Objective Identification of Occluded Quadrants in Midlatitude Cyclones:

Method and Some Climatological Applications

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ABSTRACT: A novel automated, objective scheme for identifying occluded mid-latitude cyclones from gridded data sets is described and employed to construct a limited climatology of such storms as well as composites of their thermodynamic and kinematic structures. The climatology (2006-2011) is derived from the MERRA-2 reanalysis and reveals differences in the distribution of occlusions between the hemispheres. Northern Hemisphere occlusions are most frequent in winter (DJF) and are found poleward of the mean tropopause-level jets in both the Atlantic and Pacific basins. In the Southern Hemisphere, however, occlusions are almost never found equatorward of 45°S and are most frequent during autumn (MAM).

The identification scheme accommodates stratification of occlusions based upon the value of 700 hPa $\theta_e$ in their characteristic thermal ridges. Composites of six groups of occlusions, based upon this distinction, are constructed. The composites reveal notable differences in the thermodynamic structures among these six groups with more poleward (lower $\theta_e$ or ”colder”) storms exhibiting shallower, less developed thermal structures as compared to their lower latitude (higher $\theta_e$ or ”warmer”) counterparts. These differences are attended by contrasts in the intensity of upward vertical motions in the trowal of the various composite storms, demonstrating that ”warm” storms are associated with greater latent heat release than ”colder” storms. It is suggested that these coincident differences between ”cold” and ”warm” storms provides further evidence of the fundamental importance of latent heat release to the development of occluded thermal structures.
1. Introduction

The relationship between the three-dimensional (3-D) thermal structure and the distribution of clouds and precipitation in cyclones was first suggested by Bjerknes and Solberg (1922) in their conceptual model of the mid-latitude cyclone, which has come to be known as the Norwegian Cyclone Model (NCM). The NCM described how the amplification of the nascent cyclone distorted the polar front, the globe-girdling boundary separating polar air to the north from the tropical air to the south into the cold and warm fronts of the storm structure. The so-called warm sector, a region of homogeneously warm air between the two fronts, extended downward to the surface. The thermal evolution of such cyclones involves changes in both the vigor of the individual frontal zones and in their orientation with respect to one another. The dynamical processes that control this evolution are also responsible for producing the secondary circulations to which the characteristic cloud and precipitation distribution in cyclones - linear bands of varying widths along the cold and warm fronts and a cloud head poleward and westward of the storm center - can be accurately attributed.

A notable element of the post-mature phase of the cyclone life cycle as described by the NCM was the process of occlusion first conceived by Tor Bergeron (Jewell 1981). Among the structural changes that characterize the occluded stage are the adoption of an increasingly equivalent barotropic structure in the vertical as well as the development of a lower tropospheric thermal ridge connecting the sea level pressure (SLP) minimum to the peak of the warm sector (Schultz and Mass, 1993; Martin, 1998a,b; 1999a,b; Posselt and Martin, 2004; Schultz and Vaughan, 2011). According to the NCM, the air occupying the thermal ridge originated in the surface warm sector and was forced to ascend by the intersection of the cold and warm fronts as the cyclone occludes. The resulting structure consists of an axis of maximum $\theta$ ($\theta_e$) (in both horizontal and vertical cross sections) embedded within a region of reduced static stability between two significant baroclinic zones, as depicted in Fig. 1. Despite the sometimes fierce debate regarding the mechanisms that might operate to produce it (e.g. Stoelinga et al., 2002; Schultz and Vaughan, 2011), there is little disagreement that such a configuration represents the canonical thermal structure of a warm-occluded cyclone.

A more fully 3-D representation of the warm-occluded thermal structure was developed in a series of papers over the course of more than a decade by scientists at the Canadian Meteorological
Service (CMS) (Crocker et al., 1947; Godson, 1951; Penner, 1955; Galloway, 1958, 1960). These studies noted the ubiquity of a westward slope to the crests of the thermal wave at successive heights in occluded cyclones. Penner (1955) referred to this "sloping valley of tropical air", as it had been previously described by Godson (1951), as the trowal (trench of warm air aloft).

Borrowing terminology from the NCM, the trowal essentially marks the 3-D sloping intersection of the upper cold frontal portion of the warm occlusion with the warm frontal zone. The observation that the cloudiness and precipitation characteristic of the occluded quadrant of the cyclone bore a closer correspondence to the trowal position than to the weak surface warm-occluded front led the Canadians to regard the trowal as the essential structural feature of a warm-occluded cyclone.

Consistent with the definition given by Penner (1955) and the description given by Godson (1951), the trowal can be approximately located either as a ridge of high (equivalent) potential temperature (or 1000-500 hPa thickness) on a horizontal cross section, or more precisely as a 3-D sloping canyon in an isosurface of (equivalent) potential temperature as shown in Martin (1998a, 1999a).

A schematic illustrating the trowal conceptual model is given in Fig. 2.

Compelling evidence supporting these earlier observational findings comes from a number of more recent finescale numerical modeling studies of occluded cyclones (Schultz and Mass, 1993; Reed et al., 1994; Martin, 1998 a,b) that have illustrated the structure and thermal evolution of, and airflow through, the occluded quadrant. These studies have identified a coherent airstream, originating in the warm sector boundary layer, that ascends cyclonically in the occluded quadrant of the cyclone. Martin (1998b,1999a), noting a spatial relationship between the path taken by this airstream and the trowal in his case, referred to this airflow as the "trowal airstream". By considering the insightful along- and across-isentrope partition of the Hoskins et al. (1978) $Q$-vector first described by Keyser et al. (1994), Martin (1999a,b) provided a dynamical explanation of the relationship between the development of the characteristic thermal structure in the occluded quadrant of cyclones and the associated ascent that supports this airstream. Consistent with forced ascent in a nearly saturated environment, the developing occluded thermal ridge is often associated with substantial latent heat release (LHR).

Martin (1998a) noted that some occluded cyclones are associated with a characteristic tropopause-level potential vorticity (PV) structure consisting of an isolated, low-latitude high-PV feature that is connected to a high-latitude reservoir of high PV by a thin filament of high PV— a structure he
termed the "treble clef" (Fig. 3a). Given the relationship between tropopause-level PV and the
thermal structure in the underlying troposphere (Hoskins et al., 1985), the horizontal juxtaposition
of two upper-level positive PV anomalies of unequal magnitude, separated by a relative minimum in
PV (such as along line A–A’ in Fig. 3a) depicts the canonical warm-occluded thermal structure (Fig.
3b). From the perspective of the NCM, the sloping warm column beneath the upper-tropospheric
PV minimum in Fig. 3b represents warm sector boundary layer air that has been lifted during the
occlusion process. In three dimensions, the warm axis identifies the position of the trowal which,
as mentioned earlier, tends to be a focus for precipitation production in the occluded quadrant
of cyclones. Thus, the clouds and precipitation in the occluded quadrant of a cyclone are often
nearly coincident with an upper-tropospheric PV minimum. The strong connection between the
morphology of the upper-tropospheric PV and the underlying occluded thermal structure, coupled
with the known diabatic influence on vertical PV redistribution (e.g. Hoskins et al. 1985, Raymond
1992), provided a convenient framework for Posselt and Martin (2004) to investigate the influence
of LHR on the formation of an occluded thermal structure.

Comparing full physics (FP) and no LHR (NLHR) MM5 simulations of a major winter storm,
Posselt and Martin (2004) found that the former depicted the canonical, troposphere-deep, warm-
occluded structure while the latter produced only a shallow, poorly developed one. Their analysis
showed that direct dilution of a local, upper-tropospheric PV maximum by mid-tropospheric LHR
initiated formation of a local, upper-tropospheric PV minimum, or low PV tongue, to the northwest
of the surface cyclone center. The production of this PV minimum initiated a cutting off of
the upper-tropospheric PV anomaly associated with the surface development. The associated
upper-tropospheric circulation then forced the advection of low (≤ 1 PVU) values of PV into the
developing PV trough. This combination of kinematic and diabatic processes acted to produce
both the tropopause PV treble clef as well as the underlying warm-occluded thermal structure in the
FP simulation. In contrast, though an adiabatic kinematic tendency for production of a treble clef
PV morphology also operated in the NLHR simulation, the resulting PV and thermal structures
were weaker and slower to evolve than those produced in the FP simulation. Thus, the authors
suggested that LHR plays an indispensable role in the production of the characteristic occluded
thermal structures observed in nature.
A number of methods have been proposed for objective identification of cold and warm fronts (e.g. Hewson, 1998; Hewson and Titley, 2010; Berry et al., 2011; Simmonds et al., 2012; Schemm et al., 2018 and references therein). Naud et al. (2012;2015) employed satellite-based radar and lidar profiles (CloudSat, Stephens et al., 2002; CALIPSO, Winker et al.,2009) to explore the cloud and precipitation distributions associated with objectively identified cold and warm fronts and how these distributions relate to the larger scale environment. Although occlusions are a well-studied meteorological phenomena (e.g. Schultz and Mass, 1993; Martin, 1998a,b, 1999a,b; Stoelinga et al., 2002;, Posselt and Martin, 2004; Schultz and Vaughan, 2011), there is no automated method of occlusion detection. Consequently, it has not been possible to explore the cloud and precipitation distributions of a very large number of occluded quadrants observed in a wide range of locations and environmental conditions.

Extratropical cyclones (ETCs) are responsible for the largest share of the global redistribution of heat required to offset latitudinal differences in radiative transfer. Since the occluded quadrants of these storms are known to be regions of significant moisture convergence and attendant LHR, occluded cyclones provide a key physical link in the global energy and water cycles. As we peer into the future with sophisticated global climate models (GCMs), it is essential that these models faithfully reproduce increasingly detailed aspects of the life cycles of the individual weather systems involved in these global cycles. This paper will lay the foundation for a comprehensive assessment of the climatological characteristics of occluded mid-latitude cyclones and attendant evaluation of the skill with which a GCM can reproduce the canonical occluded structure and precipitation characteristics.

Central to the present study will be the description of an objective scheme that identifies the occluded quadrants of cyclones from gridded reanalyses and/or climate model output. The method will then be employed to construct the first global survey of occluded cyclones. In Section 2, we describe details of the objective identification scheme. Some results of its application to five years of MERRA-2 reanalysis data are presented in Section 3. Included in this presentation are a limited global climatology as well as composites of the thermal structure and vertical motion distributions of occluded cyclones observed in the Northern Hemisphere over 5 recent winters. A discussion of the results and an outline of future work to be undertaken using the identification scheme are offered in Section 4.
2. Automation of Occlusion Identification: Methodology

a. Data

This study uses data from the second iteration of NASA’s Modern-Era Retrospective analysis for Research and Application (MERRA-2) gridded reanalysis output (Gelaro et al., 2017). In particular, air temperature along with sea-level pressure (SLP), geopotential height, specific humidity and vertical velocity are utilized to objectively identify occluded ETCs and subsequently portray aspects of their structure and evolution. The MERRA-2 data is available on a 0.625° × 0.5° horizontal grid with 42 vertical levels spanning from 1000 hPa to 3 hPa. For purposes of evaluation of the objective identification method to be described later, the study also employed the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010) data set, from which the same variables were available at 64 vertical levels with 38 km spatial resolution.

b. Objective Identification Parameter

Since occlusion represents the beginning of the post-mature phase of a cyclone’s life cycle, many (though not all) storms that occlude do so near their peak intensities. This study determines the time of peak intensity as the time at which either the central SLP reaches a minimum or when the pressure depth has reached a maximum, then choosing whichever phenomenon occurs first. Pressure depth is defined as the difference between the outermost closed SLP contour and the central pressure in Polly and Rossow (2016).

An occluded thermal ridge (OTR) serves as a two-dimensional (2-D) proxy for the 3-D trowal, the essential structural feature of the occluded quadrant. Therefore, it can be confidently identified using any of several thermodynamic variables, including potential temperature (θ), equivalent potential temperature (θₑ) and 1000-500 hPa thickness. Since the OTR routinely extends through a substantial depth of the troposphere, 1000-500 hPa thickness, denoted as Φ’, was chosen as the focal variable for the objective identification scheme as it best captures the full 3-D structure of the OTR. The analysis was facilitated by coarsening the native resolution of the MERRA-2 data by a factor of 2. Hence, the thickness fields were processed on a 1.25° × 1° horizontal grid. Objective identification of the OTR is based upon examination of the functional form of the divergence of
the unit vector in the direction of $\nabla \Phi'$, given by,

$$\hat{n} = \frac{\nabla \Phi'}{|\nabla \Phi'|}.$$  \hfill (1)

The divergence of (1), $\nabla \cdot \hat{n}$, takes the form,

$$\nabla \cdot \hat{n} = \nabla \cdot \frac{\nabla \Phi'}{|\nabla \Phi'|} = \frac{\nabla^2 \Phi' |\nabla \Phi'| - \nabla \Phi' \cdot \nabla |\nabla \Phi'|}{|\nabla \Phi'|^2}$$ \hfill (2)

using the quotient rule. Since the sign of the resulting expression diagnoses the presence of a thermal ridge, while the denominator serves only as a scaling factor, the OTR finding function, $F_f$, is simply the numerator of (2).

$$F_f = \nabla^2 \Phi' |\nabla \Phi'| - \nabla \Phi' \cdot \nabla |\nabla \Phi'|.$$ \hfill (3)

Negative values of $F_f$ indicate convergence of the unit vector and the presence of a thermal ridge, while regions with positive $F_f$ signify divergence, and therefore, a thermal trough. In order to highlight the areas of $\nabla \cdot \hat{n}$ that are also associated with the largest thermal contrasts, the final form of the finding function (referred to as $F$) is weighted by the magnitude of the thickness gradient.

$$F = F_f |\nabla \Phi'|.$$ \hfill (4)

Unprocessed fields of $F$ contain small-scale features that can cloud the intended thermal ridge identification results. To avoid such obfuscation, only values of $F$ less than $-1 \times 10^{-9} \text{m}^{-1}$ ($F_{\text{max}}$) are considered and a 5-point smooth is applied to avoid excessive noise in the output. The example shown in Fig. 4a depicts the thermal structure of an occluded cyclone over the north Pacific basin. Contours of $F$ to the west of the cyclone center are not germane to identification of the OTR and can be neglected. The remaining feature is an extended region of $F < F_{\text{max}}$, some of which clearly coincides with the axis of the 1000-500 hPa thickness ridge, while another portion appears just ahead of the cold frontal thickness gradient. The vertical cross-section along A-A' in Fig. 4a cuts through that section of the $F$ field that elongates along the thermal ridge from the low pressure center into the warm sector.
That cross-section (Fig. 4b) shows evidence of the canonical warm occluded thermal structure with an axis of maximum $\theta_e$ between two baroclinic zones, the warm and cold fronts, sloping poleward with height. Martin (2006) characterizes the location at which the axis of maximum $\theta_e$ intersects with the ground as the position of the surface warm occluded front. As is generally the case, a plume of maximum vertical motion associated with the main updraft of the storm appears to be better collocated with the leading edge of the upper-level cold front than with the surface occluded front. The isobaric topography of the 303 K moist isentrope from this case is shown in Fig. 4c. This particular isentrope was chosen as it lies near the warm edge of both the cold and warm fronts in the occluded thermal structure. The trowal, indicated by the bold dashed line, clearly coincides with the northern portion of the $F < F_{max}$ region. Extensive testing using the same analysis technique on each candidate cyclone identified in the north Atlantic and north Pacific basins from December 2007 to February 2008 was performed to validate the accuracy of the objective identification scheme. In order to develop a robust, data set-independent technique, an element of that testing was employment of a collection of input data sets including NCEP CFSR as well as NCEP-NCAR reanalysis data (Kalnay et al., 1996).

c. The cluster tracking method

Automating the use of the $F$ parameter presents the unique opportunity to identify all ETCs undergoing occlusion as well as construct composites of elements of the thermodynamic and kinematic structure of the occluded quadrant. Given its versatility, $F$ can be employed using output from any gridded data set, such as those produced by standard numerical weather prediction (NWP) forecast models and/or global climate models (GCMs). This study employs the cyclone database introduced in Naud et. al (2012; 2015), which tracked and identified storms using the NASA Modeling, Analysis, and Prediction (MAP) Climatology of Mid-Latitude Storm area (MCMS) algorithm developed by Bauer and Del Genio (2006) and Bauer et al. (2016) applied to the ERA-Interim 6-hourly (hereafter, 6h) SLP fields (Dee et al., 2011). The MCMS algorithm searches for local minima in SLP and tracks them through time. Qualifying cyclones must not travel more than 720 km in any 6h interval of their life cycles but must travel at least 700 km, exist for at least 24 hours, and reach a minimum SLP of less than 1010 hPa.
The full track of each identified storm in the MERRA-2 database was considered and divided into individual snapshots, depicting the instantaneous state of the cyclone every 6 hours. Automating the use of the OTR finding function, $F$, to identify cyclones that are occluded involves several assessments at each 6h time for candidate cyclones. First, the individual cyclone tracks have to be identified. Figure 5a provides an example of the track of a sample cyclone that occurred over the northeast Atlantic in early January 2008. The cyclone’s time of peak intensity is clearly indicated as is its position every 6h from 0600 UTC 6 January to 1800 UTC 8 January. To ensure computational efficiency, a limited area stretching from -10° to +20° longitude and ± 20° latitude from the storm center, is then considered at each 6h analysis time.

The OTR finding function is then applied within this area, flagging any values of $F < F_{\text{max}}$. The collection of such points, in the prescribed limited area, for 1200 UTC 6 January 2008 are indicated by the black and red crosses in Fig. 5b (and similarly for other times in Figs. 5c-e). Any such grid points are not considered if the standard deviation of the surface elevation at that grid point, and its 4 adjacent points is greater than 300 m, $\text{STDSurf}_{\text{max}}$. Such points in the example storm are indicated with a blue triangle in Figs. 5b-e. Remaining grid points meeting the threshold in $F$ qualify for further consideration only when at least 8 ($N_{\text{min}}$) contiguous neighbors constitute a cluster and that cluster is located to the east of the SLP minimum (note 12 such grid points in Fig. 5b). Such qualifying clusters have a black diamond surrounding a black cross in Figs. 5b-e. In order to have identified an occluded cyclone, and its OTR, qualifying clusters must at least partially overlap in a cyclone-relative grid at consecutive 6h times as illustrated in Fig. 6 for the 6-7 January 2008 cyclone. This confirms that the cyclone center and the qualifying cluster are moving in tandem. Additionally, the first appearance of a qualifying cluster in a cyclone’s track history (e.g. the cluster at 1200 UTC 6 January in Fig. 5b) must have been located within a distance of 300 km ($D_{\text{max}}$) of the cyclone center in order for the cyclone to qualify as occluded and be included in the subsequent composite analyses. Finally, if a cluster is identified (1) only once during a cyclone’s life cycle, (2) at several non-consecutive 6h time steps, or (3) in a consecutive series that ends before the cyclone reaches its peak intensity, that storm and its cluster are not considered in any subsequent analyses. These various disqualifications reflect the intentionally conservative nature of the scheme which is designed to minimize false identification. Though such a design may overlook some weak occlusions, given the large number of candidate storms, the
slightly conservative approach adopted here is unlikely to lead to mischaracterization of the global
climatology or composite structures.

This procedure can be applied to any gridded data sets with only slight modifications made based
upon horizontal grid spacing. Resolution-based adjustment made to several of the parameters
involved in the method are summarized in Table 1. The parameters $F_{max}$, $N_{min}$, and $STDSur_{f_{max}}$
were determined to exhibit a linear dependence on grid resolution. $D_{max}$ is an absolute distance
and, therefore, its magnitude remains the same for all three grid spacings.

Employing each 6h OTR identification, the following procedure was employed to build composite
vertical cross-sections through these features. The procedure is best described using a schematic
version (Fig. 7) of a single 6h identification period (such as those shown in Figs. 5b-e). First,
a regression line (in latitude and longitude) is calculated through the cluster of the grid points
constituting a qualifying cluster (blue crosses in Fig. 7). That line, the solid gray line in Fig. 7,
represents the thermal ridge axis and its longitudinal range is bounded by the dashed red lines.
At the median longitude of the thermal ridge axis, a transect is drawn perpendicular to the axis.
Finally, the thermal ridge axis line is slid along the transect line until it reaches the 700 hPa $\theta_e$
maximum. Synoptic experience suggests that the occluded thermal ridge rarely extends above
350 hPa. Consequently, though a number of other choices might also serve the purpose, 700 hPa
represents a mid-tropospheric level (free from excessive boundary layer influences) by which to
normalize the position of the axis of the thermal ridge. The intersection of the transect line and the
adjusted thermal ridge axis is then the midpoint of a 3000 km long transect line along which any
variable ($\theta_e, \omega, T$, etc.) may be obtained. In order to produce composites of the vertical structure
through the OTR, each such transect is preserved and then they are all averaged together to produce
the composite vertical cross-section of the given variable. Because the middle of each transect
is, by construction, coincident with the maximum 700 hPa $\theta_e$ for that particular cross-section, it
is possible to create separate composite occluded structures based upon ranges of their maximum
700 hPa $\theta_e$ values.
3. Climatological Applications

a. Global distribution of occluded cyclones

Employing the objective identification method just described, a global distribution of occluded identifications can be constructed. Here we consider the 5-year period from 2006-2011 and utilize the MERRA-2 data (1.25° × 1°). Figure 8a shows the NH winter (DJF) cumulative distribution of 6h occluded identifications over those five years and reveals that, in the north Pacific, occluded cyclones populate the basin poleward of the mean jet with distinct maxima in the southern Sea of Okhotsk, east of the Kamchatka peninsula, and in the Gulf of Alaska. Wintertime occlusions in the north Atlantic basin are concentrated in a strip running from the mouth of the Labrador Sea to the southeast coast of Greenland. These same regions harbor smaller numbers of occluded cyclones during the NH spring (MAM) (Fig. 8c). Occluded storms effectively disappear during the NH summer (JJA) (Fig. 8e), and quickly become reestablished in NH autumn (SON) (Fig. 8g).

The distribution in the SH is different in many respects. The wintertime (JJA) distribution shows almost no occluded cyclones equatorward of 45°S, except in the lee of the Andes (Fig. 8b), a noted genesis maximum during austral winter (Hoskins and Hodges, 2005). By spring (SON), occluded cyclones appear largely along the coast of Wilkes Land (120°E) and Princess Elizabeth Land (80°E) (Fig. 8d) with that distribution thinning further by austral summer (DJF) (Fig. 8f). Autumn (MAM) is the season with the greatest number of occluded cyclones in the SH (Fig. 8h), with another maximum off the coast of Enderby Land (45°E).

b. Structure of composite Northern Hemisphere wintertime occlusions

Further detail regarding the wintertime distribution of NH occlusions is afforded by stratifying all such systems by the value of the 700 hPa $\theta_e$ maximum along the thermal ridge axis. Figure 9 shows the number of occluded cyclones in 6 bins constructed such that each bin contains the same fraction of the total number of occlusions in the 2006-2011 analysis period. Two-thirds of all the identifications had 700 hPa $\theta_e$ maxima in the range of 293K to 313 K. The geographic distribution of occlusions from each of these 6 bins is shown in Fig.10. Not surprisingly, stratification by 700 hPa $\theta_e$ maxima effectively separates sub-populations of occlusions by latitude, with the lowest (highest) $\theta_e$ maxima occurring at high (low) latitudes.
Figure 11 presents the results of constructing composite vertical cross-sections of $\theta_e$ through each of these 6 varieties of occlusions. Recall from Fig. 9 that the 700 hPa $\theta_e$ maxima of those comprising Bin I range from 275K to 293 K. In this ”coldest” bin, the OTR notably does not exhibit any vertical tilt (Fig. 11a), suggesting that these storms have a shallower and less developed occluded thermal structure than those occurring at lower latitudes. These cyclones appear to cluster near coastlines – especially around Kamchatka and southeast Greenland (Fig. 10a). This circumstance may influence their composite structure compared to those cyclones found farther out at sea. The successively ”warmer” occlusions (Fig. 11b-f) all exhibit axes of maximum $\theta_e$ that clearly tilt poleward, as in the canonical thermal structure.

The composite vertical motions in the vicinity of the OTRs of these different collections of occlusions are shown in Fig. 12. It is immediately apparent that the ”warmer” occlusions have stronger upward vertical motions within their OTRs and that their composite vertical motion plumes share the poleward tilt of their respective axes of maximum $\theta_e$. The magnitude of $\omega$ is a function of the forcing for ascent modulated by the local static stability. As noted in reference to Fig. 10, stratifying the occlusions by 700 hPa $\theta_e$ maxima in their OTRs amounts to a sorting by latitude. Thus, the ”warmer” (i.e. lower latitude) storms are consistently farther south over warmer SSTs and are therefore likely characterized by weaker stratification in their warm sectors prior to occlusion. Martin (1999a) showed that synoptic-scale forcing during the process of occlusion (namely, positive vorticity advection (PVA) by the thermal wind (Sutcliffe, 1947)) thrusts some portion of this warm sector air aloft into the trowal. Since nearly all occluded cyclones shown in Fig. 9, occurred in regions where PVA by the thermal wind is routinely involved in development, we suggest that the robust differences in response to such forcing, as manifested in the notable differences in vertical motion, are at least partly, and perhaps largely, a function of the decreasingly stable stratification at lower latitudes.

4. Discussion and Conclusion

The post-mature phase of a mid-latitude cyclone is characterized by a 3-D, sloping thermal ridge, that scientists at the Canadian Meteorological Service termed the trowal (trough of warm air aloft). The trowal is the essential structural feature of a warm-occluded cyclone, and its development not only links to cyclone dynamics, but also influences the distribution and intensity of precipitation.
Though a number of studies (e.g. Schultz and Mass, 1993; Martin, 1998a,b; 1999a,b; Posselt and Martin, 2004; Schultz and Vaughan, 2011) have considered the aspects of the structure, evolution and dynamics of occluded cyclones, there has been no attempt to develop an automated, objective scheme to identify occlusions in gridded data sets. Consequently, current understanding of the structural evolution dynamics and cloud and precipitation distribution associated with occluded cyclones is derived exclusively from the analyses of individual case studies. In order to expand this rather limited perspective on investigations of the occluded stage of the cyclone life cycle, this study describes an automated method to objectively identify such storms and illustrates its applications to the analysis of the global distribution of occluded cyclones, as well as to the construction of composite cross-sections through the OTR.

The detection method, quantified using the $F$-parameter defined in (4), arises from evaluation of the divergence of the unit vector in the direction of the 1000-500 hPa thickness gradient. Regions of convergence (divergence) of the unit vector identify thermal ridges (troughs). With only minor empirical adjustments, we find that the $F$-parameter consistently and accurately identifies the OTR, and therefore, occluded cyclones, in any gridded data set. Coupled with a cyclone tracking algorithm, $F$ can be used to identify the position and track of occluded cyclones around the globe. In this paper, we considered such distribution over the time period of 2006-2011 using the MERRA-2 data set.

The analysis reveals that Northern Hemisphere occlusions occur most frequently during the winter season (DJF) and most often poleward of the mean jet in the Pacific basin and in a strip from the Labrador Sea to the Greenland coast in the Atlantic ocean. On the other hand, occlusions tend to occur poleward of 45°S throughout most of the year in the Southern Hemisphere, and maximize in frequency in SH autumn (MAM). Binning NH winter occlusions according to the value of their respective 700 hPa $\theta_e$ maximum along the thermal ridge axis allows for further categorization of the storms, as well as new insights regarding the influence of the temperature and moisture of warm sector air on the robustness of the resulting occluded thermal structure. Two-thirds of all occlusions had a maximum 700 hPa $\theta_e$ in the range of 293-313 K, while the extremes ranged from as low as 275 K to as high as 335 K. Thus, occluded cyclones were found to occur over a wide range of latitudes during the NH winter. Perhaps unsurprisingly, the analysis found that the intensity of the composite vertical motion in the trowal was generally inversely proportional to the latitude at
which the occlusion occurred, presumably as a result of less stably stratified air being found in the
occluded quadrants of warmer storms. The "colder" occlusion composite also suggested that such
high latitude cyclones tend to have a shallower version of the canonical occluded thermal structure,
while exhibiting less tilt to the axis of maximum $\theta_e$.

The variability in occluded thermal structures and in the intensity of the vertical motion char-
acterizing the 6 varieties of occlusions examined here are almost certainly physically related.
Martin (1999a) found that that convergence of the along-isentrope ($\bar{Q}_s$) component of the $Q$-vector
(Hoskins et al., 1978), closely related to PVA by the thermal wind (Sutcliffe, 1947; Trenberth, 1978)
simultaneously accounts for the production of the OTR and provides the predominant dynamical
forcing for ascent in the occluded quadrant of cyclones. The trowal air stream, a cyclonically
ascending air stream that originates in the warm sector boundary layer and flows through the trowal
is supported by this quasi-geostrophic forcing. The fact that the "warmer" occlusions in the present
analysis have both higher $\theta_e$ feeding the trowal air stream and larger vertical motion within the
trowal leads them to also produce larger amounts of LHR in the occluded quadrant. Additionally, as
the maximum 700 hPa $\theta_e$ in the trowal increases, so does the robustness of the associated occluded
thermal structure (Fig. 11). The coincidence of these structural characteristics in the composites
depicted here offers new evidence for the suggestion made by Posselt and Martin (2004) that the
canonical occluded thermal structure is fundamentally dependent on LHR.

A forthcoming paper will utilize the objective identification scheme illustrated here to construct
composites of the cloud structure, microphysics and precipitation characteristics of a global dis-
tribution of occlusions based on observations from satellite-based radar and lidar profiles. Also
underway is an evaluation of the global distribution of occlusions as portrayed in a free-running
integration of different versions of the GISS GCM (Kelley et al., 2020). Preliminary results of
that analysis suggest that model extratropical cyclones tend to form farther north than those in the
reanalysis. And though the model does produce occlusions that appear realistic, it does so nearly
twice as frequently as the reanalysis. These and other questions regarding the nature of occluded
cyclones in a warmer climate can now be considered quantitatively in light of the success of the
objective identification method outlined here.
References


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<th>MERRA-2 (1.25° × 1°)</th>
<th>MERRA-2 (2.5° × 2°)</th>
<th>NCEP-NCAR (2.5° × 2.5°)</th>
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</thead>
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<td>$F_{max}$</td>
<td>-10^{-9} m^{-1}</td>
<td>-0.5×10^{-9} m^{-1}</td>
<td>-0.5×10^{-9} m^{-1}</td>
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<td>$N_{min}$</td>
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<td>4</td>
<td>4</td>
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<tr>
<td>StdSurf$_{max}$</td>
<td>300 m</td>
<td>150 m</td>
<td>150 m</td>
</tr>
<tr>
<td>$D_{max}$</td>
<td>300 km</td>
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Table 1. Parameter values for each data set and grid resolution used in this study.
Fig. 1. Occluded thermal structure observed over the central United States on 0000 UTC 20 January 1995. (a) 700 hPa equivalent potential temperature ($\theta_e$) at the above time. $\theta_e$ labeled in K and contoured every 2 K. Cross-section along line A-A’ shown in Fig. 1b. (b) Vertical cross-section of $\theta_e$ along line A-A’ in Fig. 1a (from St. Cloud, MN (STC), to Peoria, IL (PIA), to Nashville, TN (BNA) to Peachtree City, GA (FFC) at the aforementioned time. Solid lines are moist isentropes labeled in K and contoured every 3 K. Dashed line indicates the canonical axis of maximum $\theta_e$ that slopes upward and poleward in a warm occlusion. Light (dark) shading represents the cold (warm) frontal baroclinic zone involved in this occluded structure. Adapted from Martin (1998a).
Fig. 2. Schematic illustration of the trowal conceptual model. The blue shaded surface represents the warm edge of the cold frontal baroclinic zone. The pink shaded surface represents the warm edge of the warm frontal baroclinic zone. The thick dashed line (marked "TROWAL") represents the 3-D sloping intersection between the cold and warm frontal zones characteristic of warm occlusions. Schematic precipitation band is indicated as are the positions of the surface warm, cold and occluded fronts. Dark solid line through the precipitation band represents the projection of the trowal to the surface. Adapted from Martin (1999a)
Fig. 3. (a) Schematic tropopause-level potential vorticity (PV) illustrating the treble clef structure characteristic of warm occluded cyclones. PV is labeled in potential vorticity units (PVU) (1 PVU = $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$) and shaded every 1 PVU starting at 1 PVU in lightest shading. (b) Schematic representation of the thermal structure associated with horizontally juxtaposed upper-level positive PV anomalies (as along A-A’ in Fig. 3a). Thin solid lines are schematic isentropes ($\theta$). The thick solid line is the dynamic tropopause. The dashed line indicates the axis of the maximum $\theta$, which extends from the upper-tropospheric PV minimum to the surface. From Martin (1998b)
Fig. 4. (a) Sea-level isobars (solid blue) and 1000-500 hPa thickness (dashed red) analysis from the Climate Forecast System Reanalysis (CFSR) valid at 0000 UTC 1 January 2008. Isobars labeled in hPa and contoured every 4 hPa. Thickness labeled in dm and contoured every 6 dm. Negative $F$-parameter shaded in yellow and contoured every $1 \times 10^{-9}$ m$^{-1}$, starting at $-1 \times 10^{-9}$ m$^{-1}$. (b) Vertical cross-section of $\theta_e$ and $\omega$ along line A-A' in Fig. 4a. $\theta_e$ labeled in K and contoured every 3K with the 303 K isentrope colored red. Yellow shading shows negative $\omega$ contoured every $-2 \mu$bar s$^{-1}$. (c) Isobaric topography of the 303 K $\theta_e$ surface from the same CFSR data set. Thin dashed white lines are isobars on that surface and the thick dashed line is the location of the trawl.
Fig. 5. Illustration of the cluster tracking method. (a) Track of a cyclone in the north Atlantic from 0600 UTC to 1800 UTC 8 January 2008 from the MERRA-2 reanalysis data. Crosses represent the position of the cyclone center at each 6h time, red squares indicate times at which a qualifying cluster deemed the storm occluded, and 'Peak' indicates the time and location of the storm’s peak intensity. (b) 1000-500 hPa thickness (blue solid lines) and sea-level isobars (dotted black lines) at 1200 UTC 6 January 2008 from the MERRA-2 reanalysis data. Thickness (m) is contoured every 60 m. SLP (hPa) and contoured every 4 hPa. Red and black crosses are grid points at which $F < -1 \times 10^{-9}$. Blue triangles are grid points where $STDSur_{f_{\text{max}}}$ exceeds 300 m. Green star is the location of the SLP minimum. Black crosses with gray shaded squares represent grid points in a qualifying cluster (see text for explanation). (c) As in Fig. 5b but for 1800 UTC 6 January 2008. (d) As in Fig. 5b but for 0000 UTC 7 January 2008. (e) As in Fig. 5b but for 0600 UTC 7 January 2008, time of peak intensity.
Fig. 6. Cyclone-relative grid with SLP minimum at (0,0). Sets of colored crosses represent the group of grid points in each of the 6 qualifying clusters from the 6-7 January 2008 cyclone portrayed in Fig. 5.
Fig. 7. Illustration of the method by which the composite cross-section transect line is determined in the objectively identified occlusions. Blue crosses are schematic grid points constituting a qualifying cluster. Green solid lines are 700 hPa $\theta_e$ isentropes. Red solid line is the cross-section transect line.
Fig. 8. Distribution of all 6h occlusions identifications organized by hemisphere and season. Color bar refers to the number of occlusion identifications per \(5^\circ \times 5^\circ\) box in (a) NH winter (DJF), (b) SH winter (JJA), (c) NH spring (MAM), (d) SH spring (SON), (e) NH summer (JJA), (f) SH summer (DJF), (g) NH autumn (SON), and (h) SH autumn (MAM).
Fig. 9. Cumulative distribution function of all NH wintertime occluded identifications stratified by the 700 hPa $\theta_e$ maximum along their respective thermal ridge axes. The 6 categories are referred to as Bins I-VI in the text.
Fig. 10. Geographic distribution of occlusions in (a) Bin I, (b) Bin II, (c) Bin III, (d) Bin IV, (e) Bin V, and (f) Bin VI as identified in Fig. 9
Fig. 11. Composite vertical cross-sections of $\theta_e$ through the OTR in occlusions comprising (a) Bin I, (b) Bin II, (c) Bin III, (d) Bin IV, (e) Bin V, (f) Bin VI as identified in Fig. 9. Black solid lines are $\theta_e$ isentropes labeled in K and contoured and shaded (according to legend) every 3 K. Thin dotted line at $x = 0$ in each cross-section identifies the intersection of the composite transect line and the adjusted thermal ridge axis. Distance along the cross-section is indicated in km; positive for poleward and negative for equatorward.
Fig. 12. Composite vertical motions through the OTR in occlusions comprising (a) Bin I, (b) Bin II, (c) Bin III, (d) Bin IV, (e) Bin V, (f) Bin VI as identified in Fig. 9. Thin solid (dashed) lines are upward (downward) vertical motion labeled in units of dPa s$^{-1}$ and contoured every 4 dPa s$^{-1}$ starting at -2 (2) dPa s$^{-1}$. Thicker gray lines in each panel are three consecutive $\theta_e$ isentropes from the respective panels in Fig. 11, each centered on the isentrope that straddles the midpoint of the cross-section at 700 hPa.