# AN EAST COAST WINTER STORM CLIMATOLOGY AND PROJECTED FUTURE TRENDS

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## ABSTRACT

Densely populated major cities along the U.S. East Coast suffer substantial societal impacts due to extratropical cyclones occurring within the winter months of October-April. To mitigate damages and assist the nation in preparing for extreme winter weather in a changing climate, a full climatology of East Coast Winter Storms (ECWS) has been created using NCEP/NCAR reanalysis data from 1950-present day utilizing a cyclone-tracking algorithm that uses sea level pressure and a maximum wind threshold. The observations show an increase in maximum winds and no change in minimum pressure since 1950. After assessing changes in frequency and intensity based on minimum pressure, maximum winds and geographical location in the historically observed period, the cyclone-tracking algorithm was applied to historical and high emissions future scenarios utilizing data from seven models from the Coupled Model Intercomparison Project Phase 5. The models accurately represent historically observed minimum pressure, but under represent maximum winds and storm counts. Future models project a decrease in frequency but no change in intensity. Investigation of storm structure and lifecycle within the models is needed, in addition to a model dependent wind threshold.

## 1. INTRODUCTION

Virtually every facet of society is affected by the weather produced by East Coast Winter Storms (ECWS). However, highly populated urban centers are hardest hit. Citizens health and safety become threatened, and the convenience in which they live their every day lives can be affected. Buildings and property incur damages, businesses and schools are forced to close, the cost of snow removal can increase, as well as travel hubs experiencing airline delays and cancellations.

There are numerous notable ECWS in recent memory. The March 1993 “Storm of the Century” spanned the entire coastline causing tornadoes in the South, blizzard conditions in the North, over 200 deaths and more than six billion dollars in damages (National Weather Service, New York, NY WFO 2013). The blizzard of ’78 produced heavy snowfall of 30-90cm, large drifts from Virginia to Maine, and winds so strong that the Boston airport tower had to be evacuated (U.S Department of Commerce, 1978; Kocin and Uccellini, 1990; Maglaras et al. 1995). A March 2-5, 1960 storm left nine-meter high snowdrifts in areas of North and South Carolina, impassable roads, and areas in which food supplies had to be airlifted (Maglaras et al. 1995).

Mather et al. (1964) created one of the first climatologies of ECWS using coastal storm and water damage reports, and weather summaries from media sources and found a moderate-major storm affected the New York and New Jersey coastline every 1.4 years. Zishka and Smith (1980) showed maximum cyclogenesis parallel to the shoreline at roughly 5° off the coast from

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South Carolina to Canada. Davis et al. (1993) used wave heights and winds to create a climatology of EWS and attributed beach erosion to storms producing waves in excess of 1.6 meters.

The most up to date climatology was created by Hirsch et al. (2001) covering the years of 1948 and 1951-1997 using an automated cyclone tracking algorithm and NCEP/NCAR reanalysis data. In contrast with other tracking methods, Hirsch et al. (2001) used sea level pressure (SLP) and a maximum wind speed threshold to identify cyclones. The climatology found 12 storms per winter season, with an average minimum pressure of 992.7-hPa, and 20.5 m/s maximum winds. Interannual and decadal variations in intensity and frequency of ECWS was also evident in Hirsch et al. (2001). Increased frequency was attributed to El Niño, with little or no change in frequency during La Niña events. However, 20 years have passed since the completion of that study. Frankoski and DeGaetano (2010) used the tracking algorithm of Hirsch et al. (2001) to evaluate precipitation associated with ECWS but with a focus on snow and rainfall and connections to hydrology.

However, to reduce the societal impacts of ECWS it is necessary to evaluate and understand how ECWS will evolve in a changing climate. While most climate models project a decrease in frequency of winter cyclones along the U.S. East Coast (Zhang and Wang 1997, Knippertz et al. 2000, Colle et al., 2013) changes in intensity are much less certain. This contradicts Turner et al. (2016) who show stronger storms in the mid-latitudes caused be anthropogenically forced increasing green house gas emissions.

To better understand the characteristics of ECWS and how they may vary in a changing climate, this study extends the Hirsch et al. (2001) climatology from 1950-2016 and applies the Hirsch et al. (2001) tracking algorithm to climate model simulations through year 2100. The goal of this study is to evaluate the ability of climate models to simulate ECWS and provide further clarity on the projected intensity of storms in a changing climate.

## 2. DATA & METHODS

To create the observational climatology, NCEP/NCAR Reanalysis 1 data (Kalnay et al. 1996) from 1950-2016 at 2.5° x 2.5° horizontal resolution was used. Required data included six hourly SLP and zonal and meridional wind from the closest model level to the surface (0.995 sigma level).

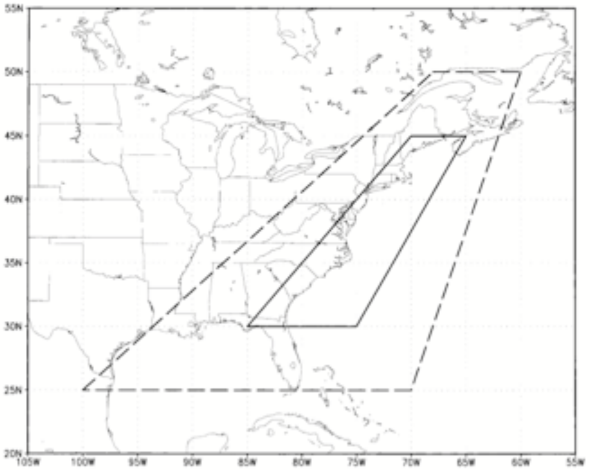


**Figure 1:** Boundaries of area used to identify ECWS, from Hirsch et al. (2001)

The cyclone-tracking algorithm developed by Hirsch et al. (2001) begins by searching for low-pressure systems between the months of October-April within the outer dashed domain of Figure 1. This polygon is bound by 60°W and 68°W at 50°N and by 70°W and 100°W at 25°N. To be classified as an ECWS the identified system must meet the following criteria:

1) Located within inner solid polygon of Figure 1, 65°W and 70°W at 45°N and by 75°W and 85°W at 30°N. This is the primary ECWS cyclogensis region according to Whittaker and Horn (1981).
2) Closed low circulation
3) General south-southwest to north-northeast movement
4) Winds >10.3 $ms^{-1}$ (20 kt) sustained for at least one 6-hour time period

First, the low-pressure system is located within the outer dashed polygon and the algorithm records its time, location, minimum pressure, and maximum winds. Next, it verifies the criteria above starting with location (within inner polygon), and then moving onto closed circulation where 80% of the 32 adjacent pressure values must be at least 4 hPa higher than the minimum (Colucci 1976, Zishka and Smith 1980). South-southwest to north-northeast movement is defined as past movement from 169°-259° for decaying storms and future movement to 349°-79° for mature storms. Finally, the wind speed threshold is applied. The threshold was selected based on Thurman (1983), and is also the criteria that produced the wave heights used by Davis et al. (1993) to quantify storm impacts. To satisfy the wind threshold, at least 6 of 26 points within the inner polygon must exceed the threshold.

Storms that enter the domain and are closed lows but do not satisfy the wind threshold or motion requirement are termed non-ECWS but are still retained in the study for purpose of comparison to ECWS. The identified storms are classified geographically into Northern (>35°N Latitude), Southern (≤ 35°N latitude), or Full Coast (must transverse both sectors).

A total of seven climate models (for details see Table 1) were used from the coupled model intercomparison project phase 5 (CMIP5; Taylor et al. 2012). Historical years included 1950-2005, with future simulations from Representative Concentration Pathway 8.5 (RCP8.5) the highest emissions scenario from 2006-2100. As for the reanalysis, six-hourly SLP and lowest model level u-wind and v-wind was acquired from the models and regridded to the same resolution as the reanalysis data.

**Table 1:** Detailed list of CMIP5 climate models utilized in this study.

| Modeling Center | Model | Institution |
|---|---|---|
| CSIRO-BOM | ACCESS1.0 | CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia) |
| IPSL | IPSL-CM5A-LR | Institut Pierre-Simon Laplace |
| IPSL | IPSL-CM5A-MR | Institut Pierre-Simon Laplace |
| IPSL | IPSL-CM5B-LR | Institut Pierre-Simon Laplace |
| NOAA GFDL | GFDL-CM3 | NOAA Geophysical Fluid Dynamics Laboratory |
| NOAA-GFDL | GFDL-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory |
| NOAA-GFDL | GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory |

## 3. RESULTS

### a) Minimum Pressure

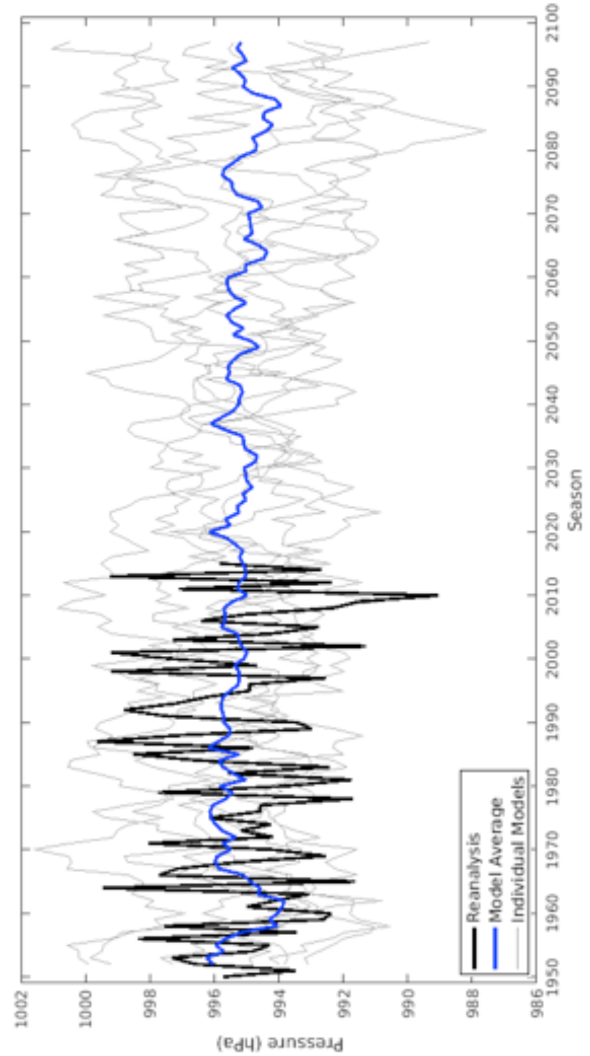


**Figure 2:** Average seasonal ECWS minimum pressure (hPa) from the reanalysis solid black line, model mean blue line, and individual models gray.

Minimum pressure is a traditional measure of the intensity of cyclones. The time series of ECWS seasonal minimum pressure from the reanalysis and CMIP5 models are shown in Figure 2. In the historical period, it is evident that the models accurately represent the magnitude of minimum pressure. Average minimum pressure in the reanalysis was 995.1 hPa while the model average was 995.2 hPa. In terms of variability, the reanalysis experienced a range of 989-999.6 hPa versus the model average range of 990.4-1000.2 hPa. Therefore, the model mean range was less accurate than the average minimum value.

In the historical period, there is large interannual variability shown in the models and the reanalysis, but there is neither an upward or downward trend of ECWS minimum pressure. As seen in Figure 2, the multi-model mean does not project a trend in the future, although a trend is evident in some of the models.

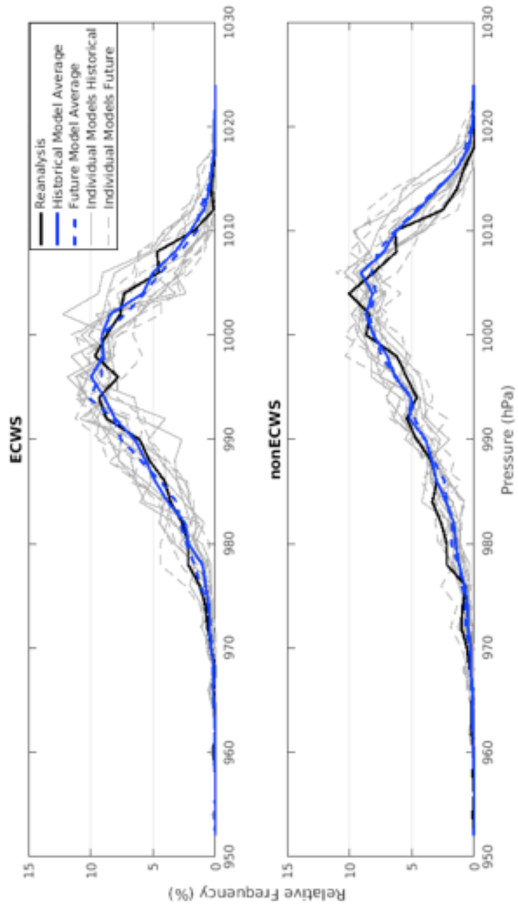


**Figure 3:** Relative frequency of minimum pressures for historical and future periods for ECWS (top) and nonECWS (bottom). Reanalysis is represented by a solid black line, historical models by solid gray lines, and future model simulations by dashed gray lines

To understand the distribution of minimum pressures of ECWS and nonECWS, the frequency of minimum pressures from the reanalysis, historical simulations (1950-1990) and future simulations (2050-2090) are shown in Figure 3. The models mirror the reanalysis distributions with some level of variability between models but the general distribution in both historical and future periods lay within the range of the reanalysis. As one would expect, ECWS are shifted toward a lower minimum pressure distribution than nonECWS.

### b) Maximum Winds

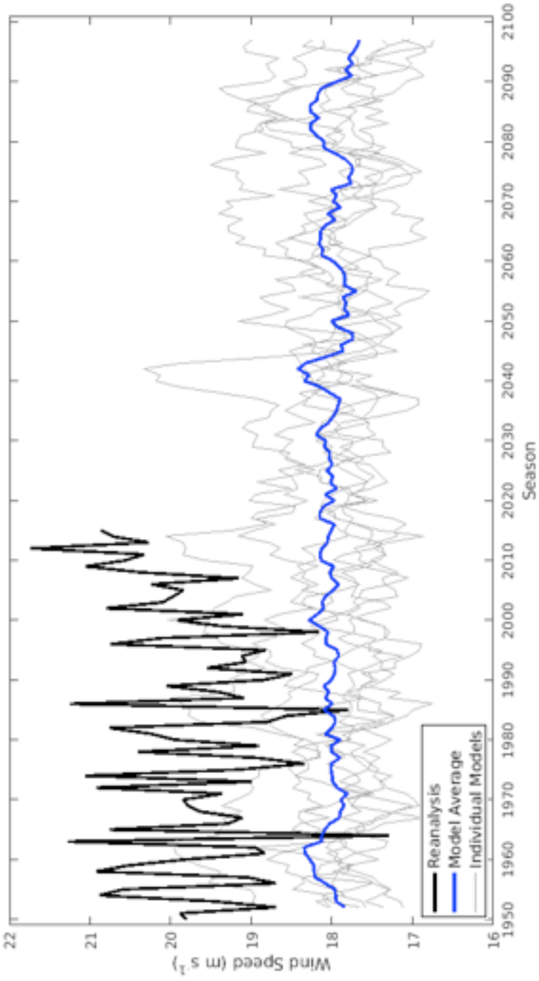


**Figure 4:** As in Figure 2, but for maximum winds.

A unique aspect of this study is that the tracking algorithm uses a wind threshold, which can give a better indication of storm impacts. The time series of average seasonal maximum winds in ECWS are shown in Figure 4. In the historical period, the average maximum wind speed in the reanalysis was 19.73 $ms^{-1}$ versus 18.01 $ms^{-1}$ in the model mean: a difference of 1.72 $ms^{-1}$. The models under estimate the maximum winds associated with ECWS in the historical period.

As for the minimum pressure (Figure 2) the maximum wind also shows large interannual variability in the reanalysis. The reanalysis ranged from 17.28-21.73 $ms^{-1}$ while the models ranged from 16.73-19.45 $ms^{-1}$. The difference between the high end of the range was 2.28 $ms^{-1}$ versus only 0.55 $ms^{-1}$ on the low end of the range. A large increasing trend in reanalysis maximum winds since 1990 is shown in Figure 4. Neither the model mean or any individual model simulates such trend. In the future, there is no clear trend in the model mean, although again, some individual models do show a trend.

Evaluating the distribution of maximum winds (Figure 5), the data shows that the models have narrower distribution shifted toward weaker maximum winds for both the historical and future periods of ECWS and nonECWS. The narrow distribution and under representation is more drastic in ECWS than nonECWS.

### c) Storm Frequency

The number of ECWS each winter season are displayed in Figure 6 for all storms and northern storms. Northern storms made up the majority of ECWS, with an average of 12 out of 16 total storms per year occurring in the Northern sector in the reanalysis. The models under represented the storm counts for all and northern classifications. The model average showed 12 total storms per season and 9 northern storms per season, meaning that the models were slightly better at resolving northern storms than storms overall. The reanalysis remains generally flat with large decadal variability and an annual range of 8-25 total storms and 5-19 Northern storms. The models, on the other hand displayed a range of 4-22 total storms and 2-18 Northern storms. The underestimation on the minimum storm counts is far more extreme than maximum storm count, with the models resolving less than half of the reanalysis. While the reanalysis experienced virtually no increase or decrease in storm count overall, the models do appear to exhibit a slight downward trend: from ~12.5 to ~10 for total storm count and ~10 to ~7.5 for northern storm count.

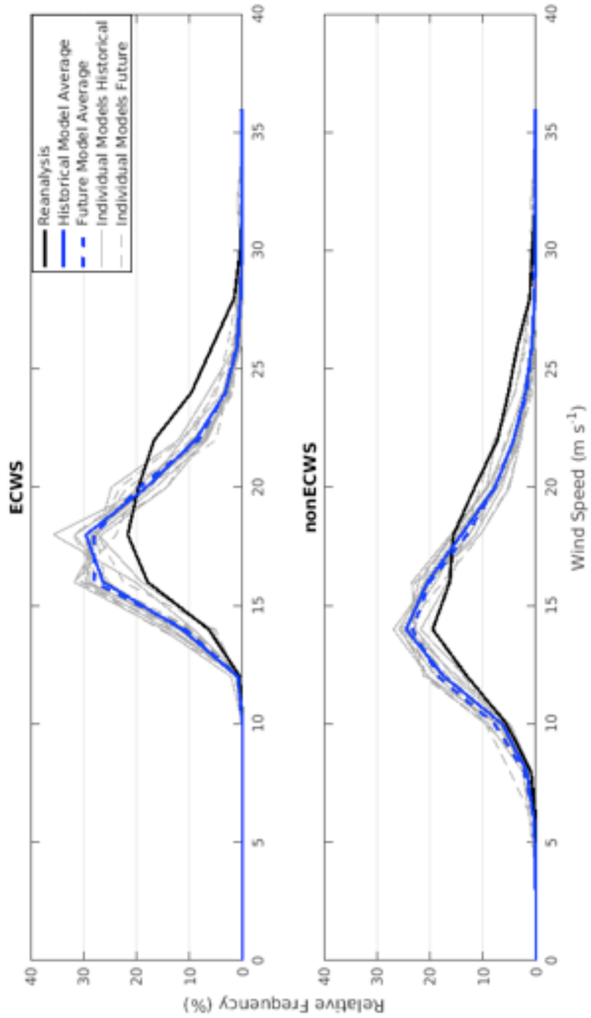


**Figure 5:** As in Figure 4, but for maximum winds.

Both Southern and Full Coast storms were relatively rare (Figure 7), however it is worth noting that the models under estimate total storm counts regardless of geographical location. The average southern storm count in the reanalysis was 2 versus 1 in the models and the average full coast storm count in the reanalysis was 3 versus only 1 in the models. The reanalysis range for southern storms was 0-6 and 0-8 for full coast storms. For the models, the range was 0-5 for southern storms and 0-7 for full coast storms. Southern storm trends in the reanalysis show a decline toward the end of the historical period, while full coast storms saw an increase. Both model means remain generally flat throughout the entire period, neither capturing the observed trends nor projecting any future increases or decreases. Summary statistics for reanalysis, and model simulations are shown in Table 2.

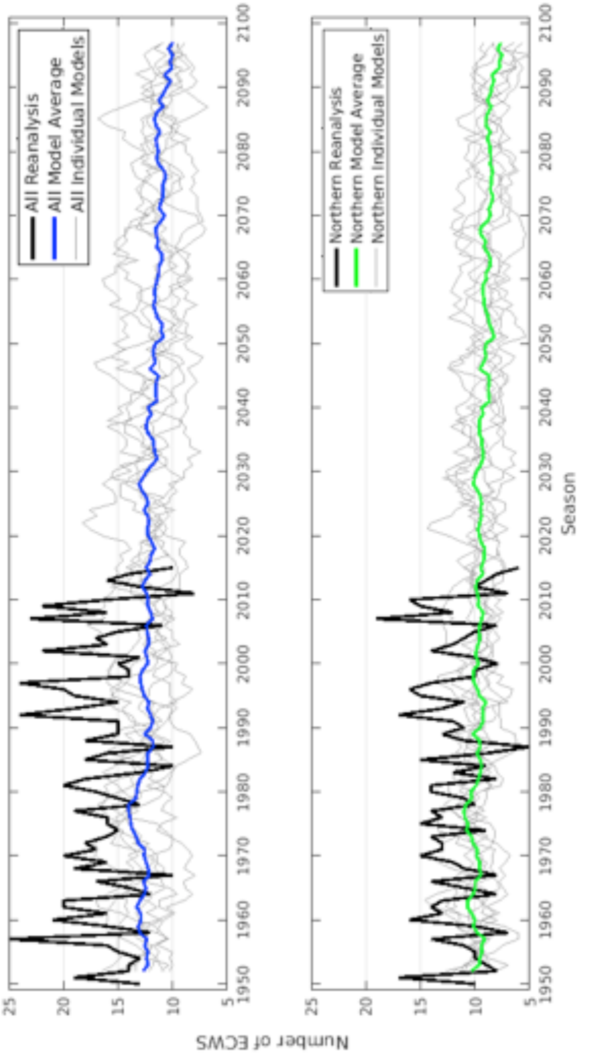


**Figure 6:** Time Series of ECWS frequency. Top plot displays all storms, bottom plot displays northern storms. Solid black line is the reanalysis, solid colored line is the model mean, gray lines are individual models.

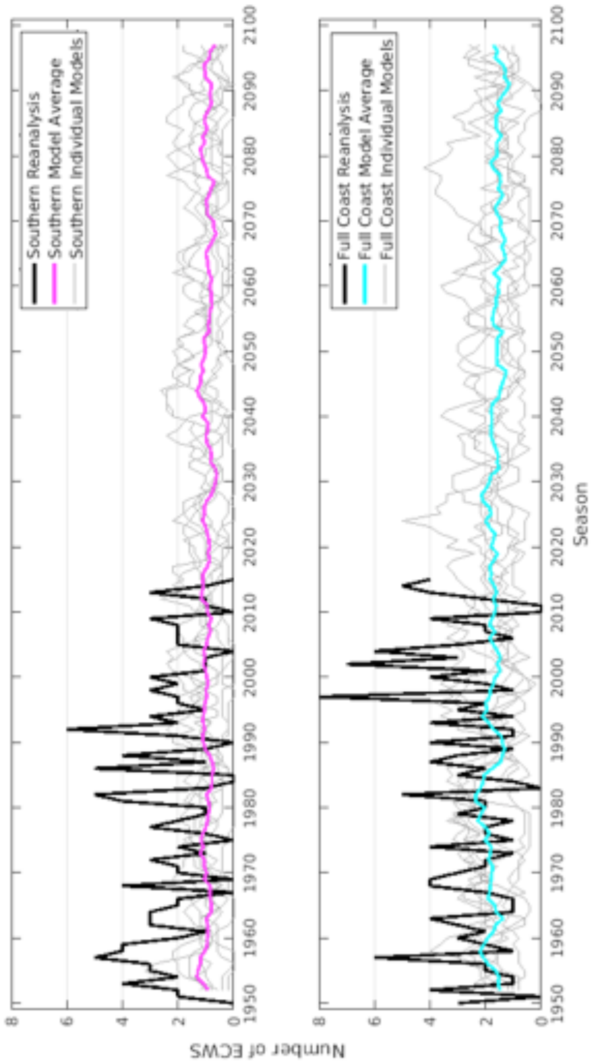
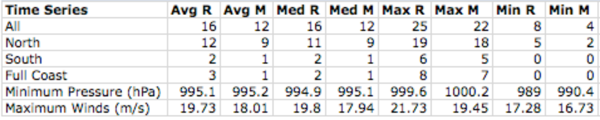


**Figure 7:** As in Figure 6, but for southern storms (top) and full coast storms (bottom).

**Table 2:** Seasonal (Oct-Apr) summary statistics for ECWS. R(reanalysis), M(models).



| Time Series | Avg R | Avg M | Med R | Med M | Max R | Max M | Min R | Min M |
|---|---|---|---|---|---|---|---|---|
| All | 16 | 12 | 16 | 12 | 25 | 22 | 8 | 4 |
| North | 12 | 9 | 11 | 9 | 19 | 18 | 5 | 2 |
| South | 2 | 1 | 2 | 1 | 6 | 5 | 0 | 0 |
| Full Coast | 3 | 1 | 2 | 1 | 8 | 7 | 0 | 0 |
| Minimum Pressure (hPa) | 995.1 | 995.2 | 994.9 | 995.1 | 999.6 | 1000.2 | 989 | 990.4 |
| Maximum Winds (m/s) | 19.73 | 18.01 | 19.8 | 17.94 | 21.73 | 19.45 | 17.28 | 16.73 |

### d) Seasonality

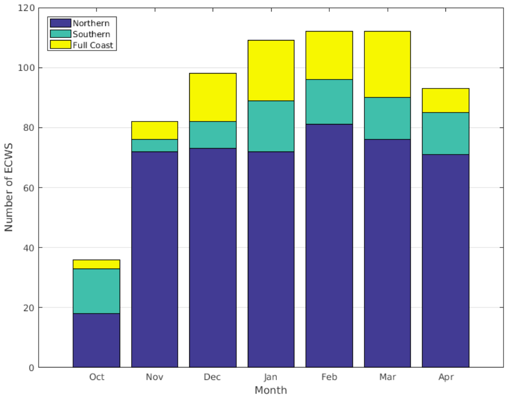


**Figure 8:** Monthly and geographical distribution of storm totals for reanalysis (1950-1990)

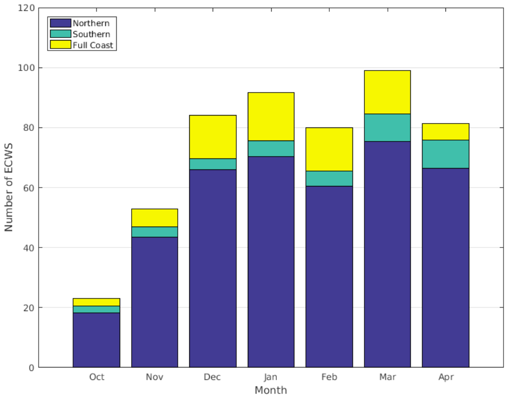


**Figure 9:** Model mean monthly and geographical distribution of storm counts in historical simulations (1950-1990)

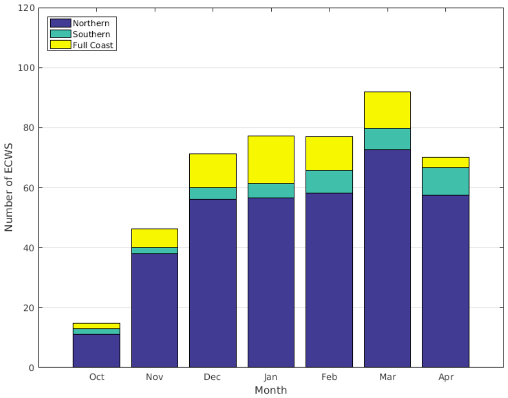


**Figure 10:** As in Figure 9 but for future simulations (2050-2090)

The timing of ECWS throughout the winter season has important implications for planning and resilience to impacts of the storms. To establish the seasonal distribution of ECWS, the monthly frequencies for the reanalysis (1950-1990), historical model mean (1950-1990), and future model mean (2050-2090) are shown in Figures 8, 9, and 10 respectively. An under representation of storm counts by the models in comparison to the reanalysis is evident across all months. The reanalysis shows a winter peak in February and March (Figure 8) while the models favor later season storms in March (Figures 9 and 10). The historical model mean shows a surprising underestimation in February (Figure 9), which is the highest numerical underestimation (Table 3) and this bias is continued in the future simulations (Figure 10). As shown in Table 3, the model mean underestimates total storm count by the largest fraction in October and November.

**Table 3:** Numerical breakdown of geographical storm counts by month, reanalysis and model averages H(historical) F(future) displaying both numerical and fractional underestimation.

| Monthly Counts | October | November | December | January | February | March | April |
|---|---|---|---|---|---|---|---|
| Reanalysis | 36 | 82 | 98 | 109 | 112 | 112 | 93 |
| Model Average H | 23 | 53 | 84 | 92 | 80 | 99 | 81 |
| Model Average F | 15 | 46 | 71 | 78 | 77 | 92 | 70 |
| # Underestimation | 13 | 28 | 14 | 17 | 32 | 13 | 12 |
| % Underestimation | 36% | 34% | 14% | 16% | 29% | 12% | 19% |

## 4. CONCLUSIONS

This study has applied a novel cyclone-tracking algorithm that utilizes SLP and low-level winds to identify observed characteristics of ECWS and evaluate the ability of CMIP5 models to simulate ECWS.

Historical observations show a large increase in maximum wind since 1990 but no change in minimum pressure. However, models underpredict the maximum wind in the historical period but accurately represent minimum pressure overall. The increasing maximum wind in the observations is not captured by the model mean or any individual models. In the future, the models project a decrease in frequency, especially for northern storms but no change in intensity. This is consistent with studies by Zhang and Wang (1997), Knippertz et al. (2000), and Colle et al. (2013)

We hypothesize that the weaker winds simulated by the models are due to a weaker pressure gradient. This could be impacting storm count due to the fixed wind threshold used in the cyclone-tracking algorithm. As expected from the wind underestimation, models underestimate storm counts. To address this, a tracking algorithm with a model dependent wind threshold should be tested for cyclone identification.

Future work includes adding models to the ensemble. Currently, there are only 7 models and a total of at least 10 are desired. Additionally, a statistical analysis of past and future trends should be completed to determine significance. It would be beneficial to investigate the storm structure and lifecycle simulated by the models to see if that has any effect on the models ability to resolve storms with this tracking algorithm.

As the models underestimate maximum winds and storm counts, it is still unclear what the future of ECWS and their respective societal impacts look like. A decrease in frequency would provide substantial relief to citizens, infrastructure, and the economy. The models accurate representation of minimum pressure confirms that no changes in intensity or potentially threatening and increasingly severe ECWS over time. Though the models under represented maximum winds, there are no trends within the maximum winds that would indicate a change in intensity either. A potential change in seasonality could drastically impact preparation and resiliency, however no conclusions can be made on the seasonality shift.

## 6. ACKNOWLEDGMENTS

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