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A COMPARISON OF ARCTIC AND ATLANTIC BASIN CYCLONE PREDICTABILITY FROM A CLIMATOLOGY AND CASE STUDY PERSPECTIVE

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A COMPARISON OF ARCTIC AND ATLANTIC BASIN CYCLONE PREDICTABILITY
FROM A CLIMATOLOGY AND CASE STUDY PERSPECTIVE

by

Peyton K. Capute

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ABSTRACT

Arctic cyclones (ACs) can transport warm, moist air into the Arctic region, which combined with strong winds may lead to rapid declines in sea ice during the summer. As a consequence, accurate sea ice predictions during the summer may rely on being able to predict cyclone-related wind speed and direction, which critically depends on the cyclone track and intensity. Despite this, there are relatively few studies that have documented the predictability of ACs during the summer, beyond a few case studies. In addition, there has been no extensive comparison of whether these cyclones are more or less predictable relative to comparable midlatitude cyclones, which have been studied in greater detail.

The first part of this thesis creates a climatology of comparable, long-duration, intense Arctic and Atlantic basin cyclones to compare the predictability of Arctic and Atlantic position and intensity forecasts over a large number of cases using the Global Ensemble Forecast System Reforecast V2. Using standard deviation (SD) and root mean square error as a proxy for predictability, Atlantic cyclone position is characterized by higher predictability relative to comparable ACs, but intensity predictability is higher for ACs. In addition, storms in both basins characterized by low ensemble SD and predictability are found in regions of higher baroclinicity than storms characterized by high predictability. There appears to be little, if any, relationship between latent heat release and precipitable water and predictability.

The source of position and intensity forecast variability of two Arctic and two Atlantic basin cyclones, similar to those analyzed in the climatology, is diagnosed using ensemble-based sensitivity analysis applied to Model for Prediction Across Scales ensemble forecasts. Results suggest that the position and intensity variability of these storms are largely associated with both upstream and downstream uncertainty of meso-scale features embedded within the larger-scale
potential vorticity (PV) features, particularly downstream ridge building, in both regions associated with cyclogenesis. Further, the intensity variability of the ACs is associated with uncertainty to thermal boundaries near the cyclone or along the sea ice edge, whereas the Atlantic basin cyclone intensity variability is sensitive to low-level temperature and moisture along the polar front proceeding the cyclones. Further, AC intensity variability appears to be most sensitive to upper-tropospheric variability earlier in the forecast, transitioning to lower tropospheric variability later in the forecast, whereas results are less clear for Atlantic basin cyclones.

An additional AC that was observed during the THINICE 2022 field campaign is analyzed to compare the optimum metrics applied to sensitivity analysis to assess the source of forecast error of European Centre for Medium-Range Weather ensemble forecasts. Sensitivity of cyclone position variability (along the major axis direction) and 500-hPa geopotential height variability within a domain encompassing a tropopause polar vortex is compared, revealing similar sensitive regions primarily to the position of an upstream PV trough and amplitude of a downstream PV ridge. However, comparing sensitivity of cyclone intensity (minimum sea level pressure) variability and low-level wind variability encompassing a low-level jet associated with the AC, are less similar. Sensitivity of low-level wind variability reveals more systematic uncertainty associated with the upper-level PV field and a low-level thermal boundary.
PREFACE

The research in Chapter 2 comprises of original work published by the author in *Monthly Weather Review* by the American Meteorological Society (Capute and Torn 2021). Permission was granted to use the published research in this dissertation; see APPENDIX A for signed letter of approval. Proper reference to the publication is provided at the end of the preface and in the respective figure captions of Chapter 2.

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# TABLE OF CONTENTS

**ABSTRACT** .................................................................................................................. ii

**PREFACE** ....................................................................................................................... iv

**ACKNOWLEDGEMENTS** .................................................................................................. v

1. Introduction ......................................................................................................................... 1
   1.1 Motivation ....................................................................................................................... 1
   1.2 Background on Arctic cyclones ..................................................................................... 2
   1.3 Background on Midlatitude and Atlantic Basin Cyclone Predictability .................. 7
   1.4 Ensemble-based sensitivity analysis ............................................................................. 12
   1.5 Outline of Thesis ........................................................................................................... 13

2. A Comparison of Arctic and Atlantic Basin Cyclone Predictability: Climatology .......... 16
   2.1 Introduction ..................................................................................................................... 16
   2.2 Data and Methodology .................................................................................................. 17
      2.2.1 Case selection .......................................................................................................... 17
      2.2.2 The Global Ensemble Forecasting System (GEFS) dataset ..................................... 19
      2.2.3 Ensemble SD and RMSE as a proxy for predictability ........................................... 20
      2.2.4 Baroclinicity and LHR approximations .................................................................. 22
   2.3 Results ............................................................................................................................ 24
      2.3.1 Arctic and Atlantic basin cyclone climatology overview ....................................... 24
      2.3.2 Arctic and Atlantic basin cyclone predictability ....................................................... 24
      2.3.3 Selecting cyclones characterized by high and low predictability ......................... 26
      2.3.4 Comparing most and least predictable storms based on intensity ....................... 27
      2.3.5 Comparing most and least predictable storms based on position ....................... 29
   2.4 Summary .......................................................................................................................... 30

3. A Comparison of Arctic and Atlantic Basin Cyclone Track and Intensity Forecast
   Variability ............................................................................................................................. 41
   3.1 Introduction ..................................................................................................................... 41

   3.2 Data and Methodology .................................................................................................. 42
      3.2.1 Case selection .......................................................................................................... 42
      3.2.2 Model Configuration / Experimental Design / Ensemble-based sensitivity analysis .. 42
   3.3 Arctic Cyclone of August 2013 ..................................................................................... 44
      3.3.1 Case Overview ......................................................................................................... 44
      3.3.2 Cyclone Position Uncertainty .................................................................................. 45
      3.3.3 Cyclone Intensity Uncertainty ............................................................................... 48
   3.4 Atlantic Basin Cyclone of January 2013 ....................................................................... 51
1. Introduction

1.1 Motivation

Arctic cyclones (ACs) are synoptic-scale features that can be associated with strong, intense winds over the Arctic Ocean region for long periods of time, which in turn lead to rapid declines in sea ice (Simmonds and Rudeva 2012; Boisvert et al. 2016; Woods and Caballero 2016; Binder et al. 2017). ACs are also responsible for transporting excess heat and moisture from lower latitudes toward the North Pole (e.g., Persson et al. 2017; Fearon et al. 2021). Over the past 40 years, Arctic sea ice extent has decreased in coverage by over 40% during the summer months (e.g., Stroeve et al. 2012; Serreze and Stroeve 2015; Simmonds 2015; Koyama et al. 2017). Sea ice loss leads to large areas of open water, which in turn results in stronger heat and moisture transfers from the ocean to the atmosphere and hence higher surface temperatures, creating a feedback cycle known as Arctic amplification (Serreze et al. 2009; Screen and Simmonds 2010a,b; Inoue and Hori 2011). Reduced sea ice concentration (SIC) and extent could have a number of societal implications, including allowing ocean vessels to travel through the Arctic during the boreal summer. Increasing activity in Arctic, such as marine shipping, extraction of oil and natural gas resources and tourism are all likely to be impacted by ACs (Crawford and Serreze 2016; Yamagami et al. 2018a,b). Several studies have suggested that predictability in the Arctic region is lower compared to other regions, such as the midlatitudes (e.g., Yamagami et al. 2018a; Sandu and Bauer 2018); however, there has yet to be a comparison study of AC predictability.

The remainder of this chapter precedes as follows. Section 1.2 provides an overview of past literature on ACs, including their temporal and spatial frequency and known features that
may impact their predictability. Section 1.3 provides an overview of midlatitude cyclone predictability. The description of the ensemble sensitivity technique used in this study are explained in section 1.4. Lastly, section 1.5 provides an overview of the following chapters.

1.2 Background on Arctic cyclones

ACs are synoptic-scale features that are responsible for transporting warm, moist air from lower latitudes as well as inducing strong winds at the surface for long periods of time (e.g., Valkonen et al. 2021). These two mechanisms may contribute to widespread Arctic sea ice depletion, particularly during the boreal summer months when sea ice extent is at an annual minimum. ACs are not to be confused with distinctive high-latitude cyclones known as polar lows that are smaller in horizontal scale, shorter lived, and are generally confined to winter-time development over the ocean (e.g., Rasmussen and Turner 2003; Boyd et al. 2022).

ACs are ubiquitous features within the Arctic region, although there are some discrepancies throughout literature and open questions on the predictability of these systems. An early study found a modest winter maximum in Icelandic low frequency from 1966–1993 (Serreze et al. 1997); however, Zhang et al. (2004) examined 55 years of ACs, finding a modest maximum during the summer months. This small discrepancy can be attributed to cyclone definition and domain differences (Zhang et al. 2004), as there is no single accepted definition of an AC across literature. Both Serreze et al. (1997) and Zhang et al. (2004) concluded however that winter cyclones are significantly more intense than summer cyclones, likely related to an increased temperature gradient between the Arctic and midlatitude regions during the winter, and therefore a stronger polar jet stream (e.g., Simmonds et al. 2008). Zhang et al. (2004) also compared ACs that originate locally in the Arctic (between 70°N and 90°N) to those that originate south of 70°N, finding less seasonal variability in intensity for cyclones that originate
locally than those that originate south of 70°N. Additionally, ACs that originate locally have a small seasonal difference in frequency with 6,860 ACs occurring in winter and 6,026 in summer (Table 2.1). Furthermore, the duration of summer ACs is longer, with maximum duration occurring in June and July (Zhang et al. 2004; Crawford and Serreze 2016), which may be particularly important for the sea ice break up. Summer AC duration is hypothesized to be longer than winter due to increased low-level temperature gradient between snow-free land and the Arctic Ocean (e.g., Zhang et al. 2004, Tanaka et al. 2012). AC frequency also varies spatially with season, as cyclone frequency is greater over the northern Atlantic and Gulf of Alaska in winter and greater over Arctic Ocean and eastern Siberia in Summer (Crawford and Serreze 2016). Winter ACs that originate in the North Atlantic tend to follow the North Atlantic storm track, as baroclinicity is highest in the middle latitudes during the winter months, aiding dynamical support for these ACs. These cyclones track into the Arctic circle before undergoing cycloysis, and are responsible for transporting warm, moist air into the Arctic region. In contrast, summer ACs that originate locally within the Arctic region do not follow a distinctive path throughout the Arctic (Tanaka et al. 2012) but may remain over sea ice for long periods of time. In summary, the consensus across literature is that summer ACs are more frequent, longer-lived, but overall weaker than winter ACs.

Understanding how regions of strong baroclinicity, influences of upper-level PV features (i.e., tropopause polar vortices; TPVs; Cavallo and Hakim 2010), and processes such as vortex coupling may impact the intensification of summer ACs is important to determine what factors may ultimately limit the predictability of ACs. Many summer ACs that develop over Eurasia, subsequently track over the Arctic Frontal Zone (AFZ), a narrow band of strong horizontal temperature gradient produced via differences in atmospheric heating over the Arctic
Ocean and snow-free land (Crawford and Serreze 2015). Although this region was thought to be related to AC development (e.g., Serreze et al. 2001), Crawford and Serreze (2016) argue that the AFZ acts as an intensifier for summer ACs. The strength and existence of the AFZ varies throughout the summer, but when in full effect, the AFZ is associated with strong low-level baroclinicity and increased surface fluxes aiding AC intensification (Crawford and Serreze 2016). In addition, ACs are unique in that fact that they are able to sustain themselves for many days due to the ample supply of vorticity via the upper-level polar vortex (Tanaka et al. 2012). Through a 3-dimensional analysis of summer ACs, positive vorticity associated with an Arctic surface cyclone was found to be coupled with positive vorticity associated with the upper-level polar vortex (Tanaka et al. 2012). Similarly, TPVs seldom exist near ACs at the time of development but are frequently associated with ACs at the time of maximum growth (Gray et al. 2021) or vertically coupled with ACs (Tao et al. 2017). Additionally, many ACs are able to sustain themselves while merging with other preexisting surface cyclones in the Arctic region (e.g., Yamagami et al. 2017).

Many AC case studies have identified a connection between TPVs and the development and evolution of ACs. In particular, the presence TPVs has frequently been linked to strong ACs (Simmonds and Rudeva 2014). A frequently studied AC, the GAC of August 2012 (GAC12), was located downstream of a TPV that supported the baroclinic growth in the development of GAC12 (Yamagami et al. 2018a). In addition, Tao et al. (2017) demonstrates that GAC12 became vertically coupled with a TPV, allowing the cyclone to persist for many days. In addition to baroclinic processes and synoptic features such as TPVs, latent heating may also contribute to the development and intensification of ACs (Zhang et al. 2023).
Compared to midlatitude cyclone predictability research, there is a relatively small amount of research on AC predictability. An exception to this is the GAC12, which has been studied in-depth, particularly by (Yamagami et al. 2018a), who found that the position of this storm was harder to forecast than the intensity. A potential hypothesis for low position predictability within ACs is the lack of prevailing easterly or westerly winds in the Arctic region, allowing AC track to be less consistent (Tanaka et al. 2012). Using operational medium-range ensemble forecasts, accurate forecasts of position and intensity were observed only 2–3 days prior to GAC12 maximum intensity (Yamagami et al. 2018a). The predictability of GAC of 2016 (GAC16) required an accurate prediction of initial baroclinic development during the early development stage and the nonlinear development of multiple upper-level warm cores, defined as regions of higher temperatures than the surrounding area identified in the lower or middle stratosphere (Tanaka et al. 2012), merging throughout the evolution was crucial to the predictability of this event (Yamagami et al. 2017). GAC16 was sustained for over a month in the Arctic by the merging of multiple cyclones, both through storms that originated locally and storms that tracked into the Arctic (Yamagami et al. 2017). It was also noted that the predictability of minimum sea level pressure (SLP) for the GAC16 was higher compared to the GAC12. Additionally, using cyclone position and intensity forecast error as a proxy for predictability, a study of 10 strong ACs occurring during the summer months from 2008 to 2016, Yamagami et al. 2018a found that predictability was lower than many global modeling systems compared to midlatitude cyclones in the Northern Hemisphere (NH). In addition, comparing 6-day 500-hPa geopotential height anomaly correlation scores, Sandu and Bauer (2018) also suggest that Arctic forecast skill, based on 6-day 500-hPa geopotential height anomaly correlation scores, is lower than in the midlatitudes.
Changes in Arctic sea ice may also play a large role in the predictability of ACs (e.g., Simmonds and Keay 2009; Zahn et al. 2018; Valkonen et al. 2021). Examining the connection between a single AC and sea ice can lead to difficulty in distinguishing causation of the relationship (e.g., Valkonen et al. 2021). Therefore, many studies have focused on a climatological analysis to determine if a connection between Arctic sea ice and cyclone activity exists (e.g., Koyama et al. 2017; Graham et al. 2019; Valkonen et al. 2021). Koyama et al. (2017) analyzed changes in cyclone frequency, intensity, and physical processes as a result of declining sea ice. Although results from Koyama et al. (2017) found increased moisture, baroclinicity, and reduced vertical static stability for years following low sea ice during the month of September (all favorable conditions for Arctic cyclogenesis), there was no associated increase in cyclone frequency or intensity. Conversely, Valkonen et al. (2021) examined the relationship between ACs and reduced Arctic sea ice, demonstrating increased cyclone count and intensity following reduced Arctic sea ice. Therefore, Koyama et al. (2017) found no connection and Valkonen et al. (2021) found a robust correlation between reduced Arctic sea ice and AC frequency or intensity, which could be attributed to different reanalysis datasets chosen or defining regions of reduced sea ice. Finocchio et al. (2020) observed shorter-term, 1–7 days, changes in summer sea-ice, concluding that non-cyclone days during June are associated with larger sea ice loss during June, cyclone-days during August are associated greater sea ice loss.

Studies have examined the ways in which AC may be responsible for changes in sea ice. Specifically, sea ice in the Atlantic sector of the Arctic Ocean has been on the decline, with a record minimum sea ice extent observed since 2015 (Graham et al. 2019). Cloudiness created by ACs that pass over this Atlantic sector, have been associated with decreased sea ice growth due to decreased radiative cooling (Graham et al. 2019). As ACs break up Arctic sea ice, ocean-ice-
atmosphere heat fluxes are enhanced. Additionally, sea ice growth was reduced for the remaining winter season after an AC had passed over (Graham et al. 2019). However, increased cloud cover associated with early summer ACs is found to slow down seasonal ice loss (e.g., Schreiber and Serreze 2020; Finocchio et al. 2020; Finocchio and Doyle 2021). In many of these studies, varying sea ice coverage has led to changes in baroclinicity and diabatic processes (Valkonen et al. 2021), which as discussed earlier, can play a large role in AC predictability. Nevertheless, many studies have suggested that the connection between ACs and sea ice is still unclear.

In an effort to better understand the predictability and thermodynamics associated with ACs, the THINICE field campaign took place in the Arctic region during August of 2022 in collaboration with French, British, and US scientists. The Safire ATR42 and British Antarctic Survey MASIN aircraft were flown from Svalbard, focusing on mid-tropospheric and low-level features associated with ACs, respectively. In addition to aircraft, WindBorne balloons were launched regularly from Longyearbyen, Svalbard and Fairbanks, AK. These balloons are unique in that they are equipped with ballast, allowing the elevation of the balloons to be adjusted in real-time, while remaining in the atmosphere for up to weeks at a time. The overall goal of using these balloons was to increase the spatial and temporal coverage of in-situ observations available in the Arctic region. Further, sensitivity analysis was used in real time to help identify sensitive regions associated with ACs, such as moist intrusions, TPVs, cloud microphysics, sea surface and sea ice.

1.3 Background on Midlatitude and Atlantic Basin Cyclone Predictability

Compared to the AC literature, there is a relatively wide range of midlatitude cyclone predictability research. Early research examined systematic errors in forecasts for key aspects of cyclone tracking and intensity predictability in early versions of the National Meteorological
Center (NMC) models (e.g., Leary 1971; Silberberg and Bosart 1982). Specifically, 36-h forecasts of the NMC six-layer primitive-equation model under forecasted cyclone intensity over the ocean and over forecasted cyclone intensity for lee cyclogenesis over the Rocky Mountains (Leary 1971). In addition, forecasted cyclone temperature between 1000- and 500-mb was too cold for cyclones over the ocean and too warm over land (Leary 1971). Similar systematic errors were found for 24- to 48-h forecasts after a refined resolution was implemented using a Limited Area Fine Mesh Model (LFM), the NMC LFM-II model. Cyclone forecasts were too slow during October and November and too fast in March and April (Silberberg and Bosart 1982). The use of ensemble prediction became operational in 1992, in which multiple forecasts are produced by slightly varying the initial states to estimate of the probability density function of forecast states (Leith 1974; Froude 2010). For example, Froude (2010) compares nine different ensemble prediction systems (EPSs) to examine the predictability of 774 NH extratropical cyclones. Froude (2010) revealed that the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble-mean and control have the highest level of skill for all cyclone properties, including position and intensity, but consistently overpredicts cyclone intensity. Further, NCEP has the largest cyclone intensity errors while significantly underpredicting intensity (Froude 2010). Overall, all EPSs exhibit less variation for cyclone intensity compared to cyclone position. EPSs use a variety of different models, refinements, initial condition (IC) perturbations, ensemble sizes, etc., therefore it is important to use a variety of verification methods when assessing the skill of a forecasting system (Froude 2010).

In addition to climatological midlatitude predictability studies, there are a numerous amount of case studies that examine model error associated with midlatitude predictability. Initial condition and model uncertainties can both lead to poorly forecasted midlatitude cyclones.
Using ensemble experiments, model uncertainty was found to be the reason for a poorly forecasted maritime North Pacific midlatitude cyclone, as larger-than-average model error, particularly in 500-hPa geopotential height, was found with lower-than-average IC error (Hacker et al. 2003). Further, the forecast error growth of an extratropical cyclone was investigated using upper-level potential vorticity (PV) perturbations to create a simulation, suggesting that IC uncertainties led to exponential error growth initially before saturation (Zhu and Thorpe 2006). In addition, model uncertainties had zero error growth initially, followed by an exponential growth and a saturation period (Zhu and Thorpe 2006).

Midlatitude cyclones have been found to be sensitive to certain synoptic features, potentially impacting their predictability. A method known as adjoint sensitivity can be used to improve forecasts by perturbing ICs with a diagnostic correction computed from sensitivity analysis of forecasts to the IC of certain atmospheric patterns. For example, a complex upstream large-scale flow pattern led to short- and medium-range forecast errors of the 25 January 2000 East Coast United States (US) snowstorm (Langland et al. 2002). Adding adjoint sensitivity-based corrections to the ICs of the 72-h forecast for this storm led to an almost 75% reduction in forecast error and an 1860-km to 105-km improvement for cyclone position (Langland et al. 2002). In addition, errors in the 96-h forecast of a trough just upstream of the snowstorm is most sensitive to initial condition errors in a further upstream trough, suggesting downstream propagation of uncertainty over time, akin to downstream development. Therefore, one way to improve short- and medium-range forecasts for significant storms is to have accurate ICs of the upstream trough patterns in operational numerical weather prediction (Langland et al. 2002). Similarly, Chang et al. (2013) examined medium-range forecasts for two extreme Pacific extratropical cyclones characterized by sensitivity to downstream development. Chang et al.
(2013) compared sensitivity of cyclone minimum pressure and longitude to sensitivity of 
principal components (PCs) of the leading empirical orthogonal functions (EOFs), finding 
noisiness and inconsistencies using cyclone minimum pressure and longitude, suggesting that
EOF-based sensitivities perform better for medium-range forecasts. Furthermore, the EOF-based 
sensitivity pattern demonstrated that deepening of the upper-level trough and strengthening of 
the downstream ridge corresponds to the strengthening of the cyclone at the verification time 
(Chang et al. 2013). In addition, a southwestward shift of the upper-level trough corresponds to a 
westward shift of the cyclone. For the second case, a similar wave train of signals propagating 
from Eurasia eastward toward the final cyclone region is apparent up to six days prior to cyclone 
development (Chang et al. 2013).

Midlatitude cyclones have also been found to be sensitive to upper tropospheric features 
such as Rossby wave packets (RWP) (Grazzini and Vitart 2015). Long-lasting RWP are found to 
be coincident with larger than average medium-range forecast skill often over the west Pacific 
and smaller than average medium-range forecasts skill over the central US and western Atlantic. 
In addition to upper tropospheric features, lower tropospheric connections to midlatitude 
cyclones, such as baroclinicity and latent heat release (LHR), have also been studied. 
Specifically, through numerical simulations, baroclinic instability in the lower troposphere was 
found to be responsible for the growth of the extratropical cyclone that damaged Queen 
Elizabeth II in September 1978, with latent heat playing an important role in the later stages of 
development (Anthes et al. 1983). Similarly, LHR had a major impact on the storm development 
of the 13 November 1981 eastern Pacific cyclone (Kuo and Reed 1988).

Although the wide range of midlatitude cyclone predictability research makes for a good 
comparison to study AC predictability, there are many known differences between these two
environments. The main difference between cyclones over the Arctic Ocean versus the Atlantic basin is the distinction between these ocean’s temperatures, particularly through the first 500 m. Warmer ocean temperatures in the Atlantic Ocean allow for greater upward latent heat fluxes, and therefore more LHR, which can lead to more intense Atlantic basin cyclones compared to ACs (e.g., Kuo et al. 1991; Haualand and Spengler 2020). In addition, Atlantic basin cyclones generally follow the north Atlantic jet stream, yielding a more defined storm track compared to ACs. However, due to the lack of prevailing easterlies or westerlies within the Arctic region (Tanaka et al. 2012), ACs have a more erratic track compared to Atlantic basin cyclones, leading to more position uncertainty. Although there are many differences between Arctic and Atlantic basin cyclones, utilizing the same methods to evaluate and compare the predictability of these cyclones may help us better understand high latitude uncertainty.

The processes that limit midlatitude cyclone predictability have been studied in-depth through the various methods discussed above. However, the processes that may limit AC predictability are far less understood. Besides the GACs of August 2012 and 2016, which are highly anomalous cases, there has been little work done on the predictability of less anomalous summer AC cases. Therefore, the goal of this dissertation is to better understand how AC track and intensity predictability compares to midlatitude, Atlantic basin cyclones and what upper-level features and low-level thermodynamics may limit summer AC track and intensity predictability in comparison to Atlantic basin cyclones. A series of hypotheses will be tested for ACs, using methods that have been successfully applied to many other atmospheric features, with the same data and methods applied to analogous Atlantic basin cyclones to compare results.
1.4 Ensemble-based sensitivity analysis

Hypotheses 2 and 3 outlined in section 1.5 is tested using sensitivity analysis applied to the model for prediction across scales (MPAS) ensemble forecasts of both Arctic and Atlantic basin cyclone properties. Sensitivity analysis is a quantitative technique of determining how forecast metrics (i.e., cyclone track and intensity) are related to cyclone properties impacted by certain changes in specific forecast variables (i.e., temperature, height, precipitable water; PW, etc.) at earlier times. Earlier versions of estimating sensitivity techniques include adjoint and singular vector-based methods, which use a linearized version of the model (e.g., Errico and Vukicevic 1992; Rabier et al. 1996). However, in addition to requiring an adjoint of the model, these methods assume linear growth of forecast errors. This assumption can break down at longer forecast times or for primarily nonlinear processes (i.e., moist processes), potentially leading to inaccurate representations of the error growth in the atmosphere. Ensemble-based sensitivity techniques (Ancell and Hakim 2007; Torn and Hakim 2008) estimate sensitivity of non-linear, full-physics ensemble forecasts of varying initial condition parameters. The sensitivity of forecast metric $J$ (a function of the model state) to a model state variable $x_i$ is estimated from a $M$ member ensemble of forecasts via:

$$\frac{\partial J}{\partial x_i} = \frac{\text{cov}(J, x_i)}{\text{var}(x_i)} \tag{1.1}$$

where $J$ and $x_i$ are $1 \times M$ ensemble estimates of the respective quantities computed form the forecast ensemble, $\text{cov}$ represents covariance and $\text{var}$ denotes variance (Ancell and Hakim 2007; Torn and Hakim 2008). Ensemble-based sensitivity analysis computes the linear regression between ensemble estimates of a forecast metric and ensemble estimates of forecast fields at an earlier lead time. Therefore, assuming the forecasts have already been run, this technique is
computationally inexpensive. Further, assuming initial condition differences within the model are consistent with analysis error, ensuring an accurate estimate of forecast uncertainty, ensemble-based sensitivity analysis is adaptable to a wide variety of phenomenon, including ACs.

Ensemble-based sensitivity analysis has been used to estimate the sensitivity analysis of many atmospheric phenomenon such as tropical cyclones (e.g., Zhang and Sippel 2009; Torn and Cook 2013), African Easterly Waves (e.g., Torn 2010), extratropical transition (e.g., Torn and Hakim 2009; Torn 2010b), Southern Great Plains convection (e.g., Torn and Romine 2015; Torn et al. 2017), midlatitude cyclones (e.g., Hakim and Torn 2008; Chang et al. 2013; Lamberson et al. 2016), and Arctic cyclogenesis following a TPV (Johnson and Wang 2021). Therefore, this method is applicable for estimating the sensitivity of position and intensity uncertainty for Arctic and Atlantic basin cyclone forecasts to a range of features and processes in the atmosphere. All ensemble-based sensitivity figures in this dissertation show only statistically significant sensitivity at the 95% confidence level.

1.5 Outline of Thesis

This thesis examinations four main hypotheses:

H1) The predictability of Arctic cyclone track and intensity is indistinguishable from comparable midlatitude cyclones

H2) Forecast errors associated with tropopause-based features upstream of cyclones significantly limit Arctic cyclone tracking and intensity predictability compared to Atlantic basin cyclones

H3) Forecast errors associated with diabatic processes, such as LHR, within the cyclone warm sector limit Arctic cyclone intensity predictability
H4) Sensitive regions associated with ACs are comparable when using cyclone position and intensity metrics and EOF-based metrics centered around features associated with ACs, such as TPVs.

The following processes are used to test these hypotheses:

1. Create a climatology of comparable Arctic and Atlantic basin cyclones.
2. Assess the overall track and intensity predictability of Arctic and Atlantic basin cyclones using the climatology.
3. Select Arctic and Atlantic basin cyclones to assess position and intensity uncertainty using ensemble-based sensitivity analysis.
4. Compare sensitive region associated with position and intensity metrics to using field-based metrics for an AC observed during the THINICE 2022 field campaign.
5. Assess how well the balloons launched during THINICE 2022 observed the sensitive regions.

The remainder of this dissertation is organized as follows. Chapter 2 examines a climatology of long-duration, intense Arctic and Atlantic basin cyclones and assesses track and intensity predictability using standard deviation (SD) and root mean square error (RMSE) as a proxy. Chapter 3 compares two Arctic and two Atlantic basin cyclones similar to those examined in the climatology discussed in Chapter 2, using ensemble-based sensitivity analysis to assess track and intensity forecast uncertainty to upper-level features and low-level thermodynamics. An AC observed during the THINICE 2022 field campaign is used to compare track and intensity metrics and EOF-based metrics to assess the sources of uncertainty for this storm in Chapter 4. Further, Chapter 4 also evaluates how well the balloons launched during THINICE
2022 sample the sensitive regions of this storm. Lastly, Chapter 5 provides an overview of the results found in this thesis and discusses the potential avenues for future work.
2. A Comparison of Arctic and Atlantic Basin Cyclone Predictability: Climatology

2.1 Introduction

The purpose of this study is to compare the predictability of long-lived, intense midlatitude cyclones within the western Atlantic basin with cyclones in the Arctic Ocean. Here, practical predictability will be measured by evaluating the ensemble-mean error and ensemble SD from the Global Ensemble Forecasting System Reforecast, version 2. Practical predictability uses realistic uncertainties in both the forecast model and initial and boundary conditions when assessing predictability (Lorenz 1969; Zhang et al. 2006). The Atlantic basin could have more dynamical factors that might promote position variability and fast cyclone intensification; however, the Arctic basin is not as well observed as the Atlantic, so there is likely more analysis uncertainty in the Arctic (Bromwich and Wang 2005). Therefore, H1, the predictability of AC track and intensity is indistinguishable from comparable midlatitude cyclones, is tested. In addition, it is expected that cyclones characterized by large SD are found in regions of large baroclinicity and LHR, as compared with cyclones characterized by low SD.

The remainder of this chapter is outlined as follows. Section 2.2 covers the data and methods used to create a climatology of intense, long-lived cyclones, cyclone tracking, and statistical calculations performed in this study. Section 2.3 compares Atlantic and AC predictability and examines a few large-scale parameters for cases characterized by large and small SD. Section 3.4 provides a summary of the results and conclusions.
2.2 Data and Methodology

2.2.1 Case selection

This study compares the predictability of Arctic and Atlantic basin cyclones during two different seasons over a long period of time. For the Arctic, the focus is on summer months (June–August) so as to capture cyclones that may be responsible for sea ice break up (e.g., Crawford and Serreze 2016). By contrast, extended winter month (November–March) Atlantic cyclones are examined, as cyclones are most frequent in this region during this time of the year, and because they have been extensively studied (e.g., McCabe et al. 2001). Comparing cyclones for these two seasons is justified because baroclinic environments are similar on average during the Arctic summer and Atlantic basin winter, measured by the mean Eady growth rate (EGR) (not shown). This occurs as baroclinicity shifts poleward in the Northern Hemisphere from winter to summer, associated with the seasonal shift of the polar front jet stream and storm tracks (Hoskins and Hodges 2002, 2019). In addition, the presence of the AFZ during summer months contributes to enhanced baroclinicity in the Arctic region (Crawford and Serreze 2016).

A subset of cyclones in both regions are selected from the Sprenger et al. (2017) cyclone climatology, which makes use of 6-hourly 1° ECMWF reanalysis (ERA-Interim; Dee et al. 2011) data from 1985 to 2016. The Atlantic basin was chosen to represent midlatitude cyclones as they are well studied and allow for similar case numbers to compare. Atlantic cyclones are selected if the cyclones’ reference time occurred within the region characterized by the highest storm track density in the basin (denoted in Fig. 2.2 by the black polygon). The reference time, denoted as $t_0$, is defined as the time step when the difference between the environmental pressure and cyclone minimum SLP, referred to as pressure depression, first exceeds 12 hPa. This value represents the largest depression that occurred for all cyclones in both the Atlantic and Arctic basins; therefore,
it represents a uniform benchmark for cyclones in both basins, since the environmental pressure varies between basins. The reference time occurred most commonly during the developing stage of the selected cyclones. All forecasts from 5 days prior to the reference time up to the reference time were computed and show consistent results to what is presented here, except for ∼4-day position variability that shows slightly higher SD for the Atlantic (not shown). However, for brevity, only forecasts initialized 1 and 3 days prior to \( t_0 \) are shown in this study. For the Arctic, a cyclone was considered here if at least 80% of the 6-hourly positions lie north of 70°N. This condition was used in order to capture cyclones that develop in or near the Arctic region and spend a majority of their life cycle in the Arctic Ocean, which could in turn impact Arctic sea ice. In addition, this condition was used to eliminate cyclones that originate in the midlatitudes and subsequently move into the Arctic region, often during cyclolysis (AC tracks are shown in Fig. 2.2).

The focus of this study is on long-duration, intense cyclones, which are more likely to impact Arctic sea ice. As a consequence, the cyclone must have a track within the Sprenger dataset that lasts at least 3 days (twelve 6-h time steps). Here, the most intense cyclones in each basin are identified using the accumulated pressure depression (APD), which is calculated as:

\[
\text{APD} = \sum_{t=1}^{N_{\text{time}}} (P_{\text{environment}} - P_{\text{central}}),
\]

where \( P_{\text{central}} \) is the pressure center and \( P_{\text{environment}} \) is the pressure of the last closed contour on a 1-hPa interval\(^1\). The sum is calculated every 6-h over the duration of each storm in the Sprenger et al. (2017) dataset. This metric is similar to the accumulated cyclone energy, or ACE, metric, which is used to measure the time-integrated tropical cyclone activity over a storm and/or

---

\(^1\) **Pressure center** and last closed contour are reported in the Sprenger dataset.
one season (e.g., Zhan and Wang 2016; Davis and Zeng 2019). The cumulative distribution function of APD for Arctic and Atlantic basin cyclones is computed to select cyclones that exceed the 85\textsuperscript{th} percentile of APD for each respective basin to use in this study (Fig. 2.1). The 85\textsuperscript{th} percentile was chosen as a similar standard to capture the strongest storms in each basin without having to account for the more intense cyclones in the Atlantic basin. For the Arctic the 85\textsuperscript{th} percentile is equivalent to an APD of 250 hPa, yielding 100 cyclones, whereas in the Atlantic the 85\textsuperscript{th} percentile is equivalent to an APD of 450 hPa, yielding 89 cyclones (tracks shown in Fig. 2.2).

2.2.2 The Global Ensemble Forecasting System (GEFS) dataset

The predictability of Arctic and Atlantic basin cyclones is evaluated by averaging ensemble-mean errors and ensemble forecast SD as a function of lead time for a comparable number of storms. Specifically, the GEFS Reforecast, version 2, 1\textdegree 6-hourly dataset (Hamill et al. 2013) is employed, which consists of 11 ensemble members (control + 10 perturbed members) initialized each day at 0000 UTC during 1985–2016. The GEFS reforecast employs the GEFS ensemble prediction system that went into operations in February 2012. Until 2011, the ensemble-mean initial condition came from the Climate Forecast System Reanalysis (Saha et al. 2010). After that, the ensemble-mean analysis is the operational GFS analysis. Initial condition perturbations determined using the ensemble transform technique with rescaling (Wei et al. 2008). The interested reader is directed to Hamill et al. (2013) for additional details about this system.

The GEFS reforecast dataset was chosen because it provides 89 Atlantic and 100 Arctic cases from which to test this hypothesis about AC predictability. Furthermore, unlike a typical operational forecasting system, there have been minimal changes to the model over this time
period, which eliminates the possibility that the results could be impacted by the continuous operational forecast model improvement that have occurred over this 30-yr period. However, note that increases in observations over time may influence forecast skill. In addition, observations are sparser in the Arctic than in the Atlantic basin (Bromwich and Wang 2005).

Cyclones are tracked within each ensemble member and each initialization time that occurs 5 days prior to and up to the reference time by finding the maximum in 925-hPa area-averaged\(^2\) relative vorticity. GEFS reforecasts are only initialized at 0000 UTC; therefore, cyclones with a reference time at 0600 or 1200 UTC are shifted to the closest initialization time prior and cyclones with a reference time of 1800 UTC are shifted to the closest initialization time after, similar to (Torn 2017).

2.2.3 Ensemble SD and RMSE as a proxy for predictability

In this study, Arctic and Atlantic cyclone predictability is evaluated by considering both the ensemble-mean root-mean-square error (RMSE) and ensemble SD in cyclone position and minimum SLP, with higher error and larger SD indicating lower predictability. Average ensemble RMSE and SD is calculated using the number of available storms at each time step (numbers shown along the top of Fig. 2.3). The statistical significance of the difference in the SD and RMSE is determined via the t test every 6-h. The GEFS position and minimum ensemble SD is found to be smaller than the RMSE, signifying that the ensemble is underdispersive (Fig. 2.3).\(^3\) Nevertheless, the GEFS ensemble SD appears to be able to distinguish between low- and high-error cases. One way to demonstrate this is to employ an error–spread Pearson correlation skill

\(^2\) NCL’s uv2vrF_Wrap function was used to compute vorticity using spherical harmonics. Area-averaged vorticity is then used to calculate circulation over a 700-km radius.

\(^3\) In Fig. 2.3a,c, 0-h relative to \(t_o\) corresponds to a 24-h forecast, whereas 0-h relative to \(t_o\) corresponds to a 72-h forecast in Fig. 2.3b,d.
score, which was introduced by Hopson (2014). This metric compares the correlation between individual forecast ensemble-mean errors and SD with what is expected for a perfect ensemble prediction system, given the variation in the forecast SD present in the ensemble system. This metric is defined as:

\[ SS_r = \frac{r_{forc}}{r_{perf}} \]  

(2.2)

where \( r_{forc} \) is the correlation between the ensemble-mean error and SD for all cases at a given forecast hour, and \( r_{perf} \) is the correlation that would come from a perfect EPS system, given the variability in the ensemble SD [see Hopson (2014) for a derivation of this]. Here, a value of 1 indicates that the correlation between ensemble-mean error and SD is equivalent to what one would expect for a perfect ensemble prediction system with a given range of SD.

Fig. 2.4 shows this skill score for Atlantic and Arctic cyclones as a function of hours since \( t_o \) for forecasts initialized 1 and 3 days prior to \( t_o \). The position forecast skill scores appear to exceed 0.6 for most times, except for after 36-h for both Atlantic and Arctic cyclones for the −1-day forecasts (Fig. 2.4a,b). Furthermore, the cyclone minimum SLP skill score is also generally above 0.6 for all lead times, except for Atlantic basin cyclones prior to 18-h (Fig. 2.4c,d). Regardless, this calculation suggests that the ensemble SD does provide a relatively skillful estimate of the error at most lead times and hence can be used as a complementary measure of predictability in this study along with the ensemble-mean error.

Cyclone position and minimum SLP increase with lead time and have different units; therefore, a standardized SD is calculated to determine track and intensity ensemble variability in both basins. It is given by:
standardized SD = \frac{SD_{\text{storm}} - \overline{SD}}{\overline{SD}}. \quad (2.3)

Here, $SD_{\text{storm}}$ is the SD in either position or minimum SLP for each individual storm and $\overline{SD}$ is the average SD in position or minimum SLP each basin. From this calculation, the top quartile of storms can be identified, which in turn represents the most variable storms, and vice versa. The statistical significance of the difference between these quartiles is determined using bootstrap resampling without replacement. This method proceeds by randomly selecting two subsets of unique cases from each basin and running 10,000 times to determine the probability of obtaining the difference by random chance.

2.2.4 Baroclinicity and LHR approximations

There are several potential mechanisms that could explain the difference between Arctic and Atlantic cyclones that are relatively more or less predictable. Based on previous studies, these processes could include both dry and moist dynamics, which can be measured using baroclinicity and LHR. To evaluate the potential role baroclinicity and LHR play in the predictability of these storms, area-averaged EGR and a proxy of column-integrated LHR, respectively, are evaluated from ERA-Interim reanalysis data, which is the same dataset used in the Sprenger cyclone climatology. Using the 6 hourly ERA-Interim dataset that was converted to a $1^\circ$ fixed grid, these parameters are computed for the most and least predictable storms in each basin. Here, EGR is used as a measure of baroclinity and is computed via:

$$EGR = 0.31 \frac{f |\partial v/\partial z|}{N},$$ \quad (2.4)

where $f$ is planetary vorticity, $N$ is the Brunt–Väisälä frequency, $z$ is the vertical coordinate, and $v$ is the vector horizontal wind calculated between 850 and 400 hPa (Hoskins and Valdes 1990).
Area-averaged EGR has been used to examine the role of surface baroclinicity for an Arctic storm case study by Tao et al. (2017). Baroclinicity, or EGR, can contribute to the maintenance of a cyclones’ intensity. Therefore, it is important to determine the role EGR plays in the predictability of these cyclones.

Unfortunately, the ERA dataset does not explicitly contain an estimate of LHR; therefore, the residual of the column-integrated water budget equation is used as a proxy for the column-integrated LHR. Specifically, the column-integrated LHR is computed via:

$$C - E = \text{LHR}_{sfc} - \frac{1}{g} \frac{\partial}{\partial t} \int_{S}^{T} q \, dp - \int_{S}^{T} \left( \frac{\partial u q}{\partial x} + \frac{\partial v q}{\partial y} \right) dp,$$

where $\text{LHF}_{sfc}$ is surface latent heat flux, the second term is the Eulerian derivative of vertically integrated water vapor, and the third term is vertically integrated horizontal moisture flux convergence. The left-hand side of this equation is condensation $C$ minus evaporation $E$, which is used as a proxy for column-integrated LHR. For this study, area-averaged EGR and LHR are computed for each time step within a 700-km radius. Cyclones are characterized by upward and downward motion and hence latent heat releases in different locations within the cyclone, which may not be consistent from across all storms. As a consequence, an area average over a circle centered on the storm may not represent the mean LHR. Furthermore, ACs are often characterized by erratic motion; therefore, there is no reasonable method for computing area-averaged LHR, either in a cyclone-relative framework, or even in a framework aligned with the motion of the cyclone. As a consequence, the area-averaged LHR metric only considers points that are above the 50th percentile of LHR within 700-km of the cyclone center, which in turn limits the metric to grid points where positive LHR might take place. For each cyclone, the 50th percentile is determined by only considering the grid points within 700 km for that particular case. For consistency, this method was applied to both Arctic and Atlantic basin cyclones.
Similarly, this method is used to calculate the amount of moisture associated with Arctic and Atlantic basin cyclones by area-averaging PW.

2.3 Results

2.3.1 Arctic and Atlantic basin cyclone climatology overview

The criteria provided in section 2.2 yields 100 summer Arctic and 89 winter Atlantic cyclones, whose tracks are shown in Fig. 2.2. A majority of summer ACs originate over Eurasia north of 60°N, consistent with Serreze (1995), and subsequently spend most of their existence over the Arctic region, often exhibiting erratic motion. By contrast, the Atlantic cyclones selected for this study originate over North America or off the east coast of the US, generally move to the northeast to the east of Greenland, and often enter the Arctic at the end of their life when they undergo cycloysis. These Atlantic storm tracks are similar to those found in previous extratropical cyclone climatologies off the east coast of North America such as Grise et al. (2013) and Bentley et al. (2019).

2.3.2 Arctic and Atlantic basin cyclone predictability

For this study, the average ensemble-mean RMSEs and ensemble SDs of minimum SLP and position are used to test the hypothesis that AC track and intensity predictability is indistinguishable from comparable Atlantic basin cyclones. To be expected, the RMSE and ensemble SD in cyclone position and minimum SLP increases with forecast lead time for forecasts initialized 1 and 3 days prior to the reference time (Fig. 2.3). For ACs, forecasts initialized 1 day prior to $t_0$ are characterized by 40-km-higher position errors and 25-km-higher position SD on average relative to the Atlantic basin; however, for most times the differences are not statistically significant (Fig. 2.3a). In addition, AC minimum SLP SD is initially
approximately 0.25-hPa higher than Atlantic cyclones; however, beginning 12-h after \( t_0 \), Atlantic basin intensity SD increases at a faster rate through the remainder of the forecast, such that the Atlantic basin cyclones have a 0.7-hPa-higher SD than ACs by 30-h after \( t_0 \) (Fig. 2.3c). In addition, the RMSE for Atlantic basin cyclones is nearly identical to the Arctic at \( t_0 \) but increases to 1 hPa by 18-h. Forecasts initialized 3 days prior to \( t_0 \) show qualitatively similar results, but with larger magnitude differences between the basins (Fig. 2.3b,d). AC position SD remains on average 52 km higher than the Atlantic basin cyclones for all forecast lead times while the RMSE is approximately 100 km greater (Fig. 2.3b). Moreover, Atlantic basin cyclone intensity RMSE and SD increases to 10 and 7.5 hPa, respectively, by 36-h, while the corresponding maximum AC intensity error and SD are 7 and 4 hPa, respectively (Fig. 2.3d). The combination of these results suggests that, on average, Atlantic basin cyclone position is more predictable than comparable AC tracks, particularly for longer lead times. Further, AC intensity is more predictable than comparable Atlantic basin cyclone intensity.

One potential explanation for these results is that cyclone motion and intensity are distinct between these two basins. This hypothesis is evaluated by computing the average intensity of each cyclone at each time step relative to \( t_0 \) within the Sprenger database. Furthermore, the average speed is calculated via the distance each cyclone traveled between each 6-h time step within the Sprenger database. During the 48 hours following \( t_0 \), the average minimum SLP decreases from approximately 995 to 968 hPa in the Atlantic basin and from 989 to 985 hPa in the Arctic, indicating that Atlantic basin cyclones become 18 hPa deeper than ACs (Fig. 2.5a). As a consequence, Atlantic basin cyclones are more likely to intensify, which in turn could provide more potential variability in cyclone minimum SLP in comparison with ACs, which tend to maintain a similar intensity throughout their life. Despite this relationship, there
does not seem to be a strong linear relationship between the intensification rate and the ensemble SD on a case-by-case basis. The correlation between the 0–48-h change in mean sea level pressure (MSLP) and the 48-h ensemble SD is −0.28 and −0.34 for the Arctic and Atlantic basins, respectively, meaning that cyclones with larger decreases in MSLP are associated with higher ensemble SD. Further, the speed of Atlantic basin cyclones is approximately 2 times as fast as comparable ACs (Fig. 2.5b), with the average speed for Atlantic cyclones being 52.5 km h⁻¹, as compared with 27.6 km h⁻¹ for ACs. Despite this, Atlantic basin cyclone position may be easier to predict, and hence have lower position variability, based on the speed of the cyclone and location of being within the Atlantic storm track, whereas there is no comparable storm track that regulates the steering flow in the Arctic region.

2.3.3 Selecting cyclones characterized by high and low predictability

The remainder of this section examines the environmental conditions that are associated with cases characterized by high variability in cyclone intensity in each basin. For each basin, the least and most predictable storms are identified based on the time average standardized SD (2.3). Here, the most-predictable cases are those that fall within the lowest quartile of standardized minimum SLP for that particular initialization time relative to \( t_o \), whereas the least predictable are those that fall into the upper quartile of standardized minimum SLP (Fig. 2.6). For forecasts initialized 1 day prior to \( t_o \), average SD for the 25\(^{th}\)-percentile cases vary slightly, such that the minimum SLP SD increases from 1 hPa to 1.5 and 2 hPa over the forecast for Arctic and Atlantic cyclones, respectively (Fig. 2.6a). By contrast, the average SD for the 75\(^{th}\)-percentile cases exhibit higher SD for AC than the Atlantic from \( t_o \) to 12-h (Fig. 2.6a). After 12-h, the SD for the Atlantic cases increase to above 5-hPa SD, while the Arctic SD levels off just above 4 hPa (Fig. 2.6a). As a consequence, the SD is 3 hPa higher for the 75\(^{th}\)-percentile than for the 25\(^{th}\)-percentile
in the Atlantic, whereas the difference is 2.5 hPa in the Arctic. A similar trend is present in the forecasts initialized 3 days prior to \( t_0 \), with approximately a 1.7-hPa SD difference between the Arctic and Atlantic 25\(^{th}\)-percentile cases at 48 after \( t_0 \) and a 4.5-hPa SD difference between the 75\(^{th}\)-percentile cases starting at 24-h after \( t_0 \) (Fig. 2.6b). These results, combined with the spread–error skill score presented earlier, indicate that the standardized SD method can be used to distinguish between most and least variable cases in both basins based on minimum SLP (Fig. 2.6). Furthermore, the results from the 75\(^{th}\)-percentile ACs are comparable to errors found by (Yamagami et al. 2019), who examined 26 “extraordinary” ACs. A comparison of the average minimum SLP and speed using Sprenger et al. (2017) data for the most and least variable storms in each basin shows that the most variable storms tend to have a lower minimum SLP and faster speeds for forecasts initialized at both 1 and 3 days prior to \( t_0 \) (Table 2.1). In addition, least predictable storms are characterized by a larger minimum SLP tendency on average in both basins, where tendency is defined as the difference in minimum SLP between the first timestep and the minimum value and divided over the time each cyclone took to reach maximum intensity (not shown).

### 2.3.4 Comparing most and least predictable storms based on intensity

To determine whether baroclinicity and LHR play a role in the predictability of these storms, area-averaged EGR and column-integrated \( C − P \), respectively, are calculated for the most- and least-predictable storms shown in Fig. 2.7. In both the Arctic and Atlantic basin, less-predictable cyclones are characterized by higher EGR for forecasts initialized 1 day prior to \( t_0 \) (Fig. 2.7a). The differences between the most- and least-variable storms are statistically significant (99% level) in both basins, particularly for the first 12-h after \( t_0 \) in the Arctic region and between 24- and 36-h after \( t_0 \) in the Atlantic basin for forecasts initialized 1 day prior...
to $t_0$ (Fig. 2.7a) and for the first 12-h after $t_0$ in both basins for forecasts initialized 3 days prior to $t_0$ (Fig. 2.7b). For the least-predictable storms, average EGR decreases from 0.91 to 0.60 day$^{-1}$ for ACs and from 1.04 to 0.8 day$^{-1}$ for Atlantic cyclones (Fig. 2.7a). For most-predictable storms, average EGR decreases from 0.73 to 0.6 day$^{-1}$ for ACs and from 0.96 to 0.69 day$^{-1}$ for Atlantic cyclones (Fig. 2.7a). A qualitatively similar result is obtained when repeating the calculation for forecasts initialized 3 days prior to $t_0$ (Fig. 2.7b). As a consequence, this result suggests that less-predictable cyclones typically occur in environments characterized by greater baroclinicity.

Whereas less-predictable cyclones are characterized by a clear difference in baroclinicity, the result for LHR is less clear. In the Atlantic basin, the less-predictable cyclones are characterized by higher LHR for forecasts initialized 1 day prior to $t_0$, with statistically significant differences from 12- to 30-h after $t_0$ (Fig. 2.7c). By contrast, the 75th-percentile ACs have higher LHR values only through 36-h after $t_0$, and the differences are not statistically significant for a consistent period of time. Forecasts initialized 3 days prior to $t_0$ show similar results, but with smaller discrepancies between the 75th- and 25th-percentile cases (Fig. 2.7d). These results indicate that higher LHR values are not associated with systematic differences in intensity predictability beyond the Atlantic cyclones.

Results from PW are similar to LHR such that forecasts initialized 1 day prior to $t_0$ show larger amounts of PW, particularly in the first 24-h since $t_0$ with statistically significant differences in the Atlantic basin in the first 12 hours (Fig. 2.7e). After 24-h, PW is larger for the 25th-percentile cases in both basins. Similarly, −3-day forecasts demonstrate larger PW for 75th-percentile cases in the first 12-h in the Atlantic basin and 6-h in the Arctic basin but remain lower than the 25th-percentile cases for the remainder of the forecast (Fig. 2.7f); therefore, it
appears that higher PW values are not associated with systematic differences in intensity predictability.

2.3.5 Comparing most and least predictable storms based on position

The same standardized SD analysis was done to identify the most- and least-variable cases based on forecast position variability (Fig. 2.8). The 75th- and 25th-percentile cases for the −1-day forecast show similar position SD for Atlantic and ACs, with approximately a 100-km SD difference between these two percentiles (Fig. 2.8a). However, the −3-day forecast exhibit large SD differences between the 75th-percentile Atlantic and AC basins and similar SD for the 25th-percentile cases (Fig. 2.8b). At 48-h since t₀, Atlantic position SD has a maximum difference of about 360 km, whereas Arctic position SD has a maximum difference of about 550 km at 36-h since t₀ (Fig. 2.8b).

Unlike the most- and least-predictable cases based on minimum SLP forecasts, most- and least-predictable cases based on position do not exhibit substantial differences in cyclones’ environmental properties. In particular, the 75th- and 25th-percentile cases for a −1-day forecast have similar minimum SLP and speed values (Table 2.2). In addition, the 75th-percentile storms in both basins tend to move slower than the 25th-percentile storms for −1-day forecasts. Furthermore, the 75th-percentile ACs for −1- and −3-day forecasts and Atlantic storms for −3-day forecasts reach a stronger intensity than the 25th-percentile storms, similar to what was found when the cases are sorted by minimum SLP variability. Therefore, this result suggests that although the least-predictable storms based on minimum SLP are characterized by higher intensity and faster speeds, least-predictable storms based on position are less distinguishable.
2.4 Summary

The goal of Chapter 2 is to document the practical predictability of AC position and intensity forecasts over 100 cases and compare it with 89 Atlantic Ocean basin midlatitude cyclones using the GEFS V2. This dataset contains 11-member ensemble forecasts initialized daily from 1985 to the present using a fixed model. In this study, forecasts initialized 1 and 3 days prior to the cyclone development time are compared, where predictability is defined as the ensemble-mean root-mean-square error and ensemble SD. Although Atlantic basin cyclone tracks are characterized by higher predictability relative to comparable ACs, intensity predictability is higher for ACs. In addition, storms characterized by low ensemble SD and predictability are found in regions of higher baroclinicity than storms characterized by high predictability. There appears to be little, if any, relationship between LHR and PW and predictability.
Fig. 2.1: Cumulative distribution for Arctic (blue) and Atlantic (red) cyclone APD. The top 85\textsuperscript{th} percentile is denoted by the black line. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.2: Cyclone tracks each 6-h from the Sprenger et al. (2017) ERA-Interim cyclone climatology for the 100 Arctic (blue) and 89 Atlantic basin (red) cyclones from 1985 to 2016 used in this study. The first timestep for each cyclone is denoted by a white circle. Longitude lines are plotted every 30°, and latitude is plotted every 10°. The black-outlined polygon represents the region of maximum Atlantic cyclones. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.3: Mean ensemble SD and RMSE in cyclone (a), (b) position and (c), (d) minimum SLP for Arctic (blue) and Atlantic (red) cyclones for forecasts initialized (left) 1 day and (right) 3 days prior to \( t_0 \). The blue and red numbers across the top are the number of Arctic and Atlantic cases available at that particular lead time. The black values across the top and bottom of each panel are the probability of obtaining the difference between the Arctic and Atlantic RMSE and SD cyclone values, respectively, via the t test. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.4: Average (a), (b) position and (c), (d) minimum SLP skill score $SS_r$ for all 100 Arctic (blue) and 89 Atlantic (red) cyclones as a function of time relative to $t_o$ for forecasts initialized (left) 1 day and (right) 3 days prior to $t_o$. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.5: Average (a) minimum SLP and (b) speed for all 100 Arctic (blue) and 89 Atlantic (red) cyclones as a function of time relative to $t_0$. The values across the top are the probability of obtaining the difference between the Arctic and Atlantic cyclone values via the $t$ test. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.6: Mean ensemble SD in minimum SLP for least-predictable (75th percentile; long dashed) and most-predictable (25th percentile; short dashed) storms for forecasts initialized (a) 1 day and (b) 3 days prior to $t_0$. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Table 2.1: Average minimum SLP and speed for the most- and least-variable cases as based on minimum SLP standardized SD. From (Capute and Torn 2021). ©American Meteorological Society. Used with permission.

<table>
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<th>Basin / Forecast</th>
<th>75th min SLP (hPa)</th>
<th>25th min SLP (hPa)</th>
<th>75th Speed (km h⁻¹)</th>
<th>25th Speed (km h⁻¹)</th>
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</table>
Fig. 2.7: Mean (a), (b) EGR; (c), (d) LHR; and (e), (f) PW for the least-predictable (75th percentile; long dashed) and most-predictable (25th percentile; short dashed) Arctic (blue) and Atlantic (red) cyclones for forecasts initialized (left) 1 day and (right) 3 days prior to \( t_0 \). The blue numbers across the bottom and red numbers across the top denote the probability of obtaining the difference between the most- and least-predictability cyclones in the Arctic and Atlantic basins, respectively, through bootstrap resampling. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
Fig. 2.8: As in Fig. 2.6, but for mean ensemble SD in position. From Capute and Torn (2021).

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Table 2.2: As in Table 2.1, but for storms as based on most and least position variability. From Capute and Torn (2021). ©American Meteorological Society. Used with permission.
3. A Comparison of Arctic and Atlantic Basin Cyclone Track and Intensity Forecast

Variability

3.1 Introduction

The results from Chapter 2 suggest that AC position is less predictable than Atlantic basin cyclones, but AC intensity is more predictable. In addition, Arctic and Atlantic basin cyclones characterized by lower predictability are associated with regions of higher baroclinicity. Therefore, this motivates this next chapter to examine and compare what features and dynamics may limit the predictability of individual Arctic and Atlantic basin position and intensity. The goal of this study is to examine how uncertainty associated with upper-level features and low-level thermodynamics limit the predictability of ACs compared to Atlantic basin cyclones. The hypotheses tested in this study are H2) AC track and intensity predictability is limited by errors that originate with upstream tropopause-based features compared to the Atlantic basin cyclone and H3) AC intensity predictability is limited by errors in the lower troposphere, such as temperature and moisture, particularly in the cyclone warm sector, compared to the Atlantic basin cyclone. To test these hypotheses, ensemble-based sensitivity (Ansell and Hakim 2007; Hakim and Torn 2008) will be applied to two ACs and two Atlantic basin cyclones to allow for comparison.

The remainder of this chapter is organized as follows. Section 3.2 will provide the model, data, ensemble-based sensitivity techniques used in this study. The track and intensity uncertainty of two ACs and two Atlantic basin cyclones are examined in sections 3.3–3.6. A summary of the conclusions found, and comparisons made between cyclones will be discussed in section 3.7.
3.2 Data and Methodology

3.2.1 Case selection

The August 2013 AC (AC13 hereafter) was selected from Capute and Torn (2021), as being characterized with high position and intensity variability (not shown) and a very rapid ice loss event (VRILE), where sea ice loss predominantly occurred off the coast of Russia (not shown). The AC of June 2020 (AC20 hereafter) was chosen as it provides a case study of a common occurrence in the Arctic region, which is the merging of low-pressure systems. Similarly, AC20 also coincided with a VRILE and maintained duration in the Arctic beyond 10 days, highlighting the uniqueness of summer ACs. By contrast, January 2013 and 2014 Atlantic basin cyclones were chosen for comparison that were previously studied by (Berman and Torn 2019) due to the strong downstream ridge building that accompanied this event; therefore, no additional model runs were needed. The January 2013 case did not meet the APD criteria of 450 hPa for the climatology created by Capute and Torn (2021), due to its shorter lifespan. However, this Atlantic basin cyclone is very similar in track and maximum intensity to those analyzed in Capute and Torn (2021). Forecasts initialized 1-d prior to the reference time, defined as the time step when the pressure depression first exceeds 12 hPa (e.g., Capute and Torn 2021) will be compared for each cyclone. Forecasts initialized 2- and 3-d prior have been examined and are quantitively similar to the 1-d forecast.

3.2.2 Model Configuration / Experimental Design / Ensemble-based sensitivity analysis

Ensemble forecasts initialized 1–3 days prior to cyclogenesis are generated for the Arctic and Atlantic basin cyclones using the MPAS model. MPAS is a non-hydrostatic model with an unstructured centroidal Voronoi mesh grid, allowing for more seamless transitions between grids to avoid concerns that arise from conventional nesting methods, which is particularly important
near the pole (e.g., Skamarock et al. 2012; Hagos et al. 2013; Park et al. 2014; Hashimoto et al. 2016; Ha et al. 2017). For both cases, MPAS was run with a variable resolution mesh grid (Skamarock et al. 2012), allowing for 60 km horizontal resolution over most of the globe and higher resolution refinement to 15 km over the region of interest (i.e., polar region for the Arctic cyclone and Atlantic basin for the Atlantic cyclone; Fig. 3.1). This is particularly useful in the Arctic framework, as it eliminates issues that arise with converging longitude points near the pole. The MPAS ensemble consists of 96 ensemble members, a sufficient number of members to resolve space/time covariance, while remaining computational inexpensive (e.g., Brown and Hakim 2015; Berman and Torn 2022). Ensemble forecasts are produced by varying initial conditions using a cycling ensemble Kalman filter system that employs the Data Assimilation Research Testbed (Anderson et al. 2009). All forecasts were run using the same “mesoscale_reference” physics suite, allowing to better resolve mesoscale processes, for an accurate comparison (for more details, see Skamarock et al. 2012). For more details and specifics, refer to Berman and Torn (2022). For each ensemble forecast, cyclone position is identified using the tracking methodology from Capute and Torn (2021).

Ensemble-based sensitivity is applied to forecast metrics that are functions of the model state and reflect properties of both Arctic and Atlantic cyclones. Here, cyclone position is defined as distance along the direction of largest ensemble position variability calculated via bivariate position ellipses (e.g., Hamill et al. 2013), while intensity is defined via minimum SLP. Torn et al. (2018) previously used bivariate position ellipses to calculate sensitivity of position variability within tropical storms. A bivariate normal ellipse is fit to the forecast ensemble positions at a specific time and contain 90% of ensemble members. The position metric is defined as the distance along the direction of largest ensemble position variability computed
from the resulting ellipse. These metrics are applied to a single forecast verification time to observe sensitive features to early times. The sensitivity will be computed using these cyclone-related position and intensity metrics to model state variables that may limit cyclone predictability.

For hypothesis H2, sensitivity analysis will be used to quantitatively evaluate how uncertainty associated with the location of specific upstream upper-tropospheric features (i.e., TPVs), impact both the cyclone position and intensity predictability for the aforementioned AC. In particular, sensitivity of cyclone position and intensity to forecast fields such as 500-hPa geopotential height and PV will be computed. H2 is valid if the sensitivity of the cyclone position and/or intensity to these upstream features is quantitively larger than the sensitivity of the cyclone position/intensity to other features. Similarly, to evaluate hypothesis H3, the sensitivity of the cyclone intensity to the lower-tropospheric thermodynamic fields (i.e., temperature and integrated water vapor transport; IVT) will be computed. H3 is valid if the cyclone is sensitive to fields that might be expected to be associated with LHR is larger than other fields.

3.3 Arctic Cyclone of August 2013

3.3.1 Case Overview

AC13 originates as a weak low-pressure system in the Kara Sea, off the coast of Russia at 0000 UTC 4 August 2013 (not shown). Over the next 24 hours, AC13 intensifies to 1005 hPa as it tracks eastward along the Russian coast (Fig. 3.2a). Simultaneously, an existing weak low-pressure system and associated upper-level PV feature present along 80°N and 180°E (Fig. 3.2a). While AC13 is located over the Laptev Sea at 0000 UTC 6 August with a minimum SLP of 989 hPa, the TPV begins to extend poleward and wrap cyclonically around AC13 (Fig. 3.2b). AC13
begins to move poleward just before reaching a maximum intensity of 978 hPa at 0000 UTC 7 August. At this time, the PV feature has completely wrapped around AC13, with warmer temperatures from the south extending toward the North Pole (Fig. 3.2c). Over the next 48 hours, AC13 remained close to the North Pole as a barotropic, cold-core storm before dissipating at 0000 UTC 10 August (Fig. 3.2d).

3.3.2 Cyclone Position Uncertainty

Compared to the reanalysis track of AC13, the MPAS forecast ensembles initialized 0000 UTC 5 August 2013 are on average right of track through 78-h, demonstrating that a majority of the ensemble members have a larger radius of curvature relative to reanalysis during this period (Fig. 3.3). After 78-h, the ensemble-mean is positioned to the left of the reanalysis position, indicating that many members turn more cyclonically thereafter (Fig. 3.3). The position variability of AC13 is calculated along the distance of largest ensemble variability via position ellipses for forecast hours 24 and 72 (Fig. 3.3). The position variability at 24-h is mostly cross-track, with a majority of ensemble members positioned to the right of the reanalysis position (Fig. 3.3). By contrast, the 72-h forecast position variability has components in both the along-track and cross-track directions, indicating that the uncertainty at this time is related to both the speed and direction of the ensemble members as the cyclone curves cyclonically toward the North Pole. The largest position variability occurs as the surface cyclone turns westward beginning at 72-h. The vectors at 24-h and 72-h represent the direction of largest variability at the respective forecast hour, which will be used as the position metric in the subsequent sensitivity calculation. For example, the pattern that explains the most variability for the position uncertainty at 72-h will be associated with a more poleward tracking cyclone.
To understand how the position forecast is sensitive to features in the upper troposphere, the sensitivity of 24- and 72-h cyclone position forecast along the major axis direction to the 310-K Ertel’s PV field at 12-h is calculated. This time was chosen to assess how uncertainty in certain features contribute to the position variability at two different times in the forecast and stages in cyclone lifecycle. At 12-h (valid 1200 UTC 5 August 2013) the ensemble-mean PV is characterized by an elongated upper-level tropospheric PV feature, denoted as “PV1” at approximately 80°N and 180° longitude (Fig. 3.4). In addition, PV1 contains a mesoscale short-wave trough, denoted by the thick, dashed line, protruding from PV1 just upstream of the surface cyclone at approximately 80°N and 60°E (Fig. 3.4). The largest sensitivity of 24-h position variability to the 12-h PV is located just downstream of the short-wave trough (Fig. 3.4a). Decreasing PV in the region of negative sensitivity downstream of the short-wave trough by one SD would result in an enhanced downstream ridge, yielding a 20 km poleward shift of the surface cyclone position at 24-h. In comparison, the sensitivity of 72-h position variability to 12-h PV indicates statistically significant positive sensitivity upstream of the short-wave trough and on the Canadian side of PV1 in addition to negative sensitivity downstream of the short-wave trough (Fig. 3.4b). Increasing PV by one SD of PV to the north of Svalbard near 85°N and 15°E would result in a southward-elongated PV feature and a 36 km shift to the left or north in cyclone position at 72-h. In addition, increasing PV by one SD of PV along the Canadian side of PV1 and decreasing PV by one SD of PV along the Russian side of PV1, leading to an enhanced trough on the Canadian side and enhanced ridge on the Russian side, would result in 20 km shift to the left or north in cyclone position at 72-h. This shift suggests that a more poleward cyclone position at 72-h is associated with a more cyclonic rotation of the Bering Strait short-wave trough. In addition, there is a dipole of PV associated with a secondary PV feature, denoted “PV2” over the
Bering Strait, with negative sensitivity values to the northeast and positive sensitivity values to the southwest (Fig. 3.4b). Decreasing PV to the northeast and increasing PV to the southwest of this secondary PV feature is indicative of a southwestward shift in PV2. Therefore, an equatorward shift of PV2, consequently limiting the interaction with PV1, is associated with a more poleward track later in the forecast, whereas shifting PV2 poleward would result in a more equatorward track. These results indicate that the position variability at 24-h is locally sensitive to the amplitude of the downstream ridge embedded within PV1, whereas the position variability at forecast hour 72 is sensitive to both the shape and rotation speed of PV1 as well as the location of PV2 through action-at-a-distance (e.g., Bishop and Thorpe 1994).

Results show that the largest sensitivity to the position variability 72-h into the forecast is associated with relatively small-scale troughs and ridges embedded within a larger PV feature that interact with the surface cyclone early in the forecast. To understand how these sensitive regions may impact the upper-level flow associated with members that curve westward versus members that are accelerated poleward at 72-h, we can apply statistical PV inversion to derive the upper-level winds linked to differences in PV. Statistical PV inversion uses singular vector decomposition of the ensemble forecast fields to calculate a linear operator that maps from the PV field to wind/temperature associated with it. For a complete explanation of this calculation, the reader is referred to Hakim and Torn (2008). Here, the difference in 310-K PV between the 10 most poleward members and the 10 most equatorward members based on cyclone position 72-h into the forecast is used to select the PV object to invert. For this case, the negative PV anomaly at 24-h, associated with the downstream ridge located at 80°N and 160°E with differences over 0.6 potential vorticity units (PVU) between poleward and equatorward members (Fig. 3.5). The 500-hPa perturbed winds associated with this negative PV anomaly are
characterized by anticyclonic winds centralized east of the PV anomaly minimum (Fig. 3.5). At 24-h, just before the surface cyclone merges with the upper-level PV shortwave, the ensemble-mean illustrates the PV feature denoted PV1 above, with the surface cyclone located just downstream of an embedded trough (Fig. 3.5). The 500-hPa perturbation winds consist of southerly winds of 2 to 3 m s\(^{-1}\) into the downstream ridge and northerly winds of 1 to 5 m s\(^{-1}\) into the downstream trough of the surface cyclone, working to enhance the strength of the downstream upper-level ridge/trough pattern. Therefore, ensemble members that track more poleward 72-h into the forecast are associated with a more enhanced ridge/trough pattern downstream of the surface cyclone 24 hours into the forecast associated with the early forecast PV differences.

3.3.3 Cyclone Intensity Uncertainty

Compared to reanalysis, the MPAS forecast ensembles reach a maximum intensity on average at 1200 UTC 7 August. Between 6–7 August, AC13 exhibits a 10 hPa decrease in minimum SLP and reaches a maximum intensity of 978 hPa at 0000 UTC 7 August 2013 (Fig. 3.6). The ensemble-mean maximum intensity occurs at 1800 UTC 7 August 2013 (Fig. 3.6); therefore, a majority of ensemble members reach maximum intensity approximately 12–18 hours after the reanalysis, which corresponds to the time with the largest ensemble SD in MSLP (4 hPa). Consequently, the intensity metric used for sensitivity analysis is 72-h minimum SLP, when the reanalysis reaches maximum intensity and MPAS ensemble members have the largest variability. Sensitivity to the intensity variability at other forecast times are qualitatively consistent for nearby forecast hours.
To understand how the intensity forecast may be sensitive to lower tropospheric thermodynamic features, such as frontal boundaries, the sensitivity of 72-h minimum SLP forecast to the 850-hPa temperature and IVT fields are calculated (Fig. 3.7a,b). The 24-h ensemble-mean 850-hPa temperature exhibits an enhanced temperature gradient off the coast of Russia between 80–140°E (Fig. 3.7a). Statistically significant negative sensitivity upstream of the cyclone over land centered at 72.5°N and 100°E and positive sensitivity at the location of the cyclone over the ocean at 75°N and 125°E (Fig. 3.7a). This sensitivity pattern is indicative of differences in the frontal wave over the coastline, where decreasing temperature over land by one SD of temperature and increasing temperature off the coast by one SD of temperature, associated with a stronger baroclinic zone just upstream of the cyclone center, would result in a 0.9 hPa decrease in minimum SLP at 72-h. Therefore, increasing the strength of the nascent warm and cold fronts associated with the frontal wave is associated with a more intense cyclone throughout the forecast. Similar results were found for sensitivity of 72-h intensity variability to PW (not shown). Further, sensitivity to IVT indicates that increasing moisture transport in the warm sector to the southeast of the frontal wave within the AR is associated with a more intense cyclone (Fig. 3.7b). The combination of these results suggest that the intensity of this cyclone is largely associated with the strength of this thermal boundary and to a lesser extent the moisture transport, early in the forecast.

To understand how the intensity forecast may be sensitive to upper tropospheric features, such as TPVs, the sensitivity of 72-h minimum SLP forecast to the 500-hPa geopotential height and 310-K PV fields are calculated (Fig. 3.7c,d). Similar to the position uncertainty, the intensity of this cyclone is sensitive to the shape of the large-scale PV feature, particularly to the elongated short-wave trough upstream of the surface cyclone at 24-h (Fig. 3.7c). A dipole of PV sensitivity
around this shortwave indicates that increasing PV on the western side of this short-wave trough by one SD of PV and decreasing PV to the east by one SD of PV, associated with a westward shift of the short-wave trough, would result in a 0.6 hPa decrease in cyclone minimum SLP at 72-h. In addition, the sensitivity to the 500-hPa height indicates negative sensitivity to this short-wave trough, indicating lowering the heights of the short-wave trough, therefore amplifying the trough, is associated with a more intense cyclone (Fig. 3.7d).

These results show sensitivity to both upper and lower fields, but it is not clear if the cyclone is more sensitive to one particular aspect or how these sensitivities may be related since changes in upper and lower tropospheric features can be related. Therefore, to independently quantify the upper-level and low-level contributions to intensity variability, multivariate linear regression is employed (Fig. 3.8). The advantage of this approach is that it eliminates possible cross-correlation between predictors and therefore can quantify the largest contribution of multiple predictors on the 72-h intensity. The dependent variable is the 72-h minimum SLP, and the independent variables are the upper-level PV field, area-averaged positive IVT values for a circle of radius 500 km centered around the cyclone and area averaged 850-hPa temperature for a circle of radius 250 km centered around the cyclone at individual forecast hours (Fig. 3.8). The upper-level PV field variability at each forecast hour is calculated using the principal component of 310-K PV EOF north of 60°N. Further, a 250 km radius is used to represent low-level averages nearest the surface cyclone. Between 0–12-h, the largest regression coefficient is associated with the upper-level PV field, where a westward shift up the upper-level PV trough, is indicative of a stronger cyclone (Fig. 3.8). However, beginning 24 and 30 hours into the forecast, the largest regression coefficient is to 850-hPa temperature and IVT, where increasing low-level temperature and IVT is associated with a stronger surface cyclone (Fig. 3.8). These results
suggest that the 72-h intensity variability is mostly correlated to the upper-level pattern early in the forecast but becomes more dependent on the amount of moisture and temperature nearest the cyclone between forecast hours 24 and 48 once the cyclone forms along the coast.

Previous results suggest a transition from upper-to-lower tropospheric sensitivity through the forecast, so it is worthwhile to explore how uncertainty from upper troposphere reflects on surface features with time. Similar to above, statistical PV inversion is used here to derive the low-level winds associated with PV differences between the 10 most and least intense members at 36-h to determine how these sensitive regions may be dynamically related to one another. In this case, the particular PV region chosen is a negative PV anomaly at 24-h downstream of the shortwave trough associated with PV1. There is a weak anticyclonic circulation centered just poleward of the negative PV anomaly (Fig. 3.9), although it is much stronger at higher levels (not shown). The strongest perturbation winds are associated with enhanced cyclonic circulation around the surface cyclone located at approximately 78°N and 125°E. In particular, 7–8 m s⁻¹ westerly winds are present south of the surface cyclone aiding in warm air advection associated with enhanced thermal ridge due to the development of the downstream ridge (Fig. 3.9).

Inverting the positive PV anomaly upstream of the surface cyclone did not show an enhancement of the thermal ridge (not shown).

### 3.4 Atlantic Basin Cyclone of January 2013

#### 3.4.1 Case Overview

A weak low-pressure system developed over the southwestern US at 0600 UTC 17 January 2013 in a region of upper-level divergence downstream of a trough set up over the eastern US and a ridge over the North Atlantic (not shown). Over the next 18 hours, this cyclone slowly tracks over the southeastern US before moving off the coast in between North and South
Carolina at 0000 UTC 18 January (Fig. 3.10a). Over the next 24 hours, this storm intensified to a minimum SLP of 996 hPa while moving northeast through the western Atlantic toward Greenland along a strong baroclinic zone, while the downstream ridge, represented by 2 PVU contour, continues to amplify (Fig. 3.10b). The surface cyclone moves just upstream of the amplifying PV ridge located over the North Atlantic, while merging with an extension of larger and deeper low-pressure system over much of southern Greenland, causing the surface cyclone to intensify more rapidly (Fig. 3.10c). The more intense low-pressure system off the west coast of Greenland pulls the surface cyclone northward towards Greenland. By 0000 UTC 20 January, the cyclone intensified to 948 hPa and gets cut off from the upper-level flow and begins to dissipate off the southern tip of Greenland 24 hours later (Fig. 3.10d).

3.4.2 Cyclone Position Uncertainty

In contrast to the Arctic cyclone, the Atlantic cyclone position variability is mostly along track through 48-h (Fig. 3.11). After 66-h, the position variability shifts to mostly cross-track, where some members correctly predict the cyclone curvature while others track eastward toward Europe (Fig. 3.11). Similar to above, the vectors at 36 and 72-h represent the direction of largest variability at each respective timestep. Here, the position variability at 36- and 72-h will be used in the subsequent sensitivity calculations where the pattern that explains the most variability is associated with a more northeastward and poleward tracking surface cyclone position at 36- and 72-h, respectively (Fig. 3.11).

To understand how the position forecast is sensitive to features in the upper troposphere, the sensitivity of the 36 and 72-h cyclone position forecast along the major axis direction to the 330-K Ertel’s PV field at 12 and 30-h is calculated (Fig. 3.12). These times were chosen to compare how initial time sensitivity impacts the along track variability phase versus the cross-
track phase later on. The 12-h ensemble-mean 330-K PV shows a trough over the region and a ridge over Newfoundland with a cut-off PV feature just upstream of the cyclone position at 35°N and 82°W (Fig. 3.12a,b). The sensitive regions of 36-h position variability to 12-h 330-K PV are largely associated with the cut-off PV feature upstream of the surface cyclone position, where increasing PV by one SD of PV on the eastern side and decreasing PV by one SD of PV on the western side leads to a northeastern shift of the PV cut-off (Fig. 3.12a) which is associated with a 60 km and 100 km along-track displacement in the cyclone at 36-h, respectively. In addition, positive sensitivity (increasing PV) just upstream of the short-wave trough over the Great Lakes is associated with an enhanced short-wave trough (Fig. 3.12a). Therefore, an enhanced trough and a northeastward shift of the cut-off PV feature 12-h into the forecast, would result in less interaction of the two features, resulting in a faster cyclone 12-h in the forecast. In comparison, the sensitivity of 72-h position variability to 330-K PV is maximized with the Great Lakes short-wave trough, with positive sensitivity upstream and negative sensitivity downstream, suggesting that increasing PV by one SD of PV upstream and decreasing PV by one SD of PV downstream, associated with a westward shift of the short-wave trough, would result in a 300 km northwest shift in cyclone position at 72-h (Fig. 3.12b). Further, the sensitivity to the PV cut-off here is located more south relative to the 36-h position variability. Therefore, a more poleward tracking cyclone 72-h into the forecast is largely sensitive to a westward shift of the short-wave trough, rather than the cutoff that appears important for longer range track forecasts.

Over the next 18 hours, the surface cyclone moves off the eastern US coast to over the Atlantic. The ensemble-mean PV now shows an enhanced trough over the eastern US, as this trough has merged with the cut-off trough shown in the previous time (Fig. 3.12c,d). For the 36-h position, the sensitivity to 30-h 330-K PV is largely associated with this merging short-wave
trough and cut-off feature, showing positive sensitivity associated with the short-wave trough (Fig. 3.12c). Therefore, a more poleward tracking cyclone 48-h later is associated with a faster merging of the shortwave trough and cutoff PV upstream of the surface cyclone, whereas the ensemble members that track eastward at 72-h are associated with a slower merger of these features. In addition, there is a region of negative sensitivity associated with the downstream ridge (Fig. 3.12c). Therefore, a cyclone that is located further east, or a faster surface cyclone 36-h into the forecast is associated with a more enhanced trough/ridge pattern. In comparison, the sensitivity of 72-h position variability to 30-h 330-K PV is similar, but with an additional positive region of sensitivity further downstream of the trough at 45°N and 30°W (Fig. 3.12d). Therefore, this suggests that a more amplified low is associated with a more poleward cyclone later in the forecast (Fig. 3.12d).

To better understand how these sensitive regions impact the upper-level flow between members that curve westward versus members that track eastward, statistical PV inversion is used to derive the upper-level winds associated with upper-level PV differences associated with the downstream ridge (Fig. 3.13). The ensemble-mean PV illustrates mainly zonal flow extending from the northeastern US to the northern Atlantic Ocean (Fig. 3.13). As expected, the winds around the negative difference PV anomaly are anticyclonic, with the strongest winds exceeding 10 m s\(^{-1}\) southwest of the anomaly over the Northeastern US (Fig. 3.13). The southeasterly perturbation winds are aiding in ridge building upstream of the PV anomaly and the northwesterly perturbations winds are aiding trough building downstream (Fig. 3.13). These results indicate that members associated with a more poleward track (curve westward at 72-h) are associated with an enhanced ridge and trough downstream of the surface cyclone, ultimately allowing the surface cyclone to track further poleward.
3.4.3 Cyclone Intensity Uncertainty

Forecasts initialized 1 day prior to cyclogenesis are characterized by significant intensity variability, especially compared to the Arctic cyclone (Fig. 3.14). A majority of ensemble members do not reach maximum intensity as quickly as the reanalysis, though the ensemble-mean comes within 3 hPa of the lowest SLP in the reanalysis. Therefore, the ensemble-mean is less intense at the time of maximum intensity but remains more intense as the cyclone is dissipating in reality (Fig. 3.14). Similar to AC13, the intensity variability metric used here is the 72-h minimum SLP, near the time of maximum intensity (Fig. 3.14).

To understand how the intensity variability of this storm is sensitive to upper-level feature and low-level thermodynamics, the sensitivity of the 72-h minimum SLP to the IVT, 850-hPa temperature, 330-K PV and 500-hPa geopotential height is calculated. At 12-h, the ensemble-mean 850-hPa temperature illustrates a stronger temperature gradient within the warm sector of this storm over the mid-Atlantic US compared the temperature gradient over the central US (Fig. 3.15a). Positive sensitivity downstream within the warm sector of the cyclone over the mid-Atlantic US and negative sensitivity over Mississippi and Alabama is indicative of warmer air ahead of the warm front and colder air behind the cold front. Therefore, an enhanced warm and cold front at 12-h is associated with a more intense cyclone 72-h into the forecast. The ensemble-mean IVT illustrates an atmospheric river (AR) extending from the southeastern US northeastward over the North Atlantic (Fig. 3.15b). Nevertheless, the largest sensitivity to IVT is along the polar front and not the AR (Fig. 3.15b). Further, the largest sensitivity to 330-K PV and 500-hPa geopotential heights at 12-h is to the short-wave trough over the Great Lakes and the cut-off PV feature upstream of the surface cyclone (Fig. 3.15c,d). Increasing PV (decreasing 500-hPa geopotential heights) by one SD of PV upstream and decreasing PV (increasing 500-hPa
geopotential heights) by one SD of PV downstream of the short-wave trough over the Great Lakes region, associated with a westward shift of the short-wave trough, would result in a 6 hPa decrease in cyclone minimum SLP at 72-h (Fig. 3.15c,d). Simultaneously, increasing PV (decreasing 500-hPa geopotential heights) by one SD of PV to the north and decreasing PV (increasing 500-hPa geopotential heights) by one SD of PV south of the cut-off upstream of the surface cyclone, associated with a northward shift of this PV cut-off, would result 6 hPa decrease in cyclone minimum SLP at 72-h (Fig. 3.15c,d). Therefore, a westward shift of the upper-level short-wave trough and a northward shift of the PV cut-off indicates that a merge of these 2 features at 12-h would result in a more intense cyclone at 72-h. These results are very similar to the upper-level uncertainty pattern for the position variability of this storm. The combination of these results suggests that merging the upper-level short-wave trough and PV cut-off in combination with enhanced temperature and moisture boundaries associated with this upper-level polar front at 12-h, would result in enhanced downstream development later in the forecast, leading to a more intense cyclone at 72-h.

The intensity variability of this storm is sensitive to both upper and lower fields; therefore, multivariate linear regression is again used quantify the upper-level and low-level contributions independently to intensity variability (Fig. 3.16). At 36-h, the largest regression coefficient of 0.6 is associated with IVT, where an increase of IVT nearest the cyclone center would result in a more intense cyclone at 72-h. At 42-h, the largest regression coefficient at 0.6 is to the upper-level PV pattern, indicative of a westward shift of the upper-level PV trough and eastward shift of PV cutoff upstream of the surface cyclone (Fig. 3.16). Between 48 and 54-h, a 0.7 regression coefficient to 850- hPa temperature suggests that higher surface temperatures near the surface cyclone is associated with a more intense cyclone at 72-h. These results suggest that
the intensity variability 72-h into the forecast is dependent on the upper-level pattern early in the forecast, temperature nearest the cyclone through 36-h and IVT nearest the cyclone between forecast hours 42 and 60-h as the cyclone intensifies.

The results above suggests that the intensity at 72-h is dependent on the upper-level PV 24-h into the forecast. Therefore, statistical PV inversion is used to derive the 850-hPa winds associated with the 330-K PV difference between the most and least intense members based on 72-h minimum SLP, to determine how these sensitive regions may project onto the lower tropospheric winds and near-surface fields (Fig. 3.17). The negative PV anomaly selected at 24-h spans 45–50°N and 80–70°W upstream of the surface cyclone located on the US east coast between North and South Carolina. To be expected, there is generally an anticyclonic circulation around this negative PV anomaly throughout the troposphere (not shown), penetrating toward the surface shown here as weak anticyclonic circulation (Fig. 3.17). However, the largest perturbed winds associated with this negative PV anomaly are downstream of the surface cyclone, where the perturbed southerly winds south of the PV anomaly are indicative of low-level warm air advection and strong upper-level divergence over the Atlantic (Fig. 3.17). Therefore, a more intense cyclone at 72-h characterized by downstream ridge amplification is associated with stronger divergence off the east coast, aiding in stronger cyclogenesis.

3.5 Arctic Cyclone of June 2020

3.5.1 Case Overview

AC20 has a total lifespan of approximately 10 days involving four merging events (Fig. 3.18). Fig. 3.18 shows the evolution of the ECMWF reanalysis version 5 (ERA5; Hersbach et al. 2020) track and minimum SLP where these merging events have been broken up into 5 “phases”. AC20 originated within the Arctic region at 85°N and 160°E over the sea ice at 0000 UTC 9
June 2020 (Fig. 3.18). Within 36-h, the phase 1 cyclone has merged with a low-pressure system located to the east (Fig. 3.18). The resulting phase 2 cyclone continues to track eastward and then curves equatorward at 85°N and 60°E and continues to intensify to 990 hPa at 0000 UTC 12 June (Fig. 3.18). The phase 2 cyclone merges with another low-pressure system over the Kara Sea at 0600 UTC June 13 that tracks poleward briefly (Fig. 3.18). The third merge occurs 24-h later with another low-pressure over the Kara Sea, strengthening the cyclone to 983 hPa while moving equatorward (Fig. 3.18). The fourth merge takes places 18 hours later, resulting in a weakening cyclone tracking poleward (Fig. 3.18).

The sensitivity analysis here will focus on the second and third mergers occurring during the time period of 12–17 June 2020 (Fig. 3.19a). At 0000 UTC 12 June, the cyclone is located at 84°N and 105°E with a minimum SLP of 992 hPa. Simultaneously, an upper-level PV anomaly is vertically stacked with the surface cyclone and associated with a region of low-level cold air centered near the North Pole. Over the next 24 hours, the surface cyclone tracks eastward while the upper-level PV feature rotates cyclonically (Fig. 3.19b). In addition, there is a tail of PV extending off the east coast of Greenland toward the surface cyclone with a plume of low-level warmer air to the east. This tail of PV merges with the upper-level PV feature over the pole, resulting in a wider spread region of upper-level PV and more intense surface cyclone (Fig. 3.19c). With the influence of this vertically stacked upper-level PV feature, the AC is able to strengthen to 988 hPa over the next 24 hours (Fig. 3.19d) and maintain its strength 36 hours after.

3.5.2 Cyclone Position Uncertainty

The MPAS ensemble members initialized 0000 UTC 12 June 2020 generally capture the merging events of AC20. However, there is still considerable position variability throughout the forecast, particularly after the first merge when the reanalysis loops cyclonically at 83°N and
80°E (Fig. 3.20). Through 36-h, the ensemble-mean track is positioned left of the reanalysis track whilst tracking eastward, and then beings to track right of the reanalysis after curving equatorward and remains right of the reanalysis through the forecast (Fig. 3.20). The position variability of AC13 is calculated along the distance of largest ensemble variability via position ellipses for forecast hours 36 and 84 to compare the sensitivity to position variability before and after the merging event. At both forecast hours, and throughout the forecast, the position variability is mostly across-track, indicating that the variability is associated with the motion of ensemble members as opposed to the speed (Fig. 3.20). The vectors at 36-h and 84-h represent the direction of largest variability at the respective forecast hour, which will be used as the position metric in the subsequent sensitivity calculations (Fig. 3.20). Here, the pattern that explains the most variability for the position uncertainty at will be associated with a more eastward tracking cyclone, associated with a smaller radius of curvature.

To assess how the position forecast is sensitive to features in the upper troposphere, the sensitivity of 36- and 84-h cyclone position forecast along the major axis direction to the 310-K PV field at 24-h is calculated to compare the regions of uncertainty of an early forecast hour to a later forecast hour. At 24-h, the ensemble-mean 310-K PV is characterized by an upper-level PV feature located over the North Pole, vertically stacked with the position of the surface cyclone (Fig. 3.21). In addition, a region of PV is extending off the east coast of Greenland toward the PV feature over the North Pole (Fig. 3.21). The largest sensitivity at 24-h to the 36-h position variability is to the shape and position of these two PV features (Fig. 3.21a). There is a dipole of sensitivity associated with the PV feature over the North Pole with negative values on the Greenland side and positive values on the Russian side (Fig. 3.21a). Therefore, decreasing PV on the Greenland side and increasing PV on the Russian side by one SD of PV, shifting the PV...
feature toward Russia, would result in a 30 km equatorward shift of the surface cyclone position at 36-h. In addition, there is a dipole of sensitivity associated with the tongue of higher PV extending from Greenland. This dipole suggests that increasing PV on the poleward side and decreasing PV on the equatorward side of this extension of higher PV by one SD of PV, therefore shifting the plume poleward, would also result in 18 km and 12 km across-track displacement at 36-h, respectively. Therefore, the combination of these results suggest that the 36-h position variability of this storm is most sensitive to the position and interaction of these two PV features, where a merge of these features earlier in the forecast is associated with a smaller radius of curvature in the track and a later merge of these features would result in a larger radius of curvature at 36-h. In comparison, the sensitivity to the position variability at 84-h is also largely associated with these two features, where an equatorward shift of the PV feature over the North Pole is associated with a more eastward cyclone position at 84-h (Fig. 3.21b). However, there is additional sensitivity to a PV feature moving poleward from the Bering Strait (Fig. 3.21b). The dipole of sensitivity associated with this PV feature suggests that decreasing PV on the eastern side and increasing PV on the western side of this PV feature by one SD of PV at 24-h, associated with a westward shift of this PV feature, would result in a 56 km across-track shift of the surface cyclone position at 84-h (Fig. 3.21b). This PV feature over the Bering Strait moves poleward throughout the forecast and merges with the PV feature over the North Pole at 96-h (not shown) suggesting the uncertainty with this feature impacts the position variability at 84-h and can be traced back to the beginning of the forecast.

To better understand how these sensitive regions impact the upper-level flow between members that curve eastward versus members that track further westward, statistical PV inversion is used to derive the upper-level winds associated with upper-level PV differences
related to differences in relative track motion. More specifically, subtracting 12-h 310-K PV associated with westward members from 310-K associated with eastward members at 36-h reveals a negative PV anomaly upstream of the surface cyclone embedded in the large PV vortex (Fig. 3.22). This negative PV anomaly was chosen as sensitivity of ensemble position variability revealed uncertainty associated with this feature at both 36- and 84-h and can reveal how changes within the larger PV vortex impact the position of ensemble members. The ensemble-mean PV illustrates the previously discussed large-scale PV feature over the North Pole and the tongue of PV off the east coast of Greenland (Fig. 3.22). Upper-level perturbation winds are strongest around this upper-level negative PV anomaly, with anticyclonic perturbation winds (Fig. 3.22). More specifically, the perturbation winds upstream of the upper-level negative PV anomaly are mainly southeasterly and easterly winds suggesting ridge building upstream, whereas southerly perturbation winds downstream suggest deepening the downstream PV trough (Fig. 3.22). These downstream easterly perturbation winds are pushing the surface cyclone further equatorward, resulting in a more east and equatorward surface cyclone at 36-h.

3.5.3 Cyclone Intensity Uncertainty

The ERA5 reanalysis shows that AC20 only intensifies by approximately 5 hPa over the forecast period; however, the focus here is on assessing the intensity variability associated with the merging events and maintenance of this AC (Fig. 3.23). The MPAS ensemble-mean minimum SLP is less intense compared to the reanalysis throughout the entire forecast, and aside from two timesteps, the ensemble spread does not reach the reanalysis minimum SLP (Fig. 3.23). However, the ensemble-mean does demonstrate an intensification of the cyclone as a result of the first cyclone merging event at 0000 UTC 14 June, similar to the reanalysis (Fig. 3.23). The ensemble-mean reaches a maximum intensity of 990 hPa at 0000 UTC 15 June, whereas the
reanalysis reaches a maximum intensity of 985 hPa at 0600 UTC 16 June as a result of a second cyclone merge event (Fig. 3.23). Therefore, subsequent sensitivity analysis will focus on the intensity variability after the first merge, during phase 3 (see Fig. 3.18). The intensity metric used for the following sensitivity analysis is the 72-h minimum SLP to assess the uncertainty after the first merge event at the time of MPAS ensemble-mean maximum intensity.

To assess how the intensity variability may be sensitive to lower tropospheric thermodynamic features, such as frontal boundaries, the sensitivity of 72-h minimum SLP forecast to the 850-hPa temperature and IVT fields at 24-h are calculated (Fig. 3.24a,b). The ensemble-mean 850-hPa temperature illustrates a strong temperature gradient extending eastward from the east coast of Greenland toward Svalbard, with the lowest temperatures occurring at the location of the surface cyclone (Fig. 3.24a). The largest sensitivity is associated with the temperature gradient over the North Atlantic, with positive value east of Svalbard and negative values off the east coast of Greenland (Fig. 3.24a). This sensitivity pattern suggests that increasing low-level temperature over Svalbard and decreasing low-level temperature in the North Atlantic by one SD of temperature, resulting in a stronger temperature gradient more poleward, would result in a 1 hPa decrease in cyclone minimum SLP at 72-h. Therefore, a more poleward extent of higher surface temperatures at 24-h is associated with a more intense cyclone at 72-h. Additionally, an AR is present associated with the low-level temperature gradient (Fig. 3.24b). The sensitivity suggests that a poleward shift of this AR is also associated with a more intense cyclone later in the forecast. Therefore, these results suggest that a more poleward extension of higher temperature and moisture values closer to the surface cyclone, aids in the intensification of this cyclone.
Linked to this temperature and moisture boundary is an upper-level extension of PV off the east coast of Greenland as discussed in the previous section (Fig. 3.24c,d). Similar to the position variability, the intensity variability at 72-h is also sensitive to the position of the extension of PV, with negative sensitivity to the south and positive sensitivity to the North (Fig. 3.24c). Therefore, the sensitivity pattern suggests that increasing PV to the north and decreasing PV to the south of the PV extension by one SD of PV, shifting the tongue of PV equatorward, would result in a 1 hPa decrease in cyclone minimum SLP at 72-h, and therefore a more intense cyclone. In addition to the extension of PV over eastern Greenland and northern Svalbard, there is negative sensitivity on either side of the elongated PV feature over the North Pole and positive sensitivity within the short-wave trough positioned over the coast of Russia (Fig. 3.24c). Therefore, decreasing PV within the ridges and increasing PV within the short-wave trough by one SD of PV, ensuing a more elongated PV feature toward Russia, would result in a 1 hPa decrease in cyclone minimum SLP at 72-h. Further, the ensemble-mean 500-hPa geopotential heights illustrates a cut-off upper-level low positioned near the North Pole and an upper-level ridge over Norway (Fig. 3.24d). The largest sensitivity here is associated with the geopotential height gradient over the North Atlantic, where decreasing heights off the east coast of Greenland and increasing heights east of Svalbard, therefore enhancing the upper-level geopotential height gradient further eastward, is associated with a more intense cyclone (Fig. 3.24d). Therefore, the combination of these results suggests that the intensity variability at 72-h is associated uncertainty to both the position of low-level thermal boundary over the North Atlantic and associated upper-level region of higher PV and low-level plume of warm, moist air, which are dynamically connected. In addition, the uncertainty to the mesoscale features embedded within
the upper-level feature over North Pole suggests that the intensity variability is also sensitive to
the shape of this feature and how it interacts with the North Atlantic jet.

To quantify the contributions of sensitivity independently to intensity variability,
multivariate linear regression is calculated using the 850-hPa temperature and the upper-level
310-K PV fields (Fig. 3.25). In this case, near-cyclone IVT is negligible and is therefore not
included in the calculation. The largest regression coefficient throughout the forecast is to the
upper-level PV pattern (Fig. 3.25), suggesting that the intensity variability is dominated by the
uncertainty associated with interactions between the North Pole PV feature and eastern
Greenland tongue of higher PV. The contribution from 850-hPa temperature is negligible
through 36-h; however, between 42 and 54 hours, the regression coefficient is between 0.4–0.5
(Fig. 3.25), suggesting that increasing low-level temperature nearest the cyclone during this time
period, is associated with a more intense cyclone at 72-h. These results suggest that the largest
contributing factor of intensity variability is to the upper-level PV pattern and more intense
cyclones tend to track more eastward with a smaller radius of curvature.

The relationship between the sensitivity to the low-level thermal boundary and tongue of
higher PV aloft over the north Atlantic Ocean can be examined through statistical PV inversion
to derive near surface winds associated with PV differences between the most and least intense
members at 36-h (Fig. 3.26). The negative PV anomaly analyzed here is to the equatorward side
of the tongue of higher PV over the North Atlantic at 24-h, associated with the dipole of
sensitivity that suggests a poleward shift of higher PV is associated with a more intense cyclone.
Therefore, perturbing the low-level winds associated with this upper-level negative PV anomaly
can illustrate how this tongue of PV is connected with the thermal boundary at the surface. To be
expected, there is an anticyclonic circulation around this upper-level negative PV anomaly that is
extending down at the surface (Fig. 3.26). The strongest anticyclonic circulation is to the south and west of the negative PV anomaly. Further, 3 m s$^{-1}$ southerly winds west of Svalbard are aiding in the transport of warm, moist air poleward, closer to the location of the surface cyclone (Fig. 3.26). Enhancing the poleward extent of low-level temperature and moisture will result in a stronger low-level temperature and moisture gradient to the north, enhancing baroclinicity in the region of the AC. Therefore, this upper-level negative PV anomaly is dynamically connected with the poleward extension of the low-level temperature and moisture, ultimately aiding in cyclogenesis and resulting in a more intense cyclone at 36-h.

3.6 Atlantic Basin Cyclone of January 2014

3.6.1 Case Overview

To further validate the sensitivity associated with the Atlantic basin cyclone analyzed in section 3.4, the track and intensity uncertainty of an additional Atlantic basin cyclone in January of 2014 is explored. Before tracking of this cyclone began, there were initially two enclosed low-pressure systems; one over the southeastern US and one right off the coast. These two systems merged to create the cyclone of interest off the southeastern coast of the US. Similar to the previous Atlantic basin cyclone discussed in section 3.3.2, this cyclone is also characterized by downstream ridge amplification. The resulting low-pressure system developed over the southeastern coast of the US at 0000 UTC 3 January 2014 in a region of upper-level divergence downstream with a trough positioned upstream over the central US and ridge position downstream over the western Atlantic Ocean (Fig. 3.27). Over the next 24-h, this low-pressure system tracked northeastward just south of Newfoundland, Canada and intensified to 975 hPa (Fig. 3.27). Simultaneously, the downstream ridge has amplified, aiding in the intensification of this cyclone within the region of divergence of this upper-level jet. By 0000 UTC 5 January
2014, the surface cyclone reaches its maximum intensity of 935 hPa, while merging with an existing low-pressure system in the North Atlantic (Fig. 3.27). The upper-level ridge has moved eastward over Europe and in turn the surface cyclone begins to dissipate, while continuing to track eastward (Fig. 3.27).

3.6.2 Cyclone Position Uncertainty

This Atlantic basin cyclone developed off east coast of the US, following a merge of two low-pressure systems. After these two lows merge, this cyclone closely follows the Atlantic storm track; therefore, there is not much cross-track position variability (Fig. 3.28). The ensemble-mean track is very similar to the ERA5 reanalysis track after the merge, with some small discrepancies throughout the forecast; nonetheless, this cyclone is mostly characterized by along-track variability (Fig. 3.28). In particular, the position variability is greatest at 36-h while this cyclone is rapidly intensifying, denoted by the cyan bivariate ellipse, that spans from approximately 60°W to 70°W (Fig. 3.28). Along-track variability suggests that the position of this storm is largely associated with the speed at which the cyclone is moving. The position variability at 36-h will be used in the subsequent sensitivity calculations where the pattern that explains the most variability is associated with faster tracking and therefore more northeastward surface cyclone position at 36-h (Fig. 3.28).

To understand how the position forecast is sensitive to features in the upper troposphere, the sensitivity of the 36-h cyclone position forecast along the major axis direction to the 330-K Ertel’s PV and 500-hPa geopotential height fields at 12–18-h is calculated (Fig. 3.29). These times were chosen to assess the evolution of the sensitive features early in the forecast leading up to 36-h. At 12-h, the surface cyclone is located at 78°W and 40°N, just south of the ridge axis (Fig. 3.29a). The ensemble-mean 330-K PV at 12-h illustrates a negatively tilted short-wave
trough over the Great Lakes region, with a weak PV gradient extending south toward Texas and a PV ridge over the eastern Atlantic with a tight PV gradient (Fig. 3.29a). The sensitive regions of 36-h position variability to 12-h 330-K PV are largely associated with the extension of the upstream short-wave trough and downstream ridge (Fig. 3.29a). Negative sensitivity over the Gulf coast suggests that decreasing PV in the southern extension of the short-wave trough would reduce the extension of the short-wave trough and result in a more zonal flow downstream of the cyclone. Therefore, more zonal flow downstream of the short-wave trough at 12-h is associated with a more northeastward tracking cyclone 24-h later. Further, a small region of positive sensitivity just downstream of the ridge apex in the northwest flow and negative sensitivity within the downstream trough at 40°N and 30°W, suggests that increasing PV within the northwestern flow and decreasing PV in the downstream trough, resulting in more zonal flow downstream, is associated with a more northeastward tracking cyclone at 36-h (Fig. 3.29a). The ensemble-mean 500-hPa geopotential height at 12-h also demonstrates a trough/ridge set up over the eastern US (Fig. 3.29b). The largest sensitivity is to the amplitude this trough and ridge, where increasing geopotential height within the trough and decreasing geopotential height within the ridge is associated with a more zonal upper-level jet.

At 18-h, the PV trough and ridge have shifted slightly eastward with a more distinct short-wave trough still over the Great Lakes region (Fig. 3.29c). The largest sensitivity at this time is associated with the upstream short-wave trough, with negative sensitivity in the extending from Michigan to eastern Texas (Fig. 3.29c). Decreasing PV within this short-wave trough would result in a less defined short-wave trough and therefore more zonal flow upstream of the surface cyclone. In addition, there is a region of positive sensitivity over eastern New York creating a sensitivity dipole centered at 80°W and 40°N. Negative sensitivity to the west and
positive sensitivity to the east suggests that decreasing PV to the west and increasing PV to the
east is associated with an eastward shift of the short-wave trough, leading to a more
northeastward cyclone position at 36-h. Further, the region of positive sensitivity downstream of
the cyclone has propagated eastward toward the downstream trough. Similarly, sensitivity to the
500-hPa geopotential height at 18-h suggests that increasing geopotential heights over the
southeastern US and decreasing geopotential heights over the Northeast, therefore reducing the
amplitude of the 500-hPa flow, is associated with a more north and east tracking cyclone at 36-h
(Fig. 3.29d). The combination of these results suggest that an overall more zonal upper-level
flow and an upstream short-wave trough positioned further east allows for a more north and east
cyclone position at 36-h.

To understand how the sensitive region associated with the northwest flow downstream
of the ridge may impact the upper-level flow between members that are positioned more
northeast versus southwest at 36-h, statistical PV inversion is used to derive the upper-level
winds associated with 330-K PV differences at 12-h within the downstream ridge. Inverting the
500-hPa geopotential winds associated with the positive PV anomaly downstream of the ridge
apex is associated with cyclonic circulation around the positive anomaly (Fig. 3.30). The
northerly perturbation winds upstream of the PV anomaly and southerly perturbation winds
downstream of the PV anomaly are acting to diminish the Rossby wave guide, resulting in a
more zonal flow over the Atlantic Ocean (Fig. 3.30). Further, northwesterly winds downstream
of the surface cyclone suggest an acceleration of the surface cyclone more north and east (Fig.
3.30). Therefore, the upper-level positive PV anomaly downstream of the ridge apex is indicative
of a more zonal flow, allowing the surface cyclone to have a more northeastward position (Fig.
3.30).
3.5.3 Cyclone Intensity Uncertainty

This cyclone intensifies from 1015 hPa at 0000 UTC 2 January 2014 to 938 hPa at 0000 UTC 5 January 2014, which is a 77 hPa change within 54 hours (Fig. 3.31). Nevertheless, in comparison to the previous cyclone case studies, the MPAS ensemble members demonstrate very minimum intensity variability, with the maximum ensemble spread occurring after the time of maximum intensity at 0000 UTC 5 January 2014 (Fig. 3.31). Therefore, the intensity variability metric used here is the 60-h minimum SLP, at the time of maximum intensity (Fig. 3.31).

To assess what low-level thermodynamics limit the intensity variability at 60-h, the sensitivity of the 24-h minimum SLP to the IVT and 850-hPa temperature fields are calculated. This time was chosen to assess the uncertainty of features early in the forecast to intensity variability at the time of maximum intensity. At 24-h, the ensemble-mean 850-temperature demonstrates increased temperature gradient near the surface cyclone located at 60°W and 42°N (Fig. 3.32a). The largest sensitivity is associated with the polar front with negative sensitivity over most of the Northeast US (Fig. 3.32a). This negative region of sensitivity extends southeastward along the cold front associated with the surface cyclone. In addition, there is positive sensitivity just north of the surface along the warm front associated with the surface cyclone (Fig. 3.32a). Therefore, increasing temperature along the warm front and decreasing temperature along the cold front by one SD at 24-h is associated with a 2 hPa decrease in cyclone minimum SLP at 60-h. The IVT ensemble-mean demonstrates an AR extending from the coast of the Carolinas eastward, maximized just south of the surface cyclone (Fig. 3.32b). For the 2013 Atlantic basin cyclone, the largest sensitivity of cyclone intensity variability to IVT is associated with the preceding polar front. However, in this case there is also evidence of sensitivity.
associated with the position of the AR over the Atlantic Ocean. Positive sensitivity to the north of the AR and negative sensitivity to the east of the AR suggests that increasing IVT to the north and decreasing IVT to the east by one SD of IVT, associated with a northeastern shift of the AR, is associated with a 1.6 hPa decrease in cyclone minimum SLP at 60-h. Overall, these results suggest that cyclone intensity variability at 60-h is associated with uncertainty to the position of both the low-level thermal boundary and to the position of the AR, aiding in moisture supply. However, in this case there is also evidence of positive sensitivity within the AR indicating that increasing the IVT within the AR by one SD at 24-h is associated with a stronger plume of moisture along the AR and a 1.6 hPa decrease in cyclone minimum SLP at 60-h.

Further, to assess what upper-level features limit the intensity variability at 60-h, the sensitivity of the 24-h minimum SLP to 330-K PV and 500-hPa geopotential height is calculated (Fig. 3.32c,d). At 24-h, the ensemble-mean PV field again demonstrates a negatively tilted short-wave trough just east of the Great Lakes extending southwestward over the Midwest, and a ridge just off the east coast of Newfoundland, Canada (Fig. 3.32c). The largest sensitivity to upper-level PV is to the PV ridge downstream of the surface cyclone (Fig. 3.32c). Positive sensitivity upstream up the PV ridge apex and negative sensitivity downstream of the PV ridge apex indicates that increasing PV upstream and decreasing PV upstream by one SD at 24-h, associated with a westward shift of the upper-level ridge, would result in a 1 hPa decrease in cyclone minimum SLP at 60-h. Similarly, there is a region of positive sensitivity to the downstream trough as well, suggesting an overall shift in the upper-level flow is associated with a more intense cyclone. Further, the largest sensitivity to 500-hPa geopotential height at 24-h is associated with the upstream trough, suggesting that a more enhanced trough upstream of the surface cyclone is associated with a more intense cyclone (Fig. 3.32d). These results suggest that
the intensity variability at 60-h is mostly associated with uncertainty within the meridional flow both upstream and downstream of the surface cyclone.

The intensity variability of this storm at 60-h is sensitive to both upper and lower fields; therefore, multivariate linear regression is again used quantify the upper-level and low-level contributions independently to intensity variability (Fig. 3.33). Through 24-h, there does not appear to be a stronger contributing factor; however, at 30-h, the largest regression coefficient of 0.5 is associated with 850-hPa temperature, where an increase of low-level temperature nearest the cyclone center would result in a more intense cyclone at 72-h (Fig. 3.33). At 42-h, the largest regression coefficient at 0.75 is to IVT, suggesting that increasing IVT nearest the cyclone center at 42-h, would result in a more intense cyclone at 72-h (Fig. 3.33). These results suggest that the intensity variability at 72-h is dominated by low-level thermodynamics from 30- to 48-h.

The sensitivity of the intensity variability of this Atlantic basin cyclone are sensitive to both the upper-level ridge downstream of the surface cyclone and low-level temperature and moisture near the surface cyclone. Therefore, to assess how the downstream ridge and low-level thermodynamics may be dynamically connected, statistical PV inversion is used to derive the 850-hPa winds associated with the 330-K PV difference between the most and least intense members based on 72-h minimum SLP, to determine how these sensitive regions may project onto the lower tropospheric winds and near-surface fields (Fig. 3.34). The negative PV anomaly selected at 24-h is centered at 50°N and 45°W, downstream of the surface cyclone is characterized by anticyclonic circulation throughout the troposphere (not shown), penetrating toward the surface shown here as weak anticyclonic circulation (Fig. 3.34). The largest perturbed winds associated with this negative PV anomaly are upstream of this anomaly and downstream of the surface cyclone, where the perturbed cyclonic winds are indicative of enhanced low-level
cyclogenesis and upper-level divergence further downstream along the North Atlantic storm track (Fig. 3.34). Therefore, a more intense cyclone at 72-h is characterized by greater downstream ridge amplification.

3.7 Summary

This study uses ensemble-based sensitivity analysis to assess the upper-level features and low-level temperature and moisture thermodynamics associated with position and intensity uncertainty for two ACs and two Atlantic basin cyclones using the MPAS ensemble forecasts. AC13 was chosen from a climatology of intense, long-duration ACs in Capute and Torn (2021), as it is associated with large position and intensity variability and a very rapid sea ice loss event (VRILEs; McGraw et al. 2022) and exemplifies an isolated AC. AC20 was chosen as it has many characteristics similar a common AC type that includes multiple merging events, a duration of 10 days with a prolonged track over the Arctic sea ice, and a prevailing upper-level PV feature vertically stacked with the cyclone. In addition, two Atlantic basin cyclones characterized by large downstream amplification were chosen to compare sensitive features and thermodynamics, that portray the Atlantic basin cyclones studied in Chapter 2.

For AC13, the largest position forecast sensitivity is associated with meso-scale features embedded within a large-scale PV vortex positioned over the North Pole. More specifically, a more poleward cyclone position at 24-h is associated with ridge amplification just downstream of the surface cyclone at 12-h. Further, a more poleward cyclone position at 72-h is associated with the shape of this feature on the Canadian side. Similarly, the position variability of AC20 is sensitive to both the shape of the upper-level PV feature that is vertically stacked with the surface cyclone, in addition to the interaction of this PV feature and a tongue of higher PV off the east coast of Greenland. In addition, both ACs are sensitive to a distant PV feature early in
the forecast for the position variability later in the forecast through action-at-a-distance, suggesting that the uncertainty of these smaller-scale features that interact with the larger-scale PV feature later in the forecast may be important to better understanding the position predictability of ACs.

For comparison, a similar analysis was done for a January 2013 and 2014 Atlantic basin cyclone. The largest position forecast sensitivity for the 2013 Atlantic basin cyclone is to an upper-level PV trough over the Great Lakes region and a cut-off PV feature over the southeastern US upstream of the surface cyclone and downstream ridge building. More specifically, the position variability at 36-h is more sensitive to the upstream trough and the position variability at 72-h is equally sensitive to the upstream trough and downstream ridge. Similar results were found for the 2014 Atlantic basin cyclone, where the largest position forecast uncertainty is to the position of an upstream short-wave trough and downstream ridge. In this case, a more northward tracking cyclone is associated with a more zonal flow.
Fig. 3.1: Average grid spacing for the 60–15-km variable-resolution MPAS mesh for the Arctic (left) and Atlantic (right) cyclone analyses and forecasts. Contour interval is 8 km.
Fig. 3.2: ERA-Interim reanalysis MSLP (black contours; hPa; contoured every 6 hPa), 500-hPa potential vorticity (thick white contour; 2 PVU), and 850-hPa temperature (shading; Kelvin) for (a) 0000 UTC 5 August 2013, (b) 0000 UTC 6 August 2013, (c) 0000 UTC 7 August 2013, and (d) 0000 UTC 8 August 2013. The black star indicates the location of the cyclone of interest.
Fig. 3.3: MPAS ensemble forecasts of Arctic cyclone initialized 0000 UTC 5 August 2013 (gray). The ensemble-mean position is given in blue, while the ERA-Interim reanalysis track for AC13 shown in black. 24- and 72-h position ellipses and major axis error vector denoted in yellow and magenta, respectively.
Fig. 3.4: Sensitivity of (a) 24-h and (b) 72-h MPAS ensemble position forecast to the 12-h 310-K potential vorticity (shading; km) initialized 0000 UTC 5 August 2013. Green contours are the ensemble-mean PV (PVU). The black star represents the surface cyclone position from the ERA-Interim reanalysis. The purple dotted line indicates the position of the short-wave trough.
Fig. 3.5: Region of PV difference exceeding −0.2 PVU in the 24-h 310-K PV between the poleward and equatorward members at 72-h for the forecast initialized at 0000 UTC 5 August 2013 (shading; PVU). The vectors denote the 500-hPa winds (m s⁻¹) obtained by inverting the 310-K PV field within the shaded region using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 310-K surface at the corresponding time. The yellow star denotes the reanalysis surface cyclone position at this time.
Fig. 3.6: MPAS ensemble forecasts of cyclone minimum SLP initialized 0000 UTC 5 August 2013. The ensemble-mean minimum SLP is shown in blue, +/- one SD of the ensemble-mean is in green, and the full range of MPAS ensemble members is given in gray. ERA-Interim reanalysis minimum SLP for AC13 shown in black. Forecast hours 0–18 and after 96-h are not shown due to difficulties tracking the cyclone at this time.
Fig. 3.7: Sensitivity of 72-h MPAS ensemble intensity forecast to the 24-h (a) 850-hPa temperature, (b) Integrated Vapor Transport, (c) 310-K Ertel’s PV, and (d) 500-hPa geopotential height (shading; hPa) initialized 0000 UTC 5 August 2013. Green contours are the ensemble-mean for each respective field; (a) K, (b) kg m$^{-1}$ s$^{-1}$, (c) PVU, and (d) m. The black star represents the surface cyclone position from ERA-Interim reanalysis.
Fig. 3.8: Multivariate regression coefficients where the independent variables are the shape of the upper tropospheric 310-K PV field (red), IVT (navy blue), and 850-hPa temperature (blue) at each forecast hour and the dependent variable is the 72-h minimum SLP for the forecast initialized at 0000 UTC 5 August 2013. All variables are normalized by the ensemble SD, so the units are dimensionless.
Fig. 3.9: Region of PV difference exceeding −0.2 PVU in the 24-h 310-K PV between the most and least intense members valid at 36-h for the forecast initialized at 0000 UTC 5 Aug 2013 (white contour; PVU). The vectors denote the 850-hPa winds (m s⁻¹) obtained by inverting the 310-K PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 850-hPa geopotential height and shading represents the 850-hPa temperature field. The white star denotes the reanalysis surface cyclone position at this time.
Fig. 3.10: ERA-Interim reanalysis MSLP (black contours; hPa; contoured every 4 hPa), 2 PVU 250-hPa potential vorticity (thick white contour), and 850-hPa temperature (shading; Kelvin) for (a) 0000 UTC 18 January 2013, (b) 0000 UTC 19 January 2013, (c) 0000 UTC 20 January 2013, and (d) 0000 UTC 21 January 2013. The black star represents the surface cyclone position from ERA-Interim reanalysis.
Fig. 3.11: MPAS ensemble forecasts of Atlantic basin cyclone initialized 0000 UTC 17 January 2013 (gray). Mean position track in blue. ERA-Interim reanalysis track for cyclone shown in black. Position ellipses and major axis error vector denoted at 36- and 72-h in cyan and magenta, respectively.
Fig. 3.12: Sensitivity of (a) 36-h and (b) 72-h MPAS ensemble position forecast to the 12-h 310-K potential vorticity (shading; km) initialized 0000 UTC 17 January 2013. Green contours are the ensemble-mean PV (PVU). The black star represents the surface cyclone position from ERA-Interim reanalysis. (c) and (d) same as (a) and (b) but for 30-h 310-K potential vorticity.
Fig. 3.13: Region of PV difference exceeding −0.2 PVU in the 24-h 330-K PV between the westward and eastward members at 72-h for the forecast initialized at 0000 UTC 17 January 2013 (shading; PVU). The vectors denote the 500-hPa winds (m s\(^{-1}\)) obtained by inverting the 330-K PV field within the shaded region using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 330-K (PVU). The yellow star denotes the reanalysis surface cyclone position at this time.
Fig. 3.14: MPAS ensemble forecasts of cyclone minimum SLP initialized 0000 UTC 17 January 2013. The ensemble-mean minimum SLP is shown in blue, +/- one SD of the ensemble-mean is in green, and the full range of MPAS ensemble members is given in gray. ERA-Interim reanalysis minimum SLP for AC13 shown in black.
Fig. 3.15: Sensitivity of 72-h MPAS ensemble intensity forecast to the 12-h (a) 850-hPa temperature, (b) Integrated Vapor Transport, (c) 330-K Ertel’s PV, and (d) 500-hPa geopotential height (shading; hPa) initialized 0000 UTC 17 January 2013. Green contours are the ensemble-mean for each respective field with units (a) K, (b) kg m$^{-1}$ s$^{-1}$, (c) PVU, and (d) m. The black star represents the surface cyclone position from ERA-Interim reanalysis.
Fig. 3.16: Multivariate regression coefficients where the independent variables are the upper tropospheric 330-K PV field (red), IVT (navy blue), and 850-hPa temperature (blue) at each forecast hour and the dependent variable is the 72-h minimum SLP for the forecast initialized at 0000 UTC 17 January 2013. All variables are normalized by the ensemble SD, so the units are dimensionless.
Fig. 3.17: Region of PV difference exceeding \(-0.2\) PVU in the 24-h 330-K PV between the most and least intense members at 72-h for the forecast initialized at 0000 UTC 17 January 2013 (white contour; PVU). The vectors denote the 850-hPa winds (m s\(^{-1}\)) obtained by inverting the 330-K PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 850-hPa geopotential height and shading denotes the 850-hPa temperature field. The white star denotes the reanalysis surface cyclone position at this time.
Fig. 3.18: ERA5 reanalysis track (top) and minimum SLP (bottom) for AC20 for phase 1 (red), phase 2 (yellow), phase 3 (green), phase 4 (blue) and phase 5 (brown). The black box in the right panel represents the forecast period for the subsequent reanalysis.
Fig. 3.19: ERA5 reanalysis MSLP (black contours; hPa; contoured every 4 hPa), 350-hPa potential vorticity (thick white contour; 2 PVU), and 850-hPa temperature (shading; Kelvin) for (a) 0000 UTC 12 June 2020, (b) 0000 UTC 13 June 2020, (c) 0000 UTC 14 June 2020, and (d) 0000 UTC 15 June 2020. The white star represents the surface cyclone position from ERA5 reanalysis.
Fig. 3.20: MPAS ensemble forecasts of AC20 initialized 0000 UTC 12 June 2013 (gray). The ensemble-mean position is given in blue, while the ERA5 reanalysis track for AC20 shown in black. 36- and 84-h position ellipses and major axis error vector denoted in yellow and magenta, respectively.
Fig. 3.21: Sensitivity of (a) 36-h and (b) 84-h MPAS ensemble position forecast to the 24-h 310-K potential vorticity (shading; km per SD of PV) initialized 0000 UTC 12 June 2020. Green contours are the ensemble-mean PV (PVU). The black star represents the surface cyclone position from the ERA5 reanalysis.
Fig. 3.22 Region of PV difference exceeding $-0.12$ PVU in the 12-h 310-K PV between the poleward and equatorward members at 36-h for the forecast initialized at 0000 UTC 12 June 2020 (shading; PVU). The vectors denote the 500-hPa winds (m s$^{-1}$) obtained by inverting the 310-K PV field within the shaded region using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 310-K surface at the corresponding time. The yellow star denotes the reanalysis surface cyclone position at this time.
Fig. 3.23: MPAS ensemble forecasts of cyclone minimum SLP initialized 0000 UTC 12 June 2020. The ensemble-mean minimum SLP is shown in blue, +/- one SD of the ensemble-mean is in green, and the full range of MPAS ensemble members is given in gray. ERA5 reanalysis minimum SLP for AC20 shown in black.
Fig. 3.24: Sensitivity of 72-h MPAS ensemble intensity forecast to the 24-h (a) 850-hPa temperature, (b) Integrated Vapor Transport, (c) 310-K Ertel’s PV, and (d) 500-hPa geopotential height (shading; hPa) initialized 0000 UTC 12 June 2020. Green contours are the ensemble-mean for each respective field with units (a) K, (b) kg m⁻¹ s⁻¹, (c) PVU, and (d) m. The black star represents the surface cyclone position from ERA5 reanalysis.
Fig. 3.25: Multivariate regression coefficients where the independent variables are the shape of the upper tropospheric 310-K PV field (red) and 850-hPa temperature (blue) at each forecast hour and the dependent variable is the 72-h minimum SLP for the forecast initialized at 0000 UTC 12 June 2020. All variables are normalized by the ensemble SD, so the units are dimensionless.
Fig. 3.26: Region of PV difference exceeding $-0.2$ PVU in the 12-h 310-K PV between the most and least intense members valid at 36-h for the forecast initialized at 0000 UTC 12 June 2020 (white contour; PVU). The vectors denote the 850-hPa winds (m s$^{-1}$) obtained by inverting the 310-K PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 700-hPa geopotential height and shading represents the 850-hPa temperature field. The white star denotes the reanalysis surface cyclone position at this time.
Fig. 3.27: ERA5 reanalysis MSLP (black contours; hPa; contoured every 8 hPa), potential vorticity (white contour; 2 PVU), and 850-hPa Temperature (shading; Kelvin) for (a) 0000 UTC 3 January 2014, (b) 0000 UTC 4 January 2014, (c) 0000 UTC 5 January 2014, and (d) 0000 UTC 6 January 2014. The white star represents the surface cyclone position from ERA5 reanalysis.
Fig. 3.28: MPAS ensemble forecasts of Atlantic basin cyclone initialized 1200 UTC 2 January 2014 (gray). Mean position track in blue. ERA5 reanalysis track for cyclone shown in black. Position ellipses and major axis error vector denoted at 36- and 72-h in cyan and magenta, respectively.
Fig. 3.29: Sensitivity of (a) 36-h and (b) 72-h MPAS ensemble position forecast to the 12-h 330-K potential vorticity (shading; km) initialized 1200 UTC 2 January 2014. Green contours are the ensemble-mean PV (PVU). The black star represents the surface cyclone position from ERA5 reanalysis. (c) and (d) same as (a) and (b) but for 18-h 310-K potential vorticity.
Fig. 3.30: Region of PV difference exceeding 0.12 PVU in the 12-h 330-K PV between the northward and southward members at 36-h (shading; PVU) for the forecast initialized at 1200 UTC 2 January 2014. The vectors denote the 500-hPa winds (m s$^{-1}$) obtained by inverting the 330-K PV field within the shaded region using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 330-K (PVU). The yellow star denotes the reanalysis surface cyclone position at this time.
Fig. 3.31: MPAS ensemble forecasts of cyclone minimum SLP initialized 1200 UTC 2 January 2014. The ensemble-mean minimum SLP is shown in blue, +/- one SD of the ensemble-mean is in green, and the full range of MPAS ensemble members is given in gray. ERA5 reanalysis minimum SLP for AC20 shown in black.
Fig. 3.32: Sensitivity of 60-h MPAS ensemble intensity forecast to the 24-h (a) 850-hPa temperature, (b) Integrated Vapor Transport, (c) 310-K Ertel’s PV, and (d) 500-hPa geopotential height (shading; hPa) initialized 1200 UTC 2 January 2014. Green contours are the ensemble-mean for each respective field with units (a) K, (b) kg m$^{-1}$ s$^{-1}$, (c) PVU, and (d) m. The black star represents the surface cyclone position from ERA5 reanalysis.
Fig. 3.33: Multivariate regression coefficients where the independent variables are the shape of the upper tropospheric 310-K PV field (red), IVT (navy blue), and 850-hPa temperature (blue) at each forecast hour and the dependent variable is the 72-h minimum SLP for the forecast initialized at 1200 UTC 2 January 2014. All variables are normalized by the ensemble SD, so the units are dimensionless.
Fig. 3.34: Region of PV difference exceeding −0.2 PVU in the 24-h 330-K PV between the most and least intense members valid at valid at 0000 UTC 5 January 2014 for the forecast initialized at 1200 UTC 2 January 2014 (white contour; PVU). The vectors denote the 850-hPa winds (m s$^{-1}$) obtained by inverting the 330-K PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 850-hPa geopotential height and shading denotes the 850-hPa temperature field. The white star denotes the reanalysis surface cyclone position at this time.
4. Assessing Forecast Uncertainties associated with an Arctic Cyclone Observed during the THINICE 2022 Field Campaign

4.1 Introduction

In Chapter 3, the uncertainty associated with upper-level features and low-level thermodynamics that limit the track and intensity predictability of two ACs was assessed and compared to the results of a comparable analysis of two Atlantic basin cyclones. The only metrics used for sensitivity analysis in Chapter 3 were minimum SLP for intensity variability and the distance along the major axis direction for position variability. Here, we compare using these metrics as a proxy for track and intensity variability to using PCs of leading EOFs to assess uncertainty associated with upper-level features and low-level thermodynamics representative of features associated with this AC, such as TPVs and low-level jets. One of the main motivations for gaining a better understanding of AC predictability is that it will lead to improved predictions of Arctic sea ice. Strong linkages documented between ACs to TPVs (e.g., Simmonds and Rudeva 2014; Tao et al. 2017) and intense low-level winds that may be responsible for widespread sea-ice loss make these metrics worth examining (e.g., Valkonen et al. 2021). Therefore, the goal is to assess which metrics provide better predictions of features and dynamics that limit the predictability of ACs.

During the THINICE field campaign, real-time ensemble-based sensitivity analysis using metrics defined as PCs of 500-hPa geopotential height EOFs were used to highlight the sensitive features associated with ACs during the month of August 2022. WindBorne balloons were launched from Fairbanks, AK and Longyearbyen, Svalbard, with the goal of sampling the sensitive regions associated with these ACs and overall increasing the spatial and temporal network of in-situ observations in the Arctic region. During the field campaign, four ACs were
observed within the vicinity of Svalbard (Fig. 4.1). The AC chosen for this chapter (AC22 hereafter) was the third chronological cyclone observed during the field campaign. AC22 had the longest duration, was the second most intense, and was the only AC observed during the field campaign to move over the sea-ice. The sea ice difference after the AC passed over the sea ice edge is shown in Fig. 4.1, where over 80% of the sea ice edge northeast of Svalbard was diminished. In each of the subsequent sensitivity figures, the location of WindBorne balloon observations is overlaid with the sensitivity analysis to assess how well these balloons sampled the sensitive regions associated with this AC.

This chapter proceeds as follow. Section 4.2 provides an overview of the unique data used in this chapter. Section 4.3.1 provides an overview of the case study selected, sections 4.3.2 and 4.3.3 compare the sensitive regions using cyclone position and PCs of 500-hPa geopotential EOF as ensemble sensitivity metrics, and sections 4.3.4 and 4.3.5 compare the sensitive regions using cyclone minimum SLP and 10-m wind speed EOF as ensemble sensitivity metrics. Lastly, a brief summary of the results is provided in section 4.4.

4.2 Data and Methodology

In Chapter 3, the MPAS model was used to assess the sensitivity of cyclone track and intensity variability. However, during the THINICE field campaign, ECMWF model ensemble forecasts were utilized to examine sensitivity to upper-level features, such as TPVs. ECMWF ensemble forecasts are more readily available and require minimum computing power to apply ensemble-based sensitivity analysis (1.1). Therefore, this case study will use ECMWF ensemble forecasts to mimic sensitivity analysis that can be run in real time. The ECMWF ensemble forecast utilized in this chapter consist of 51-members, a control and 50 perturbed members, and
are obtained from the THORPEX Interactive Grand Global Ensemble (TIGGE) dataset with a horizontal resolution of $1^\circ \times 1^\circ$ grid, with output every 12 hours and run for 156 hours.

An ECMWF ensemble forecast initialized 0000 UTC 15 August 2022 is used to assess the sensitivity associated with AC22; this time is approximately 1 day prior to the reference time defined in Chapter 2 and 3 days prior to maximum intensity of AC22, similar to forecast times used in previous case studies. The objective of this study is to determine if the metrics used in real time during the THINICE 2022 field campaign were the optimum metrics to observe the sensitive regions associated with this AC. Therefore, ensemble sensitivity is used to evaluate hypotheses on the relative contribution of uncertainty in upper tropospheric troughs and the lower tropospheric thermodynamics to the predictability of cyclone-related position, intensity, wind speed, and upper-level geopotential height. Chapter 3 highlights the significance of understanding uncertainty associated with upper-level PV features and low-level dynamics to AC minimum SLP and position. Therefore, to build off of Chapter 3, this chapter will compare using these metrics for intensity and position to wind speed and upper-level geopotential height metrics, respectively, as metrics for sensitivity analysis. The PCs of ensemble 10-m wind speed and 500-hPa geopotential heights EOF patterns over specified domains encompassing a TPV and low-level jet, respectively, are computed. PCs of EOFs have been used to calculate sensitivity of extratropical cyclones, warm conveyor belts, etc. (Chang et al. 2013; Berman and Torn 2022).

The paths of balloons launched during the THINICE field campaign are obtained from WindBorne. The extent to which these balloons were able to sample the sensitive regions of this storm is assessed to determine if assimilating these balloons would lead to more accurate predictions. Balloons paths are overlaid in each of the subsequent sensitivity figures. In addition,
to illustrate the impact of this AC on the summer sea ice, daily SIC data on a 25 km x 25 km grid was obtained from the National Snow and Ice Data Center (NSIDC).

4.3 Results

4.3.1 Case Overview

AC22 developed off the east coast of Iceland at 0000 UTC 15 August 2022; simultaneously, an upper-level PV trough extends off the east coast of Greenland, upstream of the surface cyclone (Fig. 4.2a). Over the next 24 hours, the cyclone tracks northward by 5 degrees latitude intensifying slowly to 1002 hPa (Fig. 4.2b). Further, by 0000 UTC 17 August 2022, the cyclone continues to intensify while a plume of warm, moist air extends from northern Europe to the south coast of Svalbard (Fig. 4.2c). During the next 24 hours, the cyclone intensifies at a faster rate to 990 hPa, while vertically stacked with an upper-level PV cut-off, resembling a TPV (Fig. 4.2d). Additionally, there is a low-level plume of warm, moist air behind the warm front of the surface cyclone, extending toward the sea ice edge north of Svalbard (Fig. 4.2d). After the surface cyclone crosses over the Greenland sea ice edge, the plume of warm, moist air continues to move eastward away from the surface cyclone, therefore eliminating the low-level support for the cyclone. The surface cyclone then transitions to a barotropic, cold-core cyclone that moves northward over the Arctic sea ice for many days, while remaining vertically stacked with the upper-level PV cut-off feature, comparable to a TPV (not shown).

4.3.2 Cyclone Position Uncertainty

The ERA5 reanalysis track begins off the east coast of Iceland, tracks north to the west of Svalbard, then curves eastward at 85°N (Fig. 4.3). The ECMWF forecast ensembles initialized 0000 UTC 15 August 2022 demonstrate mainly along-track position variability through 60-h,
(Fig. 4.3). After 60-h, the ensemble members begin to split between tracking east and west of the reanalysis track (Fig. 4.3). Ensemble members that track more westward after 60-h, have a large radius of curvature when tracking eastward, whereas members that track more to the east have a smaller radius of curvature when curving eastward at 96-h (Fig. 4.3). Overall, the largest position variability throughout the forecast is associated with along-track position variability. The vectors at 60-h and 96-h represent the direction of largest variability at the respective forecast hour, and the 96-h position variability will be used as the metric in the subsequent sensitivity calculation (Fig. 4.3). This time was chosen to assess the uncertainty to upper-level features earlier in the forecast associated with members that have a smaller radius of curvature at 96-h.

The sensitivity of 96-h cyclone position forecast along the major axis direction to the 250-hPa PV field at 12- and 48-h is calculated to understand how the position forecast is sensitive to features along the tropopause, such as TPVs, earlier in the forecast (Fig. 4.4). These times were chosen to assess the evolution of uncertainty earlier in the forecast to position variability later in the forecast. The ensemble-mean 250-hPa PV field at 12-h is characterized by an upper-level PV ridge over Greenland and PV trough over Iceland (Fig. 4.4a). Additionally, there is a PV ridge just downstream of the surface cyclone extending from northern Europe (Fig. 4.4a). The largest sensitivity of 96-h position variability to the 12-h PV is associated with the PV trough over Iceland and downstream PV ridge (Fig. 4.4a). Decreasing PV on the western side and increasing PV on the eastern side of the PV trough upstream of the surface cyclone by one SD of PV, and therefore shifting the PV trough eastward at 12-h, is associated with a 60 km along-track displacement in the surface cyclone position at 72-h. In addition, negative sensitivity associated with the downstream PV ridge suggests that decreasing PV by one SD of PV, enhancing the downstream ridge, is also associated with a 60 km along-track displacement of the
surface cyclone (Fig. 4.4a). Therefore, an eastward displacement of the upstream upper-level PV trough, closer to the surface cyclone, and an enhanced downstream ridge at 12-h, is associated with a more northward tracking surface cyclone at 96-h. At this time, there are no balloons present in the vicinity of the sensitive regions (Fig. 4.4a), indicating that assimilating observations would not lead to an improvement in the 96-h position variability associated with this cyclone.

At 48-h, the ensemble-mean upper-level PV trough has now cut off, indicative of a TPV that is now vertically stacked with the surface cyclone, centered at 72°N and 2°W (Fig. 4.4b). Further, the downstream trough has enhanced, moving over Svalbard (Fig. 4.4b). The sensitivity at 48-h is mainly associated with the position of the ridge downstream of the surface cyclone, as opposed to the trough upstream of the surface cyclone as shown at 12-h (Fig. 4.4b). A dipole of negative sensitivity over the trough off the west coast of Norway and positive sensitivity downstream of the trough, suggests that decreasing PV over the trough and increasing PV downstream of the trough by one SD of PV, associated with a northeast shift of the region between the TPV and ridge, is associated with a 60 km and 120 km along-track displacement of the surface cyclone at 96-h, respectively (Fig. 4.4b). Further, a dipole of negative sensitivity downstream of the ridge at 75°N and 60°E and positive sensitivity associated with a secondary PV ridge to the east at 75°N and 80°E suggests that decreasing PV to the west and increasing PV to the east by one SD of PV, associated with an eastward shift of the ridge over Svalbard, is associated with a more eastward surface cyclone at 96-h. Together, these results suggest that the position variability at 96-h is most dependent on the position of the ridge downstream of the surface cyclone, where an eastward shift of this ridge at 48-h is associated with a more eastward surface cyclone position later in the forecast. Three recently launched balloons from Svalbard are
able to sample the downstream sensitivity associated with the ridge east of Svalbard (Fig. 4.4b). However, the WindBorne balloons were not able to sample the sensitive regions upstream of the ridge. Therefore, WindBorne observations did not line up with the primary sensitive regions, indicating that assimilating these observations would likely not lead to an improvement in the position forecast.

Results show that the largest sensitivity to the position variability 96-h into the forecast is associated uncertainty to an upstream trough and downstream ridge early in the forecast. To understand how these sensitive regions may impact the upper-level flow associated with members that track further eastward versus members that remain more westward at 96-h, we can utilize statistical PV inversion to derive the upper-level winds linked to differences in upper-level PV. In particular, the uncertainty to the PV ridge downstream of the surface cyclone, similar to results sound in Chapter 3, will be the region of interest here (Fig. 4.5). The difference in 250-hPa PV between the 10 most eastward members and the 10 most westward members at 96-h is used to select the PV object to invert. For this case, the negative PV anomaly at 24-h, associated with the downstream ridge, consisting of a 0.2 PVU difference between eastward and westward members (Fig. 4.5). To be expected, there are anticyclonic winds around the upper-level PV anomaly centered at 74°N and 35°E, with perturbation winds around 5 m s⁻¹ (Fig. 4.5). The southerly winds associated with this anticyclonic circulation into the apex of the ridge are acting to enhance the PV ridge downstream of the surface cyclone (Fig. 4.5). An enhanced downstream ridge therefore accelerates the surface cyclone further north earlier in the forecast and is associated with a more eastward position later in the forecast. Further, cyclonic perturbation winds near the location of the surface cyclone (Fig. 4.5), are characterized by northerly winds into the apex of the upstream trough. Therefore, an enhanced upstream trough and downstream ridge
is acting to enhance the divergence downstream of the trough, near the location of the surface cyclone (Fig. 4.5).

4.3.3. Tropopause Polar Vortex Uncertainty

Sensitivity to the 96-h position variability revealed that the largest uncertainty is associated with the position of the upstream trough and downstream ridge. Here, the sensitivity to the TPV at 96-h that is vertically stacked with the surface cyclone is calculated to compare the sensitive regions between metrics. The goal is to determine if these metrics reveal similar regions of uncertainty, or if one metric reveals more organized sensitive regions than the other, ultimately to determine which metric is better for assessing upper-level uncertainty.

AC22 develops simultaneously with an emerging TPV off the coast of Greenland. The surface cyclone and upper-level TPV become vertically stacked within 48 hours of cyclogenesis. For the ECMWF forecast initialized 0000 UTC 15 August 2022, the ensemble-mean 500-hPa geopotential heights at 96-h demonstrates an upper-level low just north of Svalbard (Fig. 4.6). The variability associated with this TPV represented by 500-hPa geopotential heights is associated with lower heights to the east and higher heights to the west, exceeding 40 m each way (Fig. 4.6). Therefore, decreasing heights to the east and increasing heights to the west is associated with an eastward displacement of the upper-level TPV feature.

The sensitivity of 96-h 500-hPa geopotential heights, representing the TPV feature, to 250-hPa PV fields at 12- and 48-h is calculated to understand how the position of the TPV is sensitive to features along the tropopause earlier in the forecast (Fig. 4.7). These are the same times chosen as section 4.3.4 to assess the evolution of uncertainty to upper-level features that impact the position of the TPV north of Svalbard at 96-h. Therefore, the 12- and 48-h ensemble-mean 250-hPa PV field is same here as Fig. 4.4. The largest sensitivity at this time is associated
with the development TPV over Iceland (Fig. 4.7a). There is negative sensitivity associated with
the trough over Iceland, positive sensitivity just downstream of the trough, and negative
sensitivity associated with the downstream ridge positioned south of Svalbard (Fig. 4.7a).
Decreasing PV within the PV trough and increasing PV ahead of the trough by one SD of PV,
associated with less enhanced and eastward shift of the trough and cutting off the trough from the
PV background flow at 12-h, is associated with a more eastward positioned TPV at 96-h.
Decreasing PV in the downstream ridge, therefore enhancing the ridge over Svalbard, is also
associated with a more eastward TPV 84 hours later in the forecast. At 48-h, the TPV is now
enclosed with a maximum value of 10 PVU centered at 75°N and 18°W (Fig. 4.7b). The
upstream ridge over Greenland has tilted eastward and the downstream ridge has extended
northward over Svalbard (Fig. 4.7b). The largest sensitivity here is associated with the position
of the TPV and downstream PV ridge (Fig. 4.7b). Negative sensitivity over the southwest side
and positive sensitivity over the eastern side of the TPV, indicative of an eastward shift of the
TPV at 48-h, is associated with a more eastward TPV at 96-h. In addition, a dipole of sensitivity
associated with the downstream ridge (Fig. 4.7b), suggests that a shifting the downstream ridge
eastward at 48-h allows for a more eastward positioned TPV at 96-h. Therefore, the combination
of these results suggests that an eastward shift of the PV flow, including the PV trough upstream
of the surface cyclone, the TPV, and PV ridge downstream of the surface cyclone early in the
forecast is associated with a more eastward TPV at 96-h. These results are consistent with the
sensitivity of the position variability at 96-h, with more emphasis on the position of the TPV
early in the forecast. The sensitivity associated with the ridge over Svalbard is further
downstream here compared to the sensitivity of position variability at this time. Therefore,
WindBorne observations did not line up with either region of primary sensitivity, indicating that
assimilating these observations would not lead to an improvement in the 500-hPa geopotential forecast associated with this cyclone.

4.3.4 Cyclone Intensity Uncertainty

AC22 intensifies from 1007 hPa at 0000 UTC 15 August 2022 to 990 hPa at 1200 UTC 18 August 2022 (Fig. 4.8). ECMWF ensemble forecasts initialized 0000 UTC 15 August 2022, 24 hours prior to the reference time and approximately 72 hours prior to the maximum intensity, are characterized by increasing intensity variability throughout the forecast (Fig. 4.8). The ensemble-mean generally follows the minimum SLP of ERA5, while reaching a maximum intensity at 0000 UTC 18 August 2024, 12 hours before the ERA5 reanalysis. To examine the uncertainty of upper-level features and low-level thermodynamics associated with this intensity at the time of maximum intensification, the intensity variability at 72-h is used in subsequent sensitivity analysis.

To understand how the intensity forecast may be sensitive to lower tropospheric thermodynamic features, such as frontal boundaries, the sensitivity of 72-h minimum SLP forecast to the 850-hPa potential temperature and IVT fields are calculated at 12- and 48-h (Fig. 4.9). The 12-h ensemble-mean 850-hPa potential temperature exhibits a weak temperature gradient extending off the coast of Norway to the surface cyclone at 70°N and 8°W (Fig. 4.9a). At this time, there appears to be no statistically significant sensitivity associated with this region of increased temperatures near the surface cyclone (Fig. 4.9a). However, at 48-h, the temperature gradient tightens, as this region of warm temperatures extends north and eastward toward Svalbard (Fig. 4.9b). The largest sensitivity at 48-h is associated with the northern most region of the warm extension over Svalbard (Fig. 4.9b). Positive sensitivity over Svalbard suggests that increasing low-level temperature by one SD of temperature at 48-h, therefore enhancing the
temperature gradient upstream of the surface cyclone, is associated with a 0.2 hPa change in minimum SLP at 72-h. The ensemble-mean IVT at 12-h is characterized by an AR along the west coast of Norway, exceeding 450 km m$^{-1}$ s$^{-1}$ (Fig. 4.9c). However, similar to the sensitivity of 72-h minimum SLP to 850-hPa potential temperature at 12-h, the sensitivity to IVT is negligible (Fig. 4.9c). At 48-h, the AR has intensified over Norway of values over 500 km m$^{-1}$ s$^{-1}$ and values of over 150 km m$^{-1}$ s$^{-1}$ reaching northward over Svalbard (Fig. 4.9d). The largest sensitivity is associated with the northern extent of this corridor of moisture reaching Svalbard, where increasing IVT by one SD of IVT, therefore increasing the moisture downstream of the surface cyclone, is associated with a 0.2 hPa change in minimum SLP at 72-h. Therefore, these results suggest that the intensity forecast is not sensitive to low-level thermodynamics at 12-h, but that increasing low-level temperature and moisture downstream of the surface cyclone at 48-h is associated with a more intense cyclone later in the forecast.

The sensitivity of 72-h minimum SLP to the 250-hPa potential vorticity is calculated to the same forecast times above to examine uncertainty to upper-level features (Fig. 4.9e,f). At 12-h, the ensemble-mean is characterized by an upper-level PV ridge over Greenland, PV trough over Iceland, and a PV ridge just downstream of the surface cyclone (Fig. 4.9e). The statistically significant sensitivity of 72-h intensity variability is much less expansive compared to the position variability. However, the largest sensitivity at this time is to the ridge upstream of the surface cyclone (Fig. 4.9e). There is a region of positive sensitivity upstream of the trough over the east coast of Greenland and a region of positive sensitivity downstream of the ridge near the surface cyclone position (Fig. 4.9e). Increasing PV upstream of the ridge and decreasing PV downstream of the ridge by one SD of PV, leading to an eastward shift of the position of the ridge downstream of the surface cyclone at 12-h, is associated with a 0.2 hPa change in cyclone
minimum SLP at 72-h. At 48-h, the upstream trough is now cut off centered off the east coast of Greenland at 75°N and 15°W. Further, the downstream ridge has amplified northward and shifted eastward over Svalbard (Fig. 4.9f). The largest sensitivity at 48-h is associated with the amplification of the downstream ridge (Fig. 4.9f). Positive sensitivity in the apex of the downstream ridge suggests that decreasing PV by one SD over the ridge, enhancing the ridge northward, is associated with a 0.2 hPa change in cyclone minimum SLP at 72-h. Therefore, the position variability at 72-h is dependent on the position of the upstream trough at 12-h and the strength of the upstream ridge at 48-h. WindBorne observations were able to sample the downstream sensitivity of intensity variability forecast east of Svalbard at 48-h but they did not line up with upstream sensitive regions (Fig. 4.9). Therefore, assimilating these observations would likely not show improvement in the intensity or near-surface wind speed forecast to the north of the cyclone.

Overall, these results suggest that early in the forecast, the minimum SLP at 72-h is most sensitive to the shape of the upper-level features near the tropopause early in the forecast, and upper-to-lower tropospheric sensitivity later in the forecast. Therefore, it is worthwhile to explore how uncertainty from the upper troposphere reflects on surface features. Statistical PV inversion is used to derive the low-level winds associated with PV differences between the 10 most and least intense members at 72-h to determine how these sensitive regions may be dynamically related to one another (Fig. 4.10). The PV region chosen is a negative PV anomaly at 24-h, associated with the PV ridge downstream of the surface cyclone (Fig. 4.10). These anticyclonic perturbation winds consist of 8 m s⁻¹ southerly winds at the top of the warm air extension over northern Norway, acting to transport warmer temperature northward. Therefore, a more intense cyclone at 72-h is associated with an enhanced thermal ridge at 24-h in association
with the downstream development of the PV ridge. In addition, there are low-level, anticyclonic winds exceeding 5 m s$^{-1}$ centered at 74°N and 10°E associated with this upper-level negative PV anomaly (Fig. 4.10), suggesting that this PV anomaly near the tropopause has winds that are reflected at the surface. In addition, cyclonic perturbation winds around the surface cyclone located at approximately 70°N and 10°E, suggesting that the downstream (Fig. 4.10), upper-level negative PV anomaly is associated with a faster cyclonic wind around the surface cyclone, therefore leading to a more intense cyclone.

4.3.5 Cyclone Wind Speed Uncertainty

Sensitivity to cyclone minimum SLP at 72-h reveal no sensitive features to the low-level thermodynamics and minimal uncertainty to the upper-level PV field early in the forecast. Another way of assessing uncertainty to the intensity variability is to the wind speeds associated with the surface cyclone. Therefore, the PCs of ensemble maximum 10-m wind speed EOF at 72-h is used to assess the sensitive features of this AC and determine if more systematized sensitivity is found.

At 0000 UTC 18 August 2022, as AC22 tracks east of Svalbard, the ensemble-mean 10-m wind speed demonstrates strong cyclonic winds around the surface cyclone (not shown). The strongest wind speeds around the cyclone are associated with a low-level jet north of Svalbard, with southeasterly winds crossing the sea ice edge. The position of this low-level jet associated with AC22 has large implications for the sea ice edge at this time, as SIC is lowest during the boreal summer and easier to break up. For the ECMWF forecast initialized 0000 UTC 15 August 2022, 72 hours prior to this low-level jet moving over the sea ice edge, the ensemble maximum 10-m wind speeds illustrate a low-level jet north of Svalbard extending from the northeast coast of Greenland to the Russian Islands at 80°N and 55°E, consisting of wind speeds exceeding 30
knots (Fig. 4.11). The wind speed perturbation shows an increase of 3 knots to the north and a
decrease of 5 knots to the south of the ensemble maximum wind speed (Fig. 4.11). Therefore, the
largest variability associated with this low-level jet is to the north-south position, where the
following sensitivity pattern that explains the most variability is associated with a 3 knot stronger
low-level jet to the north at 72-h. Similar the sensitivity of intensity variability, WindBorne
observations were able to sample the downstream sensitivity of near-surface wind speed forecast
east of Svalbard at 48-h but they did not line up with upstream sensitive regions (Fig. 4.11).
Therefore, assimilating these observations would likely not show improvement in the intensity or
near-surface wind speed forecast to the north of the cyclone.

As mentioned previously, this surface cyclone is associated with an extension of warm,
moist air originating over northern Europe and stretching northward toward Svalbard. Therefore,
to understand how the maximum 10-m wind speed forecast at 72-h is sensitive to low-level
thermodynamics, the sensitivity of maximum 10-m wind speed forecast to IVT and 850-hPa
potential temperature at 12-h and 48-h is calculated (Fig. 4.12). At 12-h, the ensemble-mean IVT
is characterized by a south-north oriented AR along the west coast of Norway (Fig. 4.12a). The
sensitivity of the 10-m windspeed forecast at 72-h is relatively weak at 12-h, with the largest
sensitivity associated with the AR (Fig. 4.12a). Positive sensitivity over the northern region of
the AR suggests that increasing IVT by one SD of IVT, therefore enhancing the AR and further
extending the AR poleward, is associated with a more poleward low-level jet later in the forecast.
At 48-h, the AR has shifted eastward and is now maximized over northern Norway to 500 kg m\(^{-1}\)
s\(^{-1}\) (Fig. 4.12b). In addition, this region of IVT has extended northward toward Svalbard with a
tongue of IVT surrounding the surface cyclone (Fig. 4.12b). The largest sensitivity is to the
northern-most region of this IVT corridor (Fig. 4.12b), where increasing IVT by one SD of IVT,
resulting in more moisture transport poleward at 48-h, is associated with a more poleward low-level jet at 72-h. At 12-h, the ensemble-mean 850-hPa potential temperature is characterized by warm temperatures extending from Europe toward the surface cyclone position (Fig. 4.12c). At this time, there is minimal statistically significant sensitivity, aside from disorganized positive values associated with the extension of warm air just downstream of the surface cyclone (Fig. 4.12c), suggesting that increasing temperature is associated with a more poleward low-level jet later in the forecast. At 48-h, this extension of warm air has shifted eastward and extends toward Svalbard with tight gradients associated with a cold front over the coast of Norway and warm front over Svalbard (Fig. 4.12d). The largest sensitivity at 48-h is associated with the extension of warm air, where increasing potential temperature over Svalbard and decreasing potential temperature along the occluded and cold front, enhancing the surface cyclone’s frontal boundaries, is associated with a more poleward low-level jet at 72-h. Therefore, increasing IVT and warmer temperatures associated with this extension of warm, is associated with stronger wind speeds associated with the surface cyclone.

To understand how the wind speed forecast is sensitive to features near the tropopause, the sensitivity of maximum 10-m wind speed forecast to the 250-hPa PV field the same times as the minimum SLP is calculated for comparison (Fig. 4.12e,f). A 12-h, the ensemble-mean PV is characterized by an upper-level PV ridge over Greenland, trough over Iceland, and downstream ridge southwest of Svalbard (Fig. 4.12e). The sensitive regions of 10-m wind speed variability to the 12-h 250-hPa PV are largely associated with this PV trough, indicated by negative sensitivity to the west and positive sensitivity to the east of Iceland associated with the southern edge of the upper-level PV feature over Iceland (Fig. 4.12e). Therefore, decreasing PV on the western side and increasing PV on the eastern side of this PV feature by one SD of PV, resulting in an
eastward shift of the PV feature, is associated with a 3 knot increase of 10-m wind speed further northward at 72-h. More simply, an eastward shift of the upper-level PV feature over Iceland at 12-h is associated with a more poleward low-level jet north of Svalbard at 72-h. Further negative sensitivity associated with a downstream PV ridge over Svalbard suggests that decreasing PV by one SD over Svalbard, resulting in a more enhanced ridge downstream of the PV feature, is also associated with a more poleward low-level jet at 72-h. At 48-h, again the largest sensitivity is to the PV feature now centered at 66°N and 0° longitude (Fig. 4.12f). A dipole of sensitivity associated with this PV feature suggests decreasing PV over the southwest and increasing PV over the northeast regions, resulting in a northeast displacement of this PV feature toward Svalbard, is associated with a more poleward low-level jet at 72-h. Further, the PV ridge downstream of the cut-off PV feature has extended northward toward Svalbard and is associated with negative sensitivity (Fig. 4.12f). Therefore, decreasing PV by one SD of PV within the apex of this PV ridge, further enhancing the ridge northward, is associated with a more poleward low-level jet at 72-h. Additionally, a dipole of negative and positive sensitivity associated with a PV ridge over northern Greenland that suggests an increasing PV to the east and decreasing PV to the west by one SD of PV, associated with an eastward shift of this PV ridge closer to the cut-off PV, is associated with a more poleward low-level jet at 72-h. These results suggest the position of the low-level jet north of Svalbard associated with the surface cyclone at 72-h is largely impacted by the position of the cut-off PV feature that is vertically stacked with the surface cyclone, in addition to the position of the upstream ridge and amplitude of the downstream ridge.

4.4 Summary

This chapter examined the comparison of metrics used for sensitivity analysis during the development of an AC that was observed during the THINICE 2022 field campaign. In Chapter
only cyclone track and intensity metrics were used to perform ensemble-based sensitivity analysis for Arctic and Atlantic basin case studies. In this chapter, other metrics are explored to determine if cyclone track and intensity metrics are the optimum metrics to assess the sensitivity of ACs. Further, because this AC had implications for sea ice loss, assessing the sensitivity associated with low-level winds is worth-while.

The metric for cyclone position, the distance along the major axis direction, is compared to the 500-hPa geopotential height EOF analysis that encompassed an upper-level TPV that is vertically stacked with the surface cyclone. Both metrics revealed that the most sensitive regions are associated with the position of the upstream trough, TPV, and downstream ridge. However, the sensitivity of the 500-hPa geopotential height was more organized than the sensitivity of position variability at 96-h.

Further, sensitive regions of cyclone minimum SLP variability and maximum 10-m wind speeds EOF that encompassed a low-level jet associated with the northern circulation around the surface cyclone at 72-h were compared. Sensitivity of cyclone intensity suggested minimal variability early in the forecast but was most sensitive to increased low-level moisture and temperature and an upper-level ridge downstream of the surface cyclone. In comparison, the sensitivity to 10-m wind speed suggests that the largest uncertainty is associated with amount of low-level temperature and moisture downstream of the surface cyclone and to the position of the upstream trough and downstream ridge. In this case, sensitivity to low-level winds produced more organized sensitivity results.
Fig. 4.1: ERA5 reanalysis tracks of the four ACs observed during the THINICE 2022 field campaign. AC22 discussed in the text is denoted in black. The blue contour represents the sea ice extent valid 0000 UTC 15 August 2022 from the NSIDC. The shading represents the SIC difference between 0000 UTC 22 August 2022 and 0000 UTC 15 August 2022.
Fig. 4.2: ERA5 reanalysis MSLP (black contours; hPa; contoured every 4 hPa), 300-hPa potential vorticity (thick white contour; 2 PVU), 500-hPa geopotential height (thin brown contours; m; contoured every 50 m), and 850-hPa temperature (shading; Kelvin) for (a) 0000 UTC 15 August 2020, (b) 0000 UTC 16 August 2020, (c) 0000 UTC 17 August 2020, and (d) 0000 UTC 18 August 2020. The grey contour is sea ice extent from the NSIDC for each valid time. The black star represents the surface cyclone position from ERA5 reanalysis.
Fig. 4.3: ECMWF ensemble forecasts of AC22 initialized 0000 UTC 15 August 2022 (gray). The ensemble-mean position is given in blue, while the ERA5 reanalysis track for AC22 shown in black. 60- and 96-h position ellipses and major axis error vector denoted in cyan and magenta, respectively.
Fig. 4.4: Sensitivity of 96-h ECMWF ensemble position forecast to the (a) 12-h and (b) 48-h 250-hPa potential vorticity (shading; SD; km) initialized 0000 UTC 15 August 2022. Green contours are the ensemble-mean PV (PVU). The purple “X” represents the surface cyclone position from the ERA5 reanalysis. The lime green dots denote locations of WindBorne observations for each valid time, with the next 6 hours of data (if available).
Fig. 4.5: Region of PV difference exceeding −0.12 PVU in the 24-h 250-hPa PV between the eastward and westward members at 96-h for the forecast initialized at 0000 UTC 15 August 2022 (shading; PVU). The vectors denote the 500-hPa winds (m s⁻¹) obtained by inverting the 250-hPa PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 250-hPa PV at the corresponding time. The yellow star denotes the reanalysis surface cyclone position at this time.
Fig. 4.6: ECMWF 96-h ensemble forecasts of 500-hPa geopotential height EOF initialized 0000 UTC 15 August 2022 (shading; m) centered around a TPV. The black contours are ensemble-mean 500-hPa geopotential height.
Fig. 4.7: Sensitivity of 96-h ECMWF ensemble 500-hPa geopotential height forecast to the (a) 12-h and (b) 48-h 250-hPa potential vorticity (shading; SD; dimensionless) initialized 0000 UTC 15 August 2022. Green contours are the ensemble-mean PV (PVU). The purple “X” represents the surface cyclone position from the ERA5 reanalysis. The lime green dots denote locations of WindBorne observations for each valid time, with the next 6 hours of data (if available).
Fig. 4.8: ECMWF ensemble forecasts of cyclone minimum SLP initialized 0000 UTC 15 August 2022. The ensemble-mean minimum SLP is shown in blue, +/- one SD of the ensemble-mean is in green, and the full range of ECMWF ensemble members is given in gray. ERA5 reanalysis minimum SLP for AC22 shown in black.
Fig. 4.9: Sensitivity of 72-h ECMWF ensemble intensity forecast to the 12-h (a) integrated vapor transport, (c) 850-hPa potential temperature, and (e) 250-hPa PV (shading; SD; hPa) initialized 0000 UTC 15 August 2022. Green contours are the ensemble-mean for each respective field with units (a) kg m$^{-1}$ s$^{-1}$, (c) K, and (e) PVU. The black star represents the surface cyclone position from ERA5 reanalysis. (b), (d), and (f) same as (a), (c), and (e), except to the 48-h integrated vapor transport, 850-hPa potential temperature, and 250-hPa PV respectively.
Fig. 4.10: Region of PV difference exceeding −0.12 PVU in the 24-h 250-hPa PV between the most and least intense members valid at 72-h for the forecast initialized at 0000 UTC 15 August 2022 (white contour; PVU). The vectors denote the 850-hPa winds (m s⁻¹) obtained by inverting the 250-hPa PV field within the contour using the statistical PV inversion method outlined in the text. The thin black contours are ensemble-mean 850-hPa geopotential height and shading represents the 850-hPa temperature field. The white star denotes the reanalysis surface cyclone position at this time.
Fig. 4.11: ECMWF 72-h ensemble forecasts of maximum 10-m wind speed EOF initialized 0000 UTC 15 August 2022 (shading; knots) centered around a low-level jet. The solid black contours are positive 10-m wind speed perturbation, and the dotted black contours are negative 10-m wind speed perturbations.
Fig. 4.12: Sensitivity of 72-h ECMWF ensemble 10-m wind speed EOF to the 12-h (a) integrated vapor transport, (c) 850-hPa potential temperature, and (e) 250-hPa PV (shading; SD; dimensionless) initialized 0000 UTC 15 August 2022. Green contours are the ensemble-mean for each respective field with units (a) kg m$^{-1}$ s$^{-1}$, (c) K, and (e) PVU. The black star represents the surface cyclone position from ERA5 reanalysis. (b), (d), and (f) same as (a), (c), and (e), except to the 48-h integrated vapor transport, 850-hPa potential temperature, and 250-hPa PV respectively.
5. Summary and Conclusions

ACs are ubiquitous events that can transport warm, moist air from lower latitudes toward the pole, with potentially large implications on Arctic sea ice, particularly during the boreal summer. Therefore, better prediction of sea ice may rely on having accurate predictions of the location and intensity of ACs. The first goal of this dissertation is to better understand the track and intensity predictability of ACs in relation to midlatitude, Atlantic basin cyclones. Further, the upper-level tropopause-based features and low-level thermodynamics that limit the predictability of Arctic and Atlantic basin cyclones are assessed and compared.

The first part of this dissertation created a climatology of long-duration, intense cyclones for Arctic and Atlantic basin cyclones. Then, to further analyze the limitations of AC track and intensity predictability compared to Atlantic basin cyclones, ensemble-based sensitivity is utilized. Past literature has suggested that ACs are less predictable in comparison to other regions with larger networks of observations, but a comparison study has not been conducted yet.

Chapter 2 examines the hypothesis that the practical predictability of cyclone track and intensity forecasts for long-duration, intense summer ACs is indistinguishable from comparable cyclones in the Atlantic primary storm track. This hypothesis is tested using forecasts of 100 Arctic and 89 Atlantic cyclones are selected from the Sprenger et al. (2017) cyclone climatology during 1985–2016. The predictability of cyclone track and intensity in each basin is approximated using the ensemble-mean error and ensemble SD computed from the GEFS Reforecast dataset. For the purpose of this thesis, only forecasts initialized 1 and 3 days prior to the reference time $t_0$ are shown, although all forecasts out to 5 days prior have been evaluated and demonstrate similar results.
On average, Atlantic basin cyclone position is found to be more predictable than ACs, as indicated by the larger AC position error and SD for all initialization times, despite the fact that Atlantic basin cyclones move about two times as fast as ACs. One possible explanation is that the position of Atlantic basin cyclones may be easier to predict due to the consistent presence of a jet stream over the Atlantic Ocean, opposed to the more variable Arctic frontal zone that develops along the temperature gradient between the land and ocean during the summer (Crawford and Serreze 2016). As a consequence, ACs tend to have a more erratic track, which also might limit cyclone position predictability in this region (not shown). Simmonds and Rudeva (2014) examined five of the most intense ACs for each calendar month over a 30-yr time period, suggesting that long-duration ACs may result in the merging of cyclones, resulting in one long track. Upon closer examination, this was found to be true for multiple ACs included in this study, which also might make it difficult to obtain accurate forecast for AC tracks. Another possibility is that Atlantic cyclones are better observed, which in turn would yield lower errors.

In contrast to cyclone position, AC minimum SLP is found to be more predictable than Atlantic basin cyclones. The intensity of Atlantic basin cyclones may be more difficult to predict because cyclones in this basin are on average stronger, which in turn yields a larger range of minimum pressure center values relative to summer ACs. On average, summer ACs intensify to 985 hPa, whereas the mean intensity of winter Atlantic basin cyclones are below 970 hPa. To determine if there is a relationship that exists between intensity variability and intensification of cyclones, the correlation between the change in cyclone MSLP over the 48-h after $t_0$ and the 48-h cyclone MSLP SD was calculated for each cyclone independently for each basin. For the −1-day forecasts, a correlation coefficient of −0.28 was found for the Arctic and −0.34 for the Atlantic, meaning that cyclones that have a greater decrease in pressure tended to be associated with
higher intensity forecast SD, but this is not the only predictor. Nevertheless, there are likely other factors that could lead to the difference in Atlantic and Arctic cyclone predictability including differences in the observation network and the nature of the large-scale environment and cyclones in the basin, as discussed in the results section. Furthermore, the environmental pressure in the extratropics is higher than over the Arctic region, which in turn yields an even larger pressure depression within the midlatitudes. Moreover, greater availability of water vapor in the midlatitudes, relative to the Arctic region, can lead to deeper convection which may also impact the predictability of these storms. In addition, Atlantic cyclones examined in this study are found in regions of higher baroclinicity relative to that observed for ACs, also limiting their predictability (e.g., Torn 2017; Zhang et al. 2019).

The most- and least-variable storms based on SD are examined to understand the role of the large-scale environment on predictability in both basins. Here, the most- and least-predictable storms for position and intensity are identified via the standardized SD over the 48-h period, independently. On average, the least predictable storms for position and intensity are characterized by statistically lower minimum SLP and faster cyclone speed relative to the more predictable quartile. Past literature has suggested that cyclone predictability is limited in regions of high baroclinicity and LHR in both the Arctic (e.g., Tao et al. 2017) and midlatitude regions (e.g., Torn 2017). Therefore, area-averaged EGR and column-integrated moisture flux convergence is examined for the 75th- and 25th-percentile cases to determine whether less-predictable storms are characterized by higher baroclinicity and/or potential for LHR. For most lead times, the less-predictable storms are characterized by higher EGR relative to the more-predictable cases. By contrast, the LHR of each quartile is similar, except for −3-day forecasts in the Arctic basin, but they are not statistically significant. In the Arctic, there is strong
baroclinicity between the sea ice edge and continents, which can play an important role in the cyclogenesis of ACs, similar to midlatitude cyclones (e.g., Inoue and Hori 2011). By contrast, stratifying the cyclone cases based on the position forecast SD, indicates that the least predictable position cases are characterized by similar intensity and motion speed; therefore, the bulk cyclone properties do not appear to be tied to the position predictability.

In Chapter 2, the practical predictability of ACs is compared to Atlantic basin cyclones from a climatological perspective but did not analyze what features and dynamics may limit the predictability of these storms. Therefore, H2 and H3 are tested to examine what upper-level features and low-level thermodynamics limit the predictability of individual ACs, while using Atlantic basin cyclones as a benchmark for comparison. Ensemble-based sensitivity analysis was applied to MPAS forecasts of two case studies in each basin, comparable to the cyclones analyzed in Chapter 3. In all cases, downstream propagation of uncertainty throughout the forecast appears to play a large role in the position variability of these storms. However, downstream ridge building appears to play a larger role in the position variability of the ACs at shorter lead times, whereas the downstream ridge plays a larger pole in the position variability of the Atlantic basin cyclone at longer lead times. This phenomenon has been well documented in past sensitivity studies, particularly in the midlatitudes (e.g., Chen et al. 2017; Torn 2017; Berman and Torn 2022). Further, uncertainty to upstream features is more significant to longer lead time variability for the AC and shorter lead times for the Atlantic basin cyclone. These results are consistent with Baumgart et al. (2018) who quantified upscale error growth near the tropopause through a PV perspective for a 6-d forecast case study, finding that localized mesoscale errors maximized within 2 days, whereas contributions of upper-level PV anomalies dominate error growth near the tropopause from 2–6 days.
For all storms, the intensity variability is sensitive to both upstream and downstream upper-level PV flow and low-level temperature and moisture boundaries. For AC13, the largest intensity forecast sensitivities are to the thermal and moisture boundaries along the coast of Russia and to the position of an upstream upper-level PV trough embedded within the PV vortex over the North Pole. Further, the largest intensity forecast sensitivity for AC20 is to the interaction of a large-scale PV feature over the North Pole and an additional region of higher PV extending off the east coast of Greenland. Further, although AC20 is not positioned near the coast, the intensity of this storm is still dependent on the poleward extension of an AR and low-level temperature gradient. In comparison, the largest forecast sensitivities for the 2014 Atlantic basin cyclone intensity variability are to the position of an upstream short-wave trough over the Great Lakes region and subsequent low-level temperature and moisture associated with the polar front. Similar results were found for the 2014 Atlantic basin cyclone, but with more emphasis on the strength of an AR over the Atlantic Ocean early in the forecast. Therefore, in all cases, uncertainty to the position of an upstream short-wave trough plays a large role in the intensity variability early in the forecast, suggesting that errors in the upper troposphere appear to be the initiation of errors in cyclone intensity.

For conciseness, only one forecast time is shown for each of these case studies, approximately 24-h prior to the reference time defined in Chapter 2; however, other forecast times have been examined for each case and are consistent with the results shown in Chapter 3. Overall, H2 and H3 are partially valid as uncertainty associated with upstream features appear to play a role in both track and intensity predictability for Arctic and Atlantic basin cyclones, particularly at early forecast times. However, uncertainty to upstream features also appear to limit track and intensity predictability of both Arctic and Atlantic basin storms as well. Overall,
the results found in Chapter 3 are consistent with the sensitive features to both AC track and intensity found in Johnson and Wang (2021). These results further highlight the sensitive features of the Arctic region with many similarities found to sensitive features of midlatitude cyclones.

An additional AC case study was performed in Chapter 4 for an AC that was observed during the THINICE 2022 field campaign. The goal of this case study was to compare the cyclone-related metrics used as input into ensemble-based sensitivity analysis to determine which metrics may provide more systematic results and have more implications for sea ice predictability. In contrast to Chapter 3 that utilized MPAS ensemble forecasts, an ECMWF ensemble forecast was utilized here to mimic sensitivity analysis performed in real-time during the field campaign. The cyclone chosen to further examine from the field campaign, was the only one that tracked over the Arctic sea ice and was also vertically stacked with a TPV throughout its lifespan. Therefore, the sensitivity of 500-hPa geopotential height over a domain encompassing the vertically stacked TPV is compared to sensitivity associated with cyclone position variability. In addition, sensitivity associated with maximum 10-m wind speeds encompassing a low-level jet associated with the northern cyclonic winds around the surface cyclone is compared to sensitivity to cyclone minimum SLP.

The largest position variability throughout the developing stage of this surface cyclone is associated with along-track errors. The largest sensitivity associated with along-track position variability is to a PV trough upstream of the surface cyclone and a PV ridge downstream of the surface cyclone at 12-h. An eastward shift of the upstream ridge, therefore closer to the surface cyclone, and an amplified ridge downstream of the surface cyclone, is associated with a more eastward track later in the forecast. At 48-h, the largest sensitivity is to the position of the now
cut-off TPV feature stacked with the surface cyclone and the downstream developing ridge. A northward shift of the TPV and amplified downstream ridge is associated with a more eastward cyclone position later in the forecast. The impacts of an upper-level negative PV anomaly associated with the developing downstream ridge is assessed through statistical PV inversion that showed enhanced upper-level anticyclonic winds on the eastern side of the ridge are associated with southerly perturbation winds acting to enhancing the amplitude of the downstream ridge and enhance the region of upper-level divergence aloft of the surface cyclone. Further, using 500-hPa geopotential height around a domain that encompasses this TPV later in the forecast showed almost identical regions of sensitivity, suggesting further that the position of the surface cyclone is directly related to the position of the upper-level TPV feature.

AC22 reached a maximum intensity at 1200 UTC 18 August, just before crossing over the Greenland sea ice edge. The sensitivity to cyclone minimum SLP variability of this storm is assessed at 72-h, around the time of maximum strength. The largest sensitivity to cyclone minimum SLP is associated with increased low-level temperature and moisture over Svalbard, where increasing temperature and moisture is associated with a more intense cyclone later in the forecast. Further, an enhanced downstream ridge is associated with a more intense cyclone. Again, the influences of an upper-level negative PV anomaly associated with the development of the ridge is assessed through PV inversion. The largest perturbation winds associated with the negative PV anomaly are cyclonic winds near the surface cyclone, suggesting that the development of the downstream ridge is acting to intensify the surface cyclone upstream. In addition, the southerly perturbation winds around the surface cyclone are aiding in transporting warm, moist air further northward. In comparison, sensitivity to the maximum 10-m wind speed encompassing a low-level jet north of Svalbard suggests that a more northward extension of
warm, moist air is associated with a more northward low-level jet later in the forecast. These sensitivities are traced backward as far as 12-h, where increasing temperature and moisture associated with an AR off the west coast of Svalbard is associated with a northward shift in the low-level jet associated with the surface cyclone later in the forecast. Additionally, sensitivity to upper-level PV suggests that a northward shift of the upstream ridge over Greenland, a northward shift of the TPV and an enhanced downstream ridge are associated with a more northward low-level jet later in the forecast. Therefore, the sensitive features associated with cyclone minimum SLP and maximum 10-m wind speed do not align as well for the upper-level sensitive regions in this case.

Comparing ensemble sensitivity metrics of AC22 reveals that using cyclone position variability and PC of the 500-hPa geopotential height provide similar results to the upper-level uncertainty. However, it appears that for this case, using maximum 10-m wind speeds as a proxy for the intensity of this AC provide for comprehensive results than using cyclone minimum SLP. While many of the results from Chapter 3 corroborate findings in Johnson and Wang (2021), Chapter 4 provides unique results that may suggest using PC of EOFs reveal more systematic sensitivity results for ACs. Therefore, future studies interested in Arctic sea ice predictability would benefit from using metrics such as variability within low-level wind speed.

The importance of understanding the connections between ACs to upper-level features and low-level thermodynamics shown in this dissertation is consistent with past studies that have suggested these are the source of large errors in AC predictability (e.g., Yamagami et al. 2017, 2018a,b, 2019; Tanaka et al. 2012; Johnson and Wang 2021; Gray et al. 2021). A major limitation of this work is that only a few ACs were examined. Therefore, one avenue of future work could include a climatological assessment of sensitivity analysis, as described in Ancell
and Coleman (2022). Another potential limitation with this work is that ensemble sensitivity analysis assumes that the model portrays an accurate representation of reality; however, intrinsic biases of a model may affect the conclusions drawn from sensitivity analysis. Therefore, another possibility for future work could include IC perturbation experiments, where diagnostics calculated from sensitivity analysis are used to perturb the IC and verify the conclusions found for AC track and intensity errors. Overall, the best way increase AC predictability is by adding more observations within the most sensitive regions of ACs outlined in this dissertation, such as errors within upstream and downstream upper-level flow, TPVs, corridors of warm, moist air, and along thermal boundaries created over land, ocean and sea ice differences. Although the Windborne balloons were not able to sample all sensitive regions associated with AC22, future field campaigns would benefit from using similar balloons at a much higher spatial and temporal frequency. As an alternative, targeted dropsondes could also be used if aircraft is equipped. Exploration of Arctic predictability is still relatively recent, therefore future field campaigns focused more accurate predictions in the Arctic region should focus on the sensitive regions outlined in this dissertation.
APPENDIX A

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