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WSR-88D EVIDENCE OF A NORTHERLY BARRIER JET IN THE SACRAMENTO VALLEY

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Introduction

Terrain-induced winds occur at many locations around the world. Mono and Santa Ana winds in California, Chinook winds along the east side of the Rockies, barrier jets in Alaska and Antarctica, and the low-level jet in the Great Plains are good examples (Schwerdtfeger, 1975; Parish 1982; Smith 1979). Many of these events occur under specific synoptic conditions and thus can be anticipated.

On 9 June 1994, the WSR-88D at WSO Sacramento indicated a moderately strong jet developing along the western portion of the Sacramento Valley. This jet developed sustained wind speeds in excess of 40 kt from the north along the entire west side of the Sacramento Valley. This event began in the early morning hours and extended well into the afternoon. Many stations along the foothills reported wind gusts in excess of 20 kt with some gusts as high as 35 kt, while the WSR-88D indicated a broad area of sustained winds of over 35 kt in the 0-2 km above ground level (AGL) layer. This phenomena will be investigated to determine criteria for its development along with its possible impacts on fire weather. A reference map (Fig. 1) highlights geographical locations mentioned within the paper.

Synoptic Situation

At 1200 UTC 9 June 1994, a weak ridge of high pressure was located over the West Coast of the United States. At 500 mb, northwest flow could be seen over all the western United States extending to the Rocky Mountains (Fig. 2). At 700 mb, northwest flow was also evident, although across most of California, weak northeasterly flow had developed. This northeasterly flow was much stronger at 850 mb, particularly across the northern portion of California (Fig. 3). Wind speeds of 15 kt were reported at Oakland (OAK) from the northeast at this time, which was one of the stronger wind reports at this level in the Western Region. At the surface, high pressure was building across portions of Washington and Oregon extending into Nevada creating a northeasterly surface pressure gradient across all of northern California. A trough of low pressure existed from the Sacramento Valley to southern California.

The OAK sounding from 1200 UTC indicated that north to northeast winds existed from the surface to around 800 mb (Fig. 3). A subsidence layer from the mid-level high pressure cell existed above this. Thus, dry stable air was located above a 200 mb layer of northeasterly flow over the Sacramento Valley.

At the surface, strong winds were reported along the western side of the Sacramento Valley (Fig. 4). Knoxville (KNO), at an elevation of 670 m above sea level (ASL), reported sustained winds of 14 kt with gusts to 26 kt from the north. Thomes Creek (TCK), at an elevation of 317 m ASL, was reporting winds from the west at 8 kt with gusts to 17 kt. Brooks (BSS), at 110 m ASL, had light and variable winds at this time. Light and variable winds were being reported throughout most of the remainder of the Sacramento Valley below the radiative and subsidence inversion which was around 244 m ASL. Above this level, over the northeastern portion of California, winds were generally from a northeasterly direction at 10 to 20 kt.

By 1500 UTC, winds had begun to increase across the entire Sacramento Valley, especially the western foothills. KNO had sustained winds of 21 kt with gusts to 35 kt from the north-northeast. Winds at TCK were north-northwest at 14 kt with gusts to 24 kt. At BSS, winds were northwest at 7 kt with gusts to 15 kt. Wind speeds were strong through the Carquinez Strait as the northeasterly flow was channeled towards San Francisco and the Pacific Ocean. Wind speeds were generally light and variable along the east side of the valley, except at Chico (CHI) where winds were from the northwest at 7 kt with gusts to 11 kt.

By 1800 UTC, winds had decreased at KNO to 11 kt with gusts to 23 kt. At TCK however, winds had increased to 15 kt with gusts to 34 kt. The winds at BSS had also become gustier with gusts reported at 20 kt. Assuming standard propagation, the 1.5° base velocity product indicated north-northwest velocities of 26 kt in the 0-2 km AGL layer (Fig. 5). Outbound velocity returns could be seen in the Sacramento Delta and through the Carquinez Strait indicating the relatively stronger wind flow through that region. Wind speeds through the Carquinez Strait were still strong with gusts of over 20 kt being reported. VAD wind profiles indicated a 1.8 km thick layer of winds greater than 20 kt with the highest winds in the 600-1000 m (2000-3000 foot) AGL range (Fig. 6). Higher winds were likely farther west from the radar site. Strong westerly flow had developed on the east side of the Sacramento Valley with CHI reporting winds of 13 kt with gusts to 20 kt. The winds at Cohasset (CST) had switched to the west as well.

At 2100 UTC, winds had decreased slightly along the western foothills of the Sacramento Valley with gusts of 25 kt being reported at TCK. VAD wind profiles at this time indicated that the depth of the speed maximum had decreased to below 1.2 km AGL (Fig. 6). Gusts to 21 kt were still occurring near San Francisco in the Carquinez Strait. Along the east side of the valley, many stations reported moderate westerly winds with CHI reporting sustained winds up to 13 kt with gusts to 23 kt.

At 0000 UTC 10 June 1994, northwesterly winds continued to slowly weaken with wind gusts to 24 kt being reported at TCK. Santa Rosa (STA) was reporting strong winds from the south at 13 kt with gusts to 20 kt as northeast flow through the Carquinez Strait flowed into the Sonoma Valley. These strong winds developed as flow channeled through the Sacramento River Delta, and its associated marine layer, began to push through San Francisco and into the Carquinez Strait. This more stable air acted as a dam causing the barrier jet winds to flow northward into the Sonoma Valley. The relatively low dewpoint temperatures in the Sonoma Valley at this time suggest that this air originated in the Sacramento Valley rather than the more common marine source region. The westerly winds along the east side of the Sacramento Valley continued through 0000 UTC with CHI reporting wind gusts to 23 kt. These westerly winds extended to the 1.5 km level as seen in the Butte Meadows observation at 2300 UTC which indicated a wind shift from light northeast breezes to west-southwesterly winds with gusts to 12 kt.

After 0000 UTC, the winds began to decrease throughout the region due to the development of a radiative inversion and a gradual shift in the surface pressure gradient. The dominant surface pressure gradient became more northerly through the day and after 0000 UTC became northwesterly as the surface high pressure cell split into two centers over Washington and Nevada. This switch in surface pressure gradient from northeasterly to northerly had begun by mid-afternoon and was reflected in the decrease in winds on the west side of the valley during that time period. The radiative inversion acted to cut off any vertical mixing of momentum.

Possible Mechanisms for Development

Many mechanisms have been proposed for the development and sustenance of low-level jet maxima. These include lee mountain wave breaking (Klemp and Lilly, 1975), inertial oscillations of the ageostrophic wind (Bonner, 1968), synoptic flow over topography inducing terrain channeling (Pierrehumbert and Wyman, 1985), and convergence of momentum transfer (Browning and Wexler, 1968; Lilly and Kennedy, 1973). Some of these mechanisms can be discarded for this case by careful examination of the data.

Temporally, the data shows that a diurnal oscillation mechanism is unlikely in this case due to the weakening of the jet after sunset on 9 June and its lack of redevelopment towards sunrise on 10 June. This jet has been seen developing at various times of the day and night when the pressure gradient becomes northeasterly and persists for at least six hours under optimum conditions. This indicates that the northeasterly pressure gradient together with a specific stability profile was of vital importance in the development of this northerly barrier jet. Thus, a diurnal oscillation mechanism appears to be unlikely in this case.

Spatially, the data spatially rules out another possible mechanism. Lee mountain wave breaking is an unlikely mechanism here due to the development of the jet maximum on the windward side of the coastal mountains. No wave breaking can occur on that side of the mountains, thus ruling out this mechanism.

Terrain channeling due to synoptic flow over topography is one possible mechanism for the development of the northerly barrier jet. Since the synoptic flow over the Sacramento Valley was from the northeast, terrain channeling would induce a northerly wind over the entire valley. This explains the direction of the barrier jet, but does not explain its concentration alongside the western portion of the valley.

A study by Parish (1982) investigated southerly barrier jets which form along the east side of the Sacramento Valley under strong southwesterly flow. He theorized that this was a dominant phenomenon along the Sierra Nevada western slopes with the strongest winds found between 600-1500 m AGL. The horizontal extent of the barrier jet was at least 100 km extending into the Sacramento Valley. Magnitudes of the jet typically exceeded 40 kt.

The development of a barrier jet was conjectured to occur whenever a large-scale component of wind was directed towards a mountain chain causing the air to be forced to rise over the barrier (Parish, 1982). If the air has a high static stability, the forced ascent is resisted and appreciable deceleration occurs. This leads to damming of the stable air against the mountains and consequently an increase in pressure along the windward slopes. The resulting damming leads to a pressure gradient force strikingly dissimilar to the large-scale conditions, being directed away from the mountains. If such conditions persist for periods of time exceeding a few hours, Coriolis effects become important. The local pressure field will then support geostrophic-type motion parallel to the mountains. Of course, friction and diabatic effects must also be considered, but their combined effect is probably only of secondary importance in modifying the barrier wind. The terrain acts to confine the barrier winds mainly to the levels below the crest and some distance away from the mountain, dependent on the horizontal extent of the pressure perturbation provided by the mountain-damming.

Although the results of the Parish study were done under southwesterly flow aloft resulting in the formation of a southerly barrier jet on the eastern side of the Sacramento Valley, it can be theorized that the same phenomena may occur under northeasterly flow aloft developing a northerly barrier jet along the west side of the valley. The stability criteria is certainly satisfied by the deep layer of subsidence over the region under the upper-level ridge of high pressure. Thus, it appears that terrain channeling of northeasterly winds over the Sacramento Valley in addition to the damming of stable air along the western side of the Sacramento Valley and its associated convergence of momentum are likely explanations for the development of the northerly barrier jet in the Sacramento Valley.

Climatologically, this phenomenon should not be uncommon. Northeasterly flow across the Sacramento Valley occurs regularly, especially in the fall months of the year. This is also a time of high fire danger in the Sacramento Valley. On many of the days when this northerly barrier jet develops, a Red Flag Warning (meaning conditions are conducive for extreme fire behavior) is issued for the region. A historical occurrence of a northerly barrier jet likely occurred on 20 October 1991, the day of the Oakland Hills Fire. A very similar pattern to that which was just discussed developed over northern California and persisted for most of the day. Strong winds in excess of 55 kt were reported in the western Sacramento Valley foothills and through the Carquinez Strait by early afternoon into the evening. As the pressure gradient became more northerly, the winds began to decrease towards morning. Thus, knowing the conditions which lead to the development of the northerly barrier jet are important for local forecasters in the area and for any area where mountainous terrain exists.

Based on this study and other barrier jet occurrences, it appears that a significant barrier jet can develop when the following conditions exist:

1) A sufficient layer of northeasterly flow is present over the Sacramento Valley for at least six hours. The depth of this layer should be at least 150 mb for this phenomena to develop. Thus, forecasters should look at the 850 mb and surface charts to determine the depth of the northeasterly flow.

2) Strong stability should also be evident, as can be seen in the OAK sounding, most likely due to subsidence and nighttime radiation loss. This stable layer should extend from around 800 mb to at least as high as the terrain to maximize the strength of the jet.

3) Gusty surface winds are enhanced if this stable layer caps a slightly less stable layer, in the Sacramento Valley, allowing for vertical mixing of momentum to the surface.

Once these factors are in place and are expected to continue for a couple of hours, a barrier jet can be expected to develop along the western portion of the Sacramento Valley. This jet can reach speeds in excess of 55 kt and through vertical mixing can cause gustiness at the surface to 35 kt or greater. The jet will continue to exist until the pressure gradient changes to more northerly or easterly, or the stability decreases significantly. Through the use of the WSR-88D and through careful examination of upper-air and surface data, this phenomena will be forecasted more accurately.

References

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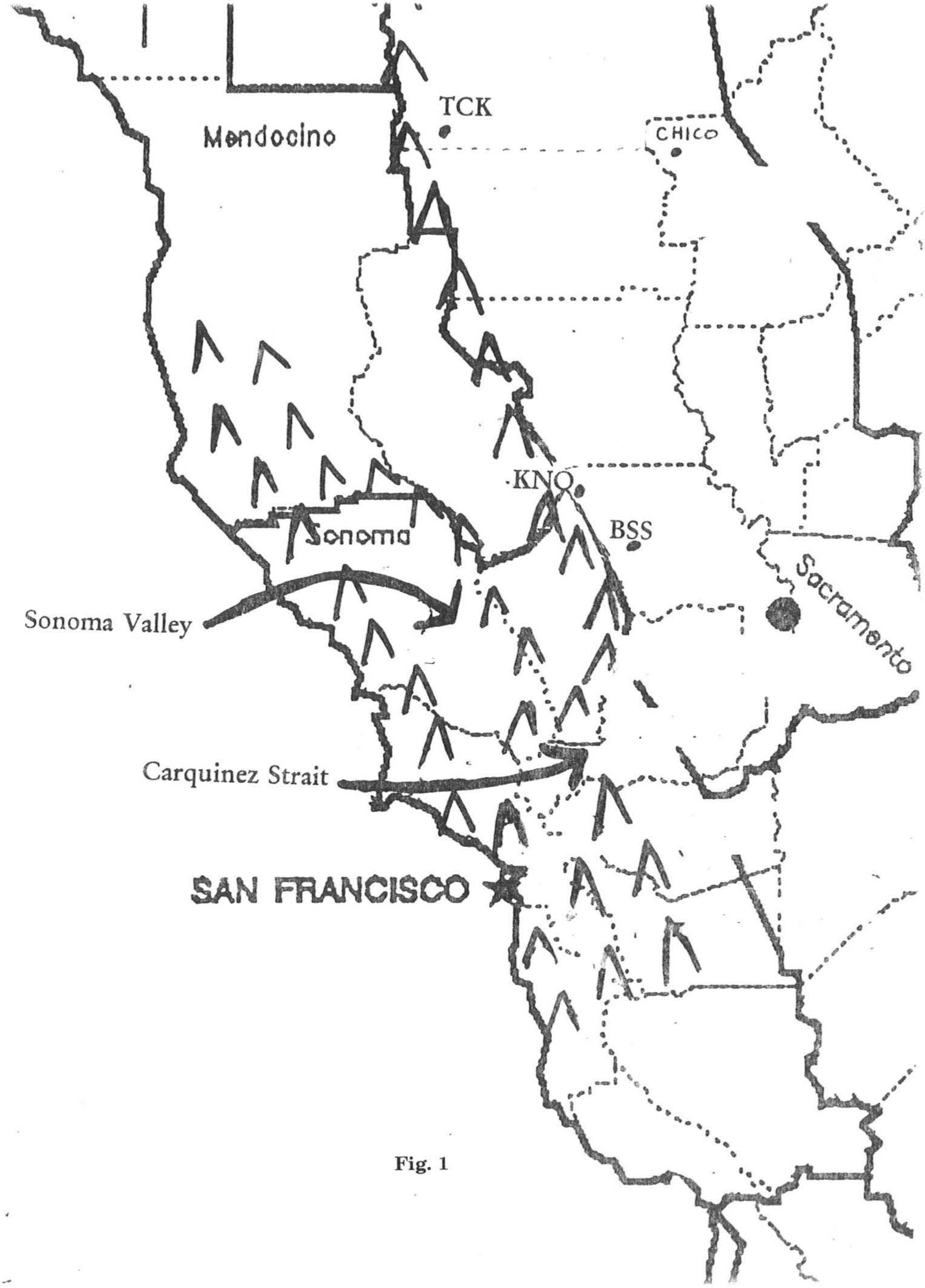


TCK
Mendocino
CHICO
KNO
BSS
Sonoma
Sacramento
Sonoma Valley
Carquinez Strait
SAN FRANCISCO

Fig. 1

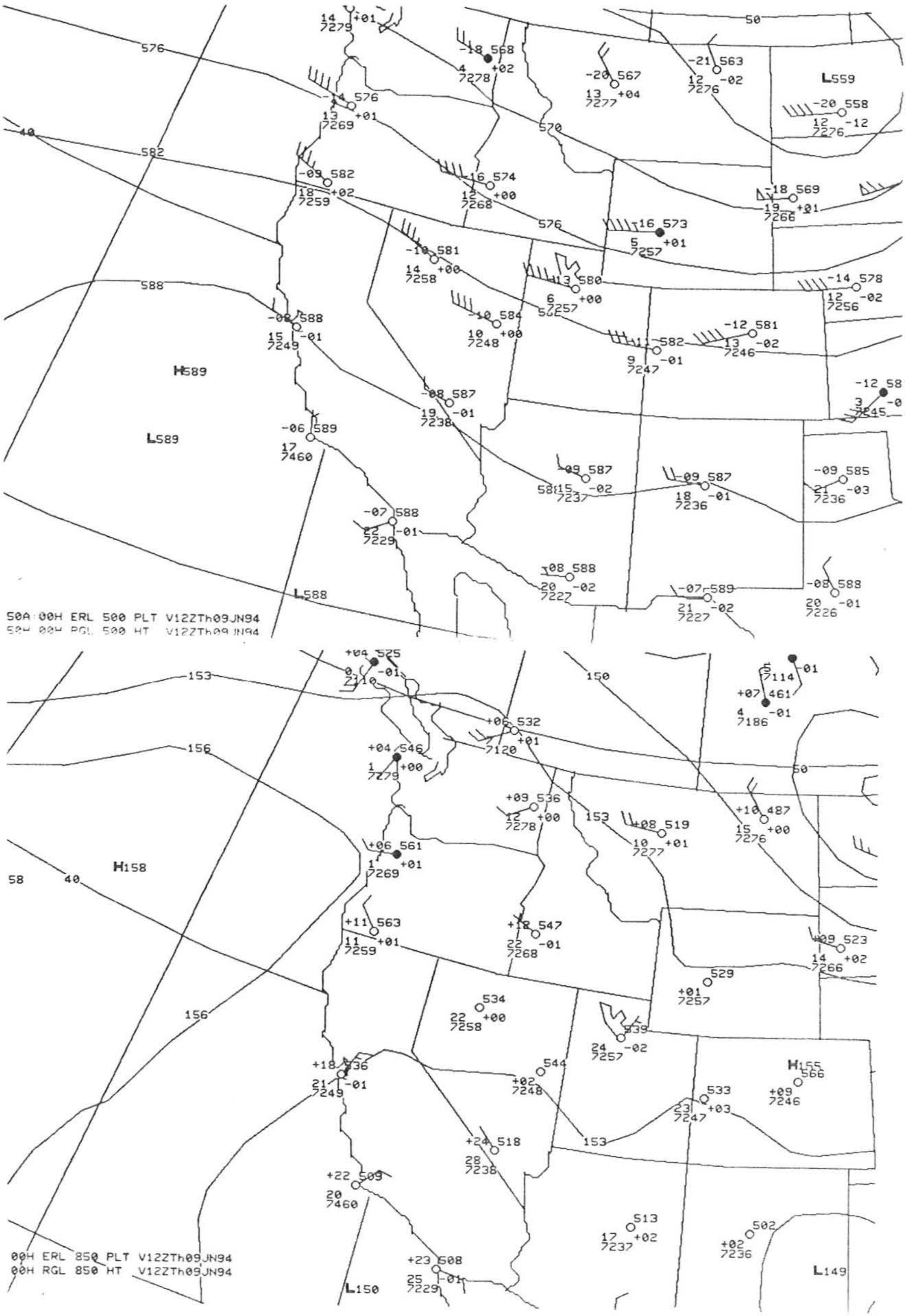


Fig. 2 1200 UTC 9 June 1994 500 mb (top) and 850 mb (bottom) plot.

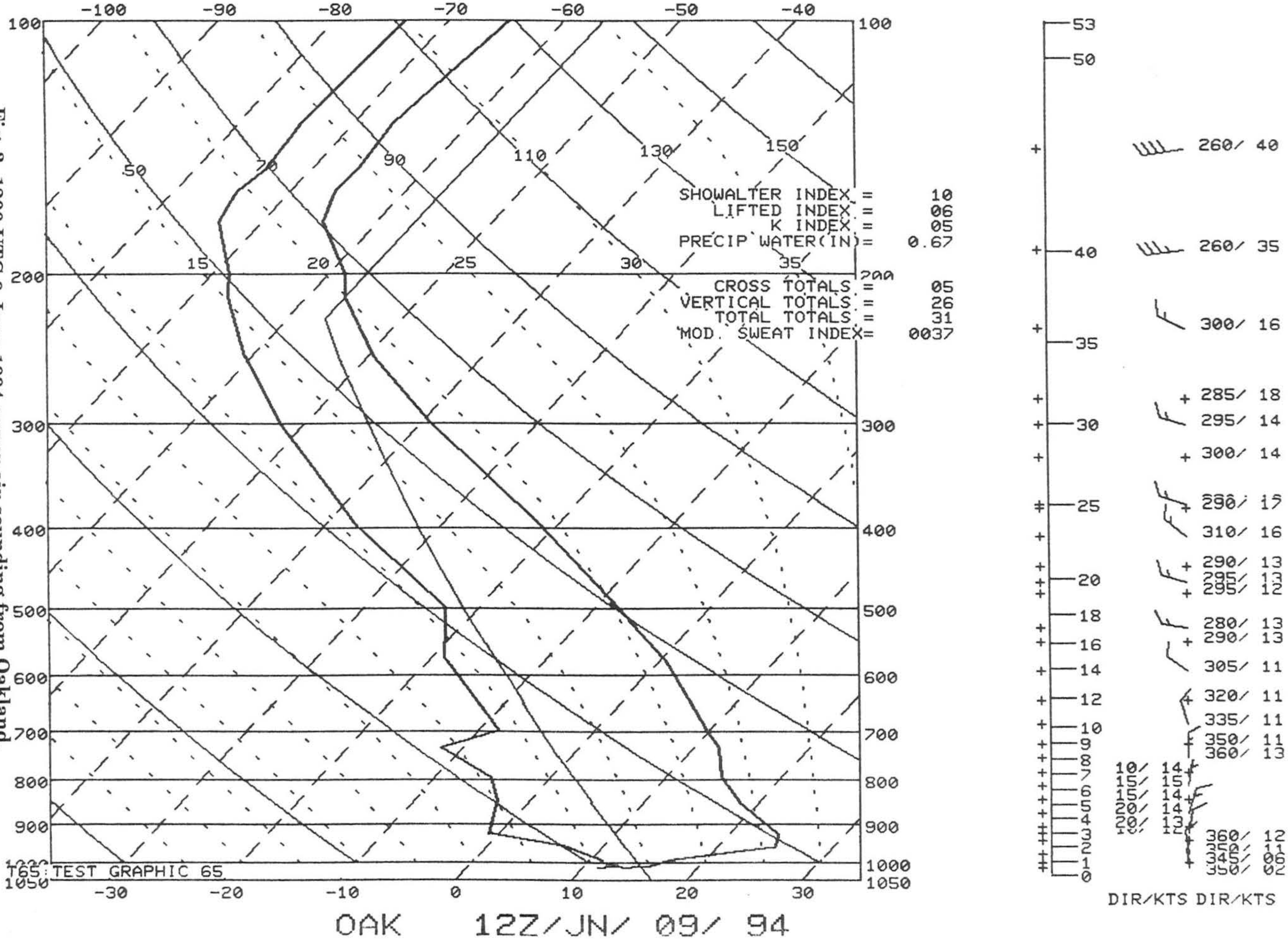


Fig. 3 1200 UTC 9 June 1994 upper-air sounding from Oakland.

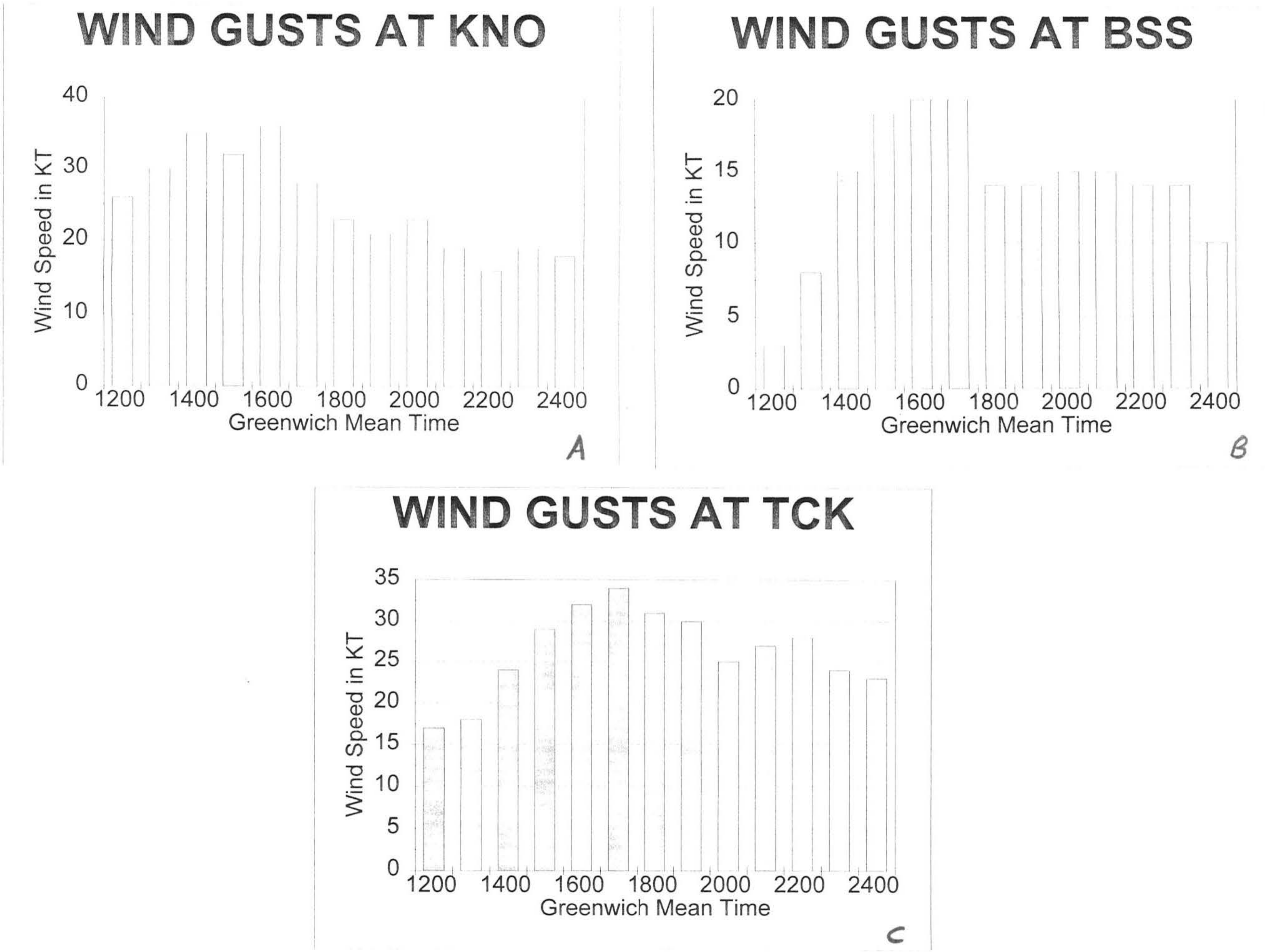


Fig. 4 Observed wind gusts at a) Knoxville, b) Brooks, and c) Thomes Creek.

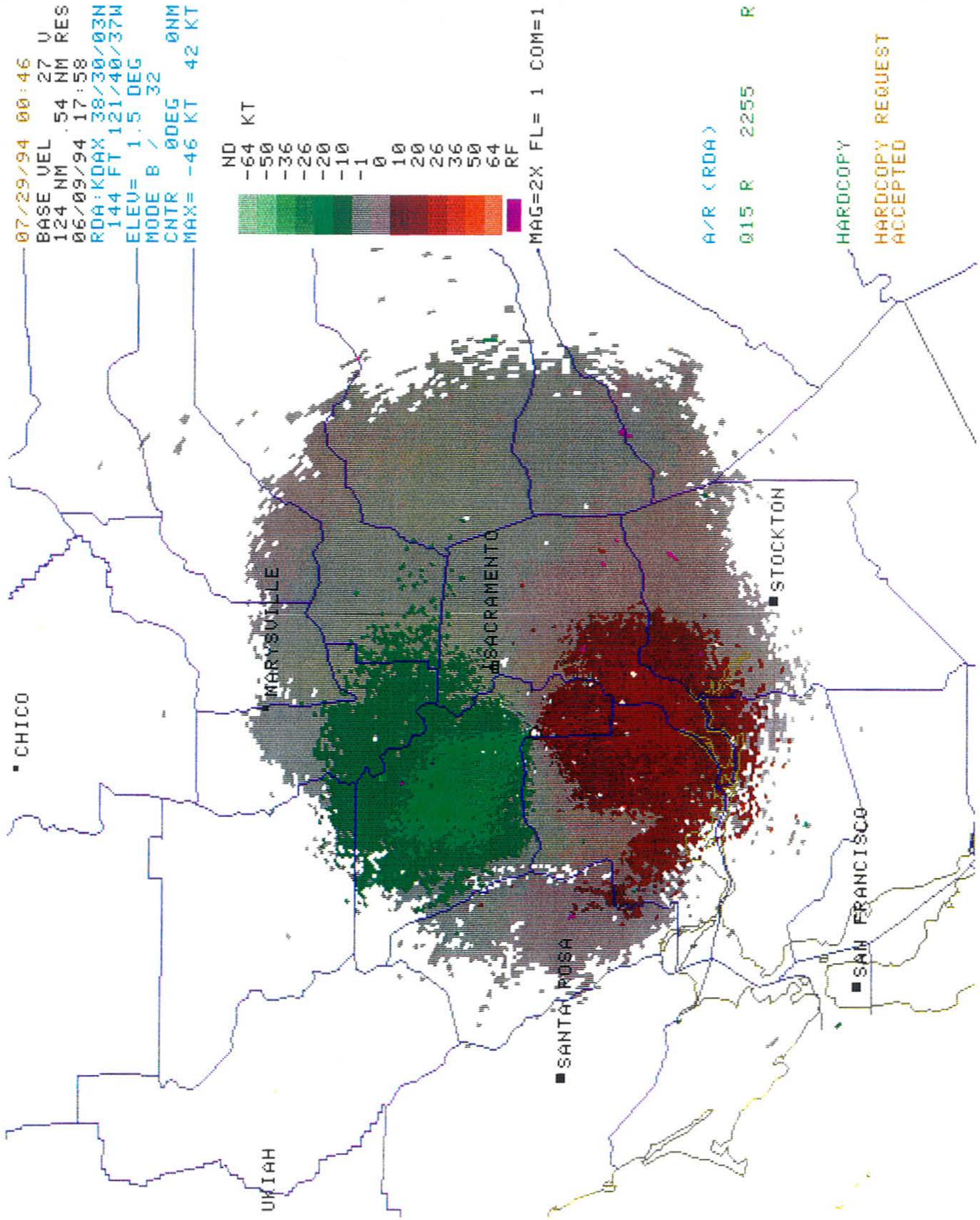
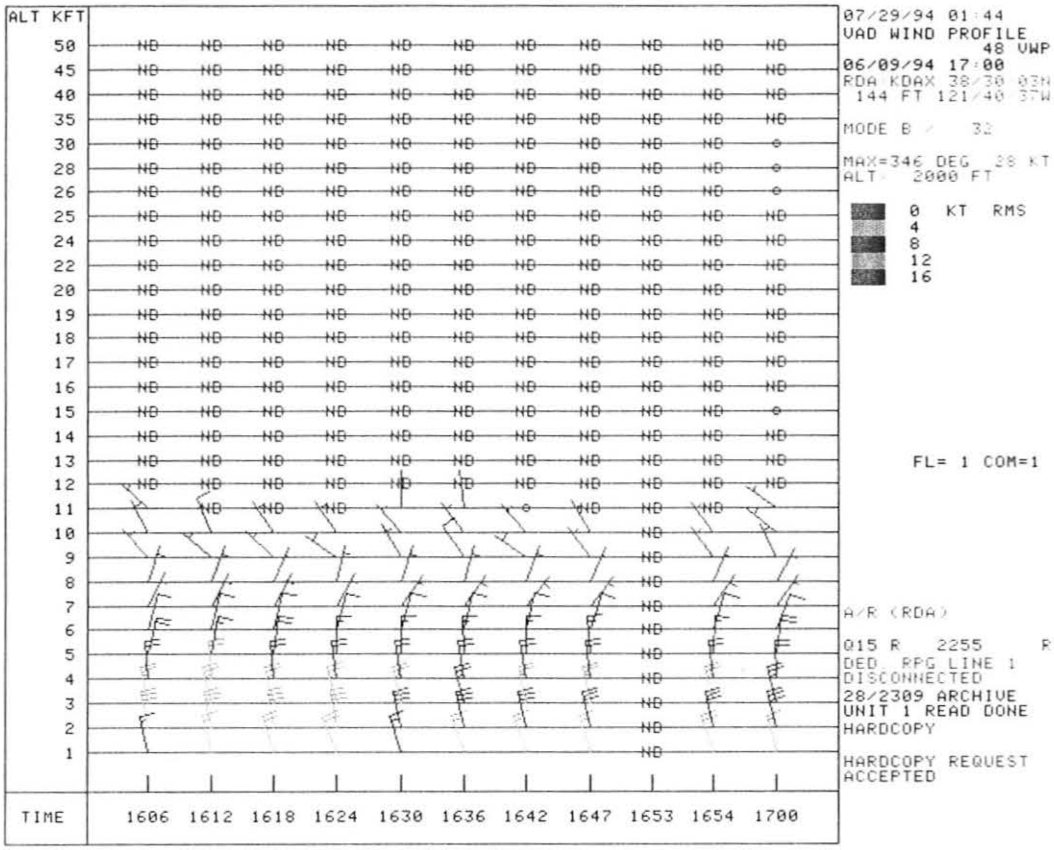


Fig. 5 Reflectivity at 1.5° elevation angle at 1758 UTC 9 June 1994 from Sacramento WSR-88D. Green is velocity towards radar, red is away.



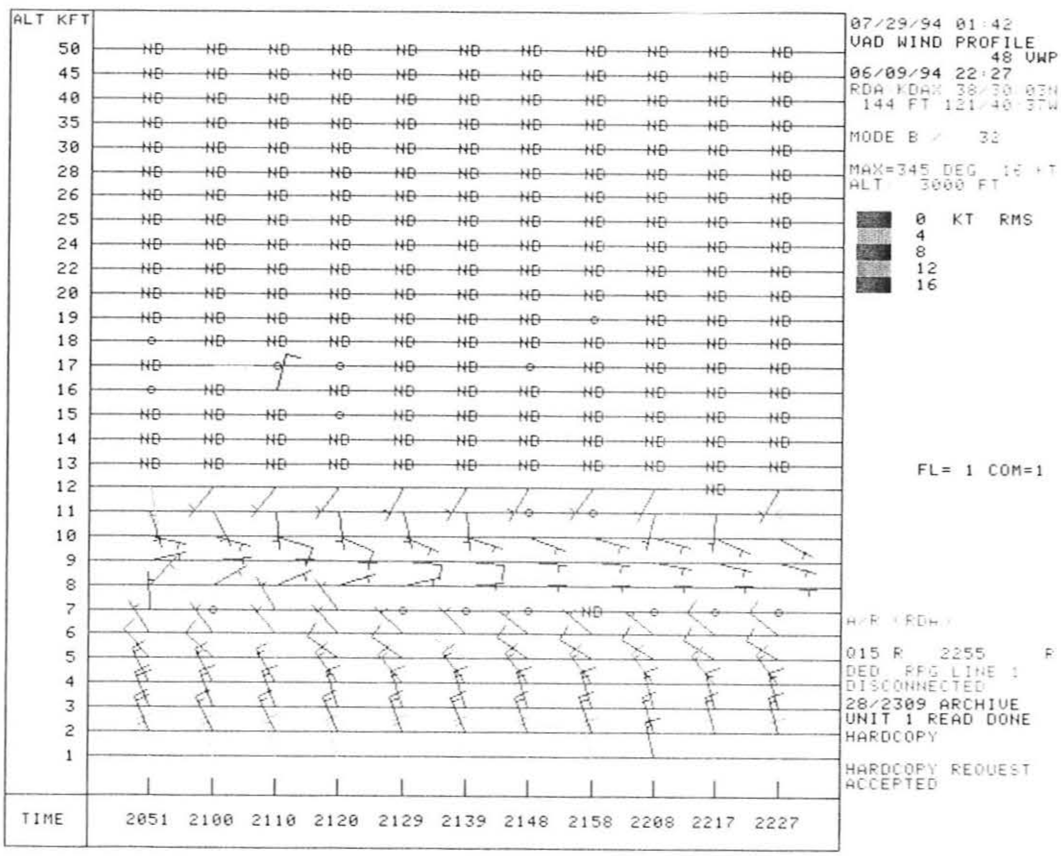


Fig. 6 VAD wind profile from the Sacramento WSR-88D. Times are along the bottom of each profile.