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TITLE Northern Arizona Basin Study, (NABS) 1989

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NORTHERN ARIZONA BASIN STUDY (NABS) 1989

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ABSTRACT

In February of 1989, during an exceptionally cold period in Northern Arizona, an experiment was conducted to better understand a frequent layer of northeast winds found in this region. This layer has been observed most often in winter near the surface at Page, Arizona, and often opposes larger scale upper level west winds. The results of this experiment improved both the temporal and the down-valley spatial resolution of the flow structure in this region during winter. The depth of the northeast wind layer was about 1 km, which is much greater than the effective plume height (about 750 m) of the coal-fired Navajo Generating Station near Lake Powell. The layer was simultaneously observed at Page and at a site 20 km southwest of the Navajo Generating Station. The down-valley extent of this layer, together with the temperature and dew point profile, is consistent with the hypothesis that the east-wind layer is a large scale manifestation of a valley drainage flow. These flows occur at night and persist throughout the day at some locations during cold winter conditions. Optical cross-wind measurements obtained parallel to Glen Canyon Dam show that the lake effect from Lake Powell can pull local pollutants from Page over the lake at night, giving them extra chemical processing time before being sampled at the Glen Canyon aerosol sampling location northwest of Page.

INTRODUCTION

Environmental scientists have recently focused attention on Northern Arizona and Southern Utah for several reasons. These reasons include the number of national parks, the pristine regions, and questions about the relative importance of potential sources of visibility degrading agents in the area. The potential sources include Los Angeles pollution, coal-fired power plants and smelter operations, local sources, and natural factors which contribute to reduced visibility. Among the natural factors, relative humidity is probably dominant, particularly in winter. Because of the comparatively low aerosol content of this region and the associated high visual ranges, long sampling times are required for chemical analysis. These relatively long sampling times, the great distances from many potential sources to pristine region receptors, and the scarcity of wind measurement locations and times combine to make trajectory analysis a much less accurate method for source apportionment in this region than in the eastern United States. The fact that the regions of special interest in the western United States are regions of complex terrain, like the Colorado River Valley, compounds the difficulties in source apportionment. Terrain driven flows are even more important in winter when low mixing and enhanced ground cooling may allow katabatic flows to persist throughout the day. These flows may be decoupled from the synoptic winds.

Numerous studies exist of meteorological parameters and pollution flow patterns from the region of the Colorado Plateau during summer (e.g. Barr, 1986). Winter studies however, are more rare (e. g. Williams, 1977, and Yu and Pielke, 1986). The Subregional Cooperative Electric Utility (comprised of the Electrical Power Research Institute, Southern California Edison, and the Salt River Project), National Park Service, Environmental Protection Agency, and Department of Defense Study (SCENES) has increased the data available for meteorological surface winds and vertical profiles in the Lake Powell Region (Balling and Sutherland, 1988). SCENES also conducted a Winter Haze Intensive Tracer EXperiment (WHITEX) in January and February of 1987. Preliminary results of the tracer and aerosol concentrations, as well as meteorology, have been reported (Malm and Iyer, 1988; and Markowski et al., 1989). Early attempts have been made to numerically model the transport trajectories during WHITEX (Stocker et al., 1988). All of these studies indicate a frequent lower level air flow pattern from the northeast in a layer about 1 km deep under light synoptic wind conditions in winter. Since the plume from the Navajo Generating Station (NGS see Fig. 1) rises to about 750 m in winter, this flow can direct the plume toward the Grand Canyon. The fact that this layer is colder than the air above and is also observed at Canyonlands National Park farther up the Colorado River Valley from Page (Sutherland, 1988) provides *prima facie* evidence that this layer is the result of a deep katabatic flow down the valley.

An experiment was conducted by our group at Los Alamos National Laboratory in early February 1989 in Northern Arizona to test the hypothesis that the northeast wind layer is a large scale flow and not a local feature of Page and Canyonlands. This experiment improved the temporal resolution of the vertical structure of the flow and extended our understanding of the flow characteristics down the Colorado River Valley between Page and the Grand Canyon.

The down-valley site was located at Marble Canyon which is about 20 km southwest of Page. We also investigated the effect of Lake Powell on the diurnal cycle of flow up and down Glen Canyon and its potential effect on local pollutants from Page.

The Lake Powell Basin has a unique combination of small and large scale terrain forcing with a lake effect in winter which makes this region particularly interesting from a mesoscale meteorological perspective. Besides the scientific interest in terrain forcing, understanding the winter flows in this region should help with the very practical problem of determining the impact of the Navajo Generating Station on visibilities at the Grand Canyon. The February 1989 experiment provided data which will help in the interpretation of the 1987 WHITEX experiment and in planning the meteorological components of future experiments in Northern Arizona.

EXPERIMENT DESCRIPTION

Fig. 1 shows a map of the region of interest in relation to the Colorado Plateau. Also shown in Fig. 1 is a terrain cross section which is highly exaggerated in the vertical (20:1). This cross section runs on a bearing of 63° from true North beginning at our rawinsonde site in Marble Canyon. The various measurement sites used in this experiment are shown on the contour map of Fig. 1. A rawinsonde took vertical profiles at Marble Canyon. At the

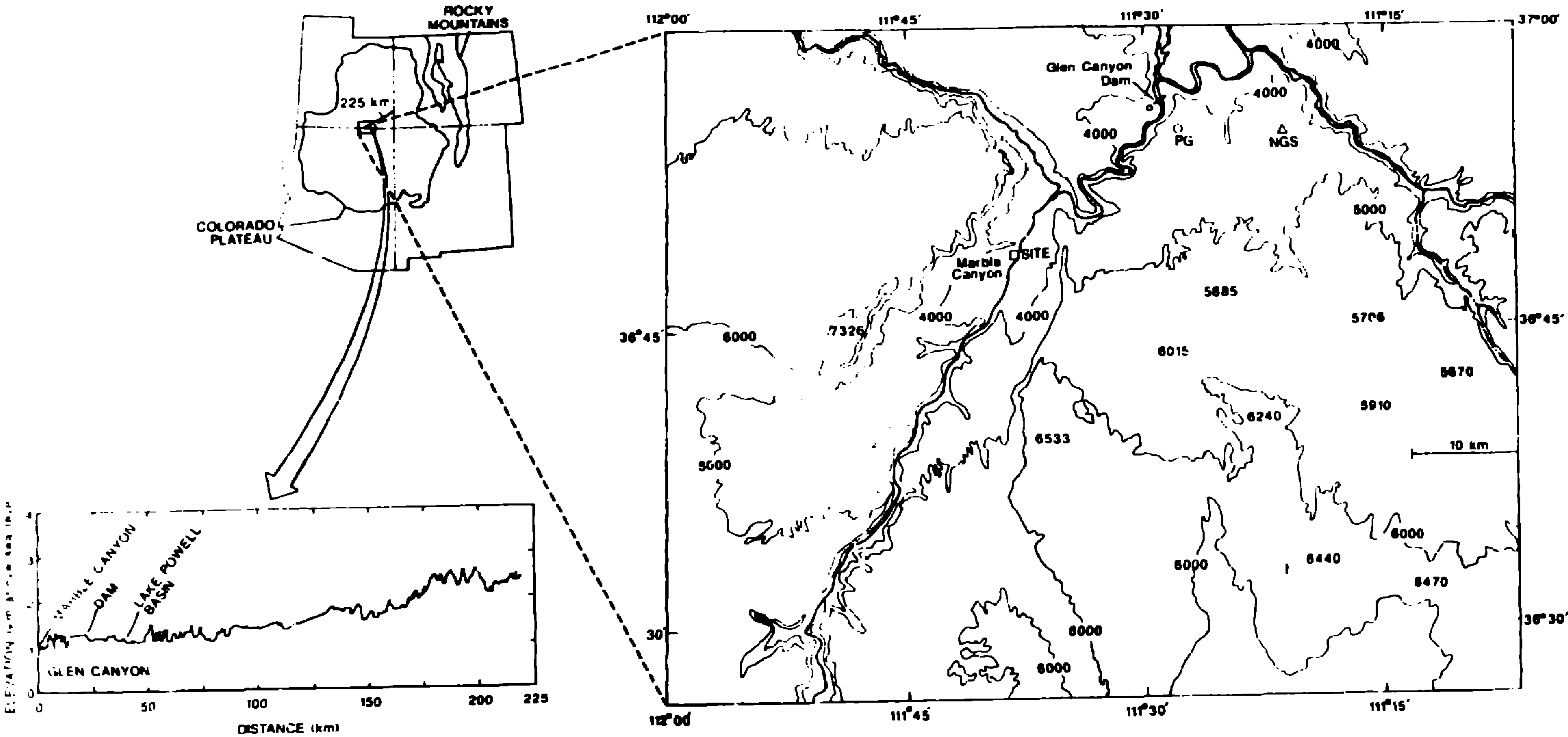


Fig. 1 Map of experiment region with locations of experiment sites (Marble Canyon, Glen Canyon Dam, PG-Boat Club, Page), and a vertical cross section of the terrain over a 225 km northeasterly segment.

Boat Club in Page, an optically tracked airsonde was employed for vertical measurements. Three measurement systems were located on or near the Glen Canyon Dam. These were:

1. A tethered balloon sounding system located on the dam,
2. An optical cross-wind sensor (Lawrence et al., 1972) located parallel to the dam to measure flow over the dam either into or out of Glen Canyon, and
3. A permanent aerosol, visibility and meteorological tower station operated by the Navajo Generating Station located on a promontory above the dam (Balling and Sutherland, 1988).

The aerosol monitoring site near Glen Canyon Dam and the airsonde location at the Boat Club provided continuity between the 1987 WHITEX and the 1989 experiments. Higher temporal resolution was achieved in this experiment by obtaining vertical profiles from the Boat Club and from Marble Canyon every three hours, beginning at 0700 MST and ending about midnight (during WHITEX profiles were obtained from the Boat Club site at 0600, 1100 and 1700 MST). Tethered balloon profiles were taken at the dam every two hours to an altitude of about 1 km. These data were taken on Feb 8 and 11. Optical cross-wind measurements were taken continuously from Feb. 7 to Feb. 12 with one minute resolution.

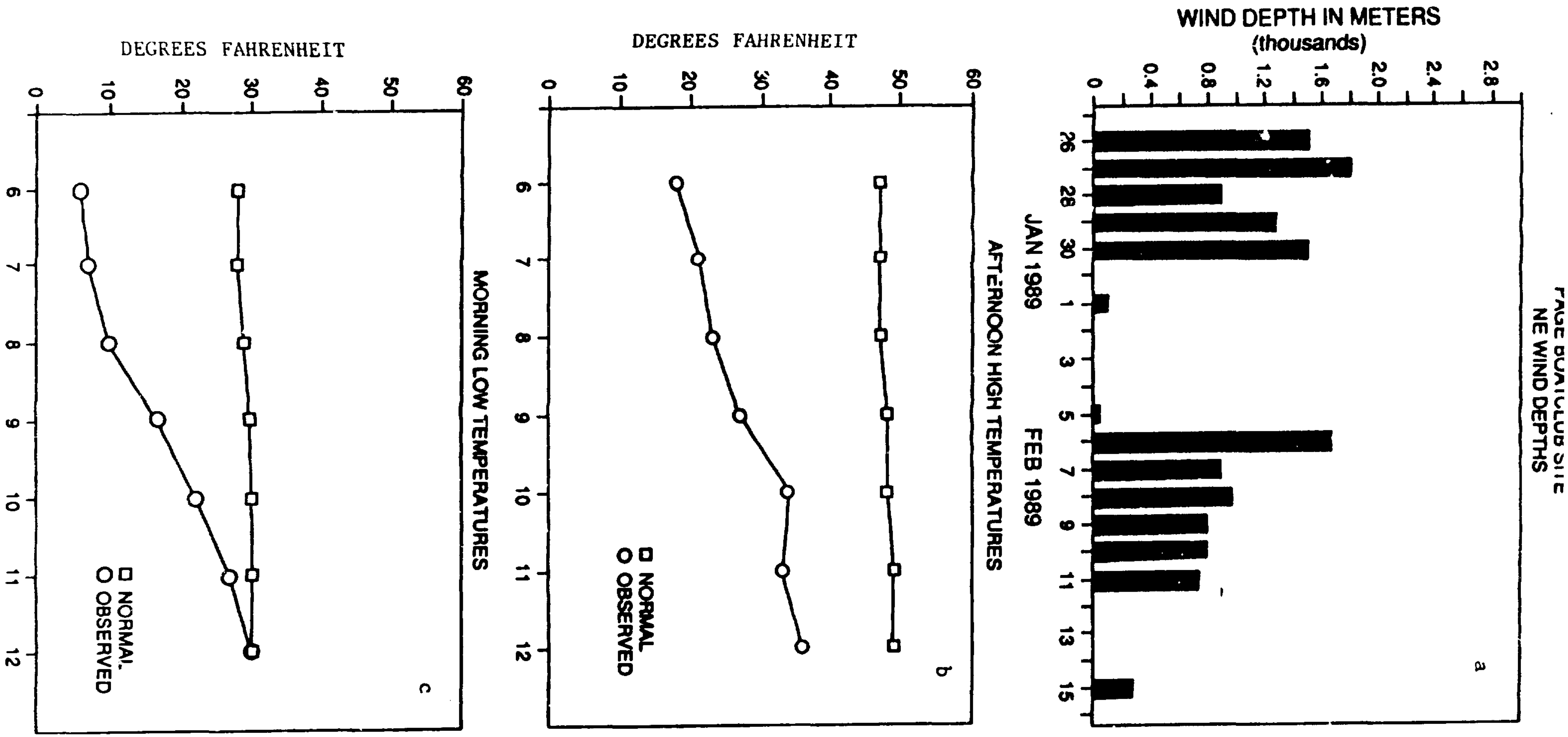
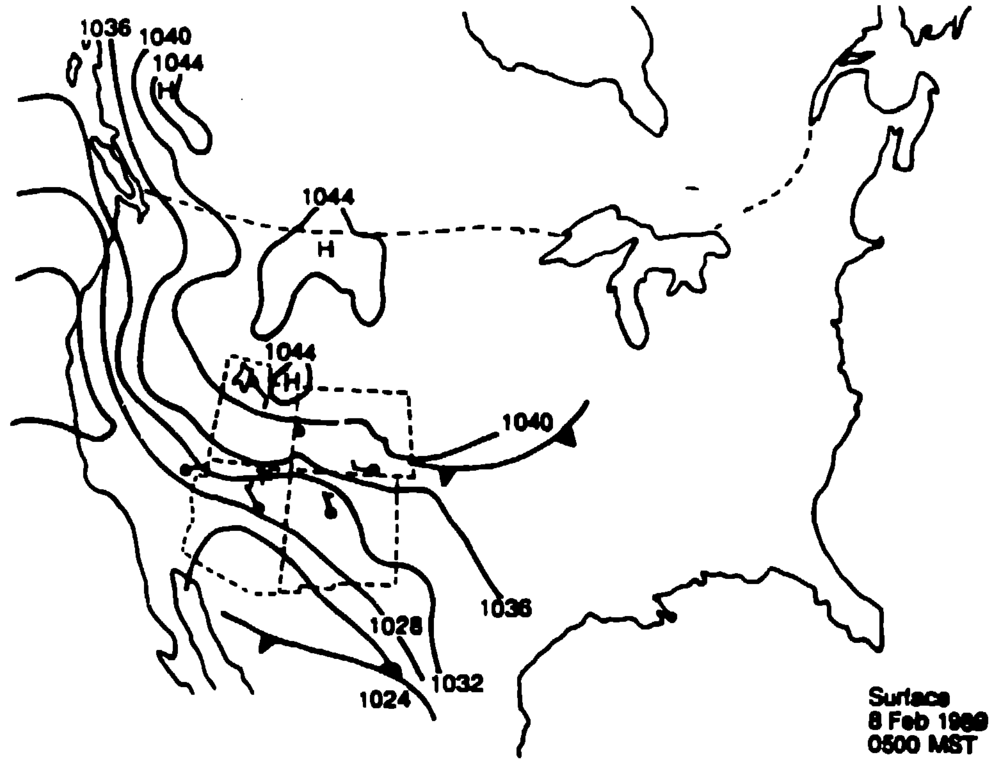


Fig. 2 Climatological context of 1989 experiment showing a) depth of NE wind layer, b) afternoon high temperatures, and c) morning low temperatures before and after experiment dates Feb. 8 and 11.

Fig. 3 a)



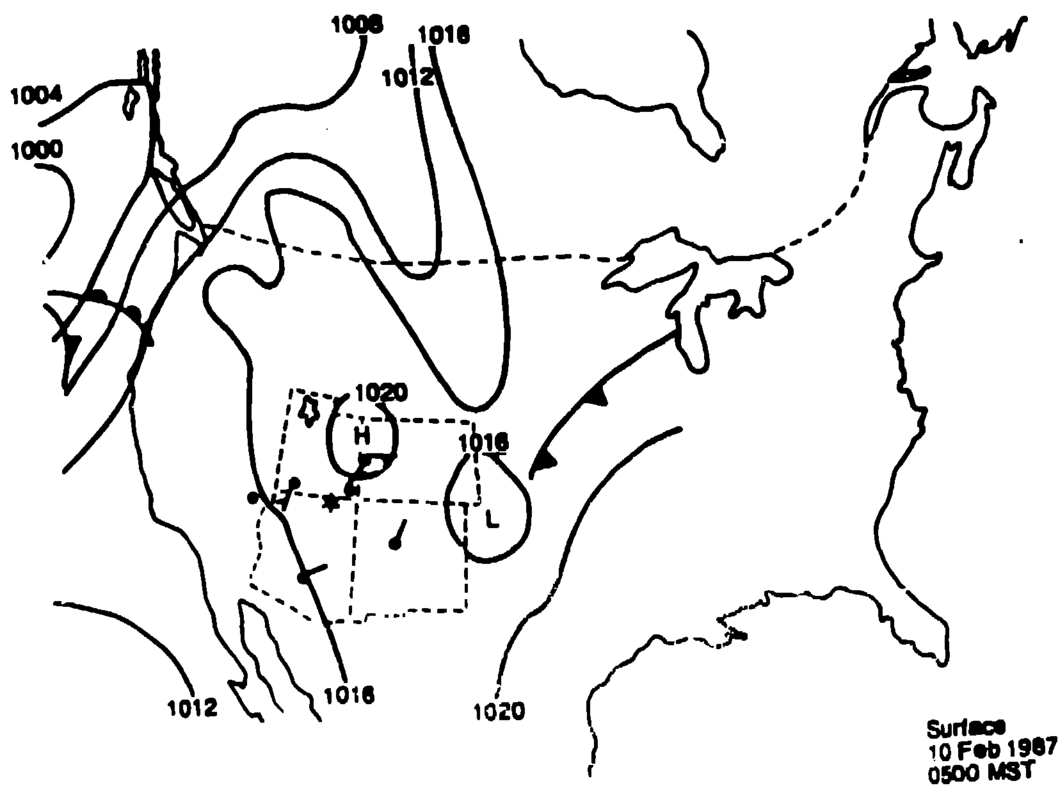
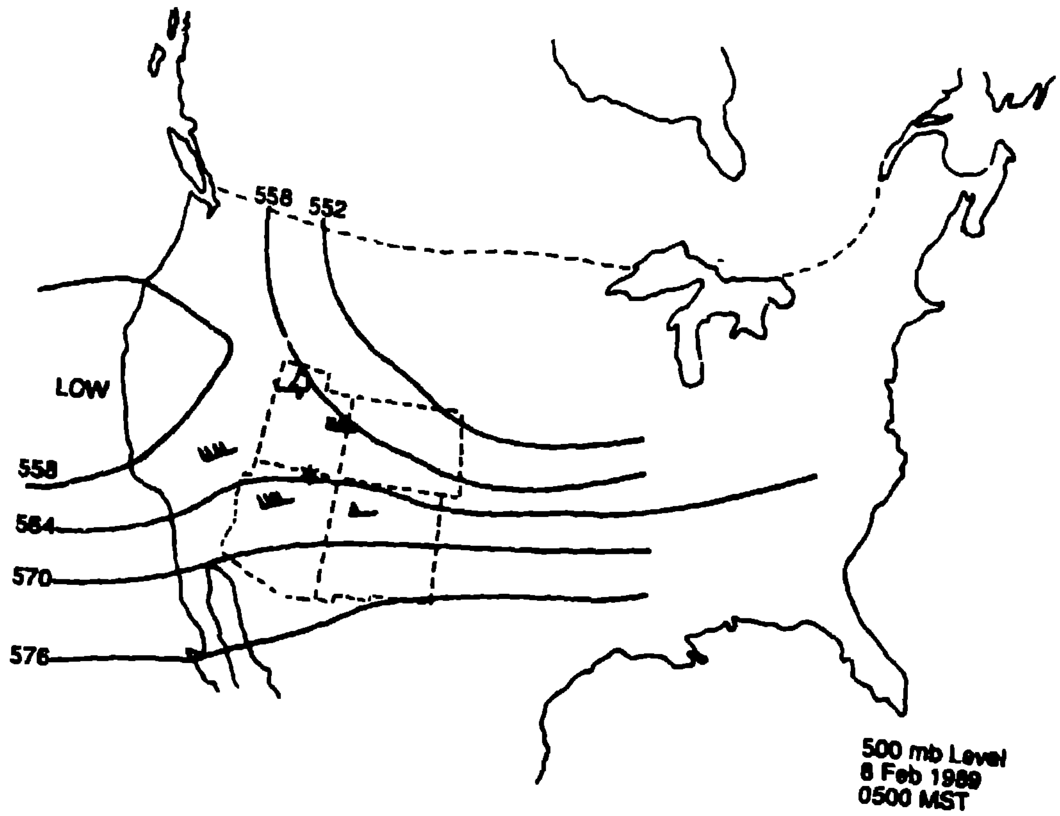


Fig. 3 Surface weather maps for the western United States for a) Feb. 8, 1989 and Feb. 10, 1987(WHITE?), b) 500 mb maps for the same days, and c) surface and 500 mb maps for Feb 11, 1989.

Fig. 3 b)


558
552
LOW
558
564
570
576
500 mb Level
8 Feb 1989
0500 MST

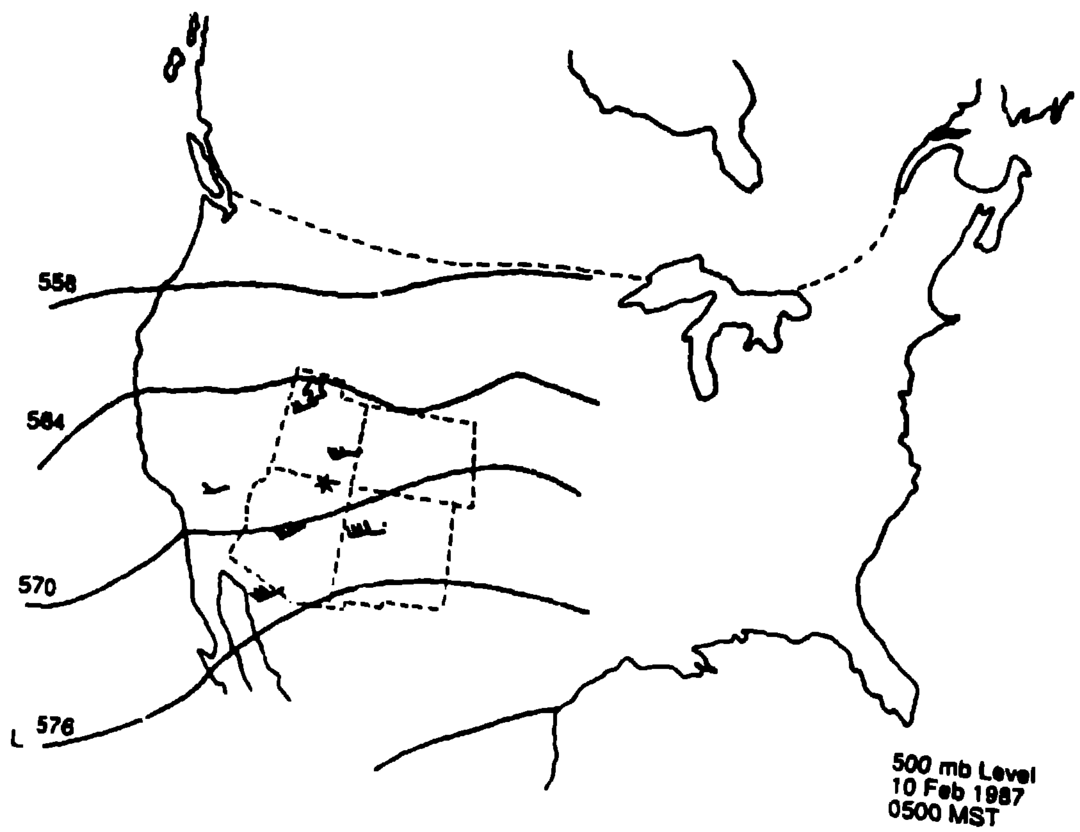
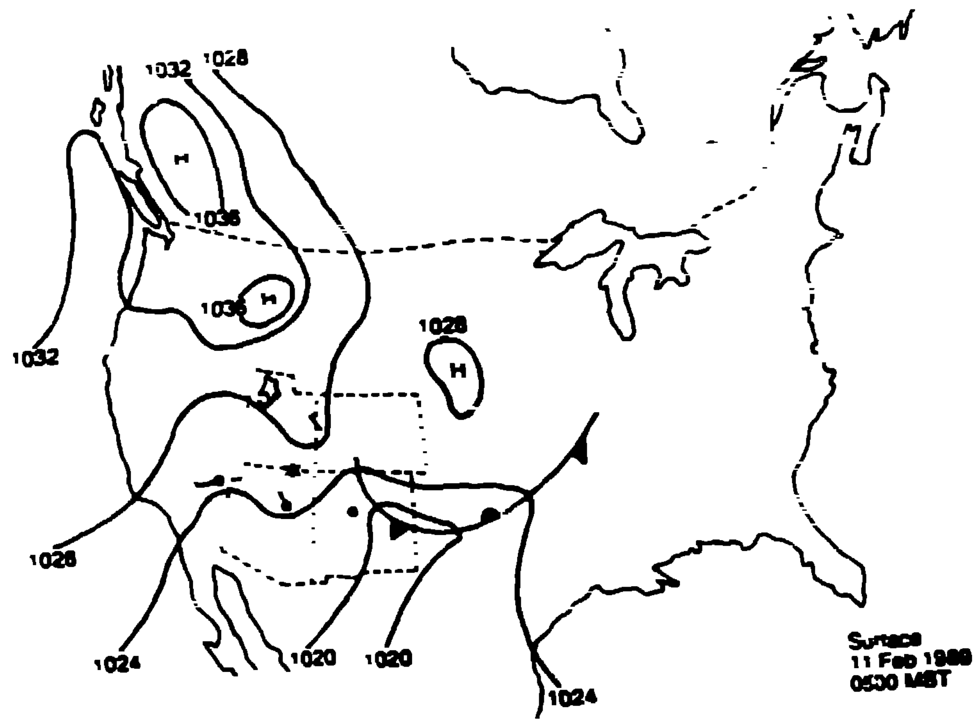
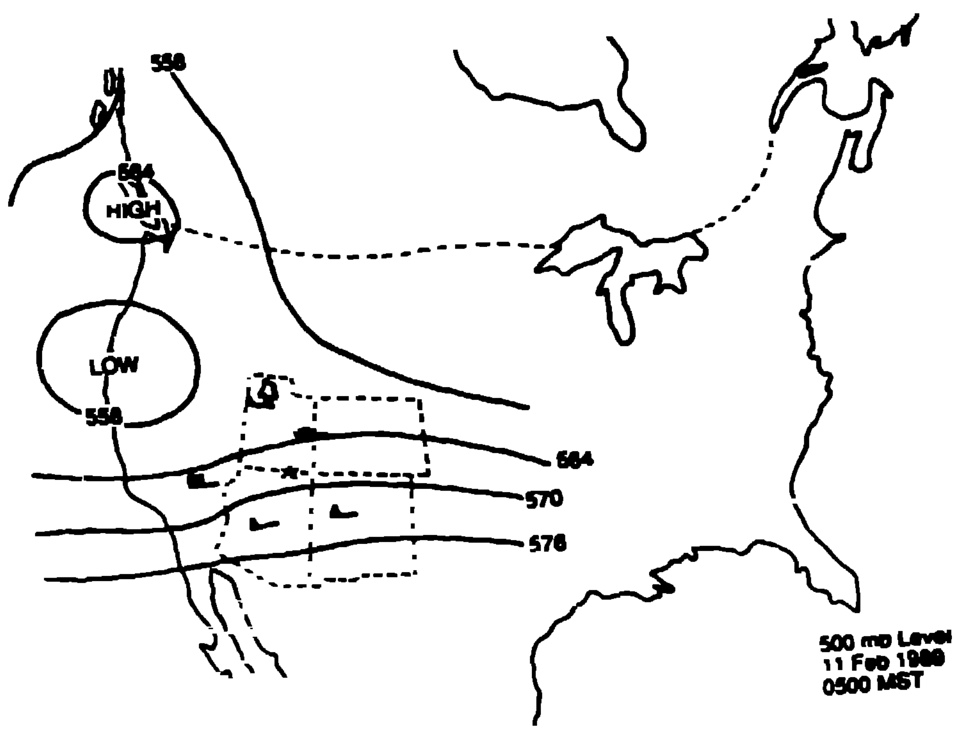

558
564
570
L
576
500 mb Level
10 Feb 1987
0500 MST

Fig. 3 c'


1032
1028
1036
1036
1032
1028
1028
1024
1020
1020
1024
Surface
11 Feb 1989
0500 MST


558
564
HIGH
LOW
558
564
570
576
500 mb Level
11 Feb 1989
0500 MST

RESULTS

The results of these experiments will be presented as 1) intercomparison of vertical profiles of wind velocity and temperature at the three sites used in the Feb. 1989 experiment, 2) a comparison of these profiles to profiles made under similar conditions during WHITEX in 1987, and 3) results from the optical cross-wind sensor. One of the most obvious results of these comparisons is the inability of the airsonde at the Boat Club, because it uses optical tracking, to obtain wind data in the presence of low clouds which occurred both during the Feb. 1989 experiment and often during the WHITEX experiment.

The climatological setting of the 1989 experiment is shown in Fig. 2. We had hoped for a cold period and were fortunate to pick the coldest period in Page, AZ., in the last four years (Ostpauk, 1989). The period was more than 20 ^{o}F below normal and was characterized by a well developed northeast wind layer and low clouds. The presence of a large Arctic air mass over the region is shown on surface and upper air weather maps in Fig. 3 for Feb 8 and Feb 11 at 1200 GMT. These maps are compared to a similar meteorological situation on Feb. 10, 1987 during WHITEX.

Profile Comparisons

The relationships between the wind and temperature profiles at the three locations are shown in Fig. 4 for six profiles at close to the same times. All the profiles in Fig. 4 are shown in height above ground level, so it is

Fig. 4 a)

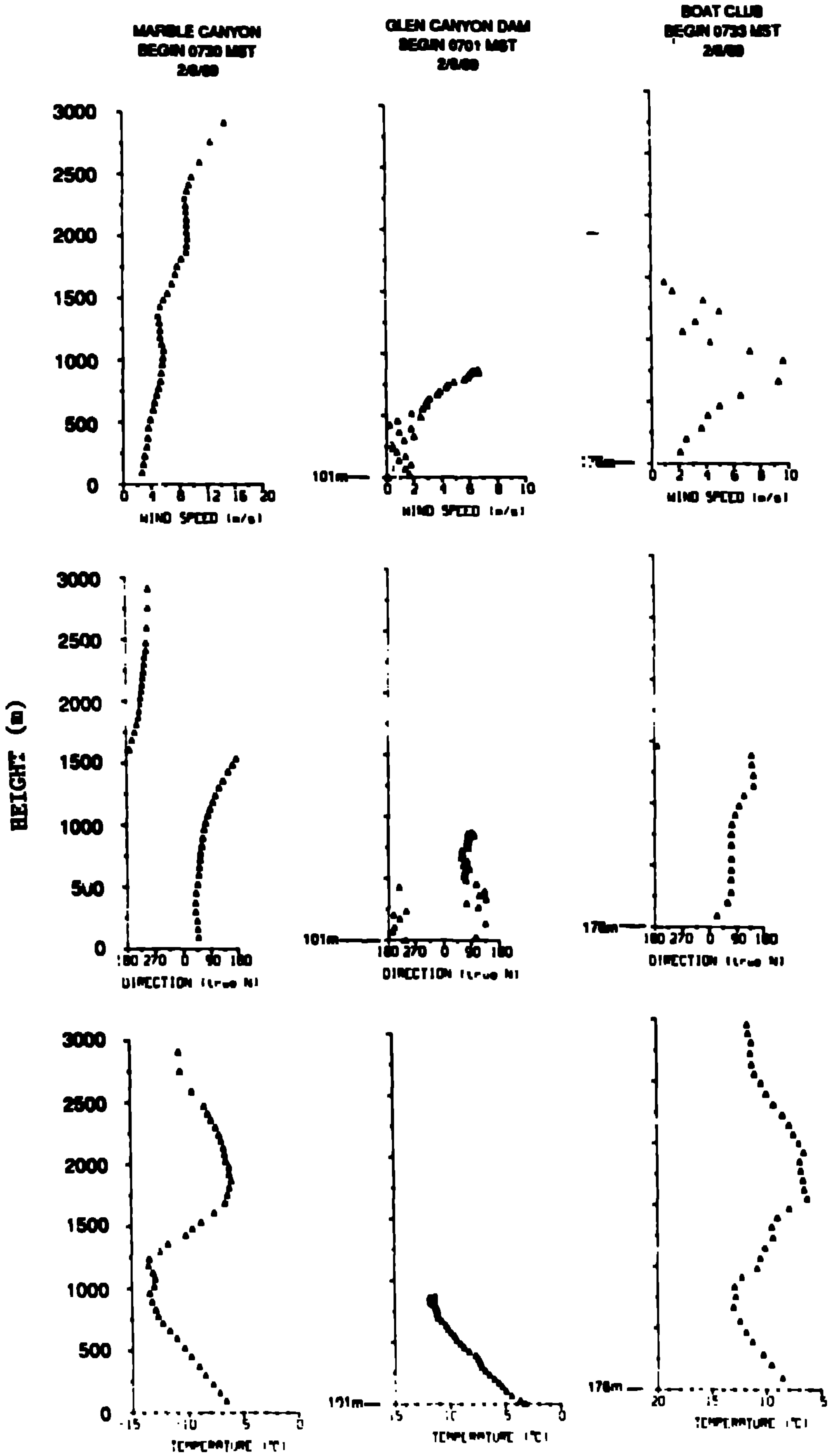


Fig. 4 Comparisons of wind and temperature profiles up to 3000 m for similar times taken at the three experiment locations

Fig. 4 b)

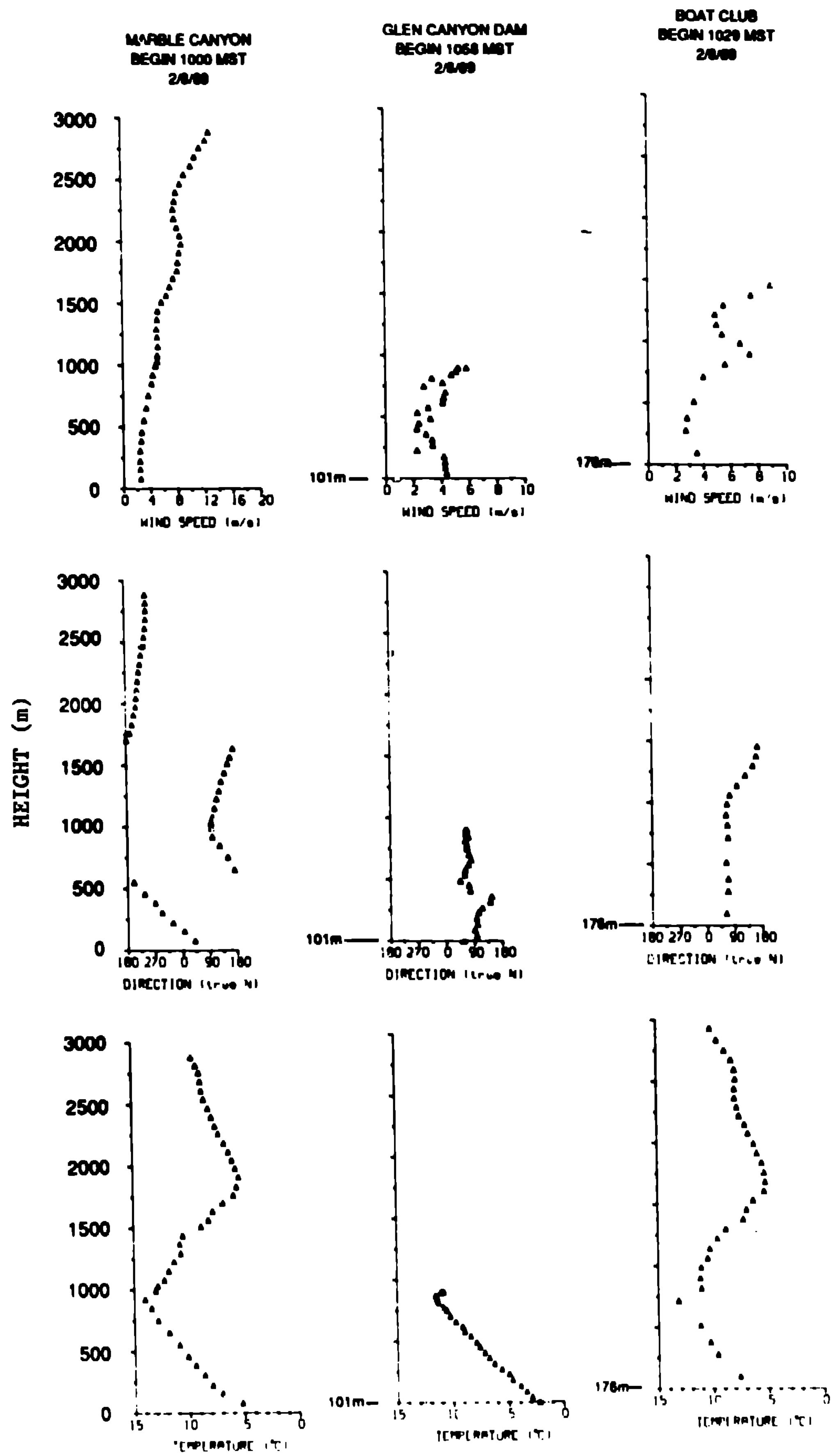
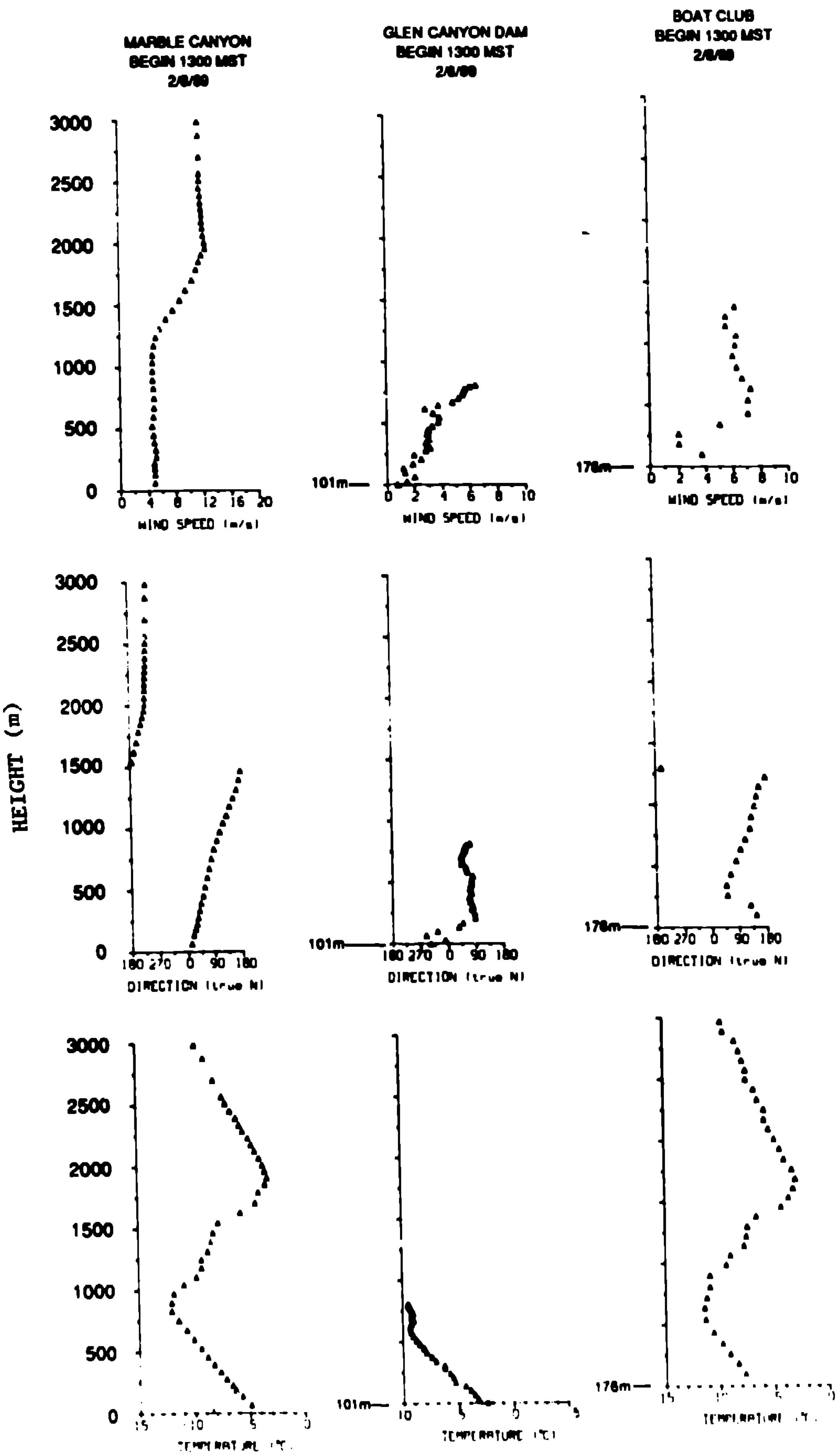

MARBLE CANYON
BEGIN 1000 MST
2/6/89
GLEN CANYON DAM
BEGIN 1058 MST
2/6/89
BOAT CLUB
BEGIN 1029 MST
2/6/89
HEIGHT (m)
101m
178m
WIND SPEED (m/s)
DIRECTION (true N)
TEMPERATURE (°C)

Fig. 4 c)



MARBLE CANYON
BEGIN 1300 MST
2/8/89
GLEN CANYON DAM
BEGIN 1300 MST
2/8/89
BOAT CLUB
BEGIN 1300 MST
2/8/89
HEIGHT (m)
WIND SPEED (m/s)
DIRECTION (true N)
TEMPERATURE (°C)
101m
176m

Fig. 4 d)

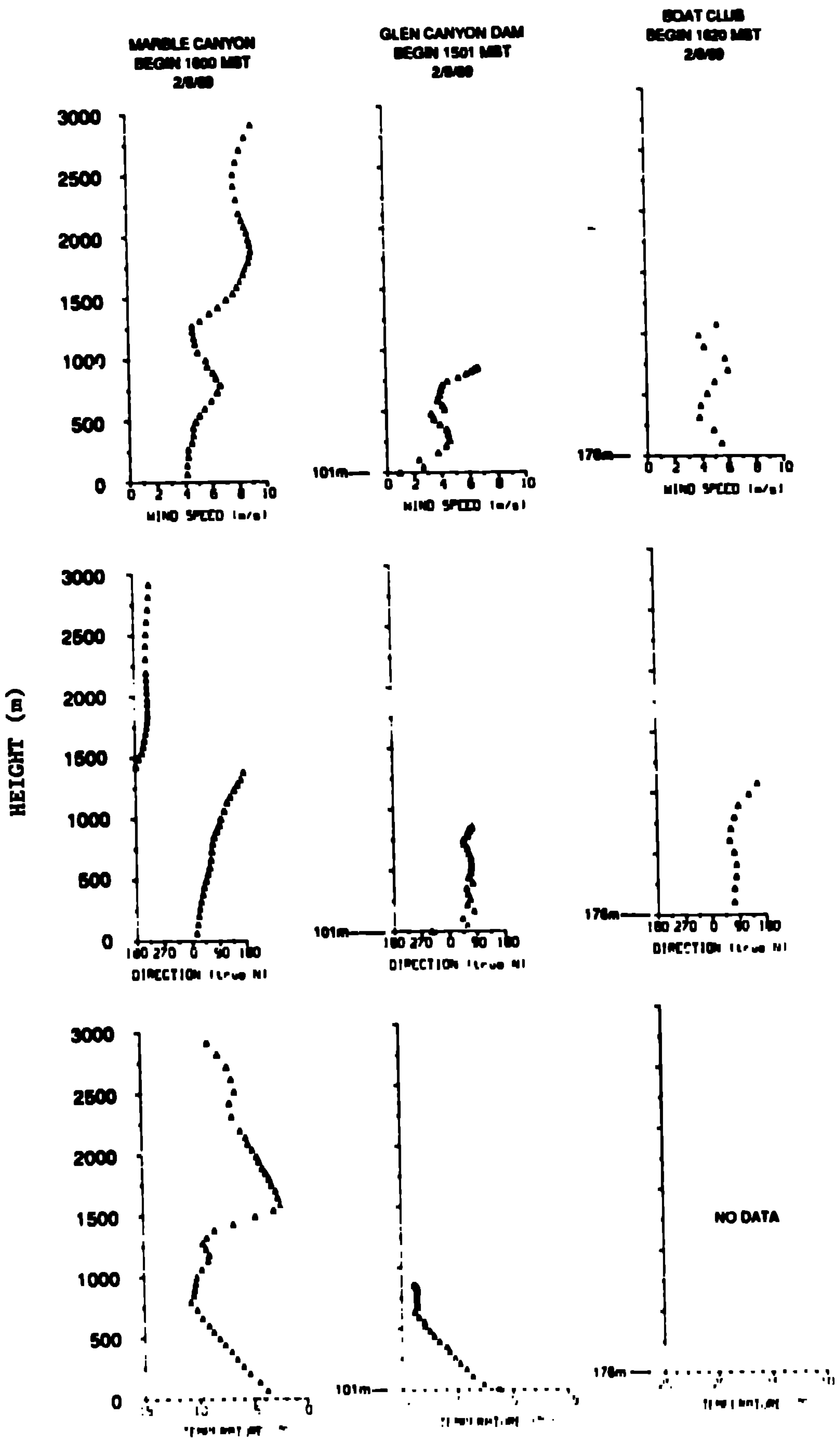

MARBLE CANYON
BEGIN 1600 MST
2/8/89
GLEN CANYON DAM
BEGIN 1501 MST
2/8/89
BOAT CLUB
BEGIN 1620 MST
2/8/89
HEIGHT (m)
3000
2500
2000
1500
1000
500
0
101m
178m
WIND SPEED (m/s)
DIRECTION (true N)
NO DATA

Fig. 4 e)

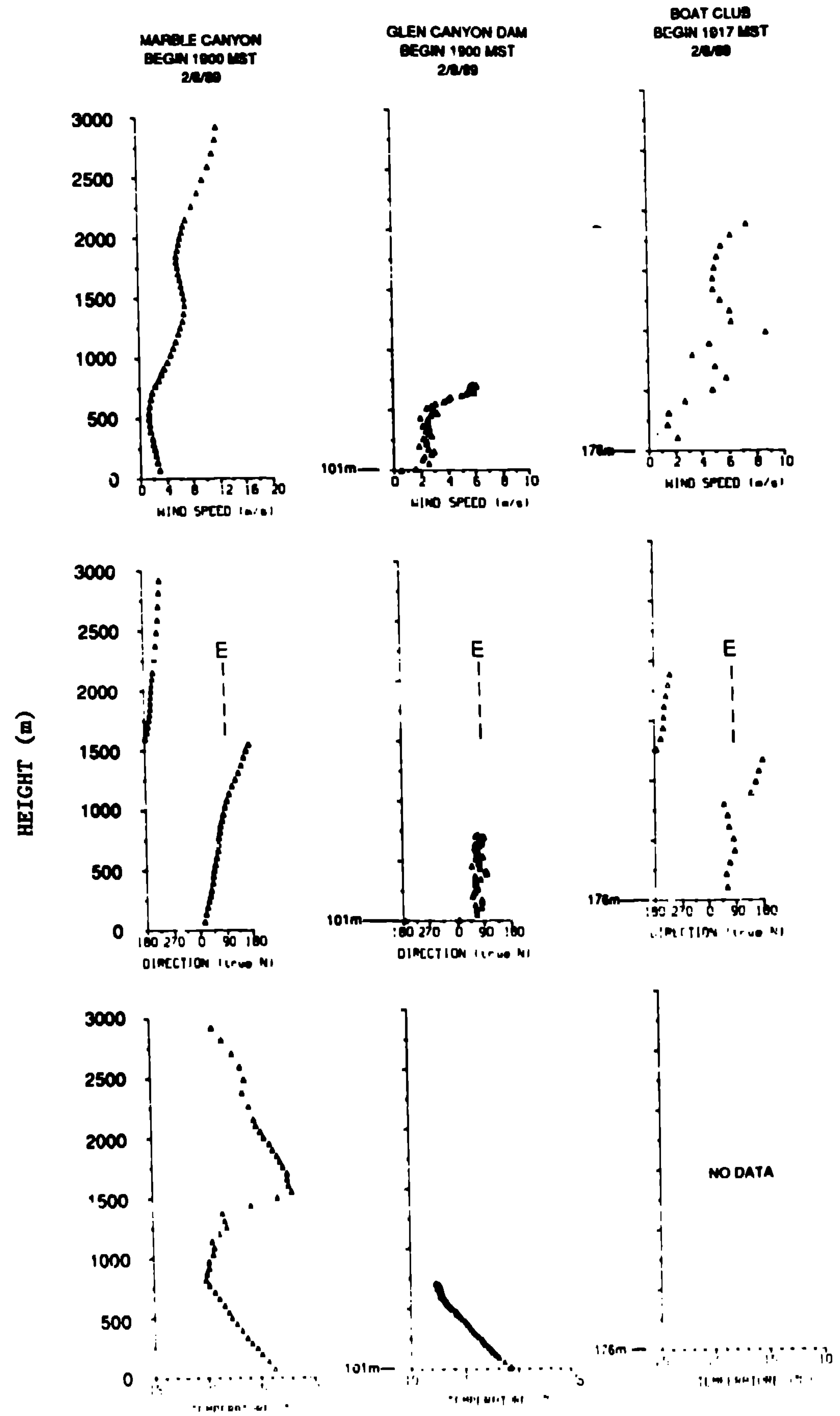
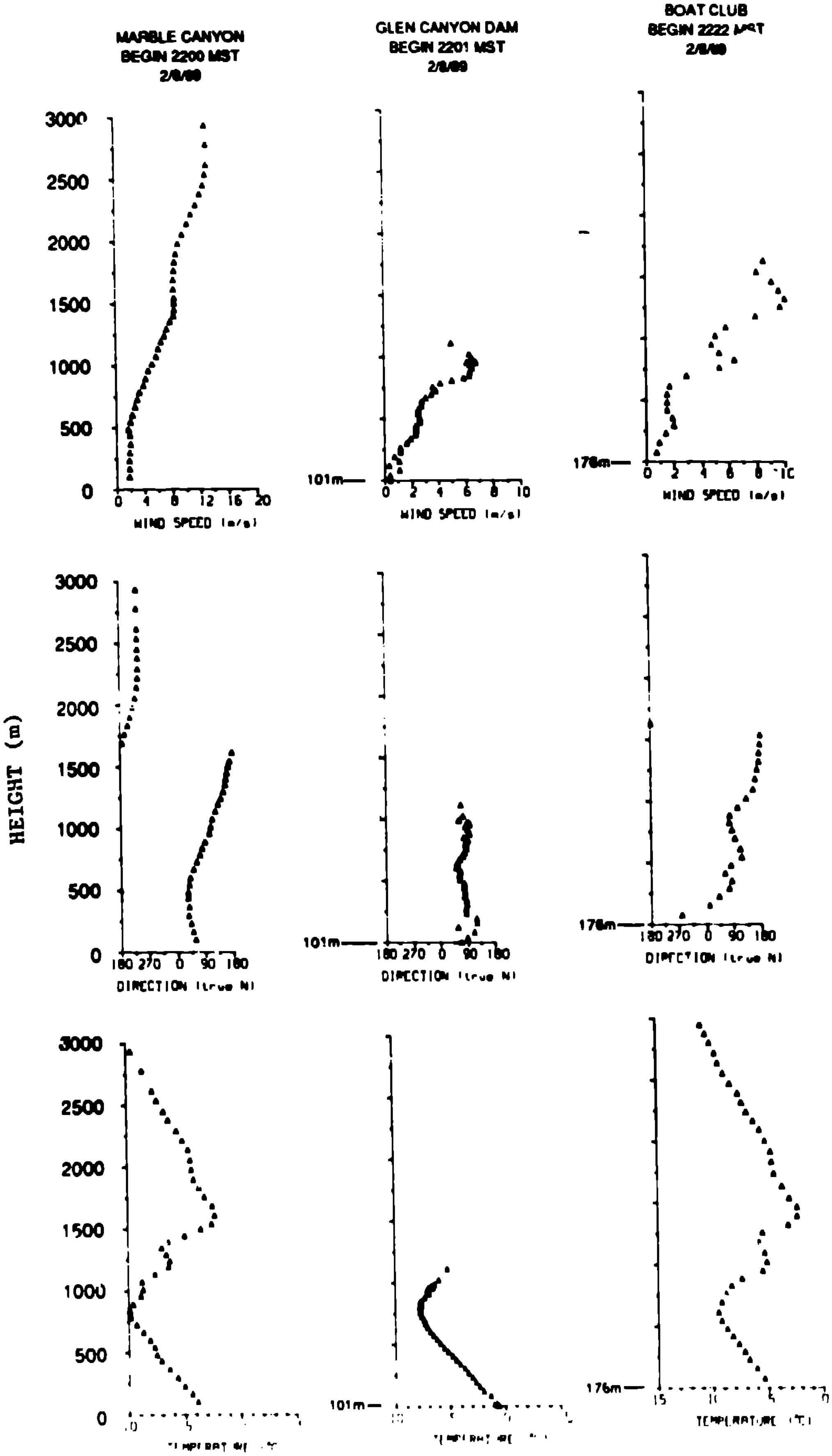

MARBLE CANYON
BEGIN 1900 MST
2/8/89
GLEN CANYON DAM
BEGIN 1900 MST
2/8/89
BOAT CLUB
BEGIN 1917 MST
2/8/89
HEIGHT (m)
WIND SPEED (m/s)
DIRECTION (true N)
101m
176m
E
NO DATA

Fig. 4 f)


MARBLE CANYON
BEGIN 2200 MST
2/8/89
GLEN CANYON DAM
BEGIN 2201 MST
2/8/89
BOAT CLUB
BEGIN 2222 MST
2/8/89
HEIGHT (m)
3000
2500
2000
1500
1000
500
0
101m
176m
WIND SPEED (m/s)
DIRECTION (true N)
180 270 0 90 180
TEMPERATURE (°C)

important to note that the dam site and the Boat Club were 101 and 277 m above the Marble Canyon site, respectively. The principal features of the comparison shown in Fig. 4 are the following:

1. The upper level winds (about 3 km ; observed only by the rawinsonde at Marble Canyon) were south-southwest throughout the day on Feb. 8.
2. The lower level winds observed at all three locations were predominantly from the east-northeast.
3. Most profiles show a peak in the east-northeast wind speeds near the level of minimum absolute temperature.
4. The temperature profiles are very similar between the Marble Canyon and Boat Club location profiles even in the lower layers.
5. Wind directions and speeds differ the most at lower levels between Marble Canyon and the Boat Club at about noon, possibly due to local surface heating effects.
6. Wind directions very close to lake level at the Glen Canyon Dam site appear to be influenced by lake heating in the night and early morning.
7. The presence of near complete cloud cover explains the fact that all the early morning and late night temperature profiles are warmer near the ground. This means that if the northeasterly winds are large scale

drainage flows down the Colorado River Valley then the radiative cooling driving the flow must originate farther up the Colorado River and at higher altitudes during the study period.

These features were also observed on Feb. 11, 1989. However, very low clouds allowed wind measurements at the Boat Club only up to a few hundred meters most of the time. Comparisons of the wind profiles on Feb. 8 and 11, 1989, are shown in Fig. 5 a) and b), respectively.

Analysis of the 850 and 700 mb weather maps for this period showed that a high pressure at 850 mb developed in central Utah on Feb. 6. As shown in Fig. 2, this was the day that the east wind layer was almost 2 km deep. After this day the high pressure region moved east of Page by Feb 9. Though southeasterly winds might be expected from this orientation the east wind layer dropped to about 1 km depth with no indication of southeasterly flow. This indicates that 850 mb synoptic conditions may enhance or erode the east wind layer but does not seem to explain its persistence in this region. The southwesterly flow observed above 2 km is consistent with the 700 mb maps. The warmer temperatures brought into the regions by this flow aloft may explain the gradual warming throughout the period shown in Fig. 2 as well as the warmer temperatures at about 2 km altitude.

Comparisons with WHITEX

Simplified diagrams of wind vectors and east wind layer depths were constructed from the vertical profile data taken

Fig. 5 a) LANL SITE – TETHERSONDE GLEN CANYON DAM, AZ 890208

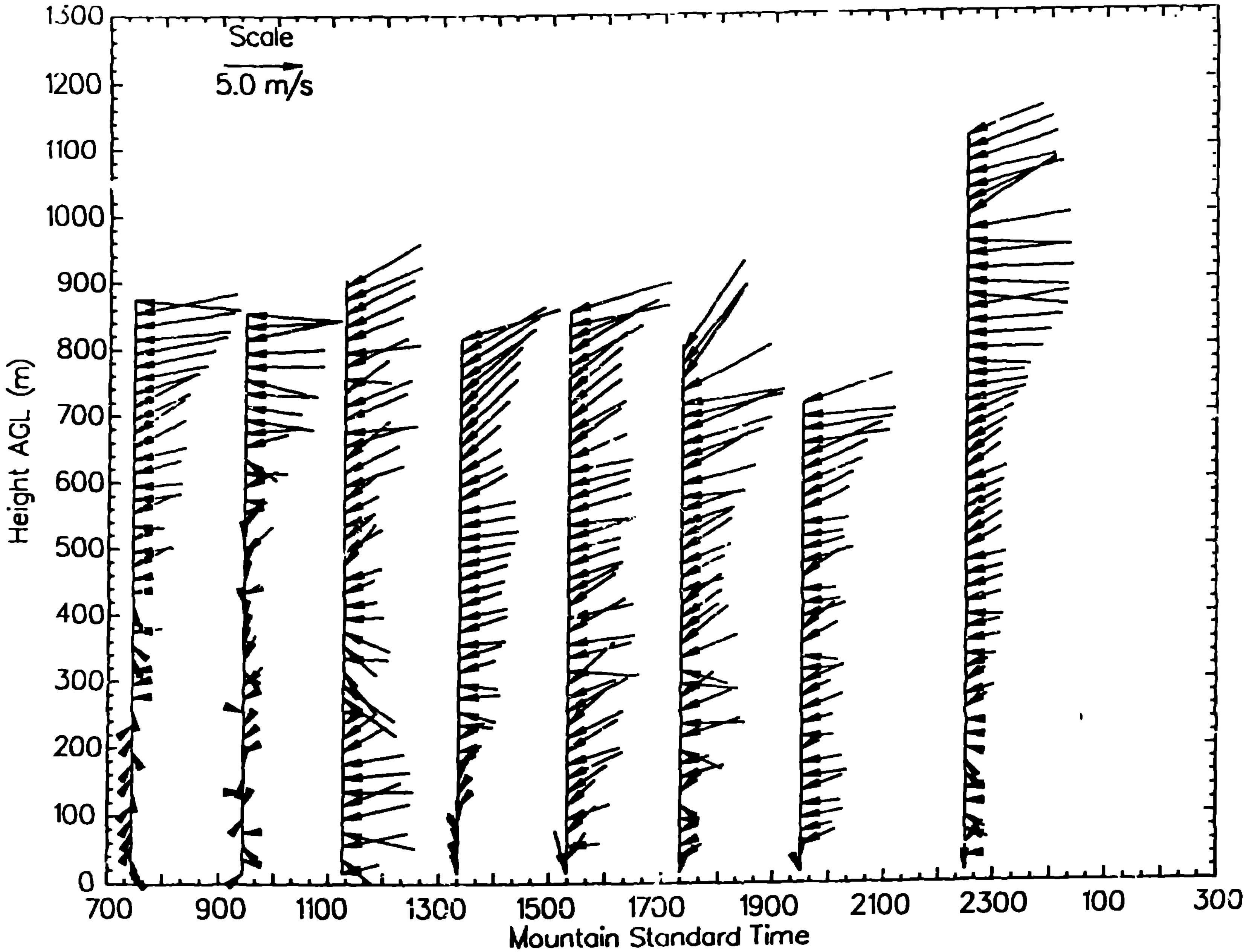
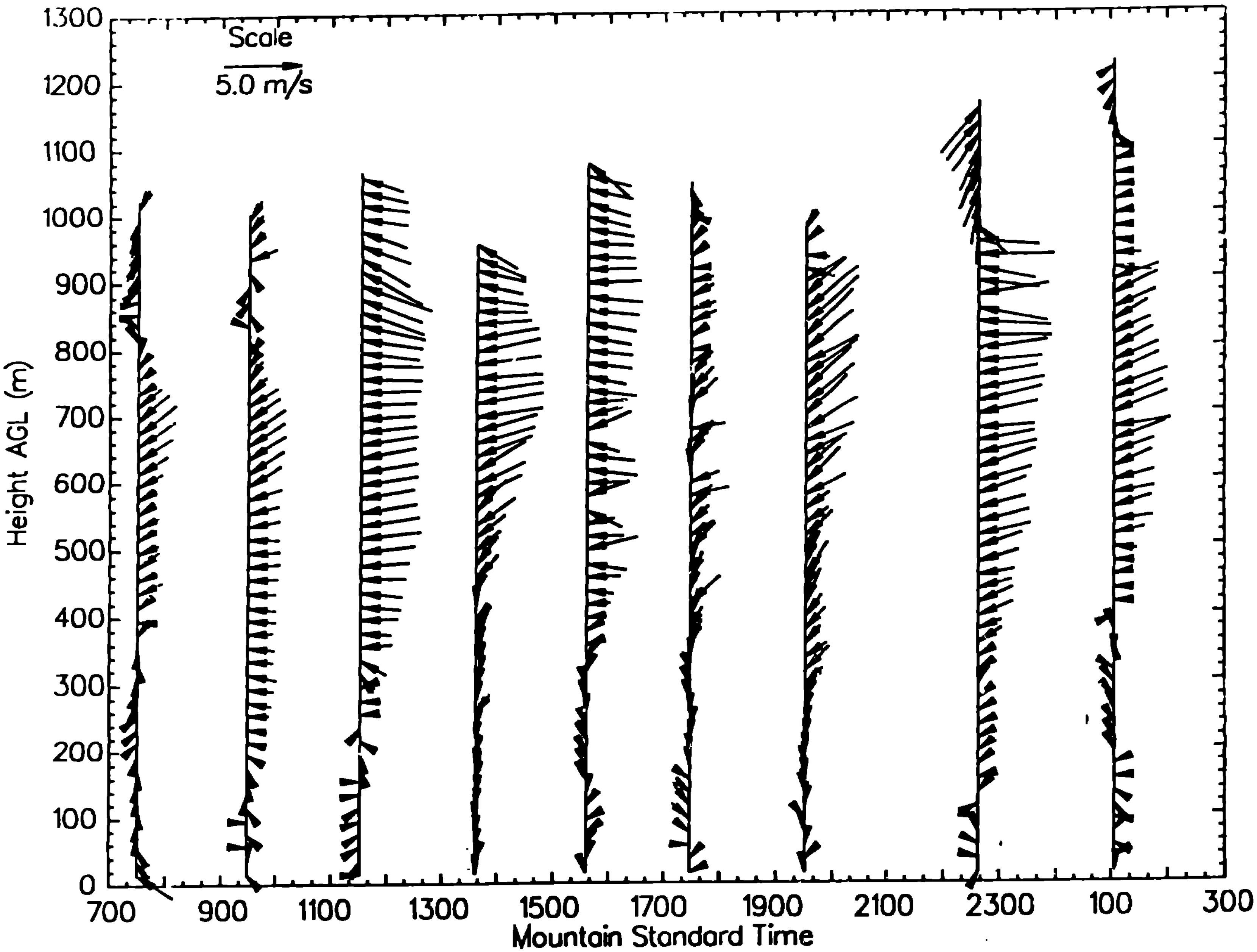


Fig. 5 Comparison of wind vector layer profiles from the tethered balloon system at Glen Canyon Dam for a) Feb. 8, and b) Feb. 11.

Fig. 5 b) LANL SITE – TETHERSONDE GLEN CANYON DAM, AZ 890211



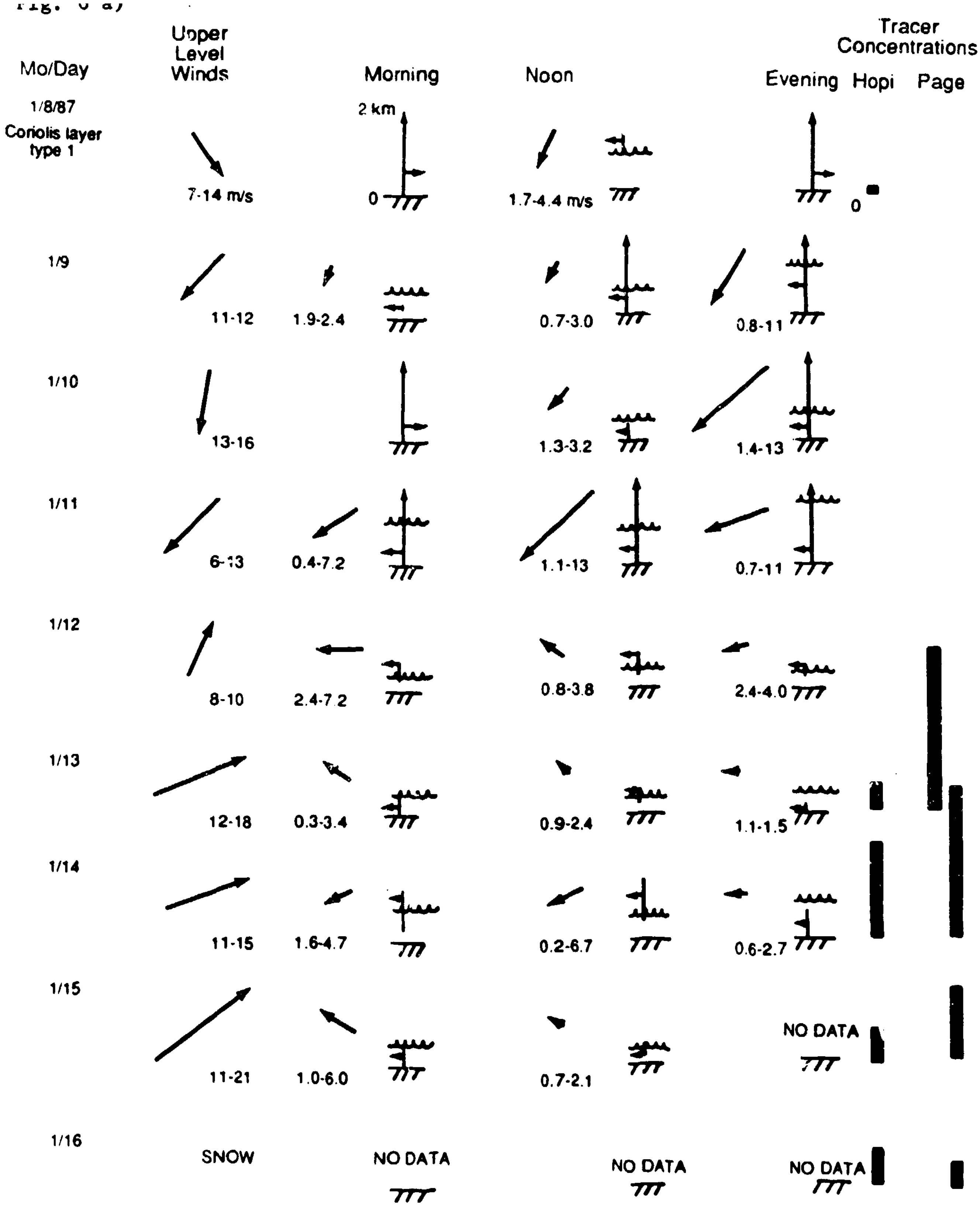


Fig. 6 Plots of estimated upper level wind vectors from the highest airsonde wind vectors at Page during WHITEX compared to estimated east wind layer depths and wind vectors in the layer (wavy line corresponds to the estimated height of marked decrease in dew point) for 0600, 1100, and 1700 MST ascents, and heavy methane tracer concentrations measured at Hopi Point (near Grand Canyon).

Fig. 6 b)

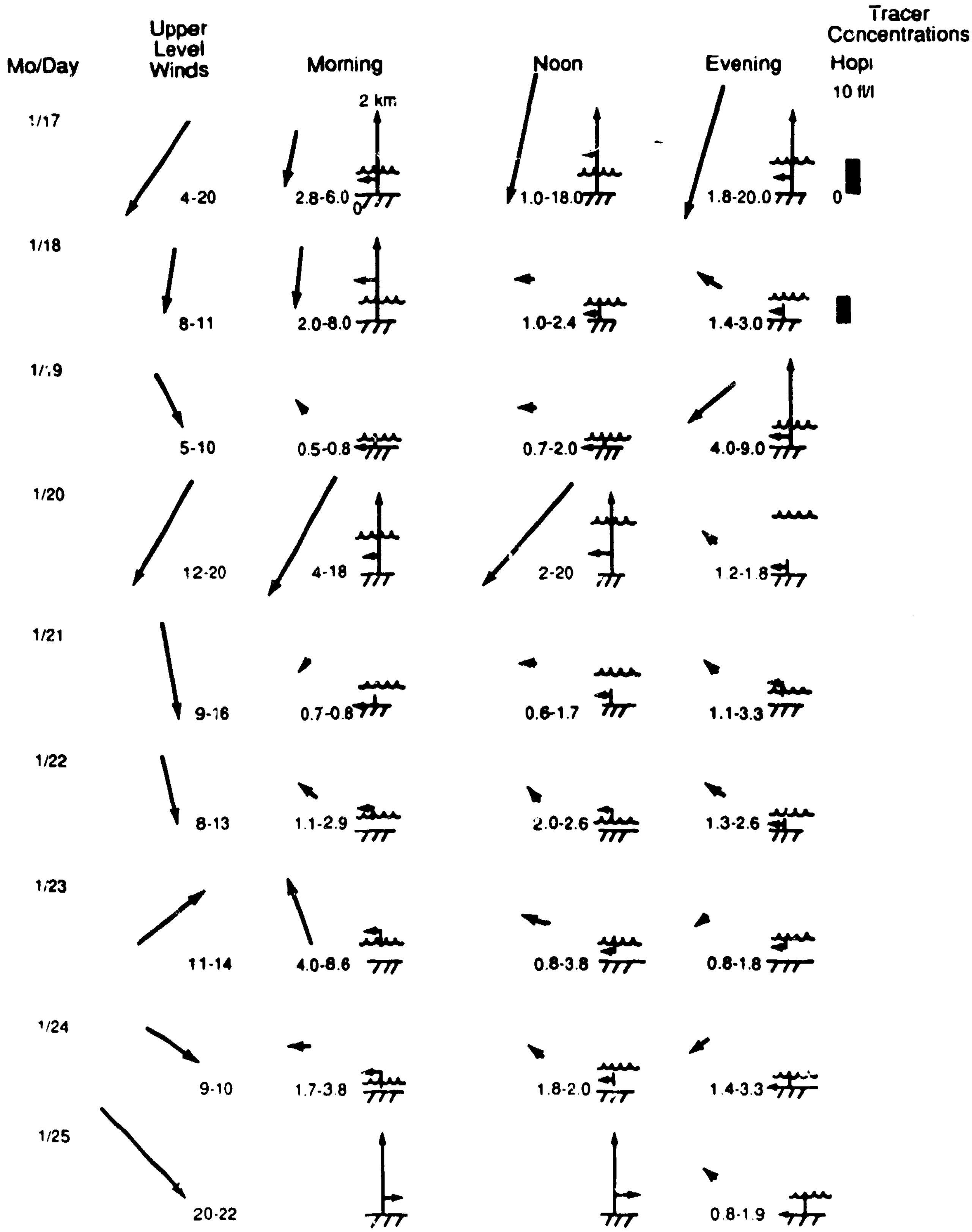
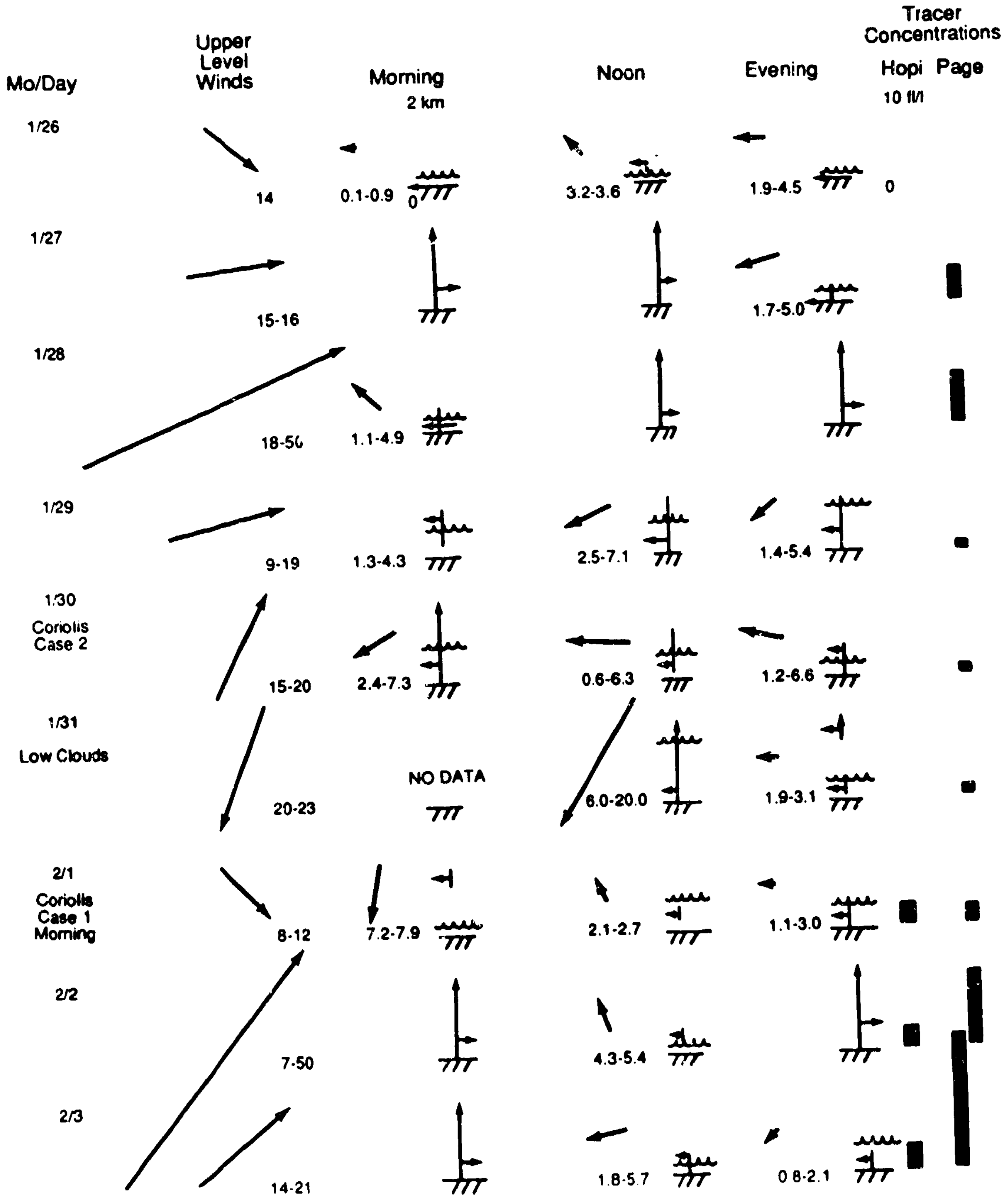
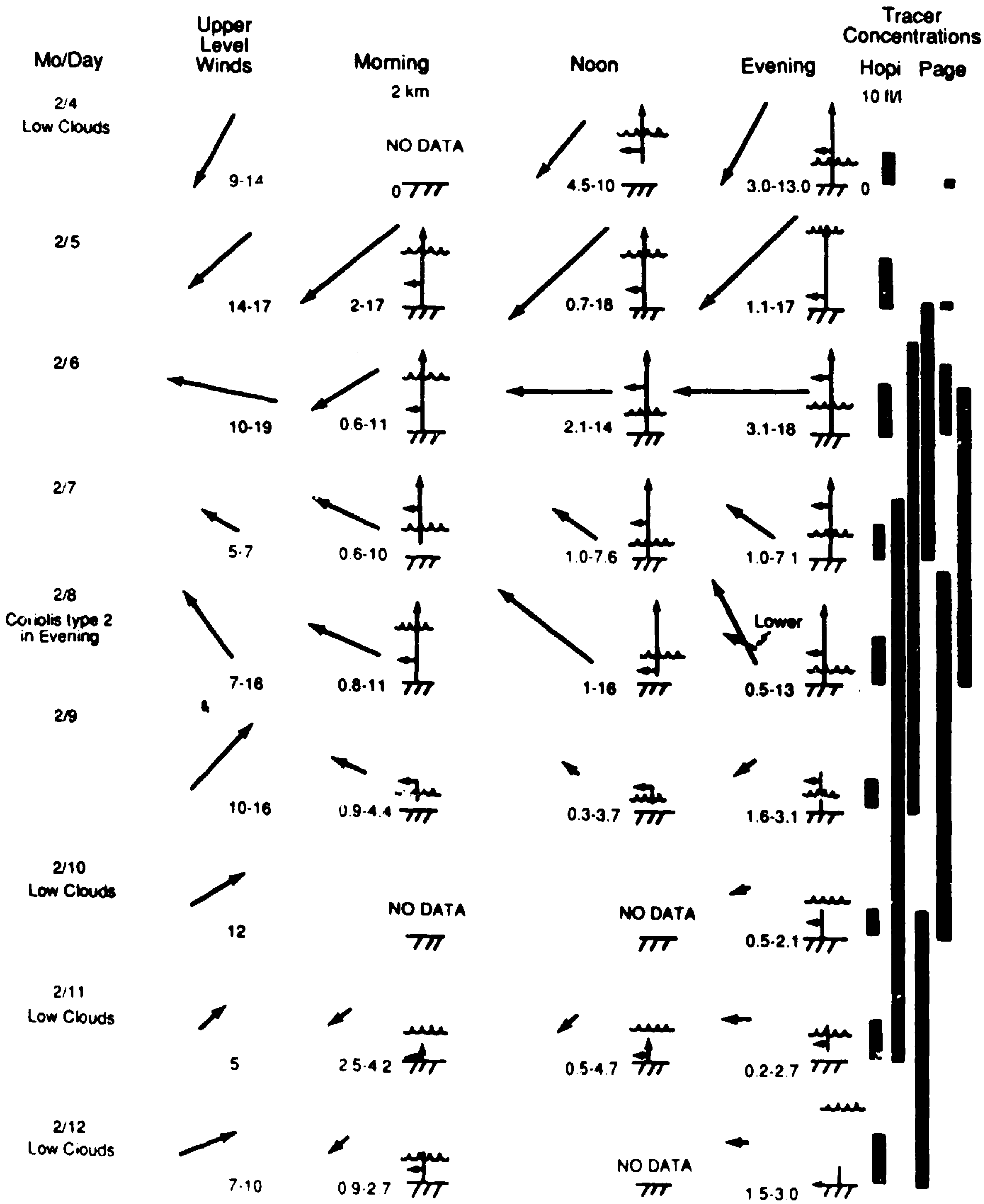

Mo/Day
Upper Level Winds
Morning
Noon
Evening
Tracer Concentrations
Hopi
10 fl/l
2 km
1/17
4-20
2.8-6.0
0
1.0-18.0
1.8-20.0
0
1/18
8-11
2.0-8.0
1.0-2.4
1.4-3.0
1/19
5-10
0.5-0.8
0.7-2.0
4.0-9.0
1/20
12-20
4-18
2-20
1.2-1.8
1/21
9-16
0.7-0.8
0.6-1.7
1.1-3.3
1/22
8-13
1.1-2.9
2.0-2.6
1.3-2.6
1/23
11-14
4.0-8.6
0.8-3.8
0.8-1.8
1/24
9-10
1.7-3.8
1.8-2.0
1.4-3.3
1/25
20-22
0.8-1.9

Fig. 6 c)



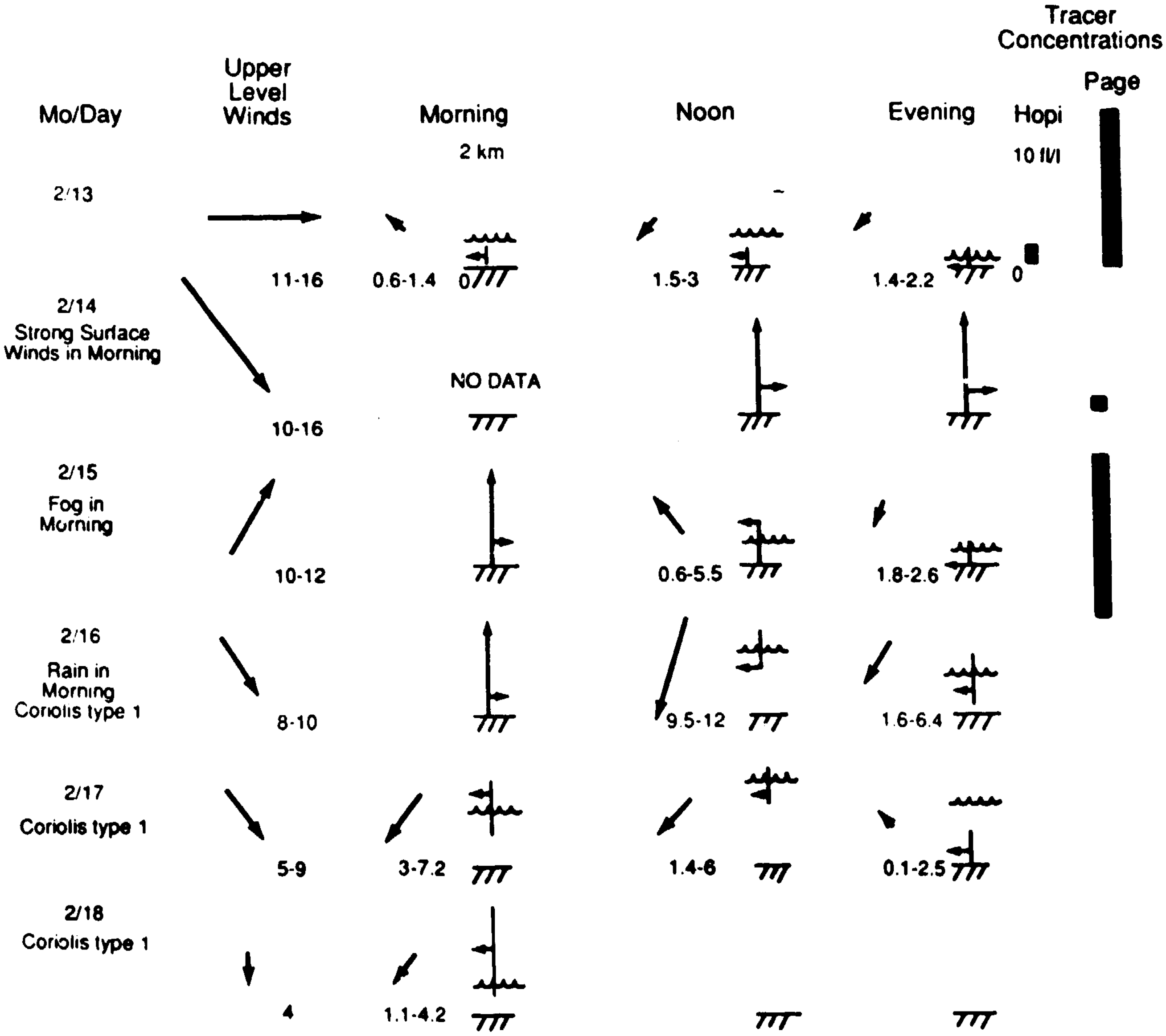
Tracer Concentrations
Upper Level Winds
Mo/Day
Morning
2 km
Noon
Evening
Hopi
Page
10 fl/l
1/26
14
0.1-0.9
0
3.2-3.6
1.9-4.5
0
1/27
15-16
1.7-5.0
1/28
1.1-4.9
1/29
9-19
1.3-4.3
2.5-7.1
1.4-5.4
1/30
Coriolis
Case 2
15-20
2.4-7.3
0.6-6.3
1.2-6.6
1/31
Low Clouds
20-23
NO DATA
6.0-20.0
1.9-3.1
2/1
Coriolis
Case 1
Morning
8-12
7.2-7.9
2.1-2.7
1.1-3.0
2/2
7-50
4.3-5.4
2/3
14-21
1.8-5.7
0 8-2.1

Fig. 6 d)



Mo/Day
Upper Level Winds
Morning
2 km
Noon
Evening
Tracer Concentrations
Hopi
Page
10 fl/l
2/4
Low Clouds
9-14
NO DATA
0
4.5-10
3.0-13.0
0
2/5
14-17
2-17
0.7-18
1.1-17
2/6
10-19
0.6-11
2.1-14
3.1-18
2/7
5-7
0.6-10
1.0-7.6
1.0-7.1
2/8
Coriolis type 2 in Evening
7-16
0.8-11
1-16
Lower
0.5-13
2/9
10-16
0.9-4.4
0.3-3.7
1.6-3.1
2/10
Low Clouds
12
NO DATA
NO DATA
0.5-2.1
2/11
Low Clouds
5
2.5-4.2
0.5-4.7
0.2-2.7
2/12
Low Clouds
7-10
0.9-2.7
NO DATA
1.5-3.0

Fig. 6 e)


Tracer
Concentrations
Upper
Level
Winds
Page
Mo/Day
Morning
Noon
Evening
Hopi
2 km
10 fl/l
2/13
11-16
0.6-1.4
0
1.5-3
1.4-2.2
0
2/14
Strong Surface
Winds in Morning
NO DATA
10-16
2/15
Fog in
Morning
10-12
0.6-5.5
1.8-2.6
2/16
Rain in
Morning
Coriolis type 1
8-10
9.5-12
1.6-6.4
2/17
Coriolis type 1
5-9
3-7.2
1.4-6
0.1-2.5
2/18
Coriolis type 1
4
1.1-4.2

during WHITEX at the Boat Club at Page (Fig. 6). This was done to compare the basic characteristics of the east wind layer and tracer concentrations measured at the aerosol sampling location near Glen Canyon Dam and at Hopi Point near the Grand Canyon (Malm, 1988). These diagrams also facilitate comparison with the 1989 experiment. The length of the arrows in Fig. 6 is proportional to wind speeds estimated from airsonde data from Page. The upper level winds are estimated from winds above 2 km altitude above Page on occasions where the ballon could be tracked that high. If the balloon could not be tracked above 2 km, the wind speeds were estimated from the highest altitudes values. The diagrams associated with each sounding shows the locations of easterly wind layers and their association with a moist boundary layer height (wavy lines) estimated from significant decreases in dew point temperature. The arrows associated with these diagrams show the estimated mean speed and direction in the east wind layer. Also included in Fig. 6 are notes about fog conditions and potential effects associated with Coriolis effects on synoptic winds flowing over Lake Powell Basin.

The period most similar between the two experiments was Feb. 10-12, 1987. Low clouds during this period of WHITEX prevented wind measurements at the effective stack height of the Navajo Generating Station (about 750 m). However, moderate concentrations of heavy methane tracer measured at Hopi Point imply the existence of an east wind layer. This

Fig. 7 a)

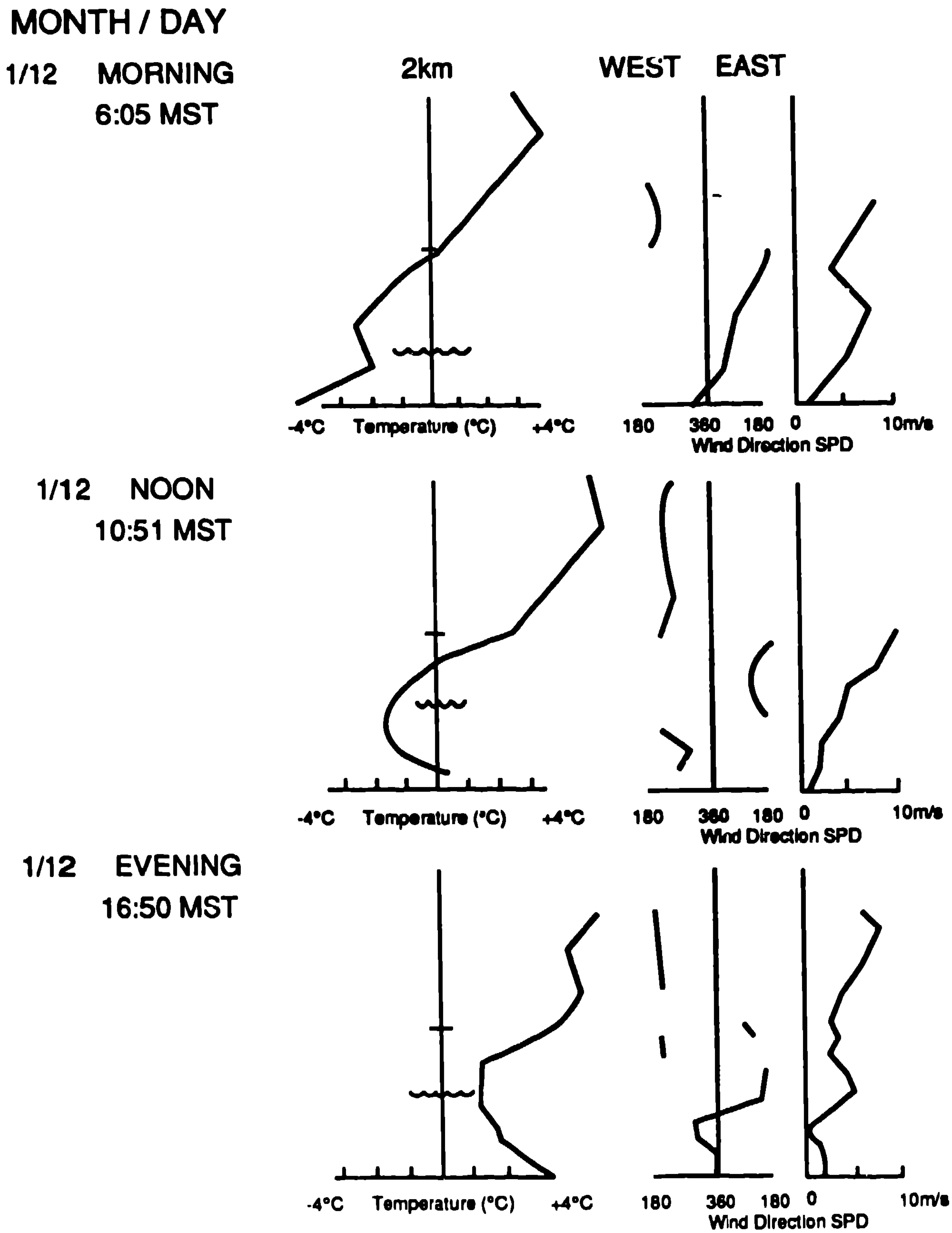


Fig. 7 Vertical profiles of temperature and wind for three periods of the day for days selected from Fig. 6 having relatively weak upper level wind speeds a) Jan. 12 b) Feb. 8, and c) Feb. 9, 1987.

Fig. 7 b)

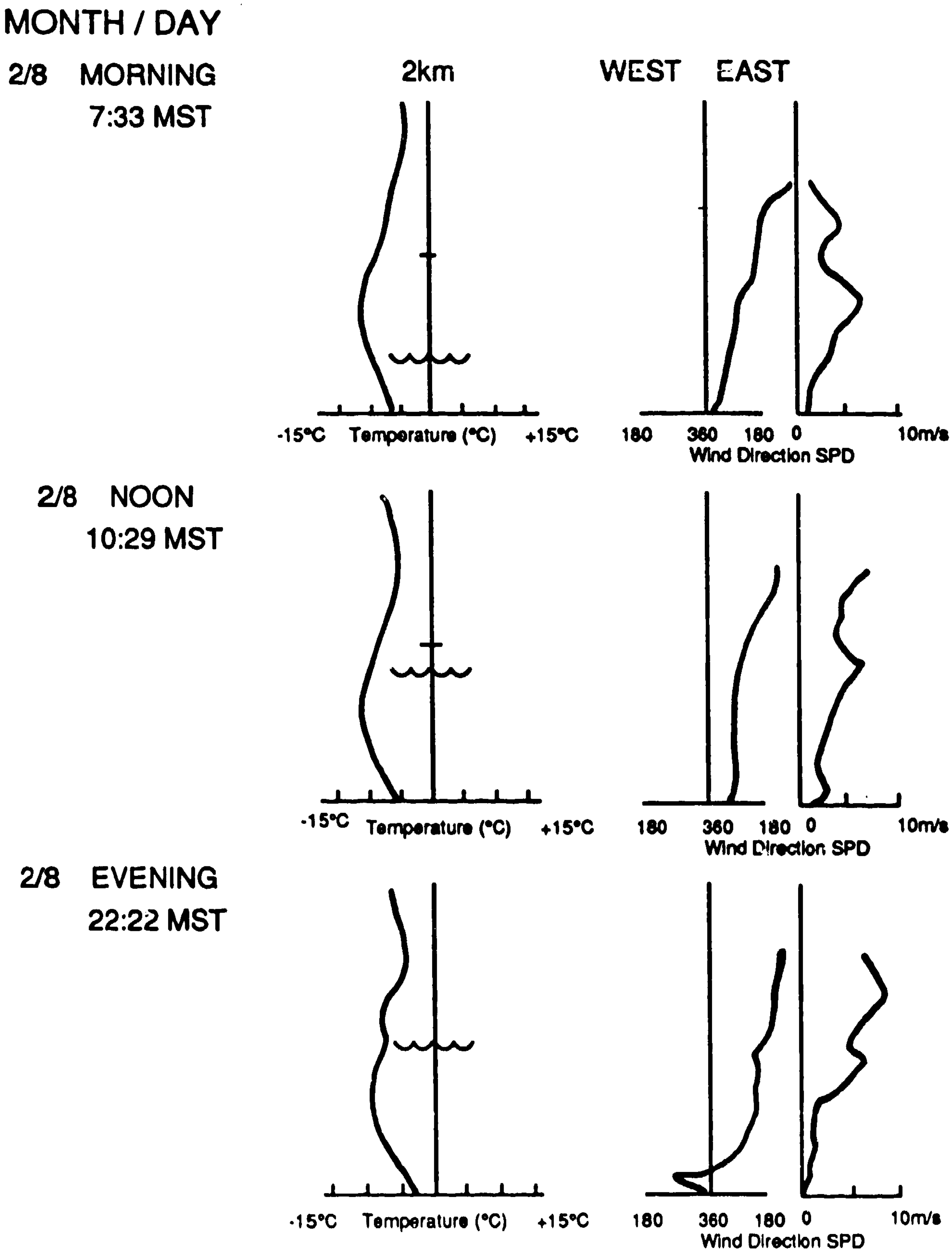
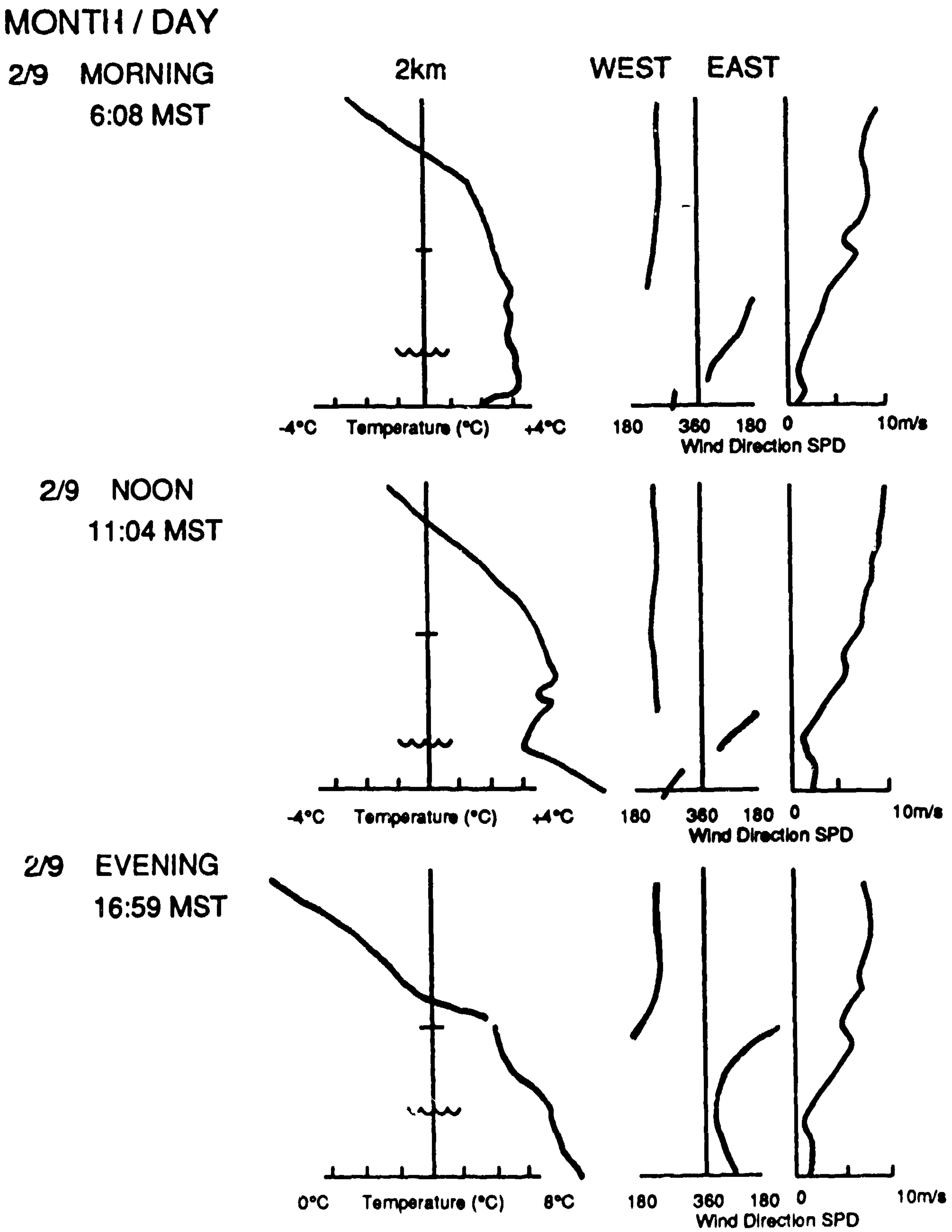

MONTH / DAY
2/8 MORNING
7:33 MST
2km
WEST EAST
-15°C Temperature (°C) +15°C
180 360 180 0 10m/s
Wind Direction SPD
2/8 NOON
10:29 MST
-15°C Temperature (°C) +15°C
180 360 180 0 10m/s
Wind Direction SPD
2/8 EVENING
22:22 MST
-15°C Temperature (°C) +15°C
180 360 180 0 10m/s
Wind Direction SPD

Fig. 7 c)


MONTH / DAY
2/9 MORNING
6:08 MST
2km
WEST
EAST
-4°C
Temperature (°C)
+4°C
180
360
180
0
10m/s
Wind Direction SPD
2/9 NOON
11:04 MST
-4°C
Temperature (°C)
+4°C
180
360
180
0
10m/s
Wind Direction SPD
2/9 EVENING
16:59 MST
0°C
Temperature (°C)
8°C
180
360
180
0
10m/s
Wind Direction SPD

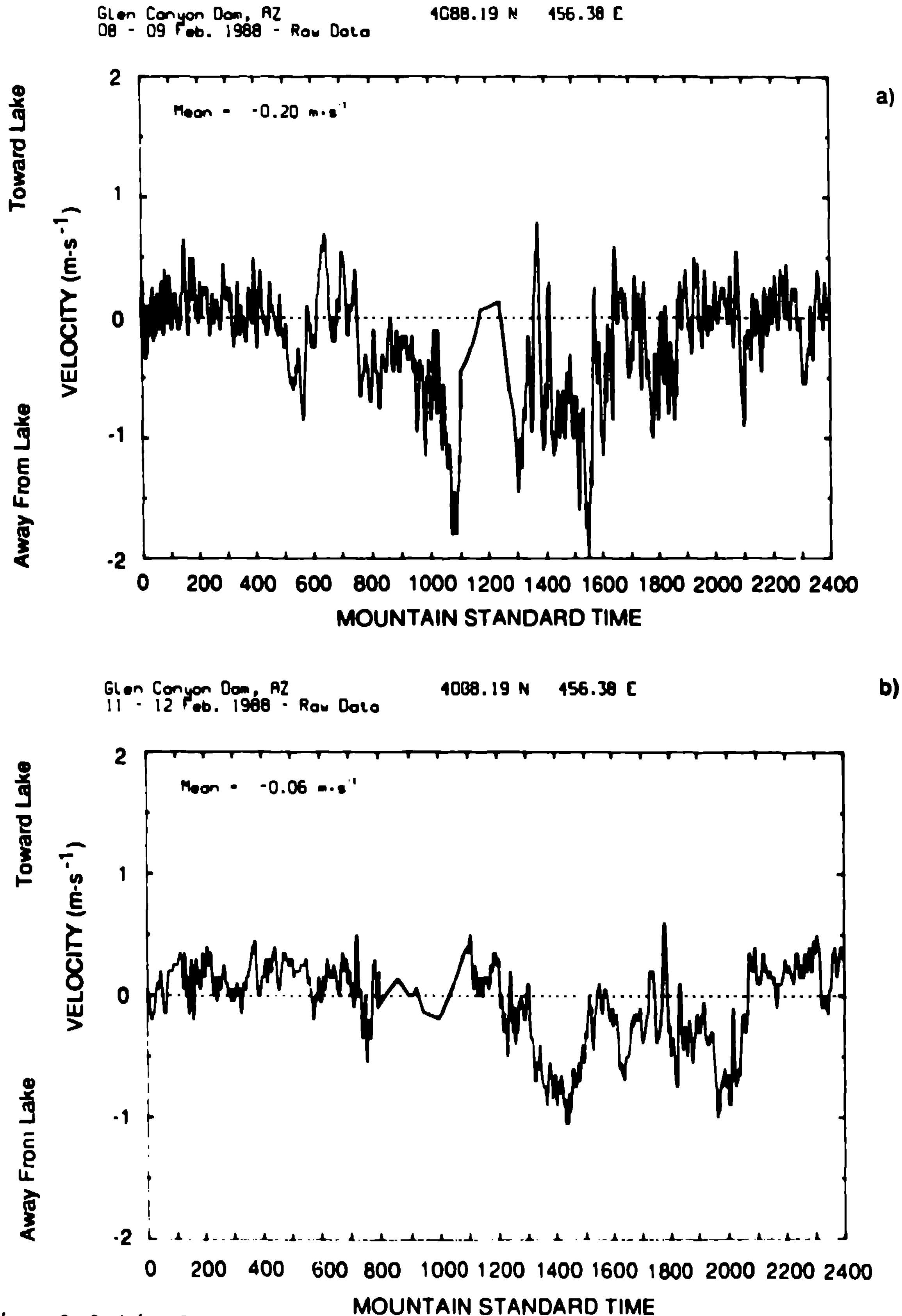


Fig. 8 Optical cross-wind sensor data taken parallel to Glen Canyon Dam showing the wind speed component over the dam (away from the lake) as negative values. Data are displayed as 1 minute averages with small portions supplemented with 30 minute averages from chart

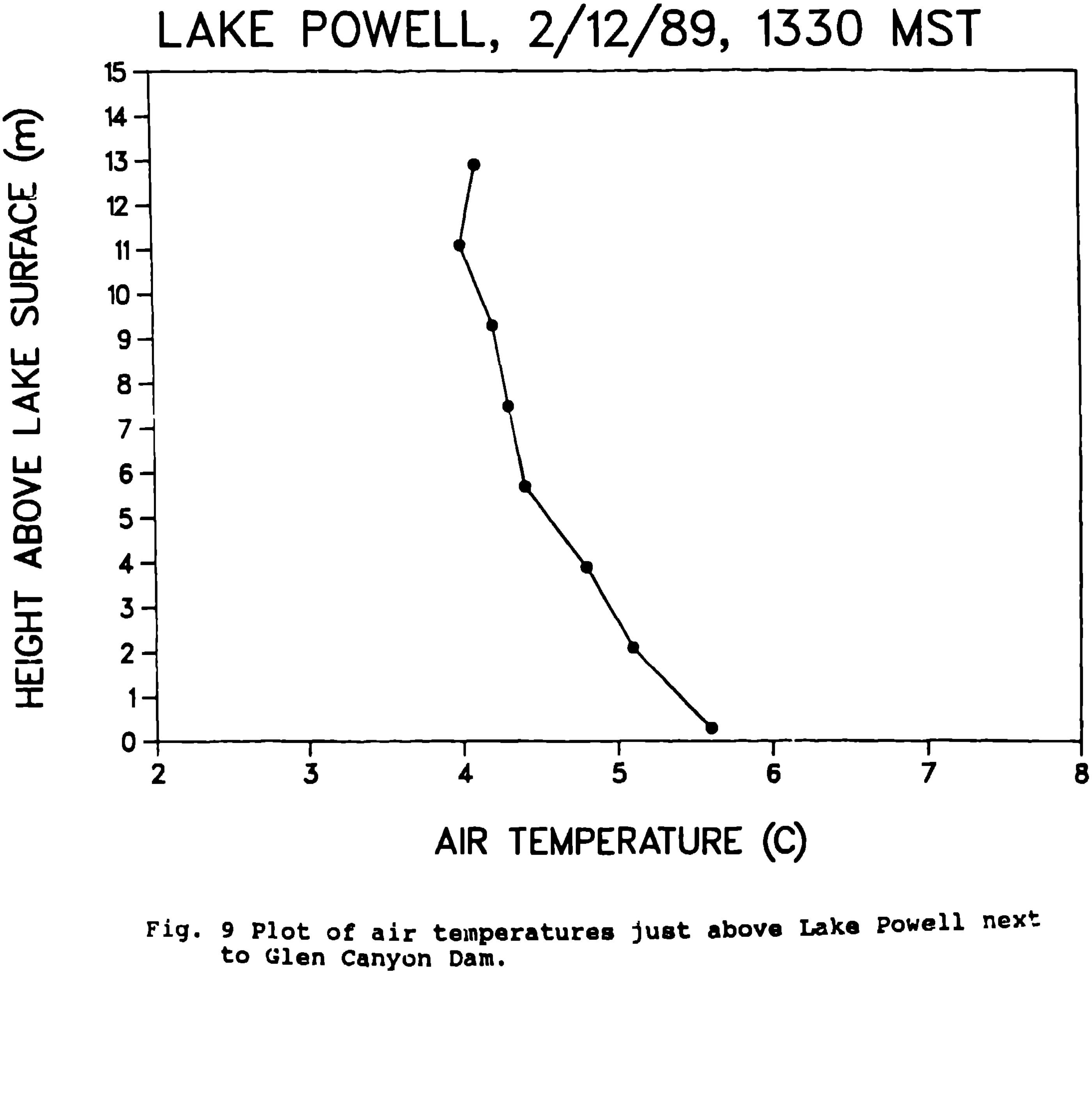


Fig. 9 Plot of air temperatures just above Lake Powell next to Glen Canyon Dam.

period was also the time with the highest combined tracer concentration, sulfate aerosol, and light extinction during WHITEX at the sampling location near Glen Canyon Dam. The 1989 data should help numerical transport and diffusion models interpret this important period during WHITEX.

Because the low clouds made assessment of upper level winds difficult (the values shown in Fig. 6 were often estimated from only one sounding during the day), other periods were looked for with the lightest upper level winds. Jan. 12 and Feb. 9, 1987, were selected for more detailed analysis for flow characteristics under light upper level wind conditions. Fig. 7 shows the vertical profiles of wind and temperature for these two days. The wavy lines in Figs. 6 and 7 represent the height where the dew point shows a change of slope to decreasing values. These profiles show many of the same characteristics as in Fig. 4, but with more of an elevated layer structure. The bottom of the east wind layer appears to be associated with a relatively moist (warm in the morning, cool later in the day) stagnant air pooling in the Lake Powell Basin. The purpose of the optical cross-wind sensor was to better understand the effect of Lake Powell on lower level flows.

Lake Effect Studies

Fig. 8 shows the diurnal cycle of the spatially averaged wind flow across Glen Canyon Dam measured with the optical cross-wind sensor. Since the optical system contains no moving parts, it is capable of measuring extremely light winds. This feature was particularly useful during this experiment as the wind speed rarely exceeded 1 m/s. Fig. 8 shows that on both days, the flow was oscillatory, but averaged a few tenths of a meter per second toward the lake at night and about half a meter per second away from the lake (down Glen Canyon) during the day. This is opposite to the normal behavior of valley flows (Clements et al., 1989). This kind of behavior is observed throughout the year at the Glen Canyon sampling site, though more pronounced in winter than summer (Balling and Sutherland, 1988). The Glen Canyon sampling site is 125 m above the dam and the optical cross-wind sensor location which implies that the lake effect, or some combination of the lake effect and basin air pooling, can have a significant vertical extent. The implication of this counter-valley flow in winter is that local pollutants (especially fireplace smoke) will drain down from the city of Page into Glen Canyon and then be drawn back over the lake to undergo significantly more chemical and photochemical processing than would otherwise be expected before being sampled at the Glen Canyon sampling site. Since some of the tracer released during WHITEX escaped at lower levels, this may help to explain some of the larger tracer concentration measurements made at Page. In order to assist future modeling of these kinds of effects, an air temperature profile was taken just above the lake behind the dam (Fig. 9).

CONCLUSIONS

The major results of the February 1989 NABS experiment showed that a deep (about 1 km) cold northeast wind layer was observed during the night and day both at Glen Canyon Dam and at Marble Canyon 20 km down the Colorado River Valley. The wind direction and speed profiles observed at Glen Canyon Dam and Marble Canyon were consistent with each other. Each profile was consistent with the hypothesis of large scale Colorado River Valley cold air drainage during winter under light synoptic wind conditions (the worst case for pollution dispersion). The optical cross-wind sensor showed that the lower level winds were light (<2 m/s) and generally directed toward the warmer lake at night and down Glen Canyon during the day. This implies that both the large scale Colorado River Valley drainage and the lake (with associated basin air pooling) effects must be taken into account to understand the local effect of the Navajo Generating Station on Page and the Grand Canyon region of Northern Arizona.

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FIGURE CAPTIONS

Fig. 1 Map of experiment region with locations of experiment sites (Marble Canyon, Glen Canyon Dam, PG-Boat Club, Page), and a vertical cross section of the terrain over a 225 km northeasterly segment.

Fig. 2 Climatological context of 1989 experiment showing a) depth of NE wind layer, b) afternoon high temperatures, and c) morning low temperatures before and after experiment dates Feb. 8 and 11.

Fig. 3 Surface weather maps for the western United States for a) Feb. 8, 1989 and Feb. 10, 1987(WHITEX), b) 500 mb maps for the same days, and c) surface and 500 mb maps for Feb 11, 1989.

Fig. 4 Comparisons of wind and temperature profiles up to 3000 m for similar times taken at the three experiment locations.

Fig. 5 Comparison of wind vector layer profiles from the tethered balloon system at Glen Canyon Dam for a) Feb. 8, and b) Feb. 11.

Fig. 6 Plots of estimated upper level wind vectors from the highest airsonde wind vectors at Page during WHITEX compared to estimated east wind layer depths and wind vectors in the layer (wavy line corresponds to the estimated height of marked decrease in dew point) for 0600, 1100, and 1700 MST ascents, and heavy methane tracer concentrations measured at Hopi Point (near Grand Canyon).

Fig. 7 Vertical profiles of temperature and wind for three periods of the day for days selected from Fig. 6 having relatively weak upper level wind speeds a) Jan. 12 b) Feb. 8, and c) Feb. 9, 1987.

Fig. 8 Optical cross-wind sensor data taken parallel to Glen Canyon Dam showing the wind speed component over the dam (away from the lake) as negative values. Data are displayed as 1 minute averages with small portions supplemented with 30 minute averages from chart recordings.

Fig. 9 Plot of air temperatures just above Lake Powell next to Glen Canyon Dam.