ONE HUNDRED INCHES IN ONE HUNDRED HOURS

The Complex Evolution of an Intermountain Winter Storm Cycle

BY W. JAMES STEENBURGH

From 22–27 November 2001, two complex Intermountain storm systems produced 108 inches of snow at Alta ski area in the Wasatch Mountains of northern Utah (Fig. 1; Steenburgh 2003). Since 100 in. fell in 100 h, local news media coined the phrases "100 inches in 100 hours" and "Hundred-Inch Storm Cycle" to describe the event (a storm cycle is a period where multiple winter storms occur in rapid succession). The storm cycle was the largest at Alta since 1991, provided a boost for preparations for the 2002 Winter Olympics, and produced substantial lowland precipitation. Salt Lake City International Airport (SLC) observed 1.27 in. of rain on 22 November, a record for a calendar day in that month, while during colder periods, up to 33 in. of snow fell in the Salt Lake City metropolitan area. The event provided an excellent example of the complex evolution of Intermountain winter storms, with storm stages delineated by the passage of large-scale weather features and their accompanying changes in stability and precipitation processes. Contrasts between mountain and lowland precipitation varied from stage to stage and storm to storm, illustrating the limitations of applying climatological precipitation–altitude relationships for short-range quantitative precipitation forecasting.

The first storm system moved through Utah from 0600 UTC 22 to 0700 UTC 24 November, producing 50 in. of snow at Alta. Time–height sections for SLC, created from hourly National Centers for Environmental Prediction (NCEP) Rapid Update Cycle (RUC2) analyses, showed an intrusion of low-θ_e air aloft several hours ahead of a surface-based cold front (Fig. 2). Widespread valley rain and mountain snow

AFFILIATION: STEENBURGH—NOAA Cooperative Institute for Regional Prediction and Department of Meteorology, University of Utah, Salt Lake City, Utah
CORRESPONDING AUTHOR: Dr. W. James Steenburgh, Department of Meteorology, 135 South 1460 East Room 819, Salt Lake City, UT 84112-0110
E-mail: jimsteen@met.utah.edu
DOI: 10.1175/BAMS-85-1-16

FIG. 1. The Hundred-Inch Storm Cycle enabled the opening of the ski season and brought a boost to Utah's ski industry and preparations for the 2002 Olympic Winter Games (top), but also caused downed trees and powerlines (center), contributed to 500 traffic accidents (bottom), and forced the closure of state highways and Interstate 15.

developed ahead of the leading-edge of low-θ_e aloft as warm advection and large-scale ascent moved over northern Utah. Precipitation during this stable stage was stratiform (Fig. 3a) and snow–water equivalent (SWE) at Alta (2946 m) was double that observed at nearby, low-elevation SLC (1288 m, Fig. 4). One contributor to this mountain–valley precipitation contrast was subcloud evaporation. Lower tropospheric dewpoint depressions over the Salt Lake Valley prior to precipitation onset were 10°–15°C.

Following passage of the leading edge of low-θ_e aloft, a layer of potential instability developed and deepened as θ_e decreased aloft and warm advection and solar insolation increased the low-level θ_e (Fig. 2). By 1600 UTC 22 November, scattered convective precipitation developed over northern Utah with strong reflectivity cores exceeding 35 dB*Z* (e.g., Fig. 3b). During this unstable prefrontal stage, convective initiation occurred over the lowlands and mountains. Alta received only 1.8 times as much SWE as SLC (Fig. 4), half the factor of 3.6 expected from climatology.

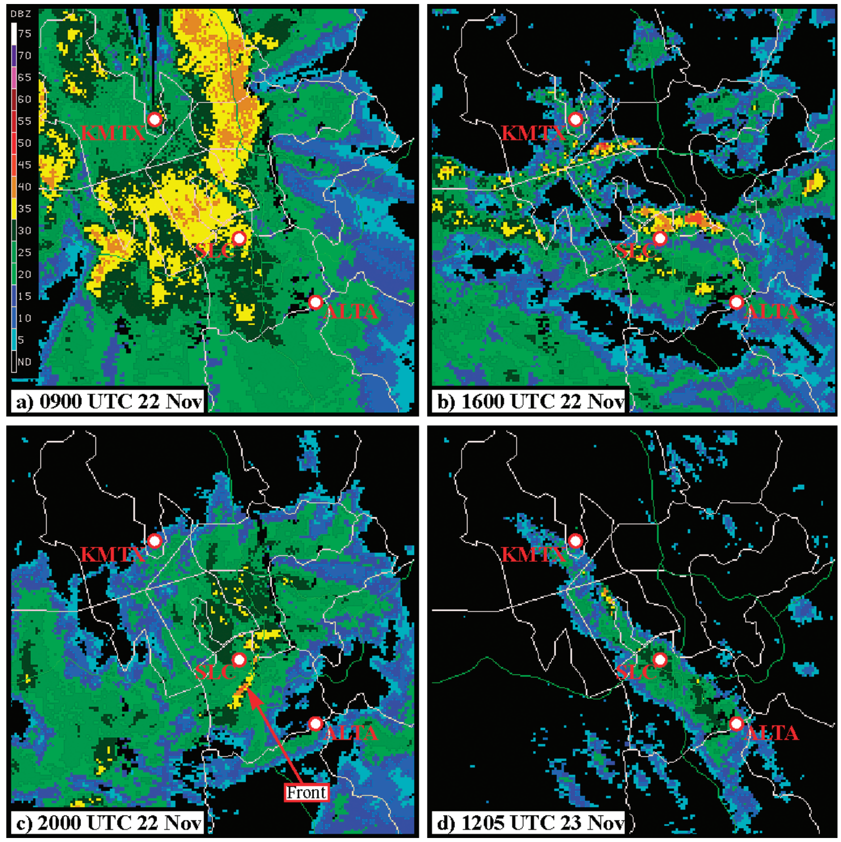

Fig. 3. KMTX lowest elevation angle (0.5°) base reflectivity analyses at (a) 0900 UTC 22 Nov, (b) 1600 UTC 22 Nov, (c) 2000 UTC 22 Nov, and (d) 1205 UTC 23 Nov. Reflectivity scale at upper left of (a).

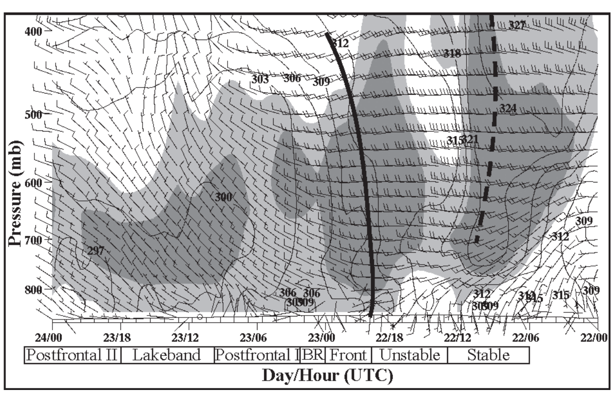

Fig. 2. RUC2 time–height section analyses at SLC from the first storm (0000 UTC 22–0000 UTC 24 Nov). Plotted are θ_e (every 3 K), relative humidity (light and dark shading denote > 70% and > 90%, respectively), and wind (full and half barbs denote 5 and 2.5 m s^{-1}, respectively). Heavy dashed and solid lines denote leading edge of low-θ_e aloft and surface-based cold front, respectively.

By 2000 UTC 22 November, the surface-based cold front was moving across northern Utah and was accompanied by a convective snowband with reflectivities exceeding 35 dBZ (Fig. 3c). Behind this feature, stratiform precipitation extended ~50 km upstream. During this frontal stage, orographic precipitation enhancement resulted in twice as much SWE at Alta as SLC (Fig. 4).

After a brief break, precipitation redeveloped after 0200 UTC 23 November as postfrontal northwesterly flow intensified, potential instability deepened (Fig. 2), and orographic and lake-effect snowshowers, which were heaviest and most frequent over the Wasatch Mountains and southeast of the Great Salt Lake, developed (not shown). This period, which we refer to as postfrontal stage I, produced 1.5 in. SWE at Alta (Fig. 4), 2.8 times more than at SLC (Fig. 4).

Beginning at 1000 UTC 23 November, precipitation was produced almost exclusively by a midlake

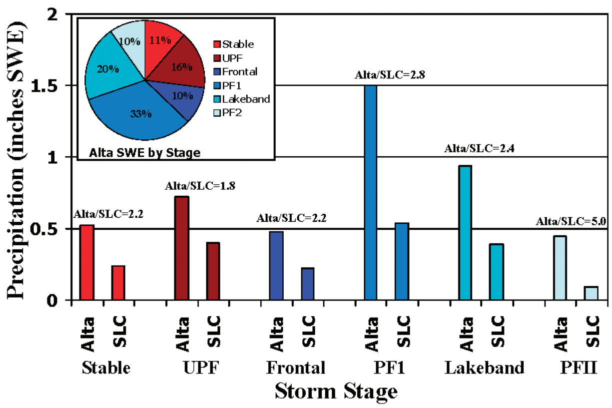

Fig. 4. Precipitation (inches of SWE) observed at Alta and SLC during each stage of first storm. Pie chart at upper left illustrates the percentage of Alta SWE by storm stage. Orographic enhancement factor (Alta/SLC) annotated.

snowband that extended along the major lake axis, over the Salt Lake Valley, and into the Wasatch Mountains (Fig. 3d). Although this was an impressive feature, it frequently shifted location so that hourly averaged precipitation rates at Alta and SLC, which were not always directly under the snowband, were smaller than observed prior to its development (not shown). Nevertheless, almost all of the SWE during this period, which amounted to 22% of the storm total at Alta (Fig. 4), was produced by the midlake band and concomitant orographic enhancement.

Postfrontal stage II began at 1800 UTC 23 November when the midlake band weakened rapidly and potential instability release and associated precipitation became increasingly confined to the mountains. This stage featured the largest contrast between mountain and valley precipitation of the first storm, with Alta receiving five times as much SWE as SLC (Fig. 4).

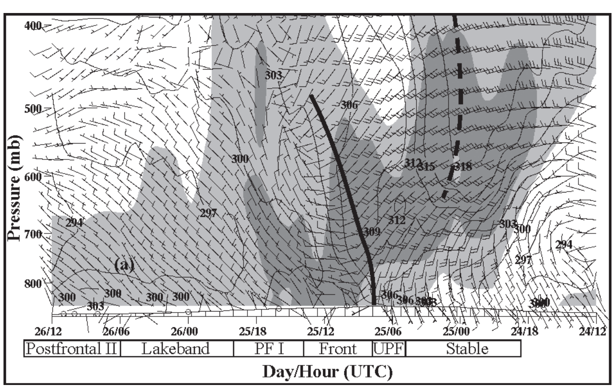

Fig. 5. Same as Fig. 2 except for second storm (1200 UTC 24–1200 UTC 26 Nov).

In total, precipitation in the unstable, postfrontal, northwesterly flow produced 63% of the total precipitation observed at Alta during the first storm (Fig. 4). Just over 20% of the storm total was produced by an orographically enhanced midlake snowband, with lake-effect processes also contributing to accumulations during postfrontal stage I. The ratio of precipitation at Alta to that at SLC varied from 1.8 during frontal passage to 5.0 during the last stage of the storm.

After a 12-h break, a second storm system produced 58 in. of snow at Alta from 1900 UTC 24 to 0300 UTC 27 November. Similar to the first storm, an intrusion of low-θ_e air aloft preceded the surface-based cold front by several hours (Fig. 5). Precipitation was initially stratiform (Fig. 6a), but embedded shallow convection developed following the passage of the leading edge of low-θ_e aloft (Fig. 6b). The contrast between mountain and lowland precipitation during the stable and unstable prefrontal stages was much larger during the second storm (cf. Figs. 4 and 7). In fact, only a trace of precipitation was observed at SLC during each stage, apparently due to subcloud evaporation during the stable stage and weaker, shallower convection during the unstable prefrontal stage. Periods where subcloud evaporation limits valley precipitation are so common in Utah that they are jokingly called "virga storms" by local meteorologists.

The surface-based cold front passed at ~0800 UTC 25 November, marking the onset of the frontal stage, which featured a convective line and a trailing region of stratiform precipitation (Fig. 6b). Limited orographic precipitation enhancement during this stage (Fig. 7) suggested that frontal circulations dominated precipitation dynamics.

After 1400 UTC 25 November, postfrontal destabilization (Fig. 5) resulted in the development of lake and orographic snowshowers (Fig. 6c). This storm stage, denoted as postfrontal stage I, was characterized by substantial orographic precipitation enhancement, with Alta observing 3.1 times as much SWE as SLC (Fig. 7). At ~2000 UTC 25 November, an intense midlake snowband developed and dominated the precipitation pattern for the next several hours (Fig. 6d). The highest precipitation rates of the storm cycle (0.3 in. SWE h^{-1}) were observed from 2200 UTC 25 to 0000 UTC 26 November, when Alta was directly beneath the snowband. Although hourly snowfall observations were not available, the 6% snow density observed for the 12 h encompassing this period yields a snowfall rate of 5 in. h^{-1}.

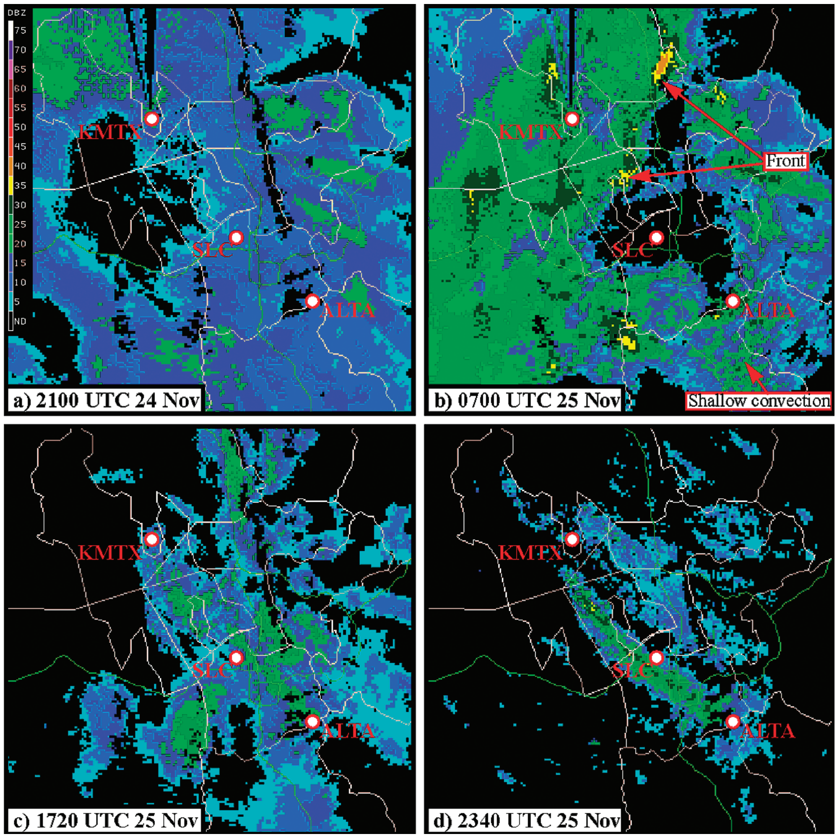

FIG. 6. KMTX lowest elevation angle (0.5°) base reflectivity analyses at (a) 2100 UTC 24 Nov, (b) 0700 UTC 25 Nov, (c) 1720 UTC 25 Nov, and (d) 2340 UTC 25 Nov. Reflectivity scale at upper left of (a).

At ~0600 UTC 26 November the midlake band dissipated, marking the beginning of postfrontal stage II, which featured periods of orographic and lake-effect snowshowers until 0300 UTC 27 November. As observed during the final stage of the first storm, precipitation was confined largely to the mountains and Alta received 14 times more SWE than SLC.

Similar to the first storm, 64% of the storm-total SWE at Alta was produced by postfrontal orographic and lake-effect snowshowers. Thirty-three percent of the storm total was produced by an orographically enhanced midlake snowband. For the entire storm-cycle, 63% of the Alta SWE was postfrontal, with 26% produced by orographically enhanced midlake snowbands. Lake-effect also enhanced precipitation during the postfrontal I stage of both storms.

The storm evolution described above is more complex than that described by Hobbs (1975) and Marwitz (1980) for the Cascade and San Juan Mountains, respectively, which feature a relatively continuous progression through stable prefrontal, transitional frontal, and unstable postfrontal stages. Complicating the evolution of each storm in the Hundred-Inch Storm Cycle was an intrusion of low-θ_e air aloft, which resulted in a transition from stable to convective precipitation ahead of the surface-based cold front. Intermountain forecasters should be aware that prefrontal surges of low-θ_e air aloft may produce significant changes in precipitation processes, snowfall rates, and the magnitude of orographic enhancement. Although the storm evolution was similar to the split cold front model of Browning and Monk (1982), it differed in that significant precipitation was found along the surface-based cold front. It also differed from the Hobbs et al. (1990) cold-front aloft model since convection was not organized along the leading edge of low-θ_e aloft. The storm evolution also illustrates the importance of postfrontal convection over Intermountain ranges and lake-effect processes over the Wasatch Mountains.

Finally, orographic precipitation enhancement during the Hundred-Inch Storm Cycle varied substantially from stage to stage and storm to storm, and frequently deviated from that expected from climatology. Such departures illustrate the limitations of using climatological precipitation–altitude relationships to infer the me-

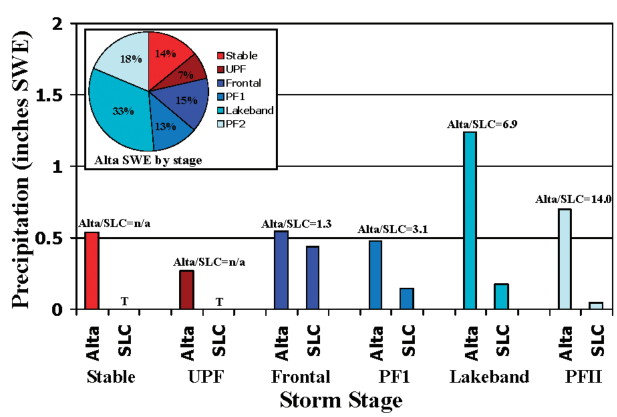

FIG. 7. Same as Fig. 4 except for the second storm.

soscale precipitation distribution over complex terrain. Such limitations will be a major challenge for precipitation downscaling in the National Weather Service Interactive Forecast Preparation System.

Acknowledgements. This work was sponsored by National Science Foundation Grant ATM-0085318 and the National Weather Service C-STAR program.

FOR FURTHER READING

Browning, K. A., and G. A. Monk, 1982: A simple model for the synoptic analysis of cold fronts. *Quart. J. Roy. Meteor. Soc.*, **108,** 435–452.

Hobbs, P. V., 1975: The nature of winter clouds and precipitation in the Cascade Mountains and their modification by artificial seeding. Part I: Natural conditions. *J. Appl. Meteor.*, **14,** 783–804.

——, J. D. Locatelli, and J. E. Martin, 1990: Cold fronts aloft and the forecasting of precipitation and severe weather east of the Rocky Mountains. *Wea. Forecasting*, **5,** 613–626.

Marwitz, J. D., 1980: Winter storms over the San Juan Mountains. Part I: Dynamical processes. *J. Appl. Meteor.*, **19,** 913–926.

Steenburgh, W. J., 2003: One hundred inches in one hundred hours—Evolution of a Wasatch Mountain winter storm cycle. *Wea. Forecasting*., in press.