Forecasting the 31 October 2004
Lake-Effect Snowstorm of the Great Salt Lake

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INTRODUCTION

Lake-effect snowstorms of the Great Salt Lake (GSL) are considered to be one of the more challenging winter forecast issues at the National Weather Service (NWS) Weather Forecast Office (WFO) in Salt Lake City, Utah (SLC). The degree of this challenge can be summed up by the fact that local meteorologists have coined the phrase Dreaded Lake Effect, or "DLE" when referring to these events. These lake-effect snowstorms can potentially produce very heavy snowfall amounts across Salt Lake City and nearby areas. One of the more significant storms, occurring on 17-18 October 1984, produced over two feet of snow and resulted in over one million dollars of property damage (Carpenter 1993). Primary forecasting concerns include occurrence, timing, intensity, duration, and preferred snowfall location(s). The small scale processes involved and sensitivities to controlling factors increase the forecasting complexities of these events. Because of this, operational numerical guidance is generally only capable of providing storm environment conditions – much like with warm season severe weather forecasting.

Fortunately, operational forecasts of these events benefit from extensive local research, thus providing a suitable conceptual model to use in operations. Carptenter's (1993) study identified twenty-eight lake-effect events of the GSL based on visual and spotter reports, and concentrated on correlating upper air data at 700 mb with storm behavior and intensity. Steenburgh et al (2000) examined 16 well-defined and 18 marginal GSL snowstorm events between September 1994 and May 1998 to identify event characteristics using WSR-88D imagery, regional-scale composite analyses, and rawindsonde-derived statistics. More recent work by Steenburgh and Onton (2001) included use of a high resolution model and observations to study the 7 December 1998 lake-effect snowstorm of the GSL. The key finding in this study was that, although the GSL is relatively small in scale compared to the Great Lakes, lake-effect events on each share similar characteristics in many ways – including the formation of thermally driven banded circulations and banded precipitation structures. Related work by Onton and Steenburgh (2001) showed that the use of even high resolution mesoscale models to forecast these events may be limited due to their sensitivity to small changes in lake-surface temperature and upstream moisture.

The 31 October 2004 lake-effect snowstorm of the GSL is used here to demonstrate the application of operational numerical guidance to forecasting the event, and especially to show how this guidance is applied to conceptual models built on previous research. This event produced snowfall amounts generally ranging between 4 and 6 inches across the Salt Lake Valley, and up to 18 inches at Alta, which is located just to the southeast of the Salt Lake City in Little Cottonwood Canyon. Although these snowfall amounts are not considered particularly heavy for lake-effect events and are considered more typical amounts, this case was chosen for this study since it effectively demonstrates the advantages of having and applying conceptual models to phenomena of these relatively fine spatial scales. A brief description of the factors key to a these lake-effect events will be described first, followed by a presentation of how these factors were used to forecast this event.

KEY LAKE-EFFECT FACTORS AND FORECAST CONSIDERATIONS

The GSL, which covers approximately 4500 km^2, is located in northern Utah just northwest of Salt Lake City (Fig. 1). Because of its high salinity, the lake typically stays unfrozen, only freezing near its very few fresh water inlets. Although Onton and Steenburgh (2001) found that the hypersaline composition of the GSL decreases moisture fluxes compared to a body of freshwater – resulting in a 17% reduction in snowfall – the absence of ice is important since it allows for sufficient moisture flux off the lake even during the winter. Lake bands that extend into the nearby complex terrain of the Wasatch Mountains will typically produce very heavy snowfall amounts due to orographic effects.

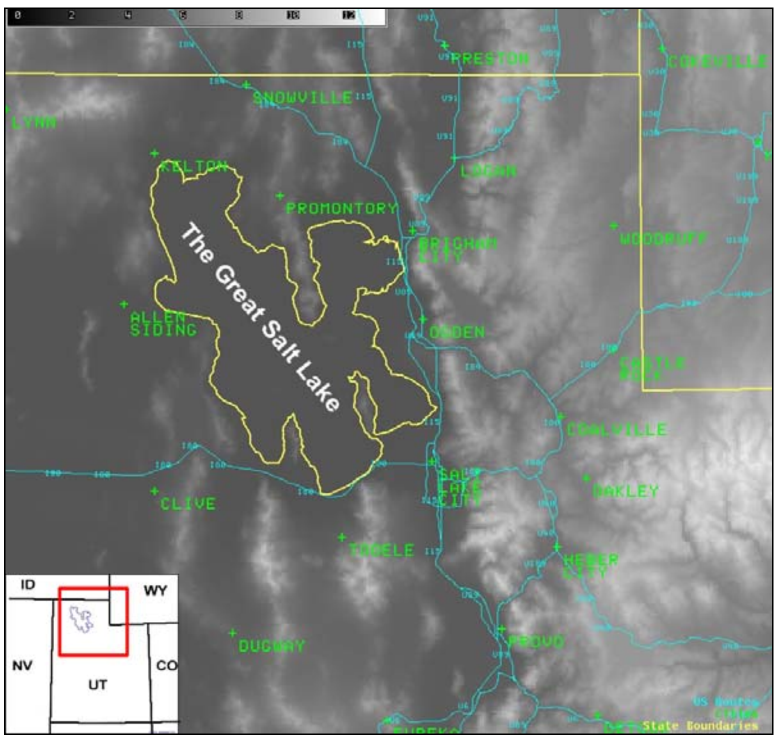

Fig. 1. Map of the Great Salt Lake area in northern Utah (shaded image is topography).

For a comprehensive look at other key characteristics and controlling factors of lake-effect snowstorms of the GSL, see Steenburgh et al (2000). In summarizing their findings, it is important to reemphasize that many of the same factors that contribute to the lake-effect events in the Great Lakes region – events that typically receive more notoriety – are similar to those that should be considered for potential lake-effect events of the GSL. These include, 1) a lake-700 mb temperature difference of at least 16^{o}C, 2) an absence of capping inversions or stable layers within 150 mb of the surface, 3) small

(< 60°) steering-layer (800-600 mb) directional shear except with weak flow, and 4) the existence of low-level convergence over the GSL resulting from sufficient lake-land temperature differences.

Lake-effect snowstorms of the GSL occur in cold, post-frontal westerly to northwesterly low-level flow. Events typically occur between the months of September to May, with onset time more often overnight when lake-land temperature differences are greatest (Steenburgh et al 2000). The direction of the 700 mb flow can have significant impacts on forecasting these events, namely a more westerly flow will result in a general "lake-enhancement" event (i.e., no well-defined lake effect band) for the Wasatch Front area from around Salt Lake City, north to Ogden. Then as the 700 mb winds turn more northwesterly, what can be considered more classic lake-effect bands will form on and be directed in the lee of lake and into the Salt Lake City metro area. Finally, a northerly wind will tend to direct the lake band west of the Salt Lake valley and over the Tooele valley.

Due to the limited ability of operational numerical models to capture the important details of lake-effect events of the GSL, it is quite common to apply conceptual models built through local research to determine the event's potential, in addition to determining the event's probable characteristics. Depending on the lead time, forecasting these events is generally limited to a yes/no forecast, determining an approximate onset time, and the expected favored locations of heaviest snowfall. Using the conceptual models allows forecasters to anticipate a potential event well in advance (e.g., several days), thereby communicating this potential threat to the media within special statements and Area Forecast Discussions. As a potential event approaches and the predictability of numerical guidance improves, forecasters develop a clearer picture of possible lake-effect scenarios. However – as is the case with warm season convective forecasting – it is typically not until near or at the start of an event that forecasters can with a degree of confidence determine expected event characteristics. Critical to this process is an understanding of the event's intensity and a more detailed picture of its likely duration and orientation of lake-effect bands.

Figure 2 is a composite Rapid Update Cycle (RUC) regional analysis at onset time of the 34 GSL lake-effect events studied by Steenburgh et al (2000). The key ingredients derived from this composite analysis are the presence of a cold and moist, northwest (post-frontal) low-level flow with little if any low-level vertical shear, general large scale vertical motion attributed to the passage of an upper level trough, and weak instability (i.e., absence of capping inversions).

By 24-hr after onset (Fig. 3), which is generally the average lifespan of these events, the surface high has moved east, resulting in decreasing northwest flow and a subsequent suite of unfavorable lake-effect conditions . The depth of the instability has also decreased due to the upper trough's position well east of northern Utah. The following section will thus concentrate on the use of this conceptual model in forecasting and understanding the 31 October 2004 lake-effect event of the GSL.

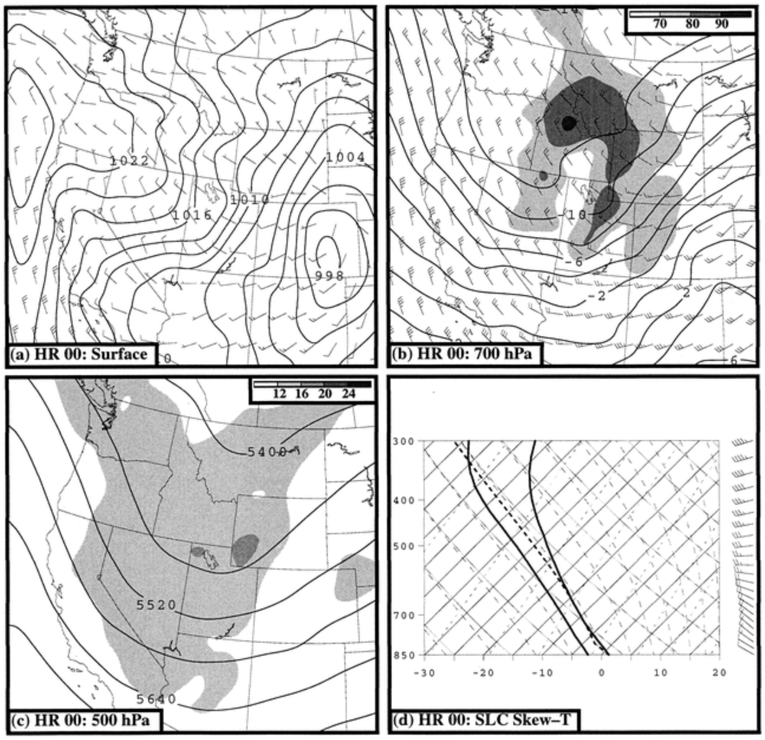

Fig. 2. Composite RUC regional analysis at the onset of lake-effect events. (a) Sea level pressure (every 2 mb) and near-surface winds (full barb and half-barb denote 5 and 2.5 m s^{-1}, respectively). (b) 700 mb temperature (every 2°C), wind [as in (a)], and relative humidity (%, shaded following scale at upper right). (c) 500 mb geopotential height (every 60 m) and absolute vorticity ($\times 10^{-5}$ s^{-1}, shaded following scale at upper right). (d) Skew *T*–log*p* diagram at SLC (*T* and T_d). Dashed line represents surface parcel ascent. Wind as in (a). From Steenburgh et al (2000).

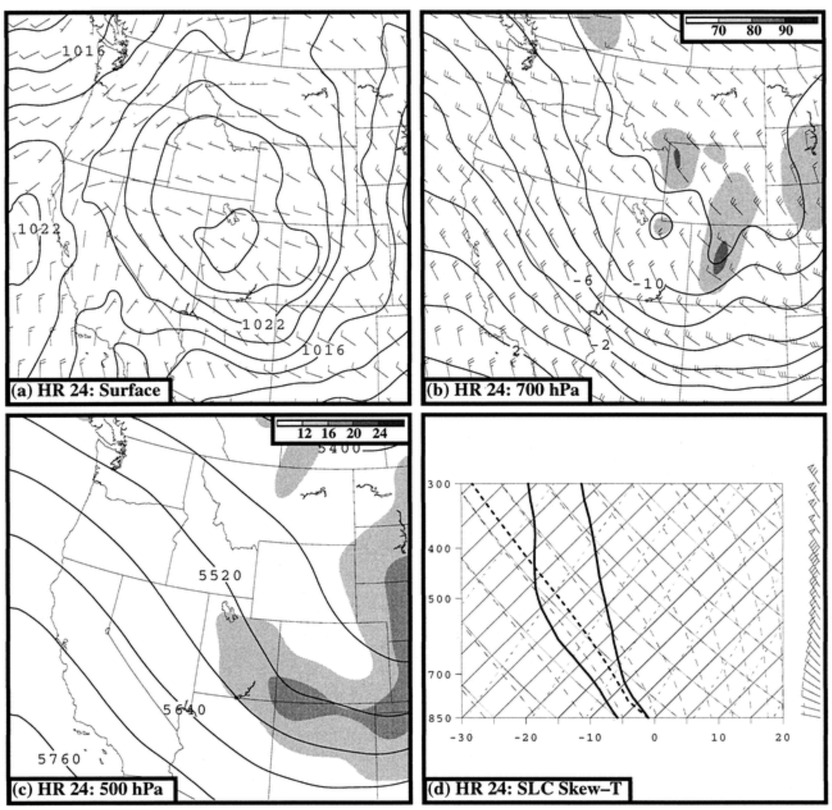

Fig. 3. Same as Fig. 2 but for 24 hr after the onset of lake-effect events (hour 24). From Steenburgh et al (2000)

OVERVIEW OF SYNOPTIC AND MESOSCALE FORECASTS

The possibility of a lake-effect event was apparent in numerical guidance several days prior to 31 October. Figure 4 shows an 84 hr GFS 4-panel forecast from 0000 UTC 28 October, valid at 1200 UTC 31 October. This 4-panel, which is intentionally set up to show similar elements to the Steenburgh et al RUC composites, reveals some of the same key ingredients needed for lake-effect development (see Fig. 2). This allows forecasters to establish critical situational awareness far in advance of a potential event. As will be shown next, favorable lake-effect signatures continued to appear in later numerical guidance runs which showed relatively good run-to-run consistency.

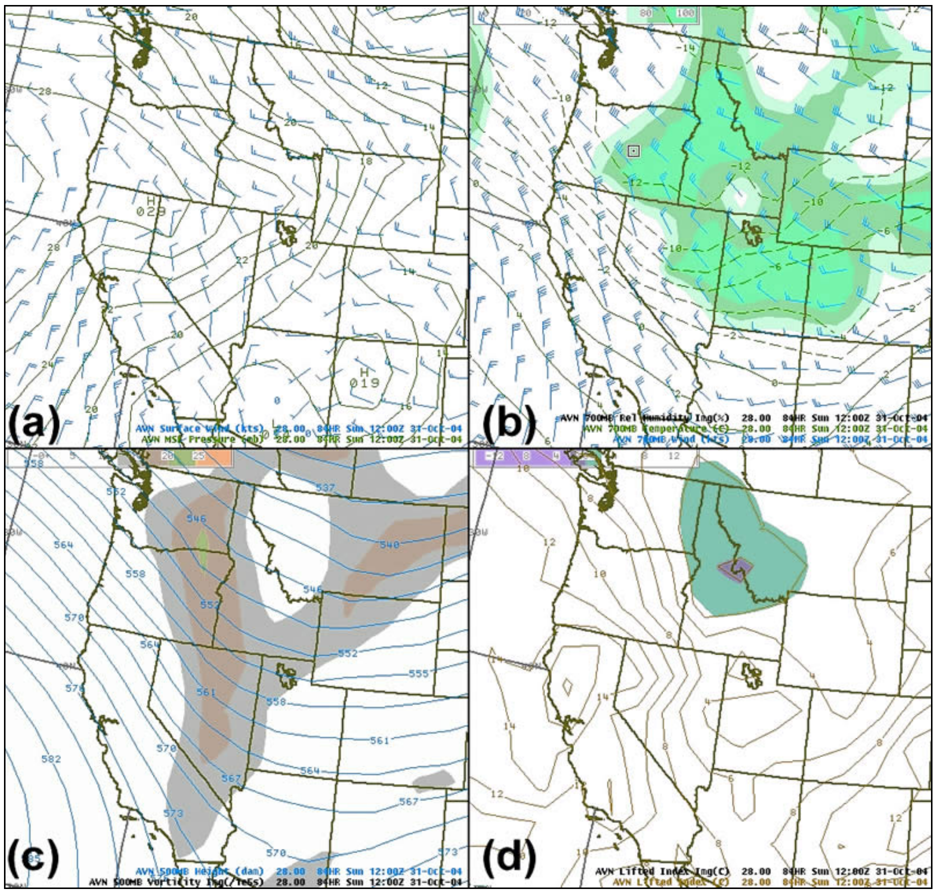

Fig. 4. GFS 84-hr forecast valid 1200 UTC Sunday 31 October 2004. (a) Surface wind (kts) and MSLP (mb). (b) 700 mb wind (kts), temperature (^{o}C), and RH (shaded, %). (c) 500 mb heights (dam) and absolute vorticity (shaded, 10^{-5} s^{-1}). (d) Surface-based lifted index (^{o}C)

The 12-hr GFS forecast, also valid at 1200 UTC 31 October (Fig. 5), depicted a cold frontal passage sometime overnight on 31 October, with the GSL area in cold and moist northwesterly flow. The upper trough position at this time was also favorable for broad upward vertical motion, which can enhance lake effect intensities. Finally, weak instability was forecast for the much of the intermountain west. A question remaining at the time was if timing of the cold front would be such that it would allow for adequate lake-land temperature differences and a resulting mid-lake convergence band. An overnight frontal passage is considered more favorable for producing this ingredient.

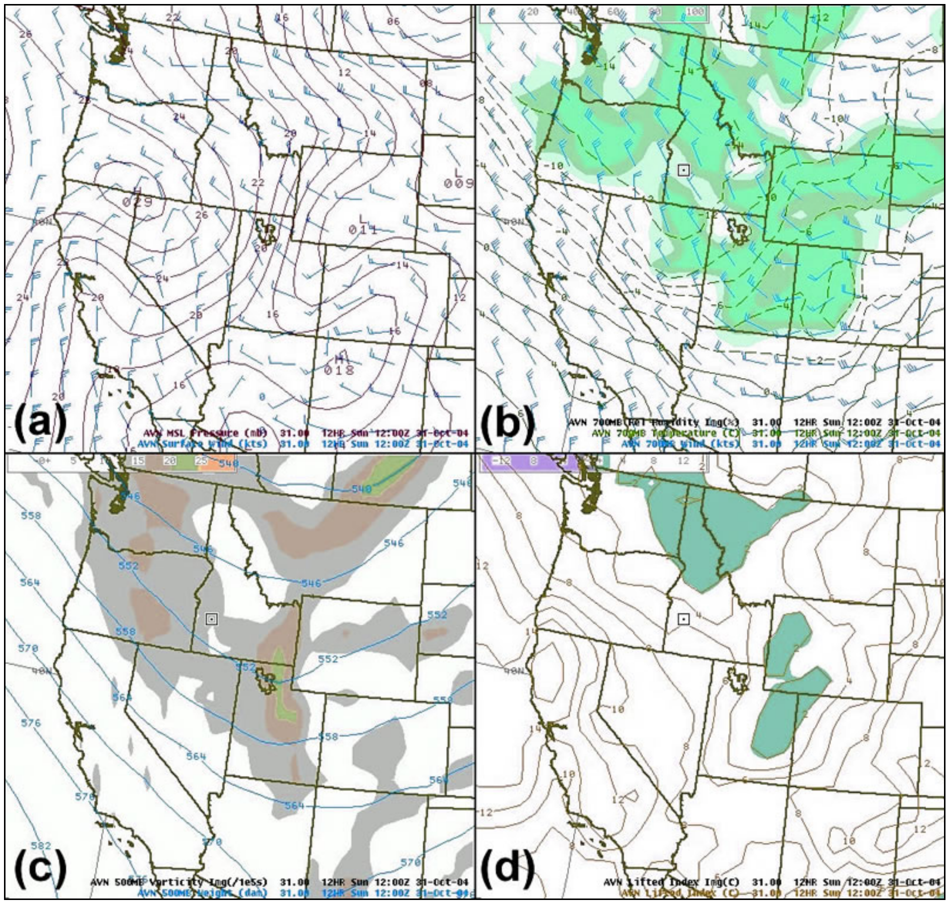

Fig. 5. Same as in Fig. 4 but 12-hr forecast valid 1200 UTC 31 October 2004.

To determine lake-700 mb temperature differences, forecasters can use either climatological values, or if available, satellite derived temperatures obtained from NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) passes (Crossman 2004). Useful AVHRR data is only possible during the absence of cloudiness. Unfortunately, a prolonged period of clouds prevented obtaining AVHRR passes prior to this event. Thus, using an average lake temperature for 31 October of 10.7^{o}C, and a forecast 700 mb temperature between -10 and -12^{o}C, computes to a lake-700 mb temperature difference of 20 to 22^{o}C – well within the optimal range (16 to 24^{o}C) for lake-effect development.

Forecast model soundings are particularly useful for forecasting lake-effect events. This allows forecasters to examine the forecast low-level wind and thermodynamic profile, and then apply this profile to conceptual models to gain further insight on the details of a potential event. For this case the 12-hr model sounding at SLC from the Eta, valid at 1200 UTC 31 October (Fig. 6), showed fairly deep instability and the absence of any capping inversions through just above 500 mb, sufficient low-level moisture, and very little low-level wind shear. Based on this low-level wind profile, the heaviest snowfall typically occurs southeast of the GSL.

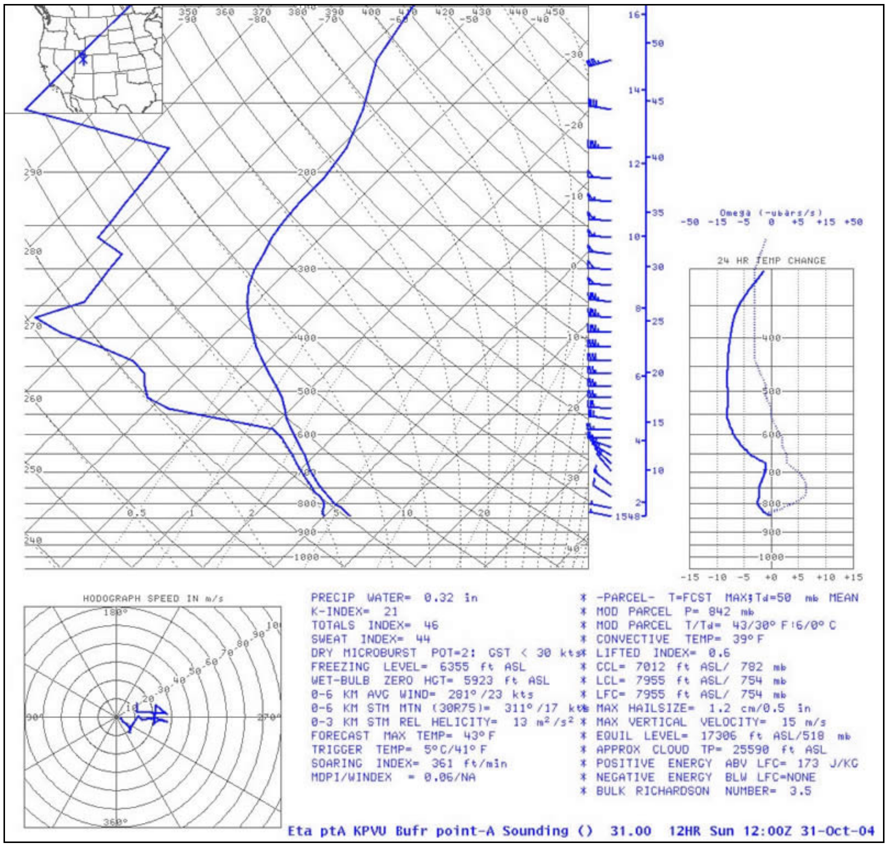

Fig. 6. Eta BUFR skewT-log*p* for SLC. 12-hr forecast valid 1200 UTC 31 October 2004.

By 0000 UTC 1 November, the upper trough was forecast to be east of the area, although plenty of low-level moisture appeared to be available to sustain continuance or redevelopment of a lake-effect band – especially considering that land-lake temperature differences would peak again with nightfall – although mid-level warming would prevent any deep lift. Another very useful tool available to forecasters is to view high-resolution model BUFR data in time-height form. Figure 7 is the Eta BUFR time-height forecast from 0000 UTC 31 October for Salt Lake City. The instability and wind profile were forecast to be most favorable starting around 1200 UTC on 31 October, but by that night (0700 UTC 01 November), the larger scale synoptic lift was expected to decrease and leave shallower orographic lift. The wind profile was also forecast to be less favorable by this time. Thus it was expected that, although lake bands may continue through part of the night, their depth and hence their intensity would decrease with time.

To show the somewhat limited capability of high-resolution model guidance to capture greater lake-effect details – especially used in plan-view – figure 8 is a 4-panel presentation of four 12-km Eta surface wind and precipitation forecasts at 3-hr intervals, beginning with a 6-hr forecast valid 1200 UTC 31 October, and ending with the 15-hr

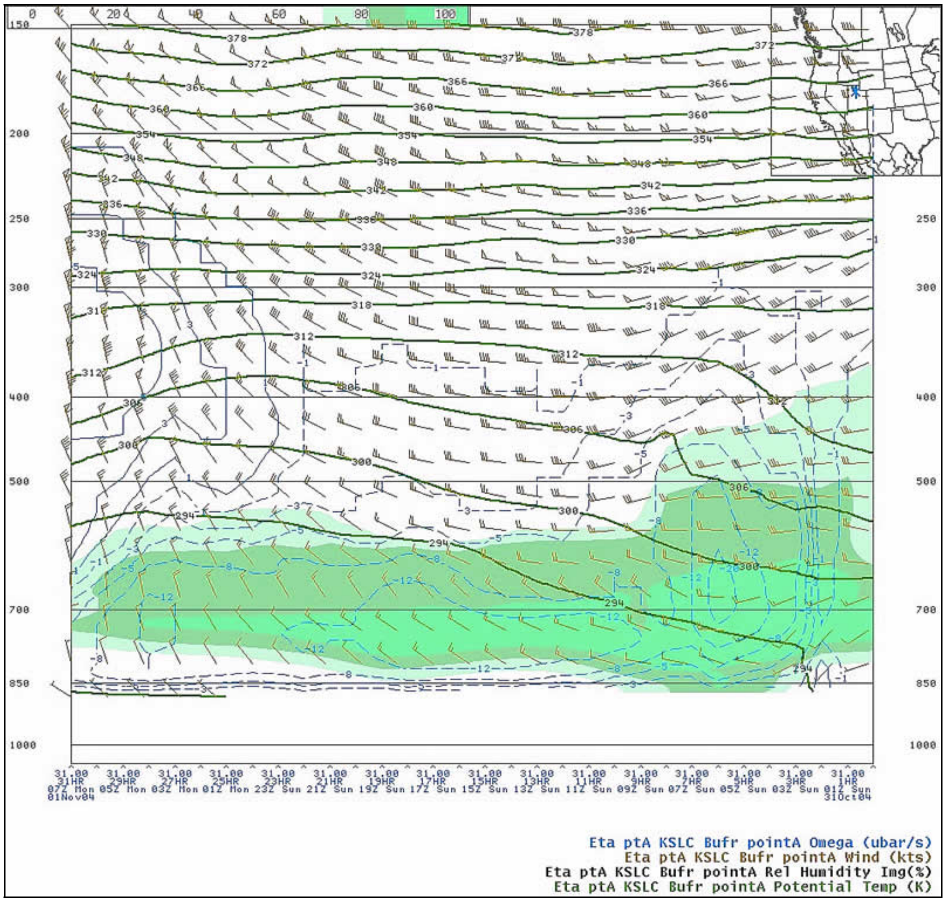

Fig. 7. Eta BUFR time-height for SLC. From right to left, initial time is 0000 UTC 31 October, ending time is 0700 UTC 01 November. Thick contours are theta (K). Wind barbs (kts). Relative humidity (shaded, %). Omega (ubar/s, dashed is upward motion).

forecast valid at 2100 UTC 31 October. Considered to be a typical model depiction for these events, the Eta12 showed general down wind lake enhancement of precipitation, and some weak mid-lake convergence. To more accurately forecast a lake-effect event, it is important that forecasters not depend heavily on model output surface wind and precipitation but rather, through understanding the physical processes of the lake-effect, to analyze model sensible parameters such as temperature, wind, instability, and vertical motion.

Based on these model forecasts, and applying these forecasts to conceptual models that build a basic understanding of lake-effect processes, a lake-effect event was expected to begin late overnight on 31 October and possibly continue into the evening hours of 01 November. A Lake Effect Snow Watch was issued by the SLC NWS WFO at 1000 PM MST 31 October for the Salt Lake and Toole valleys, valid for Sunday (31 October) through Sunday night.

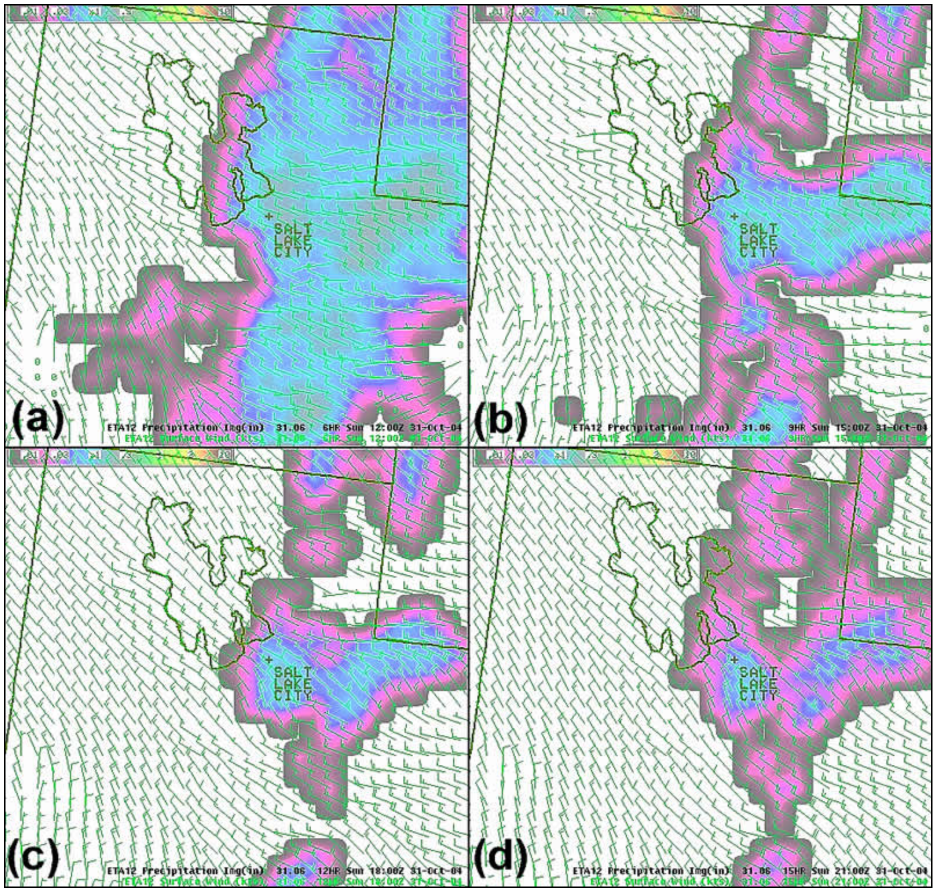

Fig. 8. Eta 12 surface wind (kts) and 3-hr precipitation (in) on 31 October. (a) 6-hr forecast valid at 1200 UTC. (b) 9-hr forecast valid at 1500 UTC. (c) 12-hr forecast valid at 1800 UTC. (d) 15-hr forecast valid at 2100 UTC.

EVENT ANALYSIS

At just after midnight MST on 31 October, the low-level cold front and baroclinic zone had entered northwest Utah. Precipitation was blanketed across most of northern Utah, primarily a result of the low-level lift along and just behind the cold front (Fig. 9a). As the night progressed, precipitation became more widespread as the first signs of a lake-effect band developed by sunrise (Figs. 9b-d). Figure 9d shows this band, which was aligned northwest-southeast and impacting the northern areas of the Salt Lake Valley and the nearby Wasatch Front. The GFS analysis for 1200 UTC 31 October (not shown) showed a moderate to strong surface pressure gradient and resulting northwesterly flow across northern Utah, sufficient low-level moisture and cold air at 700 mb, an upper-level trough axis roughly on top of the area, and weak instability across the area.

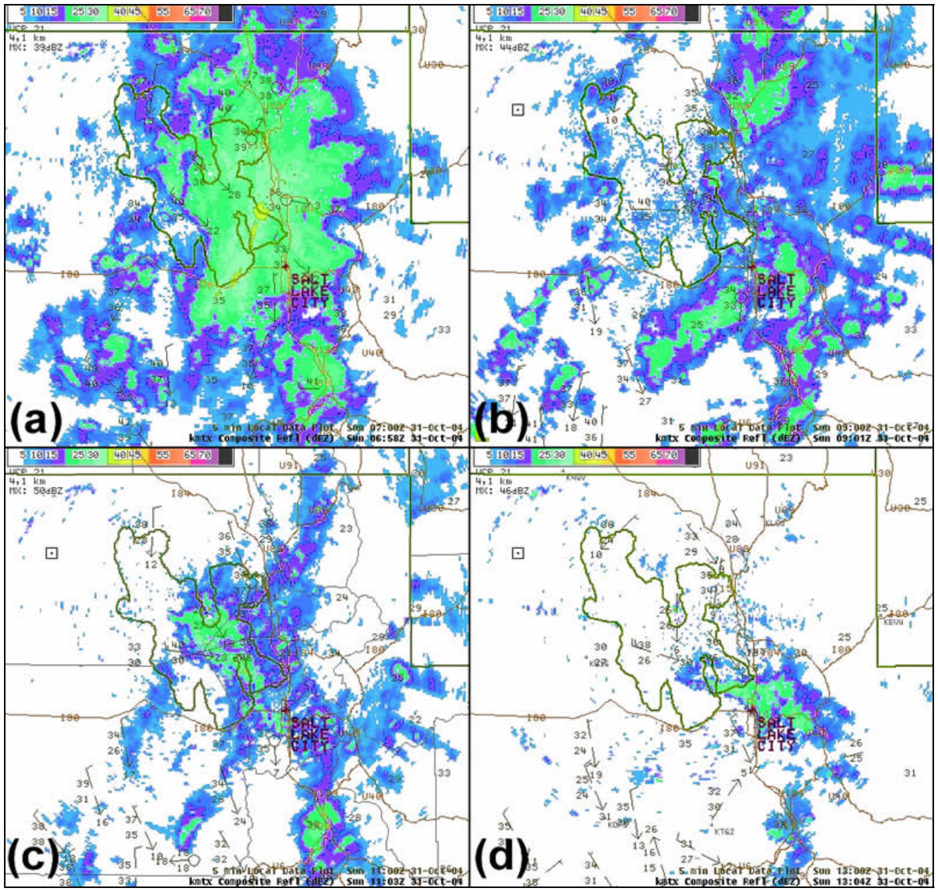

Fig. 9. Surface observations and KMTX WSR-88D composite reflectivity (dBZ) on 31 October 2004. (a) 0653 UTC, (b) 0901 UTC, (c) 1103 UTC, and (d) 1300 UTC.

The 1200 UTC 31 October rawindsonde collected at SLC (Fig. 10) shows a deep, nearly dry adiabatic lapse rate between the surface to 500 mb and, at least above a northerly surface wind, weak (< 60^{o}) directional shear up to just above 600 mb. These are all favorable ingredients for lake-effect development. Thus a Lake Effect Snow Warning was issued at 745 AM MST for the Salt Lake and Toole valleys, valid through Sunday night.

Figure 11 depicts the evolution of precipitation echoes over the next 12 hours, showing the development of a mature lake band by 1700 UTC 31 October, to eventual decay of the band by late in the afternoon when more widespread instability snow showers developed. It was by this time that the land-lake temperature difference was less and no longer able to sustain a mid-lake convergence band. The surface observations on and surrounding the lake depict the diminishing mid-lake convergence.

The precipitation structure returned to a concentrated lake band that evening under continuingly favorable lake-effect conditions. Since the low-level flow was northerly, areas south of the lake in the Tooele valley were impacted by this band. However, the band was not able to sustain a significant lifting depth due to warming aloft as the upper trough moved east by that evening, thus additional snowfall amounts were not as heavy.

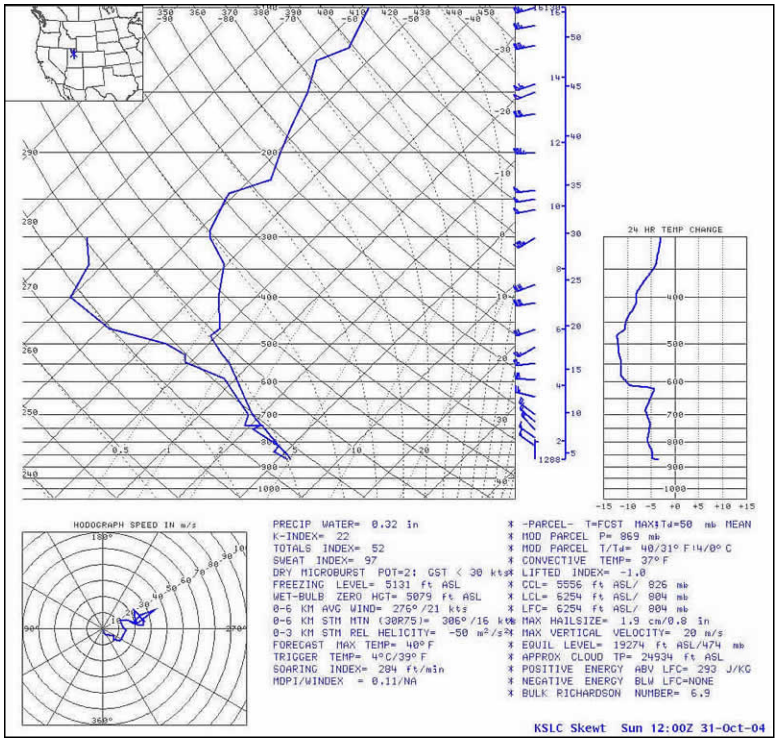

Fig. 10. Salt Lake City skew T-log*p* for 1200 UTC 31 October 2004.

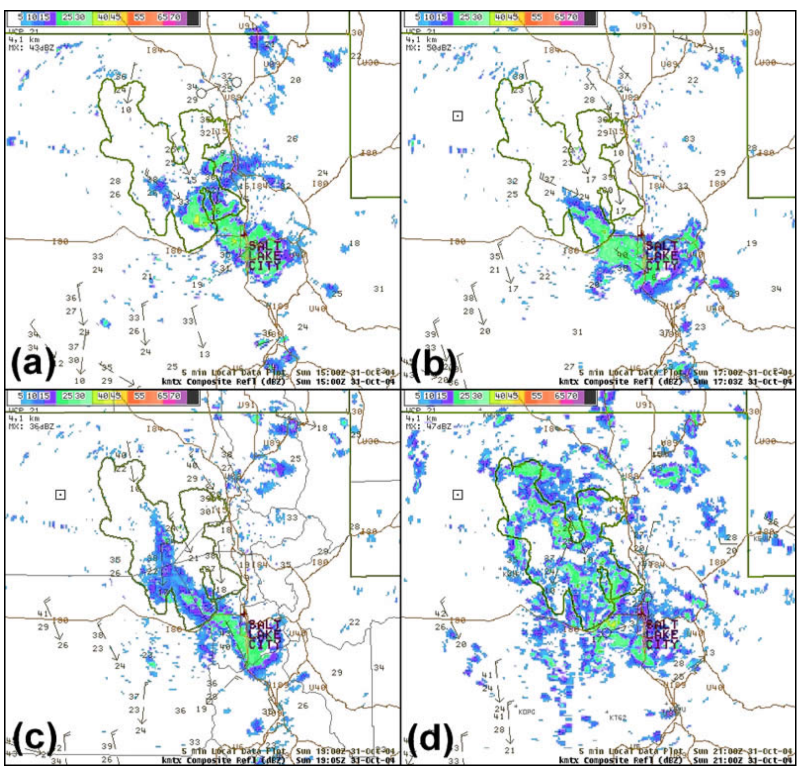

Fig. 11. As in Fig. 9 but for (a) 1500 UTC, (b) 1700 UTC, (c) 1905 UTC, and (d) 2100 UTC.

CONCLUSION

This paper examined the lake-effect snowstorm of the GSL on 31 October 2004, emphasizing the application of conceptual models developed through local research to operational numerical guidance. Although event details typically do not become apparent until near the beginning of – or even during – the event, these conceptual models allow forecasters to establish important situational awareness well ahead of the event, *and* provide an important understanding of the physical processes responsible for these events. This benefits advanced communication of the event's potential to forecast customers and partners, and ultimately can improve forecasts. Given the scale of the factors that control these events, and the sensitivities of the associated physical processes and capabilities of numerical weather prediction, it is expected that this forecast methodology will continue well into the future of operational forecasting.

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