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Using the Froude Number to Improve Orographic Snow Forecasts in the Green Mountains of Vermont

*Michael Muccilli**
NOAA / National Weather Service
Burlington, Vermont

ABSTRACT

Orographic snow is a very challenging aspect of forecasting in the northeastern United States. This paper provides a method for improving these forecasts using the Froude number. Past research has shown that variations in the non-dimensional Froude number during upslope snow events can be correlated to the nature of the orographic snow bands, and the distribution of snowfall accumulations. Twenty-five observed northwest flow orographic snowfall cases from 2007 to 2012 in the Green Mountains of Vermont are examined with a focus on the Froude number during the events. Composite synoptic analyses show 500-hPa northwest flow and cyclonic north to northwest flow at 850 hPa. In these cases, the Froude number has a critical level of 1.0, at which events lower than this critical level, the flow becomes blocked and precipitation backs up into the lower elevations of the western slopes of the Green Mountains. With Froude numbers less than 0.5, precipitation affects the Champlain Valley and the Burlington metropolitan area. At Froude numbers above 1.0, air flows more freely over the Green Mountain spine, and the majority of the precipitation falls along the mountains and downwind. The forecast Froude number, in addition to other fields from numerical weather prediction models, can assist forecasters in determining the potential for and possible distribution of orographic snow.

**Corresponding Author address*: Michael Muccilli, NOAA/National Weather Service, 1200 Airport Drive, South Burlington, VT 05403 E-mail: Michael.Muccilli@noaa.gov

1. Introduction

Orographic snow is one of the more challenging aspects of forecasting in areas of complex terrain, and more specifically in the case of this paper, Vermont. Orographic snow events are highly localized, but can evolve into high impact events that affect portions of Vermont. Depending on the mesoscale progression of events, impacts can range from only a few inches along the peaks of the Green Mountains to a highway-closing 1 to 3 foot snowfall along the western slopes of the Green Mountains and even into the Champlain Valley. One of the main ingredients for these events is the orographic lift over the terrain of Vermont (Fig. 1). The key terrain feature of Vermont is the Green Mountain chain which runs primarily north to south through the central portion of the state, with peaks as high as 1340 m (4395 ft) (Mount Mansfield).

The goal of this paper is to make it easier to identify the different regimes of orographic snow events and the distribution of heavy snow using the Froude number, as well as profiles of low to mid-level humidity, wind, and stability. In addition, a set of "most-favorable" conditions for orographic snow in three main areas (the Champlain Valley, the Western Slopes, and the Eastern Slopes as indicated in Fig. 1) will be identified.

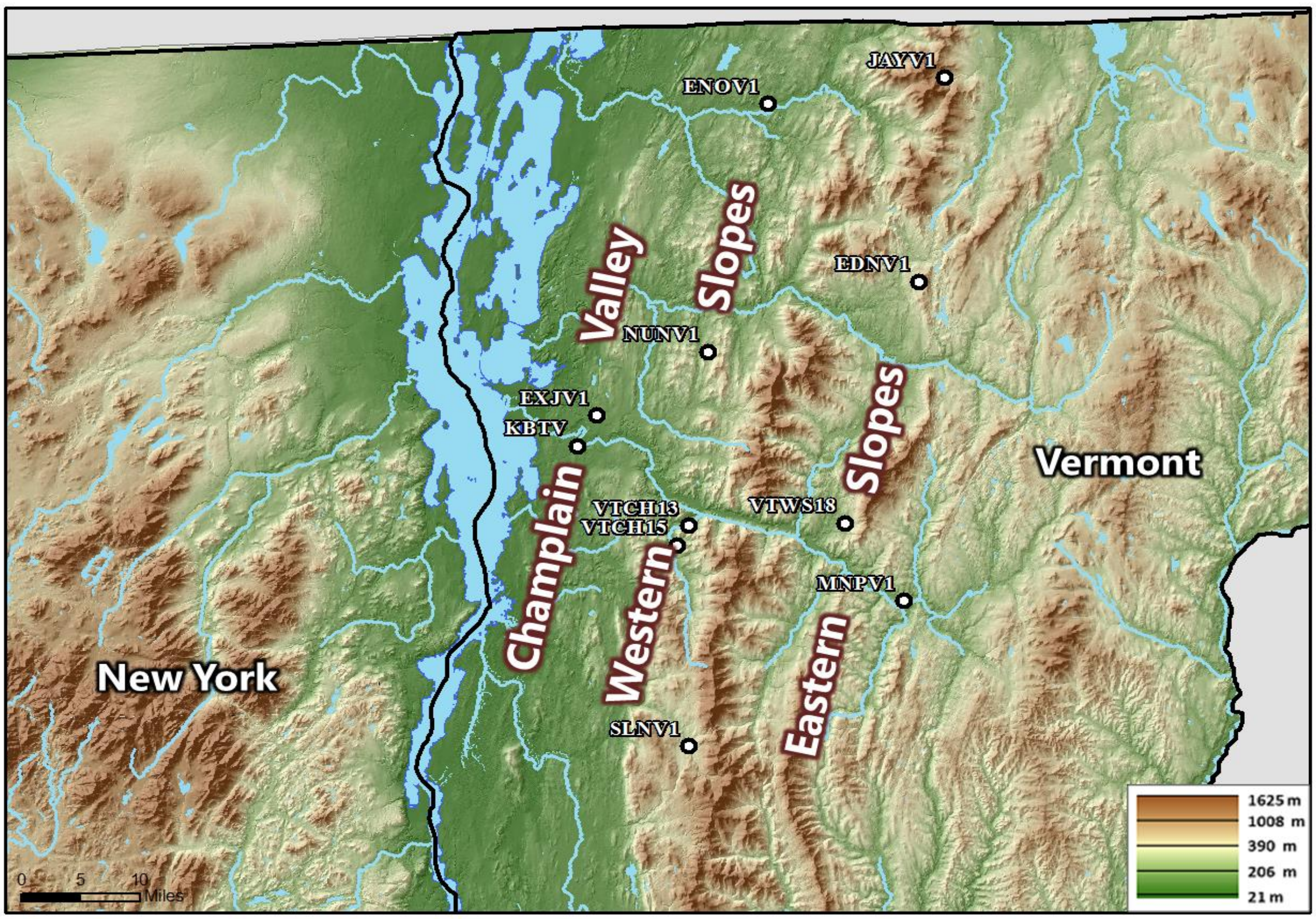

Figure 1. Locations of the Champlain Valley, the Western Slopes, the Eastern Slopes, and of the eleven sites used in Table 1. Topography is shaded blue for Lake Champlain, dark green for

lower elevation valleys, light brown for mid-elevation hills, and dark brown for higher elevation mountain.

a) Synoptic Pattern

Over the northeastern United States, northwesterly lower-tropospheric flow regimes occasionally produce periods of heavy precipitation over the higher terrain of northern New York and northern New England. This is primarily due to the interaction of the wind regime and the low level moisture with the complex terrain of the region, producing orographic precipitation.

The state of the atmosphere leading up to an orographic (upslope) snow event for the Green Mountains of Vermont has been examined in previous studies, most notably St. Jean et al. (2004). It can be characterized by an upper level trough or closed upper low progressing through the region, typically with a trailing vorticity maximum, and a surface and low level pressure system exiting the region (as shown in Fig. 2a, a daily composite of mean sea level pressure of all 25 upslope cases between 2007 and 2012), with increasing westerly to northerly flow in the low levels. The interaction of such a flow regime with the topography of Vermont enhances precipitation, especially where the low level (surface to 850 hPa) flow pattern is generally perpendicular to the local terrain. St. Jean et al. (2004) found several specific factors important to the development of significant upslope snow events. These are:

- Near-saturated conditions from the surface to ridge-top level
- Strong low level winds (>10 ms^{-1}) with significant cross-barrier component
- Equivalent potential temperature decreasing with height in the low levels
- Event duration of at least 12 hours

The daily composite synoptic pattern of all 25 upslope cases between 2007 and 2012 (for multi-day events, the day with the majority of the snowfall was chosen) shows a northwest flow at 500 hPa over the eastern United States and Vermont with a negatively tilted trough extending southeastward from eastern Canada (Fig. 2b). At 850 hPa, the composite mean shows north to northwest moist cyclonic flow over Vermont with the center of the cyclone in the Bay of Fundy between the Canadian provinces of New Brunswick and Nova Scotia (Fig. 3a). This configuration, combined with lingering low and mid-level moisture, as shown by 850-hPa relative humidity plotted in Fig. 3b, leads to the development of orographic snow showers. It is at this point when it becomes critical how the mesoscale features develop with time.

This paper aims to explain how two seemingly similar upslope events can have significantly different outcomes. For example, an event from 7 December 2010 (Fig.4) brought heavy travel-disrupting snow to the western slopes, while an event from 27 January 2010 (Fig. 5) brought the heaviest snow to the mountains and the eastern slopes. This disparity can be largely attributed to the difference between *Blocked Upslope Flow* and *Unblocked Upslope Flow*.

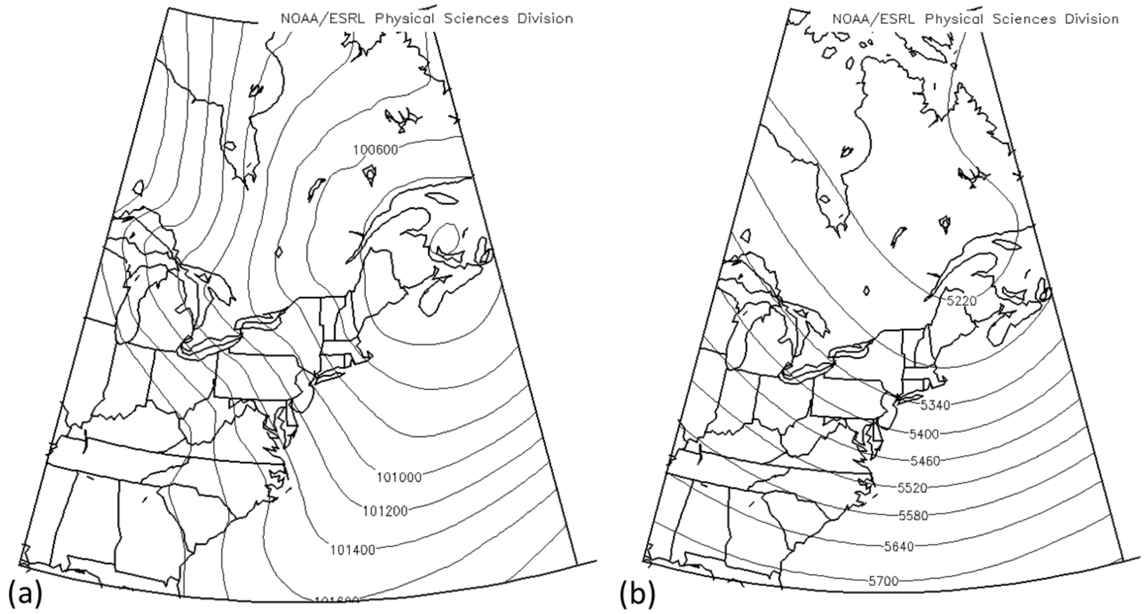

Figure 2. Composite daily mean sea level pressure (a) (solid lines, Pa) and composite daily mean 500-hPa geopotential height pattern (b) (solid lines, m) in upslope snow cases between 2007 and 2012 (NOAA ESRL 2012).

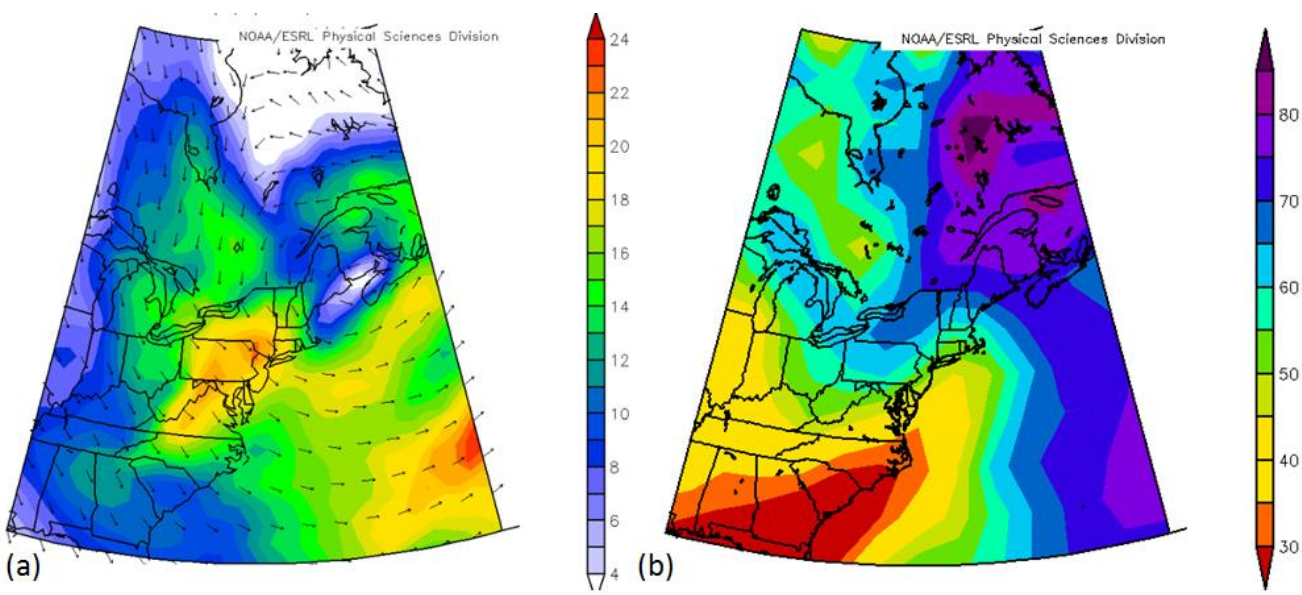

Figure 3. Composite mean 850-hPa (a) vector wind (arrows ms^{-1}) and wind speed (shaded, ms^{-1}) and (b) relative humidity (shaded, %) in upslope snow cases between 2007 and 2012 (NOAA ESRL 2012).

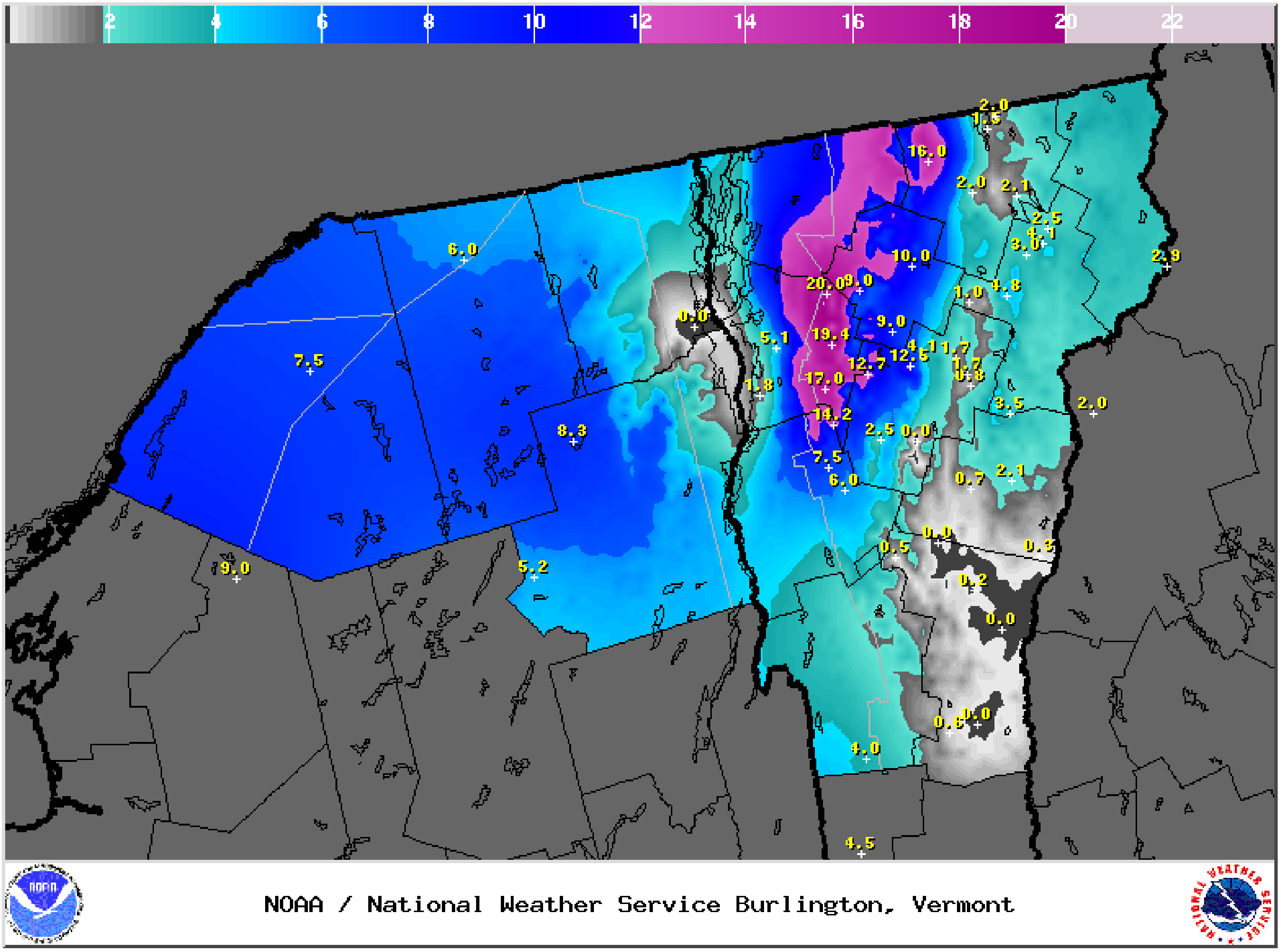

Figure 4. 24 hour snowfall distribution (color-filled, in) ending at 0700 EST 7 December 2010. Re-created from the Daily Climate Maps from National Weather Service Burlington.

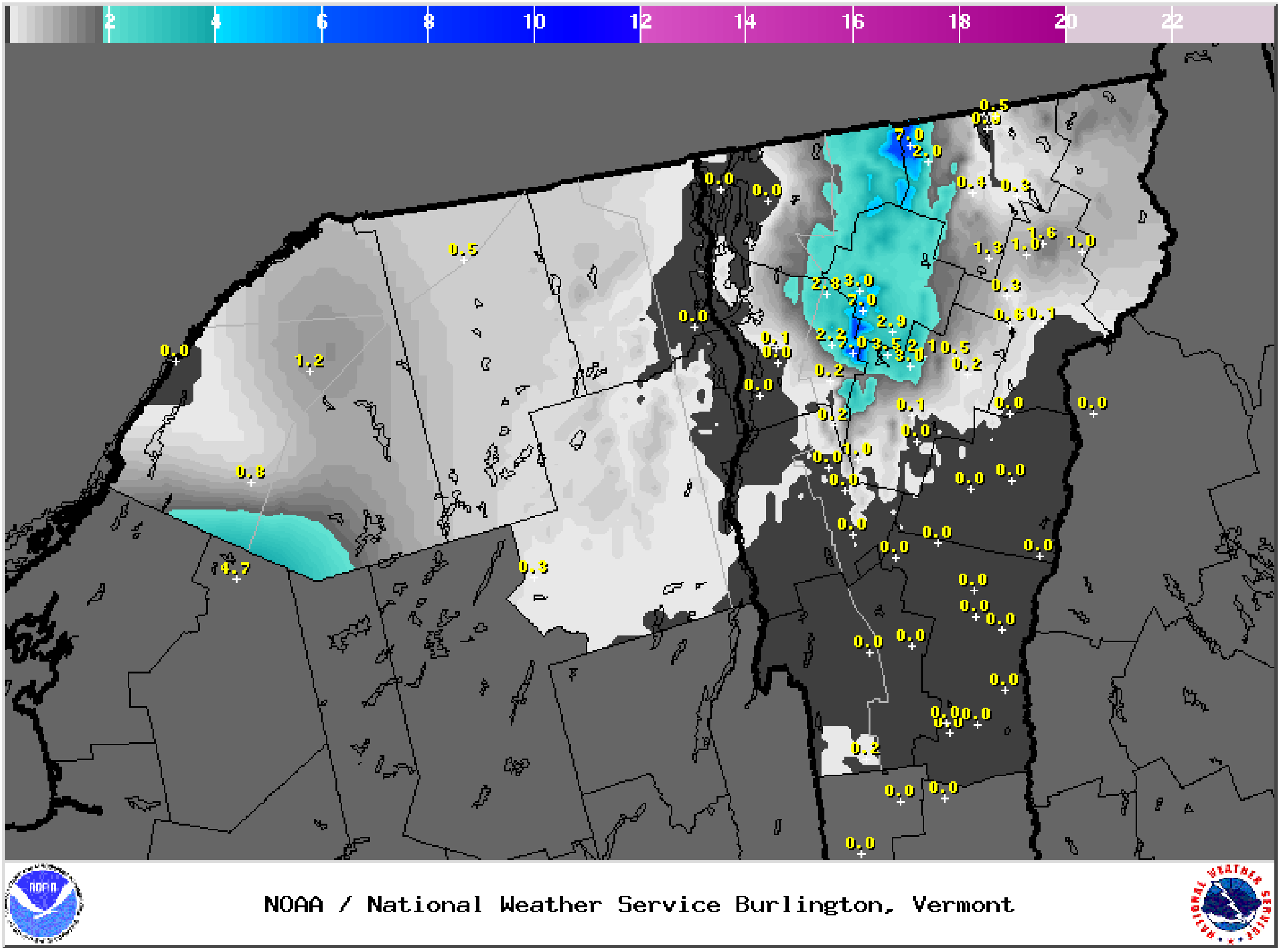

Figure 5. As in Fig. 4 except for 0700 EST 27 January 2010.

b) The Froude Number

As discussed, the distribution and characteristic of the precipitation is highly variable from case to case. It has been found in this study and previously noted studies that this variation is due to a number of variables, however the most prominent being the Froude number, and a determination if the northwest flow is *blocked* or *unblocked*.

If we consider an air parcel upstream of a mountain barrier with an initial speed relative to that boundary, U (the component of the wind speed perpendicular to the orientation of that barrier), whether or not that parcel can move over the mountain depends on three factors: U, the barrier height (h), and the static stability (σ) on the upwind side of the mountain. From the perspective of energy conservation, the increase in potential energy corresponding to the increase in altitude in reaching height h must be derived from the motion (kinetic energy) of the parcel itself. Furthermore, the kinetic energy necessary to offset this increase in potential energy during forced ascent is modulated by σ; a more stable stratification will make the parcel more resistant to vertical displacement, requiring more work. Thus, it follows that slower (faster), more stable (unstable) flow regimes are more (less) likely to result in orographic blocking.

The Froude number simplified is a ratio of the speed of the barrier-perpendicular wind to the stability of the low level air mass (as measured by the potential temperature at the surface and at mountain top). The Froude number mathematically is shown in equation 1,

$$F_r = \frac{U/h}{N} \qquad (1)$$

where U represents the wind perpendicular to the boundary, h is the height of the boundary (spine of the Green Mountains), and N is the Brunt-Vaisala Frequency, a result of the Brunt-Vaisala Equation. The Brunt-Vaisala Equation is shown in equation 2,

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

where g is gravitational acceleration, θ is the potential temperature at the surface, and $\frac{\partial\theta}{\partial z}$ represents the change of potential temperature from the surface to the mountain top, i.e. the static stability.

The result of the Froude number equation is a unit-less number that represents whether the air being advected into the mountains can make it over the mountain range or if it is too stable or the wind not strong enough and it becomes blocked along the mountains or even propagates back into the valley. When the Froude number is less than 1 (Fig. 6a), it is considered subcritical, and the flow is blocked, thus the associated precipitation is likely to fall upwind of the barrier as speed convergence induced by the slowing flow upstream of the mountain is associated with low-level upward vertical motion upwind of the mountain barrier. When the Froude number is near or slightly greater than 1, it is considered a critical level (Fig. 6b) where mountain waves are possible and precipitation is likely to fall along the barrier. And when the Froude number is much greater than 1 (Fig. 6c), the flow is considered supercritical, or unblocked, and the air will flow freely over the mountain chain, with the heaviest precipitation likely falling on the lee side of the barrier.

While there have been many studies completed on orographic precipitation events, including in the Green Mountains of Vermont, there has only been modest research using the Froude number and how it plays a role in the characteristics of an upslope precipitation event. More recently there have been several studies including the Froude number in certain portions of the world, but none in the northeastern United States.

One main focal point of research has involved the southern Appalachian Mountains, where until recently the forecasts of the northwest flow snow events in this part of the country have struggled. As discussed by Keighton et al. (2009) their struggle with low to-mid level tropospheric northwest flow snow events is quite similar to what is observed in the northeastern United States. These events are characterized by moist, upslope northwest flow that leads to very sharp snow accumulation gradients that are very strongly related to the topography. Keighton et al. (2009) investigated the Froude number and found it useful in their diagnosis of the extent to which flow is blocked by a topographic feature, in their case the southern Appalachian Mountains. Consistent with past research they found that large static stability leads to a smaller Froude number, leading to greater blocking of the flow by the mountains. Similarly, Lee and Gerapetritis (2012) found that there is a strong association between elevated Froude Numbers (greater than 1) and advisory level (greater than 5-cm or 2-in) snowfalls in the Great Smoky and Blue Ridge Mountains. This may be attributed to the increased ability of the Great Lakes moisture to reach the mountains in an unblocked regime, especially in a region with multiple significant ridgelines. These results differ slightly from this paper's Green Mountain study but this can possibly be attributed to variations in how the studies were conducted and differences in terrain regime and complexity. There are significant differences in the studies' respective scales, and where the Froude numbers were calculated. The Southern Appalachian studies include calculations well upstream of the mountain ridge in question, while this Green Mountain study's calculation site is immediately upstream of the ridge.

Numerous idealized model scenarios have also been executed, as shown by Chen et al. (2008), where they investigated the effects of the Froude number in unsaturated conditionally unstable flow over a mountain ridge. Consistent with other results, including Chu and Lin (2000), they noted that the precipitation distribution and propagation of orographically-induced cloud systems varied with the Froude number, and found four different regimes. Coincident with the lowest Froude numbers (in their modeled cases 0.262), for Regime 1 they found clouds and precipitation propagating upstream against the mean flow. They increased the Froude number to 0.524 for Regime 2 and found that the upstream propagating system became quasi-stationary over the mountain peak. Increasing the Froude number further to 0.785 for Regime 3, they observed some downstream propagation, and for a significantly larger Froude number (1.572) in Regime 4, they observed a faster advecting downstream propagating system. These results are slightly different than what was found in this paper's study along the Green Mountains, highlighting that the cutoff for upstream versus downstream propagating systems may be locally different. These differences are mentioned in Bell and Bosart (1988) who studied the Froude number in relation to Appalachian cold air damming and noted that published values of the Froude number for blocking events range from 0.5 to 2.3. As earlier mentioned, some of this variation may be due to the calculation itself, as location and heights of mountain ranges can be highly variable, and multiple ridgelines and valleys can be a challenge. It is also important to note that Chen et al. (2008) used an idealized model scenario. But all studies point to results that as the Froude number increases, the flow becomes less blocked and upstream propagation transitions to downstream propagation.

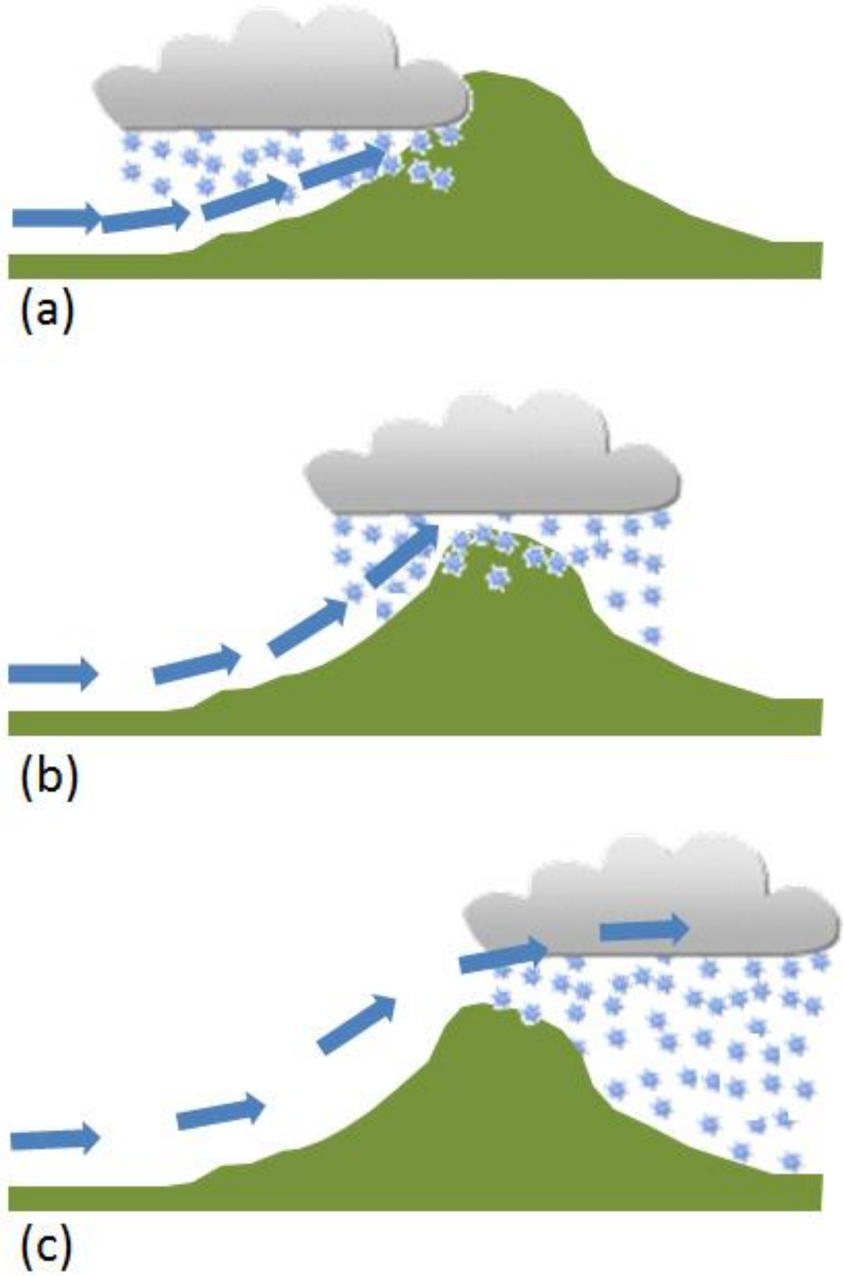

Figure 6. Blocked flow as seen on the top (a), contrasted with near critical flow in the middle (b), and unblocked flow on the bottom (c).

2. Data and methods

The Froude number represents the flow of air and how it interacts when it comes in contact with a barrier, or in Vermont's case, the Green Mountains. The Green Mountains are oriented such that within only 15 miles, the elevations rise from around 30 m (100 ft) along the Lake Champlain waterfront in Burlington to nearly 1340 m (4400 ft) on Mount Mansfield. The mountains are oriented from north to south, such that it acts as a barrier for westerly flow.

For this study, 25 low level westerly upslope flow cases were used spanning the years 2007-2012, when Daily Climate Maps (24 hour temperature, precipitation, snowfall, and snow depth observations) were readily available from the National Weather Service Weather Forecast Office in Burlington (WFO Burlington), showing the precipitation and snowfall reports and distribution. For the purpose of the Froude number calculations, North American Mesoscale Model (NAM) (Janjić et al. 2005) and Rapid Update Cycle (RUC) (Benjamin et al. 2004) forecast soundings of the day of the event at Burlington (KBTV) were used with the Froude number calculated from the mid-point of the event, as defined as the middle hour between onset and cessation of accumulating snow. The exact model run hour varied because of data availability issues, but each sounding was closely examined to ensure it accurately represented the state of the atmosphere. For the purpose of this calculation, the U wind was the component of the wind perpendicular to the Green Mountain spine at summit level, or at 270 degrees, and h was set at 4000 ft, an estimation of summit level. Burlington was chosen as the computational site since it is an excellent representation of the air upstream of the Green Mountains, is not far in distance (15 miles), and had the most readily available archived set of forecast sounding data.

Daily composite means from the 25 cases were also created using the North American Regional Reanalysis (NARR) data and plotted using the National Oceanic and Atmospheric Administration Earth System Research Laboratory Interactive Plotting and Analysis software (ESRL 2012).

Snowfall reports from eleven stations were used in the study, with two stations in the Champlain Valley, five stations along the western slopes of the Green Mountains, three stations along the eastern slopes of the Green Mountains, and one site in the Winooski Valley east of the Green Mountains (Fig. 1). The stations include National Weather Service Cooperative Observer sites (NWS Coop), CoCoRaHs sites, and the National Weather Service Office in Burlington (Table 1). Data was used from each station when it reported following each event. It is to be noted that in a few cases, a station may not have reported the next morning, thus the site was not used in that particular event.

Table 1. The eleven sites used in the Froude Number study.

Champlain Valley Sites		
Burlington Airport (KBTV)	15 miles W of the spine of the Green Mtns (341 FT)	NWS Office
Essex Junction (EXJV1)	13 miles W of the spine of the Green Mtns (340 FT)	NWS Coop
Western Slope Sites		
Enosburg Falls (ENOV1)	7 miles W of the spine of the Green Mtns (420 FT)	NWS Coop
North Underhill (NUNV1)	6 miles W of the spine of the Green Mtns (960 FT)	NWS Coop
Richmond (VTCH13)	5 miles W of the spine of the Green Mtns (715 FT)	CoCoRaHs
Huntington (VTCH15)	5 miles W of the spine of the Green Mtns (710 FT)	CoCoRaHs
South Lincoln (SLNV1)	3 miles W of the spine of the Green Mtns (1341 FT)	NWS Coop
Eastern Slope Sites		
Jay Peak (JAYV1)	Mountain in Western Orleans County (1840 FT)	NWS Coop
Eden (EDNV1)	Eastern Lamoille County (1456 FT)	NWS Coop
Waterbury (VTWS18)	Eastern Slopes in Washington County (975 FT)	CoCoRaHs
Eastern Valley Site		
Montpelier (MNPV1)	Eastern Valley Site (530 FT)	NWS Coop

3. Results

a) *Froude Number & Upslope Snow Study along the Green Mountains*

Of the selected 25 cases, 12 were *blocked* with Froude numbers less than 1, and 13 were *unblocked* with Froude numbers greater than 1 (Table 2). For further analysis, the events were grouped by the calculated Froude number; less than 0.25, 0.25 to 0.49, 0.50 to 0.84, 0.84 to 0.99, 1.0 to 1.33, 1.34 to 1.75, 1.76 to 2.0, and greater than 2.0. These groups were chosen around the hypothesis and previous works' conclusions that the Froude number has a critical level of 1, so the bins were selectively chosen to be more sensitive around 1.

The results of the study are consistent with the theory behind the Froude number. When the Froude number was greater than 1, the higher snowfall totals were found from the spine of the Green Mountains and eastward as the flow was unblocked and able to move up and over the Green Mountains (Fig. 7). For the unblocked cases, the bins used were greater than 2, 1.76-2.0, 1.34 to 1.75, and 1.0 to 1.33.

When the Froude number fell below 1, and more specifically 0.85-0.99, the heaviest snow fell along the western slopes with some significant snow making it east over the Green Mountains and onto the eastern slopes (Fig. 8a). Very little snow fell in the Champlain Valley. This type of event can be thought of as the classic blocked flow event along the western slopes. As the Froude number lowered to between 0.26-0.84, snowfall decreases along the eastern slopes and increases in the Champlain Valley (Figs. 8b, 8c). Finally when it fell below 0.25, a fairly rare occurrence during upslope cases (12% of all cases), the heaviest snow actually favored the Champlain Valley (Fig. 8d).

Given the clear distribution of snowfall, one can separate these upslope cases into three types; cases where the Froude Number is greater than 1, which favor the spine of the Green Mountains and points east; cases where the Froude Number falls between 0.5 and 1.0, which favor the spine of the Green Mountains and the western slopes; and cases where the Froude Number is less than 0.5, which favor the western slopes and the Champlain Valley. The separation between blocked and unblocked with a critical level of Fr = 1 was tested using a Student's t-test. For Burlington (KBTV) the probability of error (p) was 0.03, meaning that this separation is 97% significant. This separation was even more significant at North Underhill (NUNV1) where p = 0.001. At Jay Peak (JAYV1), the separation was not significant, where p = 0.4645. This is discussed further in section iii.

Table 2. The 25 cases used in the Froude Number and Upslope Snow Study spanning the years 2007-2012.

Blocked Cases		**Unblocked Cases**	
Date of Event	***Froude Number***	***Date of Event***	***Froude Number***
4 December 2007	0.51	26 January 2008	1.18
22 November 2008	0.94	20 February 2008	1.9
3 January 2009	0.78	21 February 2009	1.43
24 February 2009	0.88	27 January 2010	1.17
29 December 2009	0.7	1 February 2010	1.07
3 January 2010	0.07	4 February 2010	1.03
9 January 2010	0.186	15 February 2010	1.81
7 December 2010	0.98	6 January 2011	1.36
14 December 2010	0.37	15 February 2011	1.59
23 December 2010	0.12	3 January 2012	4.4
10 January 2011	0.64	30 January 2012	1.09
29 December 2011	0.91	26 February 2012	1.74
		28 February 2012	1.55

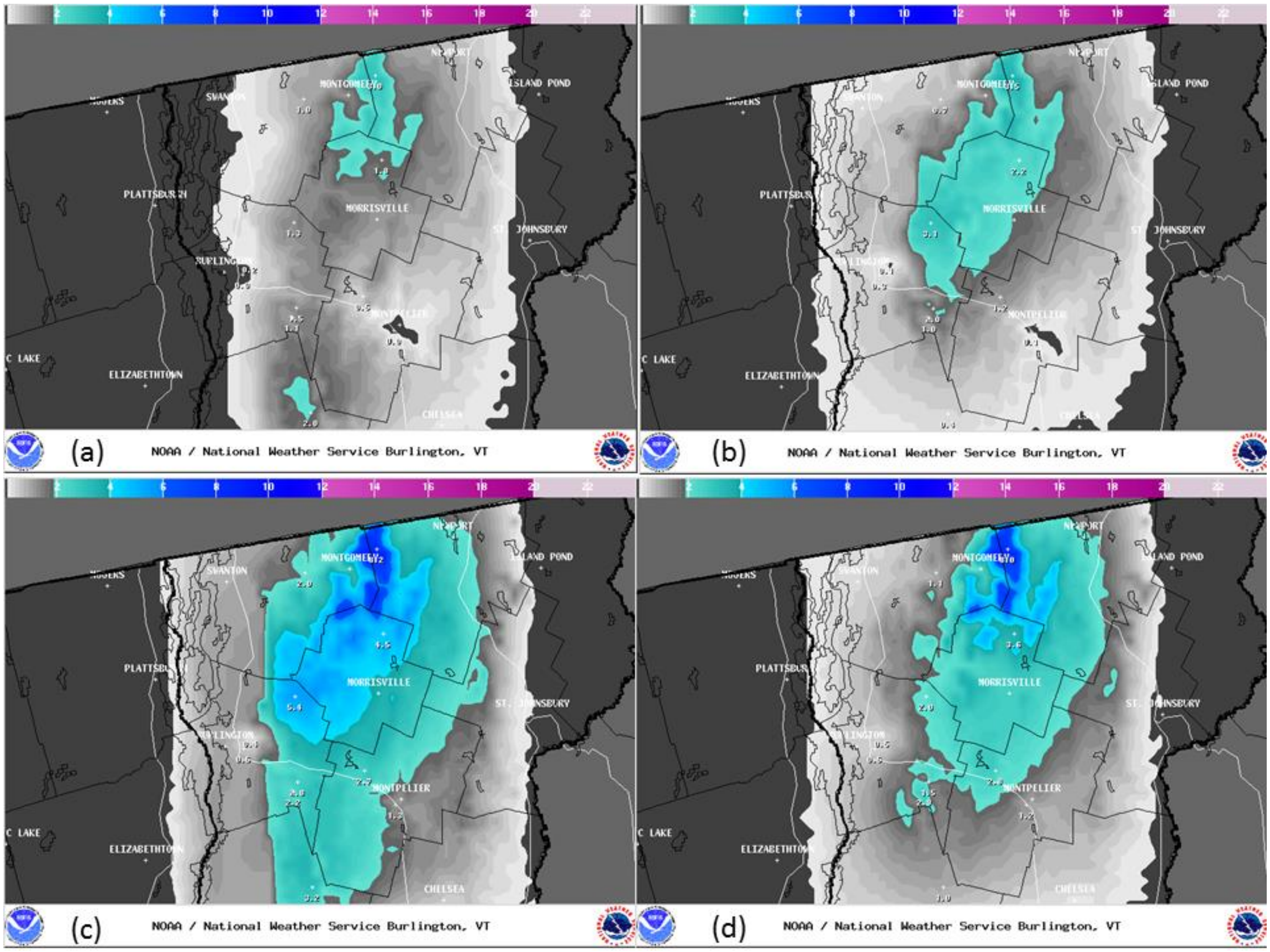

Figure 7. Composite snowfall distribution (color filled, in) for cases with (a) a Froude number greater than 2.0 (n=1), (b) a Froude number between 1.76 and 2.0 (n=2), (c) a Froude number between 1.34 and 1.75 (n= 5), and (d) a Froude number between 1.0 and 1.33 (n=5).

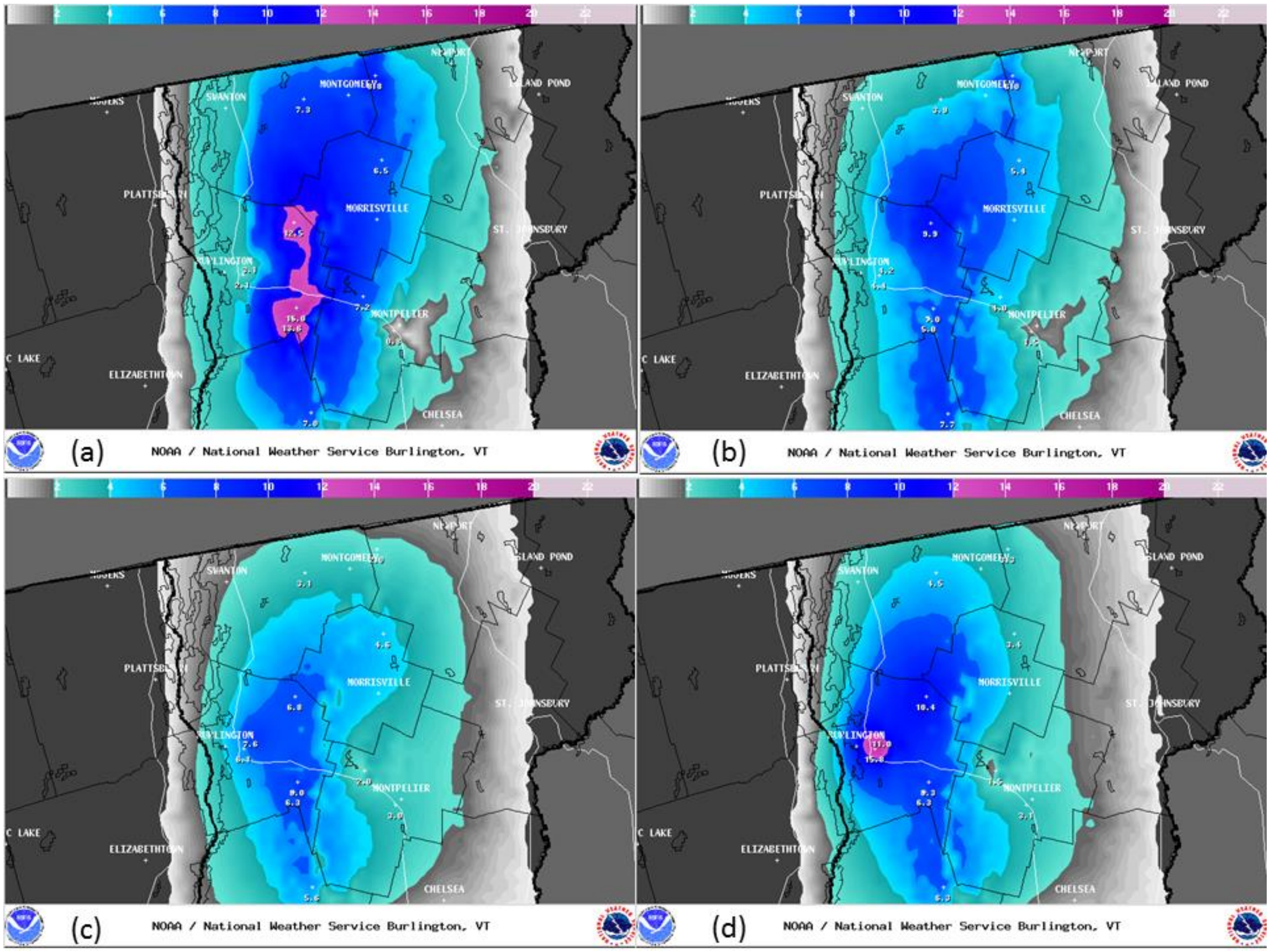

Figure 8. As in Fig. 7 except for with (a) a Froude number between 0.85-0.99 (n=4), (b) a Froude number between 0.50-0.84 (n=4), (c) a Froude number between 0.25-0.49 (n=1), and (d) a Froude number less than 0.25 (n=3).

i) Froude Number and Snow Distribution at KBTV (Champlain Valley)

In the Champlain Valley, during all upslope cases where the Froude number was greater than 1, there were no cases where warning (greater than or equal to 15 cm or 6 inches) or advisory (greater than or equal to 10 cm or 4 inches) criteria were met, and only 8% of all cases even had greater than 2.5 cm (1 inch) of snow (Fig. 9). As the Froude number fell below 1, 75% of all cases had 2.5 cm or greater of snow, 58% met advisory criteria, and 42% met warning criteria. When the Froude number fell below 0.5, these numbers increased with 100% of cases meeting advisory criteria and 75% of cases meeting warning criteria. However it should be noted that only 4 cases had Froude numbers less than 0.5.

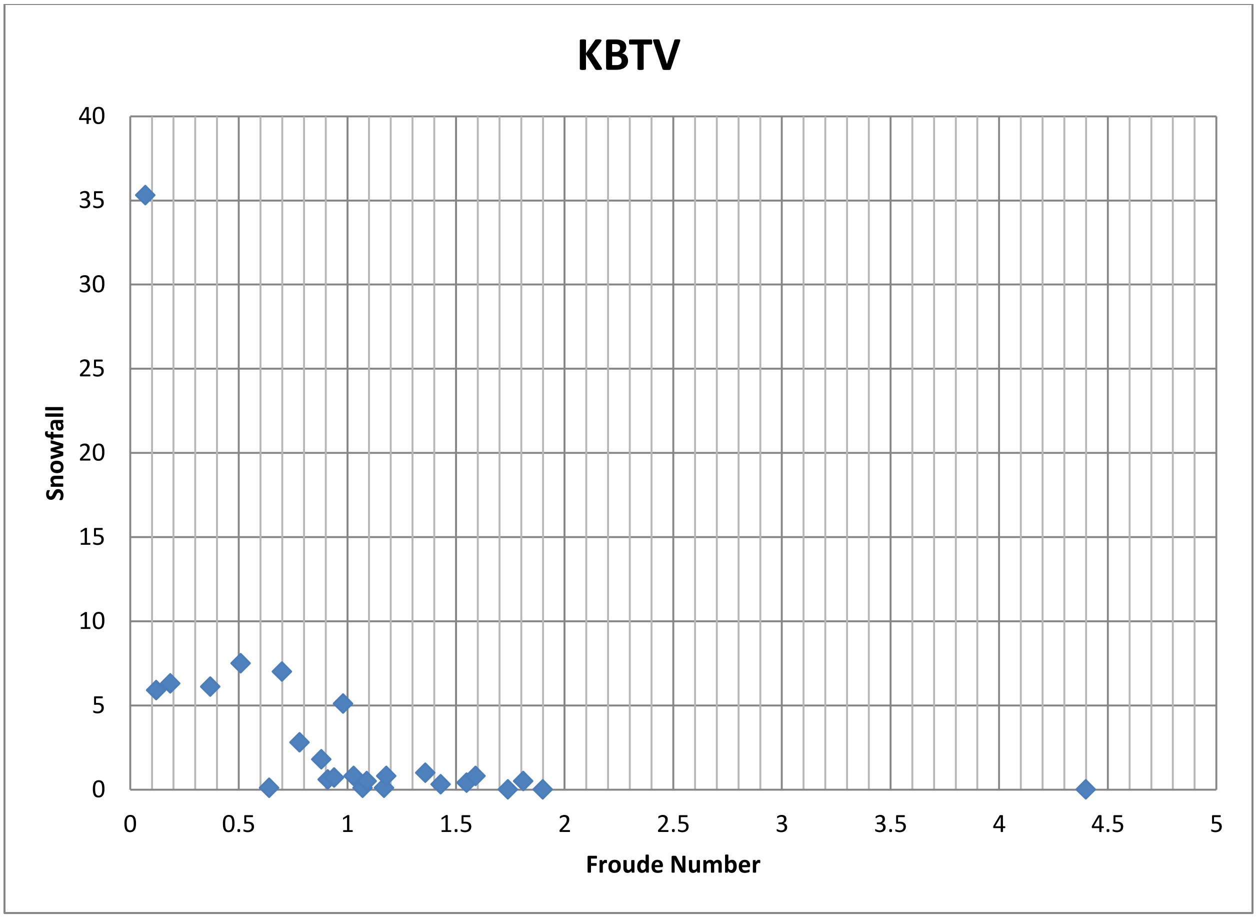

Figure 9. Snowfall amounts (inches) at Burlington International Airport (KBTV) versus the Froude number for 25 upslope snow cases between 2007-2012.

ii) Froude Number and Snow distribution at NUNV1 (Western Slopes)

During all upslope cases at North Underhill (NUNV1) where the Froude number was greater than 1, only 15% of cases met warning or advisory criteria, although 85% of cases did receive at least 2.5 cm of snow (Fig. 10). As the Froude number fell below 1, 100% of cases met warning criteria, meaning that NUNV1 has reported 15 cm (6 inches) of snow or greater in all cases where the Froude number was 1 or less.

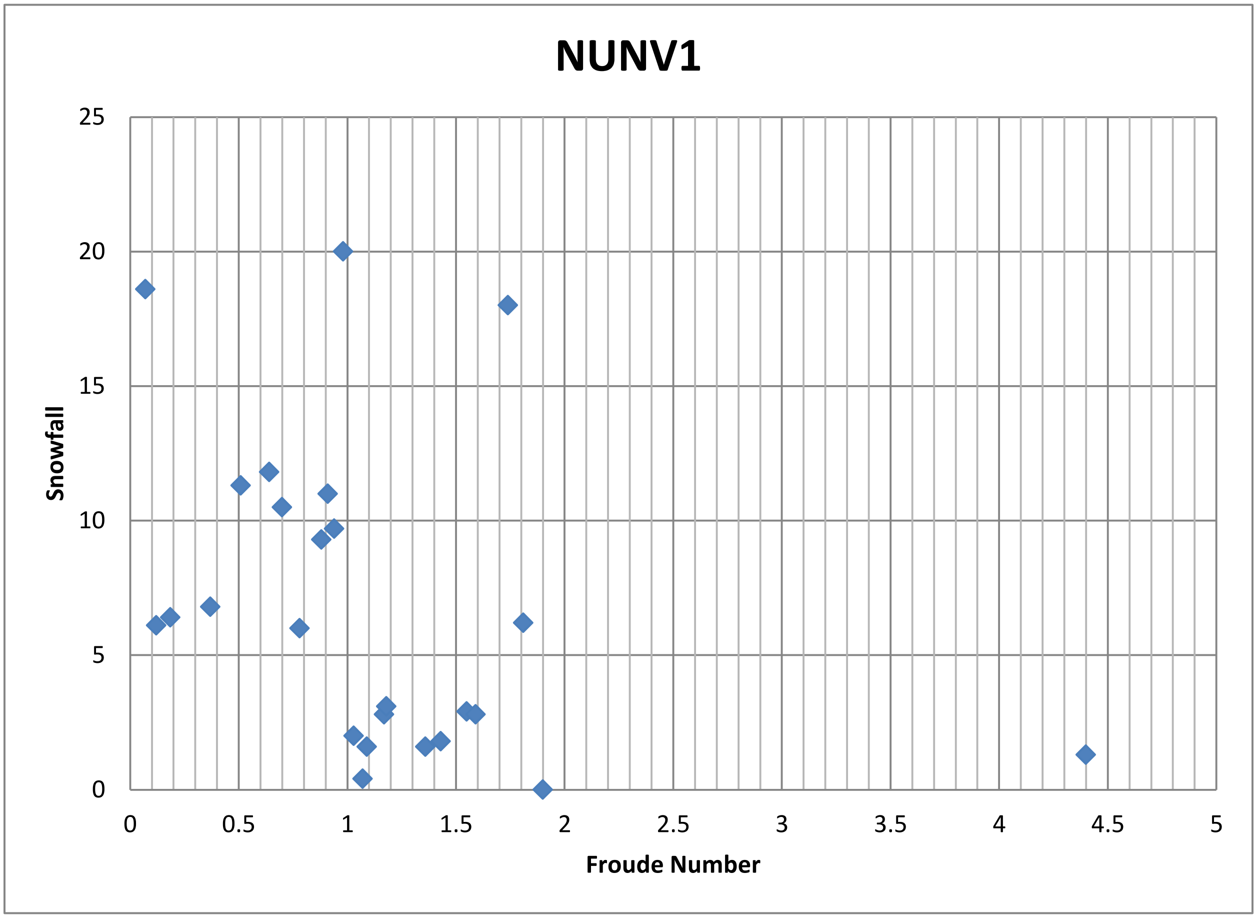

Figure 10. Snowfall amounts (inches) at North Underhill (NUNV1) versus the Froude number for 25 upslope snow cases between 2007-2012.

iii) Froude Number and Snow Distribution at JAYV1 (Eastern Slopes)

At Jay Peak (JAYV1), during all upslope cases where the Froude number was greater than 1, 54% of cases met warning criteria and 85% of cases met advisory criteria, with 100% of cases receiving at least 2.5 cm of snow (Fig. 11). As the Froude number fell below 1, these numbers decreased with 42% of cases meeting warning criteria, 67% meeting advisory criteria, and 92% of cases receiving 1 inch or greater. As the Froude number fell even lower to below 0.5, there was a significant decrease, with 0% meeting warning criteria and 25% meeting advisory criteria, although 100% of cases did still receive at least 2.5 cm of snow. The snowfall distribution (Fig. 11) suggests that for at least warning criteria snow (15 cm) at Jay Peak, favored Froude numbers are roughly between 0.85 - 1.75. This would explain the lack of statistical significance for JAYV1 when a Froude number of 1 is used as a separation.

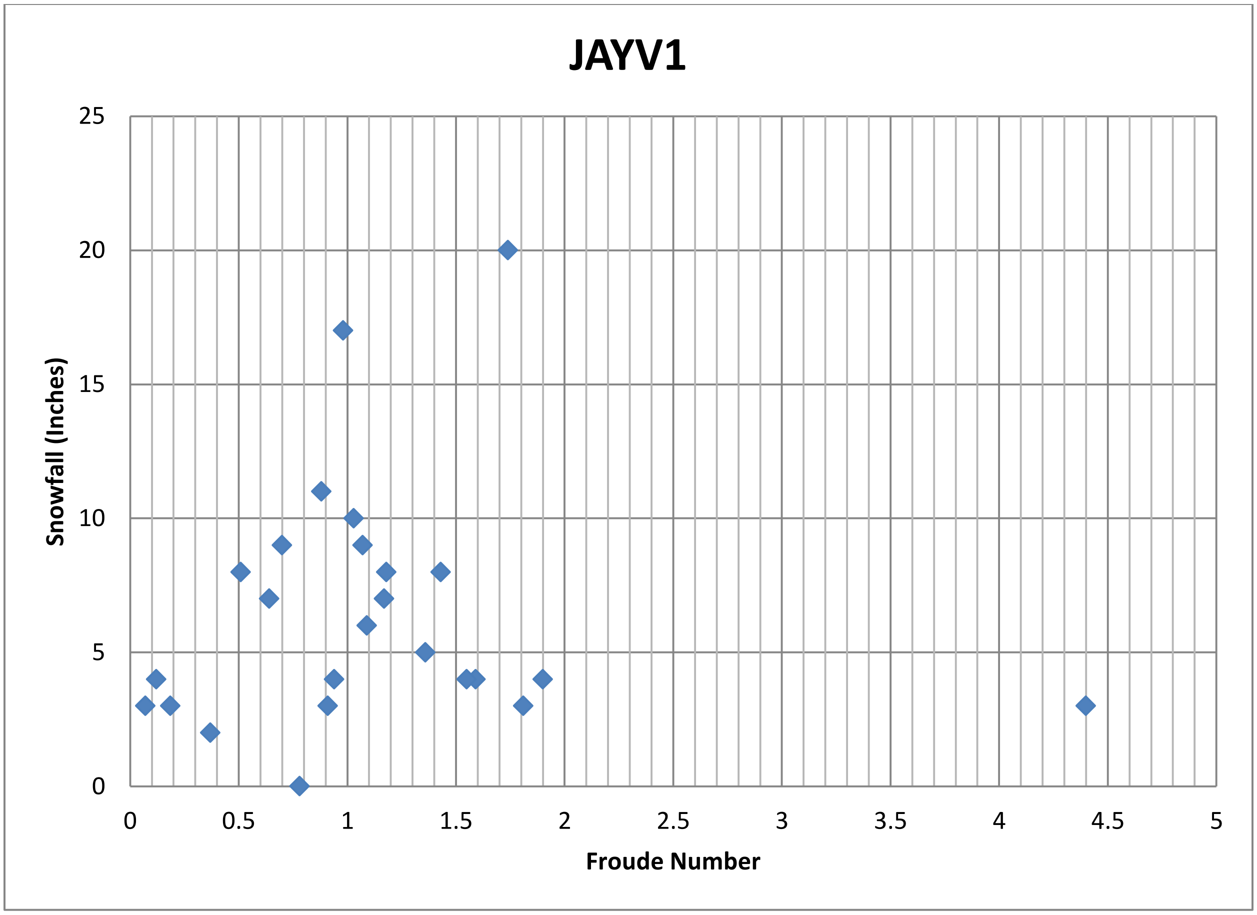

Figure 11. Snowfall amounts (inches) at Jay Peak (JAYV1) plotted versus the Froude number for 25 upslope snow cases between 2007-2012.

b) Examples

i) Froude Number Less Than 0.25

An example that falls into the category where the Froude number fell below 0.25 was the 3 January 2010 "Champlain Powder" event. The Froude number during the event was 0.07. The greatest snow amounts were directly in the Champlain Valley, with very little making it east of the Green Mountains (Fig. 12). The NAM model forecast sounding during the event shows a mixed layer from the surface to 400 m (1312 ft) above ground layer (agl), a very strong inversion with a base approximately at 400 m (1312 ft) agl and well below the mountain ridge top height, a strong veering wind profile (greater than 40 degrees of veering from the surface to 1220 m [4000 ft]), and north-northwesterly flow below the inversion (Fig. 13). For this particular case, the Brunt-Vaisala frequency (N), the static stability term in the Froude number equation, was$1.996\,x\;10^{-2}s^{-1}$, and the U component of the wind was 1.79 ms^{-1}.

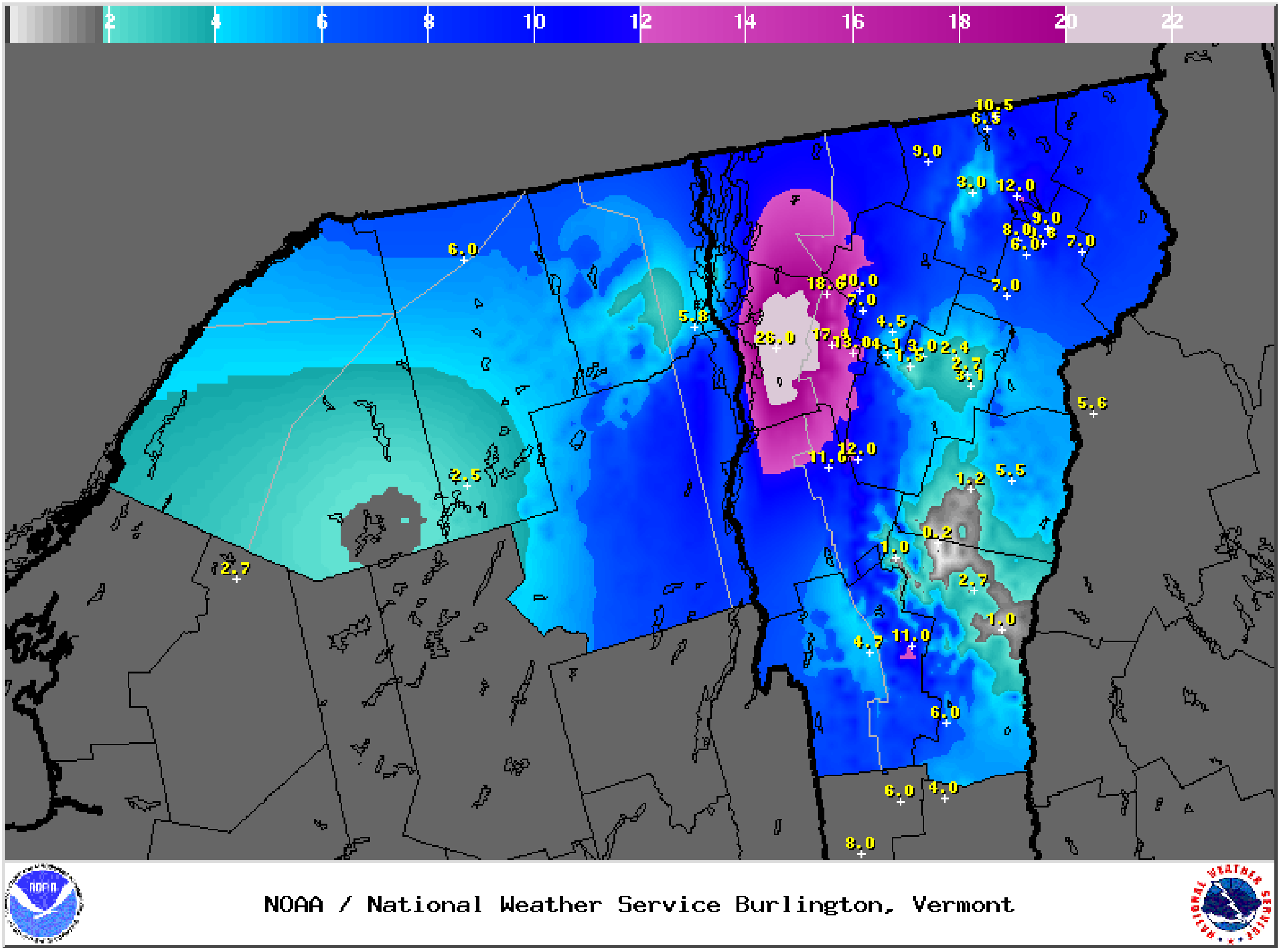

Figure 12. As in [Fig. 4](#) except ending at 0700 EST 3 January 2010.

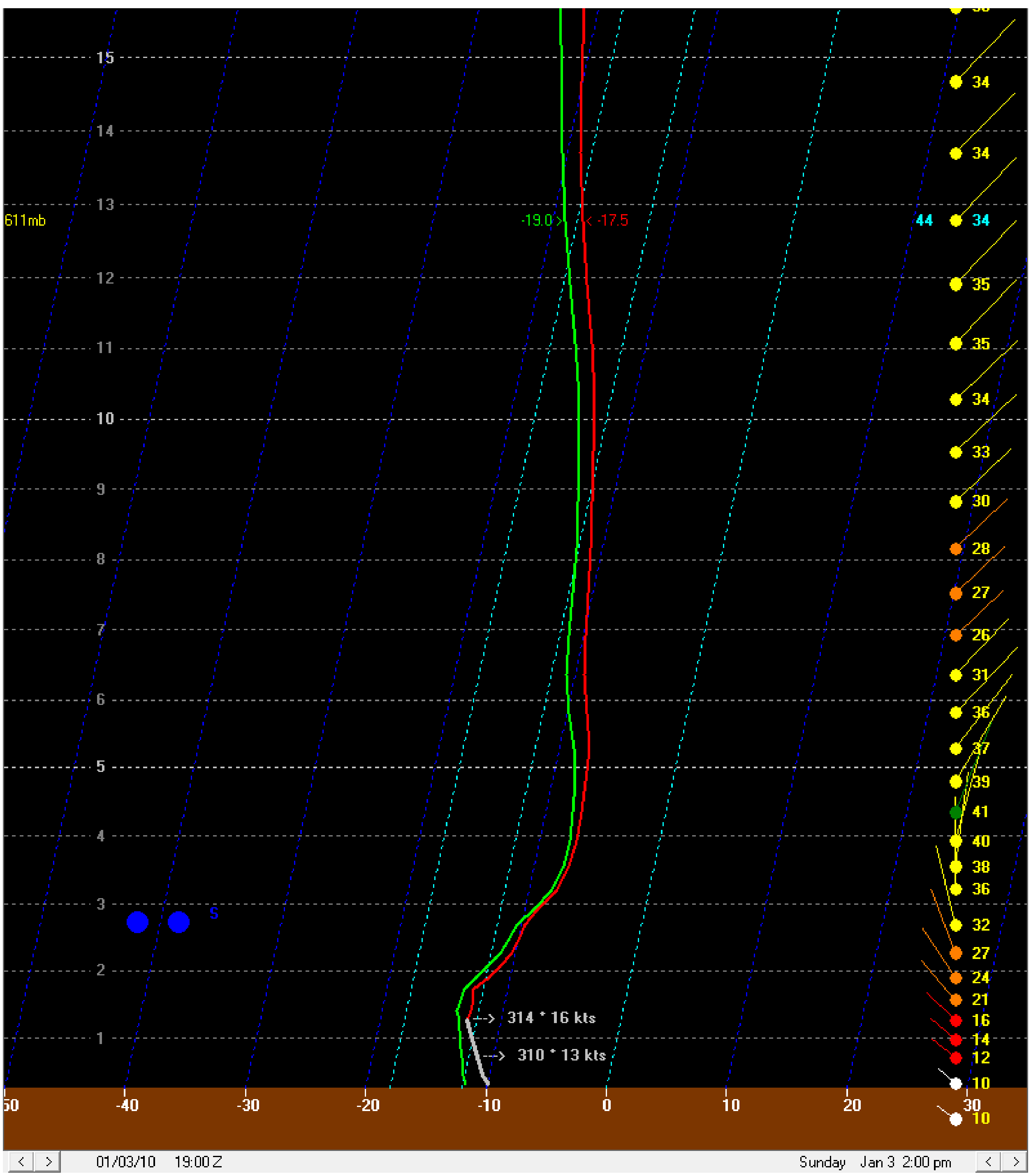

Figure 13. NAM 7-h forecast sounding at KBTV from 1200 UTC 3 January 2010 valid at 1900 UTC 3 January 2010. Diagram is a skew-T (blue dashed, °C) log P (height 10^3 ft, dashed white) where the solid red (green) line is the environmental air (dew point) temperature (°C). The environmental wind direction and speed (barb, kt) are plotted on the right.

ii) Froude Number 0.25 to 0.49

An example that falls into the category where the Froude number was between 0.25 and 0.49 was the 14 December 2010 event. The Froude number during the event was 0.37. The greatest snow amounts were in the Champlain Valley and along the western slopes, with only very minor amounts making it east of the Green Mountains (Fig. 14). The NAM model forecast sounding during the event shows a mixed layer from the surface to 670 m (2200 ft) agl, an inversion with a base at approximately 670 m (2200 ft) agl and below mountain height, a veering wind profile, and northwesterly flow below the inversion in the mixed layer (Fig. 15). For this case, N was equal to $1.403\ x\ 10^{-2}s^{-1}$, and the U component of the wind was 6.58 ms^{-1}.

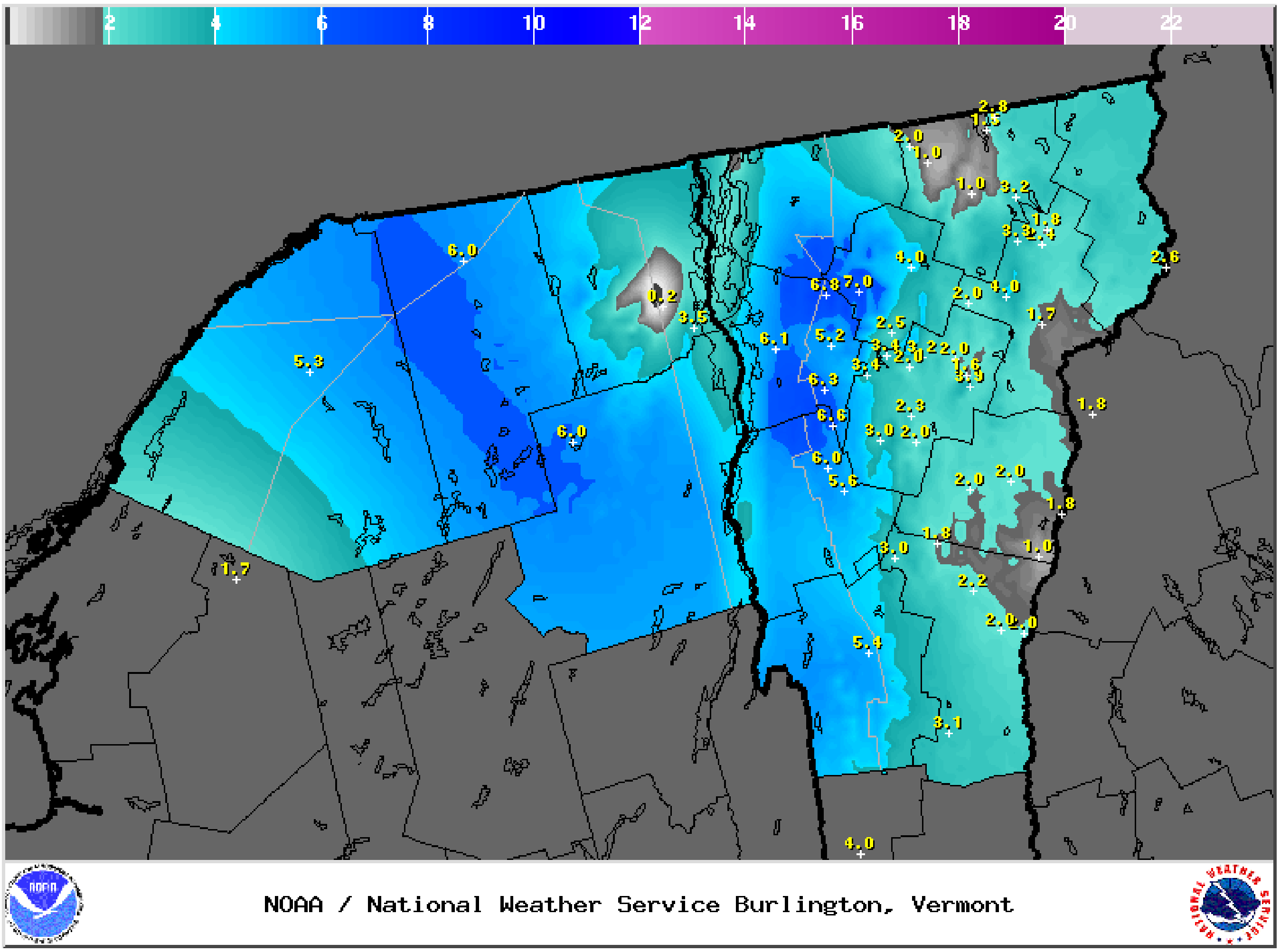

Figure 14. As in Fig. 4, except ending at 0700 EST 14 December 2010.

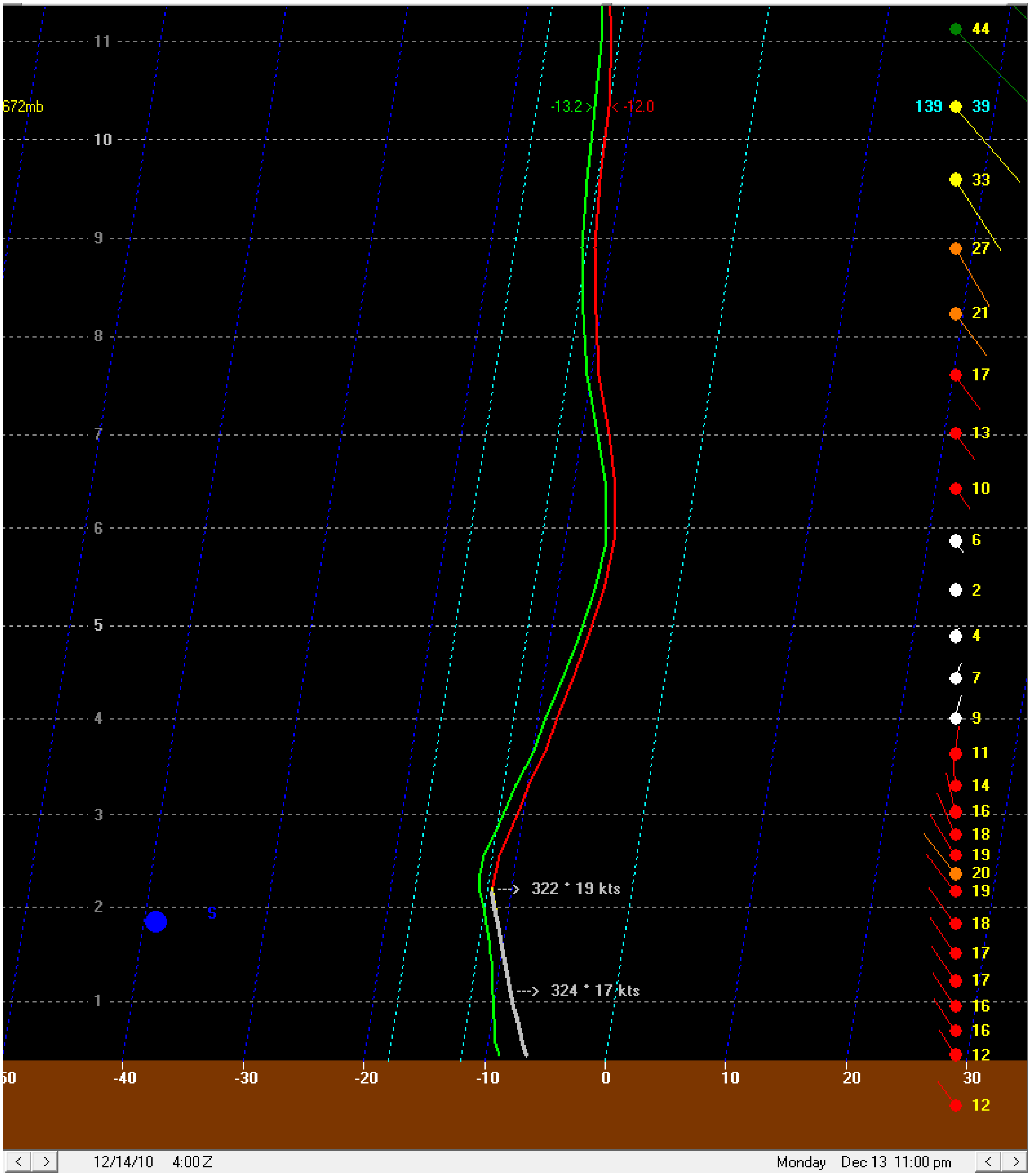

Figure 15. As in [Fig. 13](), except for a NAM 16-h forecast from 1200 UTC 13 December 2010 valid at 0400 UTC 14 December 2010.

iii) Froude Number 0.50 to 0.84

An example that falls into the category where the Froude number was between 0.50 and 0.84 was the 10 January 2011 event. The Froude number during the event was 0.64. The greatest snow amounts were directly along the western slopes with some moderate accumulations making it east of the Green Mountains (Fig. 16). The NAM model forecast sounding during the event shows a mixed layer from the surface to 850 m (2800 ft) agl, a nearly isothermal layer from 850 m (2800 ft) agl to 1310 m (4300 ft) agl to just below mountain ridge top height and northwesterly flow throughout the sounding (Fig. 17). For this case, N was equal to $9.221 \, x \, 10^{-3} s^{-1}$, and the U component of the wind was $7.72 \; ms^{-1}$.

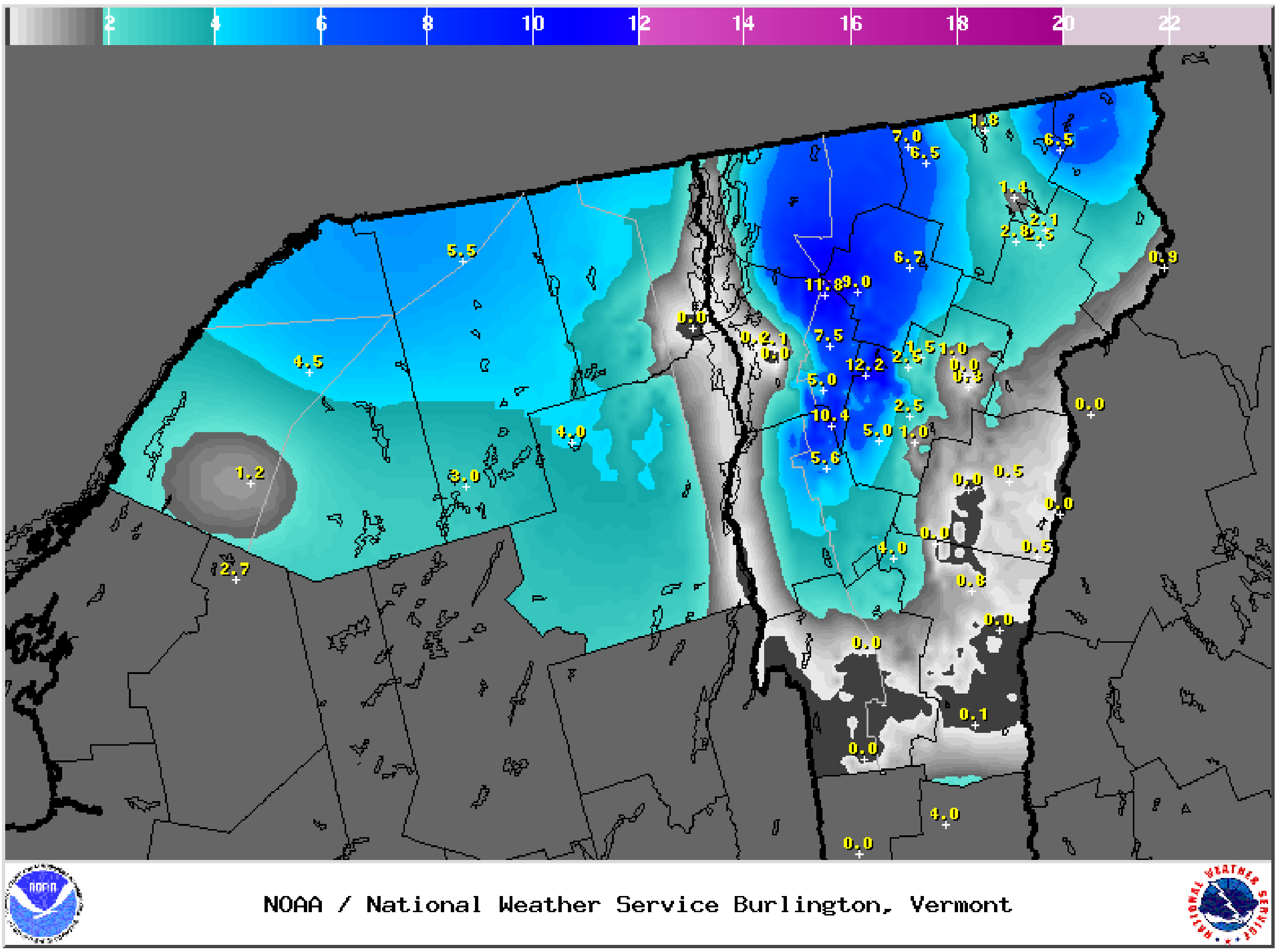

Figure 16. As in Fig. 4, except ending at 0700 EST 10 January 2011.

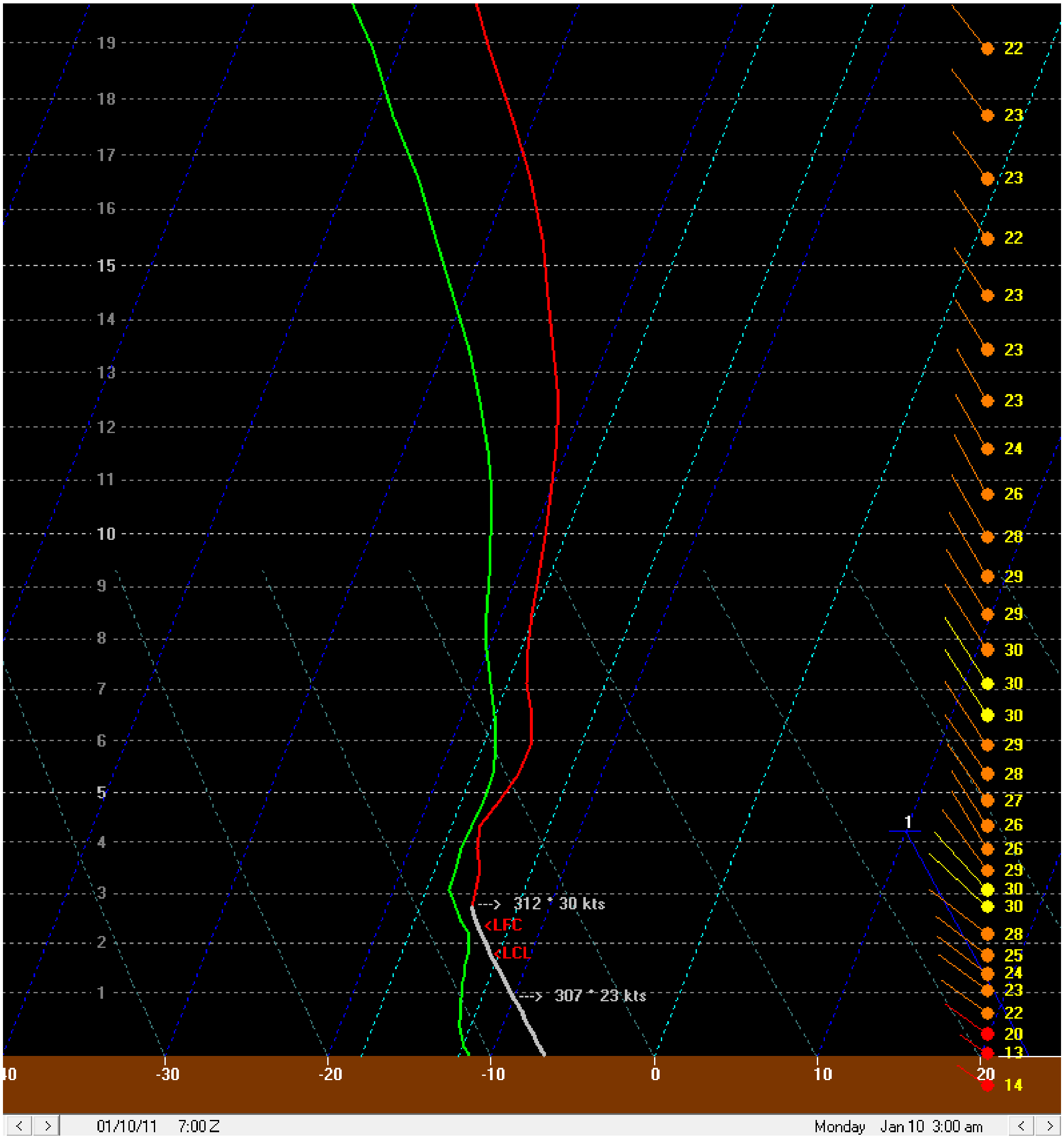

Figure 17. As in Fig. 13, except for a 19-h forecast from 1200 UTC 09 January 2011 valid at 0700 UTC 10 January 2011.

iv) Froude Number 0.85 to 0.99

An example that falls into the category where the Froude number was between 0.85 and 0.99 was the 7 December 2010 event. The Froude number during the event was 0.98. The greatest snow amounts were directly along the western slopes, with significant accumulations also making it onto the eastern slopes (Fig. 18). The classic heavy snow amounts seen in upslope cases along the western slopes typically fall into this category. The NAM forecast model sounding during the event shows a mixed layer from the surface to 850 m (2800 ft) agl, an isothermal layer from near 850 m (2800 ft) to 2070 m (6800 ft), west to northwest flow in the mixed layer, and a weak veering profile (Fig. 19). For this case, N was equal to $1.059\ x\ 10^{-2}s^{-1}$, and the U component of the wind was 13.55 ms^{-1}.

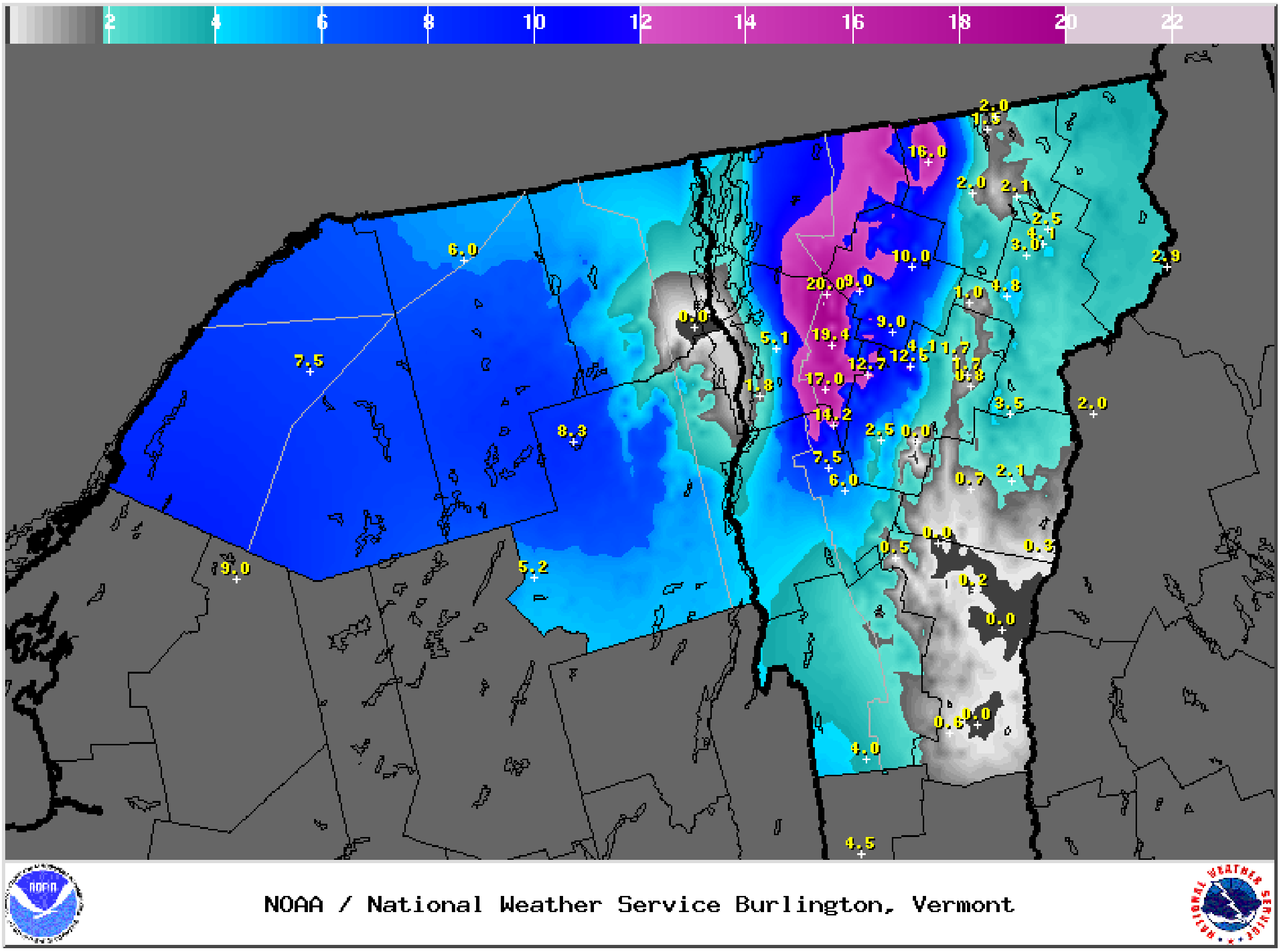

Figure 18. As in Fig. 4, except ending at 0700 EST 7 December 2010.

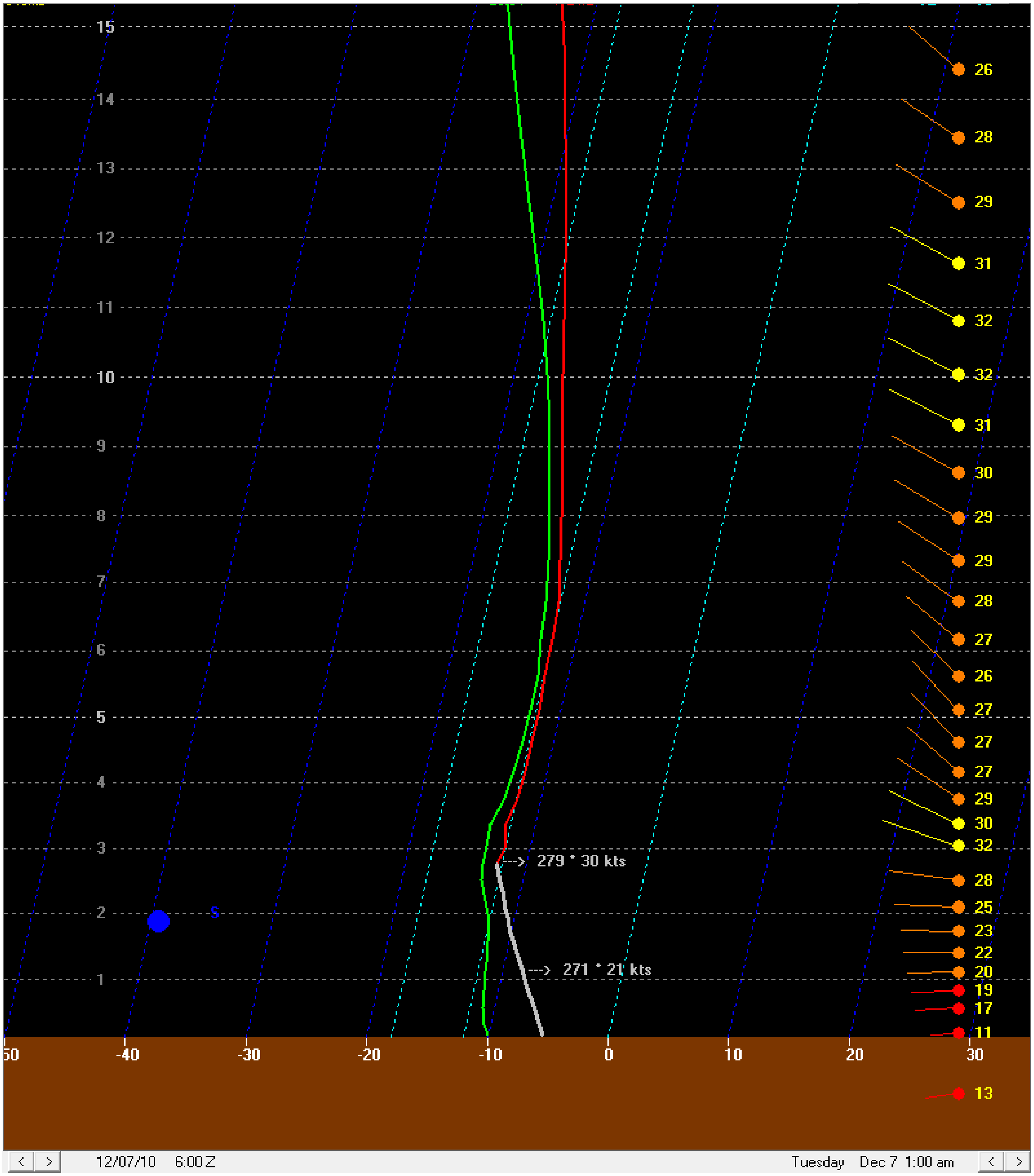

Figure 19. As in Fig. 13, except for 18-h forecast from 1200 UTC 6 December 2010 valid at 0600 UTC 7 December 2010 at KBTV.

v) Froude Number 1.0 to 1.33

Seen in Figs. 20 and 21, an example that falls into the category where the Froude number was between 1.0 and 1.33 was the 4 February 2010 event. The Froude number during the event was 1.03. Note the lack of any isothermal layer or inversion. The greatest snow amounts were along and east of the spine of the Green Mountains with snow making it as far east as the northeastern corner of Vermont. Jay Peak received the heaviest snow in this event. For this case, N was equal to $7.5\,x\,10^{-3}s^{-1}$, and the U component of the wind was 10.1 ms^{-1}.

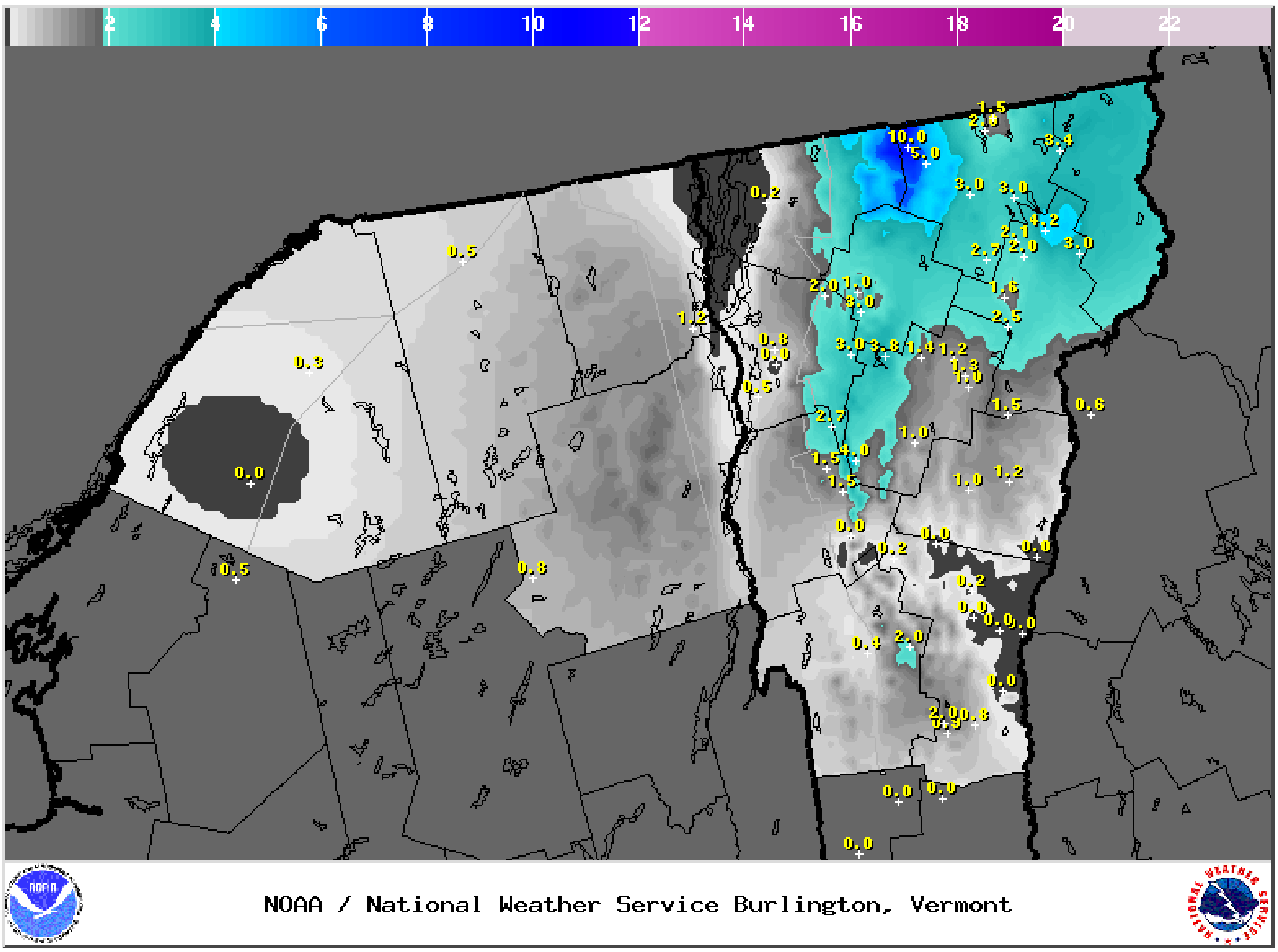

Figure 20. As in Fig. 4, except ending at 0700 EST 4 February 2010.

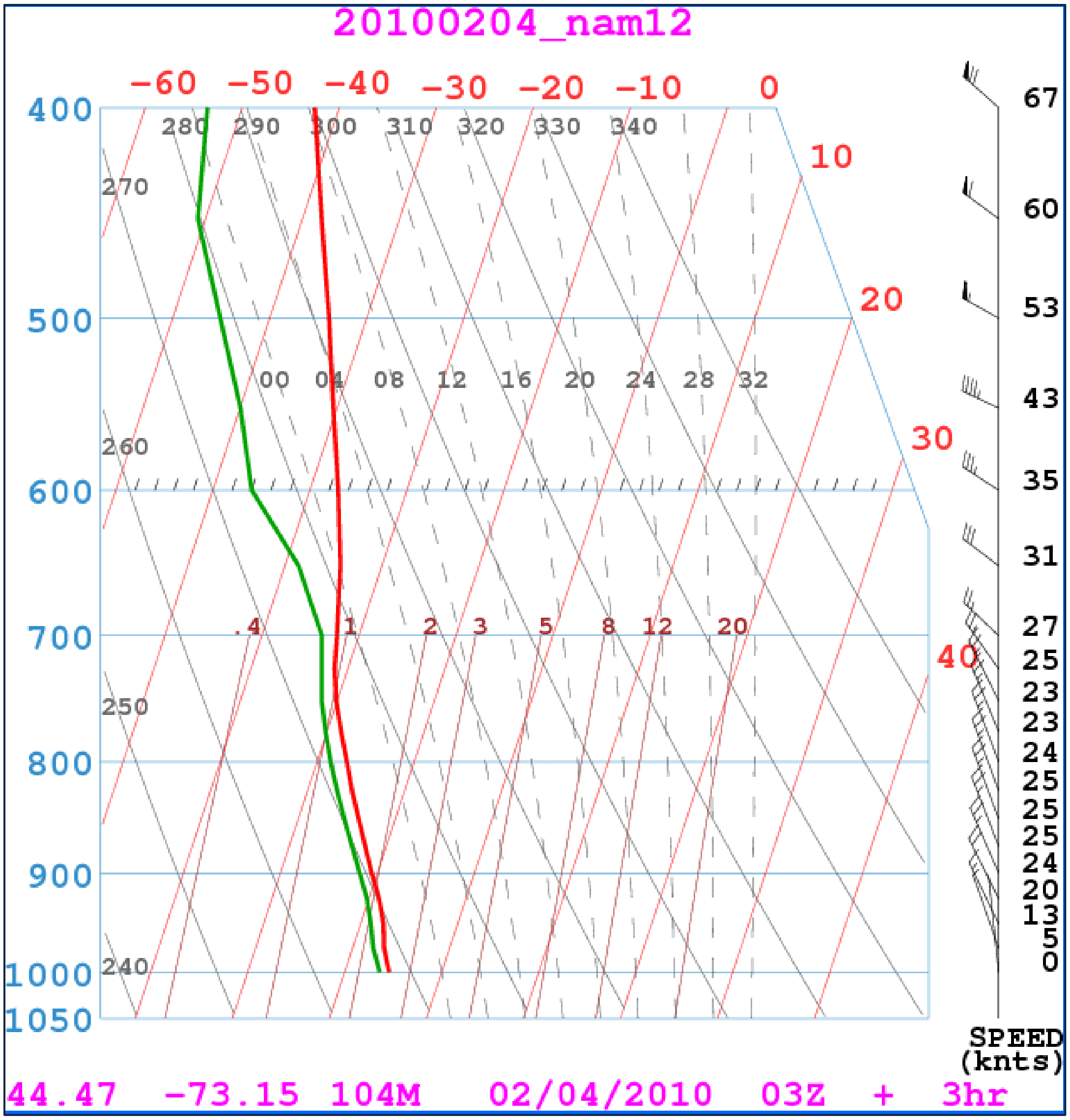

Figure 21. NAM 3-h forecast sounding at KBTV from 0000 UTC 4 February 2010 valid at 0300 UTC 4 February 2010. Diagram is a skew-T (red thin, °C) log P (thin blue solid, hPa), where the solid thick red (green) line is the environmental air (dew point) temperature (°C). The environmental wind direction and speed (barb, kt) are plotted on the right (NOAA ARL 2012).

vi) Froude Number 1.34 to 1.75

Seen in Figs. 22 and 23, an upslope snow example that falls into the category where the Froude number was between 1.34 and 1.75 would be the 21 February 2009 event. The Froude number during the event was 1.43. Note once again the lack of any isothermal layer or inversion, and the relatively strong west to northwest flow. The greatest snow amounts were along and east of the spine of the Green Mountains. Jay Peak again received the heaviest snow in this event. For this case, N was equal to $9.221\ x\ 10^{-3} s^{-1}$, and the U component of the wind was 17.2 ms^{-1}.

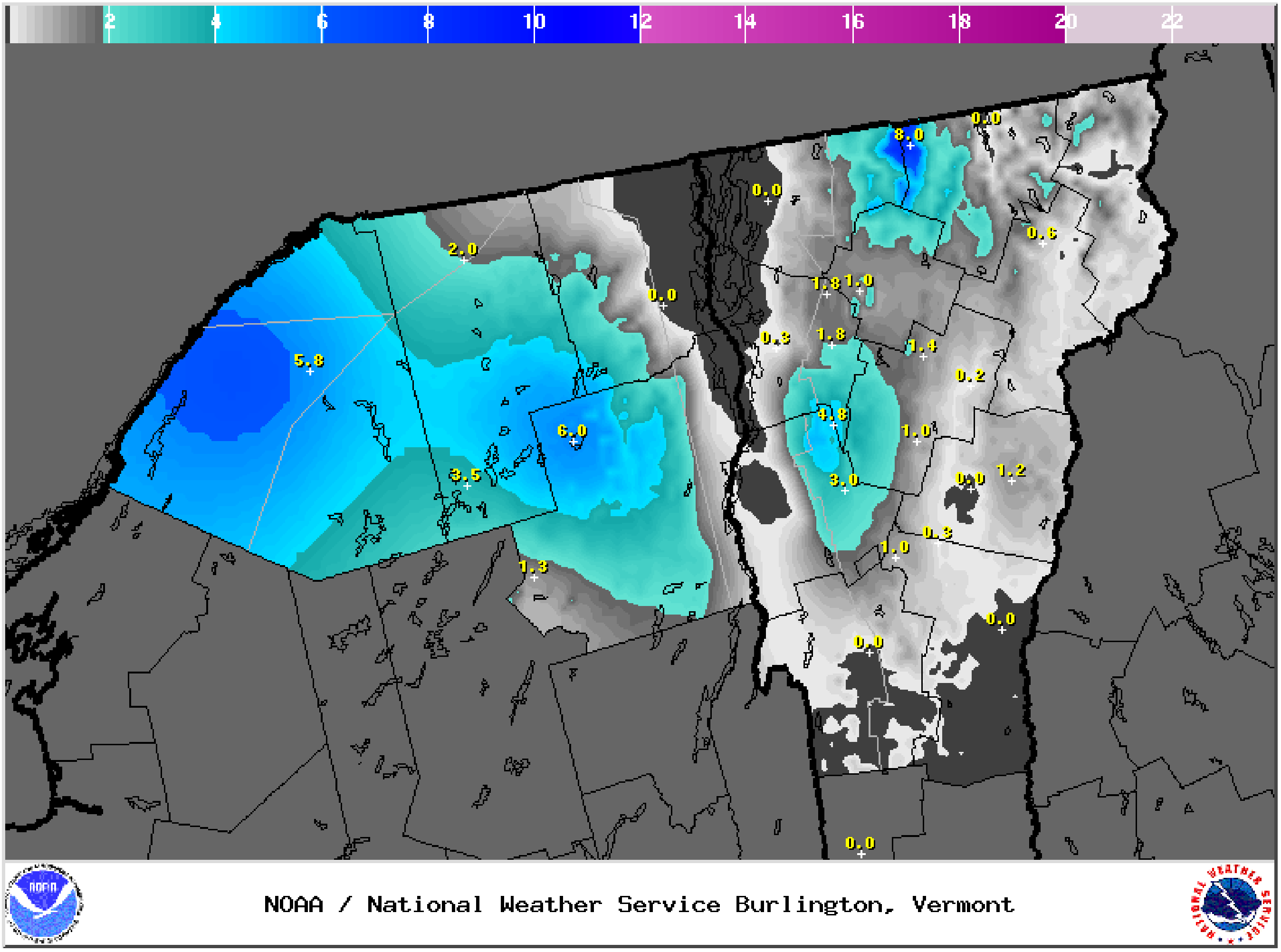

Figure 22. As in Fig. 4, except ending at 0700 EST 21 February 2009.

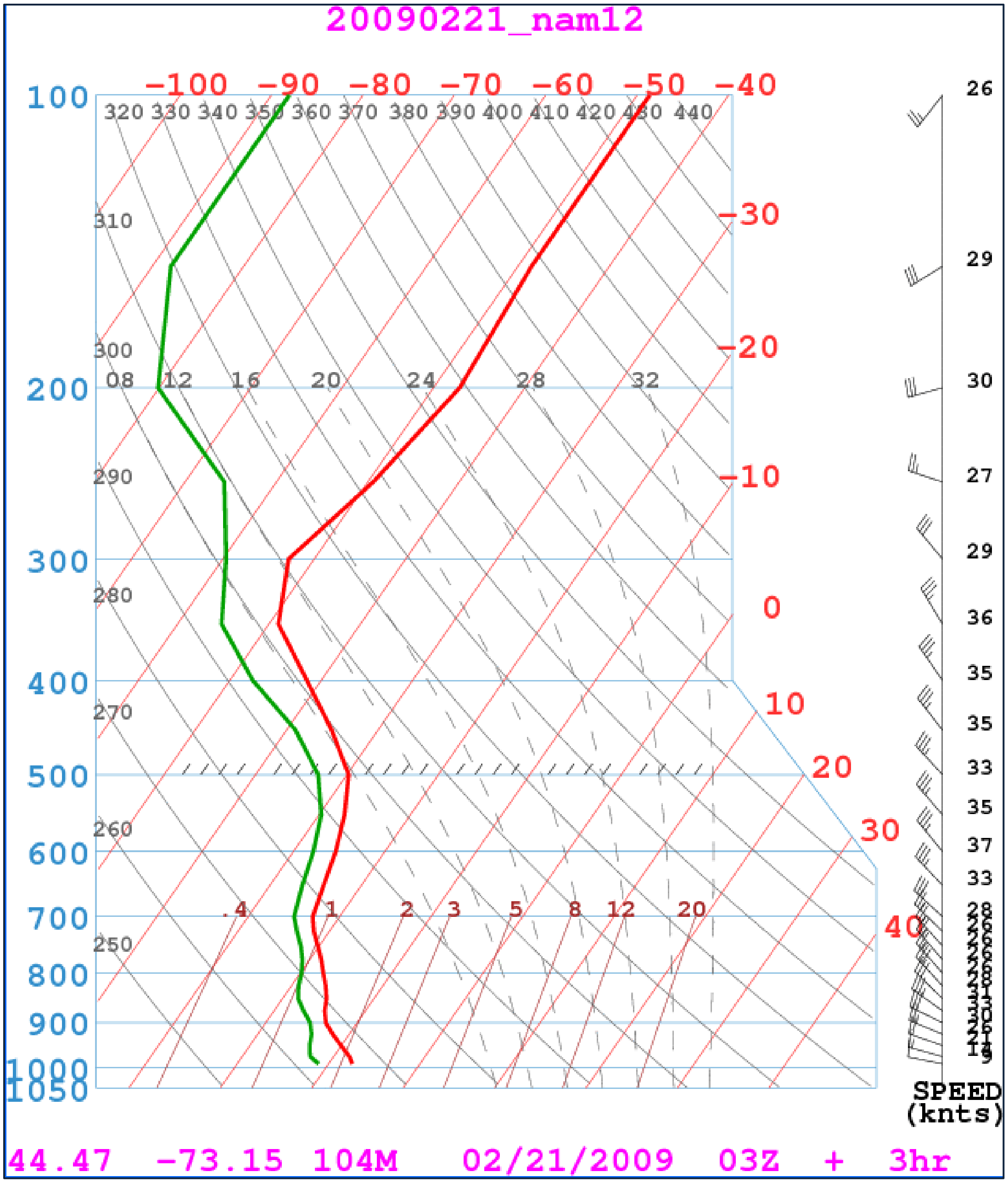

Figure 23. As in Fig. 21, except for 3-h forecast from 0000 UTC 21 February 2009, valid at 0300 UTC 21 February 2009 (NOAA ARL 2012).

vii) Froude Number 1.76 to 2.0

Seen in Figs. 24 and 25, an example that falls into the category where the Froude number was between 1.76 and 2.0 would be the 20 February 2008 event. The Froude number during the event was 1.90. Note once again the lack of any isothermal layer or inversion, with the atmosphere actually rather mixed. The flow is relatively strong from the west and even west-southwest at the surface. The greatest snow amounts were well east of the spine of the Green Mountains and into northeastern Vermont. Jay Peak again received the heaviest snow in this event. For this case, N was equal to $7.5\ x\ 10^{-3} s^{-1}$, and the U component of the wind was 18.5 ms^{-1}.

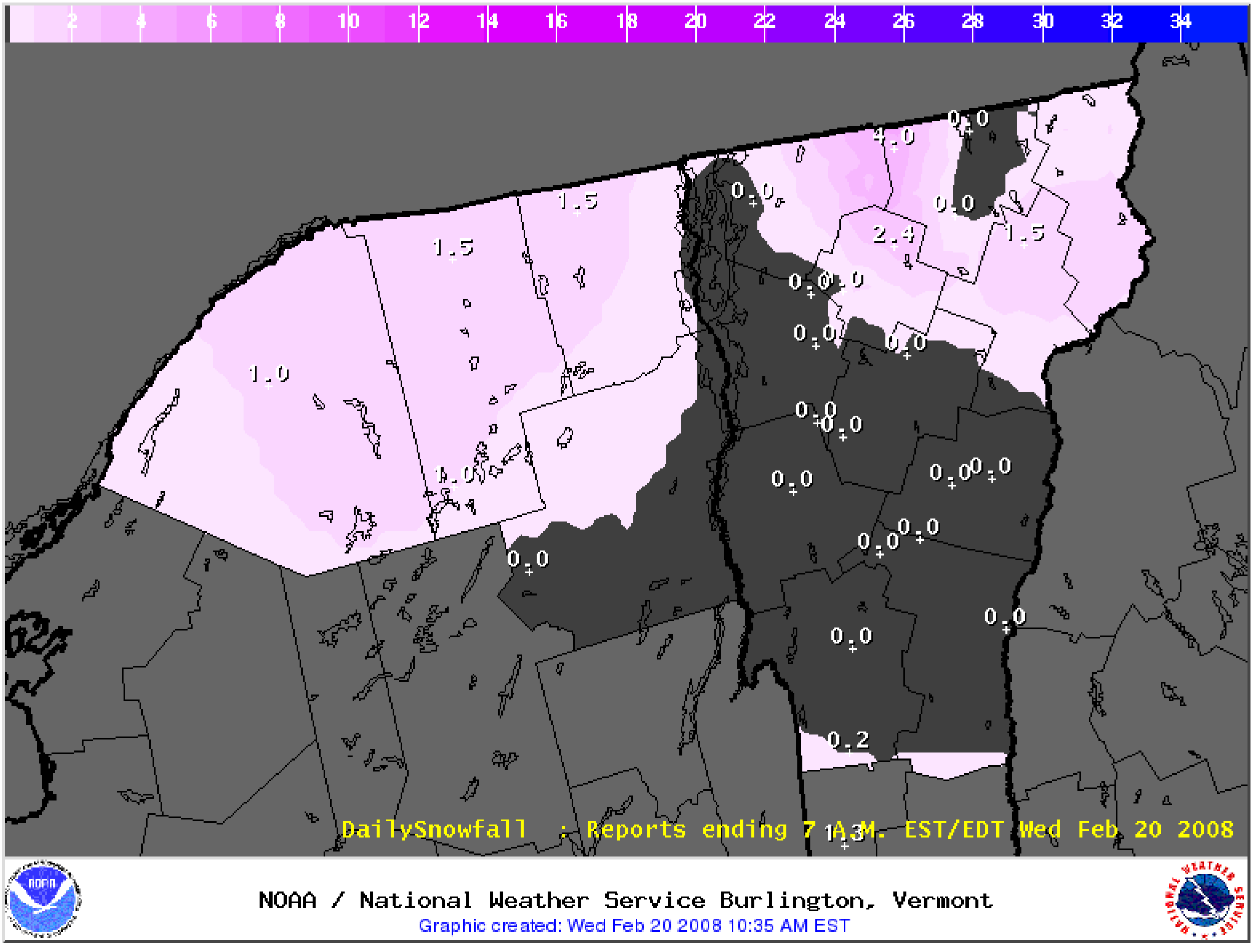

Figure 24. Daily Climate Maps from National Weather Service Burlington showing 24 hour snowfall amounts ending at 0700 EST 20 February 2008.

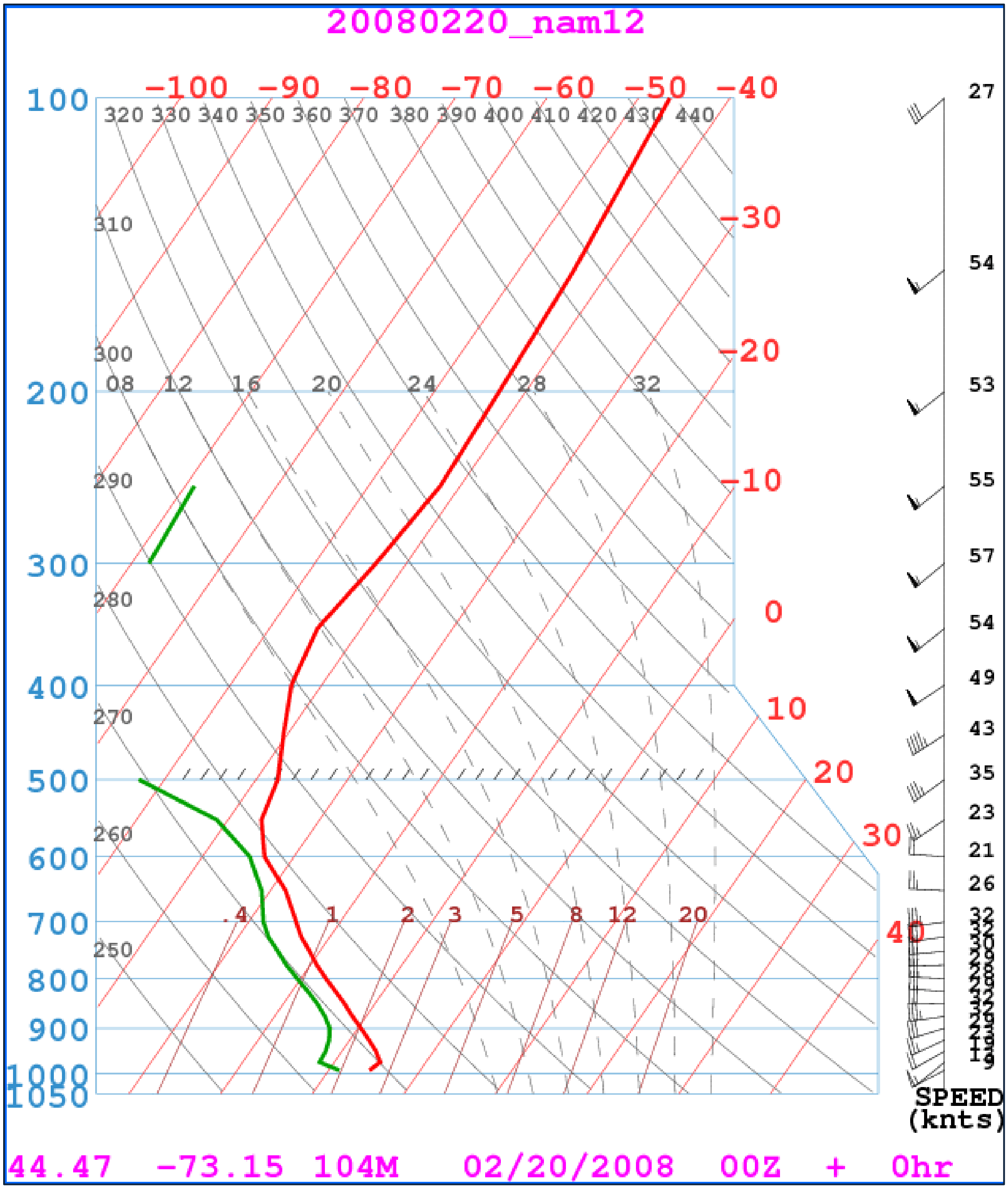

Figure 25. As in Fig. 21, except for 0-h forecast from 0000 UTC 20 February 2008, valid at 0000 UTC 20 February 2008 (NOAA ARL 2012).

viii) Froude Number Greater Than 2.0

Shown in Figs. 26 and 27, an example that falls into the category where the Froude number was greater than 2.0 would be the 3 January 2012 event. The Froude number during the event was 4.4. Note once again the lack of any isothermal layer or inversion. The snow amounts were fairly uniform across the higher elevations. For this case, N was equal to $2.555\,x\,10^{-3}s^{-1}$, and the U component of the wind was 14.77 ms^{-1}.

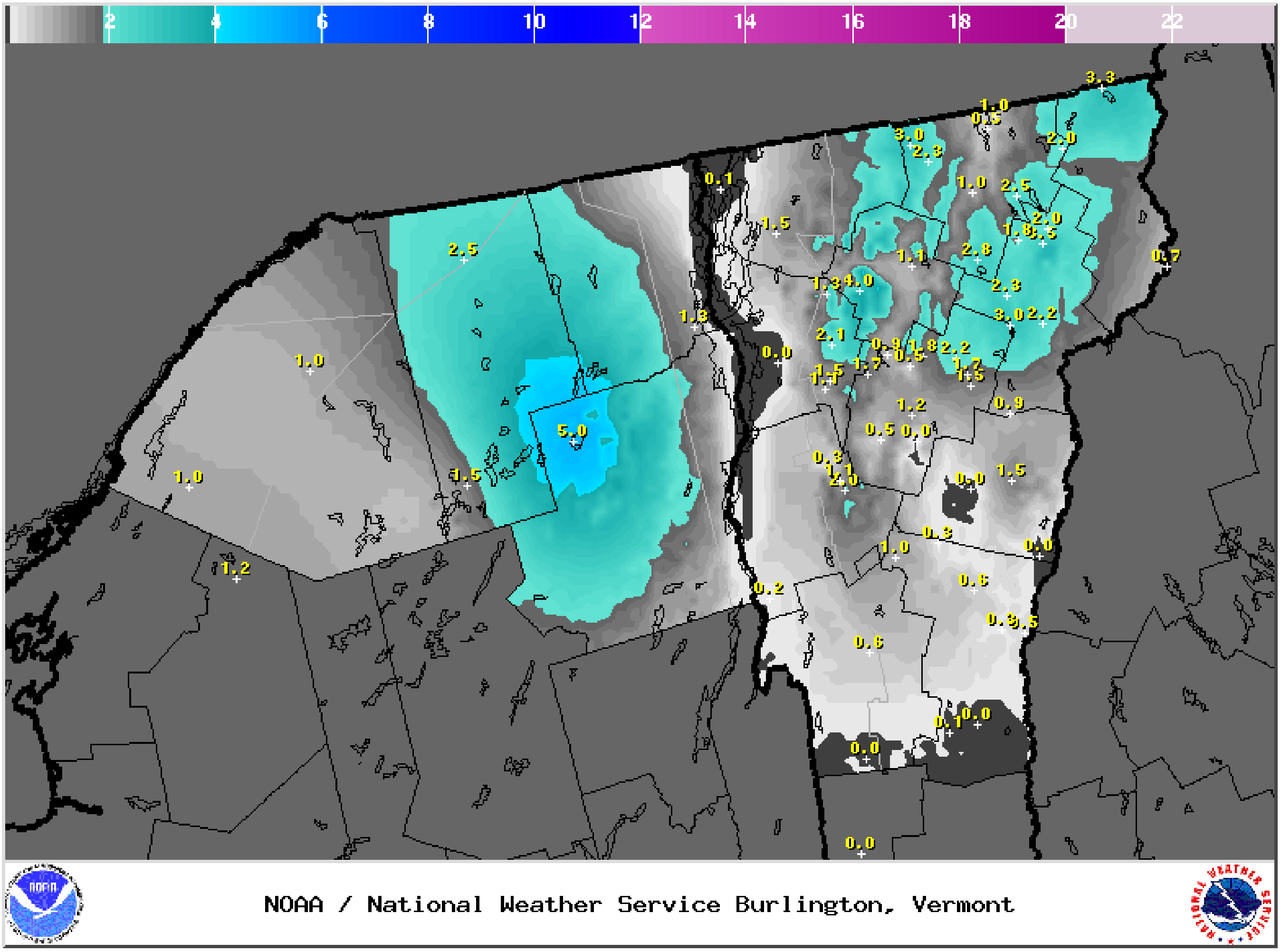

Figure 26. As in Fig. 4 except ending at 0700 EST 3 January 2012.

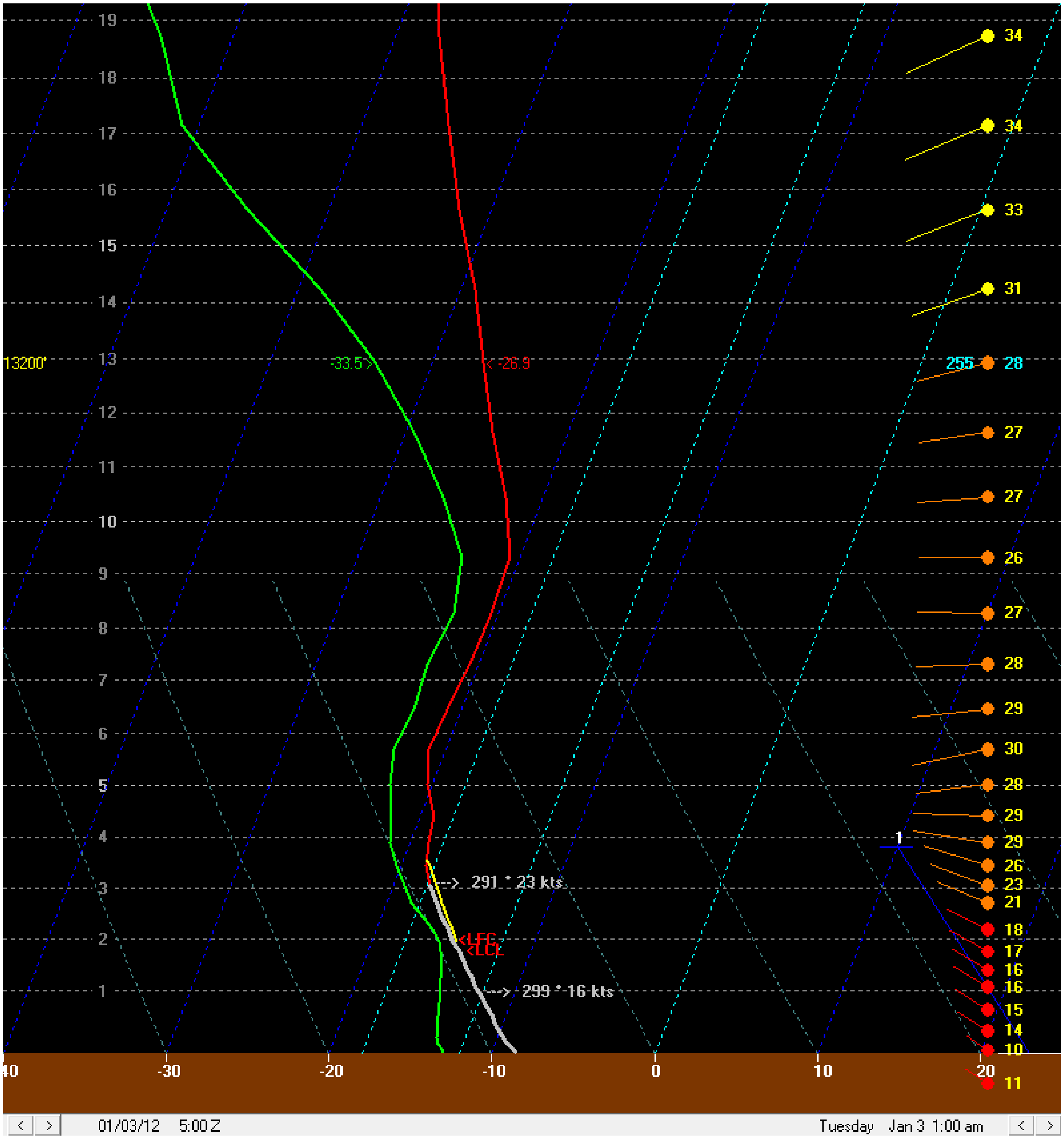

Figure 27. As in [Fig. 13](), except for a NAM 17-h forecast from 1200 UTC 2 January 2012 valid at 0500 UTC 3 January 2012.

c) Contrasting blocked vs. unblocked Cases

Through these 25 cases, there were very discernible features that separated *blocked* cases from *unblocked* cases. In addition to the Froude number itself, these included the low-level relative humidity, low level wind profiles, and stability. In blocked cases, NAM/RUC forecast soundings indicate that the Burlington (KBTV) sounding is more saturated with a surface average relative humidity of 86%, a 925-hPa average of 96%, and an 850-mb average of 99%. However in unblocked cases, the sounding is considerably drier, with a surface average relative humidity of 82%, a 925-hPa average of 89%, and an 850-mb average of 90%. At 700 hPa, there was a smaller difference between blocked and unblocked cases, but the area-wide snowfall mean increased as the 700-hPa average humidity increased (Fig. 28). In some cases this may be due to the “seeder-feeder” effect as discussed in Rutledge and Hobbs (1983) where ice particles from a “seeder” cloud grow as they fall through a lower-level “feeder” cloud, while in other cases it may simply be attributed to deeper moisture and vertical motion.

Wind direction and the vertical profile of low level winds are major factors in determining blocked versus unblocked cases. In the NAM/RUC forecast soundings for Burlington, in blocked cases, there is a distinct veering profile (usually indicative of warm air advection), with an average surface wind direction of 305 degrees (west-northwest), veering to 310 degrees (northwest) at 610 m (2000 ft), and 330 degrees (north-northwest) at 1220 m (4000 ft). An 850-hPa temperature and wind composite of the blocked cases shows warm air advection from the Gulf of Saint Lawrence in cyclonic northerly flow (Fig. 29). This was distinctly different than the unblocked cases, which featured very little directional shear with height, with 285 degrees (west-northwest) at the surface and 925 hPa, and 290 degrees (west-northwest) at 1220 m (4000 ft). Figure 30 shows cold air advection at 850 hPa in the composite mean for the unblocked cases. This veering profile is of increased importance in the Champlain Valley, where 100% of all warning criteria upslope snowfall occurred with veering blocked flow and 67% of all strongly veering blocked flow cases produced warning criteria snowfall.

The Froude number includes low level stability in its calculation, but it is generally accepted that the more stable the low level air mass is, the greater the blocking. The strongest blocked cases have an inversion well below mountain top, while the less blocked cases generally have an inversion or an isothermal layer near the mountain top, and the unblocked cases have no evidence of any isothermal layer or inversion and some are in fact well-mixed. This can be explained by the first law of thermodynamics. Greater stability would require more kinetic energy to overcome the greater work necessary to move the air up and over the mountains. When this kinetic energy is lacking (strength of the low level flow), the orographic blocking will occur. The Froude number can be expected to have a diurnal maximum and nocturnal minimum due to increased instability in the low levels during peak heating.

To summarize, characteristics of blocked flow include a Froude number less than 1, a nearly saturated KBTV sounding, a veering wind profile (generally west-northwest veering to north-northwest at 1220 m), and an inversion or isothermal layer near or below mountain-top. In most cases, this comes in the form of a geostrophic warm air advection regime, which occurs with veering flow, creating an isothermal stable layer which can induce the blockage of flow. Unblocked cases have a Froude number greater than 1, a drier KBTV sounding, very little directional shear (generally WNW throughout the sounding up to 1220 m), and a well-mixed boundary layer up to at least 1220 m).

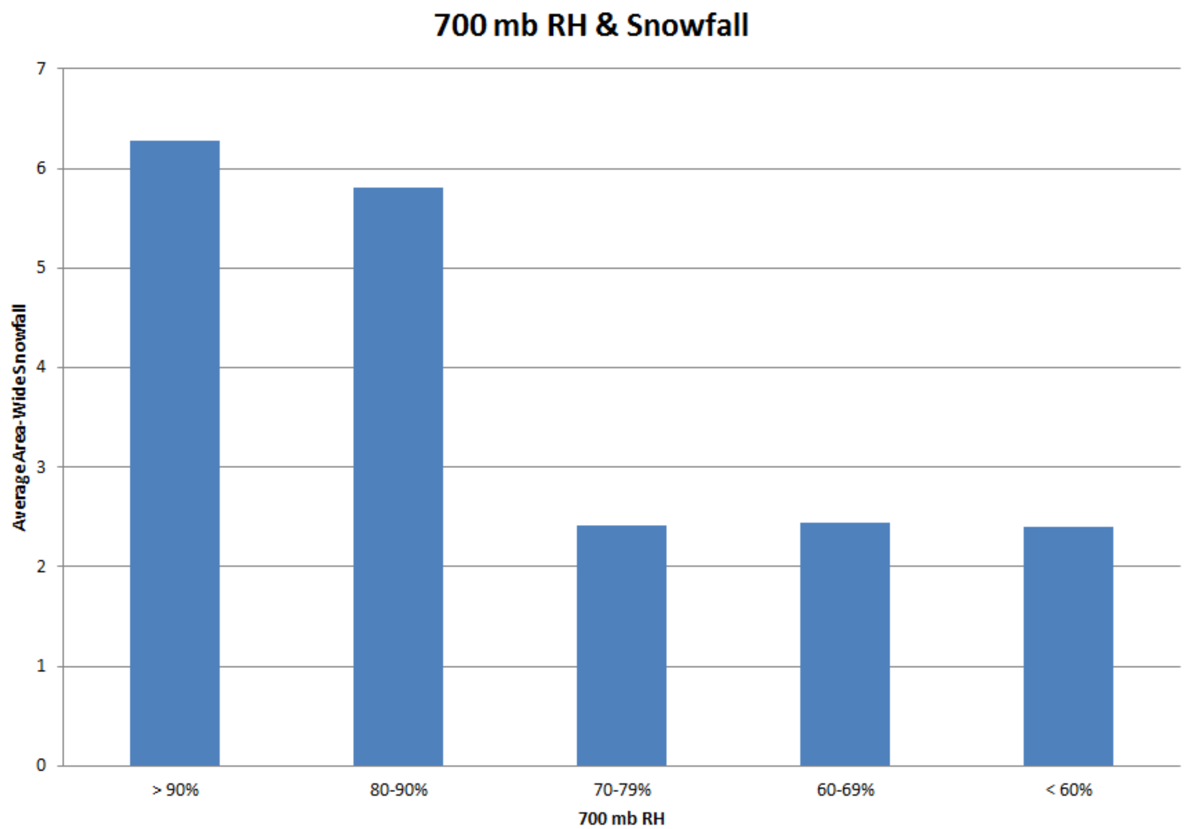

Figure 28. 700 hPa relative humidity values compared to average area-wide (11-site average) snowfall in upslope cases from 2007-2012.

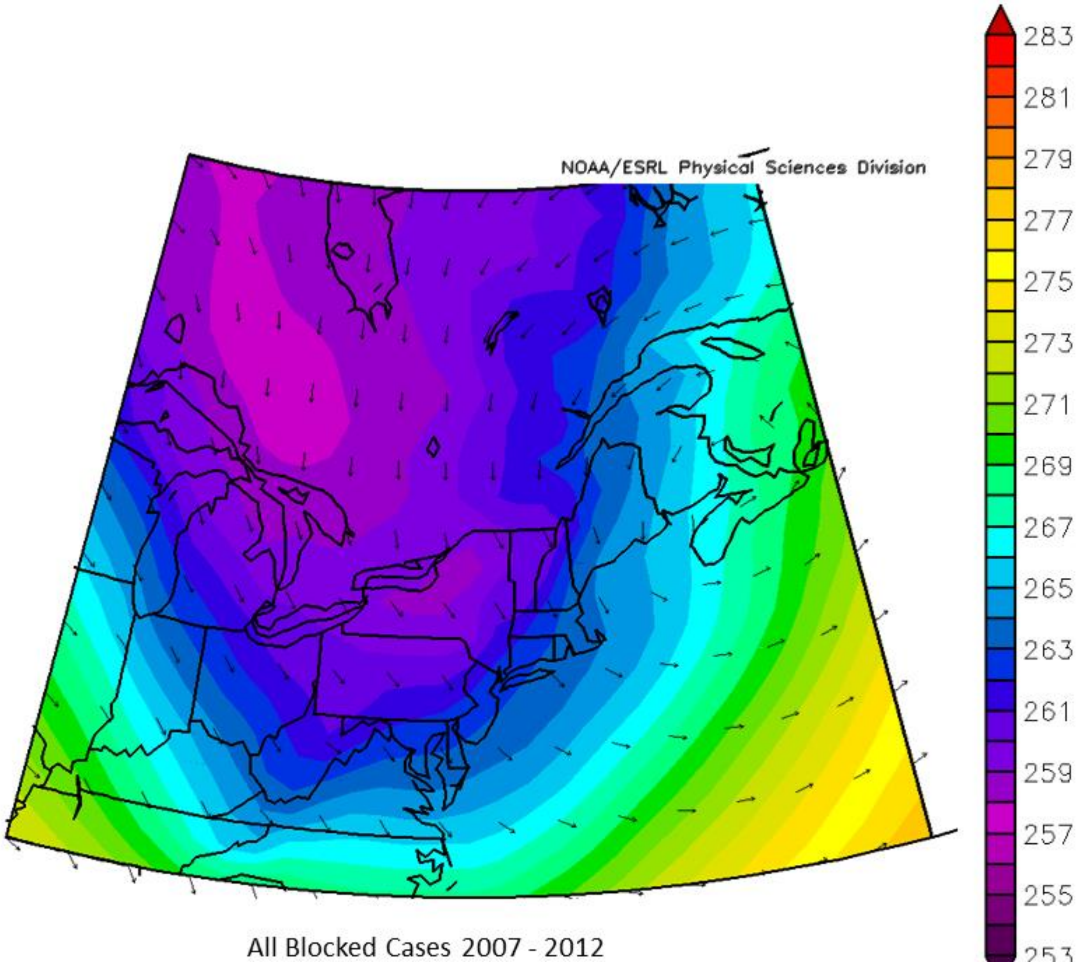

Figure 29. Composite mean 850-hPa vector wind (arrows ms^{-1}) and air temperature (color filled, °K) for blocked upslope snow cases between 2007 and 2012 (NOAA ESRL 2012).

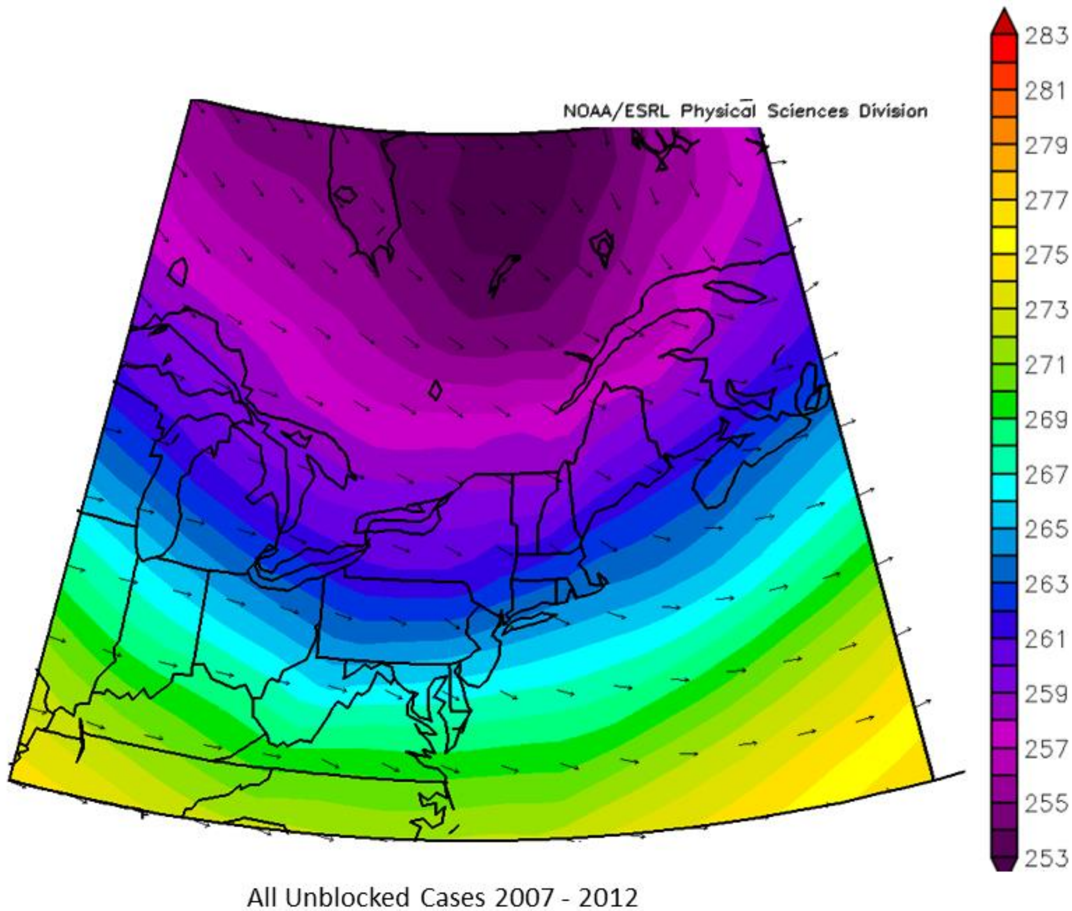

Figure 30. As in Fig. 29 except for unblocked upslope snow cases between 2007 and 2012 (NOAA ESRL 2012).

d) Three Types of Upslope Cases

This study has shown there are three main types of westerly flow upslope cases, with very different snowfall distributions. The first type is *unblocked* where the Froude number is above 1. In these cases, the spine of the Green Mountains and areas east such as Jay Peak, the towns immediately east of the spine (Waterbury and Stowe), and the higher terrain of northeastern Vermont are favored for the greatest snowfall. As an example, Figure 31 shows the composite snowfall distribution for all cases with Froude numbers greater than 1.

The second type is the *classic western slopes* upslope event where the spine of the Green Mountains and the western slope communities such as Underhill, Jericho, Richmond, Bolton, and South Lincoln are favored for heavy snowfall. This typically occurs when the Froude number falls between 0.5 and 1.0. Figure 32 shows the composite snowfall distribution for all cases with Froude numbers between 0.5 and 0.99.

The third type is somewhat rarer, where the flow is *strongly blocked* and the heaviest precipitation backs up into the Champlain Valley. Champlain Valley channeling and some lake enhancement is also believed to occur in these cases. This occurs when the Froude number is very low, generally less than 0.5. Figure 33 shows the composite snowfall distribution for all cases with Froude numbers less than 0.5.

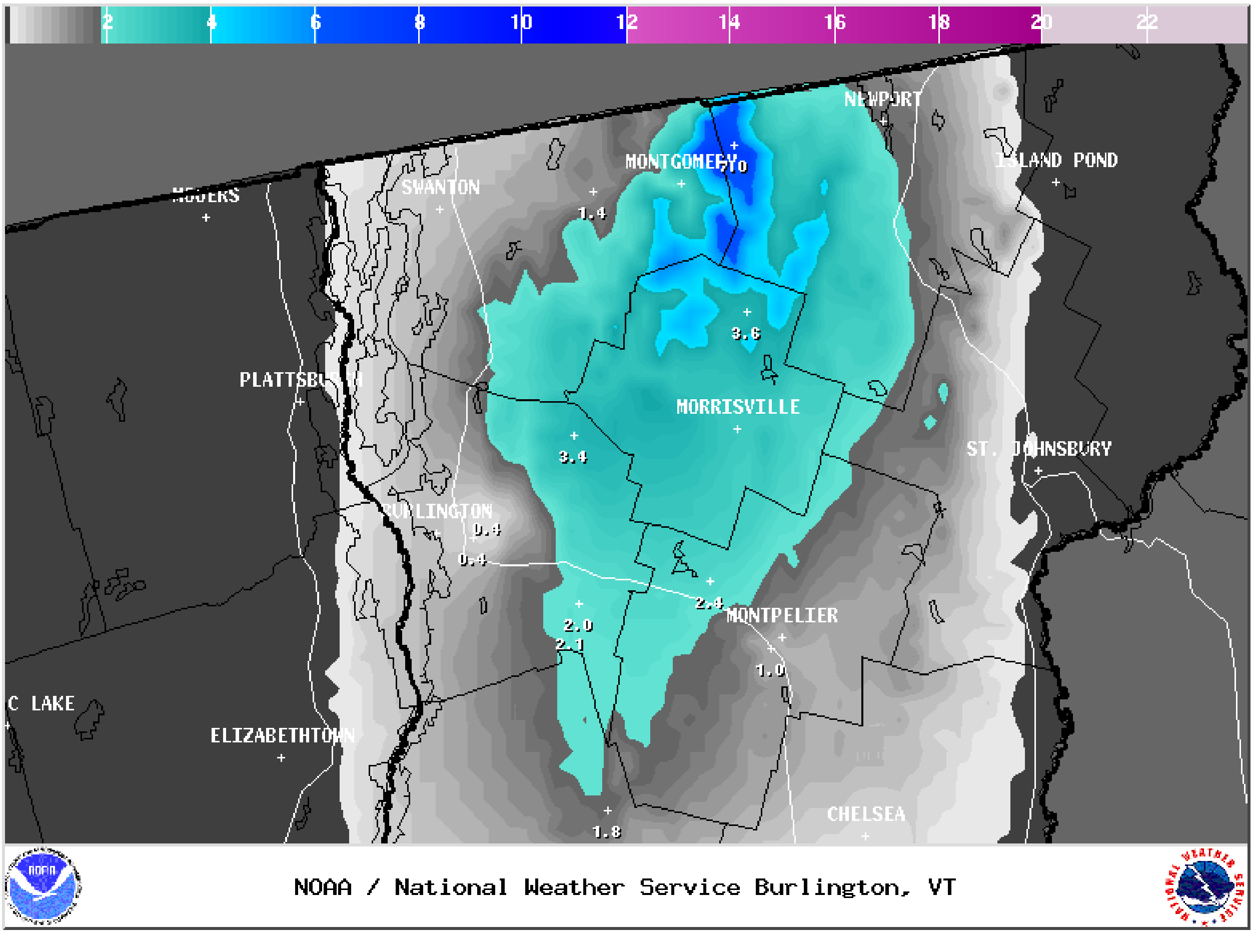

Figure 31. Composite snowfall distribution (color filled, in) for cases with a Froude number greater than 1.

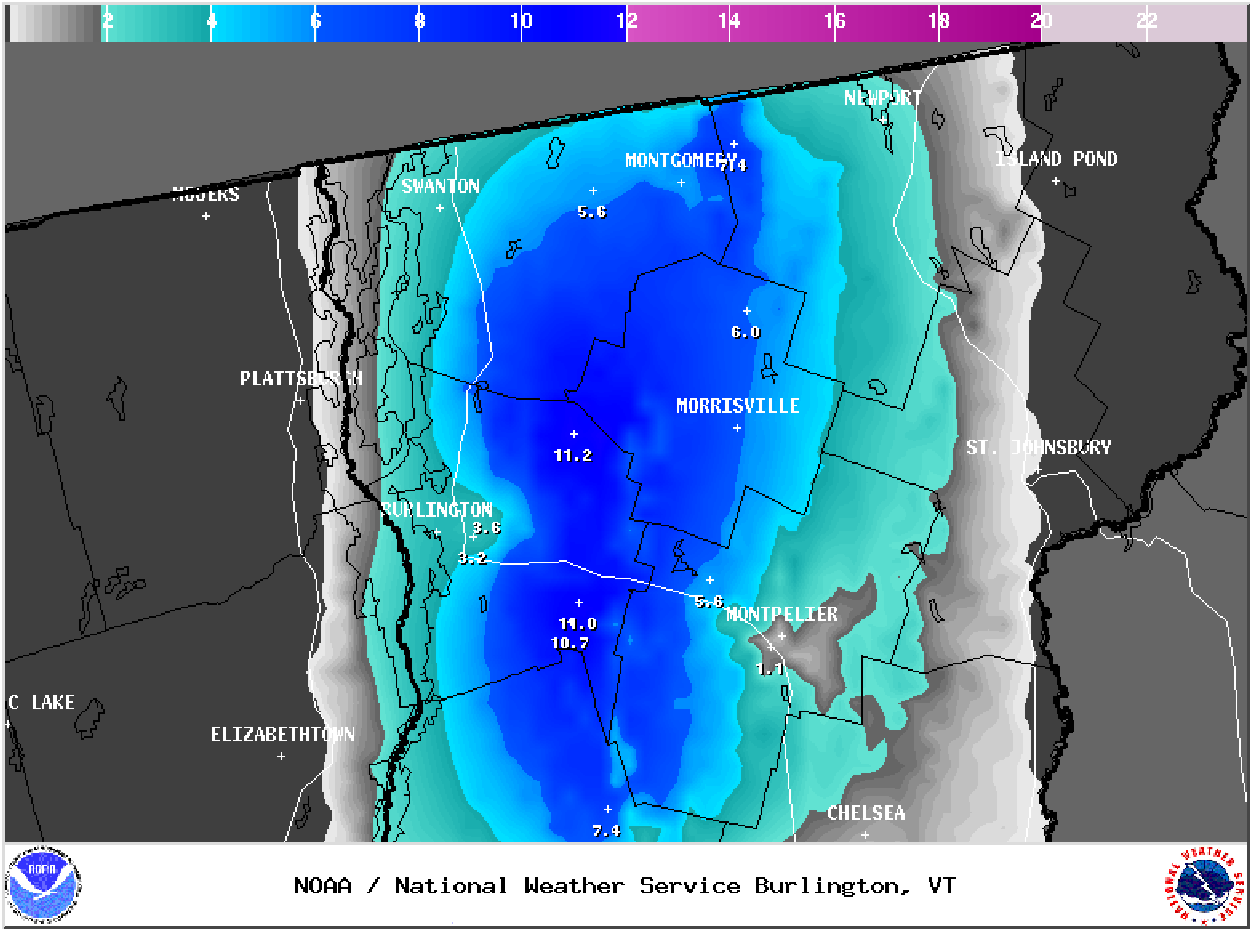

Figure 32. As in Fig. 31, except for cases with a Froude Number between 0.5 and 1.

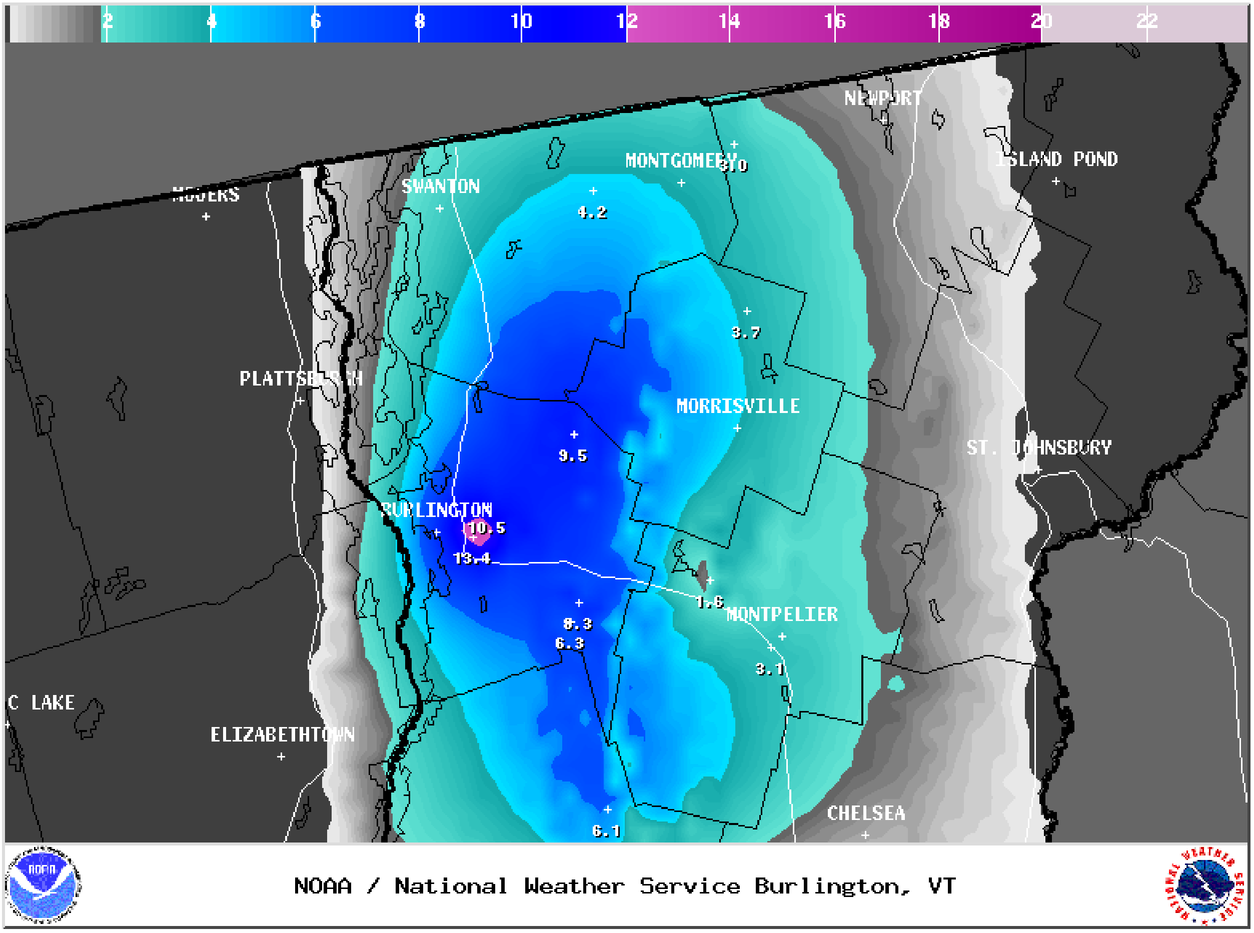

Figure 33. As in Fig. 31, except for cases with a Froude Number less than 0.5.

e) Most favorable scenarios

i) Champlain Valley (Burlington/Essex)

Through this study, it has been shown that a set of most favorable conditions exists where the Champlain Valley will be favored for heavy upslope snowfall. These conditions include a Froude number less than 1, and especially less than 0.5. The composite wind profile features a west-northwest surface wind veering to north-northwest at 1220 m. There must be a strong inversion below mountain-top and a well-saturated forecast sounding (greater than 85% at the surface, and greater 95% at 925 hPa and 850 hPa). Moist conditions at 700-hPa will also lead to heavier snowfall. The prime example for such a scenario is the 3 January 2010 case with a Froude number of 0.07 (Fig. 13).

ii) Western Slopes (Underhill, Jericho, Richmond, Bolton, South Lincoln)

It has been shown that a set of most favorable conditions exists where the western slopes will be favored for heavy upslope snowfall. These conditions include a Froude number less than 1, and especially between 0.5 and 0.99. The wind profile features a west-northwest surface wind veering to northwest at 1220 m. There must be an isothermal layer or inversion near mountain-top as well as a well-saturated forecast sounding (greater than 85% at the surface, and greater than 90% at 925 hPa and 850 hPa). Moist conditions at 700 hPa will also lead to heavier snowfall. The prime example for such a scenario is 7 December 2010 case with a Froude number of 0.98 (Fig. 19).

iii) Eastern Slopes (Jay Peak, Waterbury, Stowe)

It has been shown that a set of most favorable conditions exists where the eastern slopes will be favored for heavy upslope snowfall. These conditions include a Froude number near or slightly greater than 1, most favorable between 0.85 and 1.75. The wind profile features a westerly surface wind slightly veering to west-northwest at 1220 m. There must be no presence of a due north wind at any level in the lower 1220 m, as 0% of warning-criteria snow at Jay Peak has featured a north wind (greater than 340 degrees). There does not need to be an isothermal layer or an inversion near mountain-top, and in most cases, this would reduce snowfall on the eastern slopes. A much less saturated KBTV forecast sounding is favored (greater than 80% at the surface, and greater than 85% at 925 hPa and 850 hPa). Moist conditions at 700 hPa will also lead to heavier snowfall. An example for such a scenario is the 1 February 2010 case with a Froude number of 1.07 (Fig. 34).

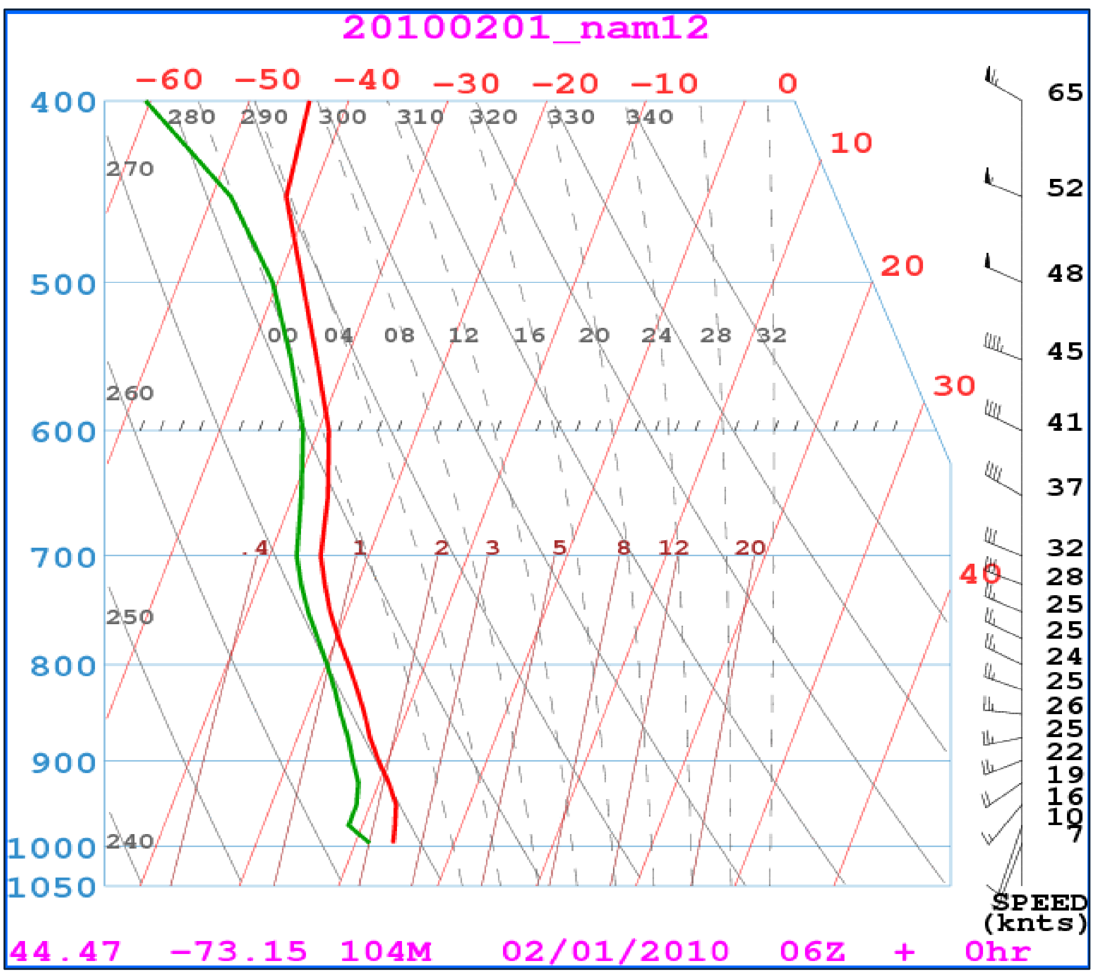

Figure 34. As in Fig. 21, except for 0-h forecast from 0600 UTC 1 February 2010, valid at 0600 UTC 1 February 2010 (NOAA ARL 2012).

4. Conclusions

Leading up to or during an orographic snowfall event, there are many things that can disrupt a well-intentioned forecast. This paper, along with others, has shown the utility of using the Froude number to improve orographic snow forecasts. Several other factors were found to affect the Froude number as well as the orientation and intensity of the orographic snow bands. Lapse rates (stability) have a significant effect, as steepening lapse rates will increase the Froude number, thus decreasing the prospect for blocked flow. The Froude number will also likely experience a maximum in the afternoon before decreasing at night with increasing static stability. Wind direction and its subtle changes are also important. A more northerly component and increased veering will increase snowfall in the Champlain Valley, while stronger westerly winds favor the Green Mountain spine and its western slopes. Increasing relative humidity at 850 hPa and 700 hPa will likely increase snow amounts, while a sharp decrease will end the upslope event more quickly.

This paper has found a distinct correlation between the Froude number and distribution of snowfall in upslope snow events. As the Froude number increases, the amount of low level blocking in the flow by terrain decreases, and the orographic precipitation can flow freely across and over the terrain. This was seen in cases where the Froude numbers were greater than 1. As the Froude number decreases, the low level blocking increases and precipitation will begin to intensify along the terrain or back-build into the lower elevations upstream of the terrain. For cases where the Froude number was between 0.5 and 1, the heaviest snow fell along the western slopes of the Green Mountains, and for cases where the Froude number was less than 0.5, the heaviest snow fell in the Champlain Valley as well as along the western slopes of the Green Mountains.

The findings of this paper have already been incorporated into daily operations at WFO Burlington, and it has been found that the forecast Froude numbers from operational numerical weather prediction models (NAM, GFS, WRF) can be a vital forecast decision aid for forecasters presented with the problem of forecasting snowfall associated with an orographic upslope flow. To calculate the forecast Froude numbers WFO Burlington uses an Advanced Weather Information Processing System, Graphical Forecast Editor smart tool, which is available upon request from the office.

5. Future Work

Additional work with the Froude number may include downslope and gap wind flows and their correlation to high wind events. The same type of study can also be applied to rainfall distribution. The Froude number may also be a helpful tool in aviation forecasting and the development or continuation of low ceilings along a mountain chain.

Acknowledgments

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