



NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety
Washington, D.C. 20594

February 14, 2022

Specialist's Factual Report

METEOROLOGY

CEN22FA035

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A. ACCIDENT

Location: Estes Park, Colorado
Date: November 16, 2021
Time: 1836 mountain standard time (MST)
0136 coordinated universal time (UTC)
Airplane: Air Tractor AT-802A; Registration: N802NZ

B. METEOROLOGY SPECIALIST

Specialist	Donald Eick National Transportation Safety Board Operational Factors Division (AS-30) Washington, D.C.
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C. DETAILS OF THE INVESTIGATION

The National Transportation Safety Board's Senior Meteorologist was not on scene for this investigation and conducted the meteorology phase of the investigation remotely, collecting data from official National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) sources including the Weather Prediction Center (WPC) and the National Center for Environmental Information (NCEI). All times are reported as MST based upon the 24-hour clock, local time is -7 hours from UTC, and UTC=Z. NWS airport and station identifiers use the standard International Civil Aviation Organization 4-letter station identifiers versus the International Air Transport Association 3-letter identifiers, which deletes the initial country code designator "K" for U.S. airports. Directions are referenced to true north and distances in nautical miles. Heights are in feet (ft) above mean sea level (msl) unless otherwise noted. Visibility is in statute miles and fractions of statute miles.

The accident airplane was being operated by Colorado Fire Aviation in support of the Kruger Rock Fire near Estes Park, Colorado. A map of the fire and approximate accident site is included as figure 1. The main wreckage site was estimated at latitude 40.3351° N, longitude 105.4774° W, at an elevation of approximately 8,535 ft.

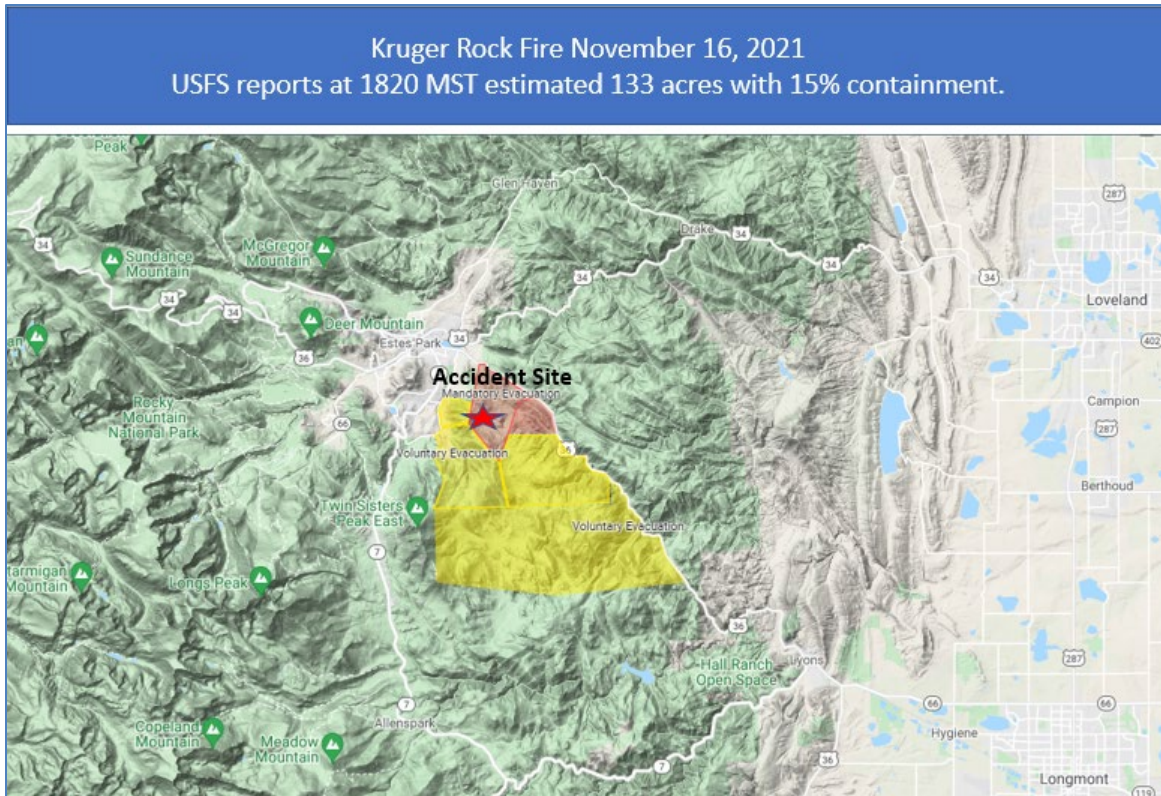


Figure 1 - Kruger Rock Fire on November 16, 2021, with approximate accident site.

The Kruger Fire was first reported about 0650 MST on November 16, 2021, as a small wildfire burning in steep terrain near Little Valley Road and Fish Creek Road, southeast of Estes Park. The cause of the fire was determined to be high winds that blew a tree onto a nearby powerline, causing the line to arc and start the fire. According to the forestry service the gusting winds, higher than normal temperatures, and low relative humidity caused the fire to spread quickly and threatened several structures in the area and resulted in multiple voluntary and mandatory evacuations across the region. The terrain where most of the fire was burning made it too dangerous to insert firefighters to battle the fire directly, and Incident Commanders requested the use of air drops from aviation resources to fight the fire.

D. FACTUAL INFORMATION

1.0 Synoptic Conditions

The synoptic or large-scale migratory weather systems influencing the area were documented using standard NWS charts issued by the National Center for Environmental Prediction (NCEP) and the WPC located in College Park, Maryland. These are the base products used in describing weather features and in the creation of forecasts and warnings. Reference to these charts can be found in the joint NWS

and Federal Aviation Administration (FAA) Advisory Circular "Aviation Weather Services", AC 00-45H change 2¹.

1.1 Surface Analysis Chart

The NWS Surface Analysis Chart valid for 1700 MST (0000Z) centered over Colorado is included as figure 2 and depicted a low-pressure system at 1001-hectopascals (hPa)² over Nebraska with a cold front extending southwestward across northern Colorado to another low-pressure system along a frontal wave over northeastern Utah. A high-pressure system at 1017-hPa was located over southwestern Colorado, with a mesoscale ridge extending northeastward over the general vicinity of the accident site. The accident site was located immediately south of the cold front in an area of a strong pressure gradient³. The station models immediately surrounding the accident site depicted westerly winds at 20 to 40 knots, clear to scattered clouds, with temperatures ranging from 60° F ahead of the front to 39° F over southern Wyoming northwest of the accident site and on the cold-air side of the front.

¹https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1030235

² Hectopascal is the standard unit for reporting sea-level pressure and is interchangeable with the term millibar (mb) with the same units. Standard sea-level pressure is 1013.25-hPa at 59° Fahrenheit (F) or 15° Celsius (C).

³ The rate of change in pressure between the high and the low-pressure areas was 16-hPa per 250 nm.

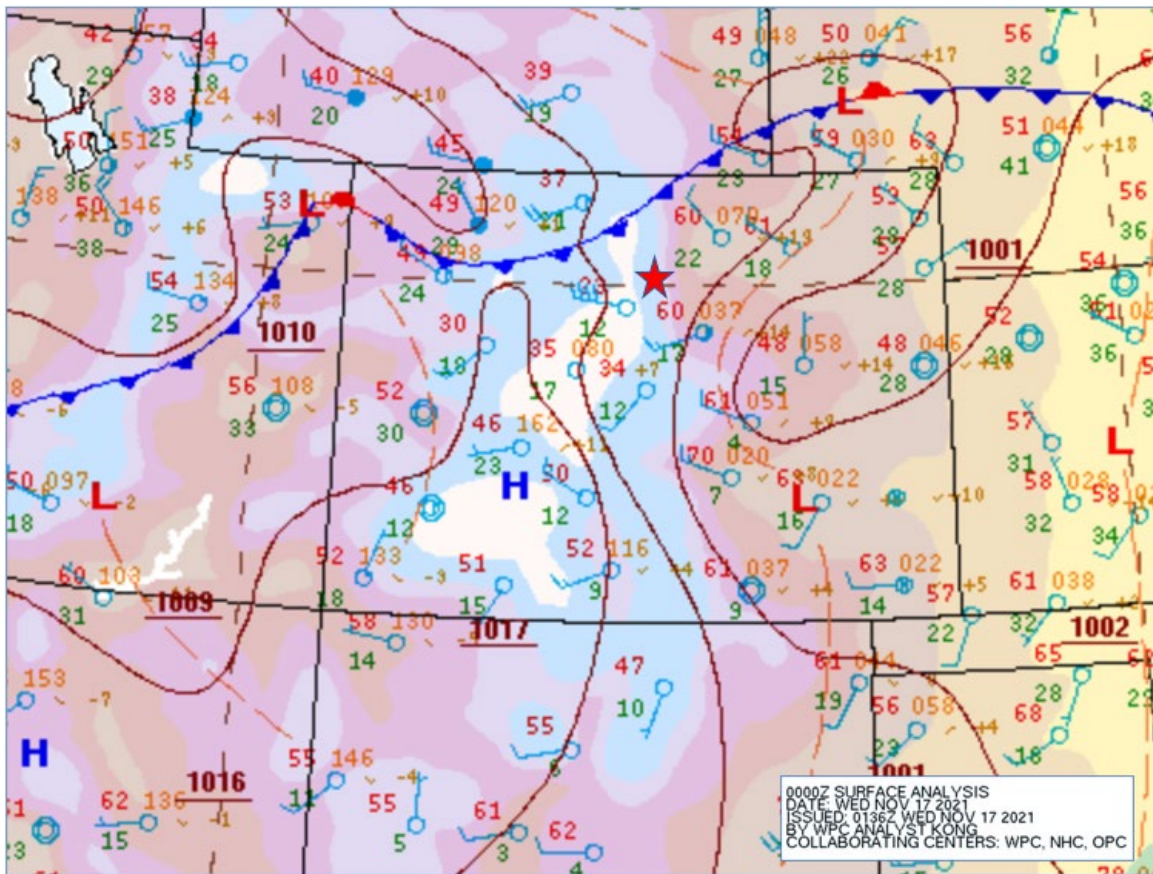


Figure 2 - NWS Surface Analysis Chart for 1700 MST over Colorado with the accident site.

The next NWS Surface Analysis chart for 2000 MST immediately after the accident is included as figure 3 with the approximate accident site marked. The chart depicted the low pressure system over Nebraska (figure 2) having moved southward into eastern Colorado now at 1006-hPa with the cold front extending westward across Colorado and located south of the accident site. The station models surrounding the accident site depicted west-northwest winds at 40 knots, with scattered to broken skies to the west and northwest of the accident site, with temperatures at 51°F immediately east and 32° F to the northwest of the accident site.

According to the FAA Advisory Circular AC 00-6B "Aviation Weather", the passage of the cold front is typically associated with a decrease then rise in sea-level pressure, a wind shift, potential frontal wind shear, and a gradually decreasing temperatures and relative humidities as the colder and often drier air advects into the area.

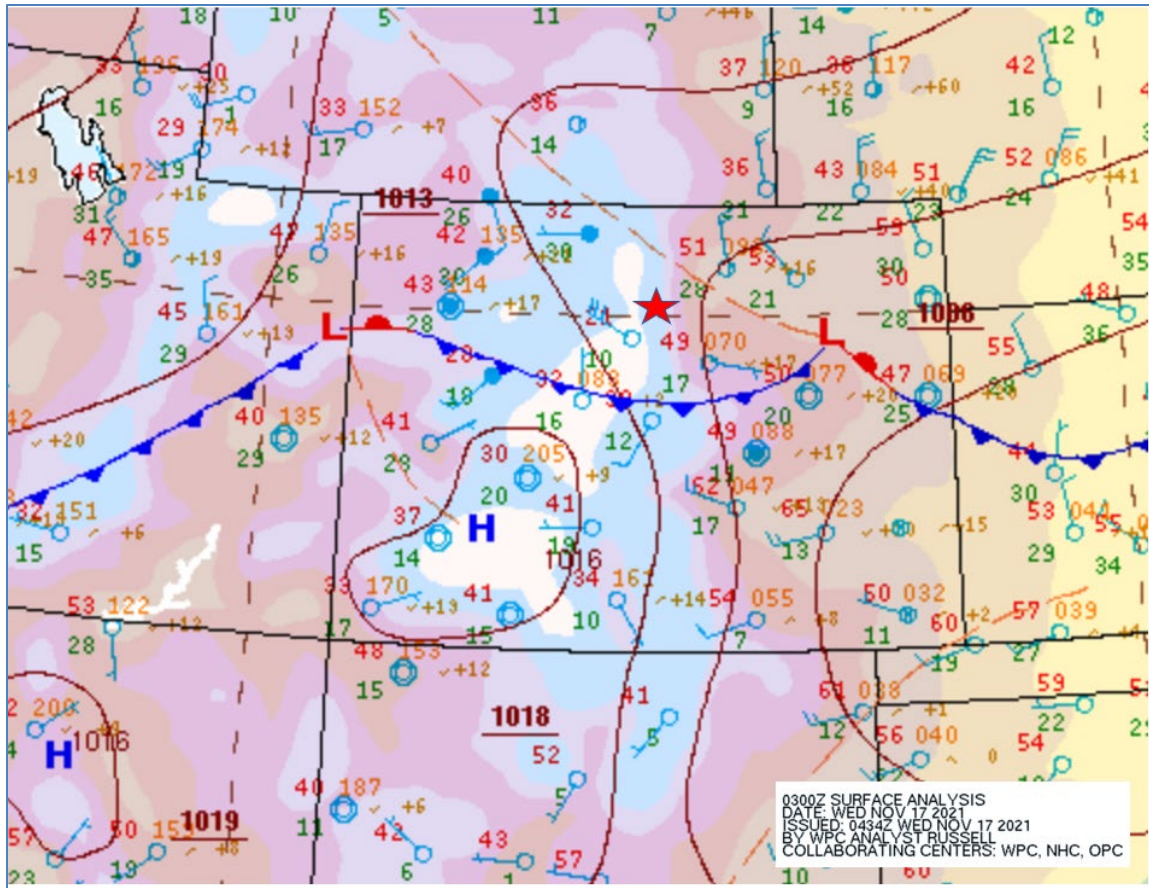


Figure 3 - NWS Surface Analysis Chart for 2000 MST over Colorado with the accident site.

1.2 Short Range Forecast

The NWS 6-hour Short Range Forecast valid for 2200 MST is included as figure 4 with the approximate accident site marked by the red star. The chart depicted the low-pressure system (figures 1 and 2) having moved from southwestern Nebraska and eastern Colorado to central Kansas with the cold front extending northwestward across Colorado into the second low-pressure system now expected to be immediately west of the accident site. A cold-core high-pressure system was depicted over Idaho. An area of snow and mixed precipitation was depicted in the vicinity of the accident site.

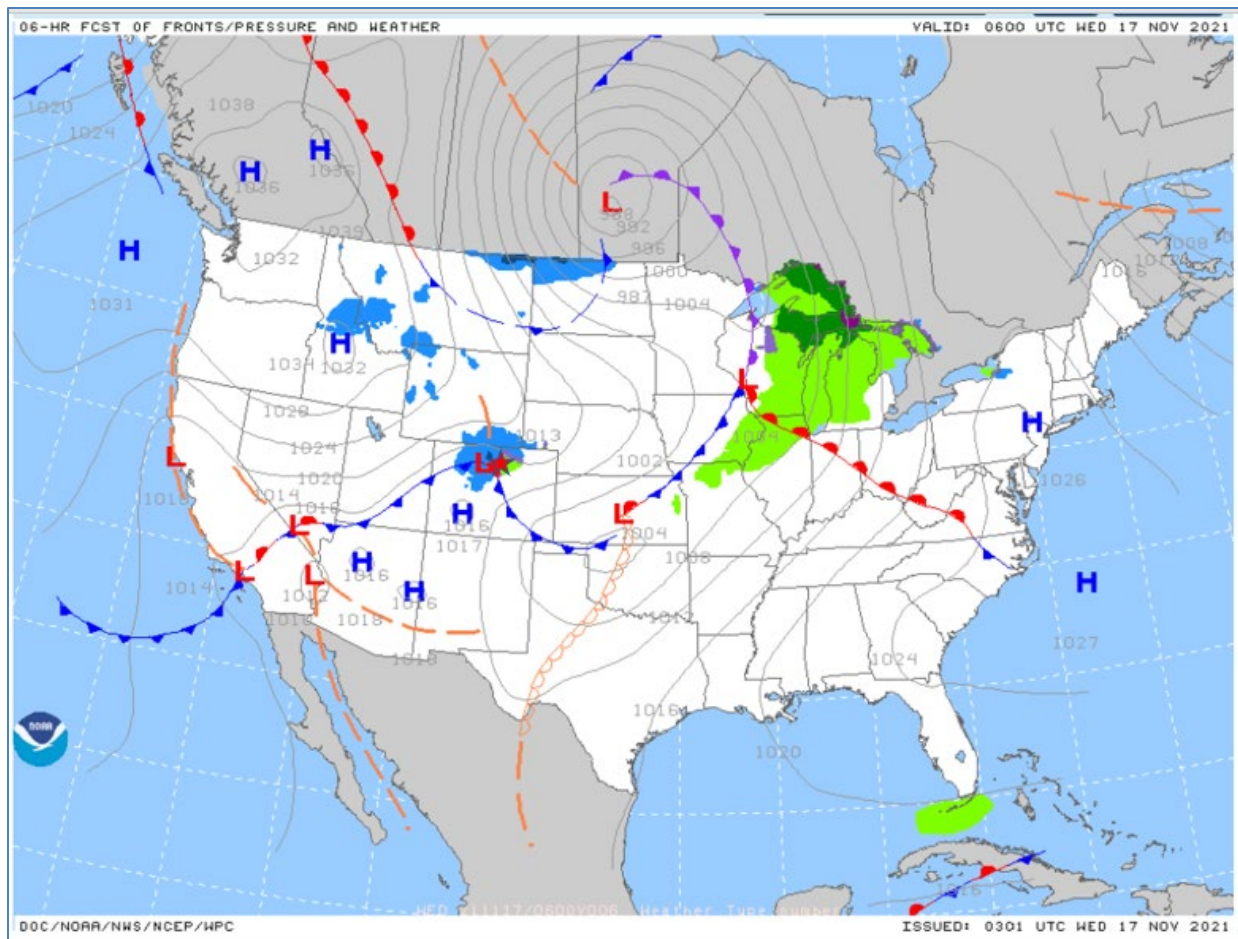


Figure 4 - NWS 6-hour Short Range Forecast valid for 2200 MST with the accident site marked.

1.3 Constant Pressure Charts

The constant pressure charts for 1700 MST obtained from the University of Wyoming archive⁴ site for 700-, 500-, 300-, 250- and 200-hPa are included as figures 5 through 9, which depicted the conditions at approximately 10000 ft, 18000 ft, 30000 ft, and 39000 ft, respectively. The charts provided contour lines of equal height, isotherms of equal temperature, with the 300-, 250-, and 200-hPa charts included color shaded isotachs of equal wind speeds greater than 70 kts in alternating color shades. The closest station model to the accident site was from Denver/Stapleton (KDNR), which provided the following information on height (meters), wind direction and speed, temperature, and temperature-dew point depression, which are provided in the following table.

⁴ <http://weather.uwyo.edu/upperair/uamap.shtml>

Level	Height	Wind	Temperature	T-Td depression
700	3,027 m (9931 ft)	260° 34 kts	6° C	18° C
500	5,670 m (18,602 ft)	295° 38 kts	-15° C	33° C
300	9,330 m (30,610 ft)	250° 73 kts	-42° C	5° C
250	10,530 m (34,547 ft)	245° 100 kts	-51° C	10° C
200	11,950 m (39,206 ft)	240° 107 kts	-63° C	15° C

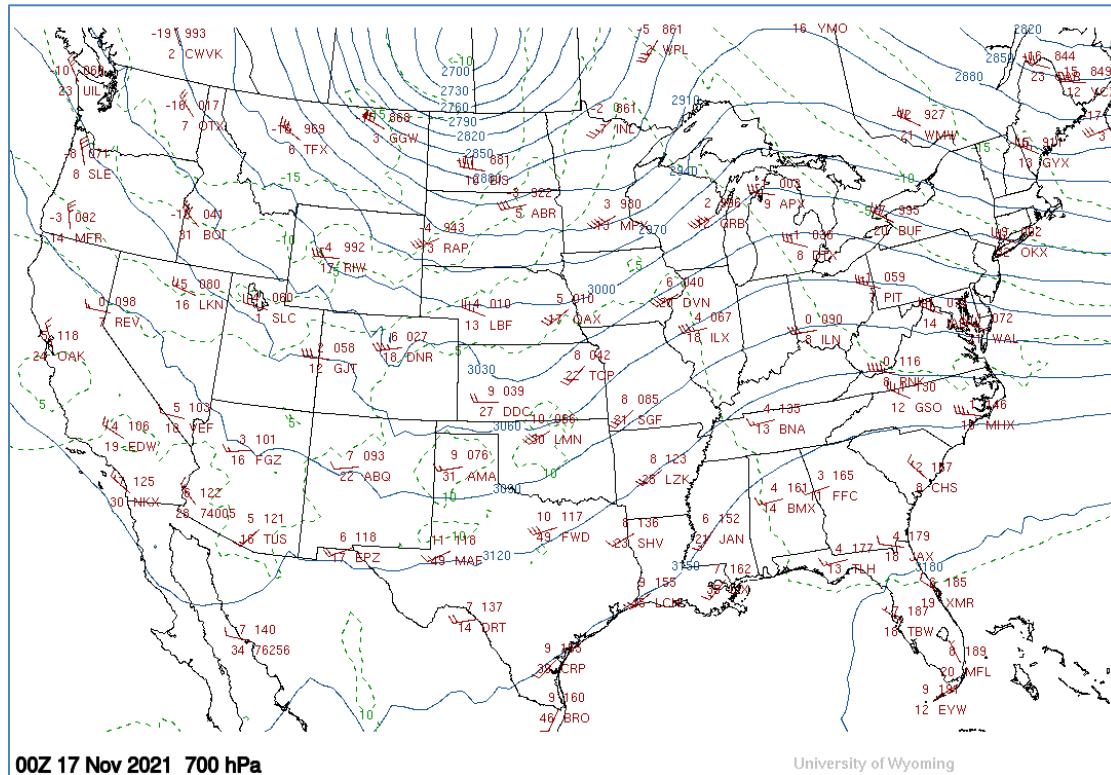


Figure 5 - 700-hPa Constant Pressure Chart for 1700 MST.

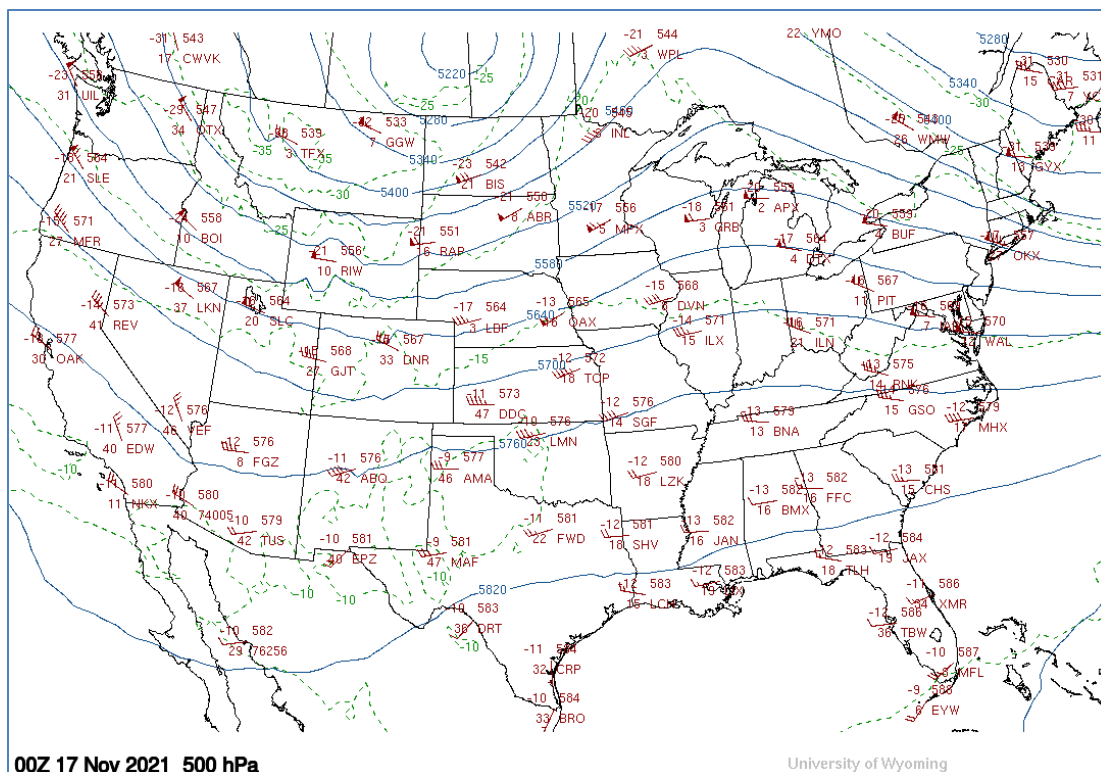


Figure 6 - 500-hPa Constant Pressure Chart for 1700 MST.

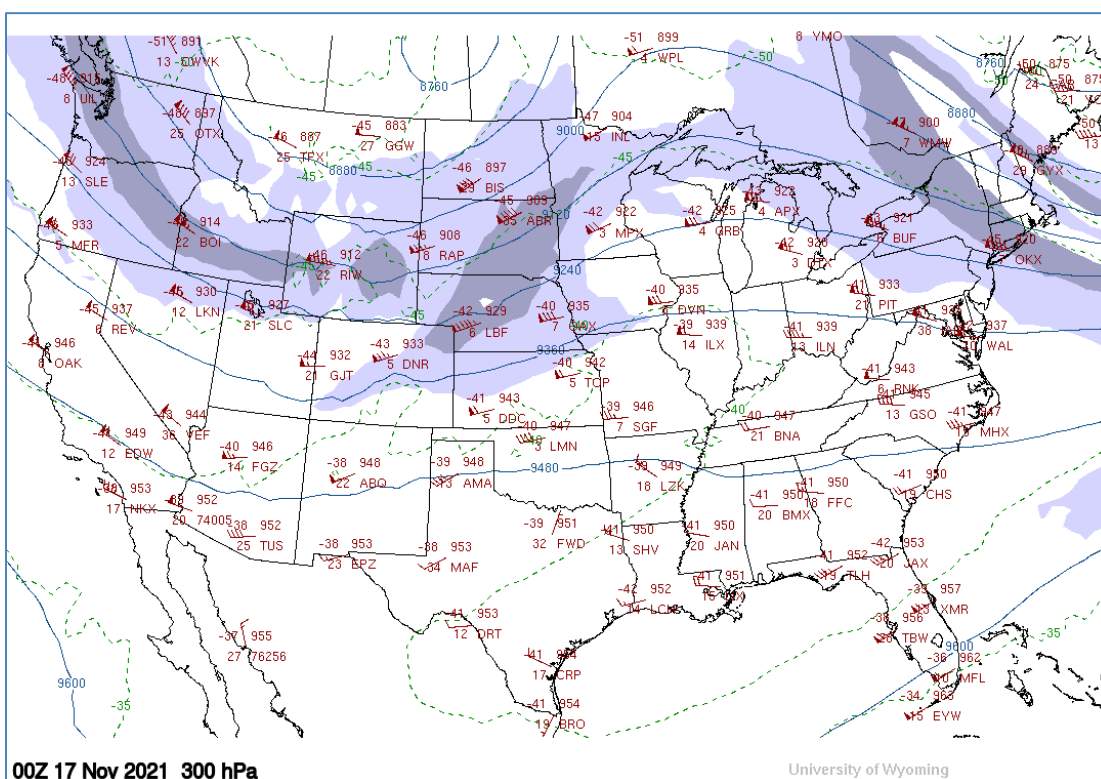
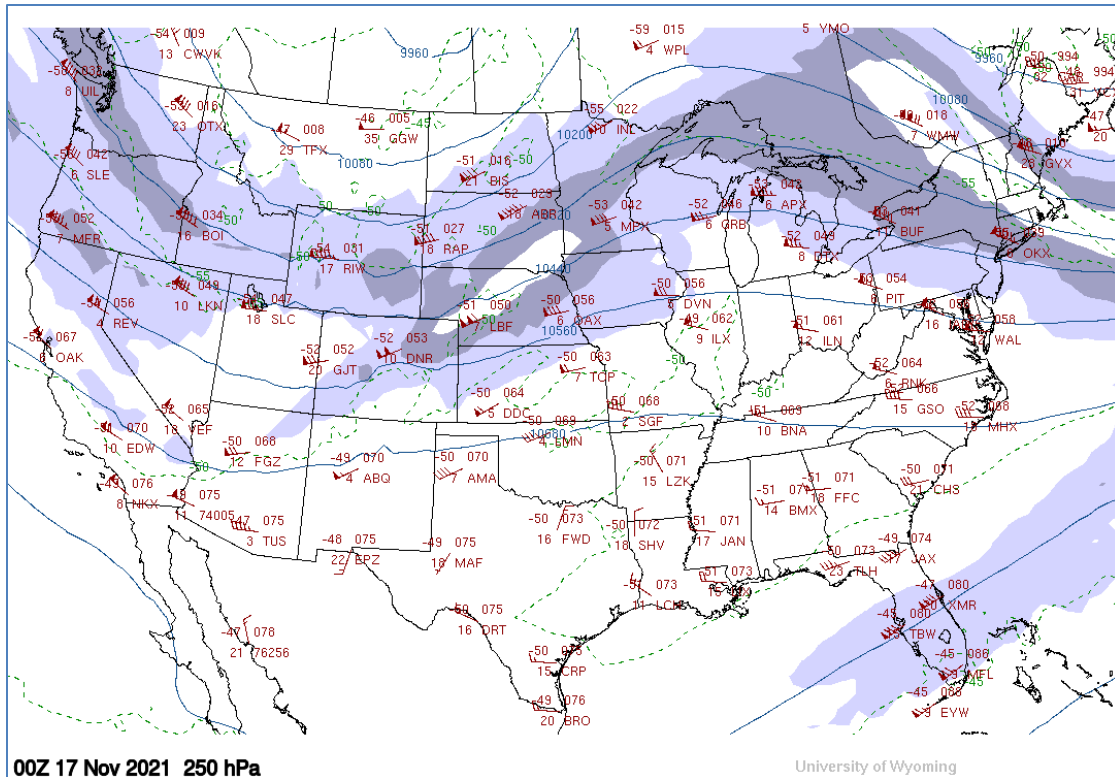


Figure 7 - 300-hPa Constant Pressure Chart for 1700 MST.



The upper air charts for 1700 MST depicted winds with 30° normal to the Rocky Mountains with winds of greater than 30 knots at the ridge level and increasing with height to 100 knots at 34,000 ft and 39,000 ft with little directional variation with height. The constant pressure charts wind profiles were favorable for the formation of mountain wave activity over Colorado during the period (section 12.0).

2.0 Surface Observations

The official observations issued surrounding the accident site were documented using Aviation Routine Weather Reports (METAR⁵) and Aviation Select Special Weather Reports (SPECI). Cloud heights are reported above ground level (agl) in the following section, and the magnetic variation was estimated at 8.5° east based on the latest sectional chart for the area.

2.1 Longmont, Colorado

The closest official weather reporting site was Vance Brand Airport (KLMO), Longmont, CO, located about 18 miles southeast of the accident site at an elevation of 5,055 ft. The airport had an Automated Weather Observation System (AWOS), which was not augmented by any human observers. The following conditions were reported at the approximate time of the accident.

Routine weather observation for KLMO at 1835 MST, automated, wind from 200° at 11 knots gusting to 17 knots, wind 170° variable 230°, visibility 10 miles or more, scattered clouds at 11,000 ft agl, temperature 17° Celsius (C), dew point temperature -8° C, altimeter setting 29.78 inches of mercury (inHg). Remarks; automated station with a precipitation discriminator, temperature 16.6° C, dew point temperature -8.4° C.

The raw observations in standard format and code between 0935 through 2135 MST to document the winds surrounding the period were as follows, with the observation above and accident time in bold type for reference.

METAR KLMO 161635Z AUTO 33004G08KT 10SM CLR 19/M06 A2975 RMK AO2 T01941057
METAR KLMO 161655Z AUTO 28011G27KT 250V330 10SM CLR 21/M07 A2975 RMK AO2 T02051071
METAR KLMO 161715Z AUTO 26020G35KT 10SM CLR 22/M09 A2974 RMK AO2 T02161094
METAR KLMO 161735Z AUTO 27020G35KT 10SM CLR 22/M09 A2974 RMK AO2 T02161086
METAR KLMO 161755Z AUTO 26021G30KT 10SM CLR 22/M09 A2974 RMK AO2 T02181088 10219
20158
METAR KLMO 161815Z AUTO 25018G27KT 10SM CLR 22/M09 A2974 RMK AO2 T02181090
METAR KLMO 161835Z AUTO 26012G24KT 10SM CLR 22/M09 A2972 RMK AO2 T02231089
METAR KLMO 161855Z AUTO 24015G24KT 10SM CLR 23/M09 A2970 RMK AO2 T02251091
METAR KLMO 161915Z AUTO 26018G28KT 10SM CLR 23/M09 A2970 RMK AO2 T02261088

⁵ Abbreviation for Meteorological Aerodrome Report, the international standard for weather observations.

METAR KLMO 161935Z AUTO 29012G20KT 10SM CLR 23/M08 A2971 RMK AO2 T02301084
 METAR KLMO 161955Z AUTO 31011G32KT 10SM CLR 23/M08 A2970 RMK AO2 T02271081
 METAR KLMO 162015Z AUTO 32016G20KT 10SM CLR 24/M08 A2970 RMK AO2 T02401080
 METAR KLMO 162035Z AUTO 29012G20KT 10SM CLR 24/M08 A2971 RMK AO2 T02411081
 METAR KLMO 162055Z AUTO 25021G33KT 10SM CLR 23/M08 A2973 RMK AO2 T02301083
 METAR KLMO 162115Z AUTO 24016G29KT 10SM CLR 22/M08 A2974 RMK AO2 T02171077
 METAR KLMO 162135Z AUTO 25009G19KT 10SM CLR 21/M07 A2975 RMK AO2 T02091073
 METAR KLMO 162155Z AUTO 28016G25KT 10SM CLR 21/M07 A2977 RMK AO2 T02071070
 METAR KLMO 162215Z AUTO 22012G20KT 10SM CLR 20/M06 A2977 RMK AO2 T02001065
 METAR KLMO 162235Z AUTO 20009G15KT 10SM CLR 20/M07 A2977 RMK AO2 T01961066
 METAR KLMO 162255Z AUTO 24016G21KT 10SM CLR 18/M06 A2977 RMK AO2 T01821064
 METAR KLMO 162315Z AUTO 25005G16KT 10SM CLR 18/M06 A2977 RMK AO2 T01761061
 METAR KLMO 162335Z AUTO 23005G14KT 10SM CLR 17/M06 A2976 RMK AO2 T01711060
 METAR KLMO 162355Z AUTO 31005KT 10SM CLR 17/M06 A2976 RMK AO2 T01651063 10243 20163
 METAR KLMO 170015Z AUTO 00000KT 10SM CLR 16/M07 A2976 RMK AO2 T01621066
 METAR KLMO 170035Z AUTO 00000KT 10SM CLR 17/M07 A2978 RMK AO2 T01651066
 METAR KLMO 170055Z AUTO 08006KT 10SM SCT110 14/M06 A2978 RMK AO2 T01431058=
 METAR KLMO 170115Z AUTO 01004KT 10SM SCT110 14/M06 A2978 RMK AO2 T01361062=
**METAR KLMO 170135Z AUTO 20011G17KT 170V230 10SM SCT110 17/M08 A2978 RMK AO2
 T01661084=**

Accident 0136Z

METAR KLMO 170155Z AUTO 24018G22KT 10SM CLR 17/M08 A2977 RMK AO2 T01661084=
 METAR KLMO 170215Z AUTO 25018G29KT 10SM CLR 17/M08 A2978 RMK AO2 T01691084=
 METAR KLMO 170235Z AUTO 23014G23KT 10SM CLR 17/M08 A2981 RMK AO2 T01671085
 METAR KLMO 170255Z AUTO 24016G26KT 10SM CLR 17/M08 A2982 RMK AO2 T01651079
 METAR KLMO 170315Z AUTO 24011G20KT 10SM CLR 16/M07 A2983 RMK AO2 T01611075
 METAR KLMO 170335Z AUTO 26008G15KT 10SM CLR 16/M07 A2985 RMK AO2 T01571070
 METAR KLMO 170355Z AUTO 25013G18KT 220V280 10SM CLR 15/M07 A2986 RMK AO2 T01541070
 METAR KLMO 170415Z AUTO 25007G10KT 10SM CLR 16/M07 A2987 RMK AO2 T01551070
 METAR KLMO 170435Z AUTO 00000KT 10SM CLR 11/M04 A2989 RMK AO2 T01131041

A review of the observations indicated westerly winds gusting from 20 to 35 knots from approximately 0955 through 1500 MST, with winds backing or changing anti-cyclonically to the southwest with decreasing winds through 1600 MST. Wind speeds decreased to less than 10 knots between 1600 through 1815 MST and shifted to the east. Winds again shifted to the south to west-southwest at 1835 MST with wind speeds increasing again immediately prior to the accident with gusts to 29 knots at 1915 MST before decreasing again at 2115 MST.

2.2 Boulder, Colorado

The next closest official weather reporting site was Boulder Municipal Airport (KBDU), Boulder, CO, located 21.5 miles south-southeast of the accident site at an elevation of 5,288 ft. The airport also had an AWOS which was not augmented and reported the following conditions at the time of the accident.

Routine weather observation for KBDU at 1835 MST, automated, wind from 070° at 5 knots, visibility 10 miles or more, scattered clouds at 11,000 ft agl,

temperature 14° C, dew point temperature -7° C, altimeter setting 29.77 inHg.
Remarks; automated station with a precipitation discriminator.

The raw observation between 1315 through 2155 MST were as follows.

METAR KBDU 162015Z AUTO 27016G30KT 10SM CLR 21/M07 A2970 RMK AO2
METAR KBDU 162035Z AUTO 30012G19KT 272V342 10SM CLR 22/M07 A2971 RMK AO2
METAR KBDU 162055Z AUTO 27014G29KT 10SM CLR 21/M07 A2971 RMK AO2
METAR KBDU 162115Z AUTO 29016G26KT 10SM CLR 21/M07 A2972 RMK AO2
METAR KBDU 162135Z AUTO 25011G20KT 10SM CLR 20/M07 A2973 RMK AO2
METAR KBDU 162155Z AUTO 24006G24KT 242V002 10SM CLR 20/M06 A2973 RMK AO2
METAR KBDU 162215Z AUTO 24021G34KT 10SM CLR 18/M06 A2974 RMK AO2
METAR KBDU 162235Z AUTO 24014G31KT 212V282 10SM CLR 18/M05 A2974 RMK AO2
METAR KBDU 162255Z AUTO 24011G21KT 172V262 10SM CLR 17/M06 A2974 RMK AO2
METAR KBDU 162315Z AUTO 25007G21KT 10SM CLR 16/M06 A2974 RMK AO2
METAR KBDU 162335Z AUTO 00000KT 10SM CLR 16/M06 A2974 RMK AO2
METAR KBDU 162355Z AUTO 17005KT 10SM CLR 15/M06 A2974 RMK AO2
METAR KBDU 170015Z AUTO 00000KT 10SM CLR 15/M07 A2974 RMK AO2
METAR KBDU 170035Z AUTO 00000KT 10SM CLR 15/M07 A2974 RMK AO2
METAR KBDU 170055Z AUTO 07007KT 10SM SCT110 15/M06 A2976 RMK AO2=
METAR KBDU 170115Z AUTO 36006KT 10SM SCT110 14/M07 A2976 RMK AO2=
**METAR KBDU 170135Z AUTO 07005KT 10SM SCT110 14/M07 A2977 RMK AO2=
Accident 0136Z**
METAR KBDU 170155Z AUTO 13004KT 10SM CLR 12/M06 A2978 RMK AO2=
METAR KBDU 170215Z AUTO 00000KT 10SM CLR 13/M07 A2979 RMK AO2=
METAR KBDU 170235Z AUTO 00000KT 10SM CLR 13/M06 A2980 RMK AO2
METAR KBDU 170255Z AUTO 11003KT 10SM CLR 13/M06 A2982 RMK AO2
METAR KBDU 170315Z AUTO 12003KT 10SM CLR 12/M06 A2983 RMK AO2
METAR KBDU 170335Z AUTO 09006KT 10SM CLR 14/M07 A2983 RMK AO2
METAR KBDU 170355Z AUTO 11007KT 10SM SCT100 13/M06 A2985 RMK AO2
METAR KBDU 170415Z AUTO 15004KT 10SM BKN100 12/M06 A2986 RMK AO2
METAR KBDU 170435Z AUTO 21006KT 10SM BKN100 13/M07 A2986 RMK AO2
METAR KBDU 170455Z AUTO 07006KT 10SM OVC100 10/M05 A2988 RMK AO2

Westerly to southwesterly winds were reported during the afternoon gusting to 34 knots and the winds subsided around 1700 MST, then shifted to the northeast at the time of the accident. No secondary period of high gusting winds was reported near the time of the accident (as was observed at KLMO).

2.3 Fort Collins/Loveland, Colorado

The next closest weather reporting station was Northern Colorado Regional Airport (KFNL), Fort Collins/Loveland, CO, located 22.5 miles east-northeast of the accident site at an elevation of 5,015 ft. KFNL had an AWOS system which was augmented by air traffic control personnel when in operation. The accident airplane departed from KFNL at approximately 1813 MDT and KFNL was reporting the following conditions at the time of departure and accident.

Routine weather observation for KFNL at 1756 MST, automated, wind from 260° at 10 knots gusting to 15 knots, visibility 10 miles or more, sky clear below 12,000 ft agl, temperature 14° C, dew point temperature -6° C, altimeter setting 29.77 inHg. Remarks; automated station with a precipitation discriminator, sea-level pressure not available, temperature 13.9° C, dew point temperature -6.1° C.

The following raw observations were reported between 0456 through 0056 MST on November 16th.

METAR KFNL 161156Z 17007KT 10SM CLR 13/M06 A2978 RMK AO2 SLP042 T01331056 10194 20128 58008
METAR KFNL 161256Z 26031G39KT 10SM CLR 18/M06 A2973 RMK AO2 PK WND 25039/1255 PRESFR SLP019 T01781061
METAR KFNL 161356Z 25023G43KT 10SM CLR 19/M08 A2974 RMK AO2 PK WND 26043/1351 SLP017 T01891078
METAR KFNL 161456Z 25032G40KT 10SM CLR 19/M08 A2972 RMK AO2 PK WND 25040/1456 SLP011 T01941078 56016
METAR KFNL 161556Z 24019G29KT 10SM CLR 19/M07 A2974 RMK AO2 PK WND 24038/1458 SLP020 T01891067
METAR KFNL 161656Z 27022G32KT 10SM CLR 19/M07 A2974 RMK AO2 PK WND 25041/1617 SLP022 T01891072
METAR KFNL 161756Z 26019G28KT 10SM CLR 20/M07 A2974 RMK AO2 PK WND 26035/1719 SLP021 T02001072 10200 20089 50004
METAR KFNL 161856Z 24017G25KT 10SM CLR 21/M08 A2970 RMK AO2 PK WND 26031/1803 SLP003 T02061078
METAR KFNL 161956Z 26011KT 10SM CLR 21/M07 A2970 RMK AO2 SLP997 RMK AO2 T02061072
METAR KFNL 162056Z AUTO 23012KT 10SM CLR 20/M07 A2971 RMK AO2 PK WND 24027/2045 SLPNO 6//// T02001072
METAR KFNL 162156Z AUTO 26024G34KT 10SM CLR 19/M06 A2970 RMK AO2 PK WND 25034/2153 SLPNO T01941056
METAR KFNL 162256Z AUTO 26012G19KT 10SM CLR 17/M05 A2973 RMK AO2 PK WND 26030/2209 SLPNO T01721050
METAR KFNL 162356Z AUTO VRB04KT 10SM CLR 14/M06 A2976 RMK AO2 SLPNO 6//// T01441056 53013
METAR KFNL 170056Z AUTO 26010G15KT 10SM CLR 14/M06 A2977 RMK AO2 SLPNO T01391061=
Accident 0136Z
METAR KFNL 170156Z 02004KT 10SM CLR 13/M06 A2980 RMK AO2 SLPNO T01331061=
METAR KFNL 170256Z 03015KT 10SM FEW110 10/M02 A2981 RMK AO2 SLPNO T01001017 52015=
METAR KFNL 170356Z 01018G22KT 10SM BKN110 10/M02 A2985 RMK AO2 SLPNO T01001017
METAR KFNL 170456Z 01015G20KT 10SM BKN100 09/M02 A2988 RMK AO2 PK WND 01026/0359 SLPNO T00941017
SPECI KFNL 170538Z 08011G17KT 10SM OVC090 08/M05 A2990 RMK AO2 PK WND 02031/0500 WSHFT 0518
METAR KFNL 170556Z 07013KT 10SM OVC090 09/M04 A2991 RMK AO2 PK WND 02031/0500 WSHFT 0518 SLPNO T00891039 10156 20078 51029
SPECI KFNL 170609Z 07016G24KT 10SM OVC090 06/M07 A2992 RMK AO2 WSHFT 0549
METAR KFNL 170656Z 07021G26KT 10SM BKN070 OVC085 03/M12 A2999 RMK AO2 PK WND 07027/0623 WSHFT 0549 SLPNO T00281122 402060028
METAR KFNL 170756Z 10014KT 10SM BKN050 OVC070 02/M13 A3009 RMK AO2 PK WND

07027/0700 SLPNO T00171133 FZRANO

The observations noted generally westerly winds gusting over 25 knots with a peak of 43 knots during the day with wind speeds decreasing immediately prior to the accident. Winds shifted to the northeast immediately after the accident from 1856 through 2056 MST.

2.4 Granby, Colorado

The next closest station was Granby-Grand County Airport (KGNB), Granby, CO, located 25 miles southwest of the accident site at an elevation of 8,207 ft. The airport also had an AWOS and reported the following conditions.

Routine weather observation for KGNB at 1835 MST, automated, wind from 270° at 6 knots gusting to 16 knots, visibility 10 miles or more, ceiling broken at 7,000 ft agl, temperature 5° C, dew point temperature -7° C, altimeter setting 29.97 inHg. Remarks; automated station with a precipitation discriminator, temperature 5.2° C, dew point temperature -6.9° C.

The following raw observations were reported between 1215 through 2215 MST.

METAR KGNB 161915Z AUTO 26021G34KT 10SM CLR 12/M08 A2994 RMK AO2 T01151078
METAR KGNB 161935Z AUTO 25020G33KT 10SM CLR 11/M08 A2993 RMK AO2 T01111081
METAR KGNB 161955Z AUTO 28016G24KT 10SM SCT080 SCT110 11/M08 A2993 RMK AO2
T01131076
METAR KGNB 162015Z AUTO 29021G27KT 10SM SCT080 OVC085 10/M08 A2995 RMK AO2
T00961077
METAR KGNB 162035Z AUTO 28015G23KT 10SM BKN085 OVC090 09/M07 A2995 RMK AO2
T00901069
METAR KGNB 162055Z AUTO 28020G25KT 10SM BKN065 OVC085 09/M06 A2996 RMK AO2
T00851056
METAR KGNB 162115Z AUTO 27019G28KT 10SM OVC065 08/M05 A2997 RMK AO2 T00771048
METAR KGNB 162135Z AUTO 26018G33KT 10SM SCT027 SCT055 OVC070 07/M04 A2996 RMK AO2
T00721045
METAR KGNB 162155Z AUTO 25020G26KT 10SM SCT055 08/M04 A2995 RMK AO2 T00751044
METAR KGNB 162215Z AUTO 25017G27KT 10SM CLR 07/M05 A2994 RMK AO2 T00721050
METAR KGNB 162235Z AUTO 26018G23KT 10SM CLR 07/M05 A2993 RMK AO2 T00731050
METAR KGNB 162255Z AUTO 25010G18KT 10SM CLR 07/M05 A2994 RMK AO2 T00681049
METAR KGNB 162315Z AUTO 25008KT 10SM CLR 06/M05 A2995 RMK AO2 T00621052
METAR KGNB 162335Z AUTO 27011G20KT 10SM SCT070 07/M06 A2996 RMK AO2 T00661060
METAR KGNB 170055Z AUTO 29004G15KT 10SM SCT070 06/M07 A2998 RMK AO2 T00581070=
METAR KGNB 170115Z AUTO 28006G16KT 10SM BKN070 05/M07 A2997 RMK AO2 T00511069=
**METAR KGNB 170135Z AUTO 27006G16KT 10SM BKN070 05/M07 A2997 RMK AO2
T00521069=**
Accident 0136Z
METAR KGNB 170155Z AUTO 29007KT 10SM BKN070 05/M07 A2997 RMK AO2 T00471070=
METAR KGNB 170215Z AUTO 32003G08KT 10SM SCT070 SCT080 04/M07 A2997 RMK AO2
T00401070=
METAR KGNB 170235Z AUTO 30004KT 10SM SCT070 SCT080 04/M24 A2997 RMK AO2 T00371245

METAR KGNB 170255Z AUTO 26008KT 10SM SCT070 04/M25 A2997 RMK AO2 T00391247
 METAR KGNB 170315Z AUTO 26008G15KT 10SM SCT070 04/M07 A2998 RMK AO2 T00381072
 METAR KGNB 170335Z AUTO 28008KT 10SM CLR 03/M09 A2999 RMK AO2 T00291092
 METAR KGNB 170355Z AUTO 28007KT 10SM CLR 02/M05 A2999 RMK AO2 T00241047
 METAR KGNB 170415Z AUTO 29008KT 10SM CLR 02/M08 A3000 RMK AO2 T00231083
 METAR KGNB 170435Z AUTO 28013G17KT 10SM CLR 02/M04 A3000 RMK AO2 T00191036
 METAR KGNB 170455Z AUTO 26013G21KT 10SM SCT016 SCT028 BKN090 03/M04 A3001 RMK AO2
 T00271036
 METAR KGNB 170515Z AUTO 28012G16KT 10SM SCT016 SCT030 SCT038 02/M04 A3001 RMK AO2
 T00181037
 METAR KGNB 170535Z AUTO 27009G15KT 10SM BKN060 BKN085 02/M03 A3002 RMK AO2
 T00201035
 METAR KGNB 170555Z AUTO 23005KT 10SM SCT020 BKN065 OVC075 02/M03 A3002 RMK AO2
 T00171033 10064 20017

2.5 Aviation Weather Center METAR Display

A display of the observations over the region at 1840 MST from the NWS Aviation Weather Center's (AWC) website⁶ is included as figure 10 with the regional radar display overlaid for the period. The station models depicted the general flight conditions and observed weather data plotted in a standard station model. The image depicted general VFR conditions prevailing over the area with generally westerly winds over the area at 5 to 15 knots, with northwesterly winds reported at KBDU and calm winds at Erie (KEIK). Two additional FAA AWOS stations associated with weather cameras were identified reporting strong westerly winds; Dakota Hill (KC99) and Berthoud Pass (K0CO)⁷ reported west-northwesterly winds of 35 to 40 knots gusting to 47 and 50 knots respectively and are documented below.

⁶ <https://www.aviationweather.gov/metar?gis=on>

⁷ Also referred to as Empire AWOS on the NOAA sectional chart

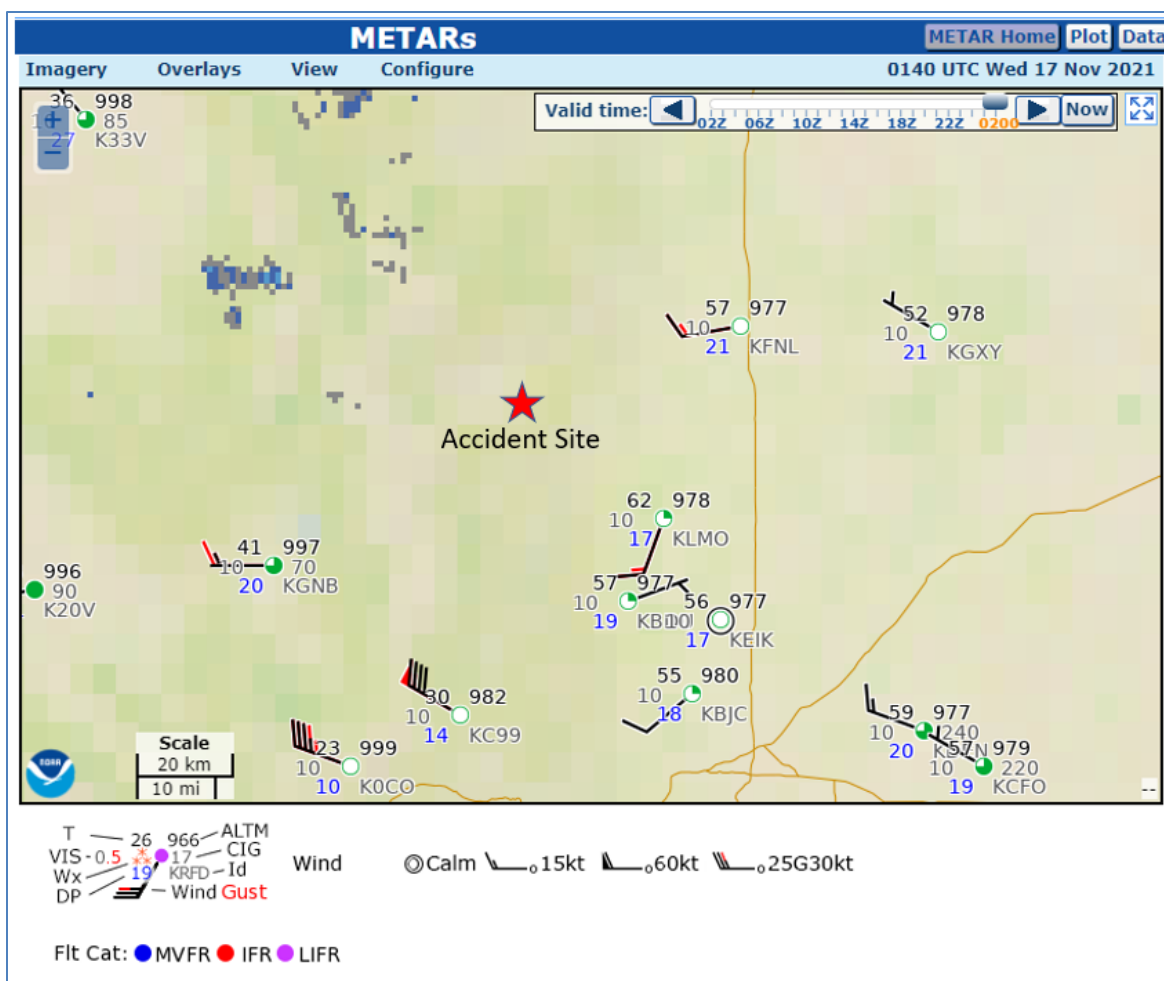


Figure 10 - NWS Aviation Weather Center's METAR display for 1840 MST with accident site.

While no useful weather camera imagery was available at the time of the accident due to the low sun angle and lack of illumination. The following conditions were reported at the time of the accident.

Dakota Hill (KC99) AWOS was located 28 miles south of the accident site (coordinates 39.869°N, -105.553°W) at an elevation of 10,938 ft. The following conditions were reported at the time of the accident.

Weather observation for KC99 at 1835 MST, automated, wind from 300° at 39 knots gusting to 56 knots, visibility 10 miles or more, sky clear below 12,000 ft agl, temperature -1° C, dew point temperature -10° C, altimeter 29.82 inHg.

The raw observations reported surrounding 1500 through 1900 MST were as follows.

METAR KC99 162255Z AUTO 28026G40KT 10SM CLR 00/M09 A2991 RMK AO2=
METAR KC99 162315Z AUTO 30026G42KT 10SM CLR 00/M10 A2991 RMK AO2=

METAR KC99 162335Z AUTO 30031G43KT 10SM CLR 00/M10 A2988 RMK AO2=
 METAR KC99 162355Z AUTO 30033G45KT 10SM CLR M01/M10 A2987 RMK AO2=
 METAR KC99 170015Z AUTO 30034G44KT 10SM CLR M01/M10 A2988 RMK AO2=
 METAR KC99 170035Z AUTO 30032G52KT 10SM CLR M01/M10 A2986 RMK AO2=
 METAR KC99 170055Z AUTO 30038G52KT 10SM CLR M01/M10 A2984 RMK AO2=
 METAR KC99 170115Z AUTO 30037G54KT 10SM CLR M01/M10 A2982 RMK AO2=
METAR KC99 170135Z AUTO 30039G56KT 10SM CLR M01/M10 A2982 RMK AO2=
Accident 0136Z

METAR KC99 170155Z AUTO 30032G52KT 10SM CLR M01/M10 A2983 RMK AO2=
 METAR KC99 170215Z AUTO 30032G52KT 10SM CLR M01/M10 A2986 RMK AO2=
 METAR KC99 170235Z AUTO 30022G46KT 10SM CLR M01/M11 A2992 RMK AO2=

Berthoud Pass (K0CO) AWOS was located 35 miles south-southwest of the accident site (coordinates 39.7945°N, -105.754°W) at an elevation of 12,477 ft and reported the following conditions at the time of the accident.

Weather observation for K0CO at 1835 MST, automated, wind from 290° at 33 knots gusting to 47 knots, visibility 10 miles or more, sky clear below 12,000 ft agl, temperature -5° C, dew point temperature -12° C, altimeter 29.99 inHg.

The raw observations reported surrounding approximately 1500 through 1900 MST were as follows.

METAR K0CO 162155Z AUTO 30035G52KT 10SM SCT030 BKN038 OVC047 M03/M11 A3000 RMK
 AO2 24743800
 METAR K0CO 162215Z AUTO 30029G46KT 10SM SCT032 BKN040 BKN050 M04/M10 A3002 RMK AO2
 503 4000
 METAR K0CO 162235Z AUTO 29032G46KT 10SM SCT037 M04/M10 A3003 RMK AO2
 METAR K0CO 162255Z AUTO 28041G56KT 10SM SCT037 M04/M10 A2998 RMK AO2
 METAR K0CO 162315Z AUTO 27037G55KT 10SM CLR M04/M11 A2998 RMK AO2
 METAR K0CO 162335Z AUTO 28041G61KT 10SM CLR M04/M11 A2995 RMK AO2
 METAR K0CO 162355Z AUTO 28039G55KT 10SM CLR M05/M11 A2997 RMK AO2
 METAR K0CO 170015Z AUTO 29033G48KT 10SM CLR M05/M11 A2998 RMK AO2
 METAR K0CO 170035Z AUTO 29032G54KT 10SM CLR M05/M11 A3001 RMK AO2
 METAR K0CO 170055Z AUTO 31025G50KT 10SM CLR M05/M11 A3000 RMK AO2
 METAR K0CO 170115Z AUTO 30031G40KT 10SM CLR M05/M12 A2999 RMK AO2
METAR K0CO 170135Z AUTO 29033G47KT 10SM CLR M05/M12 A2999 RMK AO2
Accident 0136Z
 METAR K0CO 170155Z AUTO 31026G45KT 10SM CLR M06/M11 A3000 RMK AO2
 METAR K0CO 170215Z AUTO 31029G47KT 10SM CLR M06/M12 A3000 RMK AO2

2.6 Other Remote Automated Weather Stations

The area was also reviewed for any available Remote Automated Weather Stations (RAWS) operated by the United States Forestry Service and other land management agencies, as well as the Colorado Department of Transportation. These RAWS sites are not depicted in the NWS AWC METAR display above. The RAWS data documented below have the wind data converted from miles per hour (mph) to knots for

consistency, and wind direction rounded to the nearest 5°. The peak gust is the maximum 1-second wind speed during the minute, with the maximum gust is the highest 1-second gust during the 4 hours prior to the accident. Atmospheric pressure is not recorded.

Lily Lake (CO045) a Colorado Department of Transportation (CDOT) station along Highway 7 at an elevation of 8,960 ft at coordinates 40.305 N -105.538 W, or about 3.3 miles southwest of the accident site reported the following conditions at 1849 MST.

Temperature:	41°F	Max 24-hr Temperature:	49°F
Dew Point:	15°F	Min 24-hr Temperature:	45°F
Relative Humidity:	36%		
Wind:	225° 7 kts		
Peak Gust:	28 kts		
Max Gust:	38 kts 1748 MST		

Time (MST)	Temperature (°F)	Dew Point °(F)	RH (%)	Wind (deg/kts)	Peak Wind (kts)
1748	40.6	15.8	36	225° 17	38
1758	40.5	15.6	36	225° 17	27
1808	40.1	15.3	36	225° 11	30
1818	40.1	15.3	36	225° 12	26
1828	40.1	15.3	36	225° 9	28
1839	40.3	15.5	36	225° 10	23
1849	40.6	15.1	35	225° 7	28
1859	39.9	15.2	36	225° 9	23
1909	39.9	15.2	36	270° 3	17

Estes Park (ESPC2) at an elevation of 7,892 ft at coordinates 40.366° N -105.562° W, or about 4.3 miles west-northwest of the accident site reported the following conditions at 1824 MST.

Temperature:	44°F	Max 24-hr Temperature:	57°F
Dew Point:	21°F	Min 24-hr Temperature:	44°F
Relative Humidity:	39%		
Wind:	260° 11 kts		
Peak Gust:	28 kts		
Max Gust:	39 kts 1424 MST		

Time (MST)	Temperature (°F)	Dew Point (°F)	RH (%)	Wind (deg/kts)	Peak Gust (deg/kts)
1624	45	20	37	275° 9	260° 18
1724	44	19	39	265° 13	275° 31
1824	44	20	39	260° 11	300° 28
1924	44	20	37	245° 10	265° 20

Boulder County Fire (BCFC2) at an elevation of 6,674 ft at coordinates 40.220° N -105.331° W, or about 9.6 miles southwest of the accident site reported the following conditions at 1742 MST.

Temperature: 51°F Max 24-hr Temperature: 61°F
 Dew Point: 19°F Min 24-hr Temperature: 51°F
 Relative Humidity: 28%
 Wind: 280° 7 kts
 Peak Gust: 32 kts
 Max Gust: 43 kts 1642 MST

Time (MST)	Temperature (°F)	Dew Point (°F)	RH (%)	Wind (deg/kts)	Peak Wind (deg/kts)
1542	53	21	28	265° 19	300° 41
1642	52	20	28	270° 20	275° 43
1742	51	19	28	275° 7	235° 32
1842	52	16	24	280° 15	270° 29
1942	50	18	28	280° 5	285° 22
2042	49	19	30	255° 2	285° 10

3.0 Sounding

To determine the vertical structure and state of the atmosphere over the accident site a High-Resolution Rapid Refresh (HRRR)⁸ numerical model data were retrieved from the NOAA Air Resources Laboratory using the model grid point⁹ nearest the accident site for 1800 MST. The data was then plotted on a standard Skew T log P

⁸ The HRRR is a NOAA real-time three-kilometer resolution, hourly-updated, cloud-resolving, convection-allowing atmospheric model, initialized by three-kilometer grids with three-kilometer radar assimilation. Radar data is assimilated in the HRRR every 15 minutes over a one-hour period.

⁹ HRRR coordinates were 40.34° N and -105.48° W.

diagram¹⁰ using RAOB The Universal RAwinsonde OBservation program¹¹ from the surface to 300-hPa or approximately 30,000 ft and is included as figure 11.

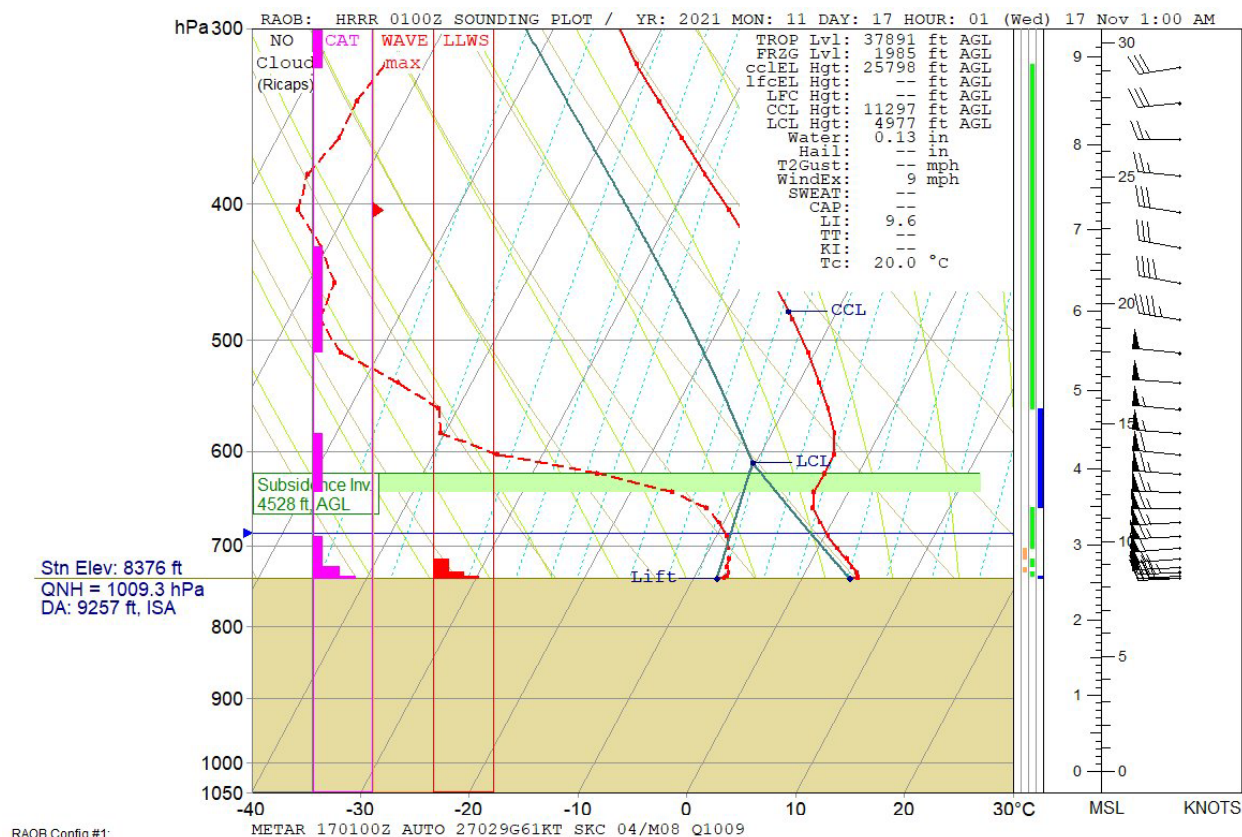


Figure 11 - HRRR numerical model sounding for 1800 MST from the surface to 300-hPa.

The 1800 MST HRRR sounding depicted an elevation of 8,376 ft with a near surface temperature of 4.0° C (39° F), a dew point temperature of -7.9° C (18° F), a relative humidity of 42%, and a density altitude of 9,257 ft. The lifted condensation level (LCL)¹² was identified at 4,977 ft agl, and a convective condensation level (CCL)¹³ at 11,297 ft agl. The freezing level was at 1,895 ft agl or 10,271 ft msl and is indicated by the blue horizontal line across the sounding diagram. An inversion due to subsidence was depicted (green bar) was depicted near the LCL between 3,066 ft through 5,333 ft agl

¹⁰ Skew T log P diagram - is a standard meteorological plot or thermodynamic diagram using temperature and the logarithmic of pressure as coordinates, used to display winds, temperature, dew point, and various indices used to define the vertical structure of the atmosphere.

¹¹ RAOB -The Complete RAwinsonde OBservation program is an interactive sounding analysis program developed by Eosonde Research Services (ERS) previously known as Environmental Research Services, The Villages, Florida.

¹² Lifted condensation level - the level at which a lifted parcel becomes saturated. The LCL height corresponds to cloud base height for forced ascent.

¹³ Convective condensation level - the level in the atmosphere to which an air parcel, if heated from below, will rise dry adiabatically, without becoming colder than its environment just before the parcel becomes saturated.

(approximately 12,000 ft through 14,000 ft msl), with temperatures remaining below freezing throughout the inversion. The precipitable water¹⁴ content was 0.13 inches. The tropopause was identified at 37,890 ft. The atmosphere was characterized as stable with a Lifted Index¹⁵ of 9.6, with the layer below 1,000 ft agl (10,000 ft msl) defined as unstable. The RAOB analysis program did not indicate any cloud layers below 18,000 ft.

The HRRR wind profile indicated a near surface wind from 270° at 29 knots with little change in direction with height, with increasing wind speeds with height through 20,000 ft. The accident airplane was operating between 10,400 ft to 9,000 ft during the period, with the last detected altitude of 9,000 ft immediately prior to the accident. The wind at 9,000 ft was from 260° at 42 knots. The mean 0 to 500 meters (0 to 1,640 ft) boundary level wind was from 265° at 55 knots. A low-level wind maximum was identified at about 12,000 ft from 270° at 67 knots, with the high-level maximum wind was identified above the tropopause at 50,300 ft wind from 260° at 77 knots.

The HRRR parameters of height, pressure (Pres), temperature (T), dew point temperature (Td), relative humidity (RH), wind direction and speed, Clear Air Turbulence (CAT) intensity, Low-Level Wind Shear (LLWS) based on the vertical wind shear, icing, and mountain wave (Wave) potential below 24,000 ft was as follows.

Height	Pres	T	Td	RH	Wind	CAT	LLWS	Icing	Wave/x-W-Turb
(ft-msl)	(hPa)	(°C)	(°C)	(%)	(deg/kts)	(FAA)	(FAA)	(AFGW)	(nm fpm max)
8376	739	4.4	-7.8	41	268/ 29			LIGHT	
8412	738	5.1	-7.2	41	269/ 27	SVR	STRNG		
8485	736	5.0	-7.0	41	267/ 38	MDT	MODRT		
8667	731	4.7	-7.1	42	267/ 46	MDT	LIGHT		
8887	725	4.0	-7.5	43	266/ 53	LGT	LIGHT		
9257	715	3.1	-7.7	45	265/ 57	LGT			
9706	703	1.7	-8.3	47	265/ 60	LGT			
10237	689	0.3	-9.0	50	266/ 63				
10815	674	-1.1	-10.4	49	267/ 65				
11442	658	-2.5	-12.3	47	269/ 66				
12123	641	-3.2	-16.2	36	271/ 67	LGT			
12904	622	-3.1	-24.0	18	274/ 65	LGT			
13709	603	-3.2	-34.1	7	276/ 61	LGT			
14627	582	-4.2	-40.4	4	275/ 57				
15666	559	-6.0	-41.8	4	275/ 54				
16740	536	-8.1	-46.8	3	275/ 52				
18001	510	-10.6	-53.6	2	277/ 49	LGT			
19365	483	-13.7	-57.1	1	279/ 45	LGT			
20844	455	-17.2	-57.6	2	282/ 38	LGT			
22280	429	-21.0	-60.6	2	282/ 32				

¹⁴ Precipitable water - The total amount of (condensed) water available within the lowest 400 mb of the sounding.

¹⁵ Lifted Index (LI) - A common measure of atmospheric instability. Its value is obtained by computing the temperature that air near the ground would have if it were lifted to 500-hPa or approximately 18,000 feet and comparing that temperature to the actual temperature at that level.

The RAOB analysis program indicated a high probability of moderate-to-severe turbulence below 9,000 ft msl (500 ft agl) with the RAOB analysis program indicating a strong vertical wind shear in the layer greater than 7 kts/1000 ft. The strongest wind shear was at 8,412 ft msl (36 ft agl) where the shear reached 11.1 kt/1000 ft and the RAOB analysis program indicated a 100% probability of severe turbulence. A strong risk of low-level wind shear also existed below 8,450 ft msl. While the basic sounding temperature and wind profile favored mountain wave formation, no predominant waves were detected by RAOB below 18,000 ft based on the 1800 MST HRRR sounding.

4.0 Satellite Imagery

The Geostationary Operational Environmental Satellite number 16 and 17 (GOES-16/17) imagery were obtained from an archive at the Space Science Engineering Center (SSEC) at the University of Wisconsin-Madison in Madison, Wisconsin, and processed using the Man-computer Interactive Data Access System (McIDAS) software. The infrared, water vapor, and visible imagery were reviewed surrounding the period, and the closest images to the accident time documented. The infrared long wave imagery (band 13) at a wavelength of 10.3 microns (μm) provided radiative cloud top temperatures with a nominal spatial resolution of 2 km. The low-level water vapor band 9 imagery had a wavelength of 7.3 μm , with a resolution of 2 km. The visible (band 2) at a wavelength of 0.64 μm provided images at a resolution of 0.5 km, but due to the low sun angle was not available at the time of the accident. The satellite imagery have not been corrected for parallax error.

The GOES-16 infrared image for 1836 MST at 6X magnification with a standard MB temperature enhancement curve applied is included as figure 12. The image depicted an area of low to middle-level clouds to the west of the accident site in a general north-to-south orientation pattern similar to transverse banding¹⁶ or trapped lee waves, with a relatively clear gap over and east of the accident site like a foehn gap¹⁷ with a band of enhanced higher clouds further east through southeast of the accident site.

Figure 13 is the GOES-17 infrared image for 1836 MST at 6X magnification with the MB temperature enhancement curve applied, which shows similar feature of transverse

¹⁶ Transverse Bands - Bands of clouds oriented perpendicular to the flow in which they are embedded. They often are seen best on satellite photographs. When observed at high levels (i.e., in cirrus formations), they may indicate severe or extreme turbulence. Transverse bands observed at low levels (called transverse rolls) often indicate the presence of a temperature inversion (or cap) as well as directional shear in the low- to mid-level winds.

¹⁷ A foehn gap is a break in an extensive cloud deck or cloud shield, usually parallel to and downwind of the mountain ridge line. Especially visible in satellite imagery, this cloud-free zone results from the strong sinking motion on the lee side of a mountain barrier during a mountain wave activity or strong downslope winds or chinook.

cloud pattern associated with orographic clouds¹⁸ over the area. An animation of the satellite imagery (attachment 1, slides 2-3) showed that most of the clouds west and east of the accident site did not propagate eastward with time with the mean wind but remained relatively stationary. The low cloud bands bordering immediately south of the accident also remained relatively stationary and were consistent with those of rotor clouds¹⁹.

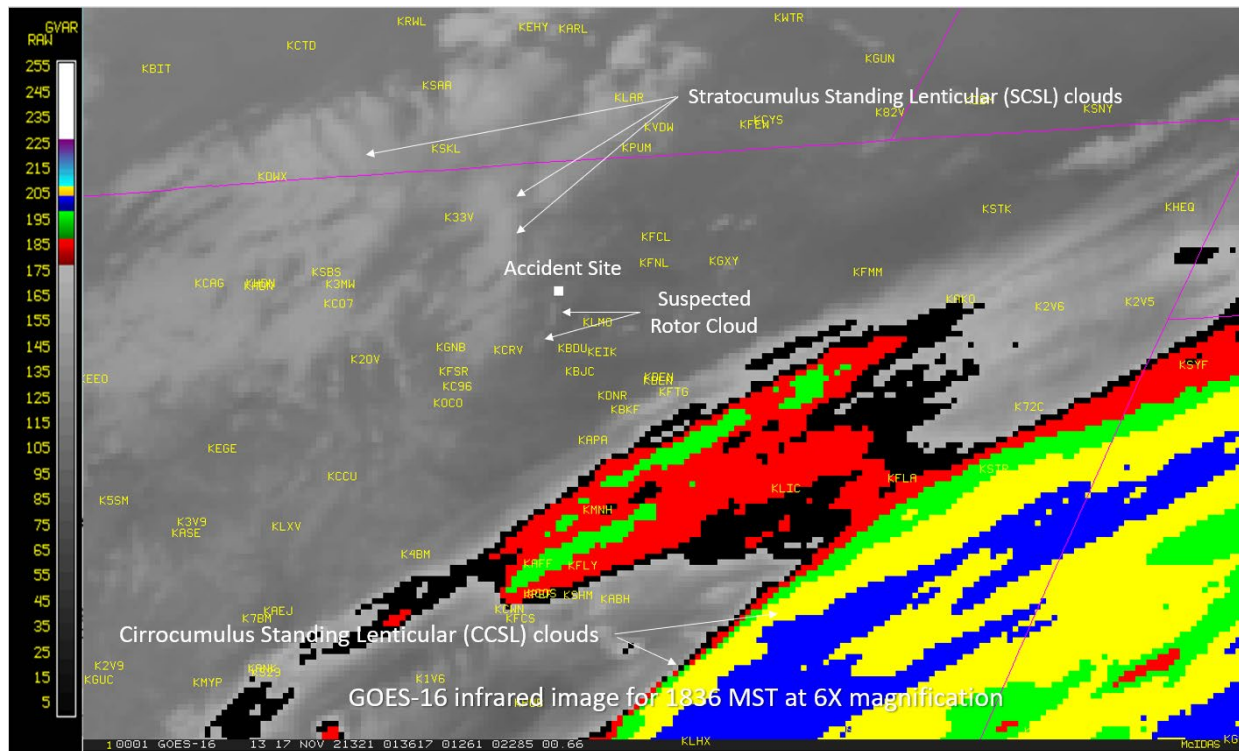


Figure 12 - GOES-16 infrared satellite image at 1836 MST at 6X magnification.

¹⁸ Orographic clouds are clouds that develop in response to the forced lifting of air by topographical features on the earth's surface, like mountains. Common orographic clouds include cap, banner, standing lenticular, and rotor clouds.

¹⁹ Rotor Cloud - A turbulent altocumulus cloud formation found in the lee of some mountain barriers when winds cross the barrier at high speed. The air in the cloud rotates around an axis parallel to the range. Also called a roll cloud.

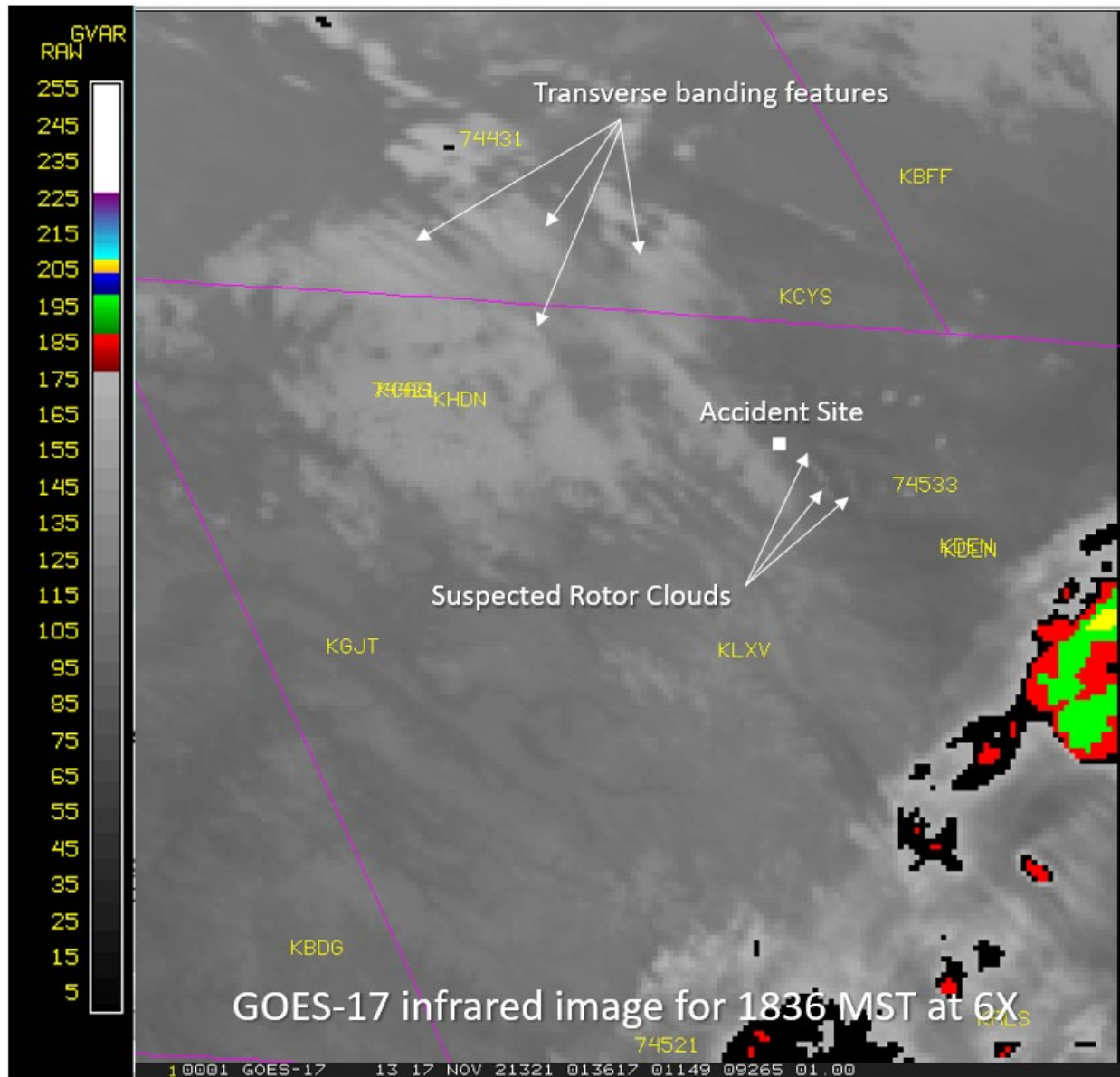


Figure 13 - GOES-17 infrared image at 1836 MST at 6X magnification.

The GOES-16 visible image for 1616 MST at 2X magnification is included as figure 14 and depicted the conditions prior to sunset over the area. The image depicted multiple layers of clouds over the area with high cirriform clouds southeast of the accident site, with an area of stratocumulus type clouds west of Estes Park, with several north-to-south oriented bands of low-level clouds consistent with rotor clouds over the future accident site.

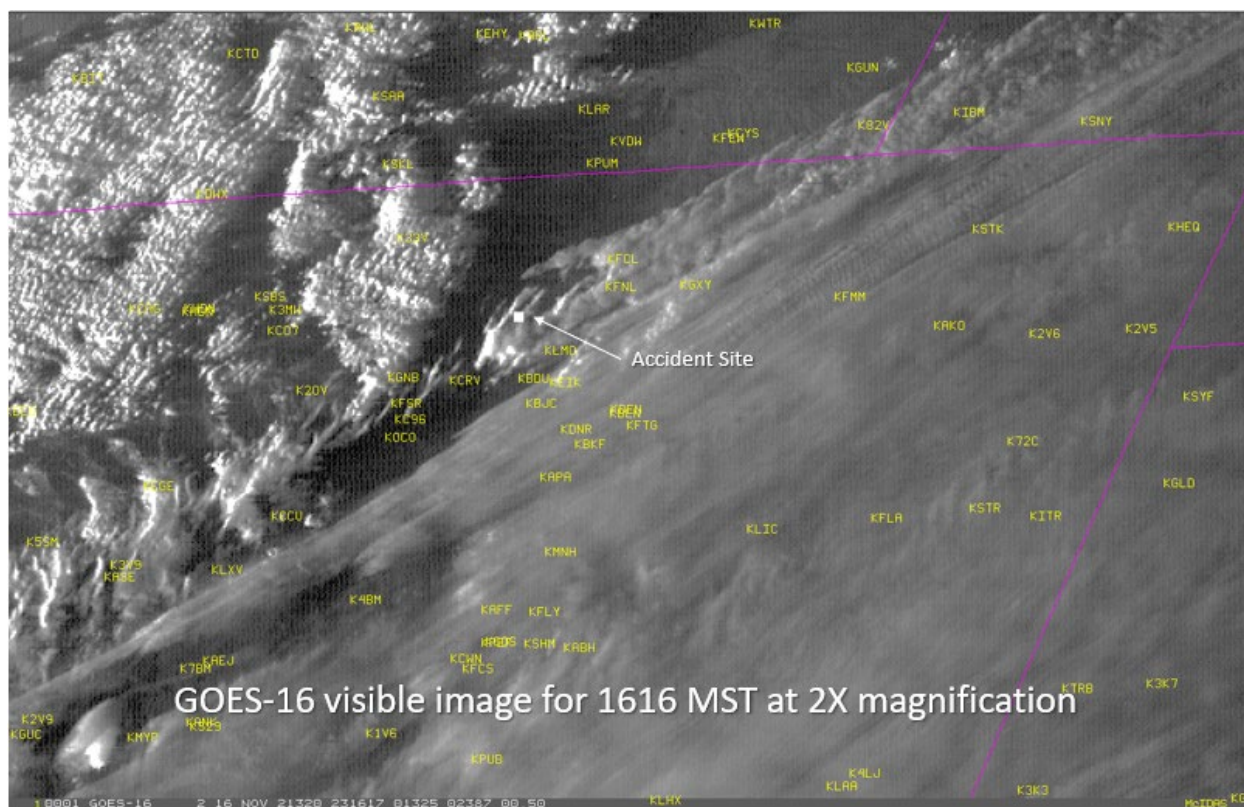


Figure 14 - GOES-16 visible image for 1616 MST at 2X magnification.

The researchers at the Cooperative Institute for Research in the Atmosphere (CIRA) collocated with the University of Colorado were contacted regarding additional meteorological support available over the area and in their review of the satellite products surrounding the period on November 16, 2021, the following satellite images were obtained and documented.

Figure 15 is the GOES-17 band 9 Mid-Level Tropospheric Water Vapor image for 1844 MST. The image depicts significant low-level drying or moisture channel darkening (orange) within the transverse pattern over northern Colorado and over the accident site with higher clouds to the southeast (purple, blue shades). The approximate accident site has been added as a white star for reference. The strong brightness temperature variation implies the presence of large vertical motions in the immediate vicinity of the accident site.

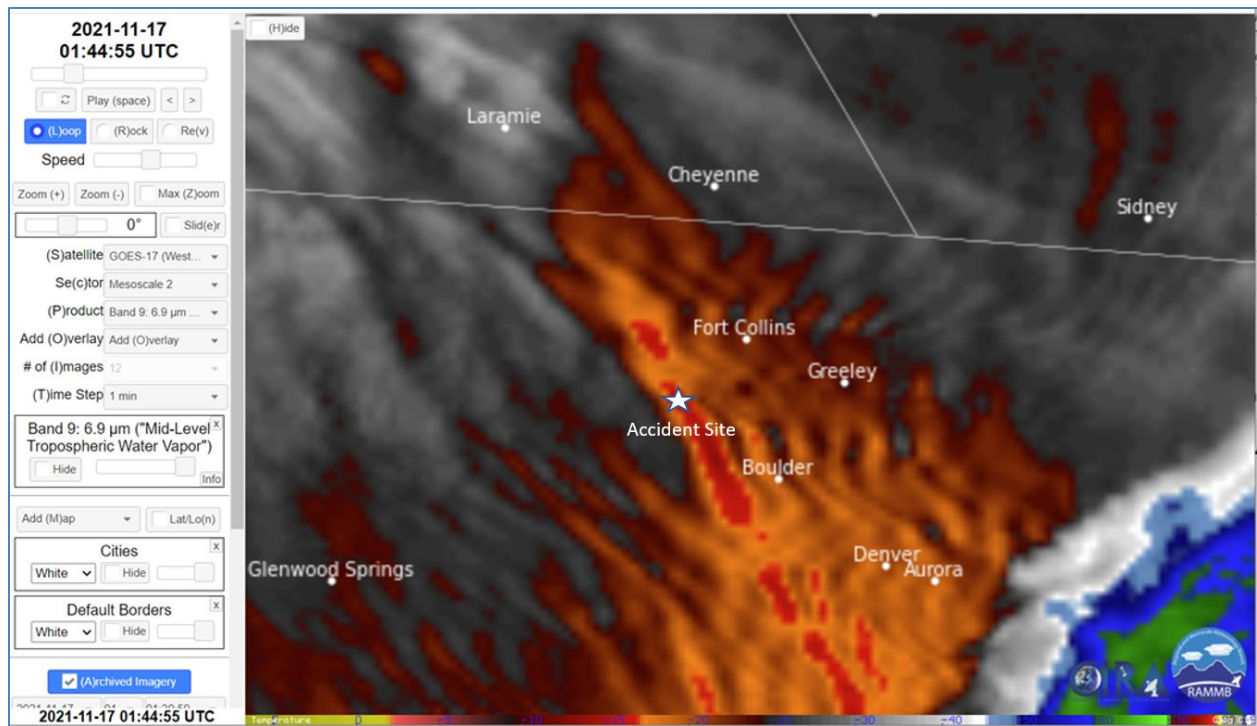


Figure 15 - GOES-17 Mid-Level Water Vapor image for 1844 MST.

Figure 16 are the GOES-17 Advanced Baseline Imager (ABI) mesoscale 2 sector over Colorado during the period, depicting the band 7 Shortwave Window with a wavelength of $3.9 \mu\text{m}$ labelled (a) on the left and the band 9 Mid-Level Water Vapor (similar to figure 15 above) for 1858 MST labelled as (b) on the right. Figure 17 is the Shortwave image also incorporated the experimental CIRA Speed Sandwich product²⁰, which blends the imagery with optical flow motions and highlights the stationary speeds of the possible roll or rotor cloud in the vicinity of the accident site²¹.

²⁰ The speed sandwich product uses optical flow or image brightness motion, to retrieve and track cloud-drift motions as to infer wind speeds. In the case of roll clouds and orographic clouds, the brightness motion is stationary, so the optical flow returns 0 m/s wind speeds, which show up as blue in the sandwich. The optical flow retrieval is described by Apke in <https://amt.copernicus.org/articles/13/1593/2020/>.

²¹ Provided by Jason Apke, Research Scientist at CIRA/CSU-Fort Collins on analysis of the conditions.

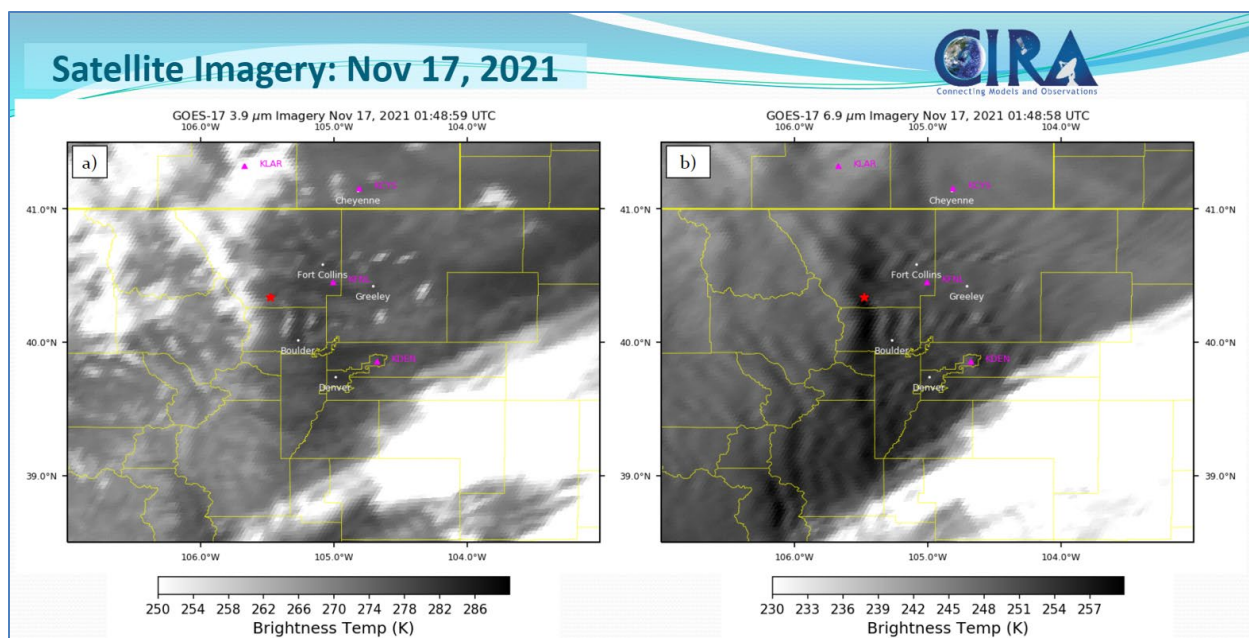


Figure 16 - GOES-17 Advanced Baseline Imager (ABI) mesoscale 2 sector imagery of the Shortwave (left) and Mid-Level Water Vapor band image (right) for 1848 MST.

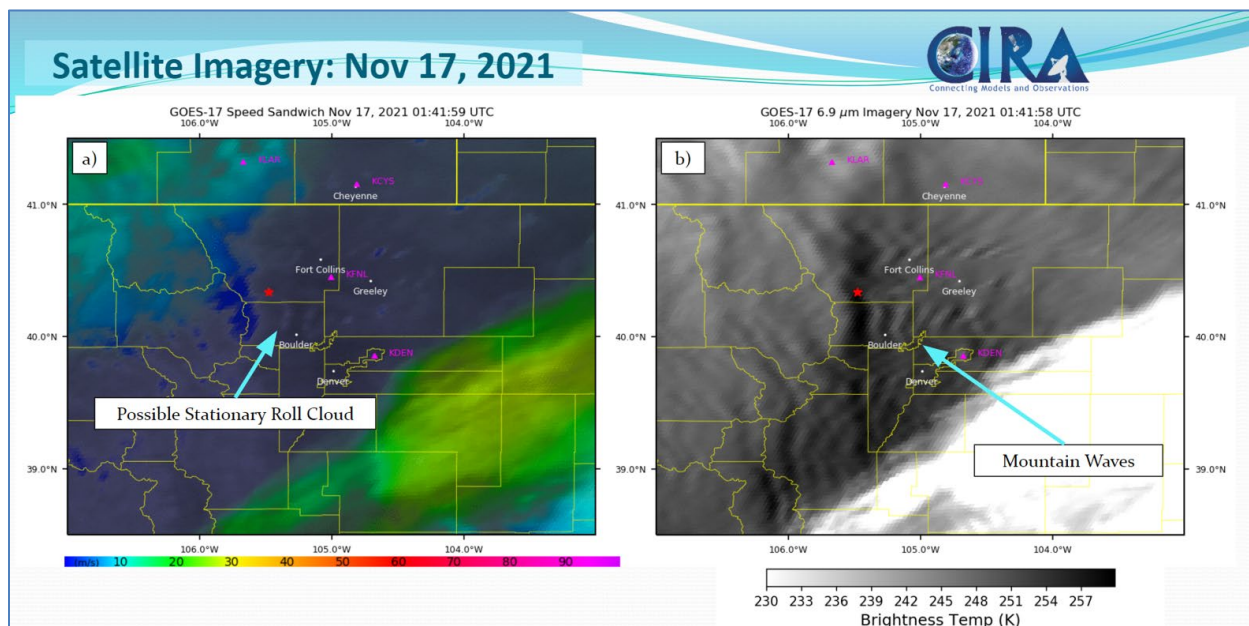


Figure 17 - GOES-17 Advanced Baseline Imager (ABI) mesoscale 2 sector imagery of the CIRA Speed Sandwich product (left) and Mid-Level Water Vapor band image (right) for 1841 MST.

5.0 Weather Radar Imagery

A review of the NWS National Reflectivity Mosaic²² centered over the area depicted no significant echoes over the accident site with several areas of echoes from 10 to 40

²² The NCEI National Reflectivity Mosaic is a depiction of the composite reflectivity radar imagery or the

dBZ²³ over the high terrain north and south of the accident site. Figure 18 is the regional view of the national reflectivity mosaic for 1835 MST, which depicted echoes of 10-15 dBZ approximately 3 miles south of the accident site. A review of the radar imagery surrounding the period also noted little motions of the echoes eastward with the mean winds and further suggested orographic type clouds or potential beam blockage and possible false returns. As a result, the closest weather surveillance radar was further documented below.

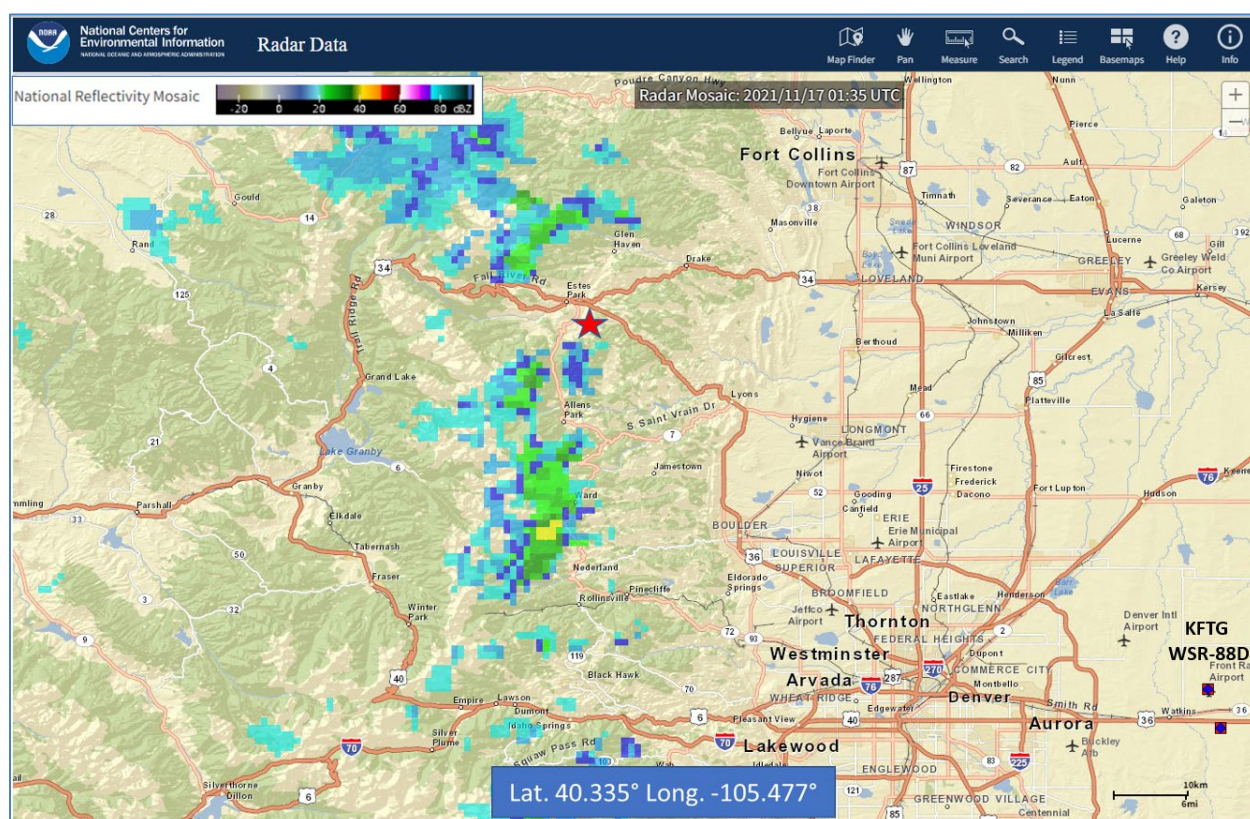


Figure 18 - National Reflectivity Mosaic for 1835 MST with the accident site marked.

The closest NWS Weather Surveillance Radar 1988 Doppler (WSR-88D)²⁴ was located at Denver Front Range Airport (KFTG) approximately 54 miles southeast of the accident site and is depicted in the lower right in figure 18. The NWS level II data were obtained from the NCEI archive for the period from 1817 through 1848 MST and displayed using the NOAA Weather and Climate Toolkit software²⁵.

maximum reflectivity in all the elevation scans from all the weather radars that are incorporated into the mosaic.

²³ Decibels, where dBZ = 10 log Ze.

²⁴ The WSR-88D is a S-band 10-centimeter wavelength radar with a power output of 750,000 watts, with a 28-foot parabolic antenna concentrating the energy into a 0.95° beam width. The radar produces three basic types of products reflectivity, radial velocity, and spectral width.

²⁵ NOAA's Weather and Climate Toolkit (WCT) is free, platform independent software distributed from NOAA's National Centers for Environmental Information (NCEI). The WCT allows the visualization and data export of weather and climate data, including Radar, Satellite and Model data.

During the period the KFTG WSR-88D was operating in the clear air mode, volume coverage pattern 32 (VCP-32) where the radar makes 9 different elevation scans in 7-minutes. This relatively slow scanning strategy is typically used when snow or light stratiform precipitation is anticipated and is depicted in figure 19. Assuming standard refraction²⁶ of the KFTG WSR-88D's 0.53° lowest elevation scan with the antenna height of 5,609 ft and at a distance 54 miles, the center of the beam was located near 10,580 ft, with the base of the beam at 7,860 ft and the top of the beam at 13,300 ft over the accident site.

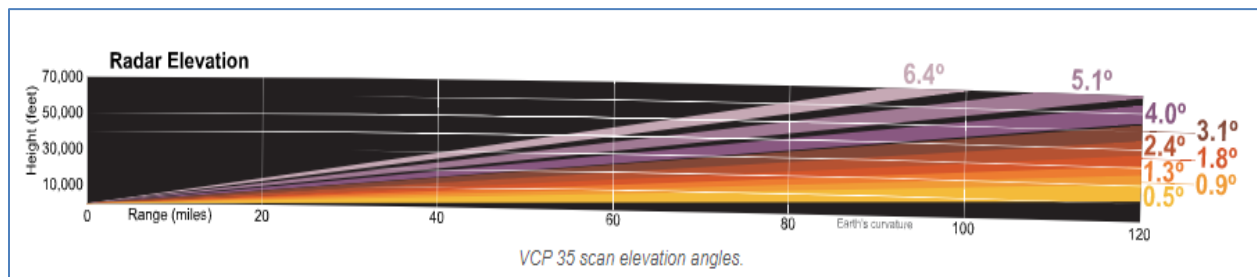


Figure 19 - Clear air mode volume coverage pattern 35 (VCP-35) by distance and height.

Reflectivity is the measure of the efficiency of a target in intercepting and returning radio energy. With hydrometeors, it is a function of the drop size distribution, number of particles per unit volume, physical state (ice or water), shape, and aspect. Reflectivity is normally displayed in dBZ and is a general measure of echo intensity. The FAA Advisory Circular AC 00-24C - "Thunderstorms" had standardized the radar intensity level terminology to four basic levels for aviation, which are defined in the following table. Air traffic control weather processors are also programmed to display these levels, with the controller instructed to describe the intensity to pilots based on the intensity levels.

Reflectivity (dBZ) Ranges	Weather Radar Echo Intensity Terminology
< 30 dBZ	Light
30-40 dBZ	Moderate
>40-5 dBZ	Heavy
>50 dBZ	Extreme

The KFTG WSR-88D 0.53° base reflectivity image for 1839 MST with a resolution of 1° x 1 km (0.54 nm) is included as figure 20 with the flight track of N802NZ overlaid in magenta. Echoes less than 10 dBZ have been removed from the image to remove some of the clutter and false returns out of the image. The image continued to depict scattered areas of echoes north and south of the accident site with reflectivities from

²⁶ Standard Refraction in the atmosphere is when the temperature and humidity distributions are approximately average, and values set at the standard atmosphere.

10 to 40 dBZ or light to moderate intensity echoes. Figure 21 is a close-up of the NWS KFTG WSR-88D 0.53° base reflectivity image over the accident site, with the closest echoes about 5 miles south of the accident site. A review of the animation (attachment 1, slide 7) of the echoes from 1712 through 1907 MST depicted the echoes remaining nearly stationary with time, with a general weakening trend in the echoes near the time of the accident.

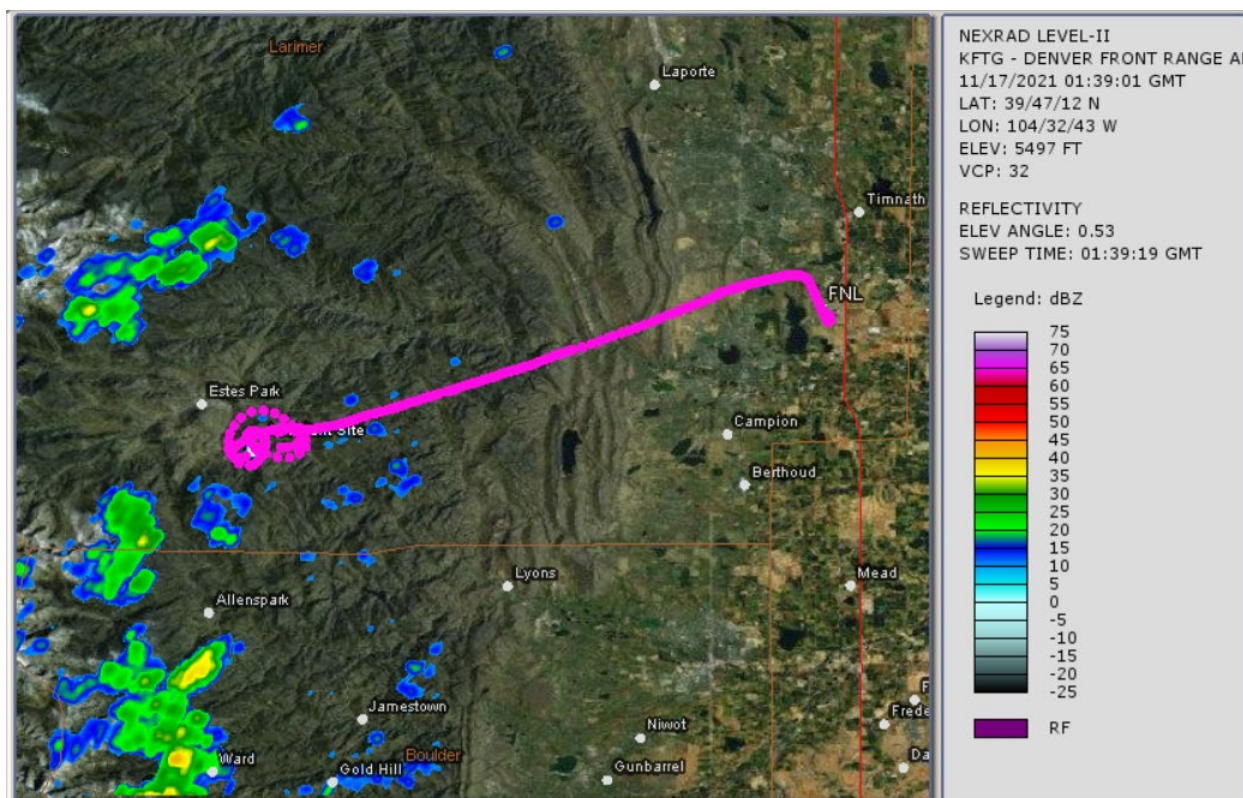


Figure 20 - NWS KFTG WSR-88D 0.53° base reflectivity image for 1839 MST with flight track.

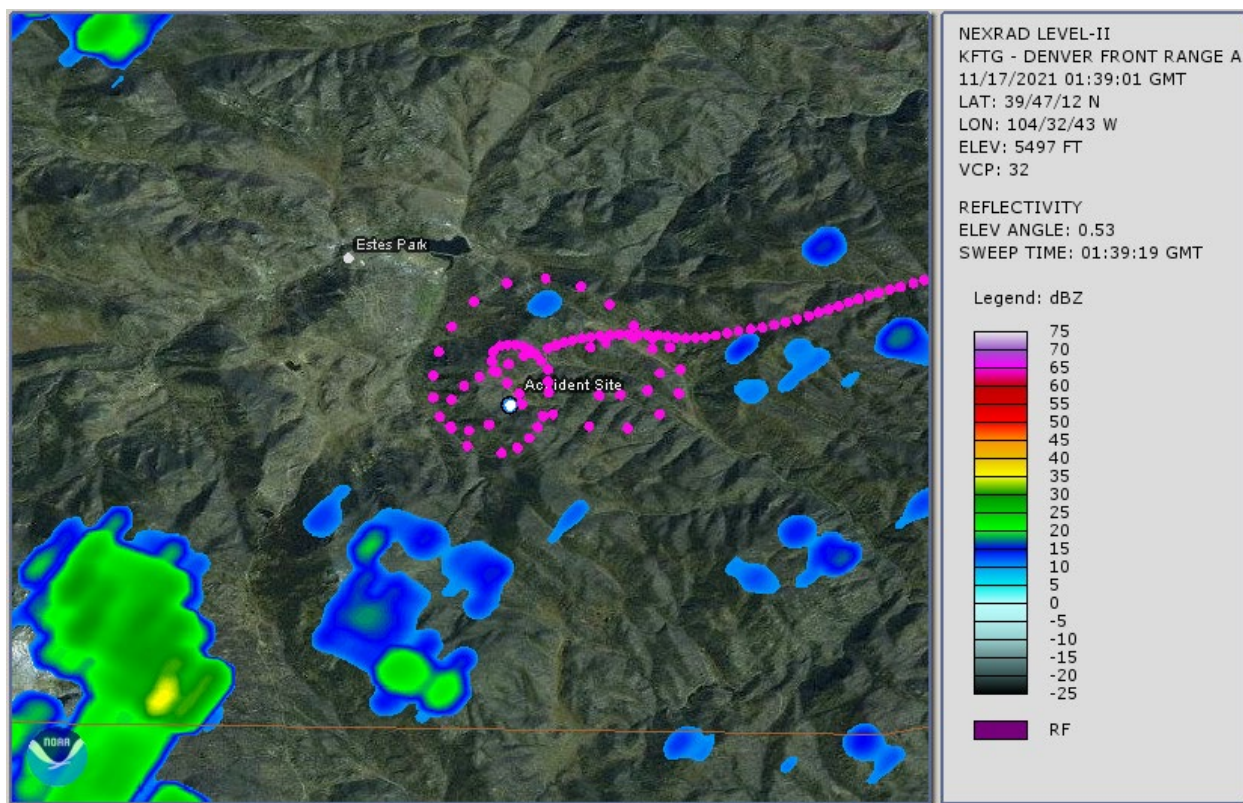


Figure 21 - Close-up of the NWS KFTG WSR-88D 0.53° base reflectivity image for 1839 MST.

A review of the NWS KFTG WSR-88D 0.53° Differential Reflectivity (ZDR)²⁷ dual polarization product did not depict any specific targets over the area and indicated the echoes were not meteorological echoes. While the Correlation Coefficient (CC)²⁸ product is included as figure 22 and depicted echoes less than 0.8 over the area in the immediate vicinity of the accident and south which further supported non-meteorological echoes over the area. While most of the echoes generally east and west of Estes Park had correlation coefficients consistent with echoes associated with clouds with water droplets.

²⁷ Differential Reflectivity (ZDR) is the logarithm ration of the horizontal polarized reflectivity to the vertical polarized reflectivity. The product provides a good indicator of the mean drop size diameter of the dominant echoes.

²⁸ Correlation Coefficient (CC) is a measure how similarly the horizontal and vertical returns powers behave among all the pulses in a sample volume and provides information about the diversity of hydrometeors. Meteorological echoes typically have CC > 0.80, with clutter, biological targets, chaff and other debris returns with CC < 0.80 to 0.20. Low CC values are also found in regions of Mie scattering, indicative of very large hail when associated with meteorological echoes.

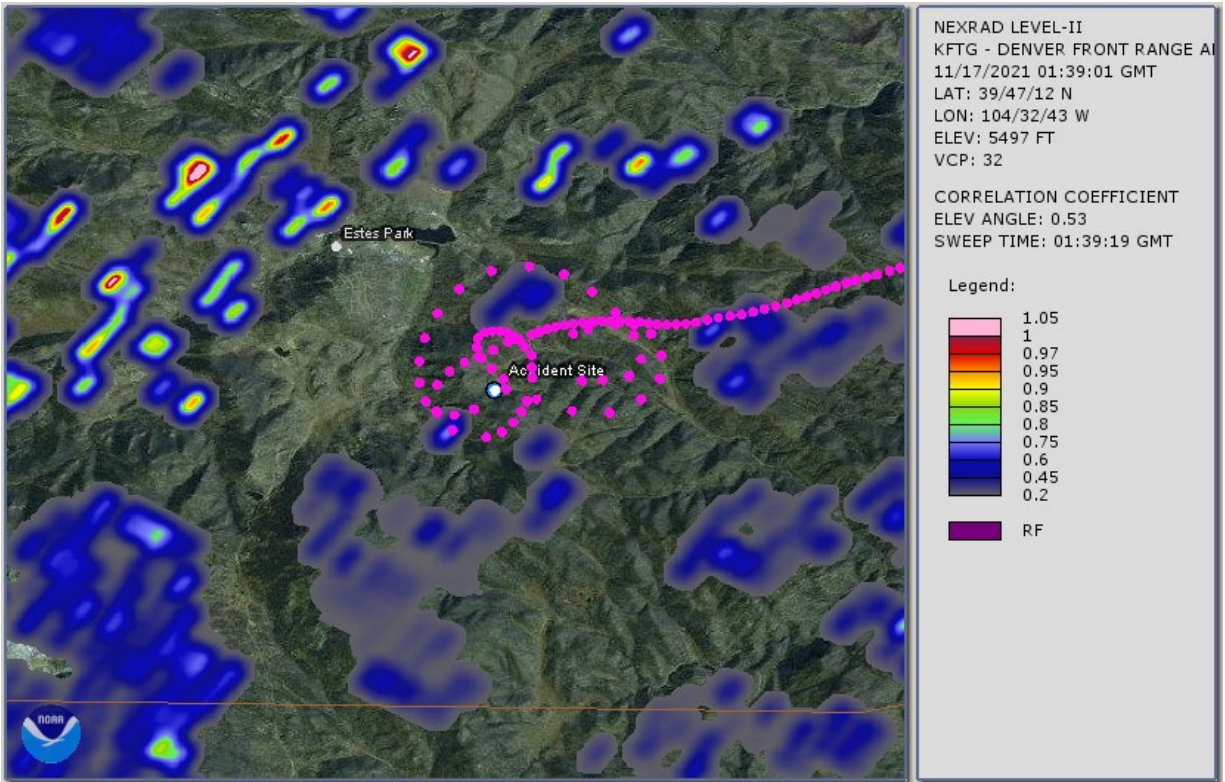


Figure 22 - KFTG WSR-88D Correlation Coefficient dual pole image at 1839 MST.

Figure 23 is the KFTG WSR-88D 0.53° mean radial velocity image for 1839 MST which provides an indication of wind flow structure and shear recognition of the atmosphere. The image depicted winds of 46.6 knots over the accident site at approximately 5,012 ft with winds generally from the west in green (towards the radar) with strong shears indicated in the non-meteorological echoes immediately south of the accident site with winds reversing to the east in red (away from the radar) and indicated possible wind shears in the echoes. Figure 24 is the spectrum width product²⁹ also depicted strong vertical shears and potential turbulence in the echoes.

²⁹ Spectrum width - measures velocity dispersion. In a radar bin, it provides a measure of the variability of the mean radial velocity estimates (movement) due to wind shear, turbulence, and/or the quality of the velocity samples. It is used to estimate turbulence associated with low-level boundaries, thunderstorms, and other mesocyclones in strong to severe thunderstorms.

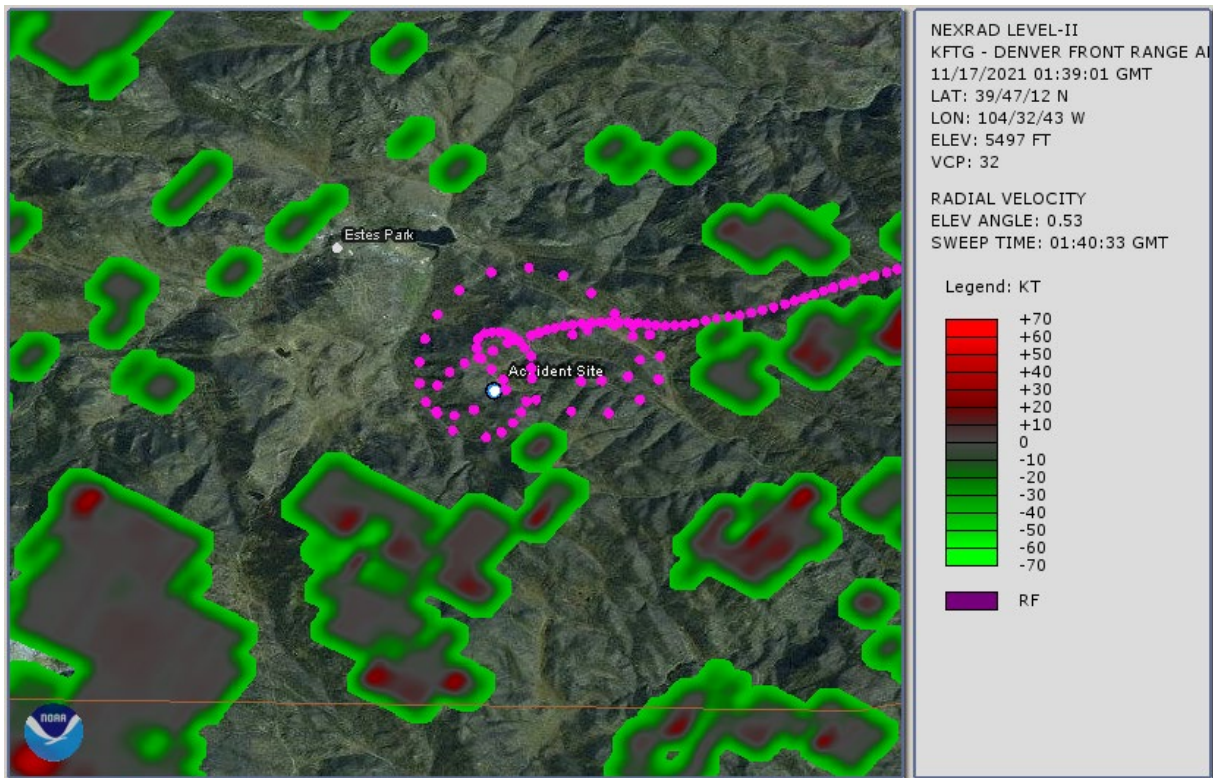


Figure 23 - KFTG WSR-88D 0.53 radial velocity image for 1839 MST.

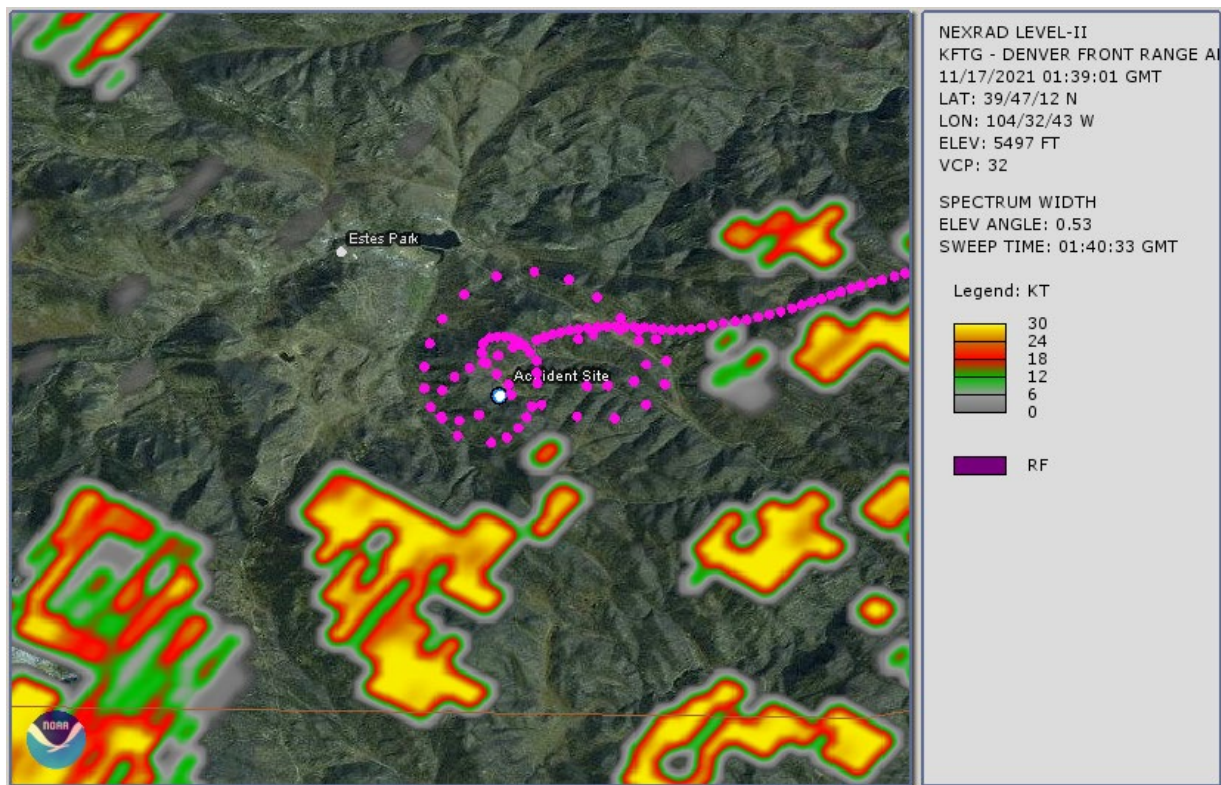


Figure 24 - KFTG WSR-88D 0.53° spectrum width product for 1839 MST.

6.0 Pilot Reports

The following pilot reports or PIREPs³⁰ were distributed into the national airspace within 100 miles between 1600 through 2200 MST below 18,000 ft. The reports are in standard code and abbreviations with height referenced to msl and time in UTC, followed by a decoded plain language report with time converted to MST. Attachment 2 is the AIM turbulence intensity and aircraft reaction definitions for turbulence.

APA UUA /OV APA/TM 2310/FL070/TP EA50/RM LLWS +10 KTS DURD RWY 35R

Centennial Airport (KAPA)³¹, Denver, CO, urgent pilot report (UUA); Over - APA; Time - 1610 MST; Altitude - 7,000 ft; Type aircraft - Eclipse 500 light jet; Remarks - low-level wind shear encountered plus 10 knots during descent to runway 35R.

APA UUA /OV APA180001/TM 2330/FL060/TP BE20/TB MOD-SEV/RM SHORT FINAL RWY 35R

APA urgent pilot report (UUA); Over - 1 mile south of APA; Time - 1630 MST; Altitude - 6,000 ft; Type aircraft - Beechcraft King Air multiengine turboprop; Turbulence - moderate-to-severe turbulence; Remarks - encountered on short final to runway 35R.

APA UUA /OV APA180001/TM 2353/FL060/TP LJ45/RM LLWS +/-15KTS ON FINAL

APA urgent pilot report; Over - 1 mile south of APA; Time - 1653 MST; Altitude - 6,000 ft; Type aircraft - Learjet 45 light jet; Remarks - low-level wind shear plus/minus 15 knots on final for runway 35R.

DEN UA /OV DEN195030/TM 0005/FL120/TP E145/TB MOD

Denver International Airport (DEN)³², Denver, CO, routine pilot report (UA); Over - 195° azimuth and 30 miles from DEN VORTAC³³; Time - 1705 MST; Altitude - 12,000 ft; Type aircraft - Embraer EMB-145 regional jet; Turbulence - moderate turbulence.

DEN UA /OV DEN270015/TM 0057/FL160/TP B737/TB MDT CHOP 110-135

DEN routine pilot report; Over - 195° azimuth and 30 miles from DEN VORTAC; Time - 1705 MST; Altitude - 12,000 ft; Type aircraft - Embraer EMB-145 regional jet; Turbulence - moderate turbulence.

Accident 0136Z

DEN UA /OV DEN315025/TM 0235/FL180/TP B763/TB MOD TURB 160-180

DEN routine pilot report; Over - 315° azimuth and 25 miles from DEN VORTAC; Time - 1935 MST; Altitude - 18,000 ft; Type aircraft - Boeing 767-300 heavy jet; Turbulence - moderate turbulence between 16,000 to 18,000 ft.

³⁰ Only includes PIREPs which were disseminated through normal weather circuits and do not include reports only broadcast to air traffic controllers via radio and not transcribed into the database.

³¹ KAPA was located approximately 55 miles south-southeast of the accident site at an elevation of 5,885 ft.

³² KDEN was located approximately 46 miles southeast of the accident site at an elevation of 5,434 ft.

³³ VORTAC - is a VHF Omni-directional Range and Tactical Air Navigation station that provides azimuth or direction from and distance from the beacon. Unless otherwise noted, the name of the VORTAC is collocated with the city.

DEN UUA /OV DEN315025/TM 0245/FL145/TP SW4/TB SEV 140-145

DEN urgent pilot report; Over - 315° azimuth and 25 miles from DEN VORTAC; Time - 1945 MST; Altitude - 14,500 ft; Type aircraft - Swearingen Metroliner IV multiengine turboprop; Turbulence - severe turbulence between 14,000 ft and 14,500 ft.

DEN UA /OV KDEN270030/TM 0306/FL170/TP B737/TB MOD DURGC 130-170

DEN routine pilot report; Over - 270° azimuth and 30 miles from DEN VORTAC; Time - 2006 MST; Altitude - 17,000 ft; Type aircraft - Boeing 737 jet; Turbulence - moderate turbulence during climb between 13,000 and 17,000 ft.

DEN UA /OV DEN090025/TM 0333/FL170/TP CRJ2/TB LGT/RM +15/-30KTS

DEN routine pilot report; Over - 090° azimuth and 25 miles from DEN VORTAC; Time - 2033 MST; Altitude - 17,000 ft; Type aircraft - Bombardier CRJ 200 regional jet; Turbulence - light turbulence; Remarks - plus 15 knots to loss of 30 knots of airspeed.

7.0 NWS Forecasts

The NWS Denver/Boulder (KBOU) Weather Forecast Office (WFO) located in Boulder, CO, was responsible for the local weather warnings and forecast over the region, and their products were documented below. The NWS AWC and WPC aviation forecasts current surrounding the period were also documented. Bold italic print highlights the valid period or other relevant information.

7.1 Terminal Aerodrome forecast

The closest Terminal Aerodrome Forecast (TAF) to the accident site was from Rocky Mountain Metro Airport (KBJC), Denver, Colorado located approximately 30 miles southeast of the accident site at an elevation of 5,673 ft. While a TAF is only valid for a 5-statute mile radius of the airport, it breaks down wind, visibility, weather phenomena, and clouds for the specific location. The forecast issued at 1625 MST was as follows.

TAF KBJC 162325Z 1700/1724 31012G20KT P6SM FEW080 BKN200

FM170300 35008KT P6SM SCT120 BKN200

FM170700 06011G18KT P6SM SCT040 SCT120

FM171000 06010KT P6SM SCT050 BKN100

TEMPO 1712/1716 BKN050

FM171600 09008KT P6SM SCT050 SCT100

FM171800 11010KT P6SM FEW050=

The forecast current from 1700 MST through 2000 MST expected VFR conditions to prevail with the wind from 310° at 12 knots gusting to 20 knots, visibility 6 miles or more, a few clouds at 8,000 ft agl, ceiling broken at 20,000 ft agl.

7.2 Area Forecast Discussion

The NWS Area Forecast Discussions (AFD) are issued by each WFO to describe the short-term weather conditions within their region with an aviation section that includes the general conditions as it relates to the creation of the TAF. These are useful for additional aviation-related issues that cannot be encoded into the TAF and provide some reasoning behind the forecast. These are generated roughly every 6 hours and corresponds to the release of the latest TAFs for that office. The AFD issued by KBOU at 1425 MST was as follows.

FXUS65 KBOU 162125
AFDBOU

Area Forecast Discussion
National Weather Service Denver/Boulder CO
225 PM MST Tue Nov 16 2021

.SHORT TERM...(This evening through Wednesday)
Issued at 225 PM MST Tue Nov 16 2021

Gusty west winds will continue through the rest of the afternoon and then slowly decrease around sunset with decreased mixing. Cold front associated with the strong storm system over the Northern Plains is marching southward across Wyoming and northern Nebraska. The main front pushes south across eastern Colorado late this evening. Ahead of the front, winds decrease and turn anticyclonic, becoming northeasterly after sunset. The stronger west winds this evening should be confined to the Front Range mountains and higher foothills, roughly above 8000-9000 feet MSL. There is some shallow moisture that comes across the mountains tonight, and should produce some light snow. Any accumulation is expected to be light and confined to the higher mountains. For the eastern plains and Urban Corridor, just expect clouds from this system overnight and into early Wednesday morning. Can't totally rule out a little light snow, but chances are only 20-30 percent. Drier returns by Wednesday afternoon with mostly clear skies prevailing. High temperatures will be much cooler with highs in the lower 40s across northeast Colorado.

.AVIATION...(For the 18Z TAFS through 18Z Wednesday afternoon)
Issued at 1015 AM MST Tue Nov 16 2021

Expect VFR conditions through the rest of the day. There is some potential for MVFR and ILS conditions overnight into Wednesday morning behind a late front, but VFR conditions are currently forecast to persist. Sustained west-northwesterly winds with gusts over 30 kt will persist through the afternoon, then gradually decrease while turning more northwesterly in the evening. A cold front will move over the area tonight, likely between 06Z and 09Z. Behind the front, winds will turn northeasterly and ceilings should fall below 6 kft. There is also a slight chance of very light snowfall at or near the terminal, but we still expect no impacts to visibility.

.FIRE WEATHER...
Issued at 225 PM MST Tue Nov 16 2021

The strong westerly winds will start to decrease around sunset. Until then, gusts to 40 mph will be possible across the plains and up to 60 mph in the mountains. Winds are expected

to become northeasterly this evening across the lower elevations. The north to northeast wind will increase late this evening as a cold front pushes through the area. Snowfall is expected to be confined to the mountains, but light snow can't be ruled out for the foothills and plains. It will be much cooler Wednesday, relative humidities will only improve a little with readings in the 20s during the afternoon. Winds will mainly be light throughout the area Wednesday.

Thursday afternoon, west/southwest winds will surface across the higher terrain, with widespread gusts 25 to 40 mph, locally higher. Combined with low relative humidity of 10-15%, this will lead to widespread elevated to locally critical fire weather conditions during the afternoon and early evening hours, mainly below 9,000 ft where fuels remain receptive. Dry conditions will shift into the plains on Friday, but with lighter winds expected, fire weather concerns should be lessened.

.BOU WATCHES/WARNINGS/ADVISORIES...

Red Flag Warning until 5 PM MST this afternoon for COZ214-216-239>241-243-245.

SHORT TERM...Meier

LONG TERM...Rodriguez

AVIATION...EJD

FIRE WEATHER...Meier/Rodriguez

7.3 Graphic Forecast for Aviation

The NWS Graphic Forecast for Aviation (GFA) a graphical depiction of surface wind, thunderstorms, precipitation, color coded general flight categories, and cloud cover bases and tops, from graphical output from the National Weather Service's National Digital Forecast Data (NDFD) with the Graphic-Airmen's Meteorological Information (G-AIRMET)³⁴ for IFR conditions, mountain obscuration, icing conditions, and strong surface wind overlaid for the enroute phase of flight. The GFA is available at the NWS AWC website and through other weather briefing services. The 3-hour GFA charts issued at approximately 1500 MST and valid for the period 1700 through 2000 MST are included as figures 25-26 with the approximate accident site marked by the red star. The GFA Surface Forecast Surface Forecast (figure 25) depicted westerly winds of 25 knots gusting to 35 knots over the general area, with no visibility restrictions noted over the area, with no precipitation expected during the period. A Graphic-Airmen's Meteorological Information (G-AIRMET) for strong surface winds over 30 knots were depicted north of the accident site over Wyoming and western South Dakota. The GFA Cloud Forecast (figure 26) depicted the accident site between clear skies and high cirrus clouds. A G-AIRMET for icing conditions was also depicted over the area and included the accident site.

³⁴ AIRman's METeorological Information (AIRMET) is a concise description of weather phenomena that are occurring or may occur (forecast) along an air route that may affect aircraft safety. Compared to SIGMETs, AIRMETs cover less severe weather: moderate turbulence and icing, sustained surface winds of 30 knots or more, low-level wind shear, or widespread restricted visibility.

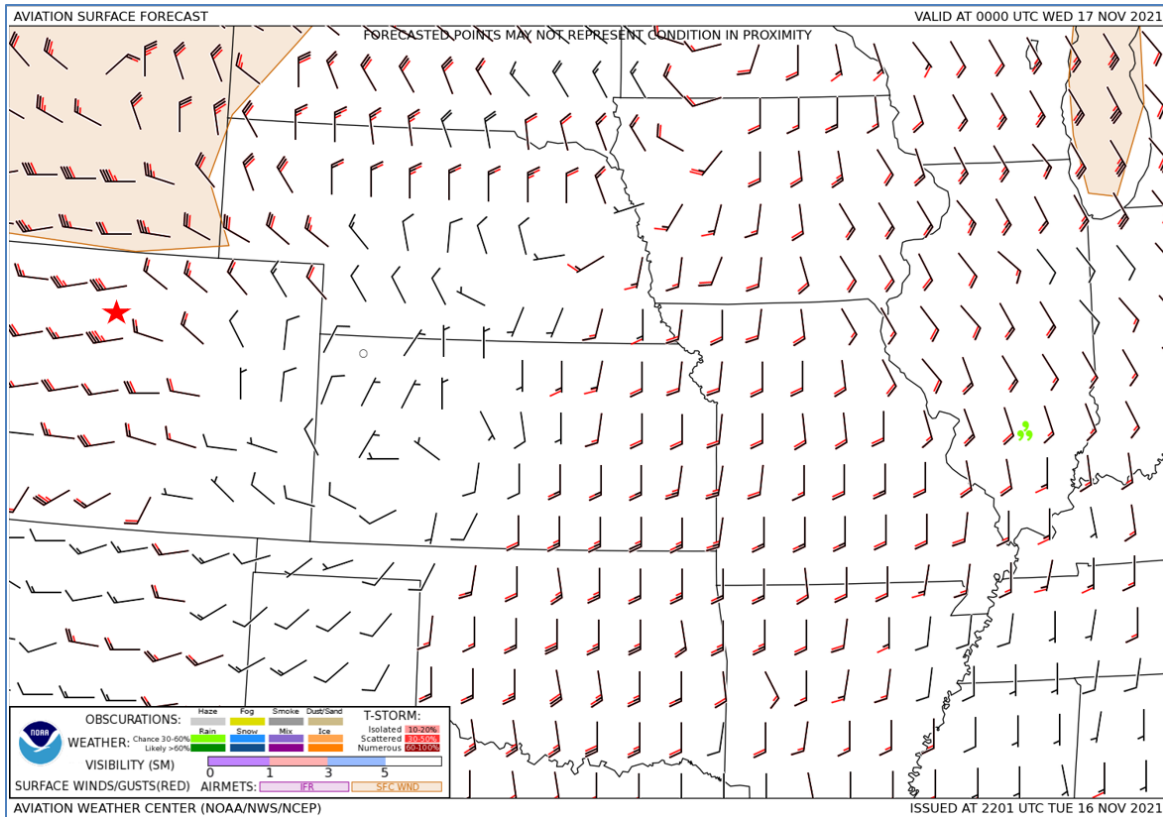


Figure 25 - Graphic Forecast for Aviation Surface forecast valid for 1700 MST.

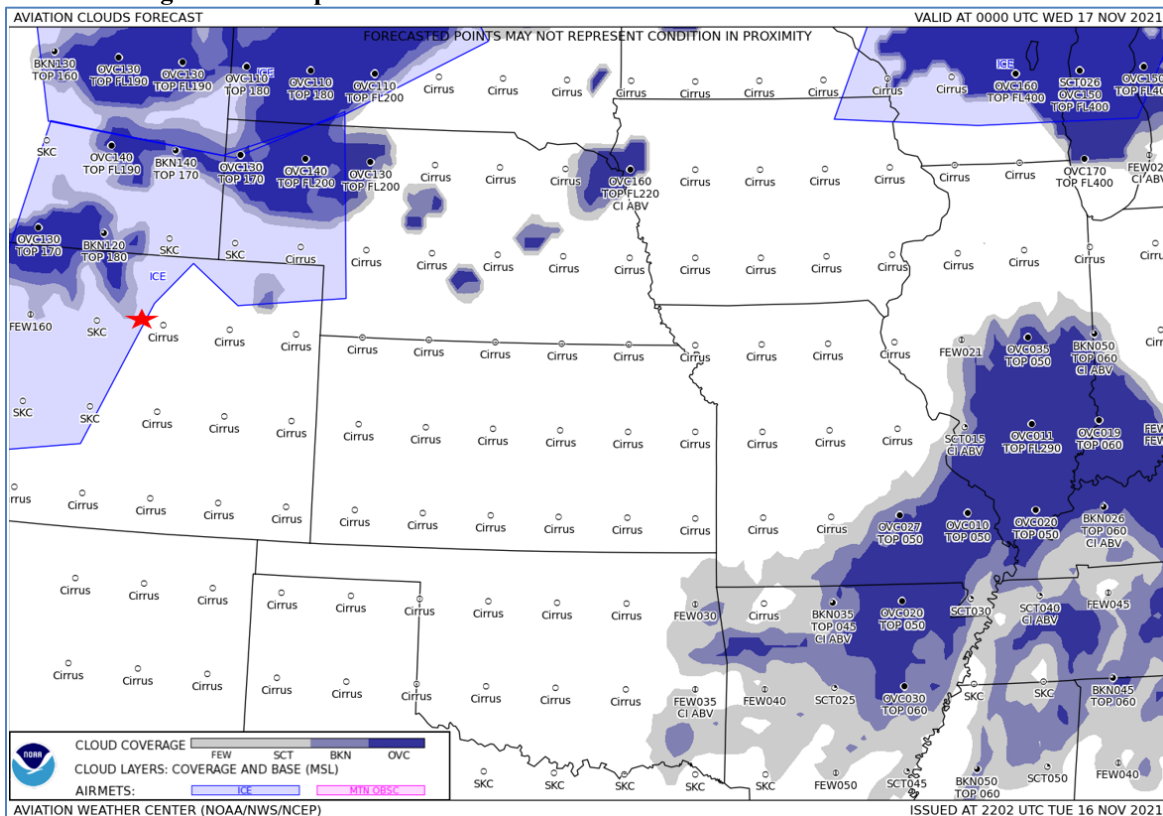


Figure 26 - Graphic Forecast for Aviation Cloud Forecast valid for 1700 MST.

7.4 Graphic Turbulence Guidance

The Graphic Turbulence Guidance (GTG) was developed by the National Center for Atmospheric Research (NCAR) and is now run operationally at NOAA NCEP and is available to users on the AWC website³⁵ from the surface to FL450 through 18-hours. The current GTG version 3.0 model (GTG3) is generated from the NOAA Rapid Refresh numerical model with a horizontal spacing of 13.5 kilometers with 50 vertical levels, and provides a computer-generated four-dimensional forecast related to the expected intensity of atmospheric turbulence provided in eddy dissipation rate (EDR)³⁶. Typical EDR varies from close to 0, "smooth", to near 1, "extreme" for most aircraft types. NCAR defines the following EDR values to various aircraft weight classes and turbulence intensities and is included as figure 27. The accident airplane fits into the light aircraft weight category³⁷.

AC weight class	Estimated EDR Threshold * 100			
	Light	Moderate	Severe	Extreme
Light	13	16	36	64
Medium (Large)	15	20	44	79
Heavy	17	24	54	96

Figure 27 - EDR values versus turbulence intensity for various aircraft weight classes.

The GTG color coded legend for a light aircraft weight category EDR values and typical associated turbulence intensity is depicted in figure 28, with values of EDR from 16-36 typically associated with moderate turbulence, and values between 36-64 associated with severe turbulence, and EDR values greater than 64 associated with extreme intensity.

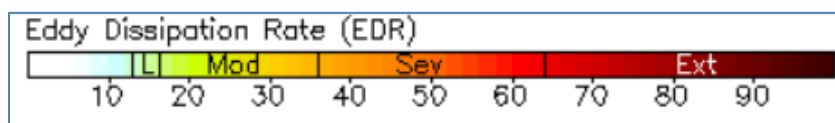


Figure 28 - EDR values for a light category aircraft.

The GTG product currently displayed for use on the NWS AWC website presently is not operationally archived by the NWS. As a result, the NTSB specialist contacted NCAR and requested to re-run the GTG for the period surrounding the time of the accident and provide a review of the conditions during the period, which is included as Attachment 3. The NCAR GTG values are in decimal format versus the NWS display contours and are multiplied by 100 for ease of interpretation. NCAR determined that the model data supported that the atmosphere was conducive for the development of mountain wave conditions with low-level trapped lee waves. The accident site was

³⁵ <https://www.aviationweather.gov/turbulence/gtg>

³⁶ Eddy Dissipation Rate (EDR) is defined as $EDR = \epsilon^{1/3}$

³⁷ Light weight class is less than 15,500 pounds maximum takeoff weight.

also located in an area of strong horizontal vorticity and vertical wind shear, which could indicate the presence of a rotor cloud; however, the model had insufficient resolution to resolve the rotors. The GTG products surrounding the period indicated EDR values between 0.4 to 0.5 $\text{m}^{2/3} \text{s}^{-1}$ or severe turbulence between 9,000 and 10,000 ft.

7.5 Winds and Temperature aloft Forecast

The Winds and Temperature Aloft Forecast (FD)³⁸ issued at 0657 MST and valid for 1700 MST and for use between 1400 through 2300 MST over the region were as follows.

FBUS33 KWNO 161357
 FD3US3
 -DATA BASED ON 161200Z
 VALID 170000Z FOR USE 2100-0600Z. TEMPS NEG ABV 24000

FT	3000	6000	9000	12000	18000	24000	30000	34000	39000
-DEN			2617+06	2733-02	2846-14	2658-26	258441	249650	740163
-GJT			2617+04	2729-03	2839-15	2840-28	264743	266751	266460
-MLS	2945-06	3045-13	2939-19	2762-27	2675-35	267346	266648	265948	
-RKS			2732	2844-09	2761-17	2775-29	277344	267152	276960

The forecast points surrounding the area included Denver (DEN), CO, Grand Junction (GJT), CO, Miles City (MLS), MT, and Rock Springs (RKS), WY. The closest forecast point was DEN which expected a wind at 9,000 ft from 260° at 17 knots with a temperature of 6° C, at 12,000 ft wind from 270° at 33 knots with a temperature of -2°C.

8.0 NWS Inflight Weather Advisories

Inflight Aviation Weather Advisories are forecasts to advise en route aircraft of development of potentially hazardous weather. Inflight aviation weather advisories in the conterminous U.S. are issued by the NWS AWC, as well as from the Center Weather Service Units (CWSU) associated with FAA air route traffic control centers (ARTCCs). There are four basic types of inflight aviation weather advisories: the Significant Meteorological Information (SIGMET), the Convective SIGMET, the Airmen's Meteorological Information (AIRMET), and the Center Weather Advisory (CWA). Inflight advisories serve to notify en route pilots of the possibility of encountering hazardous flying conditions which may not have been forecast at the time of the preflight briefing. Whether or not the condition described is potentially hazardous to a particular flight is for the pilot to evaluate on the basis of experience and the operational limits of the aircraft. At the time of the accident the following advisories were current.

³⁸ Based on the FBUS33 KWNO forecast bulletin.

The NWS had SIGMET Uniform³⁹ 15 current over the area for moderate to occasional severe turbulence below 18,000 ft due to strong low-level winds, which was reported by an air carrier A320 aircraft⁴⁰. Another SIGMET Xray⁴¹ 4 was current for severe turbulence between 25,000 and 42,000 ft due to wind shear associated with the jet stream and mountain wave activity, also reported by a Cessna Citation⁴². The SIGMETs are illustrated in the figure 29 and are followed by the text advisories. The NWS AWC also had Graphic-AIRMET Tango for moderate turbulence from the surface to 18,000 ft and low-level wind shear below 2,000 ft agl over the region at the time, included as figure 30. A G-AIRMET Zulu for occasional moderate icing conditions from the freezing level through 20,000 ft is included as figure 31.

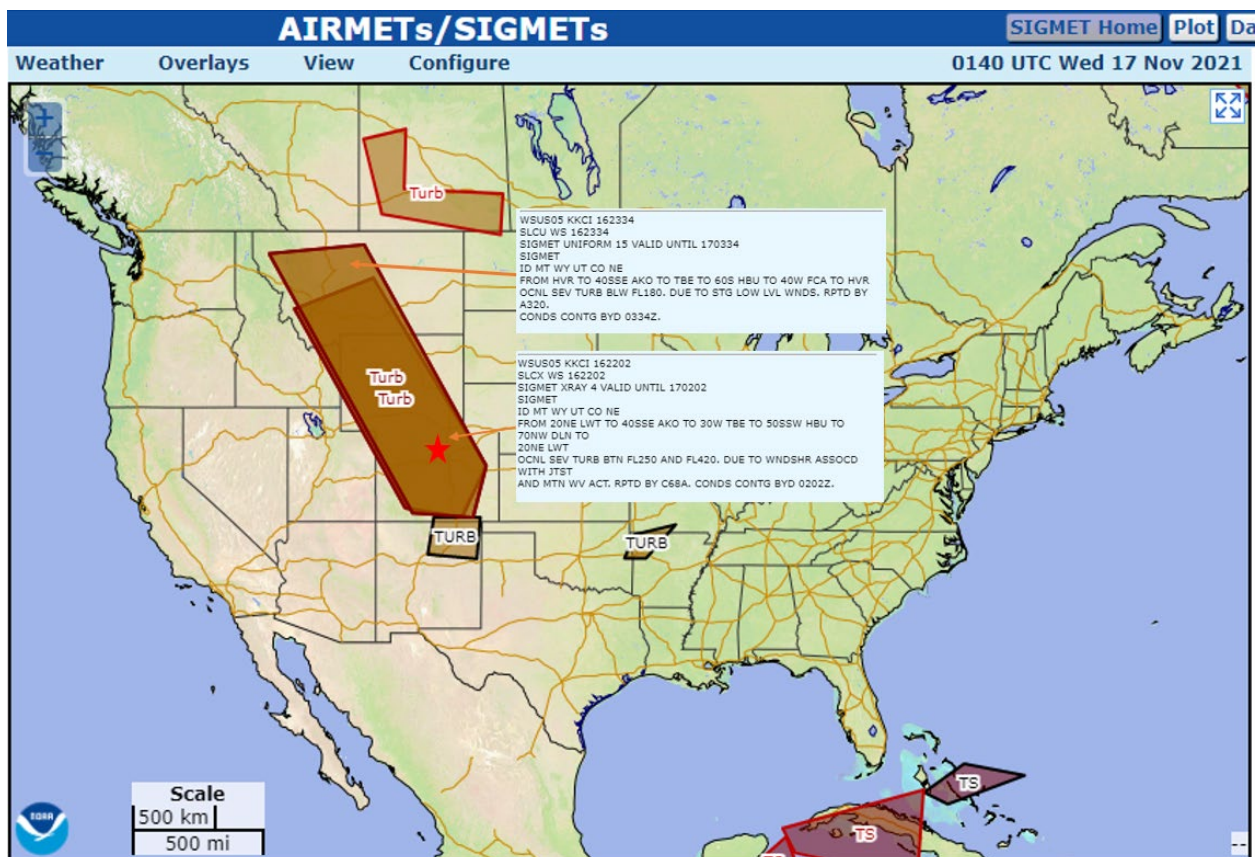


Figure 29 - Plot of SIGMET Xray 4 and Uniform 15 valid at 1840 MST with the accident site.

³⁹ SIGMET Uniform series advisory was first issued on November 14th at 1224 MST over Idaho, Montana, and Wyoming, and later into Colorado, and continued through November 16th at 2022 MST when conditions were mostly moderate reports were received.

⁴⁰ DEN UUA /OV DEN320035/TM 1830/FL155/TP A320/TB SEV 155

⁴¹ SIGMET Xray was first issued on November 16th at 0634 MST based on a report from a B767 and continued through 1920 MST before cancellation.

⁴² BZN UUA /OV BZN020010/TM 1855/FL410/TP C750/TB SEV 410 /RM CONS MOD 405 LGT 400 AND BELOW /ZLC

WSUS05 KPCI 162334
SLCU WS 162334
SIGMET UNIFORM 15 VALID UNTIL 170334
SIGMET
ID MT WY UT CO NE
FROM HVR TO 40SSE AKO TO TBE TO 60S HBU TO 40W FCA TO HVR
OCNL SEV TURB BLW FL180. DUE TO STG LOW LVL WND. RPTD BY A320.
CONDS CONTG BYD 0334Z.

WSUS05 KPCI 162202
SLCX WS 162202
SIGMET XRAY 4 VALID UNTIL 170202
SIGMET
ID MT WY UT CO NE
FROM 20NE LWT TO 40SSE AKO TO 30W TBE TO 50SSW HBU TO 70NW DLN TO 20NE LWT
OCNL SEV TURB BTN FL250 AND FL420. DUE TO WND SHR ASSOCD WITH JTST
AND MTN WV ACT. RPTD BY C68A. CONDS CONTG BYD 0202Z.

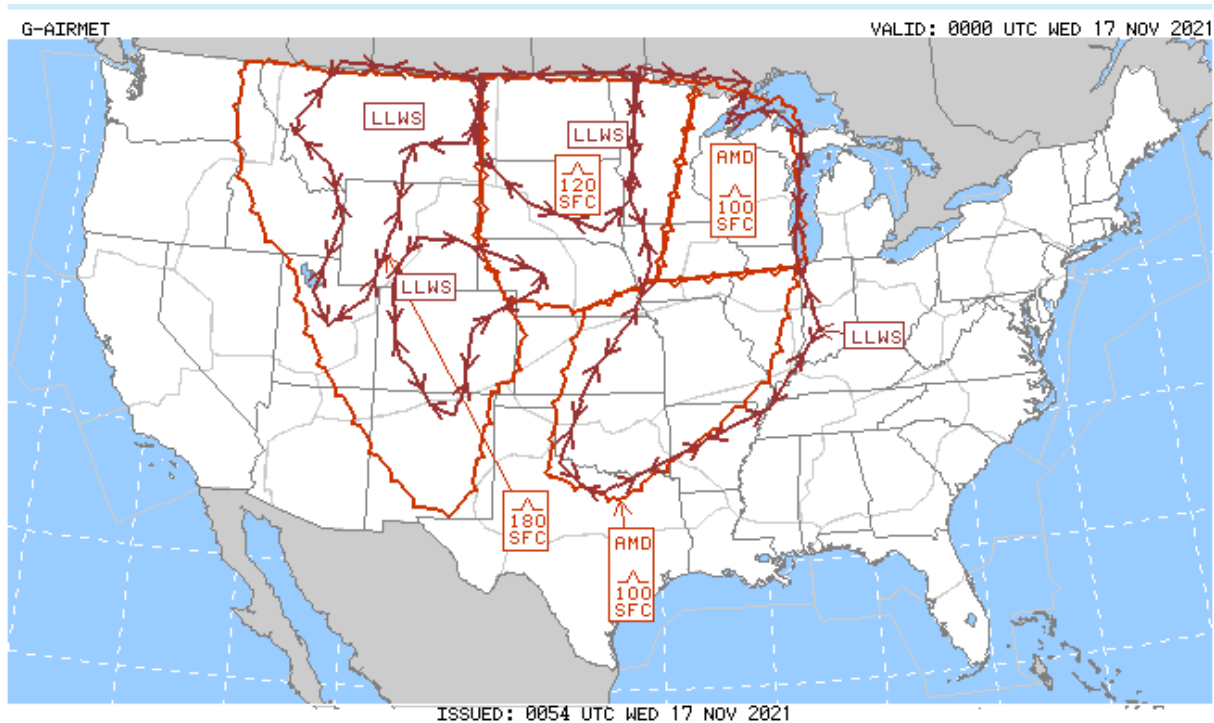


Figure 30 - G-AIRMET Tango series for turbulence and low-level wind shear valid for the period.

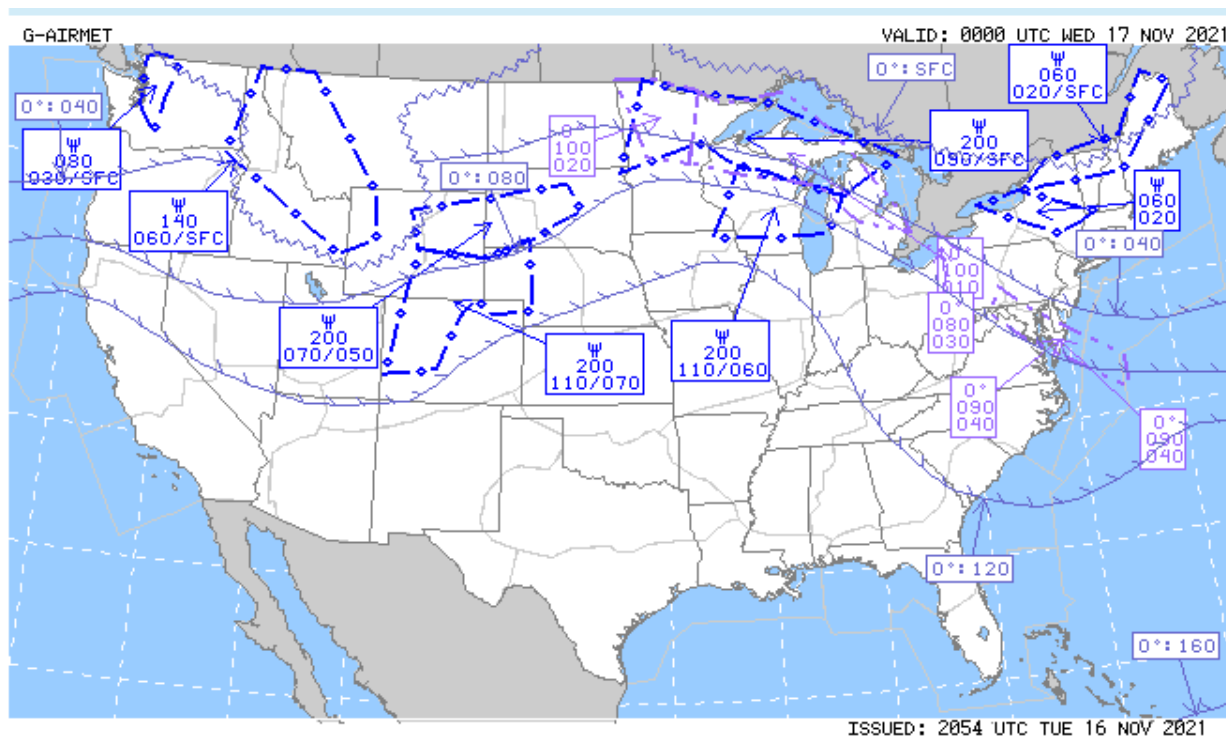


Figure 31 - G-AIRMET Zulu for occasional moderate icing and freezing level display.

9.0 Pilot Preflight Weather Briefing

A search of the FAA contract Automated Flight Service Station (AFSS) provider Leidos indicated that they and that no 3rd party vendors using the Lockheed Flight Service (LFS) system had any contact with the pilot of N802NZ on the day of the accident for any weather briefing, flight plans, or inflight weather contacts. A similar search of ForeFlight indicated they also had no contact with the pilot for any weather briefing data. It is therefore unknown what the accident pilot reviewed prior to departing on the accident flight or was aware of the inflight weather advisories current for the area.

10.0 Witness Statements

The firefighter working with T860⁴³ for the night drop operations provided his written notes and indicated that he was located on the west side of Hermit Park near an equestrian campground. He indicated that he estimated the wind to be from the northeast at 14 mph with intermittent and random gusts to 20 mph, which he estimated using the Beaufort scale and his experience. The accident pilot and he had discussed the priorities of the intended fire retardant drop and the pilot made an initial high pass

⁴³ T860 was the N802NZ firefighting designation number on the horizontal stabilizer and on the underside of the right wing to help identify the aircraft during operations.

to plan his drop. On the second and lower circle the pilot advised the firefighter that it was a little turbulent but did not seem to be stressed or abnormally concerned of the conditions. They discussed returning to base until 2200 MST when the winds were predicted to subside a bit, but the accident pilot indicated he was willing to go ahead with the drop on the next pass. The firefighter indicated that the accident pilot was making the drop and came in at a slightly lower altitude and traveling on a direction NE to SW over his position and towards the planned drop on the fire, when he observed the plane wobble then roll twice to the left based on his observation of the position lights on the tanker aircraft when he lost sight of the airplane behind the trees. A few seconds later he heard a loud thud and was unable to contact the pilot. He then called dispatch and reported the tanker aircraft down and started the crash response procedures and made a note of the bearing of 230° where he last saw the tanker aircraft. He then returned to the Incident Command Post (ICP) at about 2030 MST.

A husband and wife also witnessed the accident airplanes light roll twice before the aircraft disappeared behind some trees and impacted the ground from their home which overlooked the area less than 2 miles from the accident site. Both of them had witnessed the accident airplane during the afternoon make several passes on the fire and make a water drop. On the second flight during the early evening, they observed the accident aircraft although it was getting dark after dusk, they could still identify the aircraft lights as it made several passes. On the last low altitude pass, they believed the aircraft was going to make a drop, when they witnessed the landing light tilt to a 45° angle, and saw the aircraft's light roll, possible twice, flopping all over the place, and then disappeared. Stating that the wings on the accident airplane went vertical 90° to the ground, but not that he was turning or banking. They stated the aircraft went all the way over, like barrel rolls. A second or two after they saw the accident airplane flip, it disappeared. They did not see any fireball or hear any crash sounds. They then called 911 to report the event. The husband was watching the accident flight using binoculars during the period. With regards to the weather, they indicated that the winds had died down from the afternoon and then picked up again all of a sudden, wind was blowing at a sustained 10-15 mph with gusts to 40 to 45 mph which would rattle the trees. They also noted that 7 to 8 inch diameter trees were bending in the wind during the period. The smoke was blowing downhill towards the valley, and never bothered them. They indicated that there were 20 to 30 glows or more of small fires burning, the accident airplane never entered the smoke of the fire. The wind kept the smoke going down the valley eastward, never swirled, never appeared to interfere with the flight. A photo of their view of the fire from their window looking west at 1714 MST on November 16, 2021, prior to the accident is included as figure 32. Hermit Park meadow is visible below the smoke, with the low ridge line where the accident airplane went down to the far left. They both described the flight path on the final pass was almost level from their view out the picture window.

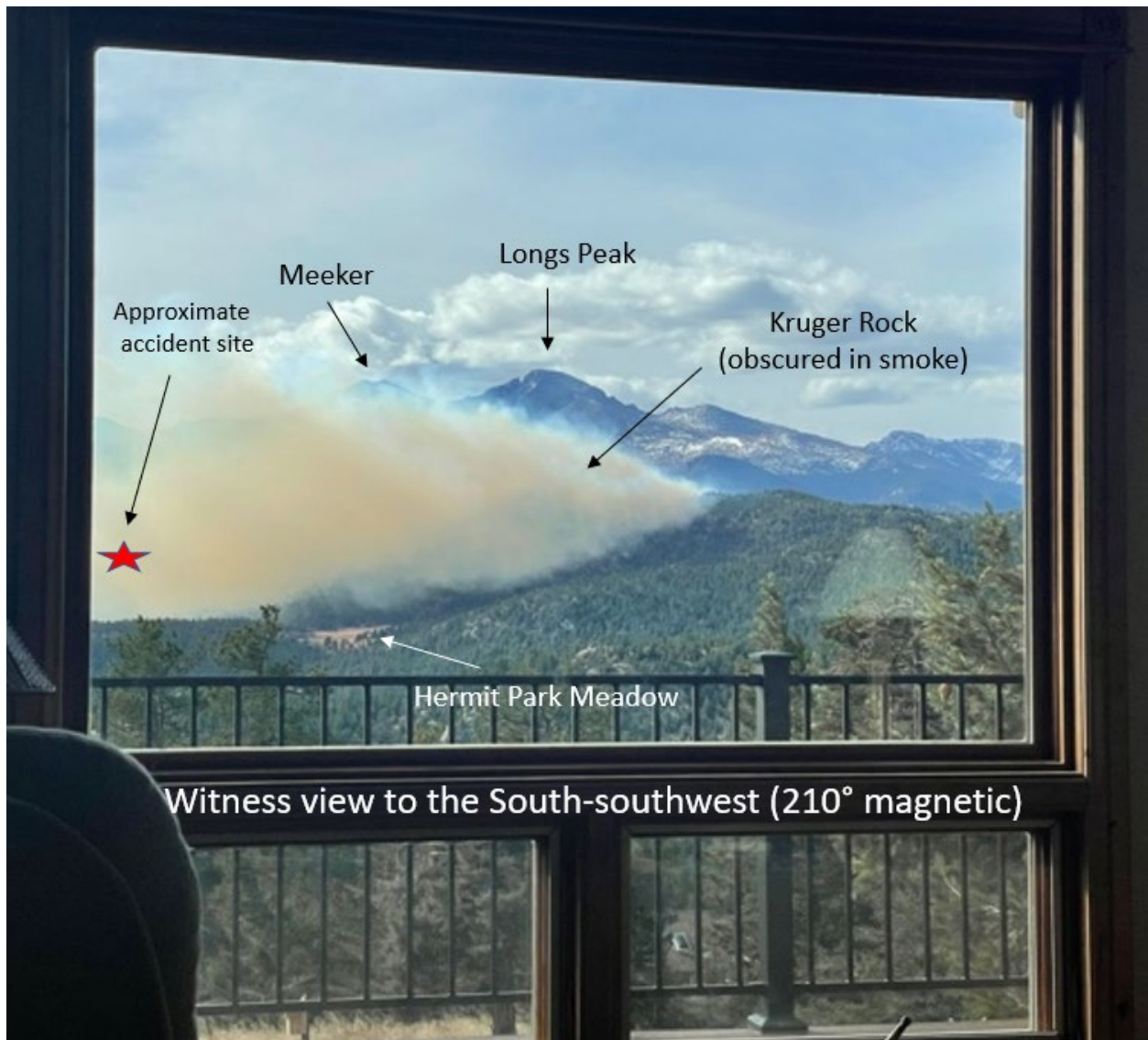


Figure 32 - Witness view of the fire at 1714 MST on November 16, 2021.

A freelance photographer who lives in the area was taking pictures of the Kruger Rock Fire on the edge of Estes Park immediately west of the ridgeline prior to the accident. He had witnessed the accident airplane come over the ridge and start dropping water on the eastern side of Kruger Rock. He indicated the airplane made several sweeps on the western side and on the eastern side, and then turned west towards the lake and highway 36. The airplane then turned eastward and started back over the ridge on a different way than he came in. He indicated he didn't photograph the accident airplane because he didn't have the right lens on his camera to shoot from such a long distance and due to the nighttime conditions. He then went back to shooting images of the fire, when suddenly a strong wind gust, which he estimated at 90 mph came through and almost blew him over from his sitting position on the ground. Seconds later, he observed a bright flash of light lit up the entire sky on the eastern side of Kruger Rock.

He then called the nonemergency dispatch number of the Este Park Police Department to share the location of the flash he had seen to help searchers located the wreck.

A security camera captured the fires burning on the ridge and the aircraft lights at the time stamp 1847:34 MST and the potential impact on the other side of the ridge at 1847:45 MST. Figure 33 is two still images from the security animation showing lights immediately below a low-layer of clouds, which are moving from left-to-right during the period, and a flash of the accident airplane hitting the ground on the opposite side of the ridge. Multiple wildfires can be seen on the right side of the image burning on the side of the ridge. The security camera was located on Rockwood Lane and facing east-northeast.



Figure 33 - Security camera images at 1847:33 and 1847:45 MST capturing the aircraft.

11.0 Astronomical Conditions

The astronomical conditions were calculated using the United States Naval Observatory's Multiyear Interactive Computer Alamac (MICA) software for Estes Park, CO. The time of the accident has been added for reference in italic bold type.

<u>Sun</u>	<u>Time (MST)</u>
Civil twilight	0620
Sunrise	0649
Sun culmination	1147
Sunset	1644
End civil twilight	1713
Accident	1836

<u>Moon</u>	<u>Time (MST)</u>
Moonrise	1538
Accident	1836
Culmination	2217
Moonset	0405

At the time of the accident the Sun was more than 20° below the horizon. The Moon was 32° above the horizon at an azimuth of 108°, with the phase a waxing gibbous with 95% of the disk illuminated.

12.0 Mountain Wave References

The FAA published Advisory Circular AC 00-57 "Hazardous Mountain Winds and Their Visual Indicators" in 1997 to assist pilots diagnose the potential for severe wind events in the vicinity of mountainous areas. The advisory circular provides information on preflight planning techniques and on in-flight evaluation strategies for avoiding destructive turbulence and loss of aircraft control. The advisory circular discussed the general formation and types of mountain wave conditions, which have been summarized below.

The illustrations are from the University Center for Atmospheric Research (UCAR) COMET web based training program "Mountain Waves and Downslope Winds" issued in July 2004.

Atmospheric Disturbances in Mountainous Areas

As strong winds move over mountains or high terrain and the atmosphere is stable, a wave will develop. The wave that forms vertical displacement of a stable air mass over a mountain or ridge can generate two forms: a vertically propagating mountain waves and trapped lee waves. The particular type of wave or combination of waves that forms depend on the nature of the mountain range and on the atmospheric properties upwind of the mountain. It is possible for both types of wave to exist at the same time, or a hybrid form where waves that are only partially trapped.

Vertical Propagating Mountain Waves

Figure 34 is a schematic of a vertically propagating mountain wave. With this type of wave feature, air that is moving nearly perpendicular to the barrier is deflected upward and accelerated as it passes over the crests and down the lee slope of the terrain. A standing wave develops vertically above the mountain crest and that the resultant wave tilts upwind with height. Note the amplitude of the wave increases with height and results in significant updrafts above the ridge at altitude. With a wave of modest amplitude where the vertical displacement of air moving through the wave is relatively limited, an aircraft flying through this region would likely experience appreciable "wave action," with altitude and/or airspeed fluctuations, but with little turbulence. However, with sufficient amplitude, the wave breaks, and localized updrafts and downdrafts occur. The consequence for a pilot flying through this region include airspeed and altitude deviations and the possible sudden onset of severe or extreme turbulence.

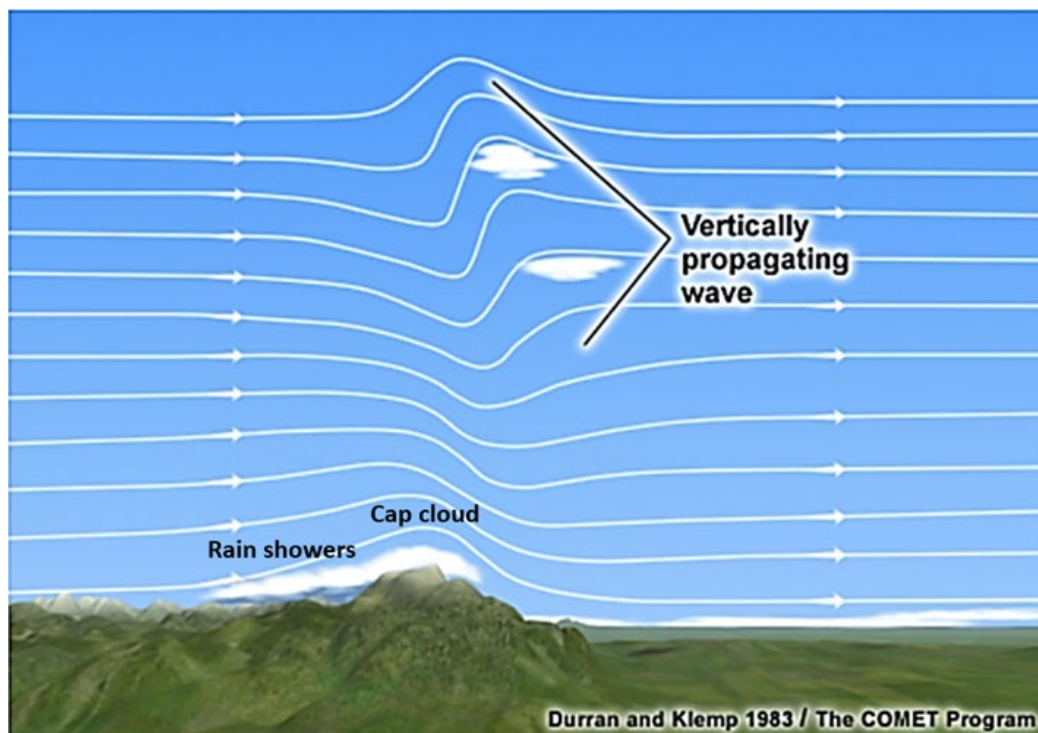


Figure 34 - Vertical propagating mountain wave.

Often accompanying these high altitude effects is the occurrence of very strong surface winds in the form of downslope winds, that creates a low-level hazard to all aircraft. Further, these extreme low-level winds often terminate abruptly in a "jump" located some distance to the lee of the mountains themselves. These features are depicted schematically in figure 35. The jump

region (or hydraulic jump⁴⁴) is frequently an area of sever-to-extreme turbulence extending to 10,000 ft or more above the surface. The jump region is sometimes marked by a line of ragged rotor clouds exhibiting very turbulent motion, with turbulence typically decreases with distance away from the jump region.

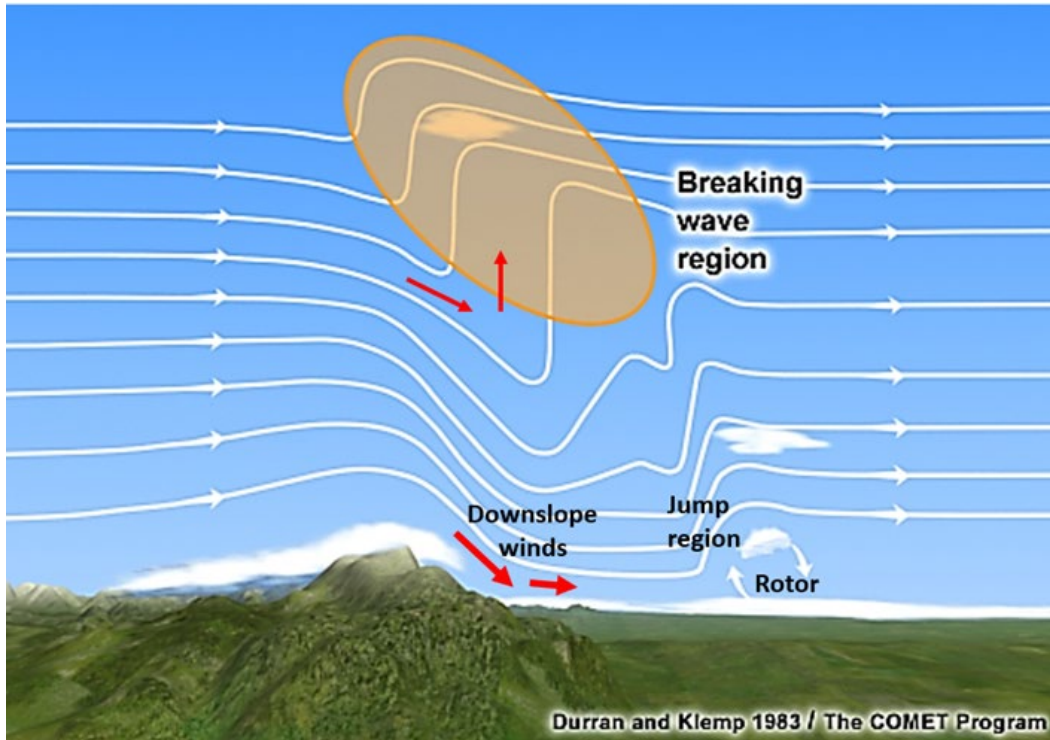


Figure 35 - Breaking vertical propagating wave with downslope winds and pressure jump.

Summary Comments on Vertically Propagating Mountain Waves

- Large-scale winds at ridge level, blowing perpendicular (or nearly so) to the ridge-line, are normally required.
- Wind speeds at ridge level are normally 20 knots or greater.
- Relatively weak vertical wind shear is present. Typically, the ratio of the wind speed 6,000 ft above the ridge-top level to that at ridge-top level is less than 1.6 when this class of wave is of operational concern.
- The atmosphere is relatively stable. If there is a steep temperature lapse rate below 500-hPa (an unstable atmosphere), with evidence of convection present, this type of atmospheric wave is unlikely to form.

⁴⁴ Hydraulic Jump - A steady disturbance in the lee of a mountain, where the airflow passing over the mountain suddenly changes from a region of low depth and high velocity to a region of high depth and low velocity.

- *Vertically propagating waves are most likely and most intense during the winter and early spring months, when the winds at ridge level are strongest.*
- *In the general prevailing westerly flow, these waves are most prevalent over mountain ranges that have a north-south orientation.*
- *Stronger ambient winds lead to a deeper wave.*
- *The greater the atmospheric stability, the shallower the wave (for a given wind speed).*

Trapped Lee Waves

Trapped lee wave are often marked by a train of altocumulus standing lenticular (ACSL) clouds extending far downwind of the mountain. They are evident as relatively straight lines or bands of clouds with clear spaces between the bands and form parallel to and down range of the mountain range. The waves that produce these cloud features are often referred to as "trapped lee waves," because the wave energy is confined below a certain altitude. The mechanism confining this energy is strong wind shear above the ridge level. Trapped lee waves are most likely to occur when the wind crosses a narrow mountain range, with a layer close to the ridge level and upstream of the mountain that has a strongly increasing wind speed with height and high stability, capped by a layer of strong flow and low stability. Figure 36 is a depiction of a trapped lee waves. Notice that this wave type of wave extends downwind from the mountain, but does not develop to a very high altitude, and has no upstream tilt, in contrast to the vertically propagating wave.

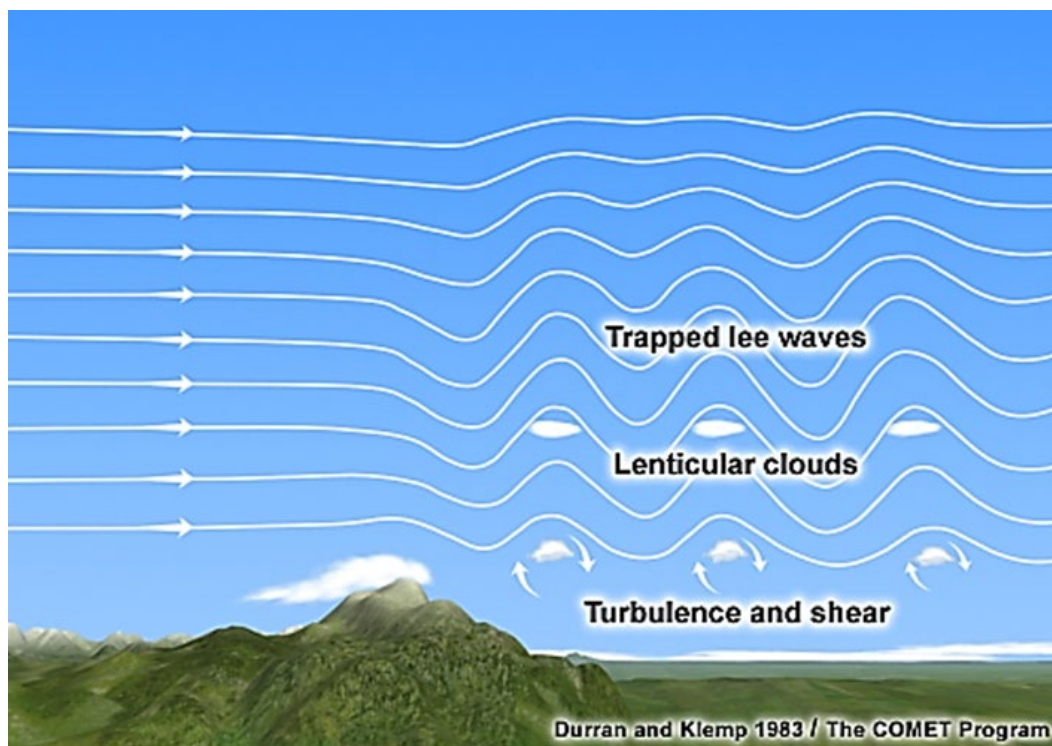


Figure 36 - Trapped lee wave and lenticular clouds.

This class of wave typically presents less turbulence hazard than do breaking vertically breaking waves, because the wave amplitude decreases with height within the "trapping layer," typically based within a few thousand feet of the ridge crest. As a result, these waves do not typically extend to as great altitude.

However, at lower altitude trapped lee waves can create strong turbulence encounters for aircraft. Cloud bases associated with trapped lee waves are typically one to several thousand feet above the ridge level, and pilot reports in the vicinity frequently indicate moderate-to-severe turbulence beneath the clouds, related to large horizontal and vertical wind shears below the cloud level.

In all cases, the forecast and/or measurement of ambient winds near the ridge level of 20 knots or more should cause pilots to presume that wave activity is present and take appropriate actions .

Summary Comments on Trapped Lee waves

- *Trapped lee waves do not propagate vertically because of the capping effects of strong wind shear or low stability above.*
- *Aircraft turbulence encounters related to trapped lee waves are generally restricted to lower altitudes, whereas vertically propagating waves can affect all altitudes.*

- Strong turbulence can develop near the bases of accompanying lenticular clouds, although such clouds may not be present.
- Forecasts of winds 20 knots or greater at the ridge level should alert pilots to the likelihood of wave activity.

Persistent Horizontal Roll Vortices (Rotors)

When mountain waves are present, it is quite common for a rotor zone to develop near or below the ridge level on the downwind side of the mountain, under a wave crest and associated lenticular clouds (if sufficient moisture is present). This is an area of potential severe-to-extreme wind shear and turbulence.

Figure 37, from Bedard⁴⁵, shows a schematic of the wind flow associated with this feature. As illustrated in this schematic, rotors typically mark the downwind terminus of a downslope windstorm. When this is the case, the rotor is really part of the "jump". Although strong rotation is typically present within the rotor zone and associated cloud, a pilot in a moving aircraft may not be able to detect such motion visually until the aircraft is quite close to the vortex. In fact, from a distance a rotor cloud may look like a rather innocuous cumulus cloud; however, the downwind side of the rotor cloud will typically be rounded in the direction of rotation or the rotor, with cloud tags or streamers at the bottom of the cloud mass. The latter features appear to be rapidly forming and dissipating, thereby giving some sense of rotation with the cloud.

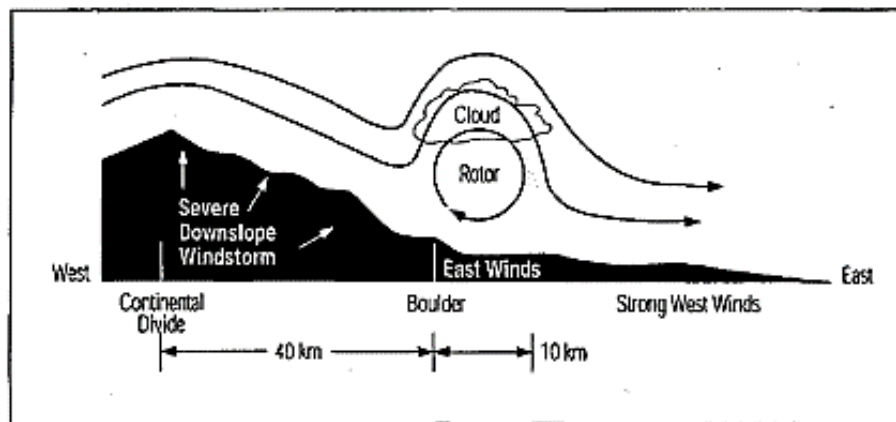


Figure 37 - Conceptual view of a mountain lee wave rotor zone (Bedard, 1993).

Because of their potential for causing turbulence and loss of aircraft control, rotor zones should be avoided. Doppler lidar measurements in rotor have

⁴⁵ Bedard, A. J., 1993: Atmospheric turbulence aloft: A review of possible methods for detecting, warning, and validation of predicted models. Washington, DC: American Institute of Aeronautics and Astronautics.

documented rotational speeds greater than 20 knots. Rotor zones are of concern not only because of the likelihood of strong turbulence in their vicinity (particularly on the upwind side of the rotor), but also because of the potential for rolling moments that could exceed the roll authority of the aircraft or otherwise lead to loss of control.

Since rotor zones can be a product of either type of mountain wave, the previously discussed forecast and observed data and the associated rules can also be applied in forecasting the likelihood of rotor zones. When waves are present, one should assume that a rotor zone exists below the ridge level and within 20 nm of the ridge. Pilots should be particularly cautious when they know or suspect that breaking vertical propagating waves or a downslope windstorm are occurring. Under these conditions, the rotor or jump zone will very likely be a location of severe-to-extreme turbulence and, in addition to horizontal axis vortices, may also contain vertical axis vortices of great intensity.

13.0 Weather Research and Forecast Model

The NTSB ran a Weather Research and Forecasting (WRF) model simulation surrounding the time of the accident using initialization data from the Global Forecast System (GFS)⁴⁶. The terrain used in WRF are provided in figure 38 for domain 2 (left) and for domain 3 (right) with height in ft, and the star depicting the approximate accident site. Figures 39 and 40 are a depiction of the WRF domain 3 topography of the west to east cross section with the accident site located in the middle of the image near the grid point 40 and depicted the isentropes or lines of potential temperature (in degrees Kelvin) and horizontal wind speeds (figure 39) in knots followed by the vertical velocity (figure 40) in feet per minute (fpm) from 1830 to 1840 MST (0130Z to 0140Z) from 800-hPa to 650-hPa. The image depicts winds of 40 to 50 knots near the ridge levels, with updrafts on the windward or west side of the ridges from 200 to 800 fpm with downdrafts of 200 to 400 fpm on the leeward or east side of the ridges or basins over the accident site. The isentropes show the wave like pattern flow of mountain wave activity over the area surrounding the period.

⁴⁶ GFS4.[1] WRF ARW (Advanced Research WRF core) version 4.1.2 was run with 3 domains with horizontal grid spacing of 8 km, 1.6 km, and 320 m. Other WRF simulation parameters included: 50 vertical levels, the multi-scale Kain-Fritsch cumulus parameterization scheme used on the outer domain, a Lin et al. microphysics scheme, a Yonsei University boundary layer scheme, Noah land surface physics, the Dudhia scheme used for short wave radiation, and the RRTM scheme for the long wave radiation.

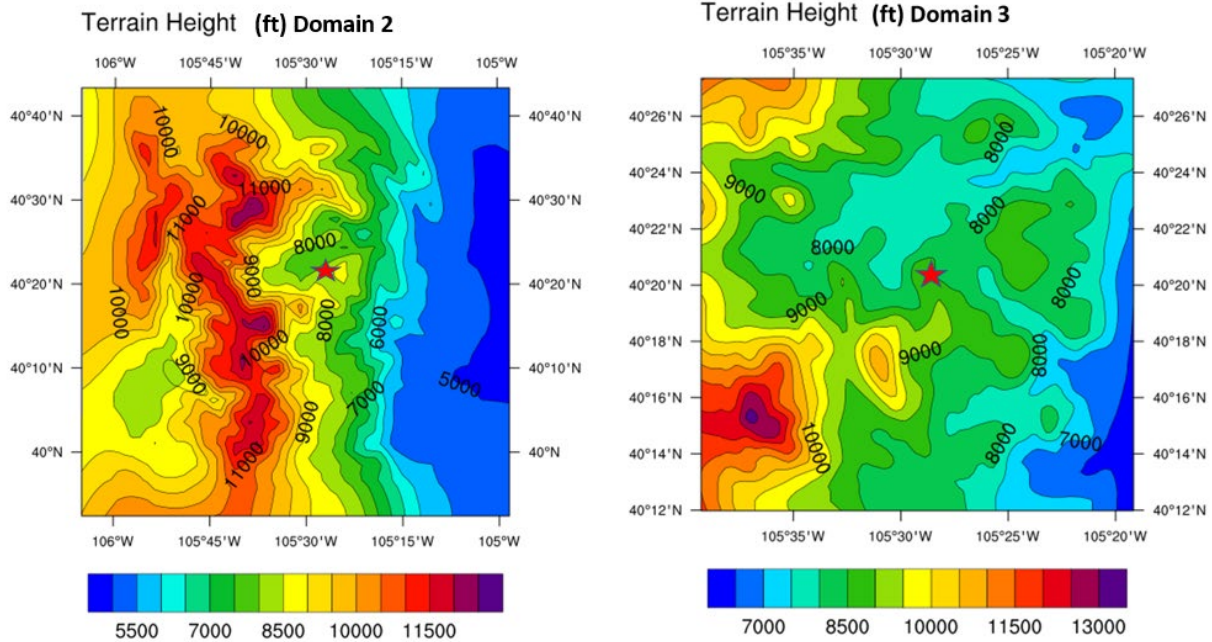


Figure 38 – WRF terrain for domain 2 (left) and domain 3 (right) with height in feet.

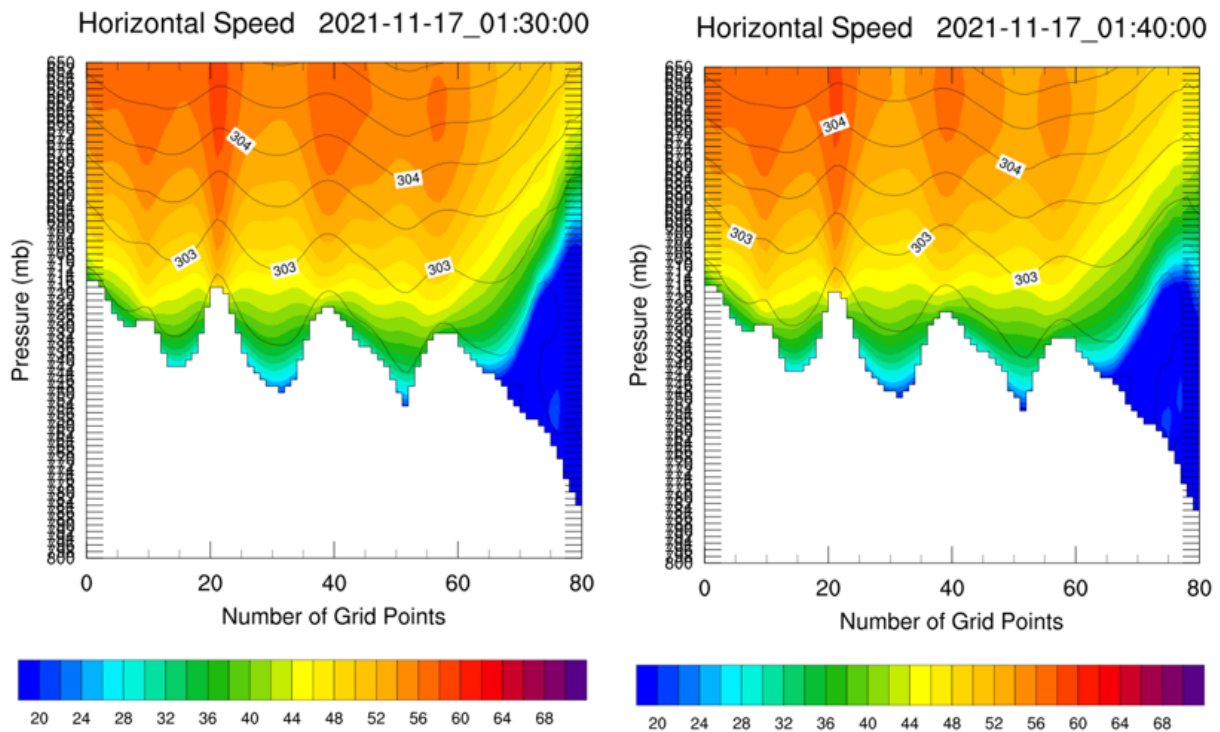


Figure 39 - WRF west to east cross section of horizontal winds at 1830 and 1840 MST.

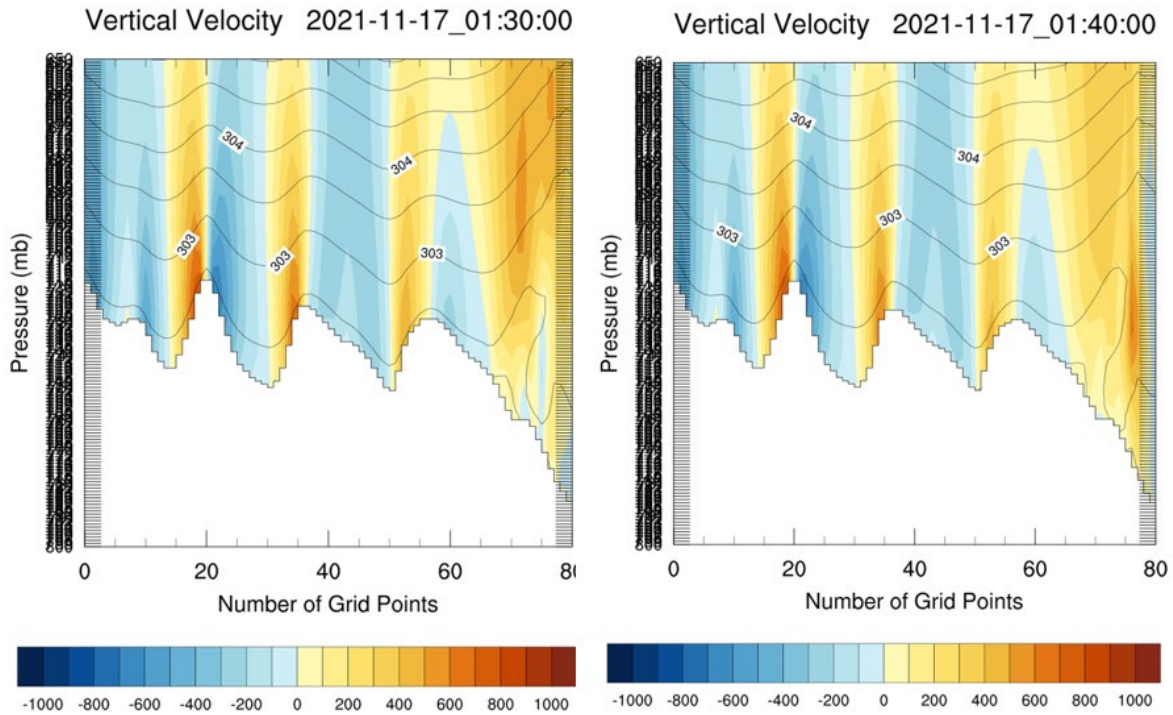


Figure 40 - WRF west to east cross section of vertical velocity for 1830 and 1840 MST.

E. LIST OF ATTACHMENTS

Attachment 1 - Satellite and weather radar imagery animation.

Attachment 2 - AIM Chart of turbulence intensity and reactions.

Attachment 3 - NCAR numerical model and Graphic Turbulence Guidance.

Submitted by:

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