**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*

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 frequency of upper-tropospheric disturbances over the NATL relative to other ocean basins 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).
		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. NATL TCs forming in the presence of an upper-tropospheric disturbance may develop from the favorable interaction of a preexisting lower-tropospheric cyclonic vorticity center with an upper-tropospheric trough (e.g., Molinari et al. 1995; Galarneau et al. 2015) 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. The results of Bentley et al. (2016) reveal that ~13.7% of NATL TCs forming during 1979–2010 develop from STCs that undergo TT, accounting for ~29% of NATL TCs forming in the presence of an upper-tropospheric disturbance during that period (McTaggart-Cowan et al. 2013).
		7. NATL STCs that undergo TT 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 warm waters of 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 (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) composited 18 STCs identified over the western and central NATL during 1999–2004, while González-Alemán et al. (2015) composited 15 STCs identified over the northeastern NATL during 1979–2011.
		11. Both studies indicate the presence of a meridional upper-tropospheric trough located over and slightly upstream of the STC center at the time of STC formation (i.e., *t* = *t*0) that approaches from the west during the previous 24 h.
		12. The orientation and depth of individual upper-tropospheric features included in each cyclone-relative composite varies across composite members at *t* = *t*0 (Evans and Guishard 2009; González-Alemán et al. 2015), suggesting that a variety of upper-tropospheric features can be associated with NATL STC formation.
		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. Paragraph saying what I’m going to be doing and how it’s different from previous studies
		15. Paragraph outlining the rest of the paper (section numbers will be linked)
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) from the global climatology of baroclinically induced tropical cyclogenesis constructed by McTaggart-Cowan et al. (2013) 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. NATL STCs that undergo TT form during April–December, with a peak in the frequency of formation during August–October. STC formation occurs more frequently over the western NATL than over the eastern NATL, with the higher frequency of formation attributed to the recurrent overlap of relatively high sea surface temperatures (SSTs) and lower-tropospheric baroclinicity in the western NATL basin (Guishard et al. 2009).
		4. Previous studies of baroclinically influenced tropical cyclogenesis have categorized NATL TC formation 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 STC formation.
		5. Visual inspection of the 250-150-hPa layer-average PV, geopotential height, and wind fields at the time of STC formation (i.e., t = t0) for all 62 NATL STCs that undergo TT results in the identification of four distinct upper-tropospheric features associated with 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:

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. (Fig. 2) Relate subjective categories to location of STCs in PC1 vs. PC2 phase space
			1. Cite Pat Harr papers for EOF analysis
			2. Phase space constructed using first two PCs of 250-150-hPa layer-average PV field
			3. RECONSTRUCT FIGURE TO DISPLAY EOF1 AND EOF2 FIELDS
			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 structure at t = t0 not capture by first two EOFs 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 the time of STC formation (t = t0).
		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 of categories
	1. (Fig. 6) Histogram of coupling index by category
2. **Cyclone-relative composite results**
	1. *Cutoff low composites*
		1. (Fig. 7) Ten-panel of cyclone-relative cutoff low composites of:
			1. 250–150-hPa PV (blue contours, every 0.5 PVU), irrotational wind (vectors, >1 m s−1), and 200-hPa meridional wind anomaly (shaded according to color bar, m s−1; shaded where significant at and above the 99% confidence interval)
			2. 250–150-hPa geopotential height (gray contours, every 5 dam) and wind speed (solid blue contours, every 5 m s−1 starting at 20 m s−1), 850–200-hPa vertical wind shear (vectors, m s−1), coupling index (red contours, °C), and PW anomaly (shaded according to color bar, mm; shaded where significant at and above the 99% confidence interval). ([Link to figure testing](http://www.atmos.albany.edu/student/abentley/research_images/mthesis/paper/composites/midlat_comp.php))
	2. *Meridional trough composites*
		1. (Fig. 8) As in Fig. 7, but for meridional troughs
	3. *Zonal trough composites*
		1. (Fig. 9) As in Fig. 7, but for zonal troughs
	4. *Subtropical disturbance composites*
		1. (Fig. 10) As in Fig. 7, but for subtropical disturbances
3. **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