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

Alicia M. Bentley, Lance F. Bosart, and Daniel Keyser

*Department of Atmospheric and Environmental Sciences, University at Albany,*

*State University of New York, Albany, New York*

**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. In the present study, the recently 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 categorized according to the upper-tropospheric feature associated with their formation prior to the construction of cyclone-relative composites. 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.

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 is more than twice the global average (~46%), likely associated with the 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, 2010), which occurs in response to the nonlinear amplification of the Rossby waveguide (e.g., Martius et al. 2008, 2010).
     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., Colton 1973); potential vorticity (PV) streamers (e.g., Appenzeller and Davies 1992)] 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; 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 ~13.7% of NATL TCs forming during 1979–2010 develop from STCs that undergo TT.
     7. Such STCs preferentially form over the western NATL (Bentley et al. 2016), likely associated with the recurrent 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; Kistler et al. 2001), 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) and González-Alemán et al. (2015) indicate the presence of a meridional trough located over and slightly upstream of the STC center at the time of STC formation that slowly approached the STC center from the west during the previous 24 h (their Figs. 7 and 5, respectively).
     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. In the present study, the recently 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.
     15. In contrast to NATL STCs in previous studies, NATL STCs in the present study will be categorized according to the upper-tropospheric feature associated with their formation prior to the construction of cyclone-relative composites.
     16. 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.
     17. The remainder of this paper is organized as follows. The data and methodology used to categorize NATL STCs that undergo TT, as well as composite the upper-tropospheric precursors associated with NATL STC formation, are described in section 2.
     18. 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.
     19. Section 4 presents cyclone-relative composite analyses of the upper-tropospheric precursors to the formation of NATL STCs that undergo TT.
     20. 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 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. (Fig. 1) Representative examples of STCs included in each category (descriptions/*N* = \_\_):

1a) Otto – 0000 UTC 27 November 2004 (cutoff low)

1b) Olga – 0600 UTC 25 November 2001 (meridional trough)

1c) Unnamed – 0000 UTC 24 July 1986 (zonal trough)

1d) Josephine – 0600 UTC 8 October 1984 (subtropical disturbance)

* + 1. Mention that 10 NATL STCs were unclassifiable.
    2. (Fig. 2) Relate subjective categories to location of STCs in PC1 vs. PC2 phase space at *t*0
       1. Describe EOF analysis (use Pat Harr papers as guides)
       2. Phase space constructed using first two PCs of 250–150-hPa layer-average PV field
       3. Shifted 250–150-hPa layer-average PV field to mean location of STC formation at *t*0
       4. Zonal Troughs and Subtropical Disturbances occupy a similar region of the PC1 vs. PC2 phase space at *t* = *t*0, but differences in their evolution between *t*0 − 120 h and *t*0 make them separate categories.
  1. *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).

1. **Climatological results** 
   * 1. (Fig. 3) Histogram of Strong TT, Weak TT, and Trough Induced pathways in McTaggart-Cowan et al. (2013) separated by category
     2. Relate to Strong TT, Weak TT, and Trough Induced locations in paper #1 (their Fig. 9)
     3. (Fig. 4) Map of locations of STC formation in the North Atlantic basin
     4. (Fig. 5) Histogram of intraseasonal variability by category
   1. (Fig. 6) Histogram of coupling index (CI) by category
2. **Cyclone-relative composite results**
   1. *Cutoff low composites*
      1. (Fig. 7) Ten-panel of cyclone-relative cutoff low composites of:

Cyclone-relative composite analyses of 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 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 color bar, m s−1), 850–200-hPa vertical wind shear (barbs and flags, kts), CI (red contours, ≤22.5°C), and SST (blue contours, ≥26.5°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 (a)–(j) denotes the composite location of STC formation at *t*0. Thick solid and dashed black lines denote subjectively identified 250–150-hPa ridges and troughs, respectively.

* 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, or 4) subtropical disturbance.
     3. 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.
     4. Composite analyses of NATL STCs forming in association with a cutoff low reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     5. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     6. (Fig. 11) Summary schematic of cutoff low composite
     7. Composite analyses of NATL STCs forming in association with a meridional trough reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     8. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     9. (Fig. 12) Summary schematic of meridional trough composite
     10. Composite analyses of NATL STCs forming in association with a zonal trough reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     11. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     12. (Fig. 13) Summary schematic of zonal trough composite
     13. Composite analyses of NATL STCs forming in association with a subtropical disturbance reveal that \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.
     14. Discuss location, and seasonality McTaggart-Cowan et al. (2013) development pathways
     15. (Fig. 14) Summary schematic of subtropical disturbance composite
     16. Additional conclusions that I haven’t thought of yet…
     17. Suggest possible differences in predictability associated with different categories

Fig. 1. Analyses showing 250–150-hPa layer-average PV (shaded, PVU), geopotential height (black contours, 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 November 2001 (Olga)], (c) zonal trough [0000 UTC 24 July 1986 (Unnamed)], and (d) subtropical disturbance [0600 UTC 8 October 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 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 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 color bar, m s−1), 850–200-hPa vertical wind shear (barbs and flags, 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 of STCs forming in association with a meridional trough (*N =* 15).

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

Fig. 10. As in Fig. 7, but of 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 select PVU contours in the 250-150-hPa layer-average PV field. Red arrows indicate the motion 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 of an STC forming in association with a meridional trough.

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

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