P1.28 A Preliminary Examination of the Elevation Dependence of Snowfall in Northeast Pennsylvania

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ABSTRACT

A collection of 78 snow events in northeast Pennsylvania from 2005-2011 was studied in order to examine the impact of elevation on snowfall amounts across that region. The event-averaged high-elevation versus low-elevation snowfall ratio for the 78 events in the study was 1.4, however, several events were identified that departed substantially from the average. The primary goal of this study is to give local forecasters an understanding of factors that modulate the impact of elevation on snowfall in northeast Pennsylvania.

In order to illustrate factors that help to determine differences in the dependency of snowfall on elevation for this area, six events with a large elevation dependency were compared to thirteen events with a relatively small elevation dependency. Results indicate that large elevation dependency is most likely for events with surface temperatures near freezing and relatively strong lower-tropospheric winds. Large-elevation dependency cases also had a tendency to occur with flow that was less blocked at ridge-top level than in low-elevation dependency events. Composite analyses indicated that high elevation dependency is most likely during events with relatively high-amplitude flow patterns with surface cyclones along the east coast. In order to further illustrate factors that determine snowfall dependence on elevation, two representative cases are shown, one characterized by large elevation dependence, and one with small elevation dependence. Output from a 2-km resolution WRF simulation is shown, to illustrate terrain-related features that may have helped to modulate the distribution of snowfall across the local area, and to demonstrate the potential utility of high-resolution modeling for these types of cases.

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1. Introduction

National Weather Service forecasters create highly detailed snowfall forecasts. Therefore, an understanding of the impact of small-scale features such as variable topography on snowfall is critical for local forecasters. Numerous studies have documented the impacts of topography on snowfall over the western U.S. (Marwitz 1980; Steenburgh 2003; O'Hara et al. 2009). Research has also noted the impact of terrain on snowfall east of the Mississippi river (St. Jean and Sisson 2004; Gaffin et al. 2003). The topography in northeast Pennsylvania is not as pronounced as in the aforementioned areas, with a difference between the lowest and highest elevations across the region of approximately 1500 feet (500 m; Fig. 1). However, this terrain has been observed to produce significant variations in precipitation across the area, with features such as rain shadows in the Wyoming Valley and precipitation enhancement over the Pocono Plateau being observed. (Brady and Waldstreicher 2001). The need for highly detailed snowfall forecasts in this heavily populated area featuring several interstate highways makes quantitative precipitation forecasts especially critical when the precipitation falls in the form of snow. The goal of this study is to provide local forecasters with some documentation on the local magnitude of elevation-induced variations of snowfall in this area, as well as some understanding on when the variation may be larger or smaller than normal.

2. Methodology

A collection of 78 snow events occurring from 2005 to 2011 was examined in order to study the dependence of snowfall on elevation in northeast Pennsylvania. For each event, snow totals were obtained from all available spotter reports and cooperative observations located within a circle with a radius of approximately 50 km (30 mi) centered on Scranton, Pennsylvania (Fig.1). The snowfall totals for each event were partitioned by elevation, with "high-elevation" reports from stations with elevations above 1500 ft (450 m) above sea-level, and "low-elevation" reports from stations below 1000 ft (320 m). Note that relatively few stations are located between 1000 and 1500 ft, as this elevation is typically characterized by a steep slope between the major river valleys, and nearby higher elevations. A "high-elevation" snowfall was then calculated for each event by averaging the reports from the high-elevation stations, and a "low-elevation" snowfall was calculated for each event by averaging the reports from the low-elevation stations.

In order to study cases when the dependence of snowfall on elevation was unusually large or small, events with an average snowfall of at least 4 inches (10 cm) were examined, and “high-dependency” events were defined as cases when the ratio between high-elevation and low-elevation snowfall was at least 1.75, while “low-dependency” events were defined as cases when the high-elevation to low-elevation snowfall ratio was less than 1.25.

Various meteorological parameters frequently used in forecasting were examined for the high vs. low-dependency cases, to determine factors that could help forecasters determine snowfall dependency on elevation. Average surface temperature and wind speed for an event was determined by averaging the hourly temperatures and wind speeds at the first order station located at Avoca, Pennsylvania (KAVP) during the period when the majority of the snow fell. Upper-air data were derived by examining BUFR data from short-range North American Mesoscale Model (NAM; Rogers et al., 2001) forecasts interpolated to the forecast point closest to KAVP valid at times of peak snowfall rates observed at KAVP. Composite fields and associated anomalies from the long-term mean were calculated from NCEP/NCAR Reanalysis data using an online application from the Earth System Research Laboratory available at www.esrl.noaa.gov/psd/data/composites/day/. High resolution model forecasts were obtained from 2-km WRF simulations run at the State University of New York at Oswego.

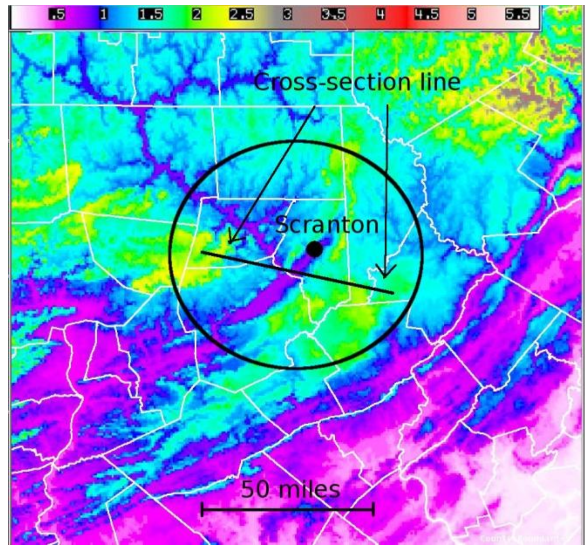
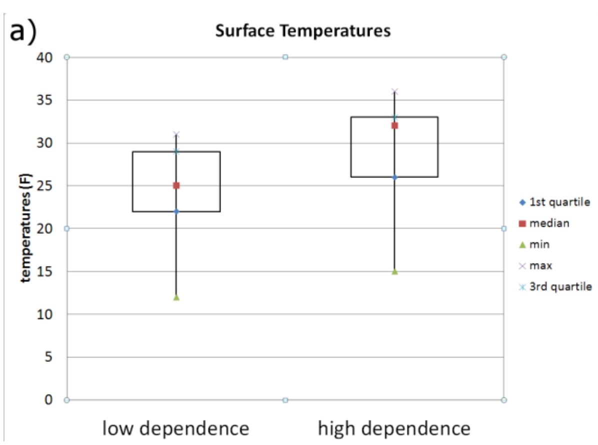


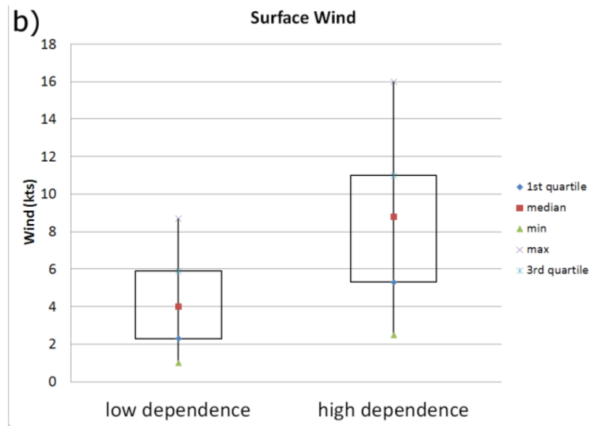
Figure 1. Topographic map of northeast Pennsylvania (shading represents elevation above sea-level with values in the legend in $1x10^3$ ft). Study area is denoted by the black circle, and cross-sectional line used in Figs. 5 and 7 is annotated.

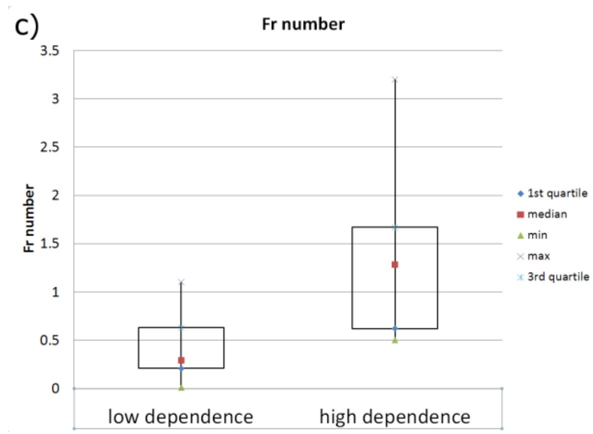
3. Results

The average low-elevation snowfall for all 78 events in the study was 3.2 inches (8 cm), while the average high-elevation snowfall was 4.5 inches (11 cm). In high-elevation-dependency cases, the average low-elevation snowfall was 4.3 inches (11 cm), and the average high-elevation snowfall was 10.5 inches (27 cm). In low-elevation-dependency cases, the average low-elevation snowfall was 6.7 inches (17 cm), and the average high elevation snowfall was 7.1 inches (18 cm).

Surface temperatures and wind speeds associated with low-dependency events were mostly lower than temperatures and wind speeds associated with the high-dependency events (Figs. 2a,b). Based on this finding, a scatter diagram of surface temperatures vs. wind speed was developed to aid forecasters with identifying high or low-dependency events (not shown). Additional analysis indicated that low-dependency events were mostly associated with lighter winds and a lower Froude number (indicating the potential for blocked flow; Mannis and Sawford 1982) at ridge top level (925-875 hPa) compared to high-dependency events (Figs. 2c,d).







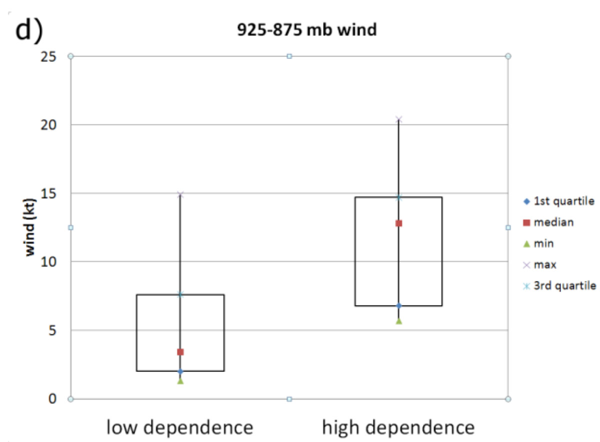
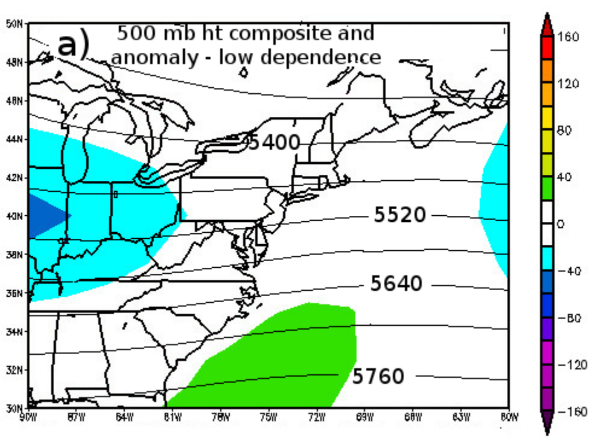
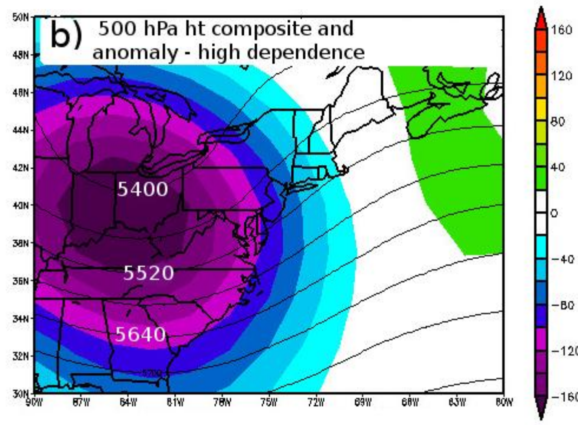
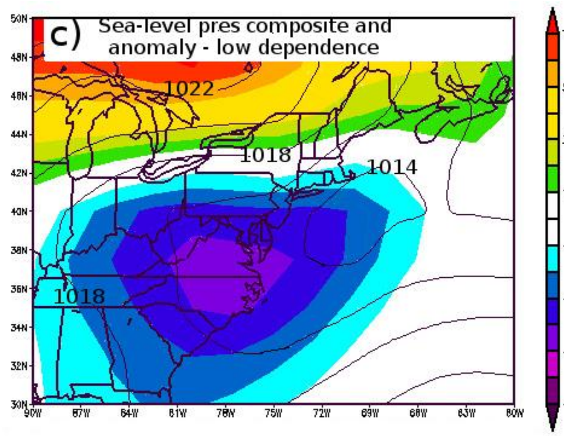


Figure 2. Box and whisker plots of a) surface temperature (°F) and b) surface winds (kt), c))the 925-875 hPa wind component perpendicular to the ridges (kt), and d) Froude number, associated with the low and high-dependency events.

500 hPa flow patterns and associated anomalies associated with low vs. high-dependency cases indicated that high-dependency events tended to occur with highly amplified troughs over the Great Lakes, while low-dependency events typically occurred with a much less amplified flow pattern (Figs. 3a-b). At the surface, both high and low-dependency events occurred with low pressure over the mid-Atlantic region (Figs. 3c-d). The high-dependency composite surface low was slightly stronger, and anomalously low pressures extended much farther north and covered a larger area. Meanwhile, anomalously low pressure in the low-dependency composite was confined to the area south of northern Pennsylvania, while anomalously strong high pressure was located over southern Canada.







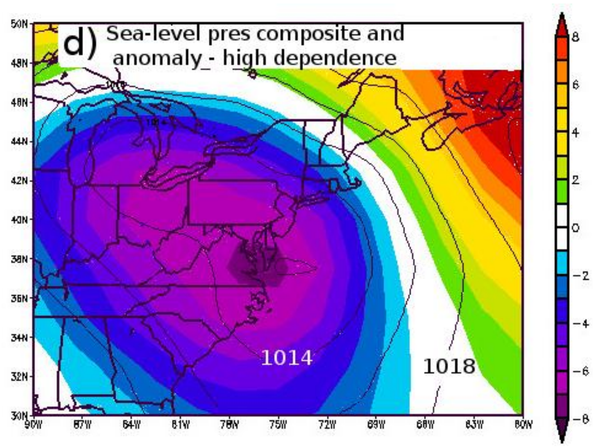


Figure 3. Composite 500 hPa geopotential heights (m) and anomalies (m) for a) low-dependence events, and b) high-dependence events. Composite sea-level pressure (hPa) and anomalies (hPa) for c) low-dependence events and d) high-dependence events.

4. Case studies

A storm on October 29, 2011 produced highly variable snowfall amounts across northeast Pennsylvania, ranging from around 1 inch (2.5 cm) at lowest elevations in the Susquehanna valley to over a foot (30 cm) at nearby higher elevations. The 500 hPa geopotential height and surface pressure fields associated with this event displayed many similarities to the high-dependence composites from this study, including highly amplified mid-tropospheric flow, and surface low-pressure along the mid-Atlantic coast (Figs. 4a,b). The average temperature at KAVP during the period of heaviest snow was near freezing (32 °F), and lower-tropospheric winds were moderately strong, averaging around 10 kts at the surface and 20 to 25 kts at ridge-top level. The Froude number, calculated at KAVP for the 925 to 875 hPa layer was 1.55, indicating the potential for flow to ride up and over nearby ridge tops, ventilating the valley with downslope flow and potentially decreasing the snowfall at lower elevations within the valley. Forecasts of vertical motion from the 12 km NAM (not shown) and a 2 km WRF simulation, in a cross-section taken across the Susquehanna valley valid at the time of heaviest snowfall indicate the development of a persistent region of upward motion on the eastern crest of the higher terrain east of the valley (Figs. 5a,b). The upward motion was particularly pronounced in the 2 km simulation, and was co-located with a persistent region of downward motion over the valley.

A storm on March 23, 2011 produced a widespread 7 to 11 inch snow event in northeast Pennsylvania, with no apparent elevation dependence. The 500 hPa geopotential height field and sea-level pressure pattern displayed many characteristics of the low-dependency composites from this study, including a zonal mid-tropospheric flow and surface high pressure building south from eastern Canada, with surface low pressure to the south (Figs.6a,b). The average temperature at AVP during the period of heaviest snow was 31 °F, which was similar to the high-dependence storm on October 29th. However the lower-tropospheric wind fields were much lighter in this event, averaging nearly calm at the surface and around 5 kt at ridge-top level. The Froude number calculated at KAVP from 925 to 875 hPa was 0.15, indicating strongly blocked flow. Forecasts of vertical motion from the 12 km NAM (not shown) and 2 km WRF in a cross-section taken across the Susquehanna valley valid at the time of heaviest snowfall did indicate a large region of strong upward vertical motion aloft over the Pocono Plateau. However persistent patterns of vertical motion tied to terrain were not evident as in the previous case (Fig. 7).

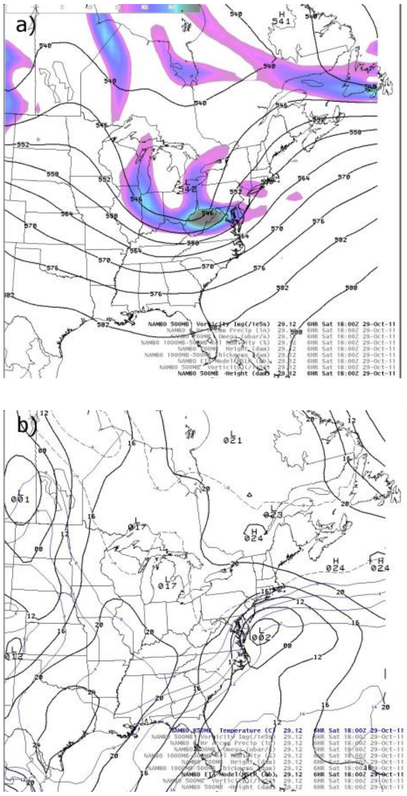


Figure 4. 6-h NAM forecast valid at 1800 UTC 29 October, 2011 of a) 500 hPa geopotential heights (dm) and vorticity ($1x10^{-5}$ s^{-1}, values greater than 15 shaded), and b) sea-level pressure (hPa) and 850 hPa temperature (°C).

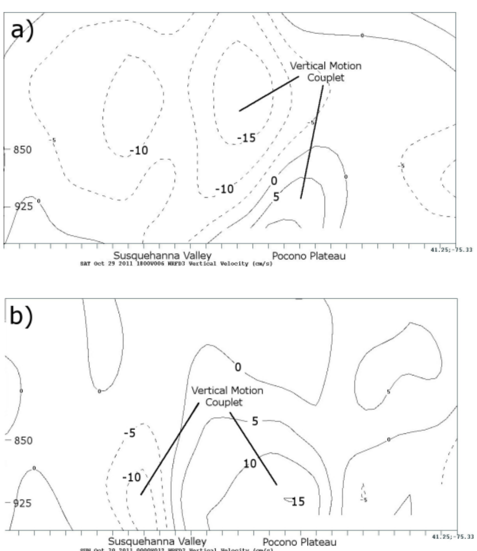


Figure 5. 2 km WRF forecast vertical motion (cm s^{-1}; upward motion is positive) valid at a) 1800 UTC 29 October, 2011, and b) 0000 UTC 30 October, 2011.

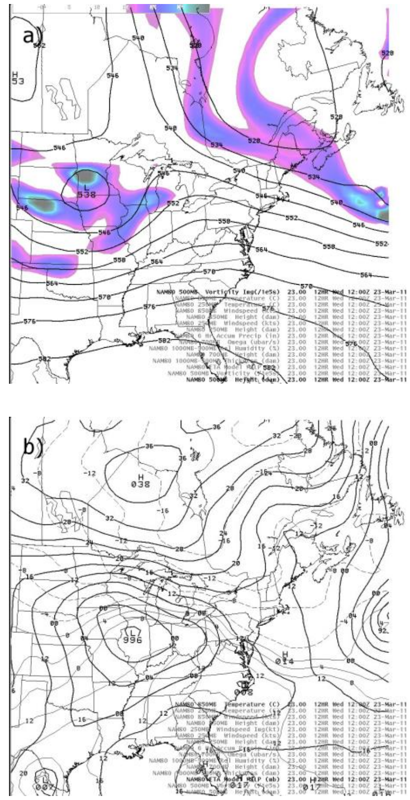


Figure 6. 12-h NAM forecast valid at 1200 UTC 23 March, 2011 of a) 500 hPa geopotential heights (dm) and vorticity ($1x10^{-5}$ s^{-1}, values greater than 15 shaded), and b) sea-level pressure (hPa) and 850 hPa temperature (°C).

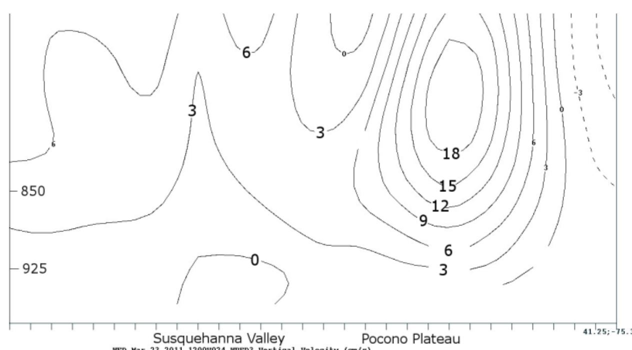


Figure 7. 2 km WRF forecast vertical motion (cm s^{-1}; upward motion is positive) valid at 1200 UTC 23 March, 2011.

5. Summary

This study examined the dependence of snowfall on elevation in northeast Pennsylvania. Results indicated that a high-elevation to low-elevation snowfall ratio of 1.4 is average for snow events in this area, however this ratio can vary widely from event to event, ranging from around 1.0 to over 20.0. Factors that appear to affect the ratio include lower-tropospheric temperature, wind speed and the blocking potential of the flow as measured by the Froude number. Patterns that favor high dependence of snowfall on elevation include a highly-amplified flow regime with a surface low pressure center over the mid-Atlantic states. Case studies indicate that high resolution models are able to realistically simulate the impact of terrain on vertical motion patterns for these events, giving forecasters a tool to anticipate high-dependence vs. low-dependence events.

REFERENCES

Brady, R.H., and J.S. Waldstreicher, 2001: Observations of mountain wave-induced precipitation shadows over northeast Pennsylvania. Wea. Forecasting, 16, 281-300.

Gaffin, D.M., S. Parker and P. Kirkwood, 2003: An unexpectedly heavy and complex snowfall event across the southern Appalachian region. Wea. Forecasting, 18, 224-235.

Mannis, P.C., and B.L. Sawford, 1982: Mesoscale observations of upstream blocking. Quart. J. Roy. Meteor. Soc., 108, 427-434.

Marwitz, J.D., 1980: Winter storms over the San Juan Mountains. Part I: Dynamical processes. J. Appl. Meteor., 19, 913-926.

O'Hara, B.F, M.L. Kaplan and S.J. Underwood, 2009: Synoptic climatological analyses of extreme snowfalls in the Sierra Nevada. Wea. Forecasting, 24, 1610-1624.

Rogers, E., T., Black, B. Ferrier, Y. Lin, D. Parrish, and G. DiMego, 2001: Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation, modified 3DVAR analysis. NOAA/NWS Tech. Procedures Bull. 488, 21 pp. [Available online at http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/; also available from the Office of

Climate, Water and Weather Services, National Weather Service, 1325 East-West Highway, Silver Spring, MD 20910.]

St. Jean, D. and P.A. Sisson, 2004: Characteristics of upslope snowfall events in northern New York state and northern Vermont: diagnostics and model simulations of several northwest-flow cases. Preprints, 20th Conference on Weather Analysis and Forecasting, Seattle, WA, Amer. Meteor. Soc., CD-ROM, 18.4

Steenburgh, W. J., 2003: One hundred inches in one hundred hours: evolution of a Wasatch mountain winter storm cycle, Wea. Forecasting, 18, 1018-1036.