14.1 PRECIPITATION SHADOWS IN THE HUDSON VALLEY

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1. INTRODUCTION

Precipitation shadows are a common feature in the rugged terrain of the western United States. The more modest relief typical of the eastern U.S., however, also features topographically influenced precipitation patterns. These are especially notable in the higher terrain of the Appalachians (Brady and Waldstreicher 2001), and the Adirondack Mountains and Catskill Plateau in New York State. Here, we examine three cases of precipitation shadows that occurred during the intensive field campaign (IFC) of the Hudson Valley Ambient Meteorology Study (HVAMS).

1.1 HVAMS

The HVAMS IFC was conducted during the fall of 2003. The IFC featured the deployment (see Fig. 1) of 9 Integrated Surface Flux Facility (ISFF) stations and the Tethered Atmospheric Observation System (TAOS) from NCAR; the Mobile Integrated Sounding Unit (MIPS) from the University of Alabama at Huntsville; the University of Wyoming King Air instrumented aircraft; NOAA's ETL wind profiler at Schenectady Airport; a sodar near the Hudson River ten miles south of Albany at Schodack Island State Park; 5 "HOBO" surface weather stations (ONSET Computer Corp., Pocasset, MA) and additional rawinsonde launches at the NWS WFO Albany. Stations not part of the IFC deployment but nevertheless used as part of long-term data analysis for the HVAMS project include NWS ASOS and Cooperative Observer (COOP) stations. Archived level II reflectivity and radial velocity data from the KENX WSR-88D site were also used for this study.

Although the main purpose of HVAMS was to examine how valley topography and land-use patterns modify the observed microclimate during fair weather regimes, deployment decisions also considered the possibility of more transient phenomena, such as severe weather outbreaks or excessive rainfall events.

1.2 *The Hudson Valley*

The Hudson Valley (the "Valley") extends northwards more than 300 km from New York City to Glens Falls (Fig. 1). Just above Albany, NY, the Mohawk River flows into the Hudson. For most of its length the valley is about 20 – 30 km wide, but narrows to less than 5 km near West Point.

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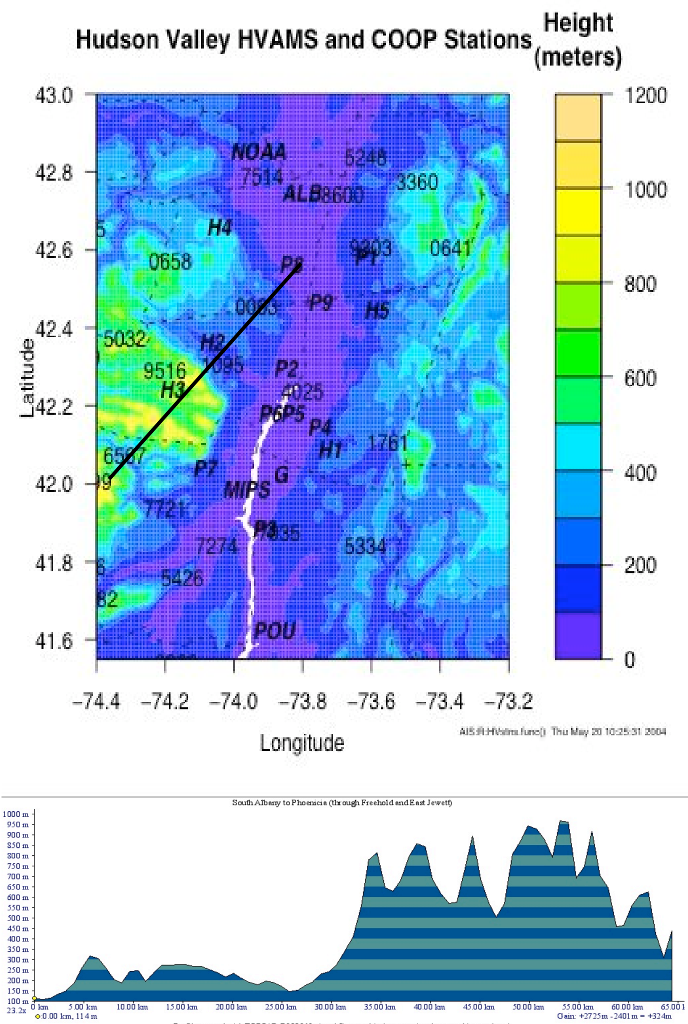

Figure 1 (top): HVAMS IFC field deployment and Cooperative Observer stations used for the referenced precipitation events during September—October 2003. Stations IDs: ISFF stations have "P" prefix, HOBOs ("H"), "NOAA" is the ETL surface station and profiler, "MIPS" is the University of Alabama, Huntsville Mobile Integrated Profiling System, "S" is the sodar at Schodack Island State Park, "G" is the location of the Anchor Station and TAOS, "ALB" and "POU" are Albany and Poughkeepsie ASOS stations, and the 4-digit IDs are the COOP stations. Bottom: topographic cross section along line in top figure from Phoenicia (6567) to South Albany Airport (P8).

The valley is a true fjord south of Troy NY, nearly 250 km north of the Atlantic Ocean. There, a two-meter tidal amplitude in the river is typical; bottomland elevation is only 3-5 meters above sea level. Valley sidewalls range from less than 100 m at White Plains to over 1000 m near at the Catskill Escarpment, but generally rise 200 - 300 m above the river.

The Escarpment is part of the Catskills, an eroded plateau west of the Hudson Valley. Between Kingston and Catskill (roughly stations MIPS to 4025), the Escarpment forms the west wall of the valley; north of Catskill, it turns to the northwest, just to the south of Catskill Creek. It is this area that will be the focus of this presentation.

2. Precipitation Events

Three heavy rainfall events occurred during the IFC: 23 September, 26-27 October, and 29 October. Each was characterized by rainfall in excess of 50 mm; during the 26-27 October event, rainfall exceeded 100 mm at a few locations. All events also featured distinct precipitation shadows in one or more areas of the valley, with rainfall amounts 20 – 60+ mm lower than observed in the surrounding higher terrain. As all three cases exhibit similar rainfall distributions, for purposes of brevity, the rest of this manuscript will focus on the 23 September 2003 case.

2.1 *23 September 2003--overview*

At 1200 UTC 23 September (subtract 4 hr for local time) a 980 hPa surface low was tracking slowly northwards over James Bay, Ontario. An occluded front trailed southwards to a triple point just west of Albany (Fig. 2)

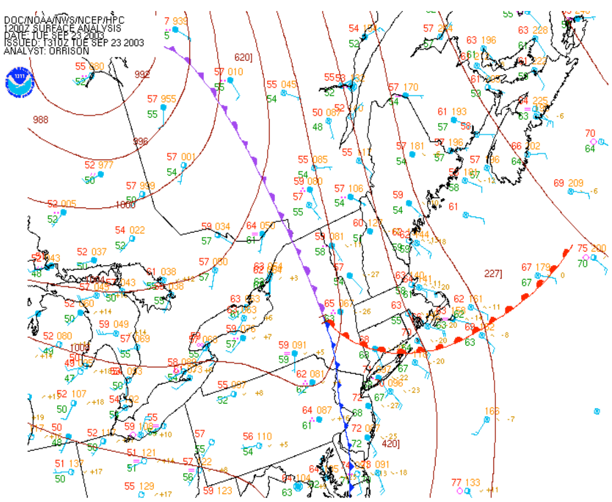

Figure 2: Surface map for 1200 UT 23 September 2003.

Since the 1200 UT Albany sounding was missing, the strength of the winds aloft was estimated from the KENX velocity azimuth profile (VAD; Fig. 3). It shows a strong jet (30 – 40 m s^{-1}) of south-southwesterly winds between 1200 and 1500 m just prior to 1200 UT. During the preceding 6-h period this profile changed very little. Low-level southeast winds slowly veered with height to the SSW, with 20 – 30 m s^{-1} south to south-southwest flow near the approximate level of the Escarpment ridge tops (~ 800 – 1200 m).

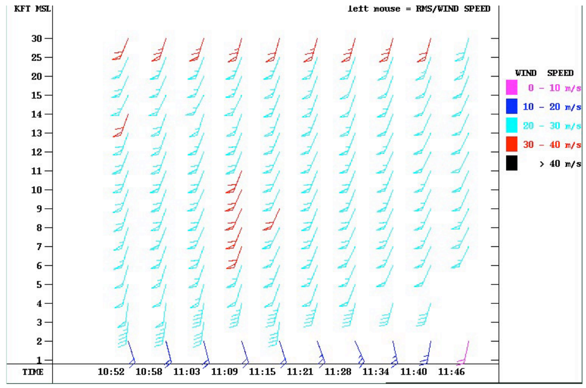

Figure 3: VAD profile from the KENX radar for 1052 – 1146 UT 23 September 2003.

Rainfall from this event was between 20 and 70+ mm, with the highest amounts over the Catskill Plateau, and the lowest (~ 23 mm) at the base of the Escarpment (Fig. 4). At station H3 (East Jewett), 50.4 mm was recorded, while at station H2 (Freehold), about 15 km to the northeast, only 23.4 mm was observed. Most of this precipitation fell within a 2 – 4 h period (Fig. 5).

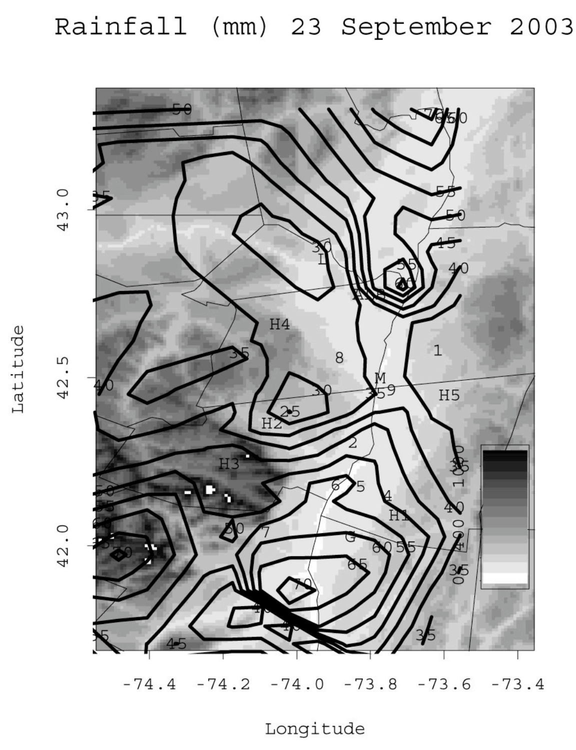

Figure 4: Rainfall for 23 September 3002.

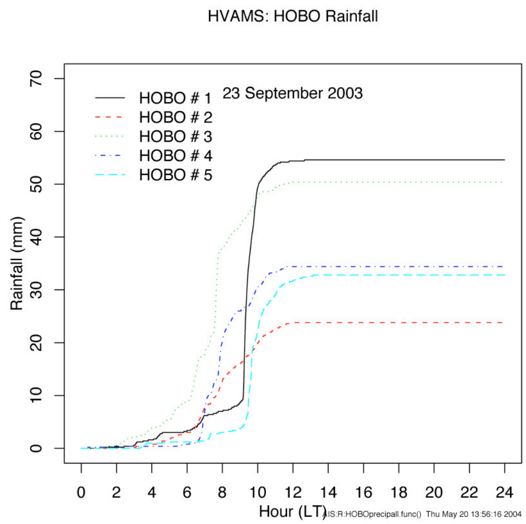

Figure 5: Rainfall from HOBO stations for 23 September 2003.

3. Mechanism

Air flowing down the Escarpment should undergo adiabatic heating and (possibly) concomitant drying. Such foehn winds are commonly observed in the lee of large mountain ranges such as the Alps or Rockies. However, in this particular case, no such warming was observed at Freehold (H3), likely because of a shallow layer of cool air that was trapped in the Catskill Creek Valley (north of the Escarpment). The precipitation shadow observed here, however, may be the result of mountain waves and/or mountain wave-induced foehn winds. Evidence of mountain waves can be detected by examining the vertical distribution of stability and wind shear over the region.

Certain conditions increase the likelihood of trapped lee or mountain waves, including a cross-barrier wind flow that is roughly perpendicular (up to 30^o) to the ridgeline, cross-barrier wind speed exceeding a terrain-dependent value of 7 – 15 m s^{-1}, and an inversion extending above the mountain ridge with weaker stability at higher levels in the upstream environment (Queney et al. 1960). Other factors facilitating the formation of mountain waves include a vertical wind profile in which the cross-mountain wind component increases with height (Scorer 1949) and the existence of a mountain barrier with a gentle windward slope and steep leeward slope (Lilly and Klemp 1979).

Since no sounding was available from Albany, model output from ASRC's Air Quality Forecast Modeling System (AQFMS), which uses the University of Athens 12 km ETA-SKIRON meteorological model (Nickovic et al., 2001) was used to examine the vertical profile for the gridpoint at East Jewett (station H3, elevation 559 m), located 15 km south southwest of Freehold (H2). The ETA-SKIRON model forecasts hourly wind and scalar fields at 14 levels from the surface to 4000 m, and a comparison of its output with the KENX VAD wind profile and the ALB 0000 UT sounding indicated general agreement.

The East Jewett sounding (Fig. 6) showed a stable layer from 950 – 850 hPa, which includes the highest terrain of the Escarpment, with a conditionally unstable layer extending to 800 hPa, and another unstable layer between 750 and 700 hPa.

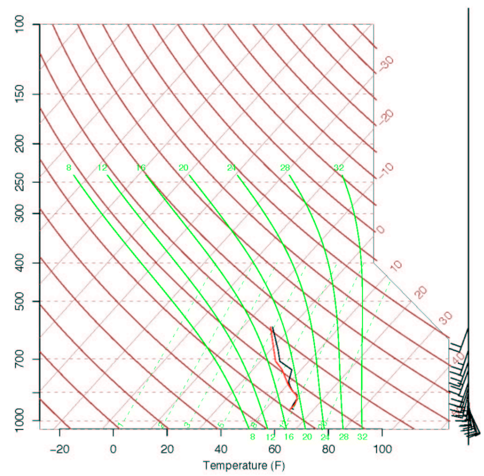

Fig. 6. Eta model sounding for 0600 UTC 23 September 2003

The Eta model sounding and VAD profile show the mean flow is south-southwesterly at the top of the conditionally unstable reflecting layer. Shortly before 1200 UTC, the Eta profile and VAD profiles show 20 – 30 m s^{-1} cross-barrier flow decreasing with height, an inversion near the just above the Escarpment, and a conditionally unstable "reflecting" layer.

4. Radar Analysis

Rainfall intensities during this event varied from 5 mm h^{-1} at Freehold (H2) to in excess of 40 mm h^{-1} at East Jewett (H3) and Lake Taghkanic SP (H1), at 202 m on the east wall of the Hudson Valley. The most intense period of precipitation was associated with a line of convection that moved through the area between 1000 and 1300 UTC. Prior to this, more modest but steady rains fell throughout the area. During this period, a time series of radar reflectivities from KENX showed a persistent minimum in reflectivity values over Freehold (not shown), with consistently higher values over the Escarpment. As the convective line approached, it became more disorganized over the Catskill Creek Valley. It regained some of its strength as it moved across the Valley and encountered the higher terrain of the Taconics.

Storm total precipitation estimates from KENX (Fig. 7) are in good agreement with those from the surface network,

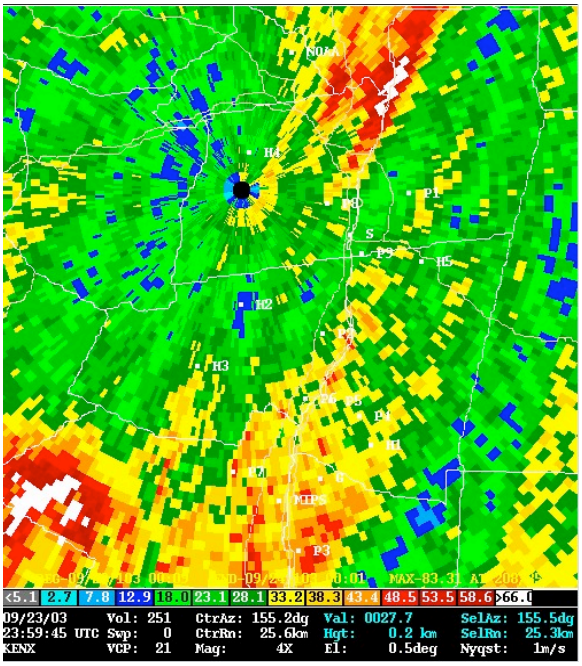

Fig. 7. KENX estimated storm total precipitation for 23 September 2003.

indicating a distinct rainfall minimum downwind of the Escarpment, from Freehold northeastwards to just north of Albany, where another precipitation maximum is found.

5. Discussion

5.1 Mountain wave analysis

The ratio of the natural wavelength of the air to the effective wavelength of a mountain is given by the Froude number

$$Fr = \frac{U}{NH} \quad (1)$$

where H is the height of the mountain, U is the mean wind speed of the flow normal to the mountain, and N is the Brunt-Väisälä frequency, defined by

$$N = \left(\frac{g}{\theta}\frac{\partial\theta}{\partial z}\right)^{1/2} \quad (2)$$

where θ is potential temperature, g is the acceleration of gravity, and z is the height above ground.

The flow that develops downwind of a mountain or ridge line is highly dependent on the ambient stability, with more stable conditions (low F_r) favoring flow around an obstacle, and larger values and less stable conditions aloft favoring flow over the obstacle. The horizontal wavelength of a gravity wave potentially formed by air moving over the terrain (Smedmen and Bergstrom 1995) is given by

$$\lambda = \frac{2\pi U}{N} \quad (3)$$

Thus, for a given stability profile, increasing (decreasing) cross-barrier flow results in mountain waves with longer (shorter) horizontal wavelengths. It further follows that greater (lesser) stability produces mountain waves with shorter (longer) wavelengths.

The eastern Catskill Plateau features several ridges aligned in a roughly west-northwest – east-southeast direction. From the KENX and Eta wind profiles the predominant wind direction was from the south-southwest, or approximately perpendicular to the ridge lines.

The Froude number for the layer just above the highest Escarpment ridge line (900 - 1200 m) ranged between 2.7 and 7, which indicative of flow that should have been able to traverse over the ridge tops and down into the Catskill Creek Valley. However, cool air pooled in the lowest layers of the valley probably resulted in winds moving down the Escarpment remaining above the surface layer.

Finally, Brunt-Väisälä frequencies and corresponding wavelengths were calculated for all Eta model layers. Wavelength values in the stable layer just above the ridgetops (~900 – 850 hPa) ranged from 15 to 30 km. This seems to favor the one broad precipitation shadow observed downwind from the Escarpment.

5. Conclusion

A broad precipitation shadow was observed northeast of the Catskill Escarpment on 23 September 2003. Vertical profiles of stability and wind shear indicate that that a mountain wave/foehn most likely was responsible for the substantially decreased rainfall amounts observed downwind from the Escarpment.

6. References

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