. Going from 1-2 a year being diagnosed in the early period of record to 6-7 in 2018 with a correlation coefficient near 0.33, the highest such in our dataset. We do not have confidence in this number being attributed to a warming climate, however, due to a large number of storms not being ranked in years prior to 1971 or not being observed. When looking at the satellite era (1971 - 2018), Tropical storms average near 4-5 in the first 10 years, compared to 7-8 in the most recent 10 years (Fig 1).

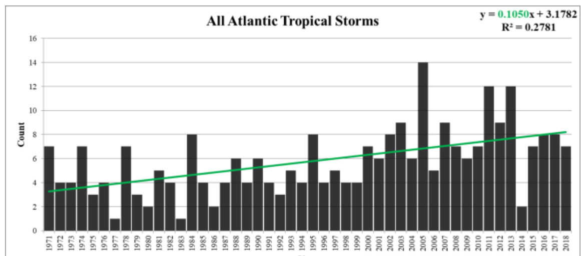

Figure 1

More important and supported well in most literature discussing the impact of climate change on hurricanes, we found a positive trend in Category 3+ hurricanes in the Atlantic. In the early period of the dataset, Cat 3+ hurricanes averaged near 0-1 a year, whereas in more recent years, that average jumps to 3-4 in 2018. Looking at the satellite period, Cat 3+ jump from 1-2 a year in the first 10 years to 2-3 in the last 10 years (Fig 2).

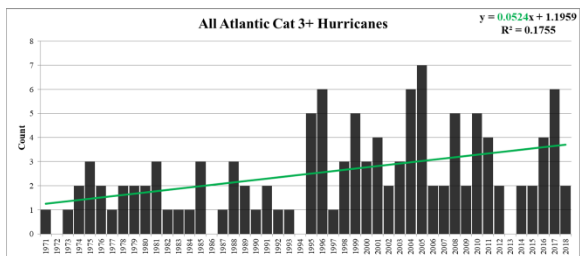

Figure 2

When looking at just land-falling hurricanes throughout the period of record, there were no distinguishable trends even with more sufficient and better records.

Storm counts by month were also analyzed for any trends in the AL Basin. Confidence was low in any trends outside of the peak of hurricane season for the Atlantic (August-October). This period did show similar characteristics to the overall trends in both the whole period of record and the satellite era. Increases in tropical storm counts and Category 3+ hurricanes were noted with relatively higher correlation coefficients compared to other categories and months (Fig 3).

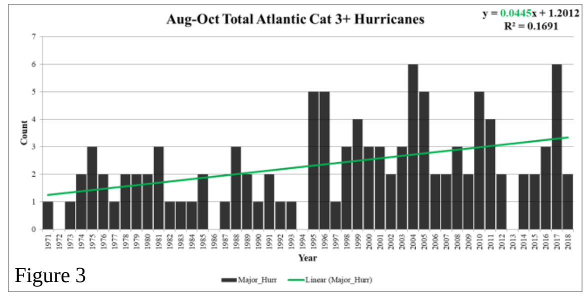

Figure 3

CLIMATE RELATIONSHIPS: Many different climate indices with known impacts on AL basin atmospheric circulations were analyzed to find correlations with storm counts for the AL basin. Most showed little to no correlation to storm counts. The few that did were relatively strong compared to other correlations. **The most notable was the correlation to the Nino 3.4 region, a negative correlation of -0.29 to storm counts in the AL basin, a common understanding by most Tropical Meteorologists but confirmed by this dataset**. A positive Nino 3.4 index indicates El Nino conditions are present, and typically El Nino's lead to enhanced shear, especially early in the peak season across the Tropical AL. The AMO also showed relatively high correlations to the storm count in the AL basin. For the peak season, storm count correlation to Aug-Oct AMO was around 0.26 meaning that a positive AMO leads to more storms. A closer look reveals that a positive AMO also leads to more major hurricanes (Cat 3+) with a correlation of 0.28. Another interesting find in this data analysis led to finding an overall positive trend in the NAO index for the months of Jan-May, which the NAO index during that period also showed a positive correlation with Jan-May storm counts. A potential inference, albeit weak, could be that an increasingly positive NAO in the early season may indicate a potential increase in early season storms. The Madden Julian Oscillation (MJO) was also analyzed for any trends as well, but nothing concrete was discovered. Typically more AL basin storms happen when the MJO is in phases 8, 1, and 2.

OUTLOOK: Based on linear trends found in our analysis (1971-2018) for the AL basin, tropical storm counts are likely to increase from an average of 8-9 in 2018-19 to 9-10 in 2030. For Cat 3+ hurricanes, the expected outlook is to go from 3-4 in 2018 to 4-5 in 2030.

Recent analyses from Geophysical Fluid Dynamics Laboratory (GFDL) indicate that based on a statistical relationship between AL sea surface temperatures (SSTs) and the Power Dissipation Index (PDI); if the SSTs continue to increase, the PDI is expected to increase by 300% in 2100. This means that the destructive potential of hurricanes would greatly increase based on an assumption that the AL SSTs will be increasing as well.

GFDL also summarize their analysis on the AL basin by stating the following, they are not confident that the frequency of storms will increase or decrease based on anthropogenic forcing, but do say with high confidence that rainfall rates will be higher in AL basin tropical cyclones, and with medium confidence that AL hurricanes will be more intense on average in a future climate.

Western Pacific & Japan Tropical Cyclones

The (North) Western Pacific (WPAC) tropical cyclone basin is the most active region for tropical cyclone (TC) activity in the world, accounting for approximately one third of global activity (Chan, 2005). The basin begins at 100E and extends to 180W. Within the basin are the Japanese islands. The primary islands Kyushu, Shikoku, Honshu, and Hokkaido are located north of 30N and generally between 129E and 146E. Likely due primarily to latitude, the main Japanese islands have seen only sporadic impacts from WPAC cyclones in any given year; however, exposure of the islands to TC activity is expected to increase during this century (Kossin, Emanuel, Camargo, 2016).

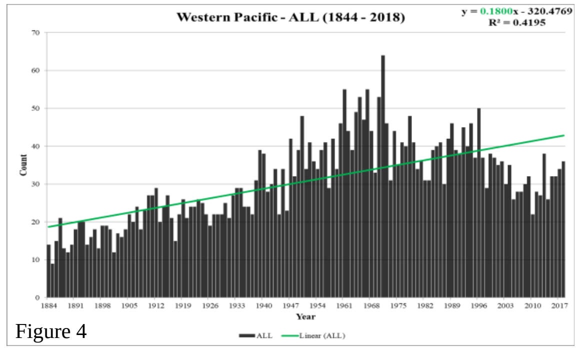

Figure 4

WPAC DISCUSSION/TRENDS: For the WPAC basin (1884-2018), there is indeed an upward trend (Fig. 4) in TC occurrence. **This upward trend is likely a function of limited data in the early years**. (The following information uses only the 1945 to 2018 period of record.) For all TCs, there is a slight downward trend in counts with an average of 27 per year. However, **tropical storm (TS) level cyclones average 9-10 per year, and show an increase over time**. Category (Cat) 1 & 2 cyclones average 7-8 per year, and show a slight decrease over time. This is due primarily to a slight Cat 1 downward trend. Cat 3+ TCs average ~9 per year and show a very slight downward trend. However, Cat 3 specifically is decreasing over time, masking **a weak uptick in Cat 4 (Fig. 5) and Cat 5 level cyclones**. August is the most active month, with September a close second.

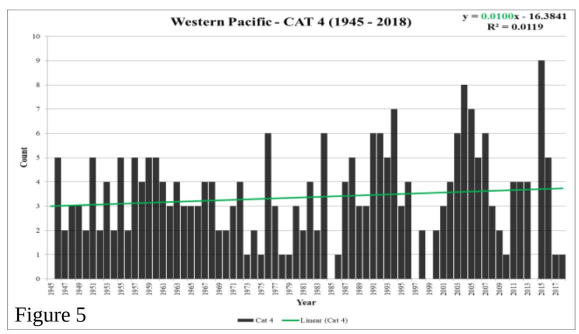

Figure 5

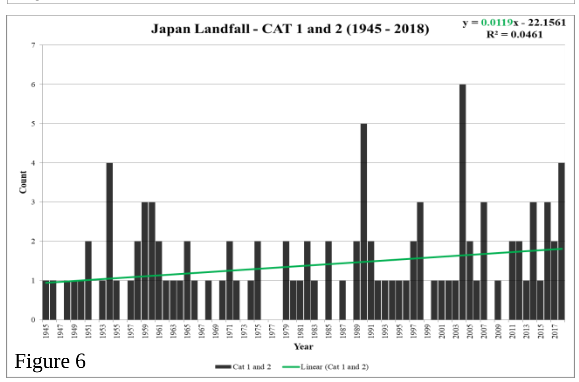

Figure 6

JAPAN DISCUSSION/TRENDS: Similar to the WPAC overall, if one uses the available data from 1911 onward, a likely non-climatological upward trend line is apparent. Likewise for the basin, it shifts to a very slight downward trend using 1945 to 2018 for all activity. Landfall categories indicate the following per year for the 1945 to 2018 period of record: Tropical Depression/Not Rated 1-2, TS 1-2, Cat 1 & 2 1-2, Cat 3+ 0-1, for a Total of 4-5 landfalls per year of any category. For TS and above, landfalls are ~3 per year. Negligible trends are evident for TS, Cat 3, and Cat 4 TCs within 1945 – 2018. (**No CAT 5s have ever made landfall in the defined area of Japan in the period of record.**) However, **Cat 1 and Cat 2 TCs show a minor**

increase over time (Fig. 6). Similar to the WPAC basin, August is the most likely month for landfall, with September a close second.

RELATIONSHIPS: Most climate indices showed only a weak or negligible correlation with activity. For WPAC Cat1 – 5 there is a decent fit with the PDO Jul-Sep correlation coefficient of 0.31 (Fig. 7). However, and of note, is the match between **Region 3.4 Jul-Sep average and Cat 3+ TCs for the WPAC basin: an astonishing 0.57 correlation exists** (Fig. 8). While still positive, Japan landfall correlation to Region 3.4 annual average is the best of the lot (0.22) for TS - Cat 5 (TS+) intensities. The second best correlation for Japan land-falling TCs is with the PMM for TS+ (0.21).

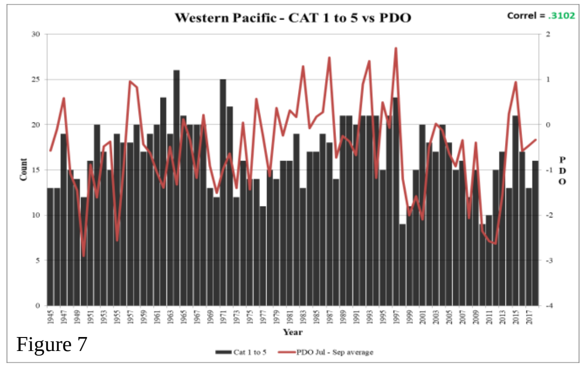

Figure 7

OUTLOOK: Based on forecast linear trends, by 2030 the WPAC basin could see an average increase of TS category TCs from 9-10 to ~13; a decrease from 7-8 to ~7 for Cat 1 & 2 TCs; and a decrease from 9-10 to ~9 for Cat 3+ TCs. While linear trends suggest fewer Cat 1 to Cat 3 TCs, they indicate more Cat 4 and Cat 5 TCs (Cat 4 from 3-4 to ~4 and Cat 5 from 3-4 to 4-5). This trade-off seems reasonable given that TCs may experience an increased incidence of intensification (Bhatia, et al., 2019). It also has been shown that warmer global sea surface temperatures tend to produce fewer global TCs overall, but more intense TCs. However, the WPAC in particular seems to evade this decrease in activity (Kang and Elsner, 2015; Emanual, 2013), thus fitting our TS level trend. **Of possible concern for Japan, is the apparent shift poleward of the location of the maximum winds** (Kossin and Emanuel, 2016).

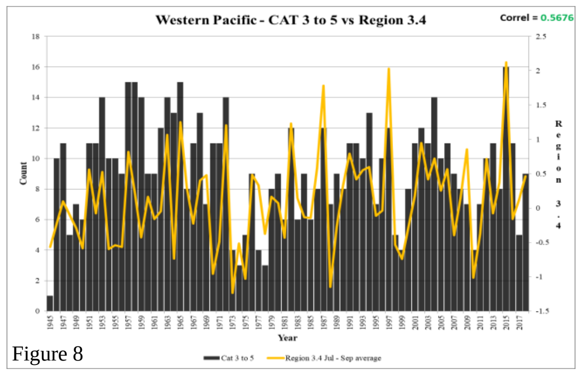

Figure 8

With regard to Japan, the linear trends suggest that by 2030, Tropical Depression/Not Rated decrease from 1-2 to 0-1; TS remain unchanged at 1-2; **Cat 1 & 2 increase from 1-2 to ~2**; Cat 3+ has a minor increase, but remains 0-1, for a Total of 3-4 landfalls per year of **any** category (down from 4-5). This is more in line with research into the impact of global sea surface temperatures on TCs (Kang and Elsner, 2015).

Eastern Pacific, Western Mexico, & Hawaii Tropical Cyclones

The Eastern Pacific (EPAC) tropical cyclone basin extends from 140W to the interior of western Mexico (WMEX). In the western portion of the basin sit the Hawaiian Islands (HII). The main islands are located between 18.5N and 22.5N and extend from about 154.5W to 169W. Likely due to size and western longitude, the islands have seen only occasional impacts from EPAC tropical cyclones in any given year.

EPAC DISCUSSION/TRENDS: For the EPAC basin (1949-2018), Tropical storm (TS) level cyclones average 7-8 per year, and show an increase over time. Category (Cat) 1 & 2 cyclones average 4-5 per year, and show a very slight increase over time. This is due primarily to a slight Cat 2 upward trend that may be based on limited data prior to 1971. Cat 1 TCS (3-4 per year) show a downward trend. Cat 3+ TCs average 3-4 per year and show an upward trend (Fig. 9); however, this too may be due to limited data in the pre-1971 time-frame. **When reviewing 1971 – 2018, Cat 3 has decreased over time, but Cat 4 and Cat 5 have increased.** Overall, there is an upward trend (Fig. 10) in TC occurrence for TS – Cat 5 (TS+). August and September are the most active months for TC activity.

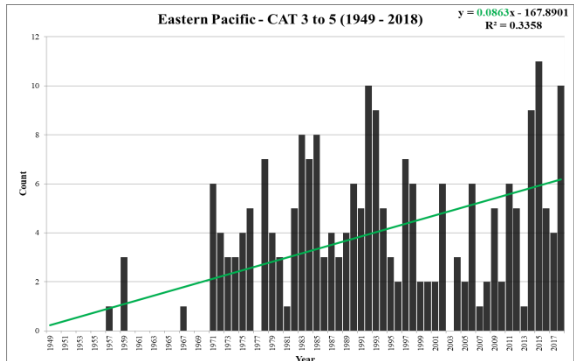

Figure 9

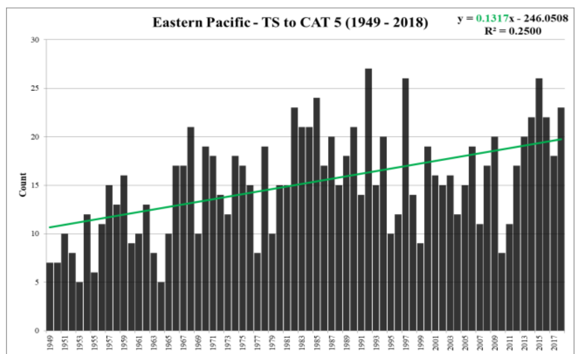

Figure 10

WMEX DISCUSSION/TRENDS: Landfall categories show the following per year for the 1949 to 2018 period of record: Tropical Depression/Not Rated ~0-1, TS ~1, Cat 1 & 2 ~1, Cat 3+ 0-1, for a Total of 2-3 landfalls per year of any category. For TS and above, landfalls are ~2 per year. TS, Cat 2 and Cat 3 all show an increase over time (Fig. 11). Cat 1 has a downward trend. Cat 4 has only occurred twice and the events are separated over the time-frame. One Cat 5 (Patricia) occurred later in the time period - 2015. Unlike EPAC basin activity, **September and October have been the more likely months for landfall.**

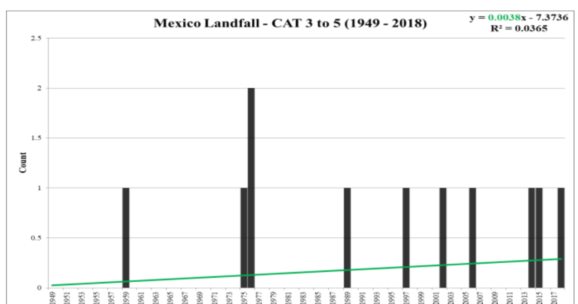

Figure 11

HII DISCUSSION/TRENDS: Very few hurricanes have struck the Hawaiian Islands since records began. Newspaper reports suggest a major hurricane struck in 1871 (Businger, Nogelmeier, Chinn, Schroeder, 2018). The islands would wait until 1959, when Cat 4 Dot made landfall as a Cat 1. Another break would lead to the destructive and costly 1992 Cat 4 landfall of Iniki. Since most TCs weaken significantly prior to landfall, the TD and NR categories may be relevant for the discussion. For all 12 landfall TCs (TD/NR included), there is a very slight upward trend for the period of record. When adding in the data from TCs that reach within 100km of the Islands, a similar upward trend exists (Fig. 12).

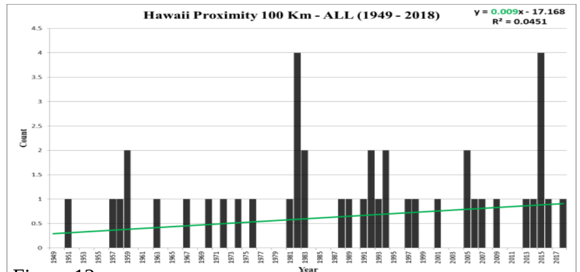

Figure 12

CLIMATE RELATIONSHIPS: Several climate indices showed only a weak or negligible correlation with EPAC activity. However, there is a decent fit with the Region 3.4 Jul-Sep average (ESRL), with a correlation coefficient of 0.44 for TS+ (Fig. 13), and a 0.34 correlation for Cat 3+. The PDO Jul-Sep average was almost as decent, with a 0.42 correlation for TS+ (Fig. 14). **While still positive, the correlation of Region 3.4 Jul - Sep average (ESRL) to Mexico land-falling TCs is 0.38 for Cat 1 - 5 intensities.** Yet, **a slightly better correlation exists with the Jul-Sep average for PDO, yielding 0.40 for Cat 1 – 5.** For Hawaii, landfall of any intensity shows similar patterns, favoring PDO Jul – Sep average and Region 3.4 Jul - Sep average (ESRL).

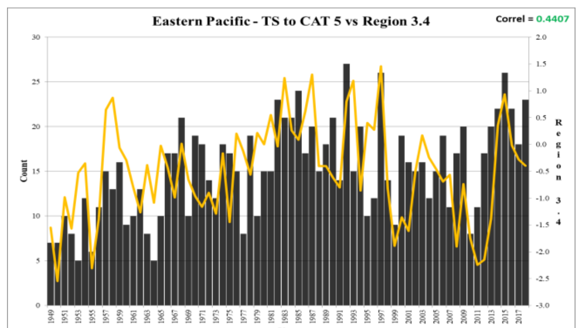

Figure 13

OUTLOOK: Based on forecast linear trends using the potentially suspect pre-1971 data, by 2030 the EPAC basin could see an average increase of TS category TCs from 7-8 to ~9; an increase from 4-5 to ~5 for Cat 1 & 2 TCs; and an increase from ~3 to ~7 for Cat 3+ TCs. Because the pre-1971 data is at issue, here are the comparisons using the 1971-2018 averages to generate 2030 outcomes: TS 7-8 to ~9; Cat 1 & 2 decreasing from 4-5 to ~4; and Cat 3 + increasing from a higher 4-5 to ~5. *The 1971-2019 based forecasts seem more representative and in line with the literature review for the basin*. **To summarize the EPAC basin: if one uses the 1971-2018 data, linear trends suggest more TSs, fewer Cat 1 to Cat 3 TCs, but more Cat 4 and Cat 5 TCs (Cat 4 from 2-3 to ~3 and Cat 5 from 0-1 to ~1 respectively).** This trade-off seems reasonable given that TCs may experience an increased incidence of intensification (Bhatia, et al., 2019). It also has been shown that warmer global sea surface temperatures tend to produce fewer global TCs overall, but more intense TCs. However, the

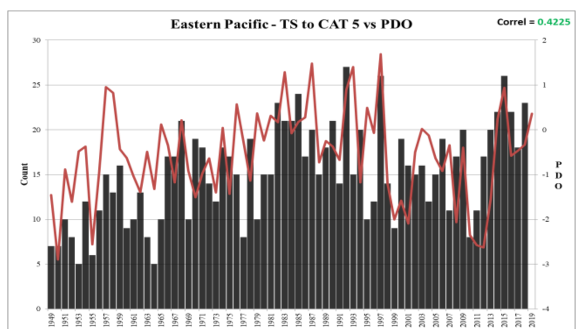

Figure 14

EPAC seems to evade some of this decrease in activity (Kang and Elsner, 2015; Emanual, 2013), with regard to TS level TCs.

Moving on to WMEX landfall information, linear trends suggest that by 2030, TS level TCs increase from ~1 to 1-2; Cat 1 & 2 decrease from ~1 to <1; and Cat 3+ shows a minor increase, but remain 0-1, for a total of 2-3 landfalls per year for TS+ categories (up slightly from ~2).

With regard to the Hawaiian Islands, no linear trends were calculated for 2030 for landfall due to a paucity of data. However, using the 100 km proximity set, an increase from <1 to ~1 occurs for TC activity (TD/NR included), which is in line with global outlooks for climate change (GFDL).

Given the correlation between various climate indices for the AL, WPAC, and EPAC basin, and an accurate estimate of conditions during a season, storm count forecasts and landfall threats could possibly improve. However, gleaning the state of the atmosphere several months ahead is difficult; furthermore, moderately strong correlations are not necessarily accurate predictions for future events. While it can readily be seen that sea surface temperatures for the globe have been increasing, (Kang and Elsner, 2015) the implication of this warming on climatological indices are still undergoing research by climatologists (Fang and Zhang, 2013; Turkington, Timbal, and Rahmat, 2018).

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*****Climate Data***

ENSO Region 3.4:

Extended:
http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO34/T+exch+table-+text+text+skipanyNaN+-table+.html
ESRL:
https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/
North Pacific Index (NPI):
https://climatedataguide.ucar.edu/climate-data/north-pacific-np-index-trenberth-and-hurrell-monthly-and-winter
Pacific Decadal Oscillation (PDO):
https://www.esrl.noaa.gov/psd/data/timeseries/monthly/PDO/
Pacific Meridional Mode (PMM):
ESRL
https://www.esrl.noaa.gov/psd/data/timeseries/monthly/PMM/pmmsst.data
Winds
http://www.aos.wisc.edu/~dvimont/MModes/RealTime/PMM.txt
QBO
https://www.esrl.noaa.gov/psd/data/correlation/qbo.data
Sunspots
http://www.sidc.be/silso/datafiles