A Synthesis of Recent Research on Precipitation in Mountain Alpine Environments

Ruping Mo

National Laboratory for Coastal and Mountain Meteorology / Pacific Storm Prediction Centre,
Environment Canada, Vancouver, BC, Canada

Corresponding author’s address:
Ruping Mo
Pacific Storm Prediction Centre, Environment Canada
201-401 Burrard Street
Vancouver, BC V6C 3S5
Canada
E-mail: ruping.mo@ec.gc.ca

Technical Report 2009-004
National Laboratory for Coastal and Mountain Meteorology
July 2009
1. Introduction

It is well known that precipitation generally increases on the windward side of a mountain barrier where air is forced to rise, and decreases on the leeward side where air descends. In fact, the amount and distribution of orographic precipitation depend on multiple factors, including air mass characteristics (static stability, moisture content, etc.), terrain characteristics (relief and shape), and microphysical processes in the cloud and the evaporation of falling drops. Under certain circumstances, therefore, heavy precipitation could also occur at the summit or on the leeward side (Browning et al., 1975; Carruthers and Choularton, 1983; Rotunno and Ferretti, 2001; Kaplan et al., 2009).

The study of orographic precipitation has long been hampered by the paucity of alpine observations. The Mesoscale Alpine Program (MAP), conducted in the European Alps in 1999 (see Bougeault et al., 2001), and the Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE), conducted in the Pacific Northwest of USA in 2001 (see Stoelinga et al., 2003), were initiated to address this problem. During these two campaigns, comprehensive data were collected from a wide variety of surface-based and airborne observations over mountainous terrains. Recent studies based on these data show a much detailed and revised picture of the orographic precipitation from earlier works. This report summarizes some of these studies that provide new insight into the orographic precipitation enhancement and its interaction with the orographically modified airflow. The relevance of these studies to the Vancouver-Whistler 2010 Olympic and Paralympic Winter Games is discussed at the end of the report.
2. Down-valley flow under heavy precipitation

When large-scale pressure gradients are weak, the differential heating/cooling along the mountain slopes can give rise to characteristic systems of air motion within the valleys. These include the downslope movement of cold air at night, known as *katabatic* wind, and the upslope movement of warm air during the day, known as *anabatic* wind (see Barry 2008). These thermally induced winds are well understood and can be easily forecast.

Steiner *et al.* (2003) analyzed the airflow within deep valleys in the presence of sustained orographic precipitation. Their study was focused on the Toce River Valley over the Alps, based on ground-based and airborne Doppler radar, surface, and upper-air data collected during MAP in 1999. They showed that orographic precipitation can strongly modify the airflow within the valleys. In particular, during persistent rainy periods a down-valley flow can form below the melting layer, as opposed to the moist up-valley flow aloft. This down-valley flow described in their paper was most evident in the airborne Doppler radar data, as shown in Fig. 1 (also see Bousquet and Smull, 2003). It developed soon after rain started and began to switch back to up-valley flow after the rainfall ceased. Its strength and depth were related to the rainfall amount, but appeared to be disconnected from the large-scale upslope flow aloft.

Based on their detailed thermodynamic analyses, Steiner *et al.* (2003) pointed out that the subsidence caused by melting and evaporation of precipitation particles makes the major contribution to the formation of the down-valley flow. They argued that cooled air from melting is heavier than its environment and thus starts to subside. Cooling from evaporation will enhance this downward motion. The subsiding air becomes concentrated
in the valleys and forms a down-valley drainage flow. This process bears some resemblance to the production of a downdraft and gust front in a thunderstorm. It differs, however, from the nocturnal drainage flow (katabatic wind), which is caused by radiation cooling under clear skies and weak synoptic conditions.

Figure 1. Wind field within the Toce River Valley and its tributaries as depicted by the airborne dual-Doppler radar analysis based on the 0949-0954 UTC P-3 flight leg on 21 October 1999 (Figure 4 in Steiner et al., 2003).
3. Shear layer accompanying precipitation events

Medina et al. (2005) used data collected from both MAP and IMPROVE to analyze and compare some frontal rainstorms over the European Alps and the Cascade Mountains of USA. Focusing on situations of stable up-stream stratification, they identified a layer of strong vertical wind shear forming at the immediate height in the subcrest layer as a persistent and characteristic feature of midlatitude baroclinic storms passing over a mountain range (see Fig. 2). This stably stratified shear layer slopes upward toward the mountain crest and is separated from the strong cross-barrier flow aloft. It persists for several hours as the storm moves across the mountains. Precipitation patterns accompanying these strongly sheared flows exhibits stratiform structure, marked by a pronounced radar bright band in the observed reflectivity pattern (Fig. 2a).

Model simulations conducted by Medina et al. (2005) indicate that the characteristic shear layer is part of the natural response of a stable flow encountering a mountain barrier. Its observed repeatability suggests a fundamental dynamical-microphysical interaction leading to the local orographic precipitation enhancement over the windward slopes of major maintain ranges. More precisely, a stable and moisture-laden flow crossing a mountain barrier will develop this low-level shear pattern, as a consequence of stability of the flow and frictional drag over the underlying surface. This dynamically induced shear layer in turn triggers turbulent overturning, which in turn promotes the concentration of precipitation over the windward slopes. The diabatic cooling associated with the orographically enhanced precipitation (e.g., Steiner et al., 2003) may also provide a highly nonlinear feedback mechanism for the maintenance and/or enhancement of the shear layer.
Precipitation patterns accompanying these strongly sheared flows are further characterized by a mid-level secondary maximum of radar reflectivity over and immediately upstream of the crest (Fig. 2). This feature is apparently associated with a terrain-induced, upward-propagating gravity wave disturbance. The wave-induced strong downslope flow and spillover of precipitation onto the lee side of the Cascade can be identified in Fig. 2.
4. Applications to the Vancouver 2010 Winter Olympics

The repeatable down-valley flow and sheared velocity pattern identified in the above-mentioned studies appear as two essential features of orographic precipitation associated with a moist, statically stable flow. The resulting conceptual model, therefore, could be applicable to the on-site weather forecast for the upcoming Vancouver-Whistler 2010 Olympic and Paralympic Winter Games.

Figure 3 shows two images of the newly installed Doppler radar in Whistler at 0330 UTC, 20 March 2009. A moist, stable southwesterly flow had spread periods of rain to the South Coast of British Columbia, including the Whistler area (Fig. 3a). The vertical cross section in Fig. 3b extends eastward (95°) from the Whistler Radar. It shows the radial velocity field with blue and green (pink and yellow) shading denoting flow toward (away from) the radar. A low-level down-valley flow can be seen between the radar and the first major mountain crest. The maximum velocity axis of the down-valley flow locates at ~0.8 km. Lying above it is the highly sheared layer sloping upward toward the first major crest. Both of the down-valley flow and the associated shear layer are apparently decoupled with the strong cross-barrier flow aloft. These features are consistent with those described in Steiner et al. (2003) and Medina et al. (2005).

Similar weather patterns are likely to occur during the upcoming Vancouver-Whistler 2010 Olympic and Paralympic Winter Games. Since alpine precipitation and wind vector are two most important weather elements for many local venue operations and competitions, a conceptual understanding of the above-mentioned orographic effects on air motions could be crucial to the Olympic forecast team.
Figure 3. Radar images scanned at 0330 UTC, 20 Mar 2009 in the Whistler area: (a) Low-elevation (2 degrees) reflectivity (PPI); (b) Radial velocity in a vertical cross-section along the 95 degree line.
References


