COLD SEASON OROGRAPHICALLY-GENERATED SNOWBANDS IN SOUTHERN MONTANA

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1. Introduction

From fall to spring, isolated mountain ranges in southern Montana generate or enhance snowbands that may persist for several hours across western and central portions of the County Warning Area (CWA) of the Billings Weather Forecast Office. These snowbands can increase snowfall totals by several inches locally, resulting in significant impacts not only to Montana's largest and most populated metropolitan area (Billings), but to major trade routes such as Interstates 90 and 94 in southern Montana. From December 2008 to January 2012, no fewer than 11 of these orographically-generated snowbands formed, resulting in significant Decision Support Services (DSS) and customer impacts. These impacts included, but were not limited to, vehicle slide-offs during the morning and evening commutes in and around Billings and delays for both inbound and outbound flights at Logan International Airport in Billings. The purpose of this Technical Attachment (TA) is to enable forecasters to better recognize, understand and forecast the causes, evolution and variability of orographically-generated snowbands so snowfall forecasts and DSS may be improved.

2. Geographical Features and Flow Perturbations

Several isolated area mountain ranges aid in the generation of snowbands in southern Montana. These mountain ranges include the Little Belt Mountains, the Big Snowy Mountains, the Crazy Mountains and the Pryor Mountains (Figure 1). All of these mountain ranges rise more than 1000 meters (m) above the surrounding plains. The Little Belt Mountains and Big Snowy Mountains are oriented west to east, with some individual peaks that rise to more than 2500 m above sea level (ASL). Oriented north to south, the Crazy Mountains have several individual peaks that rise to the 2500 m to 3400 m ASL range. Finally, the Pryor Mountains are comprised of two high plateaus that rise above 2500 m ASL and are connected by an elevated valley region.

Each of these mountain ranges act independently to perturb low- to mid-level flow and to help influence the evolution of snowbands. There are three types of flow perturbations that may generate snowbands downstream of the mountains, provided that several other tropospheric conditions are favorable.

a. Unstable

The first type of flow perturbation is flow over the mountains. This is most likely to occur when the mountains do not rise very high when compared with the surrounding plains or when the mountains are tall and the atmosphere is unstable. If wind velocities increase with height, the mean flow velocity may transition from subcritical (where the Froude number – the ratio of inertial flow to gravity – is less than 1) to supercritical (where the Froude number is greater than 1), sparking gravity wave breaking (Smith, 1985; Durran, 1986b). Wind velocities of approximately 35 knots have been found to be sufficient for this gravity wave breaking process to occur (Schär and Durran, 1997). Gravity waves will then accelerate rapidly down the leeward side of the mountains. Due to the quick descent down the mountains, a conversion of potential to kinetic energy causes the air to warm rapidly. The gravity waves will then propagate downstream as disturbances (local instability maxima) and may be detected and tracked within the potential temperature and small-scale wind fields. At the same time, the acceleration of the air flowing down the mountains generates an ageostrophic circulation that increases upward vertical motion downstream of the mountains. Figure 2 (left two panels) shows a “flow over” scenario.

b. Stable

The second type of flow perturbation, flow around the mountains, is favored when the mountains rise high above the surrounding plains and/or the lower atmosphere is very stable. When the atmosphere is very stable, acceleration of an air parcel is towards its initial position, thus the parcel oscillates vertically. In such a case, $N^2 > 0$ and the frequency of oscillation is given by N (the Brunt-Väisälä frequency). Also, Smolarkiewicz and Rotunno (1989a) found that mountain-induced flow perturbations vary substantially as a function of normalized height NH/U (where N is the Brunt-Väisälä frequency, H is the maximum height of the mountains and U is the cross-mountains wind speed). Air is forced to separate and flow around the mountains when NH/U = 3. As a result of the separation of the flow around the mountains and subsequent downstream convergence, vortex couplets are generated and continue to propagate downstream many tens of kilometers before dissipating. Due to fluctuations in upstream winds and the strength/orientation of the couplets themselves, the convergent line may oscillate from side to side. Figure 2 (right two panels) illustrates a “flow around” scenario.

c. Combination

The third type of flow perturbation is a combination of flow over and around the mountains. Flow in this scenario is complex with the potential for warm core disturbances caused by the flow over the mountains combining with vortex couplets. They will then propagate along a line of convergence downstream from the mountains. “Combination flow” scenario snowband events are difficult to identify and occur somewhat infrequently, thus an example is not included in this TA.

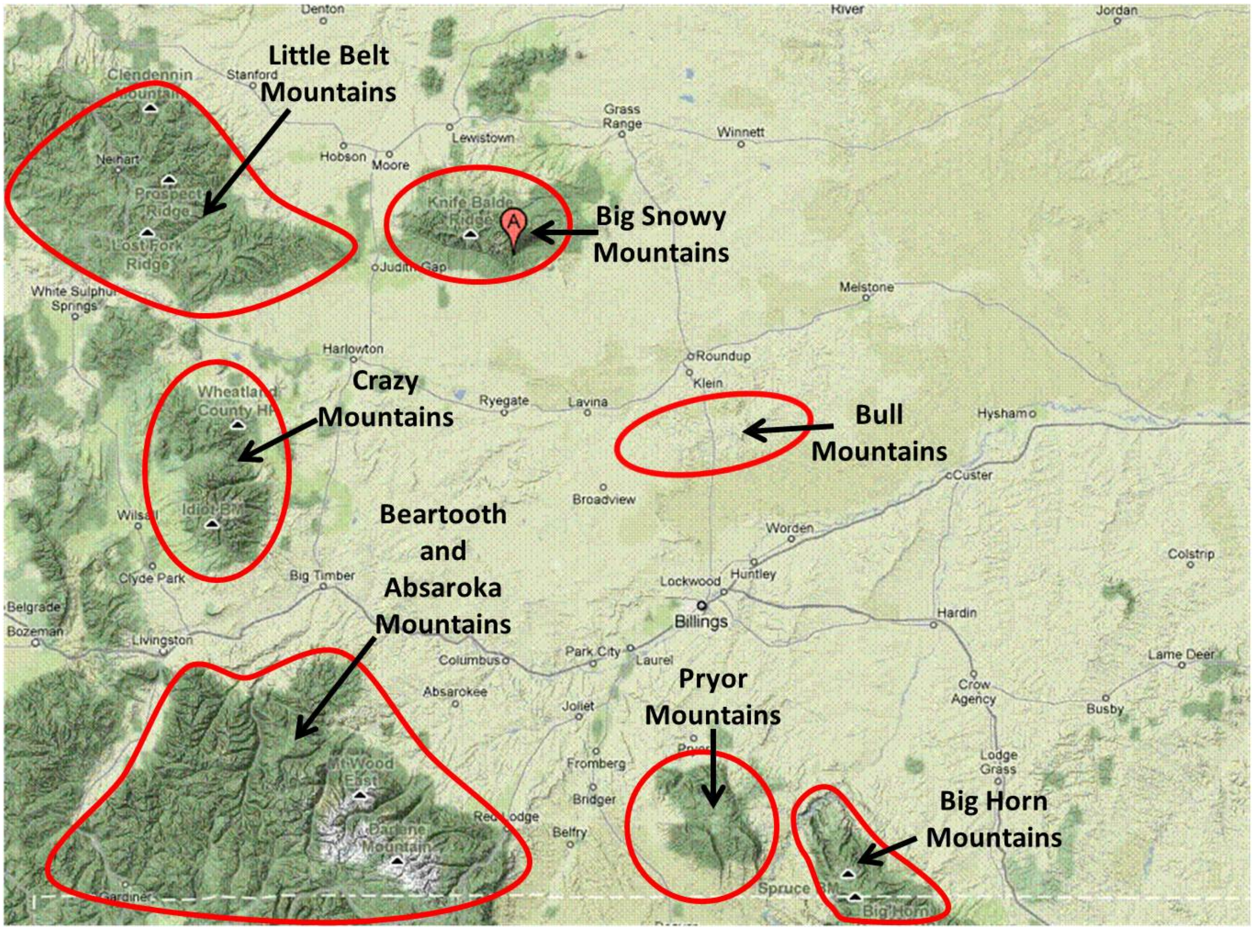


Figure 1: Mountain ranges (identified in red) in central and southeastern Montana that generate or enhance snowbands

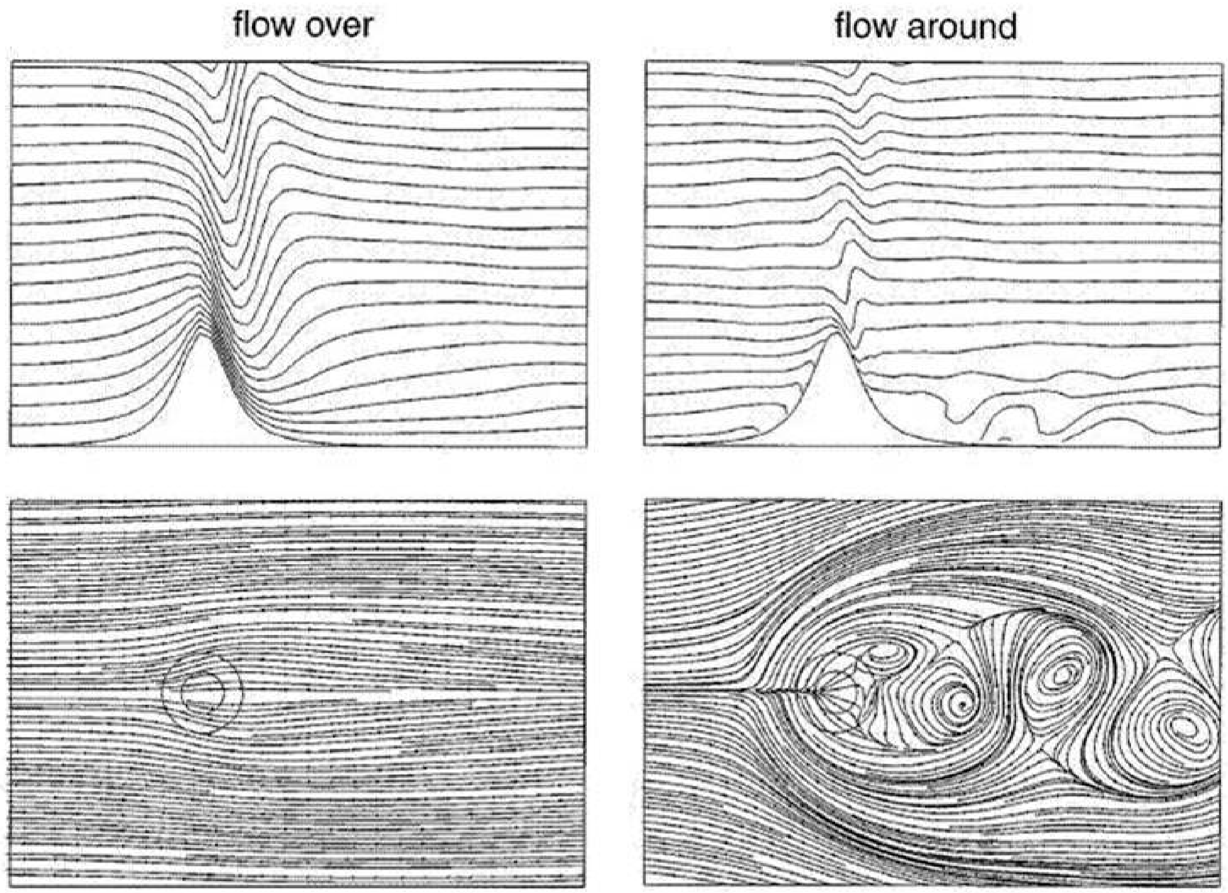


Figure 2: Illustration of "flow over" and "flow around" scenarios for dimensionless mountain heights of 1 (left panels) and 3 (right panels) from numerical model simulations. Top panels show isolines of potential temperature in a vertical cross-section through a mountain parallel to the upstream flow. Bottom panels show the instantaneous surface streamlines; flow is from left to right. Adapted from Schär and Durran (1997).

3. Upper-Level Pattern

A mean composite upper-level analysis, which included 11 days from December 2008 to January 2012 during which orographically-generated snowbands occurred, was completed for this TA. The analysis yielded information highlighted in Table 1.

Days used in the composite analysis	
2 December 2008	13 December 2008
26 March 2009	1 December 2009
5 December 2009	23 December 2009
6 May 2010	19 January 2011
22 January 2011	25 October 2011
27 January 2012	

Table 1: Days used in the composite analysis.

An analysis of upper level composite charts for the days on which orographically-generated snowbands occurred revealed a fairly sharp trough across the Pacific Northwest/Northern Rockies region. Mean vector winds were northwesterly, allowing winds to interact with and be perturbed by the mountains across central and southern Montana. It can be inferred by comparing mean vector wind composites to mean temperature composites that cold air advection was occurring (and baroclinicity was being generated) at all levels across Montana during the peak of these orographically-generated snowband events. In the mid and low levels, the atmosphere was quite moist with mean composite relative humidity greater than 70% across much of the eastern two-thirds of Montana, extending upstream into southern Canada. These high relative humidity values signified that the atmosphere at and below mountain-top level in and around the Billings CWA was favorable for cloud development and, potentially, snowflake growth. The 700 mb composite image (Figure 3) illustrates many of the important features just discussed.

A few of the orographic snowband events identified since 2008 within the Billings CWA were characterized by north to northwest winds up to 40 kts in the low- to mid-levels. These strong winds enabled the snowbands to extend far downstream, into Wyoming. When determining the likelihood of orographic snowbands, a forecaster should account for speed and directional differences between the winds in the low-levels and the mid-levels. Large differences in wind speed and direction can act to break up snowbands or not allow them to fully form due to shear processes.

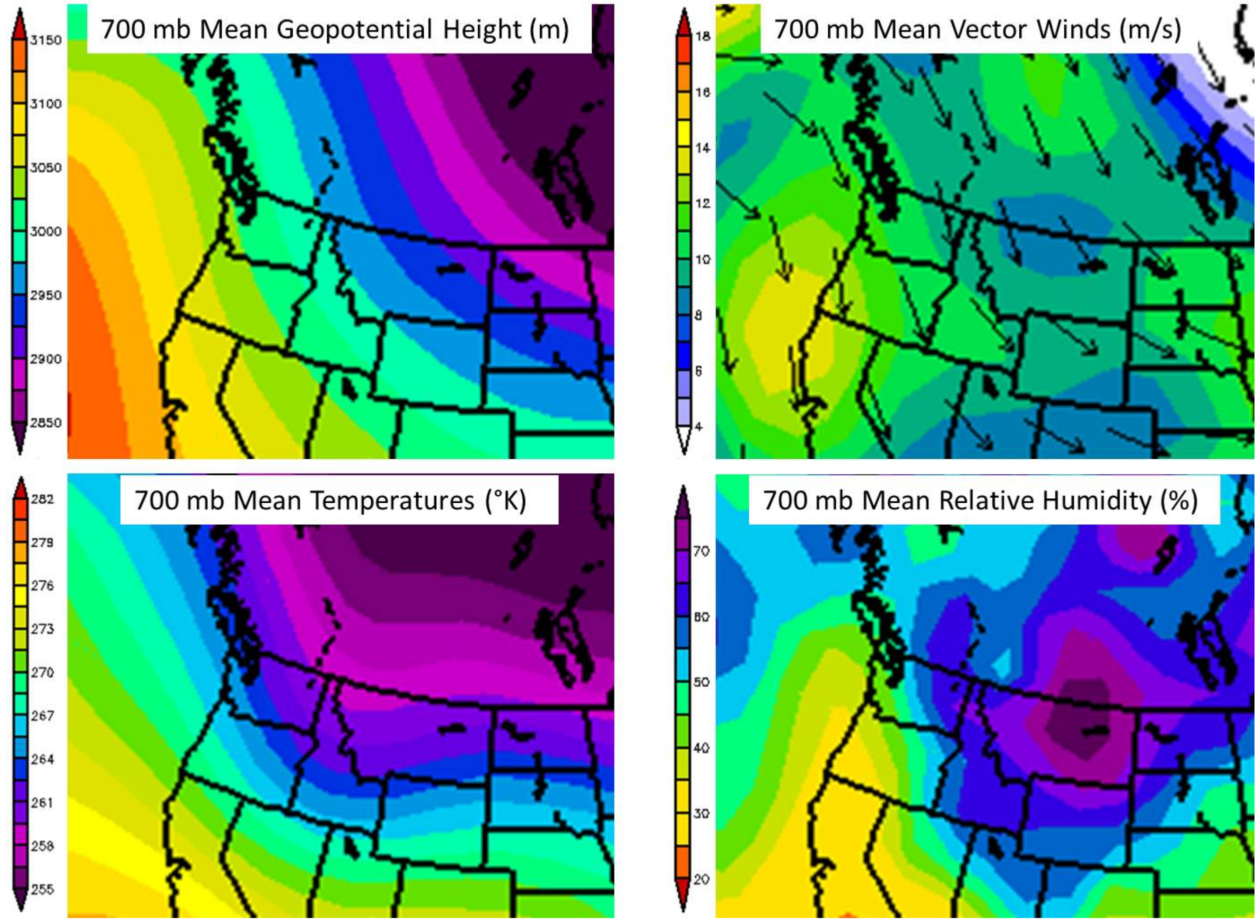


Figure 3: NCEP/NCAR Reanalysis 700 mb composite images for 11 orographically-generated snowband events from 2008 - 2012.

4. Examples of Orographically-Generated Snowbands in the Billings CWA

a. Example 1 (1 December 2009) – Unstable Type

During the early morning of 1 December 2009, enhancement to snowfall in the Billings metropolitan area occurred as a result of an orographically-generated snowband behind a cold front. There were likely several orographically-generated snowbands during this event downstream of area mountains, but this example focuses on the short-lived snowband downstream of the Big Snowy Mountains, as it was easily observed using the KBLX (Billings) WSR-88D Doppler weather radar. This particular snowband, an example of a snowband that develops when the atmosphere is unstable, developed shortly after 1200 UTC on 1 December 2009 and ended shortly before 1500 UTC on the same day. Despite the short timescale, this snowband did have DSS ramifications – it was at its peak just before and during the morning commute, thus there were several reported vehicle accidents in Billings that were attributed to the snow that was falling and the snow and ice that had accumulated on area roads.

The Great Falls (TFX) sounding provides a good surrogate to assess the airmass upstream of the Billings CWA. An analysis of the 1200 UTC Great Falls (TFX) upper air sounding on 1 December 2009 (Figure 4) revealed that the low- and mid-levels were unstable, with a small amount of CAPE and no mid-level capping inversion. Dewpoint depressions were less than 3°C (i.e. the atmosphere was moist) extending from the surface through the dendritic growth zone, which was located between 850 mb and 700 mb, up to nearly the 500 mb level. Measured sustained winds were also somewhat uniform in the low- to mid-levels, from a north-northeasterly to northwesterly direction at 15 to 25 kts below the 650 mb layer.

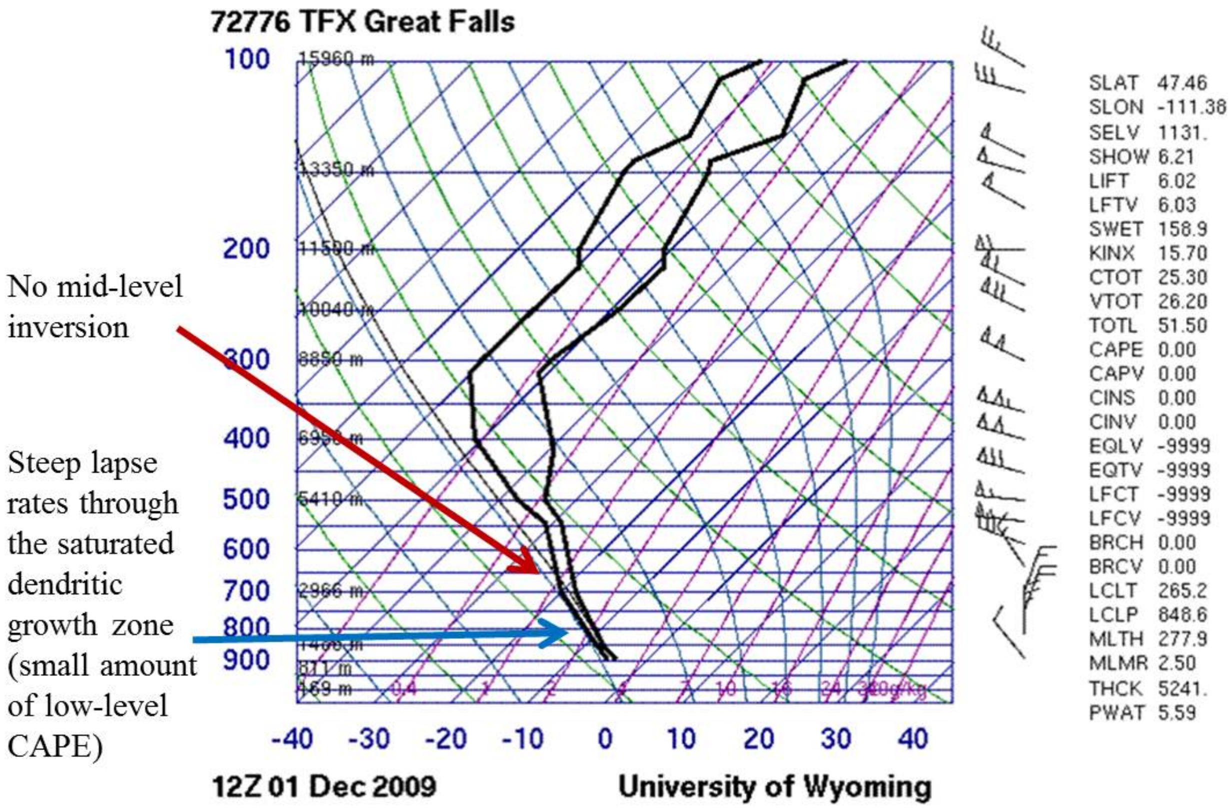


Figure 4: Atmospheric sounding from 1200 UTC 1 December 2009 from TFX, upstream of the Billings CWA. This is an example of an unstable sounding (indicated by the lack of a mid-level inversion and steep lapse rates in the low- and mid-levels) on a day during which orographically-generated snowbands were observed in the Billings CWA. Other important features include the saturation through the dendritic growth zone and the uniformity of the low- to mid-level winds.

During the evolution of an orographically-generated snowband, surface observations can provide valuable information about the state of the low-levels and impacts that the snow may be causing. Reviewing several hours of surface observations (or even just the most recent observation) can reveal important data such as where the strongest low-level convergence is, how heavy the snow is and how much the visibility is being reduced as a result of the snow.

At 1200 UTC on 1 December 2009, MesoWest observations showed areas of low-level convergence south of both the Crazy Mountains and the Big Snowy Mountains, with maximum low-level convergence occurring directly over Billings (Figure 5). Flow over the Bull Mountains (see Figure 1) appears to accelerate down the slope and turn anticyclonically into Billings, increasing the low level convergence in the region.

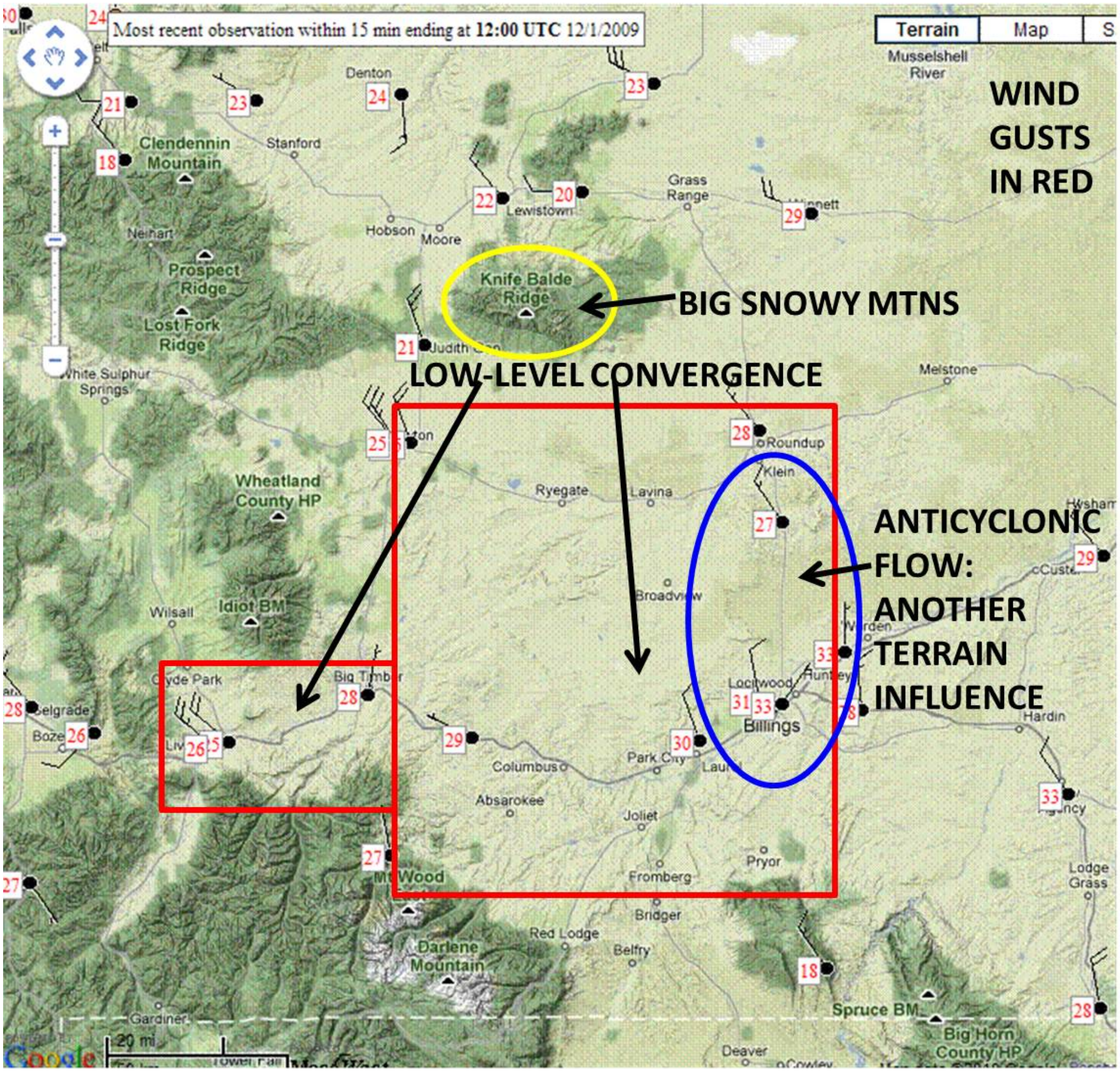


Figure 5: MesoWest surface observations at 1200 UTC on 1 December 2009. Areas of low-level/surface convergence are highlighted in the red boxes. The area inside the blue oval shows anti-cyclonic flow enhancing the low-level/surface convergence directly over Billings.

Doppler weather radar data is useful when watching the evolution of an orographically-generated snowband. Base reflectivity and base velocity data in Volume Control Patterns (VCPs) 31 and 32 are particularly helpful, especially in the lowest few volume scans. A major challenge with using VCPs 31 or 32, though, is that because the mountain ranges that generate these snowbands are well over 40 km from the radar, the bands may not be well-sampled by the radar.

Dual-polarization (dual-pol) radar products also provide beneficial information, such as the type of snow within a snowband. Typically, dry snow, as indicated by ZDR, KDP and CC, will have the potential to accumulate faster than wet snow, especially if the ground temperature is below freezing. Thus, if dual-pol radar products indicate that a snowband contains dry snow, a forecaster may be able to account for potentially higher snow accumulations when updating the forecast.

In this case, Doppler weather radar showed a band of moderate to heavy snow just behind the cold front (from Billings south), but just northwest of Billings, there is evidence of an orographically-generated snowband. This is easily seen on both the 0.5° elevation angle base reflectivity and 0.5° elevation angle base velocity images at 1318 and 1347 UTC on 1 December 2009 (Figure 6). On the base reflectivity products, this band appeared as a thin area of enhanced reflectivity values that extended back towards the Big Snowy Mountains, northwest of Billings. A thin line of convergent flow northwest of Billings, but downstream of the Big Snowy Mountains was observed in base velocity data. This thin band of convergent flow downstream of the Big Snowy Mountains, which appears as inbound winds less than 5 kts (with some embedded outbound values near 5 kts) corresponded very well with the region of enhanced values observed in base reflectivity products. It is typical to observe that the maximum convergence approaches far downstream from the Big Snowy Mountains. When considering that surface winds in the region were gusting to about 30 kts and winds in the 850 to 650 mb layer were sustained in the 25 to 35 kt range (as observed in base velocity products), the zone of maximum convergence should have started approximately 25 to 35 km downstream, and continued for many kilometers beyond that, which would place it right where it was observed.

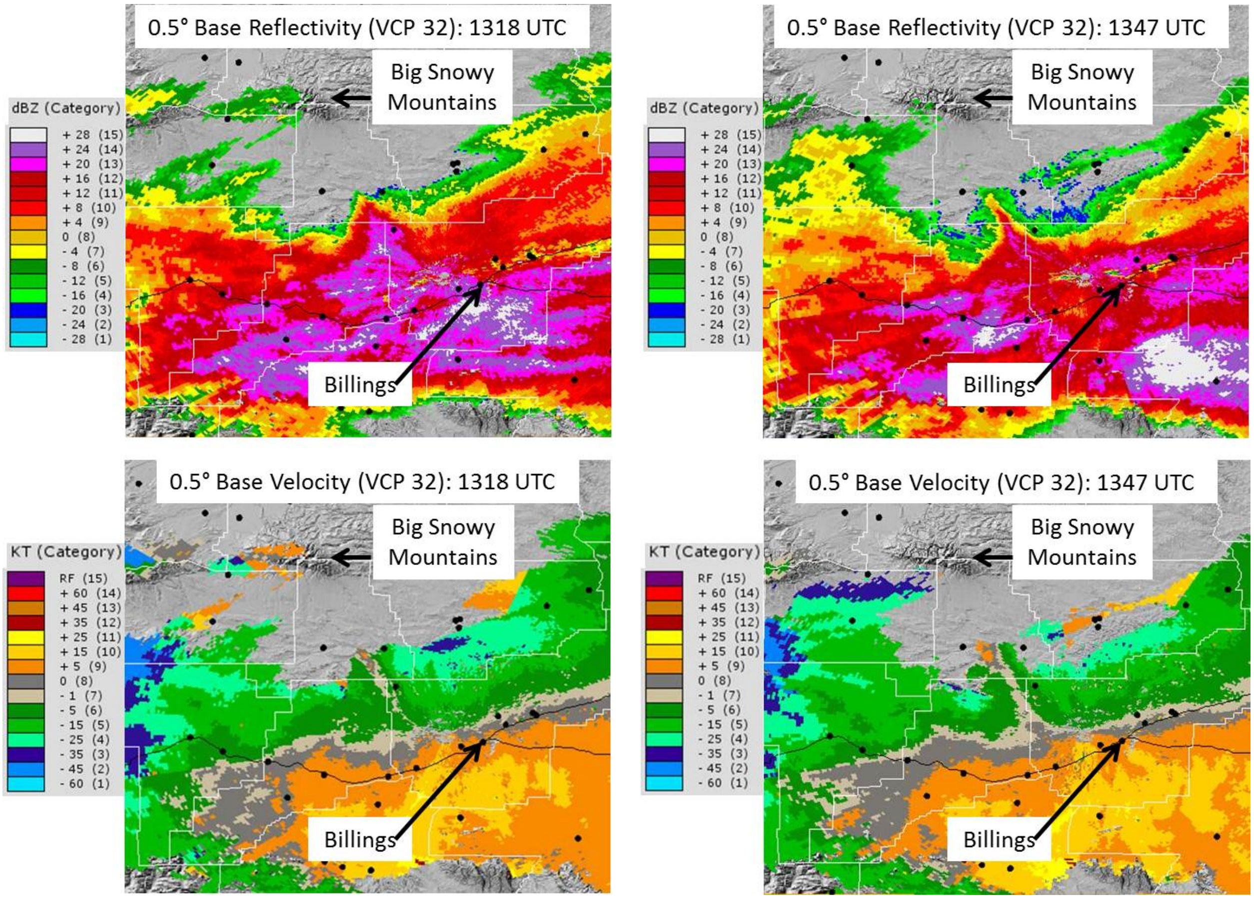


Figure 6: 1 December 2009 KBLX WSR-88D Images overlaid on a topographical map; 0.5° elevation angle base reflectivity images are on the top, while corresponding 0.5° elevation angle base velocity images are on the bottom. The black dots represent cities and towns. The Big Snowy Mountains and the city of Billings are highlighted by the arrows.

This snowband resulted in localized 1.27 to 2.54 cm (0.5 inches to 1 inch) snow accumulations across central and western portions of Billings (Figure 7). Heavier snow amounts were reported by Cooperative Weather (COOP) observers, Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) observers and storm spotters south and southeast of the Crazy Mountains, where upslope flow likely enhanced snowfall rates, durations, and accumulations.

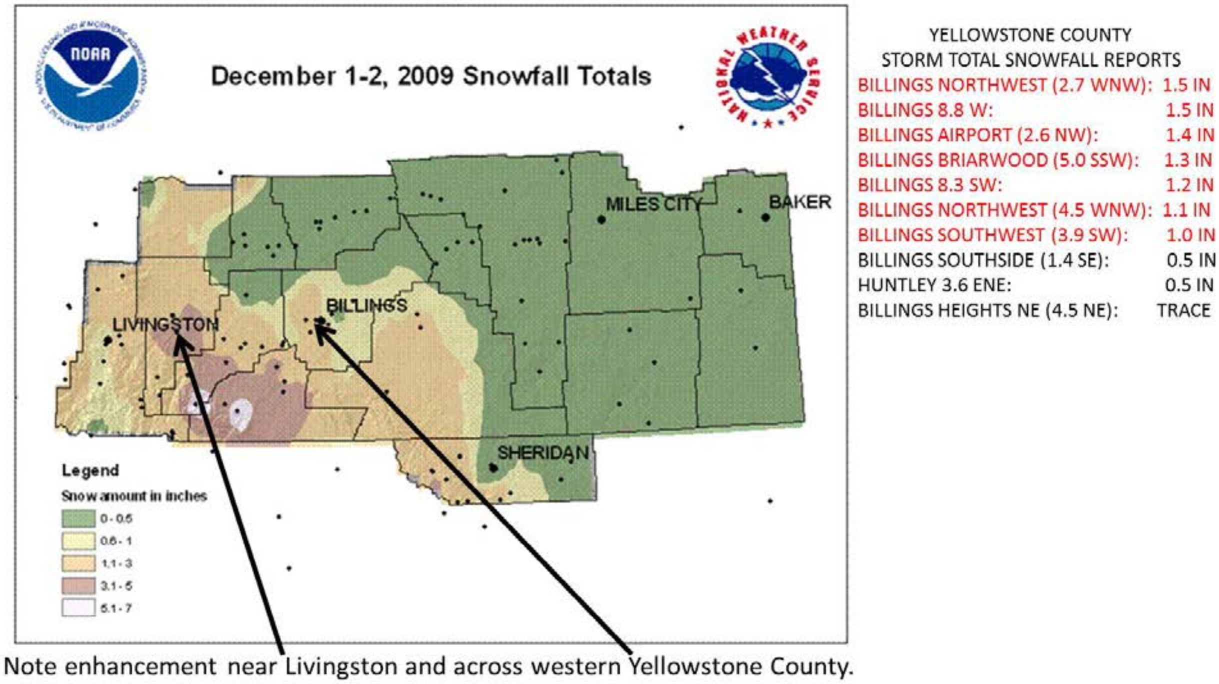


Figure 7: Snowfall totals from the 1 December 2009 orographic snowband event.

b. Example 2 (23 December 2009) – Stable Type

During the day on 23 December 2009, enhancement to snowfall in the Billings metropolitan area occurred as a result of an orographically-generated snowband. Like the 1 December 2009 snowband event, another snowband may have developed downstream of the Crazy Mountains, but due to the lack of radar data in that region, this example focuses on the long-lived snowband downstream of the Big Snowy Mountains, as it was easily observed using the KBLX radar. This snowband, an example of a snowband that develops when the atmosphere is stable, developed shortly before 1800 UTC on 23 December 2009 and persisted until that evening, over six hours. This snowband also had DSS ramifications, especially in the reported number of vehicle accidents in Billings that were attributed to the snow that was falling and the snow and ice that had accumulated on area roads throughout the day.

An analysis of the 1200 UTC TFX upper air sounding on 23 December 2009 (Figure 8) revealed that the low-levels were unstable, with a small amount of CAPE and a very strong capping inversion just below 700 mb, which forced air to flow around mountains. Dewpoint depressions were less than 3°C (i.e. the atmosphere was moist) extending from the surface through the capping inversion up to approximately 600 mb. The entire column, from the surface up to 600 mb was within the dendritic growth zone at 1200 UTC. Measured sustained winds were uniform below the inversion, from a northwesterly direction at 10 to 20 kts.

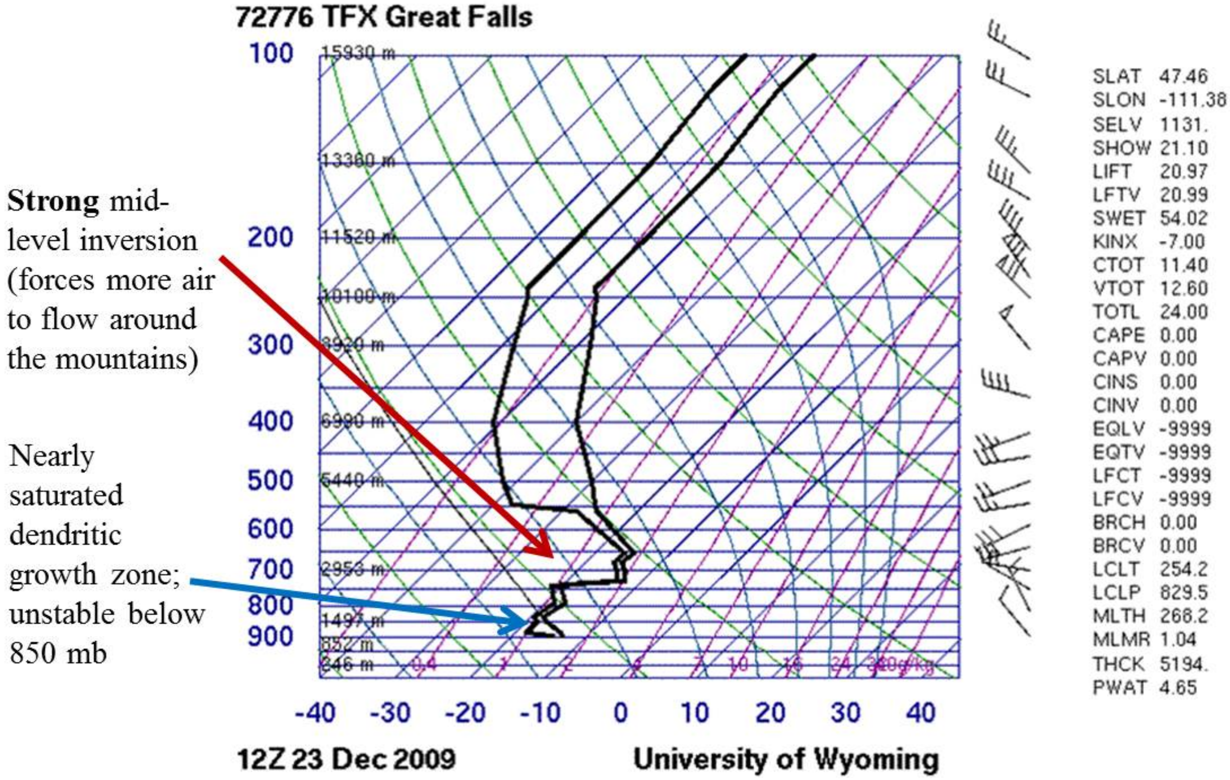


Figure 8: Atmospheric sounding from 1200 UTC 23 December 2009 from TFX, upstream of the Billings CWA. This is an example of a stable sounding (indicated by the strong mid-level inversion) on a day during which orographically-generated snowbands were observed in the Billings CWA. Other important features include the saturation through the dendritic growth zone and the uniformity of the winds below the inversion.

A MesoWest composite of surface observations at 1900 UTC on 23 December 2009, just as the most intense snow was falling in Billings, indicated that strong low-level convergence extended from just south of the Big Snowy Mountains into the Billings region. The strong convergence likely enhanced orographic snowband formation and snowfall totals locally during the event. Winds near the Big Snowy Mountains indicate that much all of the air was being forced to flow around the mountains underneath the strong mid-level inversion. Flow is strongly anticyclonic from east of the Big Snowy Mountains into Billings (Figure 9).

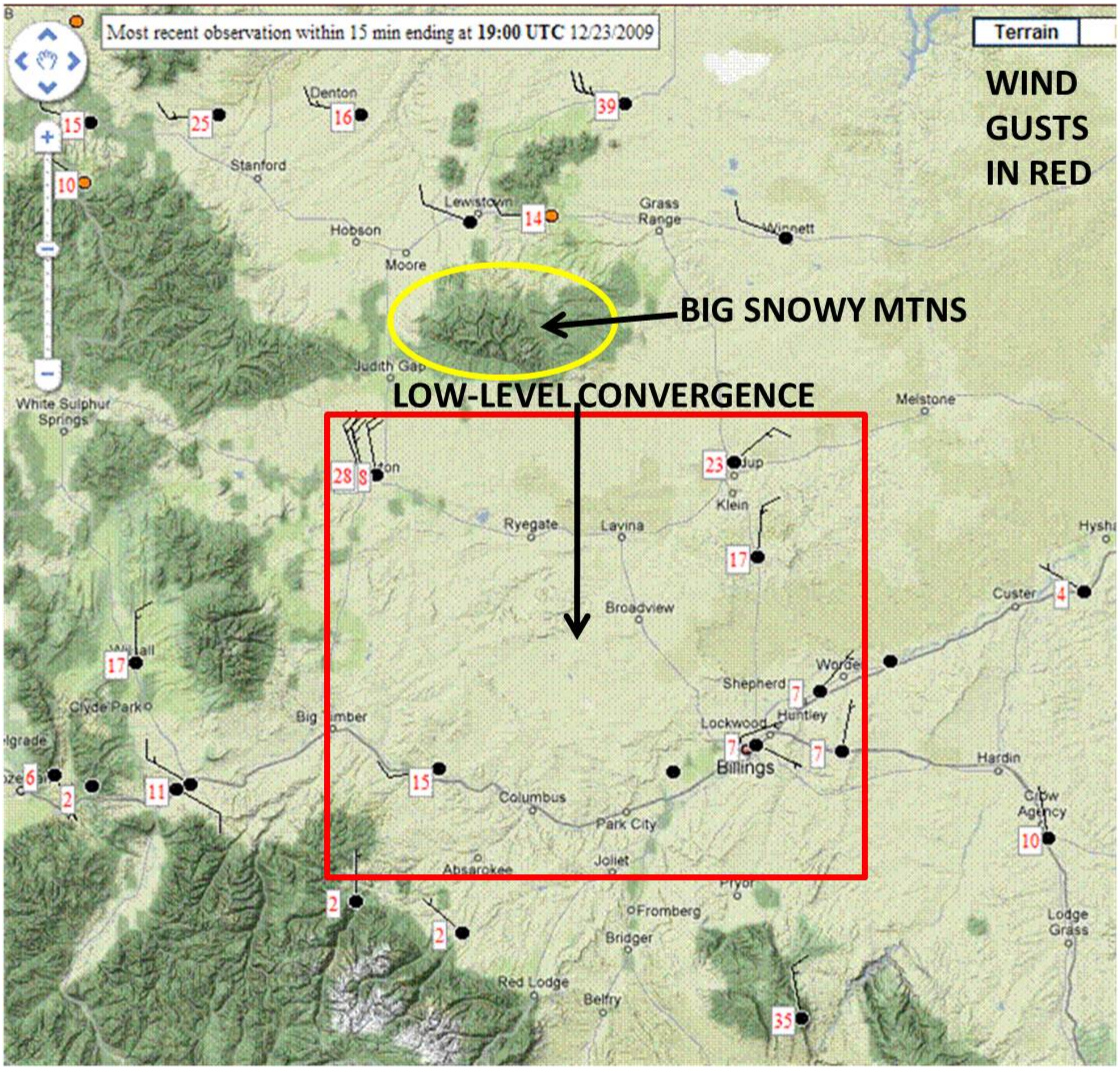


Figure 9: MesoWest surface observations at 1900 UTC on 23 December 2009. Areas of low-level/surface convergence are highlighted in the red box.

KBLX WSR-88D weather radar products showed a fairly wide orographically-generated snowband downstream of the Big Snowy Mountains, with the most intense portions directly over the Billings metropolitan area through much of the event. This is easily observed on both the 0.5° elevation angle base reflectivity and 0.5° elevation angle base velocity images at 1822 UTC and 2028 UTC on 23 December 2009 (Figure 10). On the base reflectivity products, this band was observed as a wide area of enhanced reflectivity values that extended back towards the Big Snowy Mountains, northwest of Billings. These enhanced reflectivity values correspond very well with the convergent flow on base velocity products, which appears as a large area of 0-1 kt inbound velocities with some embedded 5 kt outbound winds. This snowband resulted in enhancement of 7.6 to 15.2 cm (3 to 6 inches) to snow accumulations across central and western portions of Billings and in the Livingston region (Figure 11).

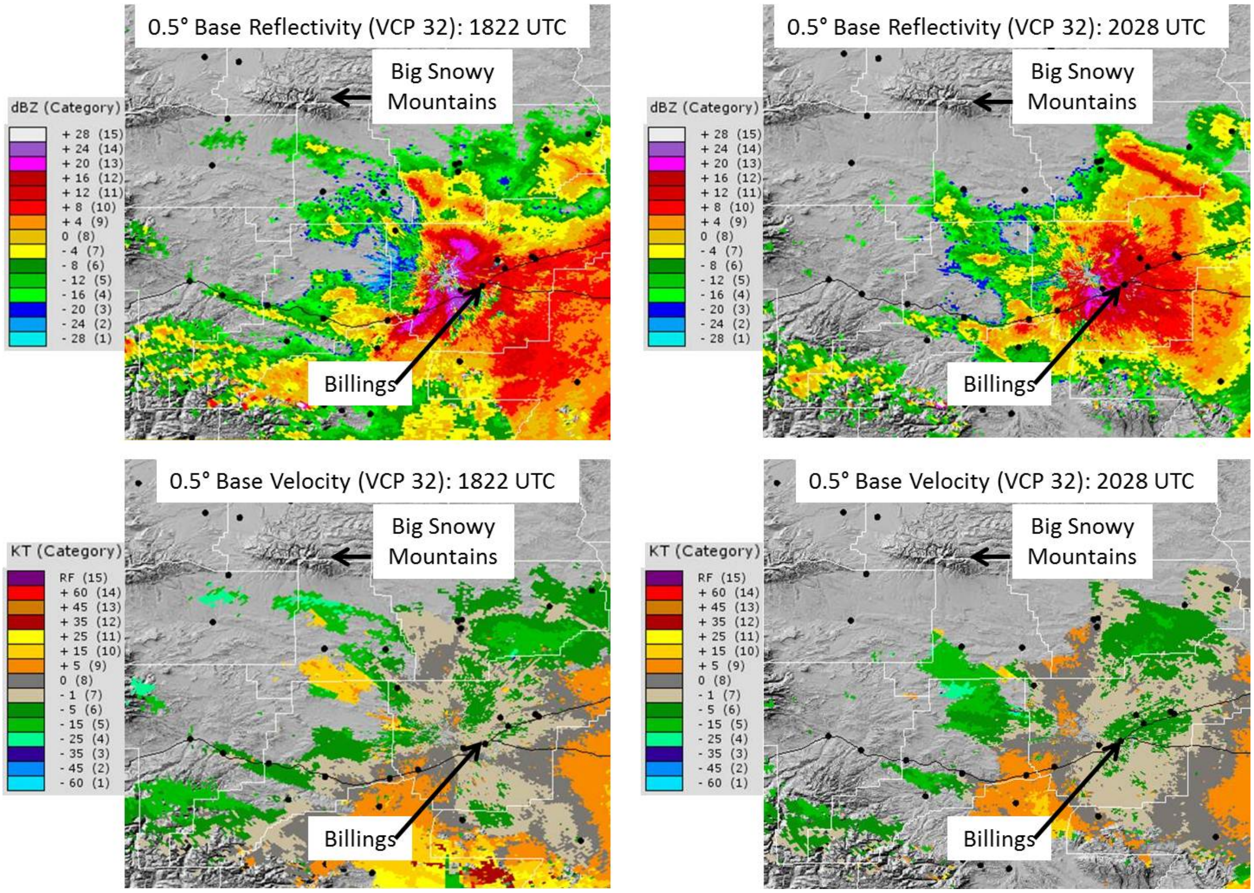
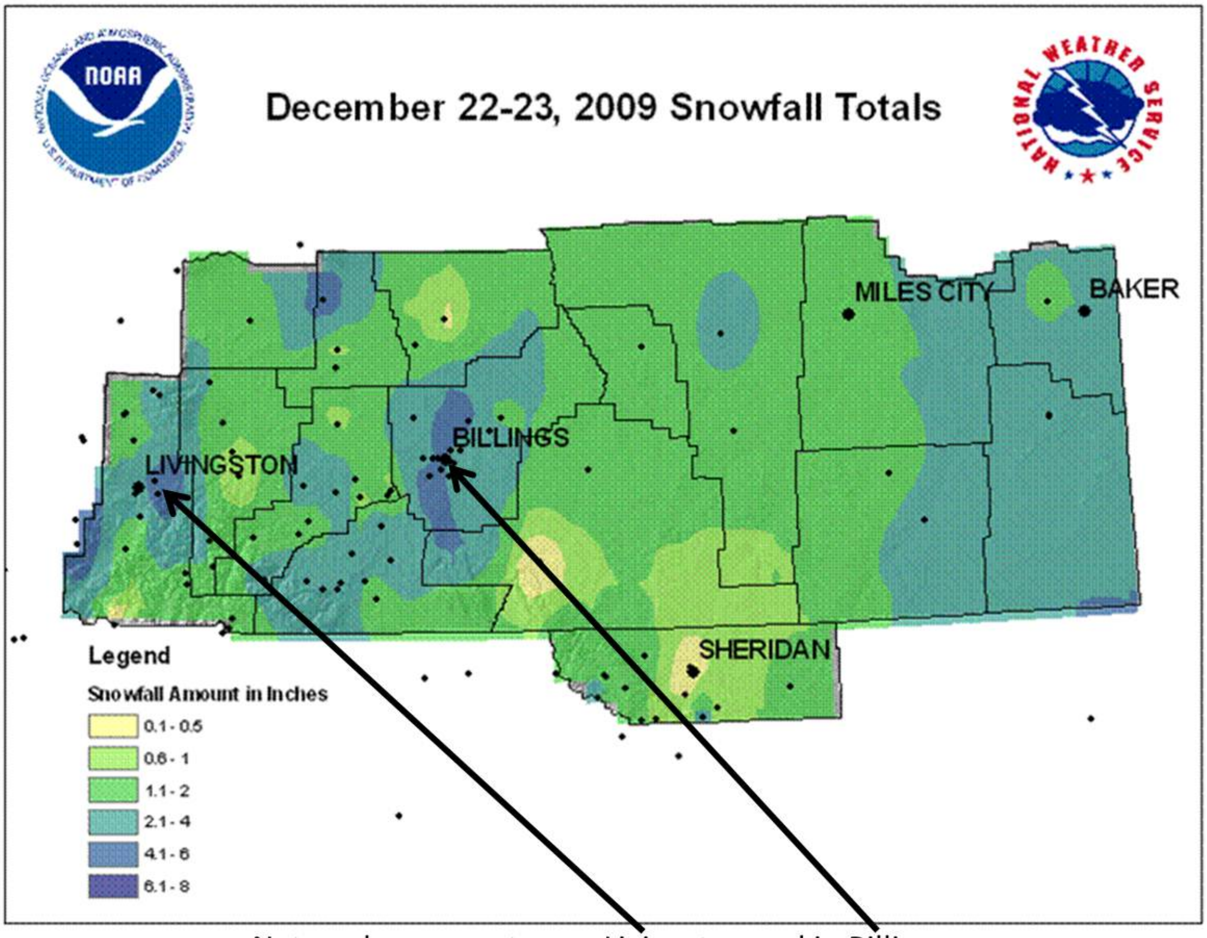


Figure 10: 23 December 2009 KBLX WSR-88D Images overlaid on a topographical map; 0.5° elevation angle base reflectivity images are on the top, while corresponding 0.5° elevation angle base velocity images are on the bottom. The black dots represent cities and towns. The Big Snowy Mountains and the city of Billings are highlighted by the arrows.



Note enhancement near Livingston and in Billings.

Figure 11: Snowfall totals from the 23 December 2009 snow event.

5. Other Important Meteorological Factors

a. Potential Vorticity Anomalies and Potential Vorticity Banners

Potential vorticity anomalies and potential vorticity banners (Aebischer and Schär, 1998) are important mesoscale features that contribute significantly to the development/evolution of snowbands or areas of enhancement within the snowbands. Potential vorticity anomalies are generated by the advection of cold frontal potential vorticity features into a region, by flow splitting around the mountains (where individual pairs of positive and negative potential vorticity anomalies are produced) and by the dissipation of turbulence in gravity wave breaking areas. Potential vorticity banners result from adiabatic advection of the potential vorticity anomalies by the wind. Because of this, potential vorticity banners can extend many tens of kilometers downstream of the mountains that generated them before dissipating. Where there is cyclonic rotation within these potential vorticity banners, areas within the snowbands or even the snowbands themselves can be enhanced due to the increased lift associated with the downstream advection of potential vorticity.

When determining the likelihood of orographically-generated potential vorticity banners, higher-resolution operational and experimental forecast models such as the Weather Research and Forecasting (WRF), with its 12 km resolution and the Rapid Refresh (RAP), with its 3 km resolution, should be among the first weather forecast models utilized, due to the small-scale nature of these streamers. Potential vorticity banners are easily detected as bands of potential vorticity advection at 700 mb in and around the Billings CWA, as this is very near mountain-top level for the Little Belt, Crazy, Big Snowy and Pryor Mountains. Due to the mountains perturbing low-level flow, potential vorticity banners are also easily detected as bands of potential vorticity at 850 mb. It is important to remember that these are small mesoscale features, so the finer the resolution an operational forecast model has, the easier it will be to find them and to track their evolution. Potential vorticity banners are not depicted well in "layers," such as the 850 mb to 700 mb layer. This is likely due to differences in vorticity generation near mountain-top level and near the base of the mountains.

b. Omega Fields

Omega is useful when determining the potential strength of orographically-generated snowbands. Ageostrophic circulations induced by flow over and around the mountains are depicted quite clearly (though their strength may be underestimated) by higher resolution operational models such as the WRF and RAP.

When diagnosing an orographically-generated ageostrophic circulation, there a few concepts to consider. Positive omega values indicate downward vertical motion just downstream of the mountains as air flows over and down the mountains. Negative values downstream of the positive values indicate upward vertical motion, where the air that was forced down the mountain has reached the ground and the momentum is forcing it to rise once again. The greater the positive and negative values, the stronger the ageostrophic flow induced by the mountains, thus, where there are larger negative values, there is stronger upward vertical motion.

Omega fields at 850 mb and 700 mb and in the 850 to 700 mb layer show up well on the WRF and RAP plan views, though due to variations in the strength of the wind fields at those levels, they may not all align in the same region. Omega values at these same levels are not as visible (i.e. the signatures do not appear as strong) in models such as the Global Forecast System (GFS) and European Centre for Medium-Range Weather Forecasts (ECMWF) as their poorer resolution tends to wash out or, to some extent, parameterize the mountains' influence on the ageostrophic circulations. When used in conjunction with other parameters discussed in this TA, negative omega values downstream of the mountains may give some indication and increase forecaster confidence that there will be sufficient low- to mid-level forcing necessary for the generation/sustainment of orographically-generated snowbands.

c. Instability, Baroclinicity and Frontogenesis

Several of the orographically-generated snowband events in the Billings CWA researched for this TA reached their maximum intensity during the daytime. This is consistent with the findings of Davis (1997), where, in his study, 16 of the 19 snowband events he studied peaked during the afternoon. This implies that daytime heating/instability, as weak as it may be during the winter months, is still strong enough to increase upward vertical motion, especially in convergent zones downstream of the mountains. Kirschbaum et al. (2007) also found that instability and convective available potential energy (CAPE) values of a few hundred J/kg provided a favorable environment for upward vertical motion in regions where precipitation bands were generated orographically.

When snowband intensity peaks earlier or later than during maximum daytime heating, other factors, such as baroclinicity and frontogenesis may be responsible. As noted previously (Section 3), baroclinicity in the low- to mid-levels was observed during orographic snowbands in the Billings CWA. In all of the orographically-generated snowband events identified since 2008, snowbands reached their maximum strength when baroclinicity and CAA in the mid- and low-levels were at their strongest. When the baroclinicity and CAA weakened, the snowbands began to dissipate.

In a 2010 paper on orographic snowbands in Colorado and Wyoming, Schumacher et al. noted a transition from several minor snowbands to one major snowband. They theorized that the lift for the minor bands was initially generated by weak low- to mid-level frontogenesis with an upslope component of motion. As the minor bands transitioned to one major band, low-level frontogenesis along a surface cold front became the dominant factor and was enhanced by a region of elevated frontogenesis. Low-level frontogenesis along and behind surface cold fronts has been noted to enhance orographic snowbands in the Billings CWA. The instability associated with frontogenesis shows up quite clearly in soundings.

6. Summary

Orographically-generated snowbands can cause significant DSS challenges across southern Montana. Providing advanced notification of these snowbands to local decision-makers, emergency managers, partners and the public can help better prepare them for any impacts that may result. To do this, a forecaster must be able to quickly and accurately determine when conditions favor the development and continuation of these snowbands.

This TA identifies several items that a forecaster should look at/for when assessing the potential for an orographically-generated snowband. These include, but are not limited to, persistent moist north to northwesterly low- to mid-level flow, low- to mid-level convergence downstream of the mountains, low- to mid-level baroclinicity/cold air advection, low- to mid-level instability and persistent lift through the dendritic growth zone. Doppler weather radar, surface observational data and upstream atmospheric sounding data can also be useful tools for both diagnosing and forecasting orographically-generated snowbands, especially in the short-term.

Acknowledgements

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