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**Heavy Snowfall Produced by Topographically Induced Winds in the Snake River Plain of Eastern Idaho. Part I: Observational Analysis**

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ABSTRACT

This study is the first of two papers concerning the dynamics of a heavy snowfall event in the Snake River Plain of eastern Idaho on 26 November 2005. Heavy snowfall occurred along the southern perimeter of the wide (~100 km) valley and in three to four mesoscale bands aligned across the valley and parallel with the post cold-frontal northwesterly flow. This event was driven by two main topographic forcing mechanisms. First, widespread precipitation resulted from a low-level barrier jet (oriented down a tight horizontal pressure gradient) ascending the Snake River Valley and spilling over the southern edge of the valley. Second, the mesoscale snow bands in the valley resulted from boundary layer convergence forced by flow through the upstream barrier, the Idaho Central Mountains, in three narrow valleys aligned with the 700 hPa wind. This case study illustrates how the unique topography of eastern Idaho contributed to near-blizzard conditions in a post-frontal regime.

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**1. Introduction**

A major snowfall event with local blizzard conditions occurred in eastern Idaho on 26 November 2005. Snow fell mainly during the afternoon hours (1900–0000 UTC) in the lower part of the eastern Snake River Plain. Trained weather spotters and local media outlets reported snowfall amounts of 25–38 cm (10–15 in) east and south of the city of Pocatello (location shown in Fig. 1a). Pocatello Regional Airport (KPIH) reported near-blizzard conditions between 1720 and 2305 UTC with moderate to heavy snow, winds over  $13 \text{ m s}^{-1}$  (25 kt), and visibilities below 1.0 km.

This study describes the evolution and mesoscale dynamics of the event, particularly, orographic mechanisms contributing to localized heavy snow accumulations. It is common for a belt or region of orographically-induced boundary layer convergence in the Snake River Plain to produce precipitation in post cold-frontal flow. Such a belt has been referred

to as a *Snake River Plain Convergence Zone* (SPCZ) (Andretta and Hazen 1998; Andretta 2002). The 26 November 2005 snowfall event was associated with a SPCZ.

This study elucidates the fine-scale structure and the dynamics of this SPCZ event. It will be beneficial to operational weather forecasters who tackle winter storm prediction in eastern Idaho and in other regions of the Intermountain West.

The morning operational NWS forecast for the lower plain predicted less than 2.5 cm (1 in) of snowfall. This study is motivated in part by the poor predictability of this event, and SPCZs in general. SPCZ events are complex and are controlled by the meso- $\beta$  scale (20–200 km) terrain, and meso- $\gamma$  scale (2–20 km) details of the topography.

This manuscript is the first of a two part study exploring the dynamics of this SPCZ event. Part I is an observational analysis which benefits from weather radar and an unusually dense surface station network. Part II will use high-resolution numerical model output to diagnose the dynamics of the event.

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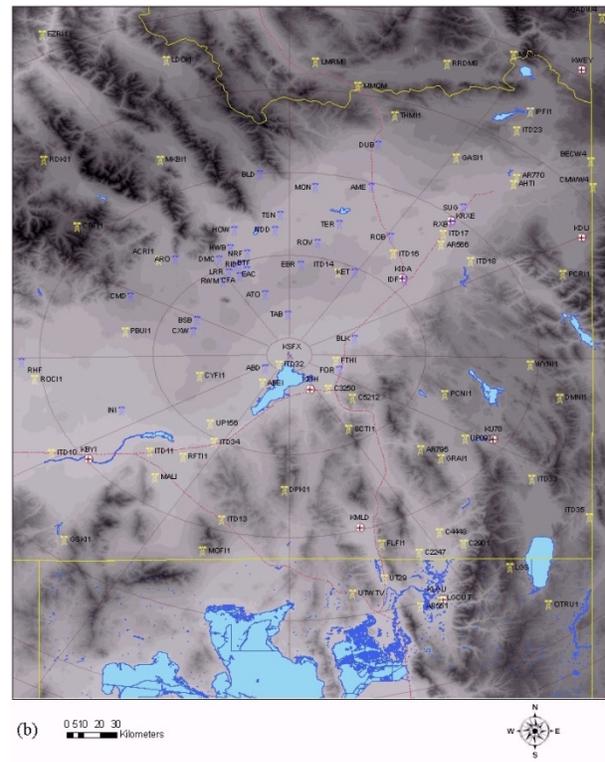
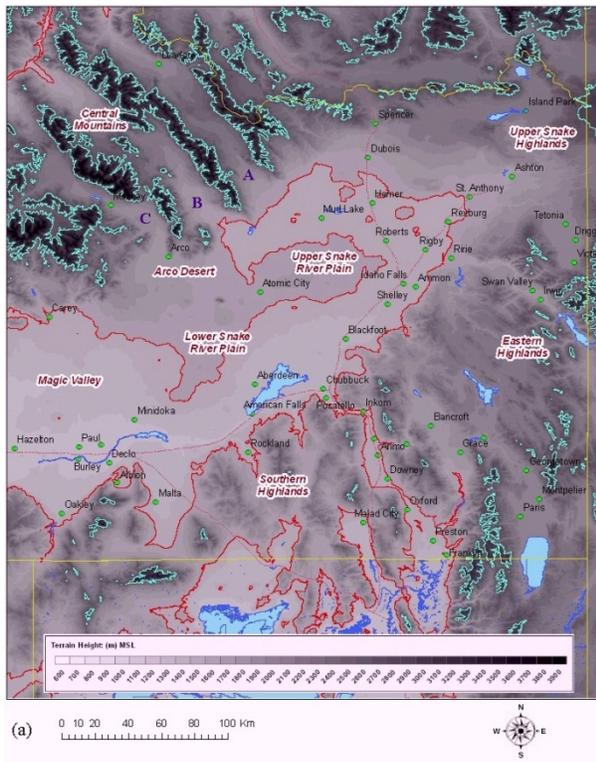
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The main objectives of this observational paper are 1) to describe the evolution of this event in terms of clouds, precipitation, wind flow, and surface temperature; and 2) to build a foundation for Part II, with model validation and exploration of dynamics. Sections 2 and 3 describe the topography and regional precipitation amounts from the event, respectively. Section 4 introduces the data sources in the study. Section 5 describes salient wind flows in eastern Idaho. Sections 6–8 discuss the mesoscale dynamics of the event using high resolution satellite, surface mesonet, and radar data sets

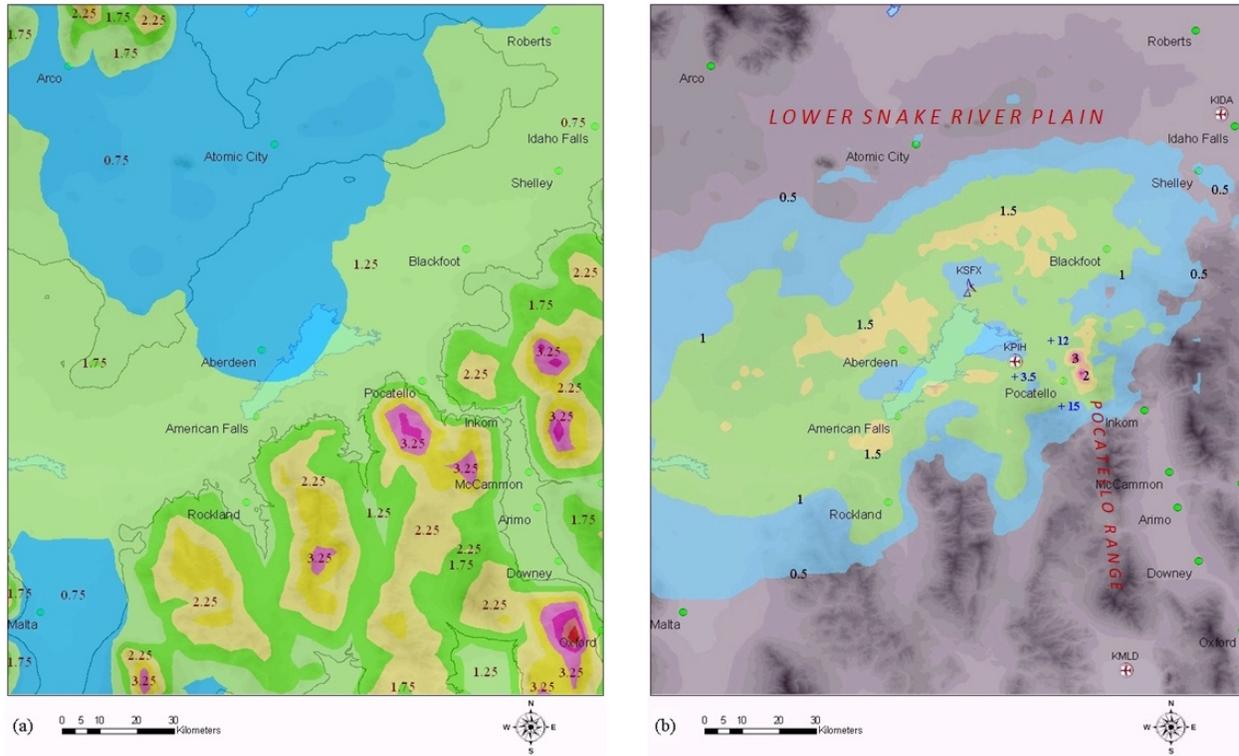
**2. Regional topography**

The geographical domain of eastern Idaho is illustrated in Figs. 1a and 1b. The two major features are the Idaho Central Mountains and the Snake River Plain. This parabolic valley is ~250 km long and ~100 km wide, curving around the Central Mountains

from the west towards the northeast. The large plain includes the Magic Valley, the Lower Snake River Plain, and the Upper Snake River Plain. This enclosed wide plain gradually ascends from ~1000 m (all heights above MSL) at the western end of the Magic Valley to ~1700 m near the eastern end of the upper plain. The Upper Snake River Plain contains a shallow, fishhook-shaped topographic depression (1500 m red contours in Fig. 1a). The Snake River Plain is bound by two rather high terrain barriers (~3000 m elevation), the Central Mountains to the northwest and the Eastern Highlands and Upper Snake Highlands to the east. Further east, into Wyoming, there are higher meridional mountain ranges. The Snake River Plain is bound by the Southern Highlands to the south, which vary from 2000 to 2500 m. Nestled along one of the ranges of the Southern Highlands is the city of Pocatello (1356 m), situated near an inflection point in the eastern part of the Snake River Plain.



**Figure 1:** a) Eastern Idaho – Digital Elevation Model (DEM) 1° terrain silhouette, state boundaries, interstate highways, water bodies, geographic regions, and cities. b) Springfield, ID (KSFx) radar location, station identifiers, and range rings. *Click images to enlarge.*



**Figure 2:** a) NCDC 30-year (1971–2000) precipitation normals (in) for November in the Lower Snake River Plain and contiguous Southern Highlands and 1500 m terrain contour (solid grey). b) Storm total liquid water equivalent (in) estimated by the KSFX WSR-88D and blue crosses representing storm total snow depth (in) reported by NWS weather spotters from 1600 UTC 26 November to 0500 UTC 27 November 2005. *Click images to enlarge.*

While the barrier to the east is rather continuous, the Central Mountains and the Southern Highlands (2500 m cyan contours in Fig. 1a) contain many narrow northwest to southeast oriented valleys connecting to the Snake River Plain. Thus, these barriers are rather porous to northwesterly flow. Of particular significance in this study, there are three to five narrow tributary valleys emptying from the Central Mountains onto the Arco Desert and Snake River Plain. The main canyons are named the Birch Creek (purple label A in Fig. 1a), Little Lost (B), and Big Lost (C) valleys. These valleys are “dry” topographic features with annual precipitation below 25 cm (10 in). The complex topography of eastern Idaho leads to varied patterns in atmospheric pressure, temperature, wind, cloudiness, and precipitation (Wendell 1972; Andretta and Hazen 1998; Andretta 2002; Stewart et al. 2002).

### 3. Snowfall distribution

The Snake River Plain is relatively dry in winter compared to the surrounding mountains, similar to other broad valleys in the interior of western North America. According to data from the National

Climate Data Center (NCDC), much of the Lower Snake River Plain receives less than 2.5 cm (1 in) of precipitation in the month of November (blue area in Fig. 2a), while the peaks of the Southern Highlands receive over 8 cm (3 in) (pink areas in Fig. 2a). The SPCZ event of 26 November 2005 brought more snow to liquid water equivalent (SWE) precipitation to the southern Lower Snake River Plain than this area typically receives in the *entire* month (Fig. 2b). The amounts shown in Fig. 2b are radar-estimated<sup>1</sup>; thus, the useful domain of this snowfall map is limited to the region of low-level radar coverage, within ~75 km from the radar and away from the mountains. The 0.5° elevation angle suffers from terrain blockage in some sectors, especially southeast of the radar. However, there is no beam blockage in this elevation angle over the Snake River Plain. The

<sup>1</sup> The relation,  $Z = 75 S^2$ , is used following Vasiloff (2001), who applied it for winter snowfall in northern Utah. Herein,  $S$  is the SWE precipitation rate ( $\text{mm hr}^{-1}$ ) and  $Z$  is the equivalent reflectivity factor ( $\text{mm}^6 \text{m}^{-3}$ ) from the 0.5° elevation scan of the WSR-88D KSFX radar. The precipitation rate is accumulated for a 13 h period to obtain the data in Fig. 2b.

data in Fig. 2b cover a 13 h period which captures the full lifecycle of the SPCZ. Since no rain was reported (only snow) and the surface wet bulb temperature mostly remained below freezing during the event (not shown), the radar-estimated precipitation didn't experience significant bright-band contamination.

Snowfall exceeding 2.5 cm (1 in) of SWE (green shade in Fig. 2b) occurred in a southwest to northeast oriented band in the central lower plain from between Aberdeen and Blackfoot to the American Falls Reservoir. A second, parallel stripe of  $> 1$  in of SWE occurred closer to the Southern Highlands. Local precipitation maxima of 5–8 cm (2–3 in) occurred near Pocatello and Chubbuck. Much of the snow fell in a 5 h period (1900–0000 UTC), during the mature stage of the SPCZ. The few available spotter reports confirmed the heavy snowfall near Pocatello and just west of the Pocatello Range (Fig. 2b).

#### 4. Data sources

This study used National Oceanic and Atmospheric Administration (NOAA) geostationary (GOES 10 platform) 4 km resolution infrared imagery (<http://www.goes.noaa.gov/>). The gridded model analysis fields were obtained from the 12 km North American Mesoscale Model (NAM), which are archived in the NOAA National Operational Model Archive and Distribution System (NOMADS) (<http://nomads.ncdc.noaa.gov/>). Furthermore, we used operational radiosonde data, available from <http://weather.uwyo.edu/upperair/>. The NOAA Forecast Systems Laboratory (FSL) disseminates Aeronautical Radio, Inc. (ARINC) Communications, Addressing, and Reporting System (ACARS) (<http://amdar.noaa.gov/>) weather data from commercial aircraft. We also used ACARS temperature and wind profiles across southern Idaho based on 1533 UTC take-off from and 2012 UTC landing at the Boise Air Terminal (KBOI), 150 km west of Burley Municipal Airport (KBYI) in Fig. 1b.

The University of Utah collects Mesowest observations (<http://mesowest.utah.edu/index.html>), across the western United States and elsewhere (Horel et al. 2002). This dense mesonet provides both real-time and archived sensible weather information. This study used 114 mesonet sites in the domain (Fig. 1a). The original (e.g., temperature) or derived (e.g., potential temperature  $\theta$ ) fields were spatially distributed on a Cartesian grid using an inverse distance weighting scheme from ESRI ArcGIS Spatial Analyst mapping software. There are many more grid points than stations, but in

the Arco Desert the typical station spacing is close to 4 km; hence, we chose 4 km as the grid spacing. The horizontal wind components ( $u$ ,  $v$ ) are gridded as scalars and then combined as a vector. Variables derived from the surface wind, such as divergence and (relative) vorticity, are calculated from the gridded ( $u$ ,  $v$ ) field and then interpolated to a 12 km grid using the inverse distance weighting interpolation method. Even a 12 km grid is overly refined, with ten times as many grid points as stations. Few stations exist in the surrounding mountains, but the station density in the Snake River Plain justifies the use of a 12 km resolution. We are particularly interested in this resolution because the distance between the dry valleys in the Central Mountains is  $\sim 24$  km, and high-resolution simulations (discussed in Part II) reveal vorticity features with a typical spacing of  $\sim 24$  km. Our exploration of observational data, presented in this paper, is driven by a quest to find similar features in the surface station and radar data.

Regarding radar data, the WSR-88D (Weather Surveillance Radar 1988 Doppler) KSFX ( $\lambda = 10$  cm) radar (Fig. 1b) is ideally located to capture much of the Snake River Plain. It is the only radar with low-level coverage there. The KSFX radar Levels II and III data were obtained at the National Climatic Data Center (NCDC) from its vast data repository <http://www.ncdc.noaa.gov/oa/radar/>. The temporal resolution of radar data is 5 minutes for Volume Coverage Pattern 11. Data sets in this paper include the equivalent reflectivity factor (i.e., reflectivity) and radial velocity.

#### 5. Typical terrain-induced flow patterns

The topographic configuration of the large crescent-shaped Snake River Plain and connecting dry valleys (e.g., Birch Creek) generate thermally-forced horizontal wind flows and associated circulations on synoptically quiescent days (Whiteman 2000). Daytime heating produces an anabatic southwesterly flow in the convective boundary layer which reaches a maximum in the early evening (Fig. 3a). The upslope flow in the smaller tributary valleys develops and peaks earlier in the day. This thermally direct flow may support afternoon convection if sufficient moisture is present, especially over the higher terrain to the east of the Snake River Plain. Downslope flow develops at night, first in the tributary valleys and later across the Snake River Plain (Fig. 3b). Katabatic northeasterly flow in the Lower Snake River Plain typically peaks shortly after sunrise. This drainage flow typically is far more shallow than the daytime anabatic flow.



Anabatic flow is more common and stronger in summer; drainage flow prevails in the cold season.

Synoptically active flow disrupts these mountain-valley thermal circulations. In particular, during cold frontal passages (Fig. 3c), northwesterly winds at the  $\sim 750$  hPa level become channeled through the narrow terrain gaps of the dry valleys, at the same time westerly post-frontal surface flow ascends the Snake River Plain. This flow often strengthens after cold-frontal passage, in response to a tightening horizontal pressure gradient, resulting in continued orographically aided precipitation over the Eastern and Southern Highlands. This point will be revisited in Section 6. When a post-frontal cold-air mass of sufficient depth settles over Montana, it subsequently spills over the Continental Divide in far northeast Idaho and katabatic flow develops in the Upper Snake River Plain. The intersection of the channeled northwesterly flow from the dry valleys and the channeled westerly flow from the Magic Valley initially form the low-level topographic convergence zone (the SPCZ) in the upper plain (Fig. 3d).

In a typical SPCZ sequence, deep frontal precipitation moves towards the east or southeast, out of the domain in Fig. 1a, before the SPCZ develops. Widespread post-frontal subsidence, as well as local subsidence in the lee of the Central Mountains, would support an argument against further precipitation. However, the confluence of the three air currents mentioned above may lead to clouds and precipitation in the expansive plain over several hours after frontal passage during the cold season (Andretta and Hazen 1998; Andretta 2002). Cold gap currents from southern Montana which spill into the Upper Snake Highlands are not significant for SPCZ formation.

## 6. Meso- $\alpha$ scale analysis

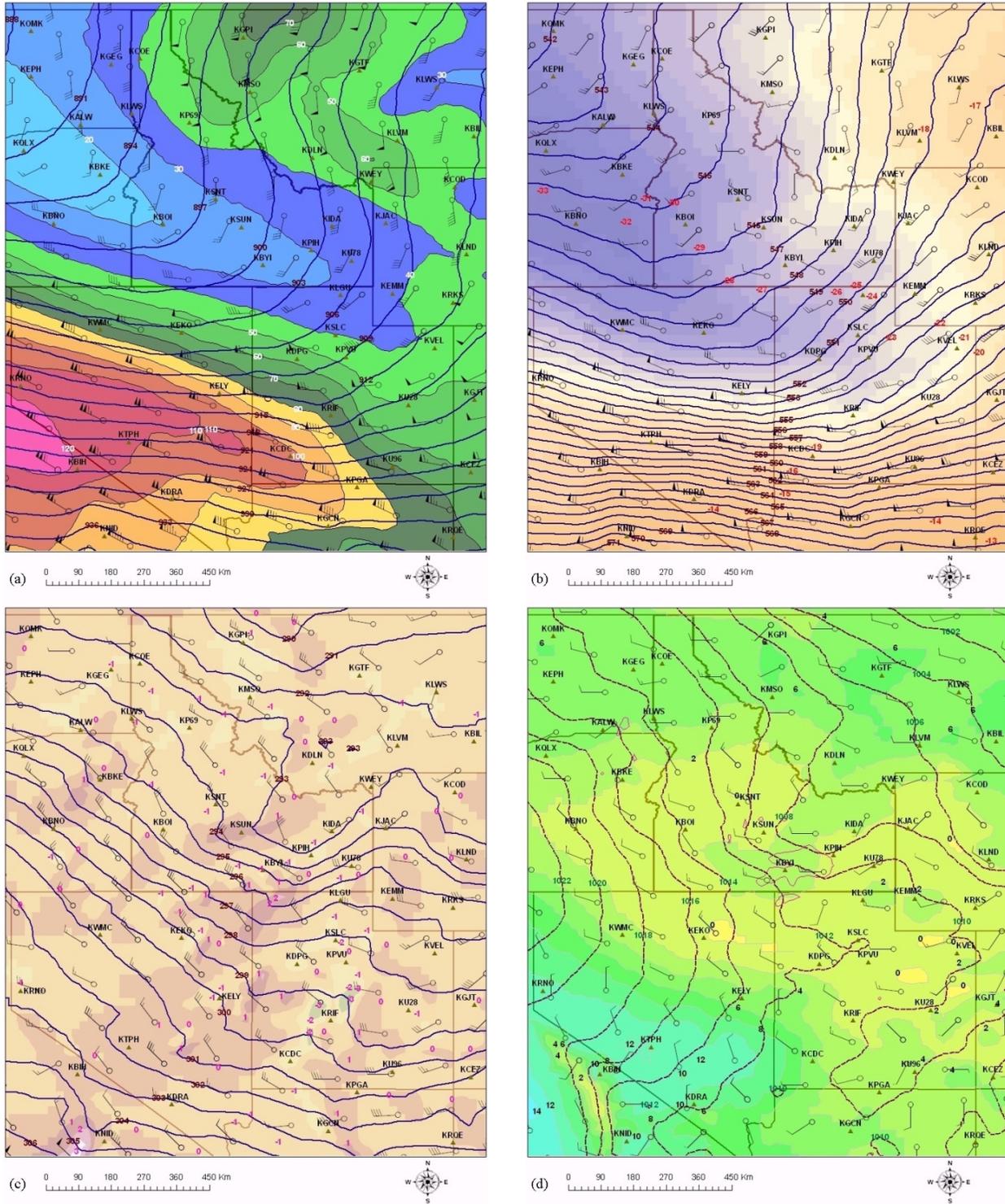
Winter-storm conditions developed and prevailed across much of the Snake River Plain between 1500 and 2300 UTC on 26 November 2005. We analyze the meso- $\alpha$  scale conditions between 1200 and 1800 UTC with the 12 km NAM 00 h analysis grids (Figs. 4 and 5). The SPCZ was best defined between 1800–0000 UTC.

The 300 hPa (Fig. 4a) analysis at 1200 UTC shows a negatively-tilted open wave trough over Idaho with a vigorous  $57 \text{ m s}^{-1}$  (110 kt) jet streak on the upstream side of the trough extending from coastal Oregon to central Nevada. The trough

and lighter winds were situated over eastern Idaho; the left exit region of the jet streak with northeasterly ageostrophic winds was situated just south of the Idaho-Utah border, resulting in divergence in southeast Idaho.

At 1200 and 1800 UTC, cold air was advected across southeast Idaho at 500 hPa (Figs. 4b and 5b) and at the lower levels (not shown). The flow was post-frontal, with winds backing with height between 700–500 hPa. Northwesterly flow of  $13\text{--}18 \text{ m s}^{-1}$  (25–35 kt) prevailed across Idaho at 700 hPa (Figs. 4c and 5c). Troughing occurred in the lee of the Central Mountains at this level and below it (Figs. 4d and 5d). This low-level trough over the Snake River Plain weakened after 1800 UTC but remained stationary, apparently locked to the terrain. The trough was also associated with low-level rising motion in a belt over and aligned with the Snake River Plain (Figs. 4c and 5c). At 1800 UTC, this rising motion peaked near the northerly periphery of the upper plain. This is one of the meso- $\alpha$  scale signatures of a developing SPCZ.

The MSL geostrophic flow was northerly but the actual surface wind was westerly in the Snake River Plain (Fig. 5d). This wind was part of a  $> 10 \text{ m s}^{-1}$  (20 kt) low-level jet blowing down-gradient across the Snake River Valley, peaking in strength over the Magic Valley. The mean sea-level pressure gradient considerably tightened between 1200–1800 UTC to 10 hPa along a 400 km long transect from KBOI to KU78 (Figs. 4d and 5d). As the pressure gradient force increased, the region of surface winds over  $10 \text{ m s}^{-1}$  (20 kt) expanded and covered most of southern Idaho. Doppler radar data (see below) indicated that these winds were part of a westerly low-level jet that follows the Snake River Plain, partially blocked by the Southern Highlands. Thus, this jet can be called a barrier jet (Parish 1982). A quasistationary, 1004 hPa surface low was situated over west-central Wyoming near Lander, with a cold-frontal trough evident through Utah (Fig. 4d). The lower-tropospheric stability was low over southern Idaho because of the low 500 hPa temperatures; the lifted index was generally only +2 at 1200 UTC (Fig. 4d), and remained low for the next 12 h. The lifted index generally was higher elsewhere in the domain of Fig. 4a, including northwest of the Central Mountains, where it was about +6 at 1200 UTC. This was significant because the high stability upstream makes the flow more conducive to channeling around the Central Mountains.



**Figure 4:** 12 km NAM analyses valid at 1200 UTC 26 November 2005, all geopotential heights in dm, full wind barbs are  $5 \text{ m s}^{-1}$  or 10 kt in black: a) 300 hPa height (solid blue contours with brown labels), isotachs (blue to red shades with white labels), and wind barbs; b) 500 hPa height (blue contours with brown labels), temperature ( $^{\circ}\text{C}$ , blue to red shades with red labels), and wind barbs; c) 700 hPa height (blue contours with brown labels), vertical velocity in  $\text{Pa s}^{-1}$ , positive values indicate ascent (brown shades with pink labels), and wind barbs; d) MSL pressure (hPa, dashed brown contours with green labels), lifted index ( $^{\circ}\text{C}$ , green shades with black labels), 10-m AGL wind barbs, and 10-m AGL isotachs  $>20 \text{ kt}$  (pink contours). *Click images to enlarge.*



This synoptic evolution resembled the Type A SPCZ pattern (Andretta 2002). The convergence zone lasted about 12 h and progressed through formation, persistence, and decay stages (Andretta and Hazen 1998).

## 7. Vertical structure

The high stability as evident in the lifted index ( $LI > +6$ ) northwest of the Central Mountains (Fig. 5d) suggests that the flow is likely to be channeled around the mountain obstacle and into the Snake River Plain, leading to convergence in the lee of the mountain. The argument of blocked flow around a mountain has been used to explain the Puget Sound Convergence Zone (Mass 1981; Mass and Dempsey 1985). We examine the Froude number ( $Fr$ ) over the depth of the obstacle in the upstream environment (Reinecke and Durran 2008):

$$Fr = \frac{U}{NH} \quad (1)$$

where  $U$  is the mean wind speed below the (smoothed) highest terrain,  $N$  is the mean Brunt-Väisälä frequency over the same depth, and  $H$  is the height of the (smoothed) highest terrain over the mean height of the surrounding region. The estimate clearly is subjective, given the complexity of the terrain and the uncertain definition of the upstream environment. The Central Mountains contain many peaks above 2.5–3.0 km MSL, but they are porous obstacles with deep gaps roughly aligned with the northwesterly flow (Fig. 1). The 1200 UTC sounding at Spokane International Airport (KGEF, Fig. 6a) yields a Froude number of 0.36, assuming  $H$  to be 2000 m. The condition  $Fr \ll 1$  implies that the low-level flow is blocked and can only go around the mountain obstacle. KBOI (Fig. 4a) is located on the southwestern side of the Central Mountains, or  $\sim 150$  km west of KBYI in Fig. 1b. The 1200 UTC Boise sounding (Fig. 6b) captures this flow around the mountain, as a low-level northwesterly jet up to  $18 \text{ m s}^{-1}$  (35 kt) (Fig. 6a). Note the nearly moist-neutral stratification at Boise up to  $\sim 550$  hPa, consistent with the low LI values in the Snake River Plain (Fig. 6d).

An ACARS sounding near KBOI (1533 UTC) (Fig. 6c) indicated stable conditions in the lowest 650 m and near-neutral dry and then moist conditions above, up to the lower tropopause at 525 hPa. Northwesterly flow of  $10\text{--}15 \text{ m s}^{-1}$  (20–30 kt) prevailed in this near-neutral layer. Surface data at KBOI at 1600 UTC showed a dewpoint depression of 2 K, implying a cloud base of  $\sim 250$  m AGL under the

strong low-level wind conditions. Thus, the top of the surface stable layer at 840 hPa in the ACARS sounding was saturated. In that case, the CAPE was  $< 200 \text{ J kg}^{-1}$  between 800 and 600 hPa for a parcel emerging from the top of the surface stable layer.

The low-level stable layer had vanished as a result of low-level mixing by 2012 UTC (Fig. 6d). A dry adiabatic lapse rate was present in the lowest 1.2 km, and the low-level northwesterly jet extended to the surface. High surface humidity (not shown) suggests the possibility of shallow moist convection, because there was some CAPE between 800 and 700 hPa, with minimal convective inhibition. The air above mountaintop level ( $\sim 700$  hPa) had become more stable over KBOI by 2012 UTC, capping any convection near 700 hPa where the temperature was  $\sim -15^\circ\text{C}$ . A strong barrier jet of  $13\text{--}18 \text{ m s}^{-1}$  (25–35 kt) was clearly evident in both ACARS soundings, in Fig. 6a between 300–1500 m AGL, and in Fig. 6b from the surface to  $\sim 2000$  m AGL.

As noted by Kirshbaum and Durran (2005a, 2005b), a stable capping layer aloft, low Froude number, unidirectional flow in the boundary layer, and moist neutral sounding are factors conducive to orographic flow-parallel bands of precipitation. Based on the regional soundings and ACARS data, it is evident that similar conditions were present in the thermodynamic environment of this SPCZ.

## 8. Meso- $\beta$ scale analysis

We now examine the structure and evolution of the SPCZ, by means of satellite, surface station mesonetwork, and Doppler radar data.

### a. Frontal analysis

The mesoscale analyses of surface wind, temperature, and cold front position are shown in Figs. 7b, 7c, and 7d at 0900, 1000, and 1100 UTC, respectively. We used  $\theta$  instead of temperature because of the large terrain elevation variations in the region of interest. We calculated  $\theta$  from the Poisson equation. Only a fraction ( $\sim 30\%$ ) of the Mesoscale stations report surface pressure, yet all record temperature. In order to obtain  $\theta$ , we calculated station pressure hydrostatically, integrating vertically from a baseline valley elevation (1200 m). Then we interpolated  $\theta$  (or any other scalar) from the irregular station layout to a Cartesian grid using the inverse distance weighting scheme, following Sanders and Doswell (1995) and Sanders (1999).

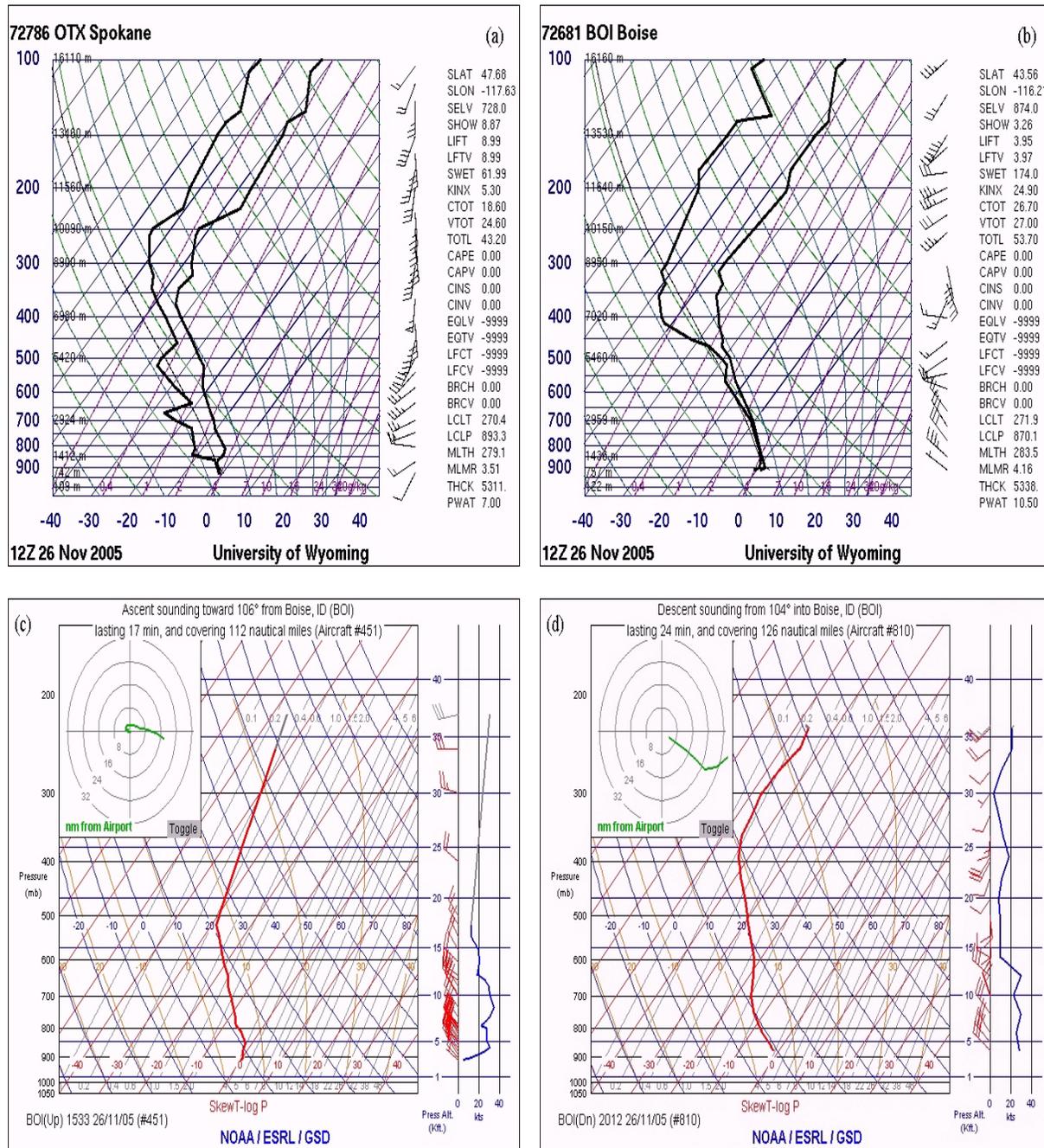


Figure 6: Skew-T representation of 26 November 2005 soundings as follows: a) radiosonde, Spokane International Airport (KGEV), 1200 UTC, b) radiosonde, Boise Air Terminal (KBOI), 1200 UTC, c) ACARS ascending from KBOI, 1533 UTC, and d) ACARS descending into KBOI, 2012 UTC. Click images to enlarge.

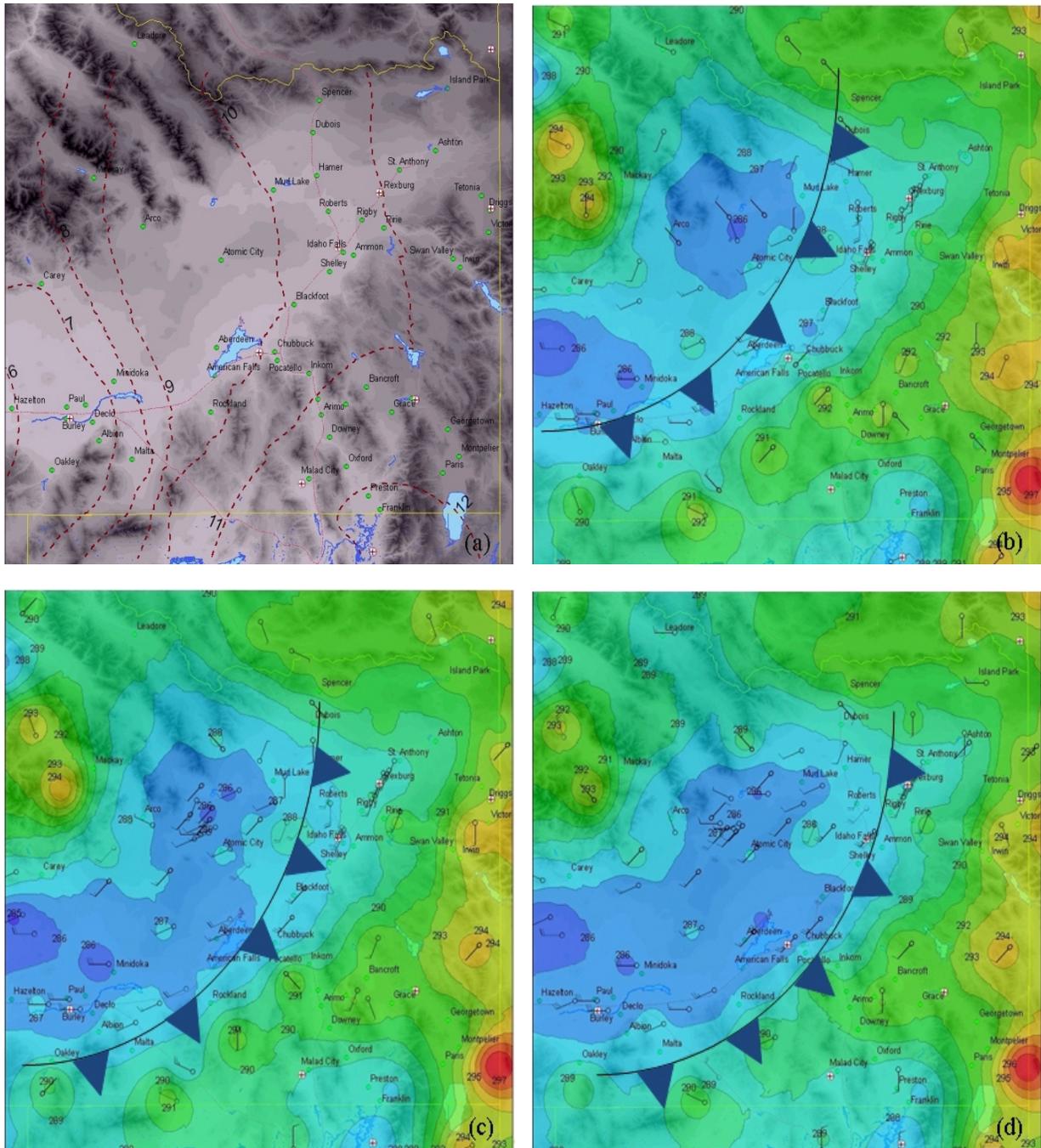


Figure 7: a) Dashed brown isochrones (in UTC hour, 26 November 2005) of minimum mean sea-level pressure (zero isallobar) with black labels; Mesowest 10-m AGL wind barbs (kt, black), 2-m AGL  $\theta$  (K) in blue (cool) to red (warm) shades, with grey contours and black labels, and surface cold front position at these UTC times: b) 0900, c) 1000, and d) 1100. *Click images to enlarge.*

The higher  $\theta$  values corresponded with higher station elevations in Figs. 6b–6c; the lower troposphere was stably stratified. While this pattern was best defined at night (Figs. 7b–7d), it persisted throughout the day. Surface temperatures did not change significantly following cold-frontal passage. In addition, the time series of station pressure were used to reveal the movement of the cold-frontal pressure trough across the Snake River Plain (Fig. 7a). The location of the cold front roughly coincided with the leading edge of cold air at  $\theta \sim 287$ – $288$  K (dark blue shades in Figs. 7b, 7c, and 7d). The minimum pressure isochrones were oriented on the warm side of the strongest  $\theta$  gradient. The configuration of this gradient and nearly coincident wind shift line represented a conventional front (Sanders and Doswell 1995; Schultz 2005).

#### b. Thermodynamic and radar evolution

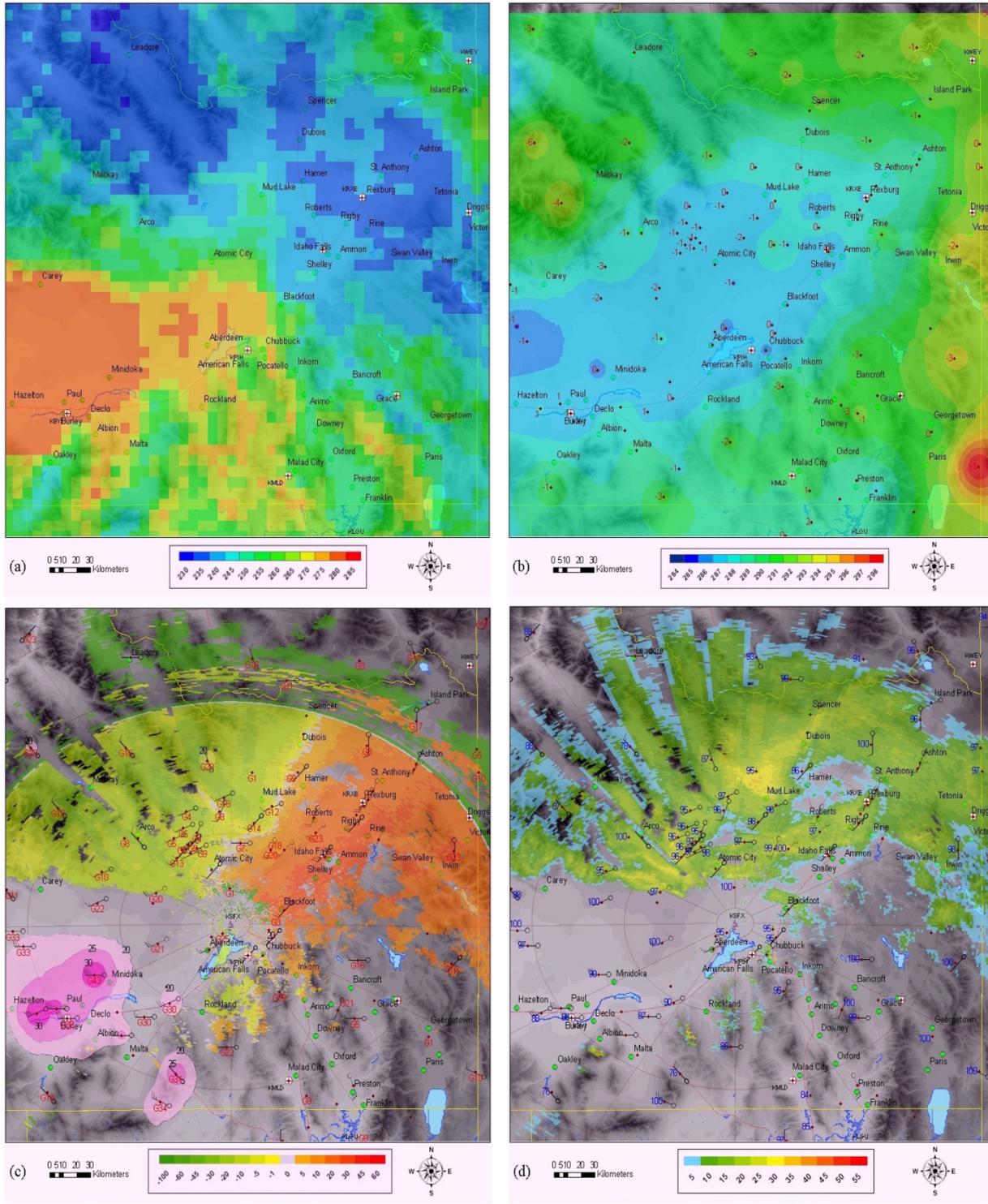
A series of three four-panel plots of GOES IR, surface station and KSFx radar data (Figs. 8, 9 and 10) is used to examine the development of the SPCZ and snowstorm in the Snake River Valley following the passage of the cold front. At 1200 UTC, low-level clouds were present over the lower plain (brightness temperature:  $260 \text{ K} < T_b < 265 \text{ K}$ ) and the Magic Valley ( $265 \text{ K} < T_b < 275 \text{ K}$ ) (Fig. 8a). Surface station and radar data indicated that precipitation fell from the deep clouds in the upper plain. Northwesterly surface flow was present already at 1200 UTC in the three dry valleys of the Central Mountains and the Arco Desert, according to surface wind measurements and the KSFx  $0.5^\circ$  radial velocity map (Fig. 8c). Strong near-surface westerly winds occurred near KSFx, as evident in the radial velocity zero isodop (grey shade). The radial velocity pattern at  $0.5^\circ$  also indicated a westerly low-level wind maximum west of the radar. This low-level maximum is the barrier jet documented by the KBOI radiosonde and ACARS soundings (Fig. 6) and 12 km NAM model output. The Mesowest data showed that this jet was best developed in the Magic Valley. Radar echoes were scarce in this region. The Southern Highlands form a very porous barrier and some of the jet flow was channeled through the gaps between the mountain ranges, resulting in strong northwesterly wind in these gaps. Light to moderate snow showers (15–30 dBZ) were scattered across the upper plain (Fig. 8d) in the post-frontal air mass.

By 1800 UTC, clouds had deepened over the Snake River Plain with colder brightness temperatures (Fig. 9a). A region of locally cold surface air ( $\theta \sim 284$ – $287$  K), centered in the Magic Valley and Lower Snake River Plain, spread

eastward during the morning hours (Figs. 9b and 10b). A serpentine zero isodop (grey shade) formed, indicating a zone of veering winds, from southwesterly near the surface to northwesterly aloft (Wood and Brown 1986). However, the asymmetry between the northern and southern parts of the radial velocity patterns suggested horizontal wind variations. The zero isodop traced out a C-shape wind signature, indicating the confluence of northwesterly flow impinging from the north and the barrier jet approaching from the southwest. The surface mesonet winds superimposed on the KSFx  $0.5^\circ$  base velocity (Fig. 9c) confirmed this confluent wind signature.

Later in the morning, the KSFx  $0.5^\circ$  base reflectivity images depicted an expanding region of generally light snow (15–25 dBZ) across the upper plain. An along-valley snow band (label B1) was present in the upper plain at 1800 UTC (Fig. 9d), from Mud Lake to Rigby. This band slowly drifted to the south over the next 6 h as northwesterly flow emerged from the Central Mountains to the Arco Desert, remaining close to the northern branch of the zero isodop (Fig. 9c). This confluence line was sufficiently strong and deep to produce ascent and a snow band (label B2). By 1800 UTC, this snow band was along the southeastern edge of the upper plain (Fig. 9d). In addition to this along-valley snow band, two more bands (labels B3 and B4) formed around 1800 UTC oriented *parallel* with the 700 hPa northwesterly steering flow and parallel with the dry valleys. These lee convergent bands,  $\sim 50$ – $70$  km long and  $\sim 5$ – $10$  km wide (Fig. 3b) (e.g., downstream of the Central Mountains), were developed best in the upper plain and along the adjacent slopes, where they merged with the southwest to northeast oriented main convergence band. Bands B2, B3, and B4 were most continuous across the upper plain between 1900 and 2000 UTC. In this SPCZ case, the cold gap currents entering from southern Montana remained absent; thus, there was little baroclinicity across the upper plain (Fig. 9b).

During the afternoon ( $\sim 2100$  UTC) hours, the brightness temperatures (Fig. 10a) cooled further along a line from Pocatello to Downey in a region of enhanced radar reflectivity (Fig. 10d). By 2100 UTC, the Doppler radial velocities (Fig. 10c) and Mesowest data showed channeled northwest flow of  $10$ – $13 \text{ m s}^{-1}$  ( $20$ – $25$  kt) at the exit regions of the dry valleys. This flow encountered the westerly barrier jet of  $10$ – $15 \text{ m s}^{-1}$  ( $20$ – $30$  kt) along the northern fringe of the Southern Highlands (Fig. 4b). The  $\theta$  differences between these two air masses were small. In fact, surface data



**Figure 8:** Imagery valid at 1200 UTC 26 November 2005: a) NOAA GOES 10 Band 4 (10.70  $\mu\text{m}$ ) infrared satellite brightness temperature (K); b) Mesowest 2-m AGL  $\theta$  (K) and dry bulb temperature ( $^{\circ}\text{C}$ , red); c) KSFX WSR-88D 0.5 $^{\circ}$  radial velocity (kt), Mesowest 10-m AGL isotachs  $>20$  kt ( $>10$  m s $^{-1}$ ) in pink filled contours, 10-m AGL wind barbs (black) and gust (red); and d) KSFX WSR-88D 0.5 $^{\circ}$  base reflectivity (dBZ), Mesowest 10-m AGL wind barbs (black), and 2-m AGL relative humidity (%), dark blue). Each full wind barb represents 5 m s $^{-1}$  (10 kt). *Click images to enlarge.*

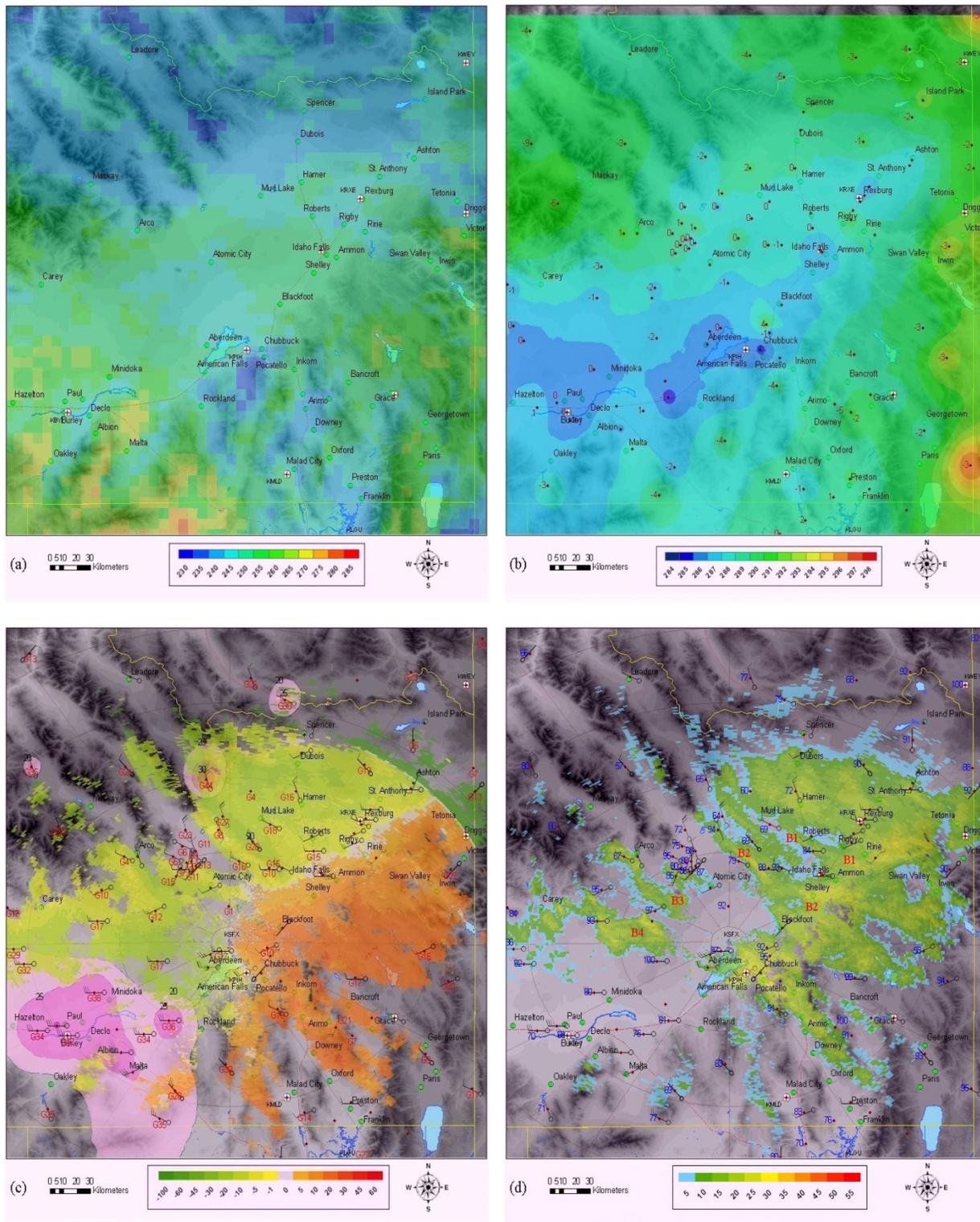


Figure 9: As in Fig. 8, except for 1800 UTC. *Click images to enlarge.*

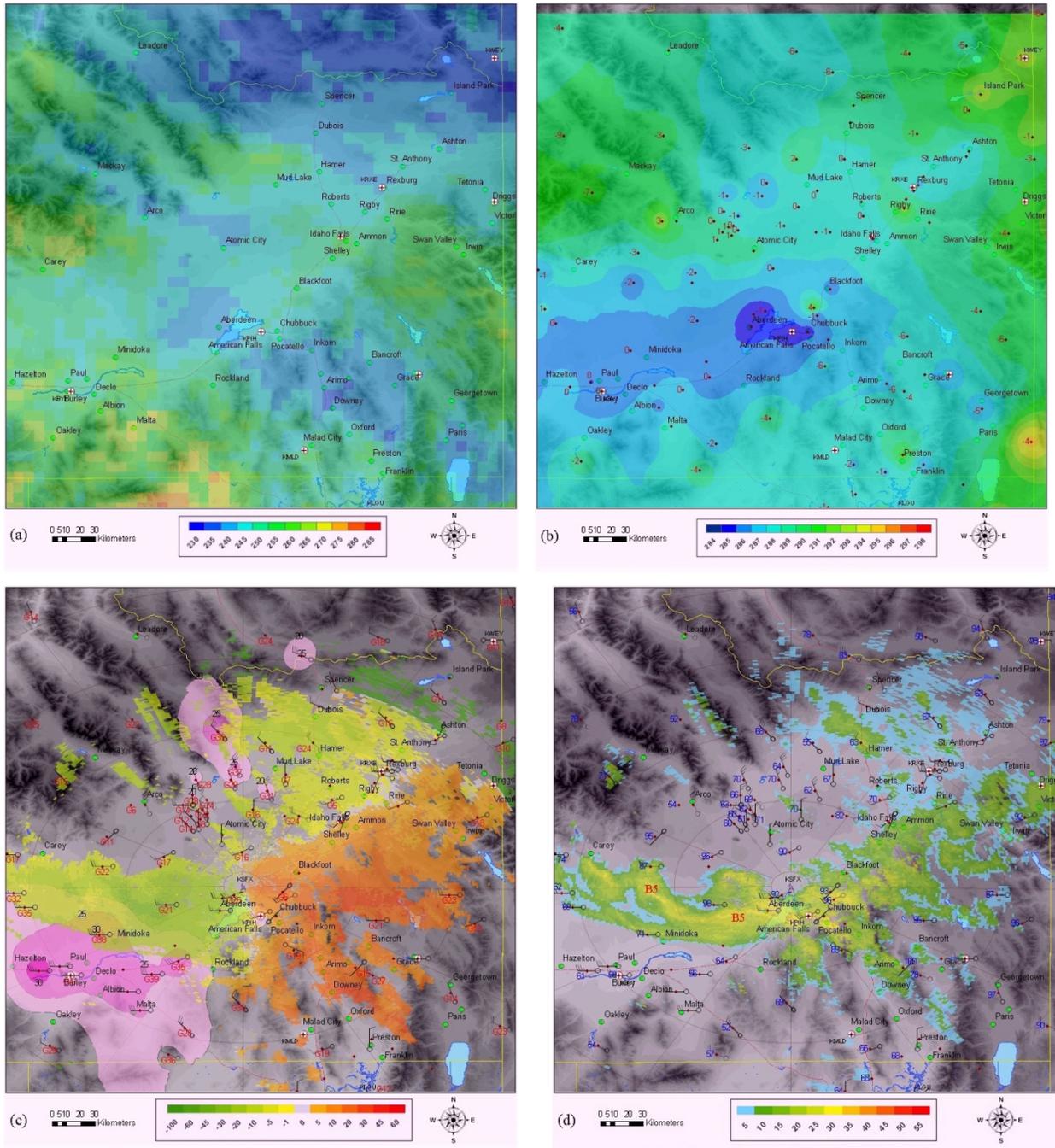


Figure 10: As in Fig. 8, except for 2100 UTC. *Click images to enlarge.*

didn't indicate frontogenesis a cross snow bands B1 or B2 in the Snake River Plain (Figs. 8b, 9b, and 10b). Nevertheless, the confluent flow was convergent; the updrafts which created the snow bands were equivalent to the low-level convergence. The orographic ascent of the barrier jet along the northern fringes of the ranges of the Southern Highlands in the Pocatello Range (east of Pocatello) led to heavy precipitation there. The numerous light

to moderate snow showers (25-40 dBZ) which were earlier south of the Arco Desert coalesced into a large solitary band (~150 km long, label B5) along the southern fringes of the Snake River Plain (Fig. 10d). This broad, crescent-shaped band and the associated convergence between the barrier jet and the northwesterly gap flow remained nearly stationary over the Pocatello area for several hours, producing light to moderate snow and a prolonged period of

snow accumulations. This period marked the peak intensity of the SPCZ. The highest radar reflectivity values (30–40 dBZ) occurred near the American Falls Reservoir, and storm-total precipitation maximum occurred just northeast of the reservoir and the KSFX radar tower (Fig. 2b). This enhancement may have been influenced by surface sensible and latent heat fluxes over the lake, sufficient to trigger shallow moist convection (Carpenter 1993; Niziol et al. 1995).

The boundary separating northwesterly from southwesterly flow remained close to the southern edge of the Snake River Plain as the SPCZ event started to dissipate around sunset (2330 UTC). Orographic snowfall along the Southern Highlands continued for several hours after 0000 UTC (Fig. 12d) but rapidly diminished in the plain. As Fig. 2b illustrates, surface reports of the snowfall >30 cm (12 in) occurred in the Pocatello area. Despite the widespread coverage of precipitation in the lower plain, a stripe of 3–8 cm (1–3 in) of snowmelt was located along the western foothills of the Pocatello Range.

### c. Kinematic structure

We now analyze divergence and vorticity based on the Mesowest 10-m AGL horizontal winds. These figures again are shown for 1200, 1800, and 2100 UTC (Figs. 11, 12 and 13, respectively). Station data of the wind components first are redistributed on a 12-km Cartesian grid, as discussed in Section 4. The divergence and vorticity fields then are derived as centered finite differences. These fields are noisy because they are based on the derivatives of horizontal winds measured at stations of highly variable density in complex terrain. They are quite sensitive to measurement errors and to non-representativeness errors. Therefore, only the general patterns are meaningful. The reader can judge the observational basis of the divergence and vorticity patterns from the station data in Figs. 11, 12, and 13. High resolution model output, presented in Part II, does not suffer from this limitation; the observed patterns nevertheless are revealing.

The divergence field was dominated by two to three northwest-to-southeast oriented bands of low-level convergence, mainly at 1800 and 2100 UTC (Figs. 12 and 13). These bands were aligned with and roughly coincide with the snow bands (Figs. 9d and 10d) and extended across the lower plain and Southern Highlands. For instance, at 1800 UTC, snow bands B1 and B2 (Fig. 9d) correspond with roughly collocated convergent surface flow (label C1) (Fig. 12a). Bands B3 and B4 were roughly

coincident with a second convergent area (label C2). At 2100 UTC, snow band B5 situated between Carey and Minidoka (Fig. 10d) corresponded with a region of flow convergence (labels C3 and C4) (Fig. 13a). Thus, these convergence belts and the associated boundary-layer circulations apparently were tied to generation of the snow bands. Dry, subsident, northwesterly flow gradually spread over the Arco Desert and Upper Snake River Plain (Figs. 8d, 9d, and 10d) which decreased the area coverage of the snow bands associated with the SPCZ.

Multiple bands of low-level convergence (labels C1, C2, C3, and C4) and divergence existed over the Snake River Plain. Furthermore, although there was some directional convergence (label C2 in Fig. 12a) near the exit regions of the three tributary valleys, these convergence bands were oriented roughly parallel to the dry valleys. The convergence bands extended south of the plain into the Southern and Eastern Highlands (Fig. 1a), where the ridgelines exhibit the same alignment. As the figures indicate, there is substantial temporal continuity, giving confidence in the validity of the analyzed fields, and suggesting that the convergence bands were due to the interaction of the mean wind with the terrain. The number and spacing of convergence bands correspond with the number of ridges and their spacing in the Central Mountains. These convergence bands, aligned with the mean wind, clearly are not trapped lee waves, which are oriented normal to the mean wind over the terrain. Surface convergence between the barrier jet and the NW flow emerging from the three dry valleys is apparent at 2100 UTC only; it is possible that this convergence is mostly elevated, as suggested by the radar radial velocity pattern (Figs. 9c and 10c). Given the small  $\theta$  difference between the barrier jet and these currents (Figs. 9b and 10b), no frontal boundary formed. Instead, the barrier jet was deflected by the Southern Highlands, producing local upslope flow and heavy snowfall in the region.

The northwest-to-southeast alignment, parallel with the dry valleys, was even more apparent in the surface relative vorticity field (Figs. 11b, 12b, and 13b). The patterns were sustained for many hours, notwithstanding the uncertainty of vorticity calculation due to the paucity of data, especially in the Central Mountains and the Southern Highlands. In general, cyclonic vorticity dominated in the Snake River Plain, especially in the early stages of the SPCZ. This background vorticity may be associated with general cyclonic turning of channeled upslope flow in the Snake River Plain (Fig. 11b) and is consistent with the troughing in the valley (Fig. 4c). The most obvious pattern across all panels is a series

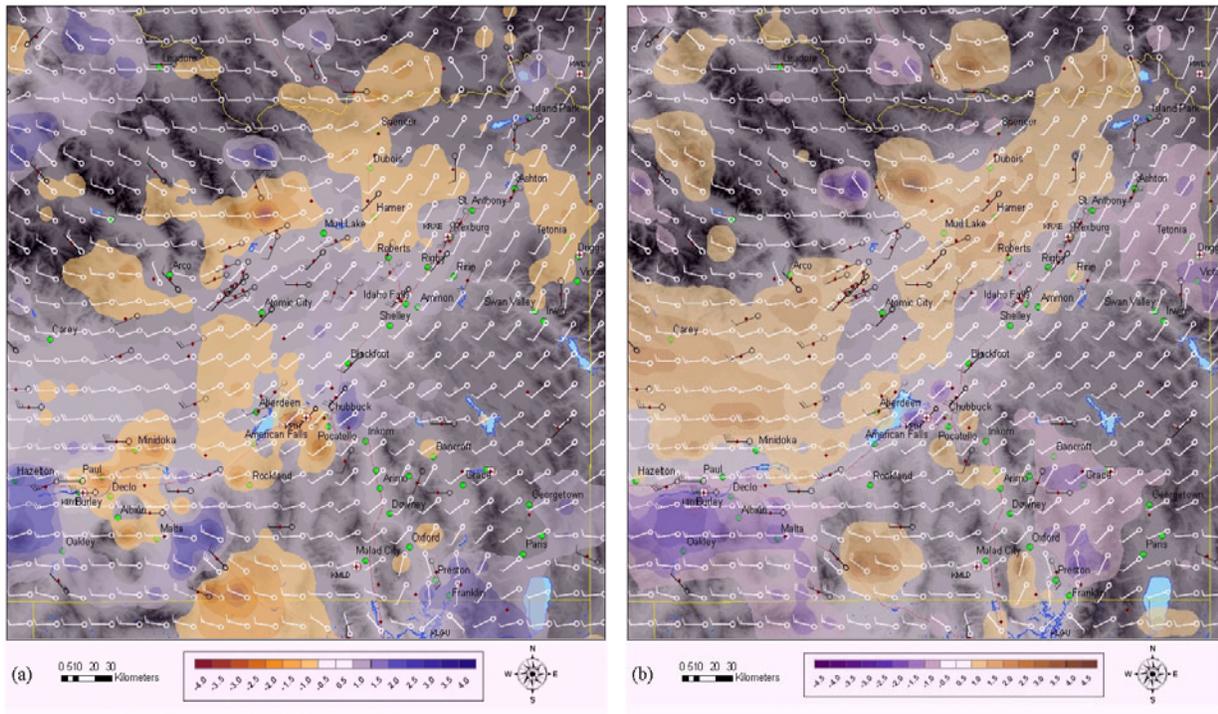


Figure 11: Mesowest – 1200 UTC a) horizontal divergence and b) vertical vorticity 4-km analyses ( $10^{-4} \text{ s}^{-1}$ ) of interpolated 10-m AGL wind. Observed 10-m AGL wind (black, barbs represent  $5 \text{ m s}^{-1}$  or 10 kt) and 12-km resolution gridded 10-m AGL wind (white, barbs represent  $5 \text{ m s}^{-1}$  or 10 kt) are shown. *Click images to enlarge.*

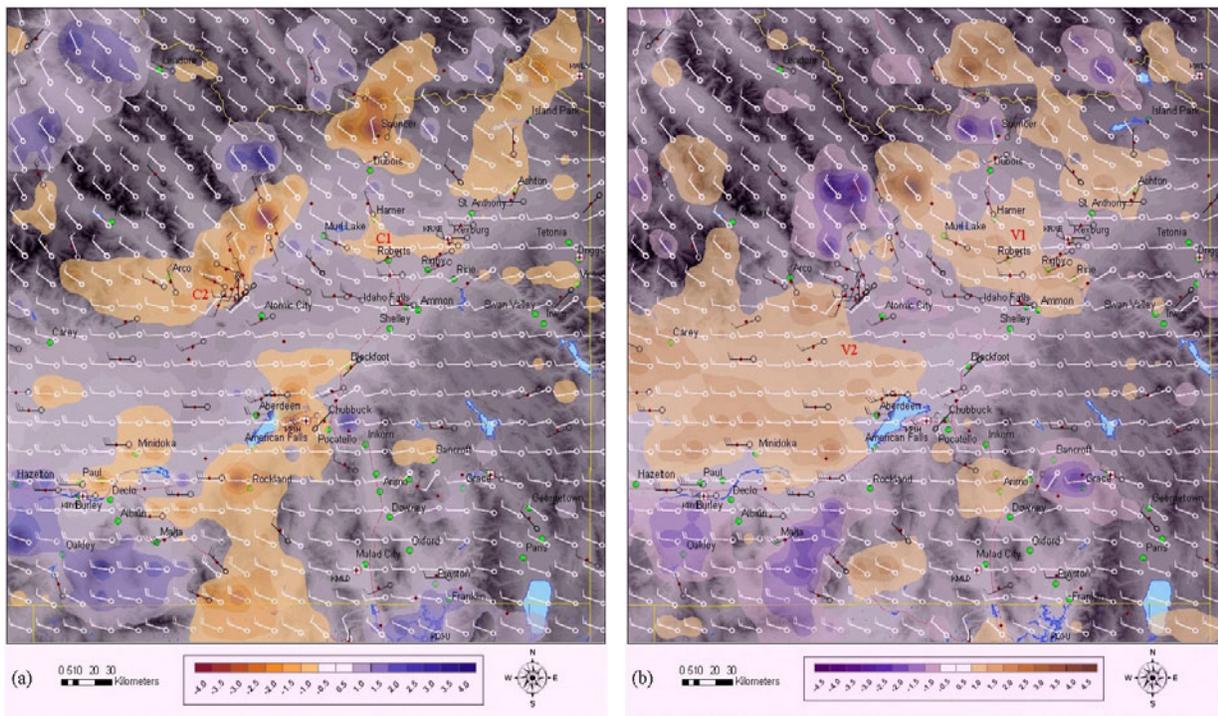


Figure 12: As in Fig. 11, except for 1800 UTC. *Click images to enlarge.*

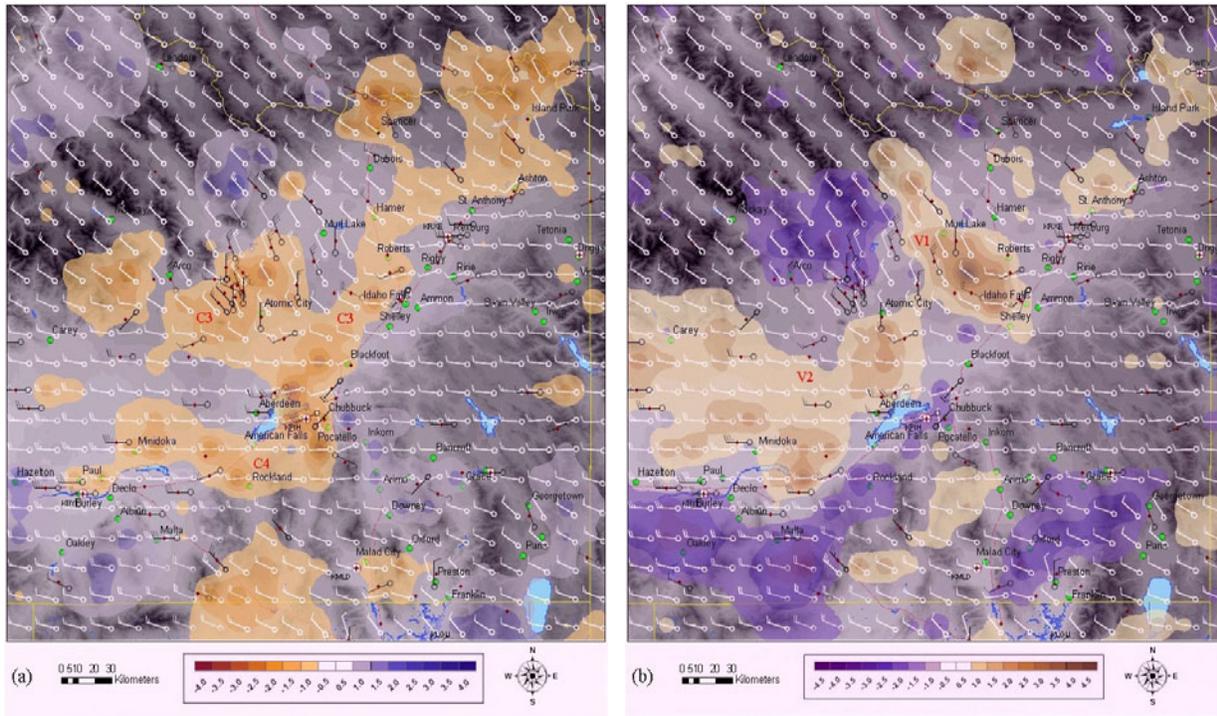


Figure 13: As in Fig. 11, except for 2100 UTC. *Click images to enlarge.*

of quasi-stationary bands of alternating positive and negative vorticity in the plain oriented *parallel* to the upstream terrain valleys and ridges. The surface data probably didn't reveal fully the extent and continuity of these vorticity bands.

The bands of cyclonic vorticity (labels V1, V2) coincided with convergence bands (labels C1, and C3) in some regions, but only partial spatial superposition is evident. This is clearly illustrated at 2100 UTC (Fig. 13). The cyclonic vorticity banner (label V1) emerging from the Birch Creek Valley (Fig. 1a) tends to persist across the upper plain in the vicinity of Roberts and Idaho Falls. This banner was mostly convergent (label C1), especially along its western margin. Another region of weak, cyclonic, convergent flow emerges from the Big Lost Valley, with local vorticity and convergence maxima between Arco and the American Falls Reservoir.

In Part II of the study, we will use high-resolution model output to investigate the origin of these vorticity bands (or more specifically, lower-tropospheric *potential* vorticity bands), and their relationship with low-level convergence and snow bands.

## 9. Conclusions

This study documented a heavy snowfall event in eastern Idaho on 26 November 2005 using

operational weather data. The region of heavy snowfall was localized in the Lower Snake River Plain along the western foothills of the Pocatello Range, with amounts varying from 3–8 cm (1–3 in) near the Pocatello Regional Airport to 25–38 cm (10–15 in) east and south of Pocatello. The snowfall was poorly predicted and fell well after the passage of the cold front in the lee of a major mountain range. This study (Part I) used observations to document the evolution of this Snake River Plain Convergence Zone (SPCZ) episode.

The heavy snowfall appears to have been driven by two principal forcing mechanisms: leeward and windward convergence. Firstly, the leeward convergence was the result of blocked flow from the northwest, reaching the Snake River Plain from the west, around the Idaho Central Mountains. This obstacle contains several deep, dry valleys. Northwestern gap currents emerged from these valleys into the Snake River Plain, where they produced several convergence and vorticity belts aligned with the wind and the valleys. Radar reflectivity maps indicated that SPCZ snowfall occurred in several bands, their widths, spacing, and orientation corresponding with the convergence and vorticity belts.

The second mechanism relates to the zonal low-level jet resulting from blocked flow circumventing

the Central Mountains. This jet gradually ascended with height across the Magic Valley and Lower Snake River Plain. This wind maximum had attributes of a barrier jet flowing along the Southern Highlands, a porous barrier along the southern periphery of the Snake River Plain. Windward convergence and orographic precipitation resulted as the jet ascended over the northernmost ridges in the Southern Highlands. Furthermore, this barrier jet converged with drier northwesterly flow emerging from the dry valleys in the Central Mountains, resulting in a belt of heavy snowfall aligned with the barrier jet, but over the central Snake River Plain, well north of the Southern Highlands. This jet was gradually squeezed to the south, resulting in a large solitary snow band over the southern margin of the Snake River Plain. This snow band persisted for several hours, resulting in heavy snowfall and near-blizzard conditions. While the flow upstream of the Central Mountains was stably stratified, the lower troposphere in the Snake River Plain was near-neutral during the SPCZ.

In Part II of this study, high-resolution WRF-ARW model simulations will be used to reproduce the observed flow and precipitation patterns, and to explore the dynamics of the SPCZ. In particular, Part II will address the origin of the well-defined, persistent (*potential*) vorticity belts, and their relationship with convergence and snow bands in the Snake River Plain. Our ultimate goal is to improve predictability of orographically-forced valley precipitation events in eastern Idaho and in other regions of the Intermountain West.

#### ACKNOWLEDGMENTS

A sincere appreciation is given to NOAA scientist William Moninger for access to ACARS data sets. The authors wish to thank the National Climatic Data Center for the NWS METAR observations and WSR-88D radial data from the KSFX site. The University of Utah supplied the online Mesowest observations. Finally, we appreciate many constructive suggestions from several reviewers: David Schultz, Kenneth Harding, and James Correia, Jr.

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**REVIEWER COMMENTS**

[Authors' responses in *blue italics*.]

**REVIEWER A (David M. Schultz):*****Initial Review:***

**Recommendation:** Accept with major revisions

**Substantive Comments:**

I want to like this paper—I want to like it a lot. The strengths of this paper are the interesting structure and evolution to the snowbands, the failure of models and humans to predict this event, the discussion of an event in a rarely studied region of the Intermountain West (Idaho), the use of multiple datasets for diagnosis, the thoroughness of the analysis, and the creative use of graphics. Unfortunately, many of these strengths end up being weaknesses because of the way they are implemented in the manuscript. My comments below focus on these fatal flaws and my major comments on the manuscript. I have many minor concerns, but until the science is solidified, I have only presented a sampling of them. Thus, these minor comments should be considered representative rather than comprehensive.

My recommendation is to combine Parts I and II into one high-quality manuscript. Thus, I am recommending revisions to this manuscript and resubmission, with evidence from the modeling work *demonstrating* the physical processes that have only been speculated upon by the authors at this stage.

*As per the guidance of EJSSM Editor Roger Edwards, this study will be a two part paper: Part I: Observational Analysis and Part II: WRF-ARW Simulations. The title of Part I has been changed to reflect the reviewer's suggestion of a cause and effect type of relationship. We hear your concerns and our comments follow below. Thank you for the very detailed and constructive review.*

**[Fatal Flaws]**

1. I am concerned about Part I and Part II manuscripts. In one paragraph on p. 19, the authors conclude through speculation that PV banners are responsible for the organization of the precipitation, but they do not test alternative ideas (discussed more in Fatal Flaw #10), leaving the true diagnostics to Part II that would justify their scientific explanation proposed in Part I. Unfortunately, scientific papers need to stand alone, and the main thrust of this manuscript (Part I) cannot be left to speculation. Because the manuscript is too long (Fatal Flaws #2 and 3, Major Comments #8 and 9), I recommend that the manuscripts be combined into one high-quality and well-justified manuscript.

*We have omitted the discussion of PV banners because of the lack of concrete, supporting, observational evidence and have focused on the mechanisms of windward and leeward convergence. In Part II, 3D model output from WRF/ARW simulation will be used to map PV, leading to a clearer description of the PV banners, their origin, and their impact on precipitation formation. The new version of the manuscript has been trimmed to 20-21 pages with 15 figures.*

2. The manuscript is too long and has too many unnecessary figures. The manuscript is 25 journal pages long and 18 figures (many with four panels). If the manuscript made the most out of these figures, I wouldn't have as much of a problem, but these 18 figures are not made to work for the manuscript. Many figure panels are not even discussed in the text, leading to the 2 immediate question of why they are included in the manuscript at all. Perhaps relevant for a technical memorandum or a post-mortem of the storm, this many figures are not needed for a scientific article. These are the figures that I think are not necessary: 1b, 4a, 2b,c, 3, 4, some of the panels in 5, 6, 7, 8b, some of the panels in 9, 11, 13, some of the panels in 14, and some of the panels in 15. The few values in Fig. 18 could be printed overtop one of the other maps (e.g., Fig. 17).

*The new version of the manuscript has been trimmed to 20-21 pages with 15 figures. In addition, we have enlarged some of the figures and cropped other ones for clarity and discussion. The figure inventory has been revamped entirely and addresses these concerns.*

3. Too much tangential material is presented. The authors should focus on the story to tell, not on diversionary topics. Ingredients-based thinking can help focus your manuscript. Major Comments #8 and #9 have more to say about unnecessary material. One example occurs on pp. 1–2: The SPCZ appears too early for the reader to have any context for this material. Wait until after you present evidence of a SPCZ in your data before introducing this material.

*We have included new sections which explain the different wind flow patterns in eastern Idaho. This occurs in the proper order of the paper. The tangential information has been removed from the revised paper.*

4. The figures are unreadable at the scale they are published. The text is too small. Figure 16 is printed at the right size to be readable. Nonstandard color schemes are used (for example, for radar imagery). Choices of colors are less than ideal (e.g., yellow lettering in Fig. 1a). Many color figures have no color scale for reference. Too much white space in between panels prevents them being expanded in scale. Too many gradations in scale (e.g., Fig. 12) prevent a quantitative assessment of values. The maximum should be 5 scales, which is all the human eye can distinguish quantitatively. In Fig. 17, blue shading over-prints the other colors.

*All these issues have been addressed and fixed in the paper. For example, the radar reflectivity and base velocity plots contain a legible standardized color scale comparable to those used by the NWS RIDGE radar web pages.*

5. The authors do not appeal to an ingredients-based thinking. Instead, all kinds of figures are presented to the reader, often with little context for why we are being shown these figures. For example, deep moist convection requires lift, instability, and moisture. Convective snow requires deep, moist convection, plus below-zero temperatures and other microphysical constraints that are underdeveloped in the manuscript (e.g., Wetzel and Martin 2001; Schultz et al. 2002, comments on Wetzel and Martin; Schultz and Vavrek 2009, to appear in *Weather*). The paper could be organized by discussion of these ingredients in order. Instead, instability, for example, is discussed on pp. 4, 8, and 12.

*We agree. The revised paper contains “ingredients-based” thinking with emphasis on the (theoretical) windward and leeward valley convergence mechanisms.*

6. Too often, nonscientific or nonsensical statements are made.

a. “This convergence...formed as a result of the westerly low-level jet..., producing surface winds....” (p. 19)

b. “the jet converged” (p. 24)

c. “There is some evidence that these low-level PV banners tended to harbor convergent flow” (p. 24) [PV was never calculated. Convergence is *associated with* advecting PV anomalies, not harbored by.]

d. “The ascent of this jet...was not baroclinic” (p. 1)

e. “This case study illustrates how the ...topography...created...blizzard conditions in a synoptic... situation and geographic... situation.” (p. 1).

f. “jet streak slowly propagated” (p. 3): Movement is advection plus propagation. The authors should say “moved” rather than “propagated” in this context, unless they are certain that advective processes were not acting to move the jet streak eastward.

g. “jet was deflected...producing heavy snowfall there.” First, jets are wind maxima and therefore respond to forces. They are not objects to be moved around. Second, other factors are involved in producing heavy snow other than the location of a jet. (In fact, a wind speed maximum is not an ingredient for heavy snowfall.)

h. “amassed potential vorticity” (p. 24)

*We agree. Some rather colloquial expressions, including all of the above phrases or sentences, have been changed into specific, precise language that can be translated into quantifiable dynamic processes.*

7. Too often, no evidence is presented to verify the authors' statements.
  - a. "these boundary-layer circulations appear to have generated the snow bands" (p. 19): What is the timeline of the circulations and the bands? Does one precede the other? Or, are the circulations a **result** of the bands?
  - b. "The lack of baroclinicity suggests that it did not ascend over the northwesterly current." (p. 24)
  - c. "unblocked flow" (p. 24) On p. 12, the authors claim the flow was blocked.
  - d. "precipitation resulted from an ascending low-level jet": the authors have not shown that a certain amount of ascent was responsible for producing precipitation. Does this sentence refer to the 400 m of ascent from going up the Snake River plain?
  - e. "With little warning" (p. 3): The authors never show that the operational forecast models failed to predict the snow nor did they show that the human forecasters failed to predict the snow.

*All statements now are corroborated by evidence in figures or the published literature. Unsupported statements are either omitted or stated as being speculative. The issue of the operational weather forecasts is discussed below.*

8. The authors have not demonstrated that PV banners (as defined by papers discussing results from the Alps) are relevant for this Idaho case. The last two paragraphs on p. 19 make the following argument.
  - a. Cyclonic vorticity is present along convergent bands emanating from the valley.
  - b. Other studies have associated banners of PV downstream of mountains.
  - c. Although we don't compute PV, we assume it is present in these banners, so the bands are the same as PV banners.

There are numerous problems with this argument. First is that no morphological similarity between the Idaho bands and the Alps PV banners has been shown. Do the bands have the same phase relationship to the topography as the PV banners in the Alps? Second, even if they were morphologically similar, the bands have not been demonstrated to be dynamically similar. The conditions for PV banner formation have not been investigated for this case. Do they form in the same environment?

*We have removed the emphasis on PV banners in the new version of the paper. In Part II, we will compute PV using model output and we will attempt to demonstrate that: (a) the modeled surface vorticity banners are similar to the observed ones; (b) the modeled surface vorticity banners are associated with PV banners whose depth corresponds with the height of the highest terrain over the valley; and (c) that these banners organize precipitation. In Part I, we use the observational network to document the existence of bands of surface vorticity and surface convergence.*

The authors have thoroughly documented this case. They have suggested a previously undocumented effect resulted in the banded precipitation (PV banners). Yet, they present no evidence that PV banners are present. As such, this paper cannot be published on speculation alone.

9. How typical or atypical is this case? The authors present no data that suggests how unusual this amount of snow is.

*This event yielded more snowfall than other SPCZs but is typical in terms of the spatial distribution of localized heavy snowfall near Pocatello versus other documented SPCZs (e.g., Andretta and Hazen 1998).*

10. The best science is where a suite of hypotheses are proposed, then tested against the available data. The remaining hypotheses are then the most likely explanation. Unfortunately, the authors did not approach their work this way. They proposed a candidate mechanism (PV banners), then made little effort to demonstrate that PV banners were present and that they preceded the precipitation.

*The revised paper has the following hypotheses: (1) under suitable synoptic conditions post-frontal precipitation in the Snake River Plain of eastern Idaho occurs in the form of bands roughly aligned with*

*the flow above the upstream terrain and with the upstream valley/ridge system; (2) these precipitation bands are roughly coincident with bands of surface convergence; and (3) the convergence bands are roughly collocated with cyclonic vorticity bands in the plain. Hypotheses related to PV banners will be discussed in Part II of the paper.*

11. It would make sense to separate out the discussion of the initiation of the snow bands from their linear organization, but the authors appear to intricately tie the two together. I am not sure that combining initiation and organization is necessarily the best way to obtain the most effective understanding of the case.

*We believe that much insight can be gained by examining the origin of the snow bands over the Snake River Plain. Initiation and organization are intricately linked, especially since the bands are rather short-lived. Thus, the revised manuscript still examines the banded structure of precipitation and surface in a chronological sequence.*

### **[Major Comments]**

1. The title gives the audience no idea about what is contained within. For 99.9% of the audience, the date of the snowstorm will not mean anything. I suggest retitling the manuscript to something like, “Convective snowbands in eastern Idaho associated with *<physical process or processes>*.”

*The title has been changed to the proposed recommendation, although the term “convective” has been omitted; the convection was weak, local, and short-lived.*

2. So many times, I see vague, nonquantitative terms expressed. These include: “significant snowfall/rising motion” (reserve the term “significant” for statistically significance), “heavy snowfall”, “deep postfrontal flow”, “unusual patterns in atmospheric pressure...”, “intense convergence zone,” “some CAPE between 800 and 700 mb,” “deep low-level jet,” and “upper-level flow decreased in speed from 20 knots...” These should be quantified wherever possible.

*The text now is more quantitative, although a balance is needed among clarity, fluency of the text, and quantitative precision.*

3. The term “low-level jet” is introduced on p. 4, but the wind profiles showing the low-level jet are not shown until p. 13. Also, given the variety of different low-level jets that may occur at night due to decoupling with the PBL, I suggest changing the term to “low-level wind maximum” or “barrier jet.” (If the latter, then demonstrate more clearly that the flow is trapped against the barrier.)

*We agree and have changed this term to read barrier jet. We have shown the geographical confinement of this wind maximum, upstream of elevated terrain, and cited the Parish 1982 study as a key reference on the low-level topographic barrier jet.*

4. I am confused about the flow being “roughly normal to the convergence bands.” If so, how do the PV banners play a role, where these are parallel to the bands?

*While the barrier jet is roughly normal to the convergence bands, the 700 hPa steering flow is roughly parallel with the convergence bands. The text has been clarified in the revised manuscript.*

5. The paper is poorly motivated and organized. The first sentence of section 1 says a surprise storm happens. The second and third sentences give the snow amounts. The fourth sentence talks about this case. I am disappointed that no discussion of what the specific forecast (operational NWP or human) was for this case. (Are we to take the authors’ word that this was a “surprise”? How much of a surprise?) This would be a good place to present the snow depth map (Fig. 18). Then, the methods (“state of the art GIS scenes”) and goals (“mesoscale dynamics”) are introduced.

*The specific NOAA NWS weather forecast from the Pocatello/Idaho Falls office is provided for reference.*

IDZ021-270430-

LOWER SNAKE RIVER PLAIN INCLUDING  
THE CITIES OF...POCATELLO...BLACKFOOT...AMERICAN FALLS  
322 AM MST SAT NOV 26 2005

.TODAY...CLOUDY WITH SCATTERED SNOW SHOWERS. WINDY. LESS THAN ONE INCH  
SNOW ACCUMULATION. HIGHS 31 TO 38. SOUTHWEST WINDS 20 TO 30 MPH WITH GUSTS  
TO 40 MPH. AREAL COVERAGE OF PRECIPITATION 50 PERCENT.  
.TONIGHT...MOSTLY CLOUDY WITH A SLIGHT CHANCE OF SNOW. BREEZY...COLDER. LOWS  
13 TO 22. SOUTHWEST WINDS 15 TO 25 MPH. GUSTS UP TO 35 MPH IN THE EVENING.  
CHANCE OF PRECIPITATION 20 PERCENT.

*Based on this forecast of expected snowfall accumulation of less than 1 inch, it appears that the heavy snow event was a "surprise". Based on the area forecast discussions, the models did not do a very competent job of predicting the snowfall. The snowfall maps (Fig. 15) will remain at the end of the paper and are a follow-up to the discussion of the dynamics.*

6. Citations are included, but little reason is given for why these citations are relevant. These three are just a sampling.

- a. Hoenisch (2008): Are we to assume that Montana is similar to the Snake River Valley?
- b. Citations at the top of p. 3, first paragraph. Why are these papers cited in a big long list? Put them into context, if they are relevant. Otherwise, omit them.
- c. P. 14: Why are Carpenter and Niziol et al. cited for the zero isodop?

*These citations have either been removed or corrected in the revised manuscript. We kept some of the references on page 3 which relate to precipitation and flow patterns in eastern Idaho.*

7. The authors keep referring to post-cold-frontal flow, but the cold front is never shown. If never shown or discussed, why not just say northwesterly flow with geostrophic cold advection in the lower troposphere (if that is what is occurring). Schultz and Doswell (2000, *WAF*) argued that many "fronts" in the western U.S. are not frontal in character. Sanders (1999) has also made similar arguments.

*We agree. The frontal analyses at 09, 10, 11, and 12 UTC are included in the new version of the paper. These mentioned references have been cited as necessary in the amended text of the manuscript.*

8. I don't really see the point of the wet-bulb maps. You could simply say what the ranges of near-surface values were. The spatial distribution does not seem important to your point (i.e., it was cold enough to snow).

*We agree. We have removed these wet bulb plots from the paper, and simply stated that the surface wet-bulb temperature was just low enough for snowfall.*

9. P. 8, last paragraph: This paragraph seems an example of one ripe for trimming. You don't discuss the relevance of this warm anomaly to anything else about the storm.

*We have removed this comment of the warm anomaly from the paper.*

10. P. 12, A recent paper suggests that using the Froude number to determine flow blocking needs caution:

Reinecke, P. A., and D. R. Durran, 2008: Estimating topographic blocking using a Froude number when the static stability is nonuniform. *J. Atmos. Sci.*, **65**, 1035–1048.

*We were not aware of this relevant study. The revised manuscript acknowledges this point.*

11. PV banners have numerous citations, but the authors only single out one (p. 23) and state that they are associated with synoptic-scale lee cyclogenesis.

*We have removed all PV banner discussions and references from the paper.*

12. There are a suite of recent articles by Daniel Kirschbaum on orographic bands, yet these papers are not cited within this manuscript. I suggest that there might be some relevance of this work to the authors' research.

*We are familiar with some of this work and intend to add these references in the model study (Part II) of the paper.*

13. I don't understand why the observed precipitation amounts are shown at the end of the paper. Why not at the beginning?

*We disagree for the reason given above.*

*[Minor comments omitted...]*

### **Second review:**

**Recommendation:** Accept with major revisions

I remain disappointed with this manuscript. Sometimes the authors did not address my concerns from round 1. Other times they did not address my concerns satisfactorily, and other times they did improve the manuscript. In addition, I find new issues, both major and minor, that require addressing before the manuscript can be acceptable for publication. To address these comments will require another round of reviews, unfortunately.

### Major unresolved issues from the first round of reviews:

1. I am not convinced that a Part 1/Part 2 split is workable in the manner that the authors are trying it. First, there are enough unresolved issues that are left to the elusive Part 2 that frustrate me during the reading of Part 1. I am a big fan of an article standing by itself. I am not convinced that reading Part 1 of this manuscript teaches me something new, so that the numerical simulations would seem to be required to obtain that understanding. For example, the authors refer to banners, but have left it to Part 2 to describe these features. Therefore, they have no evidence that they are indeed banners.

Second, multiple-part manuscripts that depend on each other should be submitted together. That way, the reviewers can assess how these two manuscripts tie into each other. What happens if your model simulations reveal errors in your observational study that have already been published? Then, those errors remain in the literature.

Third, how do the authors know what kind of figures, maps, and analyses are needed in Part 1, if Part 2 isn't written?

*This will be a two part paper. We have significantly revamped Part I to give it enough robustness so it can stand alone as a published product.*

2. In response to my comment "too much tangential material is presented...wait until after you present evidence of a SPCZ in your data before introducing this material", the authors go through two sections of the paper (sections 4 and 5). I felt that this material was presented well before it was needed. Again, it feels like the authors are setting up the readers to see a convergence zone. I would rather see it from the data first, then be told about the conceptual model.

*We have streamlined the paper and addressed this concern.*

3. The figures have not been made more readable. More details to follow in the review.

*We have overhauled all the figures and have zoomed and enlarged the domain of interest in eastern Idaho. In other figures, the point sizes of the text labels were increased.*

4. Colloquial and incorrect scientific explanations remain. Details follow in the review.

*We agree and have corrected the text.*

5. Unsupported statements remain. Examples follow in the review.

*We agree and have corrected the text.*

6. The authors have said that they have addressed the operational weather forecasts (human and model), but they did not. Their response was not implemented in the paper, nor did they talk at all about the operational NWP output. They showed the forecast, but didn't describe it in the text. Thus, I am not convinced that this was a forecast scenario that was doomed to fail. The authors have failed to motivate this paper. If the event was a true forecast bust, then that should be interesting enough to motivate the paper, but the authors don't do that.

*We agree and have corrected the text. The paper has been motivated in the revamped Introduction.*

7. The authors state "Based on the area forecast discussions, the models did not do a very competent job of predicting the snowfall." But, they don't show the model output. The authors should defend their statements.

*We agree and have focused on the poor operational forecast of ~1 inch of snow in the lower plain. The model output statement has been removed from the paper.*

8. The authors have not addressed whether this event is typical. Their response was inadequate. "This event yielded more snowfall than other SPCZs but is typical in terms of the spatial distribution of localized heavy snowfall near Pocatello versus other documented SPCZs (e.g., Andretta and Hazen 1998)." What is climatology for these events?

*We agree and have expanded the Introduction to address your concerns. A climatology of SPCZs has been published in Andretta (2002) and a more vigorous treatment of climatological wind flows in an updated SPCZ climatology is a subject of Mr. Andretta's ongoing Ph.D. dissertation.*

9. The authors claim the following hypotheses: "The revised paper has the following hypotheses: (1) under suitable synoptic conditions post-frontal precipitation in the Snake River Plain of eastern Idaho occurs in the form of bands roughly aligned with the flow above the upstream terrain and with the upstream valley/ridge system; (2) these precipitation bands are roughly coincident with bands of surface convergence; and (3) the convergence bands are roughly collocated with cyclonic vorticity bands in the plain. Hypotheses related to PV banners will be discussed in Part II of the paper." There are problems with this. First, what distinguishes postfrontal events where precipitation forms from those where precip doesn't form? Because the authors don't present a climatology or any discussion of the frequency of these events, the audience is left wondering how frequent these bands are. Second, do bands form every time the large-scale flow is postfrontal? Third, by the continuity equation, you would expect near-surface convergence underneath precipitation bands (i.e., associated with ascent). So, the "hypothesis" that precipitation bands are "roughly coincident" with surface convergence should be eliminated from consideration.

*While certainly relevant and germane, these research questions are much more general from the specific SPCZ event that we are documenting in this paper. Some of these questions are being addressed in Mr. Andretta's ongoing Ph.D. dissertation. They are not the topic of this paper.*

So, after the dust settles, what is left of the manuscript that is a novel contribution to the literature? The formation of unforecast snowbands in postfrontal flow in southern Idaho is documented in 21 pages with difficult-to-read graphics. These bands are associated with vorticity and may be PV banners, but to know that we would have to await Part 2. I would rather see one single focused paper that presents this case succinctly and with some rigor than this one sprawling manuscript and a second expected.

*[Minor comments omitted...]*

**Third review:**

**Recommendation:** Accept with minor revisions

The authors have improved the manuscript, but there are still issues that need to be addressed for this manuscript to be acceptable for publication.

*[Minor comments omitted...]*

**REVIEWER B (Kenneth Harding):**

**Initial Review:**

**Reviewer recommendation:** Accept with revisions

**General Comments:** First, I'd like to thank the authors for conducting an observational analysis of a difficult forecast issue. Projects can often start with the modeling phase and leave out the necessary observational study. This type of research is exactly what operational forecasters need.

Overall, I believe the manuscript is well written and referenced. The main issue I have involves the graphics presented. Many, if not most, are unreadable due to their size. Full page graphics such as figure 16 were easily read, but figures containing topography or meteorological data were difficult to read (Figs. 1, 4). The VAD wind profiles of figure 9 and nearly impossible to decipher. Many graphics lacked a color scale (example: Figs. 4 and 5). Operational forecasters thrive on the graphics presented and will find them interesting if they are made more readable.

*The quality of the graphics has been improved in the revised paper.*

One other item I'd like to see diagrammed is the combination of forcing from the jet structure and the PV banners. This may be in part 2 of this study, but a diagram showing a conceptual model of the dynamics associated would be beneficial.

*We agree that a sketch showing a conceptual model of the dynamics of SPCZ evolution is needed. We will leave this task to Part II of the manuscript where supporting evidence will be given of the existence of PV banners. Thank you for the review.*

*[Minor comments omitted...]*

**Second review:**

**Reviewer recommendation:** Accept with minor revision.

**General Comments:** I very much enjoyed reading the paper. Operational forecasters will better understand and be better equipped to forecast future events like the one documented in this study. I don't have any major questions or concerns with this submission and suggest it is very nearly ready for publication.

The graphics are much improved. Although several are still small and a bit difficult to read, overall, they are certainly acceptable. The use of color and additional graphics (such as the arrows in figures 2 and 3) make the information much easier to read and digest.

*We have made significant changes to the figures and resized them according to your concerns. Please also note that any of these figures can be extracted from the manuscript and resized to user preferences in a graphics editor.*

**REVIEWER C (James Correia Jr.):****Initial Review:**

**Recommendation:** Reject.

**General Comments:**

I had a hard time writing this review, so I apologize if this is choppy. I read the paper enough times and was equally confused between the abstract, body, and conclusions of the paper. Something here is amiss. You have two mechanisms: banded precipitation from PV banners, and the solitary band formed from the low level jet, presumably. You make the case for all snow, little baroclinicity, post frontal environment. You speculate for some kind of isolated convection. There is speculation that what you see in the surface fields are PV banners. This clearly needs to be tested in a modeling framework as the surface data are not dense enough to draw any realistic conclusions.

I just do not make the clear connections on how all of this formed this heavy snow event. Nor did I see how this paper can help forecasters in this region anticipate an event such as this. This was one of the goals of the paper. There are a lot figures here that make small points, which should be removed (potential temperature, wet bulb temperature, relative humidity). There are a lot other figures which need to be culled to reveal the main points. The features of the flow need to drawn in on some maps, like the low level wind speed maximum, the PV banners, the snow bands. Perhaps focusing on the time period 1500-2100 UTC rather than 1200-0000 UTC? Perhaps you need to sell me more on what you want to test in the modeling paper. What story is the focus for the modeling paper? Then come back to this paper and present what is truly important. As with most observational papers, there is seldom enough data. That being said, can you really diagnose an event such as this with surface data?

*We hear your concerns and have addressed them with these changes. First, the text more clearly explains two convergence mechanisms. In the case of banded precipitation across the valley aligned with the 700 hPa steering flow, we demonstrate that surface convergence and vorticity fields are roughly aligned with these bands. We defer the explanation in terms of possible orographic PV generation in Part II (WRF-ARW model study) of the paper, in which the dynamically consistent 3D model output is used to support these results. In the case of precipitation on the windward side of the Southern Highlands, we describe this aspect in terms of a zonal barrier jet. Second, as you suggest, the revised manuscript focuses on the 18 and 21 UTC analyses. Third, some marginally important figures have been removed, such that the total number of figures has been reduced from 18 to 15. The revised text is more focused on the two mechanisms mentioned above, and has been trimmed from 25 to 20-21 pages. Thank you for the thorough and constructive review.*

**Summary:** The paper presents the local surface conditions associated with a surprise heavy snowfall event. It is speculated that convergence bands associated with PV banners, and a flow blocked low level jet contributed dynamically to the event.

**Major Comments:**

1. PV banners are not even discussed in the introduction. How do low-level PV banners contribute to the process of snowfall production?

*This question is explored further in Part II of the study.*

2. The models did poorly in producing snowfall, or did poorly in terms of the overall forecast evolution? The analysis in figures 2 and 3 suggest the NAM is capable of detecting the signature of SPCZ.

*The operational NAM model and the NWS forecast poorly predicted snowfall in the Snake River Plain. This is discussed in the Introduction section of Part I of the paper. We intend to explore the SPCZ precipitation spatial and temporal patterns using 4 km WRF-ARW model output in a separate paper (Part II).*

3. There is ample speculation with regard to PV banners at the surface. Does surface vorticity of a rather course mesonet actually depict these features? What is the resolution of the grid and how far away from a grid point is the surface data contributing?

*Derived quantities such as convergence and vorticity amplify the uncertainty (error) in the wind measurements, due both to instrument uncertainty and lack of representativeness of point measurements over the area across which differentials are computed. It is remarkable that the observational network in this rather complex terrain environment is sufficient to reveal basic convergence and vorticity patterns, reasonably matching high-resolution model output. The observed (u, v) components are spatially interpolated at a grid resolution of ~7 km before computing the derived fields. This resolution is coarse compared to the typical station spacing in the Upper Snake River Plain (~10 km), but fine compared to the typical spacing in outlying areas of the domain shown. We use an Inverse Distance Weighting (IDW) scheme to interpolate these derived fields. Diagnosis of model output, reserved for Part II, demonstrates that the near-surface PV pattern is very similar to the surface relative vorticity pattern. This is not surprising because stability (the other term in PV) varies little compared to vorticity.*

4. Given all of the soundings shown, is the vertical gradient of potential temperature significant enough to yield a dynamical response such that ascent is generated by the banner?

*The ascent in the convergence bands normal to the valley and in the barrier jet is close to moist-neutral, so it hardly affects the temperature and surface pressure fields. In other words, the lack of low-level stratification is sufficient to cause ascent.*

5. Half of the figures lack a description of what is being color shaded and at what intervals. It was difficult at best to read the maps let alone interpret them.

*Legend keys have been added to the figures, and the font and resolution are now larger. The reader can zoom in if the full page view is inadequate.*

*[Editor's Note: Authors since have provided full-resolution figures for hyperlinking, taking advantage of that capability in EJSSM.]*

6. I found the radar wind profiles to be of little use since nearly half the wind barbs are yellow and unreadable. Care should be taken to make a complete figure from this data carefully showing the feature of interest and its evolution. The ascending low level speed maximum is depicted in 50 minute chunks, with

gaps 2 hours long. I was not able to discern, based on these plots, if this feature being analyzed was indeed a classic low level jet (see Bonner 1968).

*The figures showing VAD wind profiles have been omitted. It did show a low-level wind maximum (Parish 1982), although the WSR-88D radial velocity data and NAM model output suggest that the barrier jet is better developed west of the radar.*

7. Mesoscale snow bands: where? I see areas of reflectivity but as far as actual isolated snow bands that are referred to, I only see the main band in Figure 12c. These bands need to be labeled for clarity.

*The snow bands are labeled with capital letters in the revised manuscript (Section 6).*

8. I needed to search the references to see the terrain features printed on a map so I could follow the discussion. Not every reader will be so familiar with a particular mesoscale region.

*All terrain features and place names mentioned in the text are shown in Fig. 1 of the revised manuscript.*

9. I was surprised to not see a time series of the snowfall or liquid equivalent that could give the reader any impression of when this event starts, ends, or when the snowfall is truly heavy across the region. Likewise, there was no surface map indicating the distribution of snowfall rates. This information is presented in the text but only vaguely. This lack of information rendered the reflectivity figures useless because there was no specific area with which to focus on. I could not construct a mental picture of where, when, and how all of the features evolved to yield the event.

*The storm-total precipitation (a radar product) is shown in Fig. 14, and snowfall plots are shown in Fig. 15. A time series of precipitation at any one point is not shown, indeed, but the Introduction section now mentions the heavy snowfall period. Time series data from the station mesonetwork and closest model grid points will be displayed and compared in Part II of the paper.*

10. You bring up a number of solid observations relating to the potential for upright convection. Are other mechanisms leading to convection possible? What about the radar data implies convection? Granularity is hardly criteria for assuming deep convection.

*The convection may have been forced with only 100 J kg<sup>-1</sup>. The presence of higher-reflectivity cores in an area of more uniform reflectivity suggests embedded convection. Note that the GOES IR satellite imagery in the afternoon hours of the event didn't indicate deep convection; cloud tops were closer to 500-400 hPa. We have removed the sentence on granularity in the revised manuscript.*

11. There was brief discussion of a cyclonic gyre in the reflectivity field. Was this feature identifiable in the velocity data?

*The cyclonic gyre is more apparent in an animation of the reflectivity field than in the Doppler velocity field. The mention of a gyre has been removed from the revised manuscript.*

*[Minor comments omitted...]*

### **Second review:**

**Reviewer recommendation:** Accept with major revision.

The paper is greatly improved, but still needs some attention enough to warrant somewhat major revision. Thank you for adding the topography section. I was able to follow the story much better. It is also much clearer what you explore in Part II, based on what was observed. The conceptual model section was great and it went a long way to help me understand the why, what and where for this event.

**Major Comments:**

1. Fragmented train of thought on why this event is presented in the first two paragraphs. Build the storyline: poorly forecast snow event which was dynamically driven by the unique terrain and atmospheric conditions that led to an SPCZ event. Let the reader in on the blizzard conditions in Pocatello even though only a few inches of snow fell.

*We have improved the text and added a new Figure 2 which highlights the precipitation in this event. This figure builds the storyline that led to the major snowfall event.*

2. Remove the content of Part II in the introduction. It serves as a distraction in its present location. You set up nicely what work is left for Part II throughout the paper but it is out of place in the introduction.

*We have adjusted the text accordingly.*

3. Figs. 4, 5, 6, 7: No color bars are shown to indicate positive or negative.

*There is no need for color bars (nor is there adequate room) in any of these figures because they all have labeled contours with additional color shadings. Furthermore, the various color tones are explained under every figure.*

4. P. 9, section 6b: I see no point to the frontal analysis. It adds very little to the discussion and does not focus on the period near 18-21 UTC. Perhaps you felt this section necessary to establish that the event took place in a post frontal environment, but the 18 UTC NAM analysis could be used to establish that.

*The SPCZ is a post cold-frontal mesoscale beta feature; the cold frontal analysis is relevant to the study and was included because at least one reviewer asked for it in a previous review.*

5. P. 9, section 6c: Is the BOI sounding close enough to the event to characterize the mesoscale environment near Pocatello? Can you make the case for the importance of this structure with the NAM 18 UTC analysis? Is CAPE necessary or relevant, and why?

*The BOI sounding is in a post cold-frontal air mass and is representative of the mesoscale environment. The 18 UTC NAM run clearly shows the low-level wind maximum expanding across the Magic Valley and the weakly positive 4 Layer Index. This feature forms the westerly wind component critical to the structure of the SPCZ. The low CAPE in the ACARS soundings coincides with the weak convective instability under the stable blocked flow.*

6. Section 6c: The section name is nondescript. Vertical structure of what? Ultimately I was left with the impression that you were trying to show that the flow was diverted around the mountains, which describes the vertical stability and dynamics of the barrier flow. I am not sure how CAPE into this section, nor how it adds much to the paper. I do think you haven't emphasized the continued cooling centered near 700 hPa, which contributes both to the stability of the layer aloft and produces a layer of neutrality in the PBL.

*As we tried to show in the section on the ACARS soundings and will again illuminate in Part II, the SPCZ forms under low potential instability (weak CAPE). There is also a unidirectional (NW or N) flow (e.g., low wind directional shear) in the PBL capped by an isothermal layer or small inversion near 400 mb. These different conditions aid in band organization and persistence downwind of the Central Mountain tributary valleys.*

7. P. 12, 3rd full paragraph: "near blizzard conditions", this information should be in the introduction. Is the timing of the blizzard conditions consistent with the conceptual model shown in figure 2d, where the onset of blizzard conditions coincides with the strongest horizontal pressure gradient?

*Yes, we agree and have moved this sentence to the beginning of the paper. The nearly 10 hPa pressure gradient from Boise to Pocatello (at 18 UTC) helped drive the strong upslope flow and blowing snow conducive to the near-blizzard conditions in the Pocatello area.*

8. P. 16: Thus these convergence belts..." The implication here is that you have proved that PBL circulations initiated the snow bands. I don't think you proved that PBL circulations initiated the snow bands since the evolution of the convergence does not match that of the snow bands. A more detailed analysis would be necessary to prove this. I think it would OK to speculate and state it as such. The companion paper should help explain what is causal.

*We agree and will test this as a hypothesis for Part II of the study.*

9. P. 18: The whole section on precipitation should be moved to give the reader some perspective on the event prior to the dynamical analysis, not after. I was bored with the section as it added very little to the dynamics in this order. Prior to reading this section, my mind was focused on Pocatello. I think it would serve your readers well to read this first, then dive into the dynamics, and leave the reader with the dynamical story rather than ending on the precipitation.

*As you suggest, this section has been moved to the beginning of the paper.*

10. Conclusions: "NAM poorly captured" the event: meaning it failed to produce excessive precipitation? An analysis was not performed on the forecast and no evidence was presented to backup this claim. Perhaps better wording is that the NAM QPF was too low for this region, and maybe in a related way forecasters bought into the NAM forecast. Was this the case?

*We have removed this sentence from the study and instead have focused on the poor operational NWS forecast cited in the paper.*

11. Conclusions: The conclusion should be that this was an SPCZ type of event, unique to this area. To say that windward and leeward convergence is the main result, I find misleading. The conceptual model you present early on represents convergence, but there is more to it than convergence. I would stress the conceptual model and factors that created the SPCV, namely the stability, wind direction through the valley's (at 700, 850 hPa). I guess I felt like you sold yourself short in that paragraph.

*The section on the leeward and windward convergence zones has been removed from the paper. We have focused on the conceptual flow model that led to the SPCZ (see Figure 3d).*

12. Conclusions: I think you can really set up Part II in closing with the findings and what you have to gain by running a numerical test. Frame it up like a hypothesis test. Here are plenty of open questions. What is the role of the vorticity belts and convergence areas from the 3 air streams? How do the vertical circulations originate and evolve in this complex flow regime?

*We agree with this assessment and have proposed these hypotheses for Part II of the study.*

13. Conclusions: The goal should be to identify the dynamics of an SPCZ event, relate those dynamical features to the available data, and get forecasters to recognize the conceptual model so forecasters can make these events more predictable.

*We agree with your conclusion and have modified the text accordingly.*

### **Third review:**

**Reviewer recommendation:** Accept.

I finished my review and I have nothing major or minor to add. The authors have addressed my concerns.