CORRESPONDENCE

Comments on "Dynamics of Upper-Level Frontogenesis in Baroclinic Waves"

ANDREA BUZZI

Institute of Atmospheric Sciences and Climate, CNR-ISAC, Bologna, Italy

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ABSTRACT

A recent paper by Mak et al. grants the opportunity to discuss two different definitions of the frontogenetical function proposed in the literature to study the formation and evolution of upper-level fronts. This comment exposes some problems that, in this author's opinion, are related to the use of the Lagrangian tendency of the 3D (in place of horizontal) gradient of potential temperature, as adopted in the Mak et al. paper.

1. Introduction

Mak et al. (2016, hereafter MLD) deal with a (relatively—see below) novel type of diagnosis of upper-level frontogenesis embedded in numerically simulated baroclinic waves. Although some of the results are interesting, I question the significance of the 3D frontogenetical function (FF) proposed by MLD. This function is defined as $(D/Dt)|\nabla_3\theta|$, expressing the Lagrangian rate of change of the magnitude of the 3D gradient of potential temperature θ. As reported in MLD, this definition of FF is considered in Bluestein (1993, section 2.3.2) in the context of upper-level fronts (ULFs), with no specific reference. However, it seems to date back to Miller (1948). The alternative expression of FF, which MLD call the traditional FF because it has been adopted in the large majority of papers dealing with the problem of upper-level frontogenesis (e.g., Reed and Sanders 1953; Mudrick 1974; Buzzi et al. 1977; Shapiro 1981; Uccellini et al. 1985; Keyser and Shapiro 1986; Keyser et al. 1988; Hines and Mechoso 1991; Rotunno et al. 1994; Davies and Rossa 1998; Lang and Martin 2010; Martin 2014) is defined as $(D/Dt)|\nabla_2\theta|$. This form of FF expresses the Lagrangian rate of change of the horizontal (subscript 2) gradient of potential temperature (if pressure is used as vertical coordinate, $\nabla_2\theta$ is the isobaric gradient, proportional to the gradient of temperature). This definition of FF coincides with that available in the AMS *Glossary of Meteorology* (http://glossary.ametsoc.org/wiki/Frontogenetical_function), where Petterssen (1956, 200–201) is quoted, although Petterssen himself proposed it much earlier (Petterssen 1936), mainly with reference to surface fronts. One could call, therefore, the former (3D) FF "Miller's FF" and the latter (2D) FF "Petterssen's FF." However, for conciseness and in agreement with Miller and MLD, in the following the former FF is indicated as F_3 and the latter as F_2.

To my knowledge, only a few authors—namely, Newton (1954), Newton and Trevisan (1984a,b), and Keyser et al. (1986)—have taken into account, in diagnosing the dynamics of ULFs, the F_3 function, including therefore in their investigations the total time derivative of the vertical component $\partial\theta/\partial z$ of $\nabla_3\theta$—namely, the rate of change of the static stability. However, in all the above papers the analysis of the evolution in time of $\partial\theta/\partial z$ is treated as distinct from the rate of change of $|\nabla_2\theta|$. More specifically, Newton (1954) writes and evaluates two separate equations for $D\theta_y/Dt$ and $D\theta_z/Dt$ (y and z being the cross-front and the vertical coordinates, respectively). The opportunity of separating the vertical from the horizontal components of F_3 is also clearly presented and discussed in the book by Palmén and Newton (1969, sections 9.3 and 9.4). Newton and Trevisan (1984a,b) distinguish between frontogenesis, reserving this word for F_3, and clinogenesis, which for them denotes F_2 (term clinogenesis, meaning genesis of a baroclinic zone, apparently did not find followers). However, in their companion papers Newton and Trevisan emphasize the important role of clinogenesis in the formation of upper-tropospheric fronts under gradient

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Corresponding author address: Andrea Buzzi, CNR-ISAC, Via Gobetti 101, Bologna I-40129, Italy.
E-mail: a.buzzi@isac.cnr.it

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wind conditions, while they consider the evolution of static stability of fronts separately from the other components of (3D) frontogenesis, as in Newton (1954) and Palmén and Newton (1969). Finally, Keyser et al. (1986) consider F_3 for studying frontogenesis in a 2D (x, z) model. Yet, in their introduction they remark that the vertical derivative of potential temperature must be properly scaled before the total gradient is evaluated. Quoting from them, "Defining straight fronts in terms of variations of potential temperature and absolute momentum in the cross-front vertical plane appears to have the advantage of quantifying frontal structure in a manner that is compatible with conventional depictions of fronts in the form of vertical cross sections. Nevertheless, a problem with this definition lies in the difference of several orders of magnitude between the cross-front and vertical scales of frontal zones (100–200 km compared with 1–2 km). Consequently, describing fronts in terms of magnitudes of gradients of potential temperature and absolute momentum in transverse vertical planes may be of questionable utility, since these quantities are dominated by their vertical components" (p. 840). I agree that a proper scaling is necessary to evaluate F_3; however, the arbitrariness of the specific aspect ratio being adopted still makes a quantitative evaluation of F_3 problematic if $|\nabla_2\theta|$ and $\partial\theta/\partial z$ are not considered separately.

2. Comparison between F_2 and F_3 frontogenetical functions

MLD say that that "F_3 is a necessary and sufficient metric for quantifying the rate of development of ULFs" (p. 2713). Based on it, MLD analyze the evolution of a ULF growing in simulated baroclinic waves, also by decomposing F_3 into different components (diabatic, geostrophic, and ageostrophic) and comparing the results with those obtained by applying the traditional FF—namely, F_2 (note that this decomposition of F_3 is made in terms of the operator D/Dt, not of the operand $|\nabla_3\theta|$). MLD claim that their results, which indicate a strong spatial correlation between the simulated ULF and F_3, prove the validity of F_3 as a measure of upper-level frontogenesis. I doubt that invoking a good spatial matching is a robust argument for preferring F_3 to F_2, even though a comparison between their Fig. 8 (F_3 and its components) and Fig. 11 (F_2 and its components) seems to favor F_3. Actually, Figs. 8 and 11 of MLD refer to cross-section AA′, which seems to be located very close to the maximum of ULF intensity (see their Fig. 4)—that is, not in the ULF entrance where the largest frontogenesis should be experienced by air parcels entering the front. Therefore, the comparison between F_3 and F_2 does not seem to be pursued in the most appropriate location with respect to the ULF-jet system (perhaps cross-section BB′, in its southern part—see again their Fig. 4—should be more adequate than AA′ to represent the frontogenetical region, but the corresponding distribution of F_2 is not shown).

Nevertheless, I do not intend to discuss in more detail the quantitative results presented in MLD. Rather, I will focus on the underlying logic of using F_3 and its physical significance in comparison with F_2. The first problem I have is that F_3 is not a metric that characterizes fronts only. In fact, it can be significantly large (positive or negative) also in cases of Lagrangian rate of change (intensification or weakening) of an atmospheric stably stratified layer in the absence of baroclinicity—for example, in cases of air parcels moving into or out of quasi-horizontal layers of high static stability that do not necessarily constitute fronts (Danielsen 1959). Although I agree that ULFs are generally associated with high values of static stability, I consider that the distinctive thermodynamical and dynamical property of a front is its high baroclinicity, according to the classic definition of front (in the AMS *Glossary of Meteorology*: a "layer of large horizontal density gradient"; http://glossary.ametsoc.org/wiki/Front). From the point of view of dynamic meteorology, the forcing term of the (inviscid) equation representing the rate of change of the 3D vorticity vector is the baroclinic term $c_p\nabla_3\theta \times \nabla\pi$, where $\pi = T/\theta$ is the (nondimensional) Exner function and c_p is the specific heat at constant pressure. This term, which is the source of almost all atmospheric circulation systems including fronts, is zero if $\theta = \theta(\pi)$. Thus, $|\nabla_3\theta|$ can be very large without producing any circulation. To produce circulation θ must vary along a pressure or π surface. Since to a first approximation pressure surfaces are level, it is the horizontal variations of θ that produce circulation and, therefore, are dynamically important.

The second problem, strictly related to the argument of Keyser et al. (1986) mentioned above, is that using an isotropic metric in which the vertical and horizontal components of a 3D gradient are taken together without applying a proper scaling is not justified for atmospheric fronts. Doing that implies that the magnitude of $\nabla_3\theta$ is largely dominated by its vertical component, which is proportional to the static stability, as known by MLD (p. 2708, right column). So, in the absence of anisotropic scaling in the evaluation of F_3, the total time derivative of the dynamically significant horizontal gradient of θ is normally overcome by the total time derivative of static stability.

In other words, the application of F_3 as in MLD risks providing mainly a measure, even in cases of real fronts, of the dynamics of intensification (or weakening) of $\partial\theta/\partial z$. This may explain, for example, why in MLD the role of $F_{3\mathrm{A}}$ (ageostrophic components of the flow) is by far the dominant effect on frontogenesis as evaluated with F_3. So, the deformation of the velocity vector field in a vertical plane crossing a ULF, coupled with $\partial\theta/\partial z$, tends to become the prevailing factor in the evaluation of F_3, since $\partial\theta/\partial z$ is much larger than $|\nabla_2\theta|$. This effect (i.e., the compression of the isentropes in the vertical) is analogous to the deformation frontogenesis in the horizontal plane. If F_2 is considered instead, the vertical velocity still plays an important role in frontogenesis, but through the coupling of its horizontal variations with $\partial\theta/\partial z$ (tilting frontogenesis). The two processes are dynamically different and, according to most authors (see the reference list in the introduction), only the second one contributes substantially to upper-level frontogenesis.

I propose the following two additional conceptual examples to try to clarify the physical differences between F_2 and F_3. The first is significant in the context of upper-level frontogenesis, although it represents only an ideal kinematic process: a pure rotation[1] of the vector $\nabla_3\theta$ in its vertical plane, without change of its magnitude, would not be associated with frontogenesis (or frontolysis) according to F_3. In contrast, rotation of $\nabla_3\theta$ in the vertical plane associated with strong horizontal gradients of vertical velocity represents the prototype of a very important, often dominant, frontogenetical effect (i.e., the tilting mechanism), according to F_2. Almost all the papers in the literature dealing with ULFs agree with the fact that, at variance with low-level fronts, this tilting mechanism represents a main contribution to total frontogenesis in the entrance region of the front–jet system, at least in some stage of the ULF life cycle. It represents a locally indirect thermal circulation, as opposed to the direct circulation normally characterizing low-level fronts (Eliassen 1962).

The second argument in favor of F_2 is more dynamically based: a ULF is normally characterized by an upper portion of air of stratospheric origin, having high Ertel potential vorticity (PV) values typical of air of stratospheric origin (Reed and Danielsen 1958), and by a lower portion, below the (folded) tropopause, characterized by air of tropospheric origin with low PV values. In this lower portion the configuration of the sloping isentropes is similar, for some distance below the upper part of the front, to that of the upper part—that is, with comparable (though getting weaker moving downward) values of the 3D gradient of potential temperature [see, e.g., Fig. 10.10 in Lin (2007), adapted after Shapiro (1983)]. Although the horizontal and vertical derivatives of potential temperature within the frontal zone (clearly I consider here the ULF as a layer of finite width and depth) are continuous crossing the dynamic tropopause, the change in PV along the isentropes is sharp. This is accounted for mainly by sharp variations of isentropic relative vorticity, which changes sign from negative in the tropospheric air to positive in the stratospheric air within the front. Let us consider particles coming from the lower stratosphere and entering the upper portion of the front–jet system, where PV is large (on the cyclonic side of the jet): to the extent that they conserve PV, they must experience a decrease of static stability together with an increase of isentropic relative vorticity (together with positive F_2 frontogenesis). So, air of stratospheric origin that enters the upper-level front is associated with descent and weakening of static stability with respect to its original values. Conversely, tropospheric particles entering the lower portion of the ULF must experience an increase of static stability together with a decrease of isentropic relative vorticity, again for PV conservation. This means that Lagrangian changes in static stability, which tend to dominate in the evaluation of F_3, are not a distinctive feature of upper-level frontogenesis. As a consequence, the diagnosis of frontogenesis for the two regions should exclude, or at least treat separately, the evolution of $\partial\theta/\partial z$, which is opposite in sign in the two portions. Conversely, in both front portions trajectories are characterized by positive F_2 frontogenesis. So only the use of F_2 would produce consistent results throughout the ULF.

3. Conclusions

The definition of the FF in the form F_3 utilized by MLD is not new but has received little consideration so far in the meteorological literature. Most authors have preferred F_2 as the proper form of FF in dealing with the problem of upper-level frontogenesis. I can accept that there is some degree of arbitrariness/subjectivity in choosing one or the other, and I consider the MLD paper as a useful contribution in contrasting and complementing the two frontogenetical functions. However, I have expressed some reasons why F_2, based solely on the total derivative of the horizontal (or isobaric) gradient of potential temperature, should be preferred to F_3 in diagnosing the dynamically significant processes associated with upper-level frontogenesis.

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[1] Note that some authors (Keyser et al. 1988; Lang and Martin 2010; Martin 2014) have introduced the concept of rotational frontogenesis, but meaning the rotation of $\nabla_2\theta$ in the horizontal plane.

The application of F_3 without separating in some way the vertical component from the horizontal components of the gradient of potential temperature can hardly be reconciled with the widely accepted definition of atmospheric fronts. It may lead to misleading or at least not sufficiently enlightening results from the point of view of dynamic meteorology if it is considered a sufficient metric to study the process of upper-level frontogenesis, as proposed by MLD.

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