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Research on Increased Precipitation by Cloud Seeding: Development Phase

Geoffrey E. Hill

Utah State University
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RESEARCH ON INCREASED PRECIPITATION BY CLOUD SEEDING:

DEVELOPMENT PHASE

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Geoffrey E. Hill

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ABSTRACT

Development of several instrumentation systems for measuring atmospheric variables related to winter orographic cloud seeding was undertaken. A heated tipping bucket precipitation gage was modified both for reliable use and accuracy of data. A solid state memory device was also developed at UWRL for this project. A parachute dropsonde for measuring vertical air motion was further developed. In addition, instrumentation was placed on board an aircraft for measuring concentrations of supercooled water, ice nuclei, and ice crystals.

Airborne measurements during cloud seeding with silver iodide showed that the plumes of seeding material could be detected over a target area, and that basic factors involved with precipitation could be measured. That is, measurements of vertical motion, concentrations of supercooled water and precipitation size ice crystals along with precipitation on the ground gave a reasonable picture of the gross features of orographic storms.

Indications of seeding effects were found only very tentatively. Further study and development are planned in order to better identify seeding effects.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

The primary objective of the cloud seeding research program at the Utah Water Research Laboratory (UWRL) during the period covered by this report was to develop a capability of measuring basic variables critical to research on increasing the winter snowpack by cloud seeding. Another basic objective was to make measurements of these variables during brief, but well-controlled periods of seeding to see if well-defined responses to seeding, or "signatures," could be detected.

The measurements for which development was required were for precipitation, supercooled water, and vertical motion. Other measurements such as ice nuclei were made by existing instrumentation placed on board the Atmospherics, Inc. aircraft, which was subcontracted for the project. The greatest effort on development was spent on the precipitation measuring system. Heated tipping bucket gages were modified to ensure reliability and improve accuracy, and a solid state memory system was developed for time-accurate data storage and retrieval. A Rosemount icing rate detector was used as another measure of supercooled-water concentration in addition to the Johnson-Williams device. The vertical motion sensor was modified to retain the rawinsonde humidity measurement. For measurements of ice nucleus concentration, an NCAR counter and a rotating Millipore filter system were used; for a general account of precipitation-size ice particles a Mee ice particle counter was used.

In the search for responses to cloud seeding, the first task was to release seeding material from the air and subsequently detect its

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presence over the mountains in the vicinity of the precipitation net-
work. The measurements do indeed show the presence of these ice
nucleus plumes.

Measurements of supercooled water and ice crystal concentration
were made regularly from the aircraft. While seeding effects could well
have been present, it is clearly not possible to assess possible seeding
effects at this stage. What is needed is a more complete set of data
for many test events. Other strategies to detect signatures would also
be helpful. This type of exploratory stage will be our primary emphasis
during next winter's measurement period. The development stage should
be at a plateau by the beginning of the winter.

2.0 DEVELOPMENT OF PRECIPITATION AND VERTICAL MOTION MEASURING SYSTEMS

2.1 Precipitation Measuring System

The main effort in developing the measuring system was placed on the precipitation system. Three aspects were involved in this effort:

First, the selection of 15 sites and the installation of towers and gages were made. The network is shown in Fig. 1; these gages are placed $\sim$ 3.3 km apart in a line running across the mountain-barrier crest of the Bear River Range near Mt. Naomi. The line is long enough to sample precipitation over the upwind valley, the mountain barrier, and downwind to the valley level.

Second, modifications of tipping bucket gages were made in order to ensure reliability of operation. The main advantage of the tipping bucket gage is that discrete measurements are obtained, thereby simplifying analysis; disadvantages are that a heating system is required and in standard gage designs the heating required causes a loss of catch due primarily to evaporation. The main features related to improved gage performance during cold seasons include a propane heater ignition system, a heat control system, and a propane pre-heat design.

Third, to obtain a recording system which has high time accuracy and is computer compatible, battery powered solid state memory devices were designed and installed in the gages.

The details of this work are described in the following:

2.1.1 Gage modifications

a) Ignition system

The heating system in typical present-day gages consists of a propane burner beneath the tipping bucket mechanism. In strong winds the

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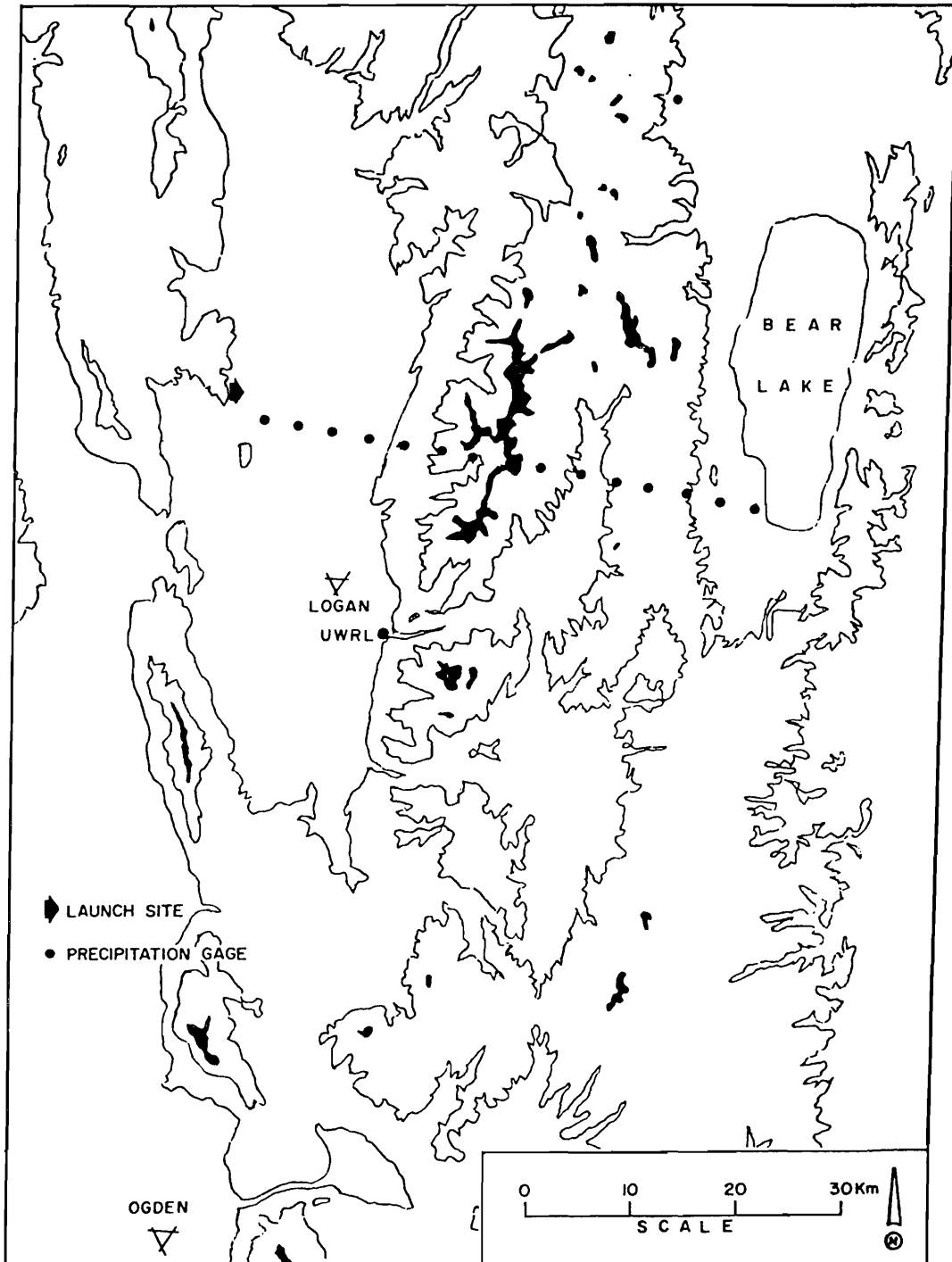
Fig. 1. Precipitation gage network. Contours: 5, 7 and 9
thousand feet msl.

propane flame may be extinguished; subsequently no useful data can be obtained until the flame is relit. In the new system reignition is provided by an electronic igniter which is activated by flameout. This igniter continues to produce sparks until the flame is relit at which time the sparker is automatically put on standby.

b) Preheated propane

When propane is cold a moderate wind may extinguish the flame; when the propane is warmed the wind required for blowout is greatly increased. Thus, our solution to the problem of flame blowout is to place three complete turns in the propane supply tube such that the flame is centered in and slightly higher than the coil of tubing. The burning propane heats the supply just before being used.

c) Temperature control

In order to minimize the loss of precipitation through evaporation it is necessary to keep the catchment section of the gage at a temperature only slightly above freezing. This is accomplished by attaching a thermal switch to the underside of the funnel and using that switch to control the propane burner. The switch also disables the electronic ignition system when no heat is needed. When heat is required the thermal switch closure turns on the propane and activates the igniter. The control system thus saves propane as well as improving on the accuracy of the data.

2.1.2 Data storage/readout system. The data recording system described herein overcomes drawbacks of tape systems and makes feasible the long term gathering of computer compatible data. This system has no moving parts, very low power requirements, and direct readout into almost any computer. It is readily

expandable to accommodate specific time and resolution requirements. CMOS Integrated Circuits (ICS) are used throughout the system to minimize power requirements and maximize supply voltage tolerance.

There are basically two strategies for recording digitized data: one is to record the time of each tip in the case of a tipping bucket, the other is to record the quantity by use of an analog to digital (A/D) converter at fixed time intervals. It is the former approach which is used in the present case.

A block diagram of the system used for tipping bucket precipitation gages is shown in Fig. 2. It functions as follows: a clock circuit continually presents to the memory a 16 bit word representing in straight binary the elapsed time from a manually selected real time reference. The resolution, which is given by the time value of the least significant bit (LSB), has been selected to be 128 s. The memory capacity with 128 s resolution is 97 d. Although the time is continually presented to the memory chips it is actually recorded only after a recording cycle has been initiated by the quantized physical variable, which in our case is .01 in. of precipitation. In summary, each recorded data word then gives two pieces of data information: (1) it shows that the physical variable has changed by .01 in. and (2) it indicates the time at which this occurred.

a) Memory system

The memory system is the heart of the data recording system. The static memory chips are interconnected so that they simultaneously record in any given memory address. The address counter is manually set to zero before the system is taken to the field. Prior to zeroing the
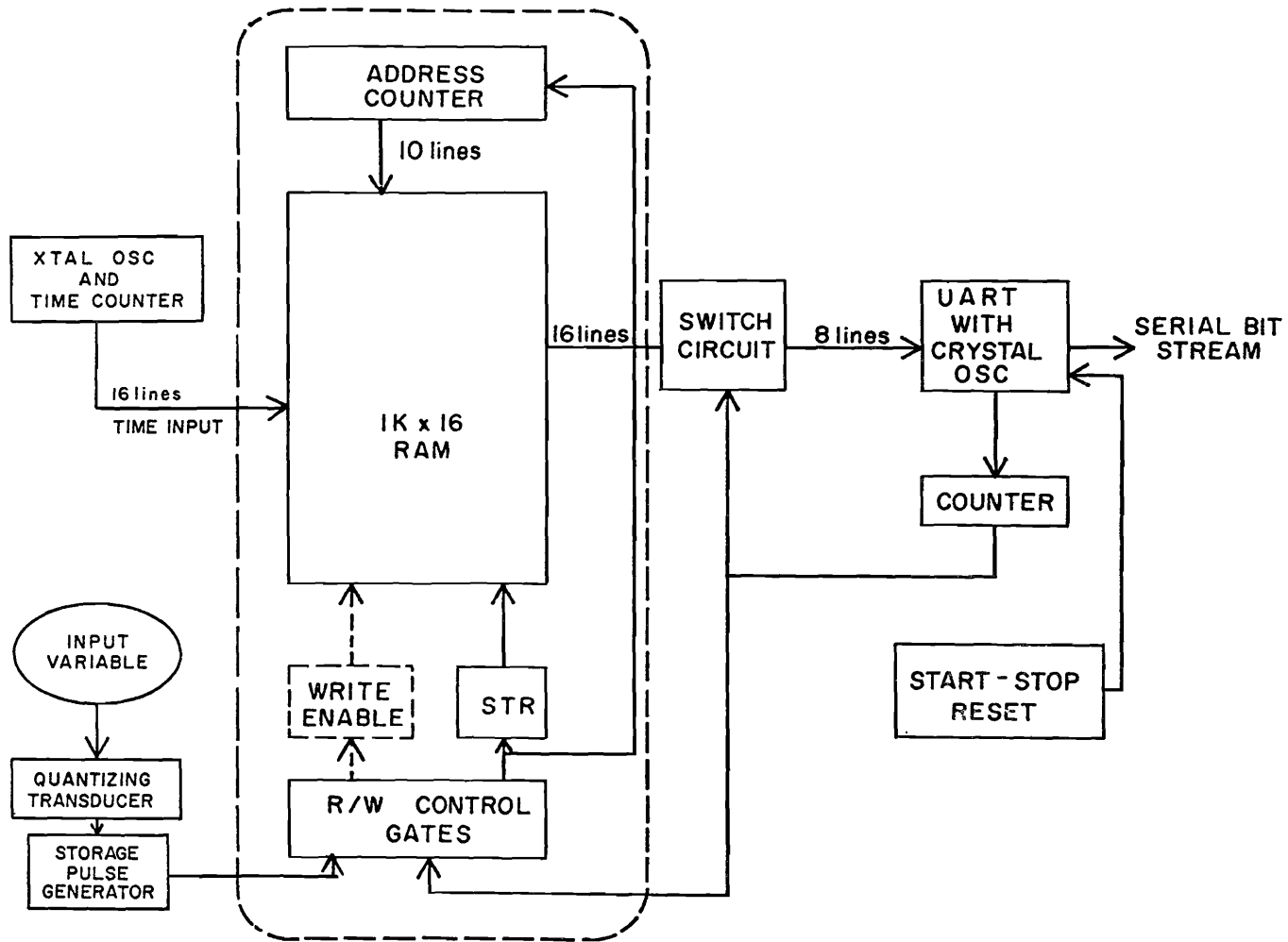
Fig. 2. Block diagram of memory system.

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address counter the memory chips are cleared by storing a zero at each

memory address. This operation is not mandatory since the data will

write over whatever is stored in the memory but starting with a clean

slate makes analysis of the computer readout easier.

b) Readout

Data stored in the memory system is read into the computer by the

interface circuit. The readout is accomplished by a control system which

first resets the address counter to zero and then sequentially pulses the

strobe (STR) input and advances the address counter until all addresses

have been read out. Currently no attempt is made to halt the readout at

the end of the actual data. The readout of the remaining zeros at the

end of the data field assures that no extraneous bits are being stored.

Data from the memory chips are converted from parallel to serial by the

UART and then fed into the computer on a serial input line.

c) Data processing

In the present design mode, where a discrete change in the input

variable initiates the storage of its occurrence time, the data are pro-

cessed by displaying that time as a date and time of day. This is calcu-

lated by first converting the 16 bit binary word into seconds and then

dividing that into minutes, hours, and days. The time period thus deter-

mined is added to the known zero time of the clock to obtain the real time

at which the event occurred. The zero time is manually set by resetting

the time counter at an accurately known instant. This time is entered

into the program to achieve the desired printout. These data are then

displayed as a sequence of times each later than its predecessor by an

amount of time dependent on the rate of change of precipitation.

2.2 Vertical Motion Measuring System

A vertical motion sensor based upon radiosonde instrumentation was developed at the Utah Water Research Laboratory for measuring vertical velocities typically exceeding about 10 cm s^{-1}. The sensor is carried aloft by balloon and released at any desired altitude, whereupon a parachute controls the fallspeed relative to the airflow (Hill and Woffinden, 1977). The dropsonde method is particularly useful in obtaining vertical motion measurements in regions inaccessible to aircraft.

The parachute is designed similar to that of Lally and Passi (1976) for uniform fallspeed and minimum swaying. Also, ripstop nylon material of low porosity was used to ensure a constant drag. The dimensions of the parachute are such that the package will have a terminal velocity between 4 and 5 m s^{-1}. The shroud lines are made of plastic-covered wire to provide sufficient torque transfer between the parachute and package to prevent twisting and tangling of the lines. Two of the wires are used as part of the release mechanism circuitry.

The release mechanism itself can be actuated in several ways: 1) the pressure contacts are counted, 2) a high-contact reference is chosen, with the lower high-reference contacts severed, 3) a timing device is installed, or 4) a receiver is used for telemetered control. All four of these methods were used during the development phase of the work. Each fulfilled a specific need. However, the telemetering method was found to be the most useful because the place of measurement could be controlled somewhat by making use of the horizontal flow. The cutting device consists of a loop of high resistance wire wound around the tethering line passing through a small plastic cylinder. The tethering line is cut in such a way that the cylinder is recovered with the package.

To avoid collecting ice on the sonde during ascent (especially when the surface temperature is near or above freezing) a thin plastic shroud is placed over the parachute and payload prior to release from the ground. Upon release, the sonde falls out of the shroud completely free of ice and snow. In winter storms, precipitation is not likely to adhere to the package at the cold temperatures at high levels. In situations where icing or wetting is present, any increased fallspeed should be found close to the ground, where such loading would be close to maximum. So far, in two winters' operations there is no evidence of ice loading to alter the fallspeed above the normal limit of accuracy of the measurements. It is recognized that precipitation occurring near or slightly above freezing would adhere to the falling sonde. However, flights are nearly always at temperatures below freezing, so only occasional measurements close to the surface would have to be eliminated from analysis.

So far, the measurements made indicate that upward motion is usually greatest at an elevation of about 400 to 800 m above the mountaintops; velocities in this region are often about 1 m s^{-1} and occasionally approach 2 m s^{-1}. Well below mountaintop levels the vertical motion is usually less than about 0.25 m s^{-1} except when downdrafts occur and the velocity reaches -1 m s^{-1} and sometimes stronger downdrafts occur (Hill, 1978).

These measurements show that ice loading in subfreezing temperatures is not a substantial problem. It is well recognized that balloons passing up through precipitation just below the freezing level may suffer large amounts of ice loading and, therefore, affect the entire ascent rate thereafter. With a shroud protected ascent and subsequent release of a parachute dropsonde in a subfreezing environment, the situation is greatly different.

3.0 ANALYSIS AND EVALUATION OF DATA

Analysis and evaluation of data are concerned with several sets of measurements: precipitation, ice nuclei, supercooled water, ice crystals, vertical motion, and other information such as obtained from rawinsondes and National Weather Service charts. During the months of February and March, 1978, there were ten 4 h periods which were studied intensively.

A summary of available data by events for the key parameters is given in Table 1. It is evident from this summary that the most complete data were obtained in the last half of the study period. This was due to

Table 1. Measurement of key parameters, Feb. and Mar., 1978.

Event	Date, Time* MST	# Precip Gages With Data	# Vertical Motion Soundings	Super-cooled Water	Ice Nuclei	Mee Ice Crystals	AgI Released	Ice Nuclei Plume Detected
1	Feb. 02 0934-1319	0	0	Yes	Yes	Yes	Yes	Yes
2	Feb. 07 2200-2348	0	0	Yes	Yes	Yes	No	-
3	Feb. 09 1735-2059	0	0	Yes	Yes/No	Yes	Yes	-
4	Feb. 15 1459-1837	0	0	Yes	Yes	Yes	Yes	Yes
5	Feb. 27 1040-1355	5	1	Yes	No	Yes	Yes**	-
6	Mar. 01 1518-1902	7	2	Yes	No	Yes	Yes**	-
7	Mar. 03 1829-2117	6	3	Yes	Yes	Yes	Yes**	Partial
8	Mar. 05 1455-1840	9	3	Yes	Yes	Yes	Yes	Partial
9	Mar. 12 1429-1805	9	3	Yes	Yes	Yes	No	-
10	Mar. 13 2027-0012	8	3	Yes	Yes	Yes	Yes	Yes

*Time period cloud physics aircraft on measurement track.

**Seeding material released but may have missed target (line of gages, cloud physics aircraft flight track).

the fact that the research measurement program was primarily in a develop-
ment stage. However, Events 1 and 4 turned out to be of value because of
possible in-cloud responses to seeding. In the last column of Table 1
it is noted whether or not the seeding plume was detected. A dash mark
is used to indicate either no seeding material was released, or the NCAR
counter was inoperative. Thus, only five events remain in which the
seeding plume could have been found. In three events a plume was found,
in one the main portion of the plume missed the target line, and in
another, the plume apparently remained below the normal flight altitude
(13,000 ft) of the cloud physics aircraft, but the plume was found during
descent to Logan. The most complete set of data was obtained for Event
10. For this reason we shall present data for this event first.

3.1 Detailed Analysis of Event 10

Event 10 covered the period from 13 March 1978 from 2000 to 0012.
In this period a weak cold front approached the measurement area, and
according to the NWS surface charts the front passed about 0030. The
surface weather chart is shown for 2300 MST in Fig. 3. This event was
a somewhat unstable one; a thunderstorm was reported at Salt Lake City
and Hill AFB from 0000 to 0100 MST. No thunderstorms were noted in the
measurement area, but some cloud buildups were observed.

a) Precipitation

Precipitation over the line network is plotted on a "standard"
graph in Fig. 4: east is to the right and the position of the 15 gages
is shown along the x-axis; time increases toward the top of the graph.
The aircraft flight path back and forth across the mountain is shown
and the expected path of seeding material is also shown. Each small
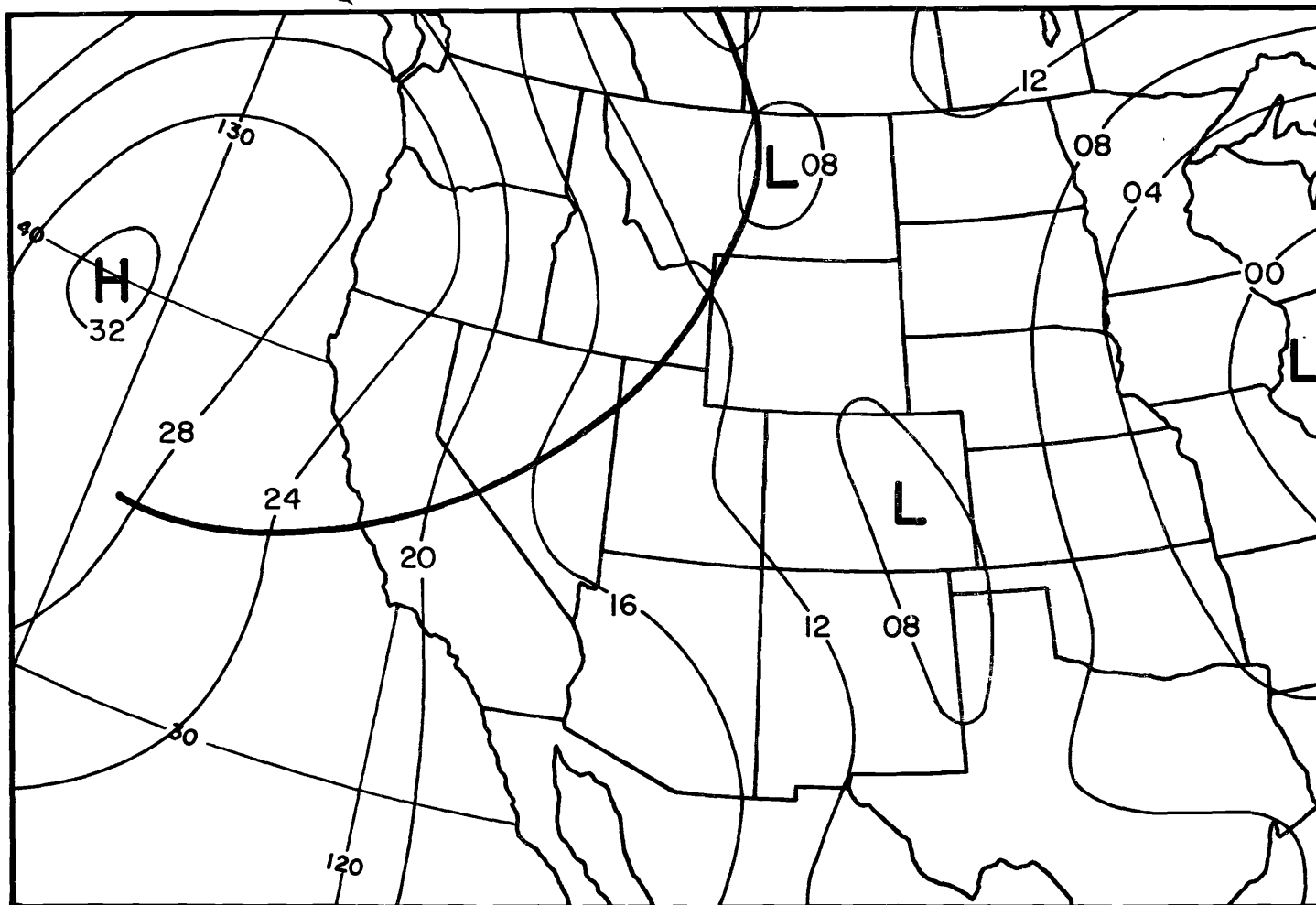
SURFACE CHART
13 MARCH 1978 2300 MST

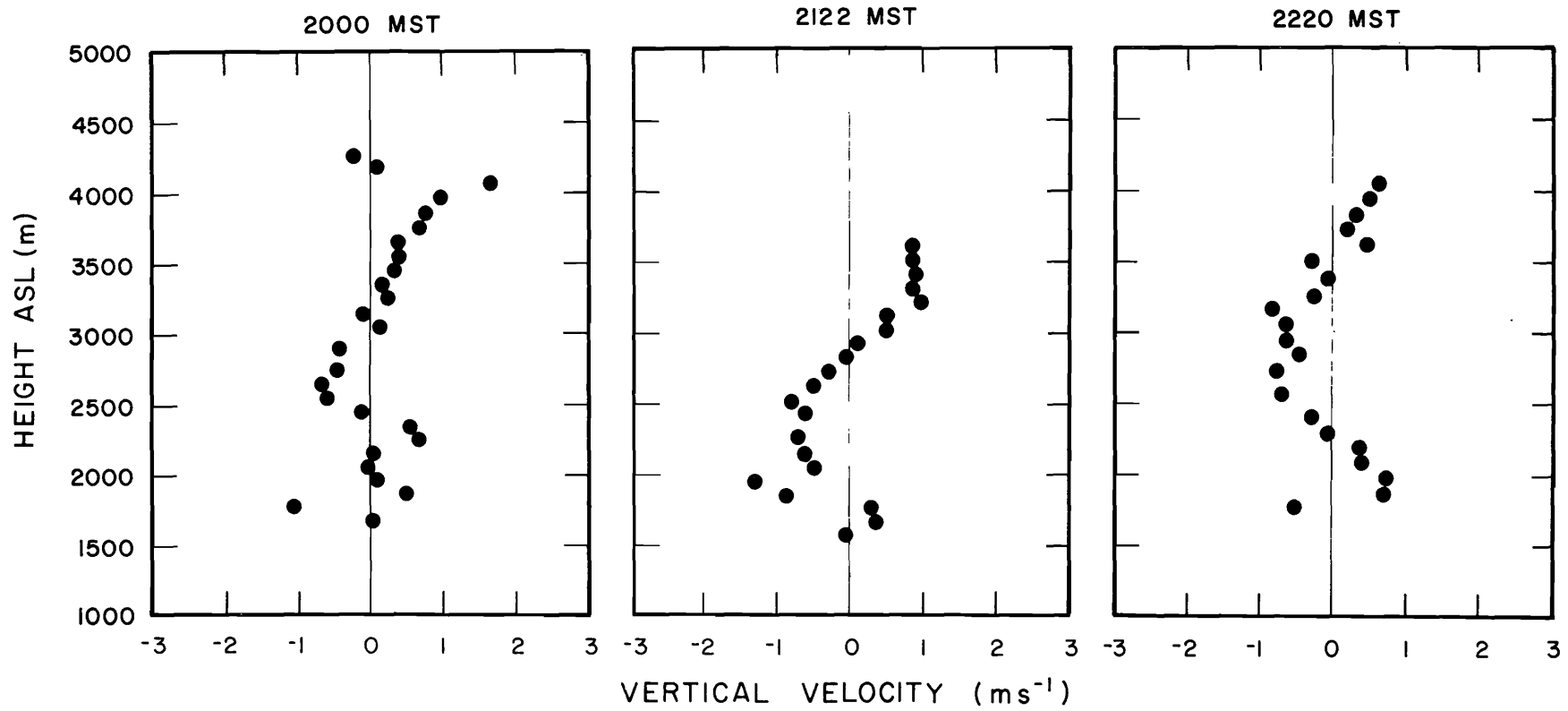Fig. 3. Surface weather chart; Event 10, 2300 MST, 13 March 1978.

Fig. 5. Vertical motion (m s^{-1}) during Event 10, 13 March, 1978.

value of about 0.75 m s^{-1}. Just above ground the motion tended to be positive. As pointed out in previous work, downward motion can be initiated by precipitation drag, especially when the vertical lapse rate of temperature is neutral or unstable (with respect to moist processes).

There are some sequential changes in the structure of vertical motion which may be of interest. The first sounding is just prior to the period of precipitation which reached the ground; the relatively weak downward motion may be associated with the initial occurrence of precipitation at the altitude between 2500 and 3000 m. By the time of the next sounding the downward motion had become more intense and deeper. This downward motion is apparently due both to precipitation drag and evaporation. Because precipitation reaching the ground is at a very low rate by this time, the downward motion is likely due primarily from evaporation. Precipitation is evidently being formed in the updraft above 3 km and evaporating in the layer below. A similar picture is found for the third sounding, except there has been an upward expansion of the downdraft, a weakening of the updraft above, and a return of a low level updraft. This sequence agrees well with the findings of last year's work.

c) Ice nuclei

The seeding aircraft released seeding material between 2115 and 2215 MST and was expected to drift with an eastward component according to the path as shown in Fig. 6. The background ice nucleus count was the highest of the 10 events. The artificial ice nucleus plume itself was not as clearly distinguishable as in other events. However, the three patches
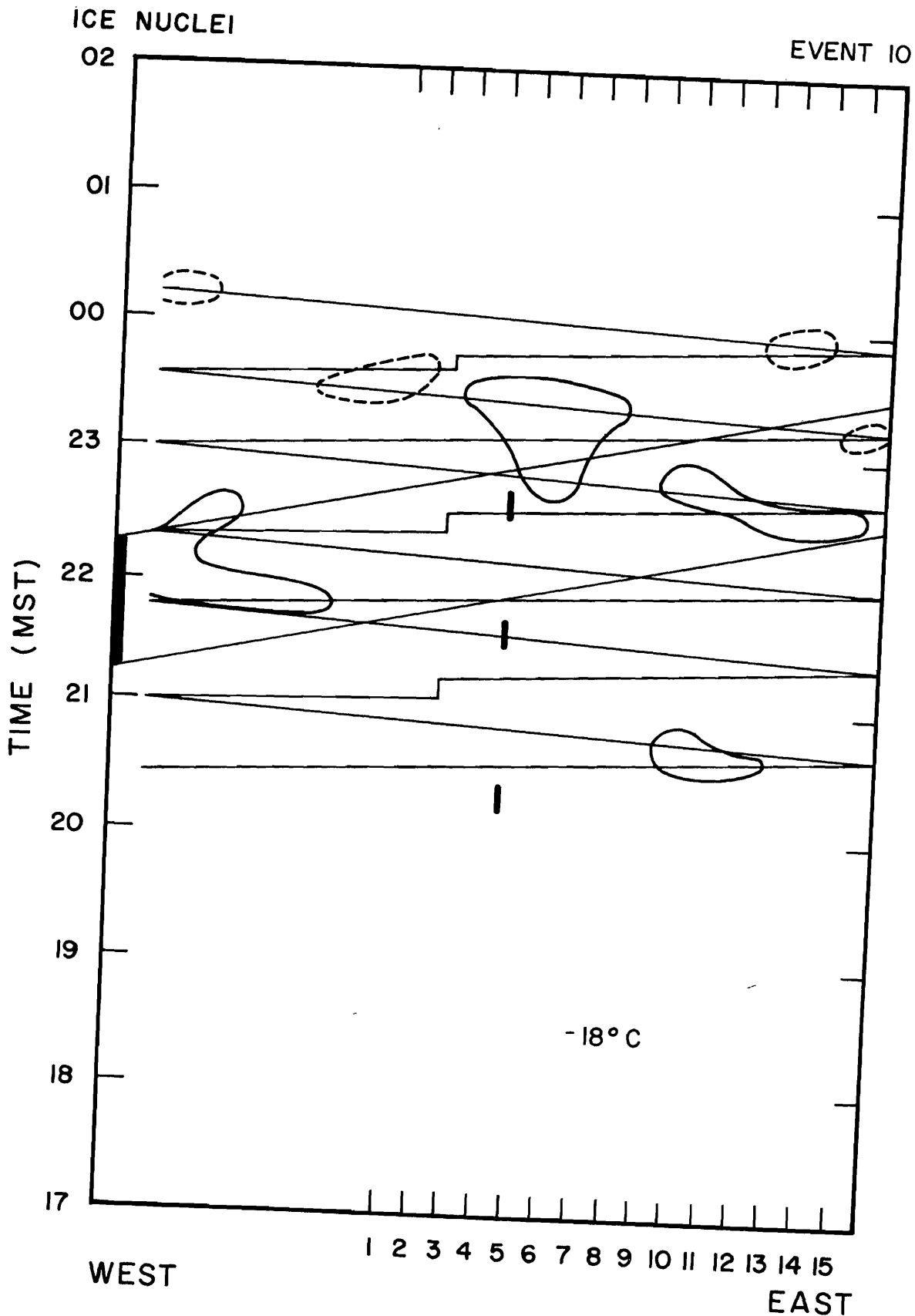
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Fig. 6. Ice nuclei, Event 10. 10 per liter enclosed by solid curve. Temperature at flight level (13,000 ft) is noted and release of seeding material is indicated by the heavy bar.

of high concentrations of ice nuclei shown in the figure are with little doubt associated with the silver iodide plume. The overall ice nucleus concentration was generally higher after the release of material than before. Evidently the material was widely scattered after release. The lack of a more or less continuous plume in the expected path is probably due to convection. This was also the most unstable event, with severe turbulence reported over Malad at the end of the event, and thunderstorms reported at Hill AFB and Salt Lake City, also toward the end of the event. The temperature at the seeding altitude of 12,000 ft was -16°C.

d) Supercooled water

Supercooled water as indicated by the Rosemount icing detector is shown in Fig. 7. The areas with some detectable supercooled water are outlined; areas with amounts estimated to exceed 0.2 gm m^{-3} are shaded. The temperature at the altitude of the cloud physics aircraft averaged -18°C. Substantial amounts of supercooled water existed throughout most of the event mainly over the higher terrain. The termination of substantial supercooled water amounts after about 2330 was due, at least in part, to the influx of drier air. However, the fact that supercooled water existed in the general presence of the seeding material is somewhat surprising, especially at a temperature of -18°C when the effectiveness of silver iodide should be high.

e) Ice particles

The Mee ice particle counter is sensitive to the relatively large ice crystals rather than the newly formed smaller ones less than about 50 μ diameter. Measurements of ice crystals are shown in Fig. 8 for Event 10. As with supercooled water, the areas of measurable ice
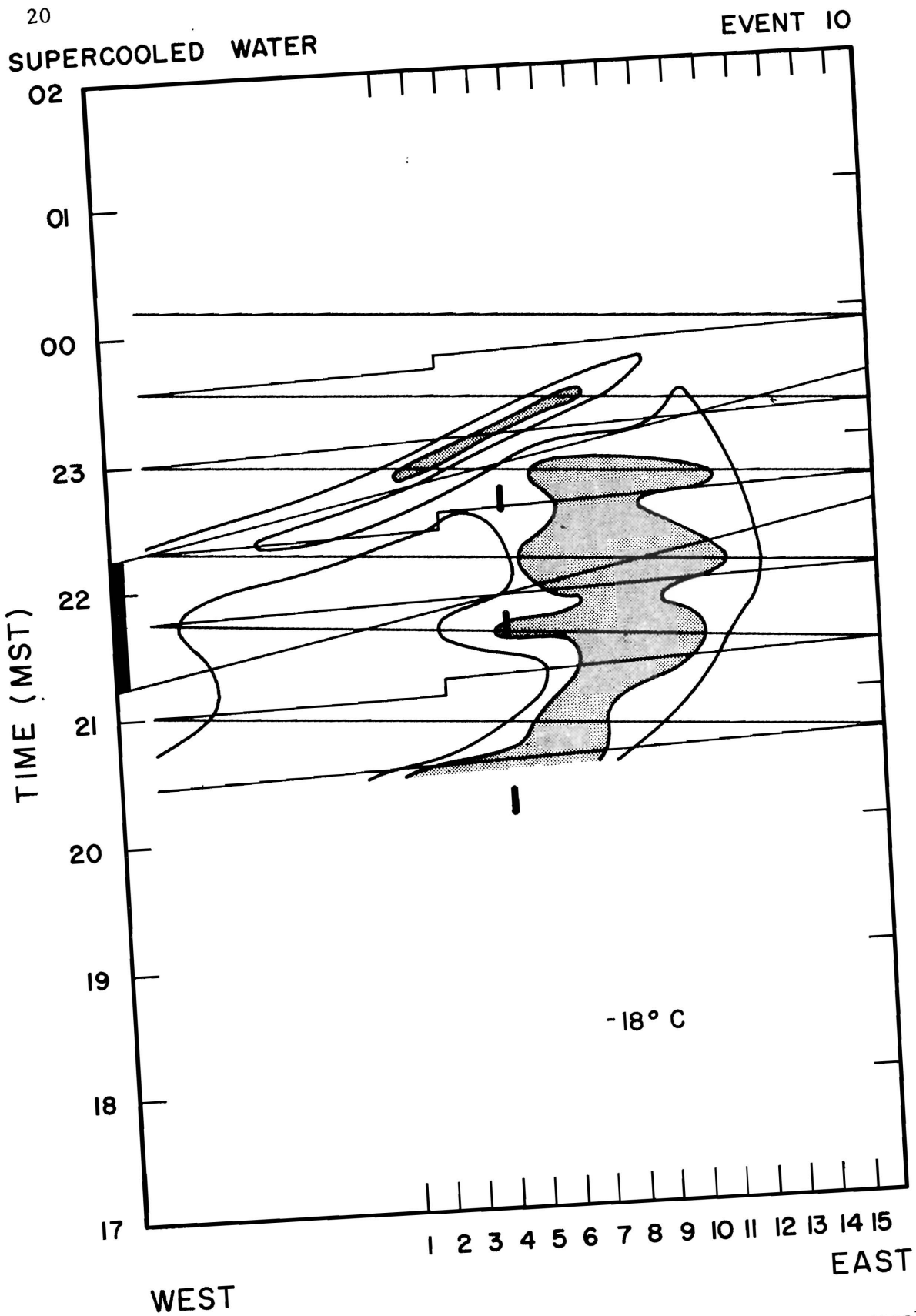
SUPERCOOLED WATER

EVENT 10

Fig. 7.   Supercooled water, Event 10. Minimum detectable supercooled water enclosed by solid curve; .2 g m^{-3} or greater is shaded area.
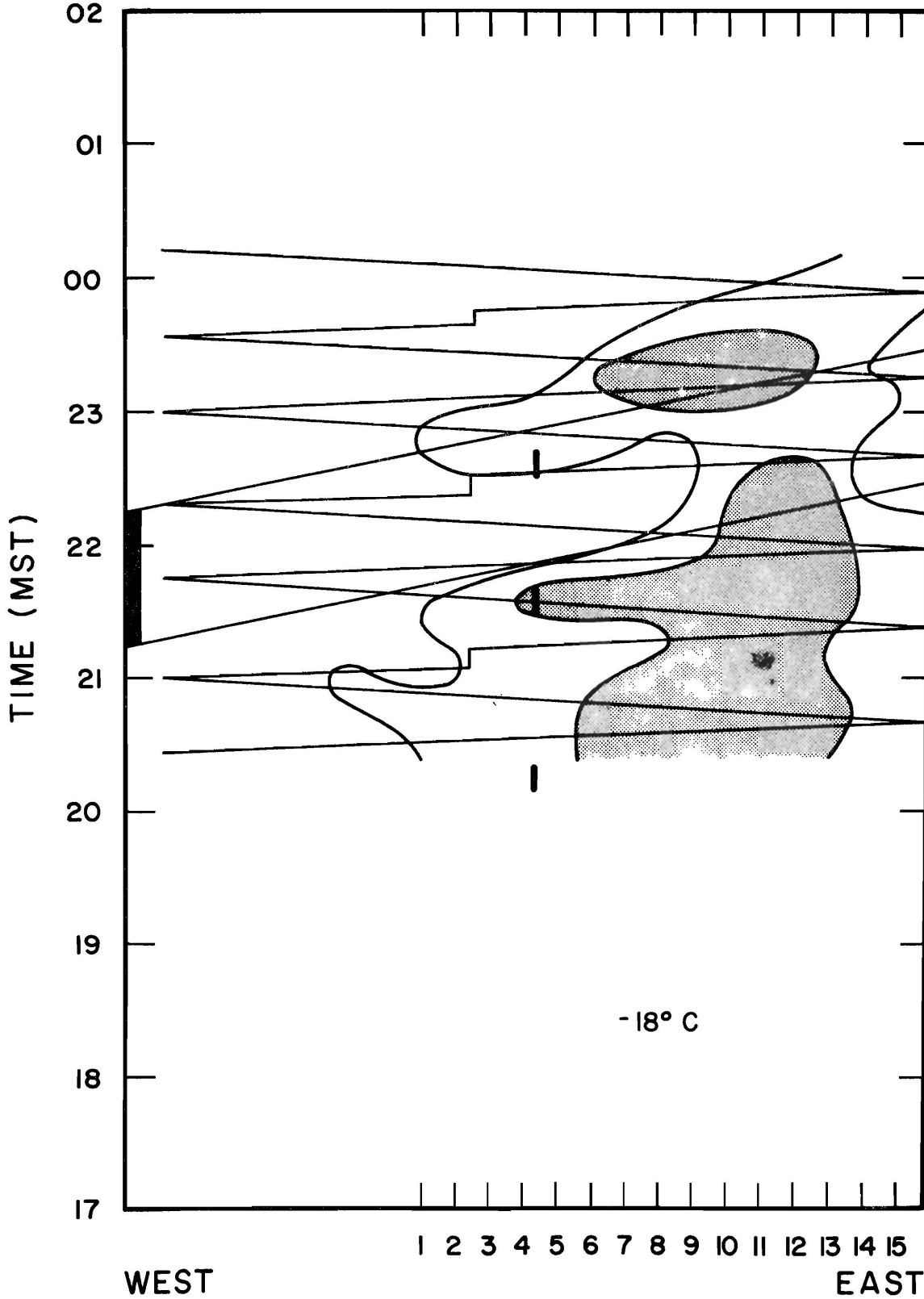
Fig. 8. Ice particles, Event 10. Minimum detectable ice particle concentration enclosed by solid curve; 100 x m^{-3} or greater is shaded area.

crystals are outlined, and areas with amounts estimated to exceed 100
m^{-3} are shaded. The high concentration at the beginning of the event
is concurrent with the cell/band of precipitation shown in Fig. 4.
Similarly the isolated patch of ice crystals toward the end of the
event over the mountains is concurrent with the isolated patch of pre-
cipitation. Thus, we have a consistent pattern between the pattern of
ice crystals as measured from the cloud physics aircraft and precipita-
tion as measured by the line network of gages.

When the pattern of supercooled water is compared with that of ice
crystals, we find an interesting feature. That is, supercooled water
is produced over the mountains between gages 5 through 10 or 11, with
an average position of slightly less than 8. Gage 8, as shown in Fig. 1,
is very near the crest of the Bear River Range. On the other hand, ice
crystals are found between gages 6 or 7 and 13 with an average position
slightly less than 10. As one might expect ice crystals grow at the
expense of supercooled water and are thus found further downstream on
the average, by about 4 km distance in this event. With a wind speed at
13,000 ft (4 km msl) of 40 kts, this difference in distance is equivalent
to only about 200 s. This time duration is generally below that required
for glaciation at $-18^{\circ}C$. In such a circumstance some of the supercooled
water evaporated on the lee side of the mountain, rather than be converted
to precipitation. Although a seeding opportunity may have existed, the
short duration of the disturbance precludes any definitive assessment of
seeding effects.

3.2 Analysis of Selected Aspects of Events 1 Through 9

As with the detailed analysis of 3.1, the basic variables for this analysis are precipitation, vertical motion, and concentrations of three cloud variables, supercooled water, ice nuclei, and ice crystals. Also, rawinsonde data and NWS data are available for analysis.

a) Precipitation

Although the winter was on the whole a wet one, storms passing through the area during the period of study were rather weak. In addition, other factors such as the timing of when to make measurements, or the time of day or week, resulted for the most part in the sampling of weak storms or weak portions of storms. As a means of obtaining a qualitative assessment of precipitation in each event the time variation of precipitation for gage 7 is shown for each event in Fig. 9 (except gage 6 is used for Event 5 because of missing data).

Only in Event 5 was precipitation widespread during the period of airborne measurements. However, the supercooled water concentration was very low. Ice particle concentrations were light at the aircraft altitudes, which in this event ranged from 4 to 5 km (13,000 to 17,000 ft). Thus, the precipitation efficiency for this event was high, i.e., substantial precipitation, near zero supercooled water concentration. The more interesting events from the point of view of seeding effectiveness are ones with high supercooled water concentrations.

b) Vertical motion

Vertical motion measurements were made as follows: Events 1-4, none; Event 5, one; Event 6, two; and Events 7-10, three. The strongest upward vertical motion was usually found above mountaintop levels by about 2,000
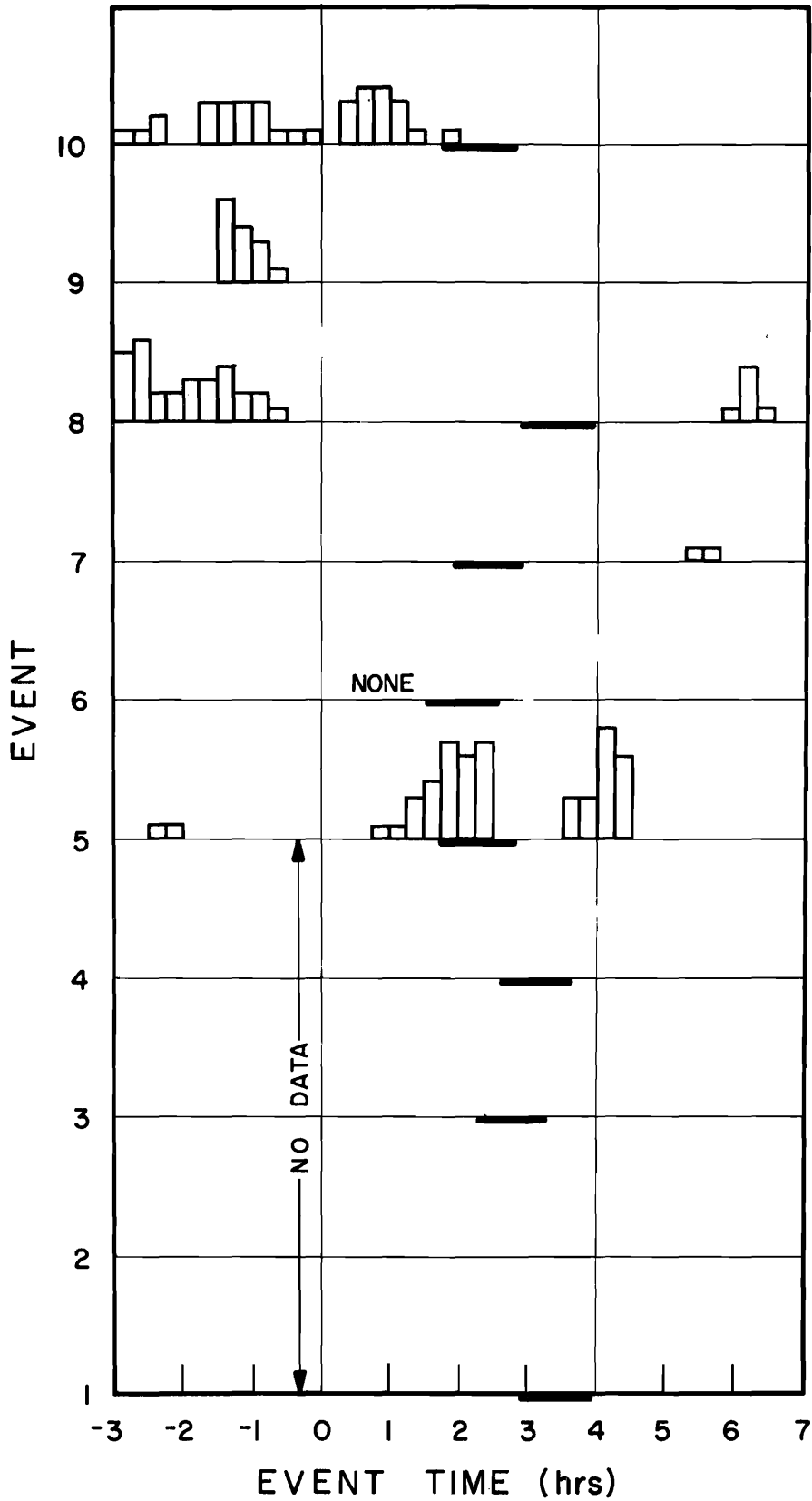
Fig. 9. Time variation of precipitation at gage no. 7,
Events 1 through 10. (Event 5 is gage no. 6.)
Full scale for each event is .10 in., and amounts
are shown over 15 m intervals.

ft or about 3.7 km msl. These maximum velocities were usually less than

1 m s^{-1} for the six events for which measurements were available, except

for Event 5 in which the upward motion exceeded 2 m s^{-1} at 3.7 km msl.

The only substantial period of strong downward motion measured was during

Event 10, previously discussed. Then the downward motion reached around

0.75 m s^{-1}. While vertical motion of these magnitudes (upward and down-

ward) is of paramount importance in determining the formation of new

precipitation particles, insufficient data exist at the present time to

develop conceptual models covering a variety of storm types. However, so

far we have discovered in previous work the existence of strong precipita-

tion forced downdrafts associated with neutrally stable or unstable

temperature lapse rates. One reason the overall picture is so complicated

is that the field of humidity itself is highly variable with time. What

is needed are measurements of vertical motion over entire storm periods

so that the pattern of vertical motion becomes clearer than at present.

c) Supercooled water, ice nuclei, and ice crystals

Supercooled water observations were made in all ten events. In

three of these, substantial amounts were found. In a fourth event (Event

2) there was also supercooled water present in substantial amounts but

the flight was aborted after about an hour, because the seeding aircraft

was not dispensing material successfully. The three events with high

supercooled water concentrations are shown in Fig. 10. In Event 7, the

concentration was so high that the flight was aborted due to heavy

accumulation of ice on the airframe. In the other two events there is

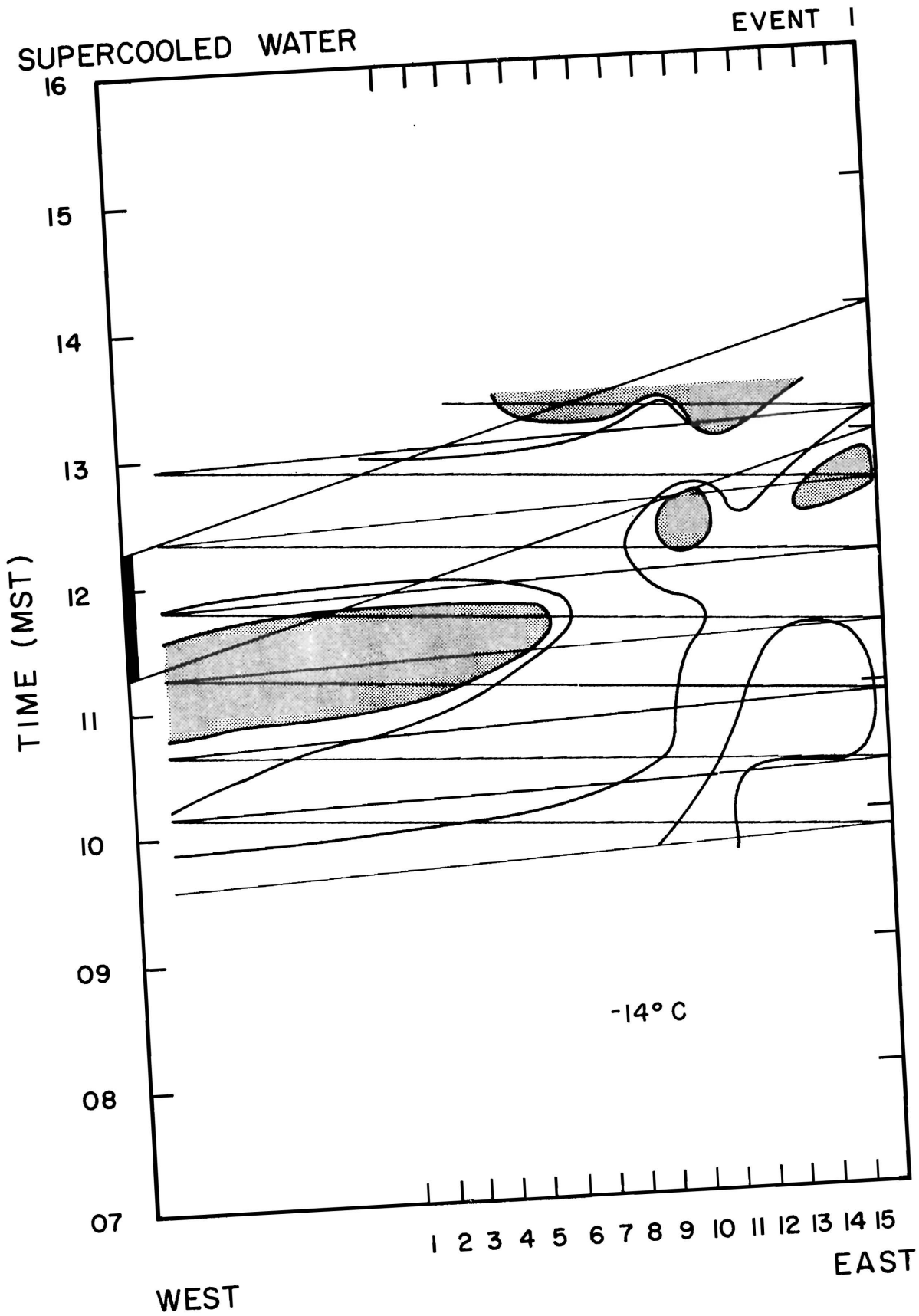an indication that seeding may have reduced or eliminated the super-
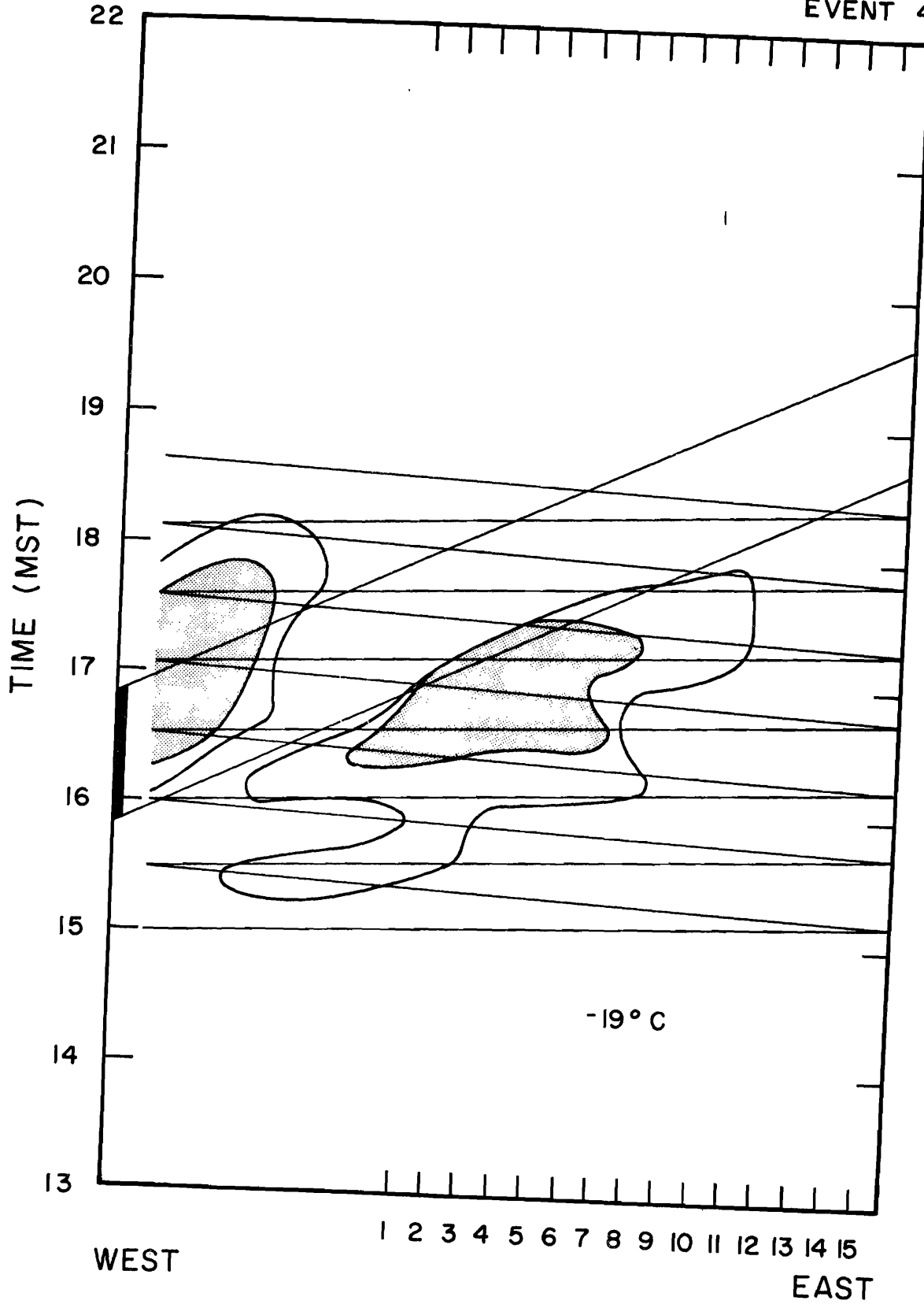
cooled water.

SUPERCOOLED WATER

EVENT 1

Fig. 10. Supercooled water, a) Event 1. (Data as in Fig. 7.)

Fig. 10. Supercooled water, b) Event 4. (Data as in Fig. 7.)
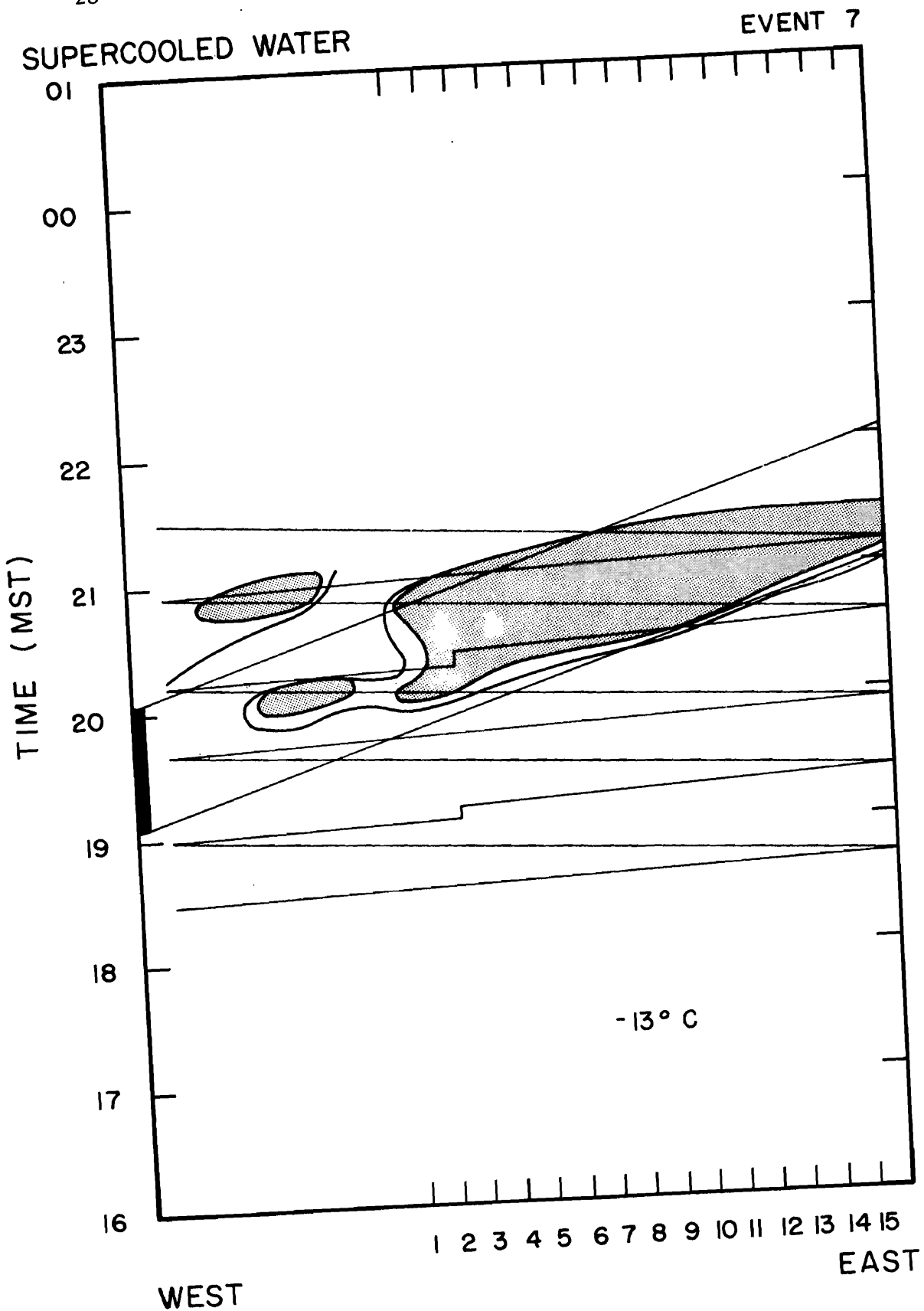
SUPERCOOLED WATER

Fig. 10. Supercooled water, c) Event 7. (Data as in Fig. 7.)

In contrast, the supercooled water of Event 7 exists primarily in
the path of the seeding material. The presence of large amounts of
supercooled water in the path of seeding material may be purely coinciden-
tal, but the possibility exists that a strong dynamic effect took place.
Vertical motion was generally positive with values reaching 30 to 60
cm s^{-1} just above mountaintop levels, but at the time of the high super-
cooled water amounts the vertical motion sounding extended only to 3.7 km
(11,000 ft), where the upward vertical motion was around 60 cm s^{-1}.

Pilot reports from surrounding locations indicate that light-to-
moderate or moderate icing was widespread in southern Idaho and northern
Utah during the period of Event 7. Thus, we are inclined to believe
that the occurrence of high supercooled water concentrations along the
expected path of seeding material was coincidental, inasmuch as other
reports of moderate icing were made in the surrounding region. The
question does remain, then, as to why the seeding material did not con-
vert the supercooled water to ice and cause precipitation. On descent
over Cache Valley to an altitude of 2,750 m (9,000 ft) the measurements
from the cloud physics aircraft indicated only a very small concentration
of ice particles. Also, only a trace of precipitation was observed at
Cornish at around 2045 MST, while no measurable precipitation was observed
over the whole network of gages at any time while the aircraft was on
track.

Inspection of the seeding plume as shown in Fig. 11 shows that
seeding material apparently was released and followed the expected track,
in general. However, the material was found in separated patches. The
reason appears to be that the flight path of the seeding aircraft was

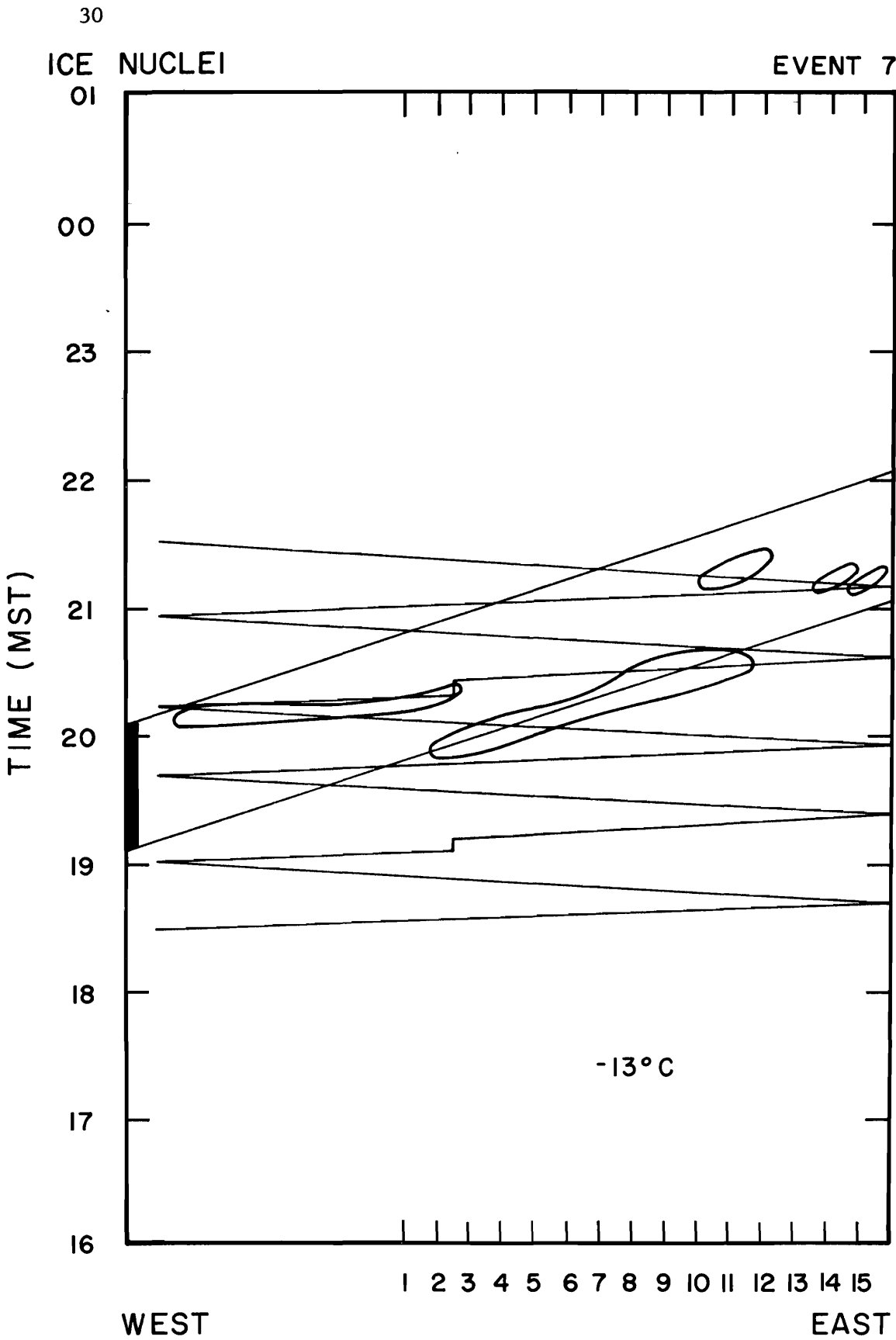ICE NUCLEI   EVENT 7

Fig. 11. Ice nuclei, Event 7. (Data as in Fig. 6.)

such that only short pulses of seeding material reached the vicinity of the cloud physics aircraft. This may be seen more clearly from Fig. 12 in which a plan view of the area is shown. The seeding material was released from track C4. Only from the southern extremity of the track could seeding material reach the measurement area. Even then a slight error in wind could account for a complete miss. The seeding aircraft passed over the southern end of the track three times. It is worthwhile to note that where seeding material actually exists the supercooled water tends to be reduced or absent. However, the overall lack of ice crystals is evident by the fact that supercooled water was still present well beyond the mountain barrier crest.

Vertical motion in this event at seeding altitude was about 0.5 m s^{-1}. If the upward motion extended a considerable distance westward, say 20 km, then the bulk of seeding material would have been carried to an altitude of around 4.5 km (14,000 to 15,000 ft). At this altitude the seeding material would be carried to the north of the line of measurements.

When all of the foregoing discussion is considered, it is most probable that the occurrence of supercooled water in large amounts just at the expected time of the passage of seeding material was coincidental rather than from some dynamic seeding effect, and that most of the seeding plume itself actually missed the target area.

In the other two events (shown in Fig. 10), in which supercooled water occurred in substantial amounts, seeding effects are apparently present. Measurements of the ice nucleus concentration in these two events are shown in Fig. 13. It is clear that artificial ice nuclei
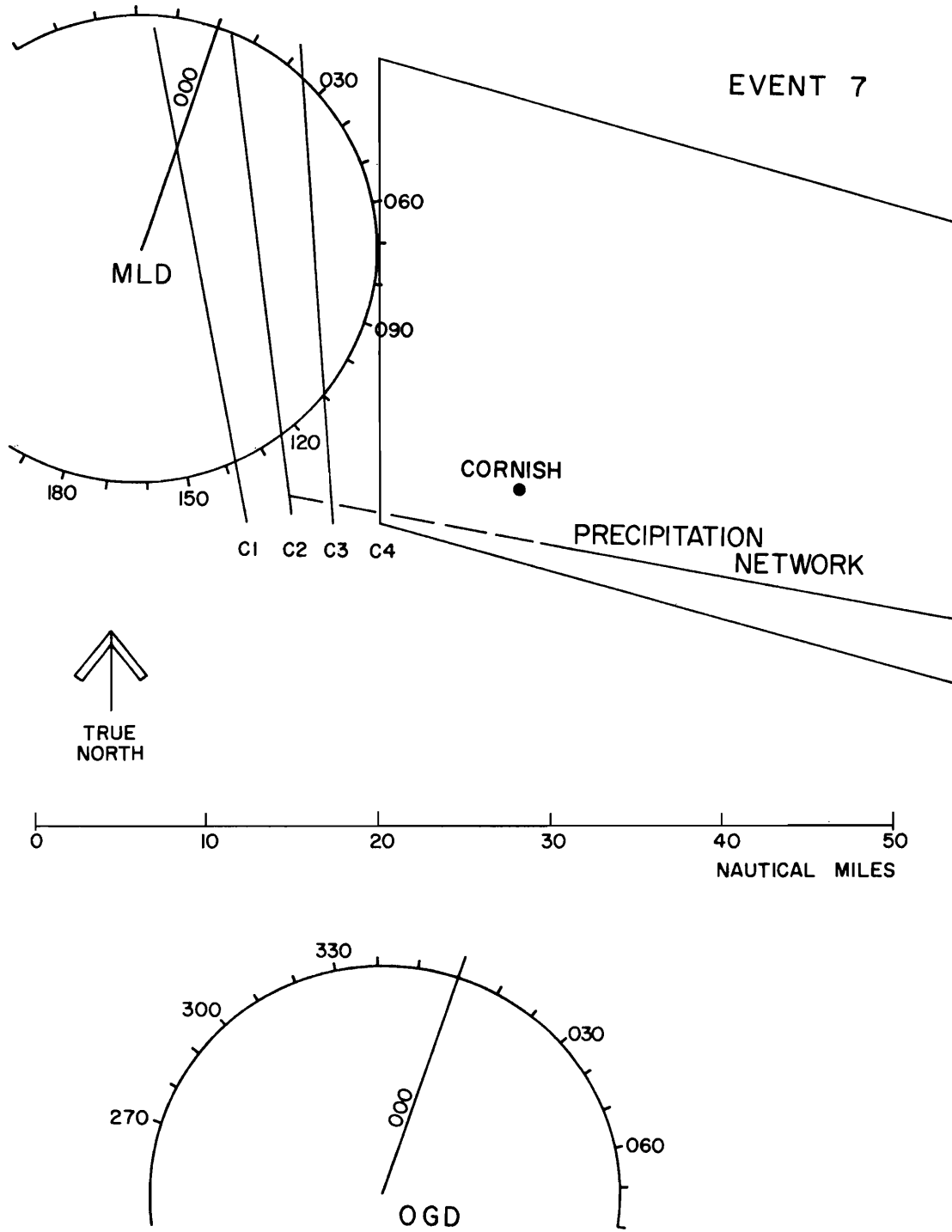
Fig. 12. Expected path of seeding material, Event 7.
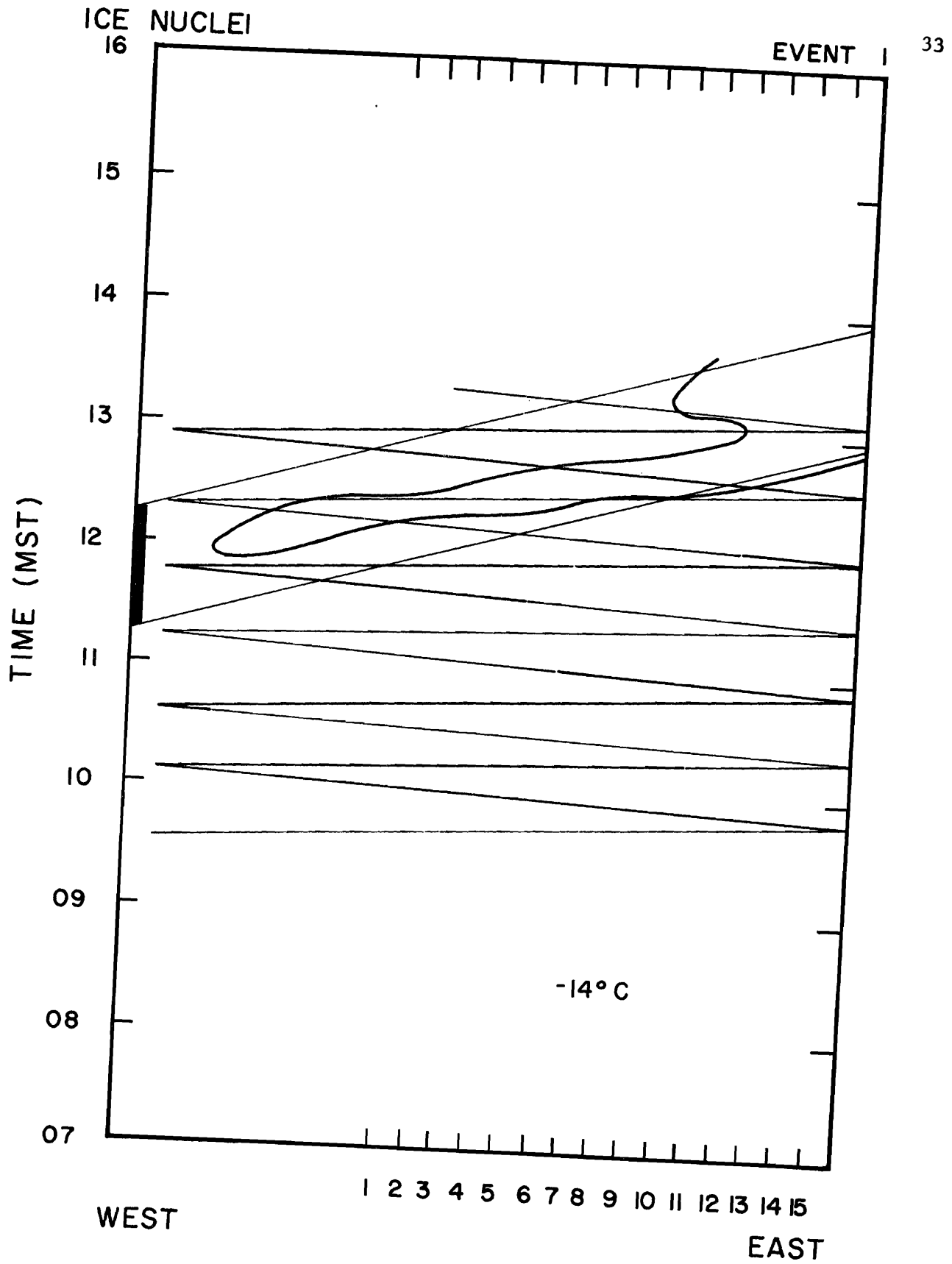
ICE NUCLEI

EVENT 1

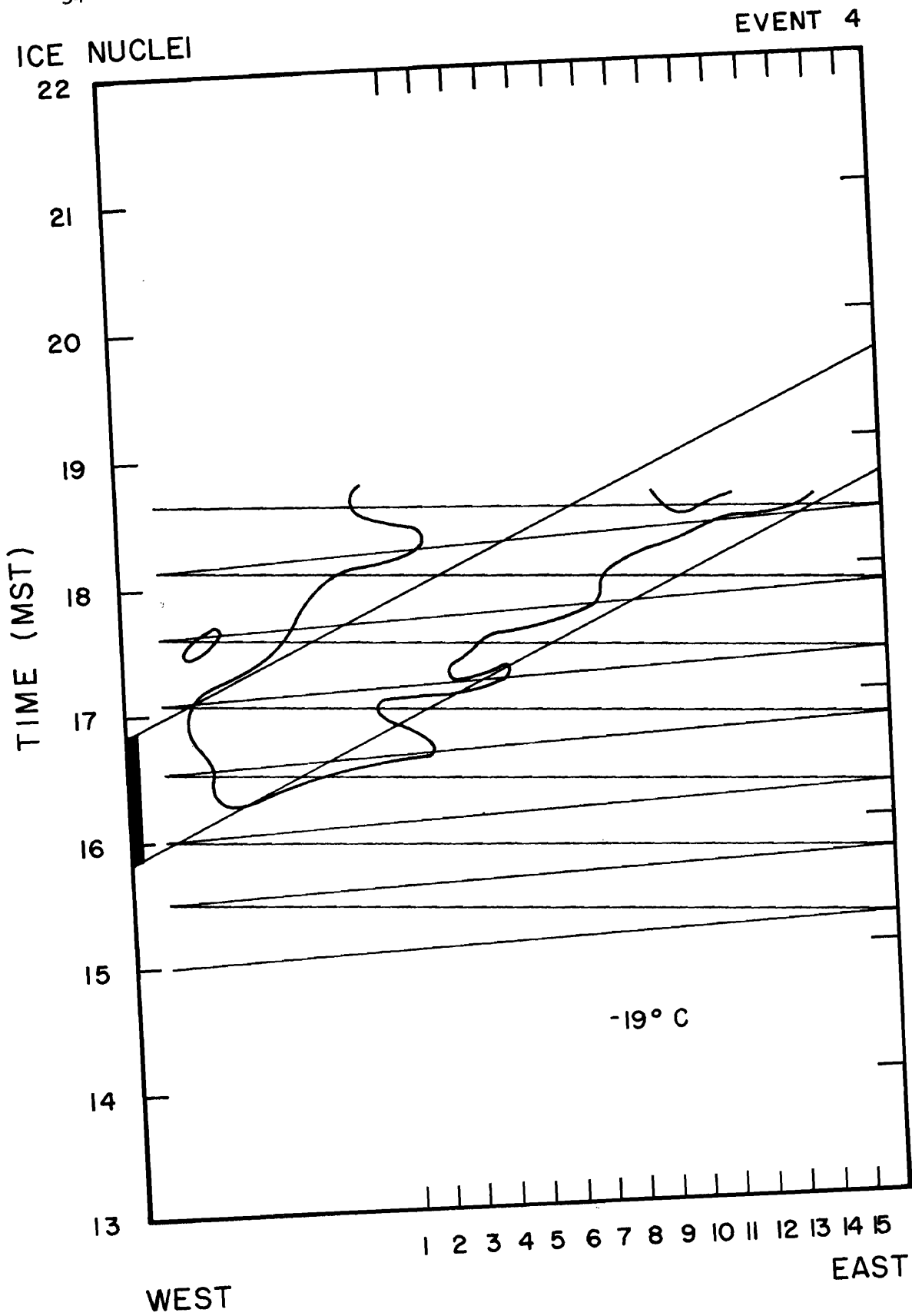Fig. 13. Ice nuclei, a) Event 1. (Data as in Fig. 6.)

Fig. 13. Ice nuclei, b) Event 4. (Data as in Fig. 6.)

followed approximately the path determined by the wind flow near seeding altitude.

Event 1 was characterized by a rather thin cloud layer at around 12,000 to 13,000 ft elevation, with a cloud top temperature of about -13°C. Unglaciated cumulus clouds formed on the lee side of the mountain range toward the end of the event. No ice was found by the cloud physics aircraft; any ice produced by the seeding probably would have been found below rather than at flight altitude. Precipitation data were not available in this event; none was observed visually at the rawinsonde site.

Event 4 was characterized by clouds in two or three layers; the cloud top temperature as estimated from the rawinsonde data was about -22°C, although higher thin clouds were present. As in Event 1, no ice was found except for occasional counts over the extreme western side of the measurement area.

However, visual observations of ice crystals were made throughout the flight; these observations indicate that ice crystals were present during much of the event, as shown in Fig. 14. Here each report is marked according to the intensity of crystals as very light, VL; light, L; and light to moderate, LM. Other visual reports are also included such as "in and out of clouds," I/O; and "on top of clouds," O/T. From these observations two things are evident; first, ice crystals grew at the expense of supercooled water, especially along the seeding plume, and second, these ice crystals being newly formed were too small to be detected by the Mee ice particle counter. In not very deep or active clouds the growth of ice crystals is too slow to be detected by the Mee instrument very soon after being formed.

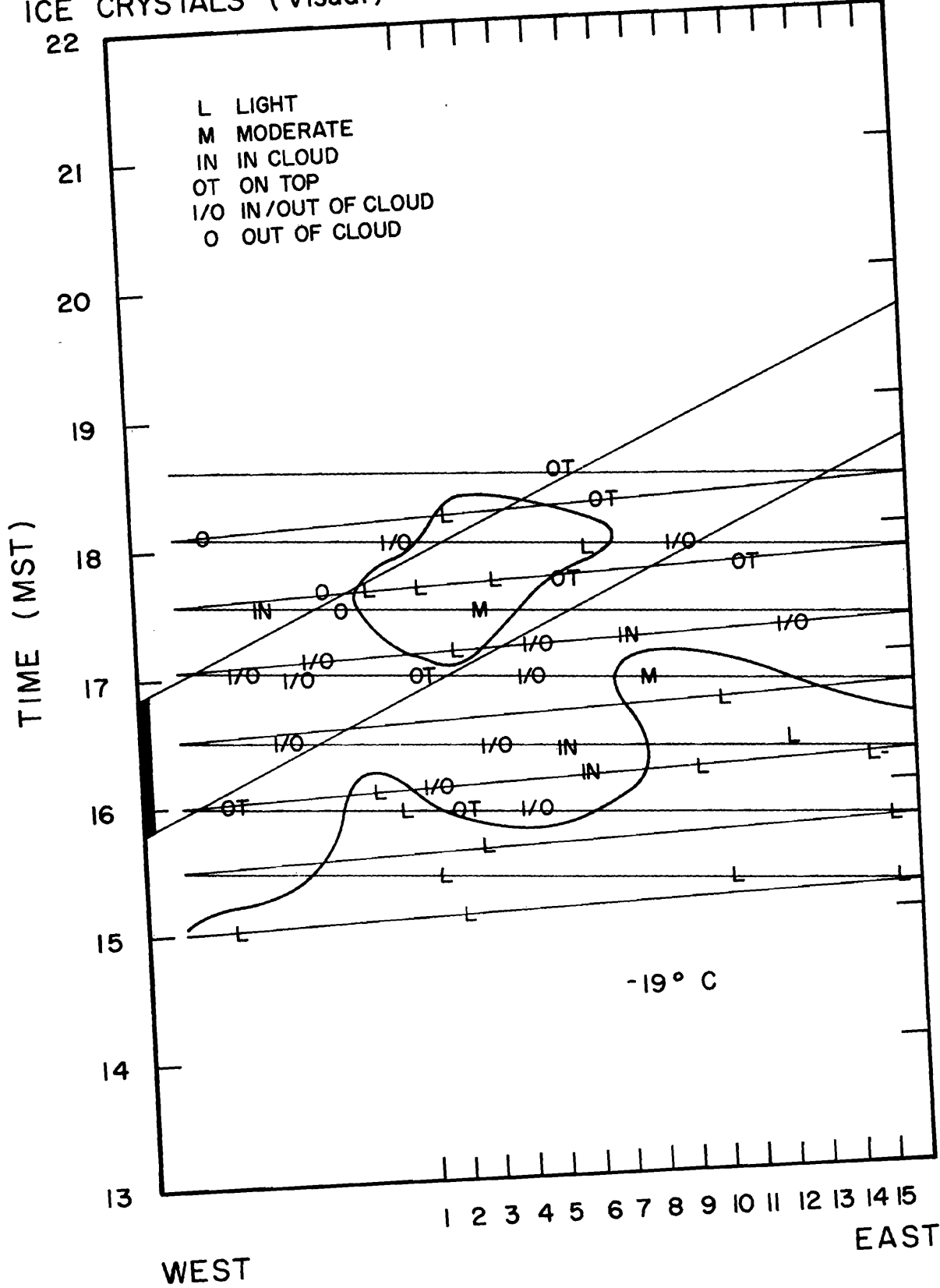ICE CRYSTALS (Visual)

EVENT 4

Fig. 14. Visual observations of ice crystals, Event 4; see text for description of observations. Contours enclose regions of visually reported ice crystals.

By the time such particles reach the ground their size may be substantial. Precipitation data were not yet available by the time of this event. Observations at the rawinsonde site and by ice crystal replications near the site of gage 10 were made. It is clear that precipitation did occur, but no relationship to possible seeding effects was evident.

4.0 CONCLUSIONS

A summary of conclusions derived from the work reported herein is as follows:

1. Precipitation as measured by a network of modified heated tipping bucket gages (with heat control) appears to be satisfactory. Detailed comparisons of these gages and other types are planned for next winter in order to fully document any differences in results. The solid state memory device has been developed to a research operational stage. That is these devices can be operated successfully in a research environment. Changes to be made in the near future should facilitate their use by others not necessarily familiar with design details. The line network of 15 gages is evidently a useful configuration inasmuch as the pattern of precipitation often changes drastically from the upwind valley to the mountain crest and beyond.

2. Vertical motion measurements are providing additional insight into the dynamics of orographic precipitation. Series of measurements over the whole storm periods need to be made in order to better understand the storm dynamics. For example, supercooled water probably is found in abundance mainly within updrafts. So far our vertical motion measurements suggest that most of the updrafts are above mountaintop levels, typically 12,000 ft msl.

3. Supercooled water measurements are made by a Rosemount icing detector and by a Johnson-Williams hot wire device. Measurements clearly show supercooled water over the mountain barrier (at 13,000 ft)

is often significantly more abundant than upwind. Reduction of super-
cooled water by seeding is indicated but not conclusive at this time.

4. Ice nuclei measurements by an NCAR counter adequately identify
the presence of artificial seeding plumes. Reliability of operation of
the instrument can evidently be a problem. However, operation has been
more successful this past winter than the one before. Operation was
successful on seven occasions and unsuccessful on three.

5. Ice crystals as measured by the Mee ice particle counter are
detectable when they are precipitation size. Newly formed smaller ones
go undetected. It would be of considerable benefit to the research
effort if an instrument capable of detecting small ice particles were
added. Presumably this would be one of the Knollenberg probes.

REFERENCES

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