Preprints for the 19th Conference on
Weather Analysis and Forecasting,
12-16 August 2002, San Antonio, TX

**7A.5**

# NONCLASSICAL TROPOPAUSE FOLDING

by

Lance F. Bosart*, Michael J. Dickinson, and Eyad H. Atallah

Department of Earth and Atmospheric Sciences
The University at Albany/SUNY
Albany, New York 12222 USA

## 1. INTRODUCTION:

The pioneering observational studies of now-classical upper-level fronts and tropopause folding by Reed and Sanders (1953) and Reed (1955) showed that upper-level fronts with a typical horizontal width and depth of 100 km and 1 km, respectively, formed in northwesterly flow downstream of a ridge in conjunction with cold-air advection. Frontal horizontal temperature gradients intensified by an order of magnitude to 10-20 C° (100km) $^{-1}$ on time scales of less than one day in conjunction with cold-air advection-driven subsidence that maximized along the warm boundary of the baroclinic zone. Through use of potential vorticity (PV) as a tracer, the Reed studies also showed that stratospheric air could penetrate deep into the troposphere in association with a tropopause fold. The Reed studies also provided motivation for Danielsen to discover the dry slot in extratropical cyclones, stimulated a new interest in identifying stratospheric-tropospheric exchange processes, and established the value of using PV as a tracer in studies of frontogenesis and cyclogenesis. Detailed reviews of classical upper-level frontogenesis and tropopause folding can be found in Shapiro and Keyser (1990) and Bosart (2002).

The purpose of this paper is to illustrate nonclassical tropopause folding that occurred in conjunction with upper-level frontogenesis in southwesterly flow (see also Schultz and Doswell 1999) and in association with a landfalling and transitioning tropical cyclone (see also Atallah and Bosart 2002). A dynamical tropopause (DT) and a potential vorticity (PV) thinking perspective is adopted for this purpose.

## 2. DATA/METHODOLOGY:

Gridded 2.5 x 2.5 degree NCEP/NCAR reanalyses and 1.0 x 1.0 degree NCEP/AVN analyses were used for all computations. Nielsen-Gammon (2001) and Morgan and Nielsen-Gammon (1998) review the advantages of applying PV thinking and adopting a DT perspective to the analysis of synoptic-scale weather systems. DT maps were prepared using the contour fill overlay method (winds were interpolated to the DT looking down) described by Morgan and Nielsen-Gammon (1998).

## 3. RESULTS:

### *(a) Upper-Level Front of 7-10 December 1978*

The period 6-11 December 1978 featured a very strong west-southwesterly flow over North America along with a gradual eastward movement of a major large-scale trough initially located over western North America. Over the 72 h period ending 00Z/10 a cyclone develops over the lower Mississippi Valley and moves northeastward while deepening modestly to 1007 hPa to a position over Nova Scotia by 00Z/9. A second cyclone forms along the trailing cold front over the eastern Ohio Valley near 00Z/9 and deepens moderately to 994 hPa just southeast of New England by 00Z/10. A very strong jet was observed in the southwesterly flow with speeds in excess of 100 m s$^{-1}$ analyzed at 00Z/9-10. The upper-level front of interest is embedded in this southwesterly flow.

Maps of potential temperature on the DT for 00Z/7-10 are shown in Fig. 1. It is apparent from Fig. 1 that the DT is quite steep over much of the US. Minor tropopause folds are apparent over the Texas-Oklahoma panhandle area and east of Florida at 00Z/7 (Fig. 1a). By 00Z/8 the tropopause fold over the Texas and Oklahoma panhandle area has moved northeastward to southeastern Nebraska (Fig. 1b). This tropopause fold region can be associated with the weak short-wave trough lifting out of the deep trough in the southwestern US and a small region of frontogenesis at 500 hPa just upstream. An area of tropopause folding west of the Baja peninsula at 00Z/8 develops into a significant tropopause fold to the east of the major trough axis over western Texas by 00Z/9 in conjunction with a strengthening of the 500 hPa temperature gradient and an increase in the 500 hPa frontogenesis. Meanwhile, the tropopause fold that had been situated over southeastern Nebraska now extends from the western Great Lakes to north of Maine as the previous weak short-wave trough rides over the ridge in confluent flow over the eastern US. By 00Z/10 significant tropopause folding is concentrated over the lower Ohio Valley

*Corresponding author address:* Lance F. Bosart, University at Albany/SUNY, Department of Earth and Atmospheric Sciences, 1400 Washington Avenue, Albany, New York 12222 USA; email: bosart@atmos.albany.edu

and the central Appalachians ahead of the major trough lifting out of the southwestern US (Fig. 1d).

Although the upper-level front case of 7-10 December 1978 occurred in southwesterly flow, it differed from classical northwest flow cases in that warm-air advection was absent in the frontogenesis region. In the Schultz and Doswell (1999) schematic (not shown) of southwesterly flow upper-level frontogenesis, cold-air advection develops behind the front in response to upstream baroclinic wave intensification and vorticity compaction in the trailing trough. In contrast, the upper-level frontogenesis in the 7-10 December 1978 case is driven by horizontal confluence that maximizes along the poleward side of the dominant baroclinic zone in response first to a weak short-wave trough lifting northeastward toward a jet-entrance region in the northern branch of the westerlies and second to the phasing of a trough in the northern branch of the westerlies with the dominant trough in the southern branch.

*(b) Hurricane Floyd: 16-17 September 1999*

Hurricane Floyd made landfall on the North Carolina coast near 09Z 16 September 1999. Subsequent to landfall, the storm moved northeastward just inland from the coast and underwent a gradual extratropical transition. Floyd was noteworthy for the very heavy rains and inland flooding from North Carolina to Maine.

Figure 2, taken from Atallah and Bosart (2002), shows maps of potential temperature and winds on the DT every 12 h for the 36 h period ending 12Z 17 September 1999. These DT maps can also be viewed as a representation of the distribution of upper-tropospheric PV. An outflow jet (winds exceeding 85 m $s^{-1}$) is located where the DT is nearly vertical ahead of an advancing trough (Figs. 2a,b). By 12Z/16 a tropopause fold is evident from West Virginia to north of Maine. Nonconservation of potential temperature (and PV) in response to diabatic heating and associated upper-tropospheric outflow originating from heavy precipitation in the vicinity and poleward of Floyd together with confluent frontogenesis likely contribute to tropopause folding. Evidence for this statement is found in the westward expansion of high potential temperature air on the DT despite winds blowing parallel to potential temperature contours at both 00Z/16 and 12Z/16 (Figs. 2a,b), and in the strong confluent flow associated with a migratory short-wave trough depicted in the tropopause fold region northeast of Maine (Fig. 2b). The PV nonconservation outflow jet signature was also noted in Hurricane David (1979) by Bosart and Lackmann (1995) and the 12-14 March 1993 Superstorm over eastern North America by Dickinson et al. (1997) and Bosart (1999).

By 00Z/17 the upper-level trough overspreads Floyd while the tropopause fold region extends downstream past Newfoundland (Fig. 2c). The tropopause remains folded in the anticyclonic outflow region immediately westward and poleward of Floyd. By 12Z/17 the DT begins to unfold just to the northwest of Floyd and it remains folded well downstream along the outflow jet channel where the approach of a second trough and its associated confluent flow likely contributes to continued folding (Fig. 2d). Tropopause folds that form in the southwesterly flow along the poleward side of tropical storm outflow jet channels likely are the result of PV nonconservation due to widespread storm-induced diabatic heating. Tropopause folds that form in these situations probably contribute to tropospheric-stratospheric exchange as deep convective cloud top debris is deposited into the lower stratosphere.

## 4. CONCLUSIONS:

Two examples of nonclassical tropopause folding are illustrated. One case occurs in confluent southwesterly flow in association with trough phasing and jet-entrance region dynamics. The other case occurs in conjunction with a divergent outflow jet outflow ahead of a landfalling and transitioning tropical storm and confluence ahead of a prominent migratory short-wave trough in the polar westerlies. Tropopause folding is possible when a deep, warm tropical air mass with an embedded hurricane reaches higher latitudes ahead of a major midlatitude trough.

## 5. ACKNOWLEDGEMENT:

This research was supported NSF Grant ATM-9912075.

## 6. REFERENCES:

Atallah, E. H., and L. F. Bosart 2002: Extratropical transition and precipitation distribution: A case study of Floyd '99. Submitted, *Monthly Weather Review*.

Bosart, L. F., 1999: Observed Cyclone Life Cycles. In: *The Life Cycles of Extratropical Cyclones*, M. A. Shapiro and S. Grønås, Eds., Amer. Meteor. Soc., 187–213.

Bosart, L .F., 2002: Tropopause folding: Upper-level frontogenesis, and beyond. A Half Century of Progress in Meteorology: A Tribute to Richard J. Reed, *Meteor. Monogr.*, Amer. Meteor. Soc. (in press).

Bosart, L. F., and G. M. Lackmann, 1995: Post-landfall tropical cyclone reintensification in a weakly-baroclinic environment: A case study of hurricane David (September 1979). *Mon. Wea. Rev.*, **123,** 3268-3291.

Dickinson, M. J., M. A. Bedrick, L. F. Bosart, W. E. Bracken, G. J. Hakim, D. M. Schultz, and K. R. Tyle, 1997: The March 1993 Superstorm cyclogenesis: Incipient phase synoptic-and convective-scale flow interaction and model performance. *Mon. Wea. Rev.,* **125,** 3041-3072.

Morgan, M. C., and J. W. Nielsen-Gammon, 1998: Using tropopause maps to diagnose midlatitude weather systems. *Mon Wea. Rev.,* **126**, 2555–2579.

Nielsen-Gammon, J. W., 2001: A visualization of the global dynamic tropopause. *Bull. Amer. Meteor. Soc.*, **82,** 1151-1167.

Reed, R. J., 1955: A study of a characteristic type of upper-level frontogenesis. *J. Meteor.,* **12**, 226-237.

Reed, R. J., and F. Sanders, 1953: An investigation of the development of a mid-tropospheric frontal zone and its associated vorticity field. *J. Meteor.,* **10**, 338-349.

Schultz, D. M., and C. A. Doswell III, 1999: Conceptual models of upper-level frontogenesis in south-westerly and north-westerly flow. *Quart. J. Roy. Meteor. Soc.*, **125,** 2535-2562.

Shapiro, M. A., and D. Keyser, 1990: Fronts, Jet Streams and the Tropopause. Extratropical Cyclones, Palmén Memorial Volume, C. W. Newton and E. O. Holopainen, Eds., Amer. Meteor. Soc., 167-191.

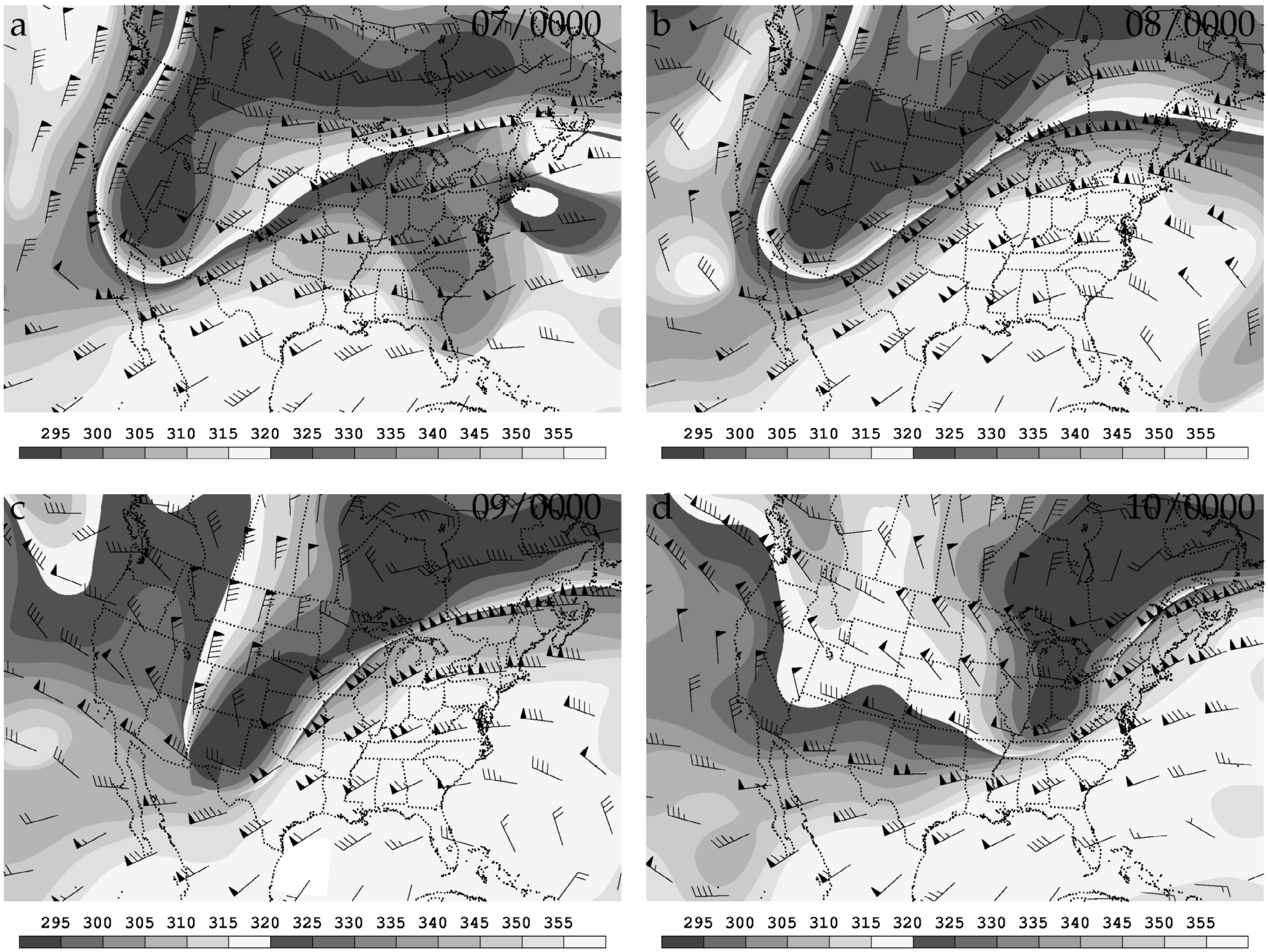


Figure 1: Potential temperature every 5 K (shaded according to the gray scale) on the dynamic tropopause (DT) defined by the 1.5 PVU surface (1 PVU=$10^{-6}$ K $m^2$ $kg^{-1}$ $s^{-1}$), and winds on the DT (computed looking down) with one pennant, full barb, and half barb denoting 25 m $s^{-1}$, 5 m $s^{-1}$, and 2.5 m $s^{-1}$, respectively, for 0000 UTC 7 (a), 8 (b), 9 (c), and 10 (d) December 1978. Plot prepared using the "contour fill overlay method" of Morgan and Nielsen-Gammon (1998).

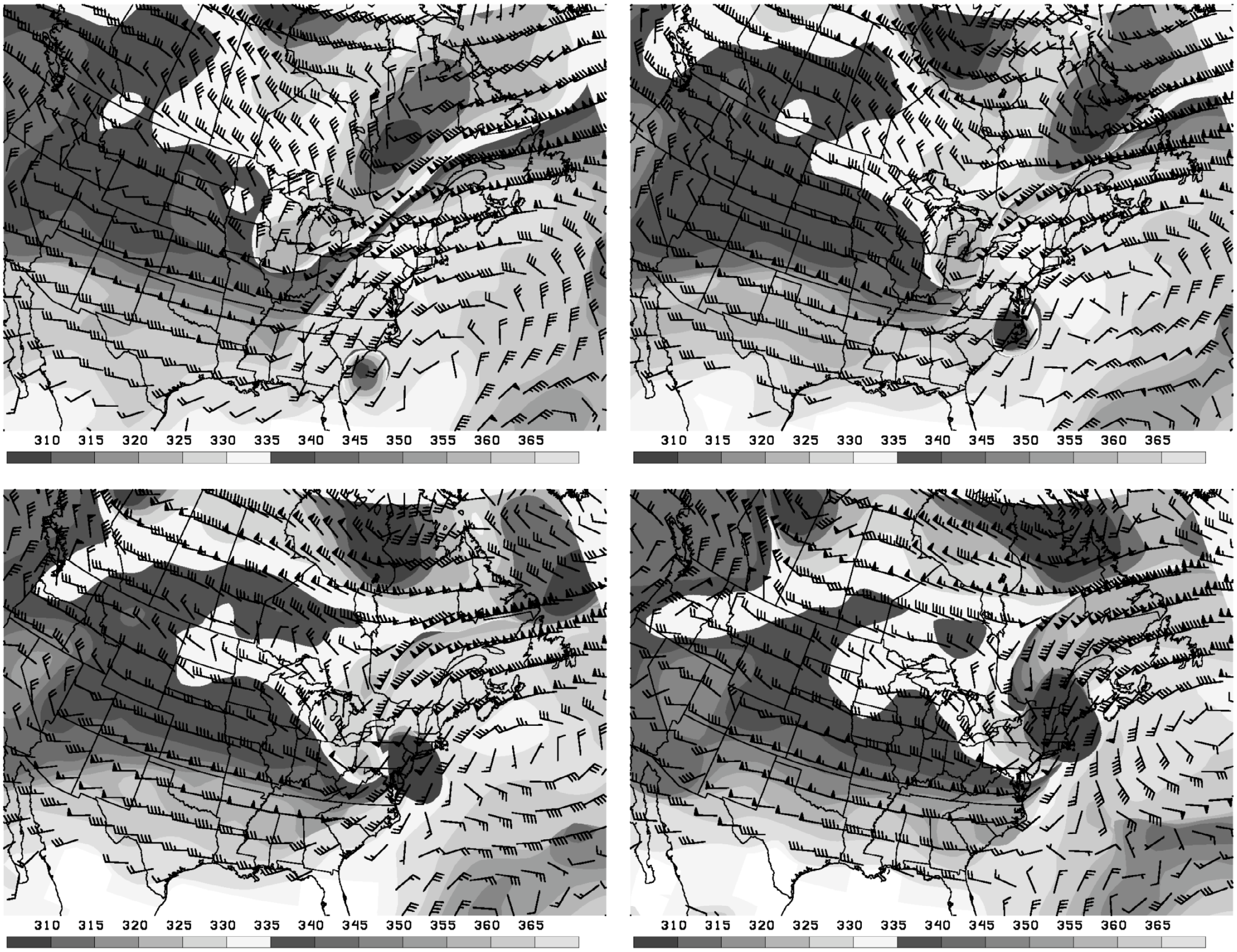


Figure 2: As in Fig. 1 except for 0000 UTC (a) and 1200 UTC (b) 16 September 1999, and 0000 UTC (c) and 1200 UTC (d) 17 September 1999.