Radiative impact on tropopause polar vortices over the Arctic

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Tropopause polar vortices (TPVs) are a commonly observed, coherent circulation feature of the Arctic with a typical radii as large as approximately 800 km. Intensification of cyclonic TPVs has been shown to be dominated by infrared radiation. Here we test the hypothesis that while radiation alone may not be essential for TPV genesis, radiation has a substantial impact on the long-term population characteristics of cyclonic TPVs.

A numerical model is used to derive two ten-year climatologies of TPVs for both winter and summer: a control climatology with radiative forcing and an experimental climatology with radiative forcing withheld. Results from the control climatology are first compared to those from the NCEP–NCAR Reanalysis Project (NNRP), which indicates a sensitivity to both horizontal grid resolution and the use of polar filtering in the NNRP. Smaller horizontal grid resolution of 60-km in the current study yields sample-mean cyclonic TPV radii that are smaller by a factor of $\sim 2$ compared to NNRP, and vortex track densities in the vicinity of the North Pole are considerably higher compared to NNRP. The experimental climatologies show that winter (summer) vortex maximum amplitude is reduced by 22.3% (38.0%), with a net tendency to weaken without radiation. Moreover, while the number and lifetime of cyclonic TPVs change little in winter without radiation, number decreases 12% and mean lifetime decreases 19% during summer without radiation. These results suggest that dynamical processes are primarily responsible for the genesis of the vortices, and that radiation controls their maximum intensity and duration during summer, when the destructive effect of ambient shear is weaker.

1. Introduction

Radiation has been shown to play an important role in the intensification and maintenance of cyclonic tropopause polar vortices (TPVs) (Cavallo and Hakim 2010; hereafter CH10). Cyclonic TPVs are frequently observed, high latitude, cold-core vortices based on the
tropopause, and play an important role in the formation of surface cyclones. The Arctic is
particularly favorable for the maintenance and intensification of cyclonic TPVs (Cavallo and
Hakim 2009; CH10), and cyclones occasionally exist on timescales of months (Hakim and
Canavan 2005). While radiative cooling directly promotes intensification, latent heating
in clouds has a weakening effect; however, clouds can also indirectly promote radiative
intensification through cloud-top cooling (Cavallo and Hakim 2009). Here, we extend the
results of CH10 by examining the impact that radiation has on a simulated climatology of
cyclonic TPVs, for both winter and summer seasons.

An understanding of TPVs is motivated in part by the fact that surface cyclones develop
in association with the dynamics initiated by TPVs (e.g. Hakim et al. 1995; Bosart et al.
1996; Hakim et al. 1996). Furthermore, TPVs are better expressed as vortical rather than
wave-like features (e.g., Hakim 2000), and due to the conservation properties of potential
vorticity (PV) and potential temperature, are well-identified in these fields and can be tracked
for long periods of time on a single PV surface (e.g., Morgan and Nielsen-Gammon 1998).
Additional studies have identified cyclonic TPVs as having the following characteristics: a
downward intrusion of stratospheric air to $\sim 500$ hPa (e.g. Uccellini et al. 1985; Davis
and Emanuel 1991; Hakim 2000; Cavallo and Hakim 2009; CH10), radii up to $\sim 1200$ km,
amplitudes of up to 50 K (e.g. Hakim 2000; Hakim and Canavan 2005; CH10), and nearly
saturated atmospheric conditions near the vortex core (Cavallo and Hakim 2009; CH10).
Furthermore, the Canadian Archipelago region has been identified as a preferred location
for intensification of cyclonic TPVs (Cavallo and Hakim 2009).

The Arctic is a suitable environment for TPVs, partially since they are isolated from
the horizontal wind shear associated with the midlatitude jet stream, allowing them to
remain in the Arctic for long periods of time. Isolation from the jet stream shields this
region from the wave dynamics occurring in the vicinity of the jet stream, and in particular
decreases the probability of adverse effects from horizontal shear. Thus, due to isolation of
the air in these features over these longer timescales, diabatic processes are able to play an
important role in intensity change. As a result of cold temperatures in the Arctic, latent
heating rates are considerably lower than in midlatitude or tropical regions, and are lower
than radiative cooling rates on average (e.g. Peixoto and Oort 1992, ch. 13), providing the
potential for radiative processes to dominate PV budgets and control TPV intensification at
higher latitudes.

A compositing study of cyclonic TPVs was performed by CH10 using a mesoscale nu-
merical model in a region of frequent vortex intensification. They show that cyclonic TPV
intensification is primarily radiatively driven, and while the effects of latent heating are
considerable, they are smaller in magnitude. Intensification was shown to result from
anomalously large (small) radiative cooling centered below (above) the vortex tropopause,
a pattern that is qualitatively similar to the corresponding relative humidity anomalies.
Seasonal composites revealed that, despite the large annual variations of solar radiation,
radiation intensifies vortices on average during both summer and winter. Motivated by
these results, this study aims to isolate the impact that radiation has on cyclonic TPV
population characteristics during both winter and summer. Numerically simulated TPV
climatologies are generated with and without radiation under the hypothesis that without
radiative feedback, cyclonic TPVs are weaker and have shorter lifetimes. Furthermore, we
expect that cyclonic TPVs will be generated in the absence of radiation, implying that while
radiative processes may be important for their maintenance, other, dynamical, mechanisms
may be more important for their genesis; however, the relative importance of radiation to
genesis is unclear at the outset.

The remainder of the paper is organized as follows. A review of the methods used
in Cavallo and Hakim (2009) and CH10 to quantify vortex intensity change are given in
Section 2. A detailed description of the numerical experiments and procedures are also be
provided in Section 2. Results for the numerically simulated climatologies with and without
radiation are presented in Section 3, including an examination of the diabatic PV tendencies
in relation to changes in the net atmospheric circulation. Conclusions and a summary are
given in Section 4.

2. Methods

a. Vortex intensity

Ertel potential vorticity (EPV), used here to define vortex intensity, is given by

\[ \Pi = \frac{1}{\rho} \vec{\omega}_a \cdot \nabla \theta, \]

(1)

where \( \rho \) is the density, \( \omega_a = \vec{\omega} + 2\vec{\Omega} = \nabla \times \vec{U} + 2\vec{\Omega} \) is the absolute vorticity, \( \vec{U} = (u, v, w) \) is the three-dimensional velocity vector, and \( \vec{\Omega} \) is the Earth’s rotational vector. Potential temperature is defined by

\[ \theta = T \left( \frac{p_o}{p} \right)^{R/c_p}, \]

where \( T \) is temperature, \( p \) is pressure, \( p_o = 10^5 \) Pa is a standard constant, \( R = 287 \) J K\(^{-1}\) kg\(^{-1}\) is the dry air gas constant, and \( c_p = 1004 \) J K\(^{-1}\) kg\(^{-1}\) is the specific heat capacity of dry air at constant pressure. Vortex intensity change can then be reasonably well quantified using the EPV tendency equation (e.g. Pedlosky 1998)

\[ \frac{D\Pi}{Dt} \approx \frac{\vec{\omega}_a}{\rho} \cdot \nabla \frac{D\theta}{Dt} \]

(2)

when considering diabatic effects alone (Cavallo and Hakim 2009). In (2), the time rate of change following the fluid is given by

\[ \frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}, \]

while the gradient operator is defined by

\[ \nabla = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right). \]
In a numerical modeling study, CH10 separated (2) into components isolating the radiative \( \dot{\theta}_{\text{radiation}} \), latent heating \( \dot{\theta}_{\text{latent heating}} \), and all other\(^1\) \( \dot{\theta}_{\text{other}} \) diabatic processes, such that (2) becomes

\[
\frac{D\Pi}{Dt} \simeq \frac{\vec{\omega}}{\rho} \cdot \nabla \left( \dot{\theta}_{\text{radiation}} + \dot{\theta}_{\text{latent heating}} + \dot{\theta}_{\text{other}} \right). \tag{3}
\]

Diagnosing (3) from numerical model data, CH10 showed that cyclonic TPV intensity change in the Canadian Arctic was largely due to radiative forcing, which result in a positive EPV tendency within the vortex, on average. Latent heating results in a negative EPV tendency, but with smaller magnitude in comparison to radiation and the net effect is for cyclonic TPVs to intensify. Additionally, no other diabatic forcings resulted in comparable EPV tendencies near the tropopause in the vortex core. Here we apply this technique by comparing numerically simulated climatologies of the Arctic with and without radiative forcing in order to isolate the impact that radiation has on the population characteristics of cyclonic TPVs. Since radiation is likely the leading mechanism for the intensification of cyclonic TPVs on average, then eliminating this effect is expected to significantly alter the characteristics of cyclonic TPVs.

\( b. \) Experimental setup

Sensitivity testing of the TPV climatology to radiation is performed here using the Advanced Research Weather (ARW) version of the Weather Research and Forecasting (WRF) model version 2.2.1 (Skamarock et al. 2005) and the WRF Pre-Processing System (WPS) Version 2.2. WRF is a mesoscale model, capable of resolving a wide range of horizontal scales associated with cyclonic TPVs, which have an average radius of about 360 km in the Canadian Arctic (CH10). Alternatively, a climate model could be used for the present analysis. However, many use a spectral grid, for which there is a singularity at the pole requiring the use of a polar filter. Furthermore, the horizontal resolution of climate models

\(^1\)Includes diabatic processes resulting from the convective and planetary boundary layer physics schemes, as well as all other explicit mixing.
Forecasts are initialized using National Centers for Environmental Prediction-National Center for Atmospheric Research Reanalysis Project (NNRP) data (Kalnay and collaborators 1996), with boundary conditions derived from six-hourly NCEP–NCAR reanalysis grids. Boundaries are updated using NNRP every six hours. These forecasts will hereby be referred to simply as WRF. Two sets of numerically simulated forecasts are performed to create a control 1990s climatology ensemble, one representing a winter simulated climatology (December, January, and February; DJF) and one representing a summer simulated climatology (June, July, and August; JJA). A vortex census for these simulations will be compared to NNRP, and winter and summer climatologies will be referred to as NNRP DJF and NNRP JJA respectively. Repeating this method in the absence of radiative forcing ($\dot{\theta}_{\text{radiation}} = 0$) gives what will be referred to as “no radiation” experiments. For each experiment, there are a total of 10 model simulations: one for each year during 1990-1999. Note that the DJF simulations begin on 1 December of the previous year; for example, the 1990 DJF simulation begins 1 December 1989. The JJA simulations begin 1 June of the respective year. Each simulation is performed for exactly 90 days.

The model configuration of CH10 is employed here, except with a horizontal grid spacing of $\Delta x = \Delta y = 60$ km, $130 \times 130$ horizontal grid points, and a model time step of $\Delta t = 300$ seconds. Simulations are performed using a polar stereographic map projection, with a center latitude and longitude of $90^\circ$N and $100^\circ$W. Note that the NNRP data are derived from a spectral model with T62 horizontal resolution, equivalent to a horizontal grid spacing of approximately 210 km, with an output resolution of 2.5°. Although this may lead to a biased comparison with WRF, it serves as a useful benchmark for comparison with previous TPV studies that use NNRP data.
c. Vortex identification

The tropopause is defined by the 2 PVU surface (1 PVU is \(1 \times 10^{-6} \text{K kg}^{-1} \text{s}^{-1} \text{m}^2\)), and cyclonic TPVs are identified and tracked using an objective tracking algorithm described in Hakim and Canavan (2005). Cyclonic vortex amplitude is the absolute difference between the last closed contour\(^2\) and the local minimum in potential temperature (hereafter the core value). Vortices are filtered as in Hakim and Canavan 2005 and Cavallo and Hakim 2009, to include only those that spend at least 60% of their lifetimes north of 65°N latitude. Higher horizontal grid resolution can result in a very fine vortex structure leading to the premature identification of the last closed contour. The algorithm is adjusted to account for this possibility by taking the median radial value as the last closed contour.

Definitions of the statistics used in the subsequent analysis follow. Vortex genesis is defined to occur by the identification of a local minimum in tropopause potential temperature that is colder than all other locations within a 650 km radius, which is roughly the vortex length scale; results are not sensitive to this choice of radius. Vortex lysis is defined to occur when a local minimum in tropopause potential temperature can no longer be identified with an existing vortex track.

3. Results

a. Mesoscale climatology simulated with full physics

We now compare the control WRF mesoscale vortex simulated climatology to the NNRP climatology. Table 1 shows the sample sizes used in the subsequent analysis. Note that since the WRF simulations are not run outside of DJF and JJA of their respective years, the full life cycles of all vortices are not identified. For example, it is possible to identify a genesis

\(^2\)To define the last closed contour, eight equally spaced radials are defined from the location of minimum tropopause potential temperature. The last closed contour is the minimum potential temperature value along the eight radials at the location of the sign reversal.
point but not a corresponding lysis point, and vice-versa for each unique vortex track. In general, the number of vortex points categorized in the following mesoscale vortex census is much greater than from NNRP, likely due to higher horizontal grid resolution. Furthermore, while WRF uses a regularly spaced numerical grid across the pole, the latitude-longitude grid and polar filter used by the NNRP likely has an impact on vortices near the pole. As the pole is geographically central to the location of TPVs, such polar filtering of data could have a considerable impact on their statistics in this vicinity.

A comparison between the NNRP and WRF seasonal composite cyclonic vortex amplitudes over a five-day period starting with the vortex origin is shown in Figs. 1a,b. Cyclones in WRF with lifetimes of at least five days tend to begin with larger amplitudes, and cyclone growth occurs for longer periods of time. Amplitude differences between WRF and NNRP are greater during the summer than during winter. Cyclone amplitudes are lower during the summer, as shown both by NNRP and WRF, and consistent with the findings of Hakim and Canavan (2005).

Probability density functions (PDFs) of the maximum cyclone amplitude of unique cyclones (represented as a percentage) are shown in Figures 2a,b. WRF maximum cyclone amplitudes are generally larger than in NNRP. Note that here, the vortex population is represented by all vortices with lifetimes of at least two days, whereas the sample represented in Figure 1 only includes those with lifetimes of at least five days. Maximum cyclone amplitudes average\textsuperscript{3} 23.8 K (18.4 K) in WRF (NNRP) during winter (Fig. 2a) and 20.0 K (13.2 K) in WRF (NNRP) during summer (Fig. 2b). Both NNRP and WRF show a secondary maximum amplitude peak of \( \sim30 \) K and \( \sim35 \) K, respectively, during winter. No secondary maximum amplitude peak is evident in either data during the summer. Given that the same algorithm was used in computing these statistics for both WRF and NNRP, differences appear to be consistent with expectations of smaller grid spacing for the WRF simulation. Cyclone radii for WRF have a mean value of 349 km (375 km) during winter (summer).

\textsuperscript{3}All differences in average amplitude and radius values are statistically significant at the 95\% significance level from a two sample difference of mean standard Gaussian \( z \) test.
compared to 734 km (768 km) during winter (summer) in NNRP (Figs. 2c,d). Again, differences in mean cyclone radius are attributed to finer horizontal scales resolved by the WRF simulation.

The lifetime of cyclones can be reasonably approximated by exponentially decaying distributions for both WRF and NNRP (Fig. 3). While the cyclone lifetime pattern in WRF is similar to NNRP during winter (Fig. 3a), WRF produces a greater number of cyclones with longer lifetimes than NNRP during summer (Fig. 3b). The maximum lifetime during the winter is 21.0 days (17.0 days) in WRF (NNRP), with an average lifetime of 5.7 days (3.5 days). During summer, the maximum lifetime increases to 39.3 days in WRF and the average lifetime increases to 8.3 days, while NNRP lifetimes remain largely unchanged with a maximum lifetime of 10.0 days and mean lifetime of 3.6 days (Fig. 3b). With regard to the longer lifetimes during summer in WRF data, we hypothesize that horizontal shear associated with the midlatitude jet stream is weaker, reducing the probability that shear may destroy the vortex, and increasing the probability that radiative processes may intensify the vortex. Moreover, if TPVs are concentrated closer to the pole in WRF compared to NNRP, then TPVs in WRF have a greater opportunity to remain isolated from the jet stream. This topic will be explored in greater detail in the following section.

The regional variability of cyclones between NNRP and WRF are now compared, beginning with an overview of their spatial track density patterns. Recall that the WRF solutions are constrained only by the NNRP boundary conditions, whereas NNRP assimilates observations. Thus the following analysis seeks to describe the statistics of the vortices, not how well the WRF forecasts of an individual event verify with analysis estimates.

During winter, NNRP cyclone track densities are highest in the Canadian Archipelago, Baffin Island, Greenland, areas along the northern Siberia Coast, and northwestern Alaska (Fig. 4a); a polar minimum in track density is notable. The highest cyclone track densities in WRF are concentrated mainly along the northern and western coast of Greenland, and over Baffin Bay, the Beaufort Sea, and the southwestern Barents Sea (Fig. 4c). Track densities
are generally greater in WRF over the Arctic Ocean, whereas they are greater in NNRP primarily over Siberia, the Bering Strait, and the Canadian Arctic (Fig. 4e). During the summer, NNRP track densities are greatest near Baffin Island, with additional maxima near Novaya Zemlya, the Greenland Sea, and the East Siberian Sea (Fig. 4b). WRF cyclones track primarily in the western Arctic Ocean, Canadian Arctic, and Greenland-Iceland-Norwegian (GIN) Seas (Fig. 4d). The overall pattern is similar to winter, where cyclone tracks tend to be greater in WRF than in NNRP over the Arctic Ocean (Fig. 4f), lending more evidence that differences are likely due to the polar filter of NNRP discussed earlier, which could act to limit vortex tracks across the pole.

To understand the differences between NNRP and WRF, we examine the time–mean flow patterns, as represented here by the composite 500 hPa height fields in Fig. 4. During winter, there is a 500 hPa height minimum over Baffin Bay, while there is a relatively strong trough axis over the central part of northern Siberia in NNRP (Fig. 4a). Large cyclone track densities are located along the periphery of the 500 hPa height minimum over Baffin Bay, and at the base of the trough axis in Siberia; that is, these climatological troughs are favorable locations for cyclonic TPVs. For WRF, 500 hPa height minima are centered over northern Canada and over northern Siberia (Fig. 4c). Cyclone track densities are focused primarily along the northern coast of Greenland and downstream of higher topography on Greenland. Genesis density is also greatest along the northern coast of Greenland (not shown); flow over topography is capable of generating potential vorticity by dissipation (e.g. Schar and Durran 1997; Chen et al. 2007), and therefore could be responsible for the higher cyclone density in this region. DJF difference fields reveal a bias towards higher 500 hPa heights in WRF, greatest near Greenland and over the Arctic Ocean near Severnaya Zemlya (Fig. 4e). During summer, both WRF and NNRP exhibit minimum 500 hPa heights near the North Pole, with the most pronounced trough axis extending equatorward from the 500 hPa height minimum toward Baffin Bay (Figs. 4b,d). A ridge is evident over Greenland, which is surrounded by two trough axes. TPV track density is relatively large upstream of the ridge axis west of
Greenland in both NNRP and WRF. Overall, 500 hPa heights are again greater in WRF, with the greatest differences over Baffin Bay, Ellesmere Island, and northern Greenland (Fig. 4f). The positive height bias in WRF is consistent with the tropospheric biases seen with respect to the Global Forecasting System (GFS) model in CH10 and Cavallo et al. (2011).

The WRF 1990s winter and summer simulated climatologies shown here provide a large, long-term, sample of TPVs with mesoscale spatial resolution. Although the simulations suffers from biases inherent to the model, they provide useful data for performing controlled sensitivity experiments, such as those considered next. This approach is advantageous in that a wider range of vortex scales are resolved than in climate data, particularly NNRP, which has been used in similar studies of TPVs. Furthermore, the mesoscale model used here employs no filtering to data near the North Pole, where TPVs likely exhibit high track density. Although WRF and NNRP differ considerably in the exact locations of cyclonic TPVs, WRF captures lifecycles of TPVs in geographically similar regions. In the following section, we compare the WRF control experiment discussed above to an identical simulation, but without explicit radiative forcing.

b. Mesoscale climatology simulated without radiation

We now examine the simulated climatological impact of radiation on cyclonic TPVs during both winter and summer, beginning with the changes to the atmospheric circulation. During winter, the zonal winds are westerly, or cyclonic around the pole (Fig. 5a). The absence of shortwave radiation leaves only longwave cooling over higher latitudes in both the troposphere and stratosphere, whereas shortwave heating offsets a portion of the longwave cooling in lower latitudes. The result is more radiative cooling at higher latitudes, and thermally balanced westerly winds. Without radiation, while the westerly jet stream near the tropopause at 45°N remains, there is an easterly stratospheric jet of \( \sim 8 \text{ m s}^{-1} \) near 70°N, which extends close to the surface (Fig. 5c). Note that the effects of radiation are
still implicitly included near the lateral boundaries (lower latitudes), resulting in cooling at lower latitudes that is absent near the center of the domain at high latitudes. In order to maintain thermal wind balance, higher zonal mean geopotential heights are necessary over higher latitudes, therefore reversing the zonal geopotential height gradient.

During summer, the midlatitude jet stream, indicated by the westerly zonal wind maximum at 45°N and 200 hPa, has less upward extent into the stratosphere than in winter (Fig. 5b). Shortwave heating is relatively greater than longwave cooling over higher latitudes during the summer, especially in the stratosphere since ozone is a strong absorber in shortwave bands. Shortwave heating is strong enough to completely offset longwave cooling in the stratosphere at higher latitudes. At lower latitudes, longwave cooling remains stronger than shortwave heating, resulting in stronger net radiative cooling over lower latitudes than over higher latitudes. Thus, the thermally balanced zonal mean geopotential height gradient in the stratosphere is of the opposite sign during summer than in winter, with higher zonal mean geopotential heights at higher latitudes, acting to reduce westerly winds with height above the tropopause. Without radiation, weak easterly zonal winds around 70°N extend downward from the model top to the surface, as the tropospheric zonal mean geopotential height gradient reverses over higher latitudes as a result of the cooling at lower latitudes near the lateral boundaries as discussed for the winter climatology (Fig. 5d). Note that the easterly winds are considerably weaker during the summer. This is due to weaker net cooling at the lateral boundaries during the summer, as greater amounts of shortwave heating is offsetting the longwave cooling. The result is a weaker meridional temperature gradients and weaker thermally balanced easterlies.

A comparison of the zonal mean meridional streamfunction with and without radiation is shown in Fig. 6. During both winter and summer, there is a high-latitude positive meridional circulation maximum centered ~70°N around 700 hPa, implying that there is ascent ~60°N and descent poleward of ~80°N. This circulation center weakens without radiation during both seasons, but also shifts slightly poleward (equatorward) during winter (summer). These
shifts in the meridional circulation are also accompanied by a poleward (equatorward) shift in
the mean latitude of cyclonic TPVs formation during winter (summer) (Figs. 7a,b). Cyclonic
TPVs generally track poleward during both winter and summer in both the control and
experimental climatologies. This is consistent with the poleward motion expected near the
tropopause inferred from the meridional streamfunction at these latitudes (cf. Fig. 6).

Regarding cyclone amplitudes, during winter, vortex amplitude increases (decreases) over
time in the full physics (no radiation) simulated climatology (Fig. 7c). By the end of the
five-day period, vortex amplitudes are 25% smaller on average without radiation. During the
summer, vortex amplitude increases at nearly the same rate for both climatologies during
the first twenty-four hours, but thereafter the amplitude decreases without radiation, and
is nearly 30% smaller without radiation after 4 days (Fig. 7d). Thus, on average, cyclones
with relatively long lifetimes tend to weaken when radiative forcing is absent.

The distribution of maximum amplitude shows that cyclones have a peak at smaller
amplitudes without radiation during both seasons, with averages decreasing from 23.8 (20.0)
K to 18.5 (12.4) K during winter (summer) (Figs. 8a,b). A secondary winter peak around
35 K is not present without radiation, which may be an indication that radiation is espe-
cially important for stronger cyclones (Fig. 8a). The shift in the amplitude distribution is
most pronounced during summer, where few cyclones obtain amplitudes greater than 30 K
without radiation (Fig. 8b). The effects of radiation on the number of vortices is modest in
comparison, with the number of unique vortex tracks decreasing by 5.2% (12.1%) without
radiation during the winter (summer)(Recall Table 1). Little change is evident in cyclone
radii between the two experiments (Figs. 8c,d). The average radius is 372 (400) km during
winter (summer) without radiation, and 349 (375) km during winter (summer) in the full
physics simulated climatology. Therefore, while radiation plays an important role in vortex
amplitude, it has a small effect on the horizontal scale of cyclonic TPVs.

Cyclone lifetimes follow nearly the same exponential decay pattern during winter with

and without radiation, with no statistically significant\textsuperscript{4} differences in longevity (Fig. 9a). Average lifetimes during winter are 5.7 days, whereas the maximum lifetime is \(~21\) days in both cases. During summer, cyclones exhibit a statistically significant decrease in lifetime without radiation, as average lifetimes decrease from 8.3 days to 7 days while the maximum lifetime decreases from 39.3 days to 34 days (Fig. 9b). The relatively greater longevity during summer than during winter may be related to a weaker meridional influence of the summer midlatitude jet stream (cf. Figs. 6a,b). This implies that lateral shear has less of an influence in the regions where TPVs are most prevalent during summer, increasing the likelihood of TPVs remaining isolated in the Arctic. Greater isolation from the jet stream provides more opportunity for the vortices to be maintained or intensified by radiative processes. When eliminating the radiative intensification of TPVs during winter, there is only a minimal impact on lifetime, suggesting that radiation has more of an influence on the vortex population characteristics at longer time scales. That is, during winter, there are more competing weakening mechanisms present that act on shorter time scales, such as dynamics or latent heating. We conclude that, given enough time, radiation will maintain cyclonic TPVs, lengthening their lifetimes.

As discussed earlier, the 500 hPa height pattern is expected to be substantially different between the simulations with full physics and without radiation. Following the discussion of the spatial variations in TPV track density in Section 3a, the locations of TPVs are therefore also expected to differ without radiation. While 500 hPa heights are locally lower over the Arctic, over the Canadian Archipelago, and over north-central Siberia in the full physics simulated climatology during winter (Fig. 10a), 500 hPa heights are locally high along a line from the North Atlantic Ocean across the Arctic Ocean and toward Siberia without radiation (Fig. 10c). As a result, the density of cyclones is reduced over the North Atlantic and central Arctic Ocean where the locally high 500 hPa heights are present without radiation (Fig. 10e). Additionally, most cyclones are focused over the Beaufort Sea and Canadian Archipelago,\textsuperscript{4}

\textsuperscript{4}Computed by testing the statistical significance of the two sample best-fit rates of exponential decay using the Student’s t-test and a 95% significance level.
closer in proximity to locally lower 500 hPa heights and where the 500 hPa flow is weaker. Note that cyclones are filtered to include only those where at least 60% of their lifetimes are poleward of 65°N latitude, and therefore tracks along the southern periphery of the 500 hPa height minima during both seasons without radiation are not included in this analysis. During summer, the lowest 500 hPa heights centered near the North Pole are located further southward near Baffin Island, Canada without radiation (Figs. 10b,d). Without radiation, 500 hPa height gradients are generally weaker, which implies the atmospheric flow is weaker at this level. A notable difference is that a ridge of higher 500 hPa heights along the western North American coast is much less pronounced without radiation, which is a region with a considerable increase in cyclone track density without radiation (Figs. 10b,d,f).

We now examine the changes to the composite structure of cyclonic TPVs without radiation. Vortex-relative composites of tropopause potential temperature are shown in Fig. 11. The composites are spatially filtered such that only those cyclones for which tropopause potential temperature at the vortex core is at least one standard deviation below the domain mean is included in the composites; fields are averaged relative the the vortex core. The one standard deviation threshold is used as a compromise between sample size and obtaining cyclone statistics on those that differ from the background. The sample sizes for the WRF full physics winter and summer cases there are 93 and 57 vortices, respectively, while for the WRF no radiation winter and summer cases there are 67 and 124 vortices, respectively. In the full physics winter simulated climatology, the composite vortex core potential temperature is 269 K, with a vortex amplitude of 30.8 K (Fig. 11a). Vortex core potential temperature is 291 K without radiation, with a vortex amplitude of 21.6 K (Fig. 11c). Note that potential temperature is greater over the whole domain in the no radiation composite (Fig. 11e), due to the absence of longwave radiative cooling as discussed earlier. However, differences are greatest in the vortex, indicating that the radiative processes have a relatively greater effect on the vortex than on the background environment. In the full physics summer simulated climatology, the composite vortex core potential temperature
is 291 K with a vortex amplitude of 28.2 K (Fig. 11b). In the no radiation composite, vortex core tropopause potential temperature is 304 K with an amplitude of 20.7 K (Fig. 11d), with reductions of tropopause potential temperature at the vortex core of \( \sim 13 \) K relative to the full physics composite (Fig. 11f). As in winter case, tropopause potential temperature is greater in the no radiation case, primarily due to domain-wide warmer temperatures from the absence of longwave radiative cooling. The difference is not as pronounced during summer since shortwave heating partially offsets the effect from longwave cooling near the tropopause.

Vertical west–east cross sections through the composite vortex show differences in potential temperature and EPV between the full physics and no radiation climatologies (Fig. 12). During winter, potential temperature changes are anomalously negative in the vortex core near the tropopause without radiation, while anomalously positive potential temperature changes are present above and below the negative anomalies respectively (Fig. 12a). Recalling equation (1), the anomalously negative (positive) vertical gradients in potential temperature differences around 500 (250) hPa in the vortex result in a reduction (increase) in EPV at the same locations without radiation, thereby reducing the EPV near the vortex tropopause without radiation. Relative humidity near the vortex tropopause is greater without radiation, as the vortices are weaker and there is a higher average tropopause (Fig. 13a). With radiation, anomalous radiative heating is centered about the vortex tropopause (Fig. 13c), and is located near where the air is anomalously dry from the downward intrusion of stratospheric air.

Under the vortex tropopause and near the surface, potential temperature is higher, partially from the hydrostatic response of weaker vortices on average, but also because background tropospheric potential temperature is higher near the center of the domain at higher latitudes. Fig. 14a shows that given the location of most frequent cyclones (near Cambridge Bay, Canada), a grid-relative line from west-to-east would place the higher background potential temperatures near the center of this line. That is, the cross sections
have a high probability of sampling vortices across the Arctic, with the higher background
potential temperatures near the center of the cross section without radiation. Similarly,
potential temperatures are higher above the vortex near 125 hPa without radiation, due
to the absence of longwave cooling that would occur over high latitudes with radiation.
Recall that over lower latitudes, some of the longwave cooling is offset by shortwave heating,
resulting in a greater potential temperature increase over higher latitudes and near the
center of the cross section without radiation. Note that due to the anomalous warming
above the vortex near 125 hPa without radiation, there is an anomalous increase in potential
temperature with height, resulting in more EPV ~250 hPa (Fig. 12c). The net EPV tendency
differences reflect the reduced radiative heating and cooling anomalies that are associated
with the dry, stratosphere air in the presence of radiative forcings (Fig. 13e).

During summer, anomalously positive (negative) differences in potential temperature are
present below (above) the vortex tropopause (Fig. 12b), resulting in less EPV in the vortex
core without radiation (Fig. 12d). Relative humidity differences are similar to the winter
climatolgy, where weaker vortices lead to relative humidity increases near the tropopause
without radiation (Fig. 13b). A notable difference from the winter case are the decreases
in tropospheric relative humidity under the vortex core, which reflects the greater amount
of tropospheric water vapor during summer. This is also evident in the radiative heating
differences where, with radiation, anomalous radiative cooling (heating) is present near areas
of anomalous decreases (increases) in relative humidity with height (Fig. 13d), consistent
with the findings of CH10. The anomalous potential temperature differences follow from the
anomalous radiative heating differences, with potential temperature decreases (increases)
located above (below) the tropopause without radiation (recall Fig. 12b).

Note that there is an asymmetric potential temperature and EPV change without ra-
diation, with the dipole-like potential temperature pattern extending eastward and upward
~1500 km from the vortex core (Fig. 12b,d). This pattern is also evident in the relative
humidity differences (Fig. 13b). In Fig 14b, it is apparent that higher potential temperatures
are more probable east of the composite vortex core in the troposphere, for the same reasons as discussed previously for the winter. The relative humidity asymmetry with higher (lower) values above (below) the tropopause east of the vortex core is primarily a response of the lower (higher) potential temperatures without radiation. The anomalous EPV tendency differences due to radiation are located near the strongest vertical gradients in the anomalous radiative heating differences (Fig. 13f). Therefore, the symmetric, dipole-like differences in EPV above and below the vortex tropopause are primarily a direct radiative response associated with moisture anomalies near the vortex, while the asymmetric changes on the eastern side of the vortex are primarily a response to changes in the background potential temperature, with respect to the locations of the cross section. Although the asymmetric pattern here can be viewed as a rather unrealistic effect of the NNRP-forced boundary conditions, it does emphasize the sensitivity that both temperature and water vapor have on TPVs, which could potentially have a greater impact over the next century as temperatures are projected to increase and sea ice is projected to decrease (IPCC 2007).

4. Summary and conclusions

Radiation has been identified in previous studies as a primary mechanism of cyclonic TPV intensification over a region of frequent cyclone intensification in the Arctic. This study explored the hypothesis that when this intensification mechanism is absent, cyclonic TPVs still form, but they will be weaker and exhibit shorter lifetimes. Here we tested this hypothesis using numerically simulated ten-year mesoscale climatologies with and without radiation during winter and summer seasons over the Arctic. Changes in vortex characteristics, atmospheric circulation, and dynamics from a potential vorticity perspective were explored.

Results support the hypothesis that radiation plays an important role in the maintenance of cyclonic TPVs. Without radiation, cyclones slowly weaken over time on average,
and the average amplitude is reduced 22.3% (38.0%) during winter (summer). The larger amplitude reduction during summer corresponds to greater vertical water vapor gradients, as tropospheric water vapor is substantially higher during summer. Vortex lifetimes decrease from an average of 8.3 days to 7 days during summer without radiation; however, no change in lifetimes is evident during winter. This result is consistent with the hypothesis that the vortices are more isolated from the lateral wind shear associated with the midlatitude jet stream during summer, allowing radiation to maintain the vortices for longer periods of time. Additionally, changes in the large-scale atmospheric circulation are observed, particularly with a weakening of the mean meridional streamfunction over higher latitudes without radiative forcings, leading to shifts in the jet stream and corresponding shifts in the locations and movement of TPVs.

The radiative intensification structure seen here is similar to that documented by CH10 for a large sample of cyclonic TPVs over the Canadian Arctic. The CH10 composites showed dipole-like radiative heating anomalies, with anomalous radiative cooling (heating) just below (above) the vortex tropopause, which was also qualitatively similar to the relative humidity anomalies. Although the diabatic intensity changes and horizontal scale of vortices studied here are similar to CH10, the horizontal scale is much smaller than those documented in NNRP data both here and in Hakim and Canavan(2005). Given that the same vortex algorithms were used in each study, these differences indicate a sensitivity to the horizontal grid spacing used on the native grids. Furthermore, vortex track density is substantially greater over the Arctic Ocean near the North Pole in the WRF-simulated climatologies, likely due to polar filtering NNRP data.

These results emphasize the important role that radiation has on maintaining and intensifying cyclonic TPVs, particularly during summer. With increasing evidence that water vapor is important with regard to the radiative structure of cyclonic TPVs, future work is needed to better quantify this relationship. This may be pursued using an idealized approach, where the complicated interactions between radiation, temperature, water vapor, and latent
heating may be more easily isolated in controlled experiments. If water vapor is important to
the ultimate evolution of TPVs, then it is also important to understand how changes in the
moisture budget associated with warmer Arctic temperatures and decreases in sea ice could
affect TPV intensity. This could be a factor, especially during autumn and winter, when
the upward-directed surface heat and moisture fluxes are estimated to be largest (Serreze
et al. 2007), increasing the potential for diabatic forcing to alter the thermodynamic heat
budget of TPVs. Recent studies with the Community Atmospheric Model (CAM) show a
strong sensitivity of the lower atmospheric circulation to projected changes in sea ice, alone,
during the winter (Deser et al. 2009; Higgins and Cassano 2009), and future studies will
examine whether these changes are further communicated above the atmospheric boundary
layer to the tropopause. During summer, surface heat fluxes are directed downward from
the atmosphere to the surface (e.g., Serreze et al. 2007), for which the low-level atmospheric
circulation could have an impact on sea ice movement (e.g., Rigor et al. 2002). Ogi and
Wallace (2007) found that summer seasons with anomalously low sea-ice concentrations
occur when the low-level atmospheric circulation over the Arctic Ocean is anticyclonic, and
cyclonic (anticyclonic) sea level pressure patterns have been linked to cyclonic (anticyclonic)
500 hPa flow over the Arctic Ocean (Serreze and Barrett 2008). It is yet to be determined
what role TPVs play, if any, on these observations, and this is a fertile topic for future
studies. Finally, the results here show that even in the absence of radiation, large numbers
of cyclonic TPVs still exist, and for considerable lengths of time. Therefore, while radiation
is important for TPV maintenance and intensification, it is apparently not essential for their
genesis, which provides another topic for future research.
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Table 1. The sample size of unique vortex tracks, vortex genesis, and vortex lysis events from cyclonic TPV tracks. See text for further details.

<table>
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<th>Experiment</th>
<th>Vortex tracks</th>
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<th>Lysis</th>
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<td>442</td>
<td>442</td>
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<tr>
<td>NNRP JJA</td>
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<td>WRF DJF (no radiation)</td>
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<td>6829</td>
<td>6747</td>
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<td>WRF JJA (no radiation)</td>
<td>5837</td>
<td>5670</td>
<td>5408</td>
</tr>
</tbody>
</table>
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1 Ensemble-mean cyclonic tropopause polar vortex tropopause potential temperature amplitude for (a) winter and (b) summer over the period 1990-1999. The solid (dashed) contour corresponds to NNRP (WRF). All cyclones survive a minimum of 5 days, so that the population is constant for all times displayed. 32

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