WESTERN REGION TECHNICAL ATTACHMENT
NO. 99-09
MAY 4, 1999

DOWNSLOPE WINDSTORM CASE STUDY WASATCH FRONT - April 23, 1999

Larry Dunn - NWSFO Salt Lake City

Introduction

On April 23, 1999, a downslope windstorm along the western side of the Wasatch Mountains of northern Utah produced wind gusts to 113 mph at valley elevations. Twenty semi tractor-trailer trucks were blown over on I-15, a construction crane collapsed, damage to hangars and aircraft was reported at the Brigham City Airport, numerous power lines were downed, and there was widespread damage to roofs, trees and small structures throughout Davis, Weber, and eastern Box Elder counties. Damage to residential property was estimated at $3-5 million. This was the strongest downslope wind event along the Wasatch Front in more than a decade (since December 15, 1988), and the 113 mph wind gusts observed at the Brigham City Airport represent a new record for observed windspeed at low elevation (<5000 feet) in Utah. Look at the Local Storm Report to see specific wind speed and damage reports.

This case study will document the event as it appeared in observations and analyses centered around 1200 UTC April 23, 1999 and will attempt to highlight the most significant aspects of this event. The next section will cover some significant concepts associated with downslope windstorms. An overview of the synoptic situation will then be provided. A section describing the observations and weather is included. Additionally, links are provided to a subset of graphics from four other downslope windstorms of similar magnitude for comparison and reference. These are the December 15, 1988, April 4, 1983, February 20, 1971, and November 11, 1978 events. Finally, the High Wind Warning issued for the April 1999 event is presented as an example that might be considered in future situations of this magnitude. It is hoped that this document will serve as a useful tool when forecasters are confronted with similar events in the future.

Concepts

Windstorms along the western side of the Wasatch Mountains occur over a spectrum of events ranging from nearly pure gap flow to other events that are characterized as mountain wave events. The strongest events, such as the April 23, 1999 event, are primarily mountain wave events, although some gap flow is present in all events. This situation is very similar to windstorms that occur along the west slopes of the Cascade Mountains in western

Washington where both gap and mountain wave events take place in easterly cross-barrier flow with higher sea-level pressure on the east side of the barrier. The literature is rich with theoretical and observational research results pertaining to downslope windstorms. Most of this work is based on regions where downslope windstorms occur on the east side of mountain ranges, in westerly flow. At this time, one of the best references for events that are similar to Wasatch windstorms are the two papers by Colle and Mass (*Monthly Weather Review*, Jan. 1998, in particular see Part II, p. 53). Much of the discussion below is taken from the results of Colle and Mass Part II, and other research, which were also presented at a COMET-sponsored NWS workshop held in Seattle in late 1996.

The following four factors were found to be most significant for Cascade windstorms:

1. Strength of the cross-barrier flow
2. Magnitude of the cross-barrier sea-level pressure gradient
3. Presence of a critical level
4. Near ridge-crest stability with lower stability above

The first two factors accounted for 82 percent of the variance in the strength of the observed winds, but the strongest events had all four factors present. The presence of a critical level was most important for events with stronger cross-barrier flow, which in turn produced wave-type events. However, it was noted that wave formation results in warming of the column and lowers the surface pressure in the lee of the mountains, which increases the cross-barrier pressure gradient. So, a wave-type event can result in stronger gap flow.

What is a critical level?

When strong flow encounters a topographic barrier, a vertically propagating gravity wave is generated. A key to mountain-wave formation is when the energy from the vertically propagating gravity wave can no longer go up, the energy may be redirected to the surface. This energy propagation is why it is possible to produce surface wind speeds at the base of the mountains far in excess of the wind speeds observed at any level in the free atmosphere. A critical level is the level in the atmosphere that prevents the gravity wave energy from continuing upward.

A critical level can be either a "mean-state" or "self-induced" type. A mean-state critical level means that it exists in the larger-scale observed or forecast data, while a self-induced critical level is generated by the mountain-wave itself, and probably cannot be observed except perhaps with a field program. A mean-state critical level is often defined as a level in the atmosphere where the cross-barrier flow goes to zero. This can be a place where the winds become very light, or where the winds become parallel to the barrier, or it can be the level where a wind direction reversal takes place (going from easterly to westerly flow). A mean-state critical level can also be a stable layer topped by an unstable layer. A fluid oscillation can take place in the stable layer, but not in the unstable layer, so the energy from the oscillation (a gravity wave) cannot propagate upward. A self-induced critical level can be visualized as the turbulence generated by a breaking wave. Consider a breaking ocean wave, where, as the wave builds and then finally breaks, a region of turbulence is created where the flow may either reverse or go to zero. This region acts to prevent energy from propagating vertically through it.

Wave breaking seems to be enhanced in the presence of "reverse shear". Reverse shear is cross-barrier flow that decreases with height. It is thought that even in the absence of a mean-state critical level, that reverse shear can lead to wave breaking, and thus, a self-induced critical level.

Synoptic-scale at 1200 UTC April 23, 1999

A deep trough had developed over the Great Basin by the morning of April 22, 1999. Jet level energy was dropping into the base of the trough with cyclogenesis forecast to take place near Las Vegas by 1200 UTC April 23. 1999. Moderately cold air over Montana was forecast to move south into Wyoming at the same time and easterly upslope and dynamic ascents were also forecast to produce 700 mb cooling over Wyoming. The forecast cyclogenesis took place. The result was a strong easterly (cross-barrier) 700 mb flow as the upper low closed off and intensified and similarly, an increasing sea-level pressure gradient between Salt Lake City, UT (SLC) and Riverton, WY (RIV) (cross-barrier pressure gradient). Below are analyses, observations, and some imagery from around 1200 UTC April 23, 1999.

500 MB
700 MB
850 MB
SEA-LEVEL PRESSURE/METARS
X-SECTION
SLC SKEWT
KMTX VELOCITY
IR IMAGE

The 500 mb analysis shows a deep closed low over the southwest United States. At 700 mb, a closed circulation exists near Las Vegas, NV. Over the Wasatch Front, cold advection is in progress with winds of 25-30 knots of cross-barrier flow indicated in the analysis. Its worth noting that the ETA progs had been forecasting 40-50 knot cross-barrier flow and the KMTX velocity image shows 40-60 knots on the upstream side of the barrier, even though the SLC SKEWT shows only about 20 knots at 700 mb. The spreading of the 20 knot SLC RAOB wind by the ETA analysis is the likely reason the 700 mb analysis is so much different than what was forecast. The radar data would appear to be more representative of actual flow conditions over the barrier. It is fortuitous that the easterly cross-barrier flow is parallel to a radial in the region that experienced the strongest winds and, that there were plentiful reflectors in the form of clouds and precipitation. It allows for a good measurement of the cross-barrier flow in this case.

The sea-level pressure difference between SLC and RIV was over 19 mbs at 1200 UTC. Given that 8 mb is often enough to generate moderate gap winds, this is an extreme value. Pressure tendencies seen in the METAR observations, show pressures rising in northeast

Wyoming, while falling over southern Nevada. Again, it is interesting to note that previous ETA forecasts were accurate in predicting this strong pressure gradient, but that the ETA analysis and sea-level reduction method were unable to draw for the data shown by the METAR observations.

The SLC SKEW-T shows a mean-state critical level near 400 mb as the winds become southerly and the cross-barrier component of the flow goes to zero. There is also a suggestion of reverse shear in the SKEW-T with the flow dropping to only 15 knots near 400 mb. Stable layers near or just above ridge-crest can also be found in the SKEW-T at 700 mb and 600 mb. There is of course some question about exactly where the SLC SKEW-T was measuring the atmosphere in this event, since the balloon was likely some distance to the west of the Wasatch Front during its ascent.

The cross-section generated from the ETA analysis shows some reverse shear around 600 mb, but no mean-state critical level until near the tropopause. It does show a decrease in stability above 500 mb where the isentropes are further apart. This less stable region above a more stable region may act as a mean-state critical level. There is also some slope to the lowest isentropes as they tilt downward on the west side of the Wasatch Mountains, but not much as the temperature contrast across the barrier is not as large as might typically be found in a mid-winter event.

In summary, the synoptic situation was nearly ideal for a strong wave-type downslope windstorm. Strong cross-barrier flow, an unusually strong sea-level pressure gradient, and a variety of indicators pointing to the presence of a mean-state critical level were all present. Additionally, the reverse-shear found in the observations and analyses suggest a self-induced critical level was also possible.

Observations and Weather

The following links display various observational data from the April 23, 1999 event.

METARS and TOPO IMAGE
UTAH MESONET
KMTX REFLECTIVITY 1109 UTC
KMTX VELOCITY 1020 UTC
KMTX VELOCITY 1050 UTC - CLOSEUP
BRIGHAM CITY OBSERVATIONS
HILL FIELD OBSERVATIONS
UNIVERSITY OF UTAH OBSERVATIONS
HAT ISLAND OBSERVATIONS
GUNNISON ISLAND OBSERVATIONS

The METAR and mesonet images show the high winds were quite localized to the lee of the Wasatch Front from northern Salt Lake County to near the Idaho border, but extended well out into the Great Salt Lake. The velocity imagery shows the strongest winds due east of the radar which is to be expected given the easterly direction of the winds. Along the I-15 corridor in Weber County, the velocity data shows 64 knots or greater winds, which is the highest wind that can be displayed with the color table. A close-up view of the velocity data at 1050 UTC shows the data is "folded" in the Ogden area. The highest winds show up as 50-64 knots outbound (purple) with a couple of pixels of even lower outbound velocity. The velocity deailiasing has failed with these winds that appear to be near 100 knots. The reflectivity data show there was scattered precipitation over the area.

The Brigham City Airport AWOS observations show the easterly winds picked up just after 0600 UTC and continued through the morning. It is interesting to note the measurable precipitation indicated during some of the strongest winds. The 113 mph gust was reported about 1/2 mile from the AWOS on a Davis-II recorder. Hill AFB observations are similar with light rain and snow reported through the wind event. Eye-witness reports confirm the precipitation during the downslope windstorm.

The strongest winds in Salt Lake County were reported at the University of Utah, where a 60 mph gust was reported at around 5:00 a.m. There were some large trees blown down in the Avenues part of Salt Lake City. Strong winds were not reported from Utah County or the Cache Valley in this event, although gusts to 74 mph were reported on Logan Peak.

Hat and Gunnison Island observations show that the strong easterly winds extended quite far downstream from the mountains in this event. Gusts of over 50 knots were reported from both sites.

Also of interest was that nearly a foot of snow fell in the mountains near Bear Lake and Monte Cristo, and 7 inches of snow in Randolf combined with 53 mph winds to produce blizzard-like conditions.

Other Major Windstorms

The following link is to a Deseret News article written just after the April 23, 1999 event, listing other significant "canyon" wind events in the past 40 years. The accuracy of this list is somewhat questionable as a check of the data from at least one event, May 23, 1970, indicates there was no windstorm on this date.

Deseret News Story

The following links display graphics from four other downslope windstorms that produced gusts in excess of 100 mph along the Wasatch Front. The graphics are generated from NMC gridded analyses, but on a rather course grid.

- 500 MB - APRIL 4, 1983
- 700 MB - APRIL 4, 1983
- SEA-LEVEL PRESSURE - APRIL 4, 1983

- 500 MB - DECEMBER 15, 1988
- 700 MB - DECEMBER 15, 1988
- SEA-LEVEL PRESSURE - DECEMBER 15, 1988
- 500 MB - FEBRUARY 20, 1971
- 700 MB - FEBRUARY 20, 1971
- SEA-LEVEL PRESSURE - FEBRUARY 20, 1971
- 500 MB - NOVEMBER 11, 1978
- 700 MB - NOVEMBER 11, 1978
- SEA-LEVEL PRESSURE - NOVEMBER 11, 1978

The 1983 event produced gusts to 104 mph near Hill AFB with many reports of 60-80 mph from Utah County northward along the Wasatch Front. The 1988 event produced gusts to 104 mph at Centerville (unofficial estimates of 110 mph since 104 was the anemometer limit) with numerous reports of 60-70 mph from Spanish Fork to the Idaho border. The 1971 event toppled 8 railroad cars near Farmington. Although the maximum reported anemometer wind was 88 mph, blown-over railroad cars suggests winds likely exceeded 100 mph. There is a media report of 110 mph gust in Bountiful with the 1978 event.

The sea-level pressure difference between SLC and Lander, WY reached 20 mb in the 1988 event and 13 mb in the 1983 event. This compares to just over 19 mb in the 1999 event. Only the analyses are available for the 1971 and 1978 events, so the exact pressure difference is unknown, but it looks to be at least 20 mb in the 1978 event.

In the 1988 event, a critical level appears to exist near 500 mb, while in the 1983 event the easterly flow is deeper. There is a strong cold advection at 700 mb in the 1983 event, while the cold advection is not as strong and is more along just the northern Wasatch Front in the 1988 event. The 1971 event is similar to the 1983, 1988, and 1999 events in that it represents a strong wave-type event with strong cross-barrier flow. The 1978 event is quite different. It appears to be driven only by the low-level pressure gradient as there is little or no cross-barrier flow and no cold advection at 700 mb.

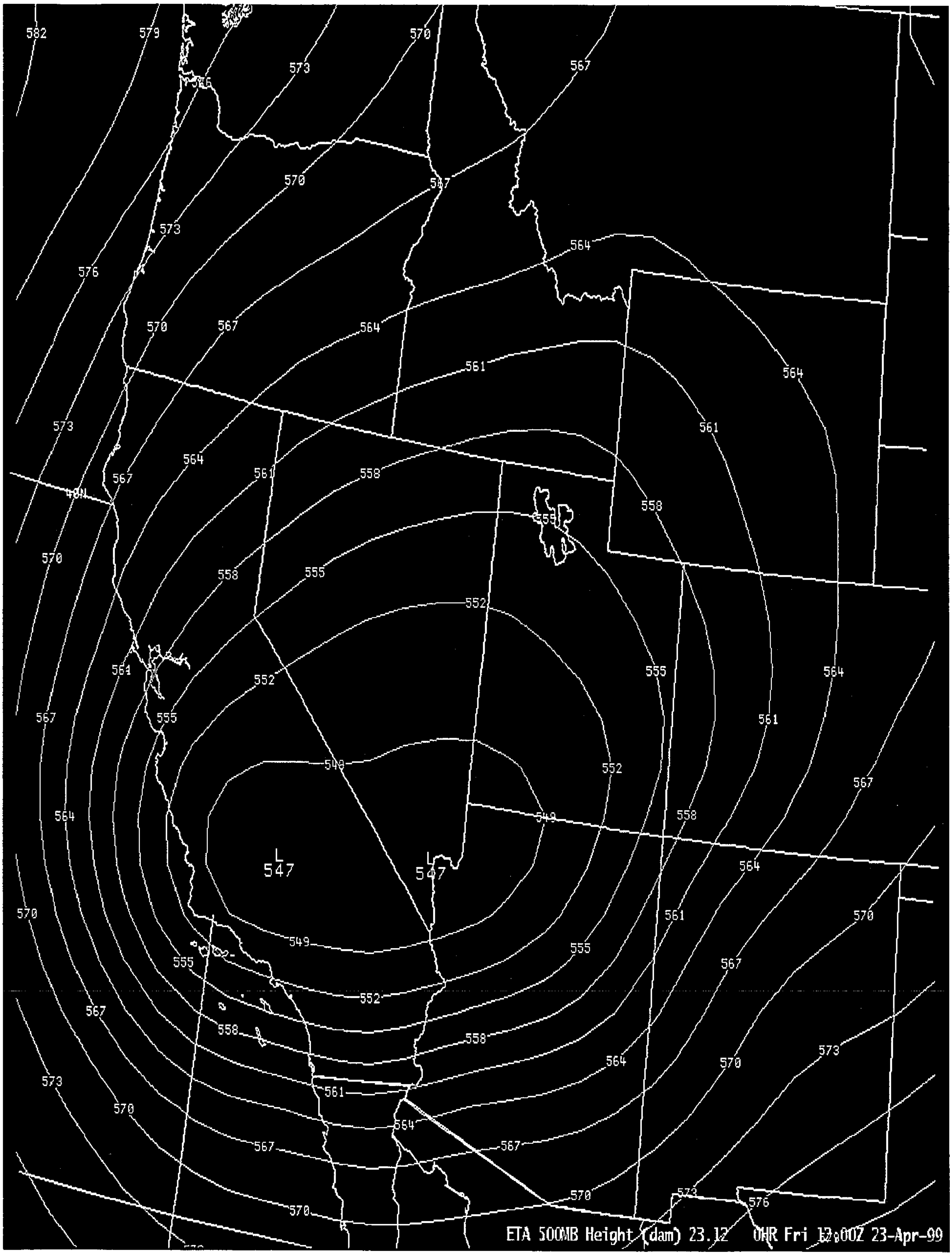
As in the 1999 event, the cross-barrier flow is difficult to determine from RAOB data. The 700 mb wind on the SLC RAOB appears to be near 20 knots in both the1983 and the 1988 events, although as seen in the 1999 event, this is unlikely to accurately represent the cross-barrier flow.

The Warning Issued for the April 1999 Event

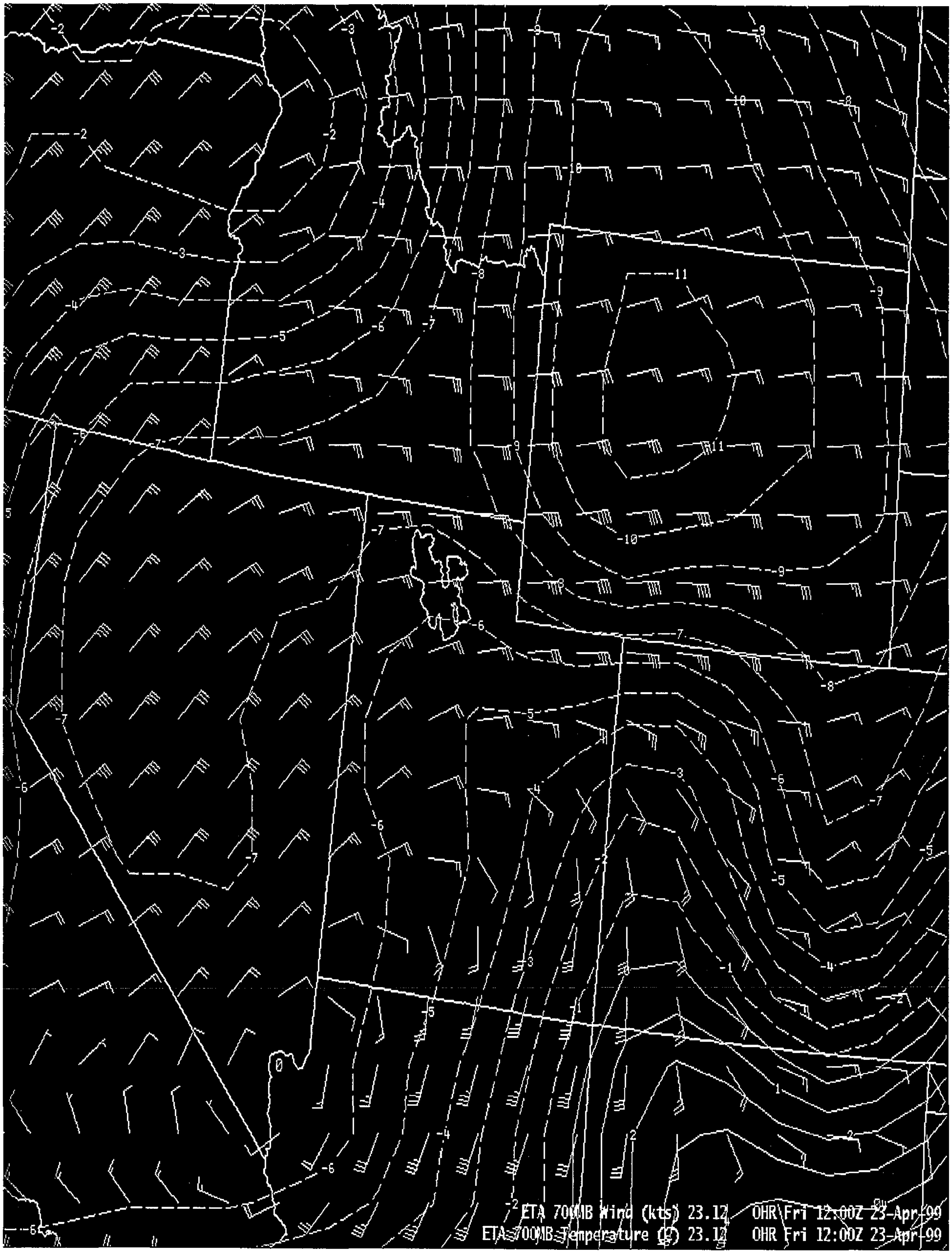
The warning issued for the April 1999 event was very strongly worded. This excellent warning is probably as strongly worded as any High Wind Warning that has ever been issued by the SLC forecast office for a downslope wind event in that it explicitly mentions the possibility of 100 mph winds.

```
ZCZC SLCLSRSLC
TTAA00 KSLC 232020 AMD

PRELIMINARY LOCAL STORM REPORT...UPDATED
NATIONAL WEATHER SERVICE SALT LAKE CITY UTAH
220 PM MDT FRI APR 23 1999

TIME(MDT)  .....CITY LOCATION..... STATE  ...EVENT/REMARKS...
           ....COUNTY LOCATION....

1255 AM    BRIGHAM CITY              UT   GUSTS 113 MPH MEASURED AT
04/23/99   BOX ELDER                      THE BRIGHAM CITY AIRPORT.
                                          (STATE RECORD)

0355 AM    BRIGHAM CITY              UT   GUSTS 102 MPH.
04/23/99   BOX ELDER                      CONSIDERABLE TREE DAMAGE
                                          AND POWER LINES DOWNS. 11
                                          TRACTOR/TRAILER RIGS TURNED
                                          OVER. I-15 CLOSED TO HIGH
                                          PROFILE VEHICLES.

0500 AM    OGDEN                     UT   CONSTRUCTION CRANE BLOWN
04/23/99   WEBER                          DOWN

0500 AM    SALT LAKE CITY            UT   GUSTS 60 MPH AT UNIVERSITY
04/23/99   SALT LAKE                      OF UTAH

0520 AM    PLEASANT VIEW             UT   ROOF BLOWN OFF A BUILDING
04/23/99   WEBER

0530 AM    CENTERVILLE               UT   GUSTS 87 MPH.  NUMEROUS
04/23/99   DAVIS                          TREES...SIGNS...POWER LINES
                                          DOWN.  I-15 CLOSED TO HIGH
                                          PROFILE VEHICLES

0530 AM    HILL AFB                  UT   GUSTS 66 MPH.
04/23/99   DAVIS

0600 AM    HAT ISLAND                UT   GUSTS 55 MPH OVER THE
04/23/99   BOX ELDER                      GREAT SALT LAKE

0630 AM    OGDEN                     UT   GUSTS 110 MPH AT WEBER
04/23/99   WEBER                          STATE UNIVERSITY

END
```

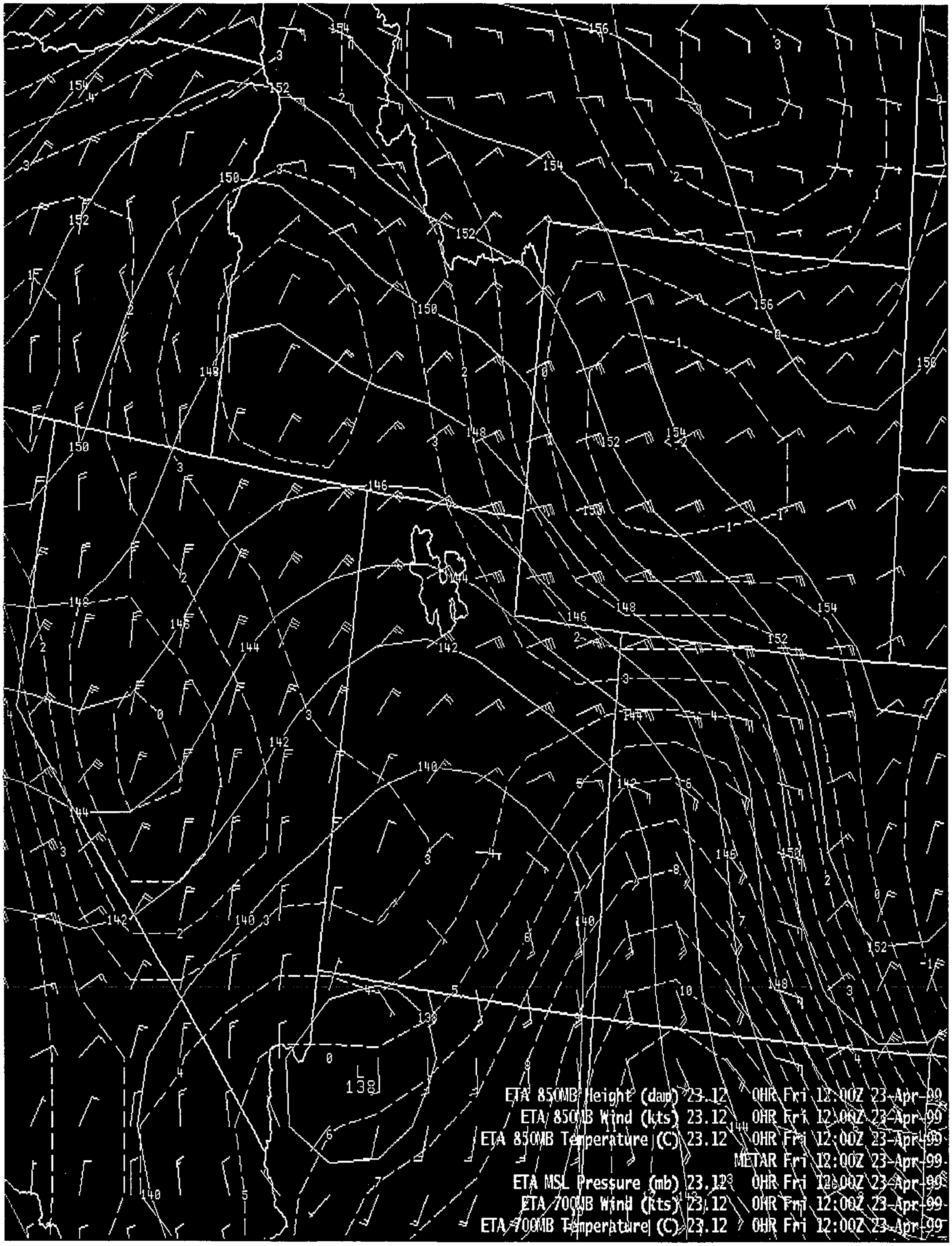
Preliminary Storm Report



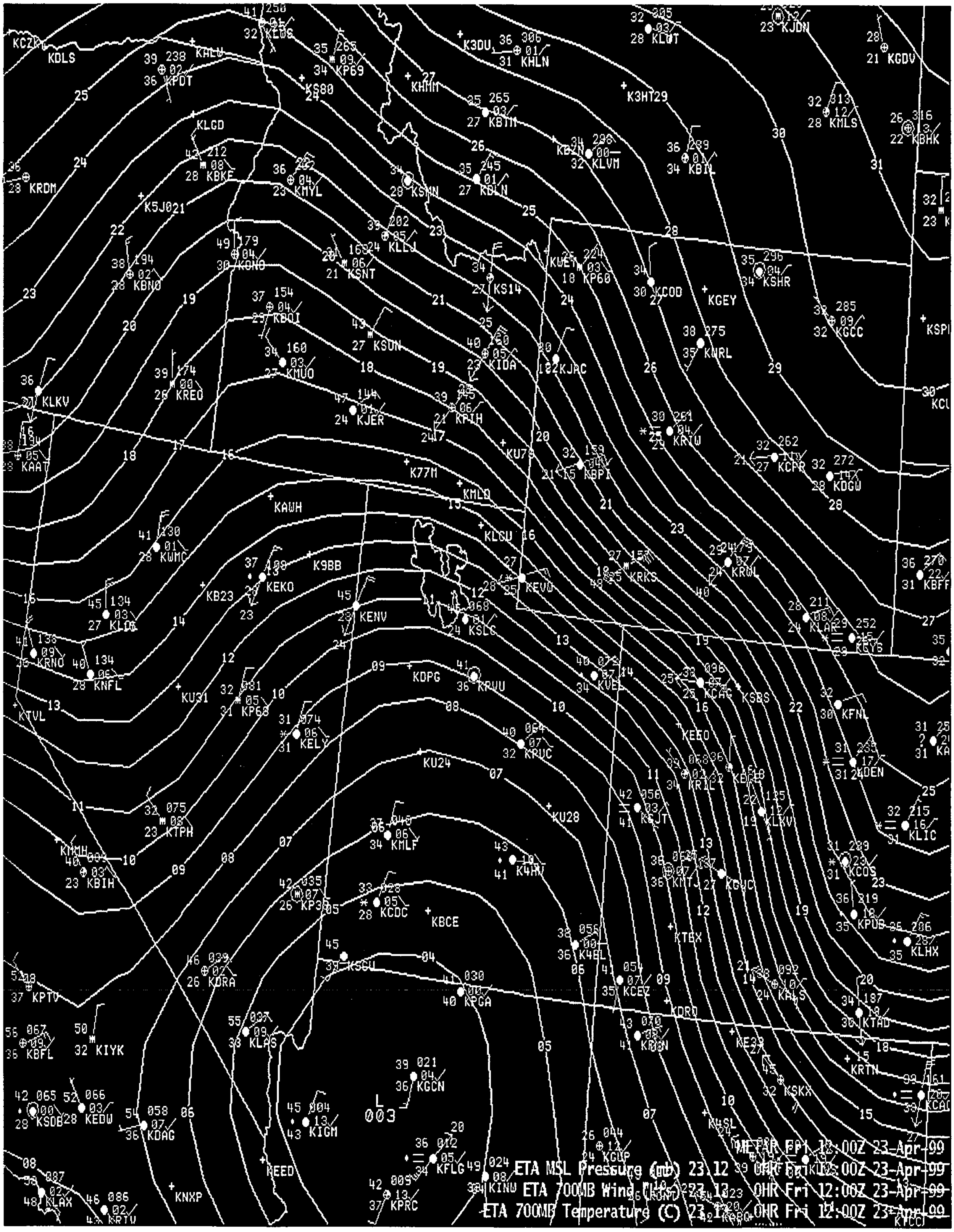
ETA 500 mb Height



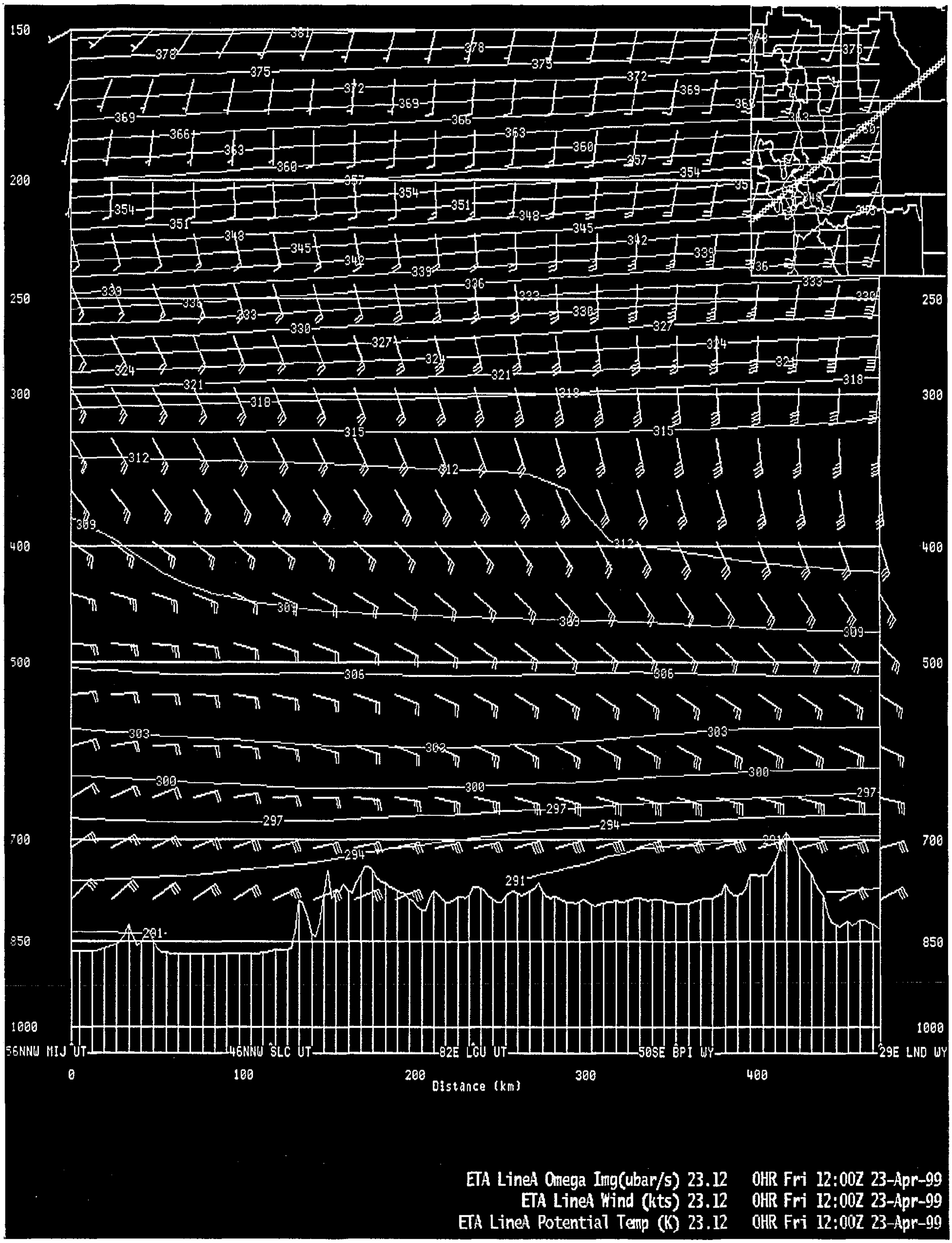
ETA 700 mb Wind



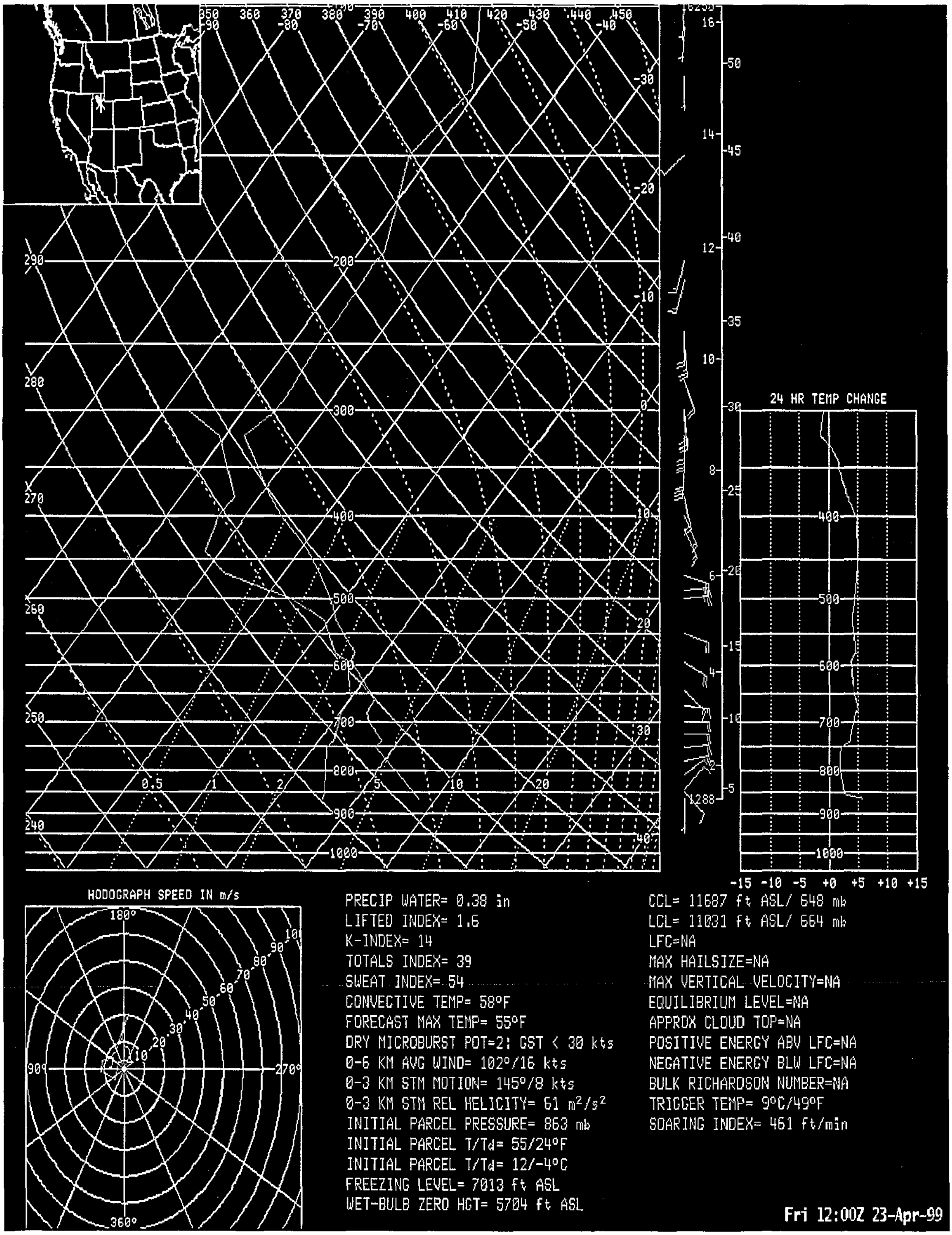
ETA 850 mb Height



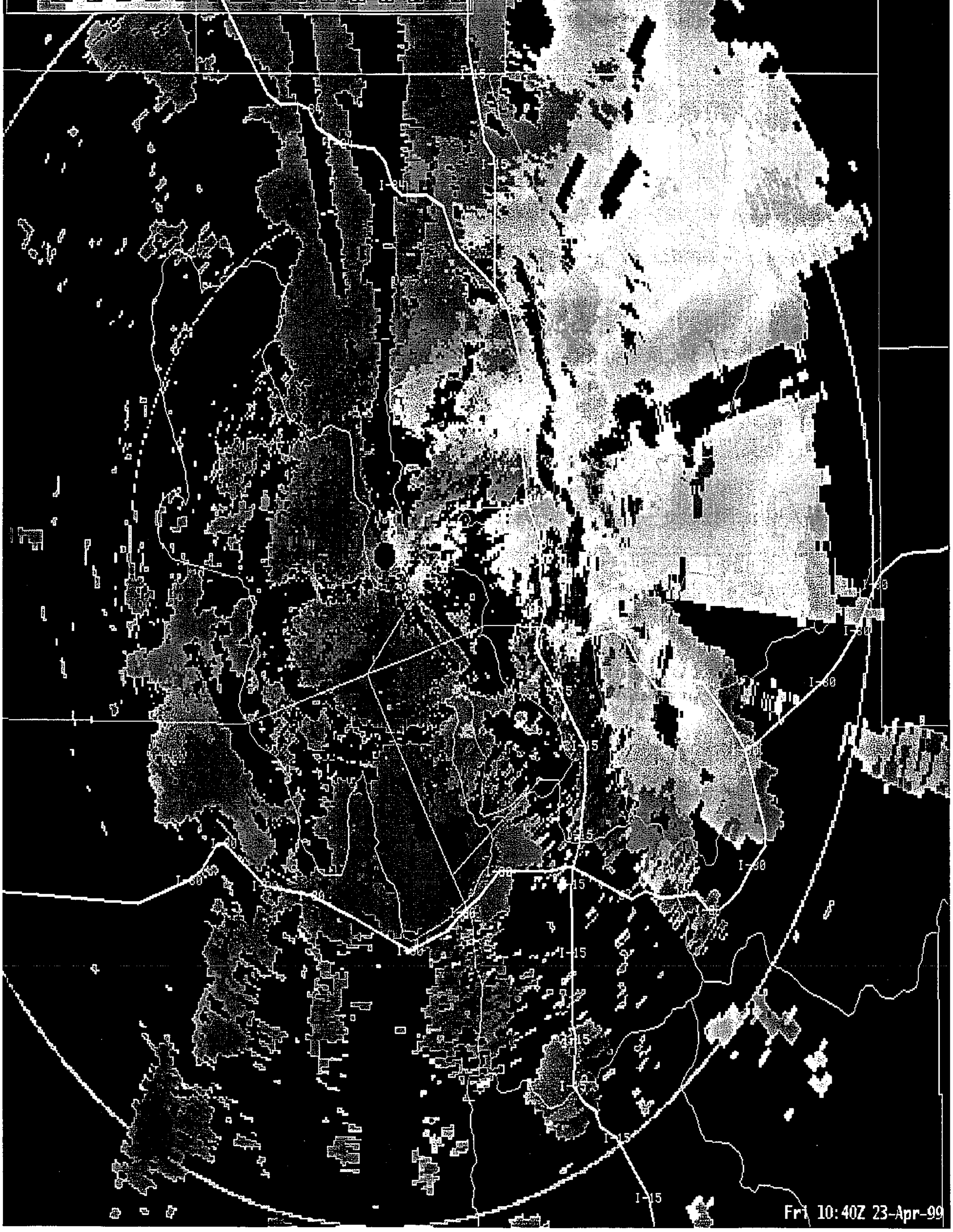
ETA MSL Pressure



ETA LineA Omega Imgage



Salt Lake City SKEW-T



Velocity

IR Satellite - Fri 12:00Z 23-Apr-99