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Notes and Correspondence
Comments on 'The influence of rotational frontogenesis and its associated shearwise vertical motions on the development of an upper-level front' by A. A. Lang and J. E. Martin (January A, 2010, 136: 239–252)

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Two previous studies by Rotunno *et al.* and Schultz and Doswell offer conflicting views on the origin of geostrophic cold-air advection that is sometimes present during upper-level frontogenesis. Although Lang and Martin (2010) claim to reconcile these two studies, this comment offers four reasons why reconciliation is not possible. First, the necessary calculations to compare the tilting frontogenesis term to the horizontal frontogenesis terms are not performed. Second, the thermal-advection tendency or isentrope-orientation tendency in the region of the developing cold-air advection is not calculated. Third, previous studies showing that the vertical terms in these diagnostics are likely associated with warm-air advection, not cold-air advection, are not disproven. This fact also may explain the predominance of relatively weak geostrophic thermal advection in climatologies of upper-level fronts. Fourth, concerns are raised about some of the statements made in Lang and Martin (2010). These comments also fix an error in Eq. (11) in Schultz and Doswell (*Q. J. R. Meteorol. Soc.* 125: 2535-2562, 1999). Copyright © 2011 Royal Meteorological Society

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1. Introduction

The stated goal of Lang and Martin (2010, hereafter LM10) is two-fold. The first is to examine how rotational frontogenesis and its associated shearwise quasi-geostrophic vertical velocity affect scalar frontogenesis in an upper-level front. The second is to examine how rotational frontogenesis and its associated quasi-geostrophic vertical velocity initiate cold-air advection along an upper-level front. LM10's calculations of quasi-geostrophic vertical velocity show the importance of the quasi-geostrophic subsidence to tilting frontogenesis. The presence of this subsidence or its role in upper-level frontogenesis is not in question. What is in question is the role of this subsidence in producing the geostrophic cold-air advection.

LM10 discuss the origin of the geostrophic cold-air advection sometimes present during upper-level frontogenesis. They confirm the importance of rotational frontogenesis to upper-level frontogenesis, first identified by Schultz and Doswell (1999) and Schultz and Sanders (2002).

These two articles demonstrate that the cold-air advection on the downstream end of the upper-level front originates from rotational frontogenesis associated with the developing vorticity maximum. These results, however, are not the only ones in the literature offering an explanation for the cold-air advection.

Specifically, Rotunno *et al.* (1994) offer a competing hypothesis. They perform idealized baroclinic channel model simulations of growing baroclinic waves and examine the intensification of an upper-level front from an initial state devoid of large temperature advection. They argue that the descending higher-potential-temperature air from aloft leads to a cyclonic rotation of the isentropes relative to the isohypses, producing geostrophic cold-air advection (pp 3389–3390). Rotunno *et al.* (1994) do not perform any explicit calculations in support of their argument, however. In contrast, Schultz and Doswell (1999) perform a climatology and two case-studies of upper-level frontogenesis over the eastern North Pacific Ocean and western North America. They conclude that the onset of the geostrophic cold-air advection in the two case-studies occurs due to the cyclonic rotation of the isentropes associated with a coincident vorticity maximum. Moreover, explicit calculations in Schultz and Sanders (2002) show that the descent emphasized by Rotunno *et al.* (1994) would favour *warm-air advection* (anticyclonic rotation of the isentropes), not cold-air advection.

LM10 advance a reconciliation between the contradictory conclusions of Rotunno *et al.* (1994) and Schultz and Doswell (1999) based upon the partition of the quasi-geostrophic vertical velocity as the key to understanding the subsidence associated with the onset of geostrophic cold-air advection. This partition separates the quasi-geostrophic vertical velocity into components associated with scalar frontogenesis and rotational frontogenesis, which LM10 refer to as transverse and shearwise vertical velocities. LM10 (p 251) conclude that 'the subsidence emphasized by [Rotunno *et al.* (1994)] and the kinematic rotation emphasized by [Schultz and Doswell (1999)] are interconnected aspects of a single, underlying dynamical process: rotational frontogenesis.'

This comment argues that the diagnostics used by LM10 are inappropriate to demonstrate their claim. Specifically, LM10 do not provide explicit calculations of the processes changing the thermal advection. Thus, LM10 cannot claim to reconcile Rotunno *et al.* (1994) and Schultz and Doswell (1999).

2. A corrected equation for Schultz and Doswell (1999)

Given the centrality of the expressions for frontogenesis in this comment, it would be prudent to correct an error in Eq. (11) in Schultz and Doswell (1999). An error in the submitted manuscript omitted $-|\nabla_H\theta|^{-1}$ in front of the tilting terms; the calculations derived from that equation are not in error. The correct version of Eq. (11) is:

$$F_n = \tfrac{1}{2}|\nabla_H\theta|(\nabla_H\cdot\mathbf{V}_H - E\cos 2\beta) + \frac{1}{|\nabla_H\theta|}\frac{\partial\theta}{\partial p}(\nabla_H\omega\cdot\nabla_H\theta), \qquad (11a)$$

$$F_s = \tfrac{1}{2}|\nabla_H\theta|(\mathbf{k}\cdot\nabla_H\times\mathbf{V}_H + E\sin 2\beta) + \frac{1}{|\nabla_H\theta|}\frac{\partial\theta}{\partial p}\mathbf{k}\cdot(\nabla_H\omega\times\nabla_H\theta), \qquad (11b)$$

3. Horizontal rotational frontogenesis terms not calculated

The analysis by LM10 only tells half of the story. They calculate only the tilting frontogenesis. But, horizontal flow is also responsible for frontogenesis, and LM10 do not calculate explicitly all three terms in the rotational frontogenesis expression (vorticity, deformation and tilting terms in Eq. (3b) in LM10 and the corrected Eq. (11b) above). They compute only one of the terms: tilting. Thus, readers are unable to ascertain the relative magnitudes of the vorticity and deformation terms compared to the tilting term. Without knowing the relative magnitudes of the vorticity and deformation terms relative to the tilting term, LM10 cannot claim to have demonstrated the importance of the vertical circulation on the initiation of along-flow cold-air advection.

Are the terms for horizontal rotational frontogenesis larger or smaller than the tilting rotational frontogenesis in the region of geostrophic cold-air advection? Are they even of the same sign? (For example, Schultz and Doswell (1999) show that the vorticity term has the *opposite* sign to the tilting term along much of the front.) Without explicit calculations answering these questions, LM10 cannot claim to have fully examined how rotational frontogenesis initiates geostrophic cold-air advection.

4. Thermal-advection and isentrope-orientation tendency equations not calculated

Although rotational frontogenesis can be a useful quantity to interpret the kinematics of a front, it does not get to the heart of the question that LM10 want to address: what causes the onset of geostrophic cold-air advection along upper-level fronts? Furthermore, the partitioned **Q**-vector approach used by LM10 assumes that the flow is quasi-geostrophic, an arguable assumption for fronts. Schultz and Sanders (2002) develop two diagnostic tools that directly address the cold-air advection and make no assumptions about the flow. Specifically, these tools are the tendency of the horizontal thermal advection and the local tendency of the orientation of the isentropes. The vertical terms in both of these tools for two upper-level fronts in different large-scale flow patterns are negligible or favour warm-air advection (Schultz and Sanders 2002) – the opposite of what LM10 claim to be important to the onset of the cold-air advection.

LM10 do not refute the validity of these tools, nor are these tools applied to their upper-level front. Nowhere is there any explicit computation of the thermal-advection tendency equation, the natural choice for assessing the processes changing the thermal advection. Want to determine the causes of the rotation of the isentropes? There's an equation for that. LM10 use an inadequate tool despite better tools being available.

5. Other concerns

This comment reveals several concerns about statements in LM10. First, LM10 state: 'vorticity rotates every vector field equally, and therefore cannot promote the *differential* rotation of $\nabla\theta$ [horizontal potential temperature gradient] relative to $\nabla\phi$ [horizontal geopotential height gradient] required to initiate along-flow *geostrophic* cold air advection' (emphasis in original) (p 240). This statement is not true. Given the direct relationship between geostrophic vorticity ζ_g and ϕ ($\zeta_g = \nabla \times \phi$), the geostrophic vorticity is incapable of rotating the height field.

Second, LM10 state that upper-level fronts have an 'observed preference' for development in northwesterly flow (p 239) and are 'more frequent' in geostrophic cold-air advection in northwesterly flow (p 250). Although two-dimensional idealized simulations of upper-level fronts (e.g. Shapiro, 1981; Keyser and Pecnick, 1985; Keyser *et al.*, 1986; Reeder and Keyser, 1988) show that cold-air advection accelerates upper-level frontogenesis through a positive feedback termed the Shapiro effect (reviewed by Keyser (1999)), observed climatologies of upper-level fronts do not support LM10's statements.

Of 149 upper-level fronts associated with landfalling cyclones over North America, Schultz and Doswell (1999) find that 44% occurred in southwesterly flow and only 14% occurred in northwesterly flow. Of those 149 fronts, only 35 (23%) occurred with increasing geostrophic cold-air advection, whereas 73 (49%) occurred with weak geostrophic thermal advection. Of the 35 fronts where geostrophic cold-air advection increased, 63% occurred in southwesterly flow and 17% occurred in northwesterly flow. Schultz and Sanders (2002) consider upper-level fronts in northwesterly flow associated with mobile short-wave trough births over North America. Of 186 upper-level fronts in northwesterly flow, only 26% were associated with increasing geostrophic cold-air advection and 55% were associated with weak geostrophic thermal advection. Thus, the results from these two studies contradict LM10's statements that upper-level fronts associated with geostrophic cold-air advection are more frequent in northwesterly flow. Even when restricted to upper-level fronts in northwesterly flow, geostrophic cold-air advection is not predominant.

Because the horizontal terms in the thermal-advection tendency equation have the opposite sign to the vertical term (section 3), the resulting sign of the temperature advection will be a result of which term is largest. Consequently, the total thermal-advection tendency may be positive or negative along any given front. This fact may help to explain why roughly half of the upper-level fronts in the two climatologies have weak geostrophic thermal advection. Thus, this possible explanation provides a testable hypothesis for further research on this topic.

6. Conclusion and pitfalls

Given these concerns, LM10 do not reconcile the competing mechanisms for the onset of geostrophic cold-air advection offered by Rotunno *et al.* (1994) and Schultz and Doswell (1999). LM10 fail to answer this question for four reasons.

First, LM10 do not address the relative importance of tilting to the rotation of the isentropes because the horizontal terms are not contoured and compared to the tilting term. Second, LM10 do not present specific calculations to examine the tendency of the thermal advection or the rotation of the isentropes (Schultz and Sanders, 2002). Third, LM10 do not refute the result that subsidence would favour warm-air advection in the area where the geostrophic cold-air advection is developing (Schultz and Sanders, 2002). Finally, LM10 make incorrect statements about vorticity and the climatology of upper-level fronts. Thus, for these reasons, LM10 do not explain the reason for the onset of geostrophic cold-air advection along upper-level fronts.

This comment also offers a testable hypothesis. The reason that cold-air advection is not predominant among climatologies of upper-level fronts is that the offsetting terms in the thermal-advection tendency equation (i.e. horizontal terms favouring cold-air advection and vertical term favouring warm-air advection) combine with the likely result being relatively weak thermal advection along the front.

Finally, this comment alerts us to two possible pitfalls to avoid. The first pitfall is extrapolating the results from a single case-study to an entire conceptual model for upper-level frontogenesis. For example, Schultz and Zhang (2007, pp 1110–1111) show that, when an idealized baroclinic wave is placed in large-scale diffluence, the relationship between horizontal terms and the tilting term in the scalar frontogenesis equation differs from that described by Rotunno *et al.* (1994). In another example, the climatologies discussed in section 5 of this comment indicate that cold-air advection in northwesterly flow is not the most common type of upper-level frontogenesis. Thus, generalizing how upper-level frontogenesis occurs – even from idealized simulations, let alone a single case-study – is risky.

The second pitfall is extrapolating the results from two-dimensional frontogenesis studies to three dimensions (e.g. Keyser, 1999; section 4 in Schultz and Sanders, 2002). For example, the idealized baroclinic channel simulation of Rotunno *et al.* (1994) indicates that trough amplification can occur in the absence of the Shapiro effect, and the idealized baroclinic channel simulation of Wandishin *et al.* (2000) indicates that tropopause folding can occur along the length of the front, not just in the regions of cold advection. Coupled with the climatologies of upper-level fronts showing that cases with weak thermal advection predominate, more remains to be told of the story on the Shapiro effect in realistic three-dimensional flows (Keyser, 1999).

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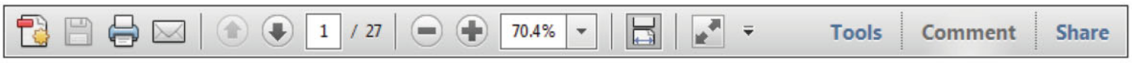

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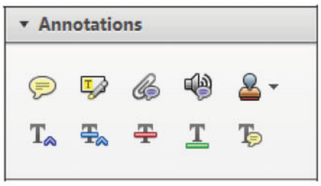

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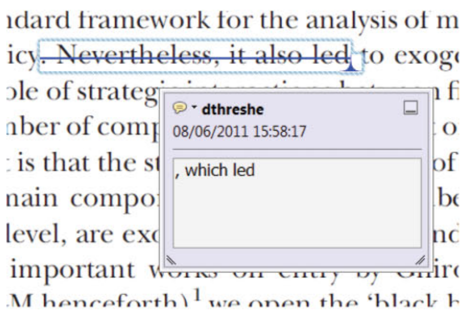

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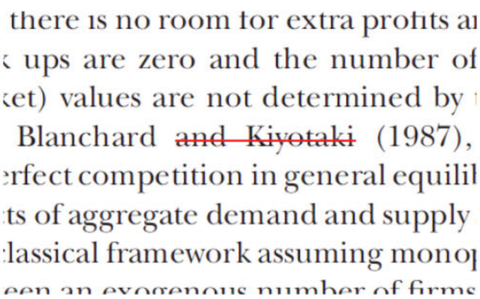

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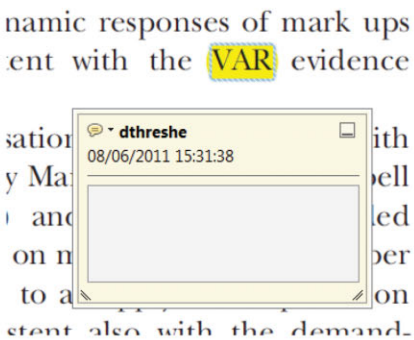

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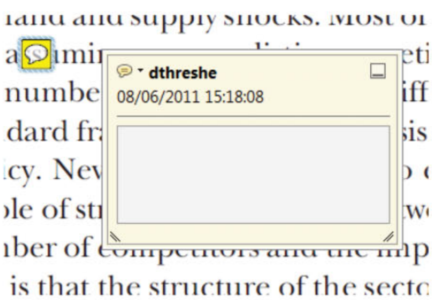

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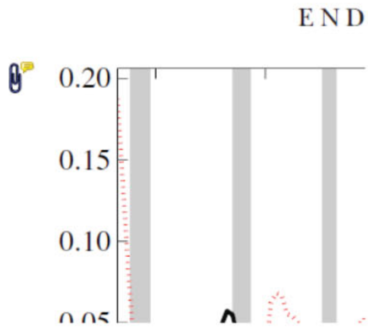

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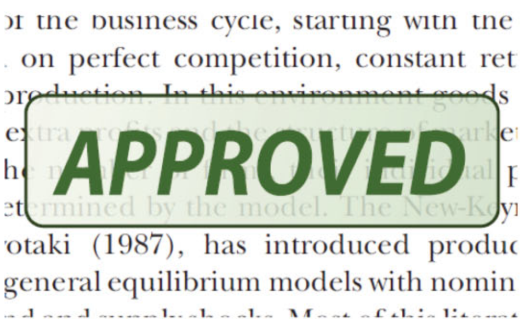

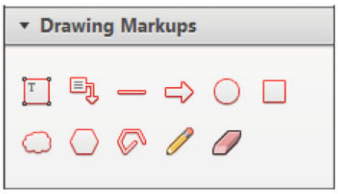

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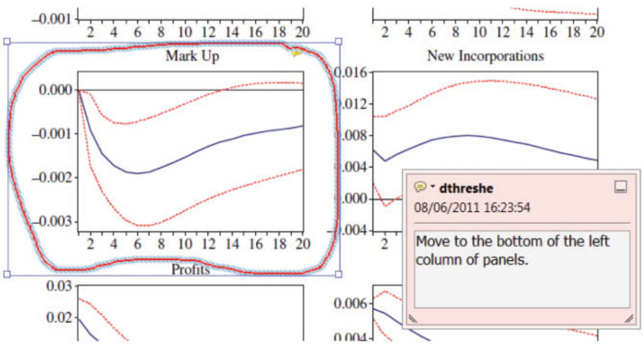

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