Growing Pacific Linkage with the Interannual Variability of North Atlantic Explosive Cyclogenesis

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Abstract

Explosive cyclones (ECs), defined as developing extratropical cyclones that experience pressure drops of at least 24 hPa in 24 hours, are impactful weather events which occur along highly populated coastal regions in the eastern United States. These storms occur due to a combination of atmospheric and surface processes, such as jet stream intensification and latent heat release at the ocean surface. Even though previous literature has elucidated the role of these processes in EC formation, the sources of interannual variability that impact seasonal EC frequency are not well known. To analyze the sources of interannual variability, we track cases of ECs and dissect them into two spatial groups: those that formed near the east coast of North America (coastal) and those in the North Central Atlantic (high latitude). The frequency of high-latitude ECs is strongly correlated with the North Atlantic Oscillation, a well-known feature, whereas coastal EC frequency exhibits a growing relationship with an atmospheric wave-train emanating from the North Pacific in the last 30 years. This wave-train pattern of alternating high-and-low pressure resulted in heightened upper-level divergence and baroclinic instability along the east coast of North America. Using a coupled model experiment, we show that the tropical Pacific Ocean is the main driver of this atmospheric wave train and the subsequent enhancement seasonal baroclinic instability in the North Atlantic.

1. Introduction

Explosive cyclones (ECs) in the North Atlantic have long been a subject of meteorological interest, largely because their complex atmospheric processes were difficult to forecast and they often result in high impact weather for the eastern coast of the United States (Bosart, 1981; Sanders, 1986; Sanders & Gyakum, 1980; Silberberg & Bosart, 1982). One impactful example is winter storm Grayson (January 3-5, 2018) which resulted in 22 deaths and approximately $1.1 billion in economic costs (LeComte, 2019). Defined as extratropical cyclones which experience a minimum surface pressure drop of 24 hPa over a 24-hour period, ECs are caused by synoptic and mesoscale interactions that result in enhanced baroclinic instability. The dynamic and thermodynamic mechanisms of explosive cyclogenesis have studied extensively, but limited records of high-fidelity data for tracking and analyzing ECs has hindered studies of interannual EC variability.

To understand how ECs may vary on interannual timescales, it is important to consider the interannual variability of the synoptic and mesoscale processes that can result in rapid cyclogenesis. In the early analyses by Sanders and Gyakum (1980) and in subsequent studies, ECs were commonly studied over warm ocean currents, like the Gulf Stream, where atmospheric and boundary-layer instability is enhanced due to latent heat release (Gall, 1976; Gyakum, 1983; Konrad & Colucci, 1988; Kuwano-Yoshida & Asuma, 2008; Minobe et al., 2008; Rudeva & Gulev, 2011; Sanders & Davis, 1988; Whitaker & Davis, 1994). Other cyclogenesis processes include baroclinicity driven by strong atmospheric temperature contrasts (Bosart, 1981; Bosart & Lin, 1984), the upper-level jet-stream and storm track (Colucci, 1985; Macdonald & Reiter, 1988; Rogers & Bosart, 1986; Ulbrich et al., 2001), and upper level divergence from enhanced upward
motion (Bosart & Lin, 1984; Pinto et al., 2009; Uccellini, 1990; Uccellini & Johnson, 1979). These processes will be broadly referred to as cyclogenesis mechanisms.

Due to the spatial heterogeneity of cyclogenesis mechanisms in the North Atlantic (C.-C. Wang & Rogers, 2001), it is important to analyze how the sources of interannual variability may vary within the North Atlantic. Specifically, this study focuses on teleconnection patterns that impact EC frequency. For example, the North Atlantic Oscillation (NAO), characterized by a meridional dipole of alternating pressure anomalies in the North Pacific, has been shown to strengthen and shift the jet stream to the north in the positive phase, displacing ECs further to the north as well (Gómara et al., 2016). However, many highly impactful ECs like winter storm Grayson form at lower latitudes along the East Coast of the United States and are unlikely to be associated with the high-latitude atmospheric changes induced by the NAO (LeComte, 2019). Additionally, Pinto et al. (2009) highlighted two epicenters for extreme cyclogenesis: one adjacent to the east coast of the United States and another east of the southern tip of Greenland (see their Figure 4c). The teleconnections which impact interannual variability in ECs for these two regions likely differ due to the geographical separation of these two cyclogenesis epicenters.

The NAO has been the focus for literature relating interannual climate variability with EC frequency and intensity. A positive NAO results in more frequent high-latitude cyclogenesis cases (Gómara et al., 2016; Pinto et al., 2009). However, analyses of potential up-stream forcing mechanisms for North Atlantic cyclogenesis mechanisms have not been extended to explosive cyclogenesis (Schemm et al., 2018). Especially for lower-latitude ECs which form along the east coast of North America, different teleconnections may impact cyclogenesis mechanisms than in the high-latitudes of the North Atlantic. Of primary interest are atmospheric teleconnections which can induce an anomalous wave-train pattern over North America, a feature which is often associated with severe winter weather. One increasingly important example is the Eastern Pacific–North Pacific pattern (EP-NP), which has been strongly linked to extreme winter temperatures and weather in recent years (Schulte & Lee, 2017). While the EP-NP pattern is most prominent during the spring, summer, or fall season, it has amplified in the recent decades during the winter (Schulte & Lee, 2017). This amplification, which has been associated with pronounced ridging events over western North America and deepened seasonal troughs over the eastern part of the continent, may potentially impact upper-level circulation features relevant for ECs along the southeast coast of North America (Schulte & Lee, 2017; Wang et al., 2014; Wang et al., 2017). The Pacific North American (PNA) pattern can also facilitate negative pressure anomalies over the Southeast United States that may impact seasonal baroclinicity and cyclogenesis mechanisms (Wettstein & Wallace, 2010).

Many of the atmospheric teleconnection patterns that span North America during the winter season are linked to the tropical Pacific Ocean, such as El Niño Southern Oscillation (ENSO) (Branstator, 2014; Ciasto et al., 2016; May & Bengtsson, 1998). Anomalous tropical heating and convection can form arcing patterns of alternating pressure anomalies through stationary Rossby wave propagation in the westerly mid-latitude flow (Held et al., 2002; Hoskins & Ambrizzi, 1993; Hoskins & Karoly, 1981). These large-scale alterations to the mid-latitude flow, combined with the impact of transient troughs and ridges (Held et al., 1989; May & Bengtsson, 1998), shift regions of baroclinicity in the North Atlantic (Schemm et al., 2018).
Given this relationship, we expect that the frequency of ECs in the North Atlantic is somewhat dependent on tropical Pacific climate variability.

Our objectives are to identify the sources of interannual variability associated with EC frequency in the North Atlantic and to determine the role of Pacific forcing in modulating EC frequency. After the methods in section two, section three documents the relationship between seasonal atmospheric circulation features and EC frequency for low-latitude coastal and high latitude ECs (defined explicitly in methods). As the results for high-latitude ECs are largely supportive of other literature, we focus on coastal ECs and their associated cyclogenesis mechanisms which exhibit a growing relationship with an atmospheric wave-train of alternating pressure anomalies that branches out from the tropical Pacific. Finally, the impacts of Pacific climate variability from sections three and four are examined with the fully coupled Community Earth System Model (CESM) in section five.

2. Methods

2.1 EC definition and tracking

Tracking explosive cyclogenesis is attainable through automated detection techniques in reanalysis data and has been performed in multiple studies (Allen et al., 2010; Gómara et al., 2016; Kuwano-Yoshida & Asuma, 2008; Reale et al., 2019). Automated tracking requires a strict definition of an EC, of which the normalized deepening rate of central pressure (NDR) is commonly used (Sanders & Gyakum, 1980). The NDR is defined in Equation 1.

\[
NDR = \frac{\Delta p \sin(60)}{24 |\sin \theta|}
\]

Equation 1. Normalized deepening rate where \(\Delta p\) is the change in central MSLP within the cyclone and \(\theta\) is the latitudinal position of the EC.

The NDR determines the raw change in mean sea level pressure (MSLP) relative to 60° latitude, to account for the negative pressure tendency from the tropics to the poles. An explosive event would result in a value equal to or greater than one, which is defined as one Bergeron.

Tracking is performed in ERA5 global reanalysis (Hersbach et al., 2020), at six-hourly data at a 0.25° resolution from 1950 through 2020. The 1950-1978 period of the data has been released as a preliminary back-extension, so tracking in this data is compared with tracking output from the National Centers for Environmental Prediction Reanalysis 1 (NCEP R1) at 2.5° resolution (Kalnay et al., 1996) and the Japanese 55-year Reanalysis project at 1.25° resolution (Ebita et al., 2011). EC tracking is done for the Northern hemisphere’s cool season, November through March, which has been identified as the most common season for ECs in the North Atlantic (Allen et al., 2010). Following Hodges and Hoskins (2002), a Fourier transform is applied to the global MSLP field at each six-hour time step to remove large scale
2.2 Sources of interannual variability

To analyze the large-scale circulation features associated with interannual variability in ECs, we first determine the frequency of ECs for the cold season within two spatial domains as defined by a previous study (Pinto et al. 2009). ECs are grouped into coastal (90°W-60°W and 10°-45°N) and high-latitude domains (60°W-0°W and 45°N-90°N), based off their latitude and longitudinal position 24 hours before the criteria for explosive cyclogenesis was met (black dots in Fig. 1b and 1c). Pinto et al. (2009) showed that extreme cyclogenesis in the North Atlantic has two distinct regions favorable for cyclogenesis near the low-latitude coast of North America and to the east of the southern tip of Greenland. There is no overlap between southwest and northeast domains to distinguish dominant cyclogenesis mechanisms (Fig. 1b and 1c).

To document the non-stationary relationship between teleconnection patterns and EC frequency, we use a 30-year rolling correlation between high-latitude/coastal EC frequency with teleconnection indices for the November-March average (e.g., EP-NP, PNA, AO, and NAO). These teleconnection indices are obtained from the National Oceanic and Atmospheric Administration’s Physical Sciences Laboratory. We then use correlation and composite analysis of EC frequency for the cold season, averaged from November through March, with geopotential height ($Z_{250}$), wave activity flux (Takaya & Nakamura, 2001), stream function, velocity potential, wind divergence, and zonal wind at 250 hPa ($U_{250}$) as well as omega at 500 hPa. These data were all gathered from ERA5 monthly reanalysis data. For composite analysis, we selected years that surpassed a threshold of one-half standard deviation above the mean for both the frequency of ECs and for the EP-NP index. To compare how the relationship of ECs and North Atlantic cyclogenesis mechanisms may have changed, we separately analyze the period from 1950 to 1984 (early period) compared to 1984 to 2019 (recent period). We chose 1984 as the cutoff year to result in an equal
sample size for comparison between the early and later period. Changing the cutoff period to any time within the 1980s does not qualitatively alter the results (not shown). The year in analysis corresponds to the year for the November and December months of a November through March average. Finally, all anomalies are defined as a deviation from climatology in each month from 1950 through 2020.

We also perform composite analysis of individual cyclone cases to examine the cyclogenesis mechanisms. This analysis uses six-hourly ERA5 reanalysis data averaged for the 12-hour period before the threshold of 1 Bergeron was met by an EC. In addition to upper-level divergence, we compute the 850 hPa temperature advection and the maximum Eady Growth Rate (EGR, Eady, 1949; Lindzen & Farrell, 1980) as a vertical average from 300-500 hPa following Pinto et al. (2009). The EGR has been used extensively to approximate baroclinic instability in a storm, following Equation 2 where $g$ represents the gravitational constant, $f$ is the Coriolis parameter, and $\theta$ represents potential temperature.

$$EGR = \left( 0.3098 \times g \times |f| \times \left| \frac{du}{dz} \right| \right) \left( \frac{g d\theta}{\theta dz} \right)$$

Equation 2. Eady growth rate

2.3 Model diagnostics in the CESM

To validate and support observational analysis, we use a modeling experiment with the National Center for Atmospheric Research (NCAR) fully coupled CESM version 1.0. This model is comprised of ocean, land, sea ice, and atmospheric components with 26 atmospheric levels and 60 vertical levels in the ocean. The horizontal resolution for the ocean and sea-ice components is approximately 1° latitude by 3° longitude at the equator with a slight decrease in resolution at high latitudes, while the atmospheric and land components are resolved on a T31 spectral grid. Model performance and settings are documented in Sheilds et al. (2012) and Chikamoto et al. (2015).

The climate model experiment used in this study is a historical simulation of 10 ensemble members coupled with ocean data assimilation system. At first, we conducted historical simulation with 10 ensemble members by prescribing natural and anthropogenic radiative forcing from 1850 to 1957. The initial conditions for each ensemble member come from 10 random years from pre-industrial control simulation. From 1958 to 2014, we activated ocean data assimilation scheme while prescribing the radiative forcing. In the global assimilation run (the GLOB run), three-dimensional ocean temperature and salinity observations are incorporated into the coupled climate model. Ocean temperature and salinity observations come from the European Center for Medium-Range Weather Forecast's Ocean Reanalysis Product (version 4) from 1958 to 2014 (Balmaseda et al., 2013). To highlight the impact of the tropical Pacific on large-scale circulation features, we conducted a partial ocean assimilation run that incorporates ocean temperature and salinity observations in the equatorial Pacific only (the eqPAC run).
The ensemble mean in the GLOB/eqPAC run corresponds to the climate response to the radiative forcing plus global/equatorial Pacific ocean forcing. Previous studies have documented the utility and applicability of this partial ocean assimilation approach and provide more detail information about the model performance (Chikamoto et al., 2015, 2016; Johnson et al., 2020; Purich et al., 2016; StuivenvoldtAllen et al., 2021).

3. Interannual Variability Of Coastal And High-latitude Ecs

The spatial distribution of our tracked ECs in the North Atlantic (Figure 1a) show the greatest density of ECs occurring along the North Atlantic storm track, which is consistent with other modern EC climatological studies (Allen et al., 2010; Gómara et al., 2016; Reale et al., 2019). Coastal cyclones have a meridionally tilted pattern in their track (Figure 1b) while high-latitude cyclones exhibit a more zonal density pattern (Figure 1c). These track patterns are consistent with the orientation of the gulf stream current and the meridonal tilt of the climatological jet stream in winter off the east coast of North America. No noticeable trends are seen in the frequency (Figure 1d) or minimum annual MSLP (not shown) of ECs within the last seventy years. However, we find a significant increasing trend in the 30-year running variance of both coastal (p=0.013) and high-latitude (p<0.01) EC frequency. This suggests that interannual variability in EC frequency has risen in the recent period that teleconnections may becoming more important for modulating EC frequency from November through March (Figure 1e). Finally, Coastal EC frequency is highly uncorrelated with high-latitude ECs (r=0.07) supporting the need to separately analyze these groups.

The relationship between coastal ECs and upper-level geopotential height has changed in the recent decades, shown by the correlation analysis in Figure 2a-c. The correlation map of $Z_{250}$ with coastal EC frequency during winter consists of positive anomalies over Alaska/Western Canada and negative anomalies over the central North Pacific and eastern North America (Fig. 2a), resembling the EP-NP pattern. However, their amplitudes are weak and insignificant, particularly for the 1950-1984 period (Fig. 2b). In contrast, we find the clearer and significant $Z_{250}$ anomaly pattern with a more prominent wave-train translating across North America for the recent period of 1985-2020 (Fig. 2c), suggesting a strengthened relationship between coastal EC frequency and the EP-NP pattern. Along with this wave-train, Figure 2c shows that coastal ECs have a weak relationship with a negative NAO-like pattern, consistent with literature observing the negative NAO results in a shift of the storm track to lower latitudes (Chartrand & Pausata, 2020). This amplified relationship in the recent period is not seen for high-latitude ECs. Rather, a prominent positive NAO pattern is consistently associated with enhanced EC frequency for the higher latitude storms.

4. Changes In Interannual Variability And Cyclogenesis Mechanisms

The wave-train pattern in Figure 2c suggests a Pacific climate influence on interannual variability of coastal EC frequency after 1985 through upper-level atmospheric dynamics. Through a 30-year rolling correlation with coastal EC frequency, Figure 3a shows that the EP-NP pattern has been highly correlated
with coastal EC frequency in the recent decades. This growing relationship is present in the frequency of coastal ECs tracked from three different reanalysis datasets, ERA5, JRA55 and NCEP R1. The PNA pattern also depicts an increase in the correlation coefficient between coastal EC frequency and the cold-season teleconnection index except for the NCEP R1 record of coastal EC frequency (Figure 3b). We also note that the and NAO and the Arctic Oscillation (AO) can have an impact on the high-latitude polar front jet (Hall et al., 2015) and their relationship with coastal EC frequency from ERA5 is increasing. However, the relationship between coastal EC frequency and the NAO and AO differs in each reanalysis dataset, introducing some uncertainty about the relationship of the arctic with coastal EC frequency. As the growing relationship of the EP-NP with coastal EC frequency is consistent in the three reanalysis datasets, it will be the focus of subsequent analysis.

The rolling correlations of the same teleconnection indices with the high-latitude EC frequency show a strong and persistent relationship between the NAO and high-latitude EC frequency (Figure S1). The relationship between the NAO and high-latitude EC frequency is consistent and significant for the entire period (1950-2020), which is documented well by other studies (Gómara et al., 2016; Pinto et al., 2009).

Figure 4a shows the correlation of the EP-NP index with \( Z_{250} \), which prominently features an arcing wave-train pattern that has a positive relationship with \( Z_{250} \) over the central tropical Pacific. The early-period correlation shows that the upper-level \( Z_{250} \) relationship with the EP-NP index was more localized to the Pacific and there are less prominent relationships over North America. For the recent period, however, the relationship with the EP-NP index has amplified. This pattern is characteristic of a tropically induced teleconnection which emanates from the central tropical Pacific. The associated wave-train features a prominent positive relationship over the western coast of North America and a deepened negative relationship over the east coast. The growing relationship between the EP-NP index and EC frequency along with the changing upper-level circulation features suggests that tropical Pacific variability could be an important driver of EC frequency and cyclogenesis mechanisms along the east coast in the recent decades.

The increasing relationship between the EP-NP and coastal EC frequency may be partially explained by the strengthening of the negative relationship between the EP-NP and upper-level \( Z_{250} \) over eastern North America. The amplified east-west dipole structure in \( Z_{250} \) over North America would likely impact EC frequency through enhanced jet stream activity and upper-level divergence associated with the amplified pressure gradient. To examine the dynamic link between the EP-NP pattern and cyclogenesis mechanisms, we made correlation maps of wind divergence at 250 hPa, zonal wind at 250 hPa (\( U_{250} \)), and latent heat flux at the surface with the EP-NP index (Fig. 5). Both 250 hPa divergence and zonal wind (\( U_{250} \)) as averages from November through March show an enhanced correlation with coastal EC frequency for the recent decades (Figure 5a-d). Upper-level divergence is an important factor to cyclogenesis in ECs and extreme extratropical cyclones because it facilitates baroclinicity that can result in rapid cyclogenesis (Baehr et al., 1999; Uccellini & Johnson, 1979; Ulbrich et al., 2009). The amplified gradient of pressure anomalies associated with the EP-NP in the recent period (Figure 4c) results in a
stronger upper-level jet stream over the east coast of North America (Figure 5d), another important ingredient for the genesis and steering of rapid cyclogenesis (Pinto et al., 2009). The relationship of the EP-NP with latent heat results in diminished surface latent heat flux (SLHF) in the recent era suggesting that the EP-NP impacts on cyclogenesis mechanisms are mostly associated with the upper-level.

All analysis to this point has been done with seasonal averages, but most of the processes that result in ECs occur on much shorter time scales. To determine if the synoptic scale cyclogenesis mechanisms associated with coastal ECs are impacted by the EP-NP pattern, we provide case composites which constitute 12-hour averages of divergence, $U_{250}$, EGR and latent heat flux for the 24-12 hours before the threshold of one Bergeron was met for each coastal EC. These composites are taken for ECs which occur during positive EP-NP events which occurred during cold-seasons dominated by a positive EP-NP had more a stronger connection with upper-level dynamics along with the jet stream position. The orientation of the jet stream shows the zonally elongated pattern during ECs for the early period (Figure 6a), while the recent period features the meridionally tilted pattern associated with enhanced divergence anomalies near the east coast of North America (Figure 6b). The EGR composites largely mirror these same features: the zonal configuration in the early period (Figure 6c) and the amplified and meridionally tilted in the recent period (Figure 6d). The upper-level circulation features induced by the EP-NP are also associated with more distinct and organized temperature gradients that extend to lower layers which can be seen clearly at 850 hPa (Figure 6e,f). In the recent period, there is a more distinct gradient of cold-air advection and warm-air advection centered on the east coast of North America, a characteristic feature of baroclinic instability. Finally, the latent heat flux composites in Figure 6g and 6h show that this local ocean forcing associated with the positive EP-NP phase has decreased in the recent period. These results suggest that upper-level atmospheric dynamics associated with the EP-NP pattern, rather than surface thermodynamics, have become a more important cyclogenesis mechanism for coastal ECs.

5 Growing Impact Of The Tropical Pacific On Coastal Ecs

The shift in the upper-level circulation features associated with coastal EC frequency and the EP-NP index can be seen in the stream function composites in Figure 7. This figure highlights that coastal EC frequency in the early period was more commonly associated with an anticyclonic circulation anomaly in the North Pacific. In the recent period, the stream function anomalies in the North Pacific have completely flipped compared to the early period (Fig. 7a and b) and are now more closely aligned with the EP-NP pattern (Fig. 7d). Additionally, the WAF (Takaya & Nakamura, 2001) shows wave energy propagation directed from the North Pacific towards the east coast of North America and the North Atlantic Ocean in the latter period.

To better depict the impact of the tropics on the emerging atmospheric wave train, Figure 8 presents composites of the positive phase of the EP-NP index with 500 hPa omega anomalies. In the last 35 years,
upward motion associated with the EP-NP was enhanced in the central and western tropical Pacific (Figure 8a, 8b). Enhanced upward motion is also present in the northeast Pacific for the recent period, with an alternating pattern of sinking and rising air that matches the observed changes in mid-latitude circulation associated with the EP-NP pattern. The linear trend in upward motion has some overlap with the composites of the positive EP-NP phase in the recent period, suggesting that climate change or low-frequency climate variability may contribute to strengthening the EP-NP pattern (Figure 8c).

These same features are supported by the 250 hPa velocity potential and divergent wind fields (Figure S2). There has been a large decrease in velocity potential in the western tropical Pacific and in the Northeastern Pacific, indicating an enhancement of upward motion within these regions, and increased potential for a source of Rossby wave activity that is known to induce atmospheric wave trains over North America (Held et al., 2002). Figure S2c shows the trend of velocity potential and divergent winds from 1950 through 2020, supporting that observed changes to the mean-state of the tropical Pacific are synchronous with the observed changes in variability.

Given the potential for a greater teleconnection associated with the EP-NP pattern sourced by the western tropical Pacific variability, the eqPAC run is a useful tool for evaluating if equatorial Pacific Ocean variability can account for the recent changes in atmospheric circulation. Figure 9 shows the composite of WAF and stream function at 250 hPa in the eqPAC run during positive EP-NP phases. The recent period shows a more pronounced atmospheric wave-train in association with the EP-NP pattern that generally matches observations. Along with observed analysis, this supports that tropical Pacific Ocean variability is the main driver of the EP-NP pattern and its recent amplification.

We also provide composites of $U_{250}$ and $Z_{250}$ anomalies for the positive phase of the EP-NP index in the early and recent periods in the eqPAC and GLOB simulations (Fig. 10). The eqPAC run depicts the EP-NP-like wave-train pattern of $Z_{250}$ anomalies for the recent period (Figure 10a,b). We find the similar but amplified wave train pattern of $Z_{250}$ anomalies in the GLOB run compared to the eqPAC run (Fig. 10c and d). As a result of wave propagation, the negative and positive $Z_{250}$ anomalies appear over the eastern North America and the North Atlantic for the recent period (Fig. 10b and d). These pressure anomalies affect the jet stream position and contributes to coastal EC frequency through upper tropospheric dynamics. Our model experiments also support that recent variability in coastal EC frequency is modulated by the EP-NP pattern, which is mainly attributed to the tropical Pacific Ocean forcing and well captured by global ocean variability.

### 6 Discussion

Our study showed that coastal EC frequency relies on the tropical Pacific forcing for the recent decades, but the extent to which this relationship will continue to amplify, diminish or asymptote is currently unknown. These changes do not appear to be associated directly with ENSO, but rather with an enhanced teleconnection source in the western tropical Pacific. Teng and Branstator (2017) showed that the ridge-trough pattern over the western and the eastern United States can largely be explained by internal
variability in the jet stream alone (Deser et al., 2012). However, Teng and Branstator (2017) also concluded that tropical forcing in the western Pacific can increase the probability of more amplified stationary wave configurations over North America, supporting results from this work.

Accelerated warming in the arctic has also been identified as a potential forcing for more amplified mid-latitude weather regimes (a review on arctic mid-latitude linkages is provided by Cohen et al., 2020), but our results highlight that the arctic forcing for coastal EC frequency would be secondary compared to the tropics (Hartmann, 2015; McKinnon et al., 2016; Palmer, 2014). Notably, the relationship between the AO index with coastal and high-latitude EC frequency is increasing for ECs tracked in ERA5 (Fig. 3d and Fig. S1), but there is observational uncertainty due to the spread between the three reanalysis datasets used in this study. In contrast, NCEP R1, JRA and ERA5 coastal EC frequency agree upon the growing relationship with the EP-NP index. Some observational uncertainty remains as objective tracking has been shown to pick up “artificial” explosive systems (Allen et al., 2010), but the strong agreement between the three reanalysis datasets supports the role of the EP-NP pattern.

The EP-NP spatial pattern in winter bears resemblance to the North American Winter Dipole (Singh et al., 2016; Wang et al., 2015) and to the Pacific-North America Pattern but correlations of these indices with the coastal ECs frequency are much weaker than that of the EP-NP index (Fig. 3). Because the EP-NP pattern dominates during the fall-spring seasons rather than winter, the impact of EP-NP pattern on the North American extreme events received less attention compared to those teleconnection patterns. Nevertheless, notable changes have been reported in the leading empirical orthogonal function (EOF) of wintertime geopotential height for November through January, which more closely resembles the EP-NP and the North American Winter Dipole patterns (Chien et al., 2019). Consistent with Chien et al., (2019), these two patterns have become drastically more correlated recently for November through March (Figure S3). Previous literatures pointed out the increasing impact of the EP-NP on temperature variability in the United States (Schulte & Lee, 2017) and the high impact of the zonal dipole of atmospheric pressure anomalies over North America (Singh et al., 2016; Stuivenvolt-Allen & Wang, 2019; Wang et al., 2015, 2017). Our research highlighted that the EP-NP pattern during the recent winter affects not only the large-scale atmospheric circulations as described by the previous studies but also extreme weather events, such as the coastal EC frequency. Therefore, our result suggests that accurate seasonal forecast of EP-NP index would be crucial to mitigate damages from severe winter storms in the east coast of North America.

7 Conclusion

This study focuses on identifying the sources of interannual variability associated with EC frequency in the North Atlantic and determining the role of Pacific forcing in modulating EC frequency. Applying the EC tracking method to the reanalysis datasets, we found two independent modes of interannual variability for coastal and high-latitude EC frequency. The variances of EC frequency show noticeable increasing trends for the 1950-2020 period. Whereas the high-latitude EC frequency highly correlates with the NAO and the AO indices for the entire analysis period, the coastal EC frequency significantly correlates with the
EP-NP index only for the recent decades. Coastal EC frequency during the last three decades exhibits a much stronger link to Pacific sourced climate variability – namely the atmospheric wave-train best characterized by the EP-NP teleconnection. Based on the observational data analysis, we found that the recent interannual variability of the EP-NP index is strongly linked to cyclogenesis mechanisms near the east coast of North America; Upper-level divergence, jet stream activity, and more organized regions of temperature advection, have all contributed to a greater association of the EP-NP pattern and coastal EC frequency. Our model experiments indicate that the equatorial Pacific Ocean forcing is the main driver for the recent amplification regarding the EP-NP impacts on the coastal ECs frequency.

Declarations

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**Author’s contributions:** JSA performed all data analysis in this paper, but the CESM climate models were ran by YC. Methodology was determined by JSA, SYW, YC, JM, and ZJ. Interpretation of analysis was aided by all authors. Data acquisition was undertaken by JSA, YC and ZJ. The first draft of the manuscript was written by JSA and all authors provided comments, edits and additional writing. The final manuscript has been read and approved by all authors.

**Data Availability:** All data used in this study can be acquired free of charge to any member of the public or by request to the corresponding author. The code used in this study can be requested from the corresponding author, at jacob.stuivenvoltallen@usu.edu.

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**Figures**
**Figure 1**

(a) Nov-Mar genesis density of all ECs captured by our tracking methods from 1950 through 2019. Tracks of (b) coastal and (c) high-latitude ECs along with the initial track point (a black marker). (d) Timeseries of EC frequency in the high-latitude (light blue) and coastal regions (red) during Nov-Mar from 1950 through 2019. (e) 30-year rolling variance of EC frequency (solid lines) along with the linear trend computed from least squares regression. Each trend is significantly different from a slope of 0 through use of the Wald Test with a t-distribution of the test statistic at the 95% confidence level.

**Figure 2**

Correlation maps of $Z_{250}$ with coastal EC frequency (top) and the high-latitude EC frequency (bottom) during November-March for (a,d) the entire analysis period, (b,e) 1950-1984, and (c,f) the recent period of 1985-2020. The black contour lines indicate the 95% confidence threshold for the correlation coefficient with the degrees of freedom equaling the number of the years in each correlation minus two using the Student’s t-test. The yellow rectangle indicates the domain for coastal and high-latitude ECs.
Figure 3

A 30-year rolling correlation between the November through March frequency of ECs tracked in ERA5 (red line), JRA55 (blue line) and NCEP R1 (orange line) with the (a) EP-NP, (b) PNA, (c) NAO, and (d) AO teleconnection indices. The time for each rolling correlation is calculated at the middle year for each 30-year period (i.e., the year 2000 corresponds to the correlation coefficient for 1985-2014). The horizontal dotted line and solid line indicate the significance thresholds for 28 degrees of freedom for the 90% and 95% confidence interval respectively. Gray shading highlights the insignificant areas.

Figure 4

Correlation of coastal EC frequency with Z250 from November through March for the entire analysis period (a), 1950 through 1984 (b) and the recent period, 1985 through 2020 (c). The black contour lines indicate the 95% confidence threshold for the correlation coefficient with the degrees of freedom equaling the number of the years in each correlation minus two.
Figure 5

Correlation of the EP-NP index with (a,b) 250 hPa wind divergence, (c,d) 250 hPa zonal wind (U250), and (e,f) surface latent heat flux for the early period (left) and the recent period (right). The black contour lines indicate the 95% confidence threshold for the correlation coefficient with the degrees of freedom equaling the number of the years in each correlation minus two.

Figure 6

Positive EP-NP case composites of (a,b) wind divergence and zonal wind at 250 hPa, (c,d) 500-300 hPa EGR, (e,f) 850 hPa temperature advection, and (g,h) surface latent heat flux. The left column represents composites for the early period (1950–1984), while the right column are composites taken from the recent period (1985–2020). The sample size is included in the top right corner of each plot, indicating the number of ECs included in the analysis.

Figure 7

Composite maps of streamfunction anomalies at 250 hPa (contour fill) and WAF (vectors) for (a) large coastal EC frequency for 1950-1984, (b) large coastal EC frequency for 1985-2019, (c) positive phases of EP-NP index for 1950-1984, and (d) positive phases of EP-NP index for 1985-2019. The sample size is included in the top right corner of each plot, indicating the number of seasons included in the analysis.
Figure 8

Composite maps of omega at 500 hPa for the positive EP-NP phases in (a) the early period and (b) the recent period. (c) Linear trend in omega computed from least squares regression for the period of 1950-2020. Stippling marks areas significantly different from a slope of 0 through use of the Wald Test with a t-distribution of the test statistic at the 95% confidence interval.

Figure 9

Composite maps of 250 hPa stream function (contour fill) and the WAF (vectors) for the positive EP-NP phase in the eqPAC run during (a) the early period and (b) the recent period.

Figure 10
Composite maps of Z250 (contour fill) and U250 anomalies (contour line) for the positive EP-NP phases in (a,b) the eqPAC and (c,d) the GLOB runs for the early (left) and the recent periods (right panels).

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