**Upper-Tropospheric Precursors to the Formation of Subtropical Cyclones   
that Undergo Tropical Transition in the North Atlantic Basin**

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**Scientific Basis and Purpose**

The opportunity to examine the structure, motion, and evolution of the various upper-tropospheric precursors to the formation of NATL STCs that undergo TT motivates the present study. The present examines the intraseasonal variability associated with the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features, as well as compares and contrasts the various upper-tropospheric precursors to the formation of NATL STCs that undergo TT. In the present study, the climatological study of Bentley et al. (2016) is used as the basis for a comprehensive cyclone-relative composite analysis of the upper-tropospheric precursors to the formation of NATL STCs that undergo TT during 1979–2010. In contrast to NATL STCs in previous studies, NATL STCs in the present study will be subjectively categorized according to the upper-tropospheric features associated with their formation. Such categorization allows for the documentation of the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features and for the construction of cyclone-relative composites on the five days prior to NATL STC formation.

1. **Introduction** 
   * 1. Tropical cyclones (TCs) forming in the presence of an upper-tropospheric disturbance (i.e., an upper-tropospheric low or trough) comprise ~21% of TCs forming globally during 1948–2010 (McTaggart-Cowan et al. 2013).
     2. The percentage of North Atlantic (NATL) TCs forming in the presence of an upper-tropospheric disturbance during 1948–2010 (~46%) is more than twice the global average, likely associated with the more frequent occurrence of upper-tropospheric disturbances over the NATL relative to other oceans where tropical cyclogenesis occurs (Nieto et al. 2005; Wernli and Sprenger 2007).
     3. Previous studies by McTaggart-Cowan et al. (2013) and Galarneau et al. (2015) suggest that upper-tropospheric disturbances associated with NATL tropical cyclogenesis typically form in conjunction with anticyclonic wave breaking (AWB) (e.g., McIntyre and Palmer 1983; Thorncroft et al. 1993; Postel and Hitchman 1999; Wernli and Sprenger 2007; Martius et al. 2008), which occurs in response to the nonlinear amplification of Rossby waves (e.g., Abatzoglou and Magnusdottir 2006; Martius et al. 2010; Zhang et al. 2016).
     4. Upper-tropospheric disturbances forming in conjunction with AWB are referred to by a variety of names [e.g., cutoff lows (e.g., Palmén and Newton 1969, their section 10.2; Nieto et al. 2005); potential vorticity (PV) streamers (e.g., Appenzeller and Davies 1992; Martius et al. 2008; Galarneau et al. 2015); tropical upper-tropospheric trough (TUTT) cells (e.g., Sadler 1976; Ferreira and Schubert 1999; Patla et al. 2009)] and have the potential to facilitate NATL tropical cyclogenesis in environments characterized by relatively low sea surface temperatures (SSTs) (e.g., Mauk and Hobgood 2012; McTaggart-Cowan et al. 2015) and high vertical wind shear (e.g., Bracken and Bosart 2000; McTaggart-Cowan et al. 2008, 2013).
     5. According to Galarneau et al. (2015), NATL TCs forming in the presence of an upper-tropospheric disturbance develop from either the favorable interaction of a preexisting lower-tropospheric cyclonic vorticity center with an upper-tropospheric trough (e.g., Molinari et al. 1995) or the tropical transition (TT; Davis and Bosart 2003, 2004) of a subtropical cyclone (STC) (e.g., Roth 2002; Guishard et al. 2007; Evans and Guishard 2009; Guishard et al. 2009; González-Alemán et al. 2015; Bentley et al. 2016).
     6. A recent climatology of NATL STCs that undergo TT constructed by Bentley et al. (2016) from the global climatology of baroclinically induced tropical cyclogenesis created by McTaggart-Cowan et al. (2013) reveals that 62 NATL TCs forming during 1979–2010 develop from STCs that undergo TT.
     7. STCs that undergo TT preferentially form over the western NATL (Bentley et al. 2016), likely associated with the frequent overlap of relatively high SSTs and intrusions of relatively cold upper-tropospheric air accompanying upper-tropospheric disturbances in that portion of the basin (Wernli and Sprenger 2007, their Fig. 6).
     8. An intrusion of relatively cold upper-tropospheric air accompanying an upper-tropospheric disturbance over the western NATL is likely to steepen lapse rates beneath the disturbance and facilitate the development of deep convection, which serves as a catalyst for STC formation (e.g., Guishard et al. 2009; Bentley et al. 2016).
     9. Previous studies by Evans and Guishard (2009) and González-Alemán et al. (2015) used cyclone-relative composite analysis to examine the upper-tropospheric features associated with NATL STC formation.
     10. Evans and Guishard (2009) constructed cyclone-relative composites of 18 STCs identified over the western and central NATL during 1999–2004 using the 2.5° NCEP–NCAR reanalysis dataset (Kalnay et al. 1996), whereas González-Alemán et al. (2015) constructed cyclone-relative composites of 15 STCs identified over the northeastern NATL during 1979–2011 using the 0.75° ECMWF interim reanalysis dataset (Dee et al. 2011).
     11. Both Evans and Guishard (2009; their Fig. 7) and González-Alemán et al. (2015; their Fig. 5) indicate the presence of a meridional trough located slightly upstream of and over the STC center at the time of STC formation that slowly approached the STC center from the west during the previous 24 h.
     12. Individual upper-tropospheric features differ in structure across composite members in Evans and Guishard (2009) and González-Alemán et al. (2015), suggesting that the upper-tropospheric precursors to the formation of NATL STCs that undergo TT may differ as well.
     13. The opportunity to examine the structure, motion, and evolution of the various upper-tropospheric precursors to the formation of NATL STCs that undergo TT motivates the present study.
     14. The present study examines the intraseasonal variability associated with the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features, as well as compares and contrasts the various upper-tropospheric precursors to the formation of NATL STCs that undergo TT.
     15. In the present study, the climatological study of Bentley et al. (2016) is used as the basis for a comprehensive cyclone-relative composite analysis of the upper-tropospheric precursors to the formation of NATL STCs that undergo TT during 1979–2010.
     16. In contrast to NATL STCs in previous studies, NATL STCs in the present study will be categorized according to the upper-tropospheric features associated with their formation.
     17. Such categorization allows for the documentation of the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features and for the construction of cyclone-relative composites on the five days prior to NATL STC formation.
     18. The remainder of this paper is organized as follows. The data and methodology used to categorize NATL STCs that undergo TT, as well as construct cyclone-relative composites of the upper-tropospheric precursors to NATL STC formation, are described in section 2.
     19. Section 3 contains climatological results, including a discussion of the intraseasonal variability associated with the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features.
     20. Section 4 presents cyclone-relative composite analyses of the upper-tropospheric precursors to the formation of NATL STCs that undergo TT.
     21. Results of the present study are discussed and conclusions are presented in section 5.
2. **Data and methodology**
   1. *Categorization of NATL STCs that undergo TT*
      1. In order to examine the upper-tropospheric precursors to the formation of NATL STCs that undergo TT, all 62 NATL STCs that undergo TT identified during 1979–2010 by Bentley et al. (2016) are separated into categories according to the upper-tropospheric feature associated with their formation.
      2. All 62 NATL STCs that undergo TT are required to form in the presence of a cold-core upper-tropospheric disturbance and be classified as TCs in the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al. 2010) during their life cycle.
      3. The time of STC formation (i.e., *t*0) is determined using the objective STC identification technique described in Bentley et al. (2016).
      4. Previous studies of baroclinically influenced tropical cyclogenesis have subjectively categorized NATL TCs based on visual inspection of the upper-tropospheric features associated with their formation (e.g., Bracken and Bosart 2000; Galarneau et al. 2015). A similar approach will be used in the present study in order to categorize NATL STCs.
      5. Visual inspection of the 250–150-hPa layer-average PV, geopotential height, and wind fields over the NATL every 24 h between *t*0 − 120 h and *t*0 in the 0.5° NCEP Climate Forecast System Reanalysis (CFSR) dataset (Saha et al. 2010) results in the identification of four upper-tropospheric features associated with NATL STC formation: 1) cutoff lows, 2) meridional troughs, 3) zonal troughs, and 4) subtropical disturbances.
      6. These four upper-tropospheric features exhibit characteristic structures and evolutions between *t*0 − 120 h and *t*0 that make them distinguishable from each other.
      7. Figure 1 shows the 250–150-hPa layer-average PV, geopotential height, and wind fields over the NATL at *t*0 for representative examples of STCs forming in association with a cutoff low, meridional trough, zonal trough, and subtropical disturbance.
      8. NATL STCs forming in association with a cutoff low [e.g., Otto (0000 UTC 27 Nov 2004); Fig. 1a] were included in the cutoff low category (*N* = 13). In order for an STC to be included in this category, the cutoff low linked to STC formation must develop in response to AWB occurring to the north of the location of STC formation between *t*0 − 120 h and *t*0.
      9. NATL STCs forming in association with a meridional trough [e.g., Olga (0600 UTC 25 Nov 2001); Fig. 1b] were included in the meridional trough category (*N* = 15). In order for an STC to be included in this category, the meridional trough linked to STC formation must approach the location of STC formation from the west between *t*0 − 120 h and *t*0 and not develop in response to AWB.
      10. Both cutoff lows and meridional troughs typically form in association with the amplification of midlatitude Rossby waves, although no latitudinal restrictions were implemented during the categorization of upper-tropospheric features.
      11. NATL STCs forming in association with a zonal trough [e.g., Unnamed (0000 UTC 24 Jul 1986); Fig. 1c] were included in the zonal trough category (*N* = 12). In order for an STC to be included in this category, the zonal trough linked to STC formation must approach the location of STC formation from the east between *t*0 − 120 h and *t*0, to the south of a region where AWB is occurring.
      12. NATL STCs forming in association with a subtropical disturbance [e.g., Josephine (0600 UTC 8 Oct 1984); Fig. 1d] were included in the subtropical disturbance category (*N* = 12). In order for an STC to be included in this category, the subtropical disturbance (i.e., relatively thin upper-tropospheric trough) linked to STC formation must develop in response to AWB occurring to the west of the location of STC formation and approach the location of STC formation from the west between *t*0 − 120 h and *t*0.
      13. A total of 10 NATL STCs that undergo TT did not form in association with a cutoff low, meridional trough, zonal trough, or subtropical disturbance and were considered unclassifiable.
      14. The subjective categorization of NATL STCs that undergo TT is tested for objectivity using an empirical orthogonal function (EOF) analysis (e.g., Richman 1986) applied to all 250–150-hPa layer-average PV fields associated with NATL STC formation at *t*0, where all 250–150-hPa layer-average PV fields are shifted so that the location of STC formation is collocated with the mean location of STC formation (27.8°N, 63.4°W).
      15. Principal components (PCs) computed from the EOF analysis are defined based on the projection of individual 250–150-hPa layer-average PV fields on the EOFs.
      16. NATL STCs with similar PCs are associated with similar patterns of 250–150-hPa layer-average PV at *t*0, suggesting that these NATL STCs may form in association with similar upper-tropospheric features.
      17. Figure 2a depicts the relationship between the subjective categorization of NATL STCs that undergo TT and the location of each NATL STC in a phase space defined by the first and second PCs of the EOF analysis (i.e., PC1 and PC2).
      18. Figure 2a illustrates that NATL STCs included in the same subjectively constructed category are located in similar quadrants of the PC1–PC2 phase space, suggesting that the structure of subjectively identified upper-tropospheric features associated with NATL STC formation are objectively similar at *t*0 to first order.
      19. Figures 2b,c, which depict the structure of the first and second EOFs (i.e., EOF1 and EOF2) in the domain within which the EOF analysis is performed, reveal the structure of the 250–150-hPa layer-average PV field described by PC1 and PC2.
      20. EOF1 describes a quasi-uniform change in the magnitude of the 250–150-hPa layer-average PV field. Higher values of PC1 are associated with overall lower values of 250–150-hPa layer-average PV, whereas lower values of PC1 are associated with overall higher values of 250–150-hPa layer-average PV.
      21. EOF2 describes a meridional dipole in the 250–150-hPa layer-average PV field. Higher values of PC2 are associated with lower values of 250–150-hPa layer-average PV to the north of the location of STC formation and higher values of 250–150-hPa layer-average PV over and to the east of the location of STC formation. Lower values of PC2 are associated with higher values of 250–150-hPa layer-average PV to the north of the location of STC formation and lower values of 250–150-hPa layer-average PV over and to the east of the location of STC formation.
      22. NATL STCs forming in association with cutoff lows and meridional troughs are associated with lower values of PC1, or overall higher values of 250–150-hPa layer-average PV, than NATL STCs forming in association with zonal troughs or subtropical disturbances (Figs. 2a,b).
      23. NATL STCs forming in association with cutoff lows and zonal troughs are associated with higher values of PC2, or lower values of 250–150-hPa layer-average PV to the north of the location of STC formation and higher values of 250–150-hPa layer-average PV over and to the east of the location of STC formation, than NATL STCs forming in association with meridional troughs and subtropical disturbances (Figs. 2a,c).
      24. The structures of the 250–150-hPa layer-average PV field described by PC1 and PC2 are consistent with the structures and processes identified during the subjective categorization of NATL STCs that undergo TT.
      25. Possible discrepancies between the subjective categorization of NATL STCs and their position in the PC1–PC2 phase space (e.g., the close proximity of NATL STCs forming in association with zonal troughs and subtropical disturbances) can be explained by considering the different evolutions of these features in the 250–150-hPa layer-average PV field between *t*0 − 120 h and *t*0 that are not captured by the EOF analysis applied to all 250–150-hPa layer-average PV fields associated with NATL STC formation at *t*0.
   2. *Cyclone-relative compositing methodology* 
      1. Composite analyses of NATL STCs that undergo TT are constructed in a cyclone-relative framework. Fields associated with each STC are shifted so that the location of STC formation is collocated with the mean location of STC formation within each category at *t*0.
      2. Cyclone-relative composites are constructed for each category from the NCEP CFSR dataset (Saha et al. 2010), which is available with 0.5° horizontal grid spacing and 6-h temporal resolution.
      3. The statistical significance of the composite 250–150-hPa layer-averaged meridional wind field is assessed with respect to a long-term (i.e., 1979–2009) climatology derived from the 0.5° NCEP CFSR dataset using a two-sided Student’s *t* test (e.g., Wilks 2006, see section 5.2.1).
3. **Climatological results** 
   * 1. All 62 NATL STCs that undergo TT identified during 1979–2010 by Bentley et al. (2016) are separated into categories in section 2a of present study according to the upper-tropospheric feature associated with their formation: 1) cutoff low (*N* = 13), 2) meridional trough (*N* = 15), 3) zonal trough (*N* = 12), 4) subtropical disturbance (*N* = 12), and 5) unclassifiable (*N* = 10).
     2. Figure 3 compares the upper-tropospheric feature associated with STC formation to the environment within which STC formation occurred, binning all 62 NATL STCs by the McTaggart-Cowan et al. (2013) development pathway associated with their formation (strong TT, weak TT, or trough induced).
     3. NATL STCs forming in association with cutoff lows and meridional troughs comprise 22 of the 30 STCs classified as strong TT (i.e., STCs forming in the presence of an upper-tropospheric disturbance and strong lower-tropospheric thermal gradients).
     4. NATL STCs forming in association with zonal troughs and subtropical disturbances comprise 16 of the 28 STCs classified as weak TT (i.e., STCs forming in the presence of an upper-tropospheric disturbance and moderate lower-tropospheric thermal gradients) and all 4 STCs classified as trough induced (i.e., STCs forming in the presence of an upper-tropospheric disturbance and without appreciable lower-tropospheric thermal gradients).
     5. These results suggest that NATL STCs forming in association with cutoff lows and meridional troughs typically form in more baroclinic environments than NATL STCs forming in association with zonal troughs and subtropical disturbances.
     6. The results of Bentley et al. (2016; their Fig. 9) indicate that a relationship exists between the McTaggart-Cowan et al. (2013) development pathway associated with STC formation and the location of STC formation in the NATL basin. The results of the present study suggest that a relationship may also exist between the upper-tropospheric feature associated with STC formation and the location of STC formation in the NATL basin.
     7. Figure 4 illustrates the location of NATL STC formation during 1979–2010, colored according to the upper-tropospheric feature associated with formation.
     8. STCs forming in association with cutoff lows and meridional troughs typically develop poleward of ~25°N over the western NATL and comprise all classifiable STCs forming over the eastern NATL.
     9. The results of Bentley et al. (2016; their Fig. 9) suggest that the majority of STCs developing poleward of ~25°N over the western NATL and eastern NATL are classified as strong TT by McTaggart-Cowan et al. (2010), consistent with the results of Fig. 3 in the present study.
     10. STCs forming in association with zonal troughs and subtropical disturbances typically develop equatorward of ~30°N over the western NATL.
     11. The results of Bentley et al. (2016; their Fig. 9) suggest that the majority of STCs developing equatorward of ~30°N over the western NATL are classified as weak TT and trough induced by McTaggart-Cowan et al. (2010), consistent with the results of Fig. 3 in the present study.
     12. A region of overlap between STCs forming in association with cutoff lows, meridional troughs, zonal troughs, and subtropical disturbances exists in the western NATL basin off the east coast of Florida.
     13. This region of overlap is likely attributable to frequent Rossby wave amplification and AWB in the western and central NATL during boreal summer (e.g., Postel and Hitchman 2001), which allows for the development of a variety of the upper-tropospheric features associated with NATL STC formation off the east coast of Florida.
     14. The results of Bentley et al. (2016; their Fig. 11) indicate that considerable intraseasonal variability is associated with the McTaggart-Cowan et al. (2013) classification of NATL STCs during 1979–2010, suggesting that intraseasonal variability may also be associated with the subjective categorization of NATL STCs in the present study.
     15. Figure 5 illustrates the intraseasonal variability associated with NATL STC formation, binning NATL STCs by the month during which they formed (April–December).
     16. STCs forming in association with cutoff lows and meridional troughs typically form during April and October–December, corresponding to the typical period of strong TT formation identified in Bentley et al. (2016).
     17. STCs forming in association with zonal troughs and subtropical disturbances typically form during June–September, corresponding to the typical period of weak TT and trough induced formation identified in Bentley et al. (2016).
     18. STCs forming in association with unclassifiable upper-tropospheric features occur sporadically during April–December and exhibit no discernible intraseasonal variability.
     19. The mean values of SST, precipitable water (PW), vertical wind shear (VWS), and coupling index (CI), averaged within a 3° × 3° box over each STC at *t*0, are given in Table 1 for STCs forming in association with cutoff lows, meridional troughs, zonal troughs, and subtropical disturbances.
     20. The CI, a measure of bulk column stability, is defined as the difference between potential temperature on the dynamic tropopause (DT) and equivalent potential temperature at 850 hPa (Bosart and Lackmann 1995), while VWS is defined as

VWS, (1)

where () is the u-component of the wind at 200 hPa (850 hPa) and () is the v-component of the wind at 200 hPa (850 hPa).

* + 1. STCs forming in association with cutoff lows exhibit the lowest mean SST and PW values, as well as the second highest mean VWS values, of any category (Table 1).
    2. Although low SST values and high VWS values have traditionally been deemed unfavorable for tropical cyclogenesis (e.g., Palmén 1948; Gray 1968; and DeMaria et al. 2001), such detriments may be overcome in regions of reduced bulk column stability (e.g., Mauk and Hobgood 2012; McTaggart-Cowan et al. 2015).
    3. STCs forming in association with cutoff lows exhibit the lowest mean CI values of any category (Table 1), suggesting that sufficient instability exists to facilitate the development of deep convection, which serves as a catalyst for STC formation (e.g., Guishard et al. 2009; Bentley et al. 2016).
    4. A complementary examination reveals that CI values are less than the 22.5°C threshold for TT derived in McTaggart-Cowan et al. (2015) for all 13 NATL STCs forming in association with cutoff lows (Fig. 6), suggesting the importance of reduced bulk column stability in their formation.
    5. STCs forming in association with meridional troughs exhibit the second lowest mean SST and PW values, as well as the highest mean VWS values, of any category (Table 1).
    6. The mean CI value of STCs forming in association with meridional troughs is considerably higher than that of STCs forming in association with cutoff lows (Table 1), with individual CI values ranging from ~5.9°C to ~45.8°C (Fig. 6).
    7. It is possible that the vertical motion required for the development of deep convection is forced by a combination of quasigeostrophic (QG) forcing for ascent and reduced bulk column stability for STCs forming in association with meridional troughs (not shown), with stronger QG forcing for ascent potentially compensating for the relatively high CI values shown in Fig. 6.
    8. The mean values of SST, PW, and VWS of STCs forming in association with zonal troughs and subtropical disturbances are fairly similar, with higher (lower) mean SST and PW (VWS) values than STCs forming in association with cutoff lows and meridional troughs (Table 1).
    9. Similarities between STCs forming in association with zonal troughs and subtropical disturbances arise from similarities in the location and seasonal distribution of their formation (Figs. 4,5).
    10. The mean CI value of STCs forming in association with zonal troughs is lower than that of STCs forming in association with subtropical disturbances (Table 1), likely associated with the presence of moister tropospheric air near the location of STC formation at t0 (Table 1) and an increase value of 850-hPa equivalent potential temperature (not shown).

1. **Cyclone-relative composite results**
   1. *Cutoff low composites*
      1. Figure 7 displays cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a cutoff low at 24-h intervals between *t*0 − 120 h and *t*0.
      2. At *t*0 − 120 h (Figs. 7a,b), a low-amplitude upper-tropospheric trough is located over the west coast of North America. This low-amplitude upper-tropospheric trough progresses eastward over the following 24 h (Figs. 7a–d), exciting downstream ridge amplification over central and eastern North America.
      3. By *t*0 − 72 h (Figs. 7e,f), continued downstream ridge amplification over central and eastern North America and subsequent trough amplification over the western NATL highlight the development of an eastward dispersing Rossby wave train (RWT; e.g., Riemer et al. 2008; Harr and Dea 2009) with alternating northerly and southerly upper-tropospheric winds extending from the west coast of North America into the central NATL.

* + 1. Individual Rossby waves constituting the RWT progress eastward and amplify between *t*0 − 72 h and *t*0 − 48 h (Figs. 7e–h), resulting in the formation of a >40 m s−1 upper-tropospheric jet over eastern North America.
    2. The upper-tropospheric ridge located over eastern North America at *t*0 − 72 h (Figs. 7e,f) develops a positive tilt over the east coast of North America by *t*0 − 48 h (Figs. 7g,h), indicative of the early stages of AWB over the western NATL.
    3. Irrotational winds >2 m s−1 are directed from west to east across the upper-tropospheric ridge axis at this time, aiding in the amplification of the downstream trough over the central NATL through negative PV advection by the irrotational wind (not shown).
    4. CI values beneath the downstream trough axis are <22.5°C at *t*0 − 48 h, indicative of reduced bulk column stability over and surrounding the location of STC formation at *t*0.

* + 1. By *t*0 − 24 h (Figs. 7i,j), the positive tilt of the upper-tropospheric ridge and meridional winds over the western NATL has become even more pronounced.
    2. The upper-tropospheric trough over the central NATL extends equatorward of 30°N at this time, resulting in an expansion of CI values <22.5°C in the vicinity of the location of STC formation (Fig. 7j). Continued AWB over the western NATL causes the southern portion of the upper-tropospheric trough to form into a cutoff low over the location of STC formation by *t*0 (Figs. 7g–l).
    3. CI values beneath the cutoff low remain <22.5°C at *t*0, indicative of reduced bulk column stability over and surrounding the location of STC formation.
  1. *Meridional trough composites*
     1. Figure 8 displays cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a meridional trough at 24-h intervals between *t*0 − 120 h and *t*0.
     2. At *t*0 − 120 h (Figs. 8a,b), an upper-tropospheric trough is located over western North America. This upper-tropospheric trough progresses eastward over the following 24 h (Figs. 8a–d), exciting downstream ridge amplification over central and eastern North America in response to enhanced southerly flow in the upper-troposphere over northern Mexico and the southern United States.
     3. By *t*0 − 72 h (Figs. 8e,f), continued downstream ridge amplification over central and eastern North America and subsequent trough amplification over the western NATL highlight the development of an eastward dispersing RWT with alternating northerly and southerly upper-tropospheric winds extending from western North America into the western NATL.
     4. Individual Rossby waves constituting the RWT progress slowly eastward and continue to amplify between *t*0 − 72 h and *t*0 − 48 h (Figs. 8e–h).
     5. The magnitude and areal extent of 250-hPa southerly winds downstream of the upper-tropospheric ridge located over eastern North America increases during this period (Figs. 8e,g) in association with the meridional alignment of the upper-tropospheric trough over the western NATL with an upper-tropospheric trough located in the northern stream over southeastern Canada (Figs. 8e–h).
     6. A broad region of 250–150-hPa layer-averaged irrotational winds >2 m s−1 develops just downstream of the upper-tropospheric trough located over the western NATL at *t*0 − 48 h (Fig. 8g), indicative of upward vertical motion and developing deep convection (not shown).
     7. The southern portion of upper-tropospheric trough located over the western NATL remains stationary and amplifies over the following 24 h (Figs. 8g–j), held in place by negative PV advection by the irrotational wind just downstream (not shown).
     8. The northern portion of upper-tropospheric trough progresses eastward during this period in association with a >25 m s−1 upper-tropospheric jet over southern Canada (Figs. 8g–j).
     9. The southern portion of upper-tropospheric trough remains stationary and continues to amplify between *t*0 − 24 h and *t*0 (Figs. 8i–l), with a relatively small region of CI values <22.5°C positioned over the location of STC formation at *t*0 (Fig. 8l).
  2. *Zonal trough composites*
     1. Figure 9 displays cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a zonal trough at 24-h intervals between *t*0 − 120 h and *t*0.
     2. An upper-tropospheric trough is located over the southwestern NATL at *t*0 − 120 h (Figs. 9a,b), deposited into the subtropics during a previous period of AWB associated with the upper-tropospheric ridge located to the east of the Canadian Maritimes (not shown).
     3. The upper-tropospheric trough remains stationary over the southwestern NATL over the following 24 h, well removed from the >30 m s−1 upper-tropospheric jet located over eastern North America during this period (Figs. 9a–d).
     4. By *t*0 − 72 h (Figs. 9e,f), a positively tilted upper-tropospheric ridge has begun to amplify over eastern North America. The continued amplification and tilting of this upper-tropospheric ridge over the following 24 h (Figs. 9e–h) is indicative of AWB occurring over the western NATL.
     5. The upper-tropospheric trough located over the southwestern NATL extends westward and becomes increasingly zonally oriented between *t*0 − 72 h and *t*0 − 48 h in response to AWB occurring over the western NATL and >10 kt easterly winds in the 250–150-hPa layer near ~30°N (Figs. 9e–h).
     6. This upper-tropospheric trough continues to extend westward over the following 24 h (Figs. 9g–j), with divergent outflow in the 250–150-hPa layer-averaged irrotational wind field suggesting the development of deep convection over the southwestern NATL and northern Caribbean by *t*0 − 24 h (Fig. 9i).
     7. The western edge of the upper-tropospheric trough reaches the east coast of Florida by *t*0, equatorward of the region of AWB (Figs. 9k,l).
     8. Northerly (southerly) 250-hPa winds >8 m s−1 (>4 m s−1) have developed on the western edge of the upper-tropospheric trough at this time (Fig. 9k).
     9. CI values over the location of STC formation decrease from ~\_\_\_°C to ~\_\_\_\_°C between *t*0 − 120 h and *t*0 (Figs. 9b,l), indicating that the atmosphere has become sufficiently unstable between 850-hPa and the DT for TT to occur.
  3. *Subtropical disturbance composites*
     1. Figure 10 displays cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a subtropical disturbance at 24-h intervals between *t*0 − 120 h and *t*0.
     2. Similar to cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a cutoff low (Fig. 7), cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a subtropical disturbance highlight AWB over the western NATL prior to STC formation (Fig. 10).
     3. In contrast to the AWB in the cutoff low composite (Fig. 7), the AWB depicted in the subtropical disturbance composite (Fig. 10) is considerably weaker, occurs at lower latitudes, and does not result in the formation of a robust cutoff low.
     4. At *t*0 − 120 h (Figs. 10a,b), alternating northerly and southerly upper-tropospheric winds extending from the eastern North Pacific into the central NATL highlight a RWT with an upper-tropospheric trough over the eastern North Pacific, ridge over western North America, and a trough over eastern North America.
     5. Individual Rossby waves constituting the RWT progress eastward and amplify over the following 48 h (Figs. 10a–f), with an upper-tropospheric ridge (trough) located over central North America (the western NATL) by *t*0 − 72 h (Figs. 10e,f).
     6. The upper-tropospheric ridge located over central North America at *t*0 − 72 h (Figs. 10e,f) amplifies and exhibits a positive tilt by *t*0 − 48 h (Figs. 10g,h).
     7. The continued tilting of this upper-tropospheric ridge and surrounding 250-hPa meridional winds over the following 24 h (Figs. 9e–h) are indicative of AWB occurring over eastern North America.
     8. The upper-tropospheric trough over the western NATL amplifies and thins between *t*0 − 72 h and *t*0 − 24 h (Figs. 10e–j) in response to negative PV advection by the 250–150-hPa layer-averaged irrotational wind field within the upstream upper-tropospheric ridge axis.
     9. By *t*0 (Figs. 10k,l), northerly (southerly) 250-hPa winds >8 m s−1 (>4 m s−1) have developed on the western (eastern) sides of the upper-tropospheric trough (Fig. 10k).
     10. CI values over the location of STC formation decrease from ~\_\_\_°C to ~\_\_\_\_°C between *t*0 − 120 h and *t*0 (Figs. 10b,l), indicating that the atmosphere has become sufficiently unstable between 850-hPa and the DT for TT to occur.

1. **Discussion and conclusions**
   * 1. In the present study, the climatological study of Bentley et al. (2016) is used as the basis for a comprehensive cyclone-relative composite analysis of the upper-tropospheric precursors to the formation of NATL STCs that undergo TT during 1979–2010.
     2. In contrast to NATL STCs included in previously constructed cyclone-relative composites of NATL STC formation (e.g., Evans and Guishard 2009; González-Alemán et al. 2015), NATL STCs in the present study are categorized according to the upper-tropospheric features associated with their formation.
     3. Such categorization allows for the documentation of the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features and for an examination of the structure, motion, and evolution of the various upper-tropospheric precursors to the formation of NATL STCs that undergo TT.
     4. Visual inspection of the 250–150-hPa layer-average PV, geopotential height, and wind fields over the NATL every 24 h between *t*0 − 120 h and *t*0 for all 62 NATL STCs that undergo TT included in the climatological study of Bentley et al. (2016) results in the identification of four distinct upper-tropospheric features associated with NATL STC formation: 1) cutoff lows, 2) meridional troughs, 3) zonal troughs, and 4) subtropical disturbances.
     5. These four distinct upper-tropospheric features exhibit characteristic structures and evolutions between *t*0 − 120 h and *t*0 that make them distinguishable from each other.
     6. The subjective categorization of NATL STCs that undergo TT through visual inspection is tested for objectivity using an EOF analysis applied to all 250–150-hPa layer-average PV fields associated with NATL STC formation at *t*0.
     7. The results of the EOF analysis indicate that the structures of subjectively identified upper-tropospheric features associated with NATL STC formation are objectively similar at *t*0, and support the subjective categorization of NATL STCs that undergo TT through visual inspection.
     8. NATL STCs forming in association with a cutoff low were included in the cutoff low category (*N* = 13). NATL STCs included in the cutoff low category are exclusively classified as strong TT or weak TT by McTaggart-Cowan et al. (2013) and typical form poleward of ~25°N during the shoulder seasons.
     9. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a cutoff low highlight the importance of downstream baroclinic development and AWB in cutoff low formation.
     10. A schematic representation of an STC forming in association with a cutoff low is shown in Fig. 11.
     11. NATL STCs forming in association with a meridional trough were included in the meridional trough category (*N* = 15). Similar to NATL STCs included in the cutoff low category, NATL STCs included in the meridional trough category are exclusively classified as strong TT or weak TT by McTaggart-Cowan et al. (2013) and typically form poleward of ~25°N during the shoulder seasons.
     12. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a meridional trough highlight the importance of downstream baroclinic development and the meridional alignment of northern and southern streams in meridional trough formation.
     13. A schematic representation of an STC forming in association with a meridional trough is shown in Fig. 12.
     14. NATL STCs forming in association with a zonal trough were included in the zonal trough category (*N* = 12). In contrast to NATL STCs included in the cutoff low and meridional trough categories, NATL STCs included in the zonal trough category are primarily classified as weak TT and trough induced by McTaggart-Cowan et al. (2013) and typically form equatorward of ~30°N during boreal summer.
     15. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a zonal trough highlight the importance of AWB along the eastern edge of the dominant subtropical high in the formation and westward progression of zonal troughs.
     16. A schematic representation of an STC forming in association with a zonal trough is shown in Fig. 13.
     17. NATL STCs forming in association with a zonal trough were included in the zonal trough category (*N* = 12). In contrast to NATL STCs included in the cutoff low and meridional trough categories, NATL STCs included in the zonal trough category are primarily classified as weak TT and trough induced by McTaggart-Cowan et al. (2013) and typically form equatorward of ~30°N over the western NATL during boreal summer.
     18. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a zonal trough highlight the importance of AWB along the eastern edge of the dominant subtropical high in the formation and westward progression of zonal troughs.
     19. A schematic representation of an STC forming in association with a zonal trough is shown in Fig. 13.
     20. NATL STCs forming in association with a subtropical disturbance were included in the subtropical disturbance category (*N* = 12).
     21. In contrast to NATL STCs included in the cutoff low, meridional trough, and zonal trough categories, NATL STCs included in the subtropical disturbance category are primarily classified as strong TT and weak TT by McTaggart-Cowan et al. (2013) and typically form equatorward of ~30°N over the western NATL during boreal summer.
     22. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a subtropical disturbance highlight the importance of downstream baroclinic development and AWB in cutoff low formation.
     23. A schematic representation of an STC forming in association with a subtropical disturbance is shown in Fig. 14.
     24. The results of the present study indicate that 37 (~60%) of the 62 NATL STCs that undergo TT identified during 1979–2010 by Bentley et al. (2016) form in association with an upper-tropospheric feature whose structure, motion, and evolution are linked to AWB.
     25. While the presence of upper-tropospheric features deposited into the subtropics during AWB has been shown to be detrimental to NATL TC formation equatorward of ~20°N (e.g., Zhang et al. 2016), the results of the present study suggest that AWB plays an important role in facilitating NATL STC and TC formation poleward of ~20°N.
     26. Questions remain unanswered concerning the influence of the various upper-tropospheric precursors to NATL STC formation identified in the present study on the predictability of developing STCs.
     27. The authors hypothesize that some of the pathways to STC formation identified in this study are inherently less predictable than others (e.g., Grazzini and Vitart 2015; Quinting and Jones 2016) and additional research is needed to address this hypothesis.

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**TABLE**

TABLE 1. Means and standard deviations of SST, PW, VWS, and CI, calculated within a 3° × 3° box centered over each STC at *t*0.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | | SST (°C) | PW (mm) | VWS (m s−1) | CI (°C) |
| Cutoff low  (*N* = 13) | Mean | 25.0 | 35.7 | 15.0 | 9.6 |
| Std dev | 2.7 | 7.7 | 7.6 | 6.0 |
| Meridional trough  (*N* = 15) | Mean | 25.3 | 42.5 | 16.0 | 20.0 |
| Std dev | 1.9 | 5.2 | 6.3 | 13.1 |
| Zonal trough  (*N* = 12) | Mean | 28.3 | 53.1 | 11.0 | 14.9 |
| Std dev | 0.8 | 5.5 | 4.8 | 7.2 |
| Subtropical disturbance  (*N* = 12) | Mean | 28.1 | 49.5 | 10.8 | 20.0 |
| Std dev | 0.9 | 5.9 | 4.2 | 9.7 |

**FIGURE CAPTIONS**

FIG. 1. Analyses showing 250–150-hPa layer-average PV (shaded according to colorbar, PVU), geopotential height (black contours, every 5 dam), and winds (flags and barbs, kt) at *t*0 for STCs forming in association with a (a) cutoff low [Otto (0000 UTC 27 Nov 2004)], (b) meridional trough [Olga (0600 UTC 25 Nov 2001)], (c) zonal trough [Unnamed (0000 UTC 24 Jul 1986)], and (d) subtropical disturbance [Josephine (0600 UTC 8 Oct 1984)]. The STC symbol in each panel denotes the location of STC formation.

FIG. 2. Graphical representation of the results of an EOF analysis applied to all 250–150-hPa layer-average PV fields associated with STC formation at *t*0. Panel (a) depicts the location of STCs in a phase space defined by PC1 and PC2. The color of each dot represents the subjective categorization of each STC, according to the legend. An X enclosed by a circle denotes the mean values of PC1 and PC2 associated with STCs included in each subjectively constructed cluster, shaded according to the legend. Panels (b) and (c) depict the structure of EOF1 and EOF2, respectively (shaded according to colorbar, PVU), as well as the mean value of 250–150-hPa layer-average PV at *t*0 for all STCs (black contours, PVU). The percentage of the variance described by each EOF appears in the lower left corner of panels (b) and (c).

FIG. 3. Frequency distribution of STC formation in the NATL basin during 1979–2010 binned by McTaggart-Cowan et al. (2013) development pathway (Strong TT, Weak TT, Trough Induced). Colored regions represent the number of STCs forming in association with a particular upper-tropospheric feature, according to the legend.

FIG. 4. Locations of STC formation in the NATL basin during 1979–2010. The color of each dot represents the upper-tropospheric feature associated with STC formation, according to the legend.

FIG. 5. Frequency distribution of STC formation in the NATL basin during 1979–2010 binned by month (April–December). Colored regions represent the number of STCs forming in association with a particular upper-tropospheric feature, according to the legend.

FIG. 6. Frequency distribution of STC formation in the NATL basin during 1979–2010 binned by CI (°C). Colored regions represent the number of STCs forming in association with a particular upper-tropospheric feature, according to the legend.

FIG. 7. Cyclone-relative composite analyses of the upper-tropospheric precursors to STCs forming in association with a cutoff low (*N =* 13). Analyses show 250–150-hPa PV (blue contours, every 0.5 PVU), irrotational wind (vectors, ≥2 m s−1), and meridional wind (shaded according to the upper color bar, m s−1; enclosed by black contours where significant at the 95% confidence interval) at (a) *t*0 − 120 h, (c) *t*0 − 96 h, (e) *t*0 − 72 h, (g) *t*0 − 48 h, (i) *t*0 − 24 h, and (k) *t*0. Analyses also show 250–150-hPa geopotential height (gray contours, every 5 dam), wind (flags and barbs, kt), and wind speed (shaded according to the lower color bar, m s−1), as well as CI (red contours, ≤22.5°C), at (b) *t*0 − 120 h, (d) *t*0 − 96 h, (f) *t*0 − 72 h, (h) *t*0 − 48 h, (j) *t*0 − 24 h, and (l) *t*0. The STC symbol in each panel denotes the composite location of STCs forming in association with a cutoff low at *t*0. Thick solid and dashed black lines denote subjectively identified 250–150-hPa ridges and troughs, respectively.

FIG. 8. As in Fig. 7, but for STCs forming in association with a meridional trough (*N =* 15).

FIG. 9. As in Fig. 7, but for STCs forming in association with a zonal trough (*N =* 12).

FIG. 10. As in Fig. 7, but for STCs forming in association with a subtropical disturbance (*N =* 12).

FIG. 11. Schematic representation of an STC forming in association with a cutoff low. Black contours depict selected PVU contours in the 250–150-hPa layer-average PV field. Red arrows depict a selected streamline of the 250–150-hPa layer-average flow. Blue shaded regions indicate the location of 250–150-hPa jets. Pink shaded regions indicate the location of CI values ≤ 22.5°C. “AWB” denotes a region where anticyclonic wave breaking is occurring.

FIG. 12. As in Fig. 11, but for an STC forming in association with a meridional trough.

FIG. 13. As in Fig. 11, but for an STC forming in association with a zonal trough.

FIG. 14. As in Fig. 11, but for an STC forming in association with a subtropical disturbance.