Searching for the Elusive Cold-Type Occluded Front

DAVID M. SCHULTZ AND BOGDAN ANTONESCU
Centre for Atmospheric Science, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester, United Kingdom

ALESSANDRO CHIARIELLO
Finnish Meteorological Institute, Helsinki, Finland

(Manuscript received 29 December 2013, in final form 22 April 2014)

ABSTRACT

According to the Norwegian cyclone model, whether a warm-type or cold-type occluded front forms depends upon which cold air mass is colder: the prewarm-frontal air mass or the postcold-frontal air mass. For example, a cold-type occlusion is said to occur when the occluded front slopes rearward with height because the prewarm-frontal air mass is warmer than the postcold-frontal air mass. This temperature difference and the resulting occluded-frontal structure in the Norwegian cyclone model is part of what is called the temperature rule. Paradoxically, no clear example of a rearward-sloping, cold-type occluded front has been found in the literature, even though the required temperature difference has been documented in several cases. This article presents the first documented, rearward-sloping, cold-type occluded front. This occluded front forms in a cyclone over the North Atlantic Ocean on 3–5 January 2003 and is documented in model output from the European Centre for Medium-Range Weather Forecasts. Cross sections through the evolving cyclone show the occluded front forms as the less statically stable warm-frontal zone ascends over the more stable cold-frontal zone. Such a stability difference between the cold- and warm-frontal zones is consistent with a previously published hypothesis that the less stable air is lifted by the more stable air to form occluded fronts, in disagreement with the temperature rule. Because warm-frontal zones and the cold air underneath tend to be more stable than cold-frontal zones and the postcold-frontal air, warm-type occluded fronts are much more common than cold-type occluded fronts, explaining why well-defined, rearward-sloping, cold-type occluded fronts are not common in the meteorological literature.

1. Introduction

The Norwegian cyclone model is a conceptual model describing the structure and evolution of extratropical cyclones and fronts (Bjerknes 1919; Bjerknes and Solberg 1921, 1922). As a part of that evolution and based upon the analyses and insight of Tor Bergeron (e.g., Bergeron 1959; chapter 10 in Friedman 1989), the Norwegian cyclone model described the process by which a mature cyclone forms an occluded front. The formation of an occluded front was described as a faster-moving cold front catching up to the slower-moving warm front and lifting the intervening warm air from the surface (Fig. 1). More recent research has shown that the wrap up of the isotherms is a more apt description of the occlusion process than the catch-up mechanism posited by the Norwegian meteorologists (Schultz and Vaughan 2011).

Denotes Open Access content.

Corresponding author address: Prof. David M. Schultz, Centre for Atmospheric Science, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Simon Building, Oxford Road, Manchester M13 9PL, United Kingdom.
E-mail: david.schultz@manchester.ac.uk

DOI: 10.1175/MWR-D-14-00003.1

© 2014 American Meteorological Society
Bjerknes and Solberg (1922) proposed that some difference in temperature across an occluded front would occur between the two cold air masses. They described the lifting of one cold air mass by the other colder one, giving the appearance of one front ascending over the other (Fig. 2). If the air behind the cold front were warmer than the air ahead of the warm front, then the cold front would ascend the warm front forming a forward-sloping, warm-type occluded front (Fig. 2a). On the other hand, if the air behind the cold front were more stable than the air ahead of the warm front, then the warm front would ride up the cold front, forming a rearward-sloping, cold-type occluded front.

Stoelinga et al. (2002) referred to the correspondence between the cross-front temperature difference and the occluded-front structure in the Norwegian cyclone model as the temperature rule. Schultz and Mass (1993) and Stoelinga et al. (2002) examined previously published cross sections of occluded fronts. Of 33 occluded fronts identified in their two studies, only 3 had the rearward-sloping structure of a cold-type occluded front, regardless of whether the temperature rule held or not. In fact, none of these three cold-type occluded fronts was well defined: one was a schematic diagram, the second had no elevated warm front, and the third could be reanalyzed as a warm-type occluded front (Schultz and Mass 1993). Thus, no cross section of a well-defined, rearward-sloping, cold-type occluded front is known to exist.

If the temperature rule does not explain the structure of occluded fronts, what does? Stoelinga et al. (2002) argued that the relative stability, not the relative temperature, on either side of the occluded front determines the occluded-front structure (what they called the static-stability rule). Specifically, if the air behind the cold front were less stable than the air ahead of the warm front, then the cold front would ride up the warm front, forming a forward-sloping, warm-type occluded front. On the other hand, if the air behind the cold front were more stable than the air ahead of the warm front, then the warm front would ride up the cold front, forming a rearward-sloping, cold-type occluded front.

Although the static stability rule explains the resulting structure when the cyclone wraps up, the rule also predicts that warm-type occluded fronts would be more common than cold-type occluded fronts (Stoelinga et al. 2002; Schultz and Vaughan 2011, p. 454). Specifically, Schultz and Vaughan (2011) argued that cold-frontal zones are generally characterized by near-vertical isentropes at the leading edge with well-mixed postfrontal air (e.g., Hobbs et al. 1980; Shapiro et al. 1985; Schultz 2008; Schultz and Roebber 2008). In contrast, warm-frontal zones are generally statically stable (e.g., Bjerknes 1935; Bjerknes and Palmén 1937; Locatelli and Hobbs 1987; Schultz 2001; Wakimoto and Bosart 2001; Doyle and Bond 2001; Kemppi and Sinclair 2011). Given these typical differences in static stability between cold and warm fronts, the static stability rule would predict that warm-type occluded fronts would be the more common type of occlusion. A cold-type occluded front would form when the cold-frontal zone was more stable than the warm-frontal zone. Yet, because cold-frontal zones are less likely to be more statically stable than warm-frontal zones suggests that cold-type occluded fronts would be relatively rare, if they even existed at all.

To the best of our knowledge, no cross section of a cold-type occluded front exists in the published literature showing the rearward slope of the occluded front and the warm-frontal zone being less stable than the cold-frontal zone. Unexpectedly, just such a well-defined, rearward-sloping, cold-type occluded front was discovered during the third author’s master’s thesis research (Chiariello 2006). Therefore, the purpose of this article is to present this cold-type occluded front and to demonstrate its consistency with the static-stability rule.

2. Case study of a cold-type occluded front

This case was found from looking at occluded fronts over the North Atlantic Ocean using model output from the European Centre for Medium-Range Weather
Forecasts at 0.25° × 0.25° latitude–longitude gridded analyses. At 1200 UTC 3 January 2003, a large-scale sub 980-mb (1 mb = 1 hPa) cyclone south of Greenland occupied the western half of the North Atlantic Ocean (Fig. 3a). A frontal wave was traveling around the larger cyclone on its south side. Petterssen (1936) frontogenesis at 850 mb was used to diagnose the regions of locations where the magnitude of the horizontal temperature gradient was increasing, indicating active fronts. The wave possessed three regions of Petterssen frontogenesis: a region along the leading edge of the cold front, a region to the northwest of the cyclone along a strong bent-back front, and a weak region along the warm front (Fig. 3a). Twelve hours later, the frontal wave was absorbed into the larger cyclonic circulation and a single, long region of frontogenesis existed along the occluded front, connecting to two maxima along warm and cold fronts at the southern end (Fig. 3b). By 1200 UTC 4 January, the low deepened to below 964 mb, as the occluded front continued to lengthen and narrow (Fig. 3c). At 300 mb, an 80 m s⁻¹ jet upstream of a strong diffluent trough was associated with the surface pressure center (Fig. 4). That the large-scale flow environment in which the cyclone was embedded was diffluent supports the formation of a Norwegian cyclone, weak warm front, and meridionally oriented occluded front (e.g., Schultz et al. 1998; Schultz and Zhang 2007).

Cross sections through the cyclone show the much stronger and more statically stable cold front compared to the warm front (Fig. 5). A cross section AA’ at 1200 UTC 3 January near the so-called surface triple point (i.e., the junction between the occluded, cold, and warm fronts), the leading edge of the cold front (indicated by the cold-air advection in blue) tilted slightly forward with a maximum static stability exceeding 11 K km⁻¹ (Fig. 5a). In contrast, the warm front featured weaker warm-air advection and static stability of 6 K km⁻¹ (Fig. 5a). At 0000 UTC 4 January, two cross sections are taken—BB’ just poleward of the triple point at 850 mb and BB’ just equatorward of the triple point (Figs. 5b,c). Cross section BB’ shows the warm-frontal zone being lifted relative to cross section BB” (Figs. 5b,c). Otherwise, the cross sections are similar to the one 12 h earlier (Fig. 5a), showing the less statically stable warm front. By 1200 UTC 4 January, the cross section through the occluded front showed a much stronger and statically more stable occluded front with relatively weak...
3. Discussion

Schultz and Mass (1993) found that several cyclones had schematic cold-type occlusions or cold-type occlusions without elevated warm fronts (e.g., Elliott 1958; Hobbs et al. 1975). Interestingly, these cases occurred over the eastern North Pacific Ocean at the end of the Pacific storm track, where it has been noted that warm fronts are relatively weak [e.g., the nonexistent warm front in occluded cyclones (Wallace and Hobbs 1977, p. 127; Friedman 1989, p. 217) or “stubby” warm front]. This synoptic environment of diffluence is favorable for weak warm fronts (e.g., Schultz et al. 1998; Schultz and Zhang 2007). This explanation differs from those offered in Stoelinga et al. (2002, 717–718) to explain stability differences between the cold and warm fronts: differential cloud cover, surface fluxes, or friction. We argue that such storms with weak or nonexistent warm fronts tend to form cold-type occlusions rather than warm-type occlusions. Specifically, by Stoelinga et al.’s (2002) static stability rule, the warm front must be less stable than the cold front. One way this can happen is to have a relatively weak warm front, possibly in diffluent flow. Such a weak warm front, when lifted in a layer, becomes even less stable. Thus, the warm front in a cold-type occlusion tends to be weak for that reason, as well.

Interestingly, the elevated cold fronts in warm-type occlusions are also weak. Near the center of the cyclone, the cold front often is weak because of frontotyphical deformation (e.g., Doswell 1984; Keyser et al. 1988;
Shapiro and Keyser 1990; Browning 1997; Schultz et al. 1998). As it is lifted over the warm front, further destabilization and weakening occurs. Such an explanation is consistent with the strongly diffluent upper-level flow in the event described in this article (Fig. 4).

4. Conclusions

The case presented in this article demonstrates that cold-type occlusions do exist, albeit to date only demonstrated in model output. The rearward-tilting cold-type occlusion was formed from the lifting of the less stable warm-frontal zone over the more stable cold-frontal zone, in accordance with the static-stability rule proposed by Stoelinga et al. (2002). This case is believed to be the first cold-type occlusion documented in the literature.

Acknowledgments. This work is based on the third author’s master’s thesis (Chiariello 2006); we thank the adviser Aulikki Lehkonen. We also thank Editor Ron McTaggart-Cowan, Mark Stoelinga, and an anonymous reviewer for their comments that improved our article. Figures 1 and 2 were drafted by Nick Sellers of CutGraphics, York, United Kingdom. Partial funding for Schultz comes from Vaisala Oyj, Grant 126853 from the Academy of Finland to the University of Helsinki, Grant NE/I005234/1 from the UK Natural Environment Research Council (NERC) to the Diabatic
Influences on Mesoscale Structures in Extratropical Storms (DIAMET) project at the University of Manchester, and Grant NE/H008225/1 from NERC to the Tropopause Folding, Stratospheric Intrusions and Deep Convection (TROSIAD) project at the University of Manchester. Funding for Antonescu comes from TROSIAD and from an AXA Postdoctoral Research Fellowship.

REFERENCES

Bergeron, T., 1959: Methods in scientific weather analysis and forecasting: An outline in the history of ideas and hints at a program. The Atmosphere and Sea in Motion: Scientific Contributions to the Rossby Memorial Volume, B. Bolin, Ed., Rockefeller Institute Press, 440–474.

Bjerknes, J., 1919: On the structure of moving cyclones. Geofys. Publ., 1 (2), 1–8.

——, 1935: Investigations of selected European cyclones by means of serial ascents. Geofys. Publ., 11 (4), 3–18.

——, and H. Solberg, 1921: Meteorological conditions for the formation of rain. Geophys. Publ., 2 (3), 3–60.

——, and ——, 1922: Life cycle of cyclones and the polar front theory of atmospheric circulation. Geofys. Publ., 3 (1), 3–18.

——, and E. Palmén, 1937: Investigations of selected European cyclones by means of serial ascents. Geofys. Publ., 12 (2), 1–62.

Browning, K. A., 1997: The dry intrusion perspective of extratropical cyclone development. Meteor. Appl., 4, 317–324, doi:10.1017/S1350482797000613.

Chiariello, A., 2006: A critical assessment of occluded fronts. M.S. thesis, Dept. of Physical Sciences, University of Helsinki, 98 pp. [Available online at https://helda.helsinki.fi/bitstream/handle/10138/21004/acritica.pdf?sequence=2.]

Doswell, C. A., III, 1984: A kinematic analysis of frontogenesis associated with a nondivergent vortex. J. Atmos. Sci., 41, 1242–1248, doi:10.1175/1520-0469(1984)041<1242:AKAOFA>2.0.CO;2.

Doyle, J. D., and N. A. Bond, 2001: Research aircraft observations and numerical simulations of a warm front approaching Vancouver Island. Mon. Wea. Rev., 129, 978–998, doi:10.1175/1520-0493(2001)129<0978:RAOANS>2.0.CO;2.

Elliott, R. D., 1958: California storm characteristics and weather modification. J. Meteor., 15, 486–493, doi:10.1175/1520-0469(1958)015<0486:CSAWM>2.0.CO;2.

Friedman, R. M., 1989: Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology. Cornell University Press, 251 pp.

Hobbs, P. V., R. A. Houze Jr., and T. J. Matejka, 1975: The dynamical and microphysical structure of an occluded frontal system and its modification by orography. J. Atmos. Sci., 32, 1542–1562, doi:10.1175/1520-0469(1975)032<1542:TDAMSO>2.0.CO;2.

——, T. J. Matejka, P. H. Herzegh, J. D. Locatelli, and R. A. Houze Jr., 1980: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones I: A case study of a cold front. J. Atmos. Sci., 37, 568–596, doi:10.1175/1520-0469(1980)037<0568:TMAMSO>2.0.CO;2.

Kemppi, M. L., and V. A. Sinclair, 2011: Structure of a warm front: Helsinki testbed observations and model simulation. Mon. Wea. Rev., 139, 2876–2900, doi:10.1175/MWR-D-10-05003.1.

Keyser, D., M. J. Reeder, and R. J. Reed, 1988: A generalization of Petterssen's frontogenesis function and its relation to the forcing of vertical motion. Mon. Wea. Rev., 116, 762–780, doi:10.1175/1520-0493(1988)116<0762:AGOPFF>2.0.CO;2.

Locatelli, J. D., and P. V. Hobbs, 1987: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. XIII: Structure of a warm front. J. Atmos. Sci., 44, 2290–2309, doi:10.1175/1520-0469(1987)044<2290:TMAMSA>2.0.CO;2.

Petterssen, S., 1935: Investigations of selected European cyclones by means of serial ascents. Geofys. Publ., 11 (4), 3–18.

Saucier, W. J., 1955: Principles of Meteorological Analysis. The University of Chicago Press, 438 pp.

Schultz, D. M., 2001: Reexamining the cold conveyor belt. Mon. Wea. Rev., 129, 2205–2225, doi:10.1175/1520-0493(2001)129<2205:RTCCB>2.0.CO;2.

——, and ——, 2008: Perspectives on Fred Sanders' research on cold fronts. Synoptic–Dynamical Meteorology and Weather Analysis and Forecasting: A Tribute to Fred Sanders, Meteor. Monogr., No. 55, Amer. Meteor. Soc., 109–126.

——, and C. F. Mass, 1993: The occlusion process in a midlatitude cyclone over land. Mon. Wea. Rev., 121, 918–940, doi:10.1175/1520-0493(1993)121<0918:TOPIAM>2.0.CO;2.

——, and F. Zhang, 2007: Baroclinic development within zonally varying flows. Quart. J. Roy. Meteor. Soc., 133, 1101–1112, doi:10.1002/qj.87.

——, and P. J. Roebber, 2008: The fiftieth anniversary of Sanders' (1955): A mesoscale model simulation of the cold front of 17–18 April 1953. Synoptic–Dynamical Meteorology and Weather Analysis and Forecasting: A Tribute to Fred Sanders, Meteor. Monogr., No. 55, Amer. Meteor. Soc., 127–143.

——, and G. Vaughan, 2011: Occluded fronts and the occlusion process: A fresh look at conventional wisdom. Bull. Amer. Meteor. Soc., 92, 443–466, doi:10.1175/2010BAMS3057.1.

——, D. Keyser, and L. F. Bosart, 1998: The effect of large-scale flow on low-level frontal structure and evolution in midlatitude cyclones. Mon. Wea. Rev., 126, 1767–1791, doi:10.1175/1520-0493(1998)126<1767:TEOLSF>2.0.CO;2.

Shapiro, M. A., and D. Keyser, 1990: Fronts, jet streams and the tropopause. Extratropical Cyclones: The Erik Palmén Memorial Volume, C. W. Newton and E. O. Holopainen, Eds., Amer. Meteor. Soc., 167–191.

——, T. Hampel, D. Rotzoll, and F. Mosher, 1985: The frontal hydraulic head: A micro-o-scale (~1 km) triggering mechanism for mesoconvective weather systems. Mon. Wea. Rev., 113, 1166–1183, doi:10.1175/1520-0493(1985)113<1166:TFHMAM>2.0.CO;2.

Stoelinga, M. T., J. D. Locatelli, and P. V. Hobbs, 2002: Warm occlusions, cold occlusions, and forward-tilting cold fronts. Bull. Amer. Meteor. Soc., 83, 709–721, doi:10.1175/1520-0477(2002)083<0709:WOCAOF>2.3.CO;2.

Wakimoto, R. M., and B. L. Bosart, 2001: Airborne radar observations of a warm front during FASTEX. Mon. Wea. Rev., 129, 254–274, doi:10.1175/1520-0493(2001)129<0254:AROWAO>2.0.CO;2.

Wallace, J. M., and P. V. Hobbs, 1977: Atmospheric Science: An Introductory Survey. Academic Press, 467 pp.