EASTERN REGION TECHNICAL ATTACHMENT
NO. 2009-03
May 2009

An Examination of Upslope Snow Events in New Hampshire and Western Maine

James C. Hayes
NOAA/NWS Gray, ME

Abstract

Snowfall generated by upslope flow is a common occurrence at higher elevations and on the windward side of mountains in northern New Hampshire and western Maine. While the geographic area affected is limited, locally heavy snowfall can occur in favored locations, impacting travel and snow removal operations. Daily snowfall from cooperative observers (COOPs) and the New Hampshire Department of Transportation (NHDOT) were used to define events for the period 2001-2007. The total snowfall from each event was then stratified into heavy, moderate and light upslope snow events, based on local warning criteria. Composites of mean snowfall were calculated for each upslope snowfall category.

A synoptic climatology of upslope snow events was created from NCEP/NARR reanalysis data. The results of the climatology were then stratified by upslope snowfall category. The low level flow (up through at least ridge top level) was found to be generally more cyclonic for heavier upslope snow events, even though wind speeds are similar for all upslope snow categories. Moisture at 850 mb generally exceeded 80 percent in the upslope region. In addition, a nearly closed circulation at 500 mb is present northeast of the area for the more significant upslope snow events.

Using these results, forecasters will be able to better identify patterns favorable for upslope snow. Once the forecaster decides on an upslope snowfall category, the mean composite snowfall maps will assist in producing a more accurate snowfall forecast.

1. Introduction

Orographic snowfall produced in a cold moist low level flow (hereafter referred to as upslope snow) is a fairly common occurrence during the cool season across the higher terrain of northern New Hampshire and western Maine. The area of interest encompasses the White Mountains in Northern New Hampshire and the Longfellow Mountains in western Maine (Fig. 1). Both mountain ranges are oriented roughly southwest to northeast, and the highest elevations lie across northern New Hampshire. The highest peaks are located in northern Grafton and southern Coos counties. While most of these events produce light snow, the more significant events can produce locally heavy snowfall in favored locations. This represents a significant forecast challenge for the meteorologists at the National Weather Service in Gray, ME (GYX), since the heaviest snow generally falls in a limited geographic area.

The goal of this project was to develop a synoptic climatology for upslope snow events for the Gray, ME (GYX) County Warning Area (CWA), which can aid forecasters in detecting patterns favorable for upslope snow occurrence. This, in turn, should lead to more accurate upslope snowfall forecasts. Improved forecasts are important for snow removal operations in these areas.

In the upslope areas, three forecast processes are important in the production of upslope snow: stable upslope, seeder-feeder and upslope release of potential instability (Horel 2004). While all three factors are important for upslope snow production, not all three are necessary for upslope snow production, nor are they equally important.

Stable ascent is forced by flow over orographic obstructions (mountains, ridges or peaks). If the air forced over the obstruction is sufficiently moist through a deep layer, precipitation can occur. Medina and Houze (2003) stated, as part of the stable upslope process, "that any strong moist flow over the windward slope of a mountain range has the ability to excite accretional growth of precipitation by cellular overturning of the upslope flow". This can produce accelerated particle growth by coalescence, riming and aggregation, resulting in greater precipitation efficiency than stable upslope alone.

Enhancement of the stable upslope precipitation can also occur via the seeder-feeder process. Hydrometeors (snow and rain) generated in synoptic scale "seeder" clouds aloft fall through the low level orographic "feeder" clouds. When temperatures in the low level clouds are below freezing, snow crystals grow via accretion and collision-coalescence. These processes also effectively scavenge low level moisture from the low level orographic clouds, resulting in more pronounced shadowing effects downstream (Perry and Konrad 2004).

If the upstream environment is potentially unstable, it can become saturated as the upslope flow ascends the terrain. Buoyant convection results in the layer releasing the potential instability (Medina and Houze 2003). When potential instability is released in this manner, the resulting convection may be shallow or deep. Both can result in substantial precipitation enhancement. Anecdotal evidence from GYX forecasters suggests that the convection is often shallow, and is difficult to observe since the radar often under samples the precipitation.

St. Jean et al. (2004) found several factors that need to be considered when forecasting upslope snow in northern New York and northern Vermont. These included a nearly saturated layer from the surface to ridge top level, strong low level winds with a significant cross barrier component, equivalent potential temperatures decreasing with height, and steep low level lapse rates. Perry et al. (2007) found that trajectories lifted from near the surface in weak to moderate cold air advection, along with a deep moist layer and high values of relative humidity at 850 mb produced the highest snowfall totals in northwest flow in the southern Appalachian Mountains. In addition, they found that mid-level synoptic subsidence was present, and that moisture was limited below 700 mb.

2. Data and Methodology

For the purposes of this study, an upslope snow event was defined as a measureable snowfall event produced entirely in a cold moist low level flow (generally below 700 mb), at three or more locations in the study area. The cool seasons (October 1st through April 30th) from 1999-2000 through 2005-2006 were examined for potential upslope events. Once upslope snow events were identified, total snowfall amounts were tabulated from COOP, NHDOT reports and spotter reports. This yielded about 160 potential events for the study period.

It is not unusual for an upslope snow event to immediately follow a synoptic snow event. This occurs as the cool, moist low level flow in the wake of the system that produces the synoptic scale snowfall becomes perpendicular to the terrain. Since the majority of the total snowfall reports came from COOP observations (who report snowfall once a day), it was, at times, unclear how much snow fell in a synoptic event, and how much fell in the subsequent upslope event. In these cases, the event was dropped from the data set since it was difficult to assign the proper total snowfall to the upslope snow event.

Filtering out these "mixed" events lowered the number of cases for the study period to 93. For each event, the storm total snowfall and snow water equivalent (when available) were collected. The events were then stratified into three categories: "heavy", "moderate", and "light".

An upslope snow event was designated "heavy" when three or more locations received six inches or more of storm total snowfall (this is the local criteria for issuing winter storm warnings for snow). A total of six events qualified as "heavy" upslope snow events. An upslope event was designated "moderate" when three or more locations received four or five inches of storm total snowfall (this is the local criteria for issuing winter weather advisories for snow). A total of 18 events were identified as "moderate" upslope snow events. "Light" events comprised all other events, when storm total snowfall was less than four inches. In total, 69 events were identified as "light" events. The events were stratified to better facilitate identifying patterns that discern more significant events from more common events.

In order to develop pattern recognition for upslope snow events, a synoptic climatology was created, using data from the Daily Average NCEP NARR Composites [Currently available at http://www.cdc.noaa.gov/cgi-bin/data/narr/plotday.pl]. Average meteorological conditions based on the list of upslope snow events were examined using this dataset. The daily composites are averages of the 0000, 0600, 1200, and 1800 UTC data, and the anomalies are based on means computed between 1979 and 2006.

From this dataset, daily composites were computed for geopotential height, temperature, relative humidity, and total wind at all mandatory levels. In addition, mean sea level pressure and precipitable water were also computed.

3. Results

a) Overview of upslope snow events

More than two-thirds of the upslope snow events that occurred during the study period occurred in December, January and February (Fig. 2). "Early" events (October and November) accounted for about 15 percent of the events, as did the "late" events (March and April). Only two upslope events occurred in April during the study period.

The total number of light, moderate and heavy upslope snow events indicates that the majority of light upslope events occurred in December, January and February. Most of the moderate upslope snow events occurred in December and January. While the sample set is very small, it is interesting to note that all but one of the heavy upslope snow events occurred in November and March.

The highest values of snow-to-liquid ratio (SLR) occurred with the heavy snow events, with the lowest occurring with light events (Fig. 3). However, the average SLR values for all upslope snow events categories were higher than the 30-year average for the GYX County Warning Area (CWA) value of about 13:1 (Baxter et al. 2005).

Low-level trajectories (1500 meters and below) were computed for all upslope snow event categories using the HYSPLIT dispersion model (Draxler and Rolph 2003). Since composite trajectories were not available from the HYSPLIT model, representative trajectories were chosen for each upslope snow category. For heavy upslope snow events, the trajectory source tended to be near Hudson Bay (Fig. 4). For moderate upslope snow events, the source region tends to be from the Great Lakes, and light upslope snow events also had a source region near the Great Lakes.

Storm total snowfall for each upslope snow event was tallied and plotted in ArcMap (Harlow and Pfaff 2004). For each upslope event, a gridded snowfall map was created from the storm total snowfall amounts across the upslope domain utilizing inverse distance weighted (IDW) interpolation (Harlow and Pfaff 2004). The resultant gridded snowfall maps were then stratified by category (light, moderate and heavy upslope events). From these, a mean gridded snowfall map was created for each category. It should be noted that the IDW interpolation does NOT take local topography into account when creating the gridded snowfall maps. Thus, the gridded snowfall amounts may not exactly match the terrain (i.e., the heaviest snowfall may not always be on the windward side of the elevation).

The snowfall maximum (greater than 12 inches) for heavy upslope events was located in northern Coos County New Hampshire, near Diamond Pond and First Connecticut Lake (Fig. 5). Diamond Pond is located on a northwest-southeast oriented ridge, and First Connecticut Lake is located in a northwest-southeast oriented valley (Fig. 6). A secondary maximum is located near Crawford Notch, on the border between Carroll and Coos counties in northern New Hampshire (Fig. 7).

It should be noted that the heaviest snowfall does not affect a large geographic area. Table 1 shows the mean snowfall for each forecast zone in the upslope area. Note that in NHZ001 (northern Coos county New Hampshire), the mean snowfall for heavy upslope events is 5.6 inches (the mean values were calculated in ArcGIS using zonal averaging techniques across the forecast zones, identified in Fig.1). This value is just below the 12 hour criteria for a Winter Storm Warning for this zone (6 inches of snow in 12 hours), and well below the 24 hour criteria of 9 inches.

The snowfall maximum (around 6 inches) for moderate upslope events is again located near Diamond Pond and First Connecticut Lake in New Hampshire (Fig. 8). There is no distinct secondary snowfall maximum for moderate upslope snow events. As might be expected, there are much lighter snowfall amounts spread over a larger area for light upslope snow events (Fig. 9).

b) Synoptic climatology of upslope snow events in the GYX CWA

Interestingly, the 850 mb composite wind speeds for all three upslope snowfall categories are fairly similar, ranging between 20 and 25 knots (Fig. 10). The main difference among the three is the amount of cyclonic signature. The flow is most cyclonic for heavy upslope snow events (as shown by the orientation of the wind barbs) and the least cyclonic for light upslope snow events.

For light upslope events, the 850 mb geostrophic flow was broadly cyclonic. For both moderate and heavy upslope snow events, the flow was much more cyclonic. The 850 mb composite geopotential heights for heavy events showed a closed system over eastern Quebec, resulting in a more northwesterly flow across northern New Hampshire and the mountains of western Maine (Fig. 11). This is important since the orientation of the cyclonic flow is cross-barrier to the highest peaks in northern New Hampshire, producing heavy snowfall in favored locations in Coos and Grafton counties.

A similar pattern was noted in the 850 mb composite temperatures (Fig. 12). Again, as was the case with wind speed, the 850 mb composite temperatures were similar for all three categories (generally between -10 ° and -12 ° C). This corresponds to the lower temperature range of the maximum dendritic snow growth zone. However, temperatures at 850 mb were one to two degrees warmer for heavy upslope snow events than other categories. While the sample size is very small, this appears to indicate that the lower levels of the atmosphere are generally slightly warmer for heavy upslope snow events.

As expected, the lowest values of relative humidity at 850 mb occurred with light upslope events, and the highest values occurred with heavy upslope events (Fig. 13). However, the composite relative humidity values for the heavy upslope events were lower than those found by St. Jean et al. (2004) and Shafer and LaVoie (2007). It is possible that the lower relative humidity values are due to the averaging which occurs during compositing. All composites showed lower relative humidity values downwind of the terrain, indicating drying occurring in the downslope.

As was the case with the 850 mb composite geopotential heights, the 500 mb flow becomes increasingly cyclonic for moderate and heavy events (Fig. 14). Additionally, there is a nearly closed system over eastern Quebec for heavy upslope snow event. While not resolved in the composite geopotential height field, the cyclonic flow over the favored upslope areas contained multiple short wave troughs in the individual cases. Additionally, moderate upslope snow events tended to have a single short wave in the cyclonic flow. This short wave was smoothed out in the composites.

All categories show a cyclonic, geostrophic flow at the surface, with heavy upslope events showing a more northwesterly flow (when compared to light and moderate events) (Fig. 15). The gradient was stronger for moderate and heavy upslope events, as would be expected with a deeper surface low.

4. Summary

Table 2 displays a summary of the results tabulated from the synoptic climatology. Many of these values are similar to those found by St. Jean et al. (2004) and Shafer and LaVoie (2007). While upslope snow events are fairly common across the higher terrain of northern New Hampshire and western Maine, there are several elements common to the more significant events.

The low-level flow (up through at least ridge top level) is generally more cyclonic for heavier upslope snow events, even though wind speeds are similar for all upslope snow categories. Moisture at 850 mb generally exceeds 80 percent in the upslope region. In addition, a nearly closed circulation at 500 mb is present northeast of the area for the more significant upslope snow events, and there are typically multiple short waves in the cyclonic flow.

For heavy upslope events, the mean snowfall maximum is located in northern Coos county New Hampshire. A secondary maximum was located in southern Coos county and northeast Grafton county, coincident with the highest elevations in the White Mountains. While the mean snowfall amounts exceed 8 inches in both maxima, the geographic coverage is limited.

Pattern recognition, based on these forecast parameters and mean snowfall maps, will allow GYX forecasters to match the expected upslope snow event category to a mean snowfall map for that category. AWIPS procedures, highlighting some of the findings from this study, have been made available to forecasters to better visualize the synoptic patterns conducive to upslope snow. The composite snowfall maps for heavy, moderate and light upslope snow events were used to create edit areas in the Graphical Forecast Editor (GFE), allowing forecasters to better represent upslope snow in the digital Probability of Precipitation (PoP), weather, Quantitative Precipitation Forecast (QPF) and snowfall forecasts.

Disclaimer

Reference to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its recommendation, or favoring by the United States Government or NOAA/National Weather Service**.** Use of information from this publication shall not be used for advertising or product endorsement purposes.

Acknowledgements

The author would like to thank Dave Radell, Scientific Services Division (SSD) at Eastern Region Headquarters (ERH) in Bohemia, NY and Dan St. Jean, the Science Operations Officer (SOO) of the National Weather Service in Gray, Maine and Steve Keighton, SOO of the National Weather Service in Blacksburg, VA for their review and valuable suggestions for this manuscript.

References

Baxter, M. A., C. E. Graves and J. T. Moore, 2005: A climatology of snow-to-liquid ratio for the contiguous United States. *Wea. Forecasting*, **20**, 729-744.

Draxler, R.R. and Rolph, G.D., 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model. NOAA Air Resources Laboratory, Silver Spring, MD. [Available at http://www.arl.noaa.gov/ready/hysplit4.html].

Harlow, M. and R. Pfaff, 2004: Using ArcMap, Version 9.3 [Available from ESRI, Inc, 380 New York Street, Redlands, CA 92373 USA or http://www.esri.com].

Horel, J., 2004: Terrain-forced mesoscale circulations. *Handbook of weather, climate and water*, T. D. Potter and B. Colman, Ed., John Wiley and Sons, Inc., 561-573.

Medina, S. and R.A. Houze, Jr, 2003: Orographic enhancement of precipitation in midlatitudes: results from MAP and IMPROVE II. Preprints, *ICAM/MAP Meeting*, Brig, Switzerland, 19-23 May.

Perry, L. B. and C.E. Konrad, 2004: Northwest flow snowfall in the southern Appalachians: spatial and synoptic patterns. Preprints, *61st Eastern Snow Conference*, Portland ME, 179-189.

Perry, L.B, C.E. Konrad and T.W. Schmidlin, 2007: Antecedent upstream air trajectories associated with northwest flow snowfall in the southern Appalachians. *Wea. Forecasting*, **22**, 324-352.

Shafer, J. and S. LaVoie, 2007: Cold season orographic precipitation in northern New England. Preprints, *32nd Northeast Storm Conference*, Saratoga, NY.

St. Jean, D., P.A. Sisson, L.F. Bosart, D. Keyser and B. Smith, 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 AMS Conference on Weather Analysis and Forecasting*. Seattle, WA, Amer. Meteor. Soc., **18**, 10-15 Jan.

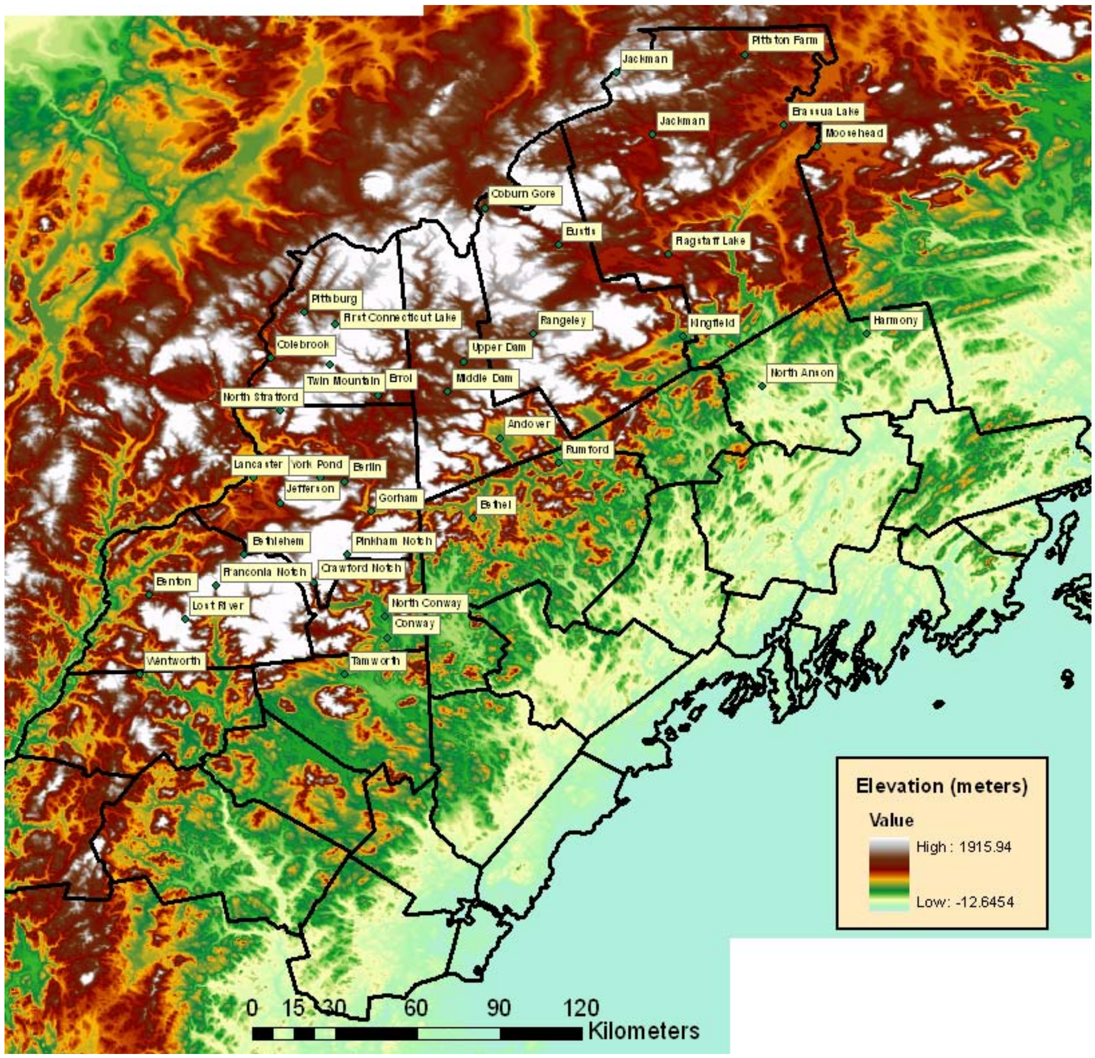

Figure 1. The Gray, ME (GYX) County Warning Area (CWA), outlined in black. The study area includes the higher elevation of northern New Hampshire and western Maine. The locations from which daily snowfall totals were available are labeled.

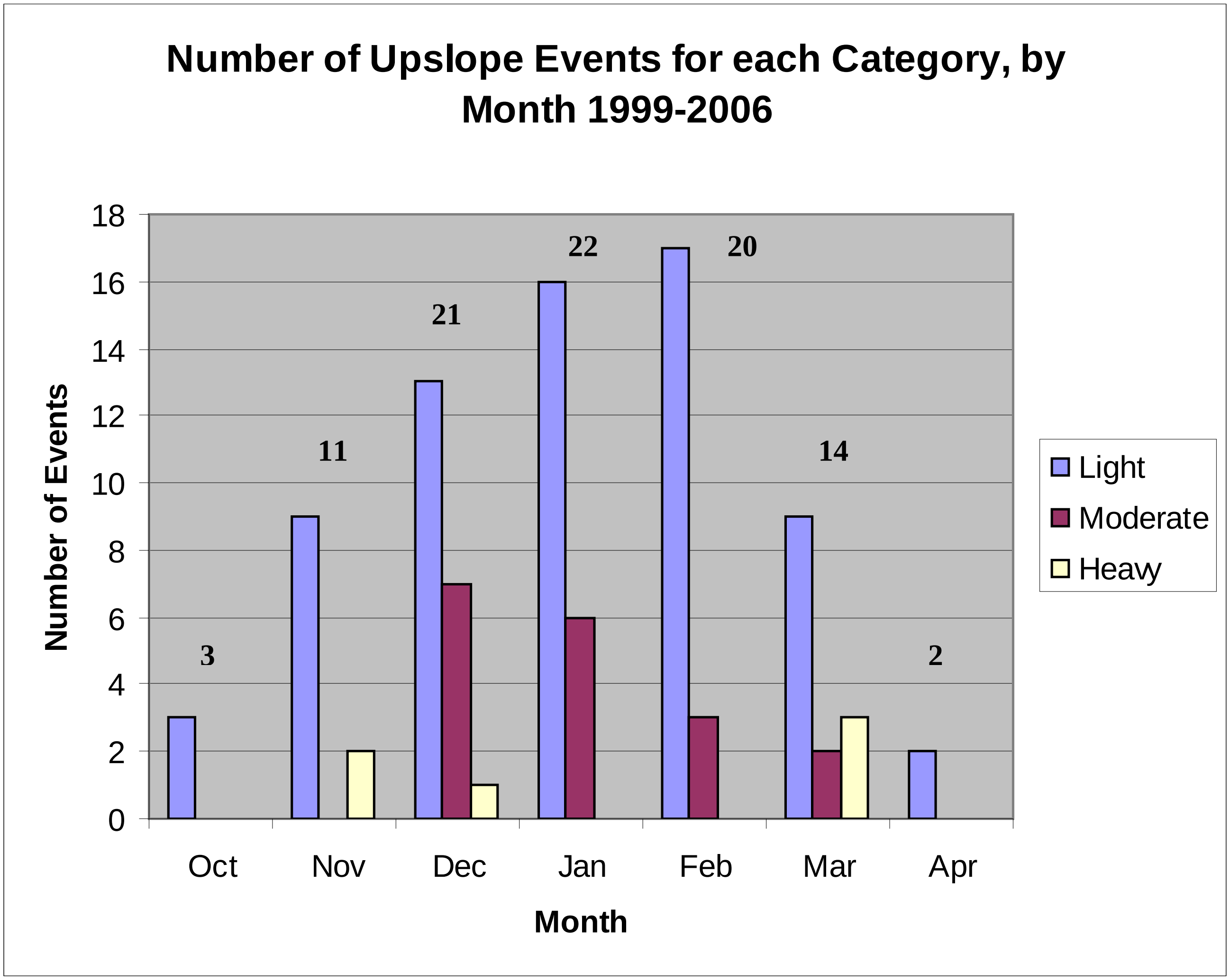

Figure 2. Number of upslope snow events, by category, per month 1999-2006. The total number of events is given at the top of each grouping.

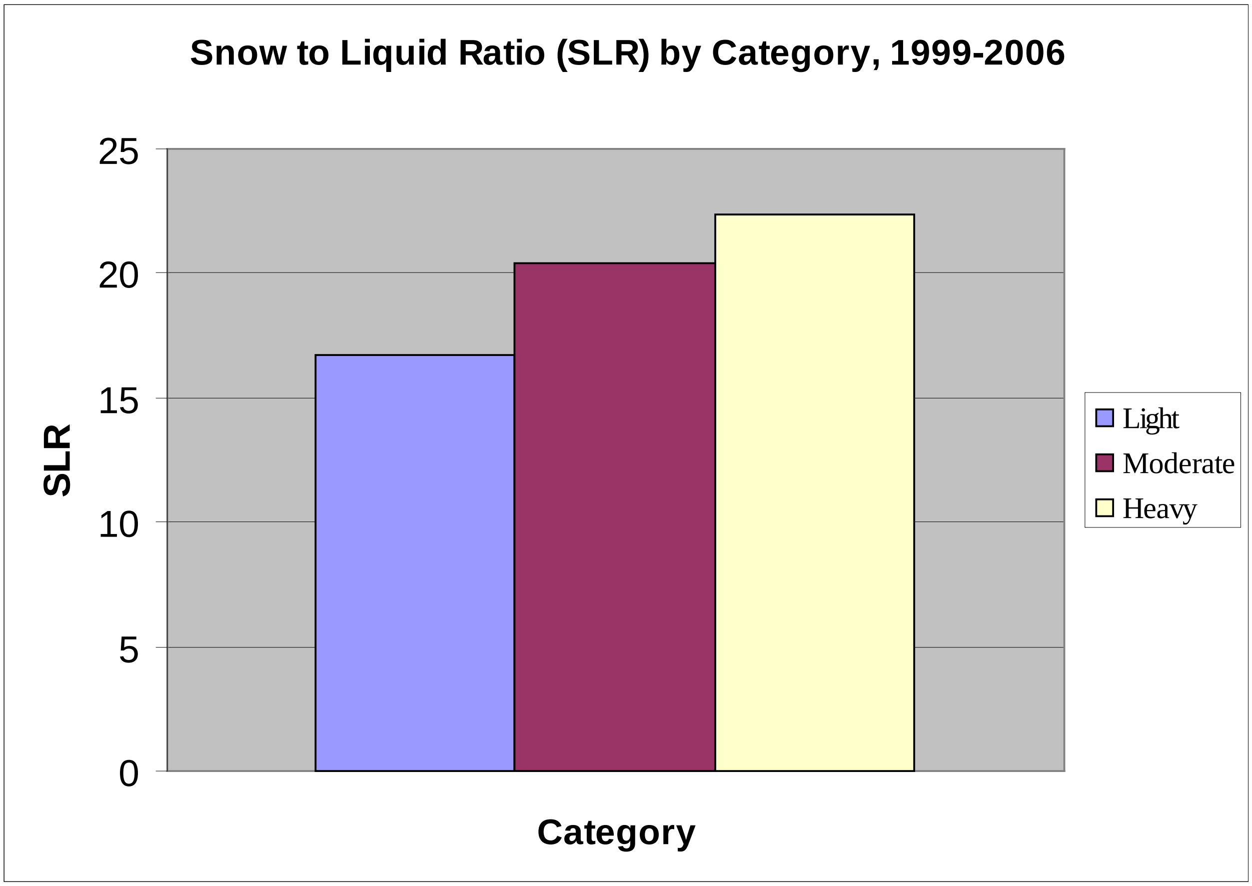

Figure 3. The Snow to Liquid Ratio (SLR) values for upslope snow events, by category. All values were higher than the 30 year average (~ 13:1) for the GYX County Warning Area.

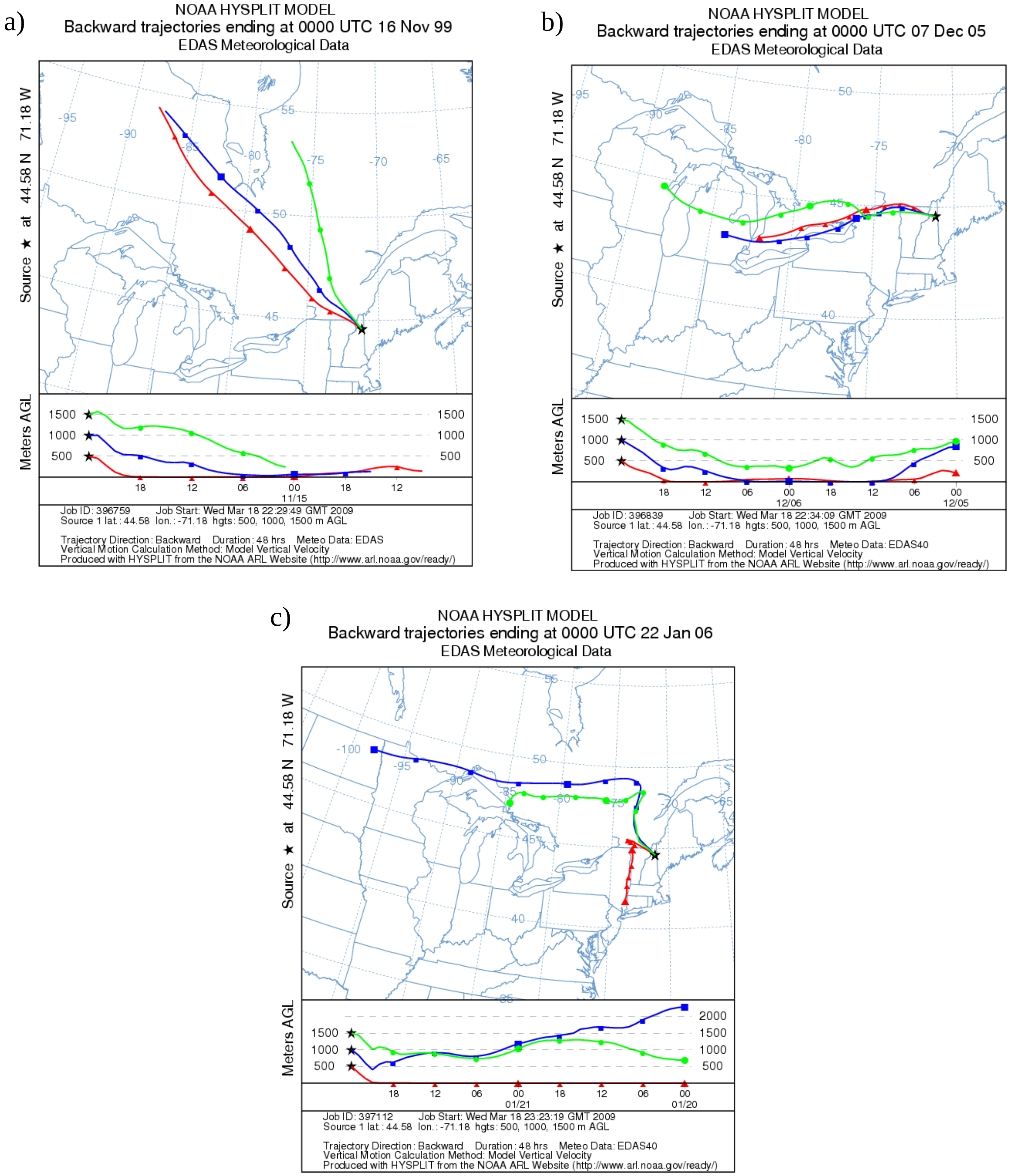

Figure 4. Low level trajectories (1500 m and below) computed from the HYSPLIT dispersion model for (a) a heavy upslope event, (b) a moderate upslope snow event, and (c) a light upslope snow event. These trajectories are representative of heavy, moderate and light upslope events, respectively.

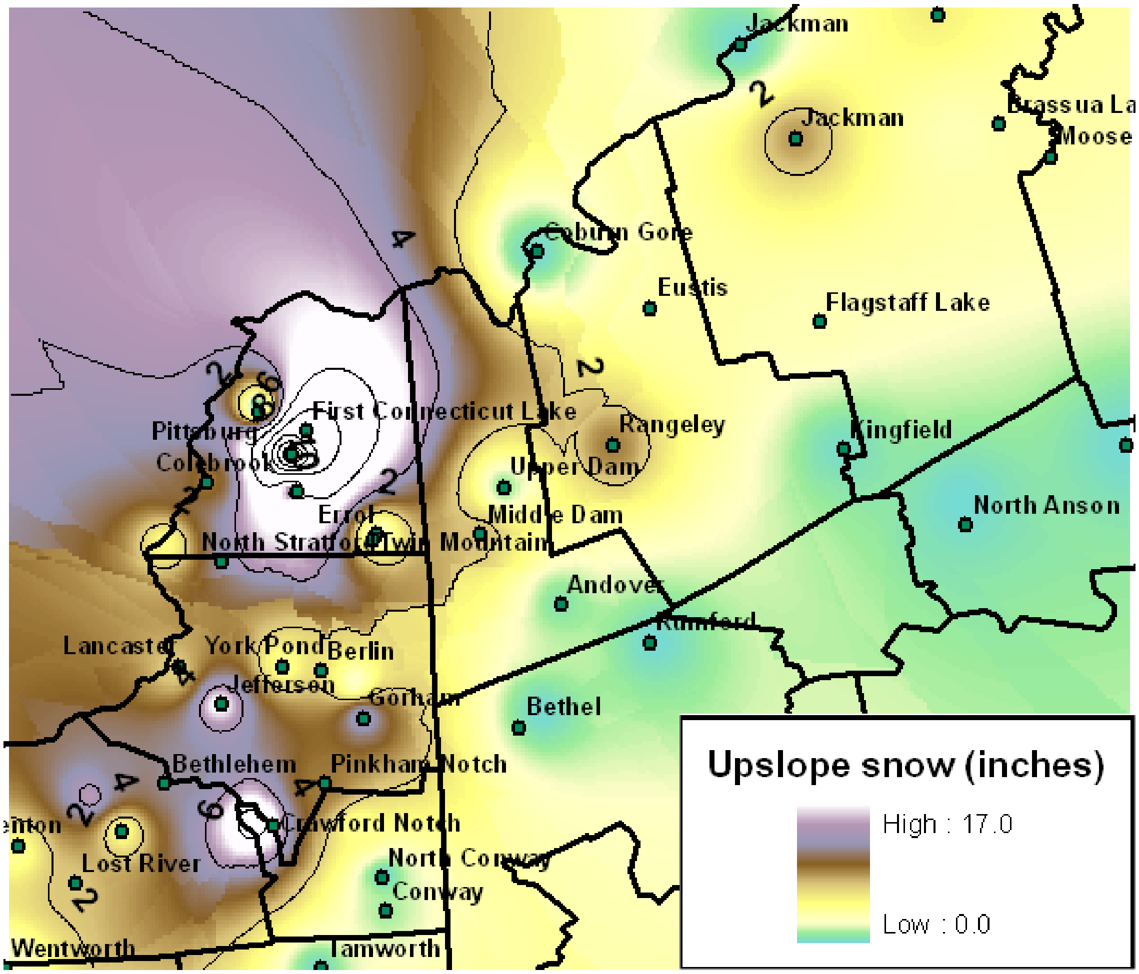

Figure 5. Mean snowfall (in.) for all heavy upslope events.

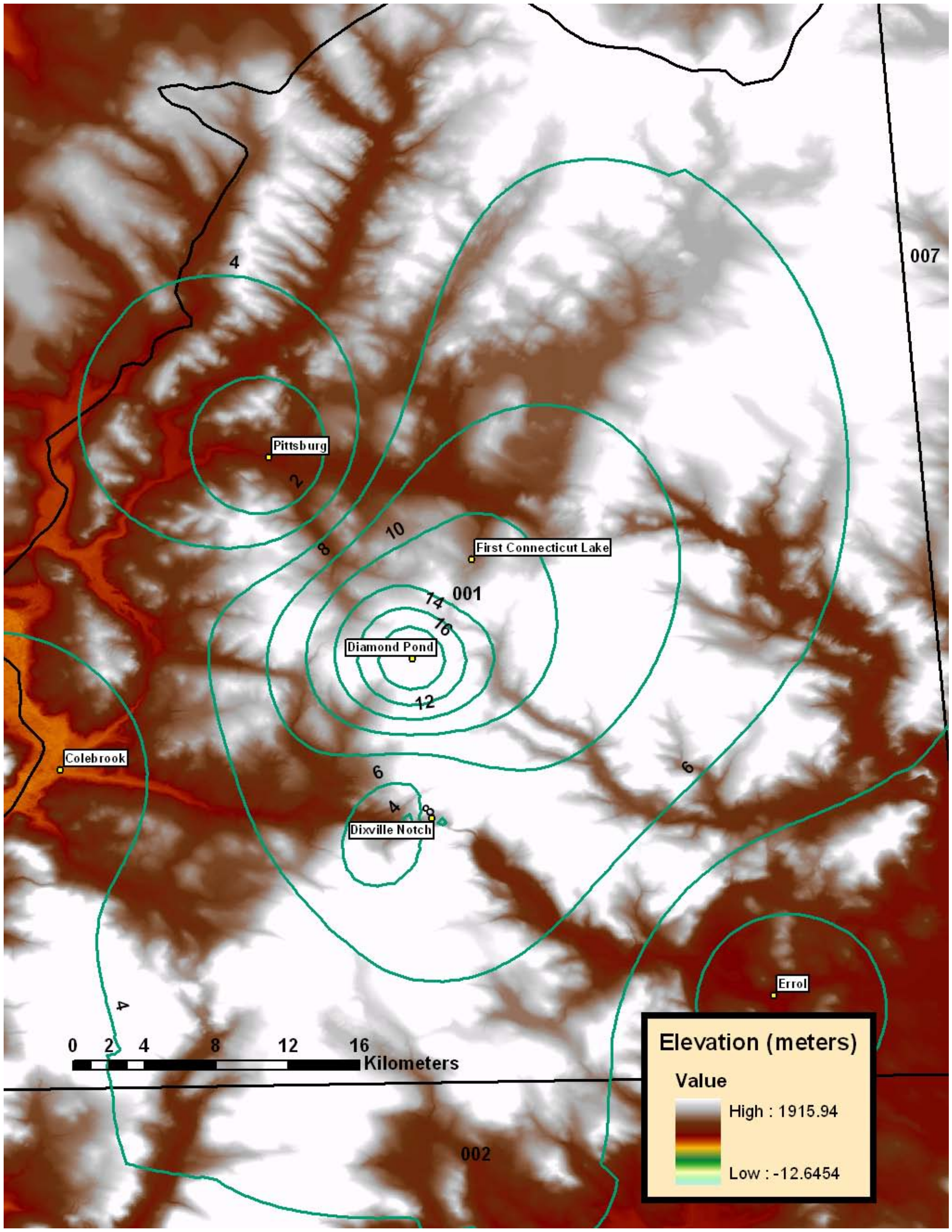

Figure 6. Digital Elevation Model (DEM) of northern New Hampshire, showing the locations of Diamond Pond and First Connecticut Lake. Isopleths of mean snowfall (in.) for all heavy upslope snow events are also depicted.

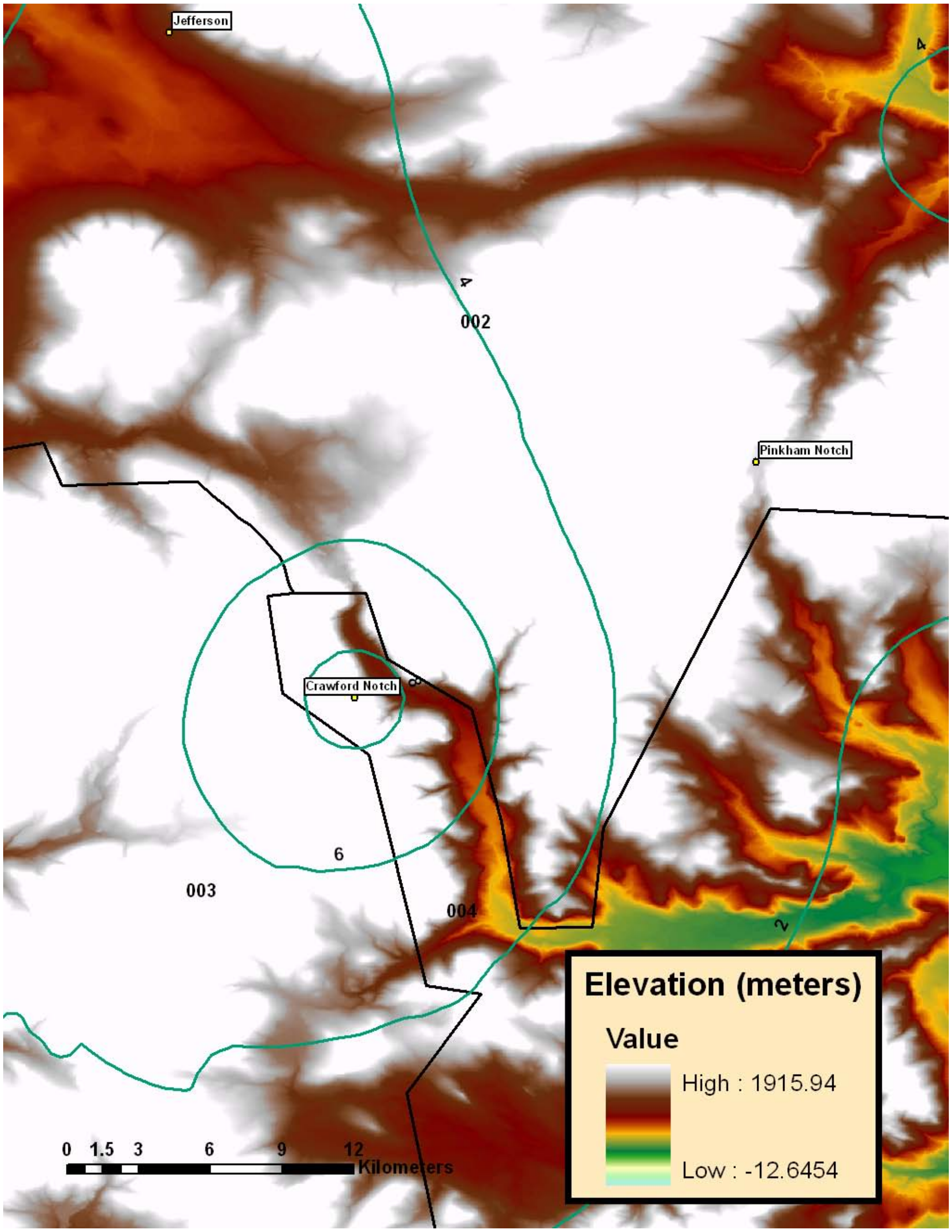

Figure 7. Digital Elevation Model (DEM) of the Crawford Notch, New Hampshire area. Isopleths of mean snowfall for heavy upslope events (in.) are also depicted.

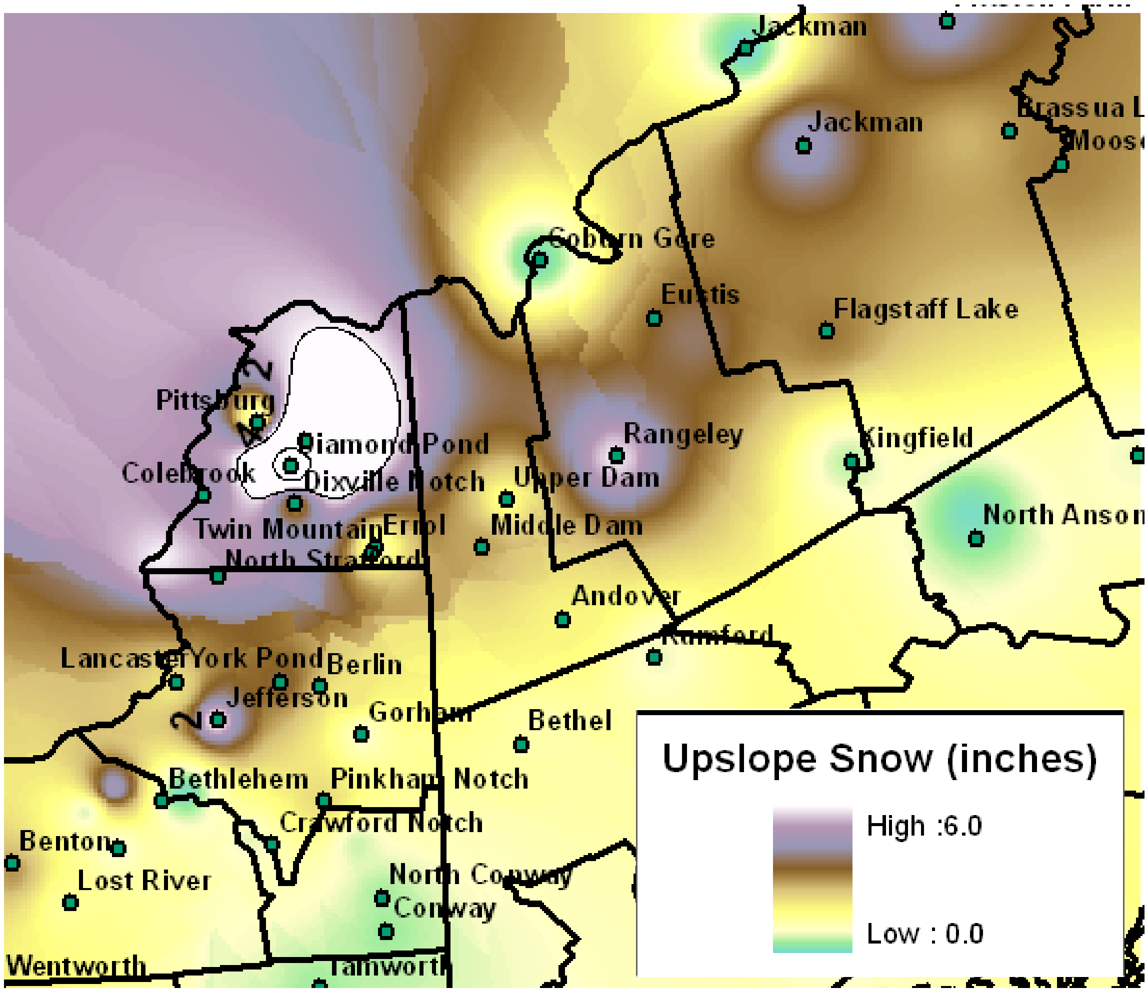

Figure 8. Mean snowfall (in.) for all moderate upslope events.

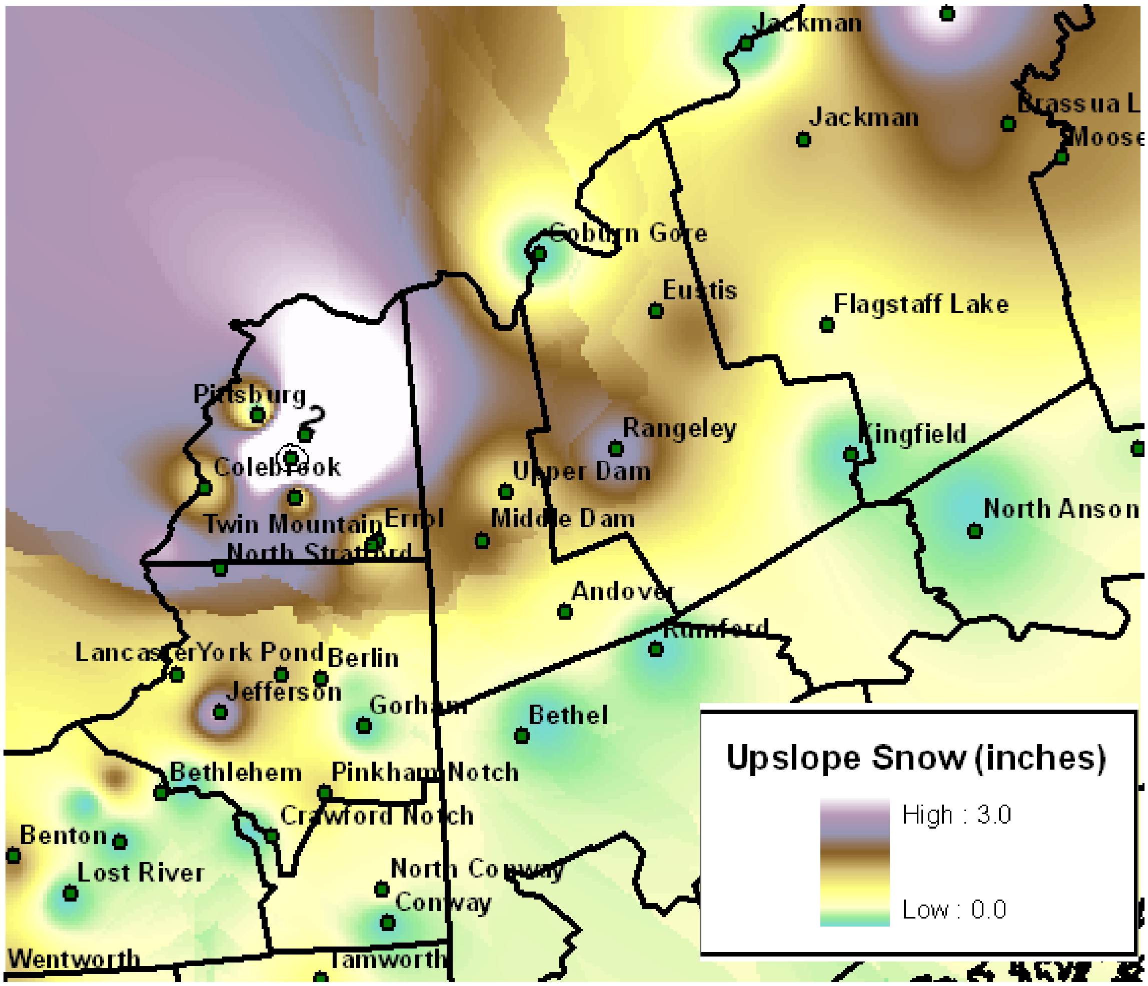

Figure 9. Mean snowfall (in.) for all light upslope events.

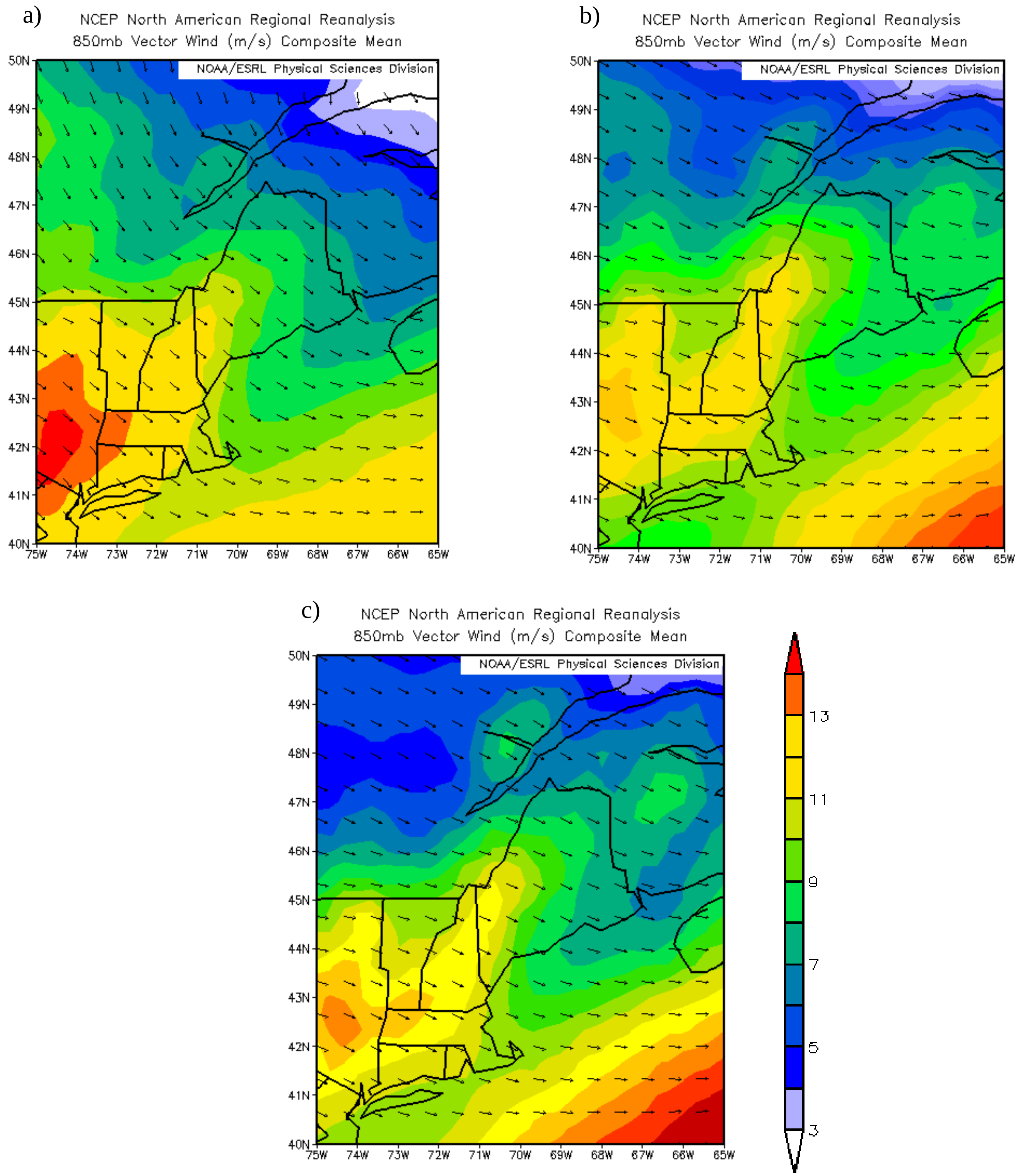

Figure 10. 850 mb composite wind speed (m/s) and direction for (a) heavy upslope events, (b) moderate upslope events, and (c) light upslope events.

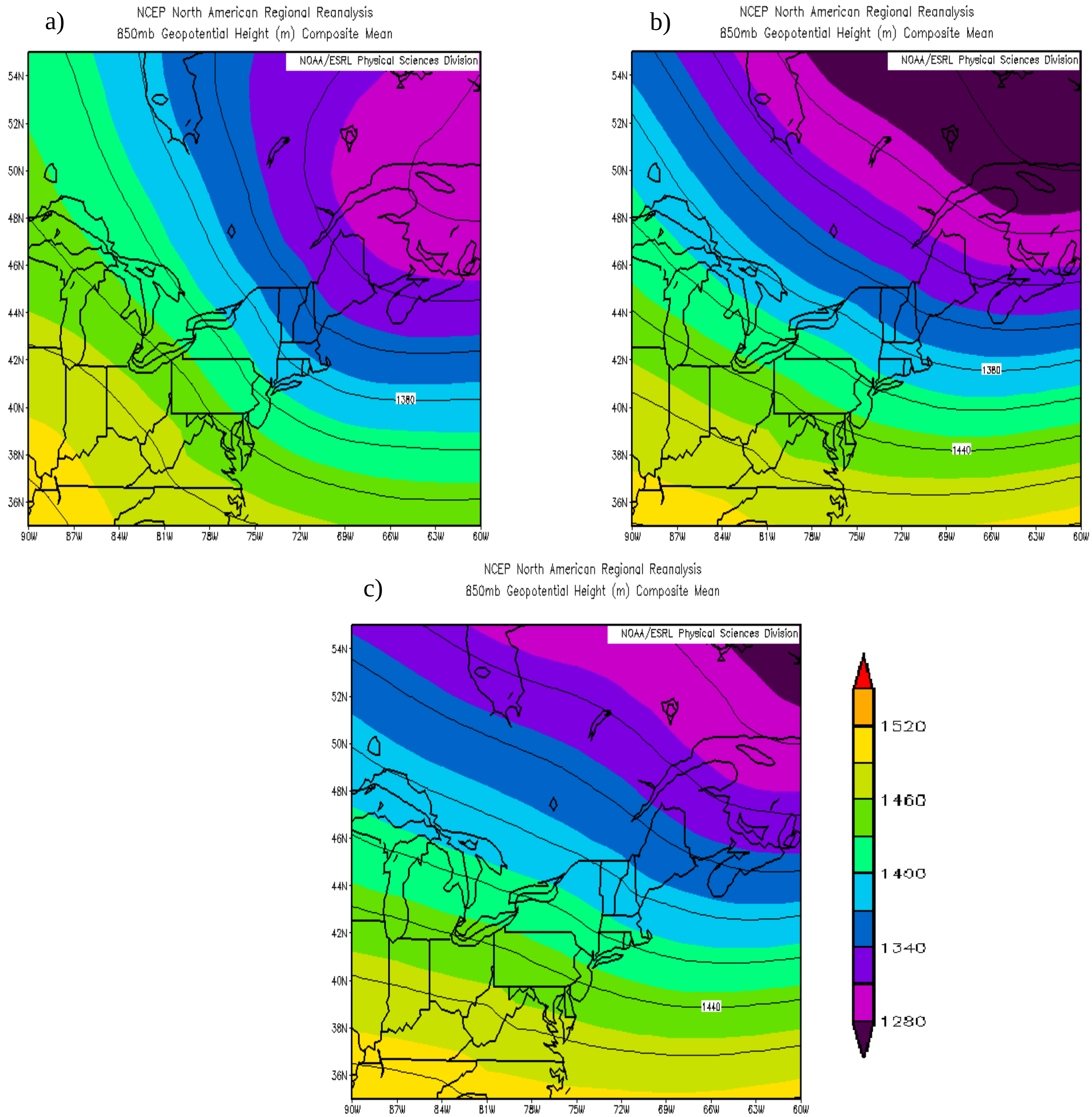

Figure 11. 850 mb composite geopotential heights (m) for (a) heavy upslope events, (b) moderate upslope events, and (c) light upslope events.

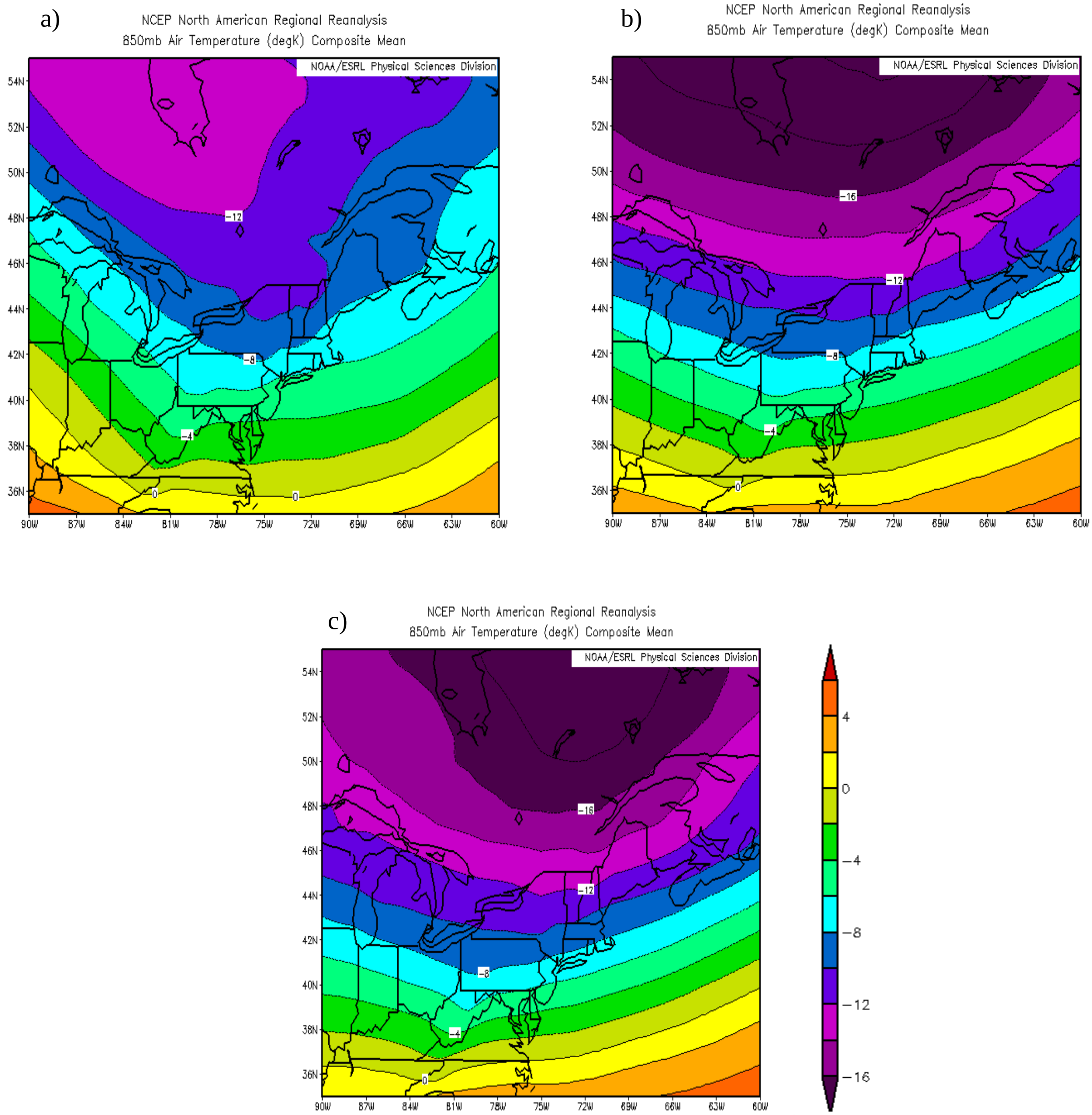

Figure 12. 850 mb composite temperatures (°C) for (a) heavy upslope events, (b) moderate upslope events and (c) light upslope events.

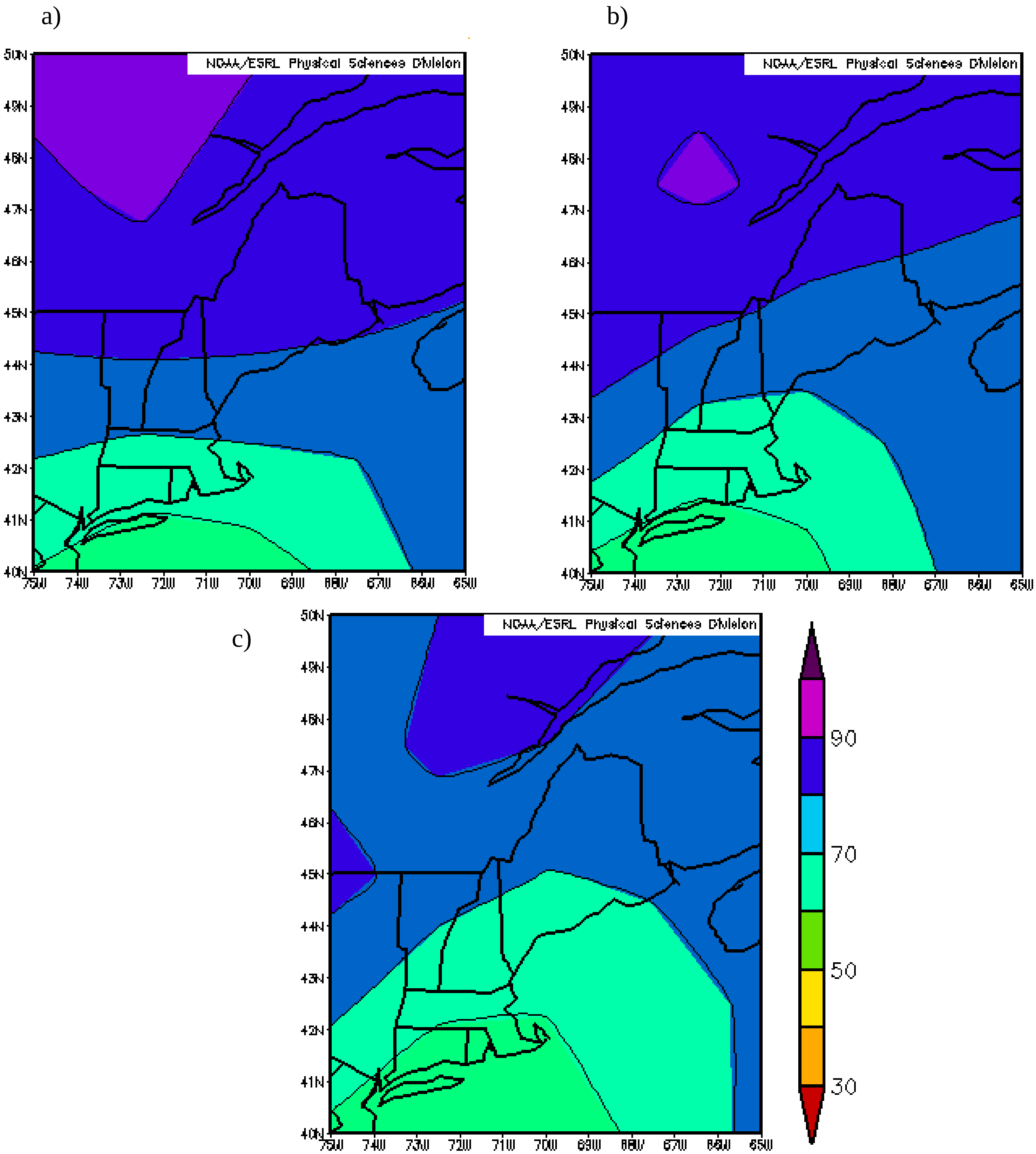

Figure 13. 850 mb relative humidity (percent) for (a) heavy upslope events, (b) moderate upslope events and (c) light upslope events.

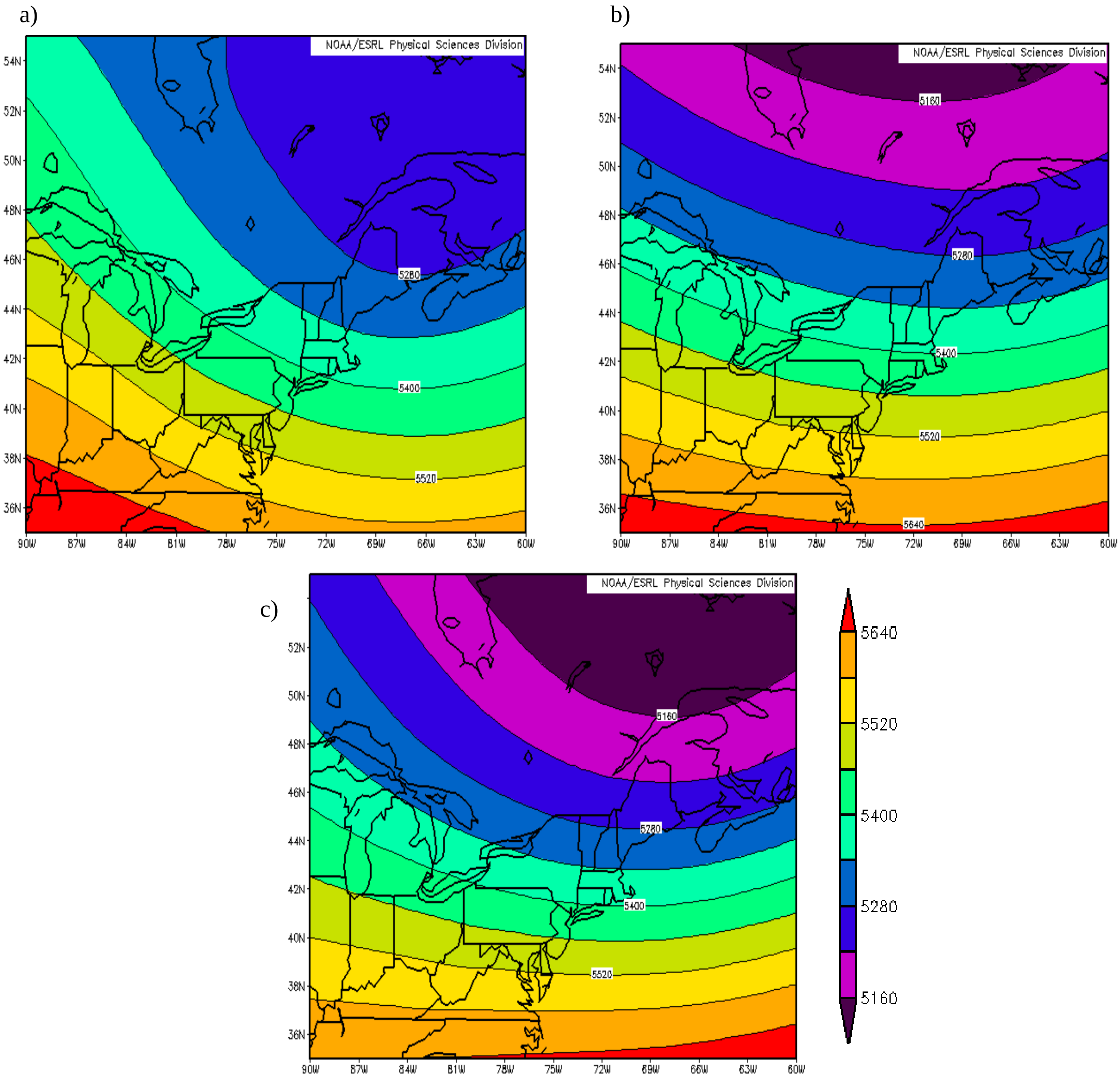

Figure 14. 500 mb composite geopotential heights (m) for (a) heavy upslope events, (b) moderate upslope events and (c) light upslope events.

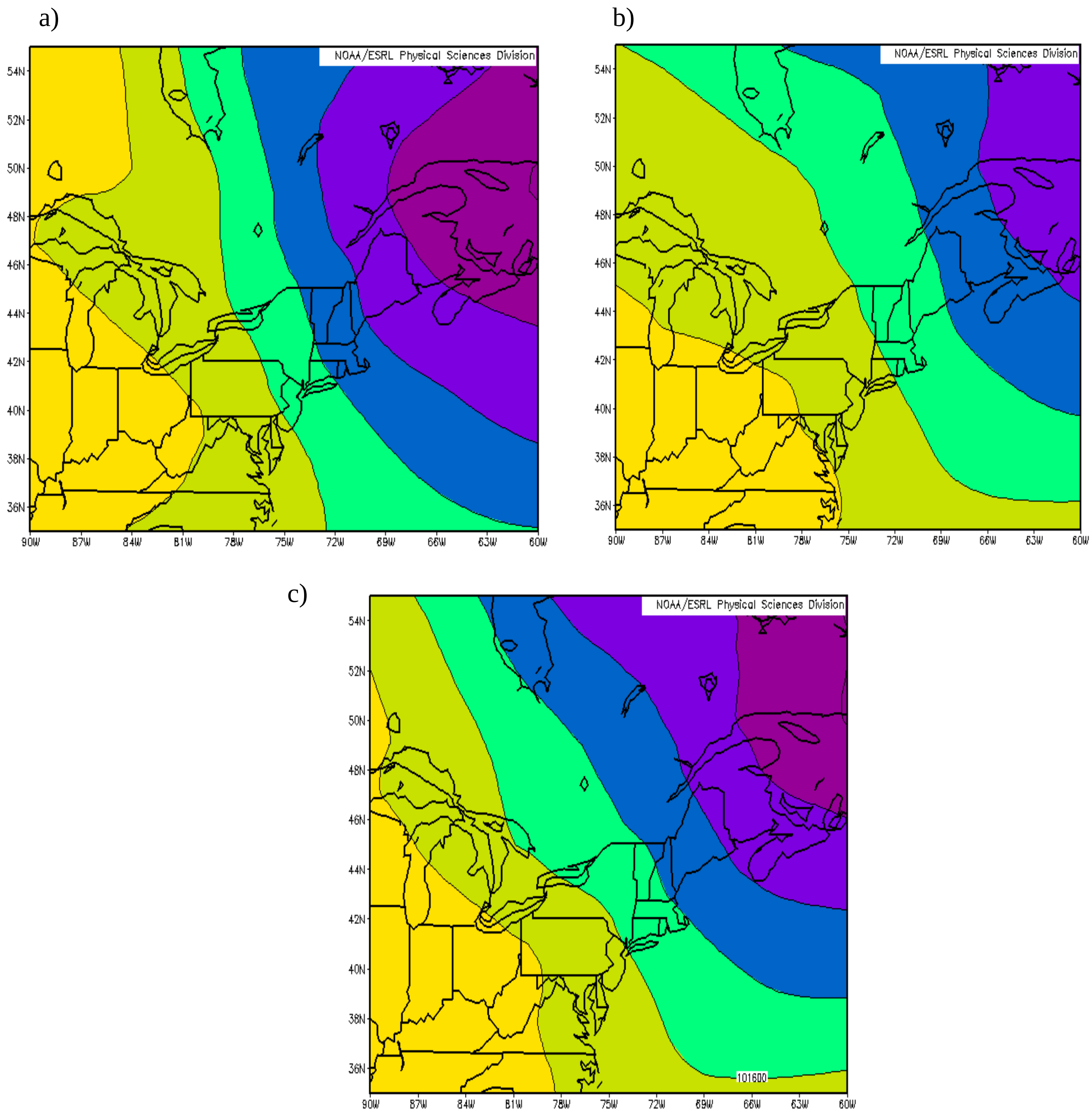

Figure 15. Mean sea level composites (mb) for (a) heavy upslope events, (b) moderate upslope events and (c) light upslope events.

Table 1. Mean snowfall, by forecast zone, for all heavy upslope events.

Forecast Zone	Zone Name	MeanSnowfall (in.)
NHZ001	Northern Coos	5.6
NHZ002	Southern Coos	3.3
NHZ003	Northern Grafton	3.3
NHZ004	Northern Carroll	1.9
NHZ005	Southern Grafton	2.3
NHZ006	Southern Carroll	1.2
MEZ007	Northern Oxford	2.0
MEZ008	Northern Franklin	1.2
MEZ009	Central Somerset	1.0
MEZ012	Southern Oxford	0.8
MEZ013	Southern Franklin	0.4
MEZ014	Southern Somerset	0.2

Table 2. Summary of forecast parameters for upslope snow events.

Element	Light	Moderate	Heavy
Plan View			
MSLP	Broadly cyclonic flow (west)	More cyclonic flow (west to northwest)	Tight cyclonic flow (northwest)
850 mb Heights	Broadly cyclonic	More cyclonic	Nearly closed circulation northeast of the study area
850 mb Wind Speed			
850 mb Relative Humidity	60 percent	70 percent	80 percent
500 mb Heights	Broadly cyclonic	More cyclonic	Nearly closed circulation northeast of the study area
Other Considerations			
Presence of Short Waves	Generally no strong short waves	Presence of a single strong short wave	Multiple short waves present
SWE	> 15:1	> 20:1	> 22:1