**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 study seeks to examine the intraseasonal variability associated with the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features, as well as compare and contrast 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 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., tropical upper-tropospheric trough (TUTT) cells (e.g., Sadler 1976; Ferreira and Schubert 1999; Patla et al. 2009); potential vorticity (PV) streamers (e.g., Appenzeller and Davies 1992; Martius et al. 2008; Galarneau et al. 2015)] and have the potential to facilitate NATL tropical cyclogenesis in environments characterized by relatively high vertical wind shear (e.g., Bracken and Bosart 2000; McTaggart-Cowan et al. 2008, 2013) and low sea surface temperatures (SSTs) (e.g., Mauk and Hobgood 2012; McTaggart-Cowan et al. 2015).
     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 of the 452 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° Interim ECMWF Re-Analysis 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. The structure of individual upper-tropospheric features differs across composite members in Evans and Guishard (2009) and González-Alemán et al. (2015), suggesting possible differences in the upper-tropospheric precursors to the formation of NATL STCs that undergo TT.
     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 seeks to examine the intraseasonal variability associated with the location and frequency of NATL STCs forming in the presence of similar upper-tropospheric features, as well as compare and contrast 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 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 associated with 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 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 between *t*0 − 120 h and *t*0 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.
      6. These four distinct upper-tropospheric features exhibit characteristic structures and evolutions between *t*0 − 120 h and *t*0 that make them distinguishable from one another.
      7. Figure 1 illustrates the 250–150-hPa layer-average PV, geopotential height, and wind fields over the NATL at *t*0 for representative examples of NATL 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 span ≥10° of longitude at *t*0.
      10. Both cutoff lows and meridional troughs typically form in response to the amplification of midlatitude Rossby waves, though no latitudinal restrictions were imposed on the categorization of upper-tropospheric features associated with NATL STC formation.
      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 of AWB.
      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 as described above 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. Principle 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 in 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.
      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. 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).
      21. NATL STCs forming in association with cutoff lows and zonal troughs are associated with higher values of PC2, or more pronounced AWB to the north of the location of STC formation, than NATL STCs forming in association with meridional troughs and subtropical disturbances (Figs. 2a,c).
      22. These results are consistent with the features and processes identified during the subjective categorization of NATL STCs that undergo TT. 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 between *t*0 − 120 h and *t*0 that are not captured by the EOF analysis 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 Climate Forecast System Reanalysis (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 composite fields 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 (i.e., 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 are more likely to form in the presence of strong to moderate thermal gradients and may form at higher latitudes than NATL STCs forming in association with zonal troughs and subtropical disturbances.
     6. The results of Bentley et al. (2016) 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 (their Fig. 9). 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 ~28°N in the western NATL and comprise all 13 classifiable STCs forming east of ~54°W. These results are consistent with the results of Bentley et al. (2016), who indicate that the majority of NATL STCs forming poleward of ~28°N in the western NATL and east of ~54°W are classified as strong TT by McTaggart-Cowan et al. (2010).
     9. STCs forming in association with zonal troughs and subtropical disturbances typically develop equatorward of ~30°N and west of ~54°W. These results are also consistent with the results of Bentley et al. (2016), who indicate that the majority of NATL STCs forming equatorward of ~30°N and west of ~54°W are classified as weak TT and trough induced by McTaggart-Cowan et al. (2010).
     10. 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. This region of overlap is likely attributed 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 formation of a variety of the upper-tropospheric features associated with NATL STC formation in the western NATL.
     11. The results of Bentley et al. (2016) indicate that considerable intraseasonal variability is associated with the McTaggart-Cowan et al. (2013) classification of NATL STCs during 1979–2010 (their Fig. 11), suggesting that intraseasonal variability may also be associated with the subjective categorization of NATL STCs in the present study.
     12. Figure 5 illustrates the intraseasonal variability associated with NATL STC formation, binning NATL STCs by the month during which they formed (April–December).
     13. 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).
     14. 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).
     15. STCs forming in association with unclassifiable upper-tropospheric features occur sporadically during April–December and exhibit no discernible intraseasonal variability.
     16. 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.
     17. The CI, a measure of bulk column stability, is defined as the difference between potential temperature on the dynamic tropopause 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 of all 13 STCs forming in association with cutoff lows are less than the 22.5°C threshold for TT derived in McTaggart-Cowan et al. (2015) (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. Due to the structure of meridional troughs associated with STC formation at *t*0 (Fig. 1b), it is possible that the vertical motion required for the development of deep convection is forced by a combination of quasigeostrophic forcing for ascent and reduced bulk column stability, allowing the mean CI value to be higher for STCs forming in association with meridional troughs than cutoff lows.
    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 likely 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 slightly moister lower-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 the presence of 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 an eastward dispersing Rossby wave train (RWT; e.g., Riemer et al. 2008; Harr and Dea 2009) with alternating northerly and southerly winds extending from the west coast of North America into the central NATL at 250 hPa.

* + 1. By *t*0 − 48 h (Figs. 7g,h), the individual Rossby waves constituting the RWT progress eastward, amplify, and result 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). 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).

* + 1. By *t*0 − 24 h (Figs. 7i,j), the positive tilt of the upper-tropospheric ridge and meridional winds over the western NATL are indicative of AWB and equatorward Rossby wave dispersion. The upper-tropospheric trough over the central NATL extends equatorward of 30°N at this time (Figs. 7i,j), resulting in a broad region 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 over the central NATL to form into a cutoff low over the location of STC formation by *t*0 (Figs. 7 g–l).
    2. 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. (Fig. 8) As in Fig. 7, but of STCs forming in association with a meridional trough (*N =* 15).
  2. *Zonal trough composites*
     1. (Fig. 9) As in Fig. 7, but of STCs forming in association with a zonal trough (*N =* 12).
  3. *Subtropical disturbance composites*
     1. (Fig. 10) As in Fig. 7, but of STCs forming in association with a subtropical disturbance (*N =* 12).

1. **Summary and conclusions**
   * 1. The present study uses composite analysis to investigate the upper-tropospheric precursors to the formation of NATL STCs that undergo TT identified by Bentley et al. (2016).
     2. NATL STCs that undergo TT were subjectively separated into categories according to the upper-tropospheric feature associated with STC formation: 1) cutoff low, 2) meridional trough, 3) zonal trough, and 4) subtropical disturbance.
     3. Discuss climatological results from section 3, including intraseasonal variability, CI, etc.
     4. Time-lagged cyclone-relative composite analysis, performed on STCs included in each category, illustrate the structure, motion, and evolution of the upper-tropospheric precursors to NATL STC formation.
     5. Composite analyses of NATL STCs forming in association with a cutoff low reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     6. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     7. (Fig. 11) Summary schematic of cutoff low composite
     8. Composite analyses of NATL STCs forming in association with a meridional trough reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     9. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     10. (Fig. 12) Summary schematic of meridional trough composite
     11. Composite analyses of NATL STCs forming in association with a zonal trough reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     12. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     13. (Fig. 13) Summary schematic of zonal trough composite
     14. Composite analyses of NATL STCs forming in association with a subtropical disturbance reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     15. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     16. (Fig. 14) Summary schematic of subtropical disturbance composite
     17. Additional conclusions that I haven’t thought of yet to place everything in broader context
     18. Suggest possible differences in predictability associated with different categories

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**TABLES**

TABLE 1. Means and standard deviations of SST, PW, VWS, and CI, calculated within a 3° × 3° box centered over each STC at the time of formation (*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, kts) at *t*0 for STCs forming in association with a (a) cutoff low [0000 UTC 27 Nov 2004 (Otto)], (b) meridional trough [0600 UTC 25 Nov 2001 (Olga)], (c) zonal trough [0000 UTC 24 Jul 1986 (Unnamed)], and (d) subtropical disturbance [0600 UTC 8 Oct 1984 (Josephine)]. The STC symbol in each panel denotes the location of STC formation.

FIG. 2. *[To be written after figure is updated/another conversation with Paul Roundy]*

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 features 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 the formation of NATL 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 200-hPa 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) and wind speed (shaded according to the lower color bar, m s−1), wind (flags and barbs, kts), and 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.