NASA CR-315

NASA CONTRACTOR REPORT

THE MOUNTAIN WAVE

by Henry T. Harrison

Prepared under Contract No. NSR 33-026-001 *by*
FLIGHT SAFETY FOUNDATION
New York, N.Y.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1965

NASA CR-315

THE MOUNTAIN WAVE

By Henry T. Harrison

Prepared under Contract No. NSR 33-026-001 by
FLIGHT SAFETY FOUNDATION
New York, N.Y.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $3.00

CONTENTS

PREFACE

The report was prepared by the Flight Safety Foundation, Inc., New York, N. Y. under NASA contract No. NSR 33-026-001 as part of FSF Project CAT to assist NASA in keeping abreast of research and development projects directed toward the alleviation of problems posed by flight in clear air turbulence (CAT).

The scope of this contract includes:

(1) Forecasting of CAT

(2) Principles of CAT detection

(3) Devices for CAT detection

(4) Incidents of CAT penetrations of drastic nature

(5) Effect of CAT on airline operation

These studies on the mountain wave type of CAT were made by Henry T. Harrison, Consulting Meteorologist, under the direction of M. Gould Beard, Director, Flight Operations Research, of the Flight Safety Foundation, Inc.

THE MOUNTAIN WAVE

by

Henry T. Harrison

FOREWORD

Aircraft experience four basic types of turbulent air:

1. Convective
2. Wind shear
3. Low level orographic
4. Mountain wave

Synoptic meteorologists will recognize how different the situations are under which those four types occur, yet the unfortunate circumstance is that each is capable of generating turbulence outside of clouds "in the clear". The result is that there is a certain tendency to categorize all turbulence outside of clouds as a unique weather phenomenon. This has been true in the areas of analysis, forecasting and reporting, and sometimes even research.

While strong mountain wave activity is relatively rare at turbojet cruising levels, it happens often enough to warrant attention. The monumental Bishop Wave Project yielded useful knowledge about the mountain wave in this country but left a number of questions unanswered. Among these was the uncertainty about how much of a hazard or an annoyance the wave would prove to be for jet aircraft operating above 25,000 feet. Kuettner's studies at Bishop did suggest that a wave can occasionally break down into a chaotic state of turbulence up to extremely high levels but it was not determined where and when this will happen. Since that time, most of the research in this country has been in the area of empirical forecasting methods developed by the airlines and by the Air Weather Service. These forecasting methods have been helpful but have fallen short of providing a complete answer, mainly because they have been limited to a few well known wave locations like Bishop, Reno, Helena, Denver and Yakima.* In Europe some useful contributions have come from Larsson in Sweden, Bérenger and Gerbier in France, Förchtgott in Czechoslovakia and by Corby, Scorer and Wallington in England; yet little is known about the climatology of the wave and how often it will be a factor in jet operations.

(*) Preliminary results of a joint Northwest Airlines-United Air Lines study of mountain wave exposure have isolated 165 locations on 30 jet routes west of longitude 100° where moderate to strong mountain waves are possible.

There is a tendency to discount wave occurrence at turbojet cruising levels. Earlier rules of thumb such as "fly fifty percent higher than the height of the mountain to avoid rough air" may be partly responsible for this. Such rules overlook the role played by the tropopause in generating or intensifying latent turbulent situations. Statistics show a higher incidence of rough air at 35,000 feet than at 25,000 at mid latitudes and individual case histories of airline incidents provide even more convincing evidence that the tropopause zone is a favored one for turbulence.

The report which follows consists of five case histories of severe to extreme clear air turbulence. All were recent, all affected jet aircraft and all were mountain wave situations.

The Clear Air Turbulence Situation at LaVeta, Colorado

1800GCT

January 18, 1964

The Incident

Two airline jet aircraft experienced severe clear air turbulence at LaVeta, Colorado within 18 minutes of one another on January 18, 1964. Seven persons were reported slightly injured on each flight and the Boeing 707 suffered structural damage as the recorder on this downwind flight gave extreme g load readings of +3.33 and -0.35. Both flights were in cruise configuration with seat belt signs reported as being turned on, the B-707 at FL 270 and the B-720 at FL 310.

In addition to the two incidents just mentioned, there were four other pilot reports of severe turbulence, seven of moderate to severe and ten of moderate clear air turbulence within a five-hour period from 1700 to 2200GCT in that general area of the Sangre de Cristo Mountains on that day.

General Weather Type

A strong mountain wave was in progress in the lee of the Sangre de Cristo Mountain Range. Using the UAL mountain wave nomogram, the sea level pressure differential across the mountains between Pueblo and Farmington was 14 millibars and the wind speed was 65 knots at 20,000 feet perpendicular to the mountain ridge. This would place the wave well into the moderate to strong area. This conclusion was further evidenced by mountain wave lenticular and rotor clouds reported at Colorado Springs, Pueblo and Trinidad. The B-720 flight reported that their turbulence occurred just as they passed under an elongated lenticular cloud lying parallel to and in the lee of the mountain range. Marked stability was shown in the upwind air mass by the sounding at Grand Junction where a nearly isothermal layer was reported between 16,000 and 18,000 feet and an inversion of 3°C at 20,000 feet.

Features of Interest

1. This was one of the worst cases of mountain wave turbulence ever reported in this country. There were 23 known cases where pilots reported moderate or worse turbulence from 7,000 feet all the way up to Flight Level 390.
2. The element of surprise should not have been involved. Both airline meteorology departments predicted mountain wave conditions.
3. This case focused attention on the exposure of JR 54 and JR 64 to mountain wave turbulence east of Alamosa. (Today JR 64, JR 102 and JR 110 converge on Alamosa from the east and pass directly over the LaVeta Pass zone in the lee of Mt. Blanca at 14,390 and Culebra Peak at 14,090.)
4. This case also supports the idea that flights should be planned to the north via Cheyenne when active waves threaten over southern Colorado and via Las Vegas, New Mexico as they develop over northern Colorado.

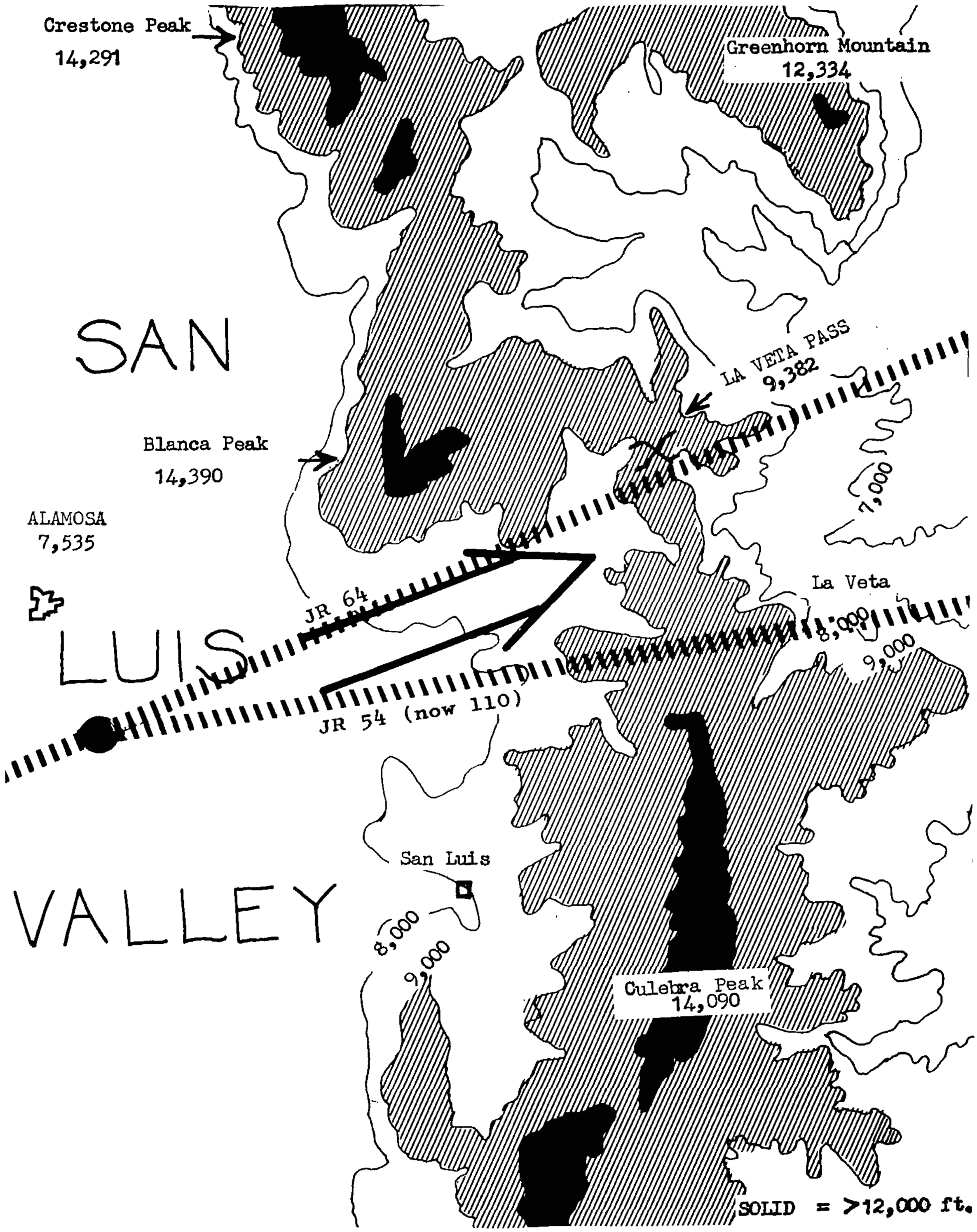


Figure 1. Plan view of the topography crossed by Jet Routes 54 (now JR 110) and 64 over the Sangre de Cristo Mountains in Colorado.

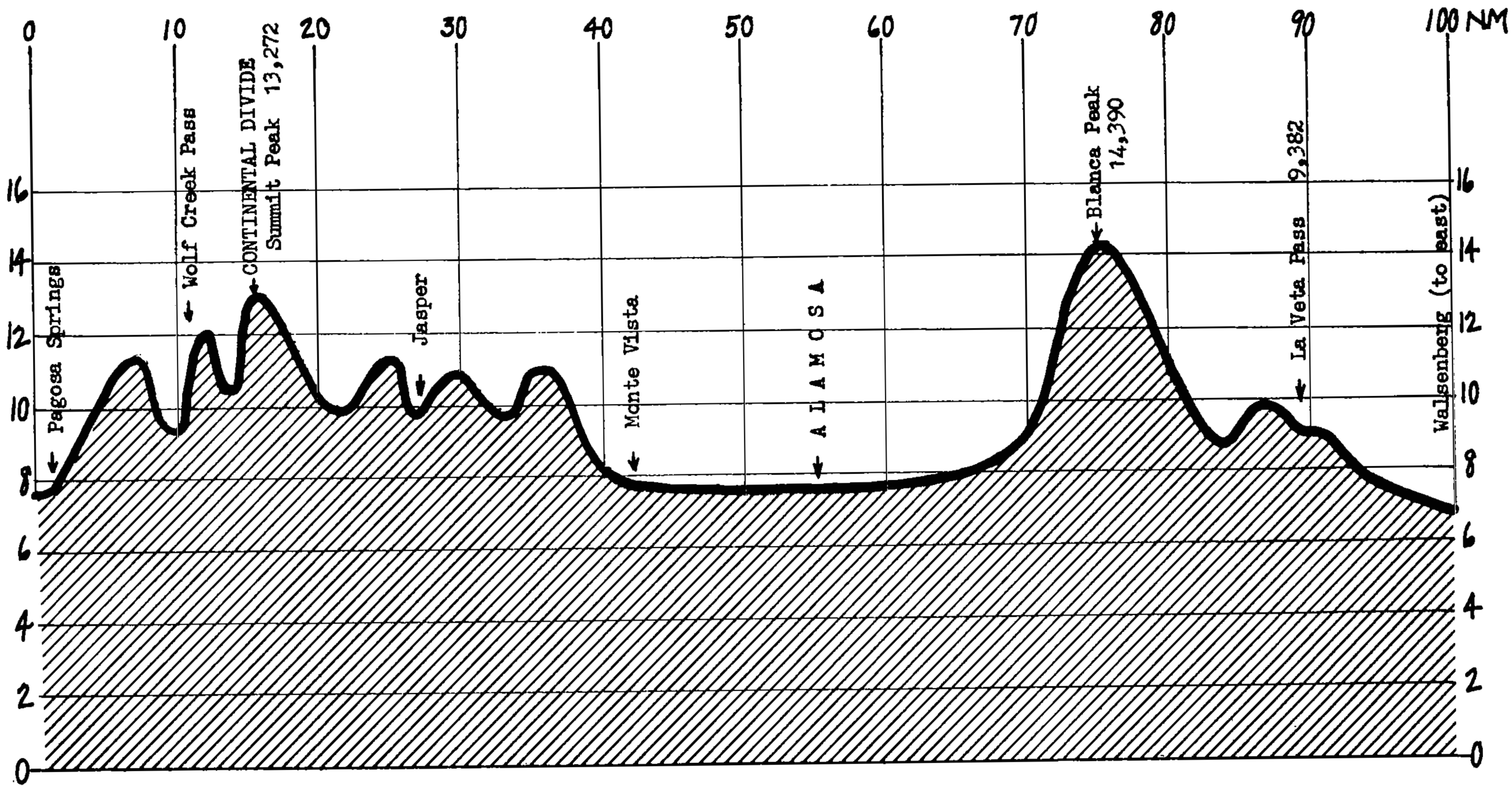


Figure 2. Terrain profile across the continental divide and the Sangre de Cristo Mountains along Jet Routes 54 (now 110) and 64.

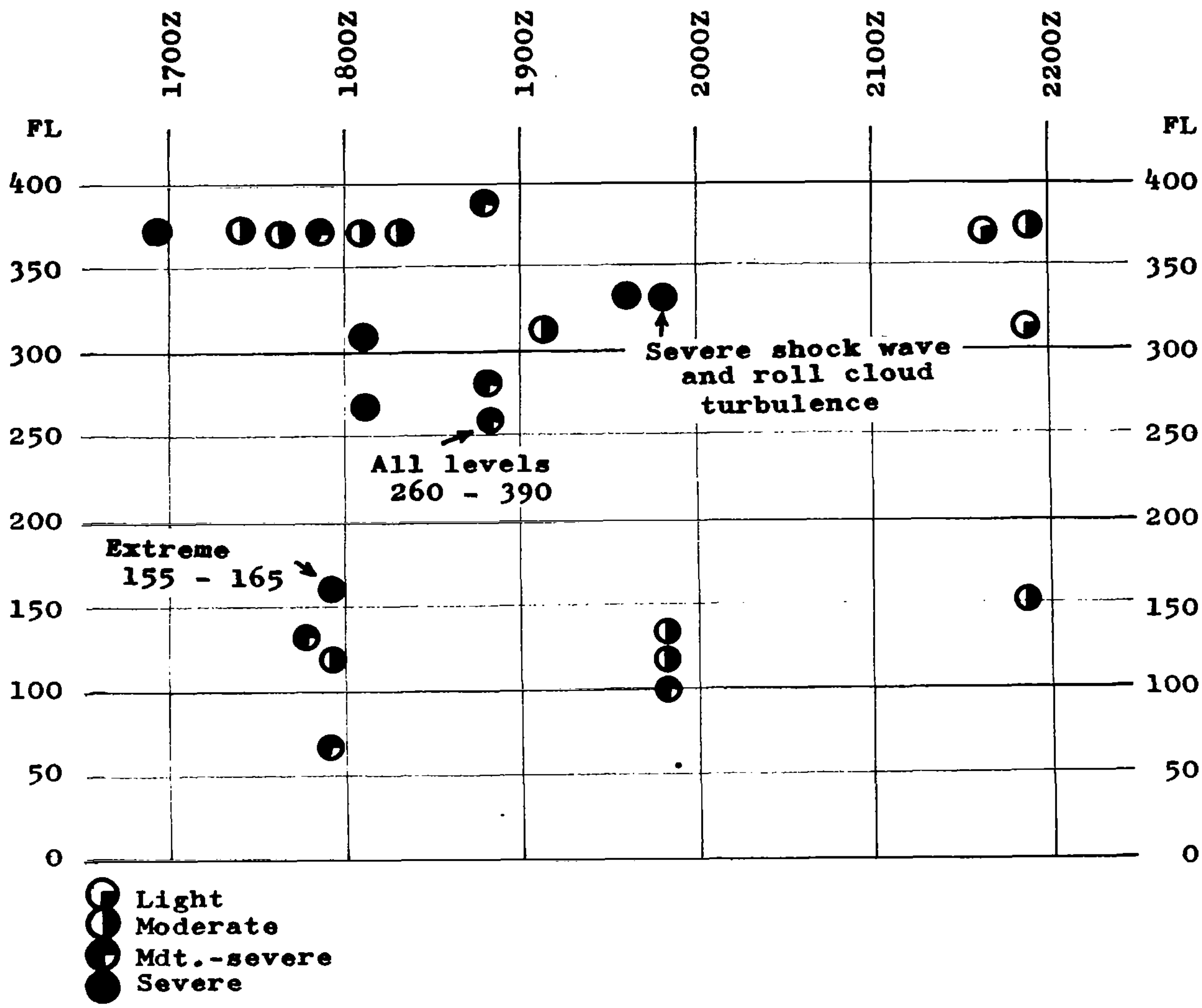
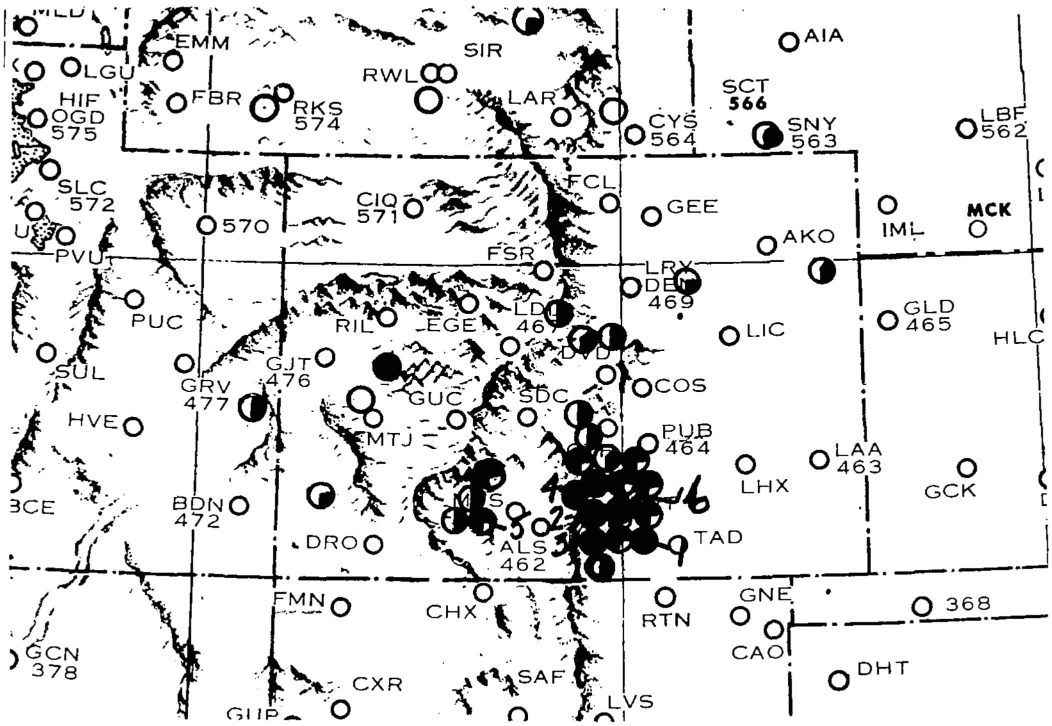


Figure 3. Time cross section of mountain wave turbulence reports west of Walsenberg, Colorado on January 18, 1964.



LEGEND

- Smooth
- LIGHT
- LIGHT TO MODERATE
- MODERATE
- MODERATE TO SEVERE
- SEVERE TO EXTREME

INDIVIDUAL REPORTS

1. "Severe shock wave and roll cloud turbulence · FL 330 32 E of ALS to 42 E of ALS". B-707

2. "Severe turbulence-unable maintain altitude" B-720 at FL 330 30 E of ALS

3. "Extreme turbulence vcnty Spanish Peaks-unable VFR westbound" 155-165

4. "Heavy side gust from left - then felt as though a bulldog had hold of the nose and was shaking it violently-lasted 70 seconds then smooth for 70 seconds then by slightly lesser turbulence for another 70 seconds-control maintained mainly by lateral control and reference to visual horizon". B-707 at FL 270 30 E of ALS. Recorder showed +3.33 to -0.35g

5. "Moderate to severe turbulence at FL 370 41 W of ALS to 38 E of ALS. Temperature varied -64° C to -56° C." DC-8.

6. "Two severe jolts at FL 310 34 NE of ALS at 1806Z Only light chop prior to this so had seat belt sign on." B-720 UAL #773

Figure 4. Pilot reports of turbulence over Colorado and southern Wyoming during a five-hour period on January 18, 1964.

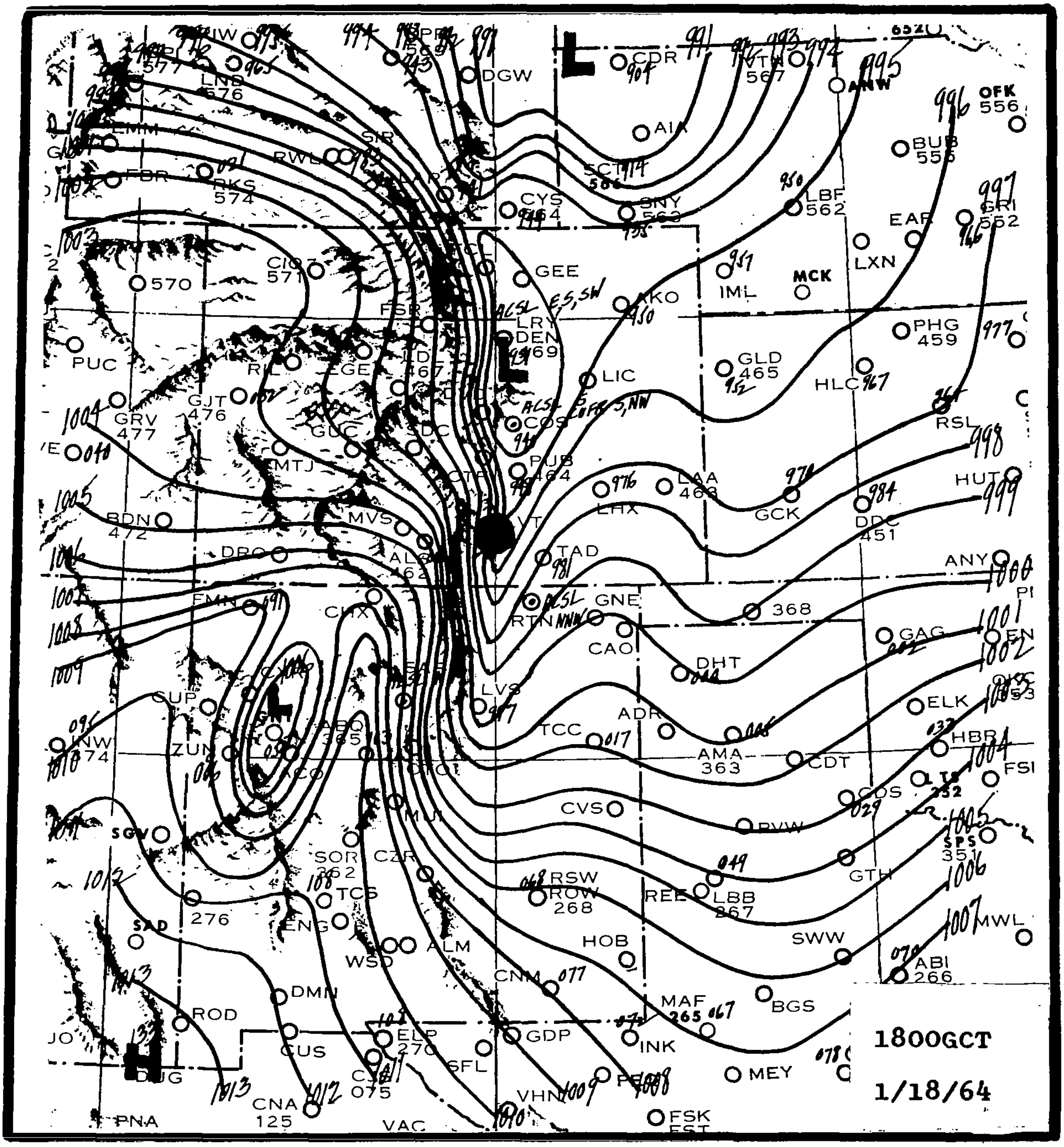


Figure 5. Sea level isobars drawn at 1-millibar intervals for 1800GCT on January 18, 1964. The sharp trough in the lee of the continental divide is a characteristic of prominent mountain waves in Colorado. It is a fingerprint which is useful in detecting wave developments along the divide from Montana down to New Mexico.

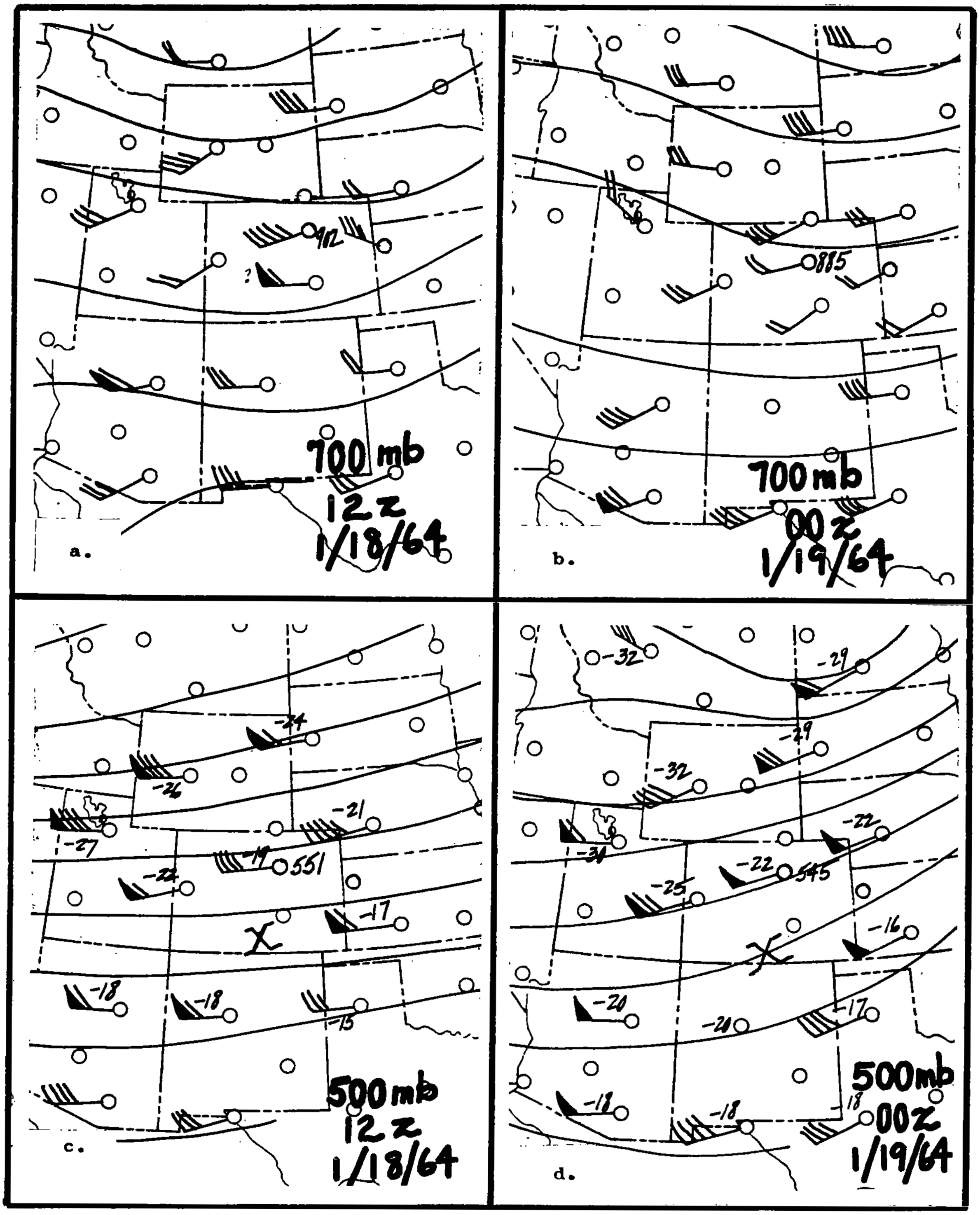


Figure 6. a. 700 mb. chart for 1200GCT on January 18, 1964; b. 700 mb. chart for 0000GCT on January 19, 1964; c. 500 mb. chart for 1200 GCT on January 18, 1964; d. 500 mb. chart for 0000GCT on January 19, 1964.

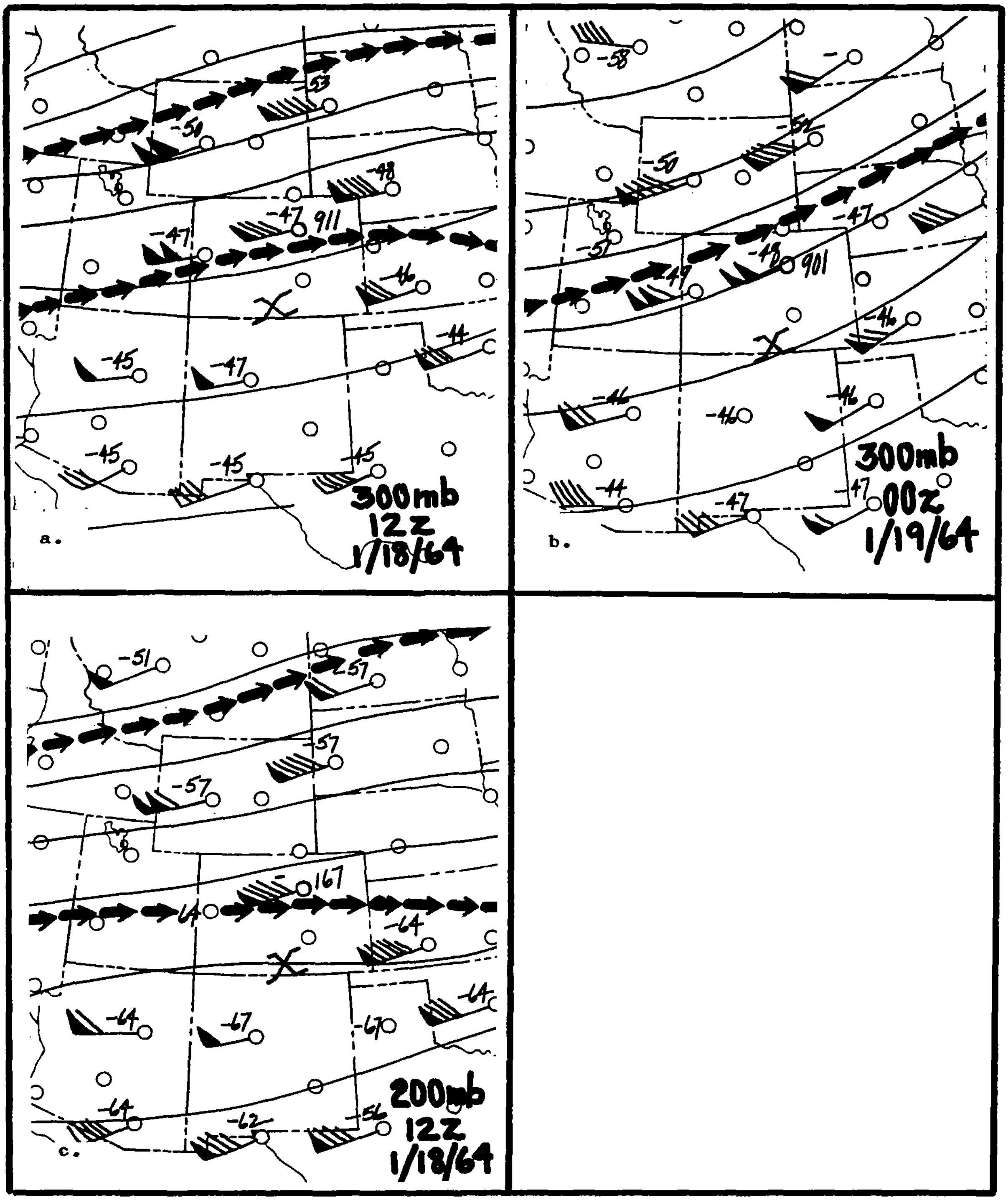


Figure 7. a. 300 mb. chart and jet stream positions for 1200 GCT on January 18, 1964; b. 300 mb. chart and jet stream position for 0000GCT on January 19, 1964; c. 200 mb. chart for 1200GCT on January 18, 1964 with jet stream positions.

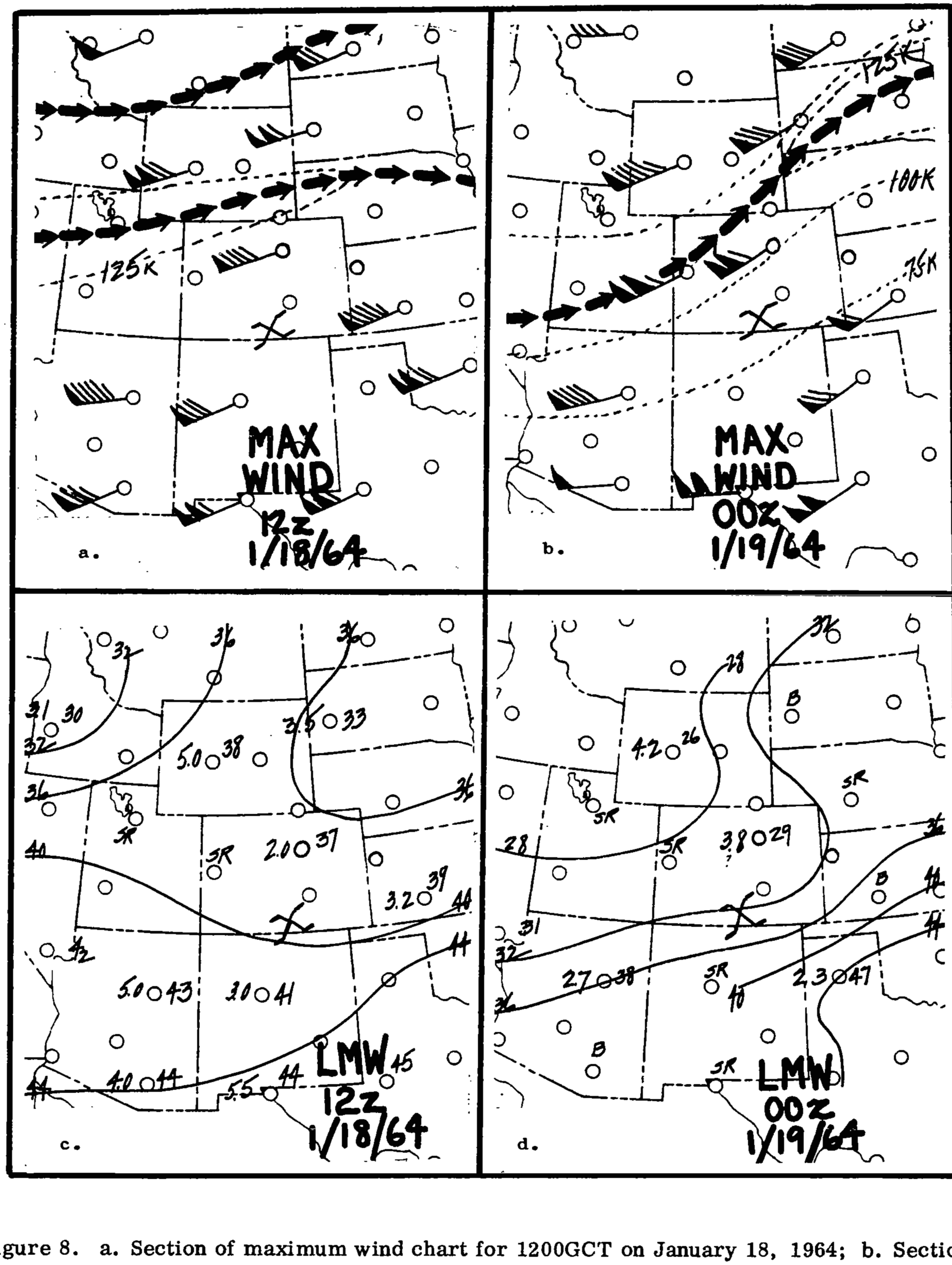


Figure 8. a. Section of maximum wind chart for 1200GCT on January 18, 1964; b. Section of maximum wind chart for 0000GCT on January 19, 1964; c. Level of maximum wind for 1200GCT on January 18, 1964; d. Level of maximum wind for 0000GCT on January 19, 1964.

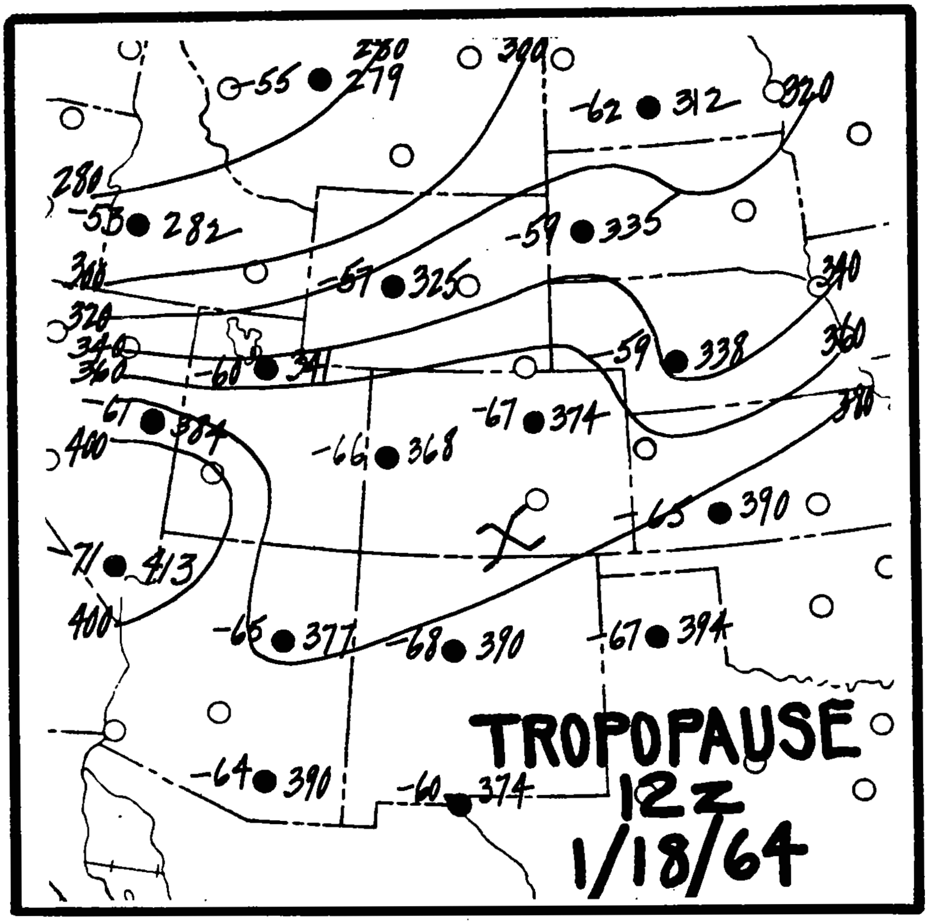


Figure 9. Section of the tropopause chart for 1200GCT on January 18, 1964. "X" marks the location of the turbulence incidents.

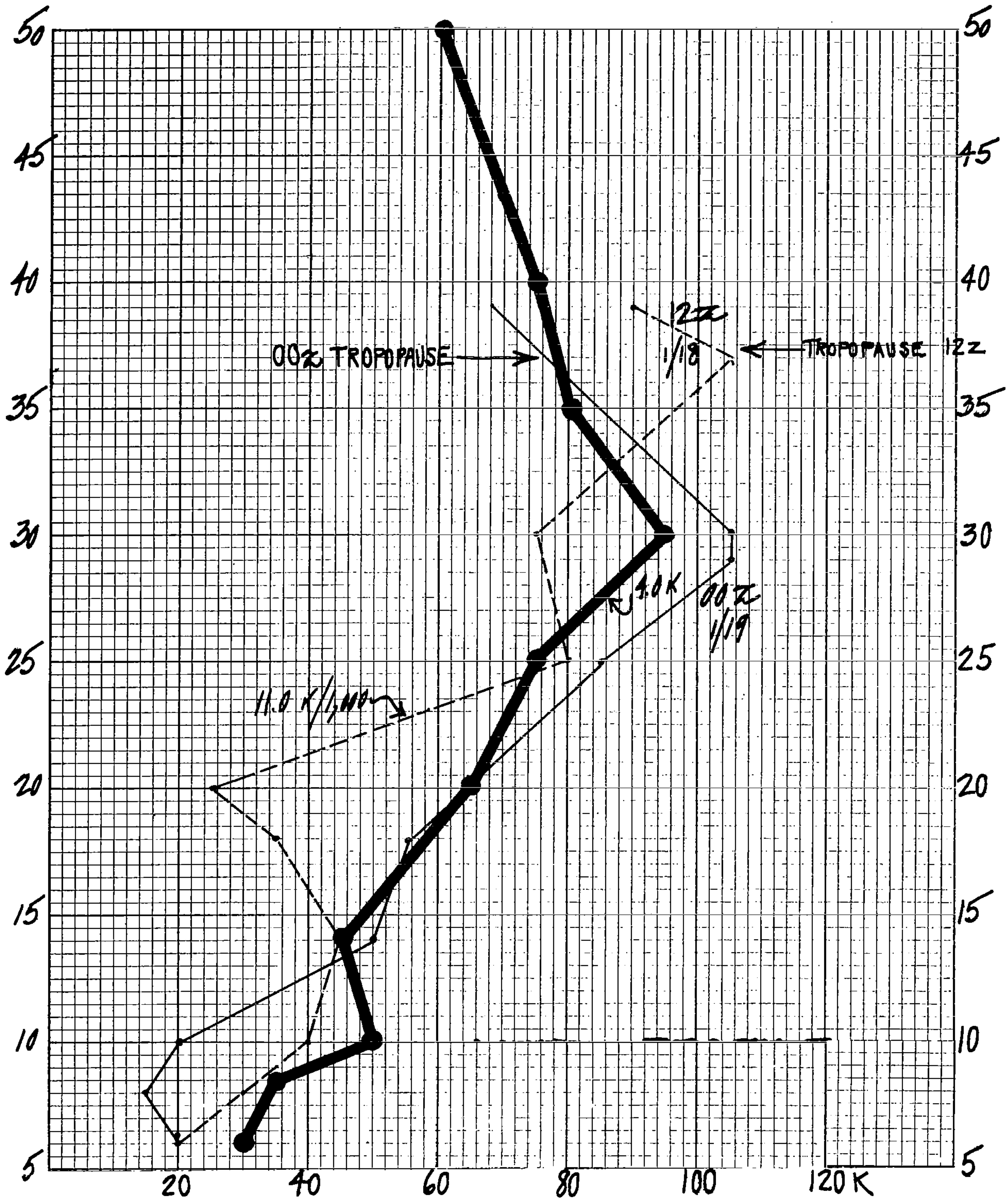


Figure 10. Wind speed profile at Denver for 1800GCT on January 18, 1964. The speed profile for six hours earlier is shown by dashed line and profile for six hours later by the solid, thin line.

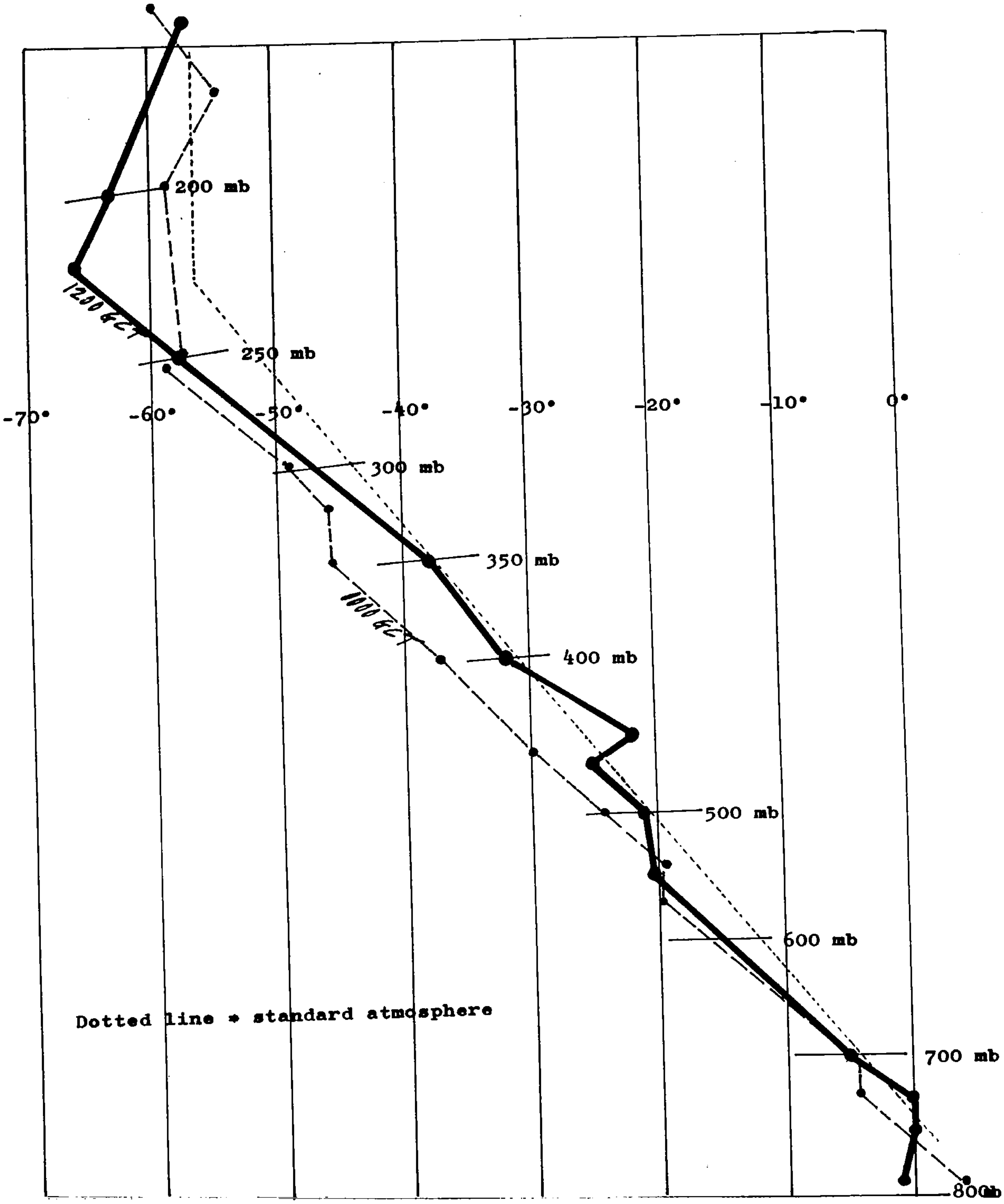


Figure 11. The upwind air mass sounding at Grand Junction, Colorado at 1200GCT on January 18, 1964. The sounding twelve hours later is shown by dashed curve. Note the stable layers between 15,000 and 28,000 feet in the troposphere.

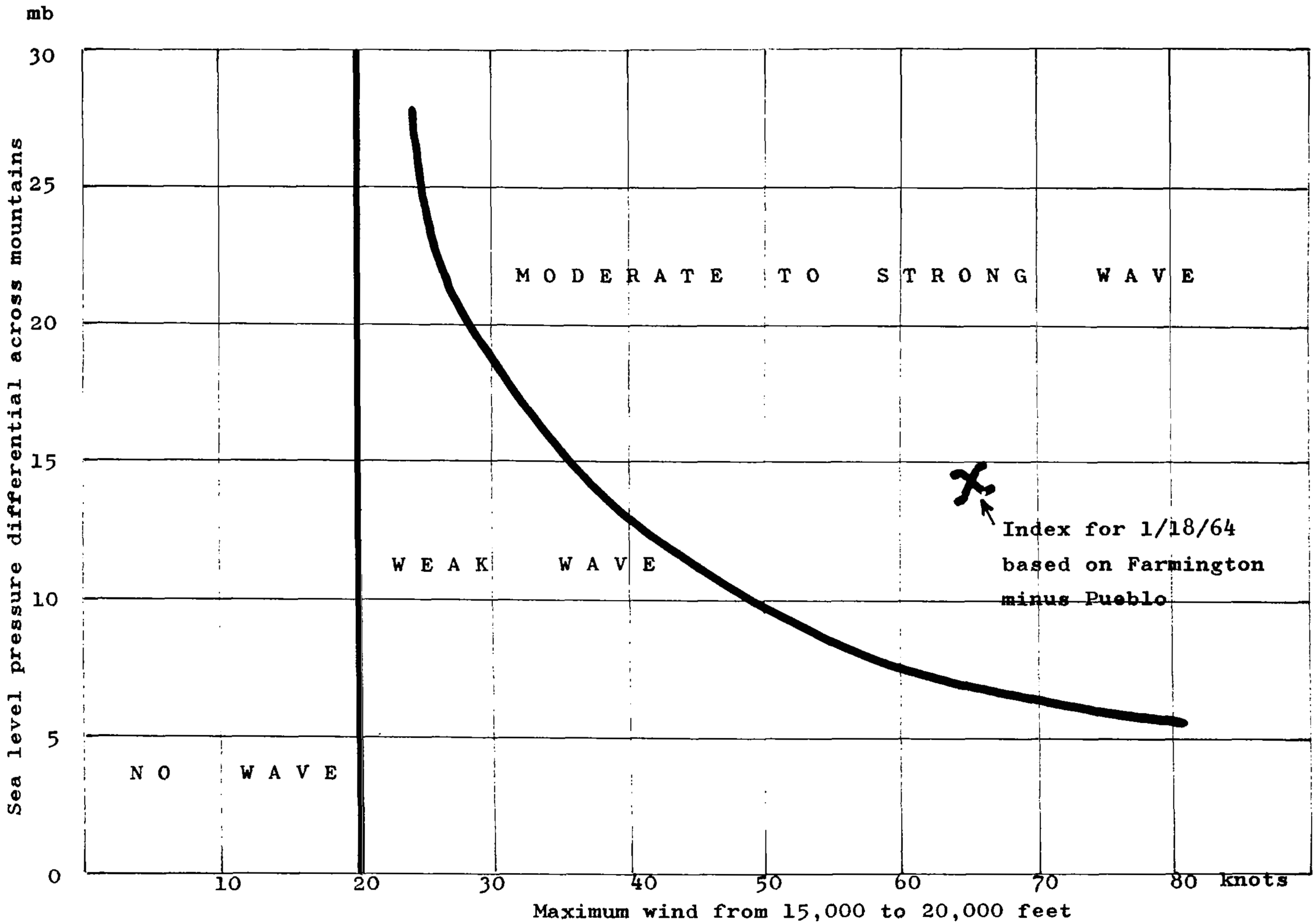


Figure 12. Index of mountain wave intensity for Sangre de Cristo Mountain Range on January 18, 1964 based on UAL system of identification and rating.

The Clear Air Turbulence Situation West of Denver

0300GCT

January 10, 1964

The Incident

A Boeing 707 encountered severe clear air turbulence at FL 280 while 38 NM west of Denver, Colorado. Mountain wave effects had not been reported but had been anticipated after the headwind component on this westbound flight increased to 80 knots. The airplane shook violently and then encountered a terrific bump - turbo-compressors became inoperative - lost a thousand feet of altitude - flight control was no unusual problem - there was no recovery maneuvering - cabin was found in disarray and several passengers had minor cuts and bruises. The pilot felt that "an unreported wind shear existed on the west edge of the mountain wave which caused the extreme turbulence we found there." (Time estimated 0300GCT)

This was the only major turbulence report received near this time but a series of cases happened later in the day farther south in the lee of the continental divide.

General Weather Type

A strong mountain wave was in progress in the lee of the continental divide over northern Colorado. The UAL mountain wave forecasting nomogram showed a wind speed of 60 knots at 18,000 feet and a sea level pressure differential of 16 millibars at the time the incident is estimated to have happened. Darkness prevented the reporting of any mountain wave clouds. In addition to the high wave index, the upwind air mass sounding at Grand Junction showed an inversion of 3°C at 6,000 feet and another of 3°C between 10,000 and 12,000 feet. This air mass stability therefore completed all of the requirements for a strong wave in the lee of the divide west of Denver.

Features of Interest

Of the four jet routes fanning out to the west of Denver, JR 30-56 and JR 60-80 catch the brunt of wave developments because they lie across Corona Pass west of Rollinsville and Loveland Pass west of Georgetown and Idaho Springs. The former is notorious as one of the biggest wave breeders in the country. The flight on January 10, 1964 was on one of those two routes, probably the one over Corona Pass since the distance given as 38W of Denver would have put it just west of Rollinsville along the average position of the first mountain wave.

Typical of big waves in the lee of the continental divide, a sharp trough in the sea level isobars appeared in the usual position about fifty miles to the east of the divide. Like many mountain waves over the Rockies, this one was a migratory wave that advanced gradually southward during the day. It will be noted, from reference to the next situation, that major turbulence occurred over southern Colorado later in the day.

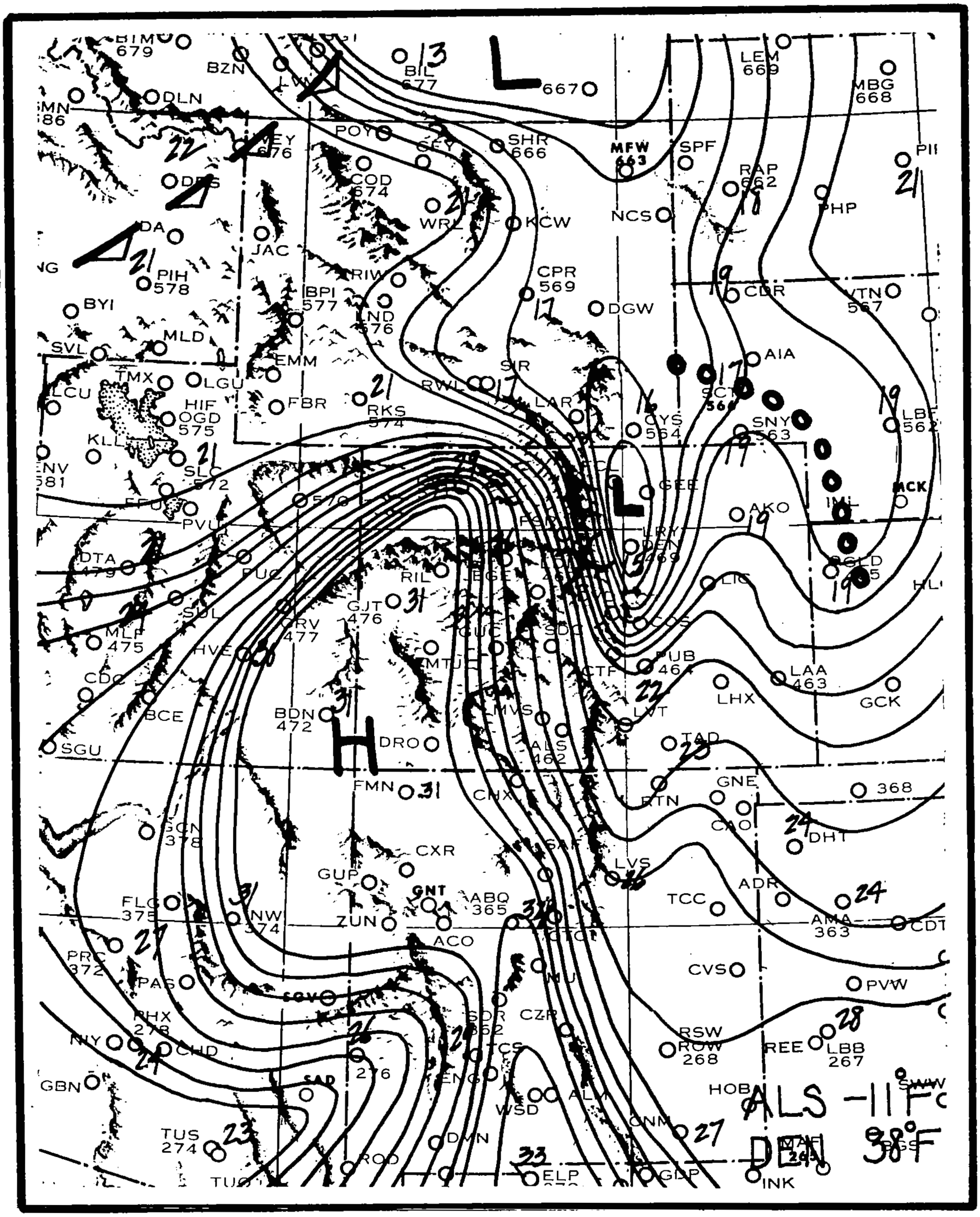


Figure 13. One-millibar sea level isobars along the middle continental divide for 0300GCT on January 10, 1964. Note the sharp lee trough in the usual position and the unusual packing of the isobars across the mountains.

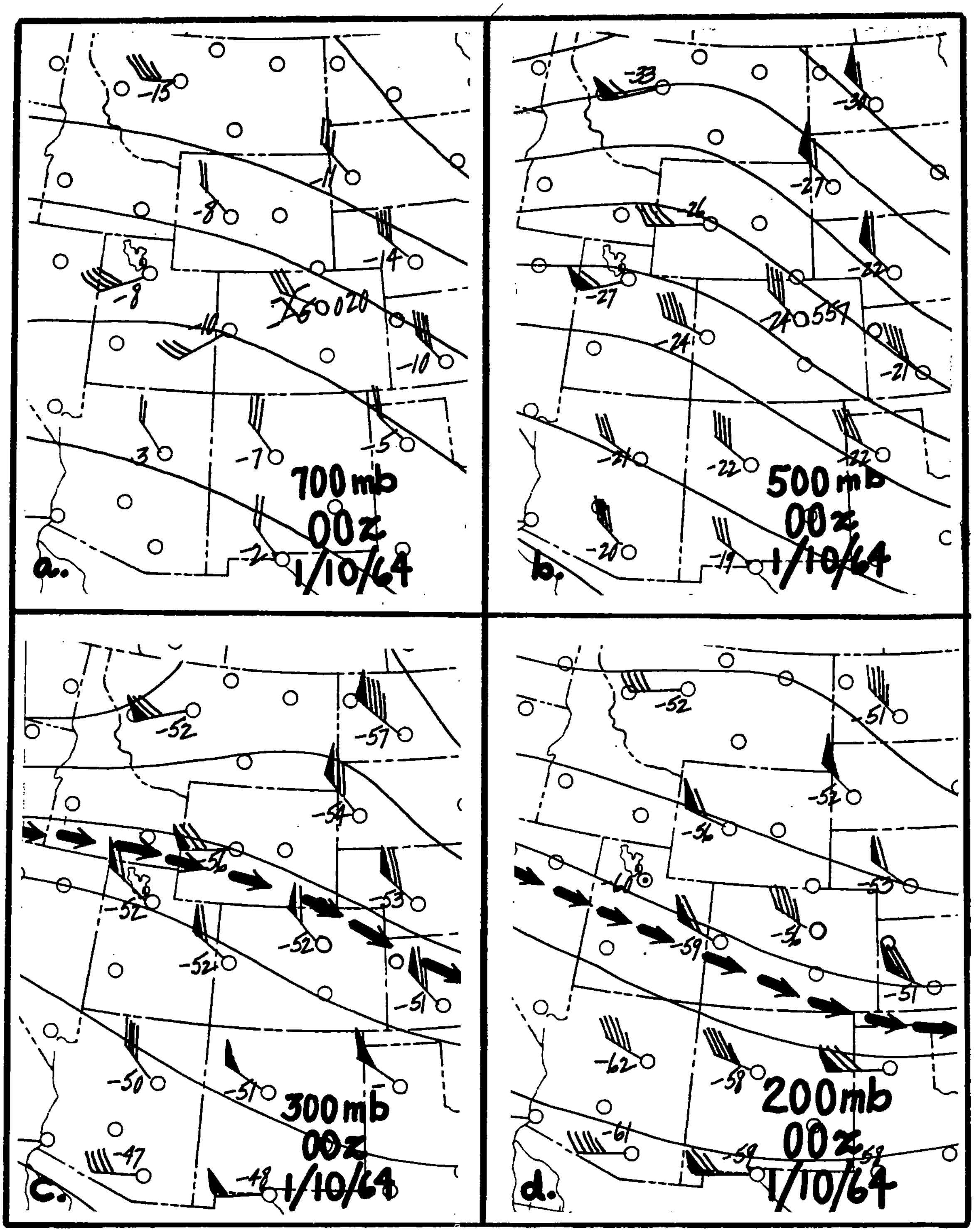


Figure 14. Sections of upper air charts for 0000GCT on January 10, 1964. a. 700 mb. chart; b. 500 mb. chart; c. 300 mb. chart; d. 200 mb. chart. NWAC jet stream positions are shown on the last two charts.

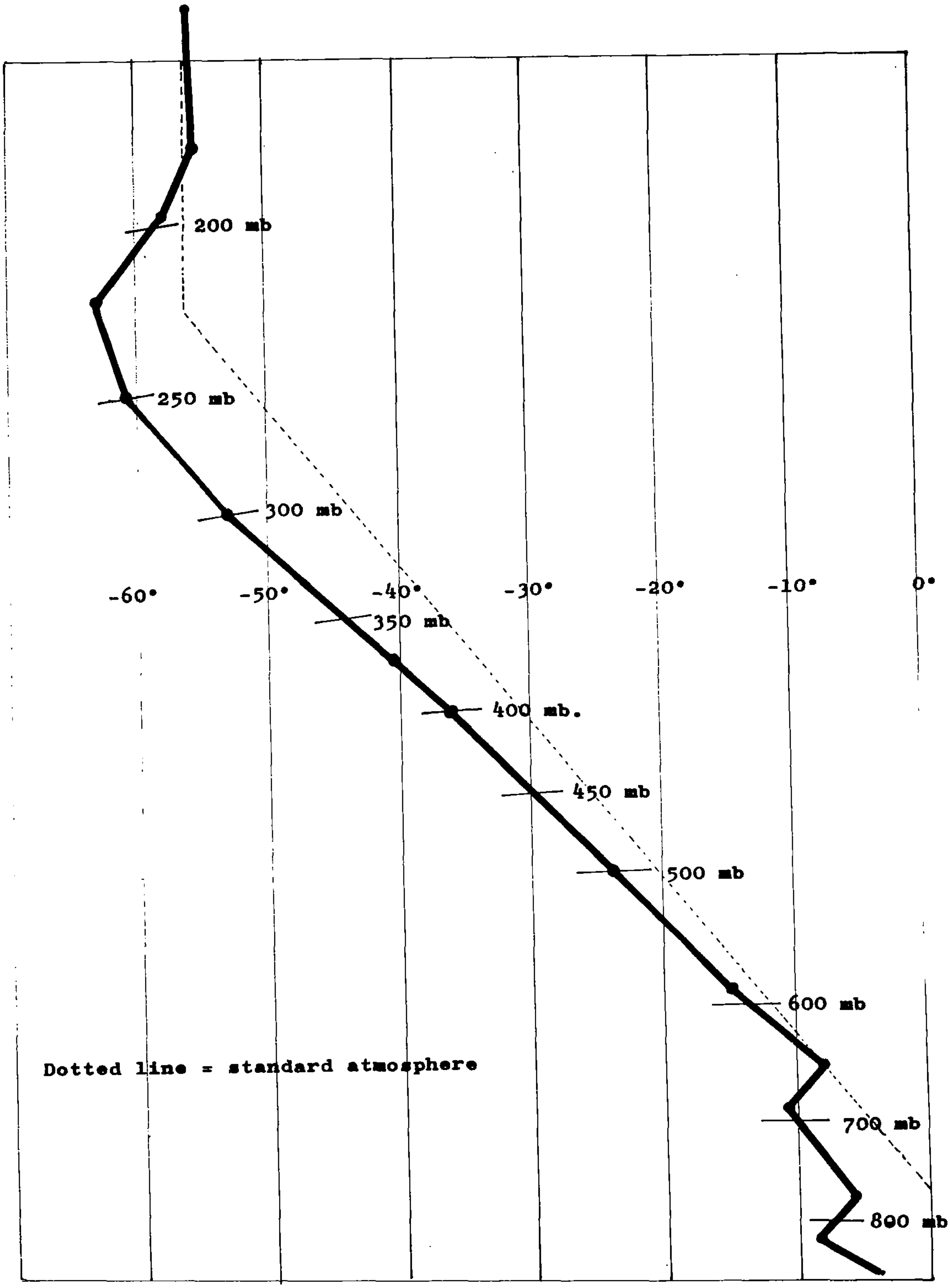


Figure 15. Radiosonde plot for Grand Junction, Colorado at 0000GCT on January 10, 1964. Note the marked stability shown in this upwind sounding.

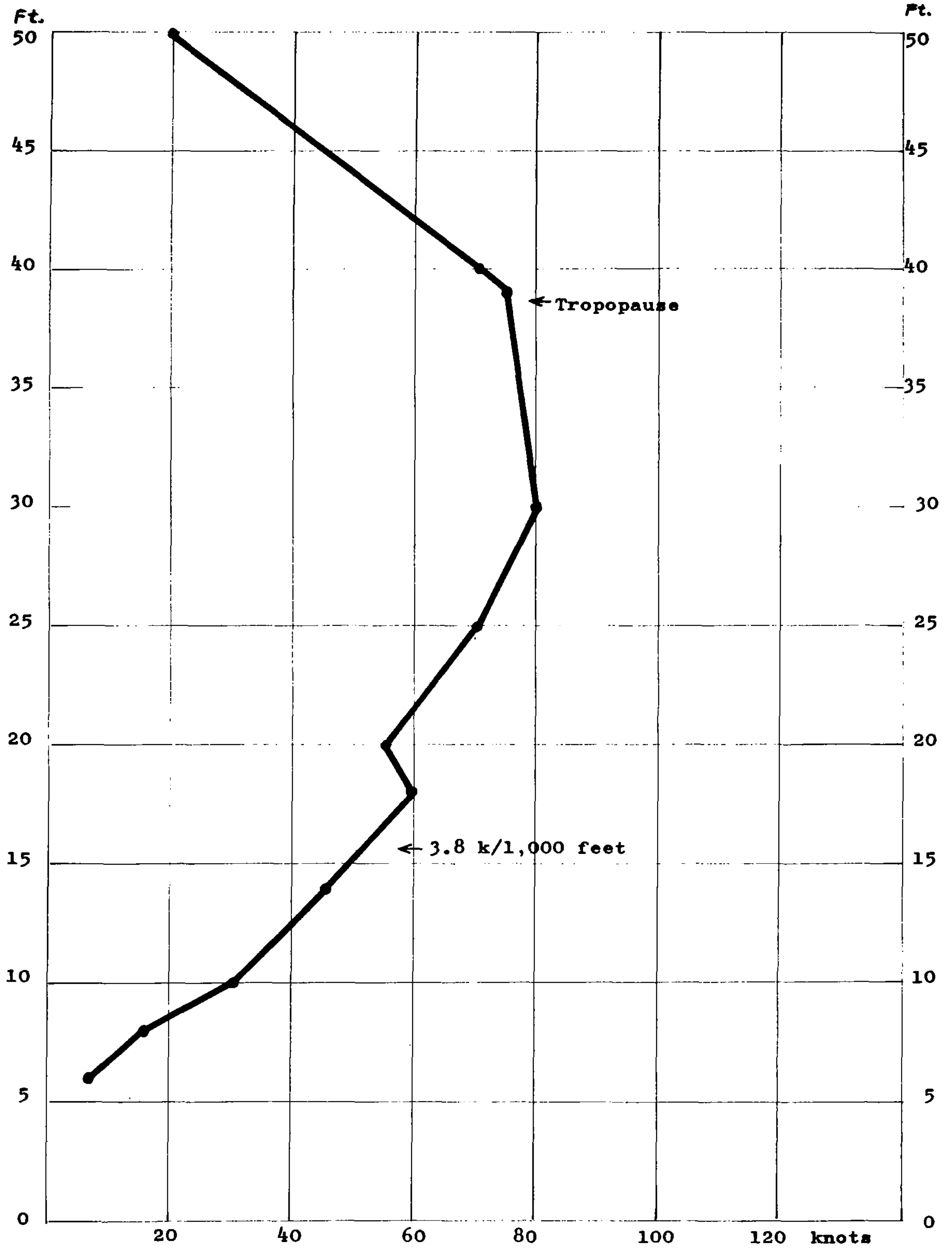


Figure 16. Vertical wind speed profile at Denver, Colorado for 1200GCT on January 10, 1964.

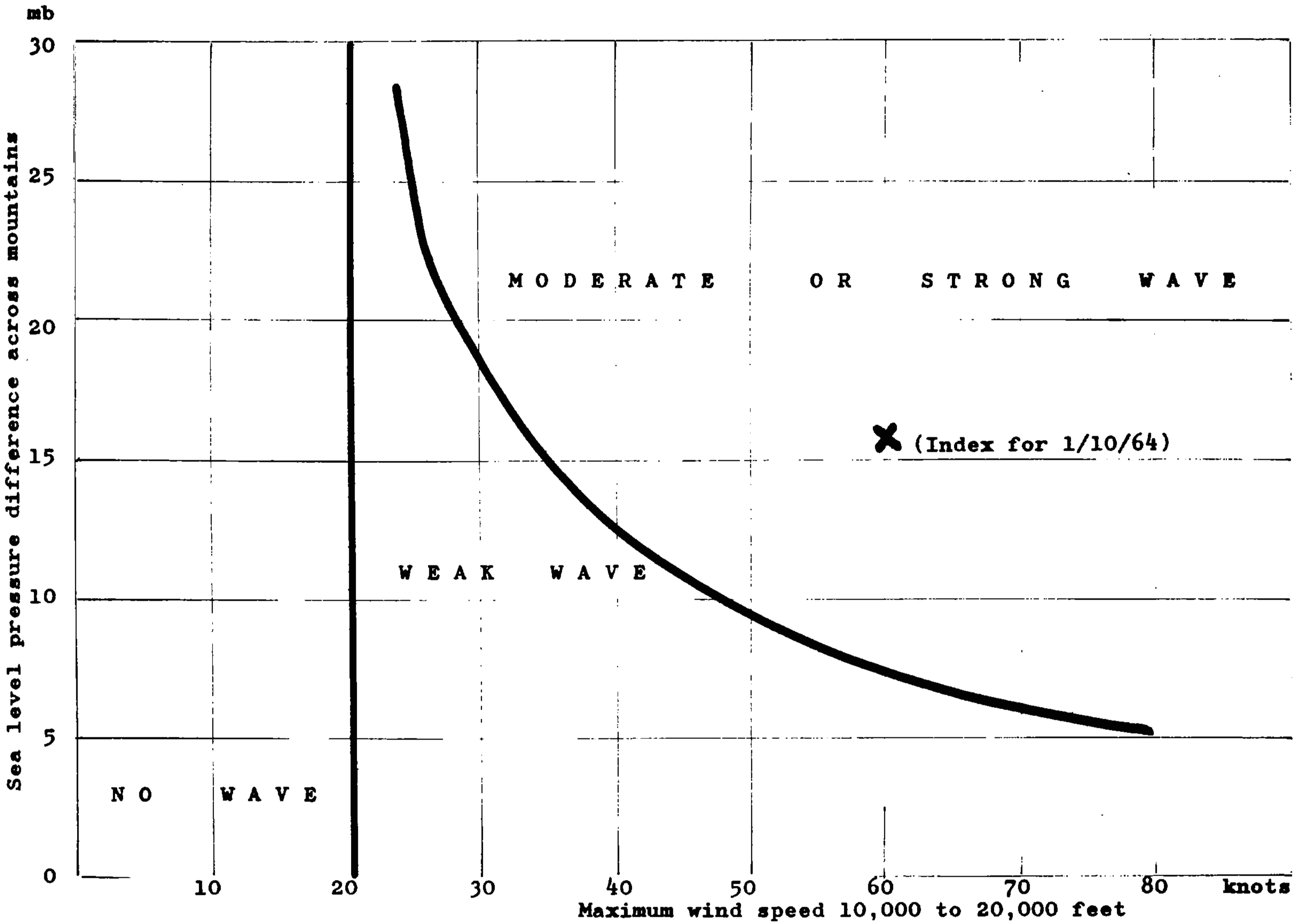


Figure 17. Mountain wave index for January 10, 1964 along continental divide west of Denver. Based on United Air Lines forecasting method for the Colorado wave.

The Clear Air Turbulence Situation at LaVeta, Colorado

1549GCT

January 10, 1964

The Incident

An Air Force experimental B-52, making test runs at low levels along the east face of the Sangre de Cristo Mountains, encountered extreme turbulence at 14,300 feet while passing adjacent to East Spanish Peak which is just southeast of LaVeta, Colorado. Vertical gusts computed at 120 feet per second tore the vertical fin from the aircraft but the crew kept it flying and eventually made a safe landing at Blytheville, Arkansas.

General Weather Type

All indications, based upon the UAL system of identification and rating, pointed to a strong mountain wave being in progress in the lee of the Sangre de Cristo Mountains starting at about 1400GCT on this date. Wind speed was 55 to 60 knots near 20,000 feet and sea level pressure differential was 9 millibars between Farmington and Trinidad. (Use of Alamosa would have made the differential 20 millibars but there is some question about how valid this pressure would be for the purpose). The upwind air mass sounding at Grand Junction showed a surface inversion and then a stable, isothermal layer near 12,000 feet which indicated that the requirements for stability were met. The index on the UAL nomogram plotted out as calling for a moderate to strong mountain wave.

Positive evidence for the existence of a wave came from the official ground observations of mountain wave lenticular clouds in this section starting at 1400GCT on this date (nearly two hours before the incident) and continuing each hour from then until 1900GCT when they were no longer reported. It is conceivable that wave clouds were present prior to 1400GCT but could not be identified because of darkness. The other incident on this date occurred in a strong mountain wave west of Denver twelve hours earlier and evidence there pointed to the wave being a migratory one which was moving southward.

Further evidence that the LaVeta incident was not an isolated case came from pilot reports of moderate CAT at FL 390 near La Junta at 1600GCT, of moderate to severe CAT between Flight Levels 320 and 390 near Santa Fe at 2100GCT and a report of moderate CAT between Flight Levels 310 and 390 near Grants, New Mexico at 2200GCT.

Features of Interest

While the extreme turbulence on this date happened down near the mountain tops, other flights did experience moderate and heavier turbulence in the clear at normal jet cruising levels. When we pair this incident with the one of the two airline jet aircraft at the same spot on January 18, 1964 it becomes evident that we are dealing with one of the worst jet exposures in the country to mountain wave activity. Waves in the lee of LaVeta Pass evidently equal the intensity of those at Corona Pass west of Denver and the most notorious of all, Bishop in California.

This case again focuses attention on the advisability of flight planning around this spot on days of known or suspected wave activity. The three Jet Routes which converge on Alamosa from the east, 64-102-110, should be avoided on days when some or all of these wave symptoms are reported:

1. Wind direction 250° to 270° at 40 knots or more between 15,000 and 20,000 feet
2. Sharp sea level pressure differential across the mountains resulting in a distinct lee trough when the isobars are drawn carefully. If in doubt, draw one-millibar isobars exactly to every sea level pressure reported.
3. Stable air noted in upwind air mass soundings

When surface stations at Colorado Springs, Pueblo, Trinidad or Alamosa start reporting lenticular clouds (ACSL's) or rotors, the wave is already in progress.

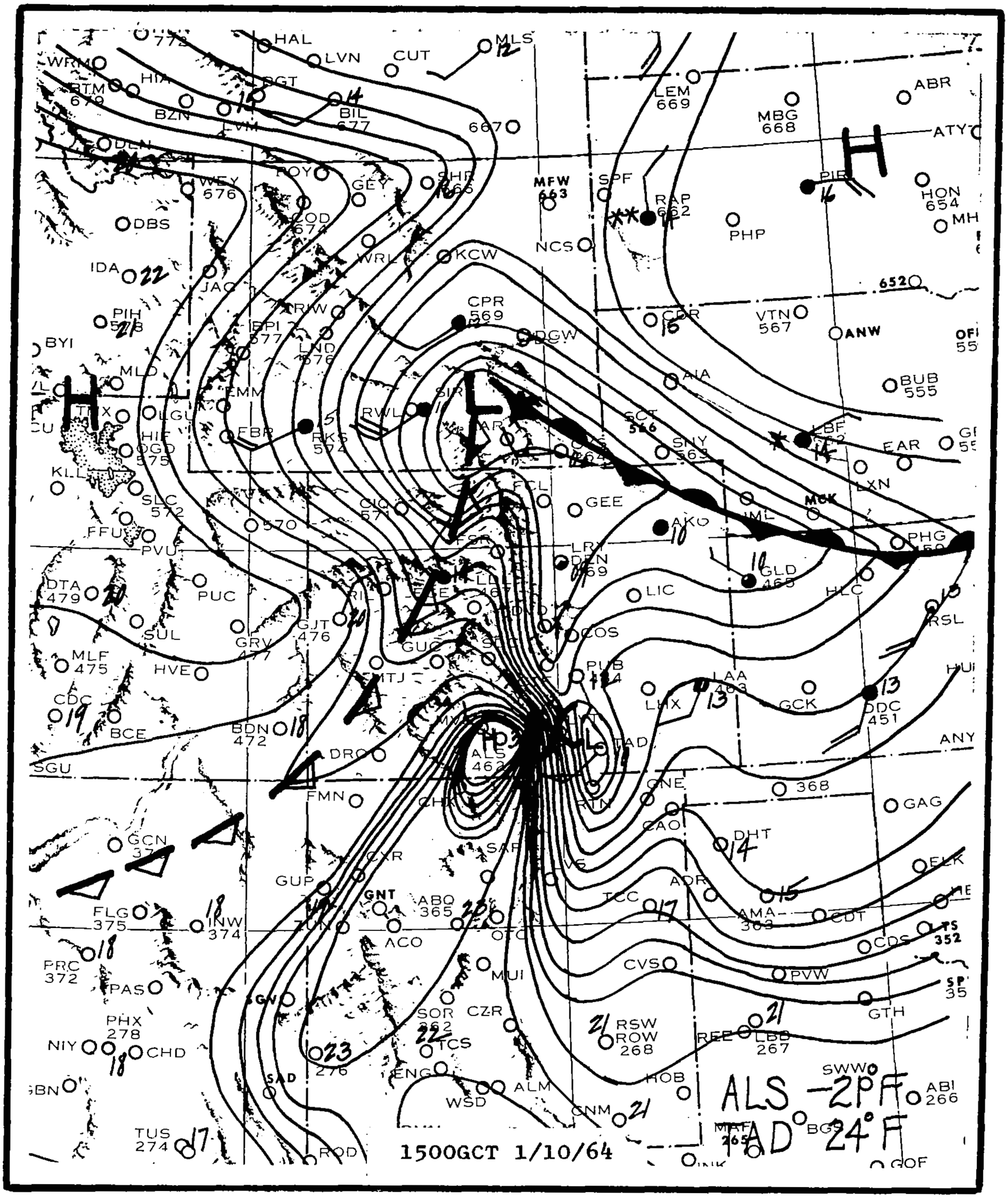


Figure 18. One-millibar sea level isobars over the continental divide area in Colorado and New Mexico at 1500GCT on January 10, 1964. Note the extreme packing of the isobars across the Sangre de Cristo Mountains. In the Denver incident twelve hours earlier the isobar packing was concentrated at that point.

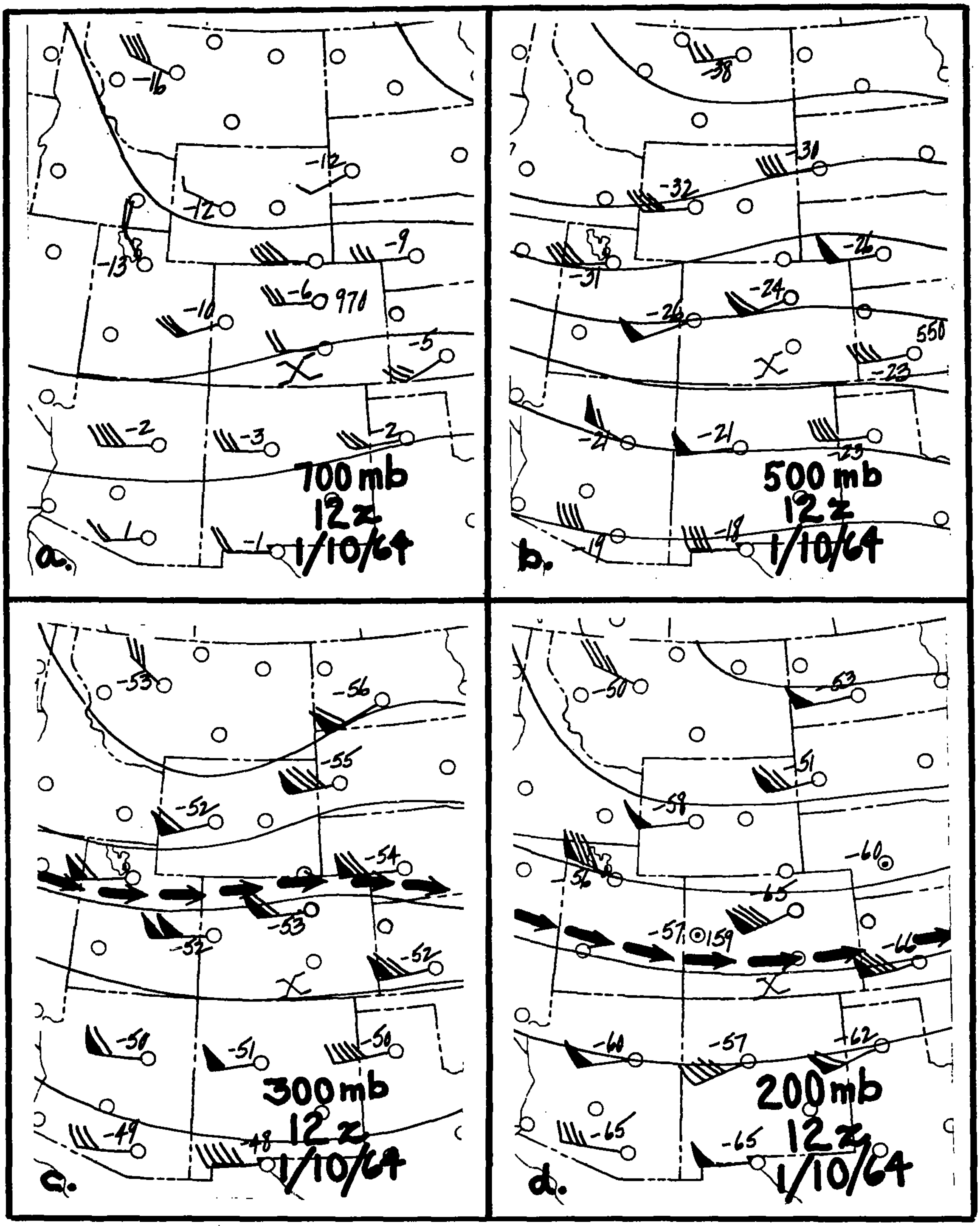


Figure 19. Sections of upper air charts for 1200GCT on January 10, 1964. a. 700 mb.; b. 500 mb.; c. 300 mb.; d. 200 mb. NWAC jet stream positions appear on last two charts.

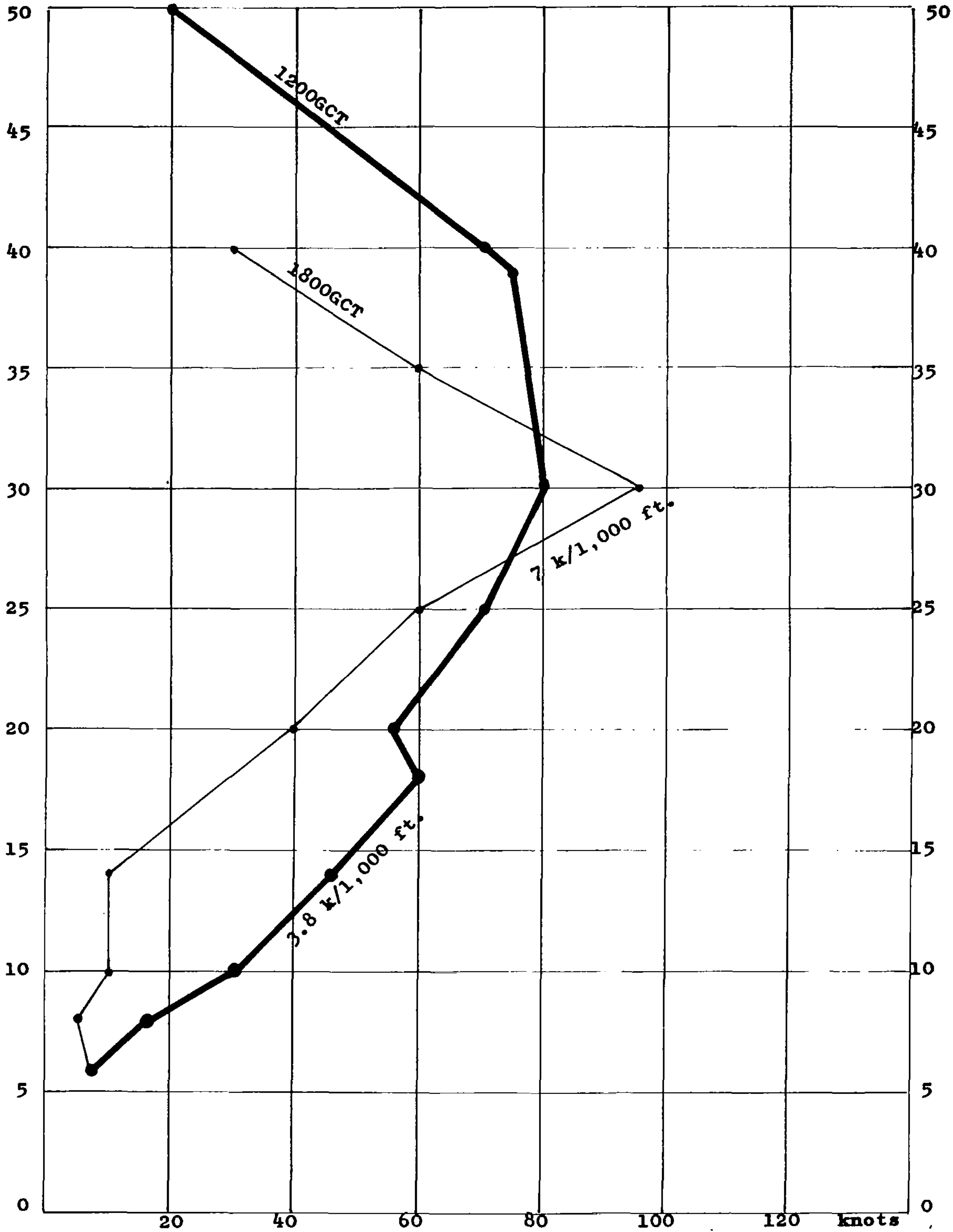


Figure 20. Wind speed profile at Denver, Colorado on January 10, 1964. Heavy curve is for 1200GCT (before the incident) and light curve is for 1800GCT (after the incident).

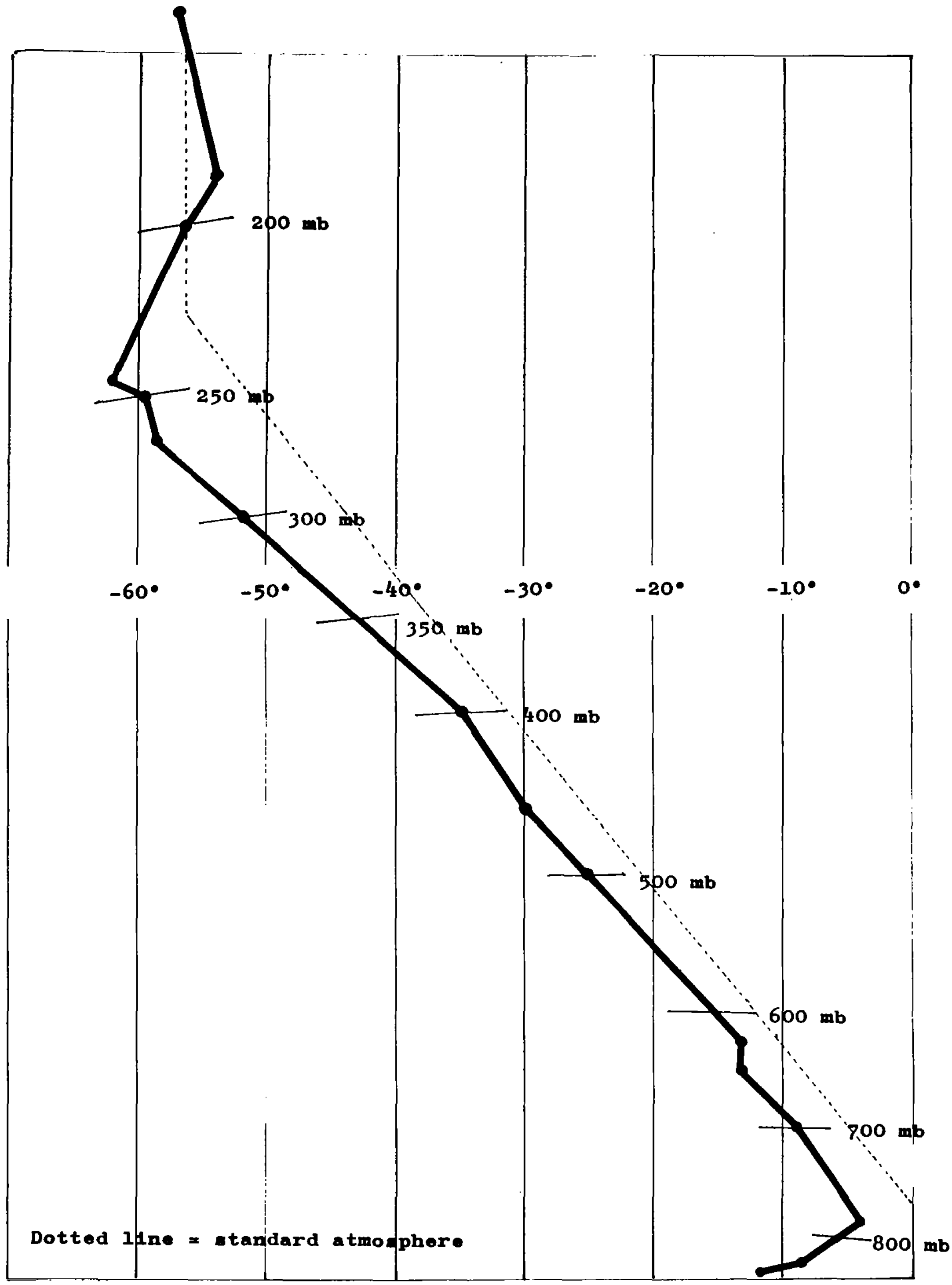
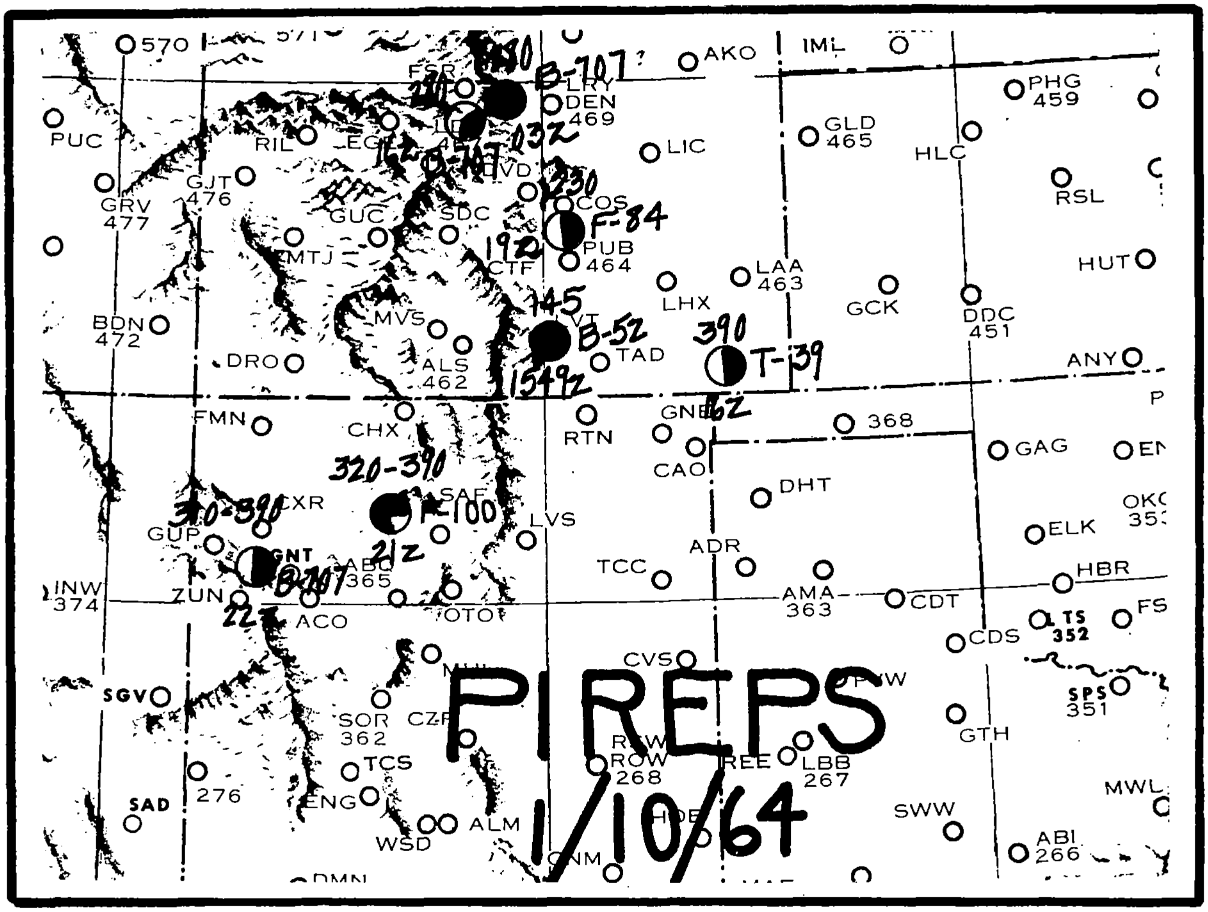


Figure 21. Air mass sounding at Grand Junction, Colorado for 1200GCT on January 10, 1964. Note that this upwind sounding from the incident shows a surface inversion plus an isothermal layer around 12,000 feet msl.



Light to moderate
Moderate
Moderate to severe
Severe

Figure 22. Location of pilot reports of clear air turbulence in Colorado and northern New Mexico on January 10, 1964.

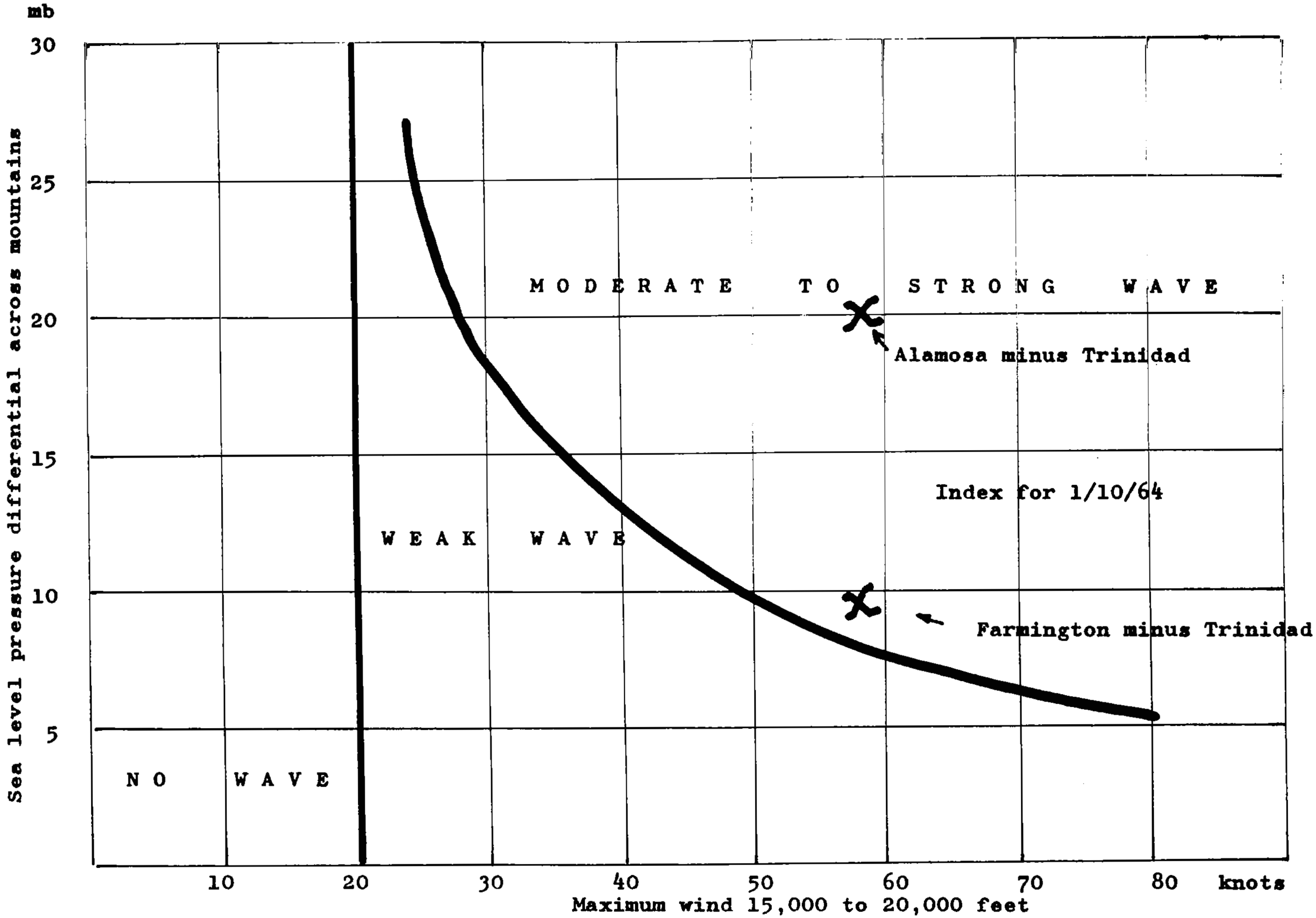


Figure 23. Index of mountain wave intensity based on UAL forecasting nomogram for Sangre de Cristo Mountain Range on January 10, 1964.

The Clear Air Turbulence Situation Near Elk Mountain

North of Ringling, Montana on JR 90

0800GCT

March 17, 1964

The Incident

A four-engine jet transport encountered moderate to severe clear air turbulence at FL 370 on Jet Route 90 while 95 NM WNW of Billings, Montana. The location was just south of Elk Mountain in the lee of the Big Belt Mountains which rise to 9,700 feet at this point in Mt. Baldy. The flight recorder revealed a range of gusts between +1.9 g and -0.1 g. One passenger and a stewardess were reported injured.

General Weather Type

A mountain wave was in progress in the lee of the Big Belt Mountains as well as along other mountain ridges in Montana starting near 2200GCT on March 16th. This was when standing lenticular clouds (ACSL) began to be reported along JR 70 west of Great Falls and JR 90 WNW of Billings. Sea level pressure differential across the mountains had been increasing during the preceding twelve hours and the usual sharp lee trough in the sea level isobars had appeared along the east face of the continental divide.

While the UAL mountain wave nomogram was designed for forecasting in Colorado, the topography in Montana is so similar that it should be applicable there also, possibly with some minor adjustments for distance between pairs of pressure difference stations. The nomogram, in this case, did give an index calling for a moderate to strong wave and this index continued to increase up to the time of the turbulence incident. Mountain wave clouds were no longer reported after 0200GCT on the 17th but this would have been expected because of darkness, there being no knownmethod of identifying such cloud forms at night unless moonlight is brilliant.

Wave clouds were actually reported during this period by Great Falls, Helena, Livingston, Lewistown and Dillon which gives some idea of the extensive nature of the wave developments in spite of the quartering wind from the northwest. Colson and others have commented on the unusual intensity to be found in some of these waves in Montana where the windflow is far from being perpendicular to the ridges. Another characteristic of the quartering wave is that it generally is a migratory system which advances progressively southward and sometimes reaches from Montana down to Colorado in twenty-four hours or less. Other positive evidence for the existence of the wave came from a jet pilot at FL 390 about 160 NM west of Billings who reported "moderate occasionally severe chop mountain wave" at 0212GCT on the 17th.

Features of Interest

This was another example of the tendency for mountain wave turbulence to be worse for jet aircraft at levels near and below the tropopause. On this date the average position of the tropopause was close to 37,500 feet in western Montana and the two mountain wave turbulence cases occurred at FL 370 and FL 390. On the other hand, flights down at FL 250 and FL 270 reported no turbulence across Montana.

This case is also a good example to show that significant mountain waves occur in the lee of many ranges and are far from being limited to the popular locations in the lee of the continental divide, the Sierras and the Cascades. A look at the terrain profile across the Big Belt Mountains lying north-south across JR 90 just to the east of the Missouri River will show why this is so. Mt. Baldy at 9,700 feet is higher than anything to the west along the divide, there is a wide open sweep for the surface air mass to gather momentum in moving southeastward from Helena down the broad Missouri Valley, and a dropoff of 4,000 feet on the lee side for the cascading air. Finally, there is a secondary lift of 2,000 feet imparted to the airmass 12 miles east of the ridge line which should have the effect of being a built-in hydraulic jump. This terrain feature is found in many of the big mountain wave profiles (Corona, LaVeta, Bishop) and it is strange that meteorologists have failed to pay any attention to it.

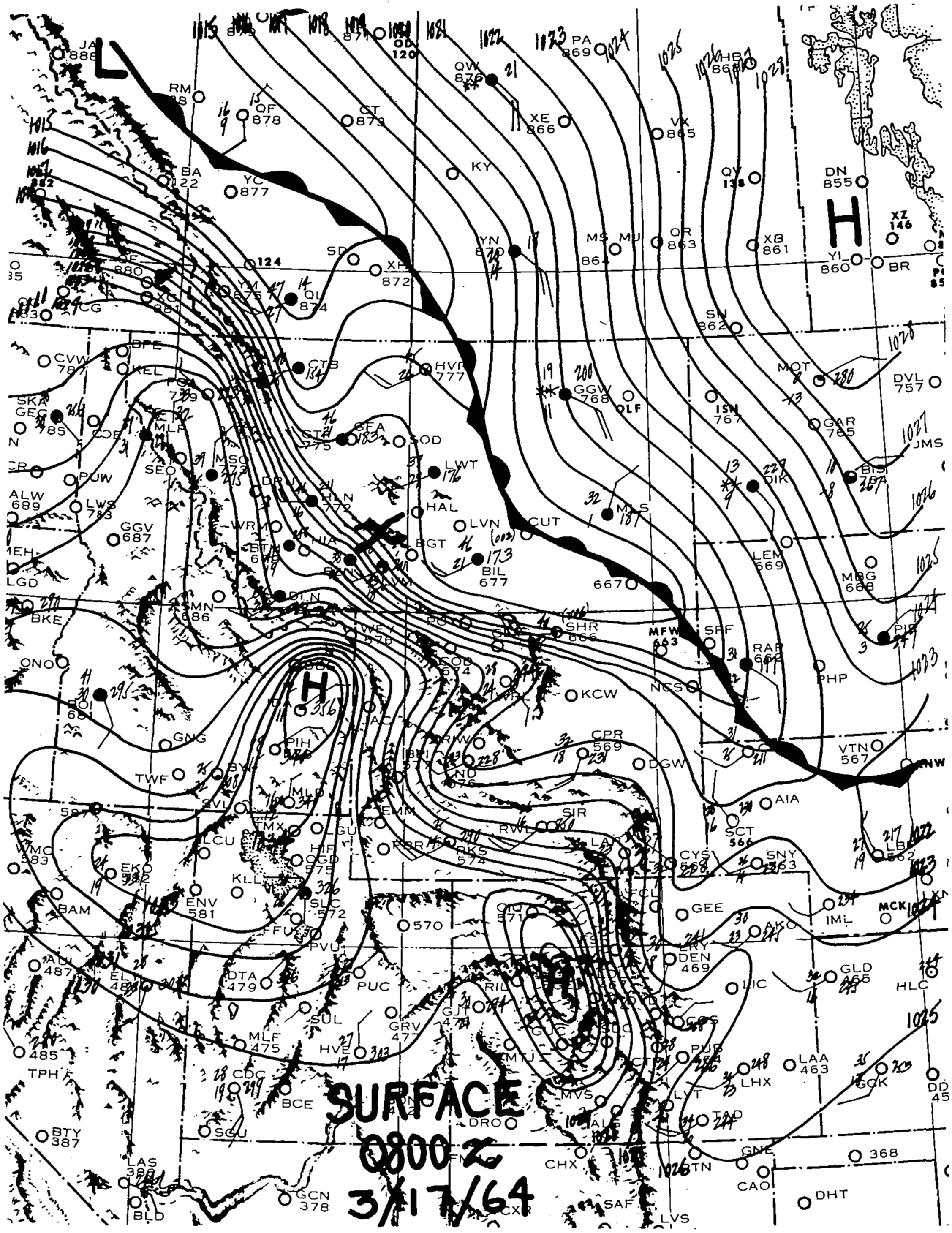


Figure 24. One-millibar sea level isobars for the Rocky Mountain area at 0800GCT on March 17, 1964. Note the characteristically sharp lee trough in Montana where the mountain wave was in progress at this time. Stability of the air mass is evidenced by the low surface temperatures west of the divide.

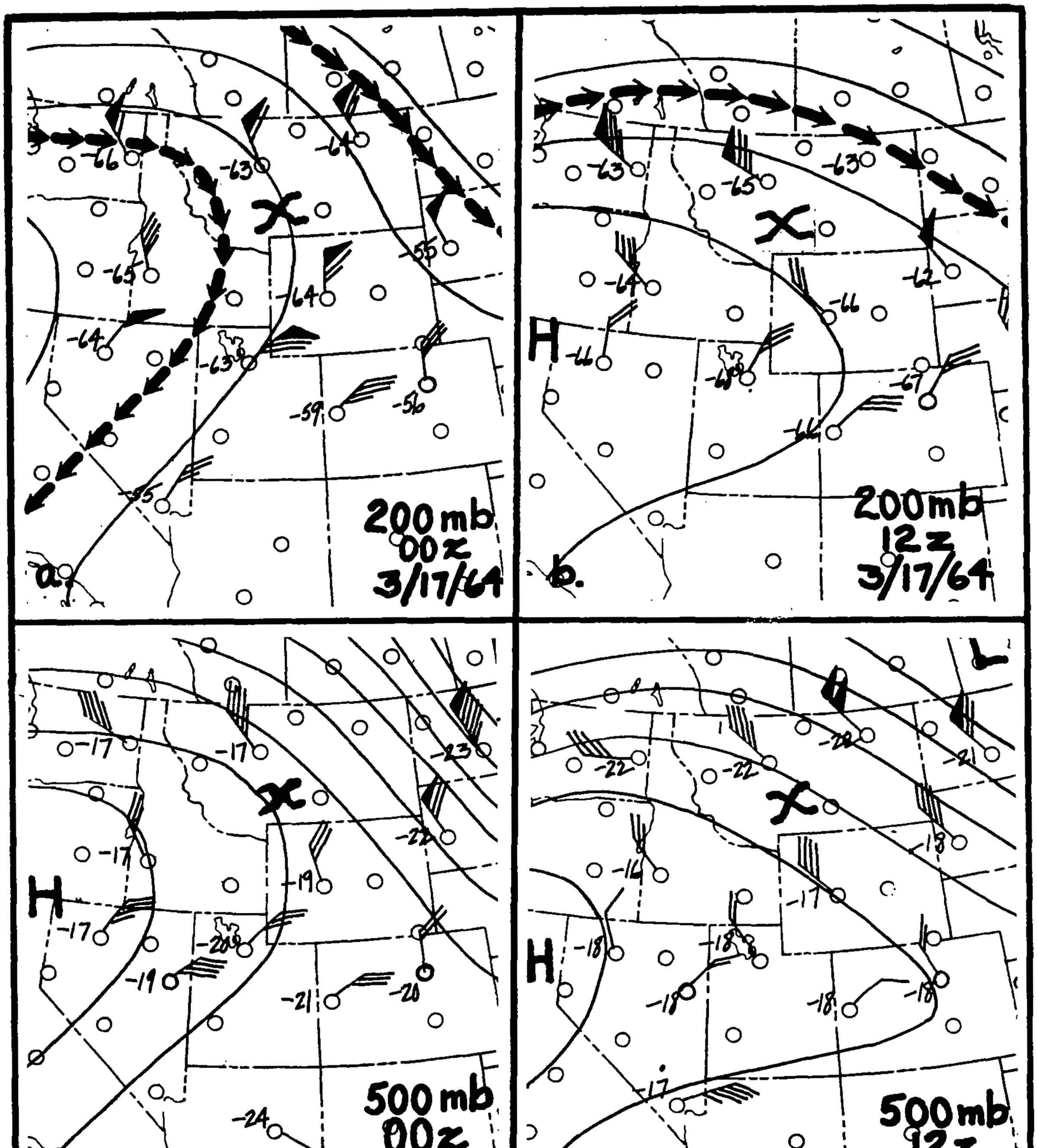


Figure 25. Sections of upper air charts for the Rocky Mountains on March 17, 1964. a. 200 mb. for 0000GCT; b. 200 mb. for 1200GCT; c. 500 mb. for 0000GCT; d. 500 mb. for 1200GCT. NWAC jet stream positions are shown on the 200 mb. charts.

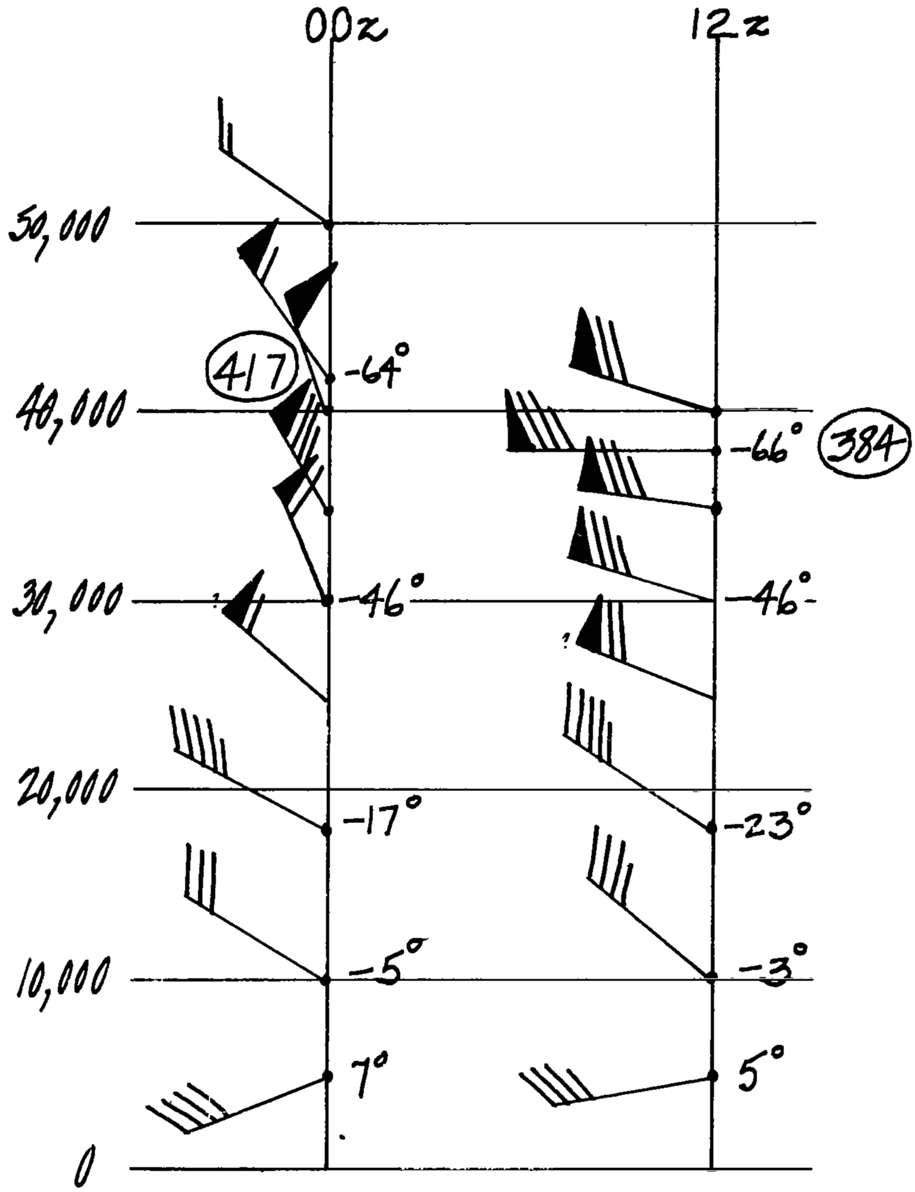


Figure 26. An abbreviated plot of the rawinsonde observations at Great Falls, Montana for 0000GCT and 1200GCT on March 17, 1964. Several features should be noted; (a) lowering and cooling tropopause, (b) increased instability above 30,000 feet, (c) increased stability between 18,000 and 30,000 feet and (d) backing of wind direction at high levels to give a more ideal mountain wave profile in the vertical.

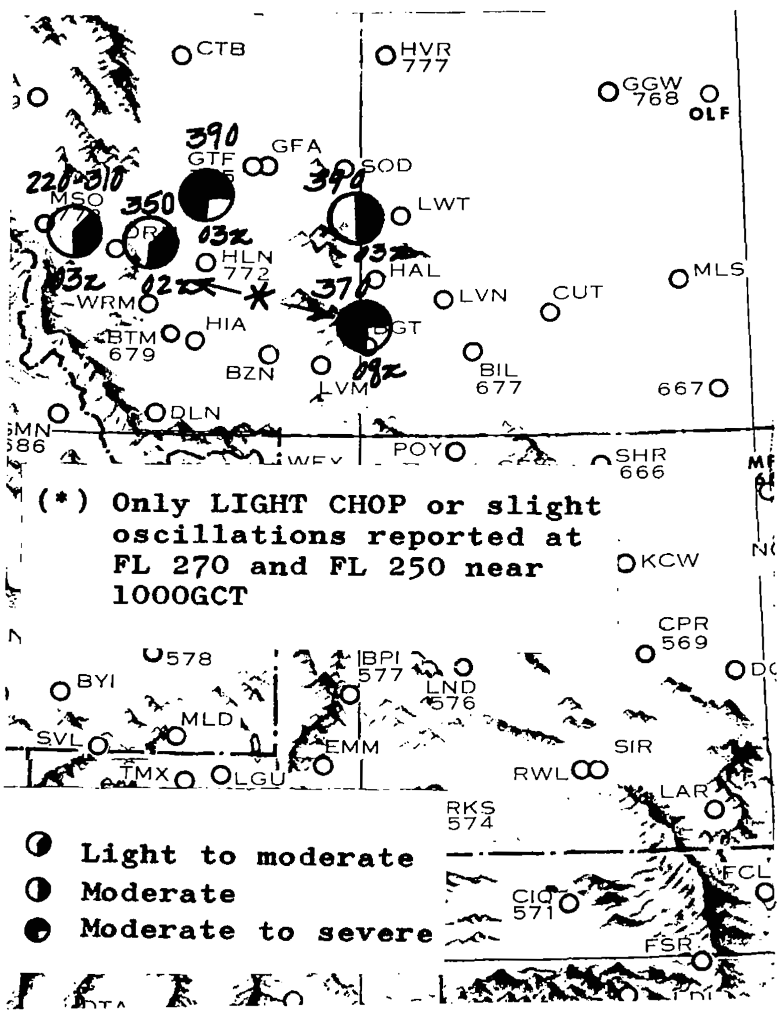


Figure 27. Location and intensity of known clear air turbulence in Montana on March 17, 1964.

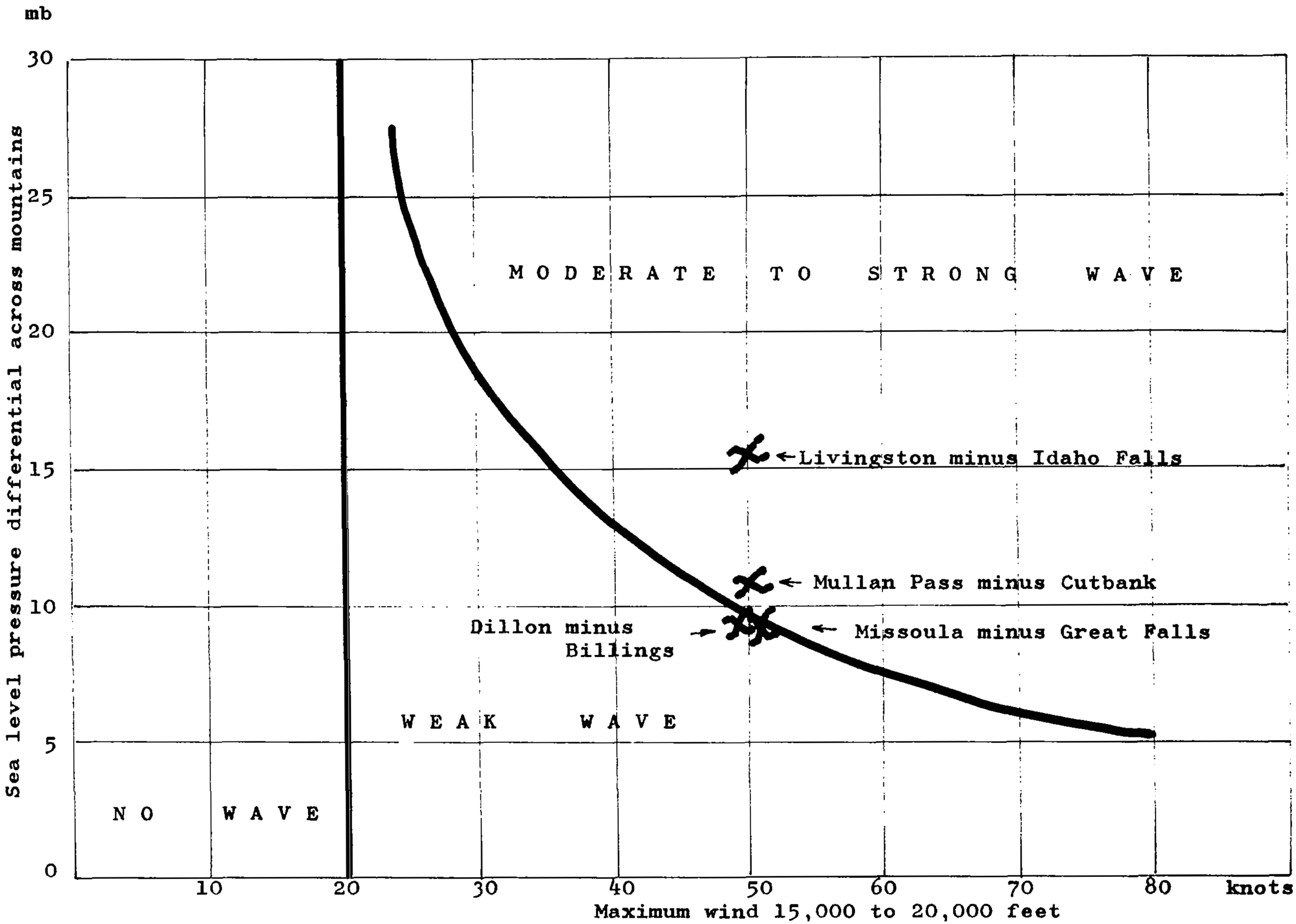


Figure 28. Intensity of the mountain wave in Montana at 0800GCT on March 17, 1964 based on index obtained from the UAL forecasting nomogram.

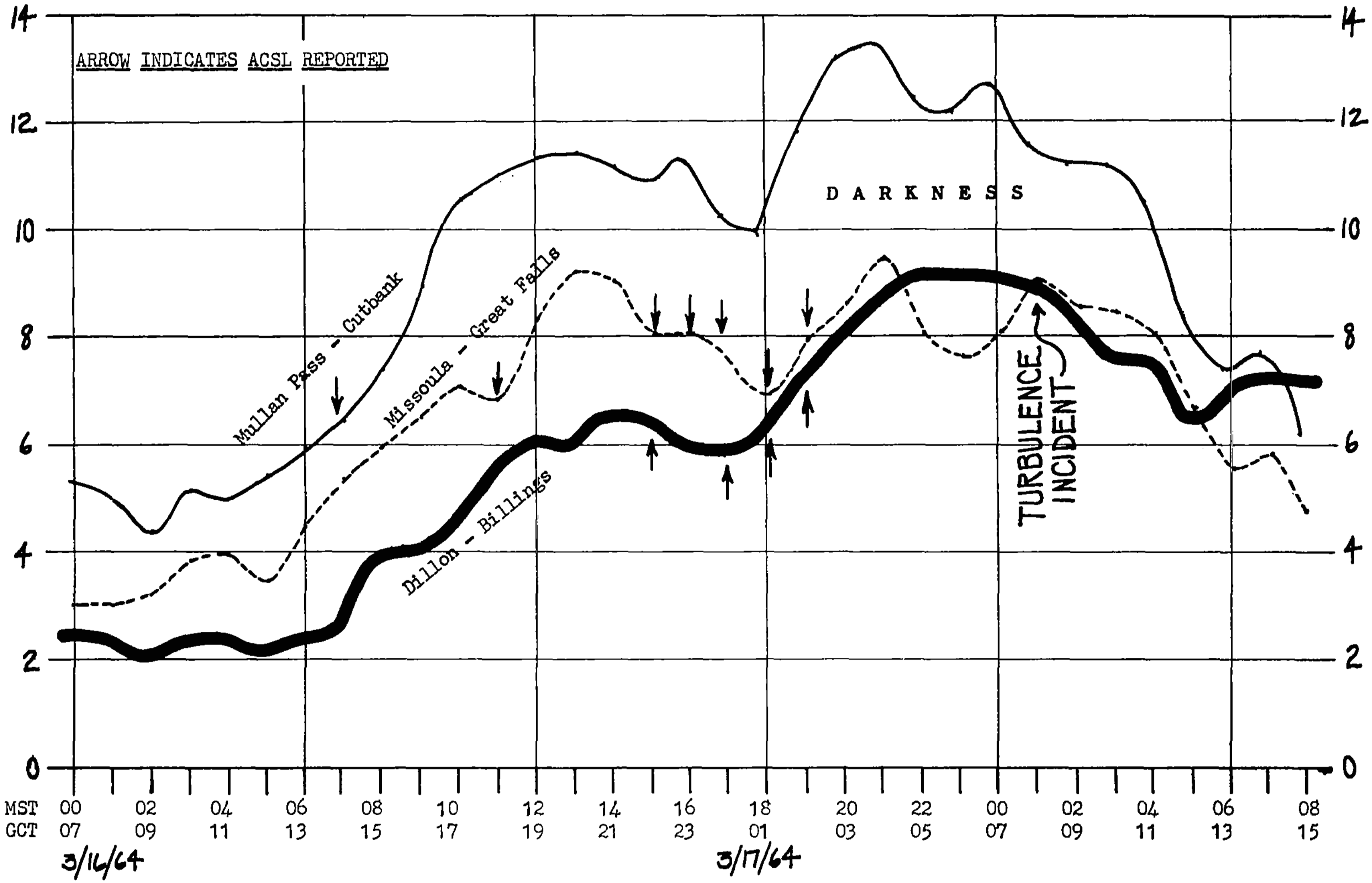


Figure 29. A plot of sea level pressure differences across the mountains in Montana on March 17, 1964. Note the general increase in the gradient as the lee trough sharpened and mountain wave lenticulars began to be reported.

The Clear Air Turbulence Situation at Salt Lake City

1800GCT

April 3, 1964

An extraordinary type of turbulence which caught everybody by surprise, caused delays to airline jet flights and much turbulence to Air Force jets operating in and out of Hill Field. Twelve separate pilot reports of turbulence running from light to moderate to extreme were received over the Salt Lake Valley near midday (local time) on April 3, 1964. One B-57 reported "extreme turbulence at 7,500 feet 5N of Salt Lake City - almost uncontrollable" and there were three other cases of severe clear air turbulence reported. While most was low level there was one case of moderate turbulence at FL 350 by a B-707. Mountain wave rotor clouds formed directly over Salt Lake City Airport causing airline flights to be held on the ground.

General Weather Type

A strong east-wind type of mountain wave was in progress in the lee of the Wasatch Mountains over Salt Lake Valley. Winds were easterly at 45 knots between 10,000 and 20,000 feet and 50 to 65 knots between 25,000 and 38,000 where the tropopause was found. The Salt Lake City Weather Bureau is to be commended for an excellent job of reporting the wave because the suddenness of the appearance of the lenticular clouds and the rotors after daylight with an east wind blowing must have been something of a shock. Lenticulars were reported throughout the day until darkness cut them off. "Roll clouds" were reported along the mountains to the east at 1800GCT which was at about the height of the wave.

While the UAL nomogram was not designed for reverse mountain waves from the east, the index on this day did in fact put the wave in the edge of the moderate to strong category with a wind speed of 45 to 50 knots at 18,000 feet and a sea level pressure difference of 12 millibars between Lander and Salt Lake City.

This spectacular mountain wave was photographed in color by Mr. Philip Williams, meteorologist in charge at the Salt Lake City Weather Bureau, and in black-and-white by Mr. W. B. Beckwith of United Air Lines. Some of Beckwith's Polaroids were taken from a DC-8 cockpit in flight.

Features of Interest

The lesson to be learned from this case is that east winds can produce just as vigorous mountain waves as the conventional west wind types if they are deep enough vertically, if the air mass has at least one stable layer, and provided the terrain profile meets wave requirements. Moreover, it means that east-wind waves will occur several times every winter somewhere over the western part of the country when deep cold LOWS are centered to the south of a N-S mountain range which has a sharp dropoff to the west. The Santa Ana complex in southern California is one example. The case is also proof of the critical role played by the terrain profile. There are numerous instances every winter when strong west winds carry stable air up over the Wasatches but the mountain wave activity that develops on the east side of the range is minor compared to that which resulted in the wave of April 3, 1964. The reason is that the cascading air falls 2,000 more feet on the west side than it does on the east slope.

Steady light to heavy snow fell all day at Evanston on the east side of the Wasatches.

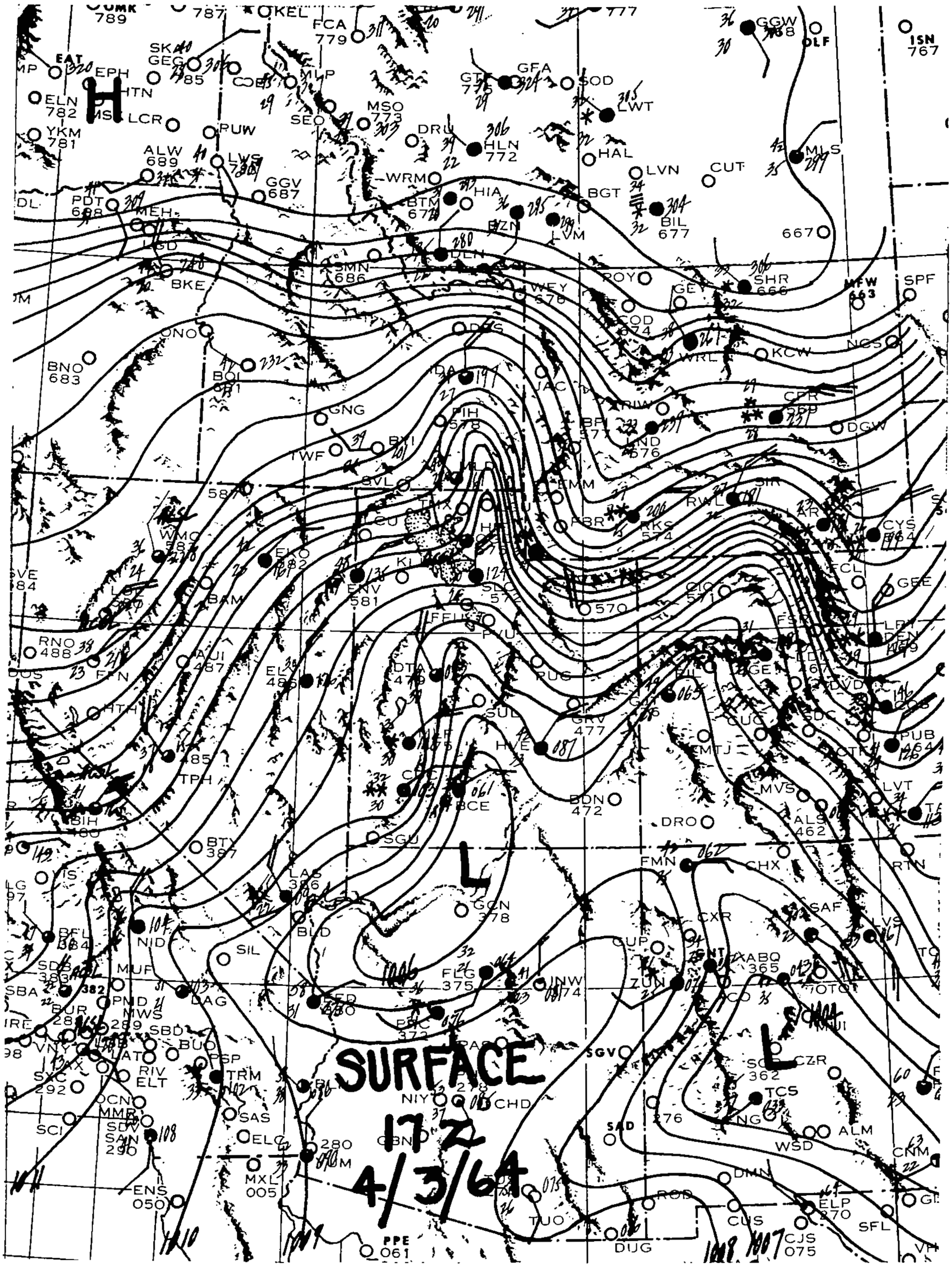


Figure 30. One-millibar sea level isobars over the Rocky Mountains at 1700GCT on April 3, 1964. Note the sharp lee trough induced to the west of the Wasatch Range by east winds of 40 to 50 knots blowing against the east side.

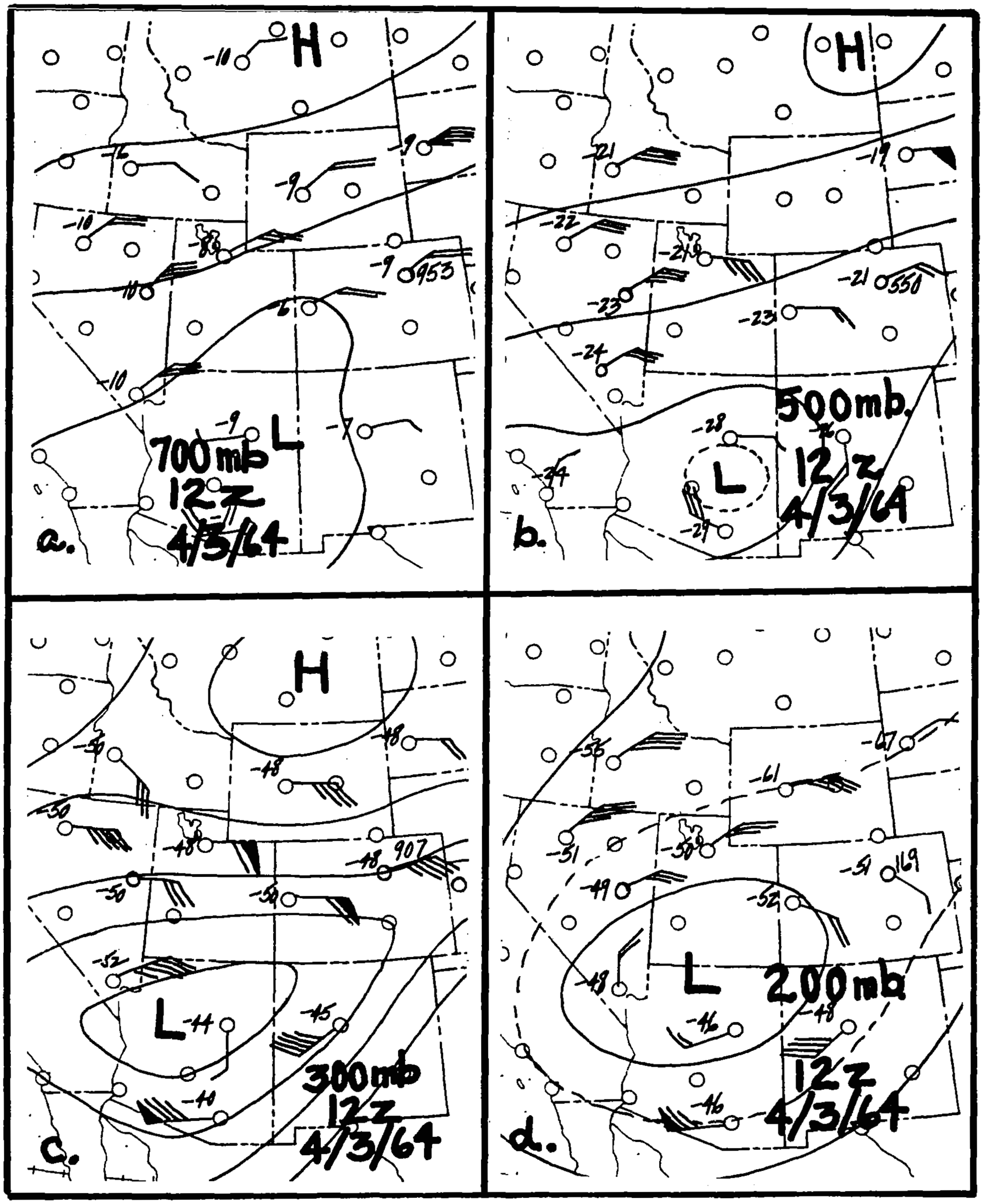


Figure 31. Upper air charts over the Rocky Mountains at 1200GCT on April 3, 1964. a. 700 mb; b. 500 mb.; c. 300 mb; d. 200 mb.

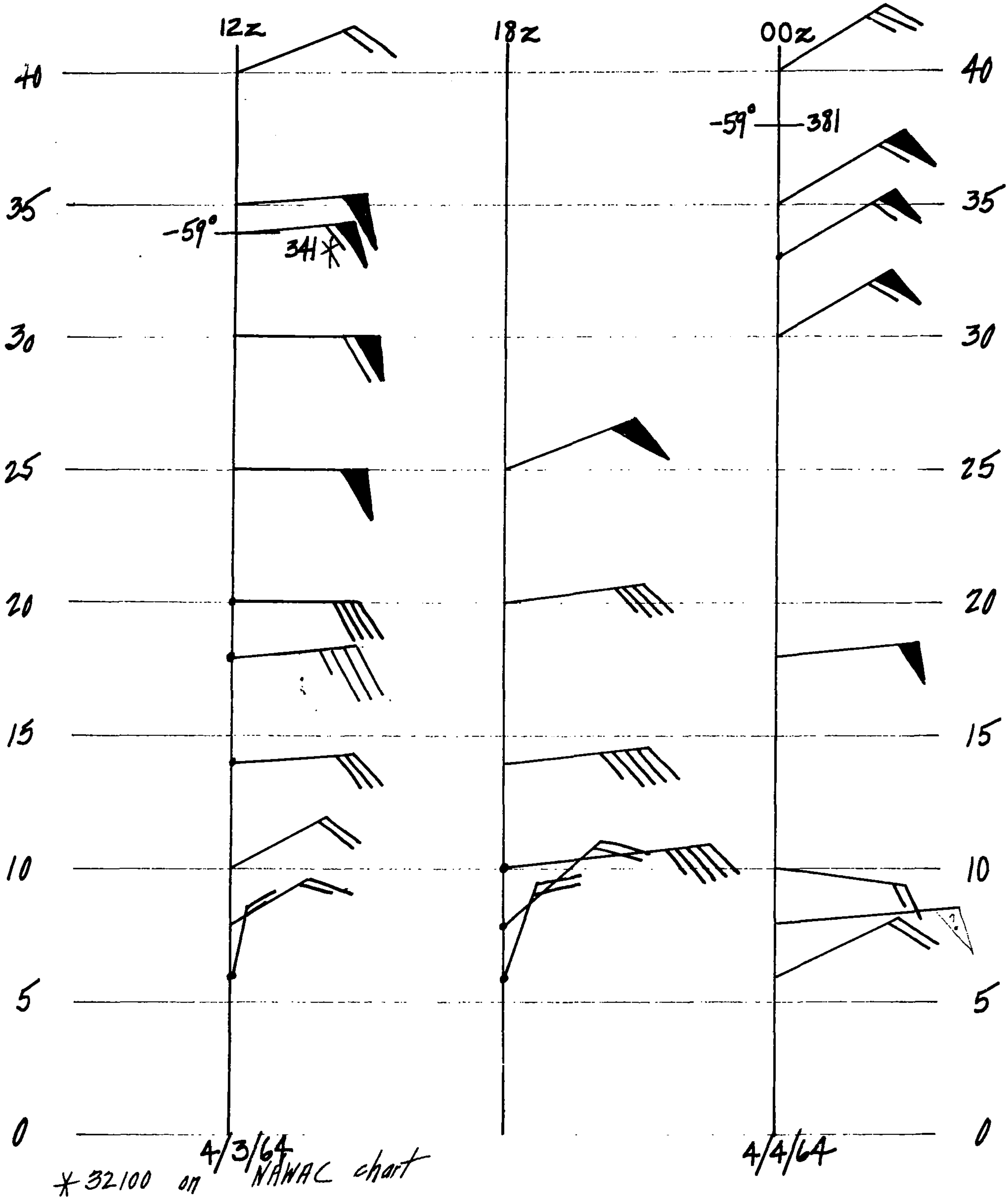


Figure 32. The vertical wind speed profile at Salt Lake City on April 3, 1964. Note the vertical shear of 25 knots in 2,000 feet starting at 8,000 at 1800GCT.

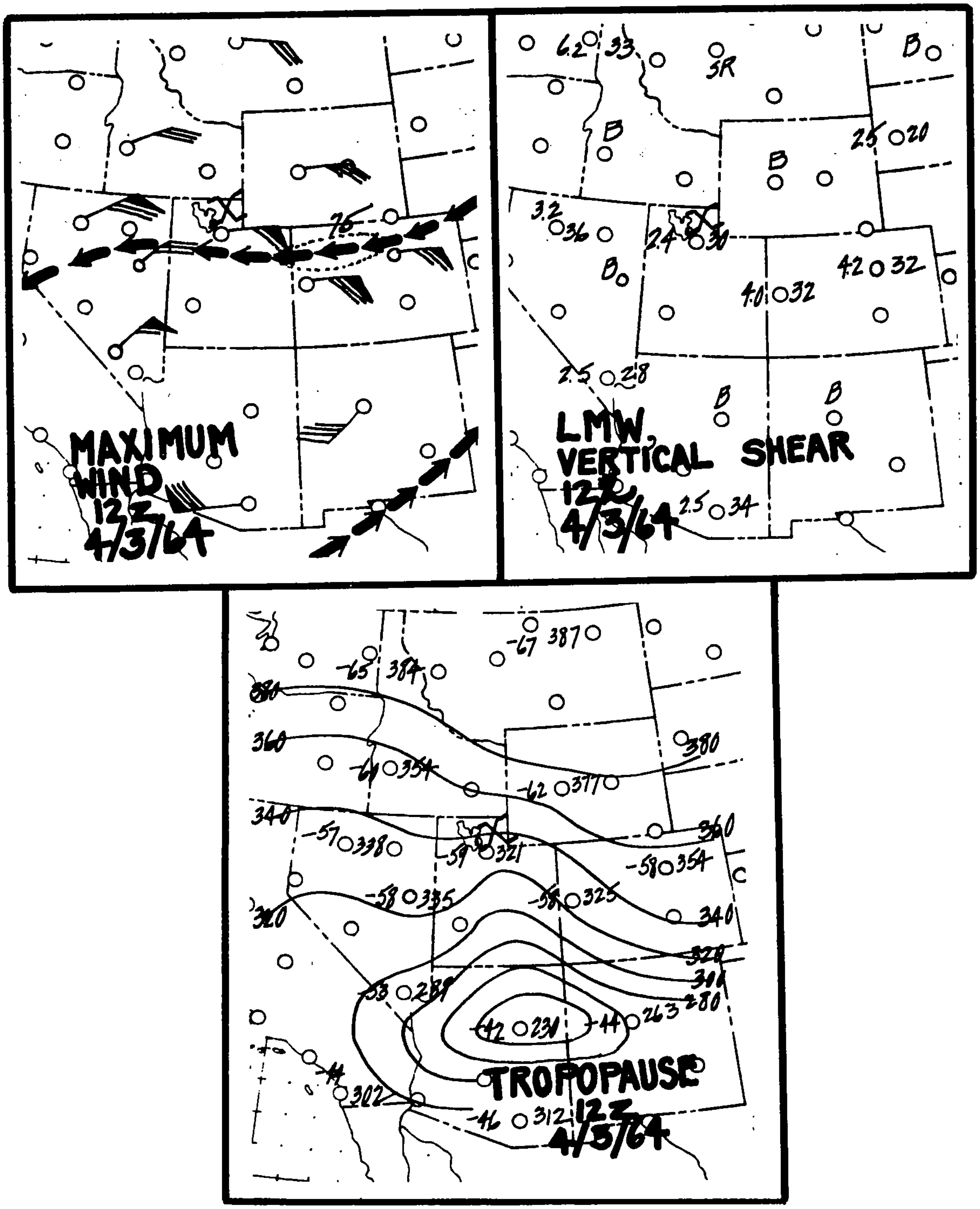


Figure 33. Additional upper air analyses for 1200GCT on April 3, 1964. a. Maximum wind chart; b. Level of maximum wind-vertical shear; c. Tropopause.

SEVERE

B-52 at low levels vicinity SLC
B-57 reported EXTREME at 7,500 5 N of SLC-"almost uncontrollable"
F-101 below 6,500 at 1725Z
C-47 on the approach to Hill AFB at 1725Z

MODERATE TO SEVERE

F-101 surface to 9,000 at 1604Z
T-39 surface to 12,000 at 1415Z
B-727 surface to 10,000 at 21Z

MODERATE

DC-8 surface to 10,000 SLC to 10 west
B-707 at 35,000 near Bonneville at 22Z

LIGHT TO MODERATE

C-47 SW of MLD at 12,000 at 18Z
B-720 SLC to OGD at 11,000 at 16Z
B-57 at 43,000 OGD to SLC

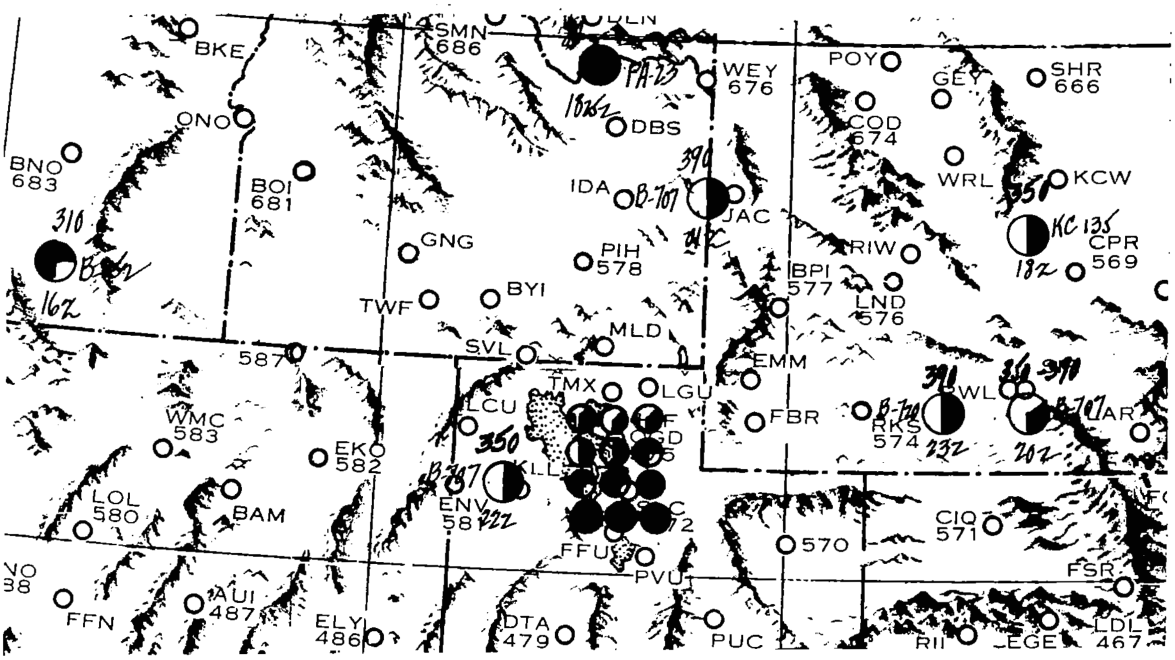


Figure 34. Pilot reports of clear air turbulence over the central Rocky Mountains near midday on April 3, 1964. Note the cluster of 12 reports in the Salt Lake Valley ranging in intensity from light-moderate to extreme.

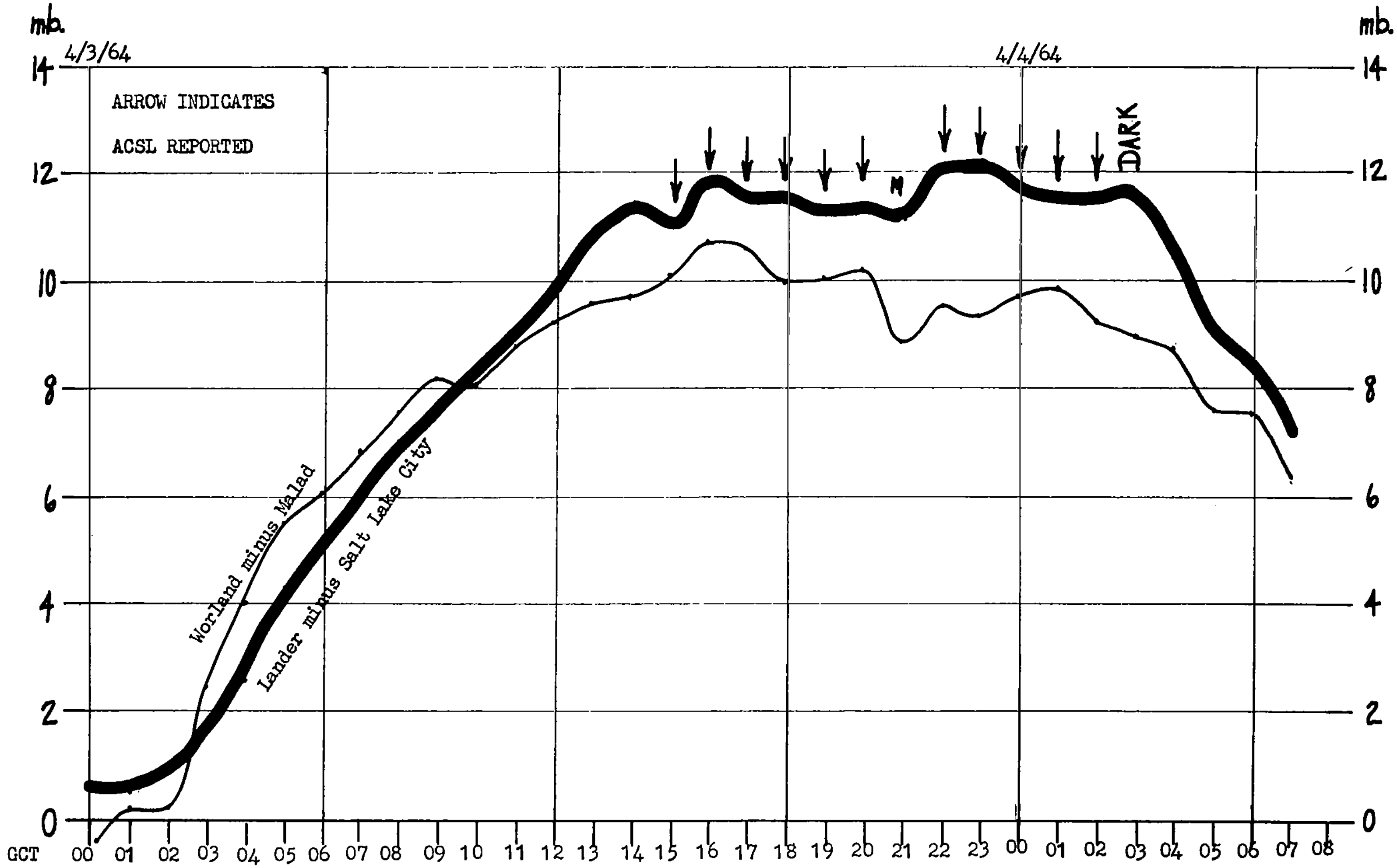


Figure 35. A plot of sea level pressure difference trends across the Wasatch Mountains on April 3, 1964.

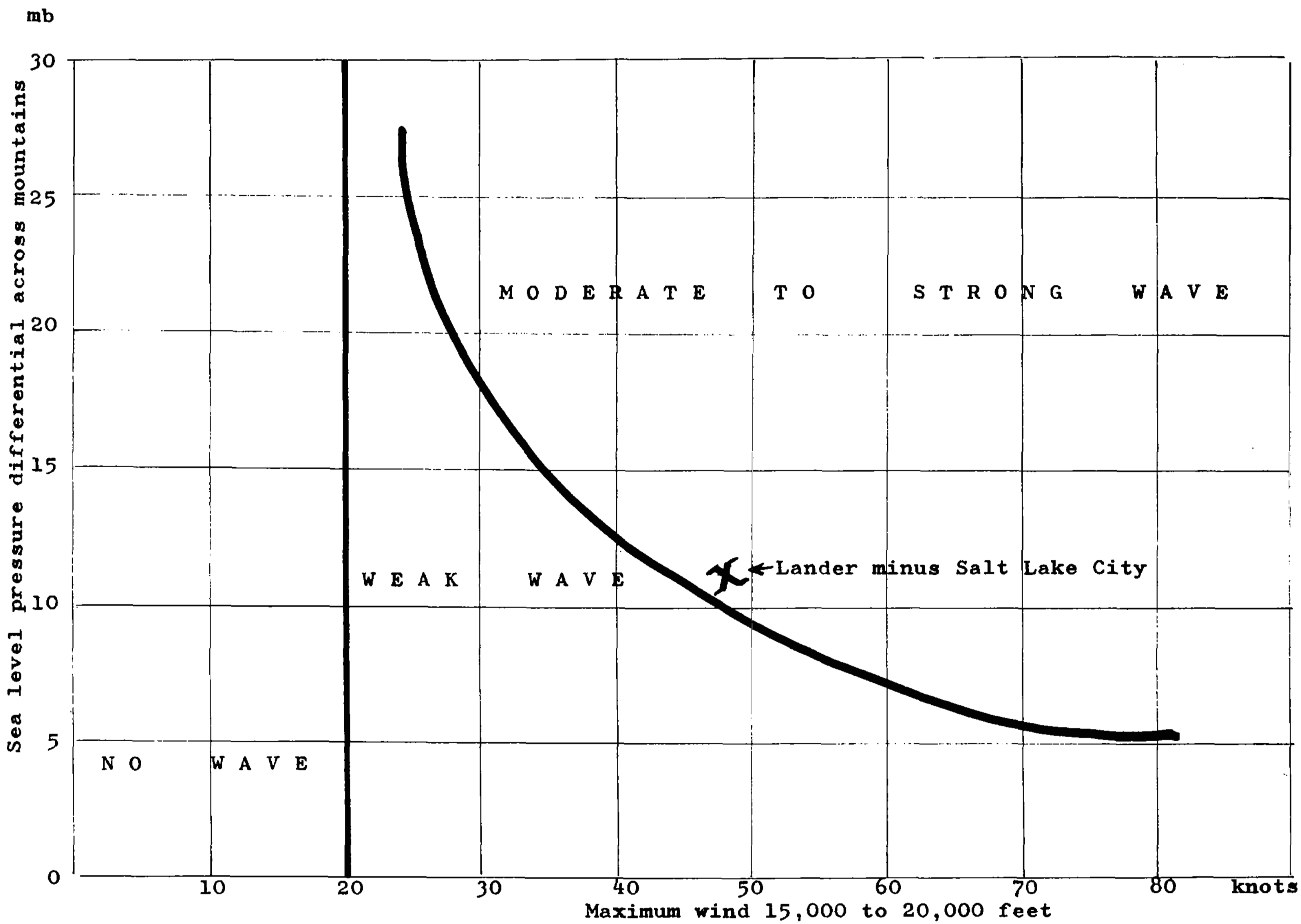


Figure 36. Index of mountain wave intensity at Salt Lake City on April 3, 1964 based on reference to UAL mountain wave forecasting nomogram.

NASA-Langley, 1965
CR-315