Upstream Influences of Orographic Blocking on Precipitation Associated with Landfalling Fronts: An Overview and Perspective

Cheng-Ku Yu*
Department of Atmospheric Sciences
Chinese Culture University
Taipei, Taiwan

1. Introduction

Much has been learned about how topography alters the upstream airflow patterns and structures through the blocking effect. Nevertheless, how these airflow modifications influence precipitation intensity associated with synoptic disturbances such as fronts has been largely unexplored and remains poorly understood. The difficulties in distinguishing orographically modified precipitation from the precipitation that was associated with baroclinic forcings also represent an unavoidable challenge for improving our understanding on this scientific topic. With detailed radar observations and numerical simulations, a number of recent articles have attempted to identify processes contributing to the evolution of precipitation associated with fronts as they made landfall and underwent obvious upstream influences of orography. These studies have proposed different kinds of mechanisms that might be responsible for the modifications of frontal precipitation by upstream effects of orography for their observed/simulated fronts. This paper provides a brief summary for these results as well as discusses their uncertainties and implications.

2. Overview

a. Modification of prefrontal vertical wind shear

When the prefrontal flow is blocked by the mountains, the vertical wind shear in the prefrontal environment is likely to be altered significantly. Changes in prefrontal ambient vertical shear may further influence the lifting at the leading edge of the advancing cold air behind the cold front (Rotunno et al. 1988; Parsons 1992). As observed and evaluated by Yu and Smull (2000), the enhancement of the prefrontal along-barrier flow due to the blocking of the low-level prefrontal flow tended to increase the cross-front vertical wind shear, which is consistent with the development and intensification of their observed narrow precipitation band coincident with the low-level frontal wind shift zone. In this manner of interaction, the orientation of the front relative to the barrier is an important factor because the cross-front vertical shear would not be modulated if the front were oriented parallel to the barrier.

b. Convergence between the enhanced along-barrier flow and postfrontal flow

In contrast to foregoing discussions, a more direct impact of orographic blocking on precipitation intensity at fronts is through the interactions between the enhanced along-barrier flow and the postfrontal flow. Stronger low-level convergence can be generated along a segment of the frontal

Corresponding author address: Dr. Cheng-Ku Yu, Department of Atmospheric Sciences, Chinese Culture University, 55, Hwa-Kang Road, Yang-Ming-Shan, Taipei 111, Taiwan
E-mail: yuku@faculty.pccu.edu.tw

boundary in which the blocked, mountain-parallel prefrontal flow bring more cross-front wind component colliding with the cold air mass. It can be also anticipated that maximum convergence is more possible to occur in regions near the intersection of the frontal wind shift zone and the barrier. Such a forcing type has been found to contribute evidently to precipitation intensification along fronts as they made landfall on the mountainous coast (Yu and Smull 2000; Neiman et al. 2004). Nevertheless, for a frontal system oriented approximately parallel to the barrier, this mechanism appears to be much less significant (Braun et al. 1997; Doyle and Bond 2001).

c. Modification of along-front flow

Surface friction has been recognized as one of the possible mechanisms responsible for the formation of the precipitation band coincident with the cold frontal wind shift zone (Browning and Harrold 1970; Keyser and Anthes 1982; Bond and Fleagle 1985; Wakimoto and Bosart 2000). The degree to which frictional convergence contributes to the vertical velocity at the top of the boundary layer is closely related to the cyclonic vorticity in the vicinity of fronts (Bond and Fleagle 1985). When variations in the winds along the front are negligible, the horizontal hear by the cross-front gradient of along-front flow is a major contributor for the frictional forcing. Yu and Bond (2002) documented a slow-moving cold front making landfall on the windward side of Vancouver Island and provided an observational perspective that the modulation of along-front flow by coastal mountains may play a role in altering the distribution of horizontal shear and hence the frictional convergence and precipitation along that front. Note that this kind of the interaction between the front and terrain can also take place even if the front is oriented parallel to the coastal barrier.

d. Upstream deceleration induced convergence

One of the most important characteristics associated with the occurrence of the orographic blocking is the upstream deceleration of the incident flow component normal to the barrier (Pierrehumbert and Wyman 1985). The flow deceleration can further result in the low-level convergence favorable for the formation of upstream precipitation (Grossman and Durran 1984). Similarly, this effect can also occur and influence frontal precipitation when low-level flow associated with fronts is blocked by mountains (Braun et al. 1997; Yu and Smull 2000). On the other hand, it is not uncommon to observe the enhanced convergence in the region where the prefrontal flow decelerates as it encounters the blocked flow near the coast (Li et al. 1997; Chien et al. 2001; Yeh and Chen 2002). In contrast to the former, which its low-level convergence caused by inherent blocking effects is confined primarily to the nearshore blocked zone, the convergence zone in the latter is located farther offshore near the seaward extent of the nearshore blocked flow.

e. Distortion of the frontal zone

It has been recognized that the onshore movement of landfalling fronts is frequently impeded by steep coastal topography due to the orographic blocking (Schumann 1987; Trier et al. 1990; Doyle 1997). Differential speed along the different segment of fronts can cause the horizontal distortion of the frontal zone, which further produces local convergence perturbation to influence precipitation intensity at fronts. Detailed analyses of recent radar observations have provided evidence that such effect can be important for modifying precipitation associated with landfalling fronts (Braun et al. 1997; Yu and Bond 2002) or an oceanic front (Wakimoto and Bosart 2000). It is noteworthy that a front is also likely to be distorted vertically when the moving speed of frontal zone at lower levels is different from that aloft. Neiman et al. (2004) documented an intense landfalling winter storm in southern California and found that the weakening of precipitation along the front was associated with the split of the front in the vertical as it encountered the nearshore blocked flow.

f. Frontogenesis

Orographic blocking can lead to the enhanced deformation favorable for the occurrence of frontogenesis immediately upstream of the terrain or within the coastal zone. Significance of this process, particularly as fronts approach the topography, has been suggested by some recent modeling studies (Braun et al. 1999; Colle et al. 1999; Colle et al. 2002). It has been generally recognized that vertical motions associated with the ageostrophic cross-front circulation generated by the frontogenesis process should be linked to the formation of frontal precipitation to some degree (Houze 1993). In this manner, the frontogenesis dynamics would play a role in influencing the precipitation intensity at fronts. However, the specific degree to which the orographically induced frontogenesis contributes to the development of frontal precipitation still lack good documentation and deserves further investigation.

3. Conclusions

Based on the results of recent observational and modeling works as discussed above, upstream influences of orographic blocking on the precipitation associated with landfalling fronts can be fundamentally classified into six forcing types: the modification of prefrontal vertical wind shear, the convergence between the enhanced along-barrier flow and the postfrontal flow, the modification of the along-front flow, the upstream deceleration induced convergence, the distortion of the frontal zone and the frontogenesis. Essentially, these orographic modifications are dependent on the orientation of frontal system relative to the orographic barrier and the nature of the blocked flow. Although in this paper the above six forcing types are discussed separately, it is expected that some of them might occur simultaneously and interact each other in real events. These more complex situations and the relative importance of the identified forcing types are worthwhile to be further addressed in future observational and modeling studies.

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