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THE ASCOT 1988 VALLEY/TRIBUTARY INTERACTION STUDY

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ABSTRACT

This paper describes a regular oscillation observed in nighttime valley air flows under relatively light upper level wind conditions. The period of these oscillations is about 20 minutes with at least one harmonic at about 10 minutes. These oscillations are important to pollutant dispersion in valley flows at night. The strong coherence of tributary flow and main valley oscillations and the fact that tributary oscillations lead valley oscillation indicate the importance of tributaries as major contributors to the cold air flow in valleys.

INTRODUCTION

Discoveries of regular long and short period oscillations in nighttime valley flows and their effects on tracer samples have been a feature of studies performed as part of the Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program (Clements et al., 1989). Long period oscillations were observed in a valley/basin system near The Geysers area of Northern California (Doran and Horst, 1981; Porch, 1982; and Neff and King, 1985). These oscillations had periods of 1-2 hours and were thought to result from regular oscillations in forcing winds, a seiche effect in the basin, or slope adiabatic heating effects. Later field experiments in a deeper more isolated valley (Brush Creek, Colorado) showed higher frequency, regular oscillations in the wind (Porch et al., 1989; Coulter et al., 1989; and Stone and Hoard, 1989). These oscillations had periods of 10-20 minutes and were best defined in a tributary flow entering the main valley. Possible causes of these oscillations include: 1) interaction of the tributary and main valley flows, 2) amplification in the tributaries of meandering main valley flow effects, or 3) interaction of both the tributary and main valley flows with a larger scale flow regularity. We cannot, at present, rule out larger scale wind regularities as no upper level wind data were available with the temporal resolution necessary to see 10 and 20 minute oscillations. However, evidence presented in this paper favors tributary flow influences on the main valley flow rather than the reverse.

ASCOT is not the only source of information on the importance of tributary flows or oscillations. Heywood (1933) presented data from a small valley with a clear 20 minute cycle in speed. Hoschele (1980) showed data revealing the influence of tributary flows deep in the Rhine Valley at night. Freytag (1987) has used measurements in the MERKUR experiments to estimate tributary contributions to the nighttime valley flow mass budget.

Evidence is accumulating that, at least in some valleys, most of the cold air flowing down the valleys has entered through the tributaries (Coulter et al., 1989; and Porch et al., 1989a). This has important consequences to pollution source siting in narrow valleys (i. e. how important is it for plumes to avoid regions above tributaries?). The fact that many valley tributaries are too small for present numerical models to resolve adds to the potential importance of their systematic study. Also, regular oscillations in the range of 20 minutes are in the awkward time frame of being too long for parameterized diffusion but too short for most diagnostic transport models to resolve even if the data were available.

Our studies of drainage flows in Brush Creek, Colorado showed a regular 15-20 minute cycle in wind flow out of a major tributary to Brush Creek Valley during well developed drainage conditions. Towers in the main valley and optical cross-wind sensors across the valley and across the tributary indicated a negative correlation between down-valley flow and flow out of the tributary. However, these instruments were not ideally placed to document this relationship. In July, 1988 we moved to a similar valley south of Brush Creek Valley called Kimball Creek Valley. There we were able to colocate enough instrumentation to determine the timing and coherence of tributary and valley flows.

EXPERIMENT DESCRIPTION

Fig. 1 shows the location and general layout of the experiment. The instruments supporting this experiment included three optical cross-wind sensors, an instrumented tethered balloon, and four tower based meteorological measurement systems. Data from one tower which was sited in Kimball Valley are not discussed as only 30 minute averages were stored. For selected periods during the experiment, a mini-Doppler acoustic sounder was operated. Also, on two nights smoke releases were performed for flow visualization using a full moon for illumination.

The optical cross-wind sensors use a technique described by Lawrence et al. (1972). This technique uses a helium-neon laser observed across a valley with two tangent sensors with the proper optical spatial filtering to give an average down or up-valley wind component. The weighting function for this system will proportion a uniform distribution of optical turbulence with a smooth function which peaks at the center of the path and goes to zero at both ends. This causes the effective height of the system to correspond to slightly below the height at the valley center for narrow valleys, and lower still as the valleys become wider. The effective height of the optical path has been derived from nighttime comparisons of optical cross-wind sensor data with tethered balloon data in two wide valleys (Porch et al., 1988), and in a tributary to Brush Creek (Porch et al., 1989b).

The three optical cross-wind sensors were deployed at nearly the same height across the valley and across two tributaries on either side (north and south) of the valley as shown in Fig. 1. One minute averages from each system were taken. The tethered balloon system was located next to Kimball Creek, near the center of the valley. Automated meteorological instruments were located on a 4 m tower near the tethered balloon system, and 3 m towers in the north, southeast, and southwest tributaries. Data were taken with 1 minute resolution for the tributary tower systems, and 30 minutes for the system near the tethered balloon.

On three nights, a mini-Doppler acoustic sounder (Coulter et al., 1989) was operated for one hour at a time at three different locations on three nights in the two southern tributaries. The sounder was also operated in one location on one night in the north tributary. On one night when the sounder was not operating, two smoke releases were conducted in the southeast tributary. Each smoke release had about a 20 minute duration. These smoke releases were photographed every minute with 30 second exposures using 1000 ASA film. The first smoke release was photographed at dusk, and the second was photographed at about 2 AM LDT in full moon light.

RESULTS

The results we will now describe will focus mainly on the optical cross-wind sensor data and comparisons with the other instrument systems to provide the vertical profile of the winds. The reason for focusing on the cross-wind sensor data is that the effective height of these systems (about 70 m above Kimball Creek and 30 m above the tributaries) is about the height of the peak in the down-valley drainage jet and, as we will see later, close to the height of maximum interaction of tributary flows with the main valley flow. Since the optical cross-wind data are continuous with 1 minute resolution, relative timing of changes in the valley and tributary flows can reveal much about the flow structure. Since the optical systems only provide the drainage wind component at a single effective height, the vertical profile must be estimated using other data.

Fig. 2 shows 17 hours of data taken with the optical cross-wind sensor across Kimball Creek Valley on 24-25 July, 1988. These data show the down-valley drainage at night as well as the evening transition from and the morning transition to up-valley winds. Conditions were similar on both the preceding and following days. Fig. 3 shows a comparison of a 7 hour drainage period selected from the data shown in Fig. 2 and measurements taken of the flow out of the southeast tributary on the same night. The insert illustrates negative correlation over the initial combined two hour segment. Examination of Fig. 3 shows an obvious regular oscillation of about a 20 minute period with a higher and lower frequency modulation. The flow is down Kimball Creek Valley at -3.7 m/s. The flow is actually slightly into the southeast tributary (about 0.1 m/s). Counter flows are common in tributaries near the height of maximum flow in the main valley (Porch et al., 1989b). Smoke releases, to be described later, showed most of the flow out of the southeast tributary was above our laser path.

An even closer examination of Fig. 3 shows a negative correlation between the major maxima in the down Kimball Creek Valley winds and the flow out of the two tributaries. This negative correlation is shown in the time-lagged correlation plots shown in Fig. 4. The negative correlation peak is not simultaneous between the valley and the tributary. Rather, the valley flow lags the tributary flow changes by 3-7 minutes. This implies that changes occur first in the tributaries, and later, the valley flow responds. This is consistent with the hypothesis that cold air builds up over about a 20 minute period in the tributaries and then flows into the main valley, slowing the main valley flow (rather like dropping bricks into a wagon moving down hill).

The spectral characteristics of the valley and tributary flows in Fig. 3 are shown in Fig. 5. These spectra show that the major period of oscillation in these data is about 20 minutes, especially in the southeast tributary. The valley and the north tributary wind spectra are also influenced by a long period oscillation of about a 45 minute period. These spectra also indicate a harmonic of about a 10 minute period oscillation. This harmonic behavior was also observed in a tributary in Brush Creek and seemed to be related to flows both into and out of the tributary, inhibiting flow contributions from the tributary sidewalls. The relative magnitude of the two major frequencies is emphasized in the coherence spectra shown in Fig. 6. The dashed lines in this figure represents to 90% confidence level for significant coherence.

Comparison of the optical anemometer data with tethered balloon measurements taken every two hours near the valley center gives an indication of what is happening in the vertical dimension. Both the cross-wind sensor and tethered balloon data were scanned to look for the clearest cases of a balloon ascent beginning during a maximum or minimum in the down-valley wind during drainage. A comparison of profiles for the two selected cases is shown in Fig. 7. For the period selected on 23 July, the down-valley wind speed showed consistent well developed drainage; in the other case (25 July), the valley drainage wind decreased precipitously. In the case of decreasing drainage winds, the drainage jet was decreased both above and below the level of maximum winds for the well developed drainage case. This height of decreased winds is also about the level of the optical cross-wind sensors monitoring flow out of the tributaries. This decrease in winds at the height of maximum valley-tributary interaction seems to imply momentum transfer at or above the height of the main valley drainage jet.

Data comparisons were also made between tower and optical cross-wind measurements in the tributaries. Fig. 8 a) shows the power spectra for the cross-wind sensors, the down-valley component of the wind velocity, and the temperature from the 3 meter towers in the north and southeast tributaries for July 23-24. Fig. 8 b) shows analogous spectra for July 22-23 for down-valley wind speeds including the spectra for the southwest tributary, and (Fig. 8 c) the north tributary. The period shown in Fig. 8 a) represented 420 data points of 1 minute values between 2200 MST on 23 July and 0500 MST on 24 July, 1988. The optical anemometer and tower wind speed component spectra are similar to the spectra in Fig. 5 for the same period on 24-25 July. The temperature spectra, however are quite different. The temperature spectra show a tendency to emphasize 8-12 minute periods over the about 20 minute oscillations in the wind component spectra. There is an actual spectral gap in the southeast tributary spectrum. Coherence between the down-valley velocities measured by the optical anemometer and tower anemometer were barely significant for periods between 10 and 16 minutes. The coherence between optical anemometer winds and temperature was significant for the north tributary (and marginally significant for the south tributaries) with flow out of the tributaries at the height of the cross-wind sensors corresponding to lower temperatures.

Time-lagged correlation functions for the parameters measured at the 3-meter towers were also analyzed for the night of 23-23 July (Fig. 9). The highest correlations were between the down-valley wind component and the vertical velocity (correlation coefficients about 0.6 in all three tributaries). The sign of the correlation implies that as the flow moves down the tributary the vertical velocity is downward also. The next highest correlations came from wind speeds and temperature comparisons between the southeast and southwest tributaries (correlation coefficients about 0.5). A similar high level of coherence between the southeast and southwest tributaries was observed on different nights with different relationships between the strength of principal oscillation frequencies and harmonics (Fig. 10). The shape of the correlation functions in Fig. 9 imply that down-valley component of the wind changes first in the southwest tributary, and the temperature changes first in the southeast tributary. Since the southeast tributary is down valley from the southwest tributary, the temperature data lag is somewhat surprising and appears to be dominated by two or three warming events. The relationship between temperature and both the down-valley wind speed component and vertical velocity is different in the three different tributaries. The sign of the cospectrum, at frequencies where coherence is significant to the 90% level, is different in the different tributaries. The reason for this difference in sign may be that in some instances velocity down the tributary brings colder air from farther up the tributary, in other cases flow up the tributary may bring colder air from the main valley, and finally flow down the tributary may bring warmer air down from above. Which of these three effects dominate is probably a function of position in the tributary and the main valley and tributary geometry.

A similar sign difference in coherence to that observed for down-tributary velocity and temperature was observed for vertical velocity and temperature. Examination of phase differences between vertical velocity and temperature at the towers showed the expected 90° phase shift for linear waves over the range of periods 15-88 minutes for the southeast tributary on the nights of 22-23 and 23-24 July (Fig. 11). The north tributary showed about a 90° phase shift in a narrow period range around 22 minutes, and for periods longer than 55 minutes. The southwest tributary shows about a 90° phase shift in the range 18-33 minute.

The oscillations revealed in the power spectral analyses are supported by nighttime photographs of smoke releases. The time evolution of a single oscillation is shown in Fig. 12. These photographs were taken at two locations near the position marked TS and to the west of ST shown in Fig. 1. The photographs on the left hand side were taken from the location on the west side of the southeast tributary. The photographs on the right of Fig. 12 were taken from the valley location near the tethered balloon site. The times on the photographs are in local daylight time (LDT). The photographs from the tributary west side show that the smoke initially flowed smoothly in a shallow plume which closely followed the tributary floor. The photographs at 2:04 and 2:08 MDT show that this flow then lifted and flowed out the east side of the tributary (the camera angle moved from the source to the tributary exit). The photograph at 2:12 MDT shows that the flow was blocked by air moving into the tributary. The photographs from the valley show the smoke flowing smoothly out the east side of the tributary until about 2:12 MDT, and then building again through 2:19 MDT. The smoke release ceased at about 2:20 MDT.

CONCLUSIONS

This paper shows that, at least in the valley studied, low frequency oscillations are a consistent characteristic of well developed nighttime valley drainage flows. The period of these oscillations is about 20 minutes with a higher frequency harmonic of about a 10 minute period. The timing of these oscillations indicates that the valley oscillation is being driven by periodic flow out of the tributary. The flow down the tributary decreases in a layer corresponding to the outflow height of the tributary flow. This leads to an negative correlation of flow down the valley and flow out of the tributary. These data are consistent with the hypothesis that cold air flow out of the tributary is blocked by cold air flow down the main valley. After the cold air accumulates, it eventually surges out into the main valley. This is caused by the fact that, by conservation of momentum, the increased mass of cold air from the tributary slows the main valley flow, which allows even more flow out of the tributary. A better understanding of this process will be needed in the future before the effect of tributaries on drainage flow and dispersion can be parameterized in numerical models.

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Hoard for their scientific support and help with the experiment, and G. Stone for his help with this manuscript.

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FIGURE CAPTIONS

Fig. 1 Map showing the locations of the Kimball Creek tributary experiment and the surrounding region of Western Colorado. Solid lines refer to optical cross-wind sensors (NT, XV and ST), and TS for instrumented tethered balloon locations.

Fig. 2 Plot of down and up-valley winds on the night of 24-25 July, 1988 from the optical cross-wind sensor across Kimball Creek Valley, showing both the evening transition to and the morning transition from nocturnal drainage flow.

Fig. 3 Seven hours of data from 2200 to 0500 MST during well developed drainage for the same night as in Fig. 2 for the cross-valley path and the southeast tributary, with a blowup of the first two hours showing the negative correlation between the two flows.

Fig. 4 a) Time-lagged correlations for data shown in Fig. 3, and b) analogous correlations for the previous and following day.

Fig. 5 Power spectra of a) the valley, b) the southeast tributary, and c) the north tributary cross-wind speeds in Fig. 3.

Fig. 6 Coherence spectra corresponding to the same conditions as Fig. 5 (dotted line corresponds to the level above which the coherence is significant at 90% confidence level and dark solid line corresponds to frequency dependent 90% confidence range).

Fig. 7 Comparison of the short term optical cross-wind data with profiles of the wind with height taken with the tethered balloon system in the valley. This comparison was for two cases. One case showed increasing flow out of the tributaries (higher negative values) and decreasing flow (lower negative values) down the valley (night of 7/25). The second case showed relatively strong steady flow down the valley and weak or counter flow out of the tributaries (night of 7/23).

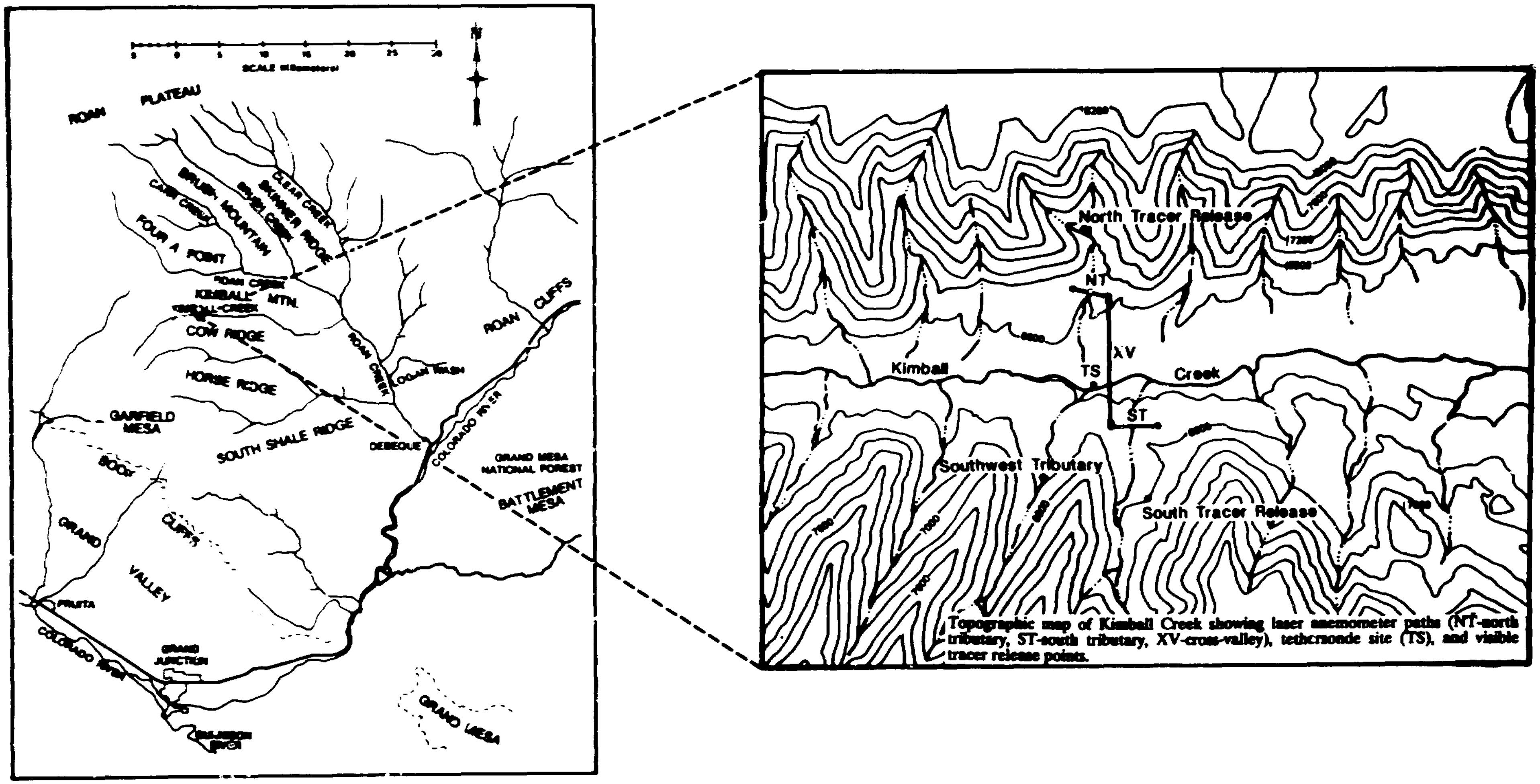
Fig. 8 Comparisons of power spectra for a) down-valley wind components derived from the optical cross-wind sensors and tributary meteorological towers measurement of this component and temperature, b) analogous spectra for the southeast and southwest tributaries on the previous day, and c) for the north tributary.

Fig. 9 Time-lagged correlation plots for the tributary measured variables with the highest peak correlation (down-valley wind speed versus vertical velocity, and down-valley wind speed and temperature between southeast and southwest tributaries).

Fig. 10 Cospectra and coherence between the down-valley component of the wind speed and the southeast and southwest tributaries for a) the night of 22-23 July, and b) the night of 23-24 July, 1988.

Fig. 11 Comparison of the phase spectra for vertical velocity and temperature measured at the tower in the souteast tributary on 22-23 July and 23-24 July, 1988 showing the expected 90° phase shift for linear waves at frequencies near the peak in the down-valley wind speed spectra.

Fig. 12 Consecutive nighttime photographs taken from the photographic location on the west side of the tributary (left side photographs), and in the valley near the tethered balloon site (right side photographs). These photographs were of a smoke release on 1 Aug. 1988 in the southeast tributary. The times on the photographs are in Mountain Daylight Time (MDT).



Topographic map of Kimball Creek showing laser anemometer paths (NT-north tributary, ST-south tributary, XV-cross-valley), tethersonde site (TS), and visible tracer release points.

Fig. 1

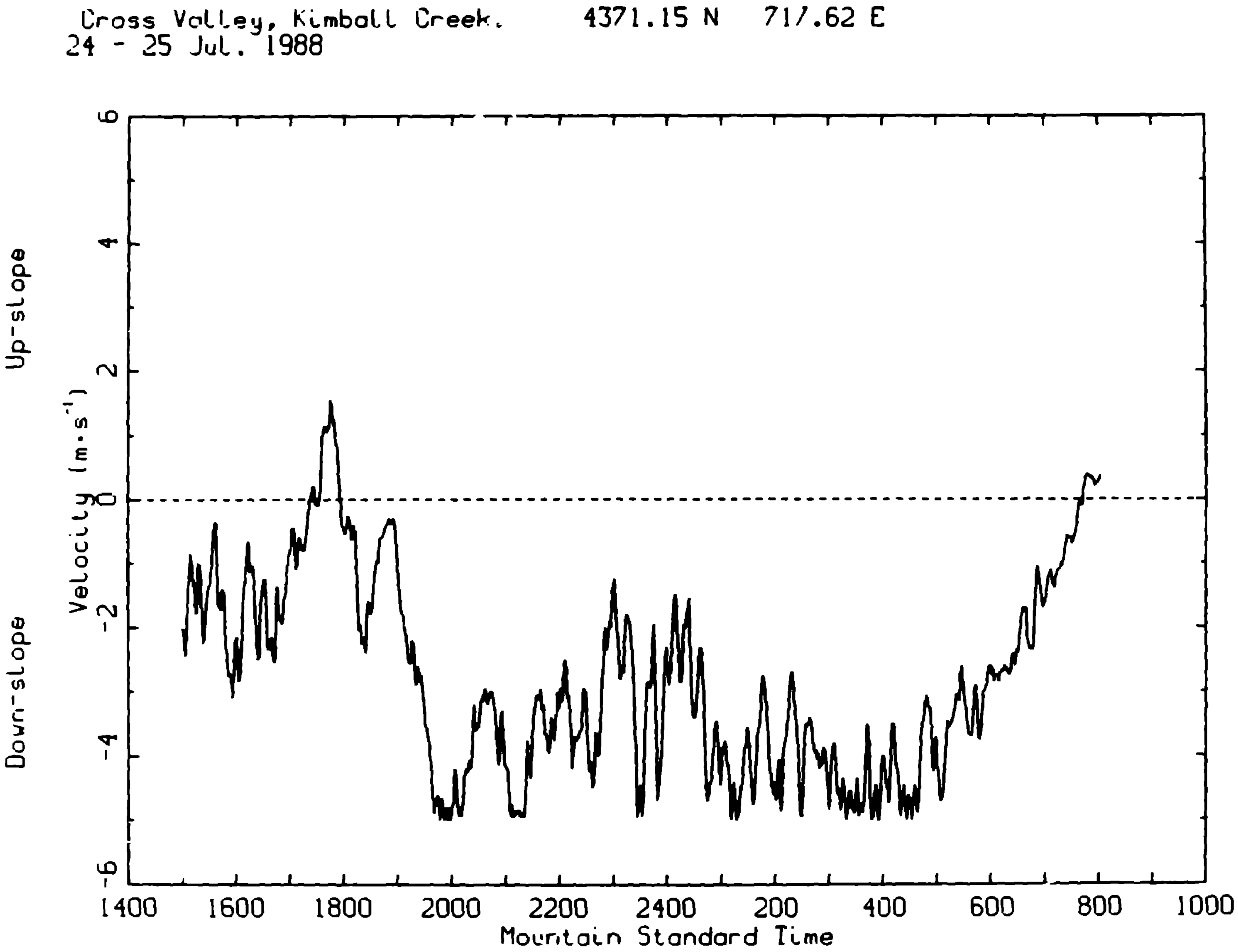

Cross Valley, Kimball Creek. 4371.15 N 717.62 E
24 - 25 Jul. 1988
Up-slope
Down-slope
Velocity (m·s⁻¹)
6
4
2
0
-2
-4
-6
1400
1600
1800
2000
2200
2400
200
400
600
800
1000
Mountain Standard Time

Fig. 2

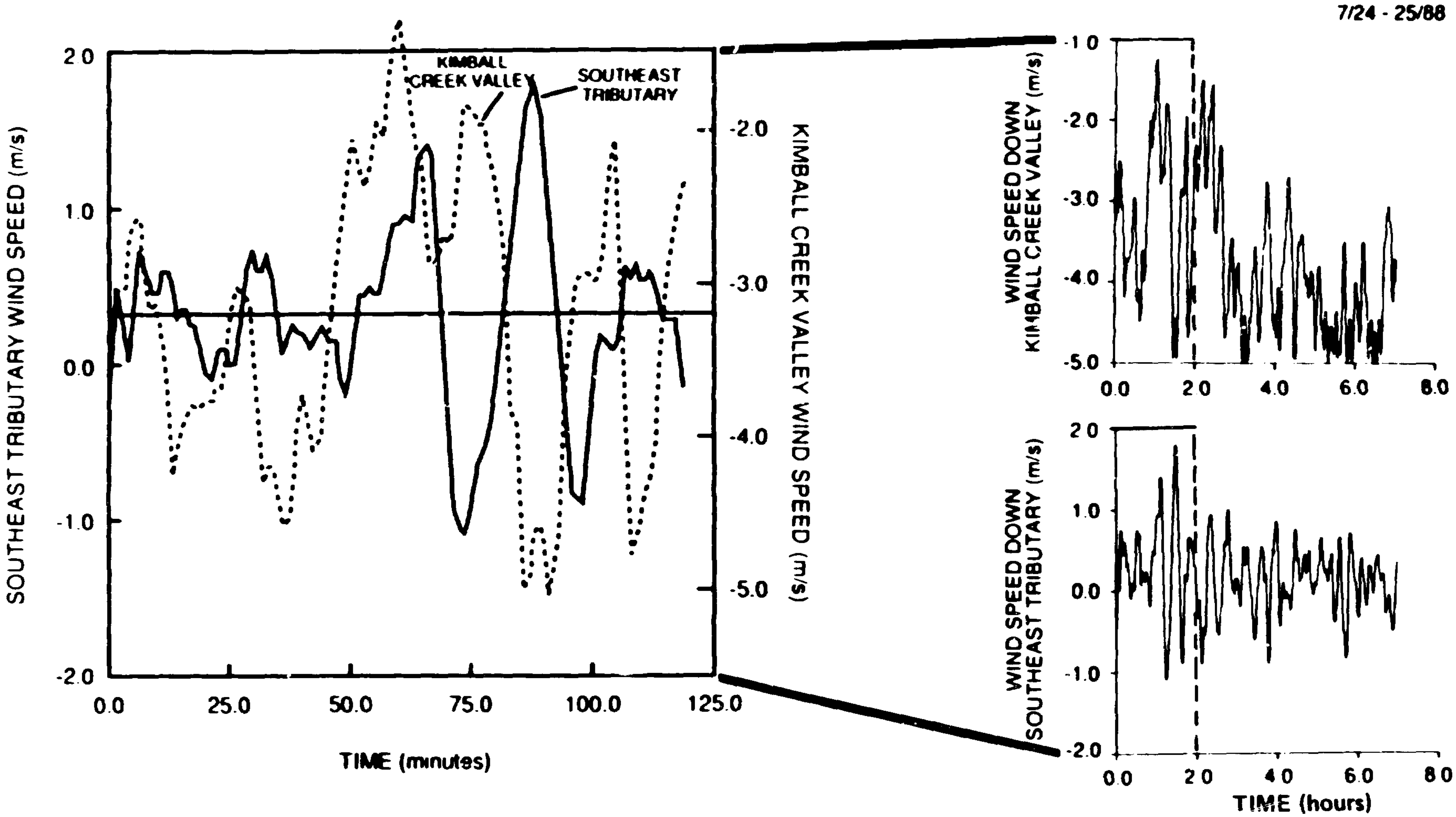

7/24 - 25/88
SOUTHEAST TRIBUTARY WIND SPEED (m/s)
2.0
1.0
0.0
-1.0
-2.0
0.0
25.0
50.0
75.0
100.0
125.0
TIME (minutes)
KIMBALL CREEK VALLEY
SOUTHEAST TRIBUTARY
KIMBALL CREEK VALLEY WIND SPEED (m/s)
-2.0
-3.0
-4.0
-5.0
WIND SPEED DOWN KIMBALL CREEK VALLEY (m/s)
-1.0
-2.0
-3.0
-4.0
-5.0
0.0
2.0
4.0
6.0
8.0
WIND SPEED DOWN SOUTHEAST TRIBUTARY (m/s)
2.0
1.0
0.0
-1.0
-2.0
0.0
2.0
4.0
6.0
8.0
TIME (hours)

Fig. 3

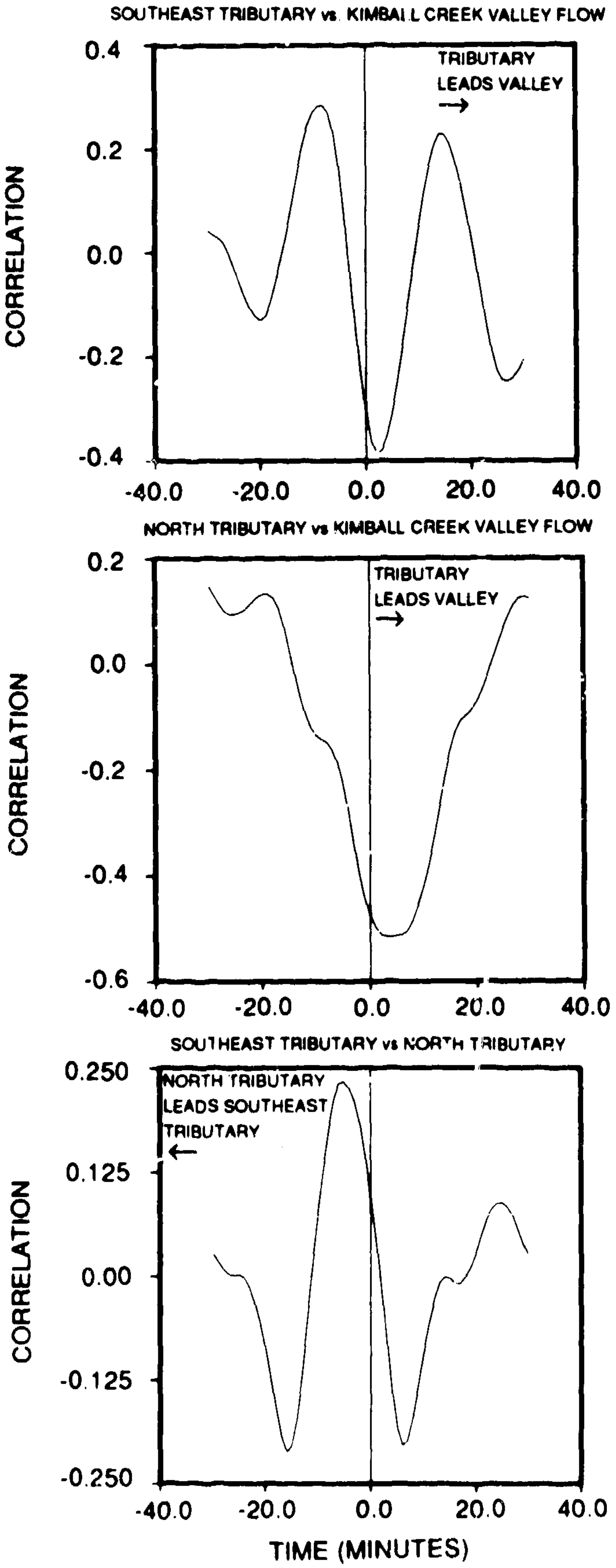

SOUTHEAST TRIBUTARY vs KIMBALL CREEK VALLEY FLOW
CORRELATION
0.4
0.2
0.0
-0.2
-0.4
-40.0
-20.0
0.0
20.0
40.0
TRIBUTARY
LEADS VALLEY
→
NORTH TRIBUTARY vs KIMBALL CREEK VALLEY FLOW
CORRELATION
0.2
0.0
-0.2
-0.4
-0.6
-40.0
-20.0
0.0
20.0
40.0
TRIBUTARY
LEADS VALLEY
→
SOUTHEAST TRIBUTARY vs NORTH TRIBUTARY
CORRELATION
0.250
0.125
0.00
-0.125
-0.250
-40.0
-20.0
0.0
20.0
40.0
NORTH TRIBUTARY
LEADS SOUTHEAST
TRIBUTARY
←
TIME (MINUTES)

Fig. 4a)

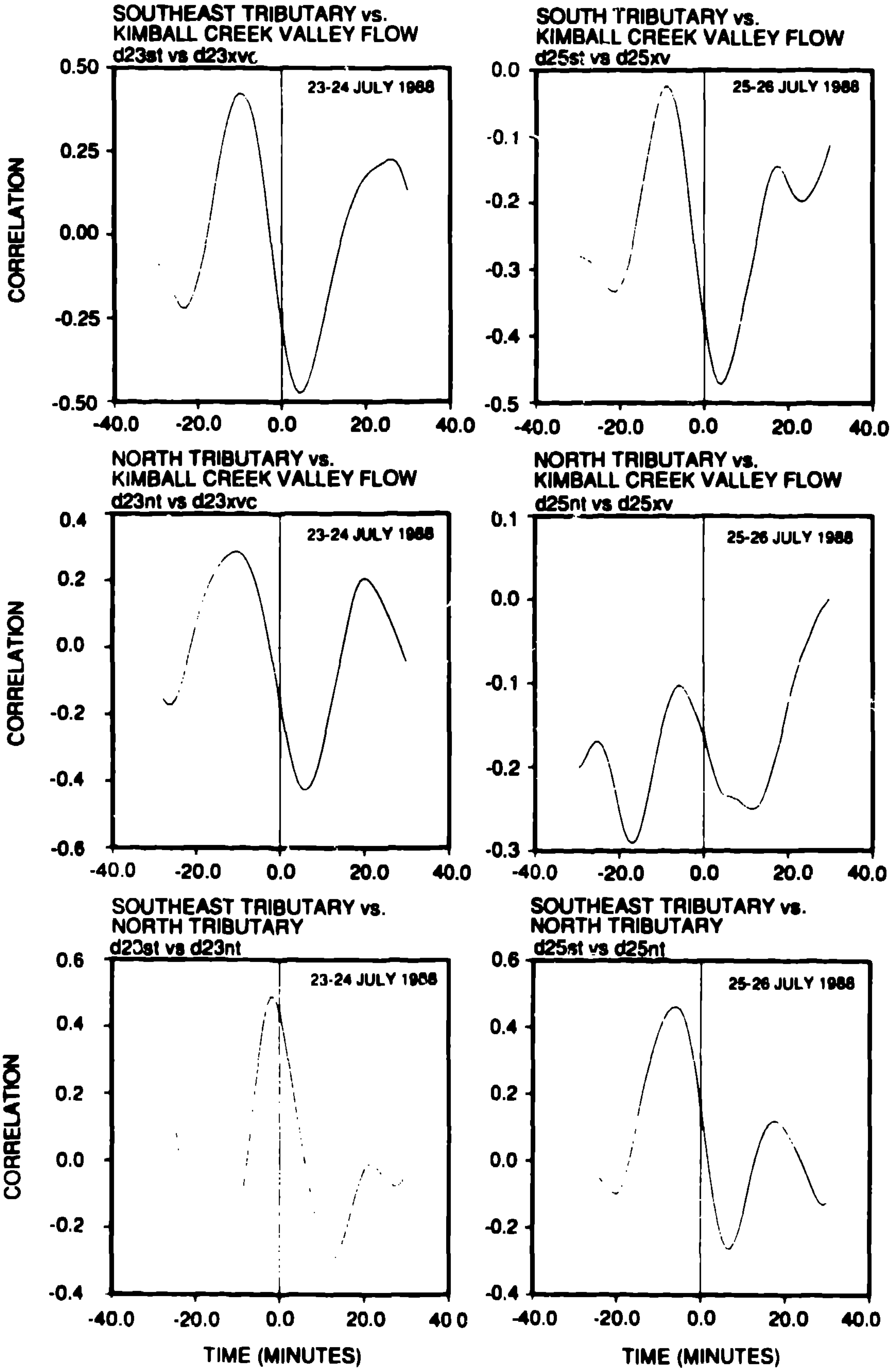

SOUTHEAST TRIBUTARY vs.
KIMBALL CREEK VALLEY FLOW
d23st vs d23xvc
23-24 JULY 1988
SOUTH TRIBUTARY vs.
KIMBALL CREEK VALLEY FLOW
d25st vs d25xv
25-26 JULY 1988
NORTH TRIBUTARY vs.
KIMBALL CREEK VALLEY FLOW
d23nt vs d23xvc
23-24 JULY 1988
NORTH TRIBUTARY vs.
KIMBALL CREEK VALLEY FLOW
d25nt vs d25xv
25-26 JULY 1988
SOUTHEAST TRIBUTARY vs.
NORTH TRIBUTARY
d23st vs d23nt
23-24 JULY 1988
SOUTHEAST TRIBUTARY vs.
NORTH TRIBUTARY
d25st vs d25nt
25-26 JULY 1988
CORRELATION
0.50
0.25
0.00
-0.25
-0.50
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0.4
0.2
0.0
-0.2
-0.4
-0.6
0.1
0.0
-0.1
-0.2
-0.3
0.6
0.4
0.2
0.0
-0.2
-0.4
-40.0
-20.0
0.0
20.0
40.0
TIME (MINUTES)

Fig. 4b)

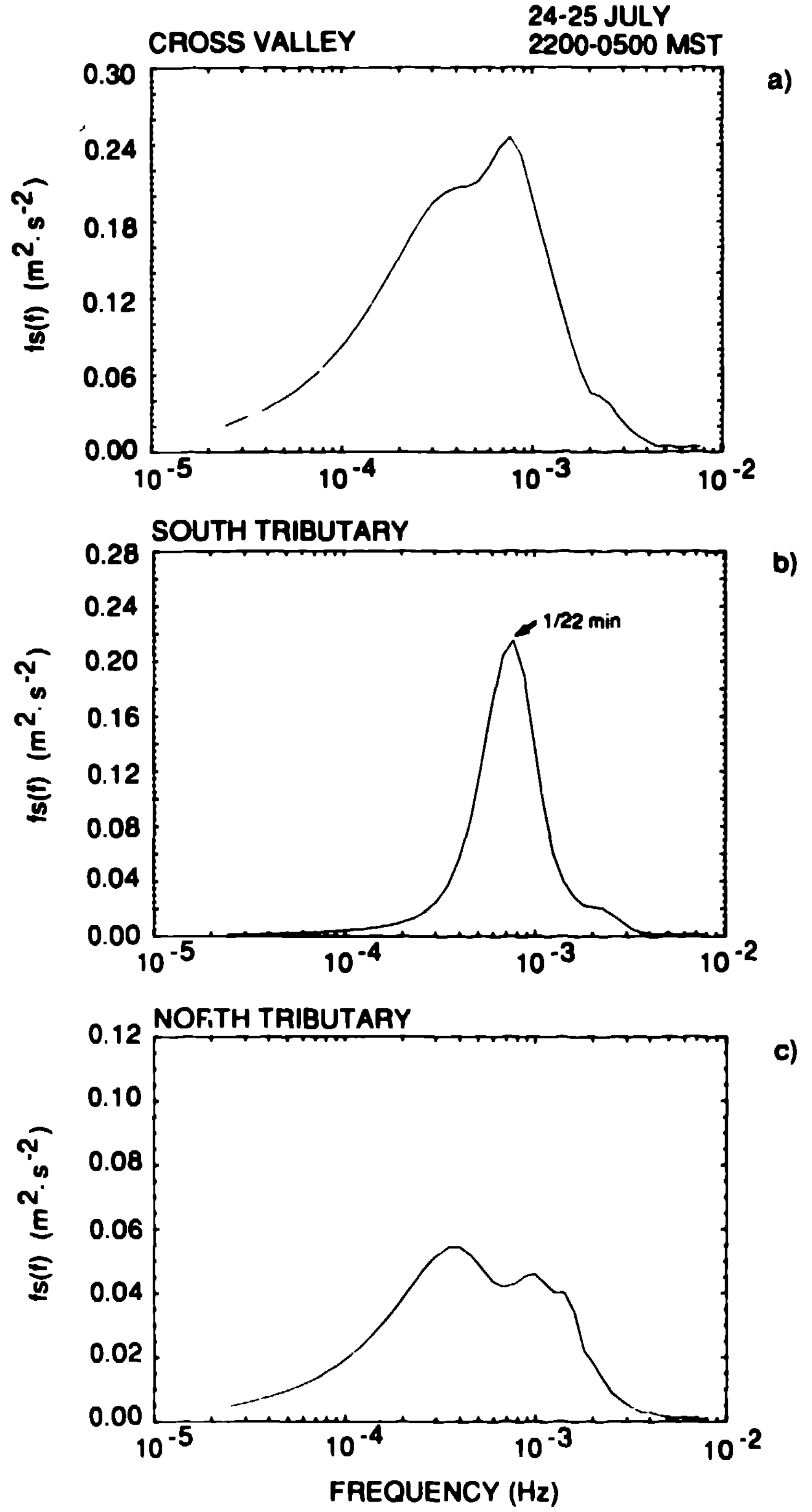

CROSS VALLEY
24-25 JULY
2200-0500 MST
a)
0.30
0.24
0.18
0.12
0.06
0.00
fs(f) (m^2·s^{-2})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
SOUTH TRIBUTARY
b)
1/22 min
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
fs(f) (m^2·s^{-2})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
NORTH TRIBUTARY
c)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
fs(f) (m^2·s^{-2})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
FREQUENCY (Hz)

Fig. 5

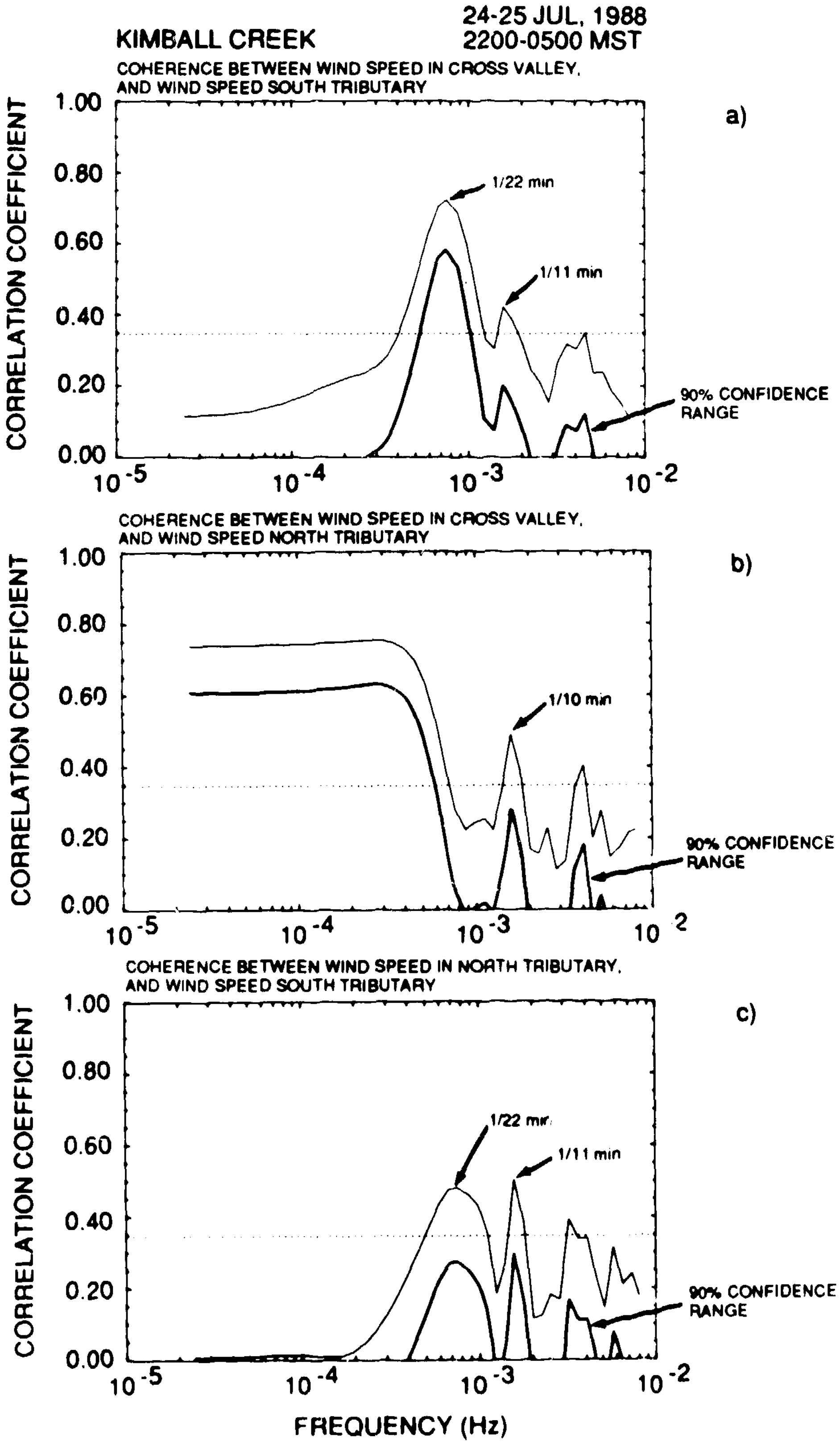

KIMBALL CREEK
24-25 JUL, 1988
2200-0500 MST
COHERENCE BETWEEN WIND SPEED IN CROSS VALLEY, AND WIND SPEED SOUTH TRIBUTARY
a)
1/22 min
1/11 min
90% CONFIDENCE RANGE
COHERENCE BETWEEN WIND SPEED IN CROSS VALLEY, AND WIND SPEED NORTH TRIBUTARY
b)
1/10 min
90% CONFIDENCE RANGE
COHERENCE BETWEEN WIND SPEED IN NORTH TRIBUTARY, AND WIND SPEED SOUTH TRIBUTARY
c)
1/22 min
1/11 min
90% CONFIDENCE RANGE
CORRELATION COEFFICIENT
1.00
0.80
0.60
0.40
0.20
0.00
10^-5
10^-4
10^-3
10^-2
FREQUENCY (Hz)

Fig. 6

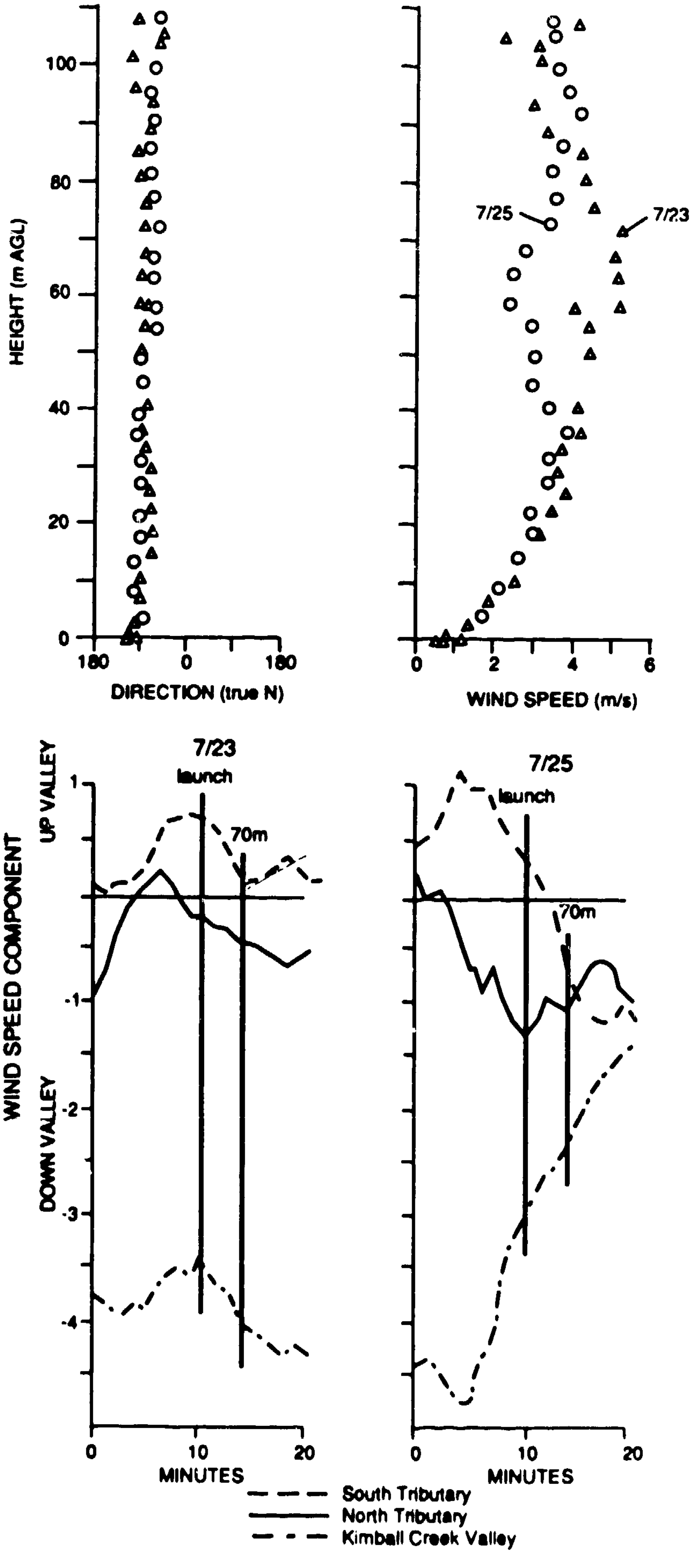
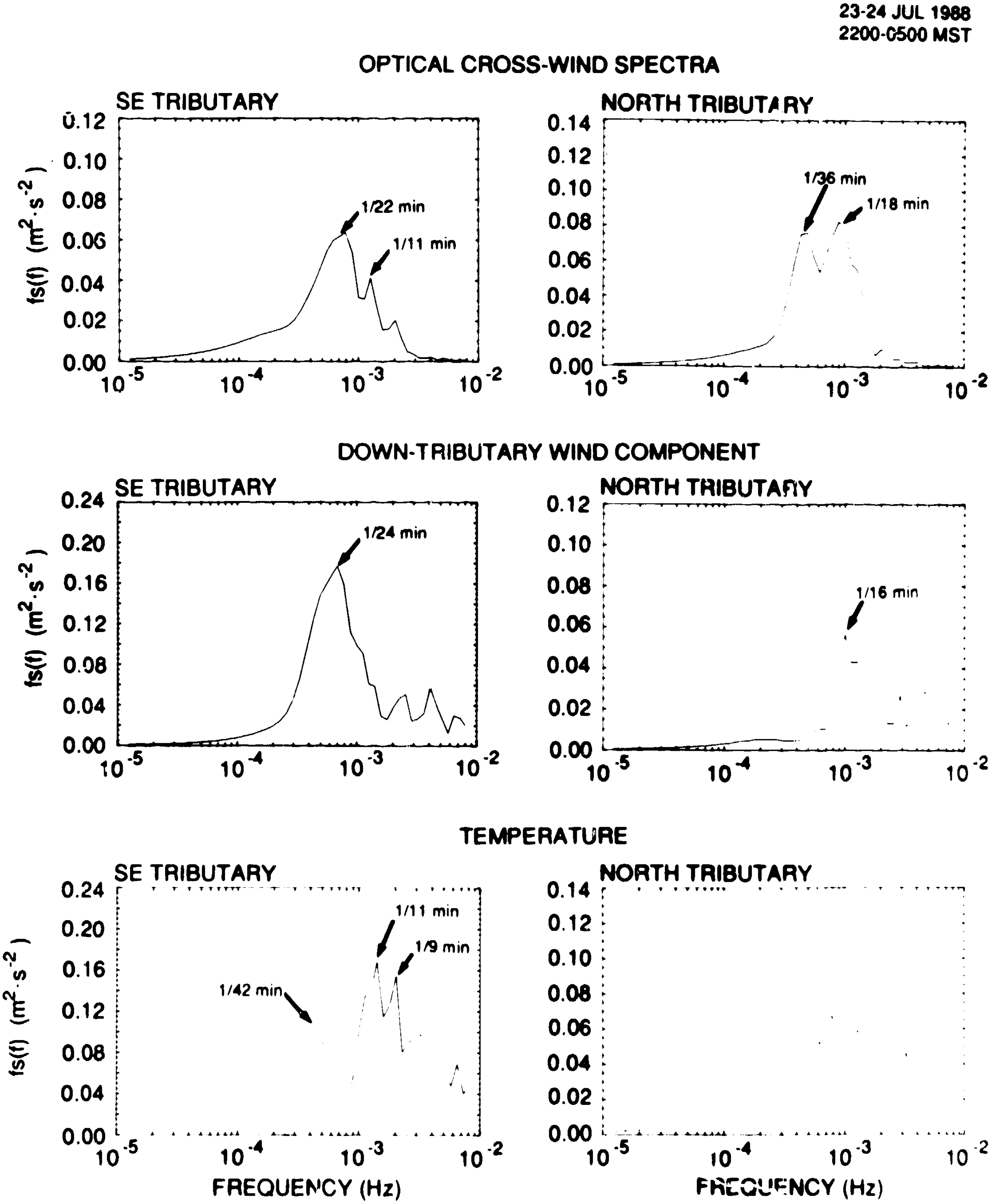

HEIGHT (m AGL)
0
20
40
60
80
100
180
0
180
DIRECTION (true N)
7/25
7/23
0
2
4
6
WIND SPEED (m/s)
WIND SPEED COMPONENT
UP VALLEY
DOWN VALLEY
7/23
launch
70m
1
-1
-2
-3
-4
0
10
20
MINUTES
7/25
launch
70m
0
10
20
MINUTES
South Tributary
North Tributary
Kimball Creek Valley

Fig. 7



23-24 JUL 1988
2200-0500 MST

OPTICAL CROSS-WIND SPECTRA

SE TRIBUTARY

NORTH TRIBUTARY

DOWN-TRIBUTARY WIND COMPONENT

SE TRIBUTARY

NORTH TRIBUTARY

TEMPERATURE

SE TRIBUTARY

NORTH TRIBUTARY

Fig. 8a)

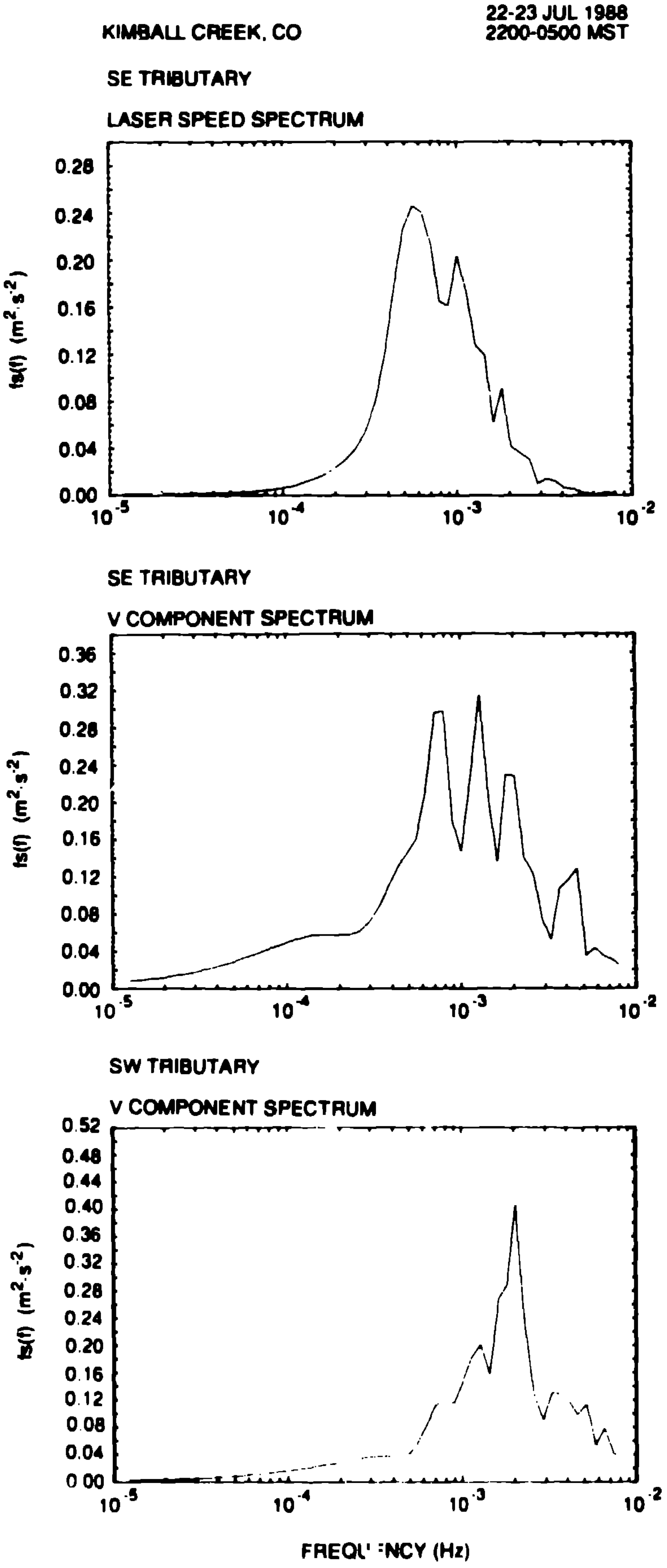

KIMBALL CREEK, CO
22-23 JUL 1988
2200-0500 MST
SE TRIBUTARY
LASER SPEED SPECTRUM
fs(f) (m^2·s^{-2})
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
SE TRIBUTARY
V COMPONENT SPECTRUM
fs(f) (m^2·s^{-2})
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
SW TRIBUTARY
V COMPONENT SPECTRUM
fs(f) (m^2·s^{-2})
0.52
0.48
0.44
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
FREQUENCY (Hz)

Fig. 8b)

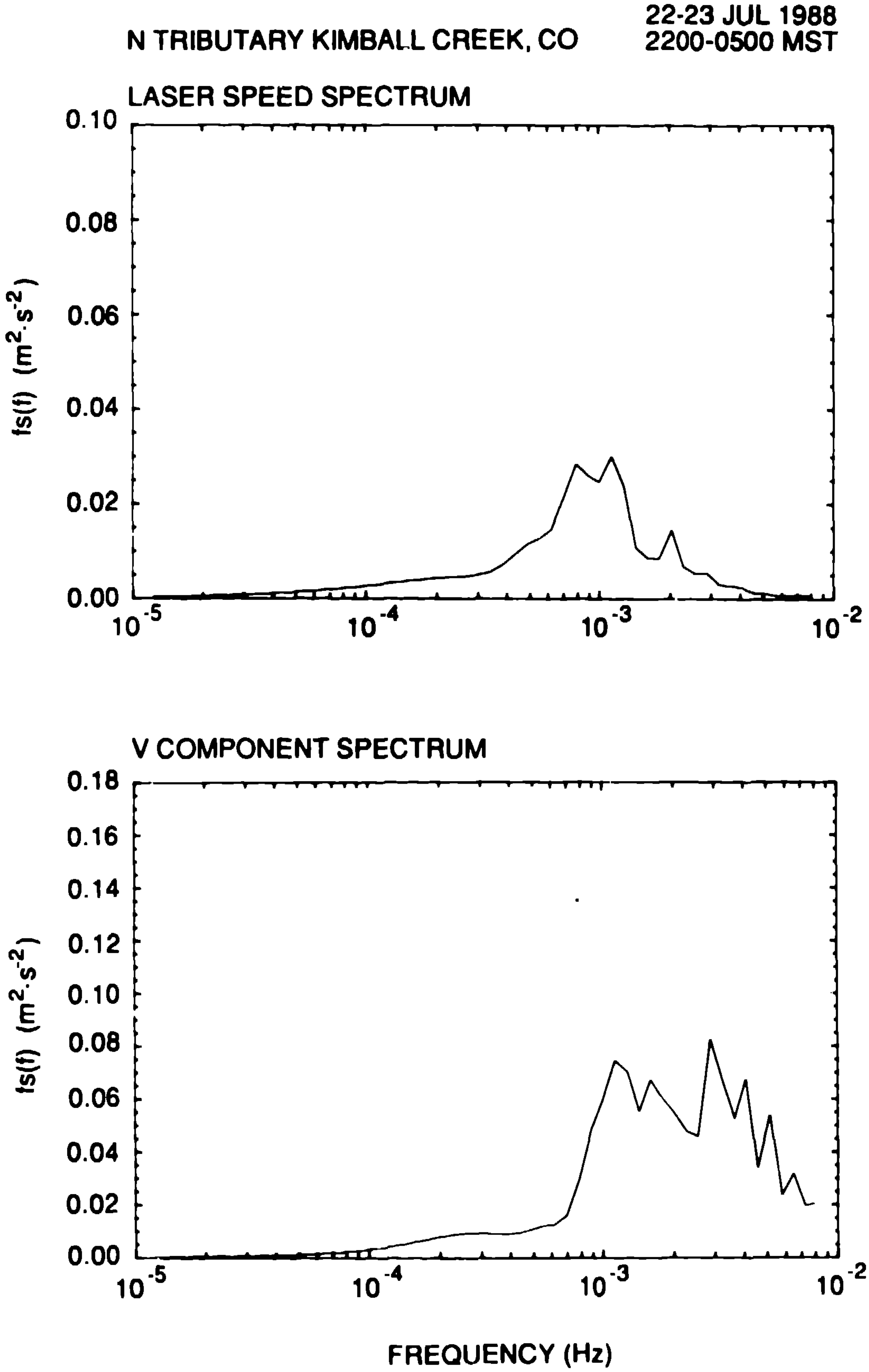

N TRIBUTARY KIMBALL CREEK, CO
22-23 JUL 1988
2200-0500 MST
LASER SPEED SPECTRUM
fs(f) (m²·s⁻²)
0.10
0.08
0.06
0.04
0.02
0.00
10⁻⁵
10⁻⁴
10⁻³
10⁻²
V COMPONENT SPECTRUM
fs(f) (m²·s⁻²)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10⁻⁵
10⁻⁴
10⁻³
10⁻²
FREQUENCY (Hz)

Fig. 8c)

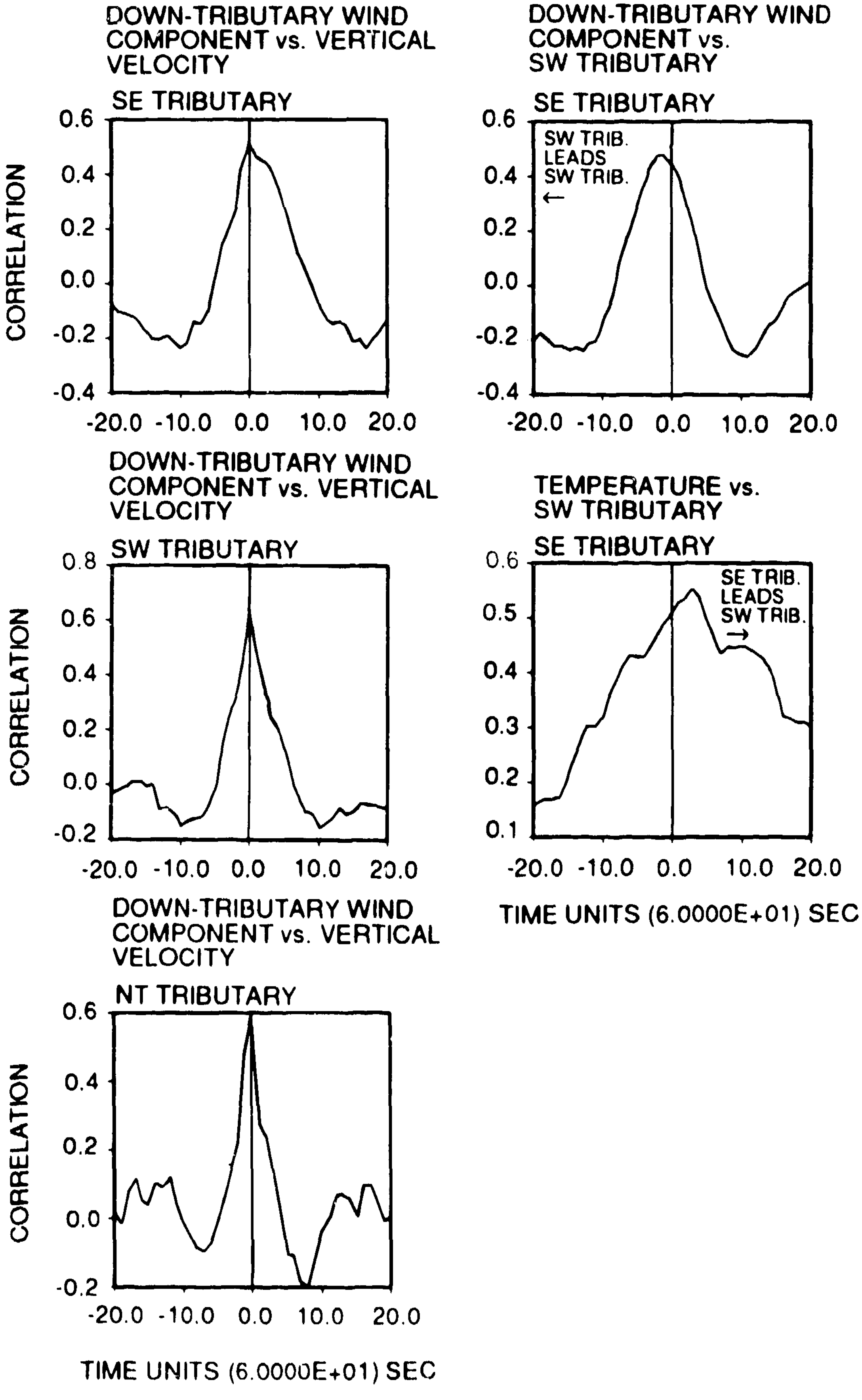

DOWN-TRIBUTARY WIND COMPONENT vs. VERTICAL VELOCITY
SE TRIBUTARY
CORRELATION
0.6
0.4
0.2
0.0
-0.2
-0.4
-20.0 -10.0 0.0 10.0 20.0
DOWN-TRIBUTARY WIND COMPONENT vs. SW TRIBUTARY
SE TRIBUTARY
SW TRIB. LEADS SW TRIB. ←
0.6
0.4
0.2
0.0
-0.2
-0.4
-20.0 -10.0 0.0 10.0 20.0
DOWN-TRIBUTARY WIND COMPONENT vs. VERTICAL VELOCITY
SW TRIBUTARY
CORRELATION
0.8
0.6
0.4
0.2
0.0
-0.2
-20.0 -10.0 0.0 10.0 20.0
TEMPERATURE vs. SW TRIBUTARY
SE TRIBUTARY
SE TRIB. LEADS SW TRIB. →
0.6
0.5
0.4
0.3
0.2
0.1
-20.0 -10.0 0.0 10.0 20.0
TIME UNITS (6.0000E+01) SEC
DOWN-TRIBUTARY WIND COMPONENT vs. VERTICAL VELOCITY
NT TRIBUTARY
CORRELATION
0.6
0.4
0.2
0.0
-0.2
-20.0 -10.0 0.0 10.0 20.0
TIME UNITS (6.0000E+01) SEC

Fig. 9

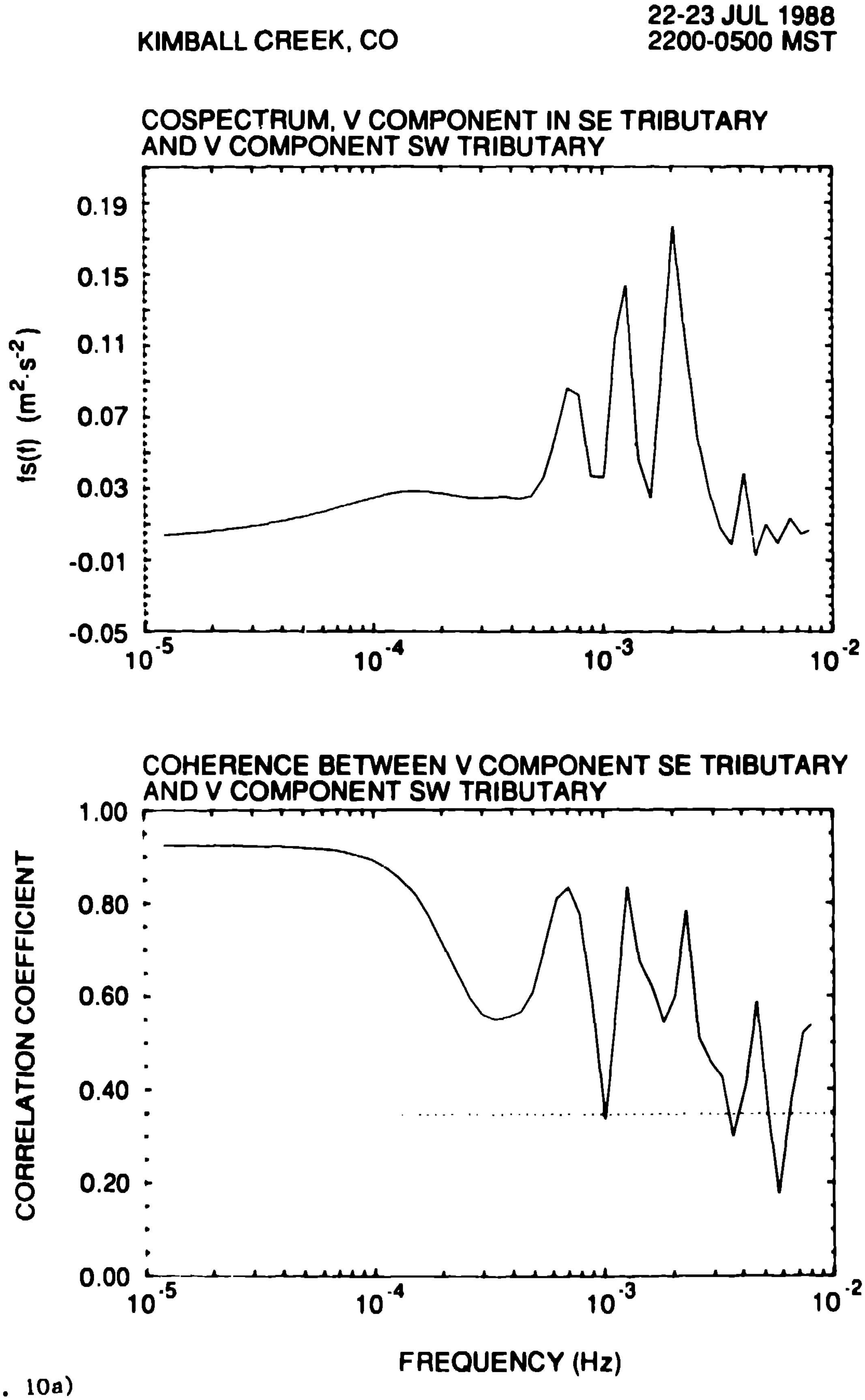

KIMBALL CREEK, CO
22-23 JUL 1988
2200-0500 MST
COSPECTRUM, V COMPONENT IN SE TRIBUTARY AND V COMPONENT SW TRIBUTARY
fs(f) (m^2·s^{-2})
0.19
0.15
0.11
0.07
0.03
-0.01
-0.05
10^{-5}
10^{-4}
10^{-3}
10^{-2}
COHERENCE BETWEEN V COMPONENT SE TRIBUTARY AND V COMPONENT SW TRIBUTARY
CORRELATION COEFFICIENT
1.00
0.80
0.60
0.40
0.20
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
FREQUENCY (Hz)

Fig. 10a)

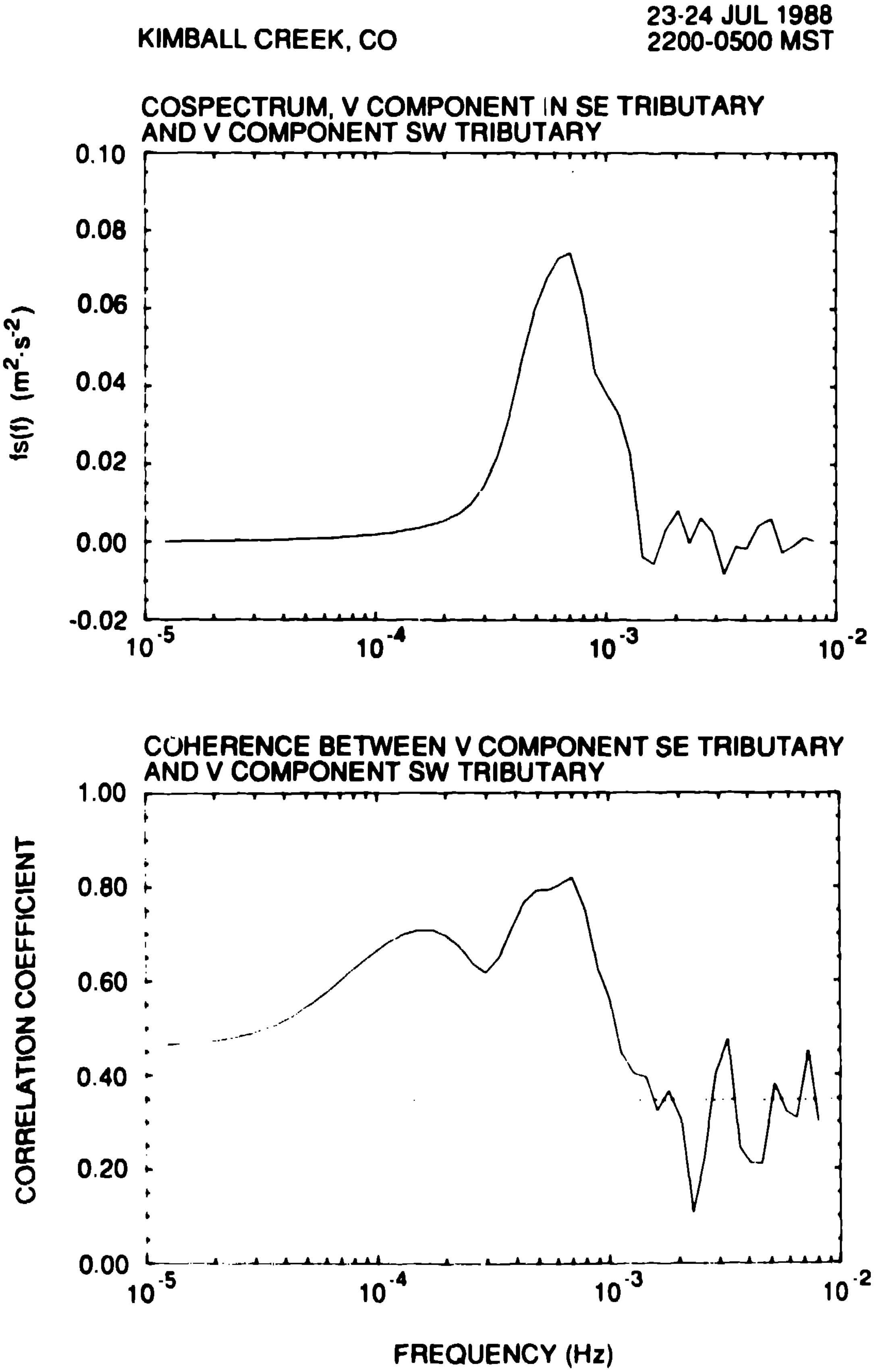

KIMBALL CREEK, CO
23-24 JUL 1988
2200-0500 MST
COSPECTRUM, V COMPONENT IN SE TRIBUTARY AND V COMPONENT SW TRIBUTARY
fs(f) (m²·s⁻²)
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
10⁻⁵
10⁻⁴
10⁻³
10⁻²
COHERENCE BETWEEN V COMPONENT SE TRIBUTARY AND V COMPONENT SW TRIBUTARY
CORRELATION COEFFICIENT
1.00
0.80
0.60
0.40
0.20
0.00
10⁻⁵
10⁻⁴
10⁻³
10⁻²
FREQUENCY (Hz)

Fig 10b)

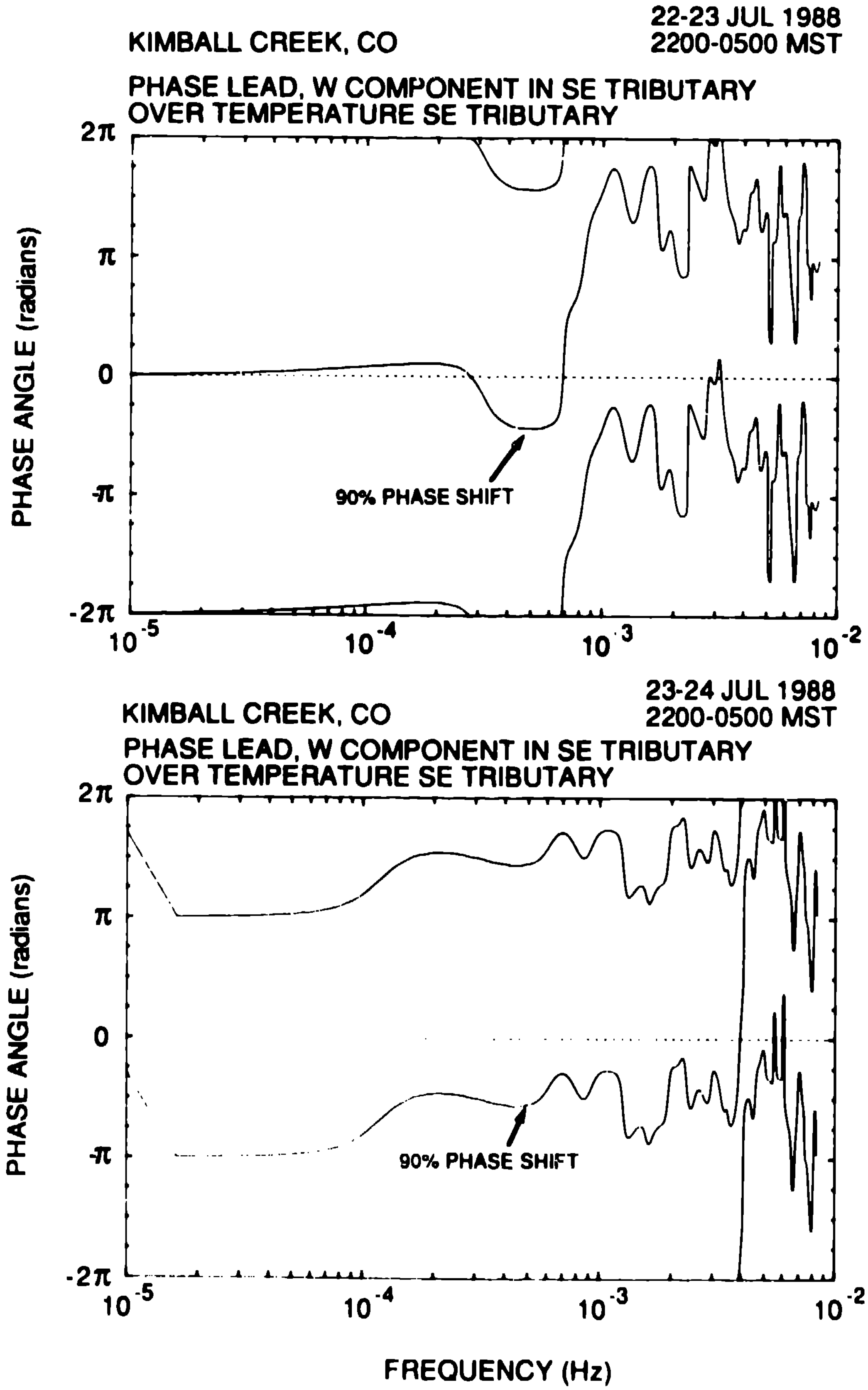

22-23 JUL 1988
2200-0500 MST
KIMBALL CREEK, CO
PHASE LEAD, W COMPONENT IN SE TRIBUTARY
OVER TEMPERATURE SE TRIBUTARY
PHASE ANGLE (radians)
2π
π
0
-π
-2π
90% PHASE SHIFT
10^{-5}
10^{-4}
10^{-3}
10^{-2}
23-24 JUL 1988
2200-0500 MST
KIMBALL CREEK, CO
PHASE LEAD, W COMPONENT IN SE TRIBUTARY
OVER TEMPERATURE SE TRIBUTARY
PHASE ANGLE (radians)
2π
π
0
-π
-2π
90% PHASE SHIFT
10^{-5}
10^{-4}
10^{-3}
10^{-2}
FREQUENCY (Hz)

Fig. 11

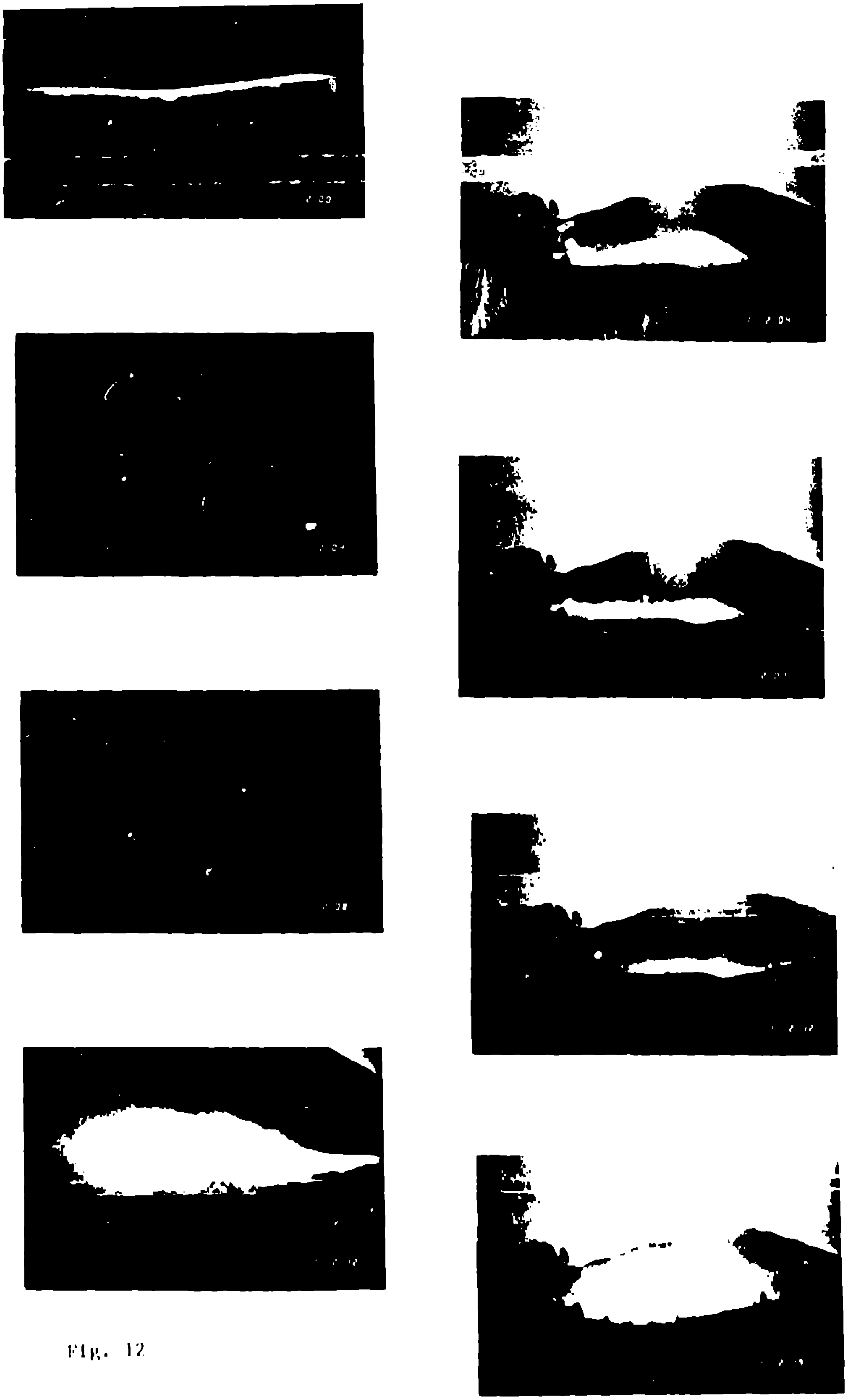


Fig. 12