Playing CSI: A Case Study of the November 12, 2009 Bozeman, Montana Snow Event

Benjamin J. Hatchett[1*], Michael L. Kaplan[2]., Darko K. Koracin[2], and John F. Mejia[2]

1. Atmospheric Sciences Graduate Program, University of Nevada Reno, Reno, NV, U.S.A.

2. Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, U.S.A.

ABSTRACT: On Wednesday November 11, 2009 the National Weather Service called for the passage of a front across southwestern Montana ahead of a weak low pressure system along the Washington coast. An estimated four to six inches of snow was forecast in the Bozeman area. However, by Thursday afternoon on November 12, over 16 inches of snow were recorded in Bozeman with up to 30 inches of snow in the surrounding mountains. The Gallatin National Forest Avalanche Center reported multiple small slab avalanches in the Bridger Mountains, with at least one partial burial. Heavy precipitation was not widespread regionally and in the days following the event a persistent local valley inversion was created that kept high temperatures in Bozeman nearly 16F below average and 20F less than other nearby stations for days. The storm was incorrectly diagnosed by the NWS as "coming right out of the Pacific Northwest…off the coast" (Benoit 2009) when in fact the storm generated ample snowfall due to unstable and unbalanced ascent resulting from interactions of the geostrophic polar jet, subtropical jet, and cold trough. Preliminary analysis indicated the potential role of convective symmetric instability in this event however the non-quasi-geostrophic nature of the unbalanced flow via jet interaction paradigm offers strong evidence for questioning this. Here we examine the meteorological conditions leading to this type of snow event as well as discuss some implications for avalanche hazard generation and persistence.

KEYWORDS: convective snowfall, spatial variability, unbalanced flow

1 INTRODUCTION

Convective snowfall events are relatively short lived (2-8 hours) but have the capability of producing snowfall rates in excess of 3 inches per hour and total accumulations greater than 8 inches (Johnson and Petrescu 2005). Commonly occurring in the central Plains and western United States during the cold season, these events are characterized by mesoscale banded precipitation occurring on the poleward side of extratropical cyclones and roll clouds oriented parallel to the mean atmospheric flow and thermal wind (Hoenisch 2005, Novak and Colle 2005). Convective precipitation bands are often associated with midlevel frontogenesis in the presence of weak moist symmetric stability and high relative humidity, (convective symmetric instability (CSI)) and can be independent of orographic forcing (Thorpe and Emanuel 1985, Nicosa and Grumm 1999, Novak et al. 2004). In areas of complex terrain snow accumulation is highly localized (Hoenisch, 2008).

*Corresponding author address: Benjamin J. Hatchett, Desert Research Institute, 2215 Raggio Pkwy Reno, NV, U.S.A. 89523; tel:775-673-7658; email: benjamin.hatchett@dri.edu

The spatially variable nature of convective snowfall events is of particular interest to avalanche professionals and backcountry users alike as it produces localized red flags that may or may not be captured in the larger-scale area forecast. These include rapid loading due to the intense precipitation and wind redistribution during or after the event. Furthermore, because orography may or may not play a role in snow accumulation patterns, aspects which may normally have little to no snowpack may suddenly become heavily loaded and unstable. Early season convective events can establish a thin snowpack which is conducive to the generation of persistent depth hoar (McClung and Schaerer 2006). These events tend to be associated with cold frontal passage and post-frontal conditions of cold temperatures, calm winds and clear skies are favorable for the generation of valley inversions and promote surface hoar growth (McClung and Schaerer 2006).

Midlatitude mountain range precipitation during the cold season is predominantly derived from advective situations (Barry 2008). The role of convection in mountain precipitation events are treated lightly in the avalanche literature. In his seminal work "The Avalanche Handbook", McClung and Schaerer (2006) mentions convection as being a very local effect and its direct contribution to winter precipitation as being very small. However, both off and onshore convection plays an important role in cold season precipitation events in the midlatitudes; e.g. Keyser and Johnson (1984), Newell and Zhu (1994), Ralph et al. (2004), Ralph and Neiman (2005), Underwood et al. (2009), and Kaplan et al. (2009).

Convective snowfall events are often under-forecasted due to the use of numerical weather models which cannot resolve the mesoscale–β convective plumes. Accurately forecasting these events is challenging and requires a deep understanding of atmospheric dynamics. However, by careful observation of easily accessible weather observation networks (soundings, satellite imagery) and model forecasts (instability indices, vorticity, velocity, temperature, height and pressure fields), e.g. the National Center for Atmospheric Research's Weather Center: http://www.rap.ucar.edu/weather/, one can diagnose 'probable' locations which are favorable for convective snowfall. We outline here a basic paradigm for cold season convective snowfall events in complex terrain in an effort to improve snowfall forecasts pertaining to these types of events as well as increase awareness of the importance of convective snowfall events in the avalanche community.

2 METHODS AND DATA

2.1 Study area

The city of Bozeman, MT, U.S.A. is located in southwestern Montana at an elevation of 1465m in the heart of the greater northern Rocky Mountains (Figure 1). The area is characterized by a highland climate of cold, snowy winters, and mild summers, receiving approximately 470mm of annual precipitation in town and 650mm in the nearby Bridger Mountains. The snowpack is considered to be intermountain (Mock and Birkeland 2000). Bozeman lies in a valley surrounded by several mountain ranges including the Bridger Mountains to the north-northeast, the Tobacco Root Mountains to the west-south-west, the Big Belt Mountains to the north, and the Madison Range to the south.

Figure 1: Western United States with star representing Bozeman, MT.

2.2.1 Meteorological Observations

The North American Reanalysis (Mesinger et al. 2006) was acquired from the NOAA National Operational Model Archive and Distribution System (http://nomads.ncdc.noaa.gov/). Data was analyzed between the period of 00Z 12-November 2009 and 12Z 13-November 2009 at three-hourly intervals. Observations included all relevant dynamic and thermodynamic fields from the surface (~850mb) to lower stratosphere (150mb) but focus on the time of heaviest snowfall at 18Z 12-November 2009.

2.2.1.1 Synoptic Conditions Preceding Event

On 12Z 12-November 2009 a cold, positively tilted upper level trough was located along the Pacific Northwest into the Central Canadian Plains (Figure 2). A strong temperature gradient is present in the lower-middle troposphere from southeastern Oregon through northeastern Montana as indicated by 1000-500mb thickness (Figure 3). A subgeostrophic polar jet streak (PJ) (75kt at 500mb) is evident from southwestern Idaho into south central Montana oriented along the maximum baroclinic zone (Figure 4). An unseasonably strong supergeostrophic subtropical jet streak (STJ) (135kt at 150mb) is propagating across southern California into southern Utah (Figure 5). Soundings at Vandenberg AFB, CA (KVBG), and San Diego, CA (KNKX) highlight the STJ's dominance of the upper troposphere (100-

250mb). Infrared and visible satellite imagery (not shown) indicates strong lateral shear and a temperature gradient in the northern Rocky Mountains, consistent with the observed dynamical fields.

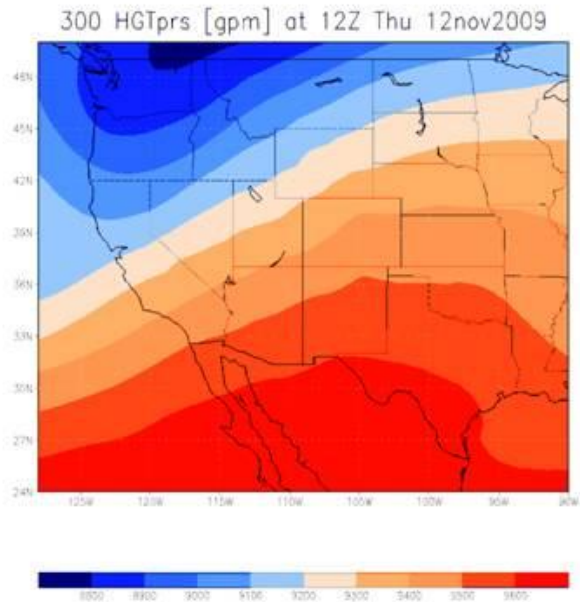

Figure 2: 300mb geopotential height.

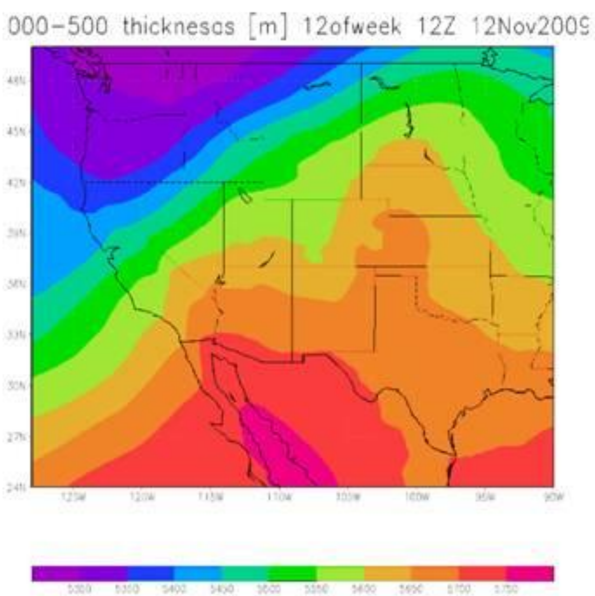

Figure 3: 1000-500mb thicknesses.

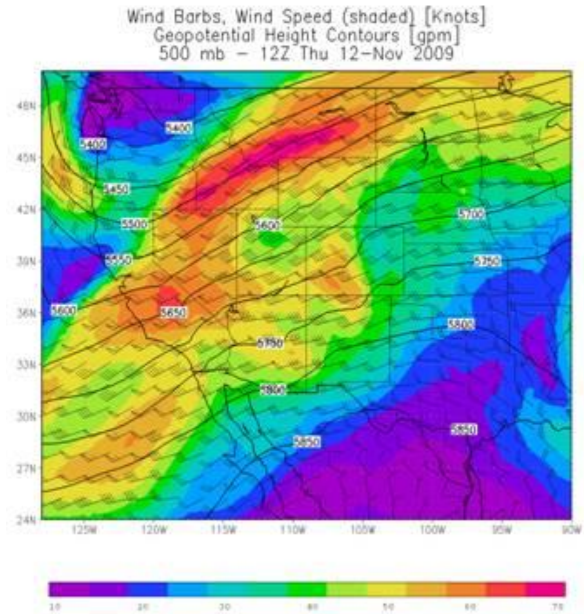

Figure 4: 500mb heights and wind velocities.

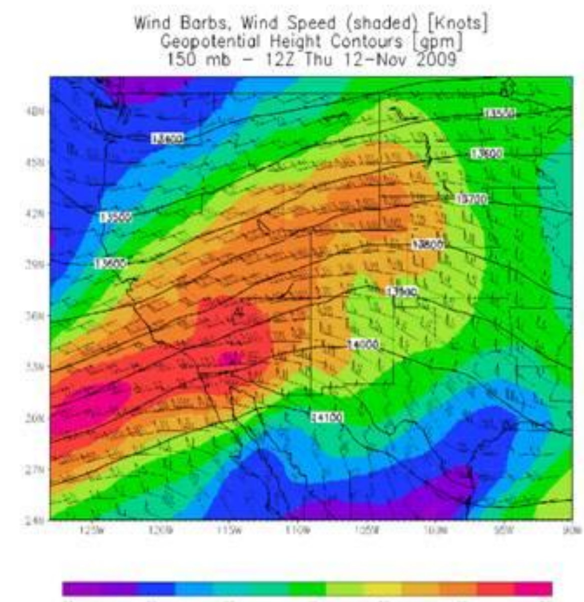

Figure 5: 150mb heights and wind velocities.

2.2.1.2 Synoptic Conditions During Event

Between 18Z 12-November 2009 and 00Z 13-November 2009, the 300mb wind field shows a leftward directed ageostrophic velocity vector (wind barbs crossing to left of height contours) over southwestern Montana and northwestern

Wyoming as the cold trough has progressed eastward and advects cold air into the central northern Rocky Mountain region (Figure 6).

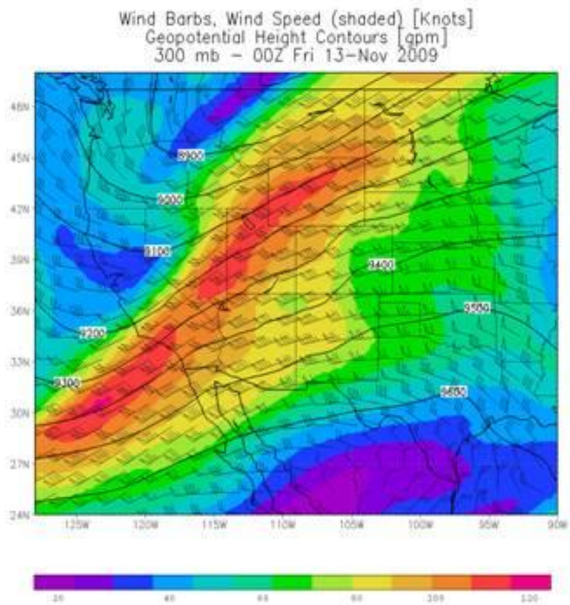

Figure 6: 300mb Heights and wind velocities. Note left jet exit region directly above southeastern Idaho and south-central Montana.

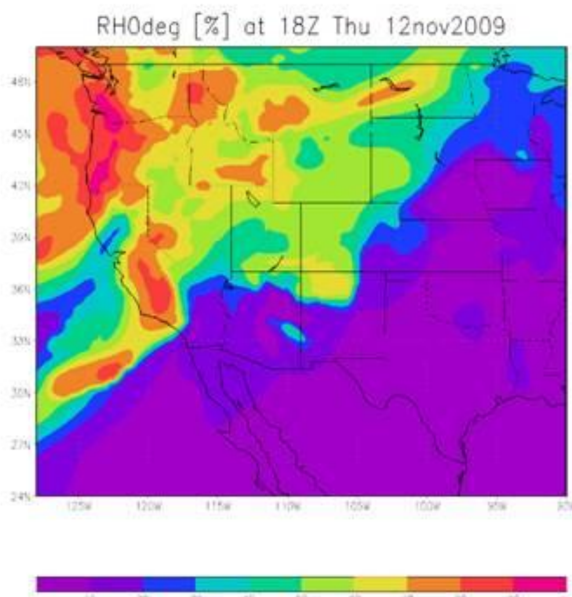

Figure 7: Percent relative humidity at the 0C isotherm. Note that moisture is present in south central Montana.

Relative humidity over south-central Montana at the 0C isotherm is greater than 70% at 18Z 12-November 2009 (Figure 7). Convective clouds at 00Z 13-November 2009 are maximized over south-central Montana, and extreme northwestern Wyoming and northeastern Idaho (Figure 8).

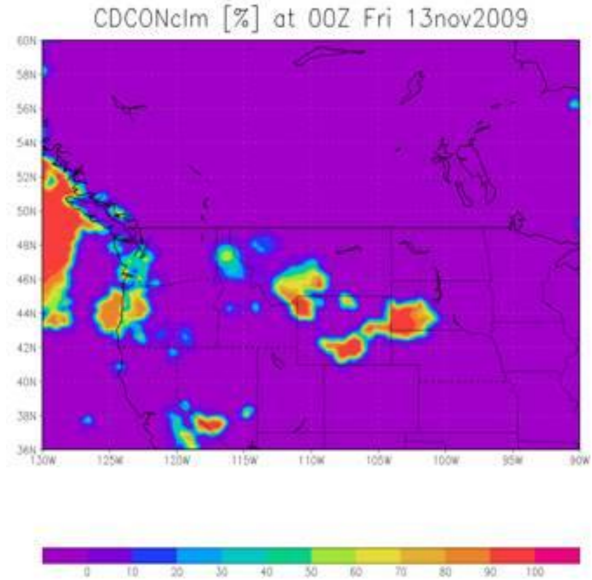

Figure 8: Convective cloud percentage. Note large values over south central Montana and extreme northwestern Wyoming.

These features indicate the possible interactive phasing of the cold pool and the two jet streaks; this is confirmed by strong upward vertical velocities at the level of non divergence (500mb) centered over the region of maximum ageostrophic flow at 21Z 12-November 2009 (Figure 9).

2.2.2 Snowpack and Avalanche Observations

The Gallatin National Forest Avalanche Center (GNFAC) provided an avalanche forecast on 12-November 2009 as well as post event avalanche imagery and incident reports. The 4pm forecast on 12-November indicated recent heavy loading on a generally shallow, early season snowpack with wind slabs sitting atop faceted layers.

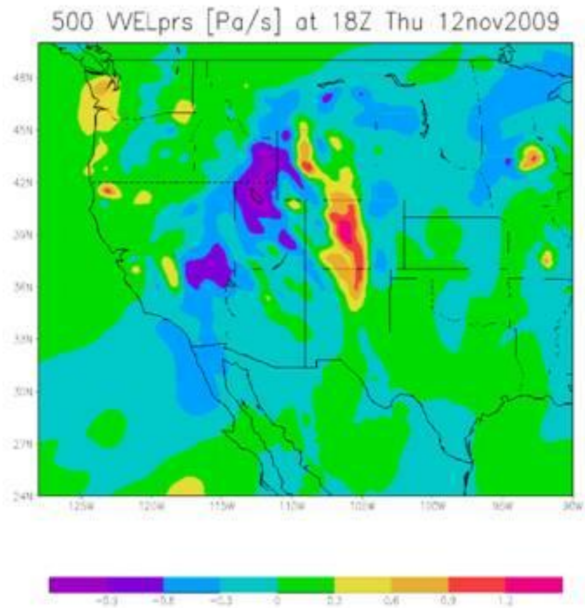

Figure 9: 500mb vertical velocities. Negative numbers indicate upward vertical motion (UVM); note core of UVM in northern Utah southeastern Idaho, western Wyoming, and southern Montana. Phasing of UVM and humidity can generate copious convective precipitation.

3 ANALYSES RESULTS

3.1 Precipitation Totals

Snow totals in the Bozeman area ranged from 16 inches to 30 inches with 18-24 inches in the mountains (Bernhardt 2010). The pattern of snowfall exhibited a classic banded form (not shown).

3.2 Avalanche and Weather Observations

The GNFAC reported several skier triggered avalanches, one partial burial, and observations of natural wind slab avalanches occurring in the Bridger Range in the days after the event. These observations are consistent with heavy loading events occurring in conjunction with moderate winds.

A significant valley inversion developed in the Bozeman area valley and lasted for many days after the event. Temperatures in Bozeman were the coldest in the state and below average while other parts of Montana experienced above normal temperatures. However, no surface hoar growth or related avalanches were observed in this case in the Bozeman region. While depth hoar developed in the region during the following weeks, this event did not appear to play an exemplary role in developing this condition.

4 DISCUSSION

4.1 Initial CSI Conclusion

The authors' preliminary findings indicated that CSI may have played a significant role in the snow event. The Great Falls, MT National Weather Service post-analysis of the event concluded that a CSI band developed in the region (Bernhardt 2010). This highlights the oft-misunderstood nature of CSI. Conditions leading to CSI events include dynamical lifting from jet circulations, strong frontogenetical lifting, high midtropospheric relative humidity, negative absolute vorticity, and relatively weak slantwise stability, i.e. static stability on absolute momentum surfaces. In this case, there was dynamical lifting, frontogenesis, and available moisture present; however as will be discussed in section 4.2, other dynamical factors strongly question the likelihood that CSI was important in this event.

4.2 Argument Against CSI

The presence of upright surface (Figure 10) and elevated convective available potential energy (not shown) consistent with negative lifted indices (Figure 11), argue for upright convection in a possible moist adiabatic unstable layer.

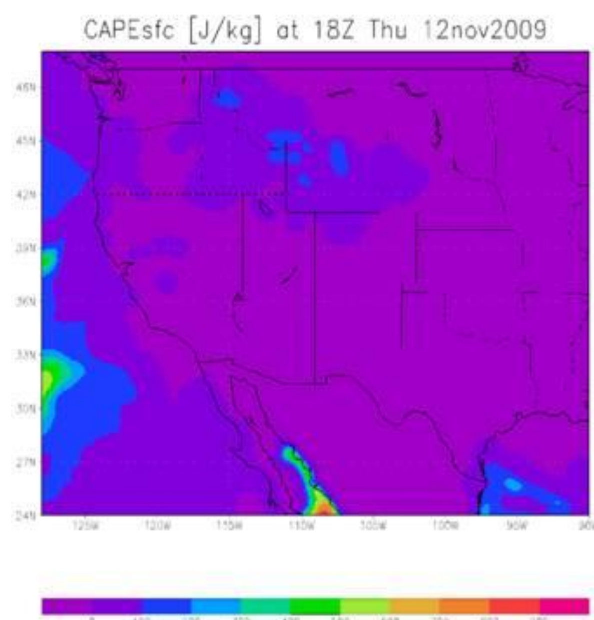

Figure 10: CAPE at the surface.

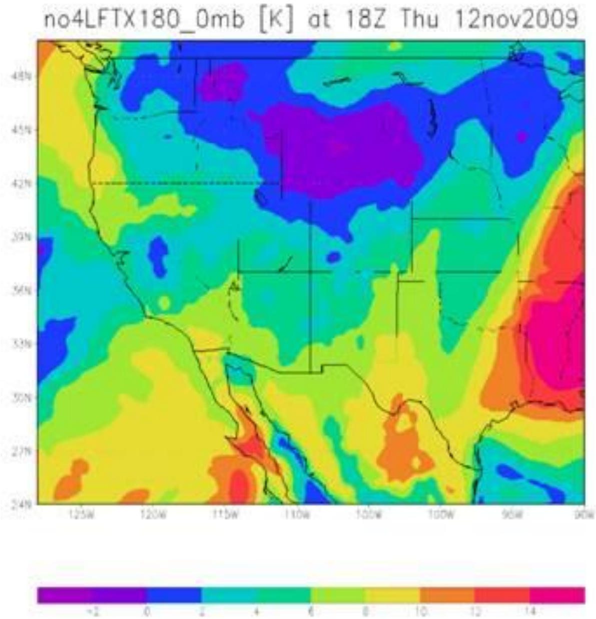

Figure 11: Lower troposphere lifted index. Lower numbers indicate less stable air. An unstable airmass exists over southern Montana.

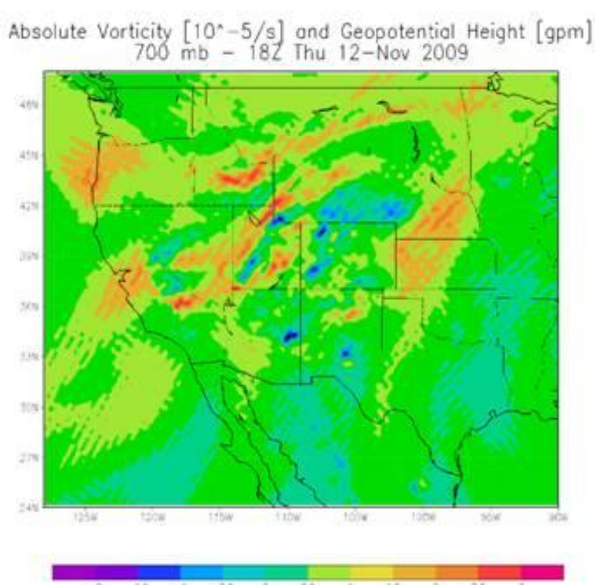

Figure 12: 700mb absolute vorticity and heights. Note the positive relative vorticity in southern Idaho and south central Montana. This region of high vorticity coincides with the region of unbalanced ascent and upper level divergence tendencies.

Such conditions do not favor slantwise convection in which the instability is oriented differently. CSI requires anticyclonic shear (negative absolute vorticity), which is not the case as shown by the positive (orange) values of absolute vorticity at 700mb which extends above 500mb (Figure 12). Cold air advection (CAA) is occurring between 500mb and 700mb (not shown). CSI is typically associated with warm air advection (WAA) above the boundary layer north of the warm front in the region of strong quasigeostrophic frontogenetical forcing. Thus, the NARR analysis gives no proof that CSI is in fact occurring.4.3 Jet Interactions and Unbalanced Flow

The interaction of the STJ with the PJ coupled with the significant CAA at midlevels is proposed to be the key forcing agent in the convective snowfall event. Synoptic scale flow will become highly ageostrophic when an upper-level (150-300mb), midlatitude jet exists in an amplifying baroclinic wave (Kaplan and Paine 1977). Ageostrophic winds transfer mass and create a thermally direct circulation which converts potential energy into kinetic energy and contributes to upper level divergence and significant upward vertical motions consistent with upper level accelerations to the left of the flow (Lin 2007). A very strong plume of momentum is being advected into Montana accompanying the southwesterly STJ flow and interacting with the falling heights driven by the cold trough and polar PJ. The juxtaposed PJ height gradient and STJ momentum gradient produce an unbalanced circulation in the STJ exit region. CAA would normally serve to force quasi-geostrophic sinking motion; however the STJ-induced velocity divergence extending across the STJ exit region is forcing upward vertical motions. The airmass is being continuously destabilized by the CAA and lifted by the leftward-directed ageostrophic circulation of the STJ, located over southeastern Idaho, and western Montana, as well as upslope adiabatic cooling from terrain-forced ascent. Significant thermal wind imbalance is achieved as a result, this is evident by the inconsistent weak backing despite the CAA in the Riverton, WY 00Z 13-November 2009 sounding (Figure 13) that should demonstrate substantial backing. The result of the phasing of the high momentum STJ with the upper level cold pool and PJ result in a significant period of unbalanced ascent as cold air is advected into the highly divergent ageostrophic jet exit region. High relative humidity values in the midtroposphere under conditions of low stability allowed significant convection to develop along the region of maximum thermal wind imbalance and result in the maximum precipitation values oriented along the region where the thermal wind adjustment signal is strongest. Convective heating allows heights to rise on the ridge to the east and strengthen the temperature gradient and maintain unbalanced STJ exit region flow.

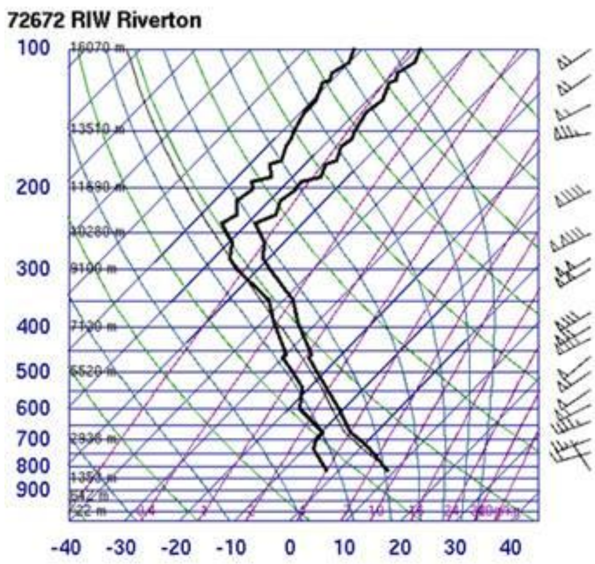

Figure 13: Rawinsonde observation at Riverton (KRIW) on 00Z 13 November 2009. Note lack of backing with height despite CAA on wind barbs to the right of the image.

5 CONCLUSIONS

Convective snowfall events in complex terrain are created by the phasing of multiscale phenomena and are difficult to understand and forecast. The Bozeman event can be summarized as follows: The mass-rich and low momentum baroclinic environment of a cold trough and PJ progress southeastward and begin interacting with the momentum rich STJ. The juxtaposition of two jet streaks creates a situation of unbalanced flow as the divergent left exit region of the STJ phases with the height gradient accompanying the entrance region of the PJ and creates a divergence tendency to form in the right exit region of the STJ. The mass and momentum fields become completely unbalanced and the mass field must adjust to the momentum field by cooling the column and destabilizing the environment through ascending motions. Downstream convective heating increases the exit region height perturbation and further enhances the baroclinic zone, as does the continuous CAA at the base of the trough. The rapid destabilization, presence of high relative humidities, and highly divergent region created by the superposition of the two jets leads to a strong imbalance in thermal wind and leftward directed ageostrophic flow regime characterized by strong upward vertical motions. In a cold, unstable environment with ascent and moisture present, favorable conditions for strong convective precipitation are established. Figure 14 presents a conceptual diagram of these interactions and can be used as a forecast tool during cold season precipitation events that do not appear to be directly related to classical quasi-geostrophic cyclonic precipitation.

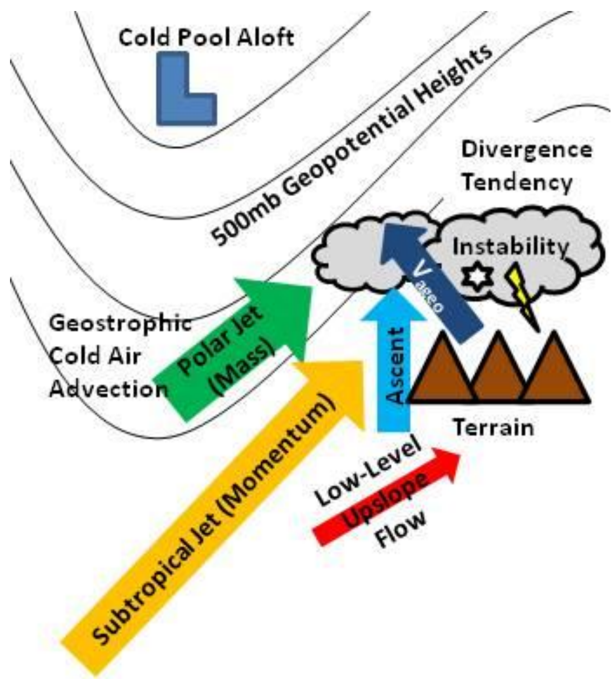

Figure 14: Conceptual diagram of convective snowfall events arising from unbalanced ascent and ageostrophic flow (V_{ageo}, dark blue arrow) via phasing of the STJ, PJ, and upper level low pressure trough. Clouds indicate the region of maximum likelihood for convective precipitation.

Improving forecasts of convective events will lead to spatially higher resolution avalanche forecasts and better understanding of the role of convective events in avalanche formation and persistence. Future work will include high resolution numerical modeling of convective events and case studies of avalanche activity succeeding convective snowfall events with sustained high precipitation rates and high total accumulations.

ACKNOWLEDGEMENTS

This study was funded by the National Science Foundation Cooperative Agreement EPS-0814372.

REFERENCES

Barry, R., 2008. Mountain Weather and Climate. Cambridge Univ. Press. 506pp.

Benoit, Z., 2009. “Heavy snow hits Bozeman, mountains.” *Billings Gazette*, November 12, 2009.

Bernhardt, D. 2010. Personal Communication.

Gallatin National Forest Avalanche Center 2009. 12-November 2009 Advisory: http://www.mtavalanche.com/advisory/09/11/12

Hoenisch, R., 2005. Convective Snow Banding over North Central Montana. NWS Tech. Attach. 0808.

Johnson, M. W., and Petrescu, E., 2005: January 2005 banded snow event using the weather event simulator, *West. Reg. Tech. Att. No.5-14*.

Kaplan, M.K., and Paine, D.A., 1977. The observed divergence of the horizontal velocity field and pressure gradient force at the mesoscale: Its implications for the parameterization of three-dimensional momentum transport in synoptic-scale numerical models. Bietr. Phys. Atmos., 50, 321-330.

Kaplan, M.K., and Coauthors, 2009. The role of upstream midtropospheric circulations in the Sierra Nevada enabling lee-side (spillover) precipitation. Part II: A secondary atmospheric river accompanying a mid-level jet. J. Hydromet. 10, 1327-1354.

Keyser, D.A., and Johnson, D.R., 1984: Effects of diabatic heating on the ageostrophic circulation of an upper tropospheric jet streak. Mon. Wea. Rev., 112, 1709-1724.

Lin, Y.L., 2007 Mesoscale Dynamics. Cambridge Univ. Press, 630pp.

McClung, D., and Schaerer, D. 2006. The Avalanche Handbook. Mountaineers Books, 342pp.

Mesinger, F., and Coauthors., 2006. North American Regional Reanalysis. Bull. Am. Met. Soc. 87, 343-360.

Mock, C.J. and Birkeland, K.W., 2000. Snow avalanche climatology of the western United States mountain ranges. Bull. Am. Met. Soc. 81(10),2367-2392.

Nicosia, D.J. and Grumm, R.H., 1999. Mesoscale band formation in three major northeastern United States snowstorms. Wea. Forecast. 14, 346-368.

Novak, D.R., and Coauthors, 2004. An observational study of cold season banded precipitation in northeast U.S. cyclones. Wea. Forecast. 19, 993-1010.

Novak, D.R. and Colle, B.A., 2005. Comparison of MM5 and WRF forecasts of the 25 December 2002 northeast U.S. banded snowstorm. Extended abstracts: WRF/MM5 Users Workshop 2005.

Ralph, F.M., and Coauthors, 2004. Satellite and CALJET aircraft observations of atmospheric rivers over the eastern north Pacific Ocean during the winter of 1997/98. Mon. Wea. Rev. 132, 1721-1745.

Ralph, F.M. and Neiman, R.E., 2005. Dropsonde observations in low-level jets over the northeastern Pacific Ocean from CALJET-1998 and PACJET-2001: mean vertical-profile and atmospheric-river characteristics. *Mon. Wea. Rev*., 133, 889-910.

Thorpe, A.J. and Emanuel, K.A., 1985. Frontogenesis in the presence of small stability to slantwise convection. J. Atmos. Sci. 42(17) 1809-1824

Underwood, S. J., and Coauthors, 2009. The role of upstream midtropospheric circulations in Sierra Nevada enabling lee-side (spillover) precipitation. Part I: A synoptic scale climatology of spillover precipitation and flooding in a lee-side basin. J. Hydromet. 10, 1309-1326.

Zhu, Y. and Newell, R.E.,1994. Atmospheric rivers and bombs. Geophy. Res. Lett. 21, 1999-2002.