

National Transportation Safety Board

Office of Aviation Safety

Washington, DC 20594



DCA24FA143

METEOROLOGY

Specialist's Factual Report

October 18, 2024

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A. ACCIDENT

Location: Gulf of America, United States
Date: April 3, 2024
Time: 0823 eastern daylight time (EDT)
1223 coordinated universal time (UTC)
Airplane: Boeing 737-7CT; Registration: N567NM
Southwest Airlines flight 4273

B. METEOROLOGY GROUP

Group Chairmen Donald Eick
National Transportation Safety Board
Office of Aviation safety
Operational Factors Division (AS-30)
Washington, D.C.

Member Michael Richards
National Transportation Safety Board
Washington, D.C.

C. SUMMARY

On April 3, 2024, at about 0823 eastern daylight time, Southwest Airlines flight 4273 (SWA4273), a Boeing 737-700, experienced severe to extreme turbulence while enroute between New Orleans International Airport (MSY), New Orleans, Louisiana, and Orlando International Airport (MCO), Orlando, Florida. Of the 4 crew and 139 passengers onboard, one flight attendant and one passenger received serious injuries, and one flight attendant minor injuries. The aircraft was not damaged. The flight was operating under the provisions of *Title 14 Code of Federal Regulations Part 121* as a scheduled, passenger flight from MSY to MCO.

D. DETAILS OF THE INVESTIGATION

The National Transportation Safety Board's Senior Meteorologist conducted most of 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), and Southwest Airlines. While

another NTSB meteorologist was embedded with the Air Traffic Control Group investigation and supported that portion of the investigation and conducted interviews at the Jacksonville Air Route Traffic Control Center (ARTCC) and Center Weather Service Unit (CWSU). This report documents the general weather products and forecasts over the region during the period and documents the pertinent meteorological parameters to the accident. All times are reported as eastern daylight time (EDT) based upon the 24-hour clock, local time is -4 hours from UTC, and UTC=Z. Airport and NWS 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. continental 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 turbulence location was based on the Flight Data Recorder (FDR) position of maximum vertical g's at latitude 28.335° N and longitude 86.432778° W at flight level (FL)¹ 370.

E. 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 Centers 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 and other products can be found in the Federal Aviation Administration (FAA) "Aviation Weather Handbook", FAA-H-8083-28².

1.1 Surface Analysis Chart

The NWS Surface Analysis for the southeast for 0800 EDT is included as figure 1 with the approximate turbulence location marked by a red star. The chart depicted a low-pressure system at 994-hectopascals (hPa)³ over western North Carolina (just off

¹ Flight Level (FL) is reference to altitude based on pressure altitude in hundreds of ft with the altimeter set to 29.92 inches of mercury (inHg) and is typically reported for aircraft operations above 18,000 ft in the United States.

² <https://www.faa.gov/regulationspolicies/handbooksmanuals/aviation/faa-h-8083-28-aviation-weather-handbook>

³ Hectopascals (hPa) is the standard unit for reporting pressure and replaces the previous term millibar (mb) with the same units. The International Standard Atmosphere (ISA) is based on a sea-level pressure of 1013.25-hPa or 29.92 inches of mercury (inHg) at a temperature of 15° Celsius (C) or 59° Fahrenheit (F).

the map) with a cold front extending south-southwestward across western South Carolina, Georgia, the Florida panhandle, and into the Gulf of America. The cold front was in the immediate vicinity of the turbulence location. An outflow boundary⁴ was depicted ahead of the cold front across central Georgia into the panhandle and was previously depicted on the 0500 EDT chart as a squall line⁵.

The station models near the accident site east of the cold front depicted southerly winds of 15 knots with temperatures and dew point temperatures of 73°F, with stations west of the front depicting northwest winds of 25 to 30 knots and temperatures near 68°F and dropping into the 40's °F over northern Alabama. Morning temperatures across central Florida were in the mid 70's °F. The closest land station was from Apalachicola, Florida, which depicted thunderstorms in the vicinity and rain.

⁴ An outflow boundary is defined as a storm-scale or mesoscale boundary separating thunderstorm-cooled air (outflow) from the surrounding air; similar in effect to a cold front, with passage marked by a wind shift and usually a drop in temperature. Outflow boundaries may persist for 24 hours or more after the thunderstorms that generated them dissipate and may travel hundreds of miles from their area of origin.

⁵ Squall line is a line of active thunderstorms, either continuous or with breaks, including contiguous precipitation areas resulting from the existence of the thunderstorms.

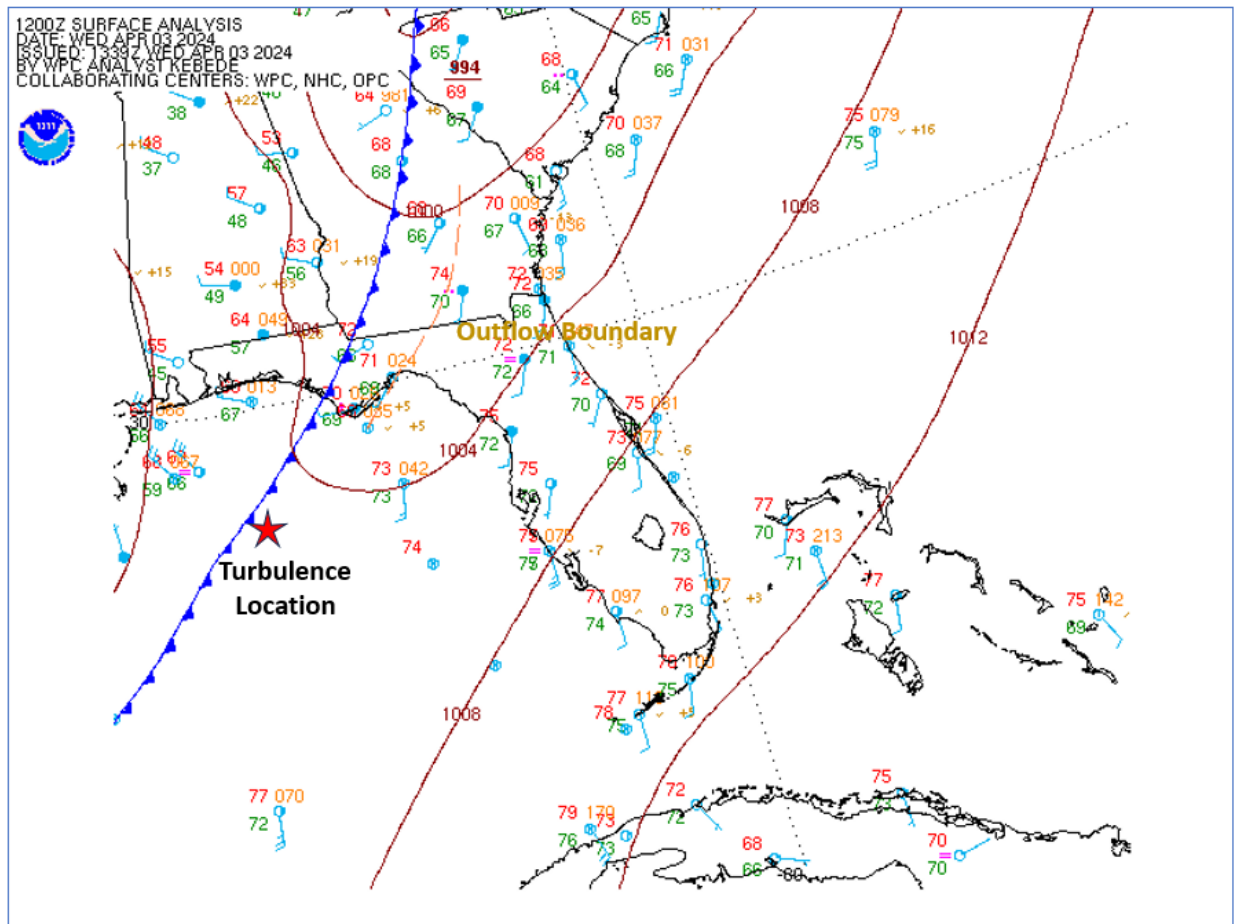


Figure 1 - Southeast NWS Surface Analysis Chart for 0800 EDT with the approximate turbulence location marked by the red star.

1.2 Constant Pressure Charts

The NWS-derived constant pressure charts for 500-, 300-, 250-, and 200-hPa obtained from the University of Wyoming's website⁶ are included as figures 2-5, where the position of the upper-level high's, low's and short-wave troughs have been annotated with the approximate turbulence location. The charts depicted the contour lines of equal height, isotherms, and isotachs above 300-hPa, along with the individual upper air station observation of temperature, dew point spread, height in decameters, 12-hour height change, and wind speed and direction. The 500-hPa chart (figure 2) provides the conditions at approximately 18,000 ft (the mean atmosphere with regards to pressure). The 300-hPa chart (figure 3) provides the general conditions near 30,000 ft, the 250-hPa (figure 4) at 34,000 ft, and the 200-hPa chart (figure 5) the conditions at approximately 39,000 ft. The turbulence location occurred between the 250- and 200-hPa charts.

⁶ <https://weather.uwyo.edu/upperair/>

The charts depicted winds on the 500-hPa chart from the west at 60 knots, and increased to 90 kts, 120 kts, and 110 kts at the upper levels. A 155 knot jet stream was depicted on the 250-hPa level moving across Mississippi, Alabama, and Georgia immediately north of the accident site.

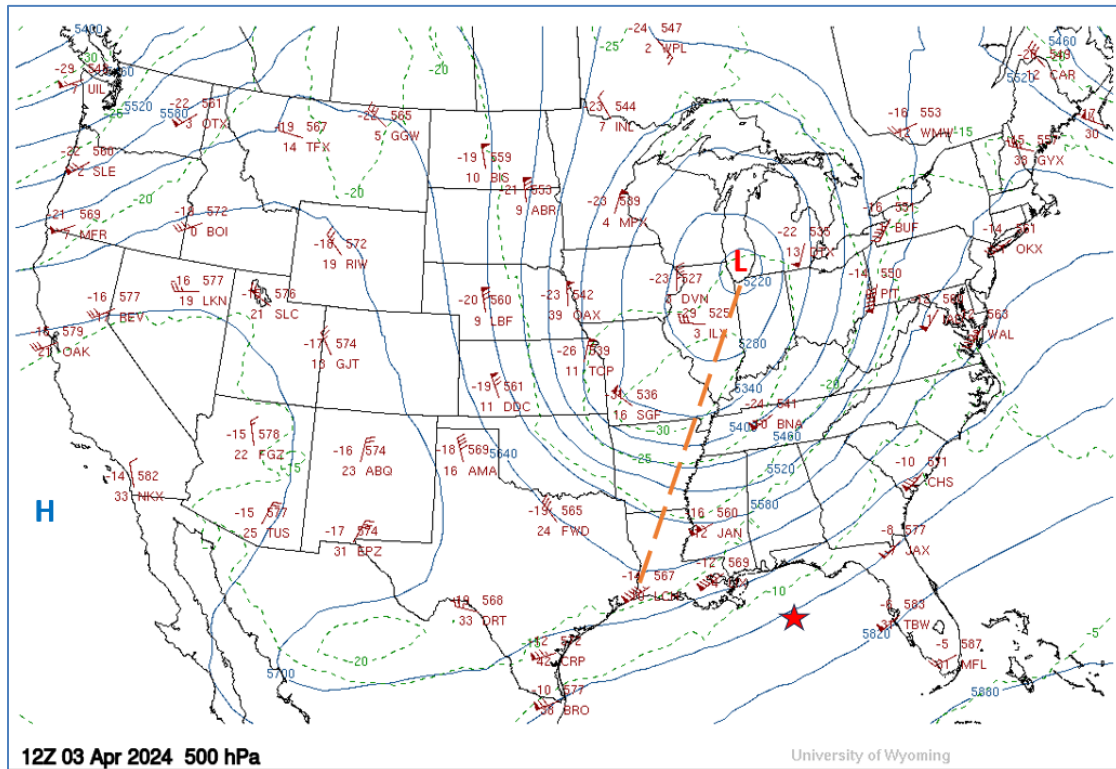


Figure 2 - 500-hPa constant pressure chart for 0800 EDT with the approximate turbulence location marked by the red star, depicting conditions at about 18,000 ft or the mean atmosphere.

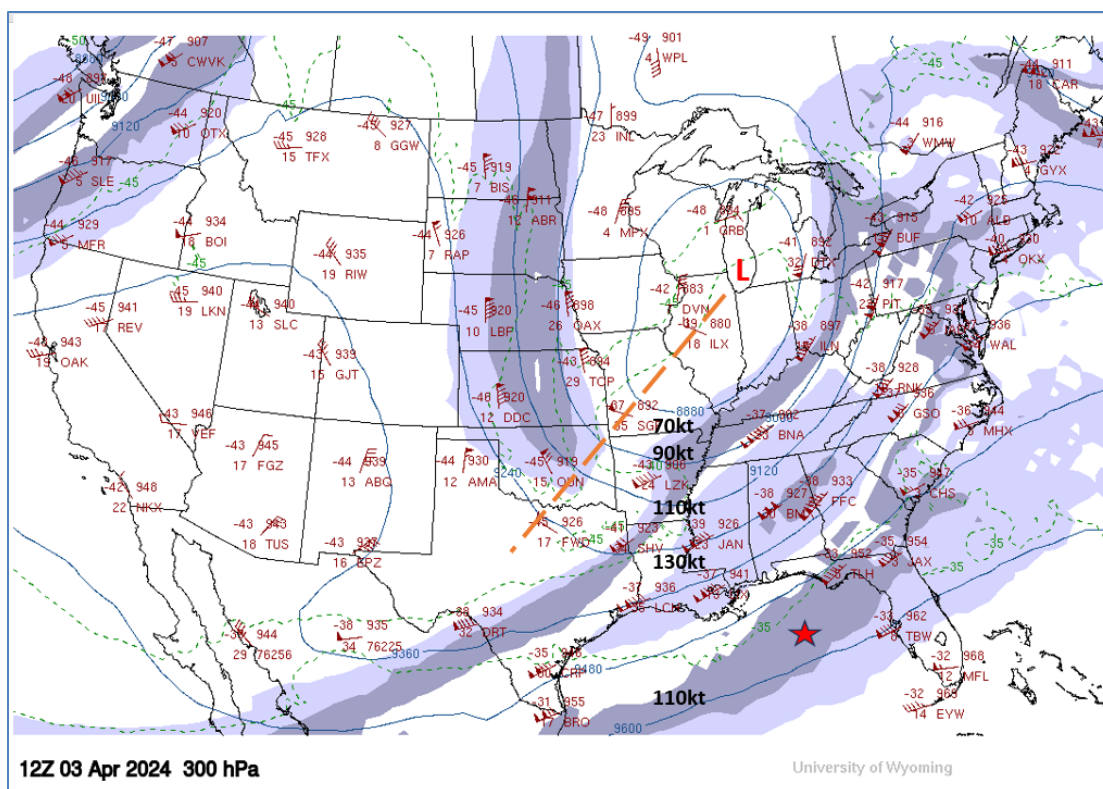


Figure 3 - 300-hPa constant pressure chart for 0800 EDT with the approximate turbulence location marked by the red star, and depicting the conditions at about 30,000 ft.

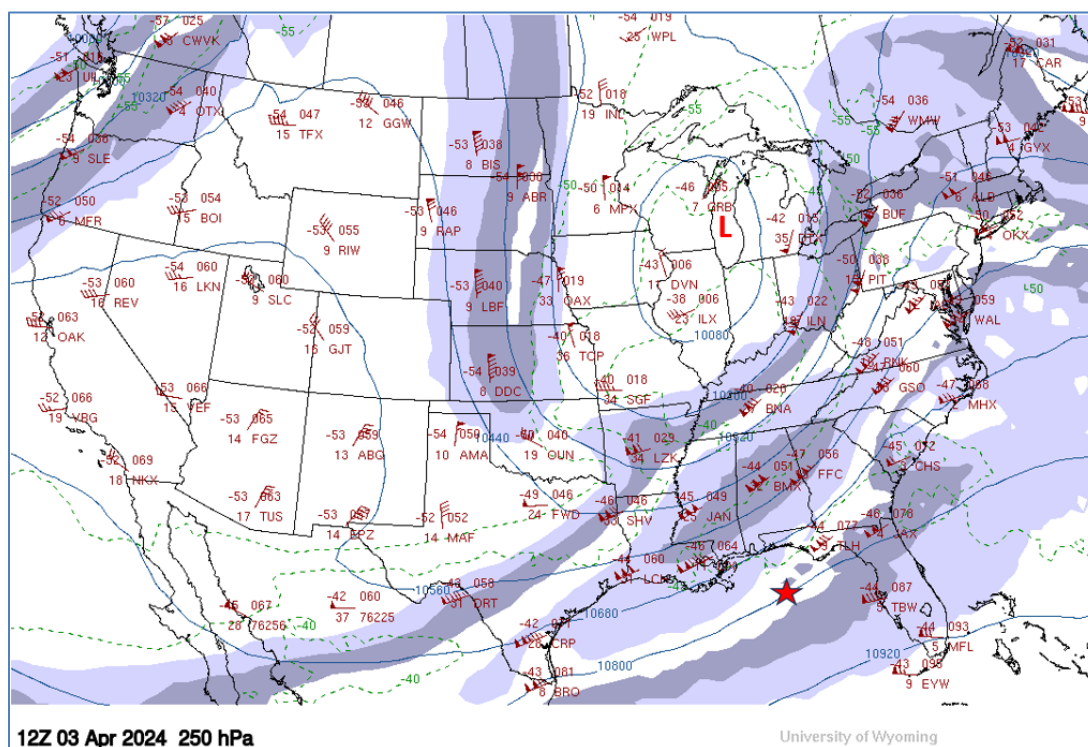


Figure 4 - 250-hPa constant pressure chart for 0800 EDT with the approximate turbulence location marked by the red star, and depicting the conditions at about 34,000 ft.

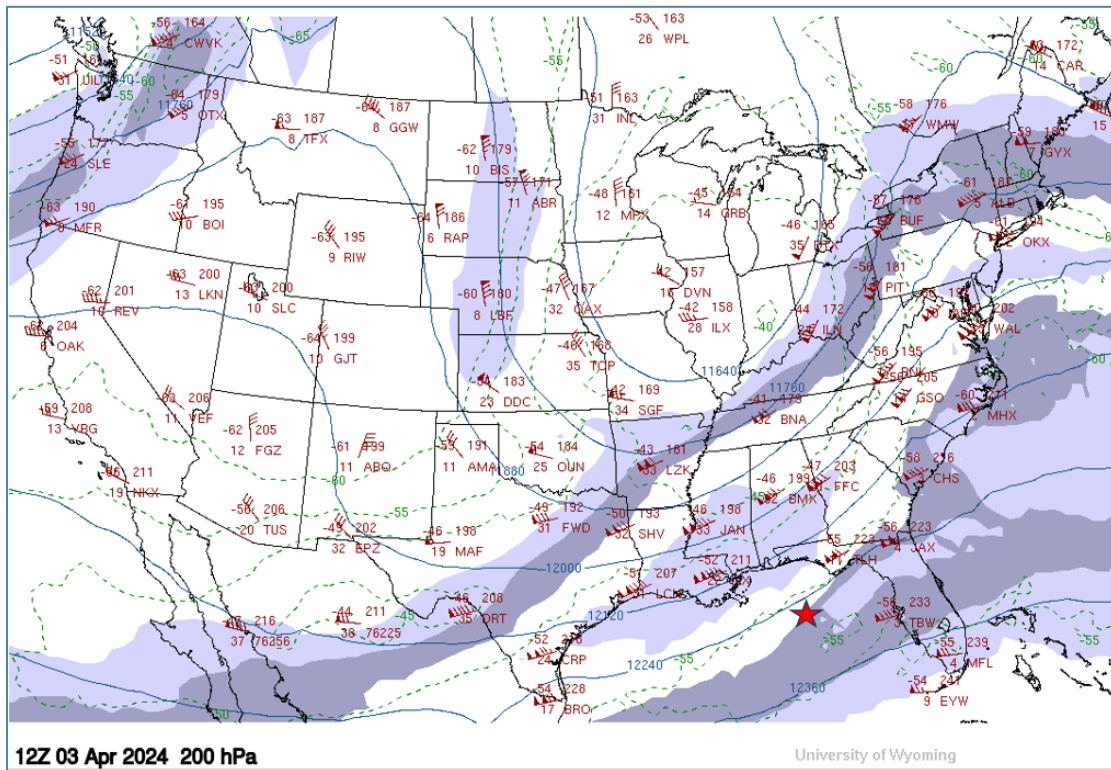


Figure 5 - 200-hPa constant pressure chart for 0800 EDT with the approximate turbulence location marked by the red star, and depicting the conditions at about 39,000 ft.

1.3 High Level Significant Weather Prognostic Chart

The NWS High Level Significant Weather Prognostic Chart valid for 1400 EDT is included as figure 6 with the approximate turbulence location marked by the red star. The chart depicted an upper-level low pressure system over Lake Michigan to FL240. A 110 knots polar jet stream was depicted moving southward at FL330 across the Dakotas, Nebraska, and turning northeastward over Oklahoma at FL310 into Arkansas, northern Mississippi, Alabama, Tennessee, and the northeast United States. While a subtropical jet stream at 110 knots at FL350 was depicted moving across Mexico northeastward across the northern Gulf of America and increased to 170 knots across Louisiana, Mississippi, Alabama and into Georgia immediate north of the turbulence location. The vertical depth of the subtropical jet was depicted extending from FL120 through FL530 with winds over 90 knots. An area of moderate clear air turbulence (CAT) was depicted along and between the two jet streams from below 24,000 ft through FL430. An area of isolated embedded thunderstorm with tops to FL420 was depicted ahead of the upper level low from the Great Lakes southward into the Gulf coastal area from Louisiana through northern Florida and included the turbulence location. The tropopause was depicted at FL500 over the southeast during the period.

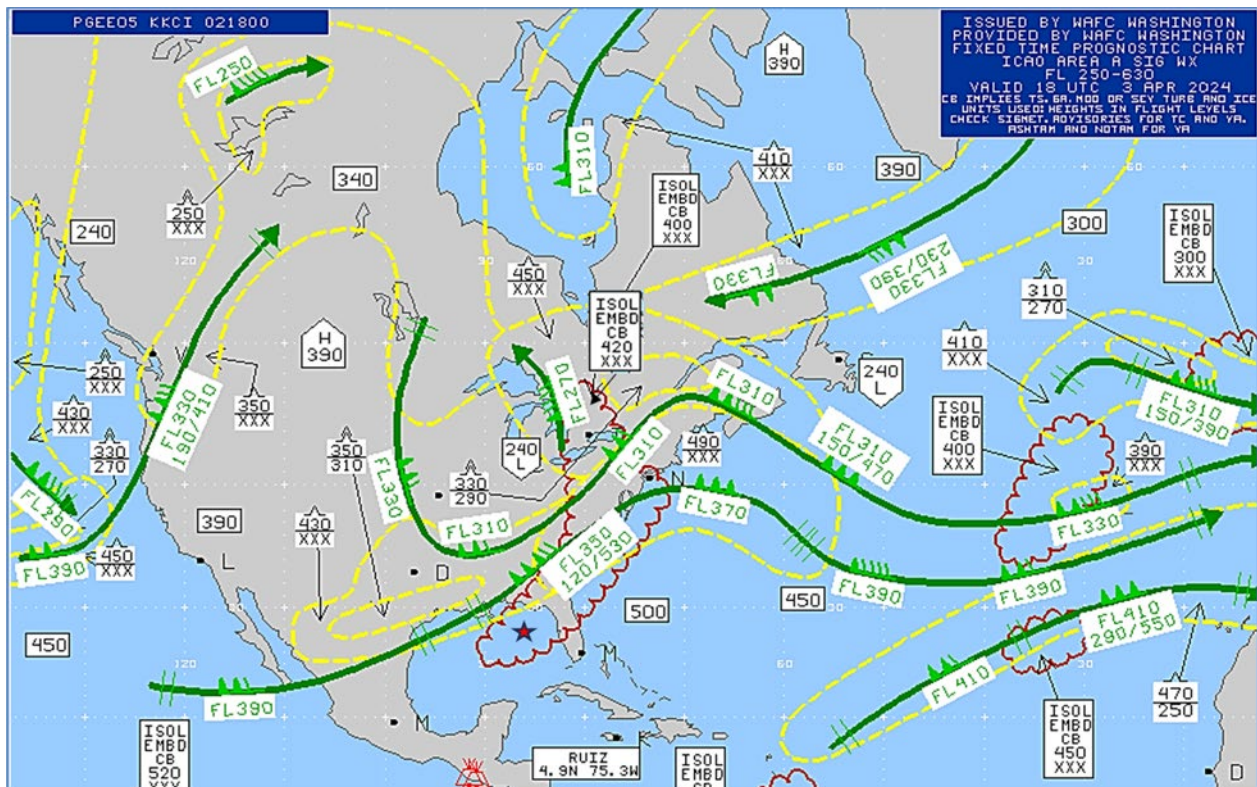


Figure 6 - NWS High-Level Significant Weather Prognostic chart valid for 1400 EDT.

2.0 Observations

A depiction of the NWS Aviation Weather Center's observations display for 0830 EDT is included as figure 7 with the approximate accident site marked by the red star and the plotted position of the initial pilot report of the severe turbulence event issued by air traffic control. The image includes a mosaic of the lowest 0.5° base reflectivity elevation scan, which depicted a broken line of echoes with maximum reflectivities of 50 dBZ⁷ or more ahead of the cold front. The radar imagery will be further documented in section 5.0 of this report.

⁷ dBZ - Nondimensional "unit" of radar reflectivity which represents a logarithmic power ratio (in decibels, or dB) with respect to radar reflectivity factor, Z. See section 5.0 of this report for more details.

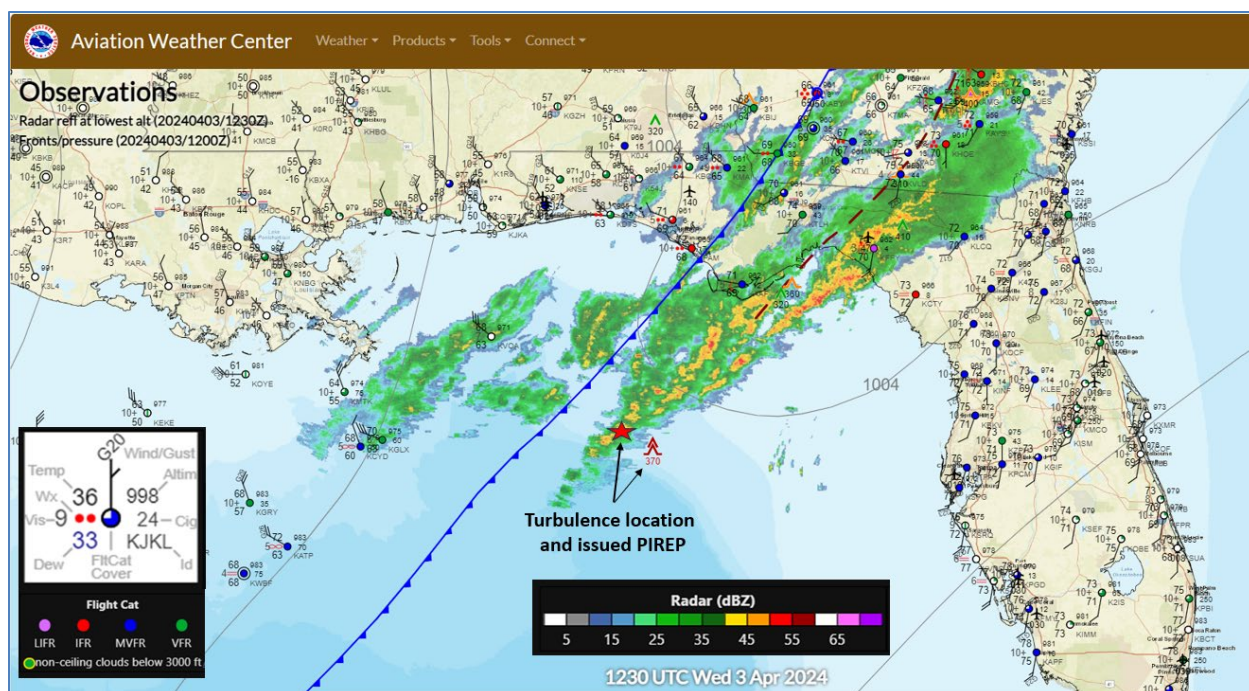


Figure 7 - The NWS Aviation Weather Center's METAR display for 0830 EDT with the fronts and regional radar mosaic for the period overlaid.

The closest land-based observation site was from Apalachicola Regional Airport (KAAF), Apalachicola, Florida, located about 110 miles north-northeast of the accident location at an elevation of 20 ft. The airport had an Automated Surface Observation System (ASOS) which was not augmented by any observer. At the time of the turbulence event the following conditions were reported. Cloud heights are provided above ground level (agl).

Special weather observation for KAAF at 0818 EDT, Automated, wind from 280° at 12 knots, visibility 5 miles with thunderstorms in the vicinity, moderate rain and mist, ceiling broken at 1,200 ft agl, broken at 2,000 ft, and overcast at 9,000 ft, temperature 22°C (71°F), dew point temperature 21°C (69°F), and altimeter 29.62 inches of mercury. Remarks: automated station with a precipitation discriminator, lightning distant southeast through southwest, thunderstorm ended at 0801 EDT, hourly precipitation 0.03 inches, temperature 21.7°C, dew point 20.6°C.

At the time of the accident, the rainfall was 1.33 inches with thunderstorms beginning at 0615 and continuing through 0801 EDT, with the maximum wind gust of 45 knots reported at 0831 EDT when the line of storms moved across the area. The general flight categories⁸ and raw observations issued surrounding the period from 0453 through 0953 EDT were as follows.

⁸ As defined by the NWS and the FAA Aeronautical Information Manual (AIM) section 7-1-7 defines the following general flight categories:

- Low Instrument Flight Rules (LIFR*) - ceiling below 500 ft agl and/or visibility less than 1 statute mile.
- Instrument Flight Rules (IFR) - ceiling between 500 to below 1,000 feet agl and/or visibility 1 to less than 3 miles.
- Marginal Visual Flight Rules (MVFR**) - ceiling from 1,000 to 3,000 ft agl and/or visibility 3 to 5 miles.

LIFR METAR KAAF 030853Z AUTO 21011G18KT 1 3/4SM BR OVC002 23/22 A2963 RMK AO2 SLP032 T02280222 56038=

LIFR SPECI KAAF 030948Z AUTO 21012KT 2SM -RA BR OVC002 23/22 A2961 RMK AO2 LTG DSNT W-N RAB34 P0000=

LIFR SPECI KAAF 031011Z AUTO 22011KT 3SM VCTS -RA BR OVC002 23/22 A2960 RMK AO2 LTG DSNT ALQDS P0000 T02280222=

LIFR SPECI KAAF 031018Z AUTO 25017G21KT 2 1/2SM -TSRA BR OVC002 23/22 A2962 RMK AO2 LTG DSNT ALQDS TSB15 PRESRR P0000 T02280222=

LIFR SPECI KAAF 031031Z AUTO 23029G45KT 3/4SM +TSRA BR BKN003 OVC008 22/21 A2963 RMK AO2 PK WND 22045/1031 LTG DSNT ALQDS TSB15 P0027 T02170211=

IFR SPECI KAAF 031038Z AUTO 24010G45KT 1/2SM +TSRA FG SCT003 OVC010 21/20 A2961 RMK AO2 PK WND 22045/1031 LTG DSNT ALQDS TSB15 P0080 T02060200=

IFR SPECI KAAF 031049Z AUTO 26025G37KT 1 3/4SM VCTS +RA BR FEW005 BKN013 OVC030 23/22 A2961 RMK AO2 PK WND 22045/1031 VIS 3/4V5 LTG DSNT ALQDS TSB15E43 P0109=

IFR METAR KAAF 031053Z AUTO 27019G37KT 1 3/4SM VCTS -RA BR FEW006 BKN011 OVC048 22/21 A2961 RMK AO2 PK WND 22045/1031 LTG DSNT ALQDS TSB15E43 SLP028 P0115 T02220211=

MVFR SPECI KAAF 031057Z AUTO 27017G37KT 4SM VCTS -RA BR SCT011 BKN030 OVC065 22/21 A2961 RMK AO2 PK WND 28026/1054 LTG DSNT ALQDS P0000 T02170211=

MVFR SPECI KAAF 031131Z AUTO 26018G25KT 4SM +RA BR SCT008 BKN060 OVC070 21/20 A2963 RMK AO2 PK WND 28026/1054 LTG DSNT E AND S AND W PRESRR P0007 T02110200=

MVFR SPECI KAAF 031144Z AUTO 27014KT 5SM VCTS RA BR SCT008 BKN055 OVC070 22/20 A2961 RMK AO2 PK WND 28026/1054 LTG DSNT ALQDS P0012 T02170200=

IFR SPECI KAAF 031146Z AUTO 26014G23KT 5SM TSRA BR BKN008 BKN055 OVC070 21/20 A2960 RMK AO2 PK WND 28026/1054 LTG DSNT ALQDS TSB46 P0012 T02110200=

MVFR METAR KAAF 031153Z AUTO 27008G22KT 4SM TSRA BR SCT008 BKN050 OVC070 21/21 A2961 RMK AO2 PK WND 28026/1054 LTG DSNT ALQDS TSB46 SLP026 P0014 60130 70130 T02110206 10228 20206 50005=

VFR SPECI KAAF 031207Z AUTO 26013G22KT 7SM VCTS -RA SCT010 BKN048 OVC090 22/21 A2963 RMK AO2 LTG DSNT ALQDS TSE01 P0001 T02170206=

MVFR SPECI KAAF 031218Z AUTO 28012KT 5SM VCTS RA BR BKN012 BKN020 OVC090 22/21 A2962 RMK AO2 LTG DSNT SE-SW TSE01 P0003 T02170206=

Accident 1223Z

- Visual Flight Rules (VFR) - ceiling greater 3,000 ft agl and visibility greater than 5 miles.

* By definition, IFR is a ceiling less than 1,000 ft agl and/or visibility less than 3 miles while LIFR is a sub-category of IFR. ** MVFR is a subset of VFR.

MVFR SPECI KAAF 031250Z AUTO 29007KT 260V340 5SM RA BR BKN010 BKN022 OVC085 22/21 A2963 RMK AO2 LTG DSNT E-SW TSE01 P0009=

MVFR METAR KAAF 031253Z AUTO 29008KT 4SM RA BR BKN010 BKN022 OVC085 22/21 A2962 RMK AO2 LTG DSNT E-S TSE01 SLP031 P0009 T02170206=

IFR SPECI KAAF 031312Z AUTO 32006KT 4SM RA BR BKN009 BKN050 OVC070 22/21 A2961 RMK AO2 LTG DSNT E P0003 T02170206=

VFR SPECI KAAF 031324Z AUTO 30012KT 6SM -RA BR SCT009 SCT050 BKN070 22/21 A2962 RMK AO2 LTG DSNT E P0005 T02170206=

IFR SPECI KAAF 031346Z AUTO 30015G22KT 8SM BKN009 BKN075 OVC100 22/21 A2965 RMK AO2 RAE39 P0005 T02170206=

IFR METAR KAAF 031353Z AUTO 31011G22KT 6SM -RA BR BKN009 BKN039 OVC110 22/21 A2964 RMK AO2 RAE39B50 SLP037 P0005 T02170206=

The observations for KAAF reported LIFR conditions due to low ceilings and visibility in dense fog prior to the thunderstorms moving through the area with heavy rain and wind gusts to 45 knots. The thunderstorms and rain continued from 0610 through the time of the accident, with the rain ending near 0939 EDT with about 1.44 inches recorded during the period.

3.0 Sounding

A High-Resolution Rapid Refresh (HRRR) numerical model⁹ was obtained from the NOAA Air Resource Laboratory for 1200 EDT over the closest grid point to the accident site. The model data was then plotted on a standard Skew T/log P diagram¹⁰ using the RAOB Analysis software¹¹ from the surface to 200-hPa (about 39,000 ft) and is depicted as figure 8.

⁹ The HRRR is a NOAA real-time 3 kilometer (km) resolution, hourly-updated, cloud-resolving, convection-allowing atmospheric model, initialized by 3 km grids with 3 km radar assimilation. Radar data is assimilated in the HRRR every 15 minutes over a 1-hour period.

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.

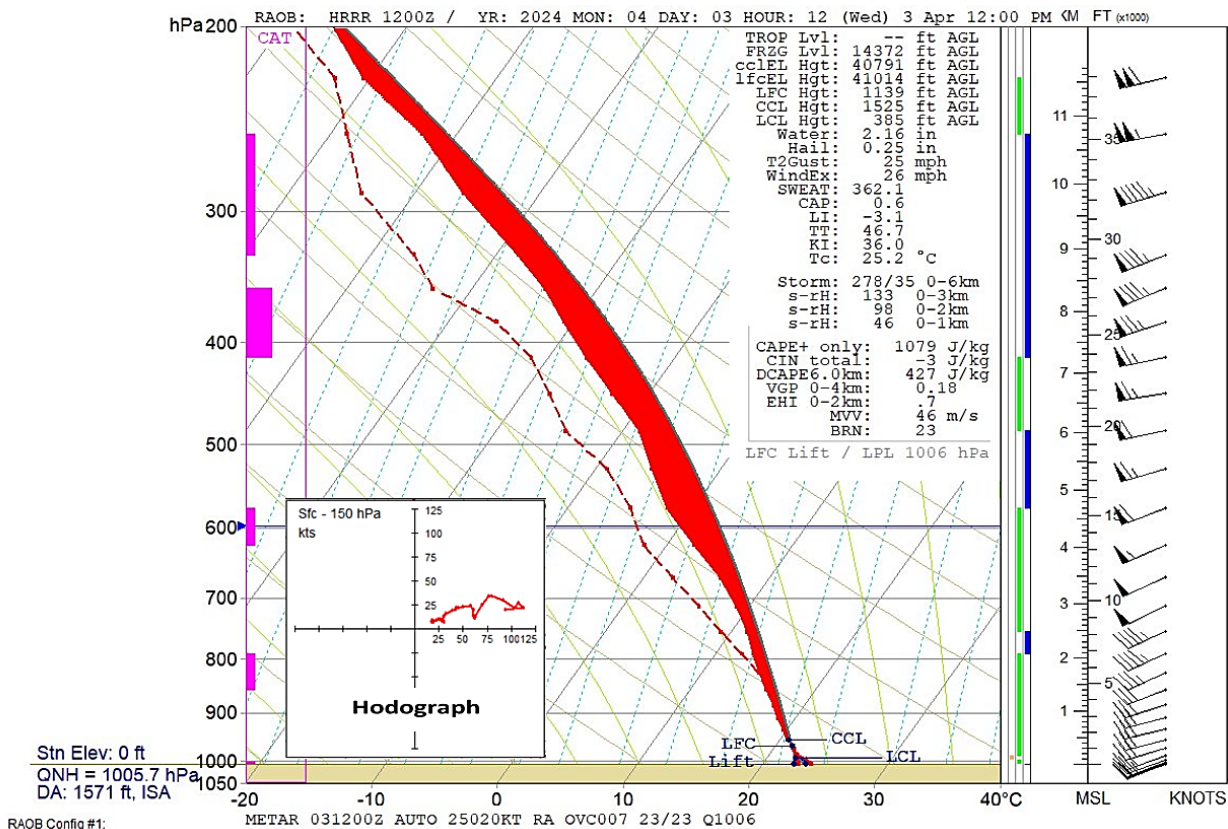


Figure 8 - A High-Resolution Rapid Refresh (HRRR) numerical model sounding over the closest grid point to the accident site for 0800 EDT depicting the vertical structure of atmosphere.

The HRRR 0800 EDT sounding over the closest grid point¹² depicted a near surface temperature of 23°C (74°F), a dew point of 22.5°C (72°F), and a relative humidity of 95%. The sounding depicted a lifted condensation level (LCL)¹³ at 385 ft agl, a level of free convection (LFC)¹⁴ at 1,139 ft agl, and a convective condensation level (CCL)¹⁵ at 1,525 ft agl. The expected cloud top of convection was estimated by the equilibrium level (LFC-EL)¹⁶, which indicated potential tops to 41,014 ft. The

¹² Grid point was based at latitude 28.92°N longitude 86.42°W.

¹³ Lifted Condensation Level (LCL) - the level at which a lifted parcel becomes saturated. The LCL height corresponds to cloud base height for forced ascent.

¹⁴ Level of Free Convection (LFC) - the level where a parcel becomes buoyant, or "warmer" than the environmental temperature at the same level. The LFC represents the bottom of the layer containing Convective Available Potential Energy (CAPE).

¹⁵ Convective Condensation Level (CCL) - 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.

¹⁶ Equilibrium Level (EL) - On a sounding, the level above the level of free convection (LFC) at which the temperature of a rising air parcel again equals the temperature of the environment. The height of the EL is the height at which thunderstorm updrafts no longer accelerate upward. Thus, to a close approximation, it represents the height of expected thunderstorm tops. However, strong updrafts will continue to rise past the EL before stopping, resulting in storm tops that are higher than the EL. This process sometimes can be seen visually as an overshooting tops or anvil dome. The EL typically is higher than the tropopause and is a more accurate reference for storm tops.

precipitable water content was 2.16 inches. The sounding was characterized as unstable with a Lifted Index (LI)¹⁷ of -3.1, a K-index¹⁸ of 39, and a Convective Available Potential Energy (CAPE)¹⁹ of 1,079 Joules/kilogram (J/kg), with a maximum vertical velocity (MVV) of the potential updrafts of 46 m/s (9,055 fpm). The freezing level was identified at 14,370 ft. The tropopause²⁰ was identified above 49,000 ft.

The sounding wind profile indicated the mean 0 to 6 km (or 18,000 ft) wind from 250° at 47 knots, with the wind at 37,000 ft from 260° at 109 knots with a temperature of -47.8°C. The vertical wind shear at 37,000 ft was approximately 2.5 knots/1,000 ft. The level of maximum wind was identified at 40,736 ft, with a wind from 260° at 115 knots.

A table of the RAOB parameters of height, pressure (Pres), temperature (T), dew point temperature (Td), relative humidity (RH%), wind direction and speed, and derived clear air turbulence (CAT), Low-Level Wind Shear (LLWS), and icing potential from the surface through 12,000 ft was as follows.

Height (ft-msl)	Pres (hPa)	T (C°)	Td (C°)	RH (%)	Wind (dir-kts)	CAT (FAA)	LLWS (FAA)	Icing-Type (USAF)
0	1006	23.4	22.5	95	246/ 20			
29	1005	23.8	22.8	94	247/ 20	LGT		
115	1002	23.6	22.7	95	247/ 24			
288	996	23.2	22.5	96	248/ 26			
549	987	22.3	22.2	99	249/ 28			
988	972	21.6	21.5	99	252/ 29			
1522	954	20.7	20.6	99	254/ 30			
2155	933	19.7	19.7	100	256/ 31			
2894	909	18.6	18.6	100	254/ 31			
3681	884	17.5	17.5	100	250/ 31			
4618	855	16.1	16.1	100	246/ 32	LGT		
5650	824	14.6	14.5	99	243/ 36	LGT		
6820	790	13.0	12.1	94	243/ 43			

¹⁷ 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. Negative values indicate instability - the more negative, the more unstable the air is, and the stronger the updrafts are likely to be with any developing thunderstorms.

¹⁸ K-Index - This index attempts to identify steep mid-level lapse rates (850-700 hPa temperature differences) in the presence of substantial moisture in the low-mid levels (850 hPa dewpoint minus the 700 hPa dewpoint depression). Values greater than 30-40 tend to be associated with deep convection, while thunderstorms are much less common with lesser values. A K-index of 39 represents an approximately 90% probability of thunderstorms.

¹⁹ Convective Available Potential Energy (CAPE) - is a measure of the amount of energy available for convection. CAPE is directly related to the maximum potential vertical speed within an updraft; thus, higher values indicate greater potential for severe weather.

²⁰ Tropopause - is the upper boundary of the troposphere, usually characterized by an abrupt change in lapse rate from positive (decreasing temperature with height) to neutral or negative (temperature constant or increasing with height). The tropopause separates the troposphere and the stratosphere.

8143	753	11.3	9.2	87	244/ 46	
9675	712	9.0	6.0	81	243/ 48	
11363	669	6.1	2.3	77	244/ 50	
13268	623	2.2	-1.8	75	245/ 55	LGT
15425	574	-2.1	-5.0	80	247/ 62	
17642	527	-5.5	-9.1	76	252/ 64	
19770	485	-8.6	-14.5	62	257/ 62	
21830	447	-12.9	-17.9	66	260/ 63	
23795	413	-17.0	-21.4	69	258/ 64	MDT
25703	382	-20.8	-26.2	62	250/ 74	MDT
27470	355	-24.2	-33.1	44	246/ 84	
29204	330	-28.2	-36.5	45	247/ 87	LGT
32357	288	-36.1	-44.2	43	252/ 96	LGT
35268	253	-42.7	-48.7	52	258/ 106	
37919	224	-50.5	-52.8	76	256/ 111	
40736	196	-56.8	-60.2	65	259/ 115	LGT

4.0 Satellite Imagery

The NOAA Geostationary Operational Environmental Satellite number 16 (GOES-16) infrared and visible 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 band 13 at a wavelength of 10.3 microns (μ m) provided a spatial resolution of 2 kilometers (km). While the visible (band 2) at a wavelength of 0.64 μ m provided a spatial resolution of 0.5 km. The images have not been corrected for any parallax errors.

Figures 9-11 are the GOES infrared imagery at 0821, 1826, and 0831 EDT at 4X magnification with a standard MB temperature enhancement curve applied to highlight the higher and colder cloud tops association with deep convection and high cirriform clouds. The turbulence location²¹ is marked by the white square. The images depict a line of convection moving across the Gulf of America with the turbulence location in an area of developing convection or cumulonimbus clouds with radiative cloud top temperatures ranging from 212 and 222 Kelvin or -51°C to -61°C during the period, which corresponded to tops between 38,000 to 46,000 ft based on the HRRR sounding. Attachment 1 is an animation of the GOES-16 infrared satellite imagery surrounding the period. Attachment 2 is the infrared satellite animation with the group energy density lightning mapper (GLM), which depicts significant amount of lightning activity along the line and in the vicinity of the turbulence location.

²¹ The turbulence location in the satellite imagery marked the peak EDR value of severe turbulence at 1224Z at Lat. 28.289° Long. 86.370° based on table in section 11.3 of this report.

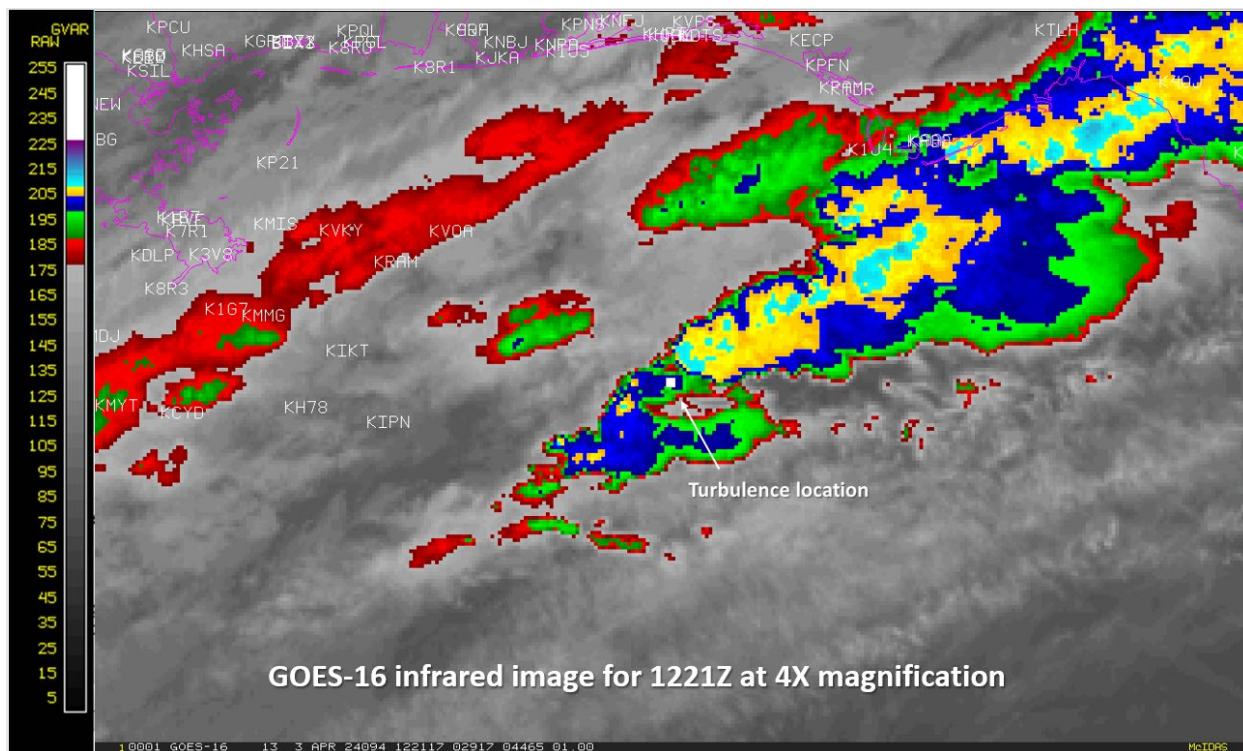


Figure 9 - GOES-16 infrared image for 0821 EDT at 4X magnification with a standard MB temperature enhancement curve applied with the turbulence location noted by the white square.

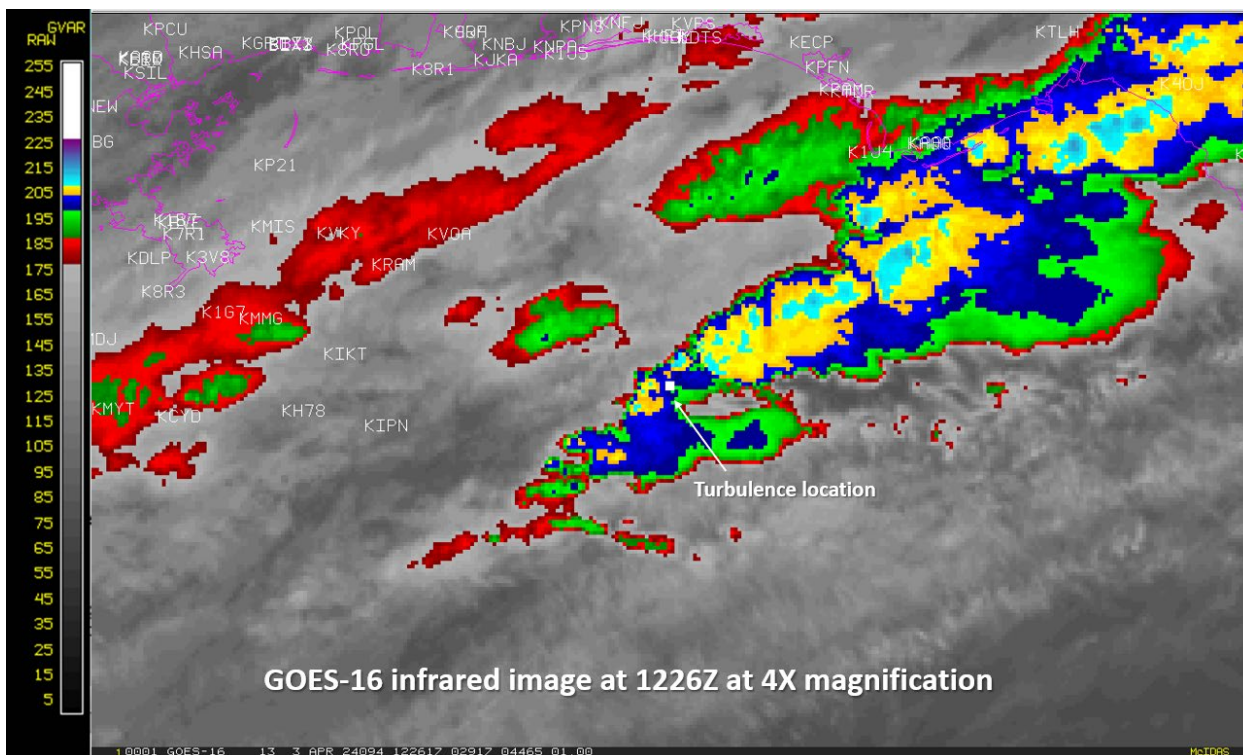


Figure 10 - GOES-16 infrared image for 0826 EDT at 4X magnification with a standard MB temperature enhancement curve applied with the turbulence location noted by the white square.

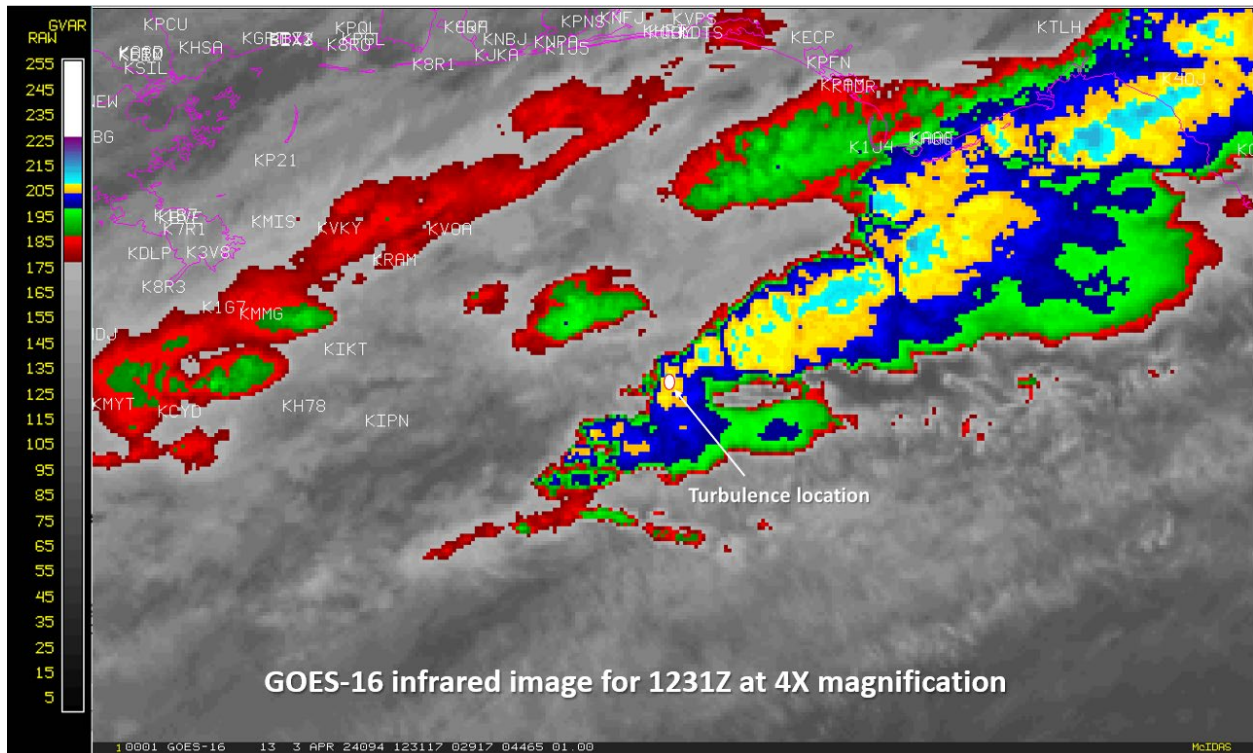


Figure 11 - GOES-16 infrared image for 0831 EDT at 4X magnification with a standard MB temperature enhancement curve applied with the turbulence location noted by the white square.

Figures 12-13 are the GOES-16 visible imagery at 2X magnification surrounding the turbulence event at 0821 and 0826 EDT respectively and shows a line of convection with several overshooting cloud tops²² in the vicinity of the turbulence location. Attachment 3 is an animation of the GOES-16 GeoColor visible imagery surrounding the period.

²² Overshooting cloud tops is a dome-like protrusion of clouds shooting out of the tops of the anvil of a thunderstorm and into the lower stratosphere. When overshooting tops are present for 10 minutes or longer, it is often an indication that the storm is severe. It forms when a thunderstorm's updraft, due to momentum from rapid ascent and strength of lifting through the storm's equilibrium level. Thunderstorms with overshooting tops are often associated with strong horizontal and vertical wind shear and lightning in the strong updraft region, both of which represent potential significant turbulence.

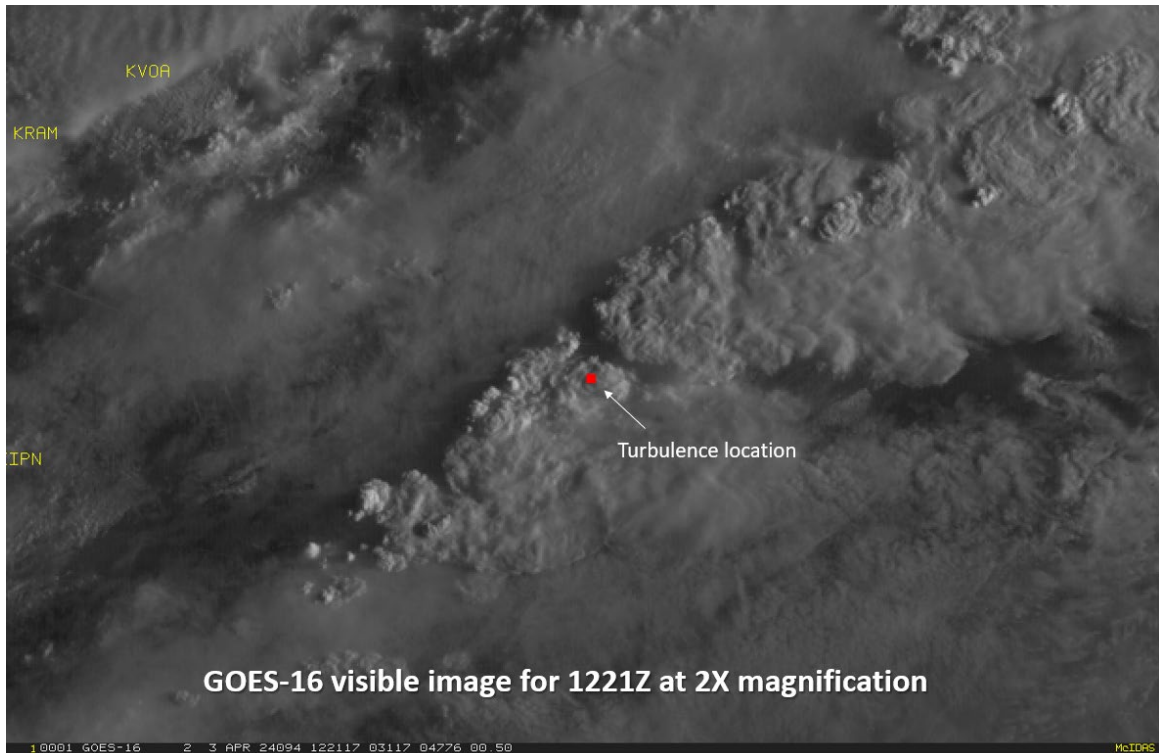


Figure 12 - GOES-16 visible image for 0821 EDT at 2X magnification with the turbulence location marked by the red square.

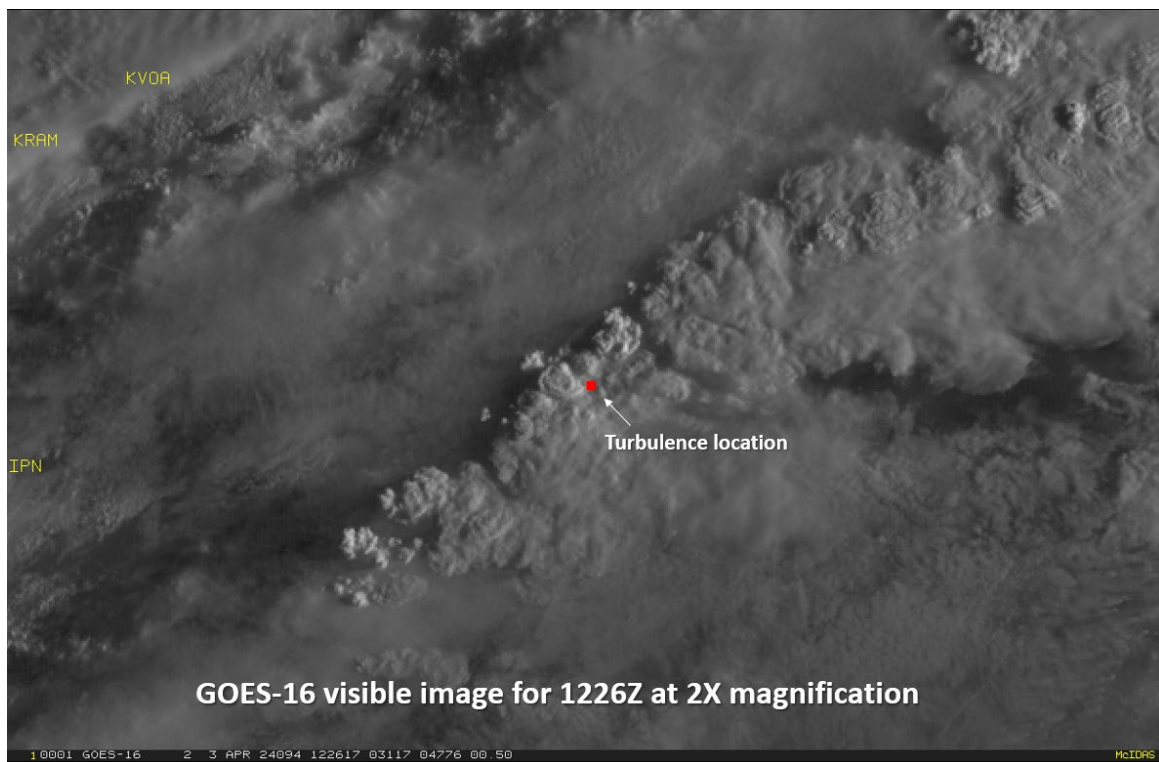


Figure 13 - GOES-16 visible image for 0826 EDT at 2X magnification with the turbulence location marked by the red square.

5.0 Weather Radar Imagery

The following weather radar imagery were obtained from the NWS NCEI National Composite Radar Mosaic archive and from the closest Weather Surveillance Radar-1988 Doppler (WSR-88D)²³ site associated with Elgin (KEVX) Air Force Base, located in the western Florida Panhandle, about 3 miles southwest of Valparaiso, Florida.

5.1 Reflectivity

Reflectivity is the measure of the efficiency of a target in intercepting and returning radio energy. With hydrometeors²⁴, 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 decibels (dBZ)²⁵ and is a general measure of echo intensity. The FAA Aviation Weather Handbook²⁶ defines echoes less than 30 dBZ as "light" in intensity, "moderate" echoes 30-40 dBZ, "heavy" with echoes of >40-50 dBZ, and "extreme" intensity with echoes above >50 dBZ. These are the new standard radio phraseology terms used by air traffic controllers to describe weather conditions to pilots as shown in the table below. Light rain is typically reported at the surface when reflectivities reach 20 dBZ, while air traffic control weather displays, and airborne weather radar typically do not display echoes less than 30 dBZ or light intensity echoes on their weather displays.

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

²³ 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, with reflectivity being the most common display of data. Coverage is outwards to 460 km (248 nm), with doppler product and higher resolution data to 230 km (124 nm).

²⁴ Hydrometeors are any product of condensation or sublimation of atmospheric water vapor, whether formed in the free atmosphere or at the earth's surface. Hydrometeors are classified as; (a) Liquid or solid water particles suspended in the air: cloud, water droplets, mist or fog. (b) Liquid precipitation: drizzle and rain. (c) Freezing precipitation: freezing drizzle and freezing rain. (d) Solid (frozen) precipitation: ice pellets, hail, snow, snow pellets, and ice crystals.

²⁵ dBZ - Nondimensional "unit" of radar reflectivity which represents a logarithmic power ratio (in decibels, or dB) with respect to radar reflectivity factor, Z.

²⁶ FAA Aviation Weather Handbook - WSR-88D Radar Precipitation Intensity Terminology (Table 24-8).

5.2 National Composite Radar Mosaic

The NWS NCEI regional view of the National Composite Reflectivity Mosaic image for 0825 EDT over the turbulence location is included as figure 14 with the approximate turbulence location marked by the red star. Figure 15 is a closeup of the same image centered over the turbulence location for better resolution of the echoes in the vicinity of the turbulence location. The mosaic images depicted a broken line of convection stretching from northern Florida southwestward across the Gulf of America. The turbulence location was located immediately over an area of echoes of 50 to 60 dBZ (extreme intensity precipitation).

Closeup view of the Radar Composite Mosaic for 0825 EDT depicting echoes greater than 50 dBZ under the flight path at the time of the turbulence.

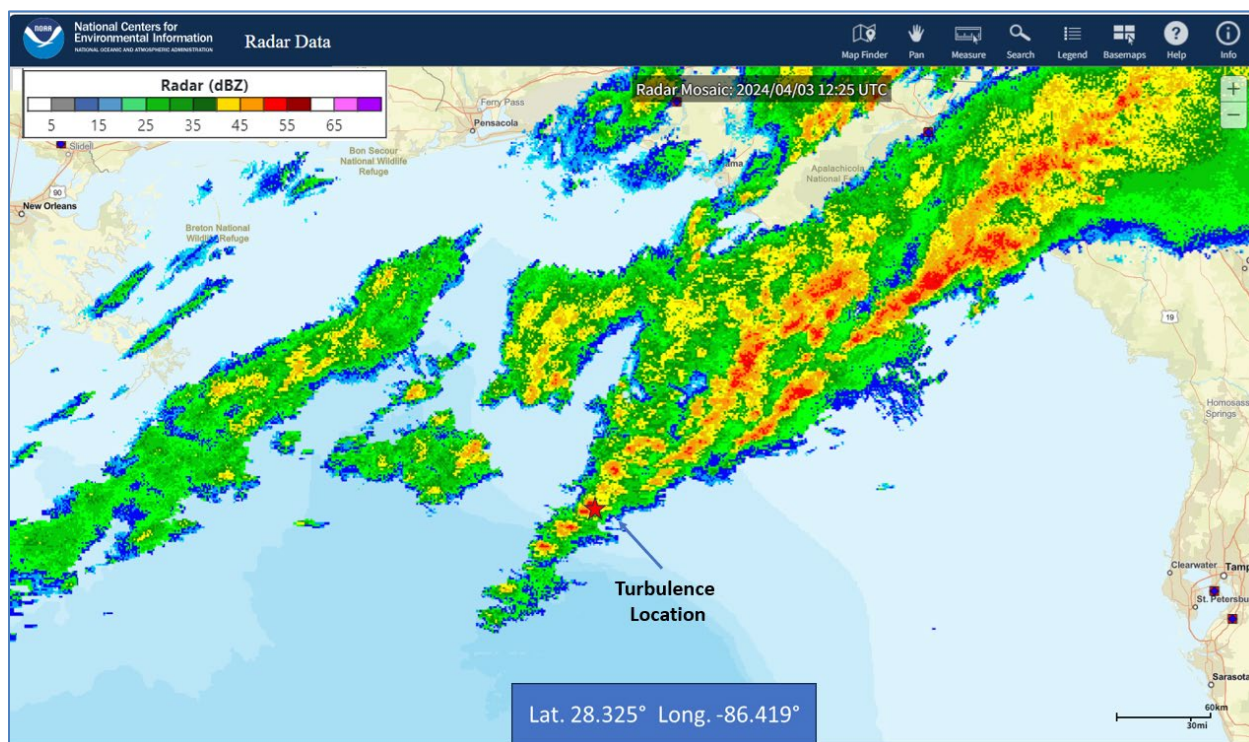


Figure 14 - NWS Regional Composite Radar Mosaic for 0825 EDT with the approximate turbulence location marked by a red star.

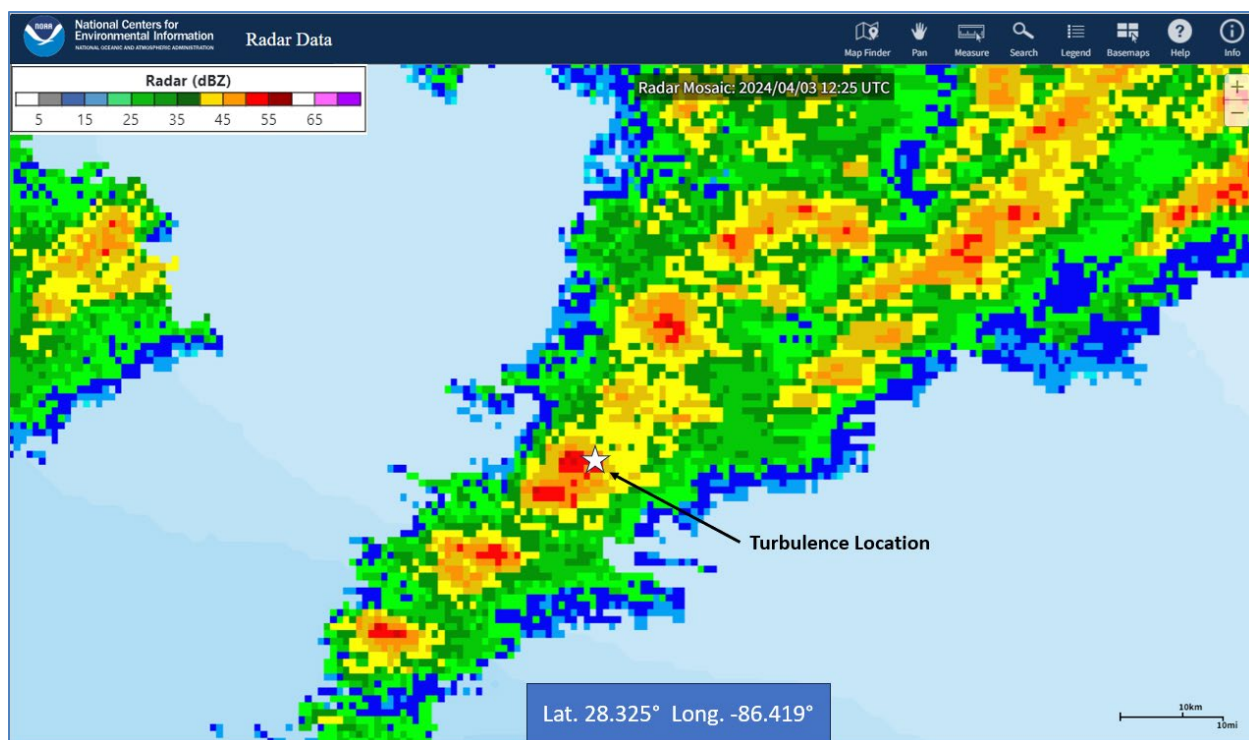


Figure 15 - Closeup of Composite Radar Mosaic for 0825 EDT with the turbulence location marked by the white star.

5.3 Volume Scanning Strategy

The KEVX WSR-88D was located about 136 miles north-northeast of the accident site. The Level II and Level III radar data were obtained from the NWS NCEI and plotted using the NOAA Weather Tool kit software²⁷. During the period the KEVX WSR-88D was operating in the volume coverage pattern (VCP) 212 where the radar makes 14 elevation scans during a 4 ½ to 5-minute period. This mode is used when significant weather echoes are present or severe weather is occurring or is anticipated. Usually, this mode will have been selected automatically due to the detection of reflectivity exceeding the predefined threshold. This scanning strategy is depicted in figure 16 and shows the various elevation scans and coverage by distance and height. The effects of the earth's curvature are also noted by the upward curved elevation scans with distance.

²⁷ 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.

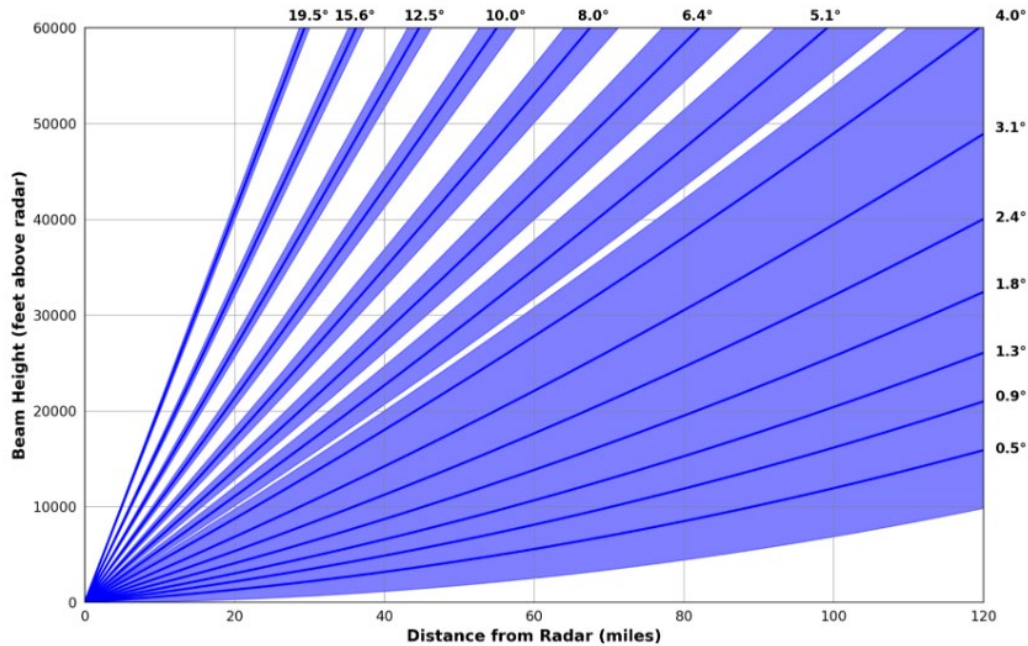


Figure 16 - WSR-88D VCP 212 scanning strategy with beam height versus distance.

Assuming standard refraction²⁸ of the KEVX WSR-88D radar beam at a distance of 136 miles, an antenna height of 222 ft, the following elevation scans and center, base and top of the beam were calculated over the turbulence location. These heights have been rounded to the nearest 10 ft.

Elevation	Center of Beam	Base	Top	Beam Width
0.5°	19,690 ft	12,840 ft	26,540 ft	13,700 ft
0.9°	25,460 ft	18,600 ft	32,310 ft	13,700 ft
1.3°	31,220 ft	24,370 ft	38,070 ft	13,700 ft
1.8°	38,420 ft	31,570 ft	45,270 ft	13,700 ft

Based on the distance from the radar, the KEVX WSR-88D 1.3° and 1.8° elevation scan extended over the altitudes, with the 1.8° scan with the center of the beam at 38,420 ft best represented the echoes at the aircrafts cruising level of FL370.

5.4 Composite Reflectivity Imagery

The long-range composite radar imagery²⁹, which depicts the highest reflectivity value from all the elevation scans for the period in dBZ, with a resolution at 1 x 1 km (0.54 x 0.54 nm). Figures 17 and 18 are the KEVX WSR-88D long range composite radar images for 0822 and 0827 EDT. The images depict the flight path overfly heavy

²⁸ Standard Refraction in the atmosphere is when the temperature and humidity distributions are approximately average, and values set at the standard atmosphere.

²⁹ WSR-88D product NCZ to 460 km or 230 nm.

to extreme intensity echoes with maximum reflectivity of 56 dBZ along the flight path which is overlay in dark gray, and the location of the turbulence.

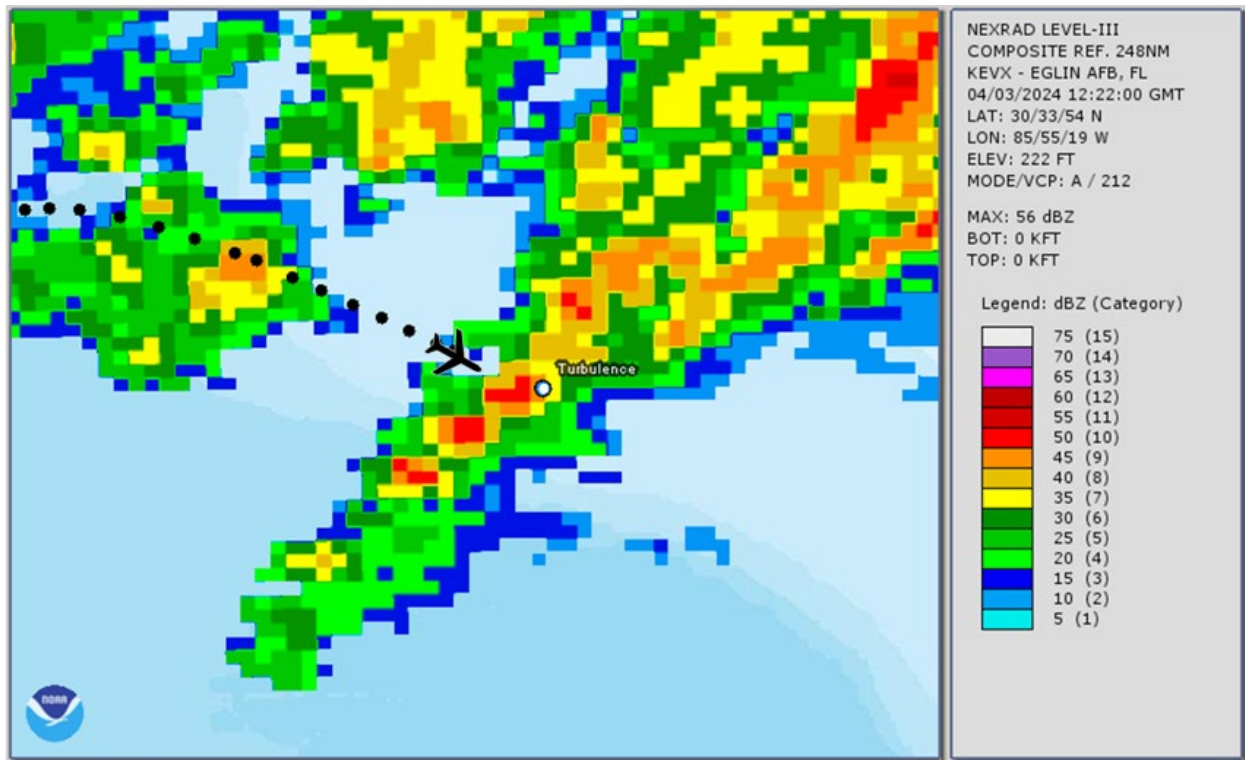


Figure 17 - KEVX WSR-88D composite radar image for 0822 EDT with the flight track overlaid.

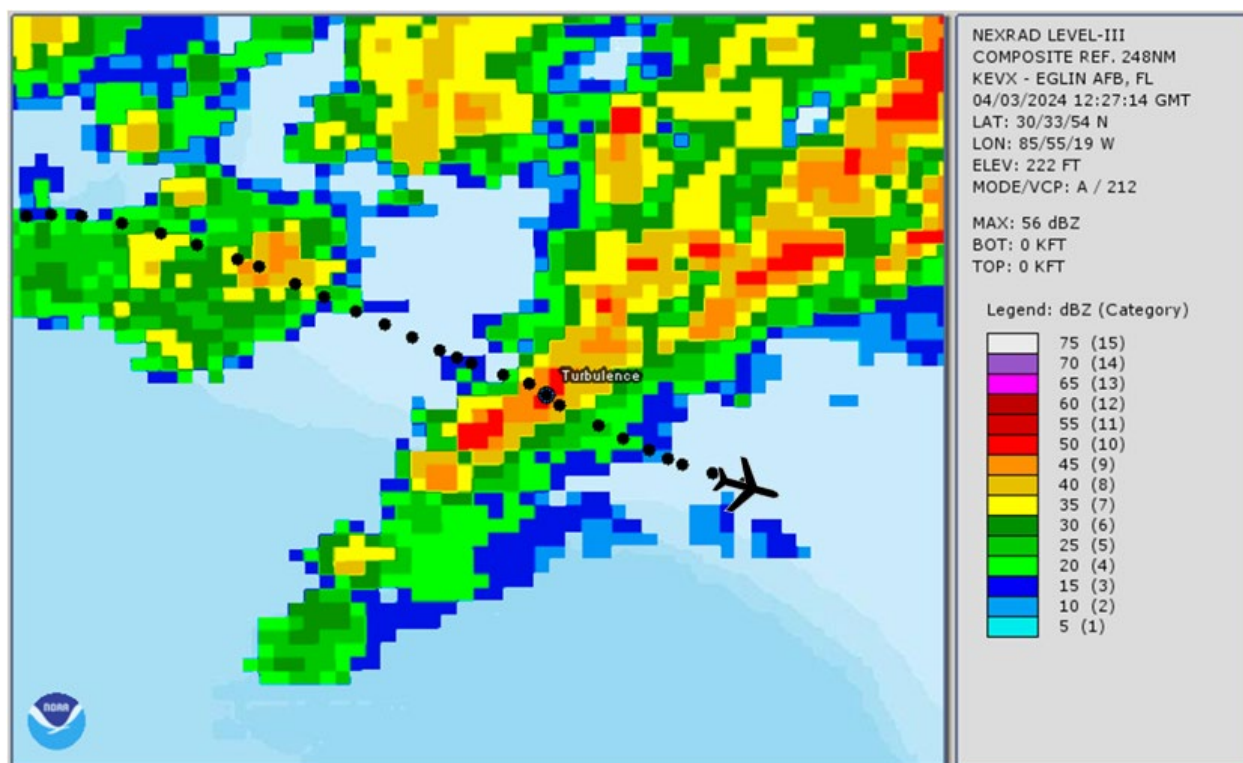


Figure 18 - KEVX WSR-88D composite radar image for 0827 EDT with the flight track overlaid.

5.5 Base Reflectivity Imagery

The KEVX WSR-88D long range base reflectivity imagery for 0.5°, 1.3° and 1.8° are included for 0822, 1824³⁰ and 0827 EDT in figures 19-24 provides a higher resolution of 1° X 4 km (2.2 nm). The images depict extreme intensity echoes of 58 dBZ on the 0.5° base reflectivity images with echoes between 25 and 22.5 dBZ light intensity at the 1.8° elevation scans.

³⁰ The 1824 EDT 0.5° base reflectivity image in figure 22 was part of the VCP-212 scanning strategy from 0822 EDT initial scan with the higher scans not available for this period.

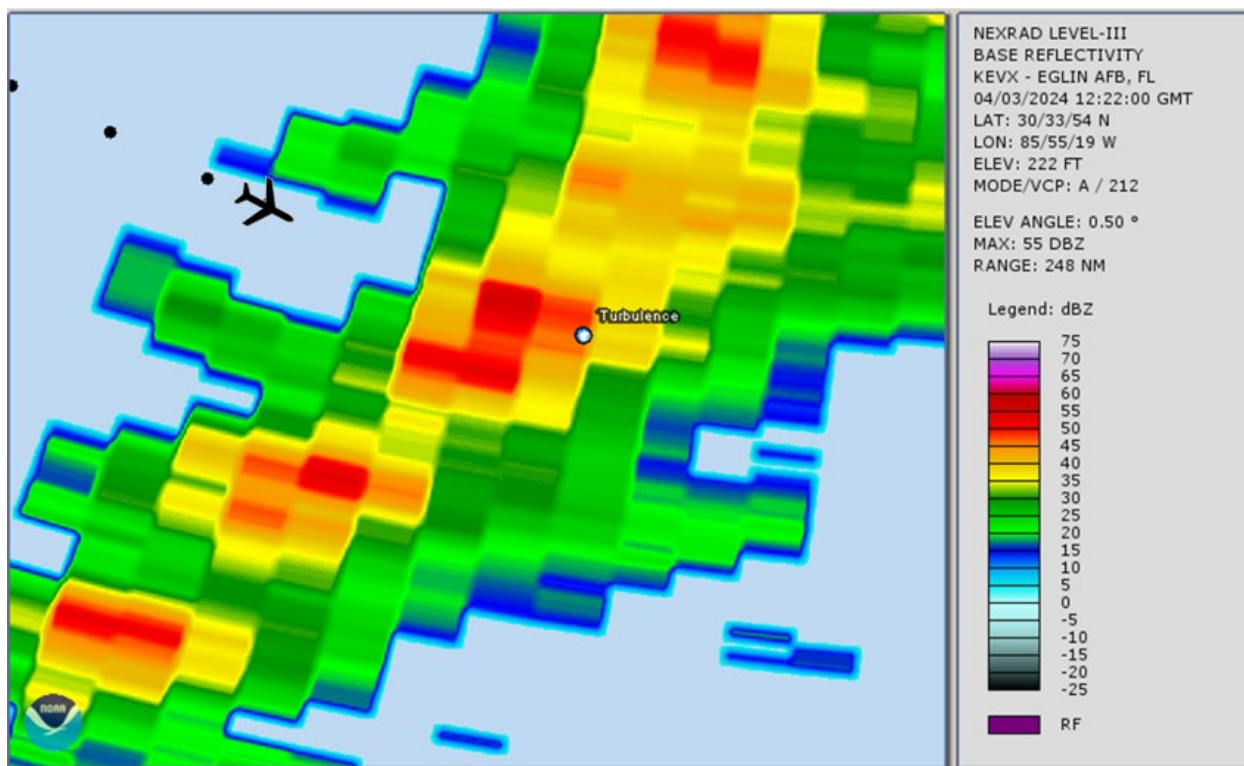


Figure 19 - KEVX WSR-88D 0.5° base reflectivity image for 0822 EDT with flight track overlaid.

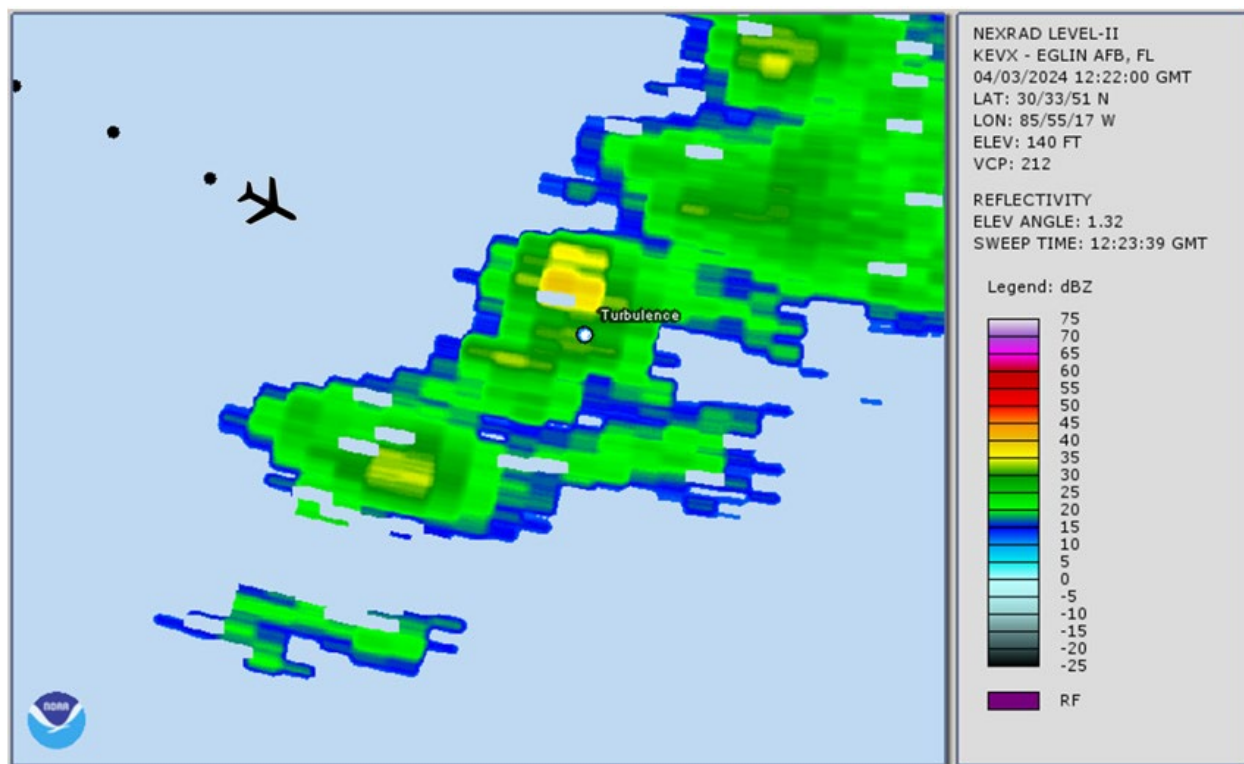


Figure 20 - KEVX WSR-88D 1.3° base reflectivity image for 0822 EDT with flight track overlaid.

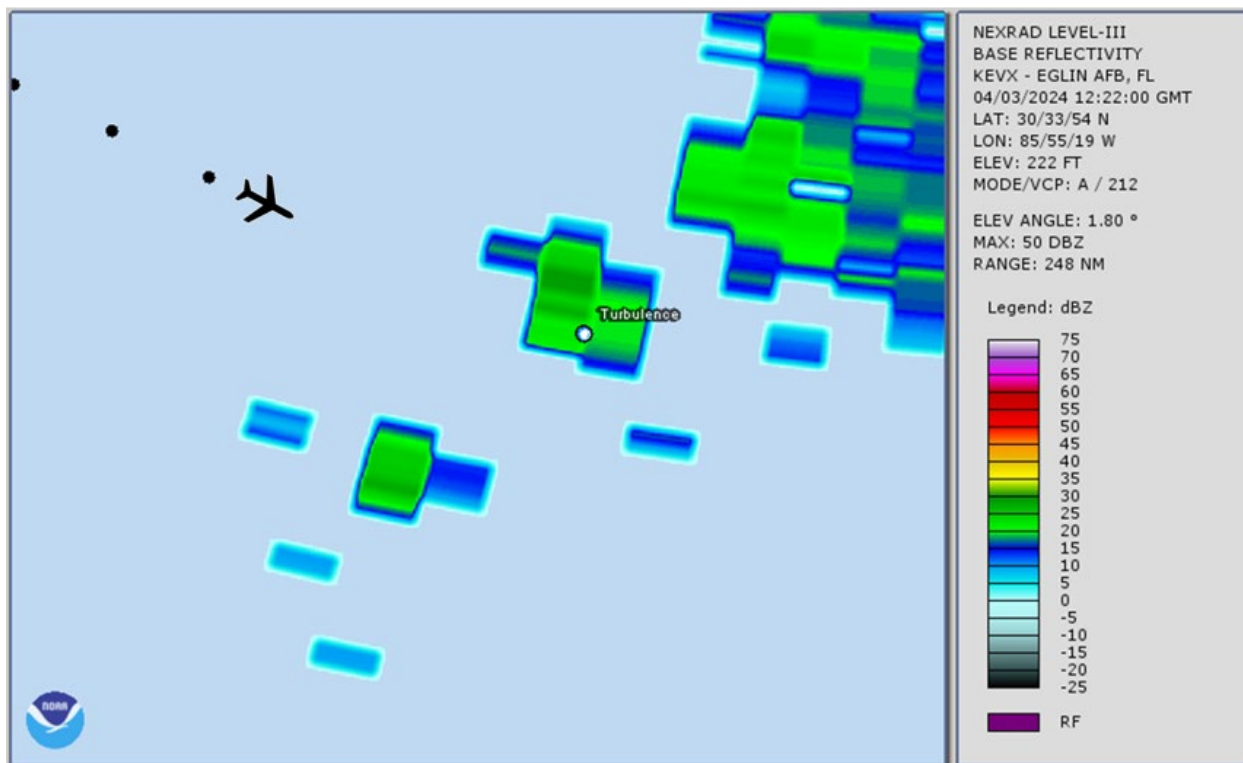


Figure 21 - KEVX WSR-88D 1.8° base reflectivity image for 0822 EDT with flight track overlaid.

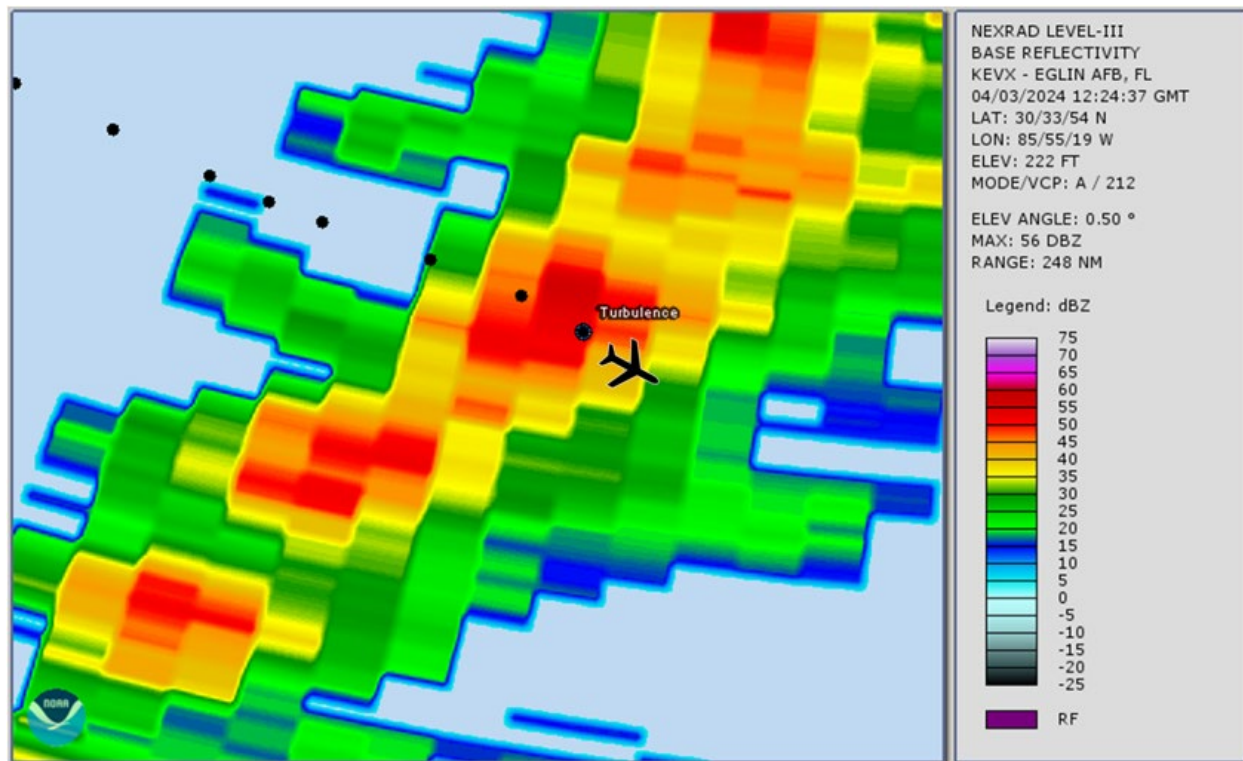


Figure 22 - KEVX WSR-88D enhanced 0.5° base reflectivity for 0824 EDT with flight track overlaid.

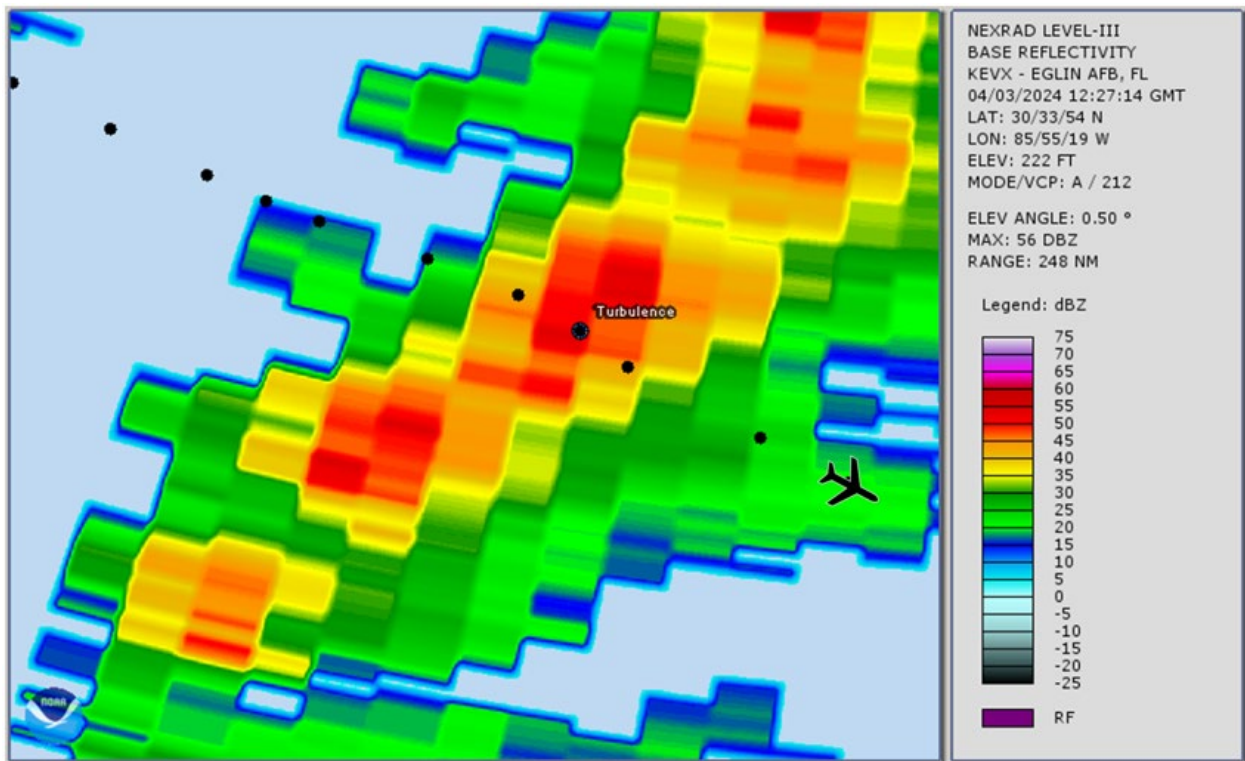


Figure 23 - KEVX WSR-88D 0.5° base reflectivity image for 0827 EDT with flight track overlaid.

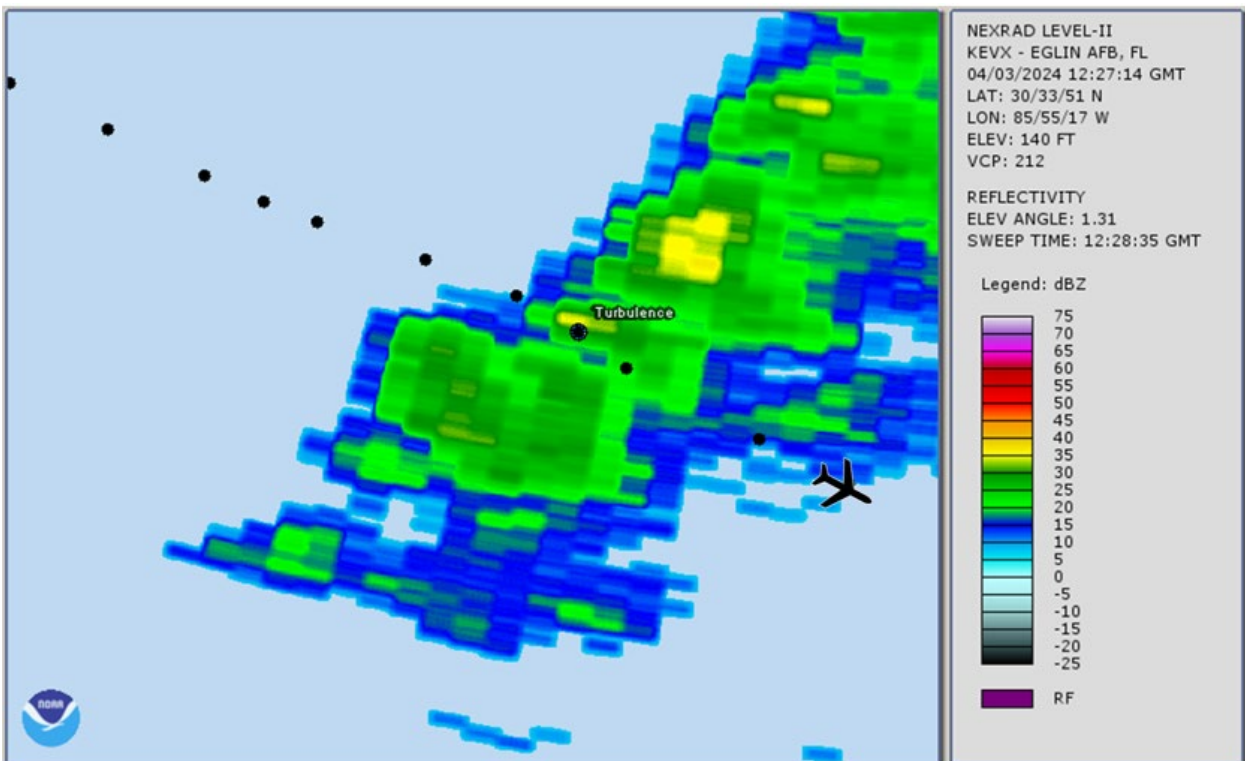


Figure 24 - KEVX WSR-88D 1.3° base reflectivity image for 0827 EDT with flight track overlaid.

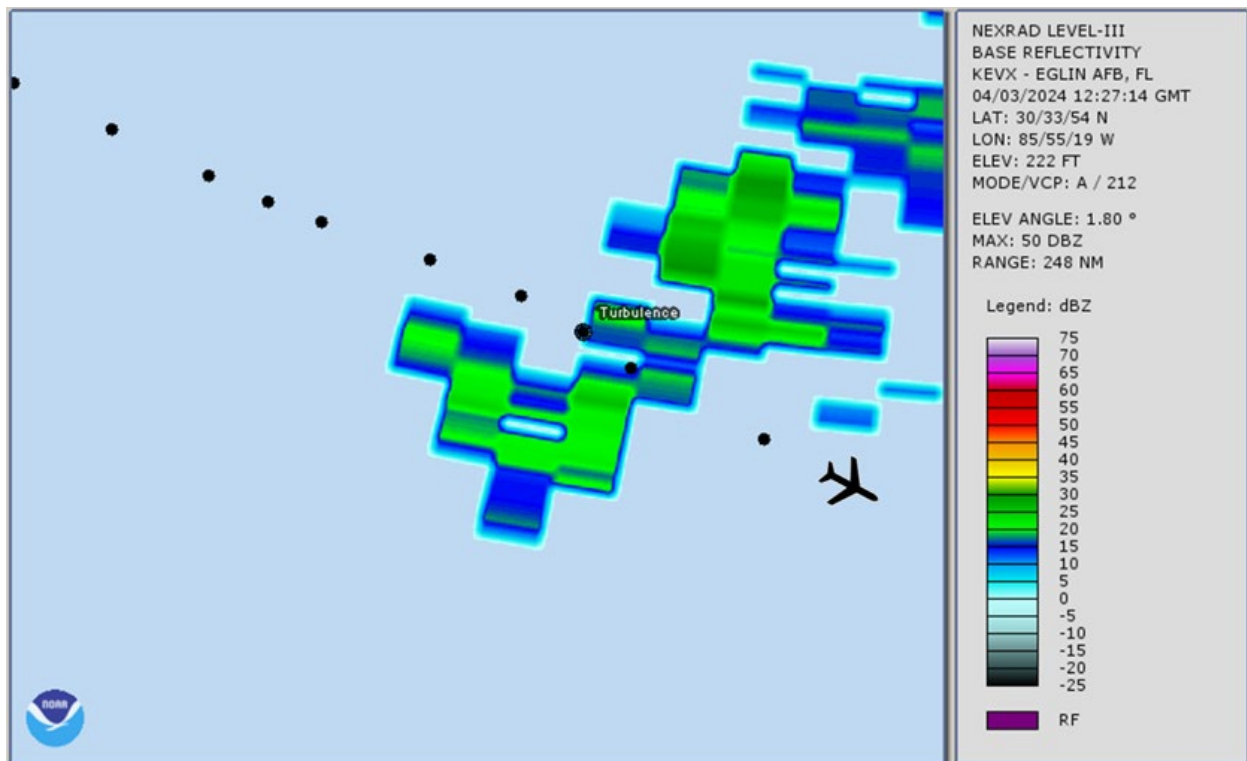


Figure 25 - KEVX WSR-88D 1.8° base reflectivity image for 0827 EDT with flight track overlaid.

5.6 Echo Tops Product

The long-range enhanced echo tops (EET) product was documented, which provides the user with an indication of the upper boundary of significant reflectivity. The product is designed to provide improved vertical estimates of precipitation tops for aviation and other interests. The product provides coverage to 186 miles with a resolution of 1 km (0.54 nm) X 1° and depicts the highest volume point of 18.5 dBZ in thousands of feet. Figures 26 and 27 are the KEVX WSR-88D echo tops product for 0822 and 0827 EDT with the flight track overlaid. The images depicted precipitation echo tops to 40,000 ft over the track.

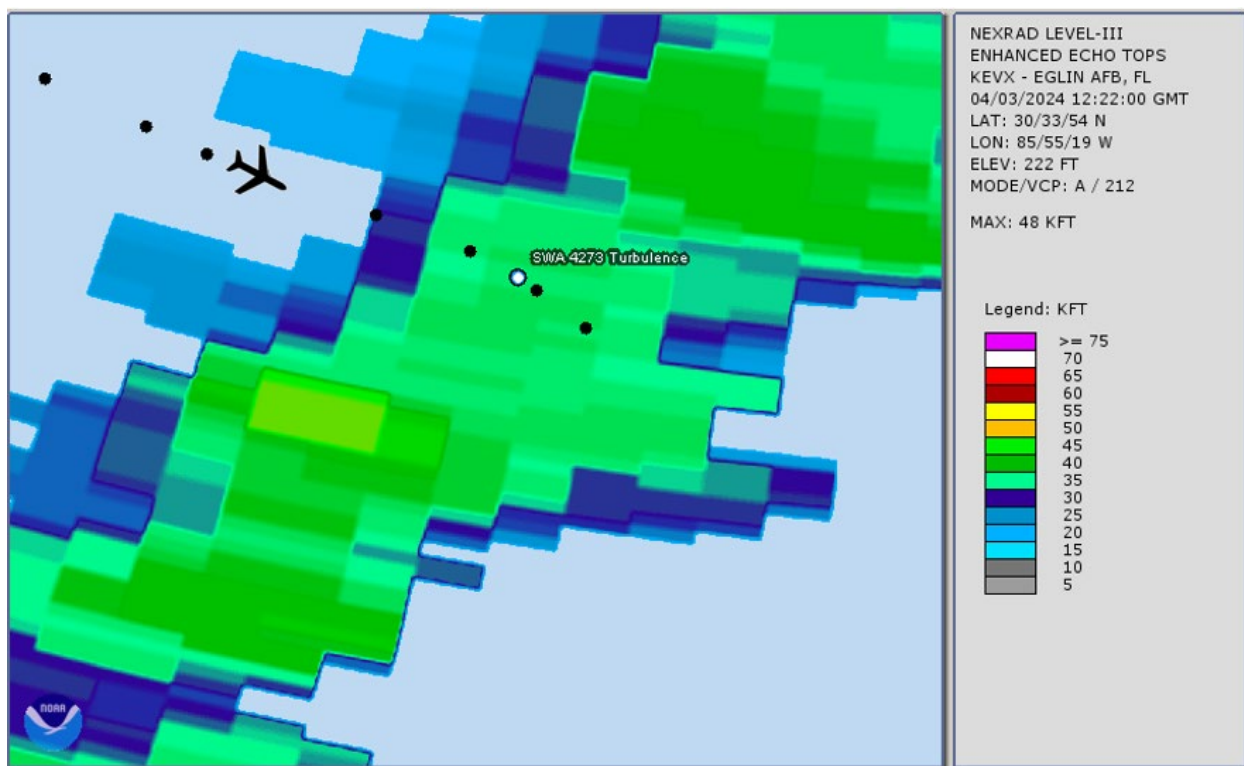


Figure 26 - KEVX WSR-88D long range enhanced echo tops product for 0822 EDT with track.

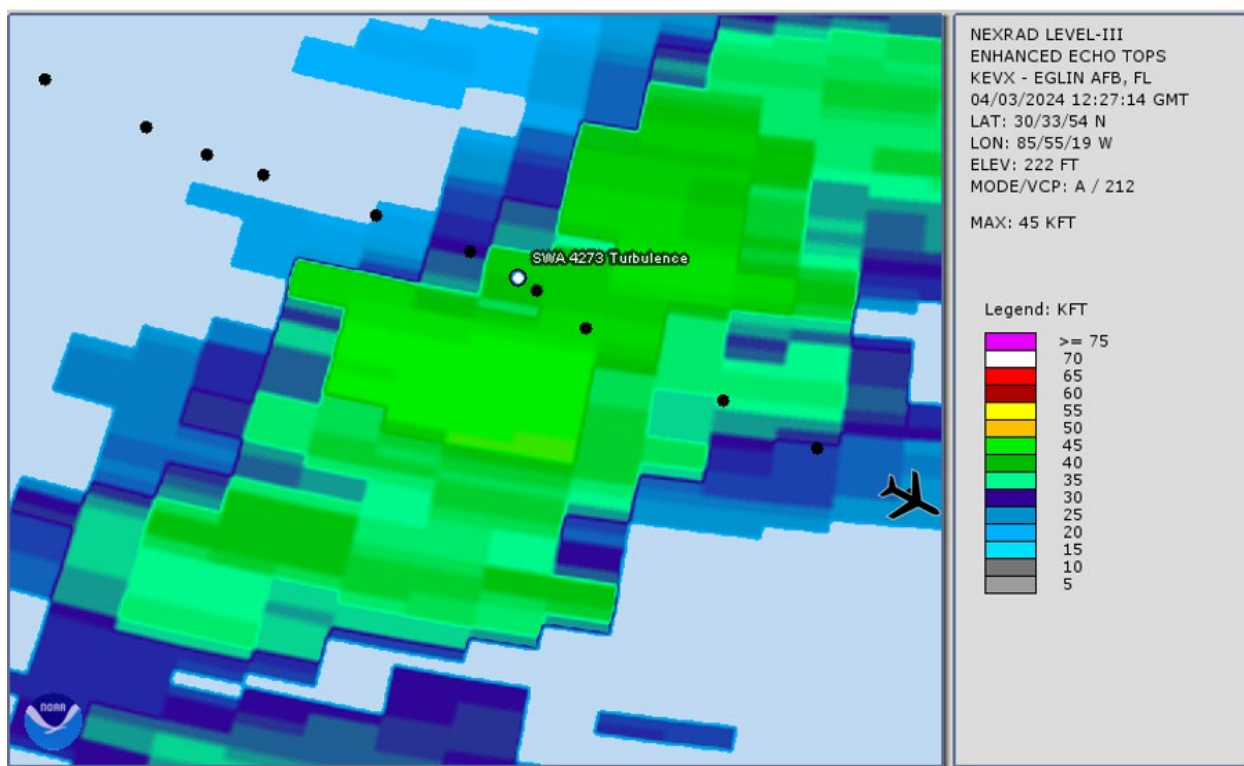


Figure 27 - KEVX WSR-88D long range enhanced echo tops product for 0827 EDT with track.

5.7 FAA Consolidated Storm Prediction for Aviation Display

The Massachusetts Institute of Technology (MIT) Lincoln Laboratory developed the Consolidated Storm Prediction for Aviation (CoSPA) for the FAA and is presently used in all the Air Route Traffic Control Centers (ARTCC) to provide improved situational awareness of weather radar, lightning, precipitation tops, movement, and the storms growth and decay potential. The imagery provides a depiction of vertical integrated liquid (VIL) precipitation levels versus echoes in dBZ, which is included in figure 28.

VIP Level	Winter Precip VIP Level			VIL (kg/m2)	Reflectivity Equivalent (dBZ)	Intensity Descriptor
	Liquid	Mixed	Snow			
	1a	1a	1a	0.03 to < 0.26	-10 to < 18	
1	1b	1b	1b	0.26 to < 0.51	18 to < 27	Light
2	1c	1c+	1c+	0.51 to < 0.78	27 to < 30	Light
3	2			0.78 to < 3.54	30 to < 41	Moderate
4	3			3.54 to < 7.09	41 to < 46	Heavy
5	4			7.09 to < 12.48	46 to < 50	Heavy
6	5	1c+	1c+	12.48 to < 32.33	50 to < 57	Extreme
	6			≥ 32.33	≥ 57	Extreme

Figure 28 - VIL Precipitation Levels.

The CoSPA image for 0825 EDT is included as figure 29, with the satellite cloud overlay and lightning turned off. The nominal standard radar coverage of 125 miles is shown light gray, the nominal extended radar coverage to 240 miles in dark gray, and no expected radar coverage depicted in black. The different ARTCC airspace boundaries are also displayed in red.

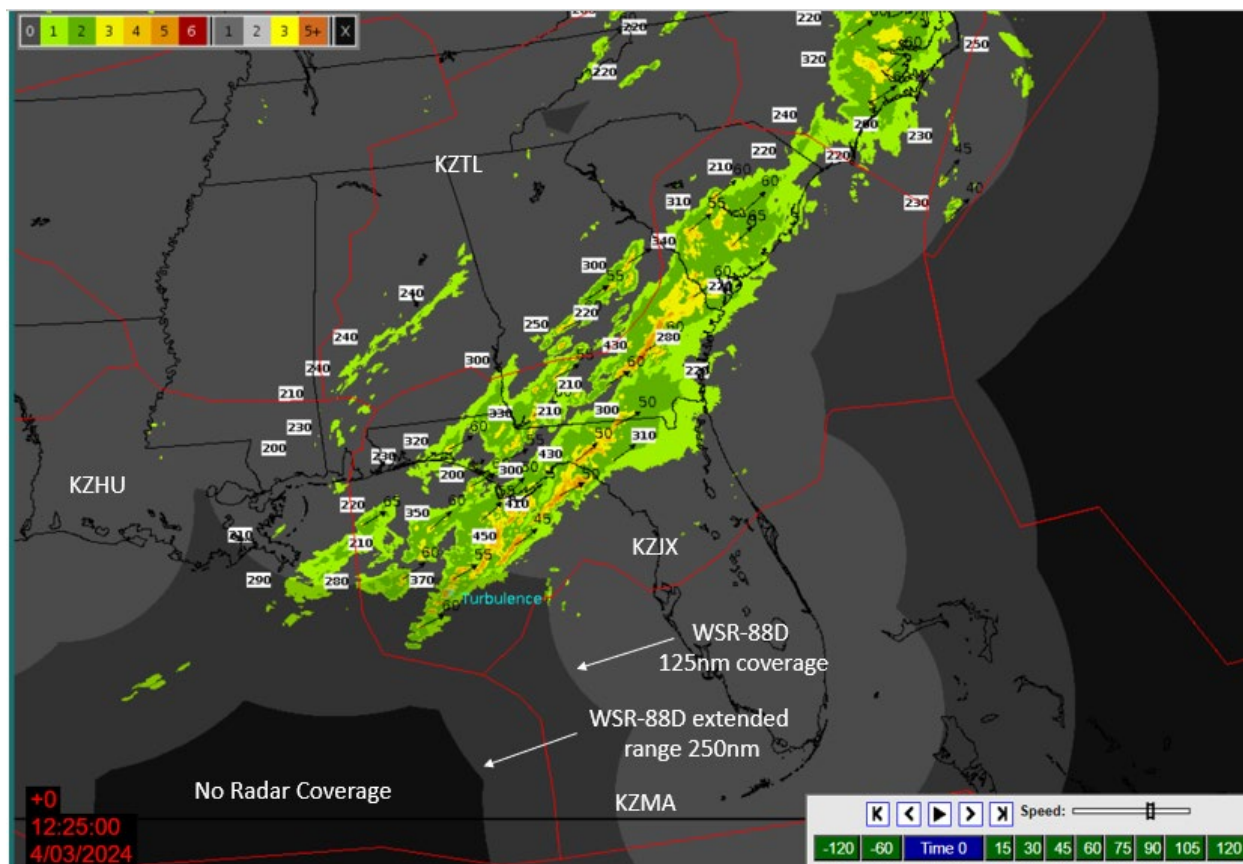


Figure 29 - CoSPA image for 0825 EDT showing coverage of radar and controlling airspace.

5.8 Offshore Precipitation Capability

The FAA's Aviation Weather Division and MIT-Lincoln Laboratory also developed the Offshore Precipitation Capability (OPC) which is designed to depict precipitation beyond normal radar coverage. The system utilizes long range WSR-88D imagery, satellite imagery, global lightning mapper data, and weather model data using machine learning to produce an estimate of precipitation for areas that lack radar coverage. OPC is merged with the CONUS radar mosaic to provide controllers with better situational awareness for offshore sectors. Both the CoSPA and OPC data were reviewed during the period, and both the CoSPA and OPC data provided similar imagery during the period in the vicinity of the turbulence location. Figure 30 is the OPC image for 0825 EDT similar to the CoSPA image above, showing additional features outside of the extended radar coverage.

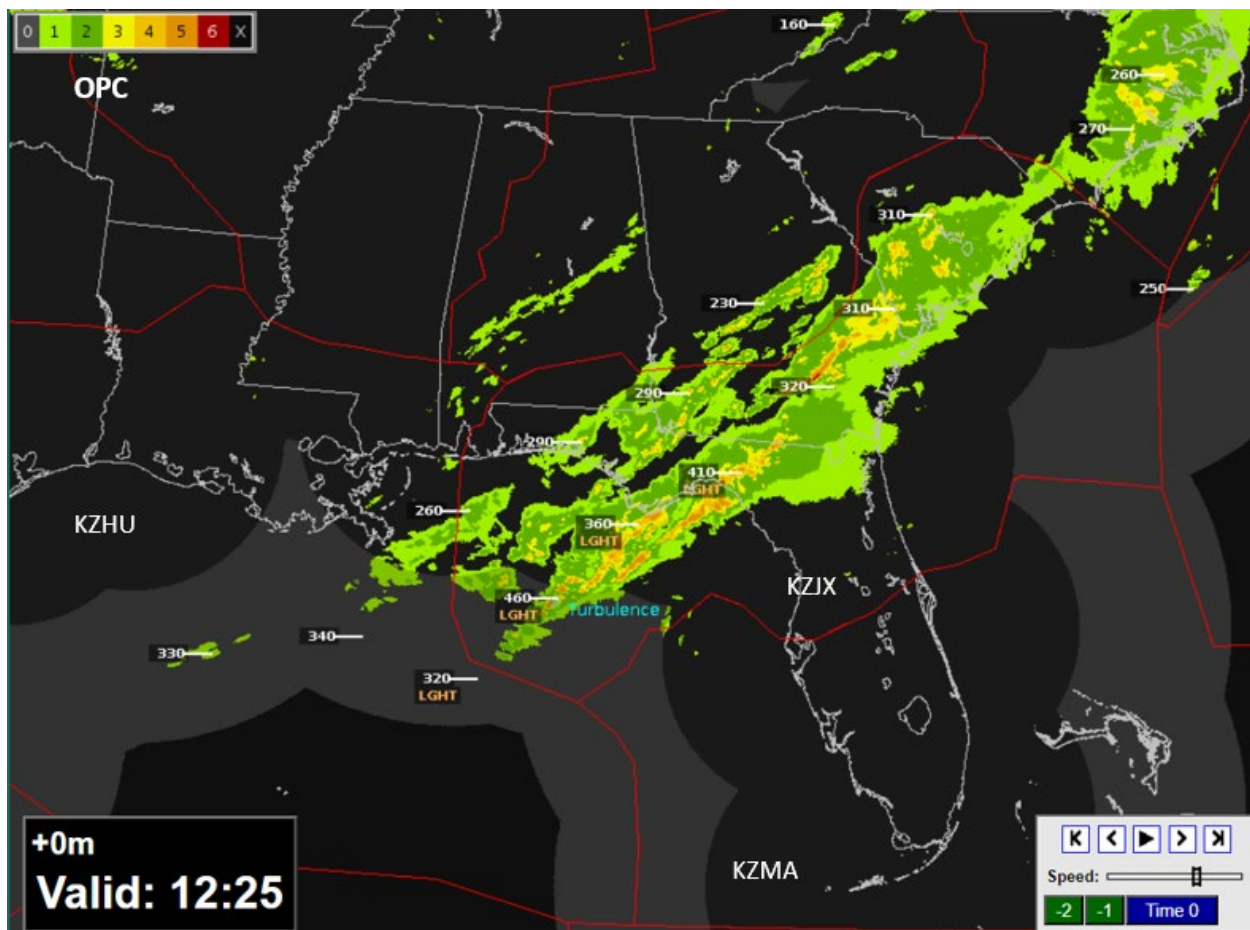


Figure 30 - OPC image for 0825 EDT with satellite and lightning data turned off.

As indicated in figures 29 and 30, very little differences were noted between the CoSPA and OPC coverage at the turbulence location. Figures 31 through 34 are the OPC images every 5-minutes between 0815 and 0830 EDT, with the satellite and cloud-to-ground lightning data (indicated by "+") added. The images depict the line of activity over the turbulence location with several embedded level 5 and 6 extreme intensity areas with tops between FL370 and FL470 moving east-northeastward towards the turbulence location (blue X) at 50 knots, with clusters of cloud-to-ground lightning associated with the stronger cells. At the approximate time of the turbulence encounter VIL level 5 extreme intensity echoes extend over the site.

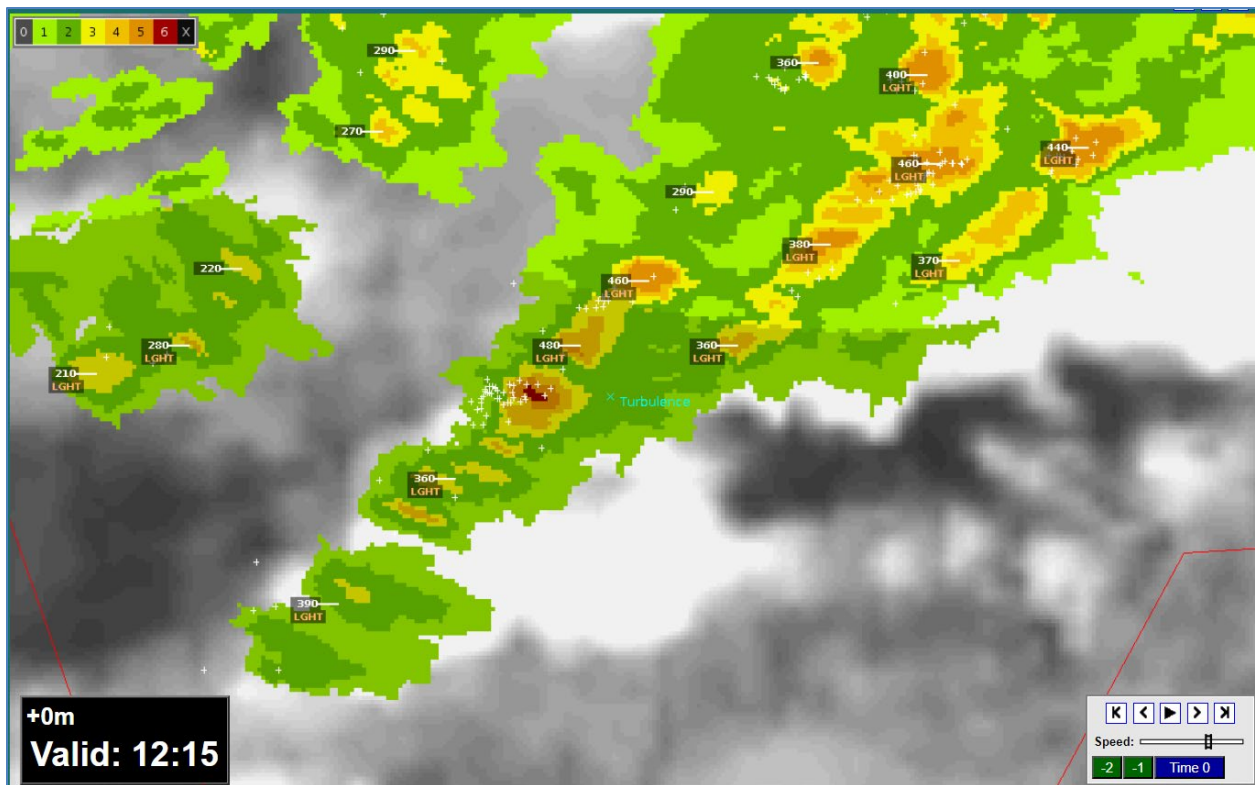


Figure 31 - OPC image for 0815 EDT with turbulence location marked in blue.

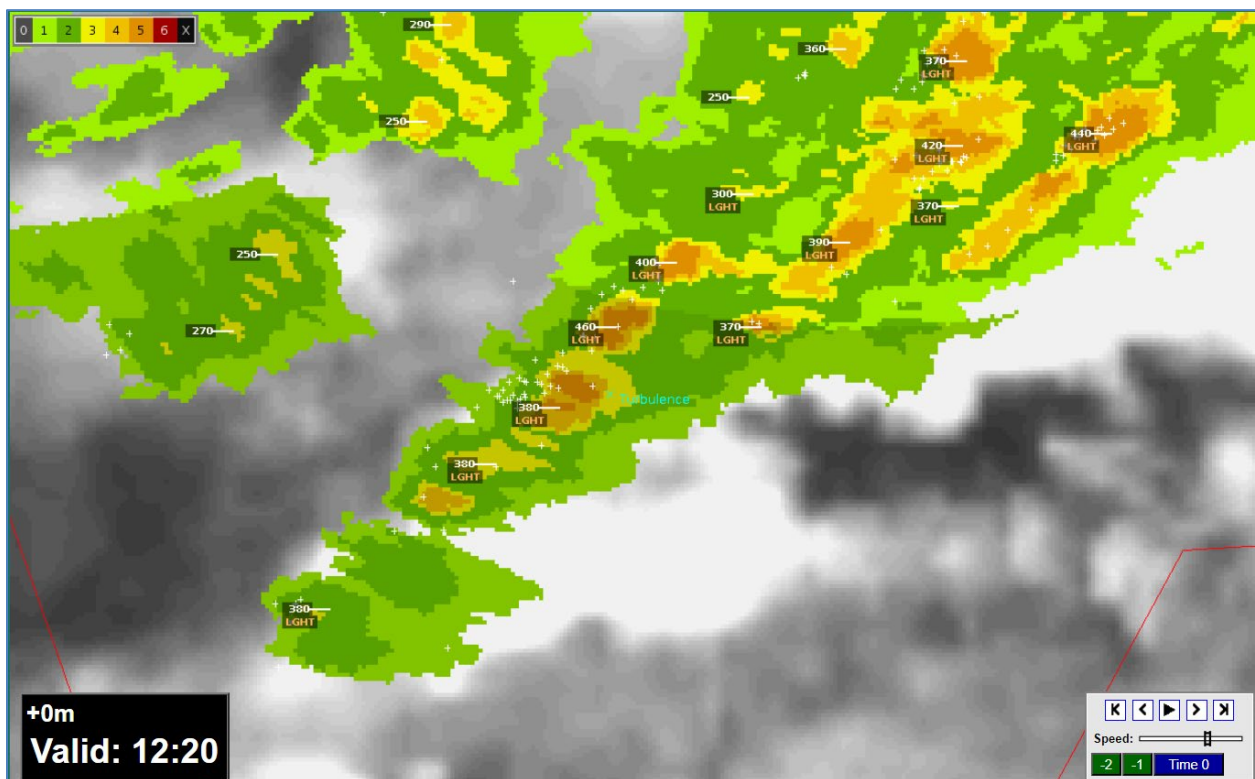


Figure 32 - OPC image for 0820 EDT over a satellite image with turbulence location.

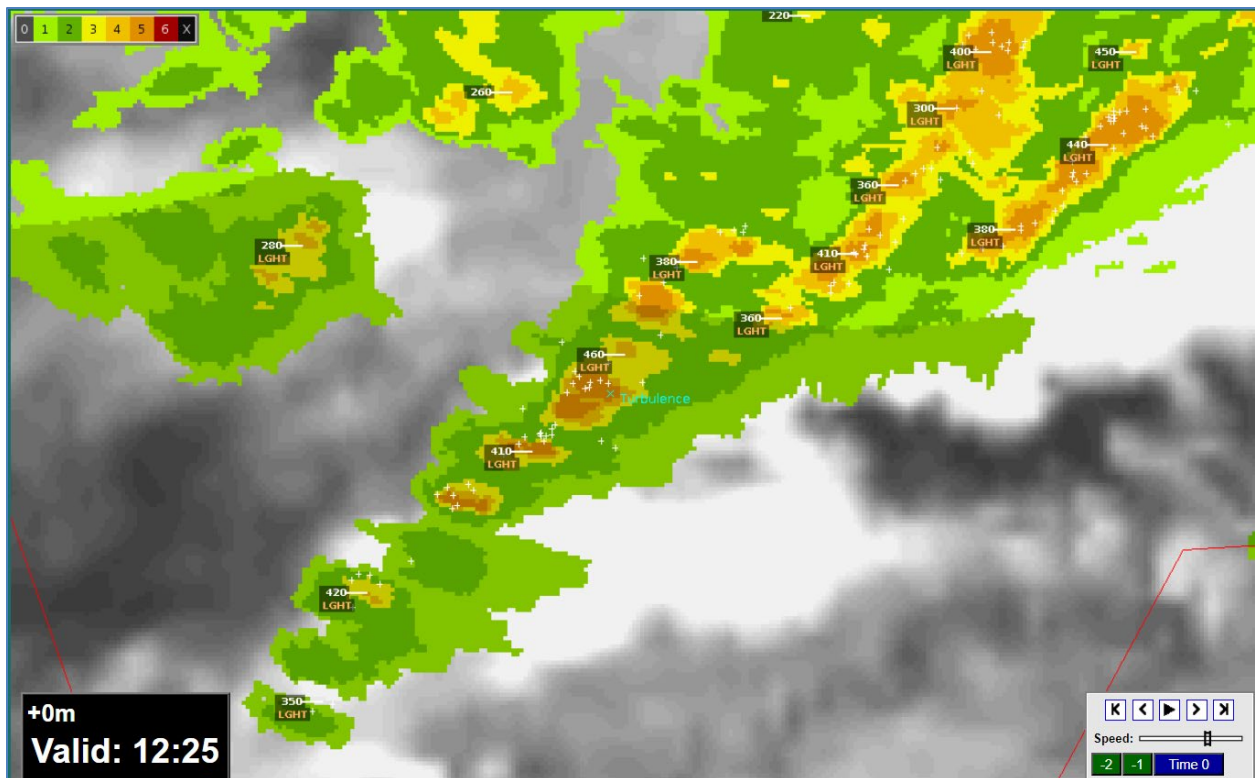


Figure 33 - OPC image for 0825 EDT at the time of the turbulence encounter.

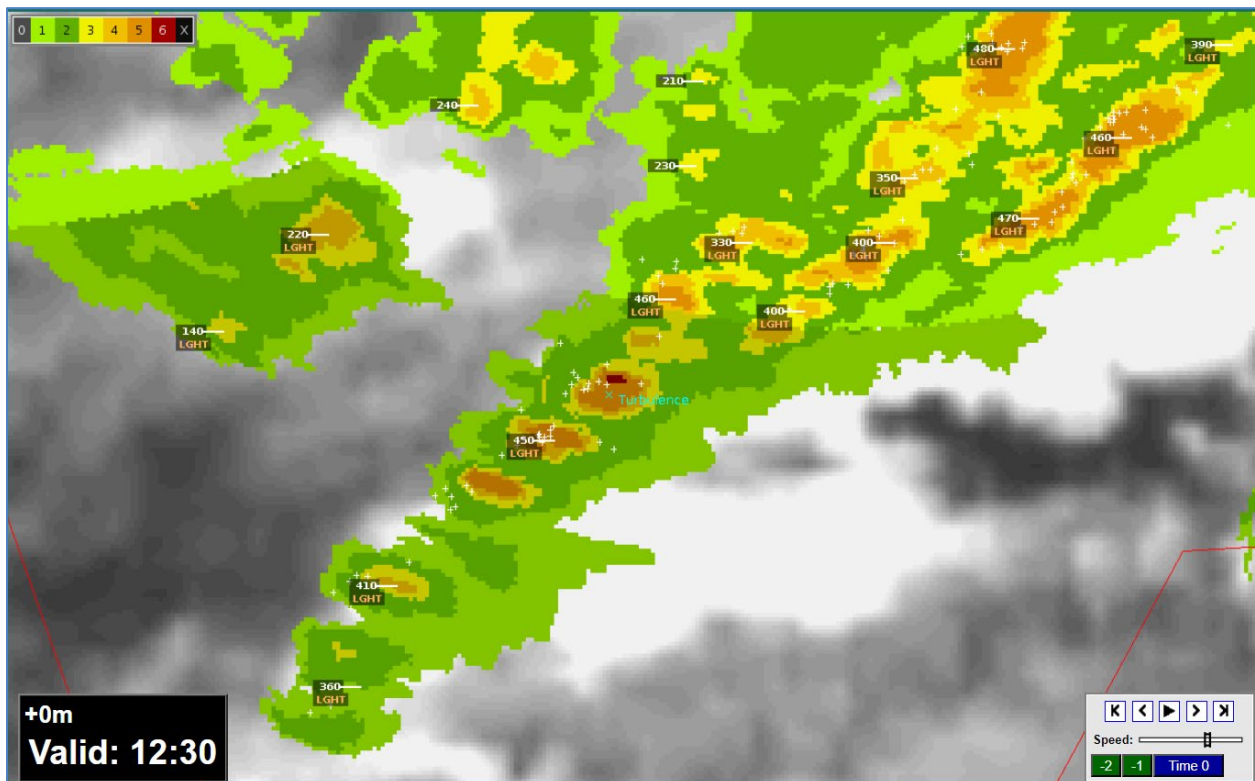


Figure 34 - OPC image for 0830 EDT over a satellite image with turbulence location.

6.0 Pilot Reports

The following pilot reports (PIREPs) were transmitted longline³¹ within 200 miles and within 2 hours prior to the turbulence encounter to an hour after the event, with emphasis on reports above FL180. The reports below are in standard code and abbreviations, with time referenced to UTC. The report associated with the Southwest turbulence encounter³² is highlighted in dark blue.

CTY UA /OV CTY160020/TM 1022/FL280/TP B737/TB CONS LGT
PNS UA /OV PNS020005/TM 1023/FL030/TP B739/SK SCT028
CRW UA /OV PSK/TM 1032/FL215/TP CRJ9/TB OCNL MOD
PNS UA /OV PNS080010/TM 1046/FL022/TP A306/SK SCT020/RM SMOOTH
TLH UA /OV SZW300020/TM 1050/FL050/TP E170/SK TOP400/TB LGT-MOD CAT/RM EXTRM RA MAI
TOP240
MCO UA /OV MCO180002/TM 1110/FL030/TP A320/SK CLR/TB SMOOTH
MCO UA /OV MCO/TM 1111/FLDURD/TP B39M/SK HZ/TB SMOOTH
PNS UA /OV PNS020005/TM 1121/FL031/TP CRJ9/SK BKN020-TOP030
VAD UA /OV OTK/TM 1130/FL310/TP A320/TB CONS LGT-MOD CAT
VAD UA /OV OTK180030/TM 1141/FL410/TP E55P/TB CONS LGT CHOP
CEW UA /OV CEW120130/TM 1143/FL320/TP E170/TB CONS LGT
AMG UA /OV AMG/TM 1144/FL400/TP B737/TB LGT-MOD CHOP
TLH UA /OV TLH194040/TM 1147/FL360/TP B738/TB MOD CAT
CEW UA /OV CEW100057/TM 1148/FL140/TP PC12/TA M01/IC TRACE LGT
PNS UA /OV PNS350003/TM 1151/FL026/TP C550/SK SCT030
PNS UA /OV PNS010002/TM 1200/FL012/TP PA28/SK SCT020
EUF UA /OV EUF160030/TM 1208/FL300/TP B752/TB MOD CHOP/RM ZTLFD-09
PNS UA /OV PNS/TM 1215/FL021/TP A319/SK BKN021
PNS UA /OV PNS340005/TM 1215/FL038/TP A319/SK BKN021 TOPS BKN029
PIE UA /OV PIE345145/TM 1224/FL470/TP GLEX/SK TOP450
PIE UUA /OV PIE280177/TM 1226/FL370/TP B737/TB SEV
SRQ UA /OV SRQ/TM 1230/FL013/TP PC12/SK BKN013/WV + OR - 10 KNOTS/RM ARR RWY 22
TLH UA /OV TLH150050/TM 1232/FL370/TP B763/TA M15/TB CONS LGT CHOP /IC LGT RIME
PNE UA /OV PNE/TM 1236/FL000/TP PC12/SK OVC006/TB MOD BLO 020/RM LLWS +/-10KT DURD RY06
GNV UA /OV GNV010030/TM 1247/FL310/TP B738/TB CONS LGT CAT
TPA UA /OV TPA/TM 1250/FL025/TP B737/SK BASE 013/RM TOPS 025
CEW UA /OV CEW230100/TM 1253/FL390/TP B738/TB LGT-MOD
CEW UA /OV CEW180150/TM 1300/FL370/TP B737/TB LGT CHOP
SRQ UA /OV SRQ270150/TM 1317/FL350/TP B738/TB MOD CHOP

A review of the PIREPs indicated no reports of severe turbulence prior to the accident, while there were numerous reports of light to occasional moderate turbulence ranging from FL215 through FL360. A report from a pilot landing at Tallahassee, FL (TLH) at 0650 EDT reported encountering extreme intensity precipitation on descent. The search did result in two PIREP over Savannah, GA (SAV) reporting severe turbulence; however, these reports were more than 400 miles

³¹ Includes only the reports official recorded and disseminated as a PIREP and may not include "ride reports" broadcasted or other conditions solicited by air traffic controllers and not entered in the formal PIREP format coding. These reports are available to users in near real-time.

³² The aircraft flight dispatcher entered the PIREP into the WSI Fusion system for dissemination.

northeast of the accident site. These reports have not been included due to the distance but were likely associated with the same line of convection moving across the region.

7.0 NWS Convective Forecasts

The common NWS convective weather forecasts and discussions generally used by the aviation community were documented. The NWS products such as Weather Watches and other mesoscale discussion designed for the public were not included if they did not extend over the turbulence location.

7.1 Convective Outlook

The NWS Storm Prediction Center (SPC) located in Norman, Oklahoma, is tasked to identify and provide timely warnings and watches for severe thunderstorms, which may produce tornadoes, large hail of an inch or greater in diameter, or thunderstorms with organized wind gusts of 50 knot or more across the continental United States. One of the products they produce and is used in aviation is the graphical and narrative Convective Outlooks (AC), which identifies where organized thunderstorms are expected during the period of the outlook, typically 24-hours. The graphic and text convective outlook is updated several times a day, with morning, afternoon and evening updates. The convective outlook chart and narrative current at the time of the turbulence encounter depicted a marginal³³ to slight risk³⁴ of severe storms over the mid-Atlantic through Florida and is included as figure 35.

³³ Marginal risk - An area of severe storms of either limited organization and longevity, or very low coverage and marginal intensity. About 2% probability of occurrence.

³⁴ Slight risk - An area of organized severe storms, which is not widespread in coverage with varying levels of intensity. About a 5% probability of occurrence.

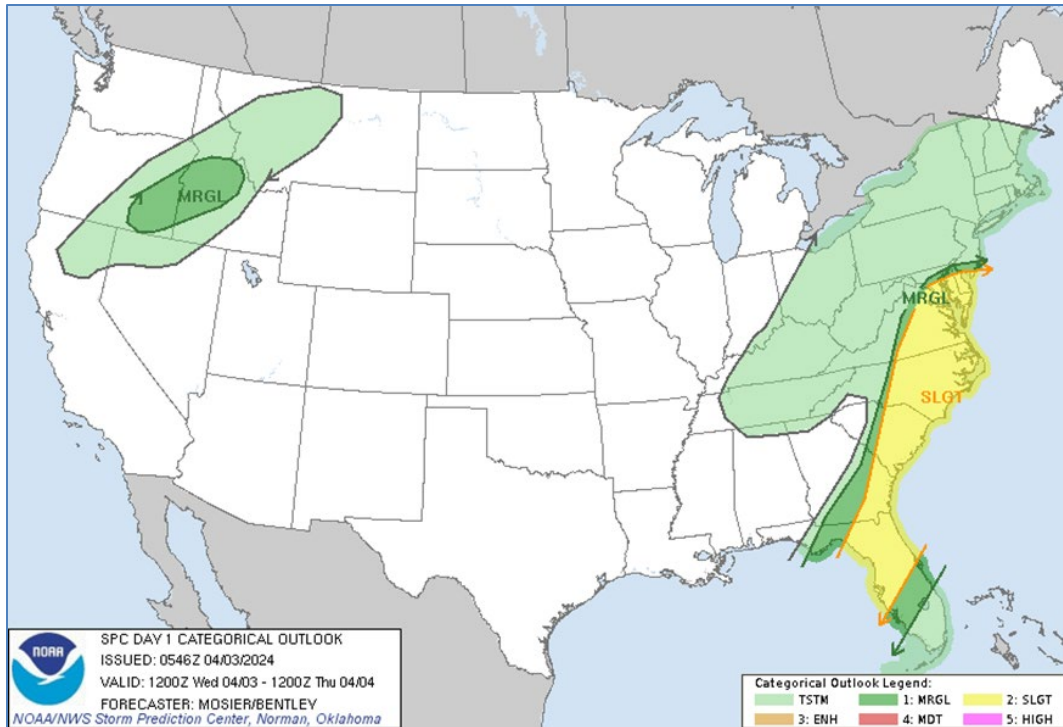


Figure 35 - NWS Storm Prediction Center's Convective Outlook issued at 0800 EDT.

SPC AC 030546

Day 1 Convective Outlook
NWS Storm Prediction Center Norman OK
1246 AM CDT Wed Apr 03 2024

Valid 031200Z - 041200Z

...THERE IS A SLIGHT RISK OF SEVERE THUNDERSTORMS FROM THE MID-ATLANTIC TO FLORIDA...

...SUMMARY...

Strong to occasionally severe thunderstorms are possible on today from the Mid-Atlantic to Florida. Primary hazard is damaging gusts, but isolated hail and a tornado or two is also possible. Isolated hail and a strong gust or two are also possible from southeast Oregon into central Idaho.

...Synopsis...

A mid-latitude cyclone is forecast to deepen/mature as it moves slowly eastward on today. Strong upper/mid-level flow will accompany this cyclone, with 120 kt of 500 mb flow extending throughout its eastern periphery from the Southeast through the Mid-Atlantic States during the afternoon and evening. Occluded surface low associated with this system currently over southern Lake Michigan will drift slowly eastward beneath the upper cyclone.

A secondary triple point low is currently developing to the southeast of the occluded low, and this low will likely be over the southwest VA vicinity later this morning. Expectation is for this low to progress northeastward throughout the day, while the cold front that extends southward from this low sweeps eastward.

Farther west, a deepening upper trough will approach the Pacific Northwest coast late tonight/early Thursday morning. Enhanced southwesterly flow preceding this trough will spread gradually eastward across the Pacific Northwest into the northern Rockies.

...Mid-Atlantic southeastward to Florida...

Thunderstorms will likely be ongoing along and ahead of the cold front mentioned in the synopsis, from the Mid-Atlantic southwestward into the eastern FL Panhandle. Air mass preceding this front will be characterized by ample low-level moisture (i.e. dewpoints in the mid/upper 60s), but poor lapse rates and relatively modest buoyancy. In contrast, robust wind fields will support strong vertical shear, with 0-6 km bulk shear likely around 60 to 70 kt. Consequently, even with limited buoyancy, a few stronger storms embedded within the broader convective line are possible. Damaging gusts are the primary severe risk, but isolated marginal hail and/or a brief tornado are also possible.

The land area ahead of the front will be limited across GA and the Carolinas where the outflow-augmented front will likely push offshore by the early afternoon. Farther north in the Mid-Atlantic, additional storm development is possible near the surface low during the afternoon as moist southerly low-level flow facilitates air mass destabilization in the wake of the morning activity. Kinematic fields will remain very strong, and these storms will likely pose a severe risk as they move rapidly northeastward. Damaging gusts are the primary risk, but a tornado or two is possible as well.

The severe threat will likely linger longer across central FL as well. Here, sufficient instability expected ahead of the front should maintain widespread storms, with shear supporting organized convection. Locally damaging wind gusts are the primary risk, along with some potential for marginal hail. Low-level flow will likely be veered but there could still be enough curvature for a brief tornado.

..Mosier/Bentley.. 04/03/2024

The bulletin was updated at 0826 EDT or at the approximate time of the accident and provided the following information.

SPC AC 031226

Day 1 Convective Outlook
NWS Storm Prediction Center Norman OK
0726 AM CDT Wed Apr 03 2024

Valid 031300Z - 041200Z

...THERE IS A SLIGHT RISK OF SEVERE THUNDERSTORMS FOR PORTIONS OF NORTHERN AND CENTRAL FLORIDA INTO SOUTHEAST GEORGIA AND FAR SOUTHERN SOUTH CAROLINA...AND FOR PORTIONS OF THE MID-ATLANTIC STATES...

...SUMMARY...

Strong to occasionally severe thunderstorms are possible today from parts of the Mid-Atlantic states to Florida. Damaging gusts and an isolated risk for a tornado or two are the primary hazards.

...Mid-Atlantic states into the coastal Carolinas and GA/FL...

Morning water-vapor imagery shows a deep-layer cyclone centered over southern Lake Michigan and this feature will slowly migrate east into OH during the period. Occluded low over southern Great Lakes will slowly fill as a secondary cyclone deepens as it moves from NC/VA this morning to south/east of Long Island late tonight. A cold front will sweep east across the Southeast and through much of the FL Peninsula.

Strong to severe thunderstorm activity this morning concentrated over the FL Panhandle and southern GA will continue to progress east to the immediate southeast of an intense mid-level speed max over the southern Appalachians. The airmass south and east of the front in north FL and southern GA will slowly heat/destabilize today despite relatively poor 850-500 mb lapse rates (reference 10z Cape Canaveral and 12z Tampa and Jacksonville raobs). Strengthening and gradually veering flow with height will support organized line segments and occasional supercell structures embedded within the convective band. A tornado or two and damaging gusts will be possible with the stronger activity through midday. As this activity pushes southeastward over north FL into the central part of the Peninsula this afternoon, wind damage will likely become the primary severe hazard of concern.

..Smith/Leitman.. 04/03/2024

7.2 Traffic Flow Management Convective Forecast

The Traffic Flow Management (TFM) Convective Forecast (TCF) is a high-confidence graphical representation of forecasted convection meeting specific criteria of coverage, intensity, and echo top height. The TCF graphics are produced every 2 hours and are valid at 4, 6, and 8-hours after issuance time. The forecast is used by air traffic control management decisionmakers in support of convective weather mitigation strategies within the National Airspace System (NAS). The TCF is used by decision makers in the ARTCC's and airlines flight operation centers. The forecast issued about 0500 EDT is included as figure 36 and depicted a medium coverage of thunderstorms extending from northern Florida into the Gulf of America at 0900 EDT with tops in excess of FL400. The areas of convection indicated were expected to have a radar reflectivity greater than 40 dBZ, coverage over 25%, and a forecaster confidence of at least of 50%. The TCF is regarded by the FAA as the single authoritative forecast for convection in the United States.

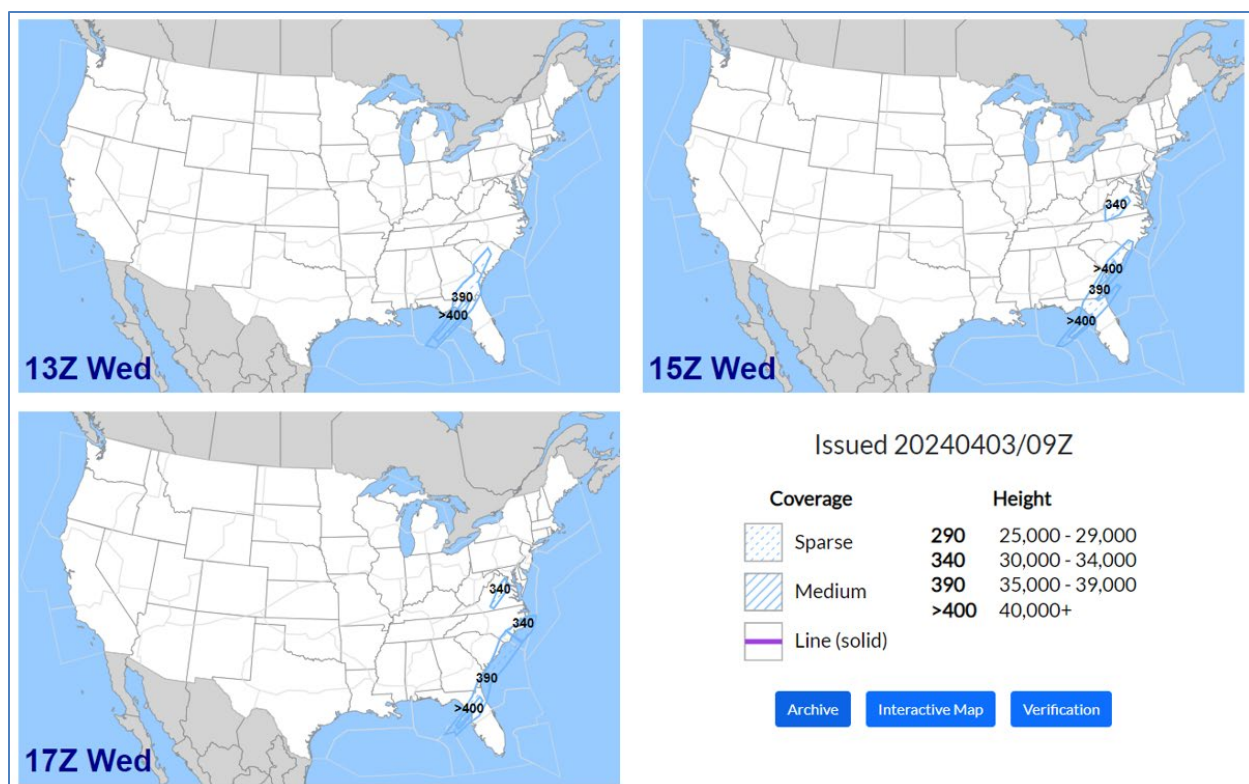


Figure 36 - TCF 2-hour, 4-hour, 6-hour thunderstorm forecast issued at 0500 EDT and current surrounding the period of the accident.

7.3 Graphic Area Forecast

The NWS AWC Graphic Area Forecast (GFA) depiction of the expected thunderstorm coverage at 0830 EDT is depicted in figure 37. The chart depicted a band of scattered thunderstorms over the area where the turbulence incurred with numerous thunderstorms to the northeast over the northeast Gulf of America and across portions of the Florida Panhandle and northern Florida, southern and eastern Georgia, and into South Carolina. The NWS Convective SIGMET and international SIGMET for thunderstorms are also overlaid for the period (see section 9.0).

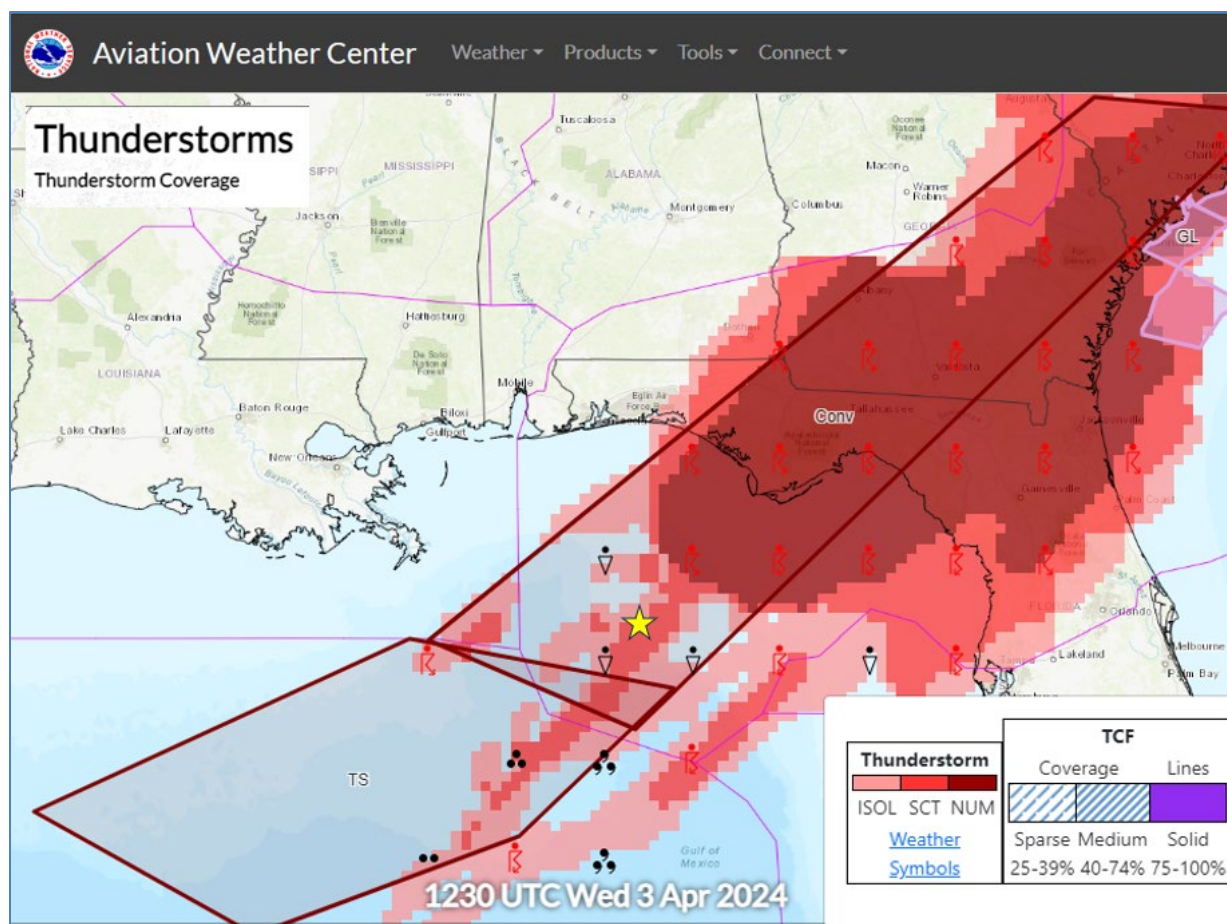


Figure 37 - NWS Graphic Area Forecast (GFA) Thunderstorm coverage for 0830 EDT over the southeast with turbulence location noted by the yellow star.

8.0 Turbulence Guidance

The FAA Aviation Weather Research Program has supported the development of several turbulence products, the primary domestic product was developed by the National Center for Atmospheric Research (NCAR) is the Graphic Turbulence Guidance (GTG), which is available on the NWS AWC website³⁵. The GTG provides a computer-generated four-dimensional forecast related to the expected intensity of atmospheric turbulence provided in eddy dissipation rate (EDR)³⁶ to provide aircraft-specific turbulence intensity values of estimated vertical wind velocity or aircraft vertical acceleration. The graphical turbulence grid is expressed in terms of EDR to the 1/3 power, i.e. $EDR = (m^2/s^3)^{1/3}$. NCAR defines the following EDR values to various aircraft weight classes and turbulence intensities, the Boeing B-737 fits into the medium weight

³⁵ <https://aviationweather.gov/gfa/#turb>

³⁶ The EDR is an aircraft-independent measure of turbulence. However, the relationship between the EDR value and the perception of turbulence is a function of aircraft type, and the mass, altitude, configuration and airspeed of the aircraft. The EDR values given above describe the severity levels for a medium-sized transport aircraft under typical en-route conditions (i.e. altitude, airspeed and weight).

category. The estimated EDR thresholds included below are multiplied by 100, as EDR values are depicted in the range from near 0 (typically smooth) to 100 (typically "extreme" for most aircraft).

The NWS AWC GTG product available to users on the website is depicted in figure 38 with the approximate turbulence location noted by the red star, with the PIREP location also plotted. It should be noted that this GTG model does not include convection and displays potential clear air turbulence from jet stream and mountain wave activity.

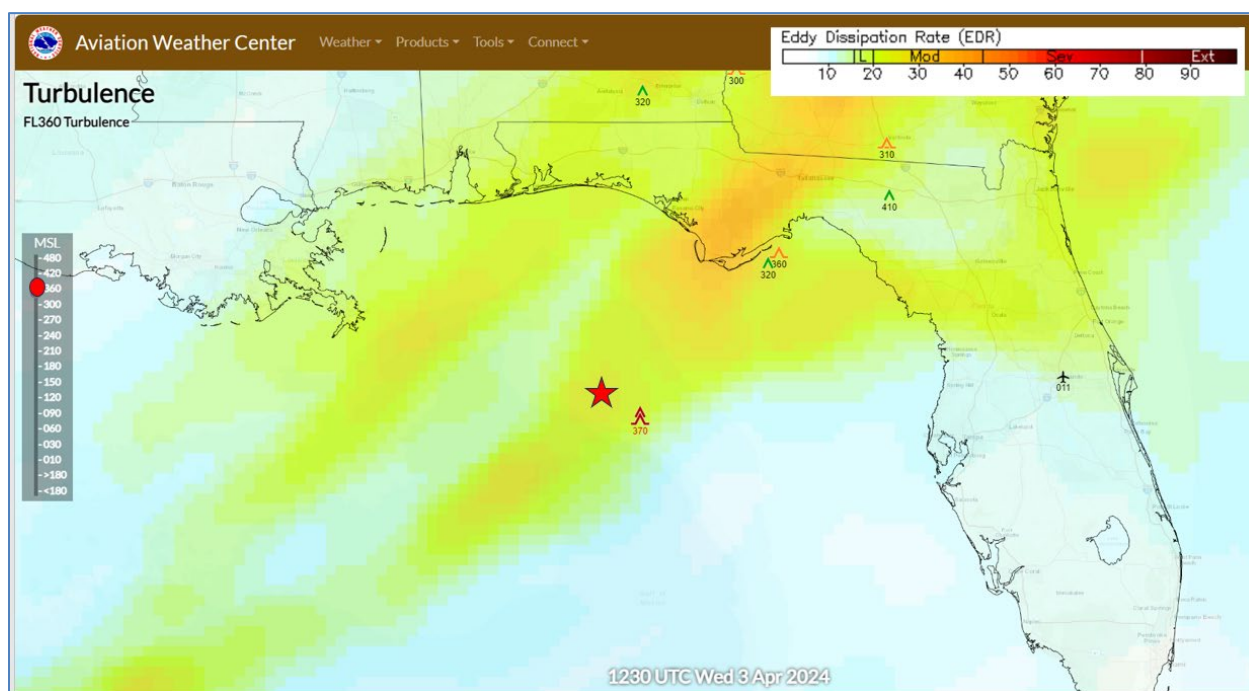


Figure 38 - NWS AWC Graphic Turbulence Guidance (GTG) for 0830 EDT with the turbulence PIREP and location noted.

NCAR has developed a newer version of the product, which includes convective turbulence and is referred to as the GTG-Nowcast (GTG-N)³⁷ and is currently being run on the NWS AWC testbed and is slated for implementation at NCEP in the future. The NTSB reached out to NCAR to run the model for the period. Figure 39 is the current version of the GTG-N forecast for the 1-hour period (left) valid for 0800 EDT and 2-hour period (right) for 0700 EDT for FL370 on April 3, 2024, with the approximate accident site marked by the star. The current model depicted EDR values less than .20 over the turbulence location with higher values northeast.

³⁷ Also referenced to as the GTG3, data provided by NCAR Julia Person.

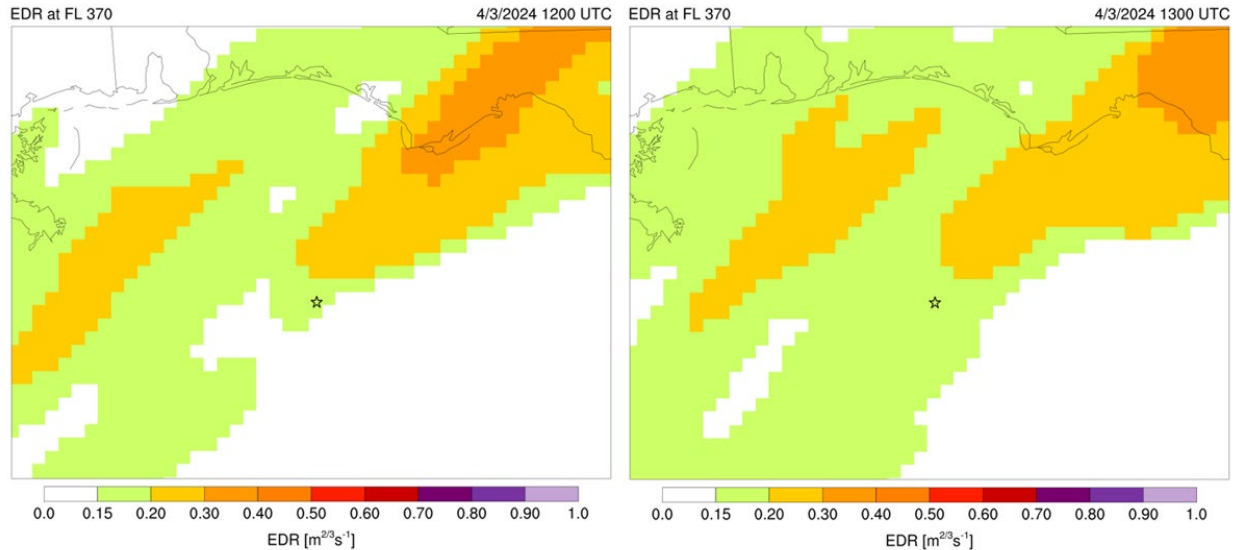


Figure 39 - Current testbed GTG-N model 1-hour forecast valid for 0800 EDT (left) and 2-hour forecast valid for 0900 EDT (right) for FL370.

The NCAR real time semi-operation GTGN v1 with input from in-situ EDR and PIREPs from the previous hour within 2,000 ft of FL370 for 0815 EDT (left) and for 0830 EDT (right) is shown in figure 40. The newer GTGN v1 shows significant improvement in detecting and forecast the developing convection and depicted EDR values of .30 to .60 over the area. While figure 41 is the GTGN v2 model which includes satellite based (GLM) lightning data and a higher resolution domain, and other improvements. Attachment 4 contains the data provided by NCAR.

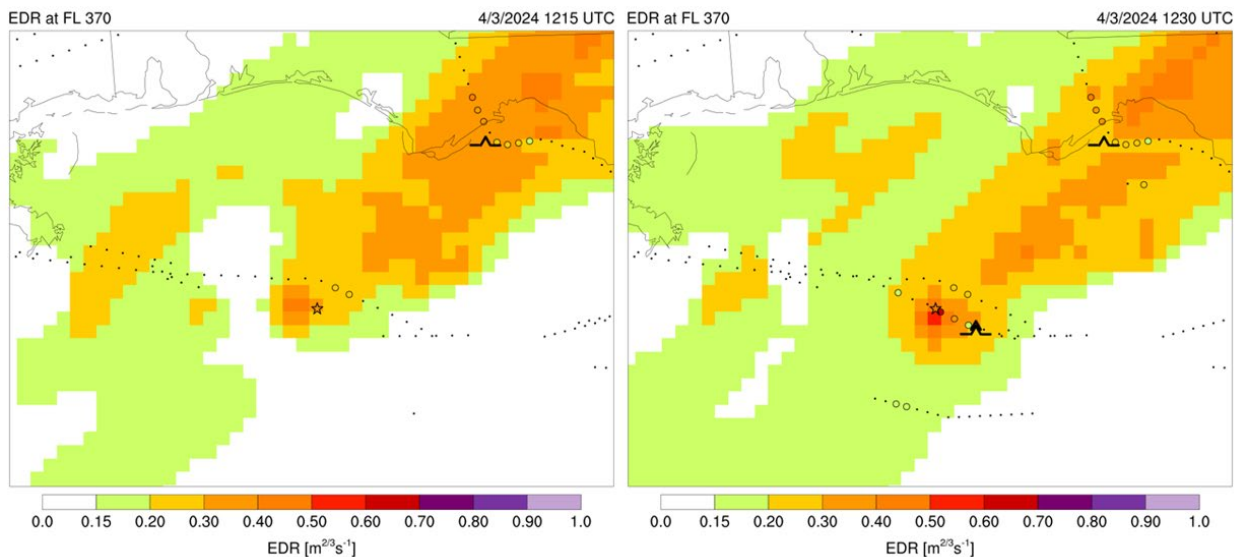


Figure 40 - Real-time semi-operational GTGN v1 valid for 0815 (left) and 0830 EDT (right) with in situ and PIREPs.

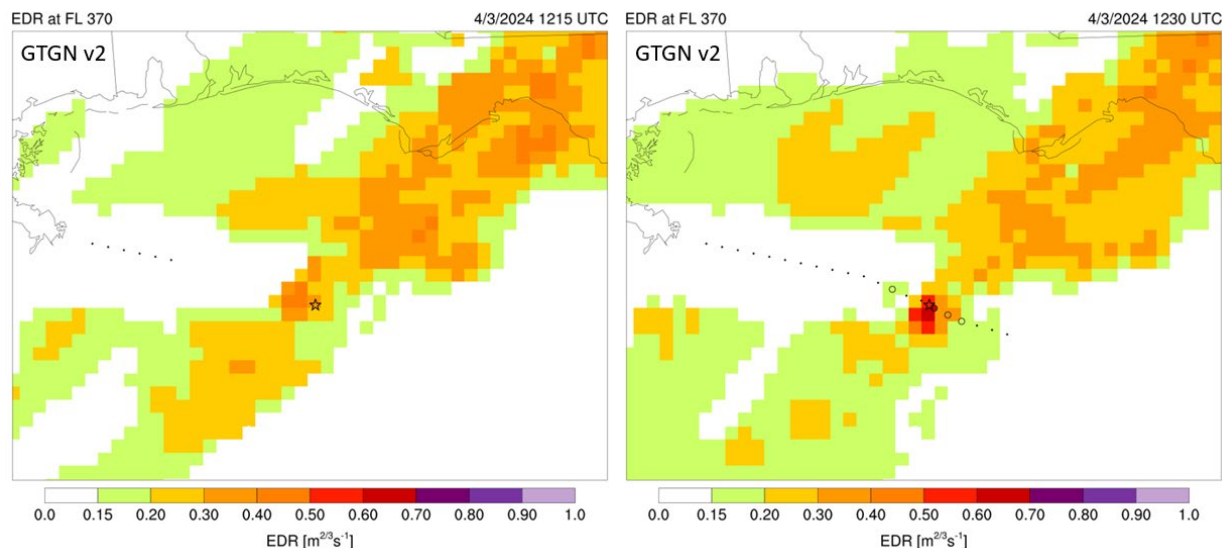


Figure 41 - GTGN v2 valid for 0815 EDT (left) and for 0830 EDT (right) with in situ and PIREPs.

9.0 NWS Inflight Weather Advisories

In-flight Aviation Weather Advisories are forecasts that advise en route aircraft of the 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) at the various 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 G-AIRMET, and the Center Weather Advisory (CWA). Inflight advisories serve to notify en-route pilots of the possibility of encountering hazardous flying conditions that 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 and/or flight dispatcher to evaluate based on experience and the operational limits of the aircraft. Once inflight weather advisories are issued, they are broadcast by FAA air traffic controllers upon issuance and available on inflight weather broadcasts.

The NWS AWC issued SIGMET Bravo 1 for the Houston Flight Information Region (FIR) at 0750 EDT for embedded thunderstorms immediately south of the accident site over the Gulf of America. At 0755 EDT or immediately after the flight departed KMSY, Convective SIGMET 44E was issued which extended over the turbulence location. The advisory was issued for an area of severe embedded thunderstorms, with the area moving eastward at 60 knots, with thunderstorm tops above FL450. The advisory warned of the potential for tornadoes, hail to 1.5 inches, and wind gusts to 60 knots were possible with the storms. The advisory also implied the potential for severe and greater turbulence. Figure 42 is a depiction of the advisories from the NWS AWC display with the weather radar image at 0800 EDT, and the approximate turbulence location.

A review of the air traffic control event logs noted that the SIGMET was broadcasted prior to the accident flight was on frequency with Jacksonville center.

Southwest Airlines has an approved Enhanced Weather Information System (EWINS) provider and issues their own advisories to control their flight operations. The government issued advisories are considered supplemental products (see section 11.1) and they issue their own advisories as the primary advisories.

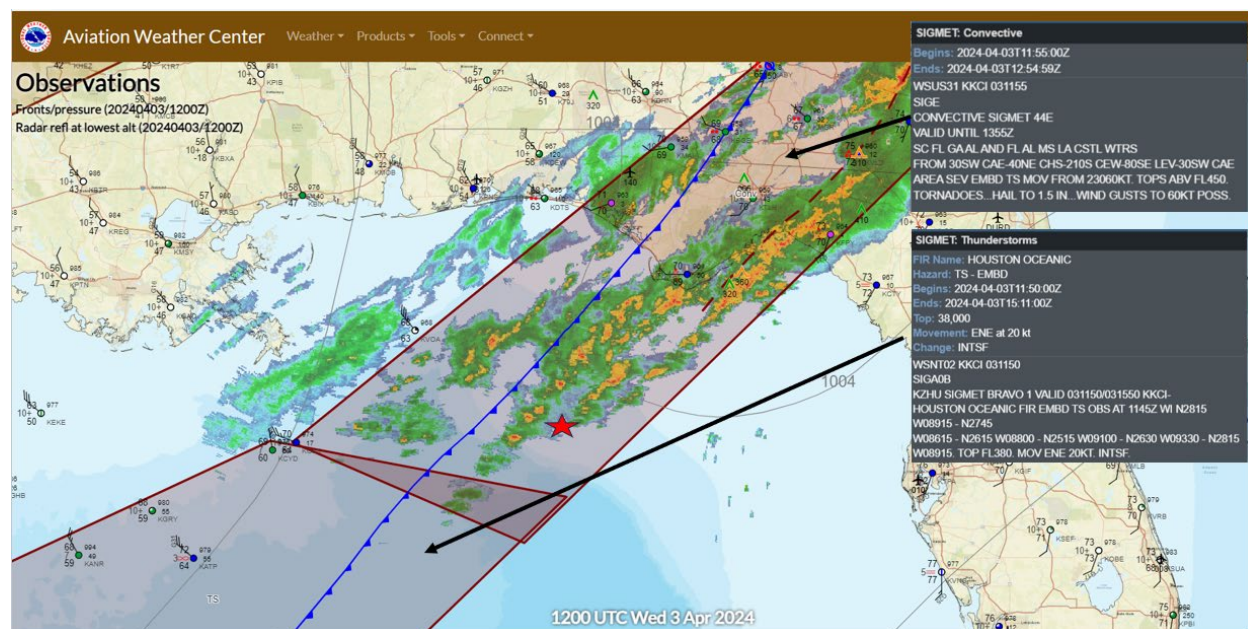


Figure 42 - NWS AWC METAR display with fronts, radar, and SIGMETs overlaid at 0800 EDT immediately after the issuance of the advisories and with the approximate future accident site.

The text version of the advisories displayed in figure 40 are as follows.

WSNT02 KNCI 031150
SIGA0B
KZHU SIGMET BRAVO 1 VALID 031150/031550 KNCI-
HOUSTON OCEANIC FIR EMBD TS OBS AT 1145Z WI N2815 W08915 - N2745
W08615 - N2615 W08800 - N2515 W09100 - N2630 W09330 - N2815
W08915. TOP FL380. MOV ENE 20KT. INTSF.

WSUS31 KNCI 031155
SIGE
CONVECTIVE SIGMET 44E
VALID UNTIL 1355Z
SC FL GA AL AND FL AL MS LA CSTL WTRS
FROM 30SW CAE-40NE CHS-210S CEW-80SE LEV-30SW CAE
AREA SEV EMBD TS MOV FROM 23060KT. TOPS ABV FL450.
TORNADOES...HAIL TO 1.5 IN...WIND GUSTS TO 60KT POSS

These advisories updated the previously issued Convective SIGMETs current for the region issued at 0655 EDT.

-MKCE WST 031055
 CONVECTIVE SIGMET 41E
 VALID UNTIL 1255Z
 NC SC FL GA AND FL CSTL WTRS
 FROM 30N FLO-30WSW ILM-140SSW TLH-130S CEW-MCN-30N FLO
 AREA SEV EMBD TS MOV FROM 24060KT. TOPS ABV FL450.
 TORNADOES...HAIL TO 1.5 IN...WIND GUSTS TO 60KT POSS.

CONVECTIVE SIGMET 42E
 VALID UNTIL 1255Z
 FL AND FL AL MS LA CSTL WTRS
 FROM 50W TLH-170SE LEV-60SSE LEV-50SE SJI-50W TLH
 AREA EMBD TS MOV FROM 25055KT. TOPS ABV FL450.

10.0 Turbulence Reference

The World Meteorological Organization (WMO) in their Aviation Hazards training guide define the turbulence intensities, aircraft response, vertical acceleration, passenger experience, and EDR values for various turbulence intensities for a medium weight category aircraft as follows.

Turbulence category	Aircraft response	Aircraft vertical acceleration magnitude (g)	Passenger experience	Approx $\epsilon^{1/3}$ ($\text{m}^{2/3} \text{s}^{-1}$) for B737 and B757 aircraft
Light	Momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw)	0.2–0.5	A slight strain against seat belts; unsecured objects may be displaced slightly; food service may be conducted with little difficulty walking	0.1–0.3
Moderate	Similar to light turbulence but greater intensity; changes in altitude, attitude, and/or airspeed occur; the aircraft remains in control at all times	0.5–1.0	Definite strain against seat belts; unsecured objects are dislodged; food service and walking are difficult	0.3–0.5
Severe	Large, abrupt changes in altitude, attitude, and/or airspeed; aircraft may be momentarily out of control	1.0–2.0	Occupants are forced violently against seat belts; unsecured objects are tossed about; food service and walking are impossible	0.5–0.7
Extreme	The aircraft is violently tossed about and is practically impossible to control; it may cause structural damage	> 2.0	Truly frightening	> 0.7

Figure 43 - WMO Turbulence Intensity Chart from light to extreme with aircraft and passenger response, aircraft vertical accelerations magnitude (g's), and eddy dissipation rate (EDR) for a medium weight category aircraft.

Light: Effects are less than those of moderate intensity.

Moderate: There may be moderate changes in aircraft attitude and/or height but the aircraft remains in control at all times. Air speed variations are usually small. Changes in accelerometer readings of 0.5-1.0g at the aircraft's center of gravity. Occupants feel strain against seat belts. There is difficulty in walking. Loose objects move about.

Severe: Abrupt changes in aircraft attitude and/or height. The aircraft may be out of control for short periods. Air speed variations are usually large. Changes in accelerometer readings greater than 1.0 g at the aircraft's center of gravity as severe. Occupants are forced violently against seat belts. Loose objects are tossed about.

Extreme: Effects are more pronounced than for severe intensity.

A search of FAA guidance material from the former Advisory Circular AC 00-24C "Thunderstorms" and incorporated in the FAA Weather Handbook mentions in section 22.8.2 general thunderstorm avoidance guidance that any thunderstorm with tops of 35,000 ft or higher are extremely hazardous and should be avoided. There is no other current guidance from the FAA for safe overflight of thunderstorms.

11.0 Southwest Airlines Information

The accident airplane was released at 0520 EDT with a planned altitude of FL390 and additional enroute fuel, and an alternate airport of West Palm Beach (KPBI), although not required by federal aviation regulations³⁸ for contingency. The flight was issued a weather document which provided the weather briefing for the route of flight.

11.1 Weather Document

The weather document issued to the flight is included as Attachment 5. The document included the departure, destination, and alternate station METARs, TAFs, and NOTAMs and field conditions, PIREPs, NWS and WSI issued Convective SIGMETs, and WSI Flight Planning Guidance (FPG) for turbulence and thunderstorms, company PIREPs. The document also included customized graphic images with the planned route of flight with Global Position System (GPS) unreliability, WSI radar summary chart with weather watches (SAW), and Convective SIGMETs (figure 44), Winds aloft at FL340 with weather advisories (figure 45), and current WSI SIGMETs (figure 46).

³⁸ FAR 121.619 – Alternate airport for destination.

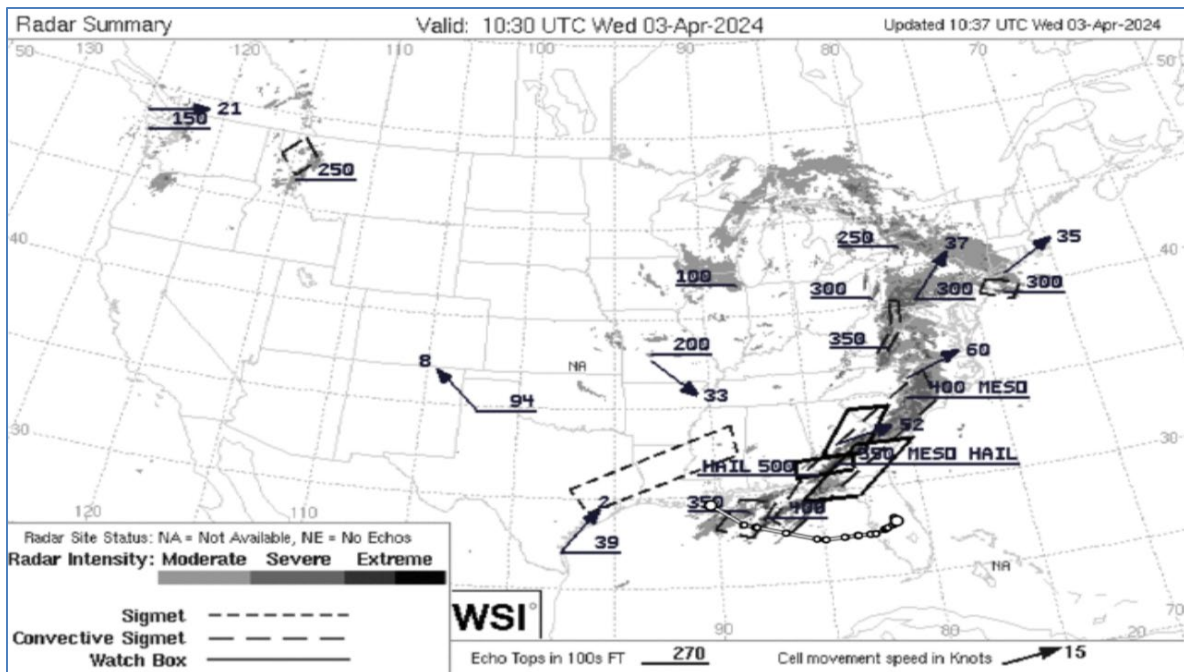


Figure 44 - Southwest Weather Document Radar Summary image for 0637 EDT with NWS Weather Watches (WW) and route overlaid.

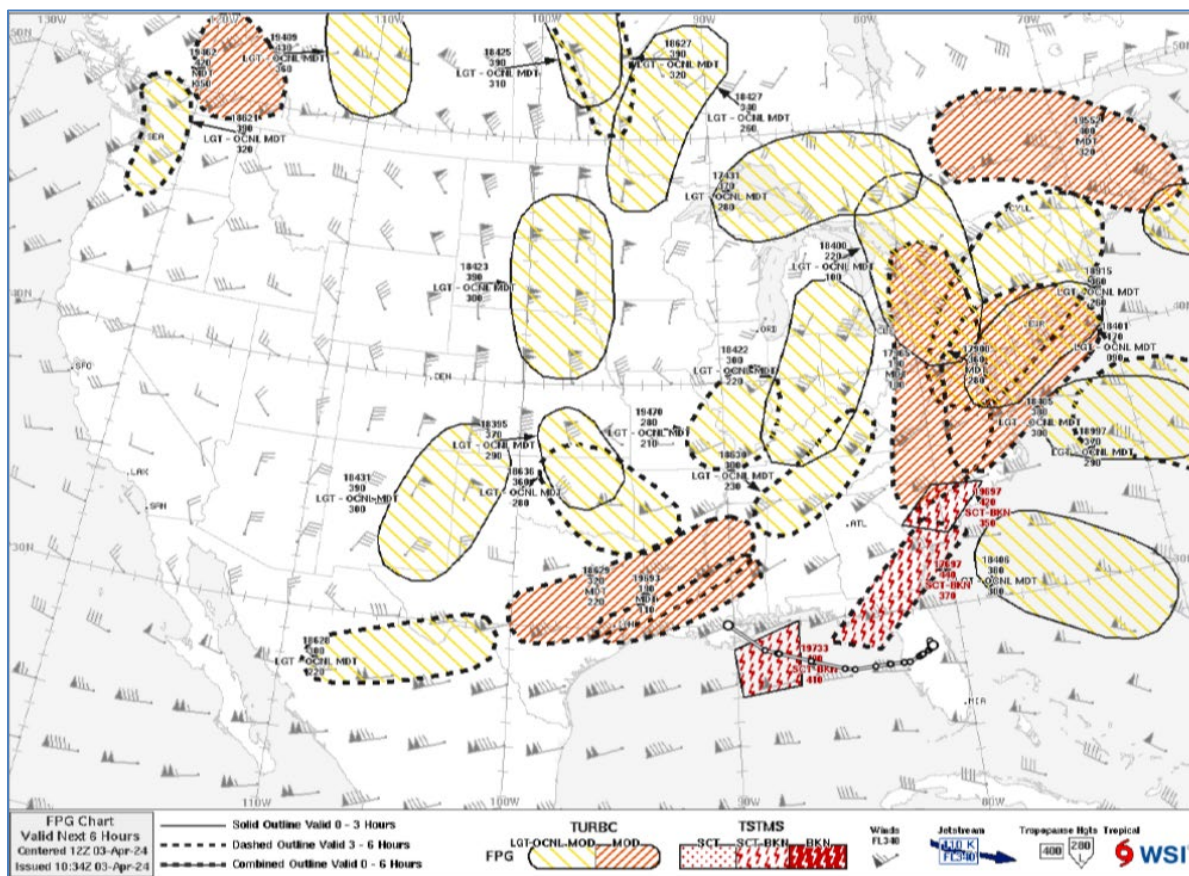


Figure 45 - Southwest Weather Document Winds at FL340 Forecast and Turbulence and Thunderstorm Advisories overlaid valid for 0800 EDT.

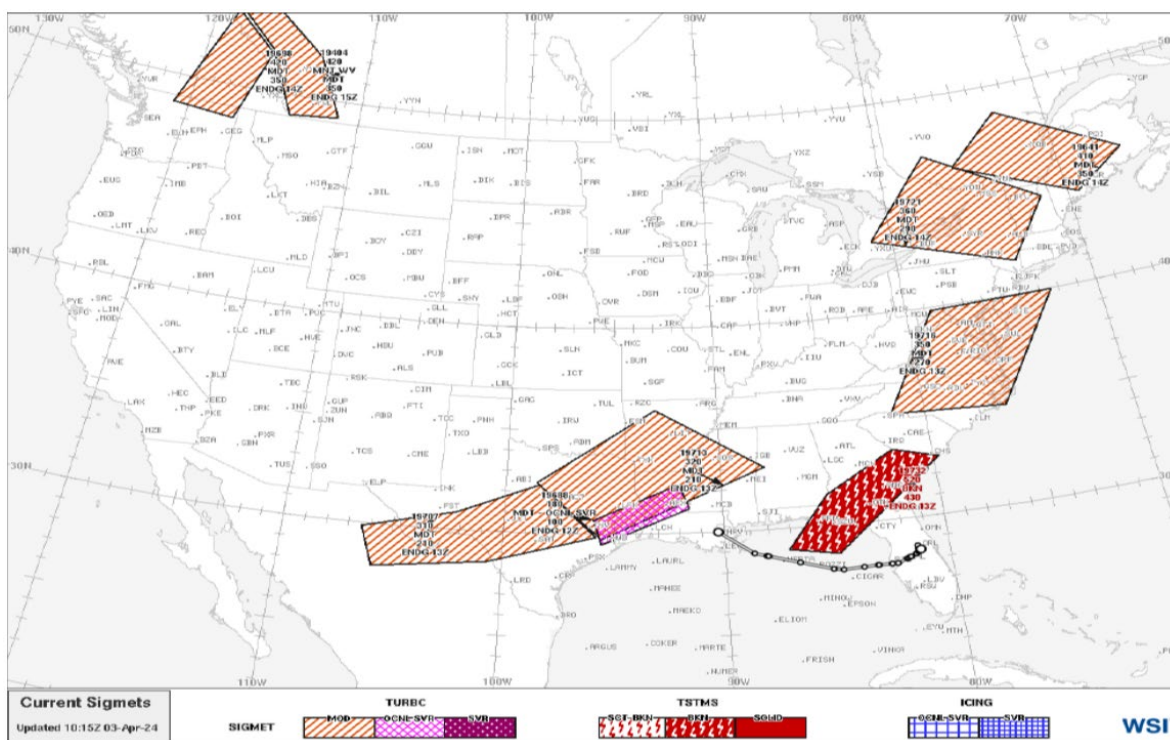


Figure 46 - Southwest Airlines issued current WSI SIGMETs issued at 0615 EDT with route of flight.

11.2 Flight Crew Statements

The flight crew statements are included in Attachment 6.

11.3 Aircraft Measurements

The table below is the mean and peak EDR recorded by the accident airplane (WN4273) between the time 0819 through 0832 EDT. NCAR research suggests turbulence severity thresholds for peak EDRs in the range of 0.3 to 0.5 for moderate and 0.5 to 0.7 range for severe turbulence for a medium weight aircraft like a B-737 type aircraft.

Time (UTC)	Latitude	Longitude	Altitude (ft msl)	Peak EDR	Mean EDR
1219Z	28.624	-88.092	36,980	0.02	0.00
1220Z	28.557	-86.945	37,010	0.02	0.02
1221Z	28.489	-86.799	36,980	0.16	0.06
1222Z	28.421	-86.654	36,970	0.02	0.02
1223Z	28.367	-86.501	37,010	0.02	0.00
1224Z	28.289	-86.370	36,730	0.62	0.30
1225Z	28.219	-86.231	36,970	0.34	0.26
1226Z	28.152	-86.090	37,000	0.18	0.10

1227Z	28.104	-85.932	36,670	0.02	0.00
1228Z	28.053	-85.776	36,980	0.12	0.06
1229Z	28.002	-85.620	36,990	0.08	0.04
1230Z	27.951	-85.465	36,980	0.08	0.06
1231Z	27.906	-85.307	36,980	0.08	0.06
1232Z	27.899	-85.138	36,990	0.04	0.04

11.4 ACARS Messages

The Southwest Aircraft Communications Addressing and Reporting System (ACARS) messages regarding the flight were as follows.

1153Z Off report from MSY at 1153Z
1157Z Weather update - WSI SIGMET for turbulence over TX and WSI SIGMET for convection along route of flight. BKN LINE OF TSTMS AHEAD OF COLD FRONT. TOPS FL430-FL550. MOV NE 25KT.
1203Z ETA 1301Z to MCO.
1204Z Weather Request - MCO ATIS
1223Z Updated ETA 1308Z at MCO
1223Z Weather Alert - WSI SIGMET-CONV. Area 85E MCN. BKN LINE OF TSTMS AHEAD OF COLD FRONT. TOPS FL430-FL550. MOV 067° 25KT.
1232Z Aircraft to Dispatch - Need 2 paramedics, FA serious injury, and 1 PAX injured. SVR turbulence.
1233Z Aircraft to Dispatch - copy at FL370 where
1236Z Aircraft to Dispatch - going to TPA
1237Z Dispatch to Aircraft - acknowledges diversion to TPA with landing data
1256Z On report from TPA
1302Z In gate

12.0 Center Weather Service Unit Support

The KZJX Center Weather Service Unit (CWSU) morning briefing was reviewed and is included as attachment 7. The morning briefing issued at 0734 EDT discussed a broken line of thunderstorms entering the western KZJX airspace and expected to move eastward into the Florida panhandle and northern Florida during the day. The briefing also discussed the potential for occasional moderate turbulence between FL200-FL430 over the airspace.

F. LIST OF ATTACHMENTS

Attachment 1 - Animation of the GOES-16 infrared imagery surrounding the period.
Attachment 2 - GOES-16 infrared imagery with GLM lightning mapper.
Attachment 3 - GOES-16 visible imagery surrounding the accident.
Attachment 4 - NCAR GTG data provided.
Attachment 5 - Southwest Airlines Weather document issued to flight with advisories.
Attachment 6 - Southwest Airlines Crew and Dispatch Statements.
Attachment 7 - KZJX CWSU morning briefing.

Submitted by:

Donald Eick
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