ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

A UN SPECIALIZED AGENCY

Turbulence and Icing

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Axiom for WPC International Desks/NWS/NOAA

ICAO

Overview

01 Introduction to Turbulence

02 Turbulence Types

03 Icing

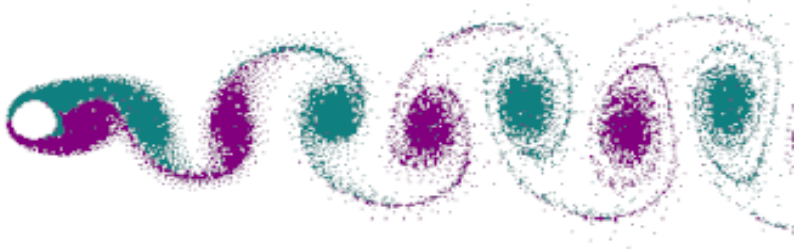
04 Case Studies

01

Introduction to Turbulence

What is turbulence?

- Sudden and chaotic changes in the movement of a fluid. In the atmosphere, results in violent changes in vertical velocity that can affect aviation.
- It is the way in which fast flow dissipates energy, limiting extreme accelerations.
- It is a function of wind speed, density and viscosity of the fluid, represented with the Reynolds Number (*Re*).



$$Re = \frac{\rho u L}{\mu}$$

Reynolds Number (*Re*), function of density (ρ), wind speed (u), distance (L) and viscosity (μ)

Reynolds Number (Re)

- Relates to the speed of the flow, density, viscosity and distance.
- Represents the ratio between inertial forces and viscous forces.
- Re value examples:

4×10^6	Person swimming
4×10^8	Blue whale
5×10^9	A large ship
1×10^{12}	Tropical Cyclone

$$Re = \frac{\rho u L}{\mu}$$

Reynolds Number (*Re*), function of density (ρ), wind speed (u), distance (L) and viscosity (μ)

Turbulent (High Re)	-Faster flow -Longer distance -Denser fluid -Low viscosity
Laminar (Low Re)	-Slower flow -Shorter distances -Lighter fluid -Viscous fluid

Importance of forecasting turbulence

- Risk for aviation: health and aircraft structures.
- Forecasting turbulence is a WMO competency that needs to be fulfilled by aviation meteorologists:
  - Warnings need to be produced with lead time. They can be updated or canceled following documented criteria.
  - If moderate or severe turbulence is forecasted, it requires indicating: start time, duration, intensity, spatial coverage and type (orographic, convective or clear air).

Turbulence categories in aviation

Established based on aircraft impacts, particularly air speed fluctuations and gusts of these.

	Aircraft speed fluctuations (m/s)	Gusts (m/s)	Impacts on passengers
Light	2.6 – 8	1.5 – 6	Passengers may be required to use seatbelts but loose objects within the aircraft remain at rest.
Moderate	8 - 13	6 - 11	Passengers require seatbelts and are occasionally thrown against them. Loose objects move about. Frequent rolling of aircraft occurs and it is hard to walk about in the aircraft.
Severe	>13	11 - 30	The aircraft may lose control momentarily, and it is difficult to maintain flight altitude. Passengers are thrown violently in their seats, and loose objects are tossed about.

Source: UK Met Office Handbook of Aviation Meteorology

02

Turbulence Types

Turbulence Types for Aviation

1) Orographic

- Induced by terrain (mountain waves, gap flows)

2) Convective (thermal)

- Induced by convection (moist convection and dry thermals)

3) Clear Air Turbulence (CAT)

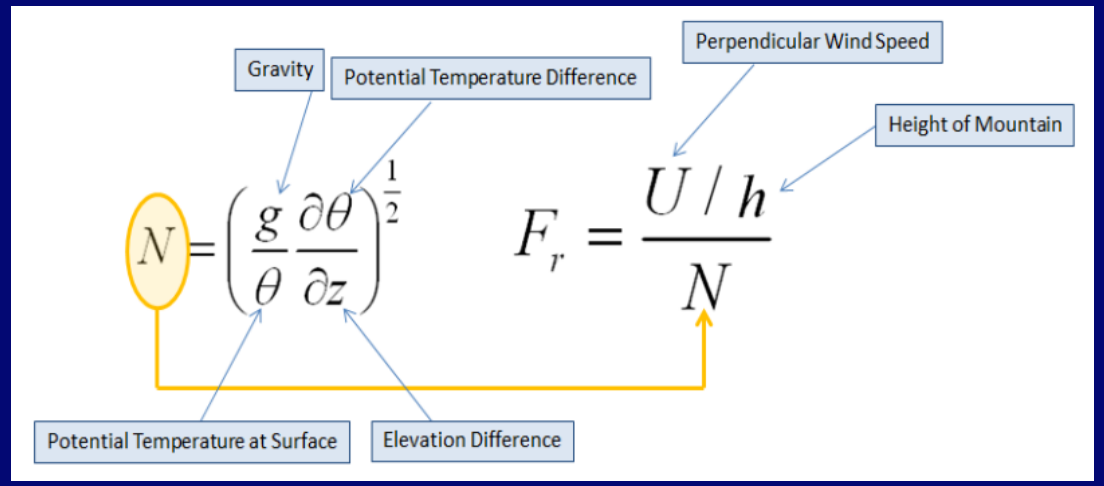
- Produced by horizontal and vertical wind shear in clear air conditions.
- Clear air signifies that it is invisible to pilots.

1) Orographic Turbulence

Turbulence can develop when fast flow interacts with terrain features, and persists downstream when a stable layer is present.

Role of flow and stability:

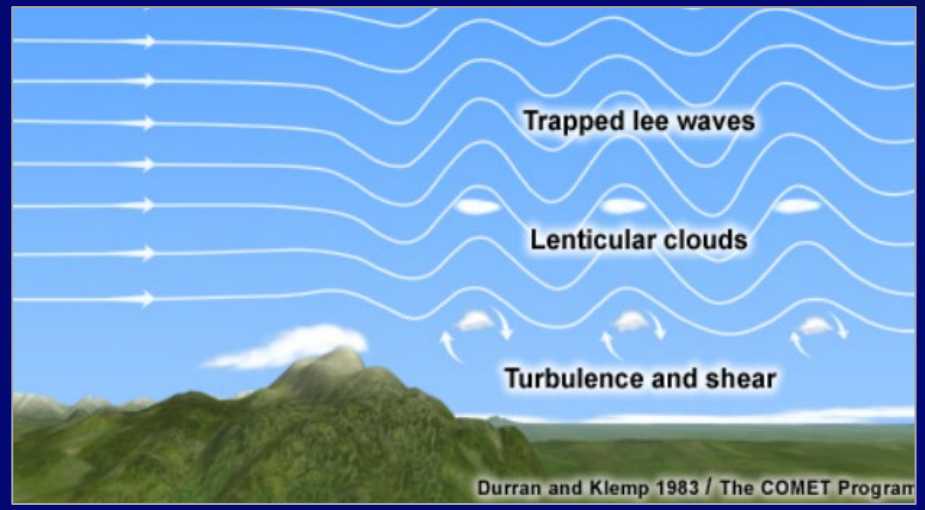
- **Fast flow:** Has a higher potential of switching from laminar to turbulent.
- **Static Stability:** Stable layers act as a means for propagation, preserving the induced waves over a long distance. Unstable layers favor energy dissipation and turbulence often decays rapidly with distance.

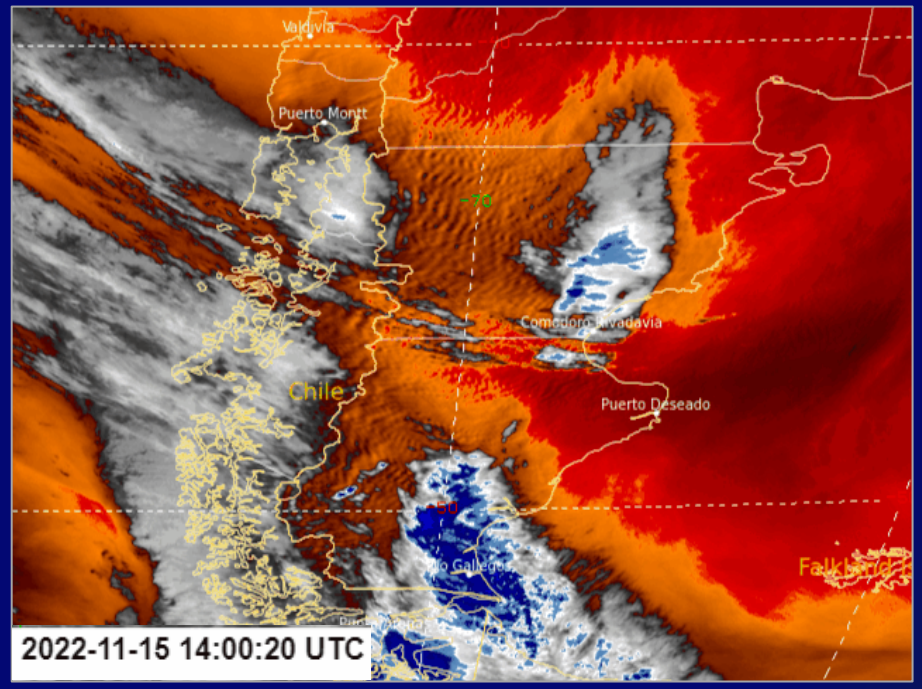


Froude Number

Mountain Waves

- They occur when accelerated flow interacts with a mountain range, developing waves and associated turbulence downstream.
- Turbulence tends to be more extreme close to the mountain range, but can extends hundreds of km downstream.
- Mountain ranges have a much stronger impact than isolated peaks.





Mountain Waves east of the Andes in South America, in the low-level water vapor GOES-16 band (source: CIRA Slider).

Mountain Wave Formation and Types

- They require a strong perpendicular component of the wind.

- Types:

  a) Trapped: When an overlying unstable layer is present and/or wind speeds increase with height.

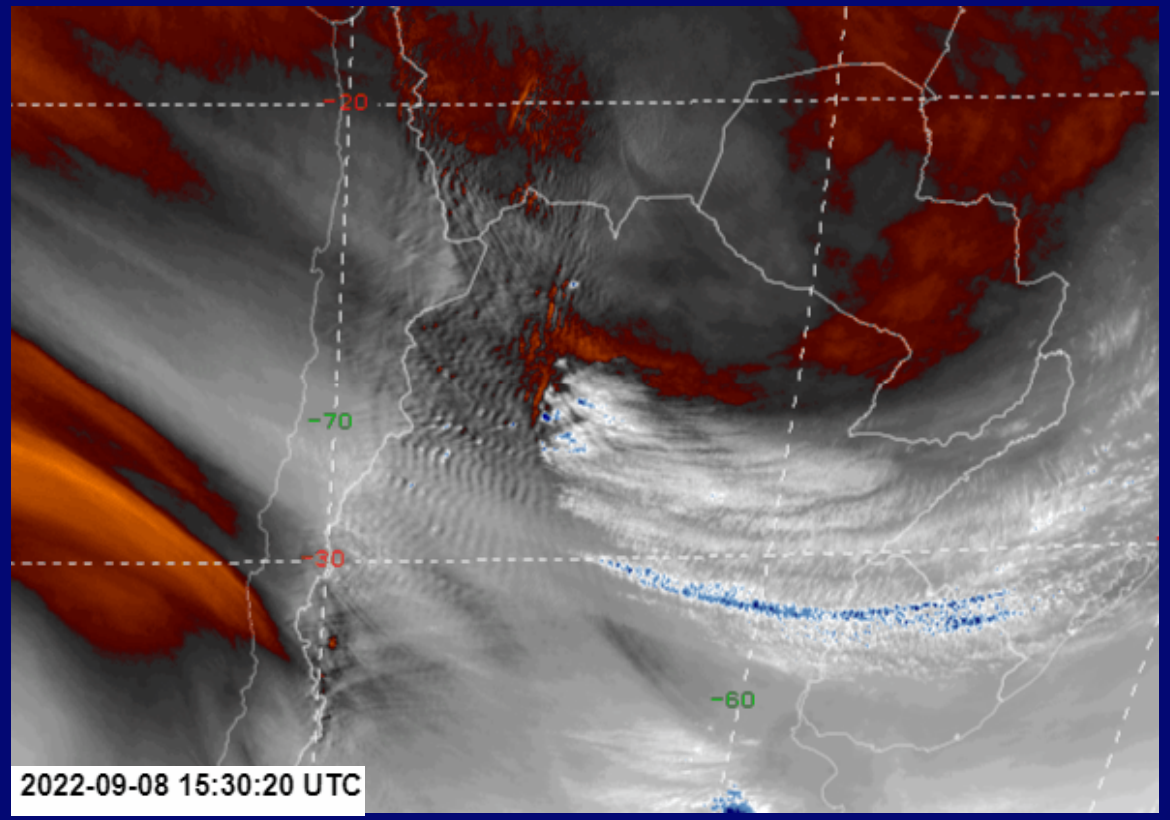
  b) Vertically propagating: When the entire layer is stable. They can reach the upper troposphere or even the stratosphere.

Example of vertically propagating waves.

Mountain Wave Turbulence in Satellite

- Water vapor imagery is likely the best tool to find mountain waves.
- It allows to find them in cloud free environments.
- The color palette matters (to help visualization).
- The most intense waves are close to the mountain range, but they can extend hundreds of km downstream.

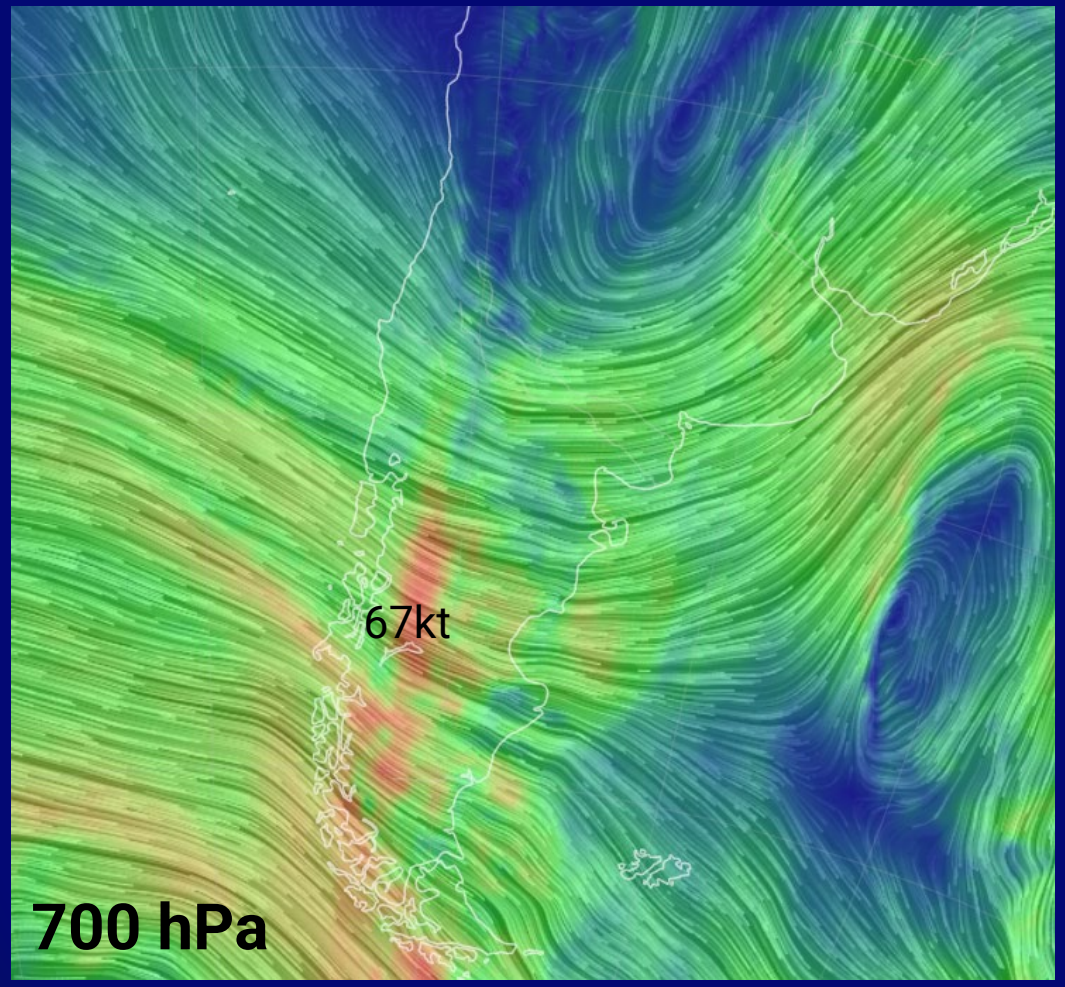
Upper Level Water Vapor (6.2um)



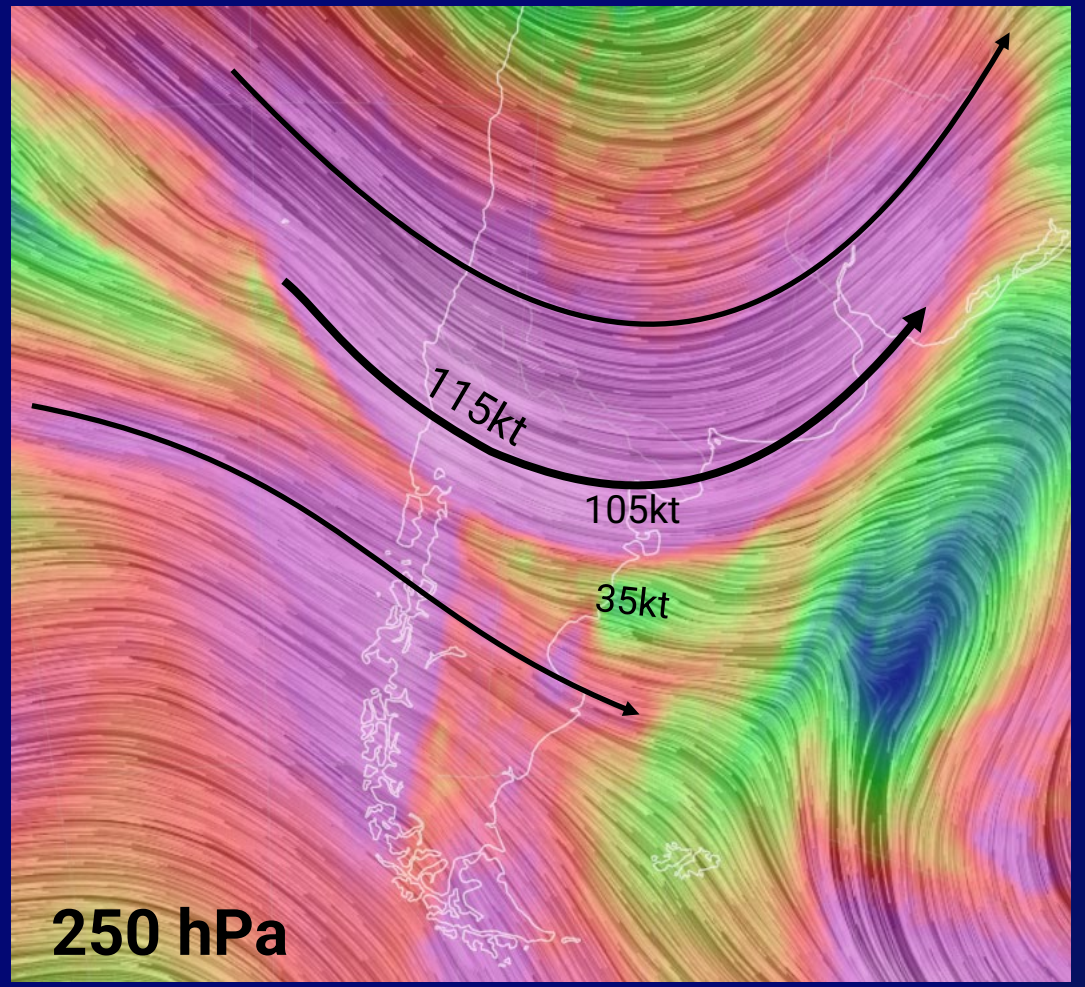
Fuente: CIRA Slider

Mountain Wave Turbulence and Flow

15-Nov-2022 18UTC



Fuente: Earthnullschool



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Mountain Wave Turbulence and Flow

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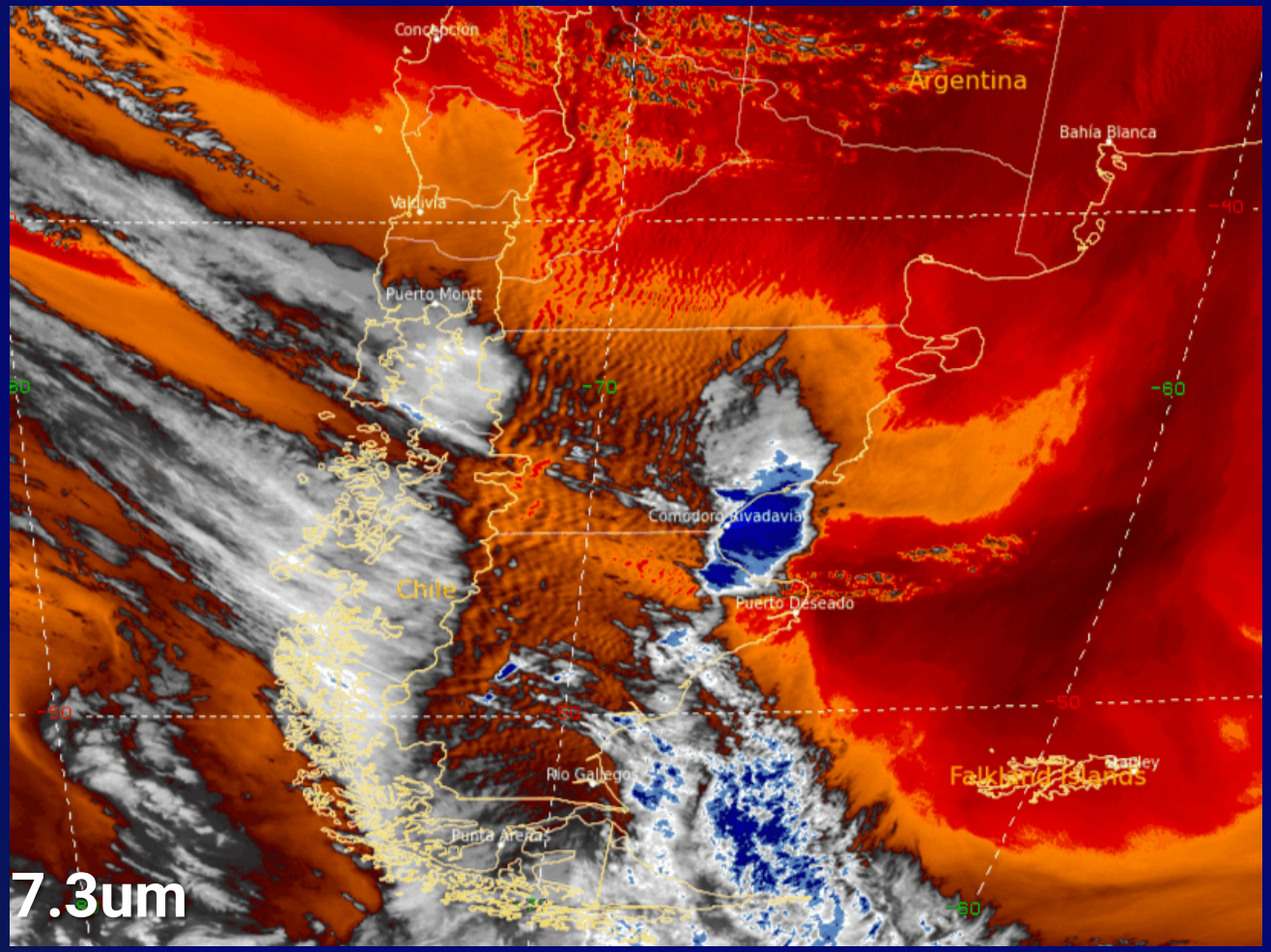
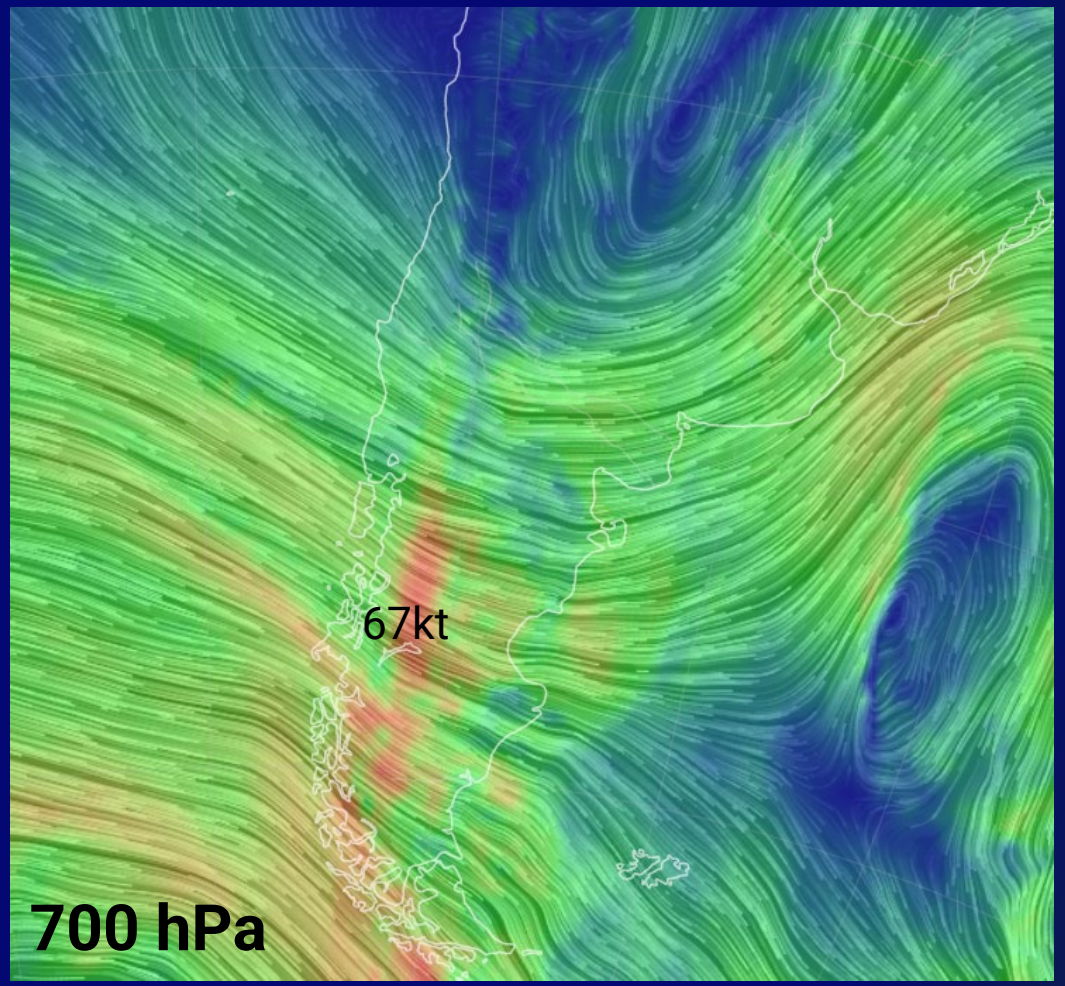


Fuente: CIRA Slider

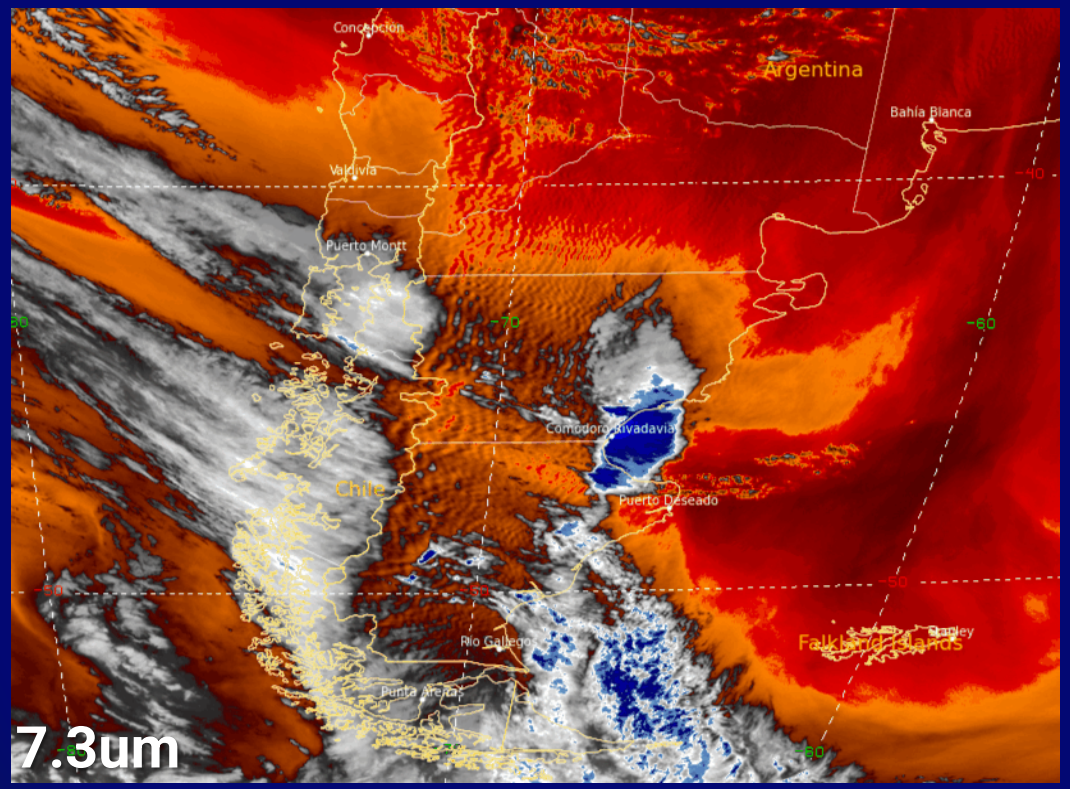


Fuente: Earthnullschool

Mountain Wave Turbulence and Flow

15-Nov-2022 18UTC

Low-level water vapor imagery helps for waves when terrain elevation is lower (e.g. 1500-2000 m). In Patagonia, imagery shows clouds disappearing east of the Andes from adiabatic compression, and mountain waves becoming enhanced.



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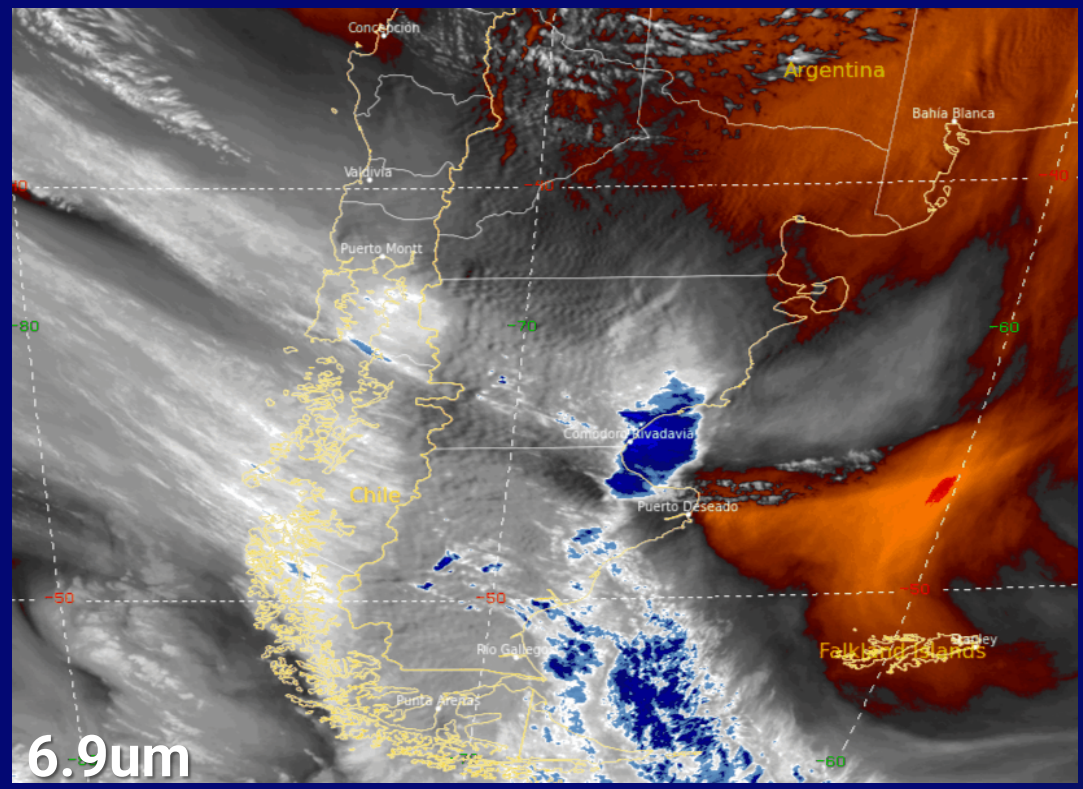
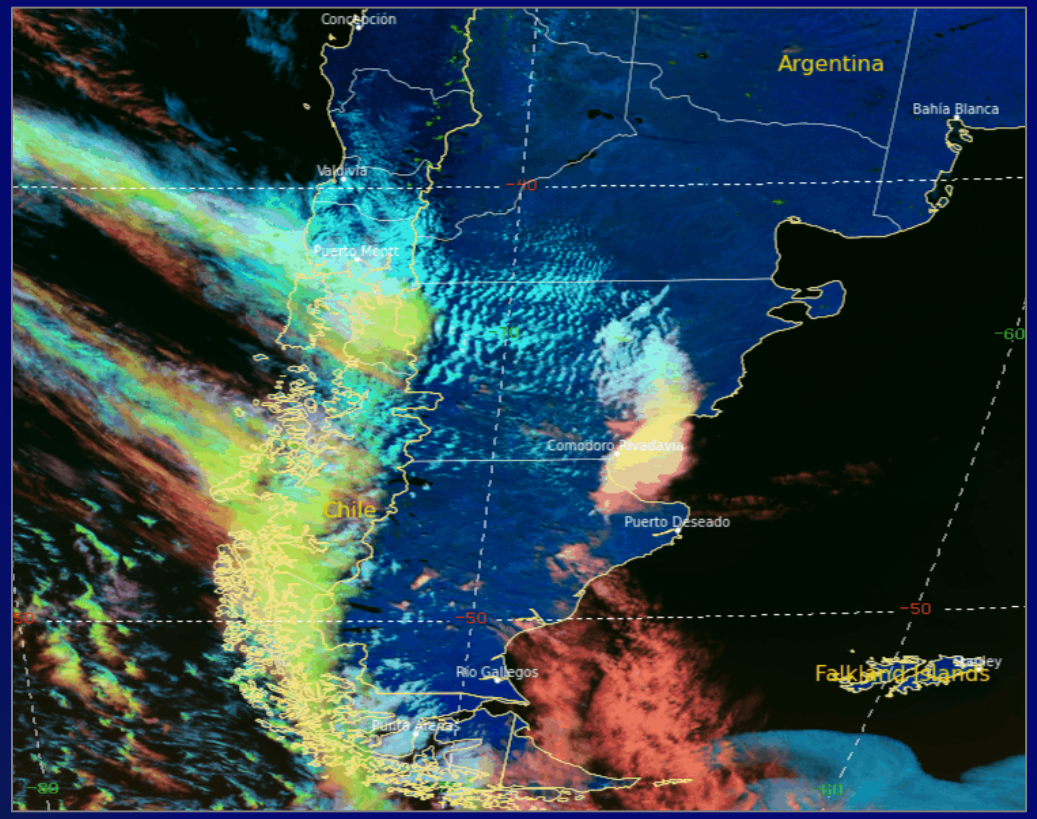


Fuente: CIRA Slider

Mountain Wave Turbulence and Flow

15-Nov-2022 18UTC

Day cloud phase distinction helps to find mountain waves ONLY WHEN clouds are present. They can be identified by quasi-stationary linear structures that are parallel to the mountain range.



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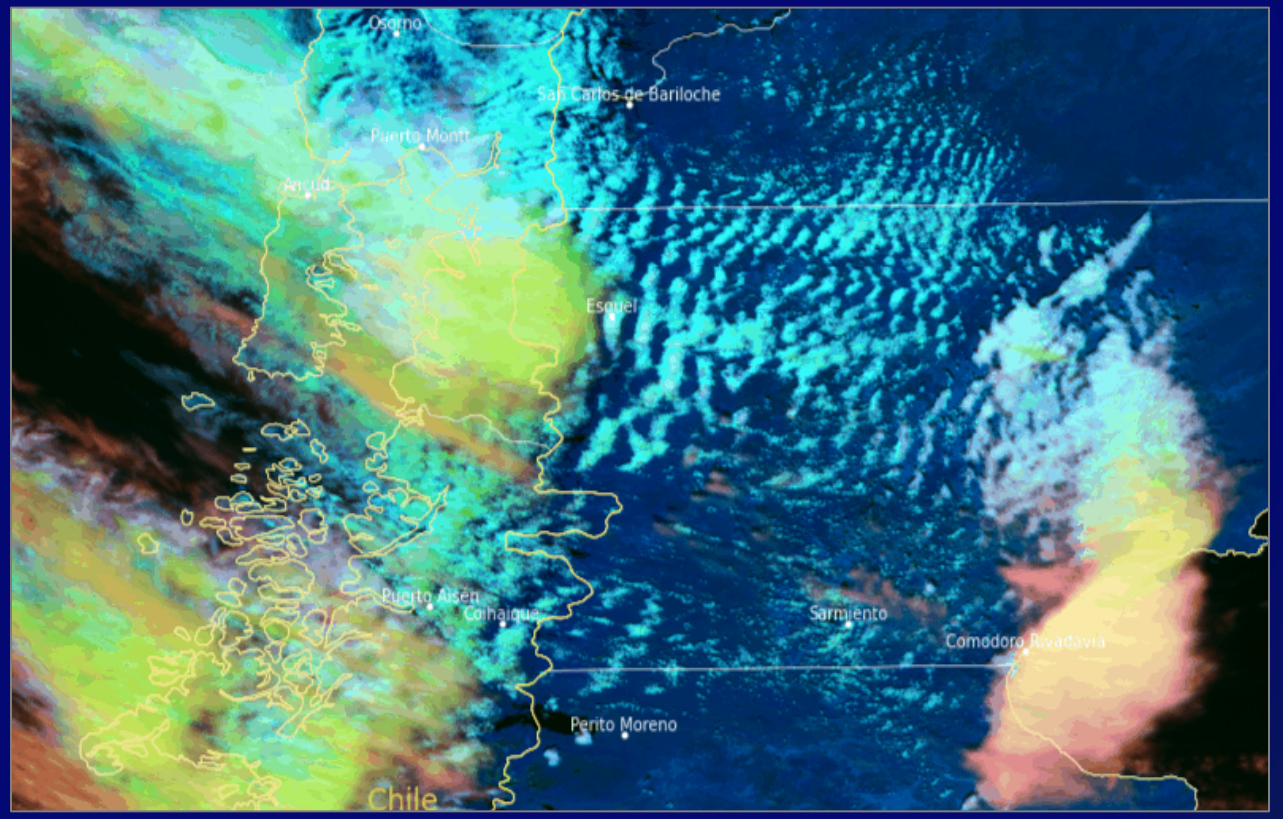
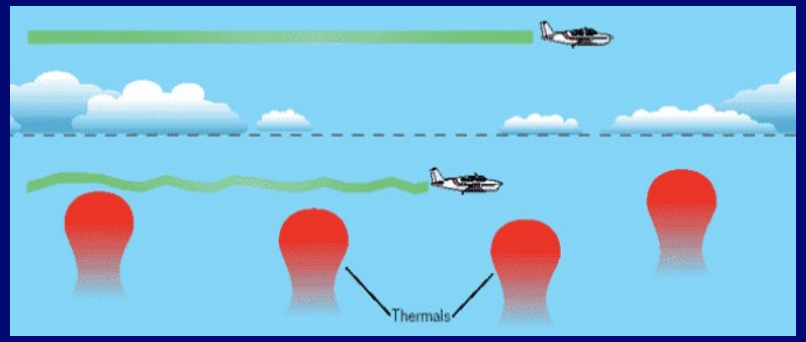


Fuente: CIRA Slider

Convective Turbulence

2) Convective Turbulence (Thermal)

- Generated by vertical motions induced by instability.
- Two types:
    a) Boundary Layer: Diurnal heating destabilizes and induces ascending thermals.
    b) Moist convection: Verticalgroth and condensation above the boundary layer forming cumulus congestus and cumulonimbus.



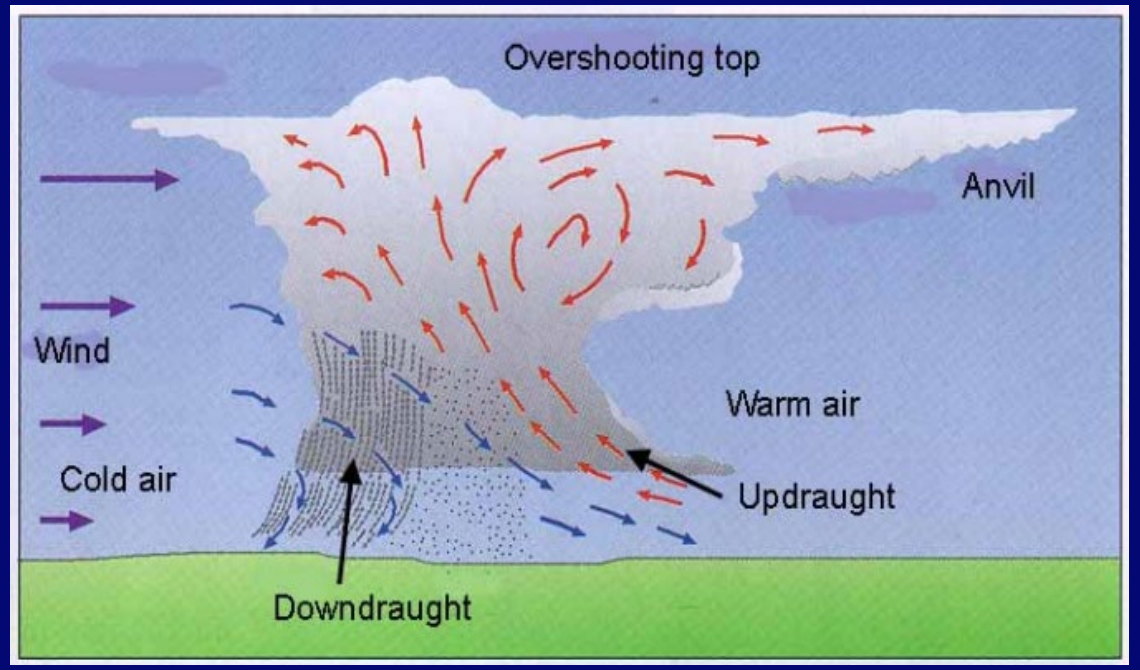
In the boundary layer

Near deep convection

Turbulence in Moist Convection

Generated by:

- Strong vertical currents inside and near the Cb.
- Strongest turbulence occurs if a pilot enters a Cb.
- Updrafts also generate gravity waves when reaching the stable layer (equilibrium level or sometimes the tropopause, where air temperature starts increasing with height).



Overshooting Tops (OT)

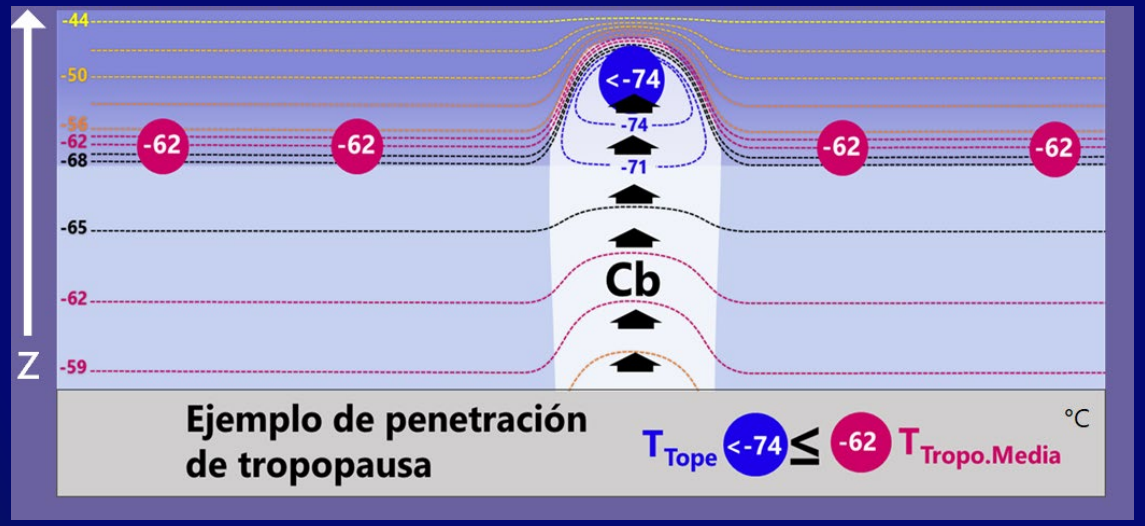
OT are portions of the top of a Cb that form over the base of the stable layer present at the anvil top.

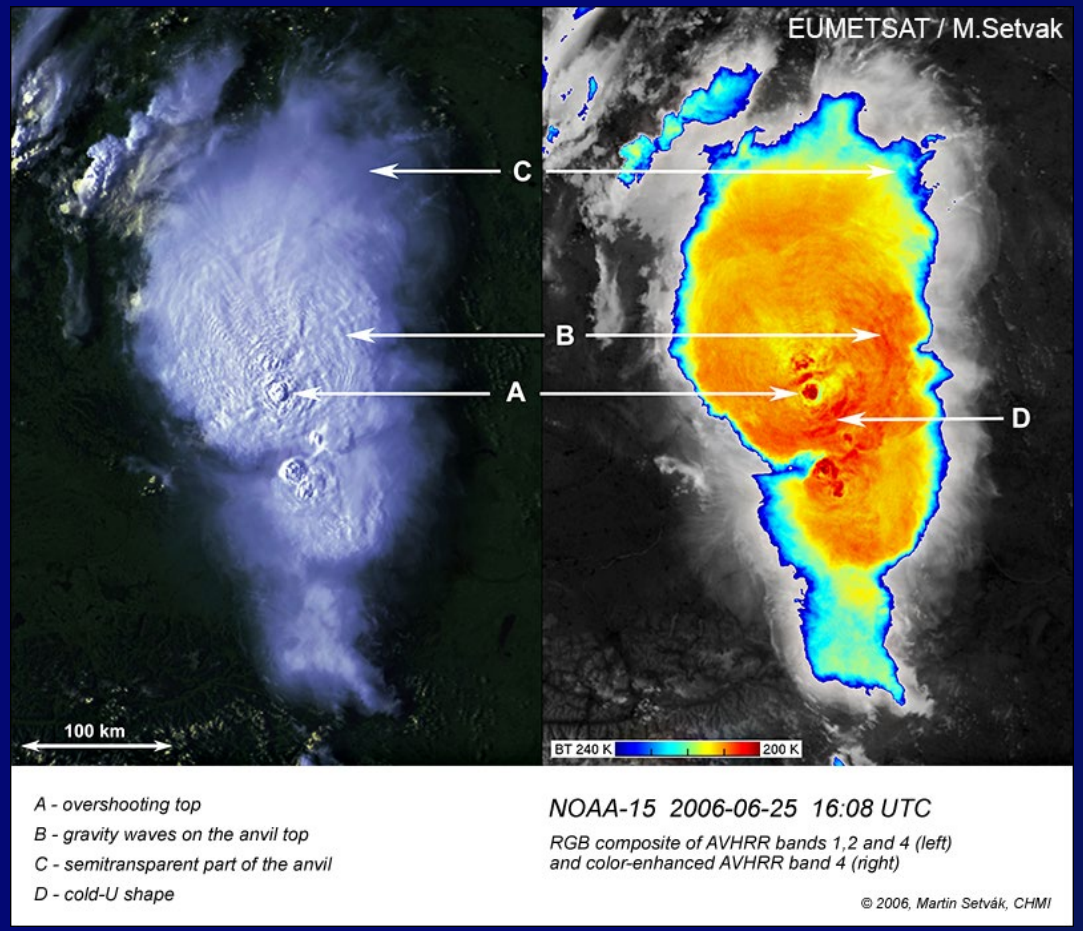
- They suggest very strong updrafts and the potential for convective turbulence.
- What causes them? Updrafts so strong that their momentum forces some parcels to surpass the stable layer, instead of stopping and spreading hozontally as the rest of the anvil does.

Source: INUMET, Taller de Tiempo Severo de 2019

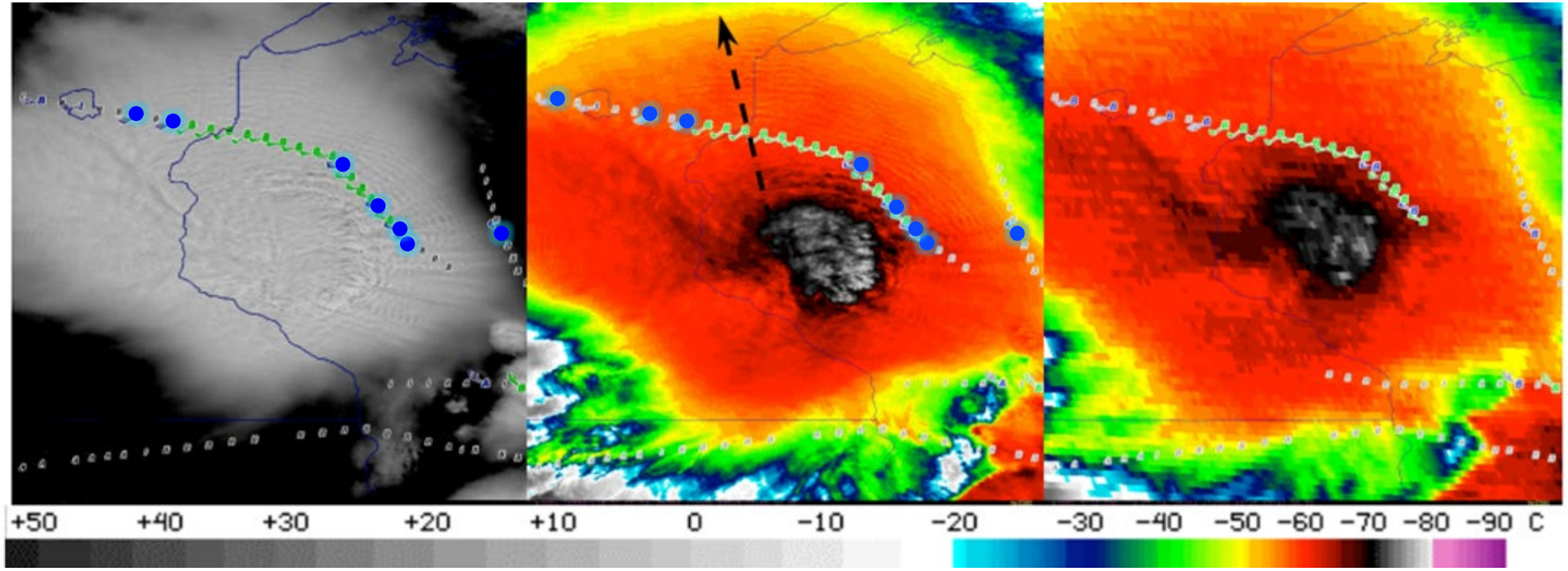
Satellite Signatures of Overshooting Tops

- Round circular structures embedded in a much broader stratiform anvil cloud.
- Temperatures are colder than the rest of the anvil.
- Gravity Waves tend to irradiate away from overshooting tops.





Convective Turbulence close to a Cb



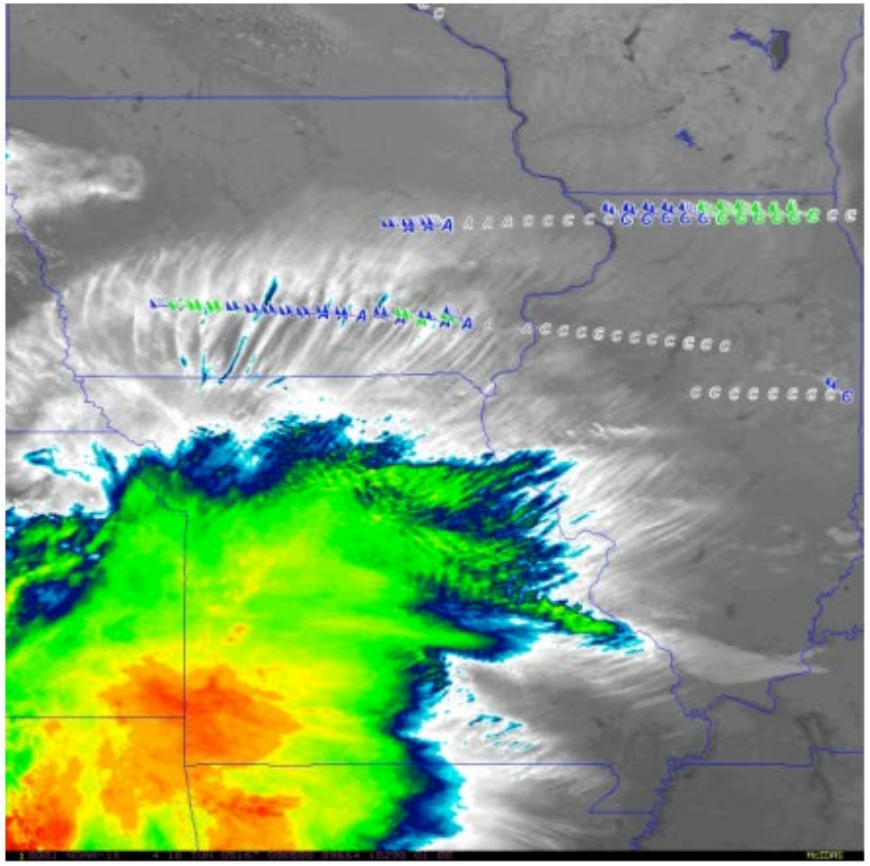
Severe Turbulence

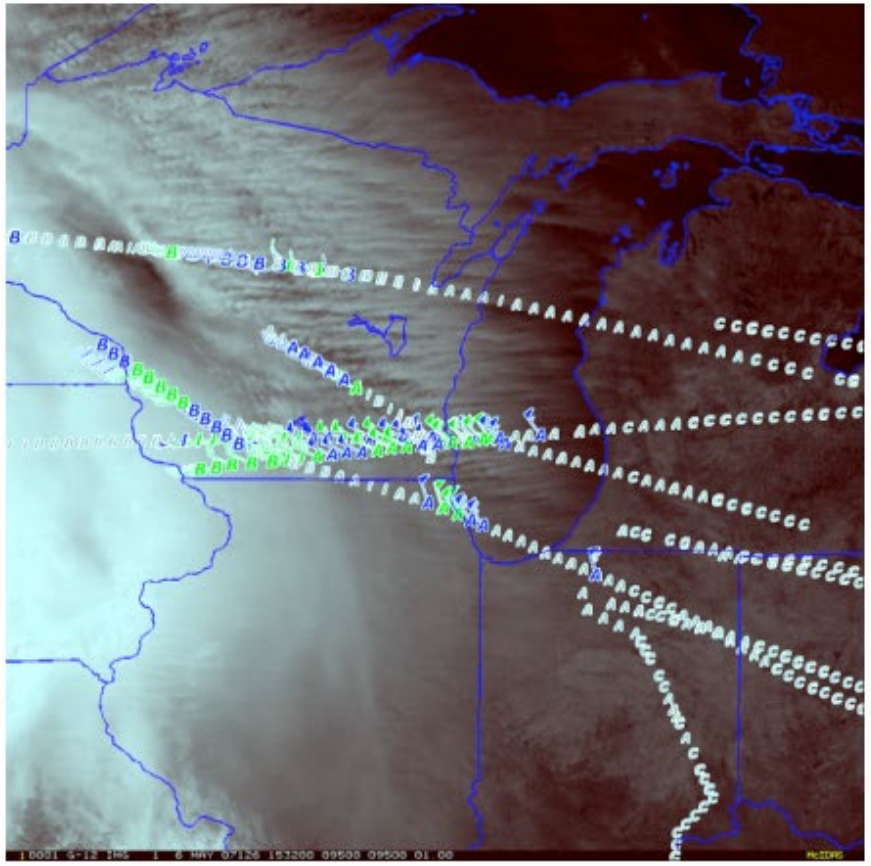
Moderate Turbulence

Light Turbulence

Figure 3: Turbulence associated with wave signatures initiated by overshooting convective tops. (left) Contrast-enhanced Terra MODIS 1 km visible channel imagery (middle) Terra MODIS 1 km 10.7 micron infrared window imagery (right) GOES-12 4 km 10.7 micron infrared window imagery at 1725 UTC on 23 July 2005. The letters plotted upon the imagery represent the relationship between the aircraft-observed and IR window brightness temperatures. "A" indicates aircraft temperature colder than satellite, suggesting flight above cloud top. "I" indicates aircraft temperature within 2 K of satellite, suggesting flight within cloud top. "B" indicates aircraft temperature warmer than satellite, suggesting flight below cloud top. "C" indicates aircraft temperature significantly colder than satellite, suggesting flight in clear sky. The color of symbols indicates severity of turbulence as estimated by EDR with blue being light, green being moderate, and red being severe. Grey indicates no turbulence. EDR observations within +/- 30 mins from the image timestamp are shown.

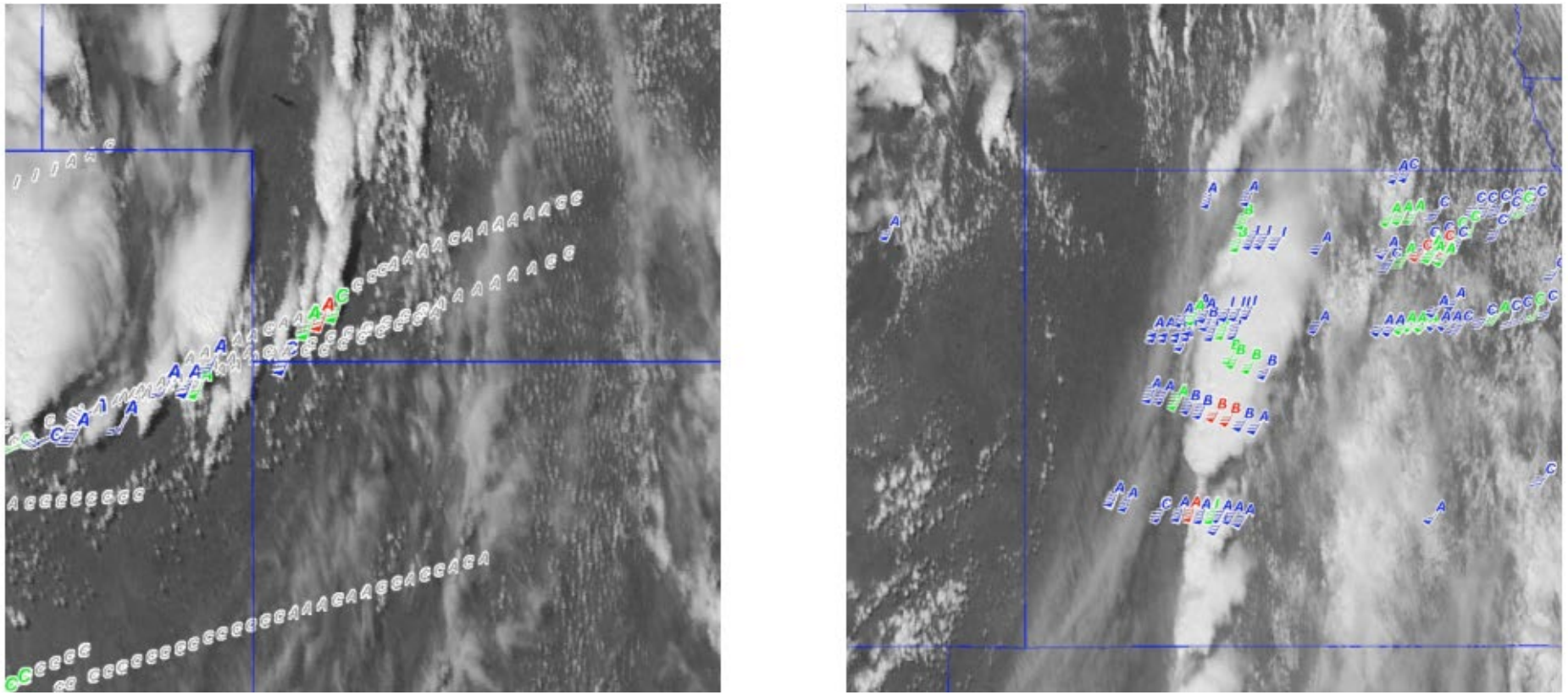
Convective Turbulence in Imagery





Turbulencia asociada a salidas a bandas producidas por un yunque (“bandas transversales”) mostrando tubulencia moderada.

Convective Turbulence events in Satellite Imagery



Turbulencia asociada a cumulus en desarrollo (izquierda) y a cúmulos maduro en imágenes visibles del GOES 12, a las 1945 UTC del 7 de mayo de 2005 y a las 1815 UTC del 5 de mayo de 2007.

Clear Air Turbulence

Clear Air Turbulence (CAT)

Definition: Turbulence generated in clear air, in regions without clouds, which is invisible to the pilot.

- Visual detection is a challenge. Ocassionally, particular cloud signatures can indicate CAT present in nearby regions.
- CAT associates with high values of wind shear, horizontal deformation and convergence in a region of limited saturation (insufficient moisture to form clouds).
- The best way to detect the potential for CAT is combining satellite products with numerical model output.

Estimating CAT strength from wind shear values

Turbulence is primarily caused by wind shear (change in wind direction and/or velocity with distance):

- Vertical and horizontal wind shear are the most common.
- Desaccelerating flow is an important source.
- Directional shear close to a thermal gradient also favors turbulence.

	Moderate Aircraft speed fluctuations 8 - 13 m/s	**Severe** Aircraft speed fluctuations > 13 m/s
Vertical Wind Shear	>6kt / 1000ft	>9kt / 1000ft
Horizontal Wind Shear	>20kt / 100 km	>30 kt / 100 km
Wind Shear by desaccelerating flow	>40kt / 1000 km	>125kt / 1000 km
Directional Wind Shear	75° change near a thermal gradient	

Source: COMET Modules

Flow Patterns that favor CAT

All flow situations that develop large horizontal and/or vertical wind gradients (wind shear) and strong vertical motion changing rapidly with distance.

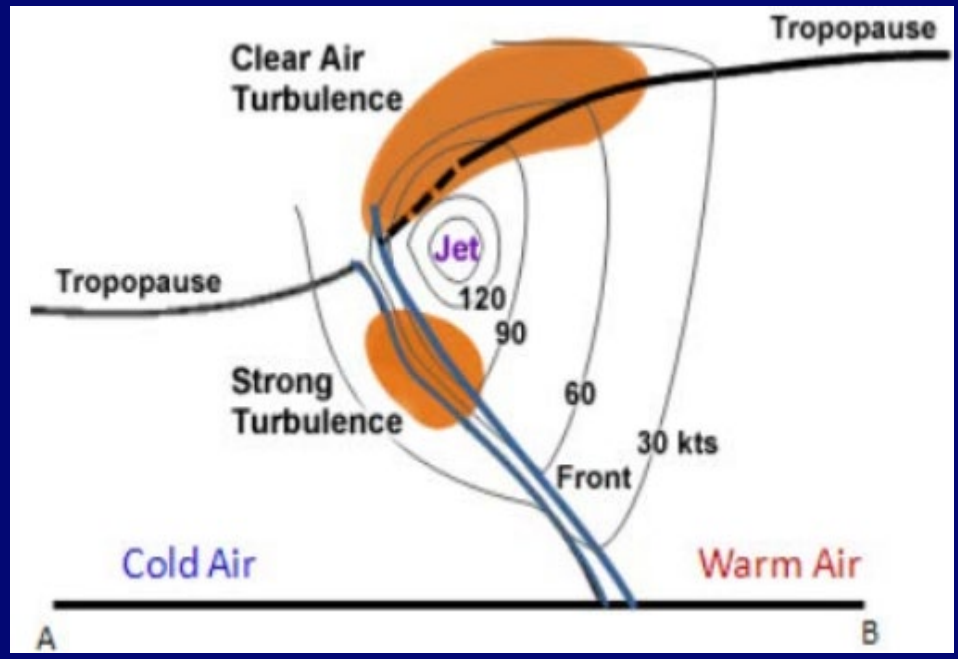
Some examples:

- **Jets:** They associate with large wind gradients/extreme wind shear and regions of strong vertical motion.
- **Periphery of upper troughs and ridges:** Enhanced wind shear from horizontal gradients of wind direction and velocity.
- **Cyclogenesis:** Strong vertical motion.
- **Tropopause folding:** Associated with jets and cyclogenesis.

Upper Jets and CAT

Upper jets are the main source of turbulence in the upper troposphere.

- It is mostly about wind shear, as jets have regions where wind speeds change rapidly with distance.
- There are other processes that highlight turbulence, such as
  - Jet-upper trough interactions
  - Jet-induced vertical motions

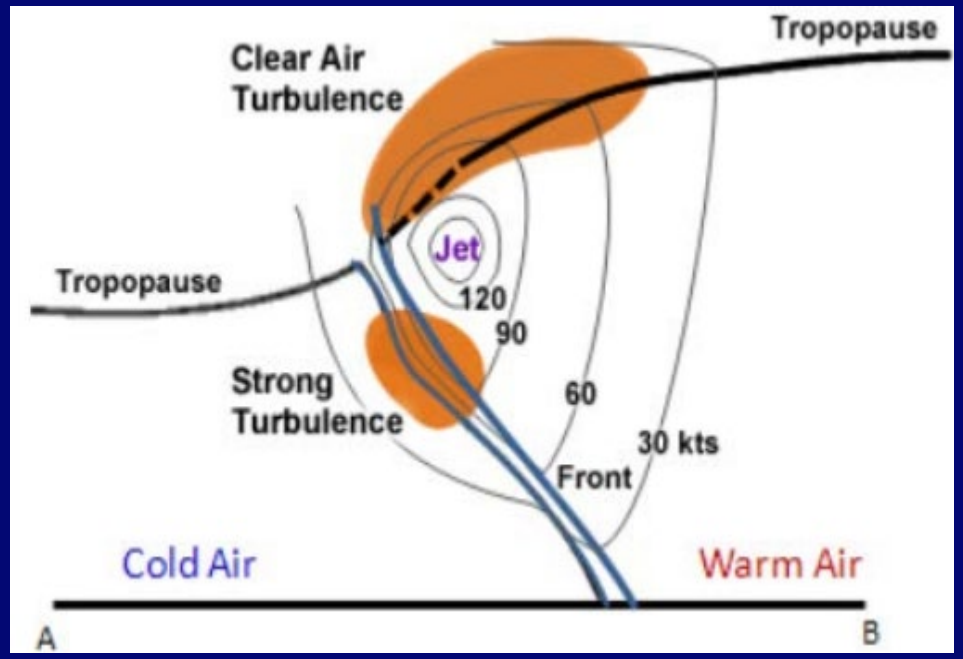


Cross section of turbulence with upper jets

Upper Jets and CAT

Briggs (1961), analyzed locations where turbulence occurred, based on 73 cases:

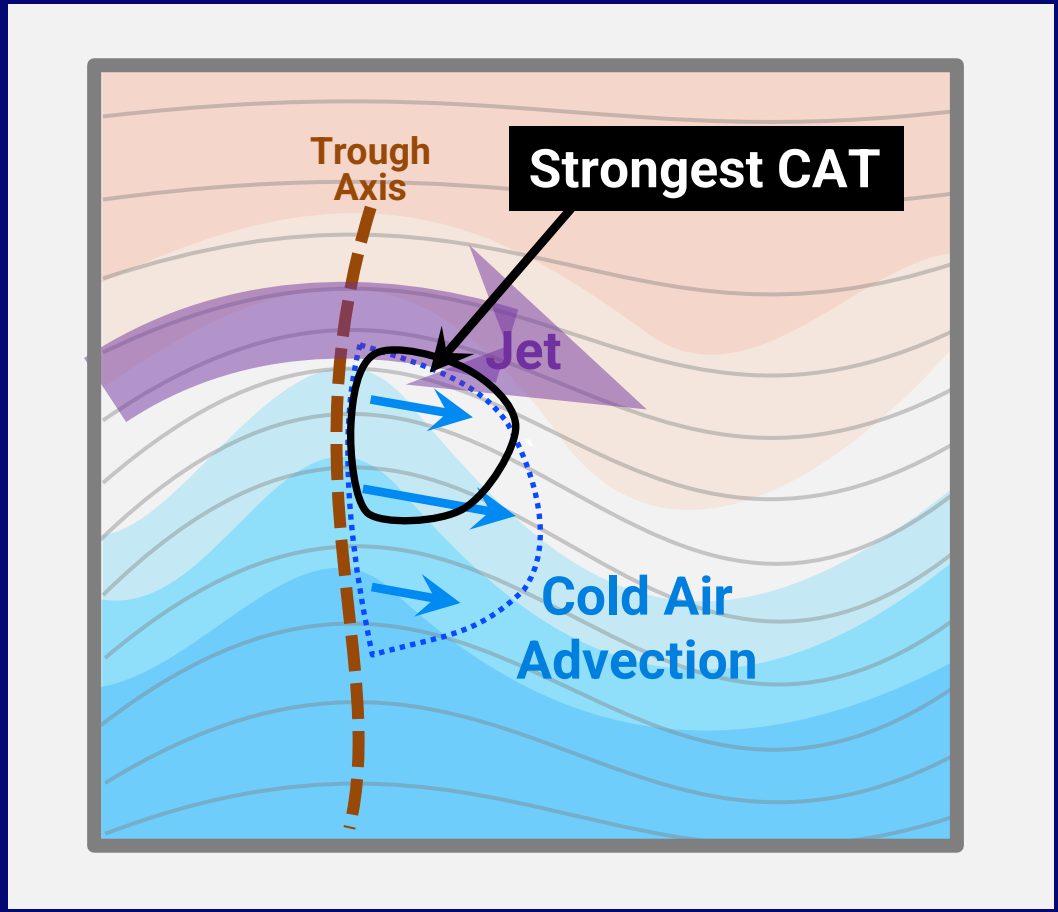
- Most cases occurred with upper troughs underlying the cool side of the jet axis.
- Turbulence is favored at less than 200km of the jet maxima and 1.5-4.5km under the tropopause.
- Also above the jet axis, where wind speeds decrease rapidly with height (wind shear).



Cross section of turbulence with upper jets

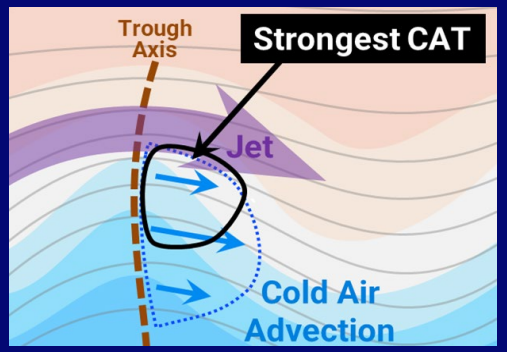
CAT and cold advection aloft

- Turbulence is most favored downstream from an upper trough, where cold advection peaks.
- Stronger if an upper jet is present along the warm side of the trough.
- If coinciding with the cold exit of a jet streak, which associated with strong dynamically-induced ascent.

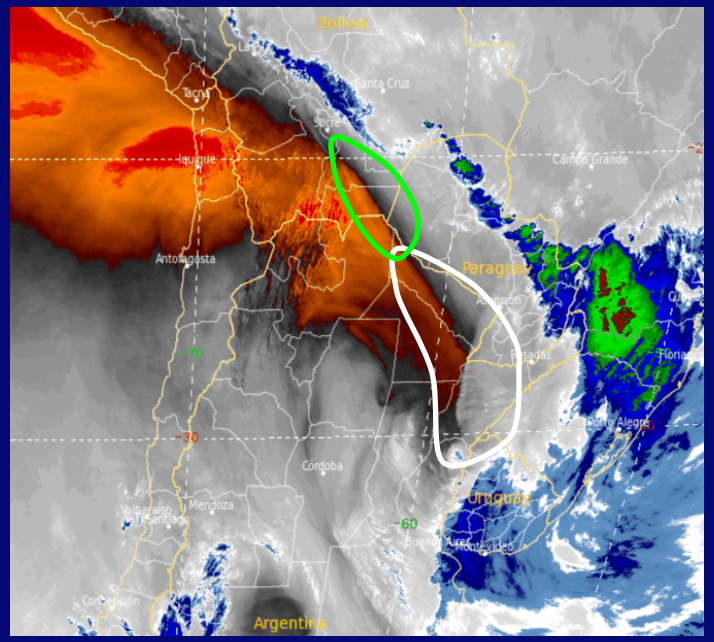


Example of CAT, 06 Oct 2022

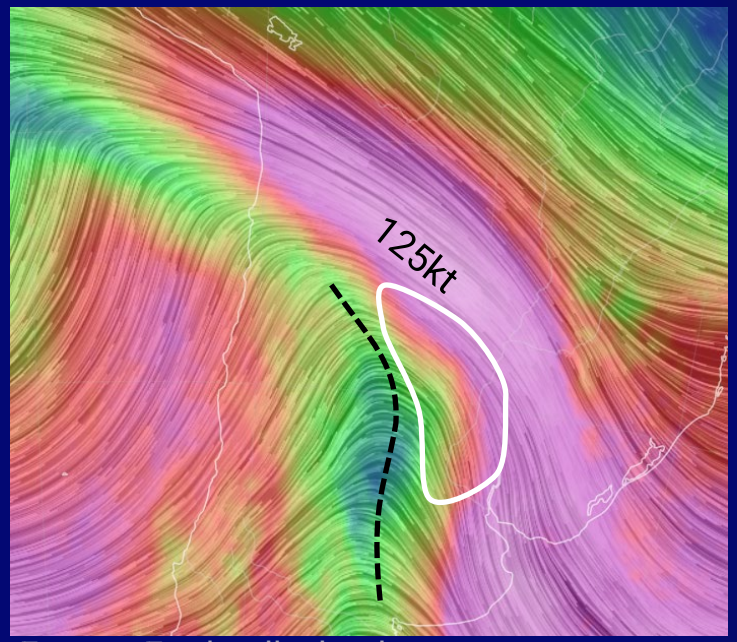
- CAT occurring downstream from the upper trough and along the cold side of the upper jet.
- Cold air advection (downstream of trough axis) in the cold side of an upper jet.



- Moisture gradients becoming tighter over the Bolivia-Argentina-Paraguay border also suggest a potential region of CAT (strengthening wind shear).



Fuente: CIRA Slider

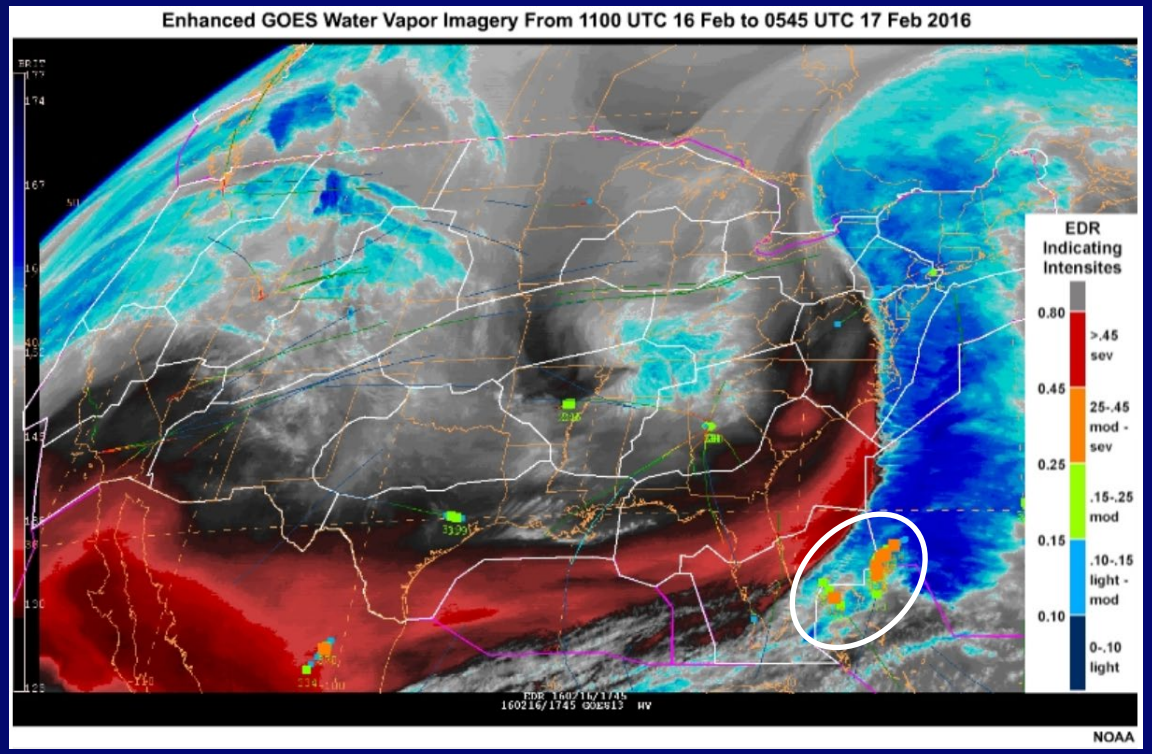


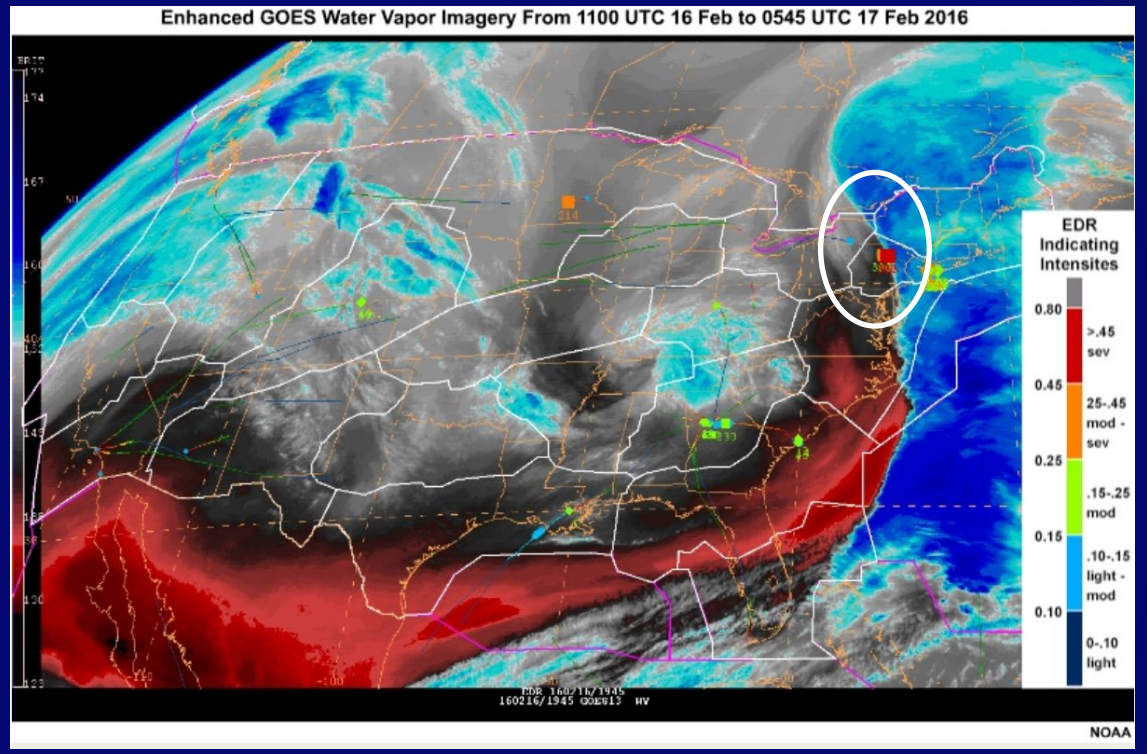
Fuente: Earthnullschool

Horizontal gradients for severe CAT: >30 kt / 1° de latitud

Cast Study 2016, USA

TAC en Imágenes: Caso Estudio USA





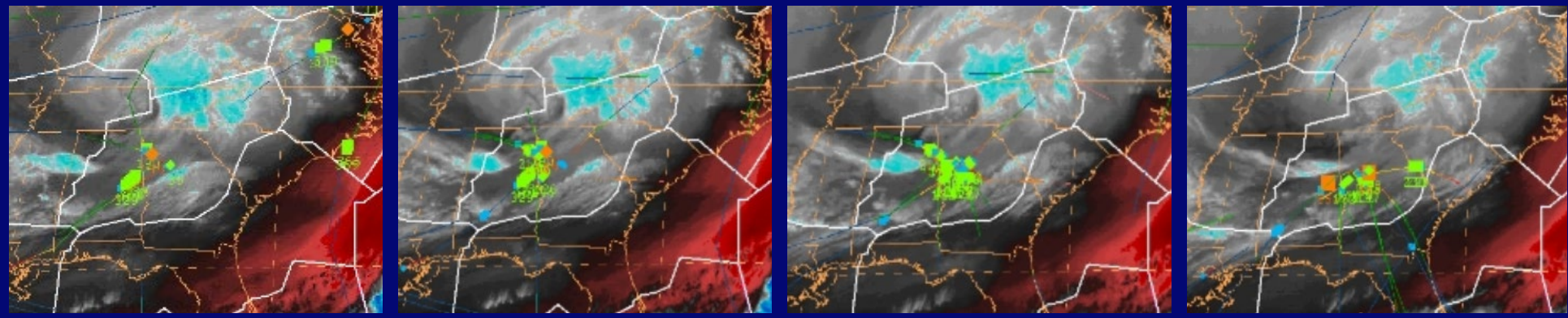
- Se puede ver en regiones de gradientes de humedad abruptos en la periferia de vaguadas de altura y cerca a chorros (Nueva York, imagen derecha).
- En las Bahamas (imagen izquierda), la turbulencia se asocial al patron de ondas de gravedad en los cirrus. Muestra la presencia de un chorro. El gradiente abrupto de humedad puede ubicarse debajo de los cirrus, pero no es totalmente evidente en las imágenes.

TAC en imágenes de vapor de agua

Turbulencia moderada a severa en Atlanta con vaguada de altura.

16-17 Feb 2016

2300 2330 0000 0030



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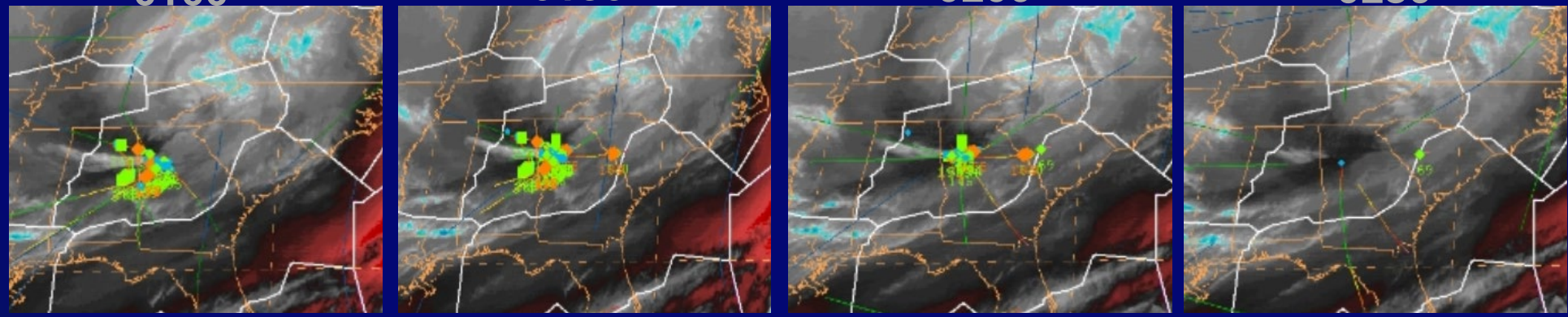
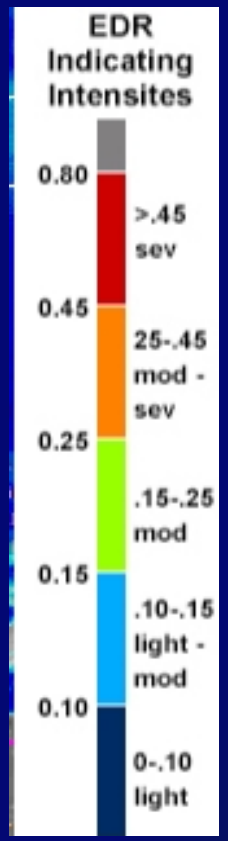
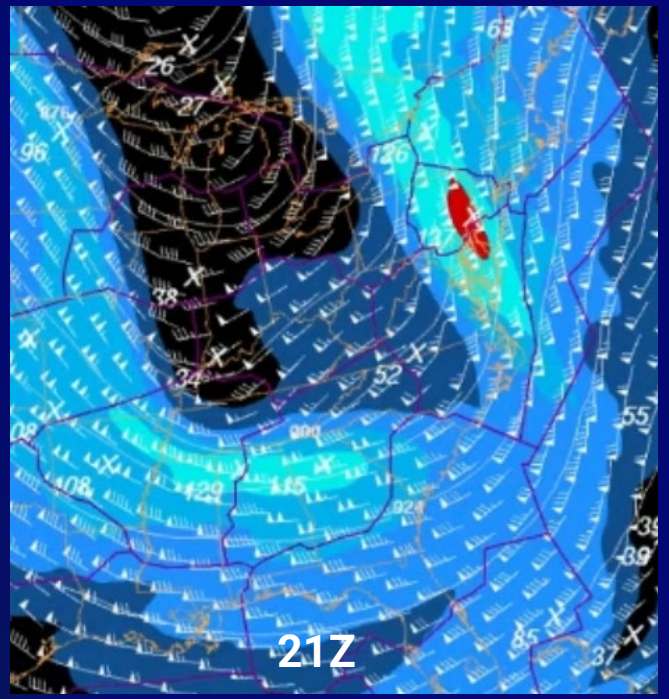




TAC en imágenes de vapor de agua

Turbulencia moderada a severa en Nueva York con chorro y plegamiento de la Tropopausa

Viento en 300 hPa



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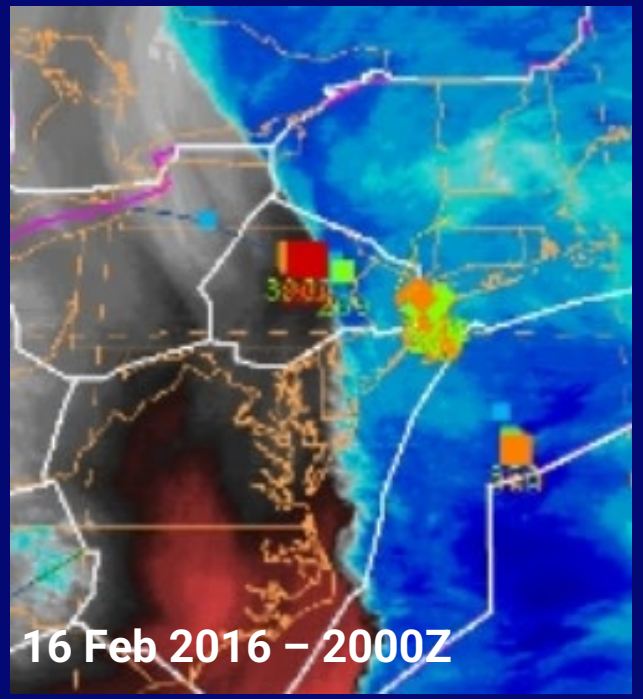
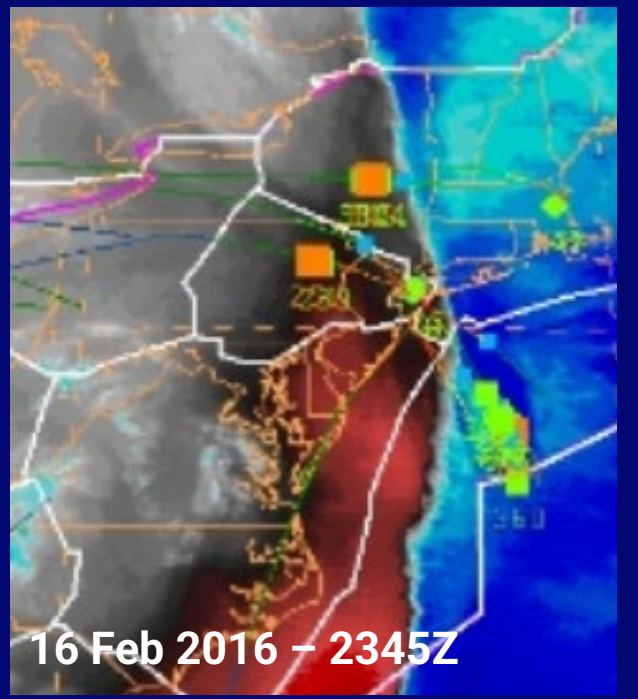
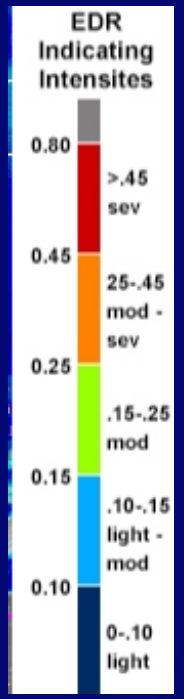


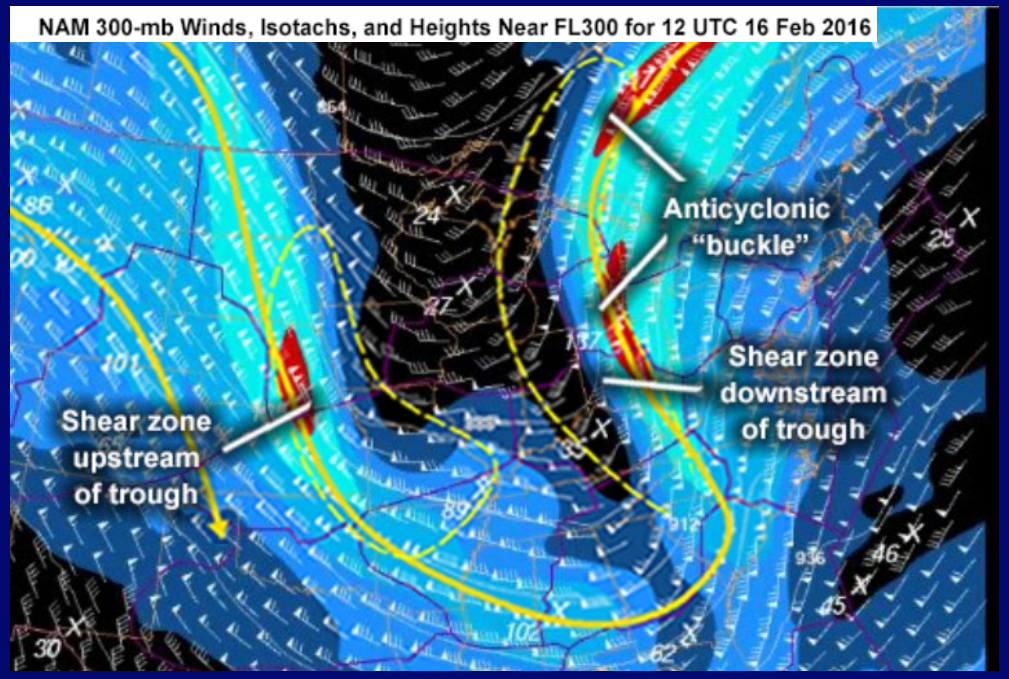
WV

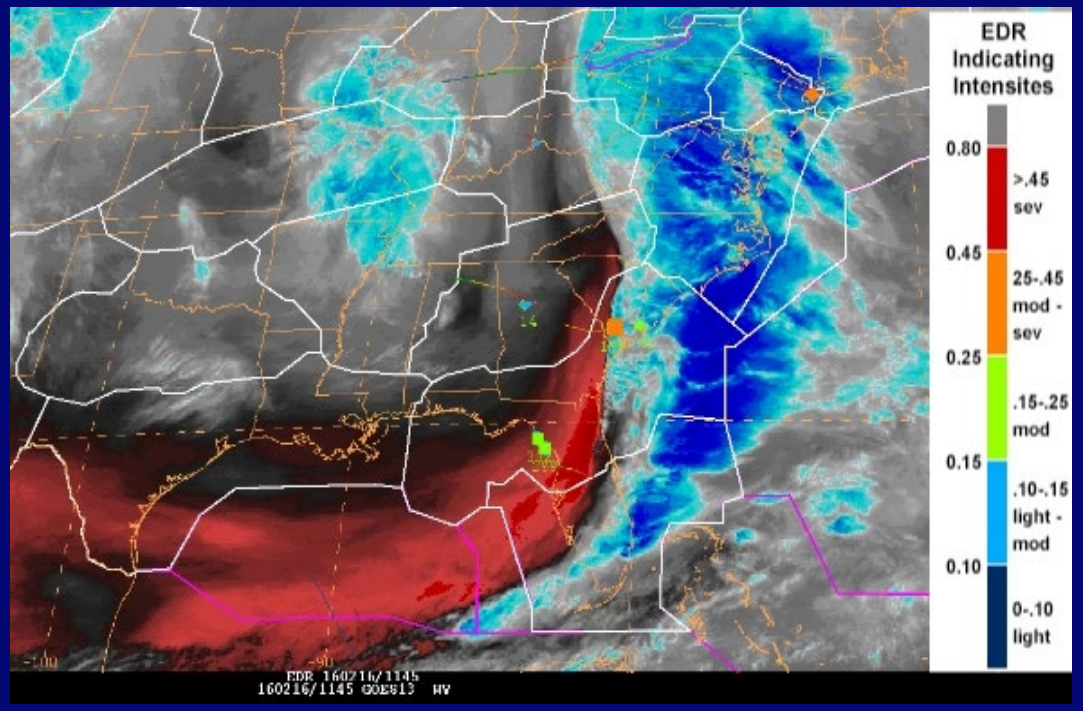




TAC en imágenes de vapor de agua

Turbulencia moderada a severa en Nueva York con chorro y plegamiento de la Tropopausa

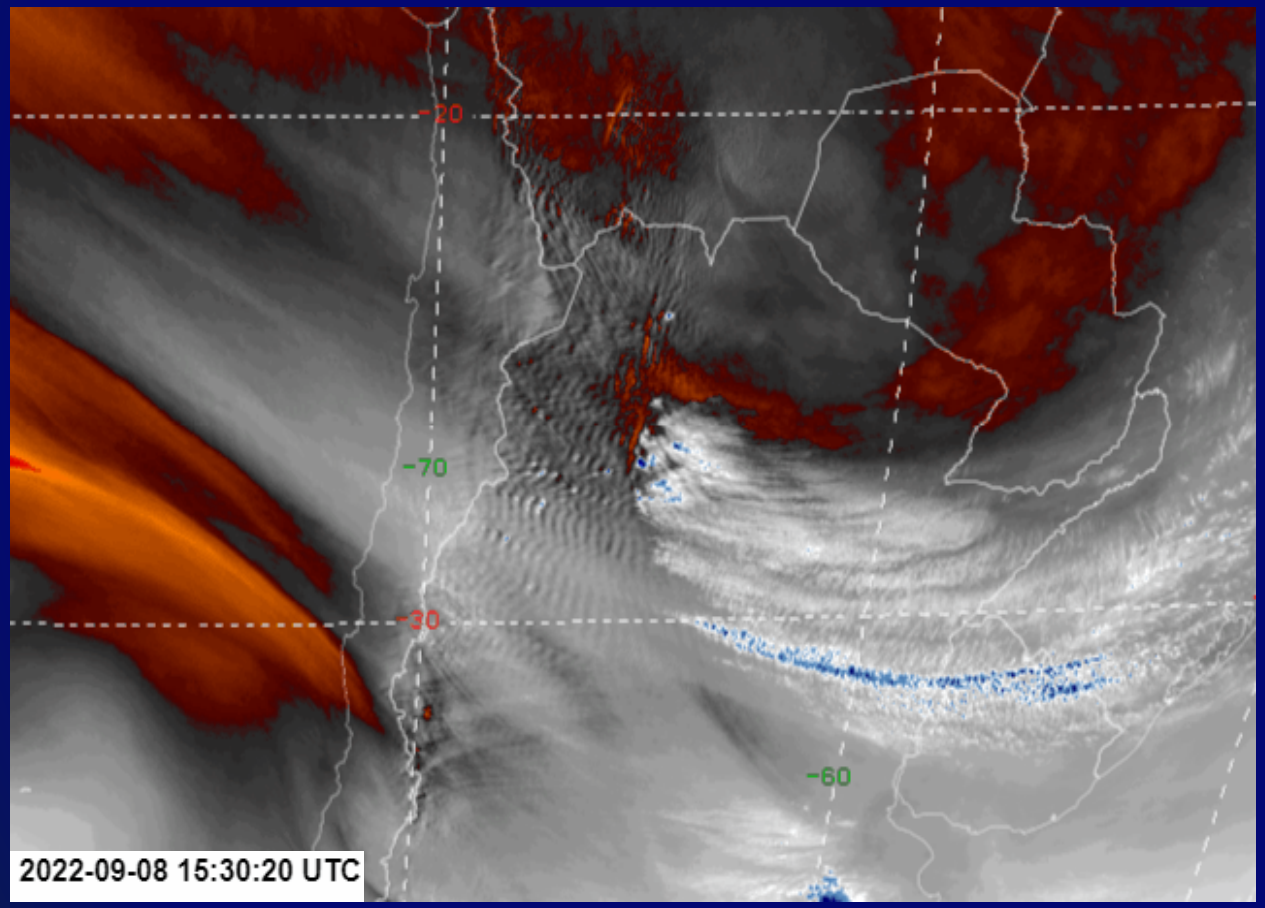




CAT Signals in Imagery

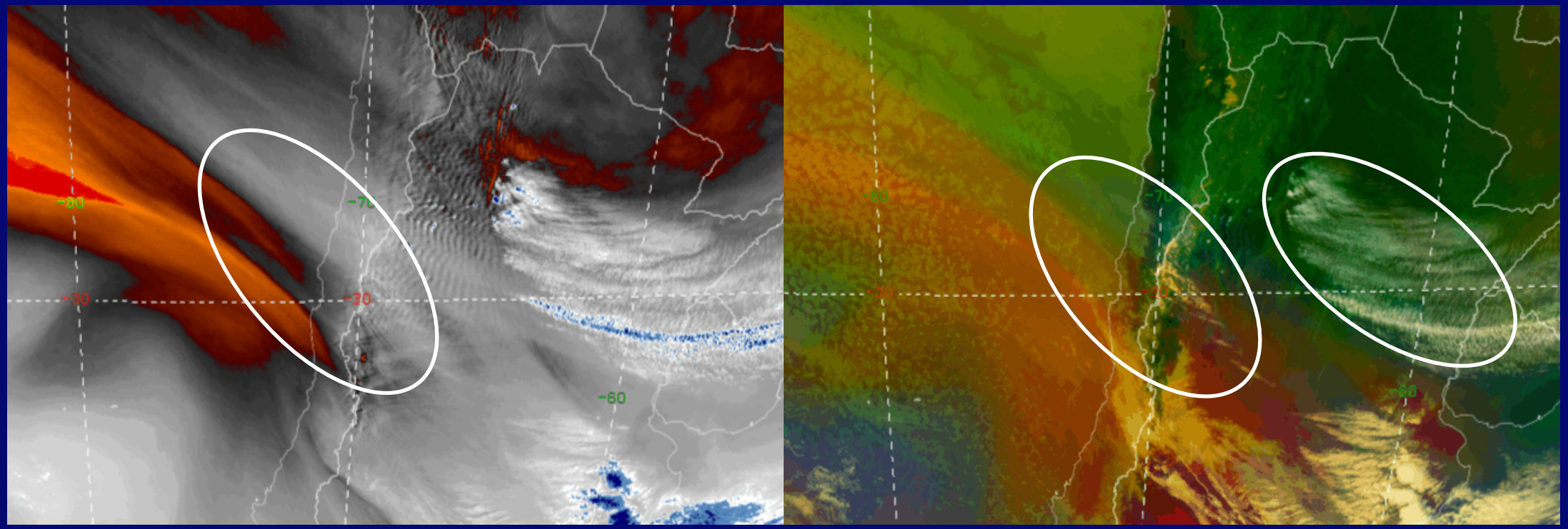
- Although satellite imagery helps to identify potential location of CAT under certain specific scenarios, it is ideal to complement the analysis using gridded data.
- Things to look for:
    1. Rapid flow, transversal banding (jets).
    2. Sharp linear moisture gradients in the vicinity of upper jets, especially if an upper trough is present.
    3. Tropopause folding/ozone intrusions (red in Airmass RGB and a sharp adjacent color gradient).
    4. Gravity wave structures.

Otros ejemplos de Señales de Turbulencia de Aire Claro en Imágenes



- Ondas de gravedad definidas sobre y flujo abajo de los Andes.
- Gradientes de humedad abruptos en forma de línea flujo abajo de la cordillera.
- Presencia de chorros, evidentes en bandas transversales en nubes Ci.
- Los gradientes extremos de humedad en el Pacífico pueden asociarse a TAC, pues se asocian a chorros en aire claro y a una Vaguada aproximándose desde el suroeste.

Vapor de agua nivel alto vs RGB Masa de Aire

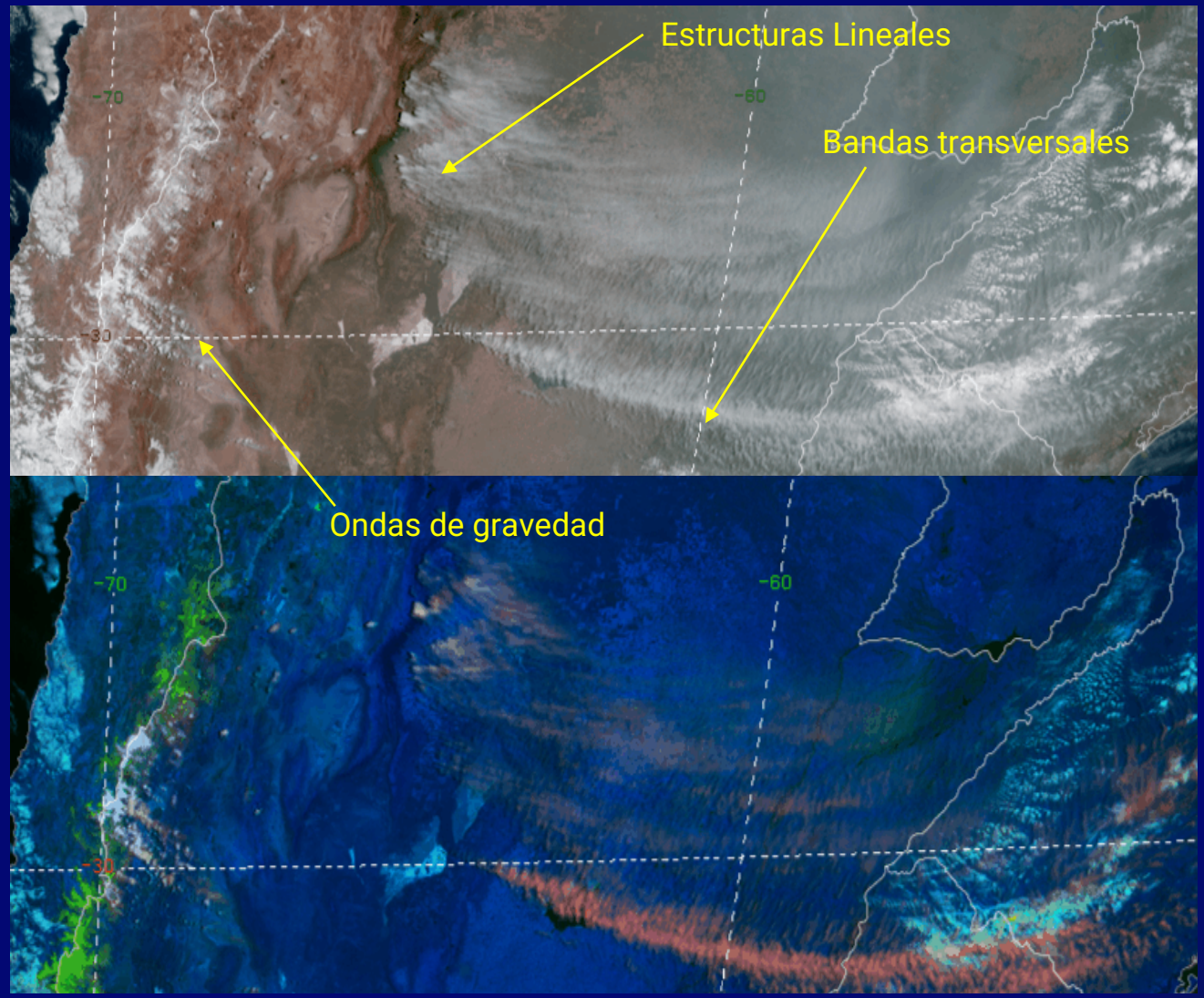


- En el Geocolor no se ven claramente las ondas de gravedad, pero los gradients de coloración sugieren una vaguada intense con potencial plegamiento de la tropopausa. El centro de Chile y regions flujo abajo se ven preocupantes.

Color	Band / Band Diff. (µm)	Min – Max Gamma	Physically Relates to…
Red	6.2 – 7.3	-26.2 to 0.6 C 1	Vertical water vapor difference
Green	9.6 – 10.3	-43.2 to 6.7 C 1	Tropopause height based on ozone
Blue	6.2 (inverted)	-29.25 to -64.65 C 1	Water vapor ~200-500 mb

Geocolor vs Distinción de Fase de Nube de Día

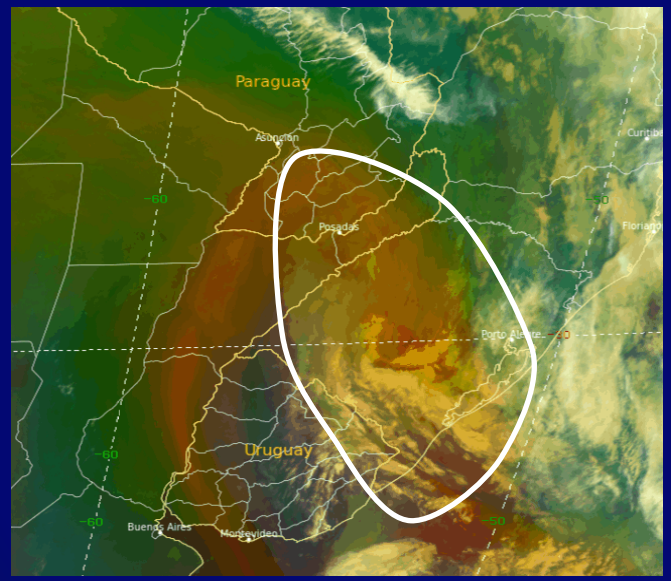
- Sólo se puede diagnosticar potencial de TAC donde existe nubosidad.
- Buscar bandas transversales y estructuras lineales a sotavento.
- Nubes en forma de ondas.
- RGB de Distinción de Fase de día muestra nubes cirrus en coloración rosa, Geocolor solo muestra la textura.

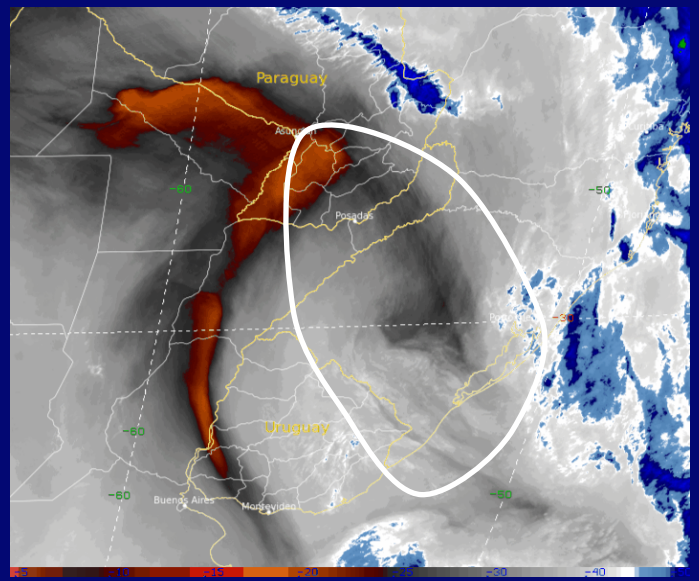


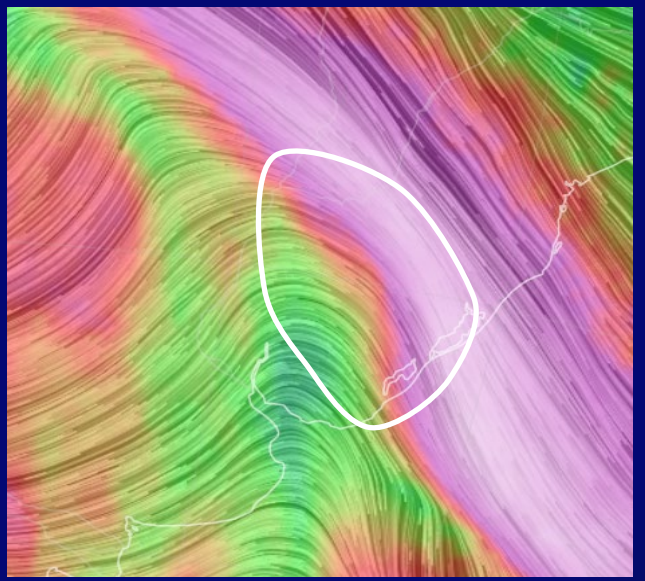
TAC y ciclogénesis

7-Oct-2022 07Z

- La ciclogénesis se asocial a TAC.
- Buscar vaguada en el lado frío de un chorro con gradientes de viento y humedad.
- Buscar rotación en las imágenes de vapor de agua.
- Buscar intrusión de ozono estratosférico (rojo) en RGB de Masas de Aire.



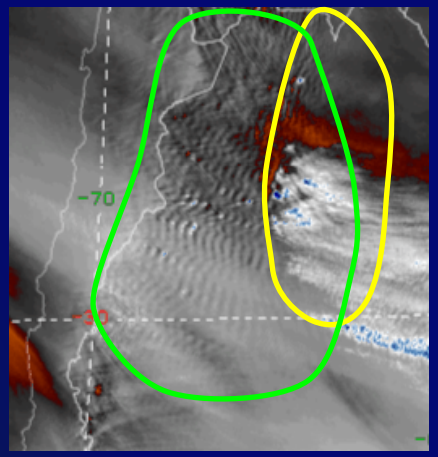
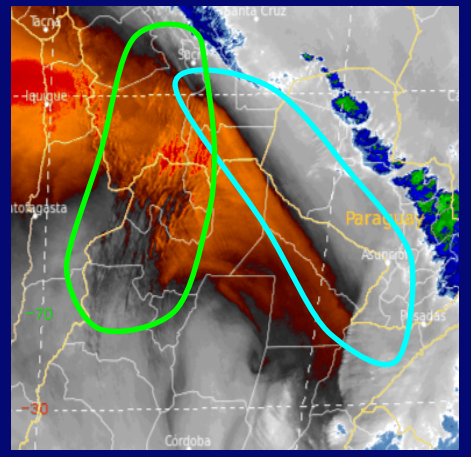
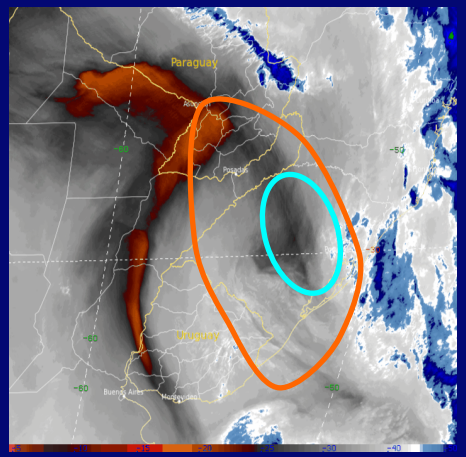
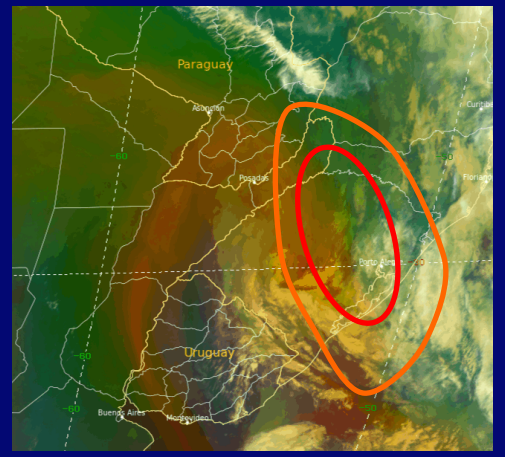
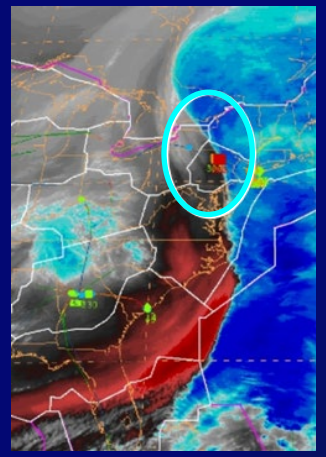




Summary: CAT in imagery

Mainly Water Vapor and Air Mass RGB

- Jet crossing a mountain range with moisture minima downstream (Foehn/Zonda?).
- Linear structures in water vapor imagery.
- Sharp moisture gradients, especially when strengthening.
- Jet maxima interacting with trough to the south (cold jet exit, downstream from trough)
- Periphery of ridges with anticyclonic jets.
- Gravity Waves.
- Cyclogenesis
- Tropopause Folding
- Negatively tilted upper troughs

Summary

Decision Tree for identifying the potential for CAT

1. Evaluate imagery and NWP fields:

   A) Find the jet axis.

   B) Find turbulence indicators (waves).

   C) Identify areas of enhanced horizontal wind shear (tightening moisture gradients, downstream from a trough axis in the cold side of an upper jet, etc).

   D) Use horizontal fields and cross sections to evaluate wind shear in the vertical.

2. Solidify your mental model.

3. Identify intersections of flying routes with CAT, and issue products as required.

03

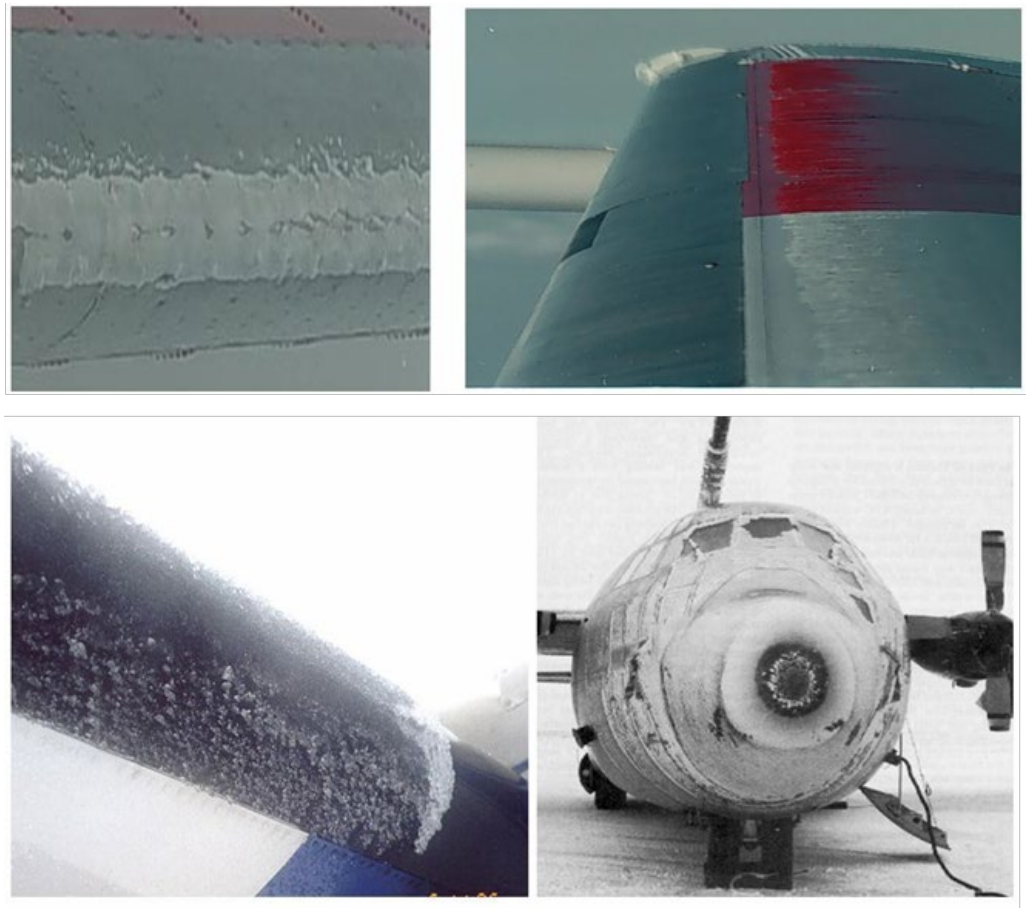
Icing

Icing in Aviation

Is the formation of ice in aircrafts due to the aggregation of supercooled water that freezes instantaneously.

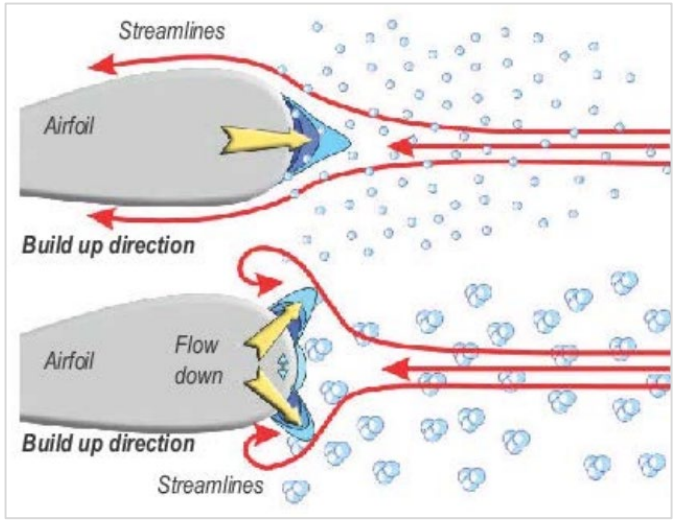
It can interfere with operations of the aircraft by affecting flotation, aircraft control and communication with the ground.

Forms in environments where of high liquid content of supercooled water or precipitation, and at temperatures of 0 to -20°C primarily.



Impacts on Aircrafts

1. **Flotation:**
   - Makes aircraft heavier
   - Affects flow dynamics that favor lift in the wings, reducing it in 30-50%.



2. **Aircraft Control**
   - Accumulation in helix can generate unbalance
   - Blocks or limits the control of the wheel and other moving parts of the wing.

3. **Visibility:** Accumulation in the wind shield.

4. **Communications:**
   - Ice accumulating on the antennas can interfere with communications.

Icing Environments

1) Temperature 0 to -20°C

- Where supercooled water exists. Ideal range= -4 to -8°C.

2) Clouds with high liquid water content

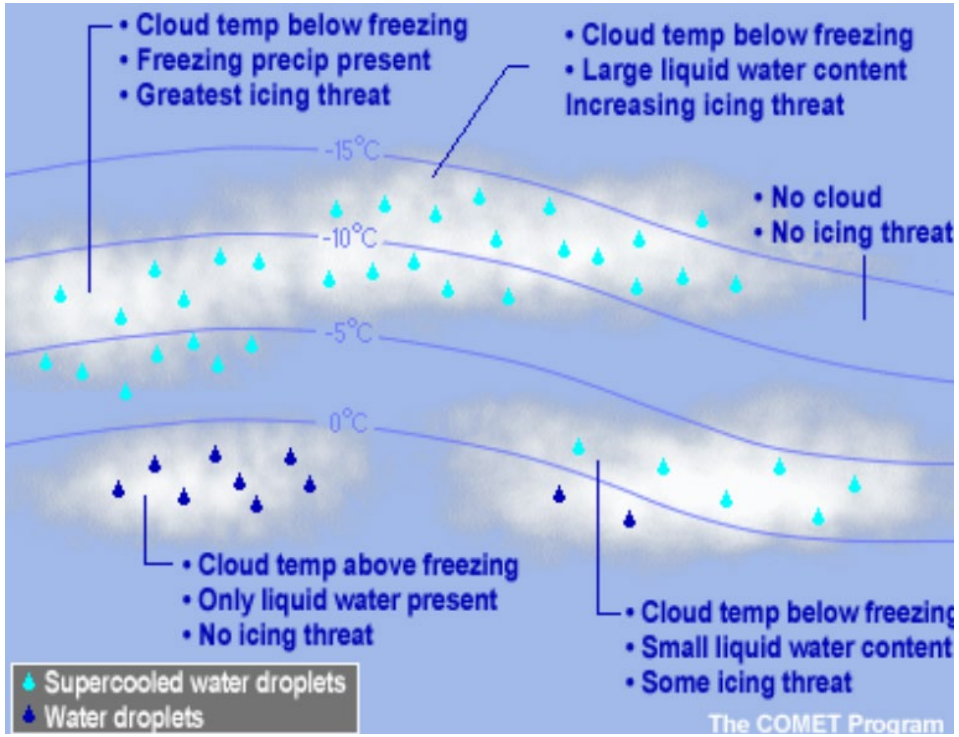
- High Cloud Water Mixing Ratio (CWMR). Means high density of super cooled liquid water
- Higher threat if precipitating

3) Relative humidity >80%

- Favors high CWMR maintenance by limiting evaporation.

4) Ascent

- Favors continued condensation by saturation and droplet growth.



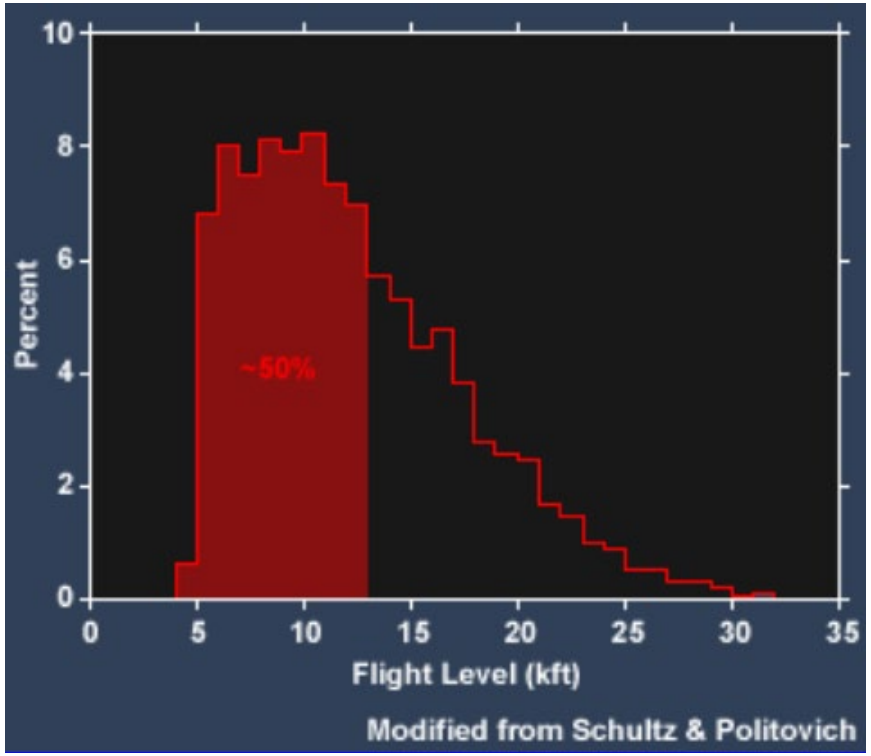
Flight Levels most affected

Extratropics:

- Most prominent in the extratropics, where extensive regions of nimbostratus with high liquid water content occur.
- Most reports occur between 5000 and 13000 ft (FL050 – FL130) or ~850 – 600 hPa.

Tropics/subtropics:

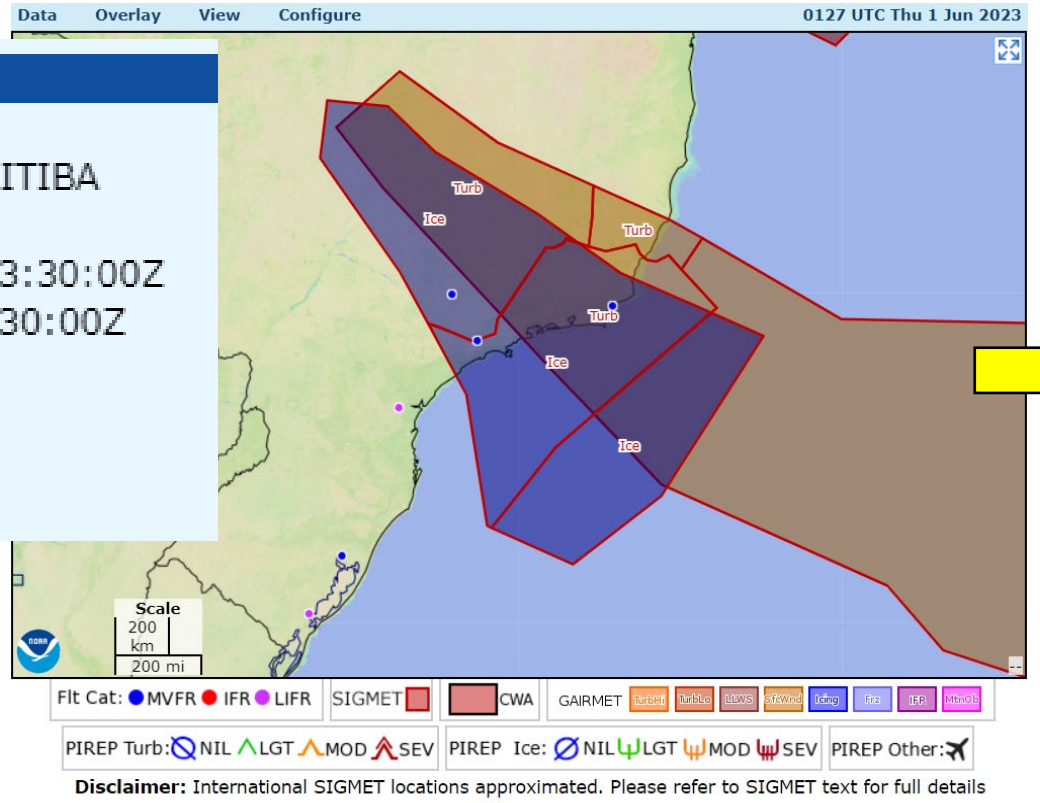
- Occurs at higher altitudes (freezing level is higher, generally 13000-24000 ft or 600-400hPa or)
- Less frequent, as high liquid water content clouds are often smaller in area, thus easier to avoid.

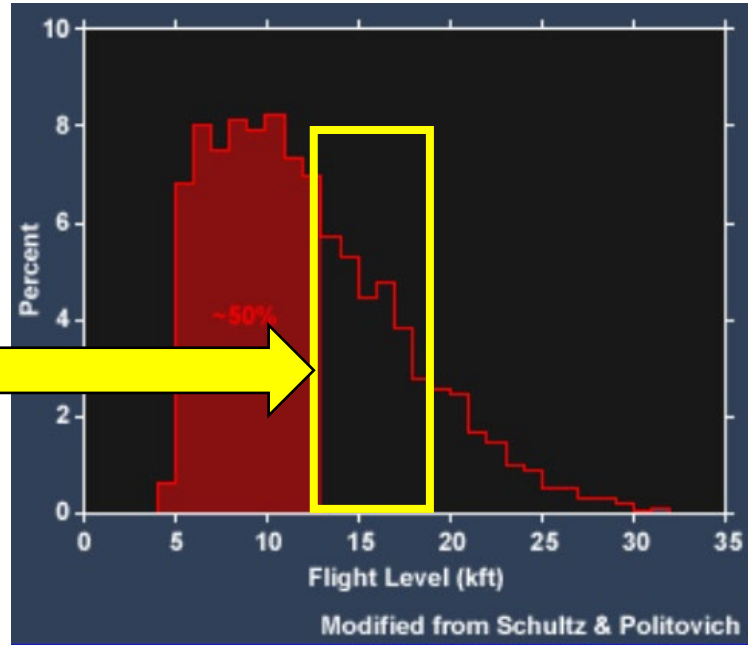


Example: Icing SIGMET in Brasil, 01 June 2023

SIGMET for 13000 – 19000 ft (600-500 hPa)

ICE SIGMET
FIR Id: SBCW
FIR Name: SBCW CURITIBA
Hazard: ICE - SEV
Begins: 2023-05-31T23:30:00Z
Ends: 2023-06-01T03:30:00Z
Top: 19000 ft
Base: 13000 ft
Move: stationary
Change: NC



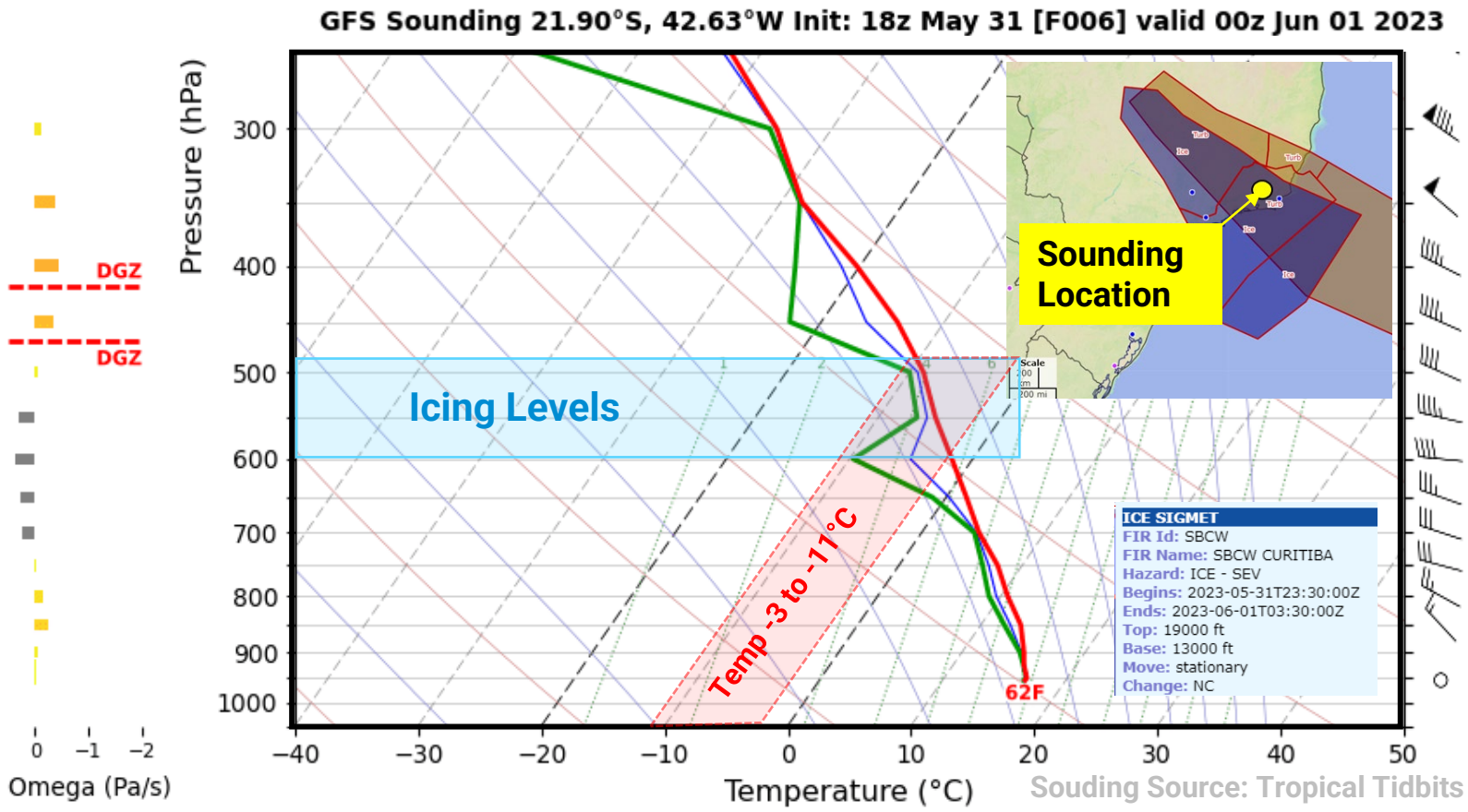


Higher up than in mid-latitudes

Example: Icing SIGMET in Brasil, 01 June 2023

Keypoints:

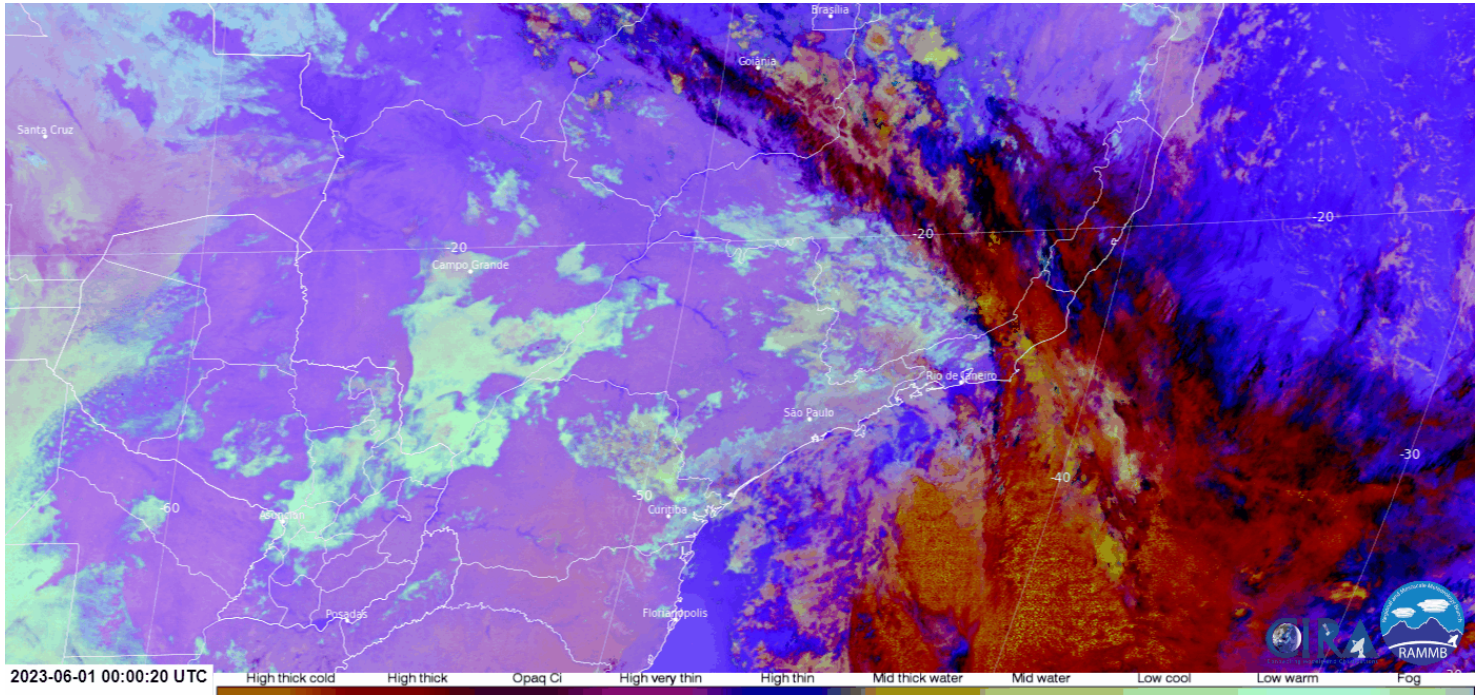
- Temperature of -11 to -1°C, (supercooled water layer).
- High relative humidity, 83-99% (close to saturation)
- Ascent (negative omegas), but in this case the model says mostly above the layer.



Example: Icing SIGMET in Brasil, 01 June 2023

Synoptic Situation

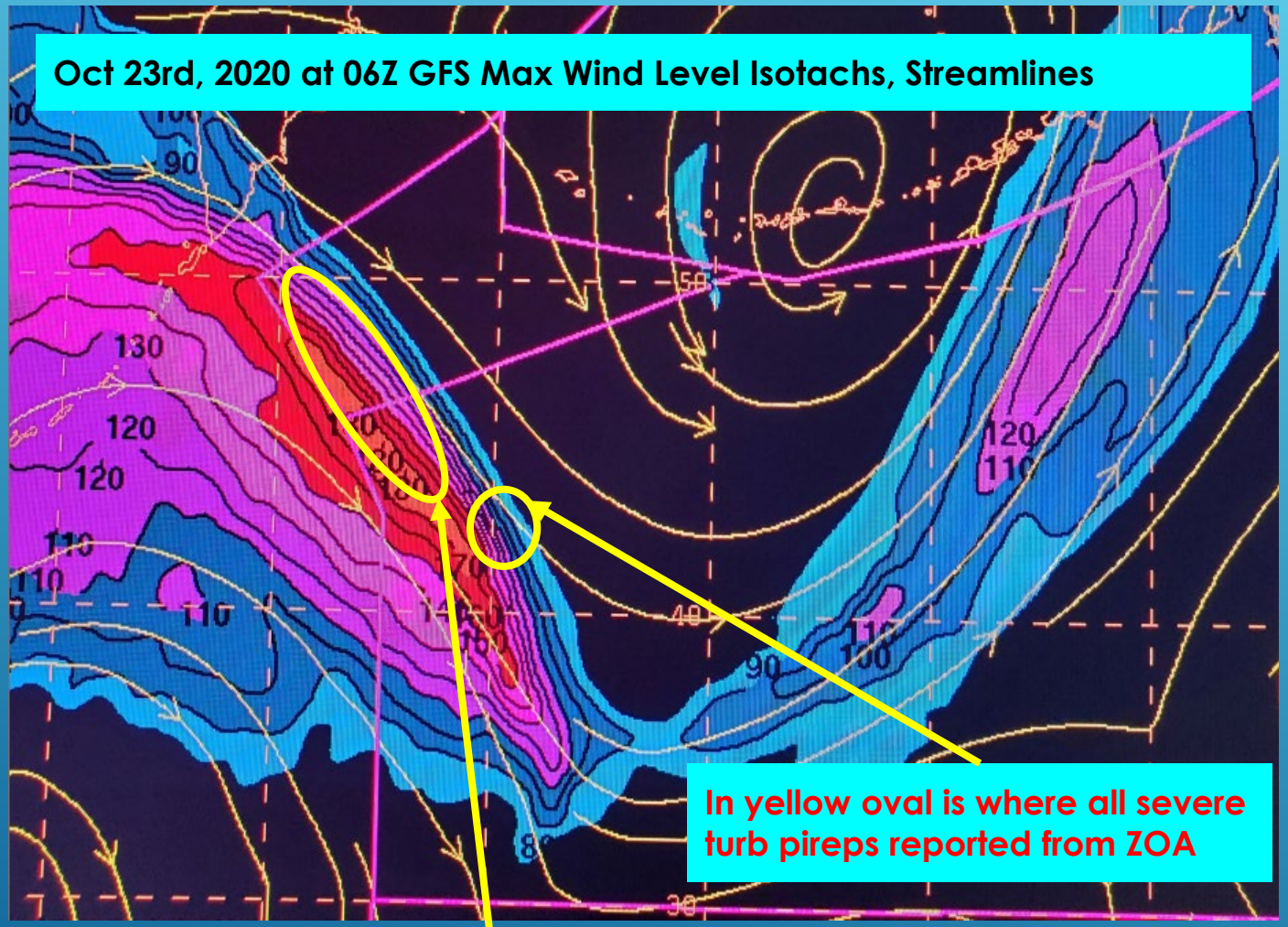
- Temperature of -11 to -1°C, (supercooled water layer).
- High relative humidity, 83-99% (close to saturation)
- Ascent (negative omegas), but in this case the model says mostly above the layer.

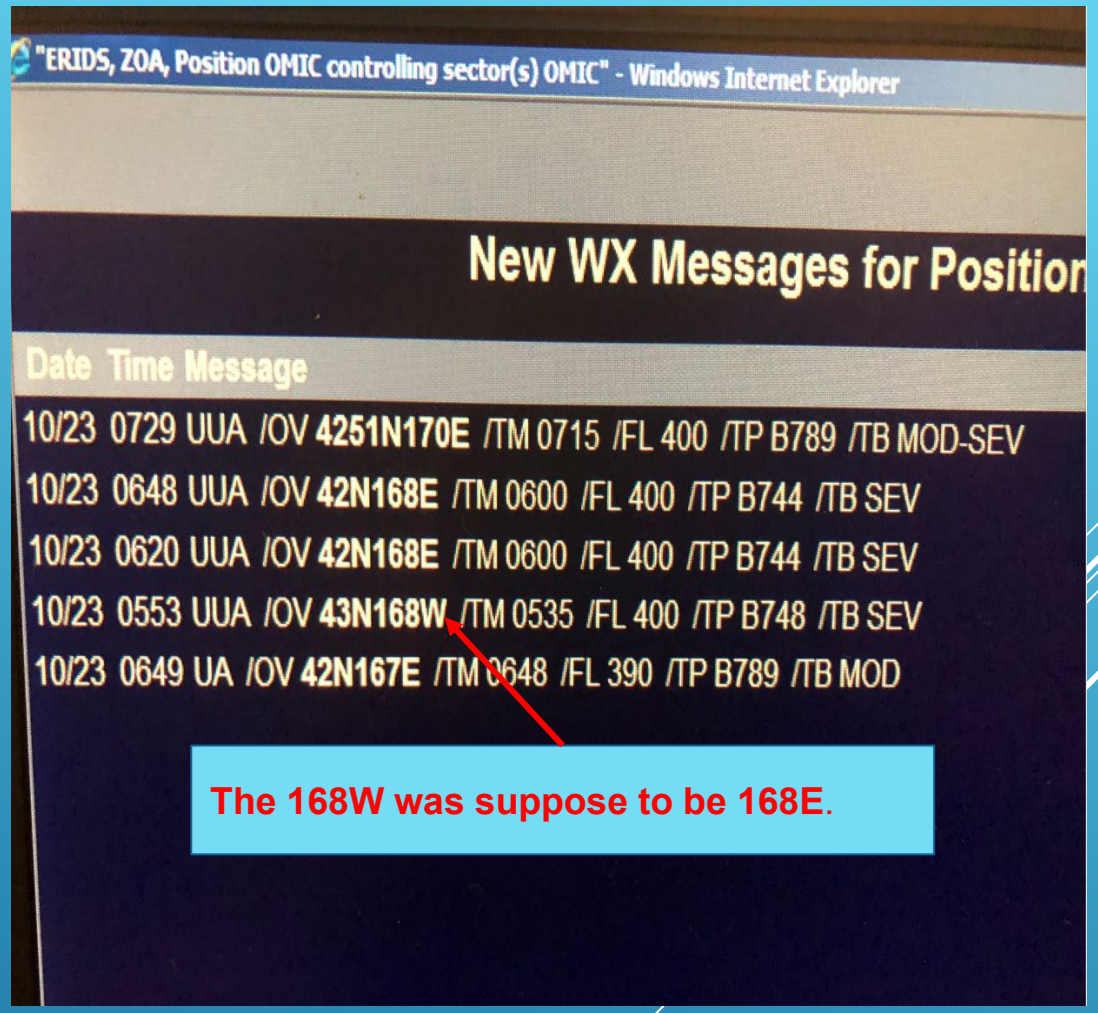


04

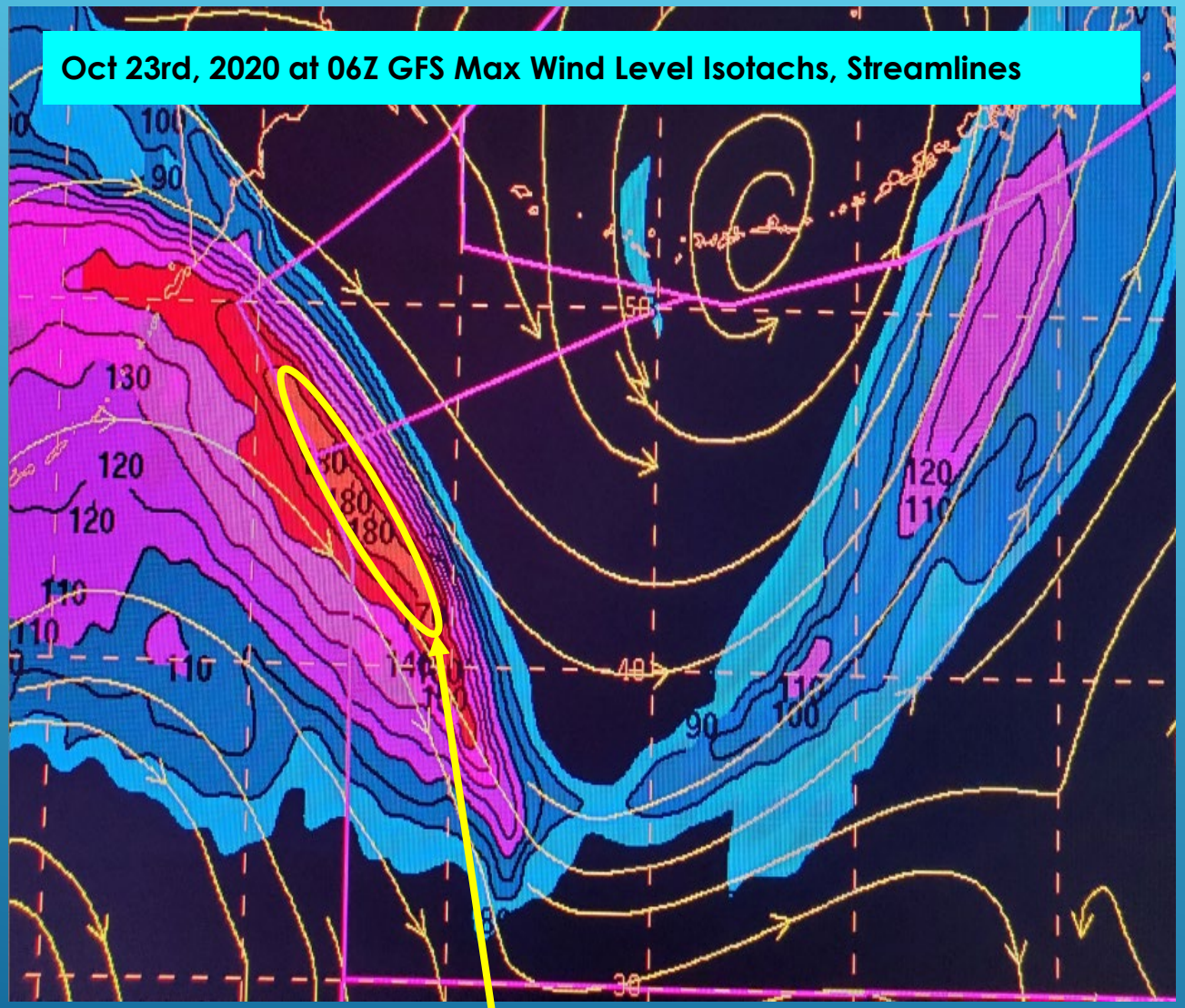
Case Studies

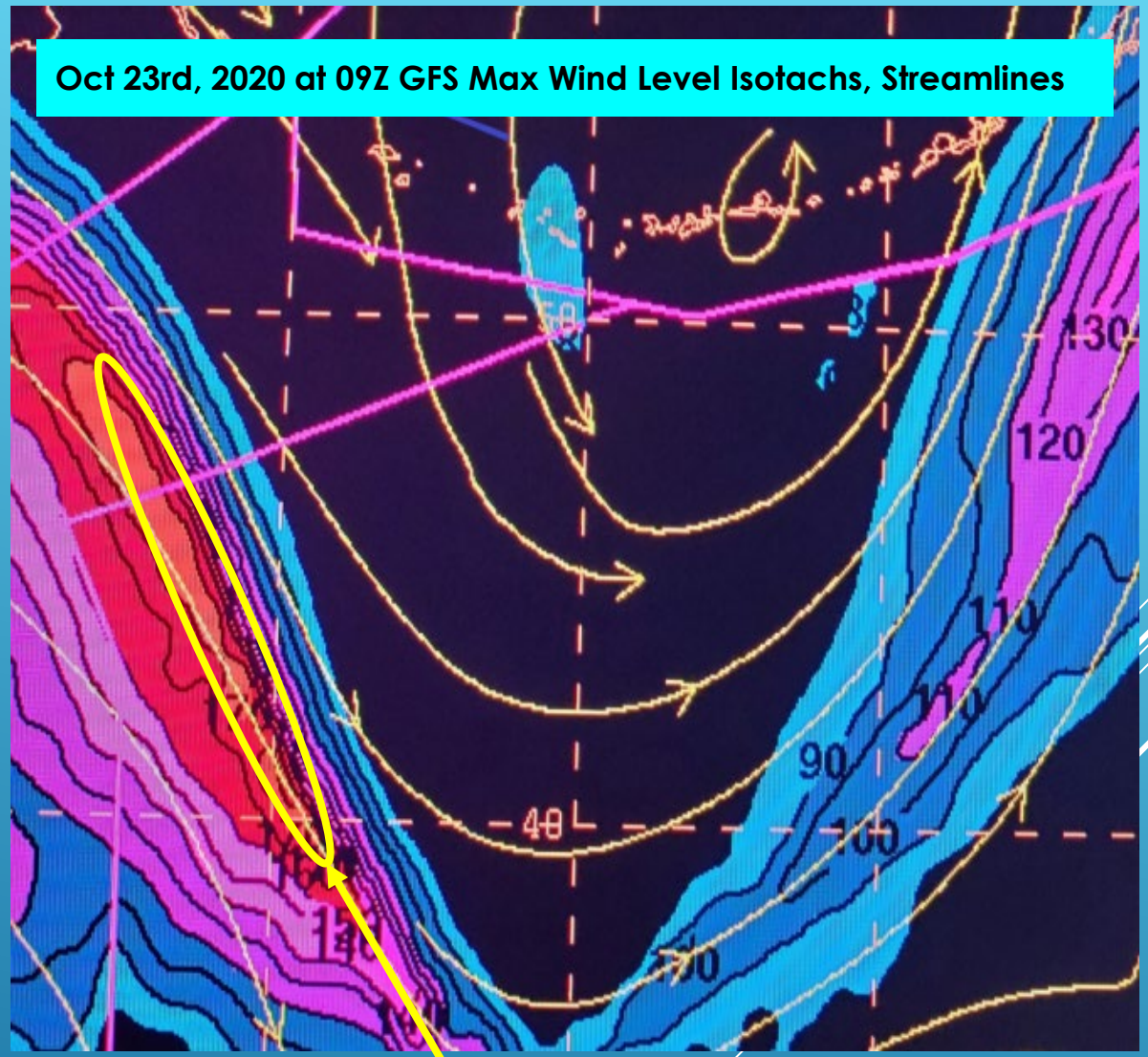
Oct 23rd, 2020 SEVERE TURBULENCE EVENT BETWEEN THE AAWU'S OCEANIC ANCHORAGE & OAKLAND OCEANIC FIRS by Perry Dehne





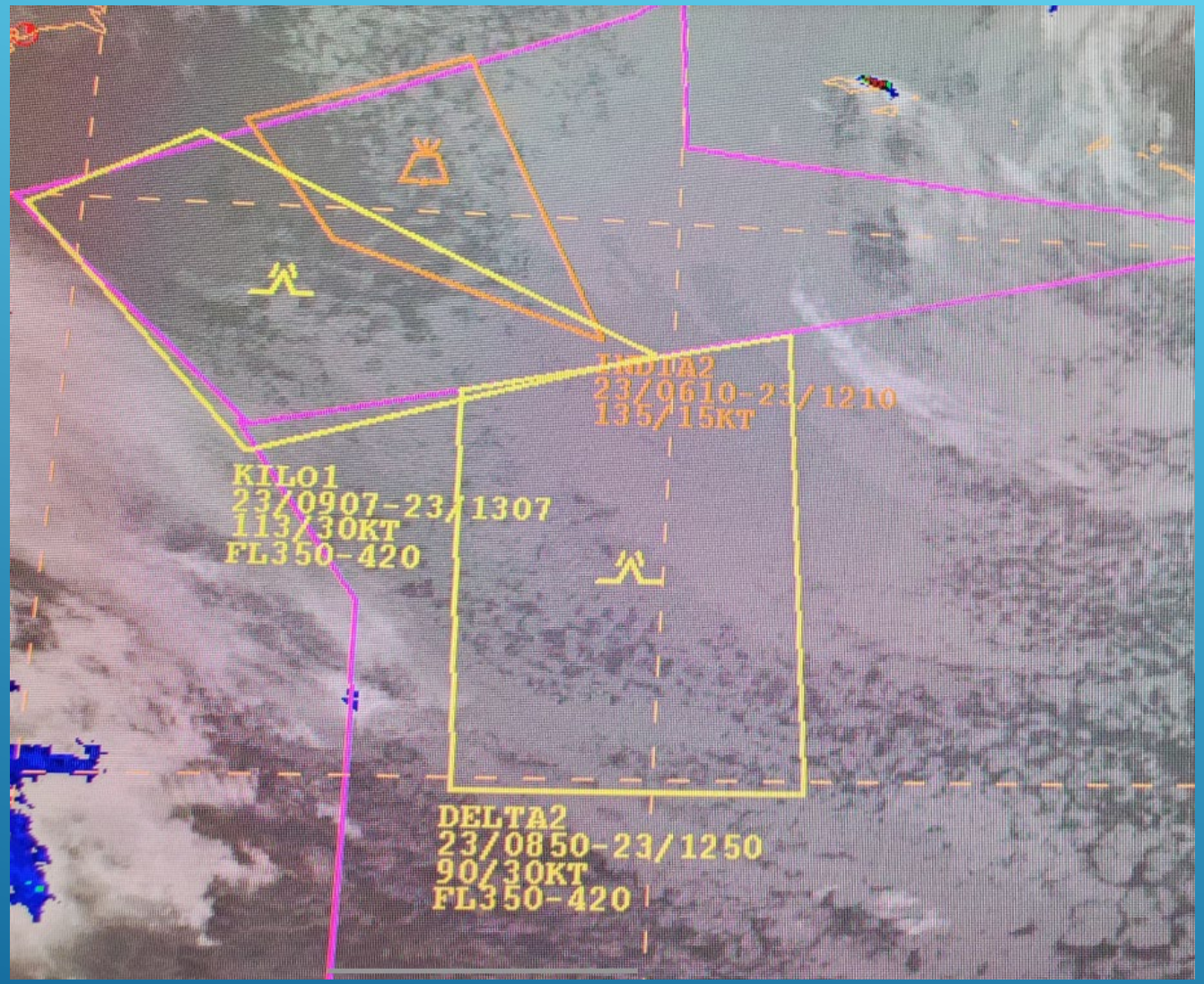
There was a strong northwest 180 knot jetstreak digging into the base of the trough. Oct 23rd, 2020 around 0730Z Oakland FAA called and reported severe turb pirep at FL400 at 42.51N 170E. I then received email with the next severe turb pireps and issued DELTA#1 SEVERE TURB SIGMET. The earliest severe turb pirep was almost 2 hrs old. ZOA had said they had trouble getting pireps into the system.

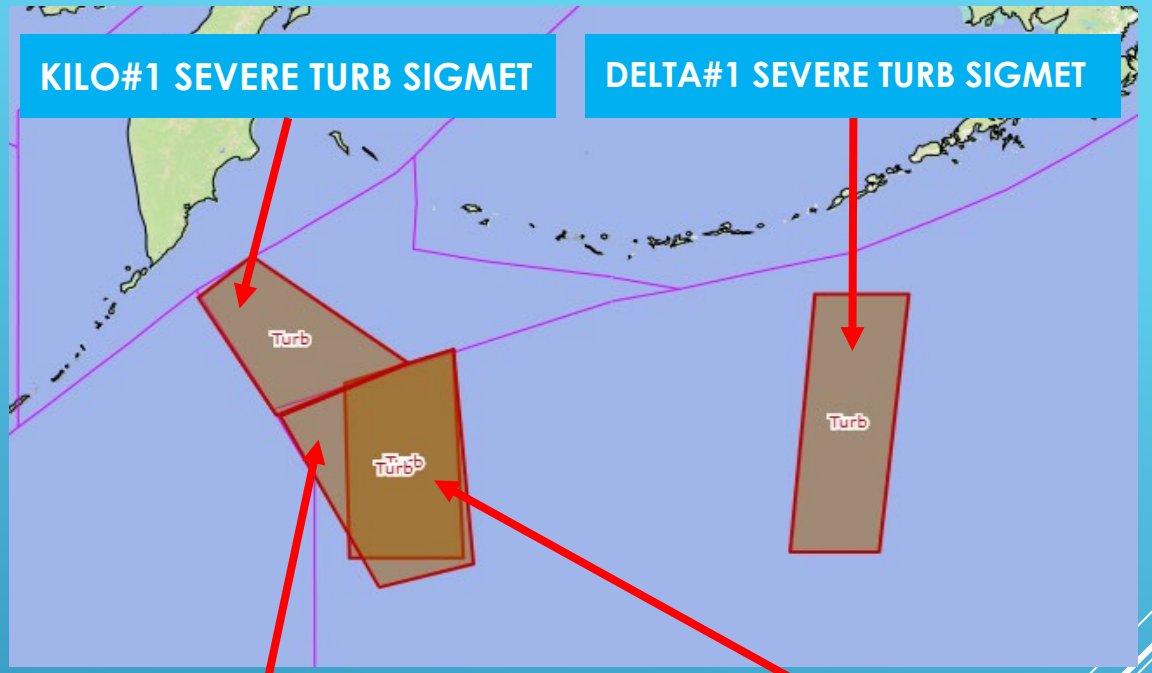




Oct 23rd/06Z, 2020 Jetstreak & Streamlines with strong northwest jetstreak as it continues around the anti-cyclonic flow around the amplified ridge axis.

Oct 23rd/09Z, 2020 Jetsreak & Streamlines with jetstreak becoming more elongated as it digs into the base of the trough.



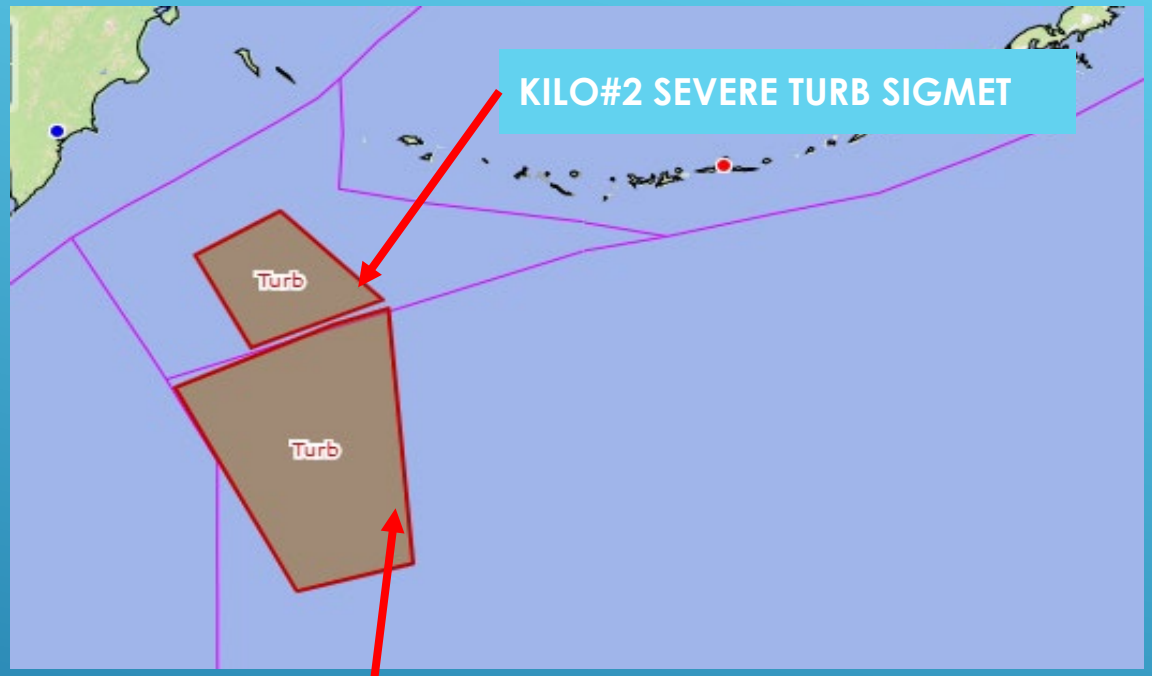


DELTA#3 SEVERE TURB SIGMET. I reissued to better match with AAWU KILO#1 sigmet.

TURB SIGMET
FIR Id: PAZA
FIR Name: OAKLAND OCEANIC FIR ANCHORAGE
Hazard: TURB - SEV
Begins: 2020-10-23T08:50:00Z
Ends: 2020-10-23T12:50:00Z
Top: 42000 ft
Base: 35000 ft
Move: E
Speed: 30 kt
Change: NC

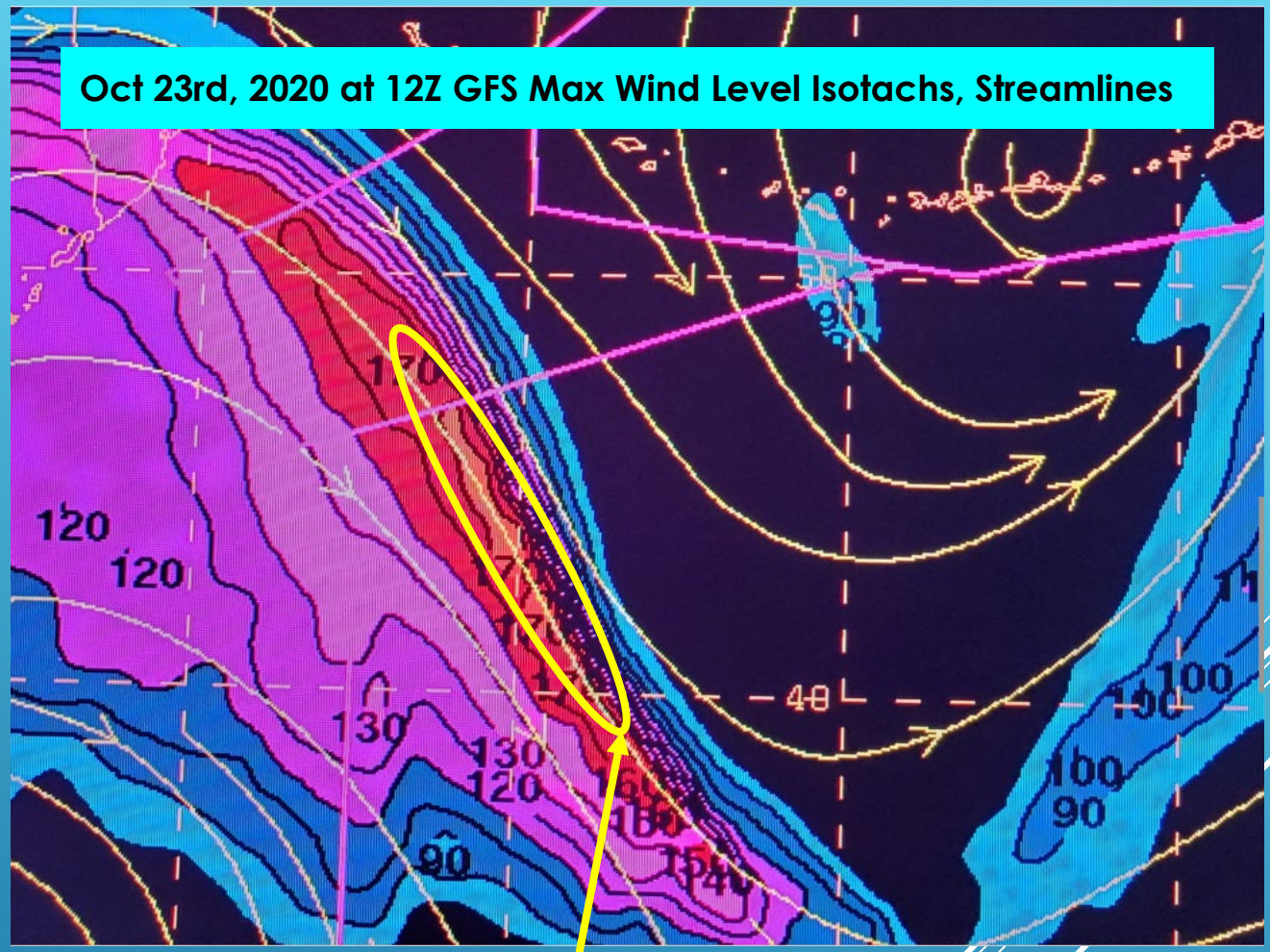
WSPN04 KKCI 230850
SIGP0D
KZAK PAZA SIGMET DELTA 2 VALID 230850/231250 KKCI-
OAKLAND OCEANIC FIR ANCHORAGE FIR SEV TURB FCST WI N4800 E17200 -
N3945 E17230 - N3945 E16645 - N4645 E16630 - N4800 E17200.
FL350/420. MOV E 30KT. NC.

I issued DELTA#1 SEVERE TURB SIGMET and updated with DELTA#2 SIGMET due to plotting the wrong longitude using 170W instead of 170E longitude. Thankfully I had notified AAWU when I had issued DELTA#1 due to habit of always keeping communication open with their office. The AAWU Lead noticed my mistake and notified ASAP. I updated again with DELTA#3 for better alignment between sigmets.



TURB SIGMET
FIR Id: KZAK
FIR Name: OAKLAND OCEANIC
Hazard: TURB - SEV
Begins: 2020-10-23T11:15:00Z
Ends: 2020-10-23T15:15:00Z
Top: 42000 ft
Base: 35000 ft
Move: E
Speed: 30 kt
Change: INTSF

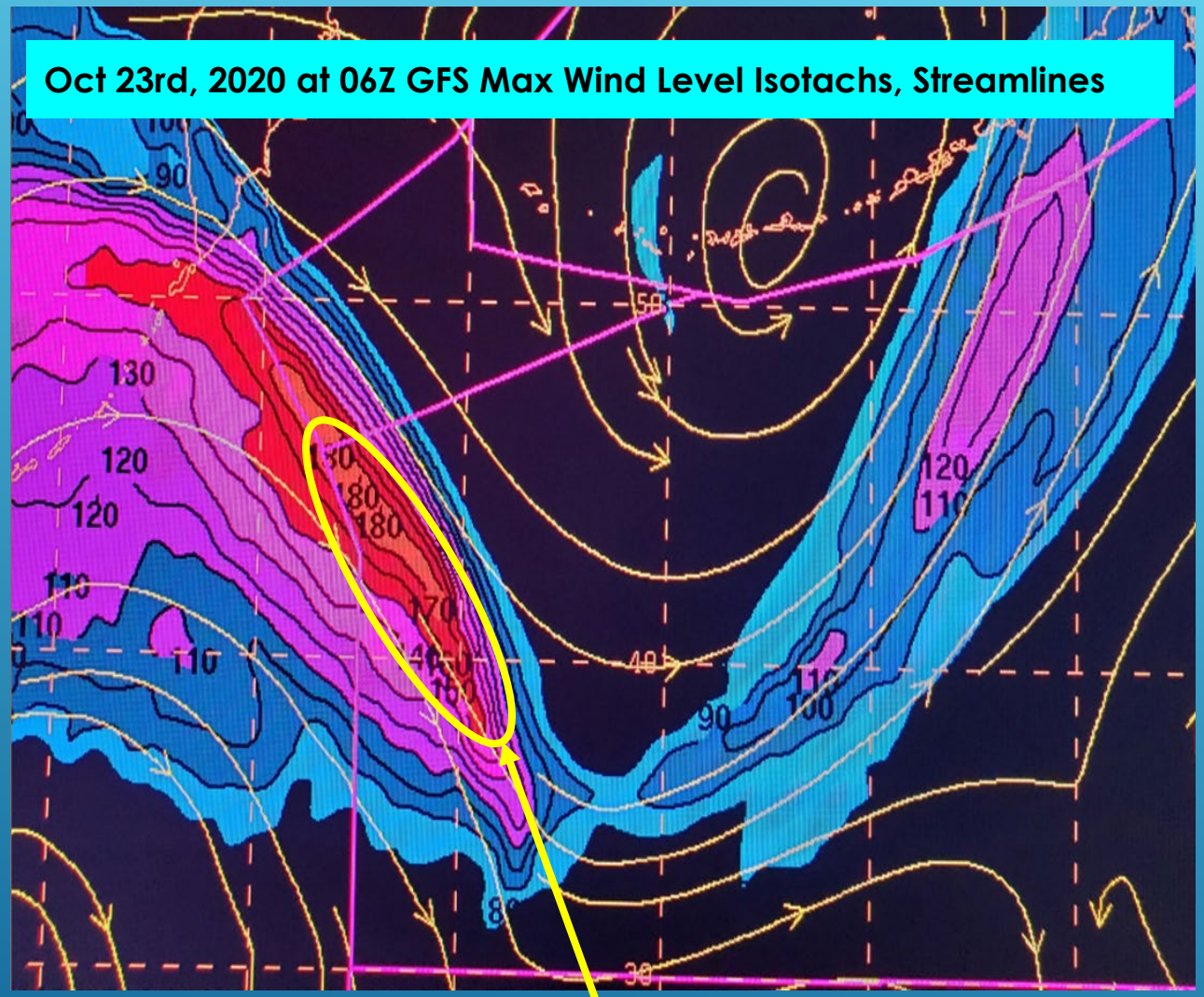
WSPN04 KKCI 231115
SIGP0D
KZAK SIGMET DELTA 3 VALID 231115/231515 KKCI-
OAKLAND OCEANIC FIR SEV TURB FCST WI N4800 E17200 - N3930 E17300
- N3830 E16815 - N4530 E16315 - N4730 E16945 - N4800 E17200.
FL350/420. MOV E 30KT. INTSF.



Oct 23rd/12Z, 2020 Jetstreak MaxWnds & Streamlines

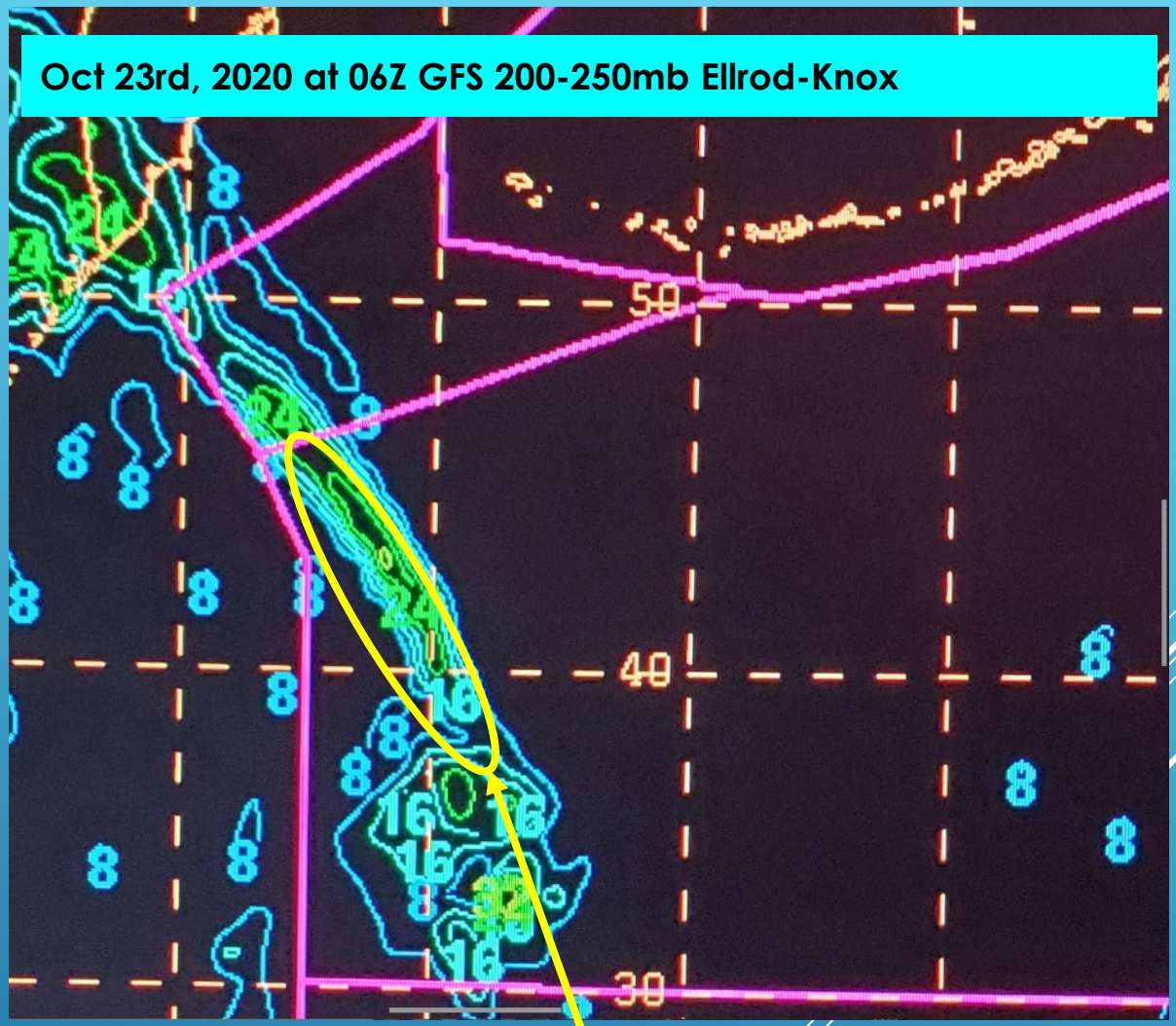
This was the final update I had done before handing over the Tropical dayshift. The strong northwesterly jetstreak was looking to move farther southeast into the Pacific ocean. I had extended over to Tokyo FIR with a sigmet they had issued. The AAWU has problems sometimes with their software on the borders, but otherwise great teamwork between the AAWU and AWC offices!

Oct 23rd, 2020 at 06Z GFS Max Wind Level Isotachs, Streamlines



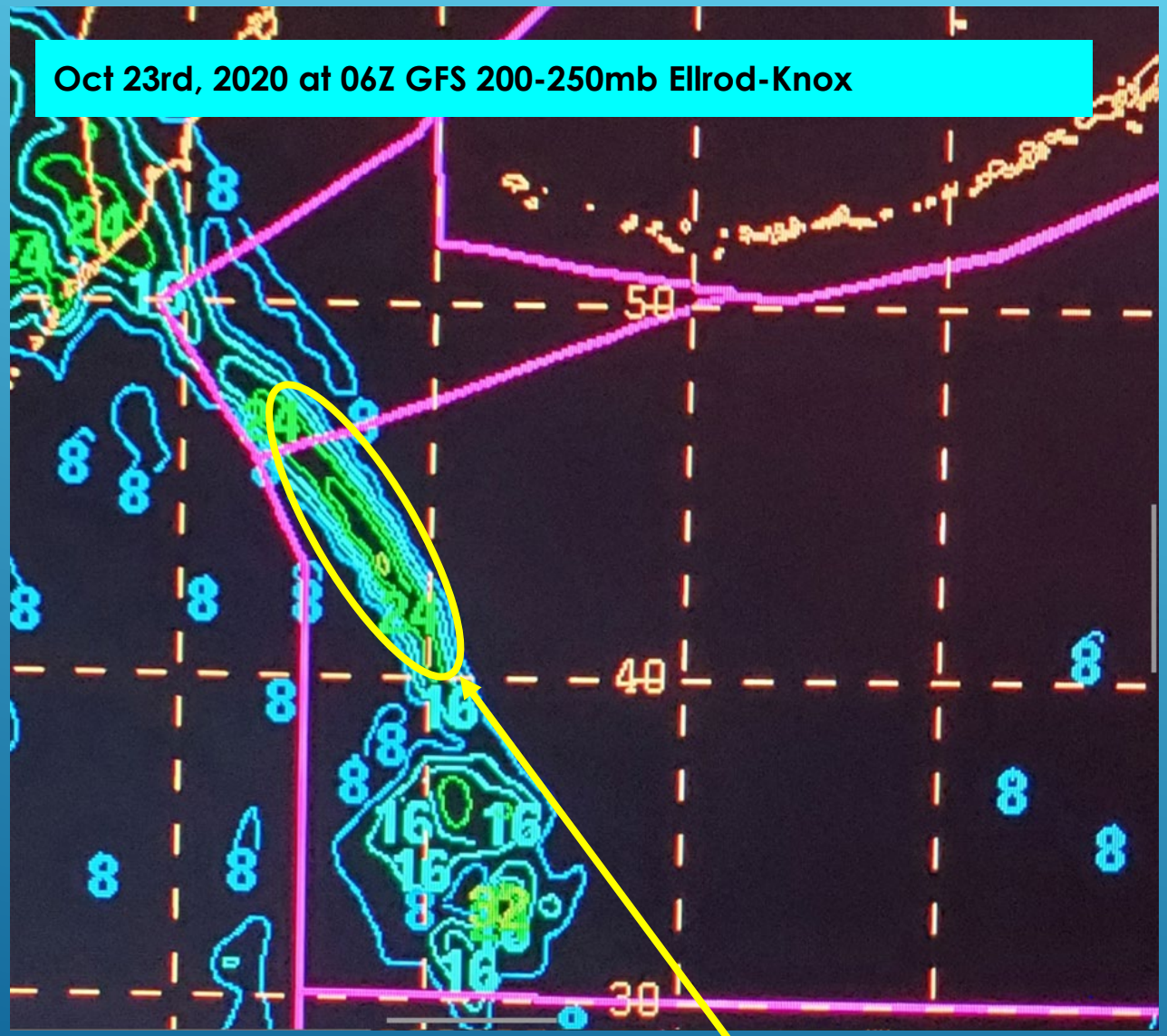
Oct 23rd, 2020 at 06Z with GFS **Jetstreak MaxWnds/Streamlines.** These are great dynamics for producing severe turb with a strong jetstreak coming over anti-cyclonic ridge and digging into base of the upstream trough.

Oct 23rd, 2020 at 06Z GFS 200-250mb Ellrod-Knox



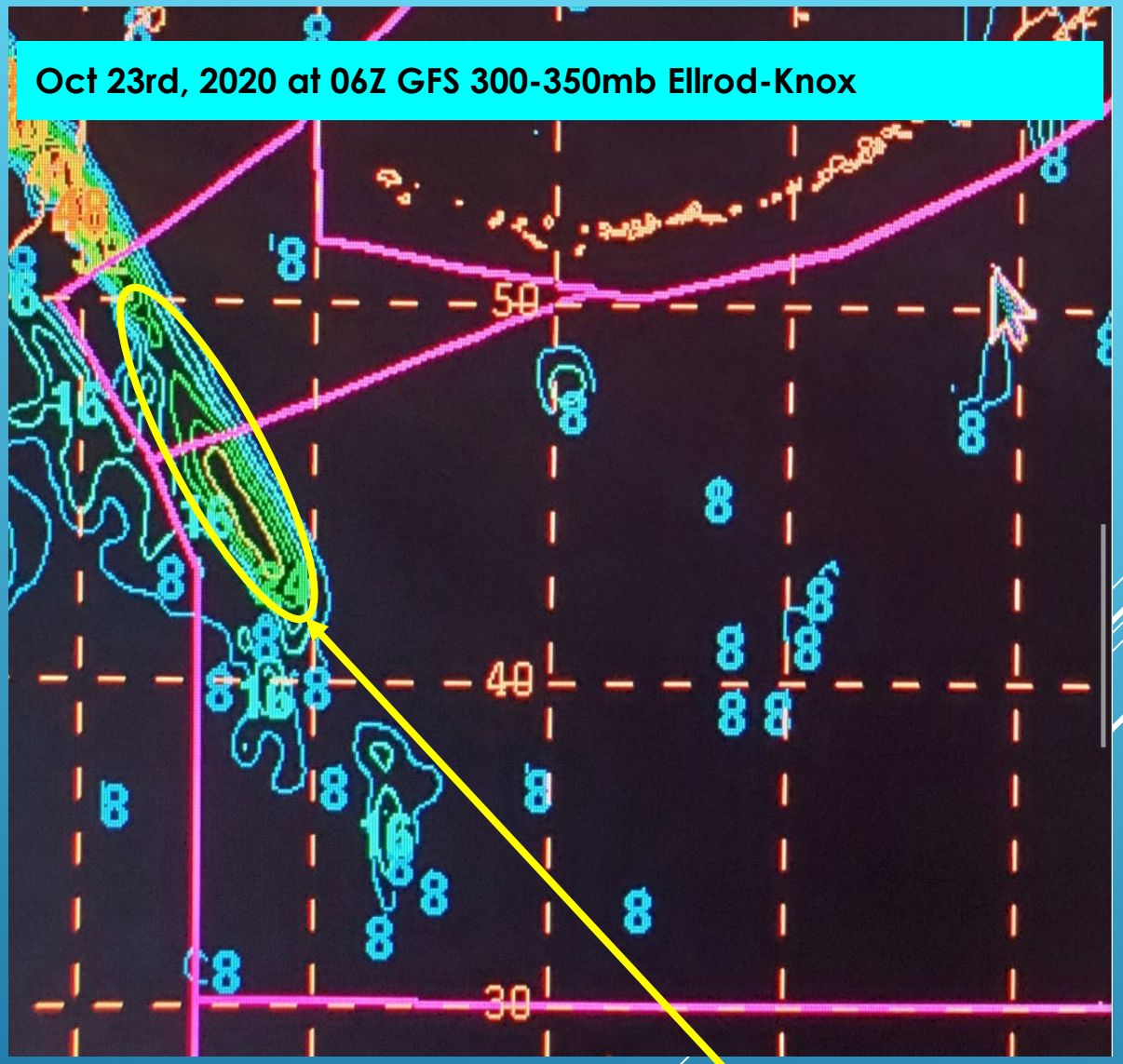
Oct 23rd, 2020 at 06Z with GFS **200-250mb Ellrod-Knox.** The Ellrod-Knox indices above look borderline moderate to severe turb potential but with the dynamics I can see why we received the severe turb pireps.

Oct 23rd, 2020 at 06Z GFS 200-250mb Ellrod-Knox

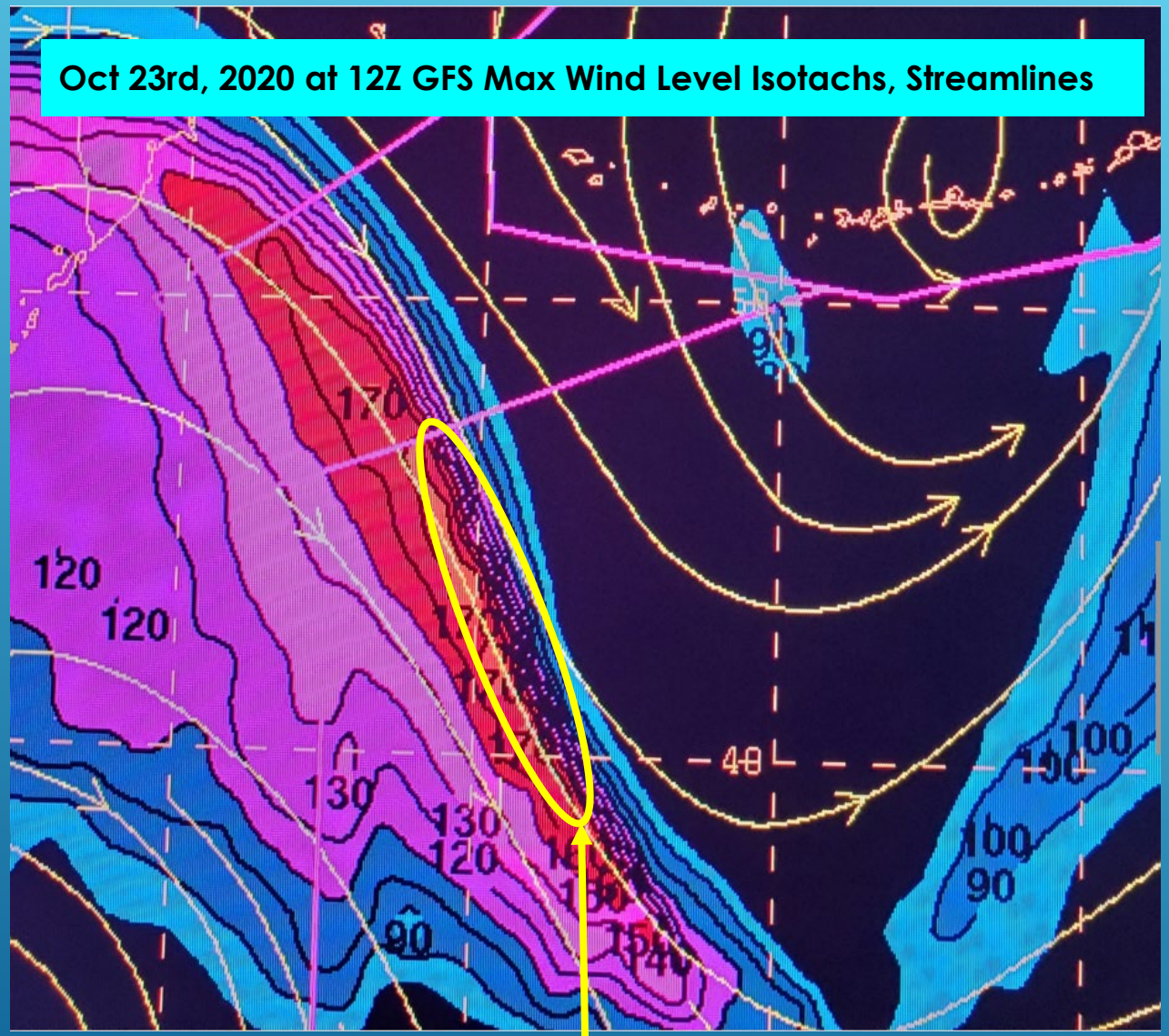


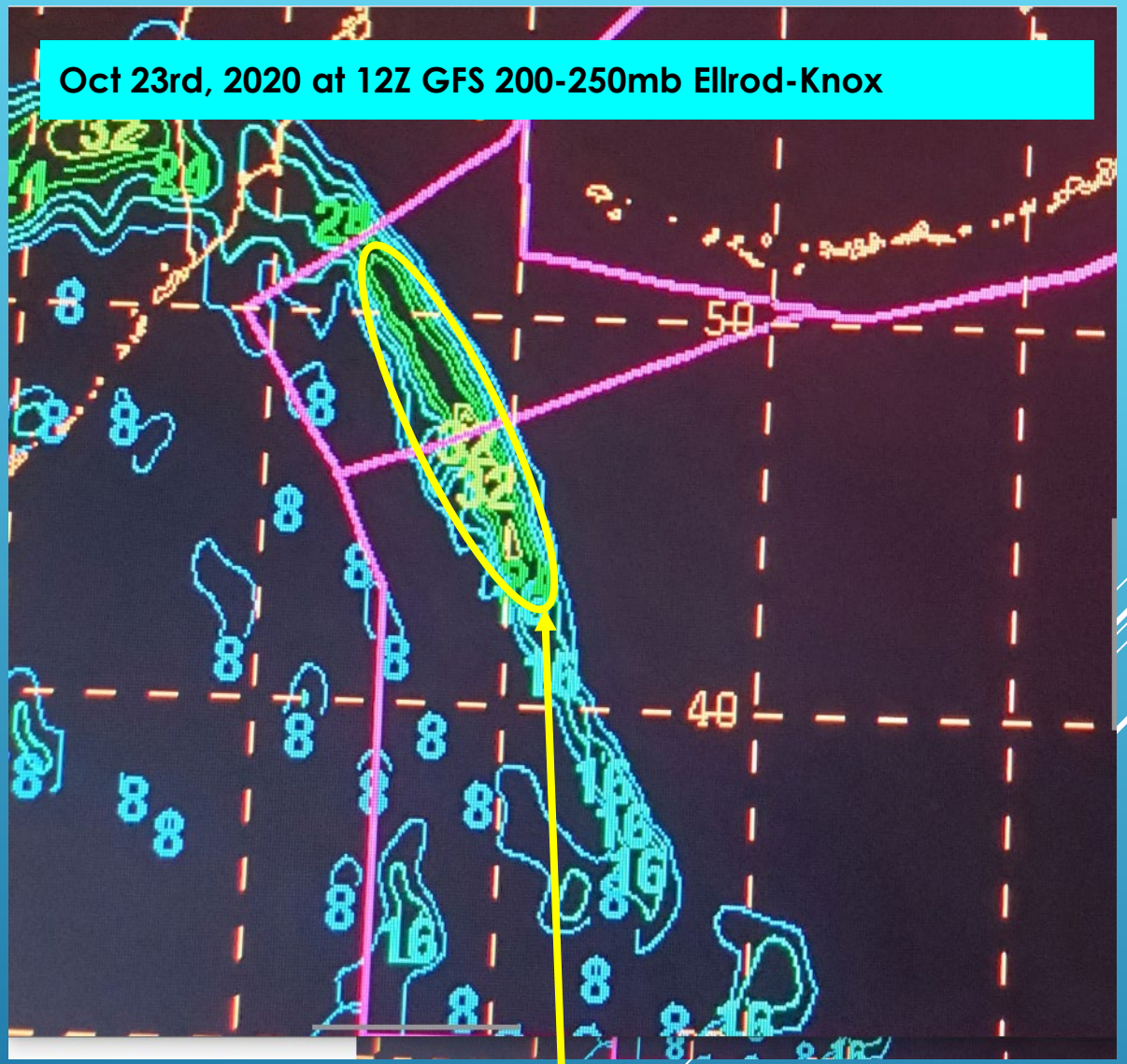
Oct 23rd, 2020 at 06Z with GFS 200-250mb Ellrod-Knox and the Ellrod-Knox indices at 300-350mb look pretty much the same for strength of possible shear turbulence.

Oct 23rd, 2020 at 06Z GFS 300-350mb Ellrod-Knox



Oct 23rd/06Z, 2020 GFS 300-350mb Ellrod-Knox and as mentioned previously the strength looks about the same as the other turbulence indices.

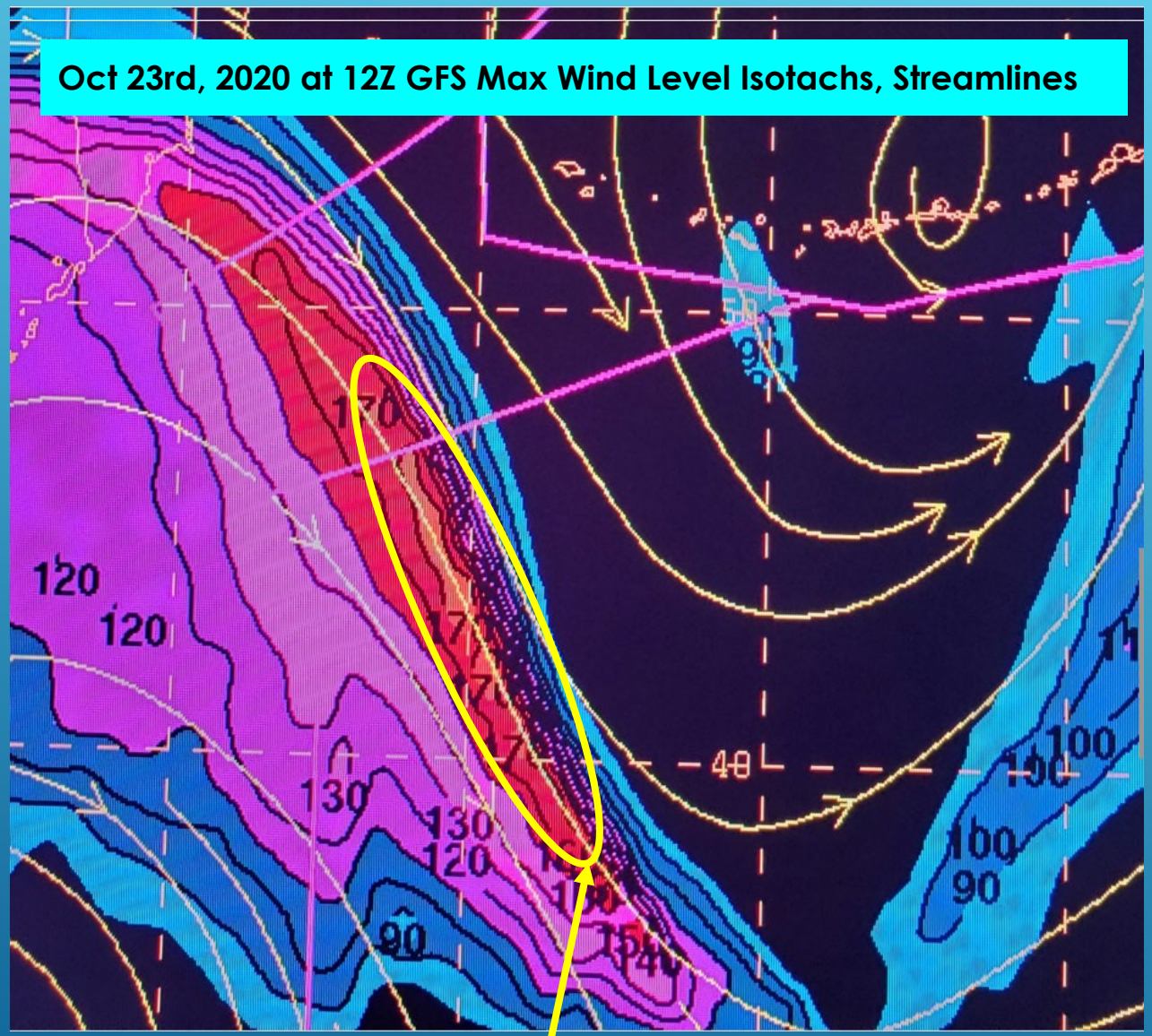




Oct 23rd, 2020 at 12Z with GFS Jetstreak MaxWnds & Streamlines continue to show the jetstreak diving farther southeast as it digs into the base of trough.

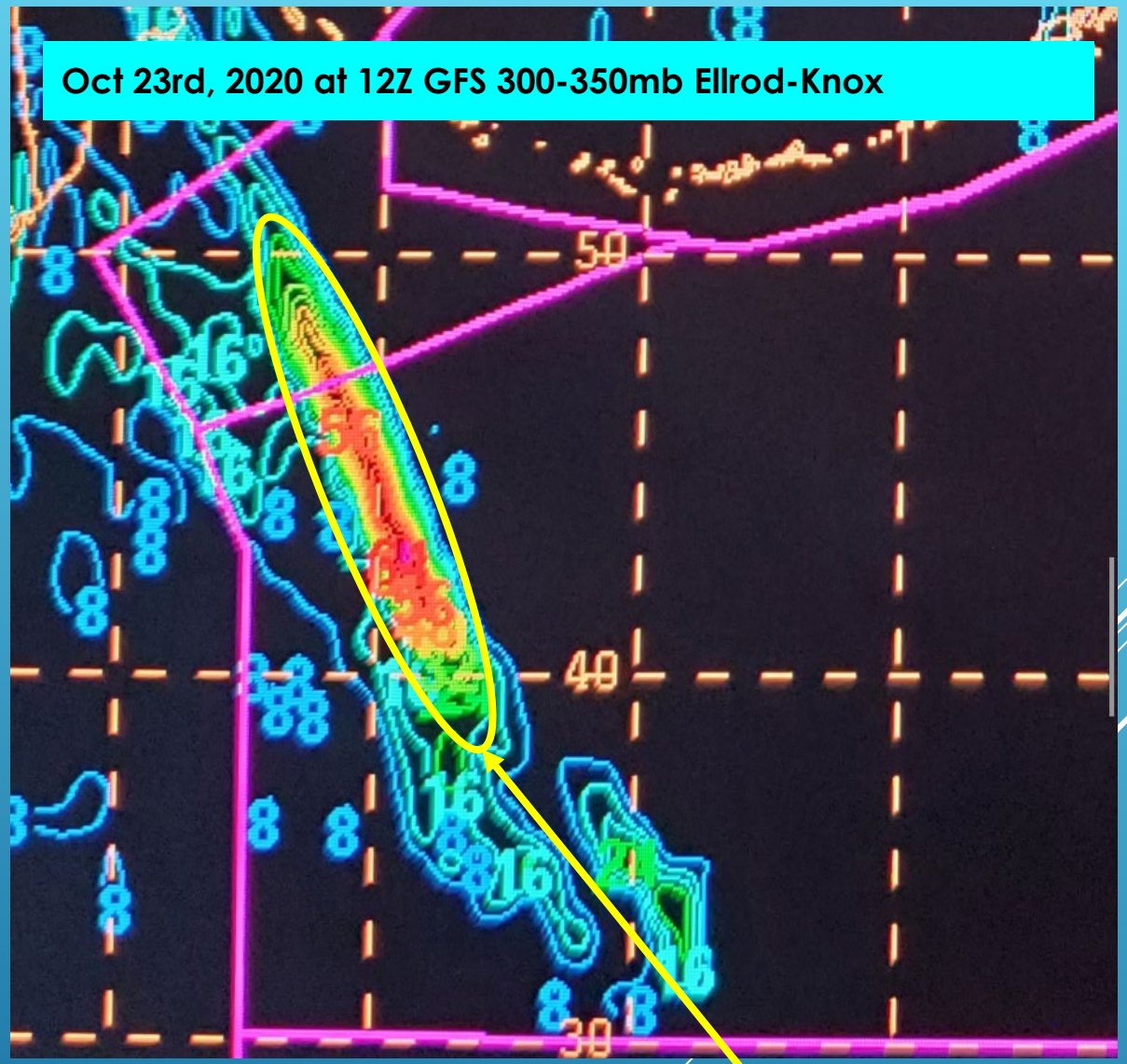
Oct 23rd, 2020 at 12Z with GFS 200-250mb Ellrod-Knox indices looks to be intensifying from the 200-250mb Ellrod-Knox at 23/06Z time-frame.

Oct 23rd, 2020 at 12Z GFS Max Wind Level Isotachs, Streamlines

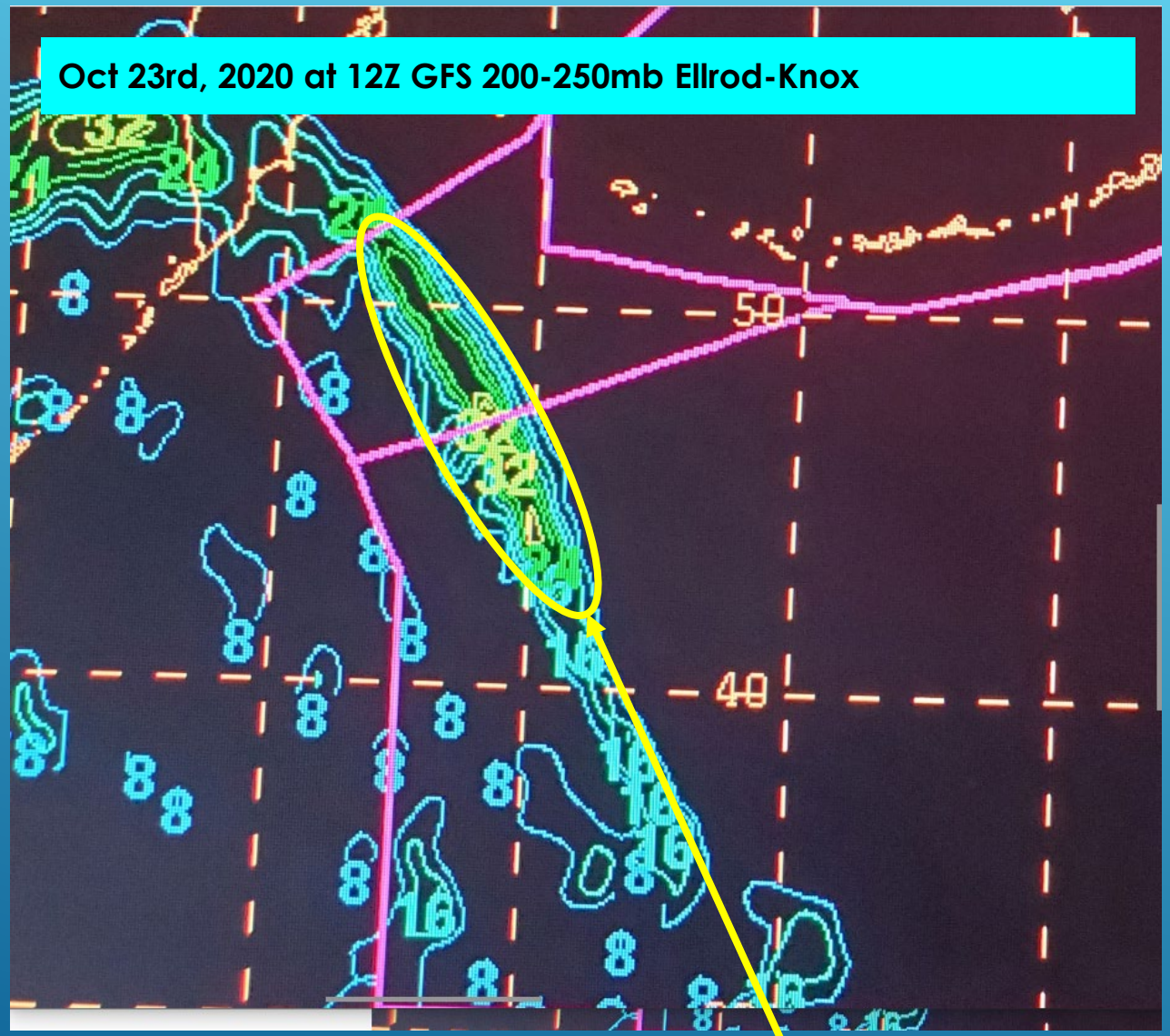


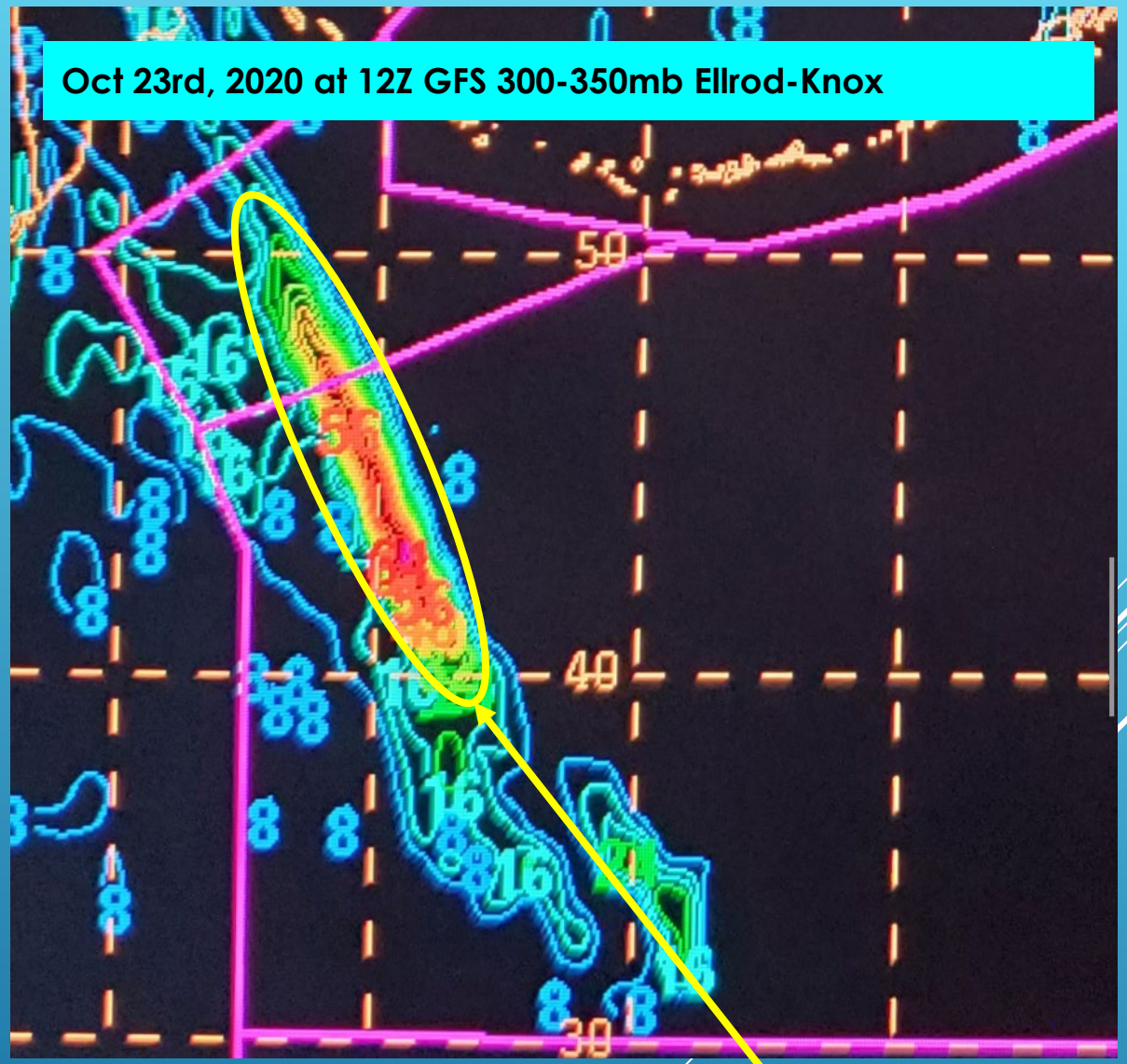
Oct 23rd, 2020 at 12Z with GFS Jetstreak MaxWnds & Streamlines remains with a strong northwest jetstreak as it moves toward the base of the upstream trough.

Oct 23rd, 2020 at 12Z GFS 300-350mb Ellrod-Knox



Oct 23rd, 2020 at 12Z with GFS 300-350mb Ellrod-Knox indices have greatly intensified and great justification for having severe turb sigmet in both FIRs.

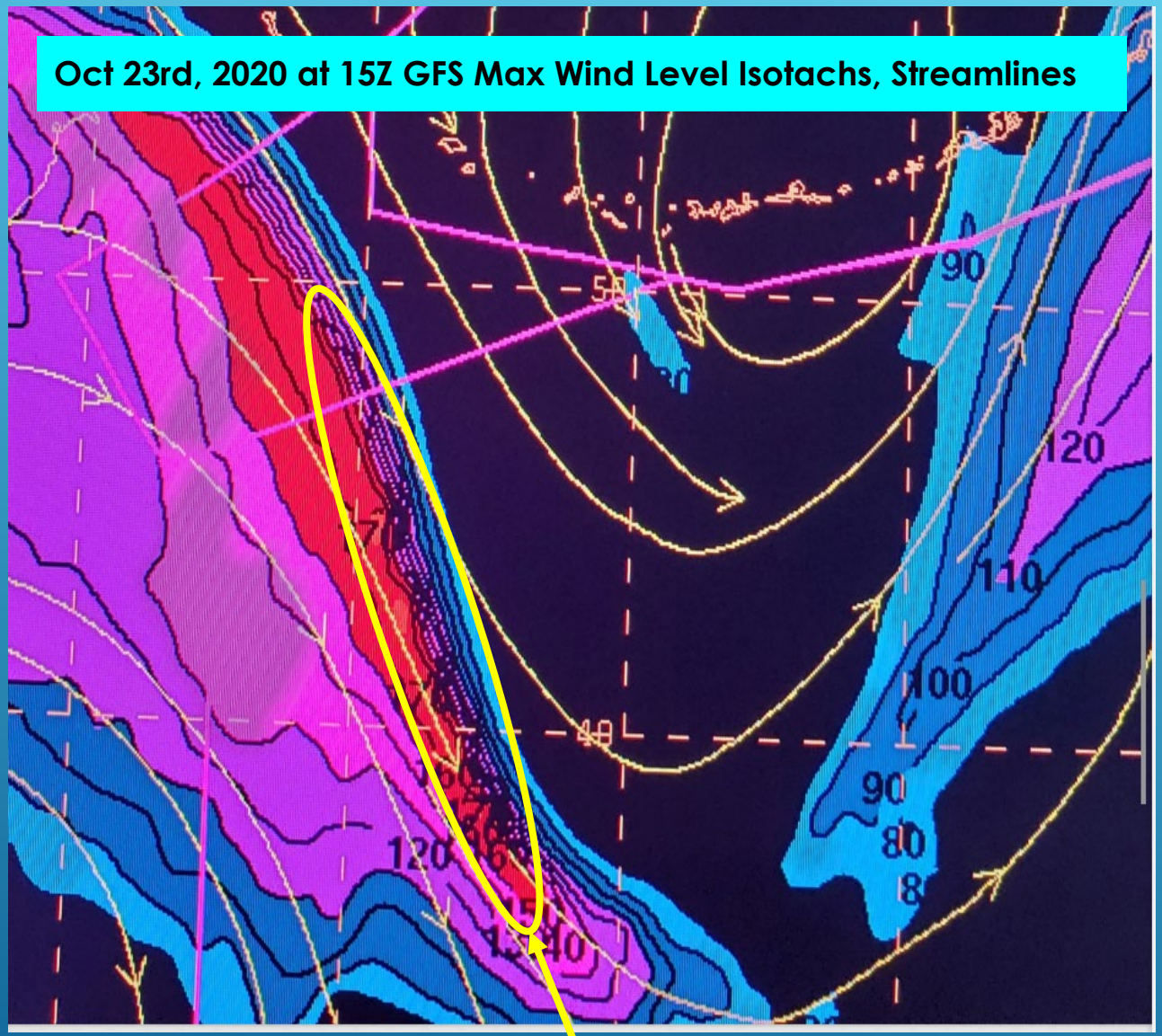




Oct 23rd, 2020 at 12Z with GFS 200-250mb Ellrod-Knox indices are good when combined with dynamics for possible severe turbulence.

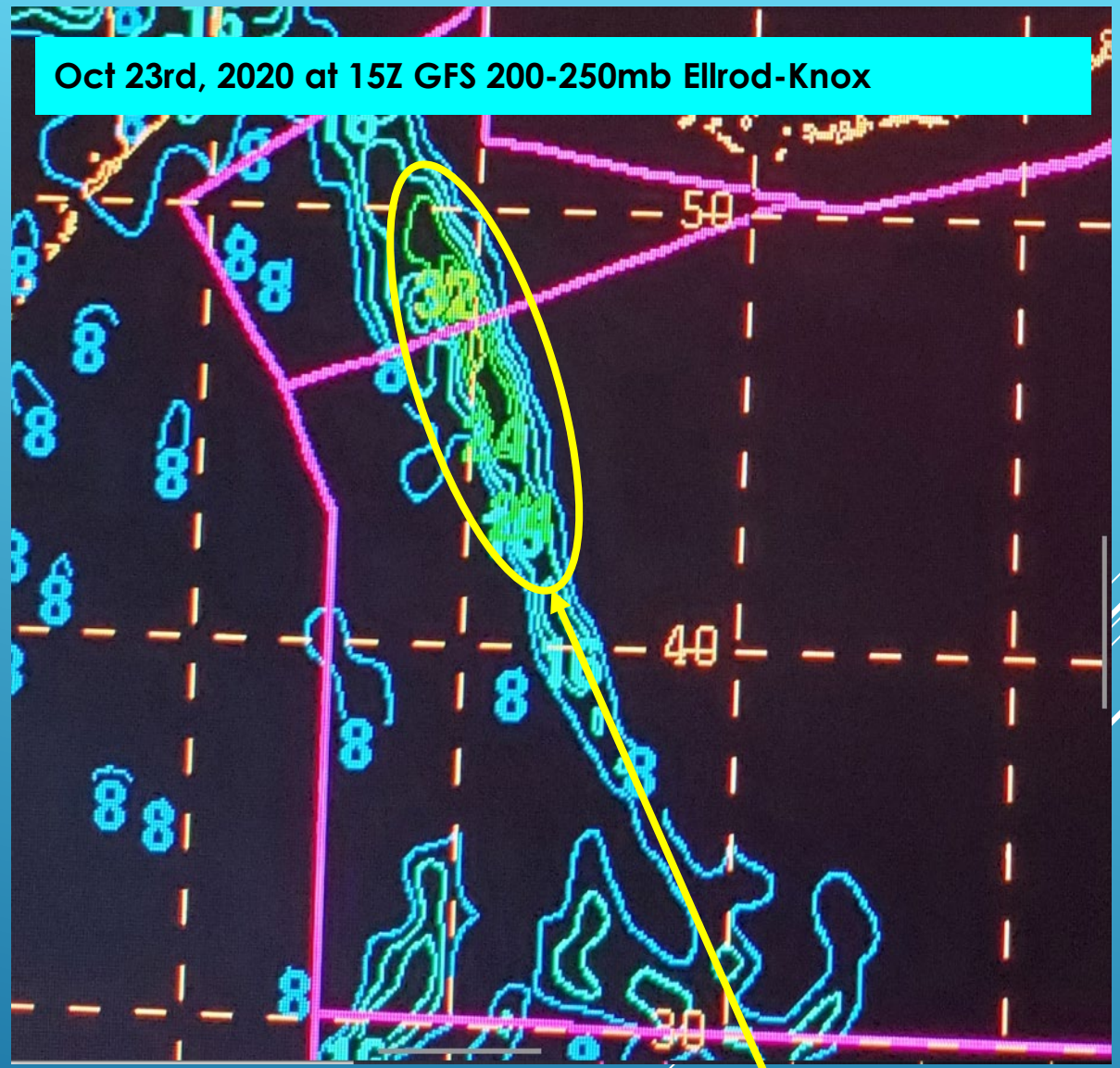
Oct 23rd, 2020 at 12Z with GFS 300-350mb Ellrod-Knox indices leave no doubt for severe turbulence coupled with strong northwest jetcore through this region.

Oct 23rd, 2020 at 15Z GFS Max Wind Level Isotachs, Streamlines



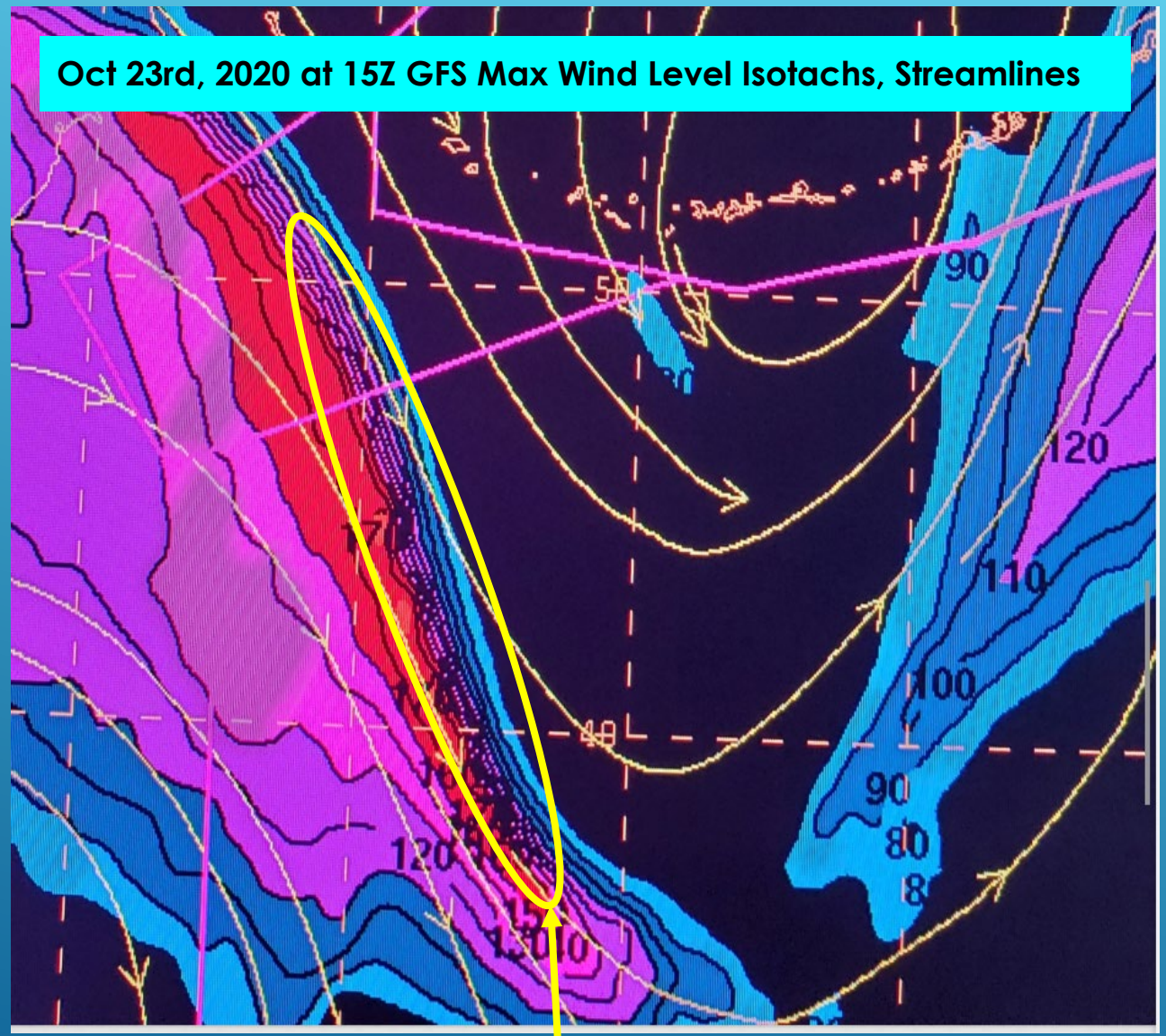
Oct 23rd, 2020 at 15Z with GFS Jetstreak MaxWnds & Streamlines continue to dive southeastward as it digs into the base of trough.

Oct 23rd, 2020 at 15Z GFS 200-250mb Ellrod-Knox



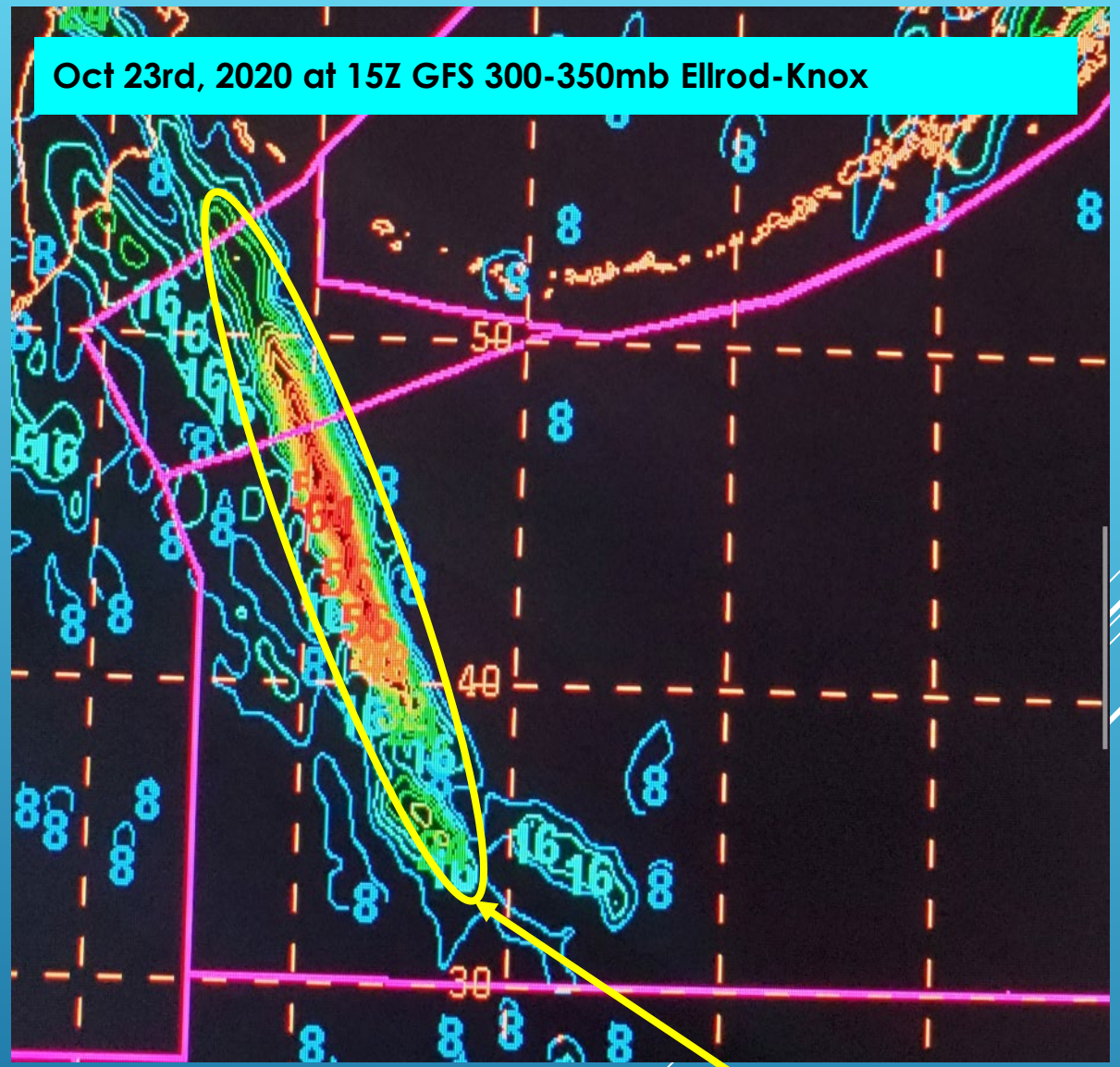
Oct 23rd, 2020 at 15Z with GFS 200-250mb Ellrod-Knox indices remained pretty close the same from the previous 200-250mb Ellrod-Knox indices from 23/12Z.

Oct 23rd, 2020 at 15Z GFS Max Wind Level Isotachs, Streamlines

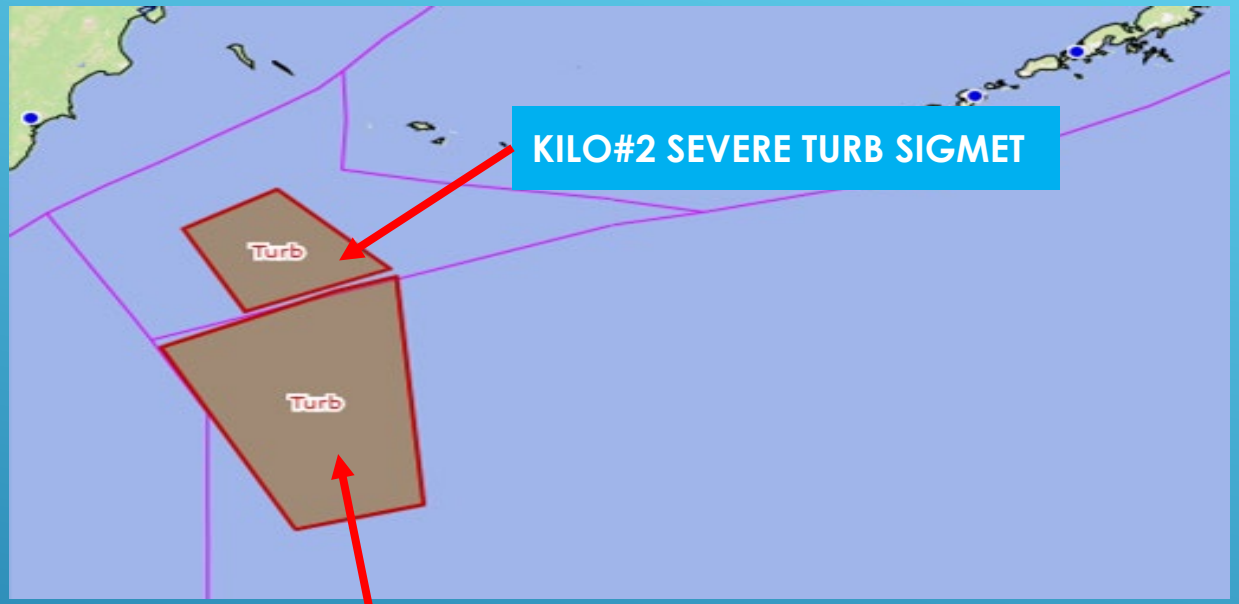


Oct 23rd, 2020 at 15Z with GFS Jetstreak MaxWnds & Streamlines continues to show great dynamics for producing possible severe turbulence.

Oct 23rd, 2020 at 15Z GFS 300-350mb Ellrod-Knox



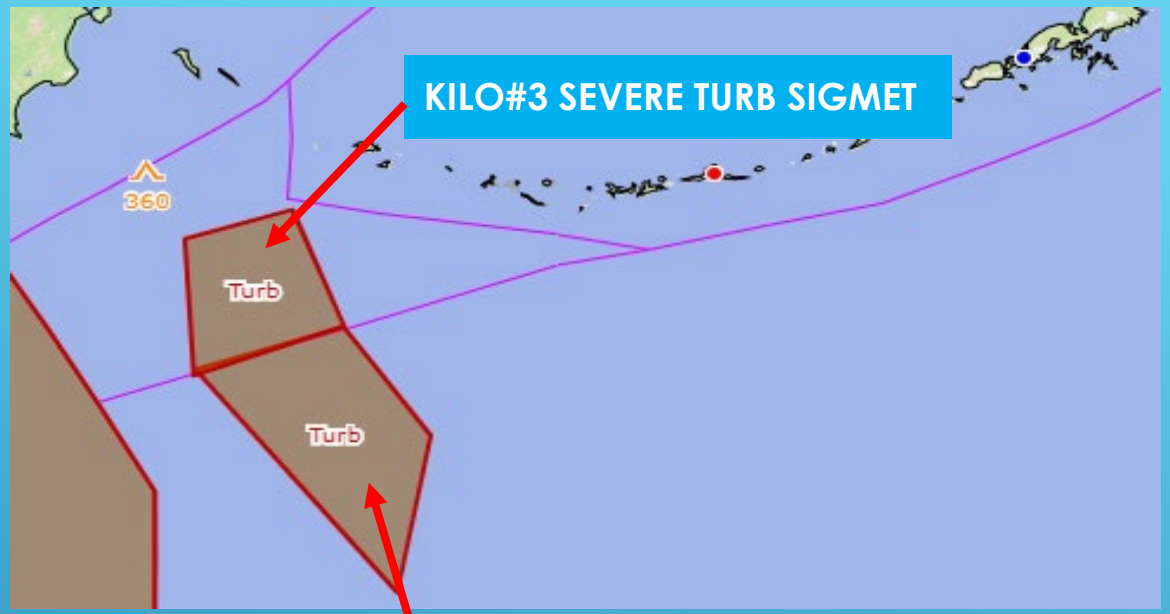
Oct 23rd, 2020 at 15Z with GFS 300-350mb Ellrod-Knox indices remain fantastic for potential severe turbulence and same as 300-350mb Ellrod-Knox from 23/12Z.



TURB SIGMET

FIR Id: KZAK
FIR Name: OAKLAND OCEANIC
Hazard: TURB - SEV
Begins: 2020-10-23T11:15:00Z
Ends: 2020-10-23T15:15:00Z
Top: 42000 ft
Base: 35000 ft
Move: E
Speed: 30 kt
Change: INTSF

WSPN04 KKCI 231115
SIGP0D
KZAK SIGMET DELTA 3 VALID 231115/231515 KKCI-
OAKLAND OCEANIC FIR SEV TURB FCST WI N4800 E17200 - N3930 E17300
- N3830 E16815 - N4530 E16315 - N4730 E16945 - N4800 E17200.
FL350/420. MOV E 30KT. INTSF.



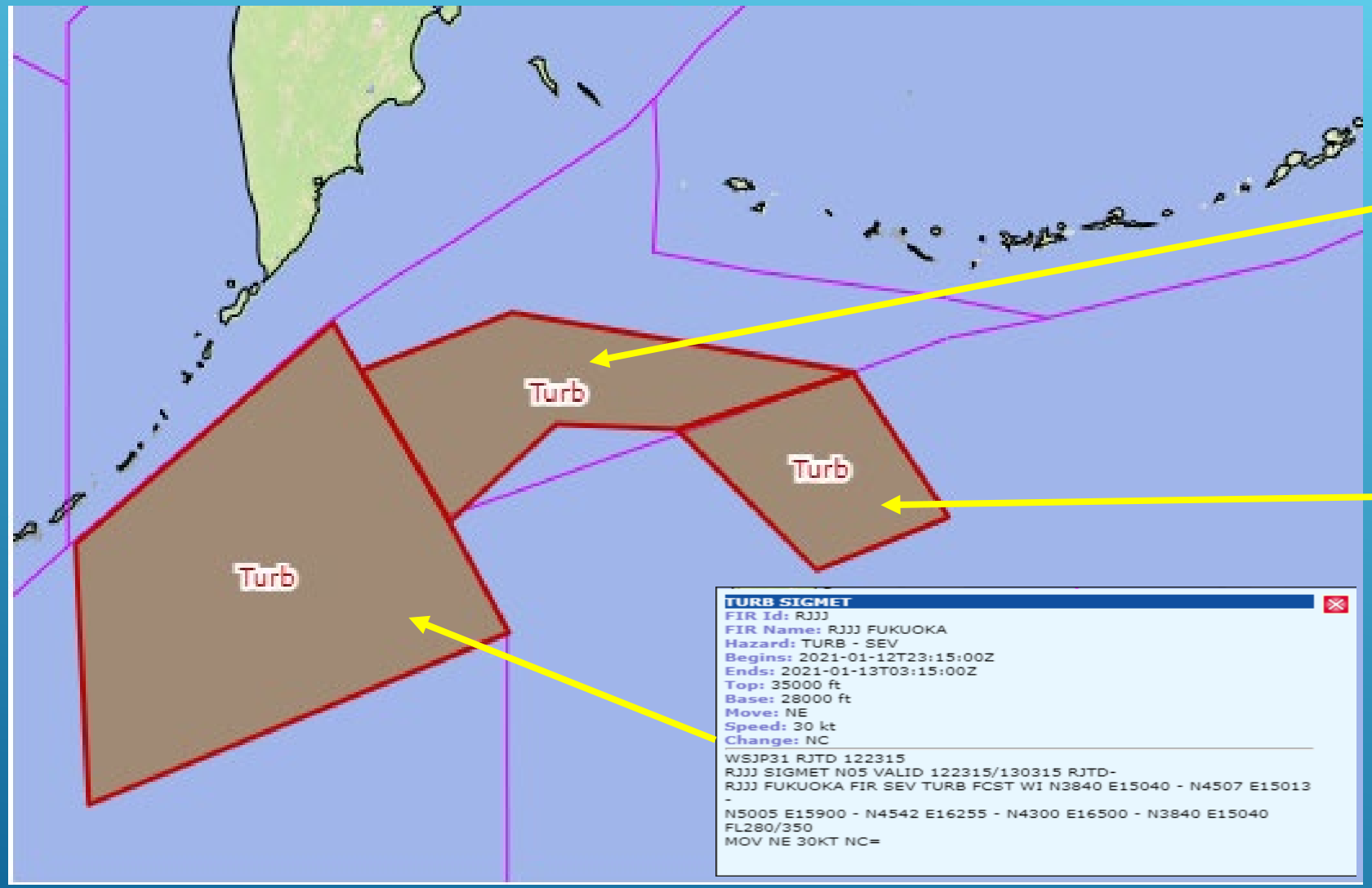
TURB SIGMET

FIR Id: PAZA
FIR Name: OAKLAND OCEANIC FIR ANCHORAGE
Hazard: TURB - SEV
Begins: 2020-10-23T15:10:00Z
Ends: 2020-10-23T19:10:00Z
Top: 40000 ft
Base: 25000 ft
Move: ENE
Speed: 30 kt
Change: NC

WSPN04 KKCI 231510
SIGP0D
KZAK PAZA SIGMET DELTA 4 VALID 231510/231910 KKCI-
OAKLAND OCEANIC FIR ANCHORAGE FIR SEV TURB FCST WI N4800 E17200 -
N4445 E17515 - N3945 E17400 - N4645 E16630 - N4800 E17200.
FL250/400. MOV ENE 30KT. NC.

The dayshift for Tropical desk did a great job coordinating with the AAWU office with the reissuance of the Delta#3 Severe Turbulence Sigmet to Delta#4.

SEVERE TURBULENCE EVENT ON JAN 13TH, 2021 THRU THE OCEANIC ANCHORAGE & OAKLAND & TOKOYO FIR'S



TURB SIGMET
FIR Id: PAZA
FIR Name: ANCHORAGE OCEANIC
Hazard: TURB - OCNL
Begins: 2021-01-13T02:00:00Z
Ends: 2021-01-13T06:00:00Z
Top: 35000 ft
Base: 25000 ft
Move: E
Speed: 40 kt
Change: INTSF

WSAK01 PAWU 130200
SIGAK1
ANCI WS 130200
PAZA SIGMET INDIA 1 VALID 130200/130600 PANC-
ANCHORAGE OCEANIC FIR OCNL SEV TURB FCST WI N5018 E16507 - N4901
E17645 - N4745 E17047 - N4752 E16637 - N4539 E16300 - N4903 E15958 -
N5018 E16507. FL250/FL350. MOV E 40KT. INTSF.
SEV TURB THREAT ASSOC W/STG SHEAR IN UPPER-RDG.

JAM JAN 2021 AAWU

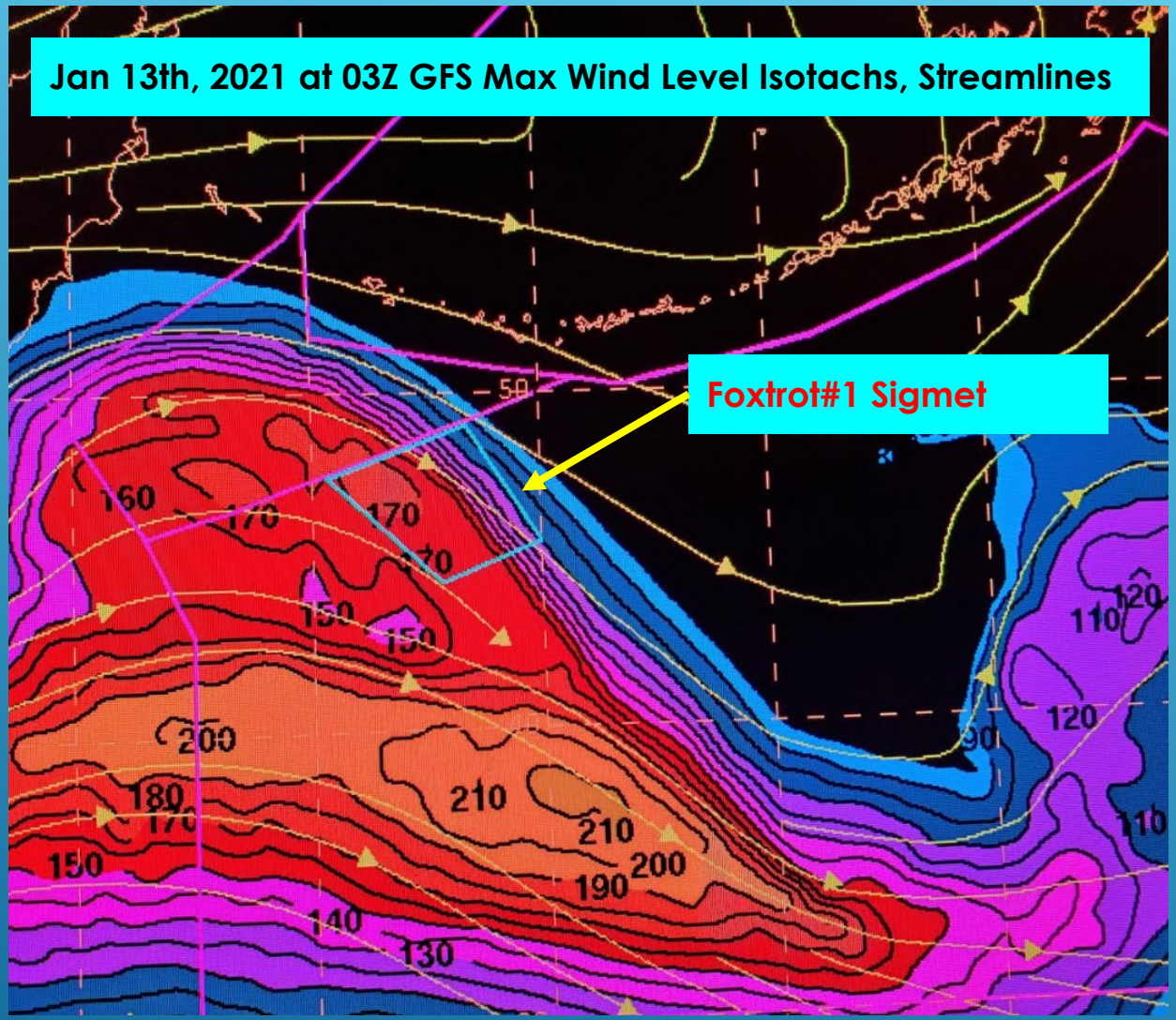
TURB SIGMET
FIR Id: RJJJ
FIR Name: RJJJ FUKUOKA
Hazard: TURB - SEV
Begins: 2021-01-12T23:15:00Z
Ends: 2021-01-13T03:15:00Z
Top: 35000 ft
Base: 28000 ft
Move: NE
Speed: 30 kt
Change: NC

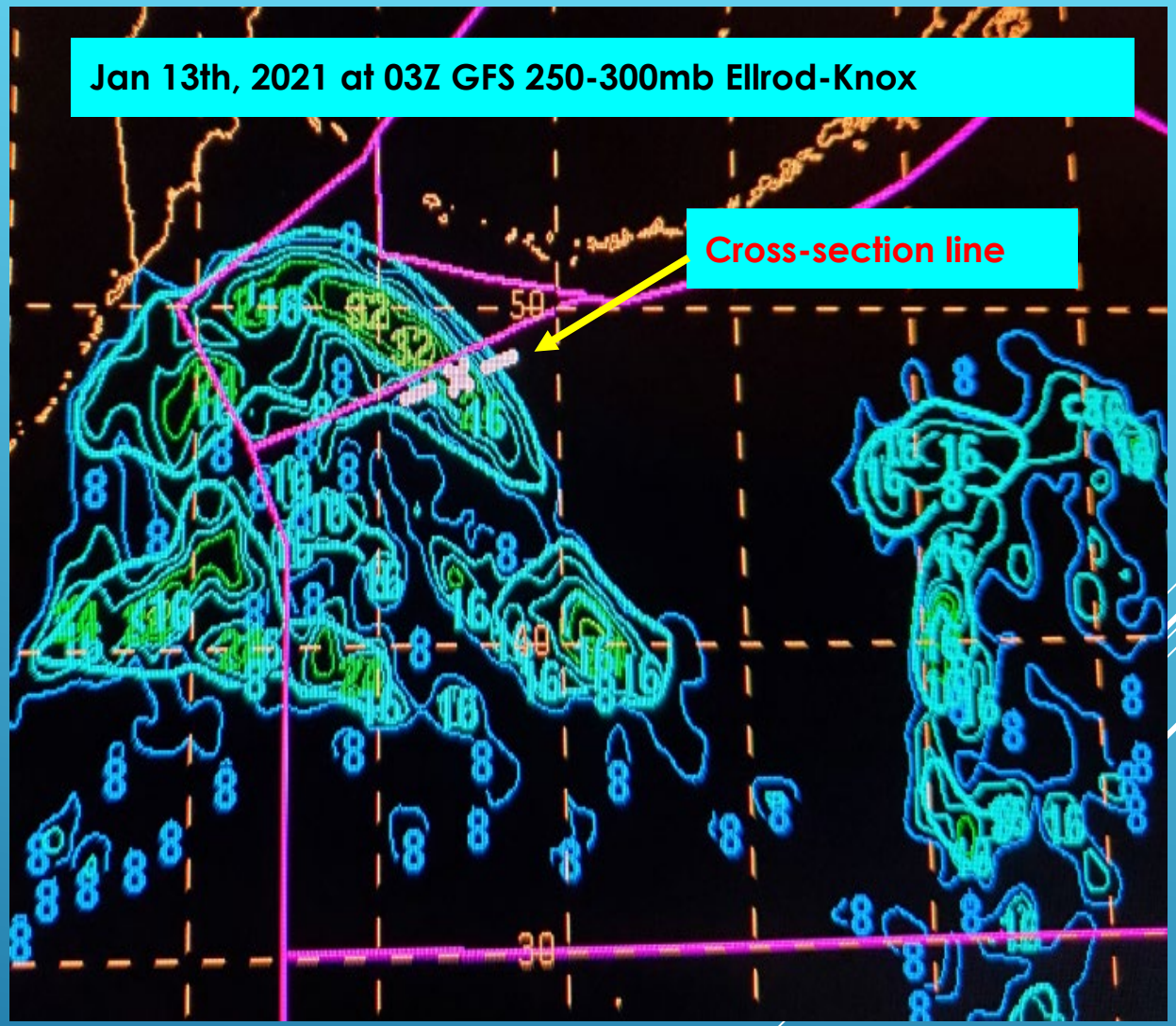
WSJP31 RJTD 122315
RJJJ SIGMET N05 VALID 122315/130315 RJTD-
RJJJ FUKUOKA FIR SEV TURB FCST WI N3840 E15040 - N4507 E15013 -
N5005 E15900 - N4542 E16255 - N4300 E16500 - N3840 E15040
FL280/350
MOV NE 30KT NC=

TURB SIGMET
FIR Id: KZAK
FIR Name: OAKLAND OCEANIC
Hazard: TURB - SEV
Begins: 2021-01-13T01:45:00Z
Ends: 2021-01-13T05:30:00Z
Top: 35000 ft
Base: 25000 ft
Move: ESE
Speed: 40 kt
Change: INTSF

WSPN06 KKCI 130145
SIGP0F
KZAK SIGMET FOXTROT 1 VALID 130145/130545 KKCI-
OAKLAND OCEANIC FIR SEV TURB FCST WI N4900 E17645 - N4545 W18000
- N4430 E17530 - N4745 E17045 - N4900 E17645. FL250/350. MOV ESE
40KT. INTSF.

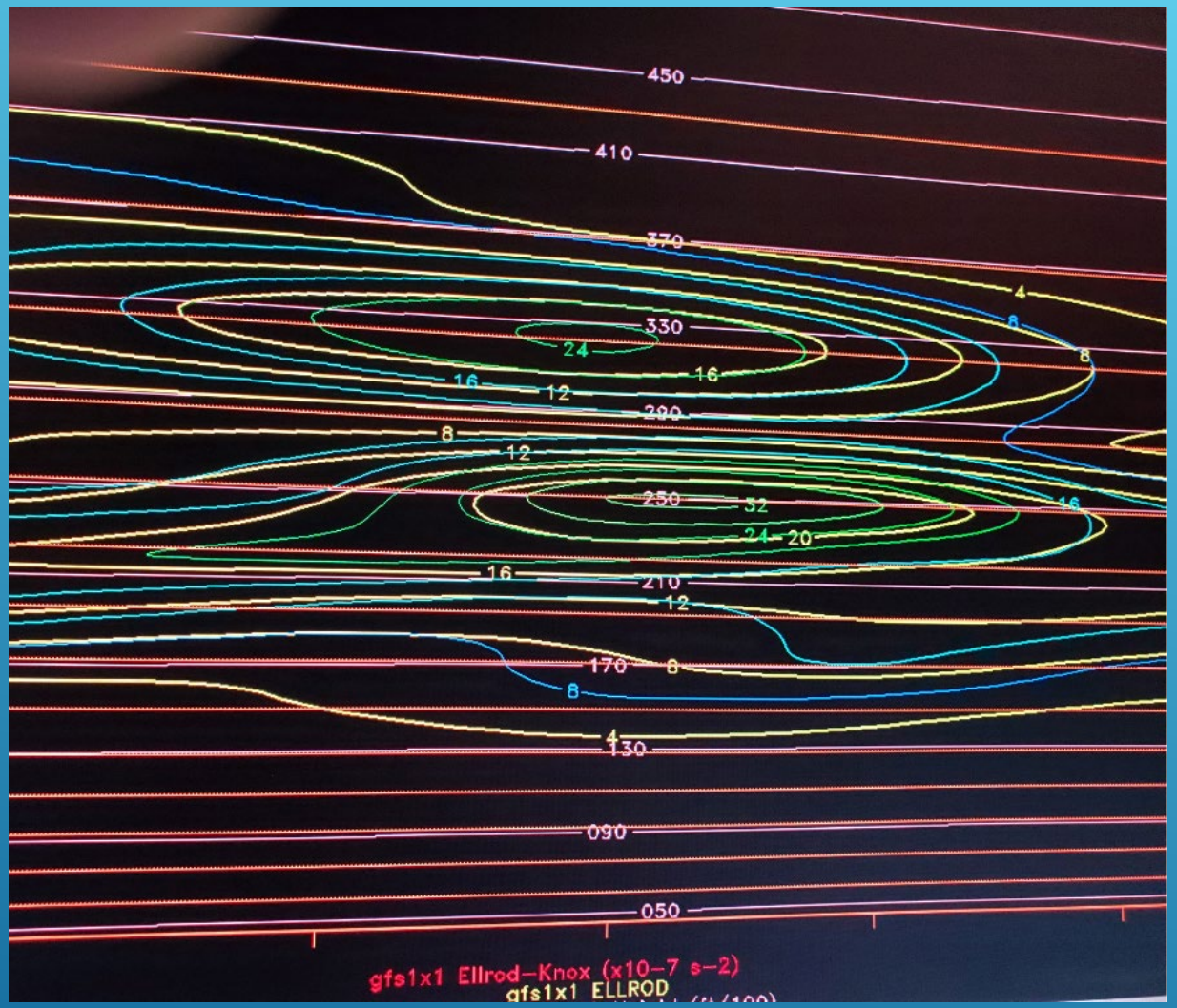
We had another strong northwesterly jet thru SW Oceanic Anchorage FIR moving through the northwest Oakland FIR. We never had any severe turb pireps for this event. We had great coordination between the AAWU and AWC offices during this event.



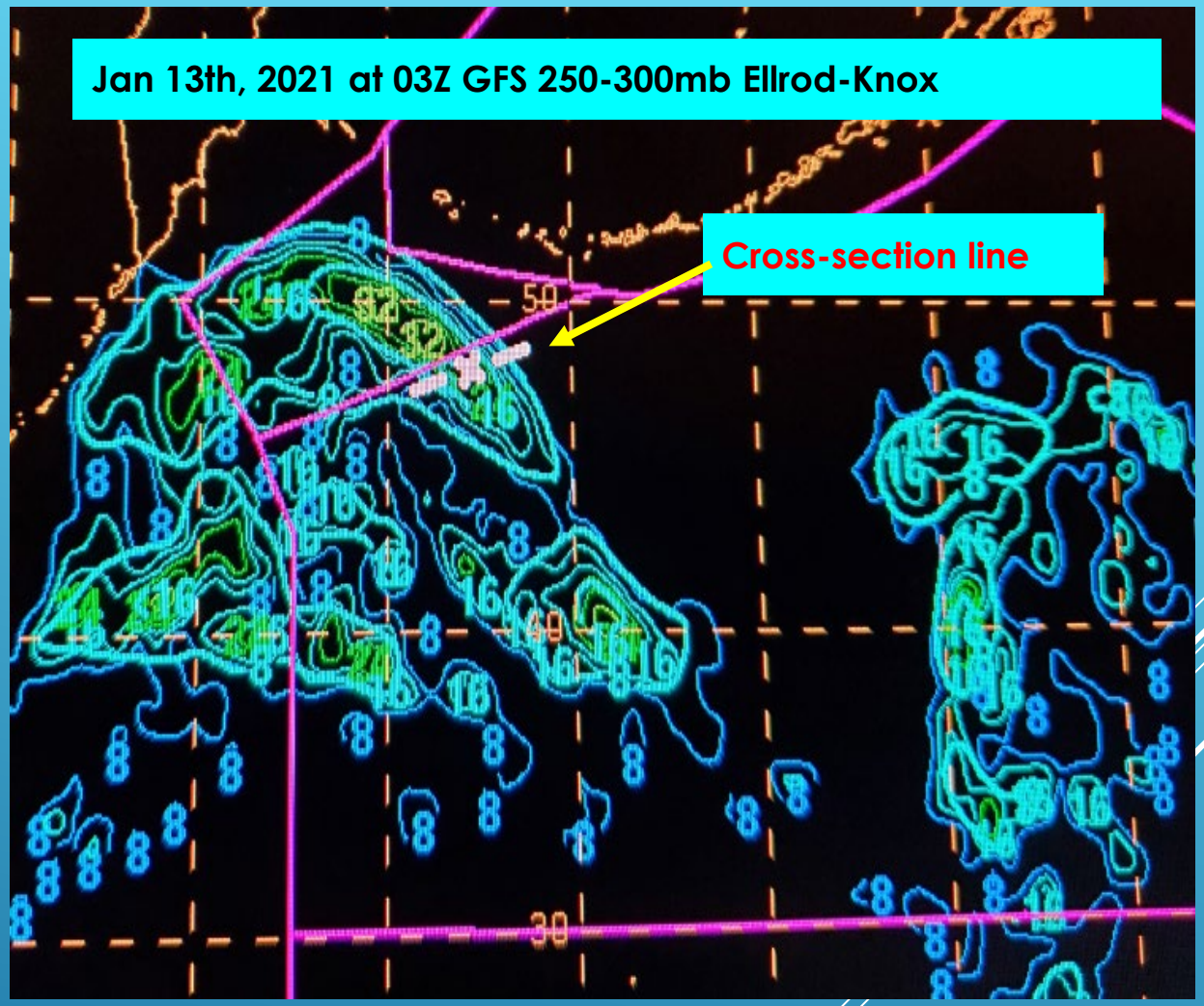


Jan 13rd, 2021 at 03Z with GFS Jetstreak MaxWnds & Streamlines strong northwesterly 170 knot jetstreak that is moving over the anticyclonic ridge.

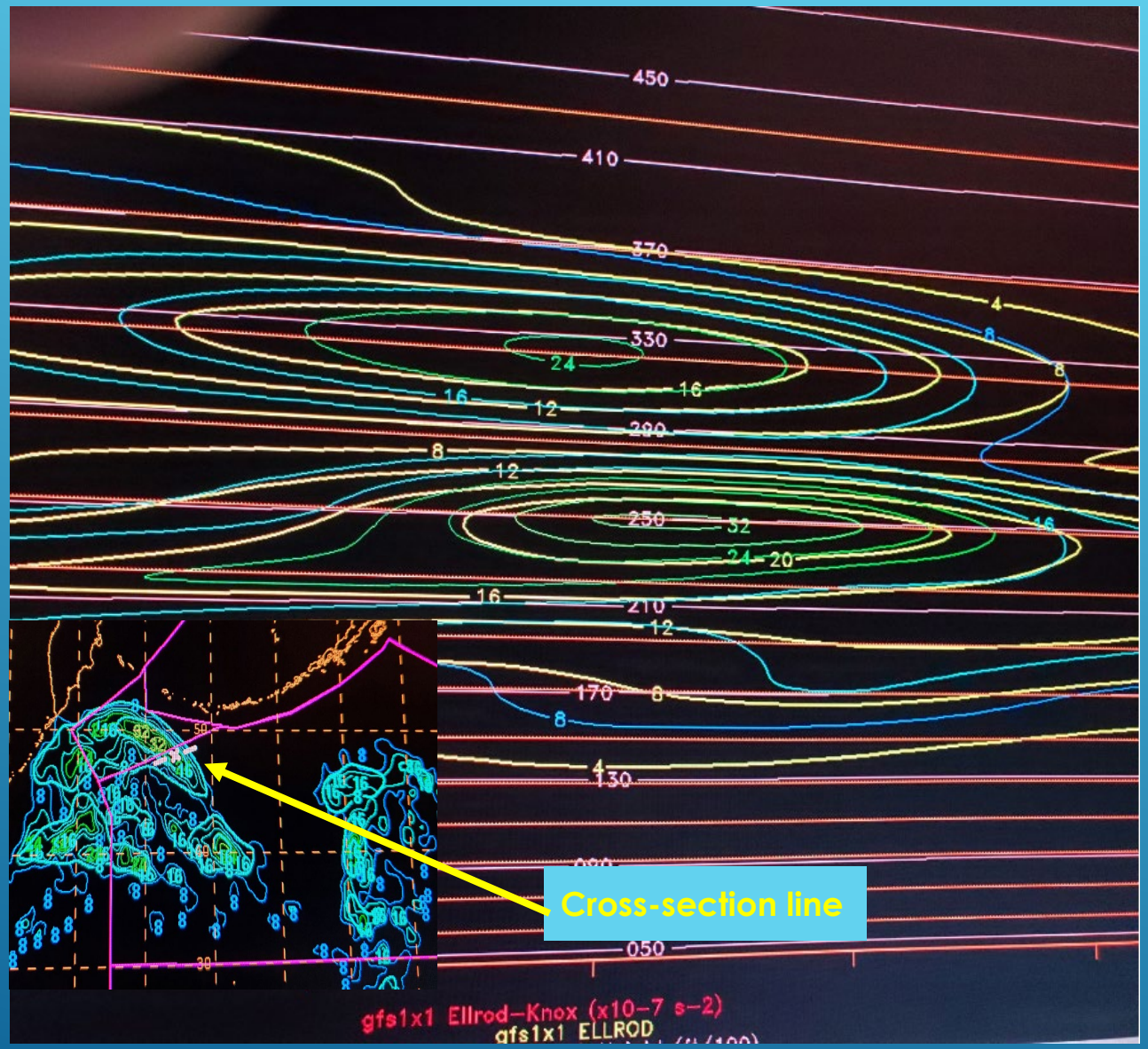
GFS ELLROD & ELLROD-KNOX 250-300mb on Jan13th, 2021 at 03Z indices were showing the potential for moderate to severe turbulence.



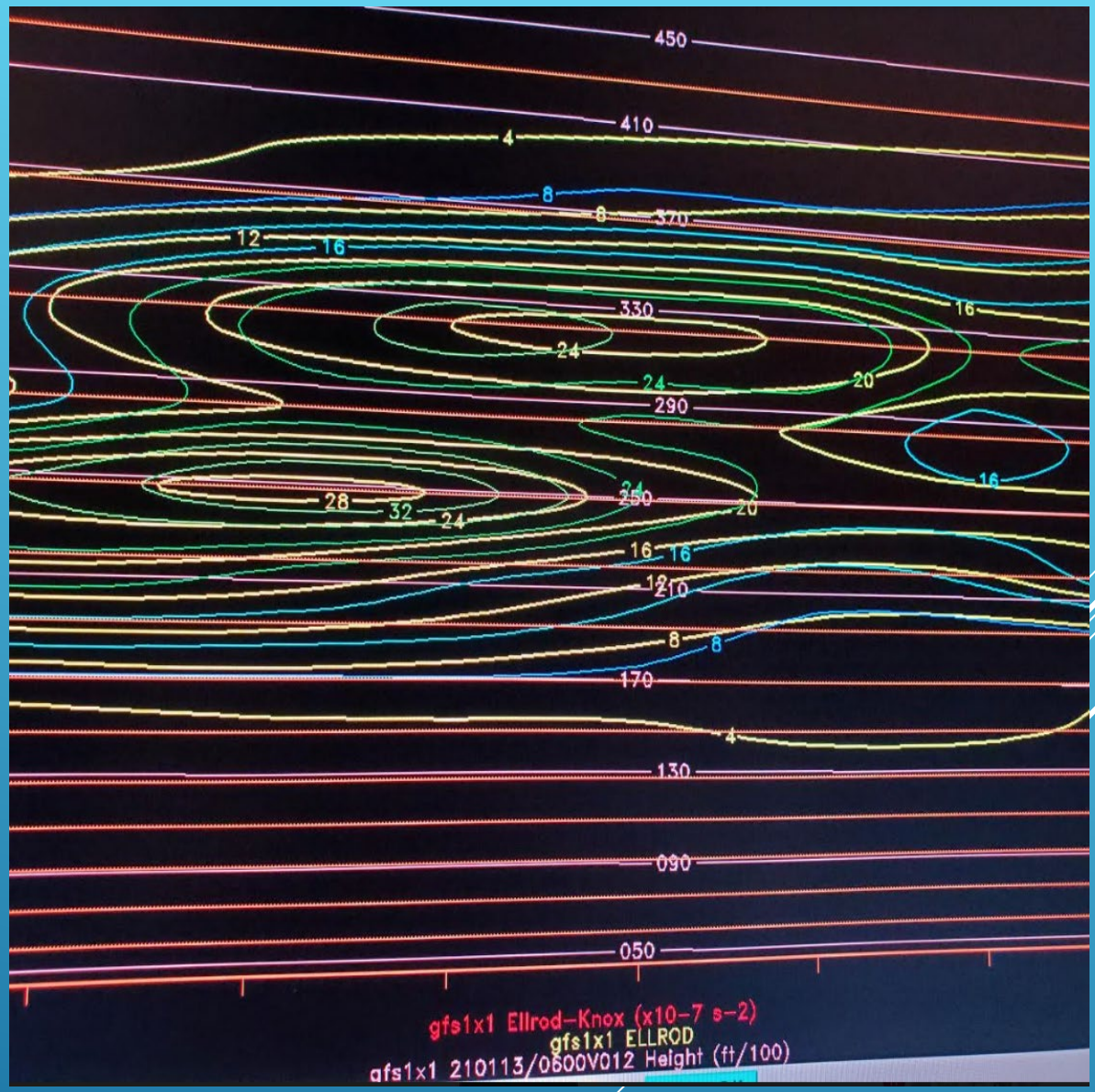
GFS ELLROD & ELLROD-KNOX cross-section for Jan 13rd/2021 at 03Z with the cross-section line shown where it was drawn on the right image.



GFS ELLROD & ELLROD-KNOX 250-300mb on Jan 13, 2021 at 03Z. The AAWU SW Oceanic Anchorage FIR had stronger turbulence indices but they will be moving into the Oakland FIR as the northwest jetstreak continues to move southeast into the Pacific Ocean.



GFS ELLROD & ELLROD-KNOX 250-300mb on Jan 13, 2021 at 03Z



GFS ELLROD & ELLROD-KNOX 250-300mb on Jan 13, 2021 at 06Z

CONCLUSION: SEVERE TURBULENCE ON OCT 23rd, 2020 -- SW OCEANIC ANCHORAGE and Northwest OAKLAND OCEANIC FIRS

- Strong northwesterly 180 knot jetstreak riding over an amplified anticyclonic ridge.
- The 180 knot jetstreak was beginning to dig into the base of the upstream trough.
- The GFS Ellrod and Ellrod-Knox indices at 300 to 350mb greatly intensified within a 6 hr time-frame as the jetstreak became more northwesterly coupled with the ridge becoming more amplified.
- There were 5 severe turb pireps reported in a 2 hr window in proximity of the 180 knot jetcore.
- Maintain strong relationships with fellow Aviation offices, which in this case study the Aviation Lead in the AAWU office caught my error in plotting of the Delta#1 Severe Turbulence Sigmet.

CONCLUSION: SEVERE TURBULENCE ON Jan 13th, 2021 -- SW OCEANIC ANCHORAGE and Northwest OAKLAND OCEANIC FIRS

- This case study had similar dynamics as the Oct 23rd, 2020 severe turbulence event through the same FIRs.
- Strong northwesterly 170 knot jetstreak riding over anticyclonic ridge. The ridge didn't get as amplified as previous case study.
- The GFS Ellrod and Ellrod-Knox indices at 300 to 350mb were not as strong but still potential for possible moderate to severe turbulence.
- There were no severe turbulence pireps reported in both the NW Oakland and SW Oceanic Anchorage FIRs during this event.

Severe Low Level Icing
Vicinity of ORD

Nov 30, 2020

Prepared by Robb Kaczmarek & Andrew Snyder

Specifics:

- Shallow cloud layer:
  - Bases: 2,500’ – 3,500’, Tops: 7,000’ – 8,000’
  - Thickest over Lake Michigan (lake effect)
  - Stratocumulus over/near Lake Michigan (steep 1000-850 lapse rates)

- Subtle wind changes an important factor:
  - Gusty NNW winds AM backed NW PM
  - West Flow config favored at ORD
  - Icing avoidance resulted in period of East Flow as winds allowed

- Minimal precipitation at ORD (spotty flurries, runways dry)

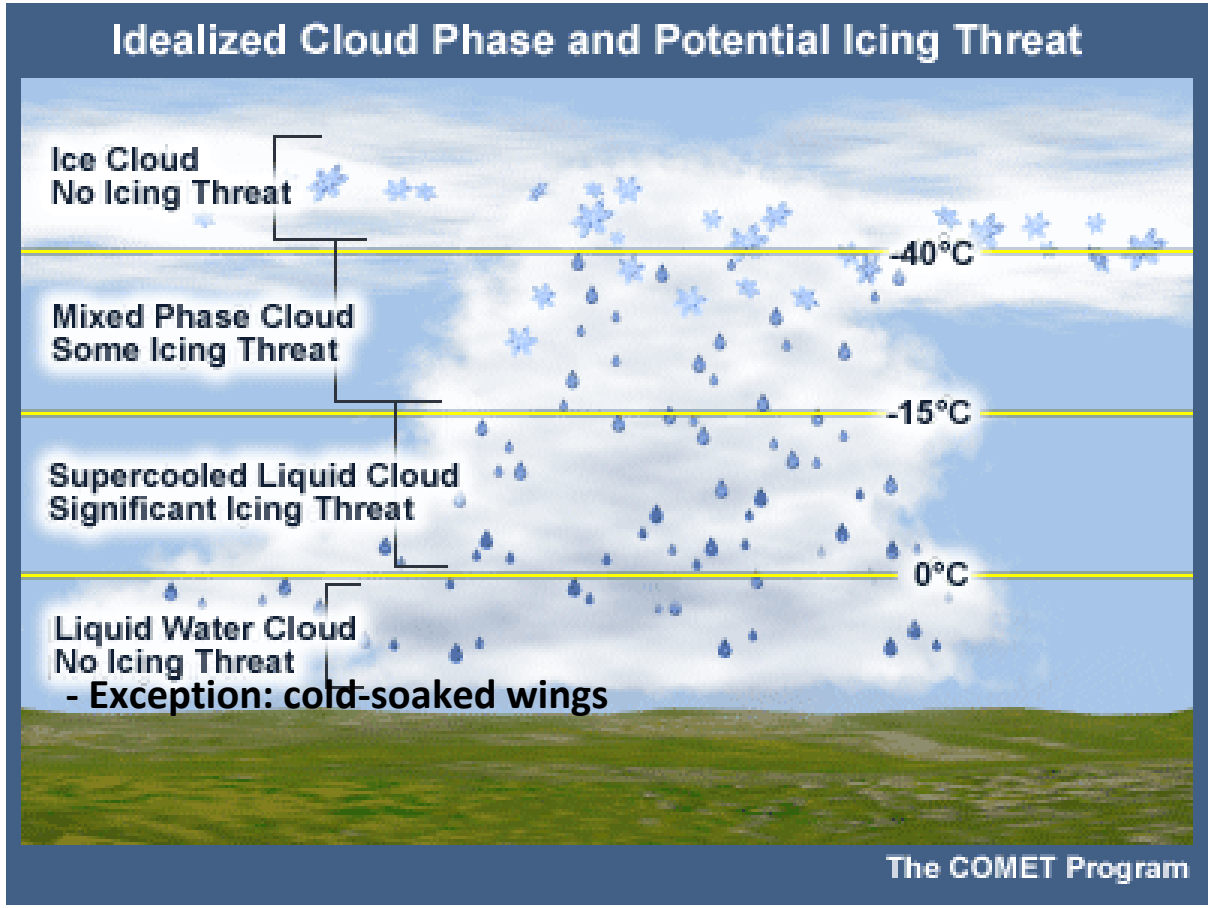
Specifics (cont):

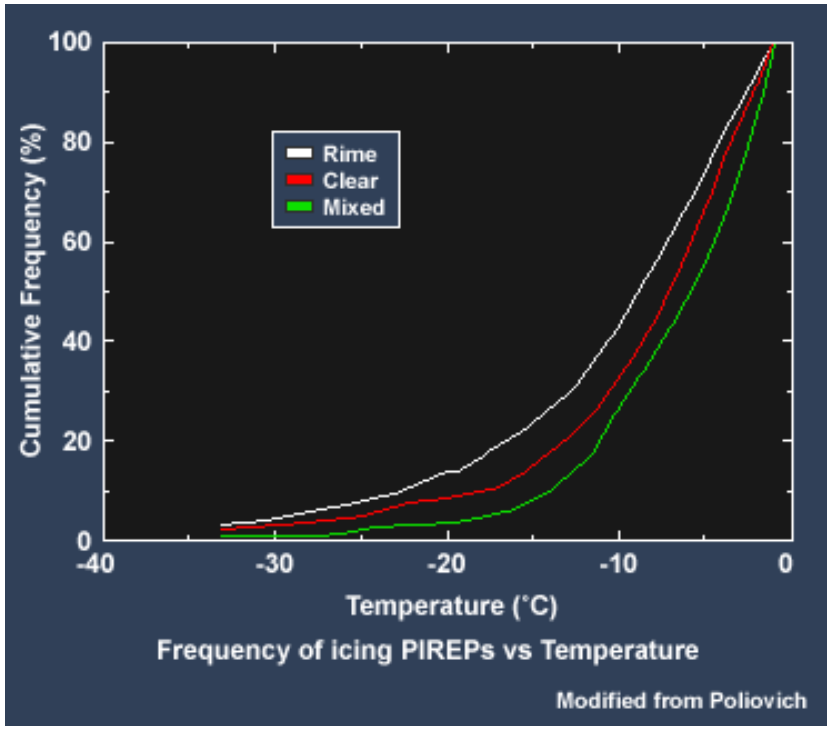
- Numerous/frequent MOD icing reports 3,000’ – 7,500’
  - Mostly rime or mixed ice, several clear
    - Phase mainly supercooled liquid, but some ice present
    - In-cloud temperatures -13.5°C or warmer

- Six SEV icing reports near ORD 3,500’ – 5,000’
  - Chicago TRACON (C90) avoidance helped mitigate risk
    - Revealed importance of timely PIREPs and forecast updates

- Surface temperatures at ORD fell below freezing → de-icing necessary
  - Significant operational impacts for UAL

Forecast Considerations
Cloud Microphysics and Icing Risk

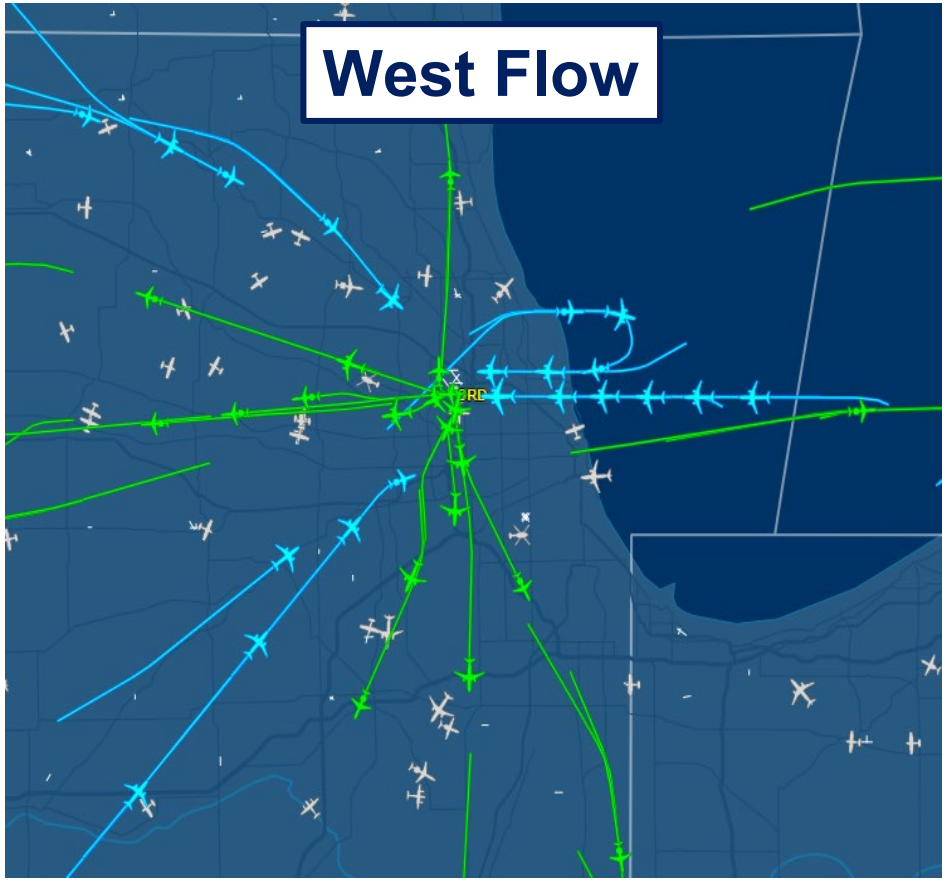


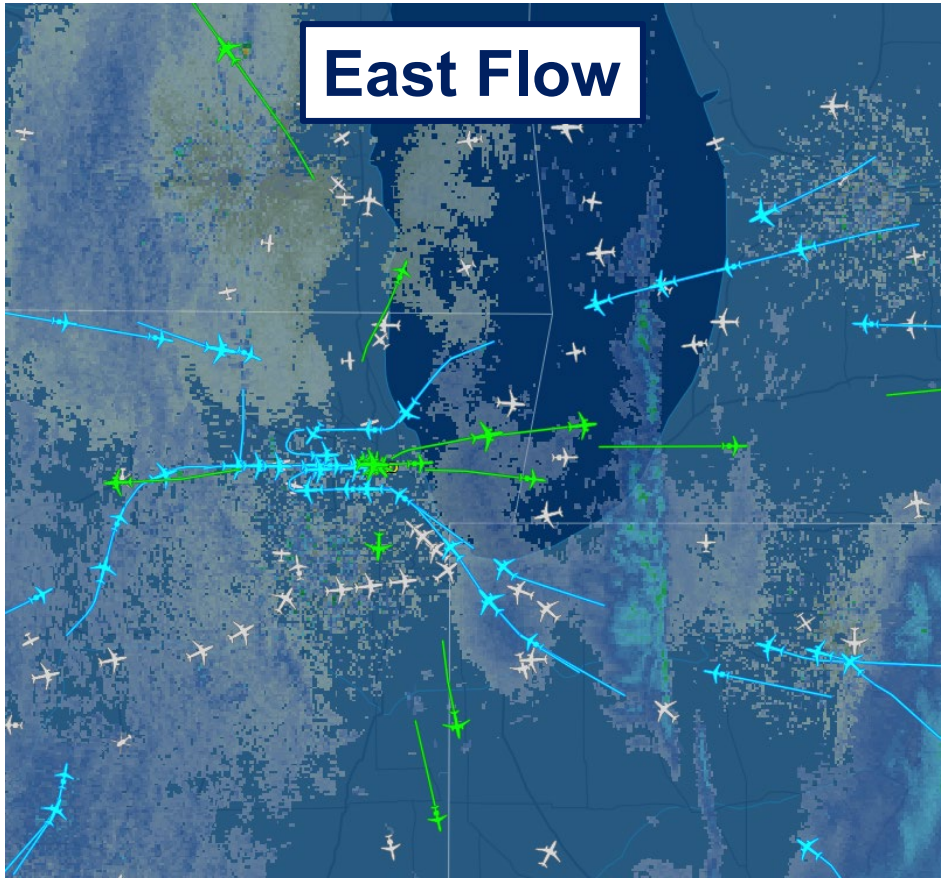


- **Relatively few icg PIREPs colder than -30°C**
- **Majority 0 to -15°C**

Images courtesy UCAR METED Program

Forecast Considerations - Airspace

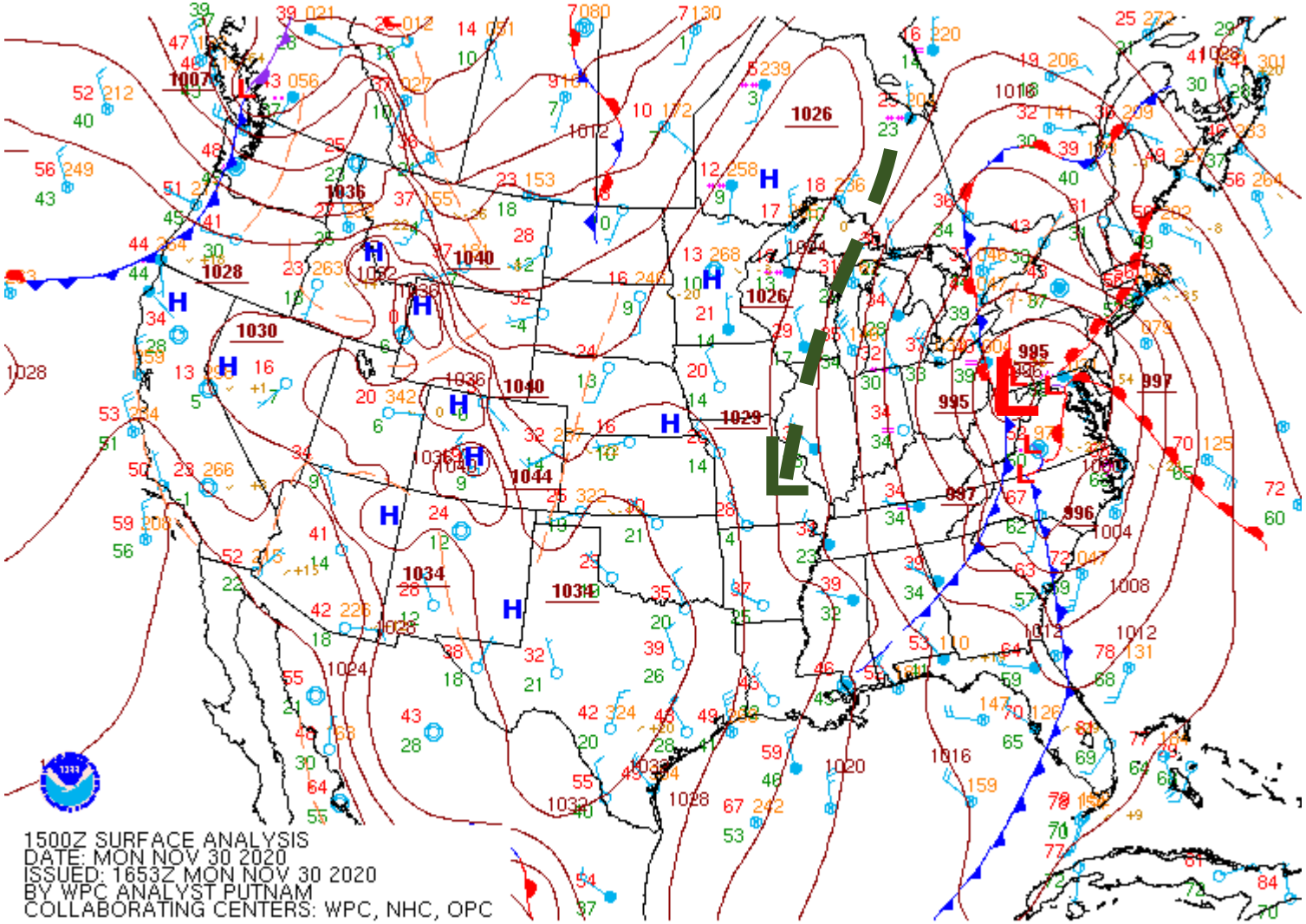




Images courtesy FlightAware

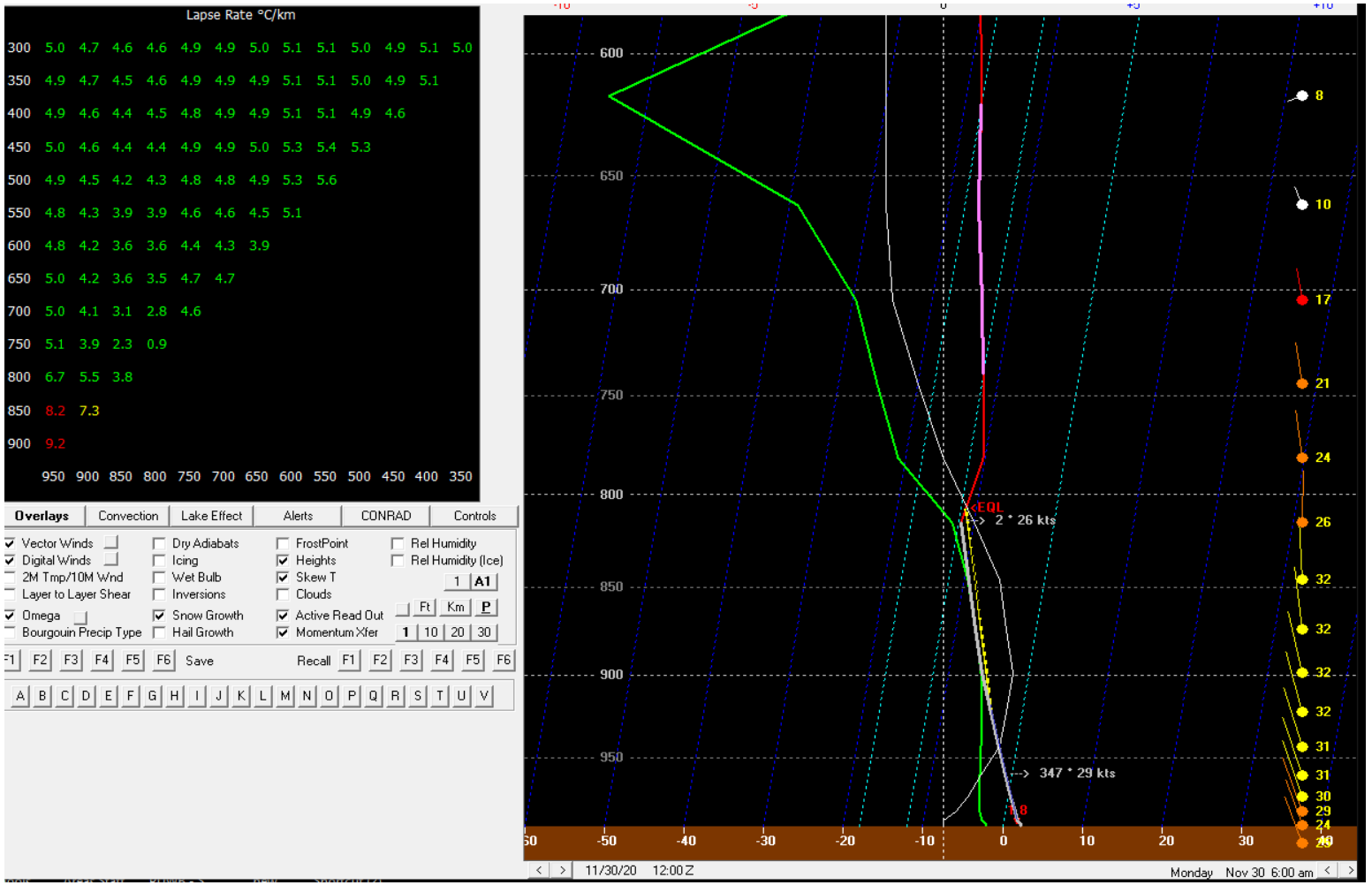
Synoptic Pattern

- Strengthening surface low in the East
- Surface high Ontario to Texas
- Persistent 500mb trough axis ~GRB to STL
- Continued low-level CAA through the day



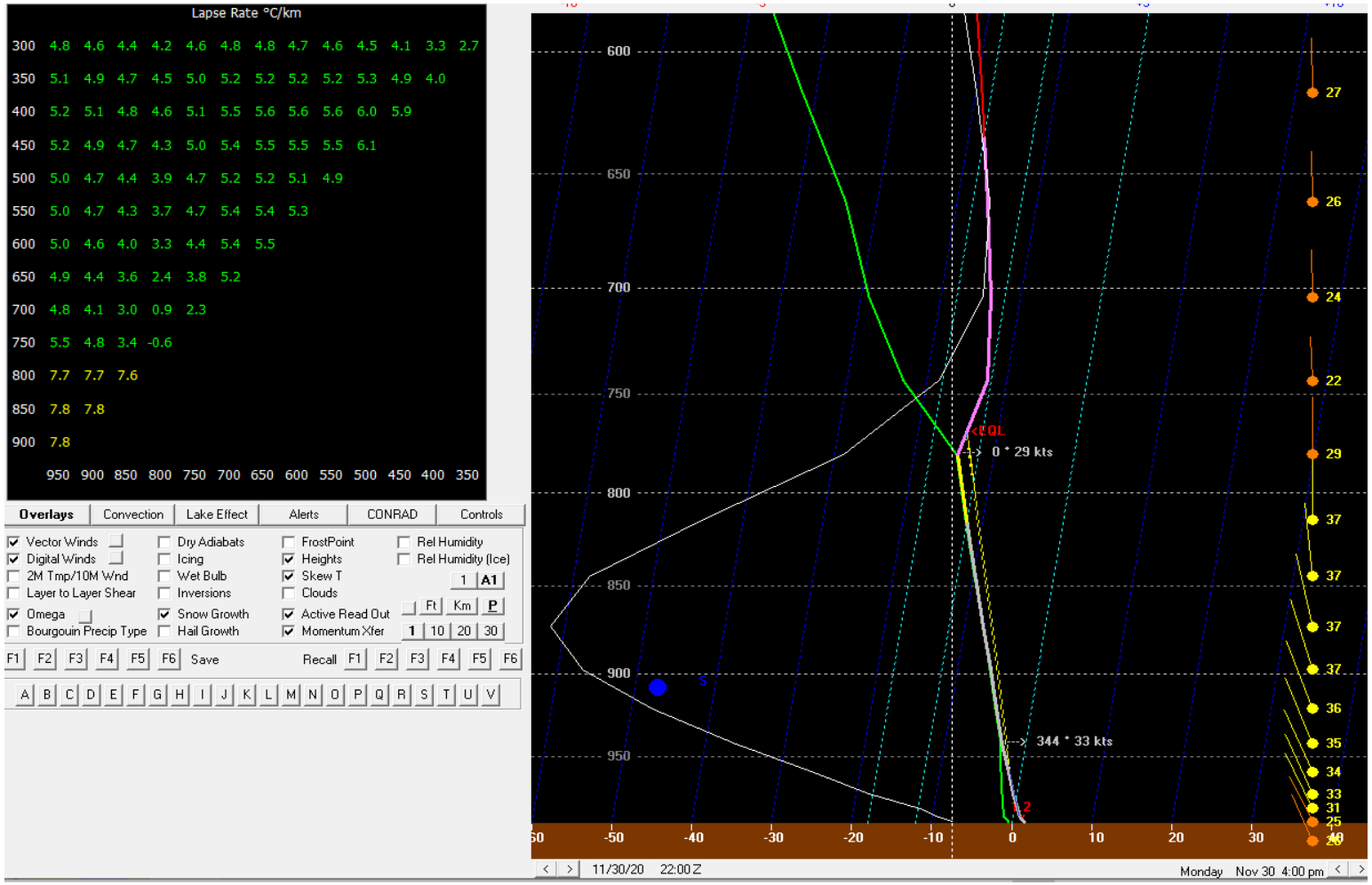
Forecast Sounding

- Forecast valid 12Z at LM2 (S Lk MI buoy)
- Steep Sfc-850hPa lapse rates
- Saturation -4° to -10°C



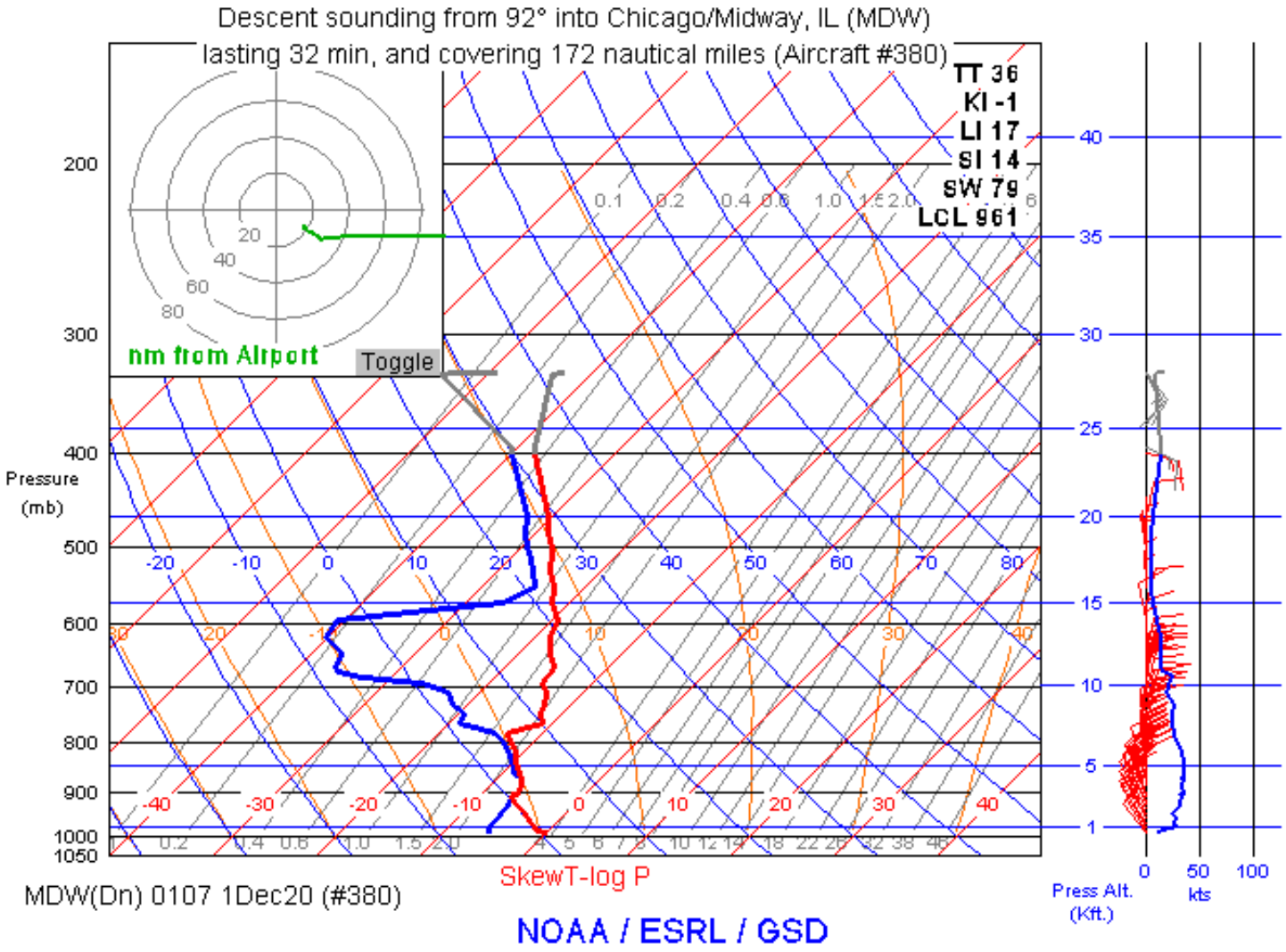
Forecast Sounding

- Forecast valid 22Z at LM2
- Sfc-850hPa lapse rates weaken slightly
- Saturation -5° to -12°C
- Max lift near 875hPa



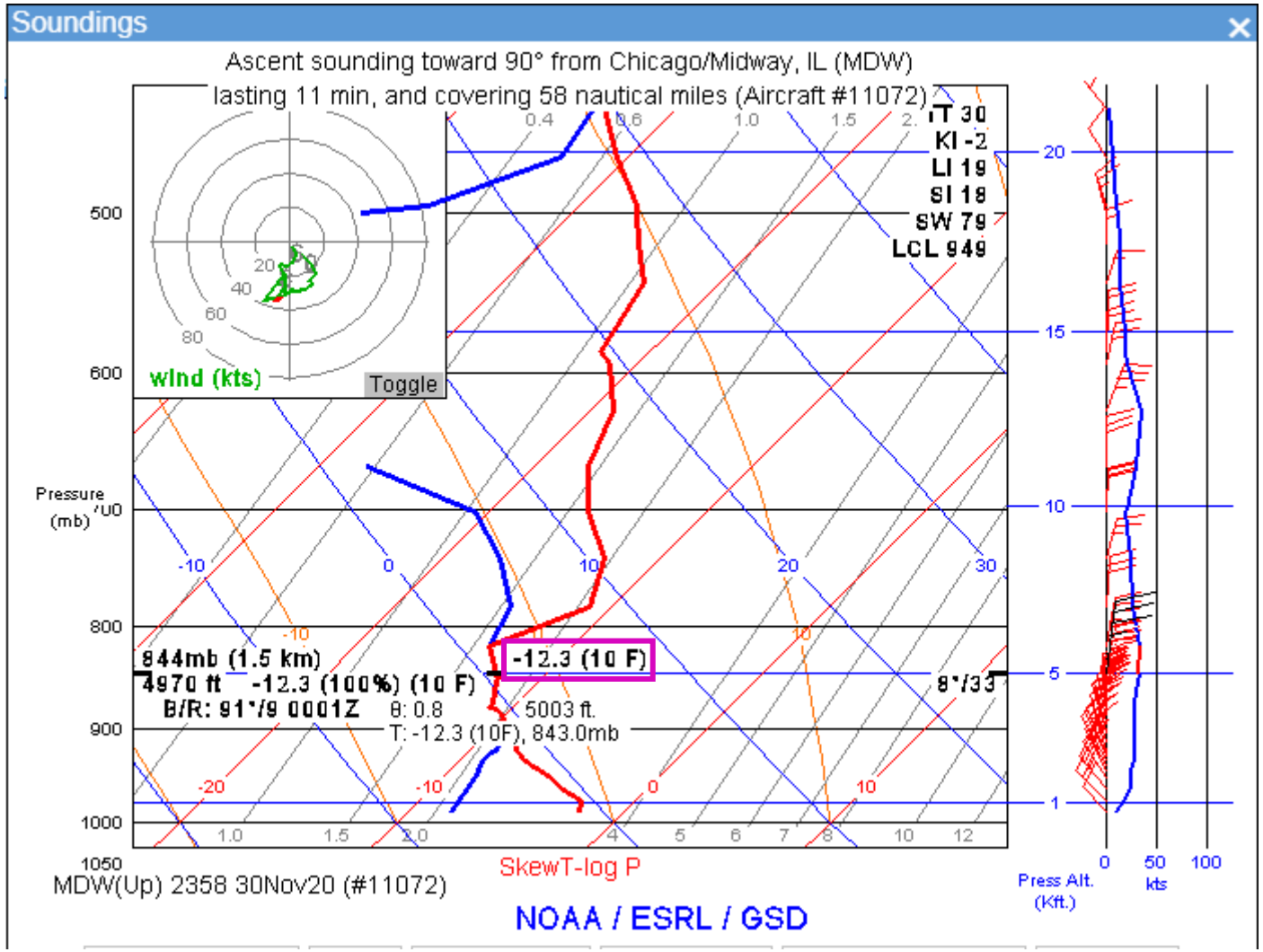
AMDAR MDW Arrival Sounding

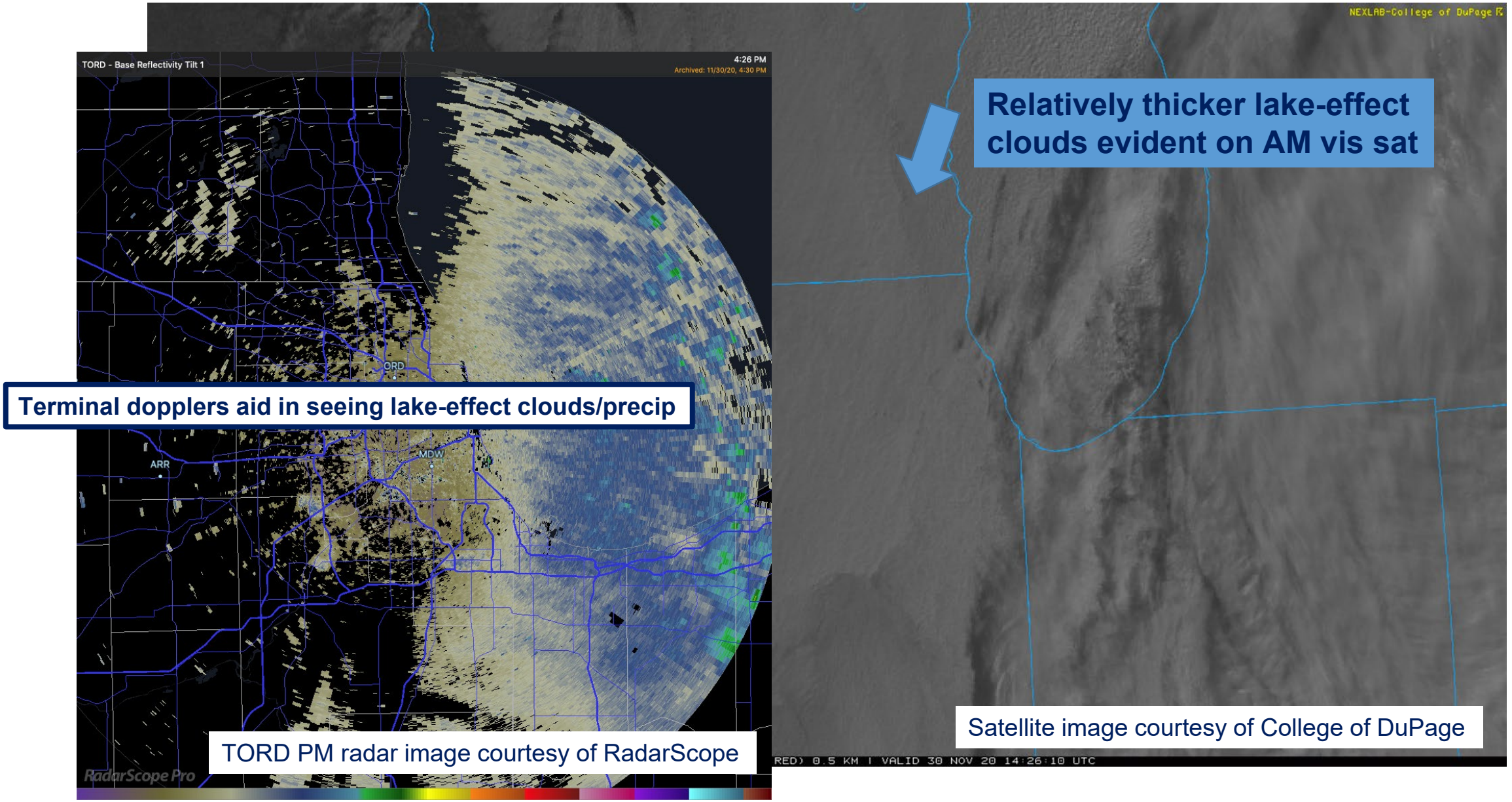
- MDW arrival traveled through lake-effect plume
- Saturation of a ~100hPa thick layer
- Unlikely that lake-effect precip being seeded by mid/high clouds (verified by radar)



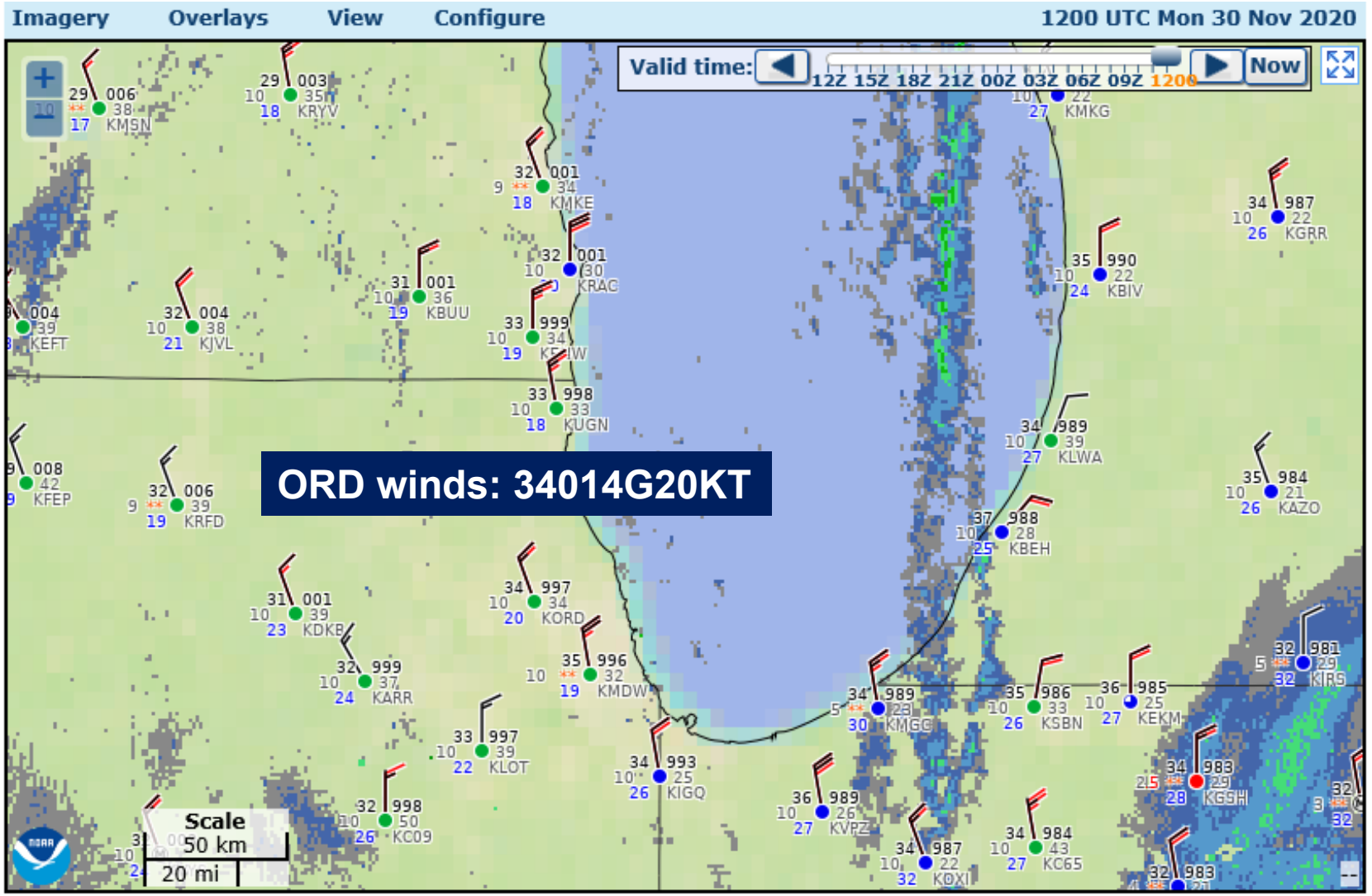
AMDAR MDW Departure Sounding

- Saturation of a ~100hPa thick layer, from ~ -8.0°C to -13.5°C
- NW winds in boundary layer
- N-NNE winds above
- Worst icing PIREPs 4,000 – 5,000’
  - Temperatures of -11° to -13°C

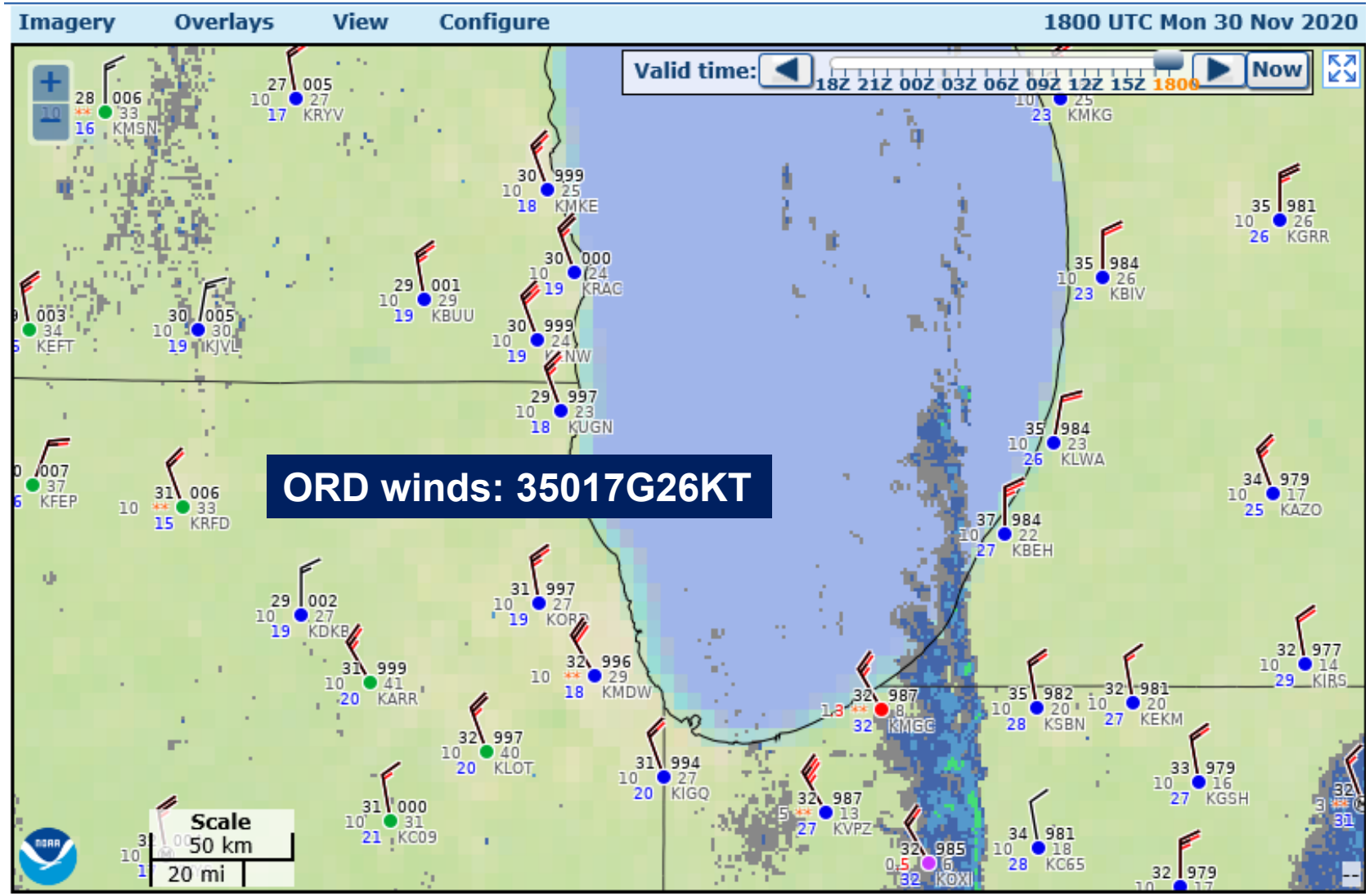



TORD - Base Reflectivity Tilt 1
4:26 PM
Archived: 11/30/20, 4:30 PM
ORD
MDW
ARR
RadarScope Pro
NEXLAB-College of DuPage
Relatively thicker lake-effect clouds evident on AM vis sat
Terminal dopplers aid in seeing lake-effect clouds/precip
TORD PM radar image courtesy of RadarScope
Satellite image courtesy of College of DuPage
RED) 0.5 KM | VALID 30 NOV 20 14:26:10 UTC

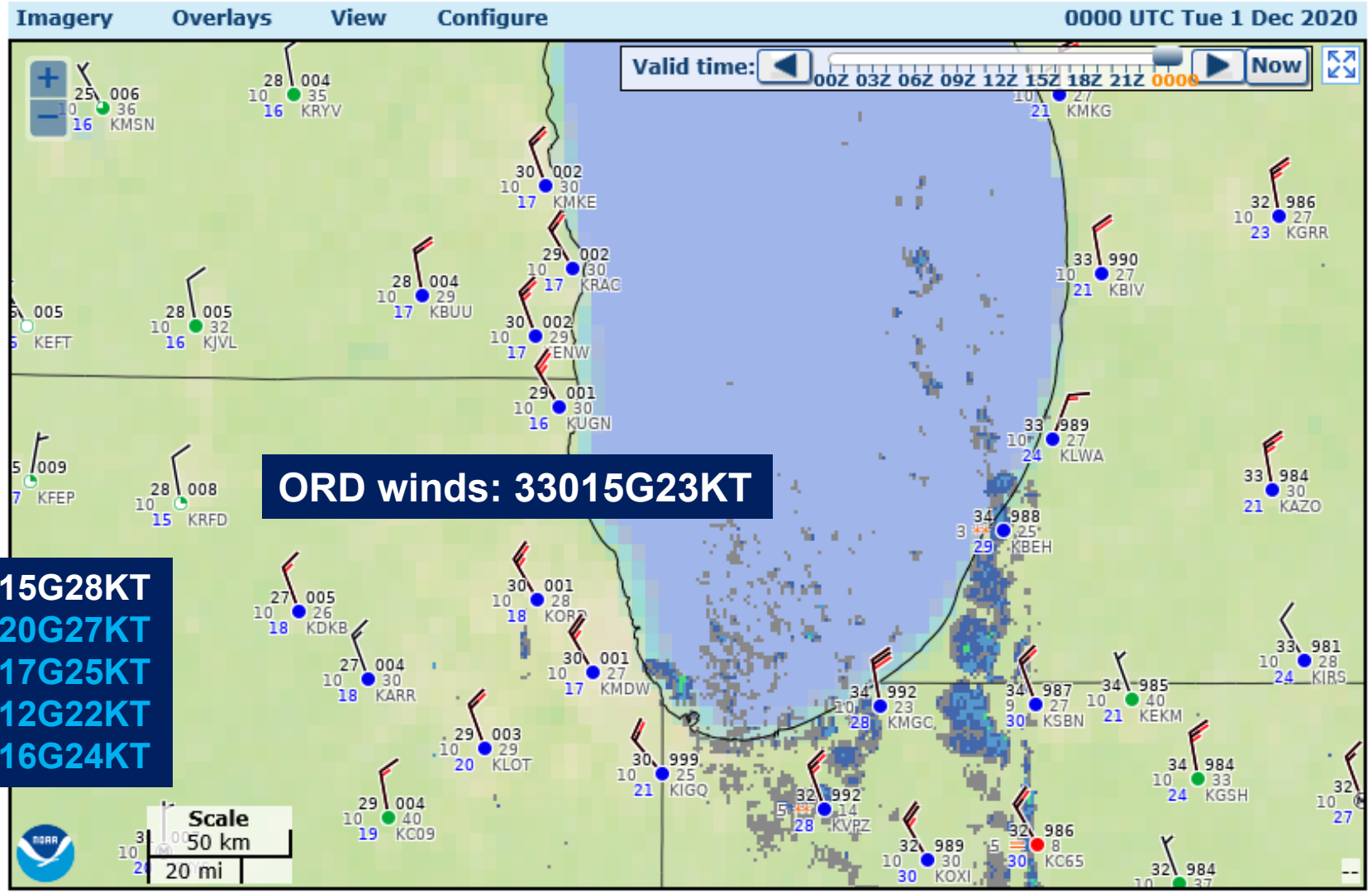
12Z Surface Map



18Z Surface Map



00Z Surface Map



19Z: 34015G28KT
20Z: 33020G27KT
21Z: 33017G25KT
22Z: 32012G22KT
23Z: 33016G24KT

Impacts to ORD, C90 and ZAU

ORD UA /OV ORD/TM 1253/FL036/TP A321/TA -6/IC MOD-SEVERE RIME ICING

ORD UA /OV OBK045020/TM 1952/FL050/TP C750/SK OVC038/TA M08/IC MOD-SEV RIME

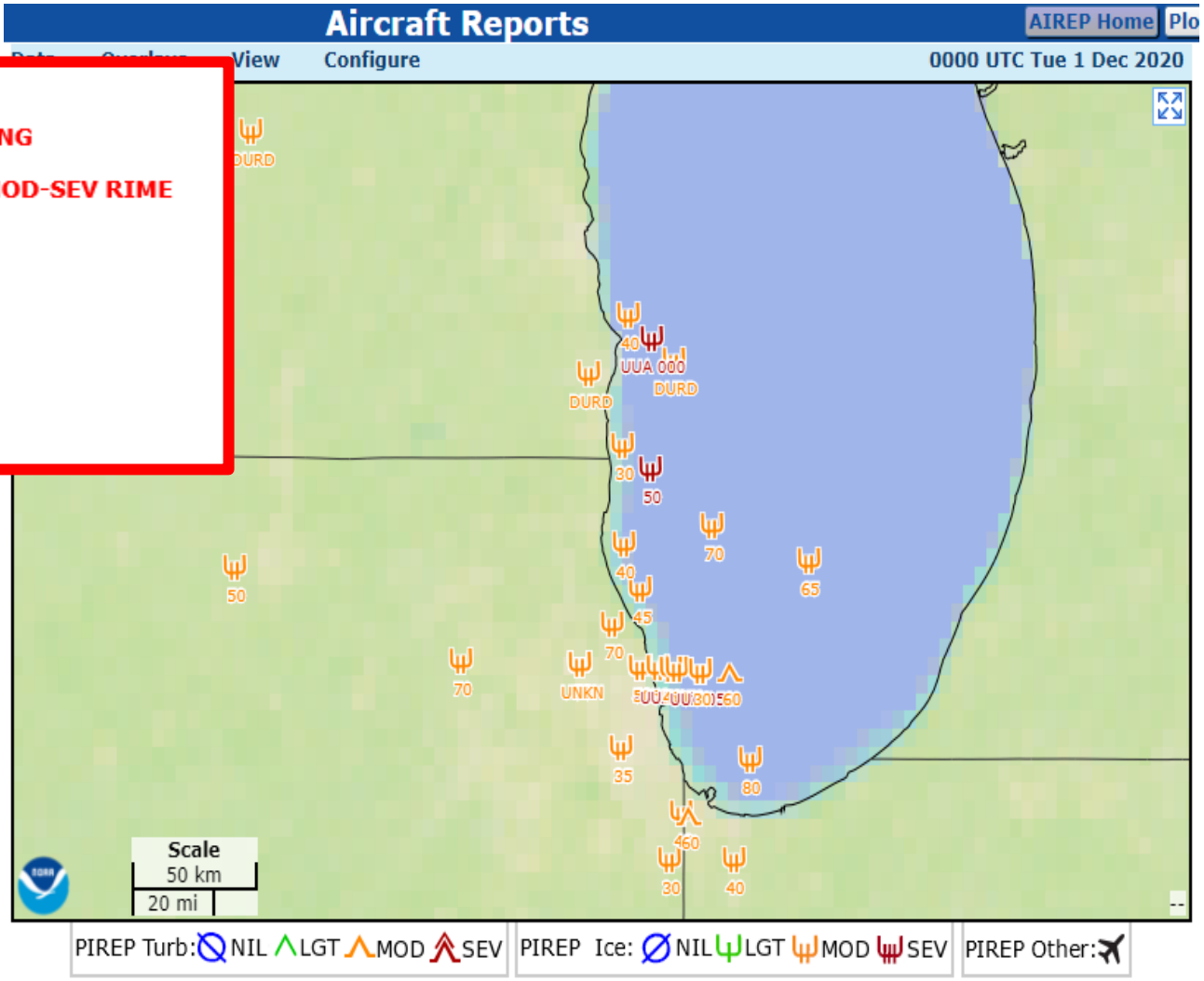
ORD UUA /OV 15 E ORD/TM 2250/FL050/TP B777/TA -10/IC SEVERE

ORD UA /OV 10 E ORD/TM 2252/FL040/TP A319/TA -10/IC MOD-HVY

ORD UA /OV 10E ORD/TM 2252/FL040/TP B772/TA -10/IC MOD TO SVR RM

ORD UUA /OV 20 E ORD/TM 2310/FL050/TP E145/IC SEVERE MIX

- 1253Z - first SEV icing PIREP
- 1305Z - ORD E flow (13Z METAR: 34016G23KT)
- CWA 101 issued for SEV ICG until 1530Z
- 1335Z, 1400Z, 1515Z: CWSU collab w/ AWC-Zulu desk for SEV icing SIGMET 3,000' – 7,000'
- 15Z – ZAU traffic management supervisor indicated ORD to stay on E flow ALAP for icing avoidance
- 17Z – CWSU PIREP solicitation charts updated for MOD-ISOL SEV icing 030-070



Impacts to ORD, C90 and ZAU

ORD UA /OV ORD/TM 1253/FL036/TP A321/TA -6/IC MOD-SEVERE RIME ICING

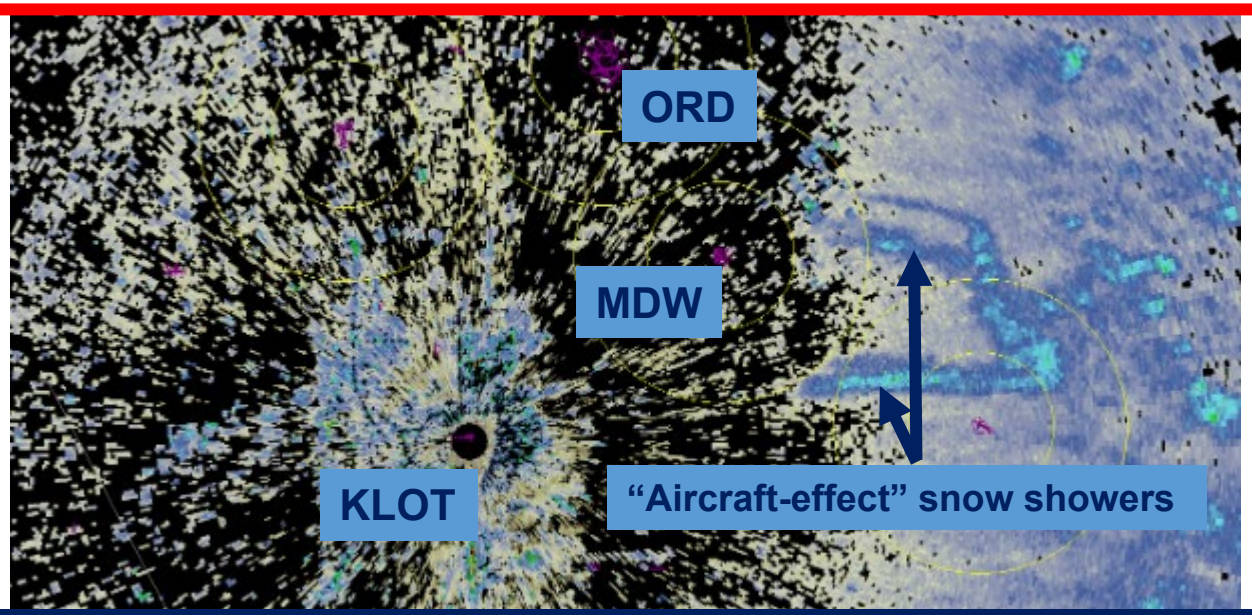
ORD UA /OV OBK045020/TM 1952/FL050/TP C750/SK OVC038/TA M08/IC MOD-SEV RIME

ORD UUA /OV 15 E ORD/TM 2250/FL050/TP B777/TA -10/IC SEVERE

ORD UA /OV 10 E ORD/TM 2252/FL040/TP A319/TA -10/IC MOD-HVY

ORD UA /OV 10E ORD/TM 2252/FL040/TP B772/TA -10/IC MOD TO SVR RM

ORD UUA /OV 20 E ORD/TM 2310/FL050/TP E145/IC SEVERE MIX



- 1835Z – LOT called to AMD ORD for MVFR cigs
- 1925Z – CWSU collab with AWC-Zulu for continuation of SEV icing SIGMET 030-070
- ~20Z – additional SEV icg report w/ update to adjust PIREP charts for ISOL SEV 025-080 based on reported cloud layers
- ~2030Z – C90 intends to go back to West Flow at ORD (33020G27KT) – too much tailwind to stay East
- 2046Z – Departures so far getting MOD icg reports east of ORD
- 21Z TAF update – extend MVFR cigs, adjust winds to 330°
- LiveATC utilized to hear near real-time PIREPs of additional SEV icing
- Winds forced C90 to maintain West Flow
- C90 mitigated icing risk by adjusting arrivals to quickly descend through cloud layer (no SEV, only MOD reports thereafter)

Impacts to United Airlines

Images and quotes courtesy of Mike Fox at UAL

“Despite the heavy Lake Effect snow remaining just east of ORD, 15-hour pitched battle with moderate and at times heavy RIME ice.”

Impacts to United Airlines - Deicing

“Average 145 – 160 gallon usage per aircraft between two and four times gallon levels generally experienced with RIME.”

“Impacted all aircraft types and surfaces from 1 to 1½ inches thick, nearly tripling removal times.”

Images and quotes courtesy of Mike Fox at UAL

Takeaways

- PIREPs!
  - Key observations for en route environment, but they are subjective
  - Their frequency may be dependent on air traffic
  - Often a delay from occurrence to reporting (sometimes as long as 10-15 min)
    - Use new/alternative tools, like LiveATC broadcast for real-time obs
  - Not always consistent (HVY vs SEV, many without severity/type qualifiers)

- Icing severity dependent on:
  - Depth and temperature of saturated layer (liquid or mixed phase)
    - Size of supercooled water droplets key to accretion
  - <u>For this case, duration of aircraft in the icing layer</u>
    - Spatial awareness - know how the airspace is designed and operates

- Forecast collaboration between CWSU, WFO and AWC as important as communicating the risks to the FAA

- Both ceiling and wind forecasts are crucial even when seeming trivial (few KT or 10°)

Low Level Stratus

SEVERE ICING

January 2023

By Shari Mutchler

A couple case studies of severe icing reported 30 November, 2020 near Chicago, then again near Buffalo 9 January 2023.

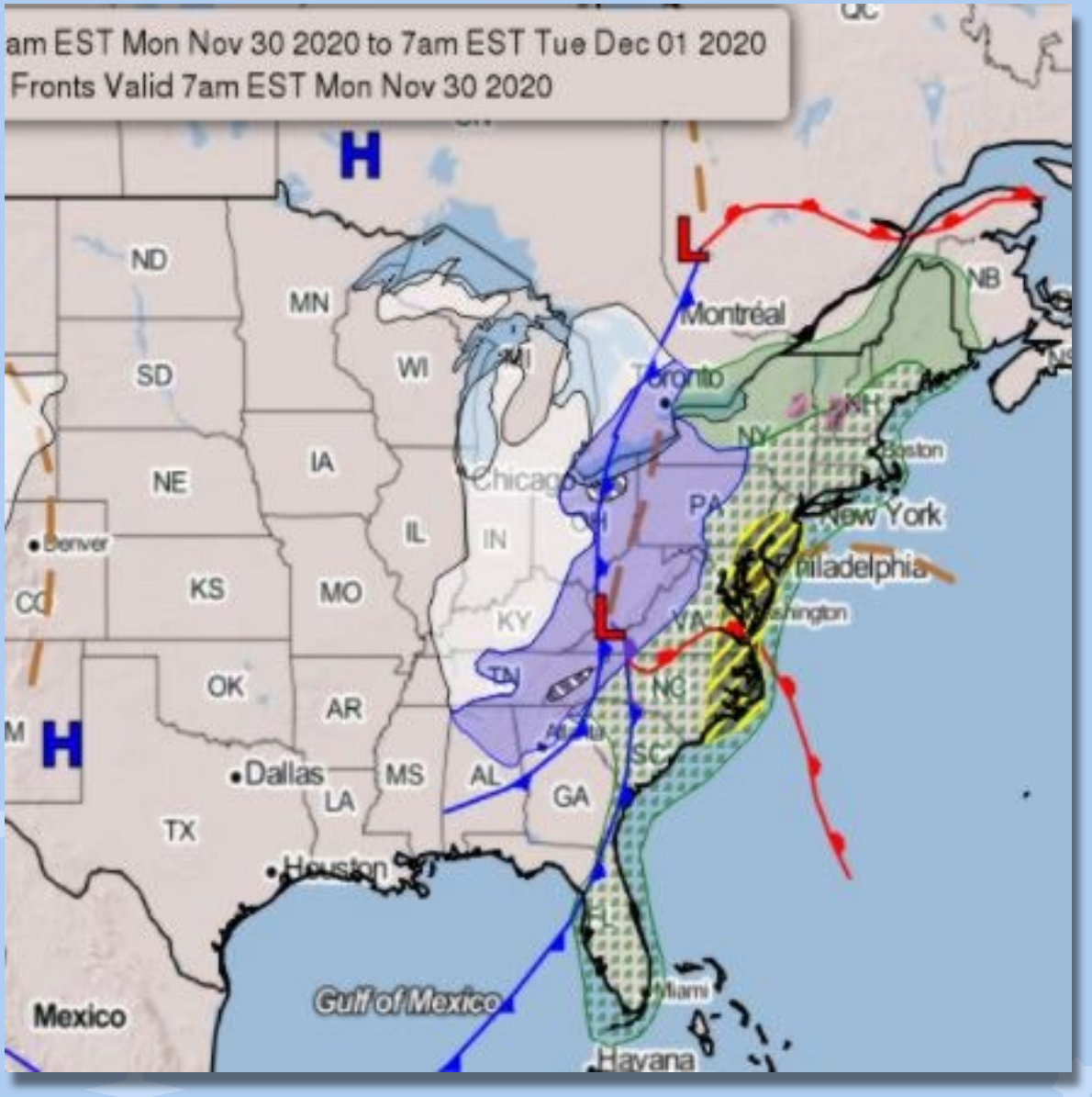
This is a very brief presentation to show a scenario in which low level stratus in the vicinity of Lake Michigan and Lake Erie made for severe icing conditions.

It is unusual to get severe icing reports, especially from larger aircraft out of a stratus layer.

The Weather scenario...

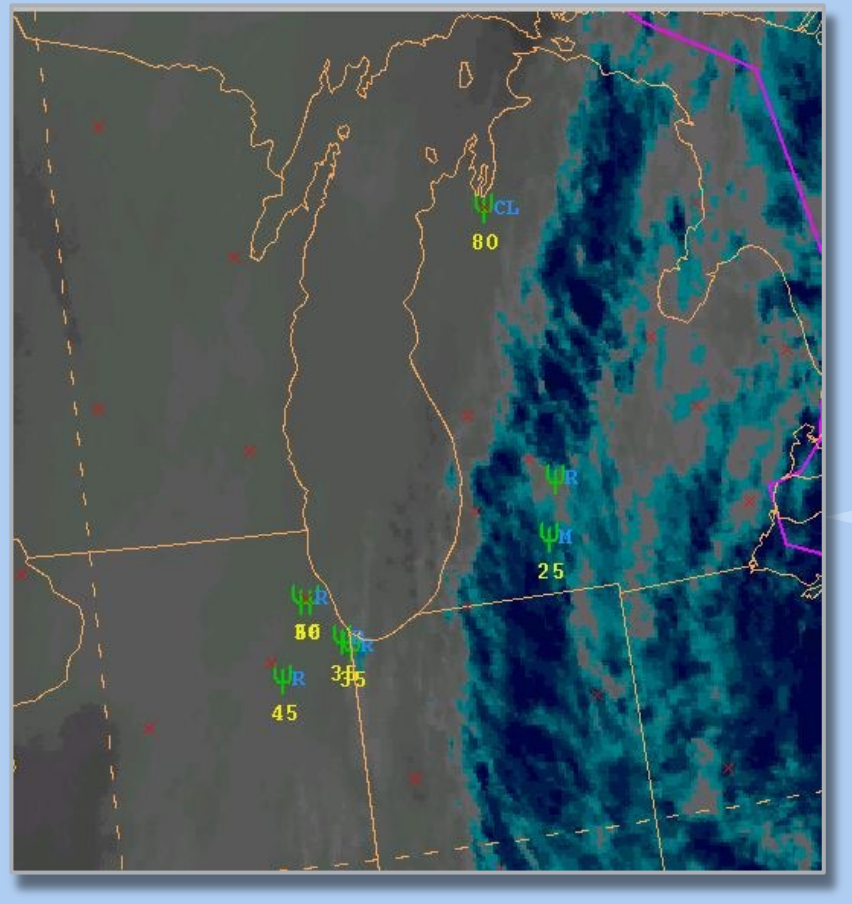
Elongated system moving northeastward towards eastern US with a variety of multiple freeze levels throughout.

Radar indicated low pressure center near southeast OH at the time a report of moderate to severe icing came in from an A320 near Chicago.

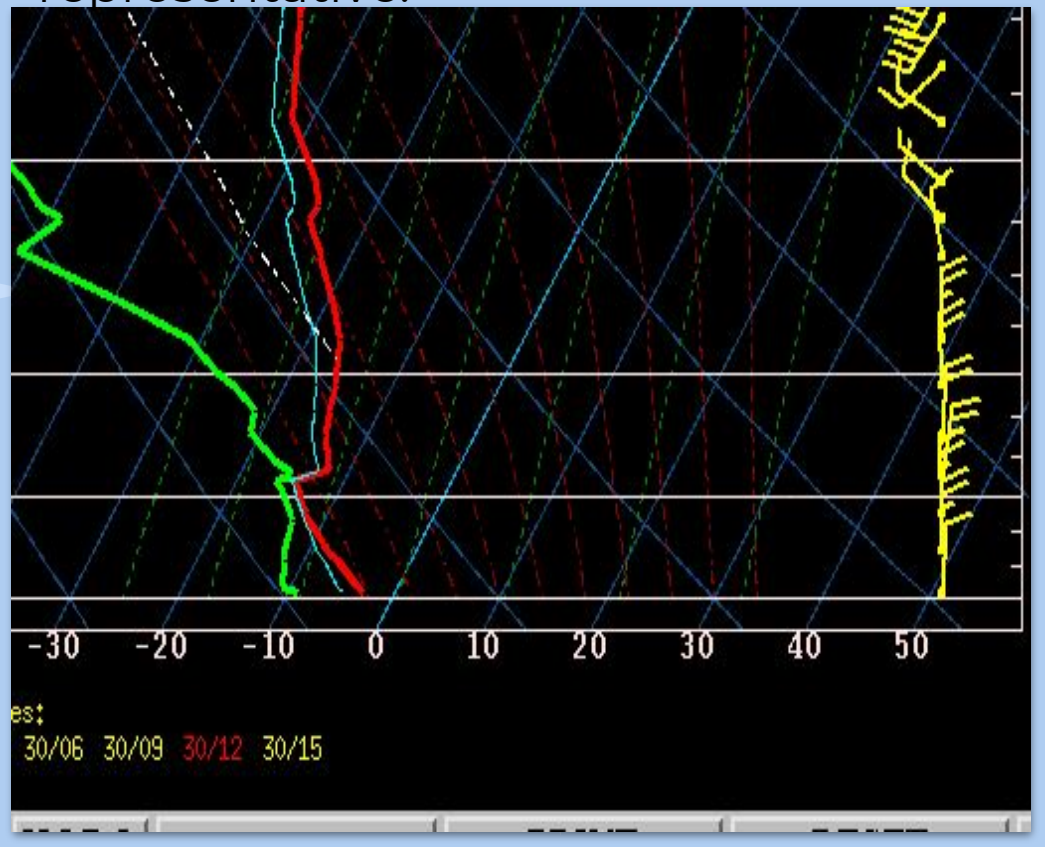


MOD-SEV icing was reported by an A320 aircraft around 7 AM CST Near Chicago.

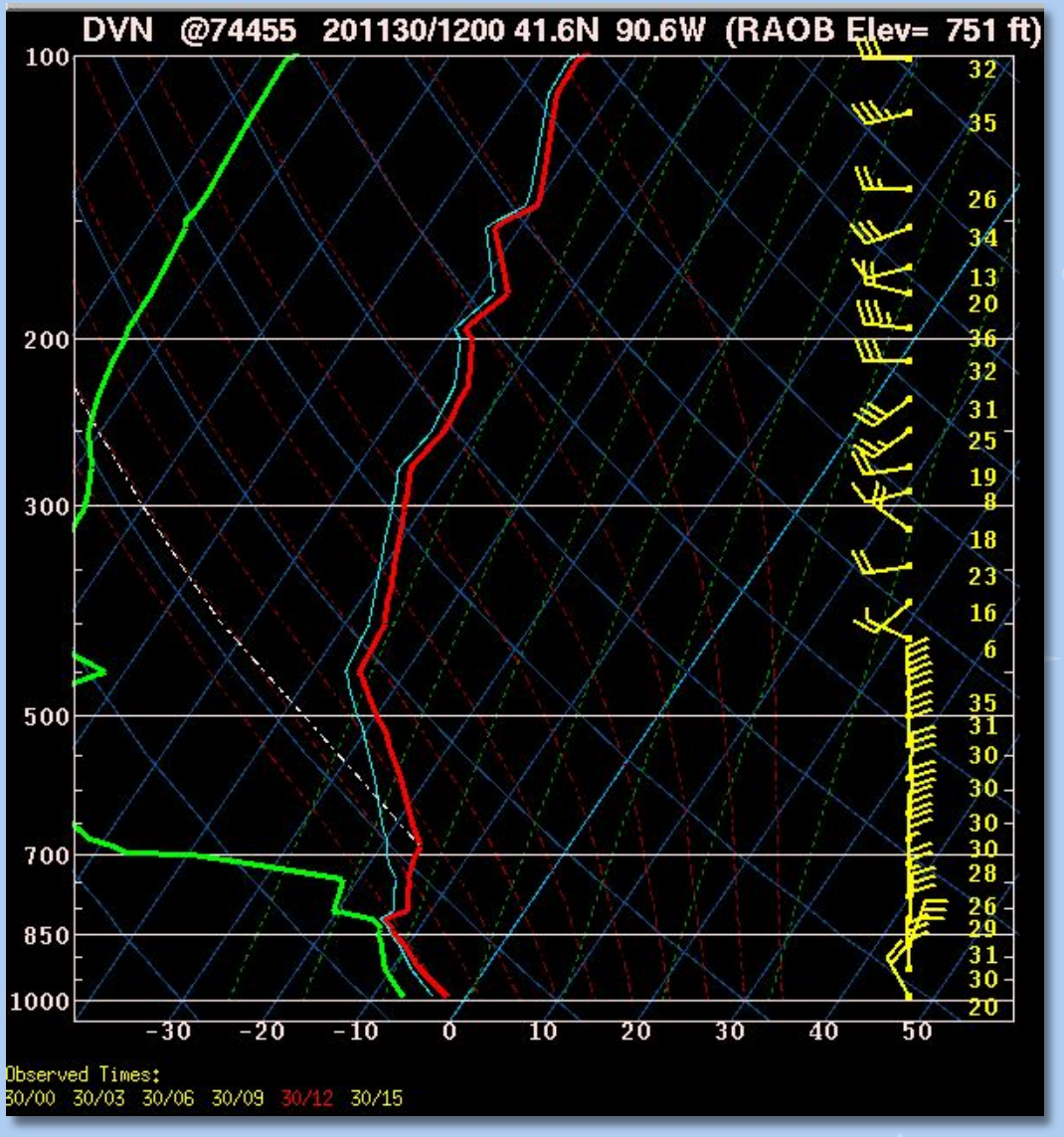
Mainly low level stratus layer was prevalent throughout Lake Michigan, WI and IL regions in the wake of an exiting weather system. The sigmet covered the route used by aircraft for take-off and landing at O’ Hare.



Even though the Green Bay sounding was “upwind” of the icing area, the Davenport sounding seemed to be more representative.



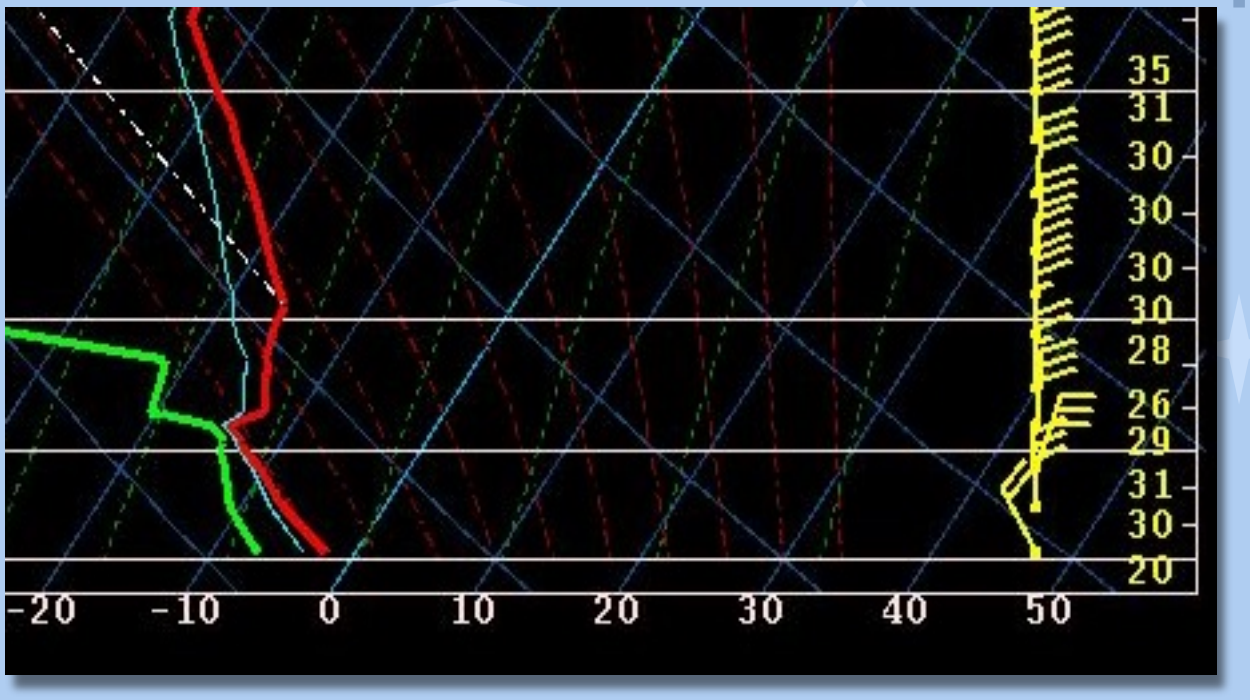
12Z Green Bay Sounding 11/30

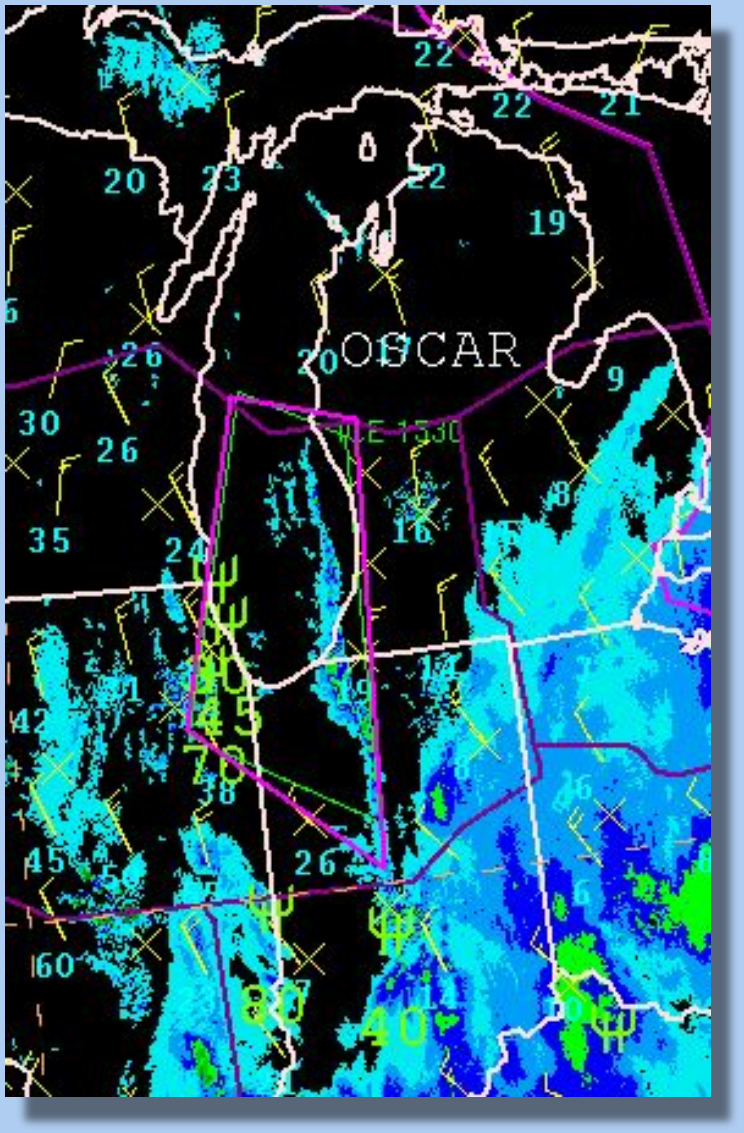


12Z Davenport Sounding 11/30

The DVN sounding shows the stratus layer in the low levels. Also to note that temperature is below freezing, with temperatures between 0C and -12C.
Winds from the north through the area created a long “fetch” over Lake Michigan leading to Chicago area. This contributed to the icing by adding more moisture to the lower levels.
The lapse rate below 850mb was steep as well, contributing to lift.

Close up of DVN sounding





Radar image showing “fetch” over Lake Michigan

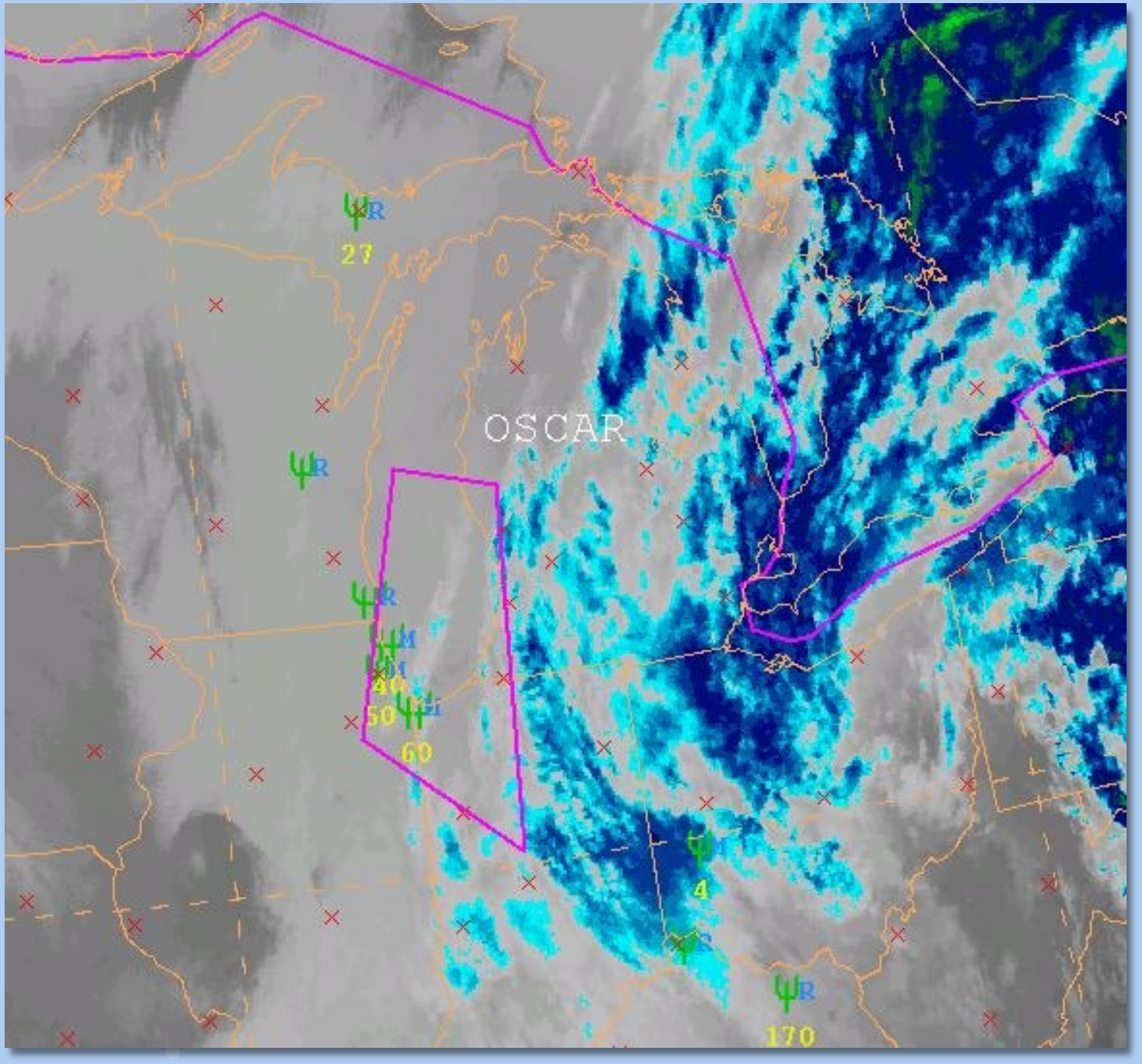
BREF Radar overlaid with wind and icing PIREPS show how moisture was transported from Lake Michigan onto shore. North wind provided the long fetch of air towards the Chicago region. Note the convective “rolls” parallel to the Michigan shore

Sigmet Oscar was issued for levels between 070 and 030 based on coordination with CWSU ZAU.

CWSU ZAU carried a CWA for the area for the first couple hours, after which we decided to run sigmet OSCAR.

It is unusual to get reports of severe icing from stratus clouds, unless aircraft are flying in the stratus for an extended period of time, such as during landing.

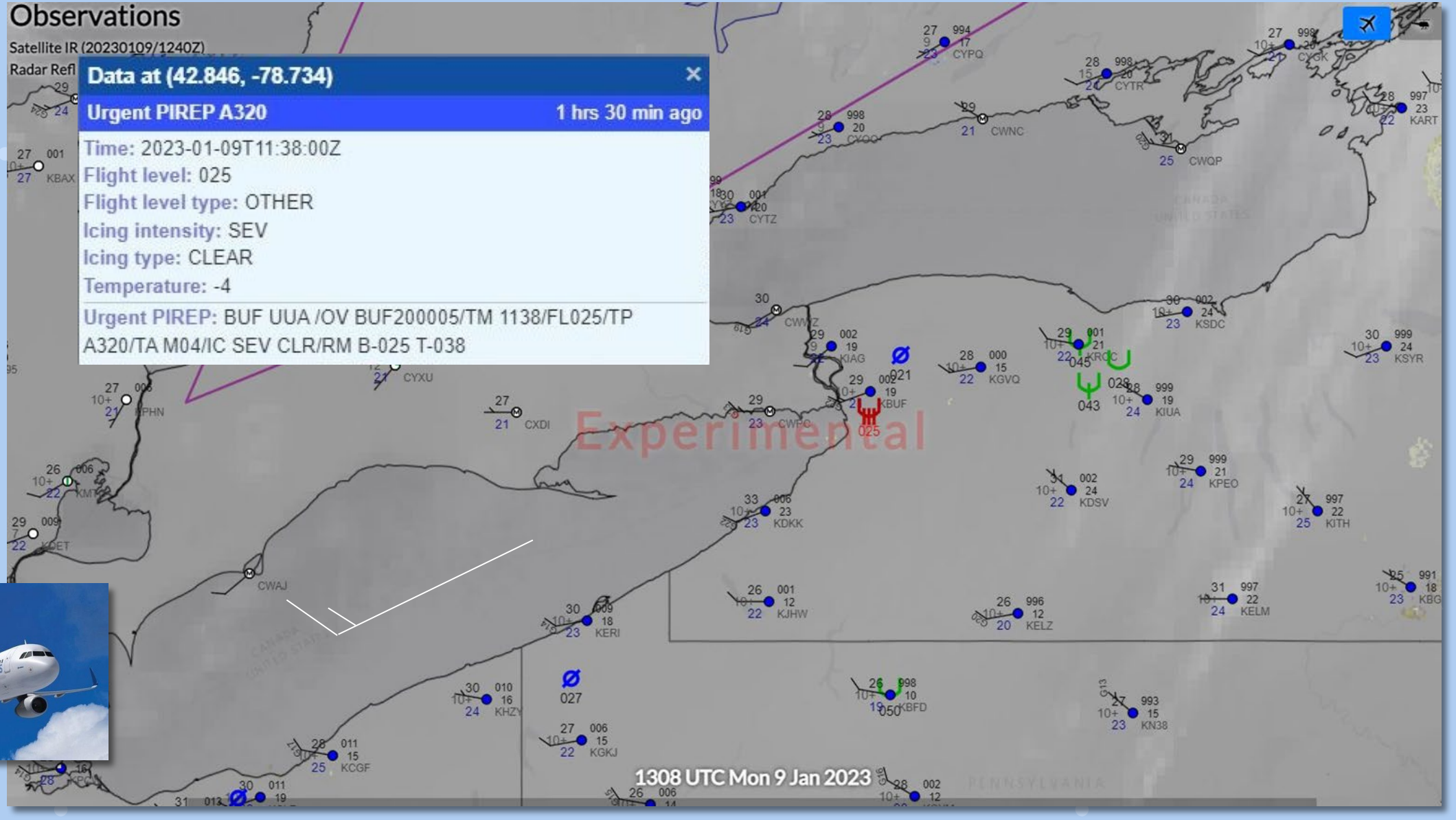
The A320 aircraft uses a “bleed air” system to keep the leading edge of the wings free from ice. A “bleed air” system routes hot air from the engines through small tubes through the wings, tail and engine inlets.



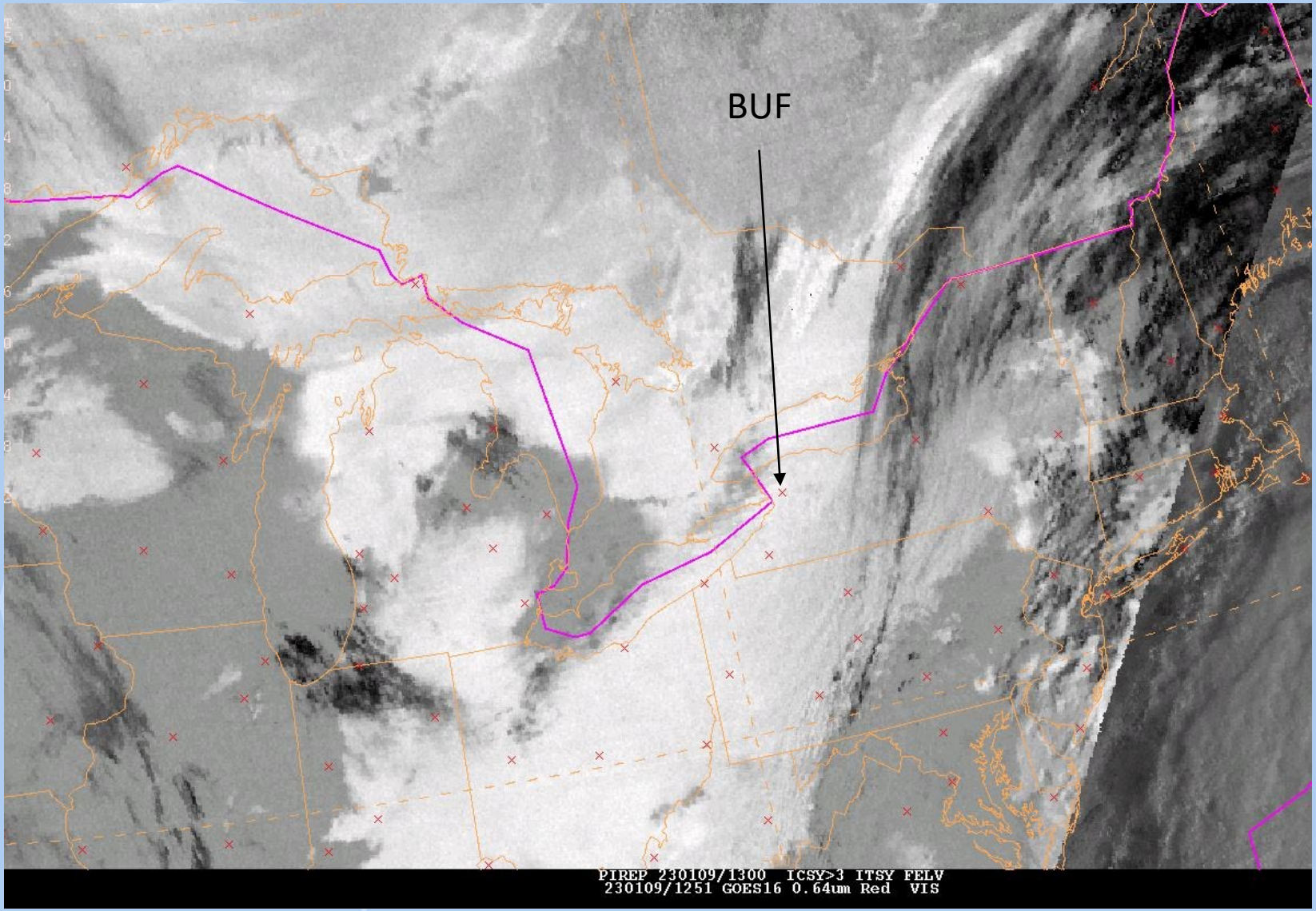
IR Satellite image shows extent of low clouds West of system exiting to the east.

A similar case from 9 January 2023 near Buffalo, NY, an A320 reported severe clear icing.

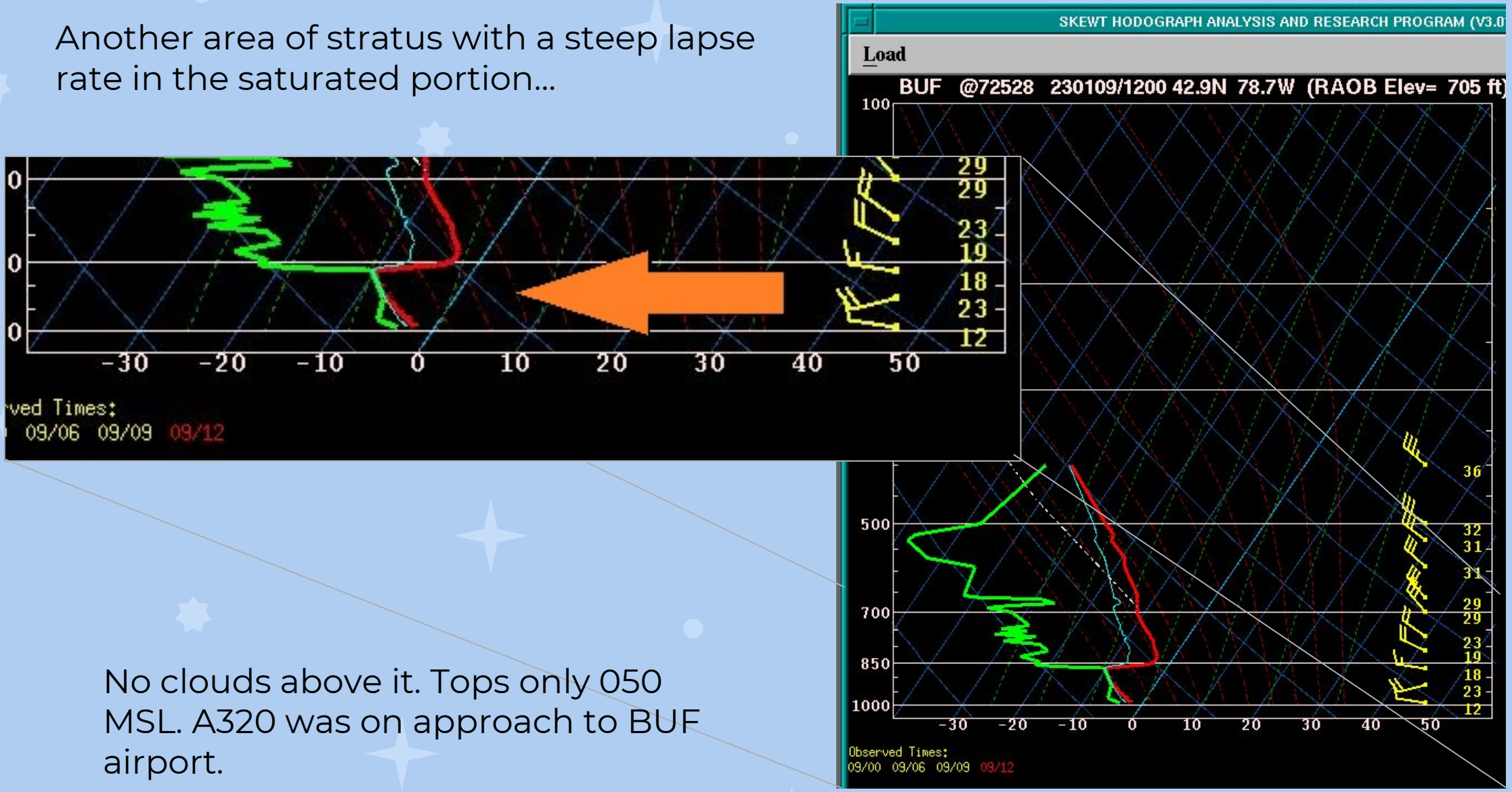
Note that the wind direction is parallel to Lake Erie, producing a long “fetch” over the water leading up to Buffalo, NY



Satellite imagery showed an expansive area of stratus that extended from the northern Great Lakes region through the OH River Valley and into New England, but only Buffalo produced a severe icing report.
This stratus was on the western edge of an exiting low pressure system, similar to previous case.

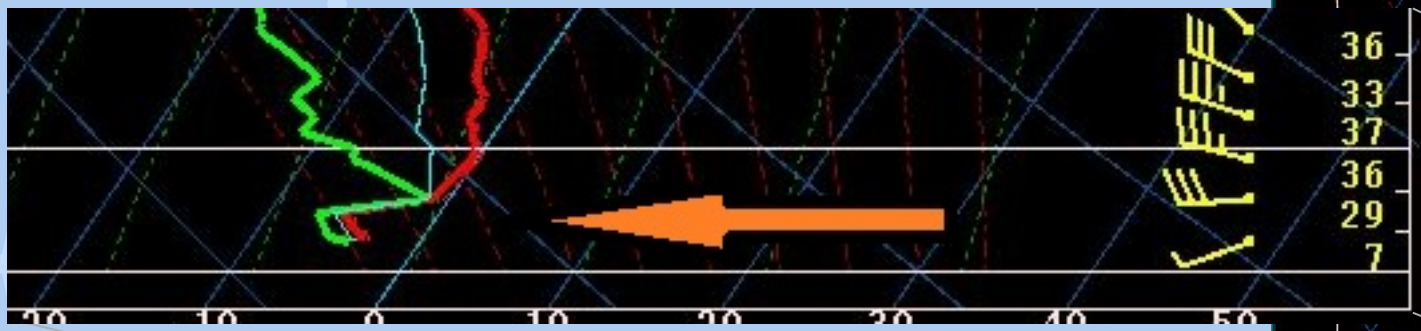


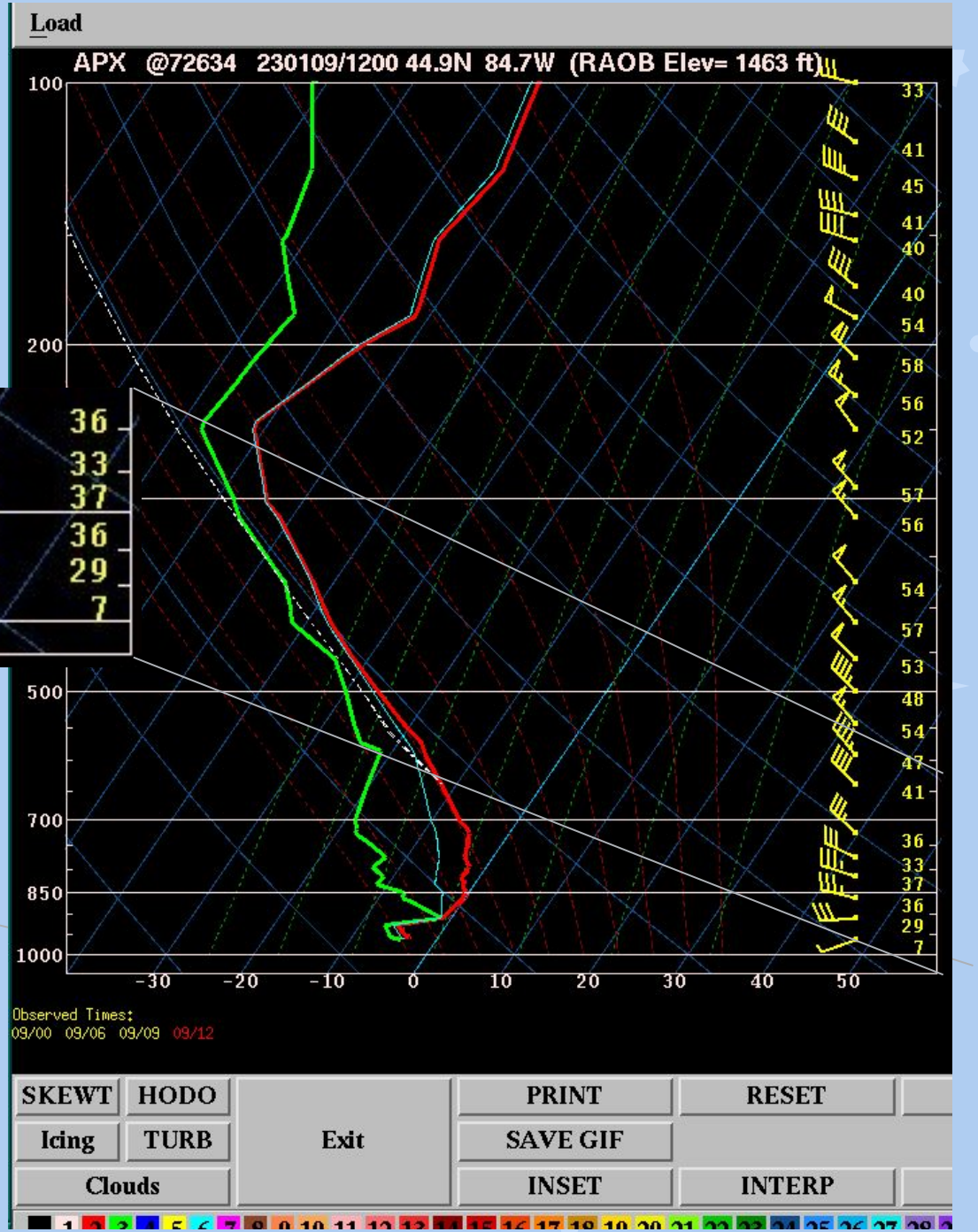
Another area of stratus with a steep lapse rate in the saturated portion…



No clouds above it. Tops only 050 MSL. A320 was on approach to BUF airport.

Compared to the Alpena, MI sounding, which was stable, and didn't produce anything other than reports of light ice.





The wind at Alpena Michigan was also off-shore (from the West,) not on-shore.

No sigmet was created for the Buffalo scenario since other aircraft reported no ice or just light ice. The report ended up being isolated.

“Fast aircraft with thin wing cross-sections are more susceptible to deteriorating aerodynamics, and hence are more susceptible to ice accretion.” WMO.(link)

OVERVIEW: **There were several great dynamics for this severe turbulence event:**

- A strong 980mb low pressure system moved just across Montana/Canadian border with cold front from the low pressure system moving through the western Montana and central Idaho before entering the Tetons towards Nov 5th, 2022 by 18Z. The winds prefrontal were strong westerly thru MT-ID-WY and tight postfrontal pressure gradient .

- The RAP 2000ft AGL winds showed strong westerly cross-barrier flow across the Tetons, Big Horn and Rocky mountains.

- The RAP 300mb winds showed the Right-front exit quadrant region jet-core over Tetons by Nov 5th, 2022 at 18Z through Nov 6th, 2022 at 00Z.

- The NAM cross-sections showed a vertically propagating wave punching through the Tropopause near 250mb.

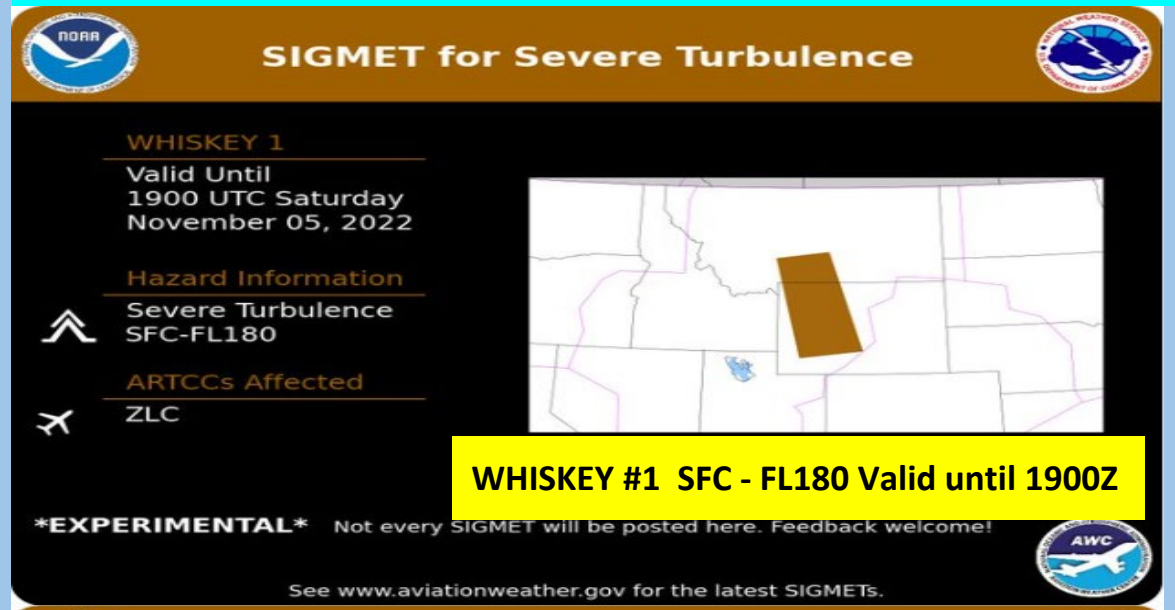
- The 700 to 500mb Lapse Rates values 5.5 C/km or less coincided in aiding in development of the vertically propagating couplets. There were severe mtn wave pilot reports over the Big Belt mountain in MT where the lapse rates were near 6.0 C/km.

- WRF showed a breaking mountain wave developed near Dubois, WY in time-frame from 11/05/12Z - 11/05/18Z.

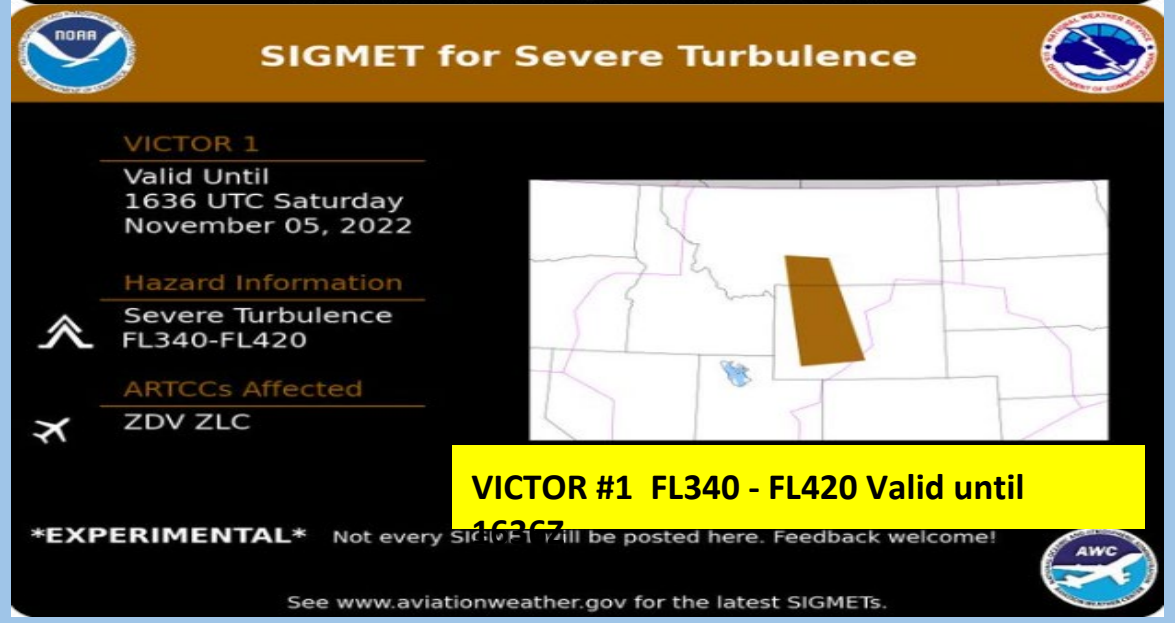
- The combination of these multiple indices and vertical shear, and strong RAPGTG Mtn wave composites resulted in SIGMETs for occasional severe turbulence below FL180 and between FL340 - FL420.

Nov 5-6th, 2022 Severe Mountain Wave Turbulence Event through Tetons & Big Horn & Northern Rockies

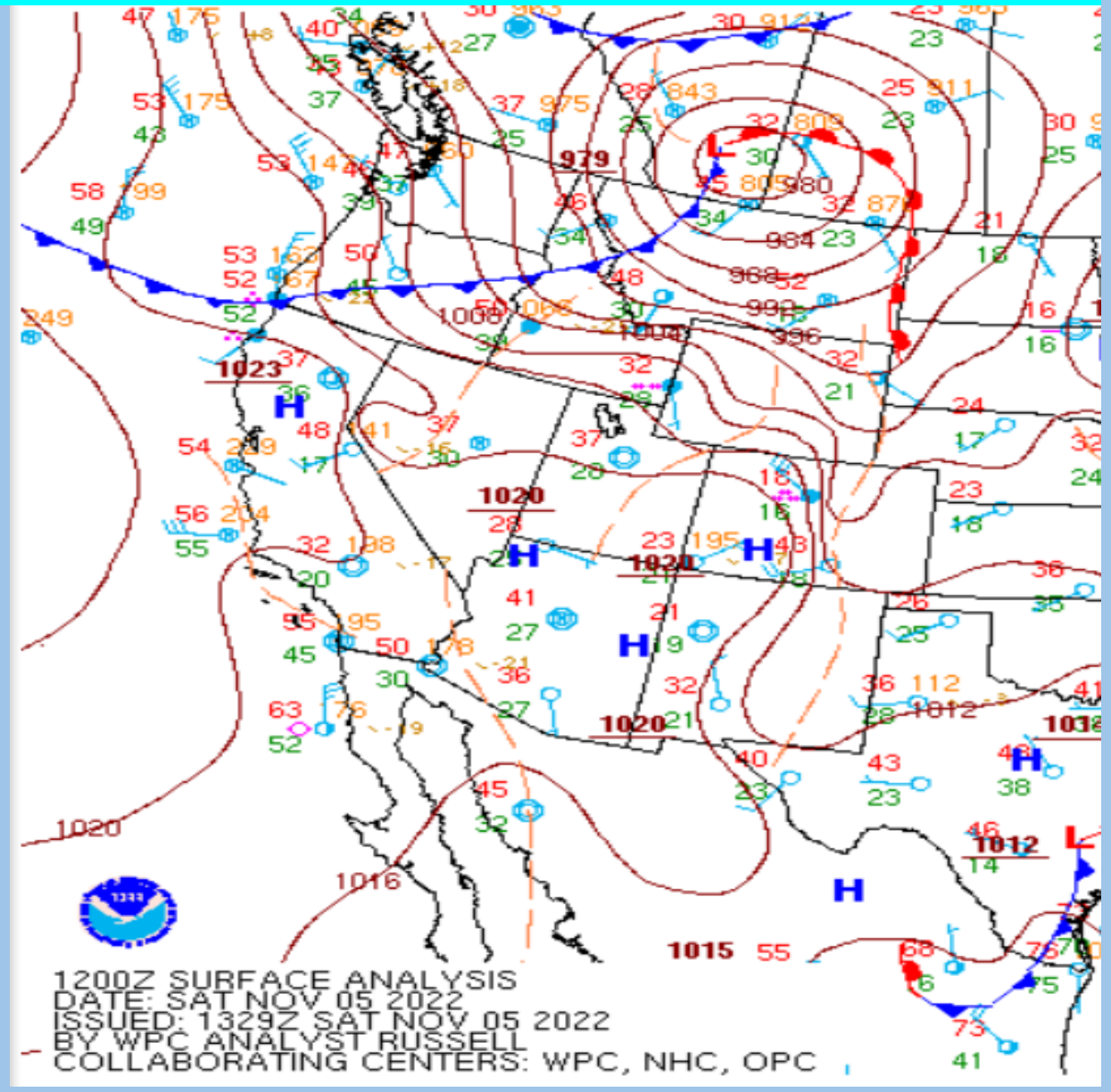
by Perry Dehne, Ryan Connelly & Emily Niebuhr



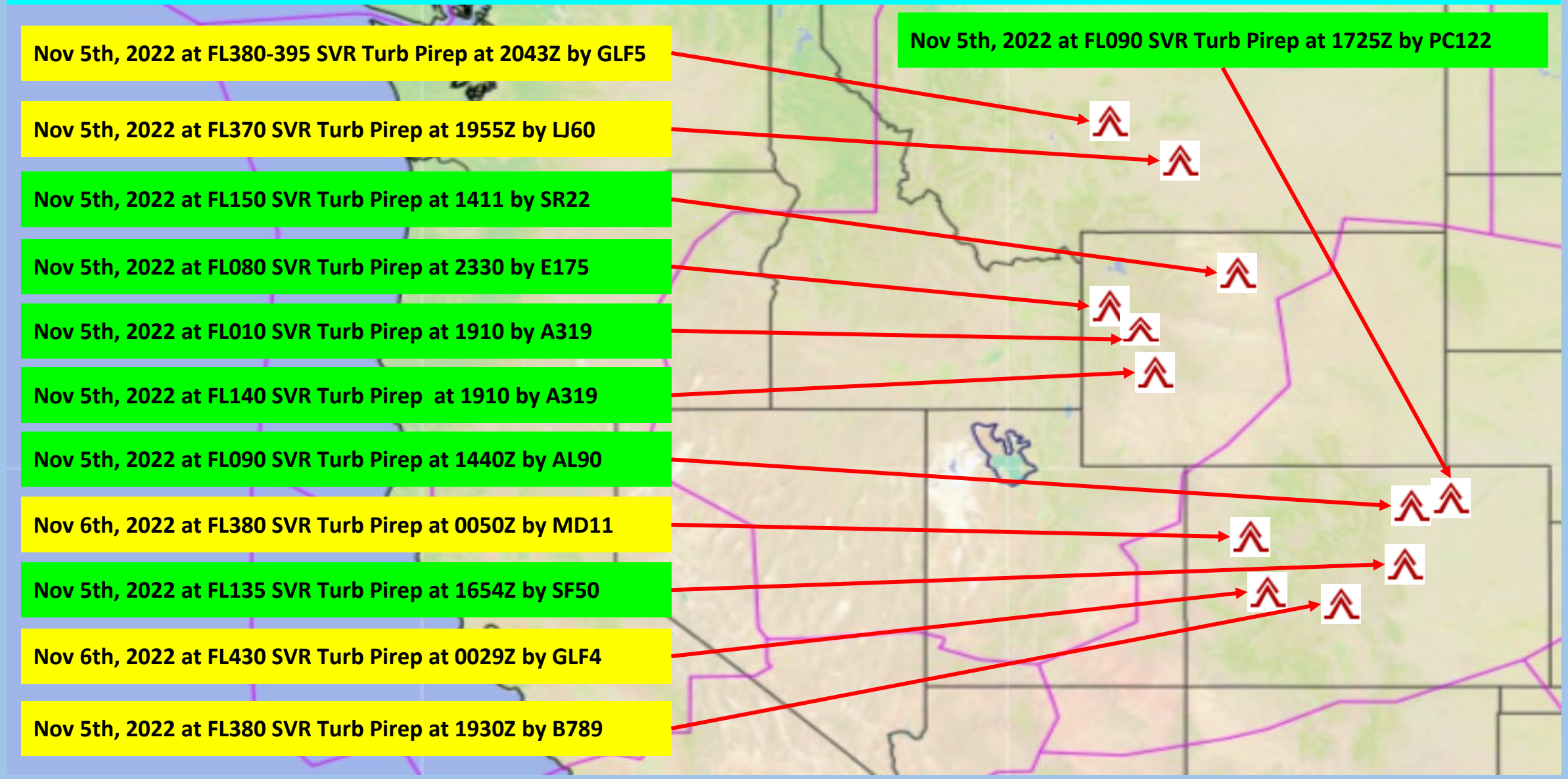
WHISKEY #1 SFC - FL180 Valid until 1900Z



VICTOR #1 FL340 - FL420 Valid until 1636Z



NOV 5th - 6th, 2022 SEVERE TURBULENCE PIREPS THROUGH THE TETONS AND THE ROCKY MOUNTAINS



MOUNTAIN WAVE INDUCED TURBULENCE DECISION TREE

Do you have perpendicular cross-barrier flow with surface wind speeds 35kts or greater? Do you have ridge top wind speeds 50kts or greater?

YES, keep going

NO, not likely

Does Satellite show Foehn gap or subsidence & any severe turbulence pilot reports?

YES, keep going

NO, not likely

Is there an inversion near the mountain tops?

(This allows for vertical propagating couplet to develop in stable region)

YES, keep going

NO, not likely

Do you have a sharp or tight strong updraft/downdraft couplet?

YES, keep going

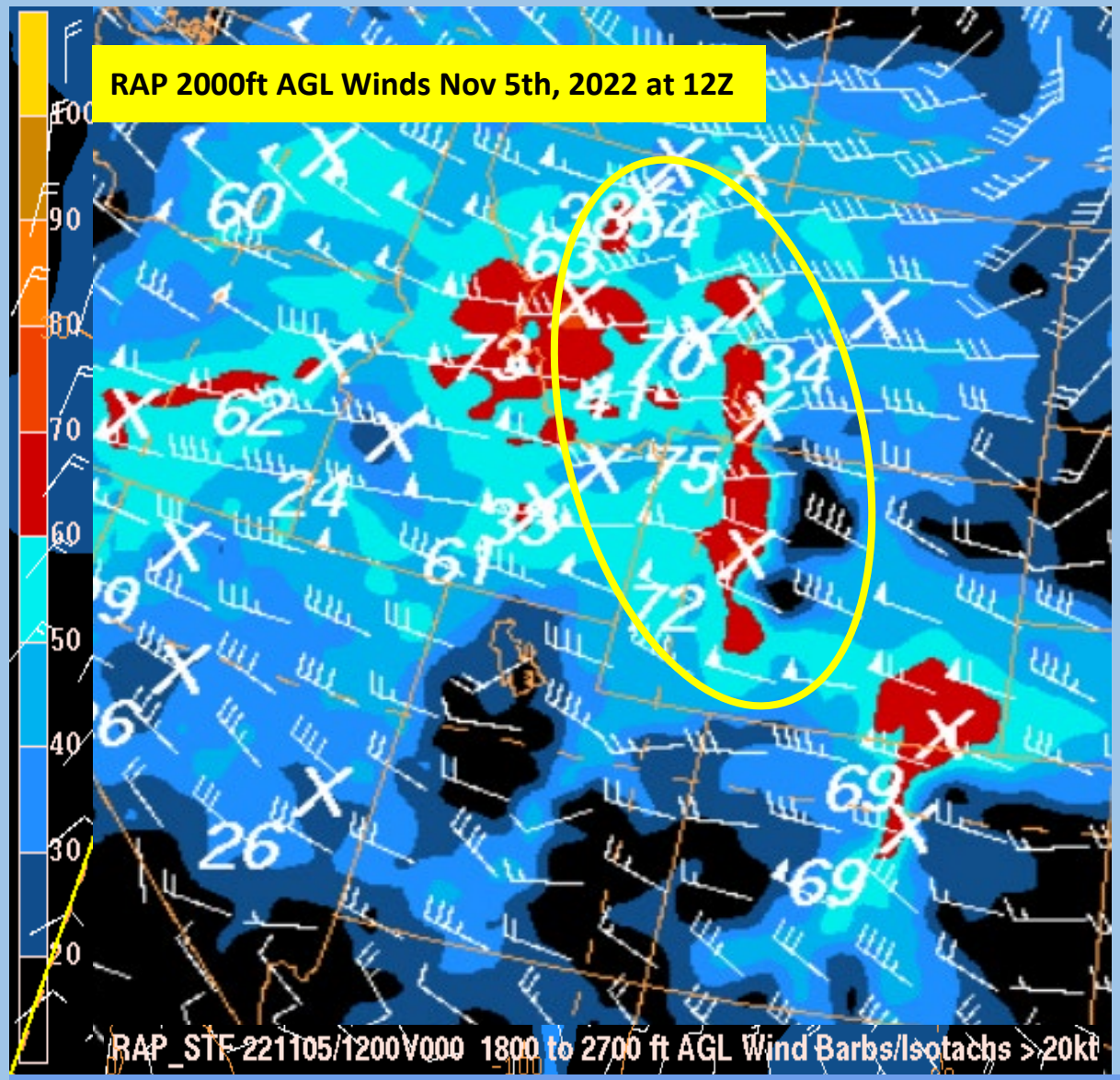
NO, monitor

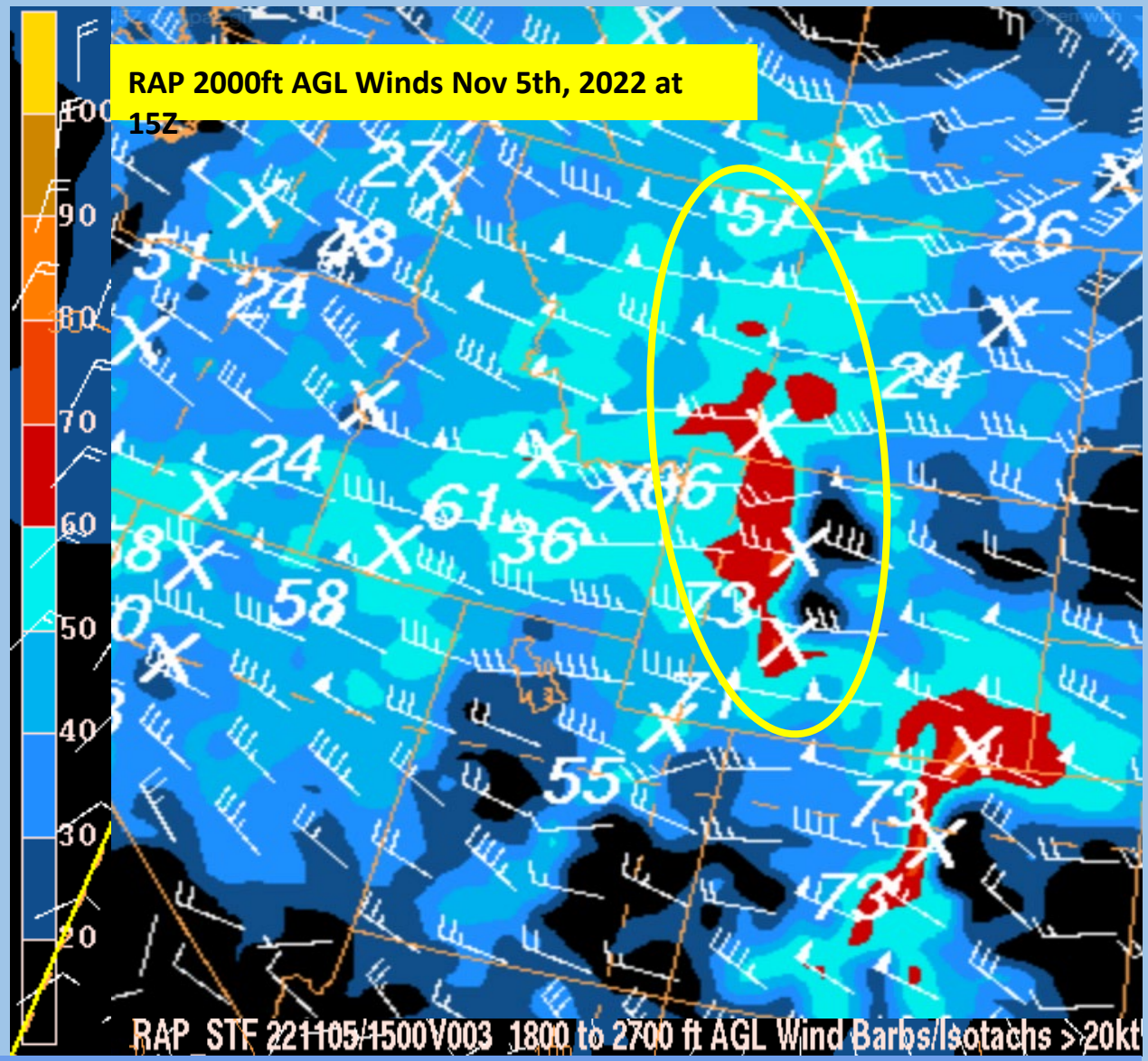
Does the strong vertical propagating motion or couplet punch through the tropopause?

YES, keep going

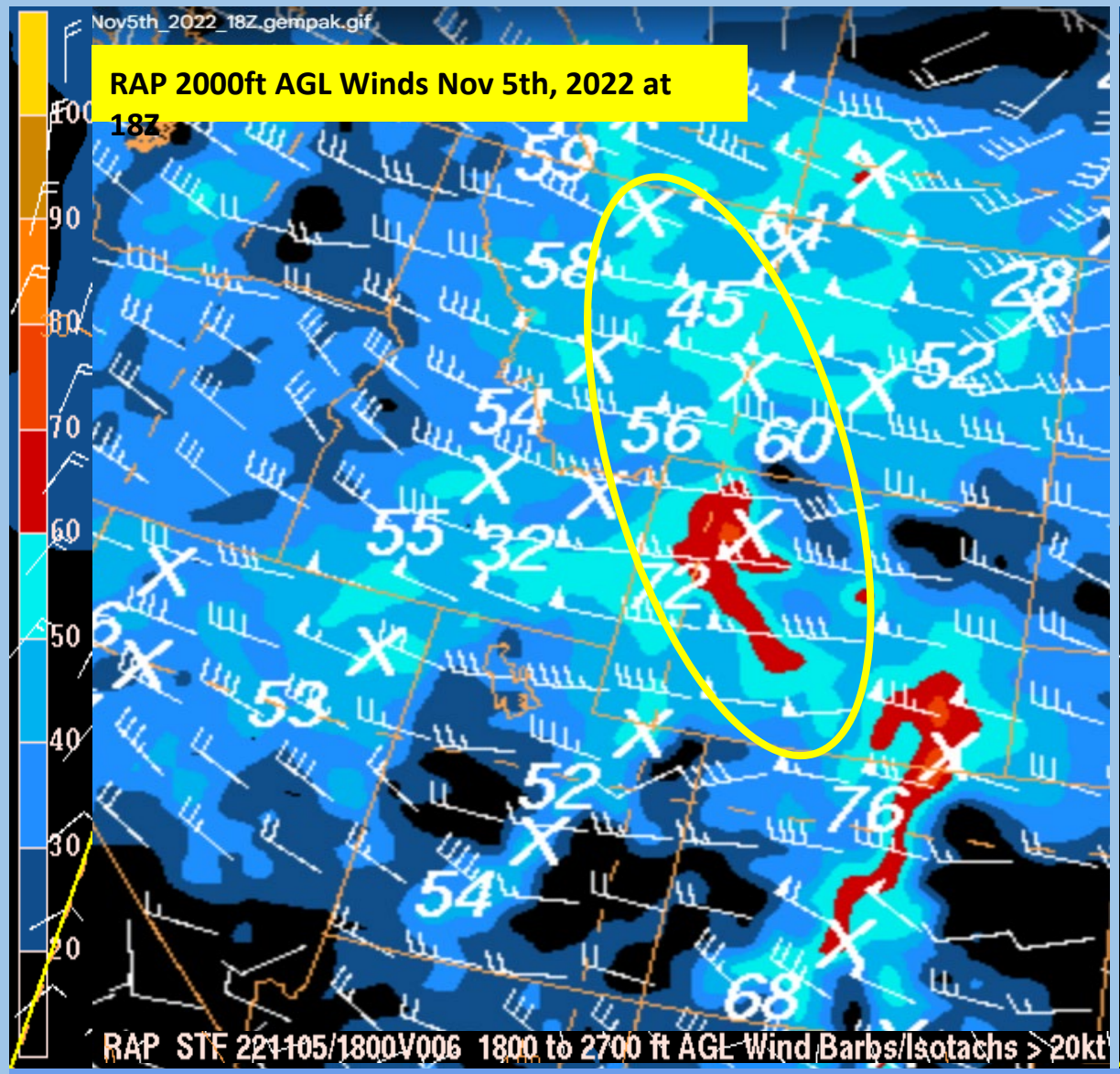
NO, monitor

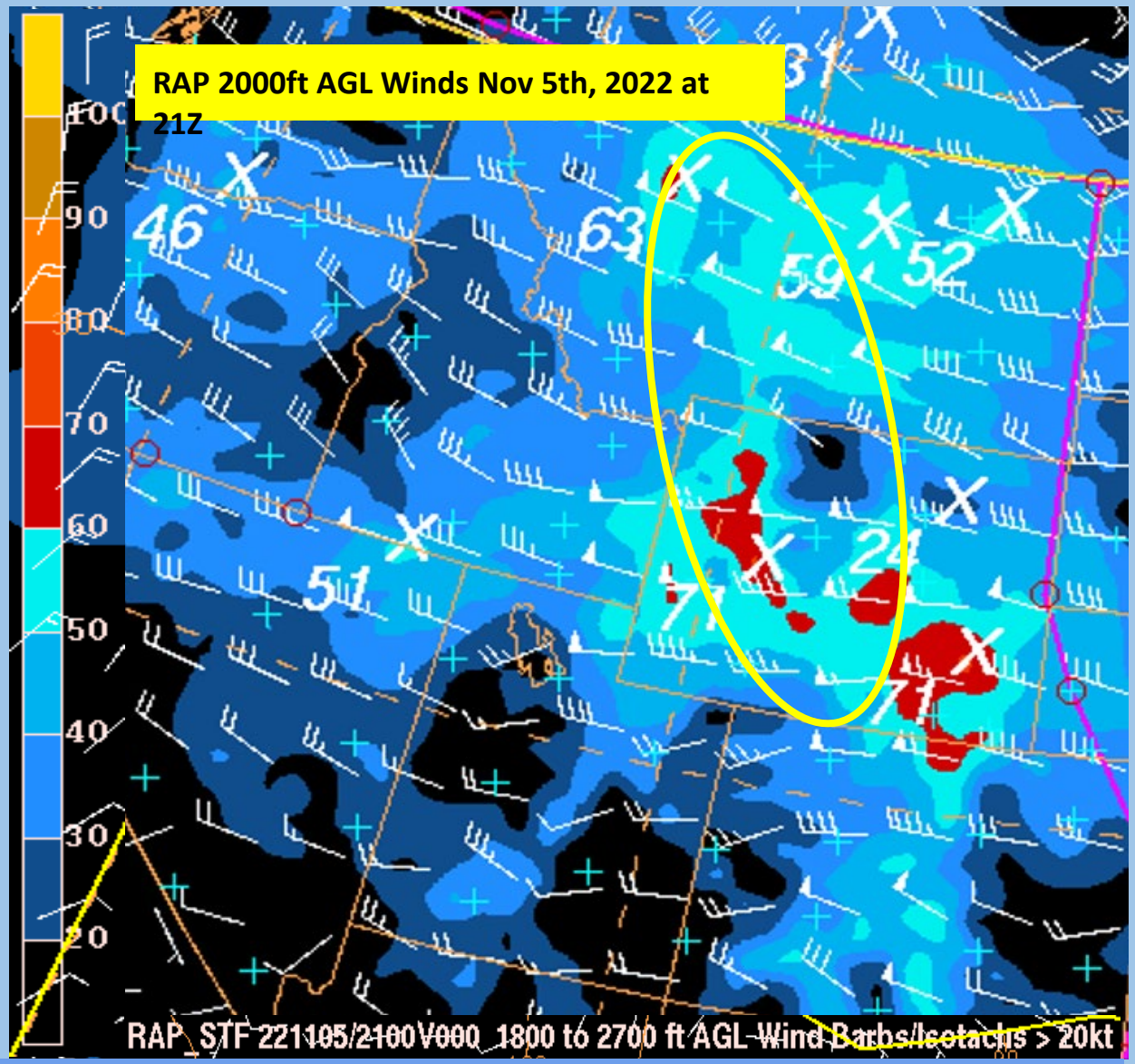
Issue the Low and/or High Severe Turbulence SIGMET



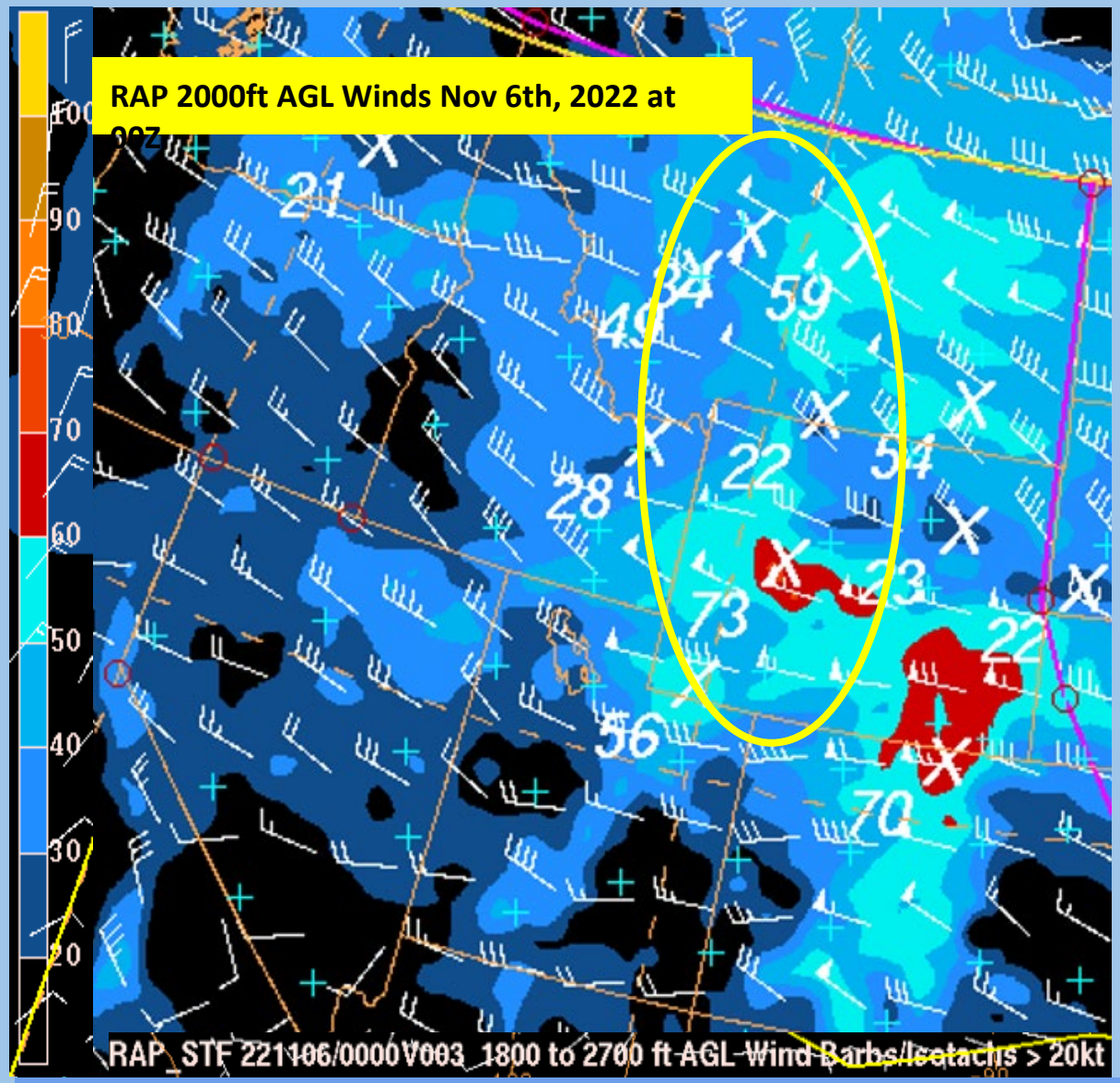


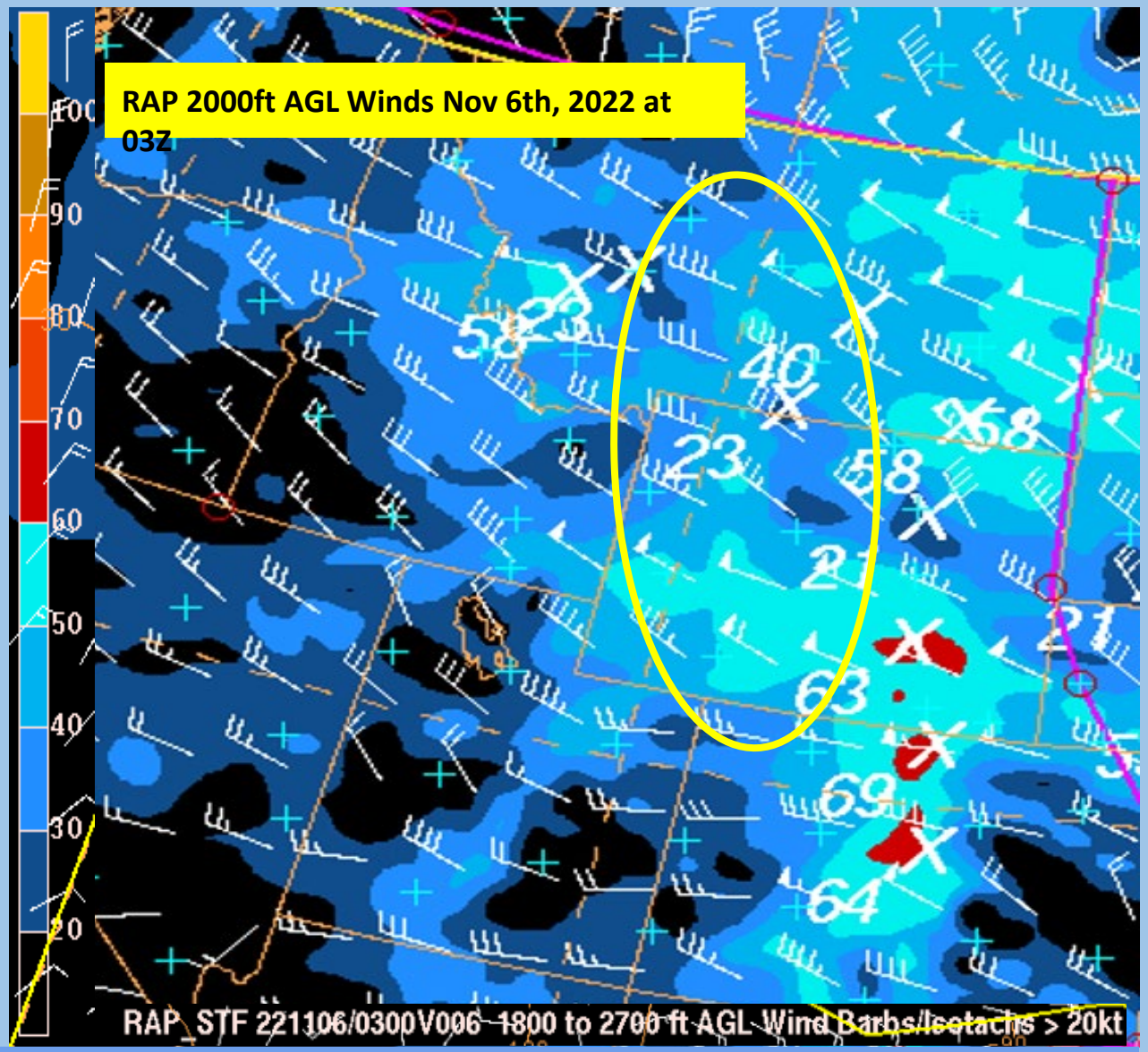
The RAP 2000 ft AGL winds in the yellow ovals were showing strong westerly cross barrier flow at 55-75 kts from 11/05/12Z - 11/05/15Z through the Tetons, Big Horn, Lewis Range and the Big Belt mountains.



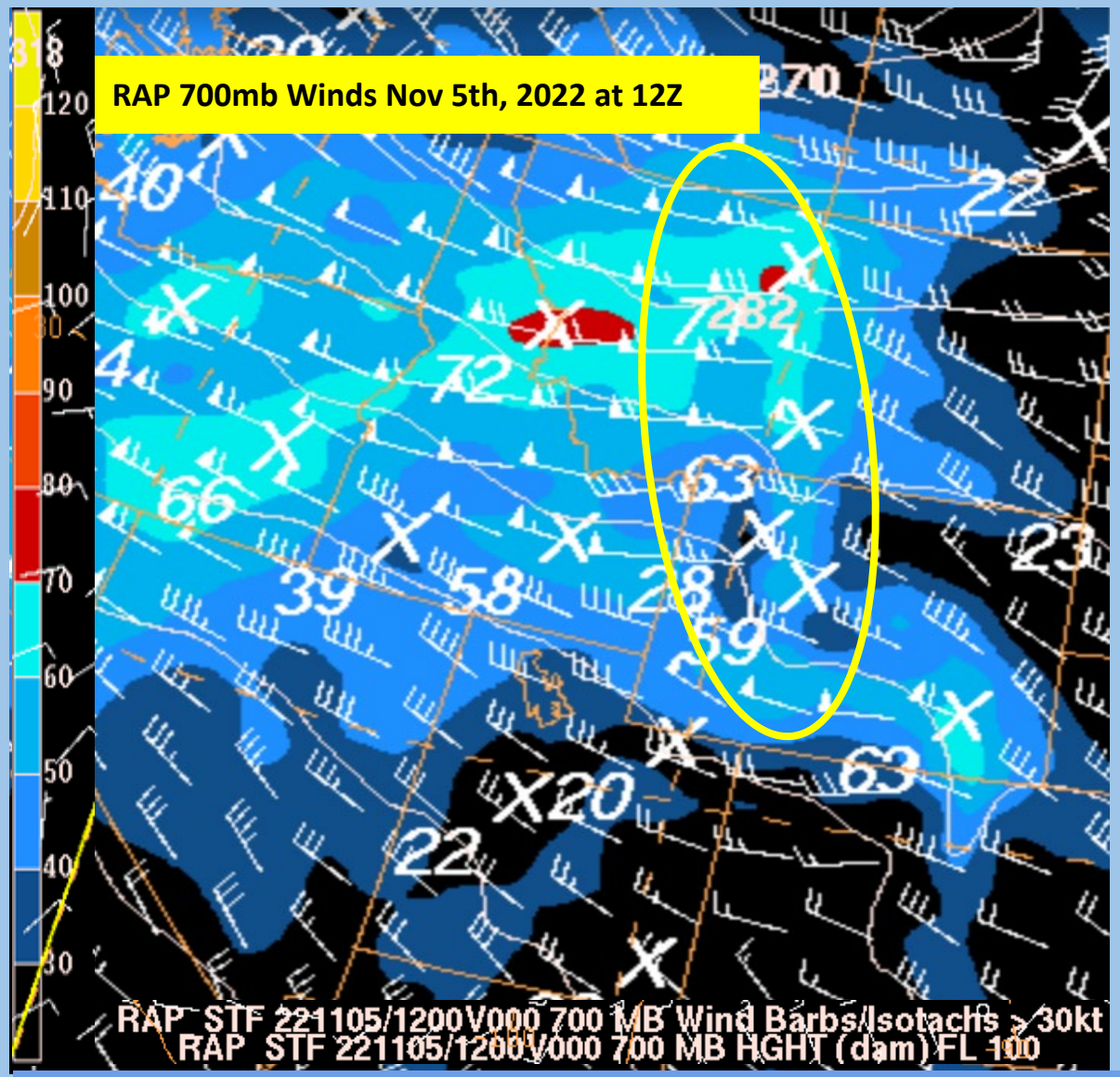


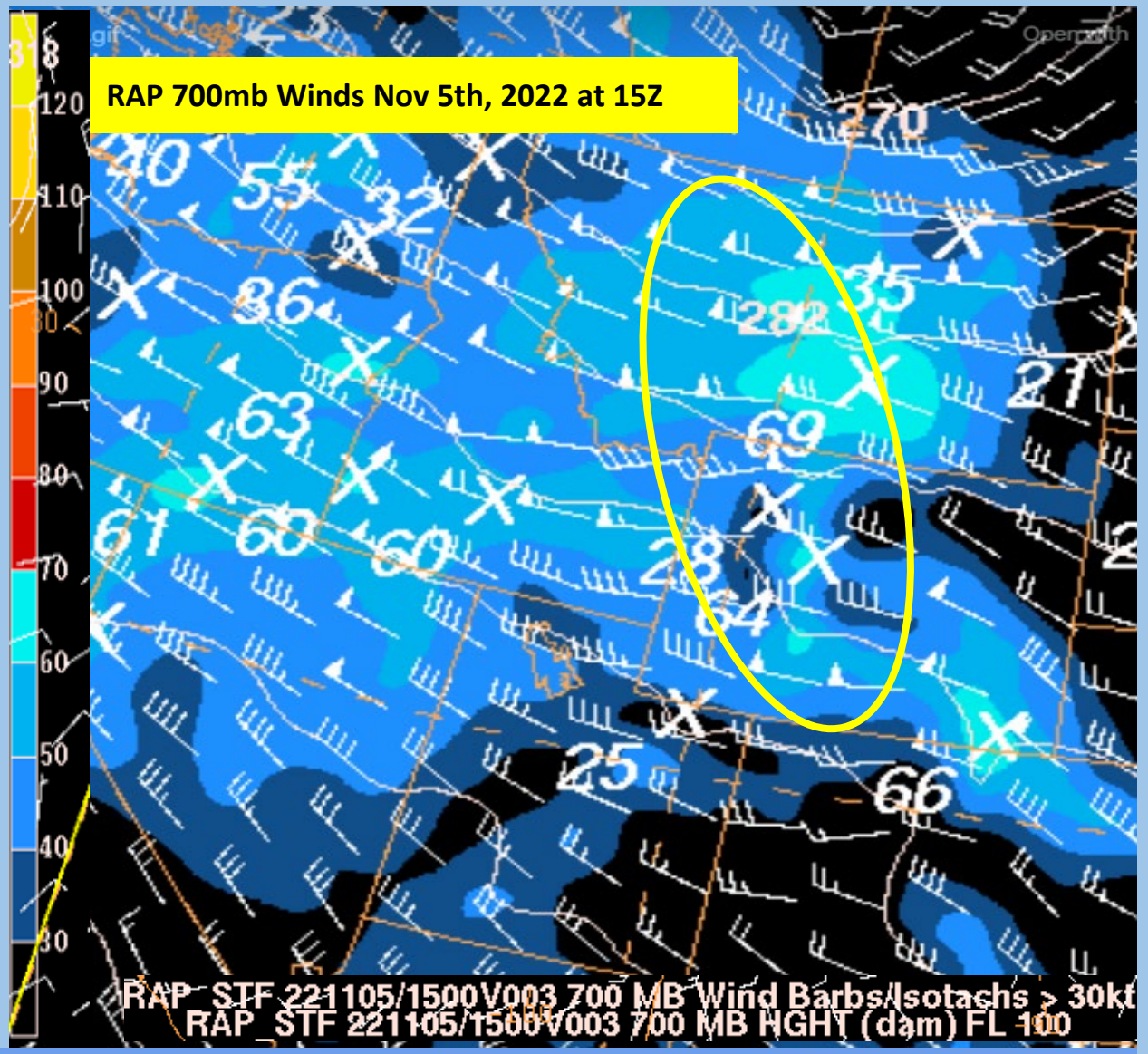
The RAP 2000 ft AGL winds in the yellow ovals remained very strong with westerly cross barrier flow at 55-75 kts through the Tetons, Big Horn, Lewis Range and the Big Belt mountains through 11/05/21Z.



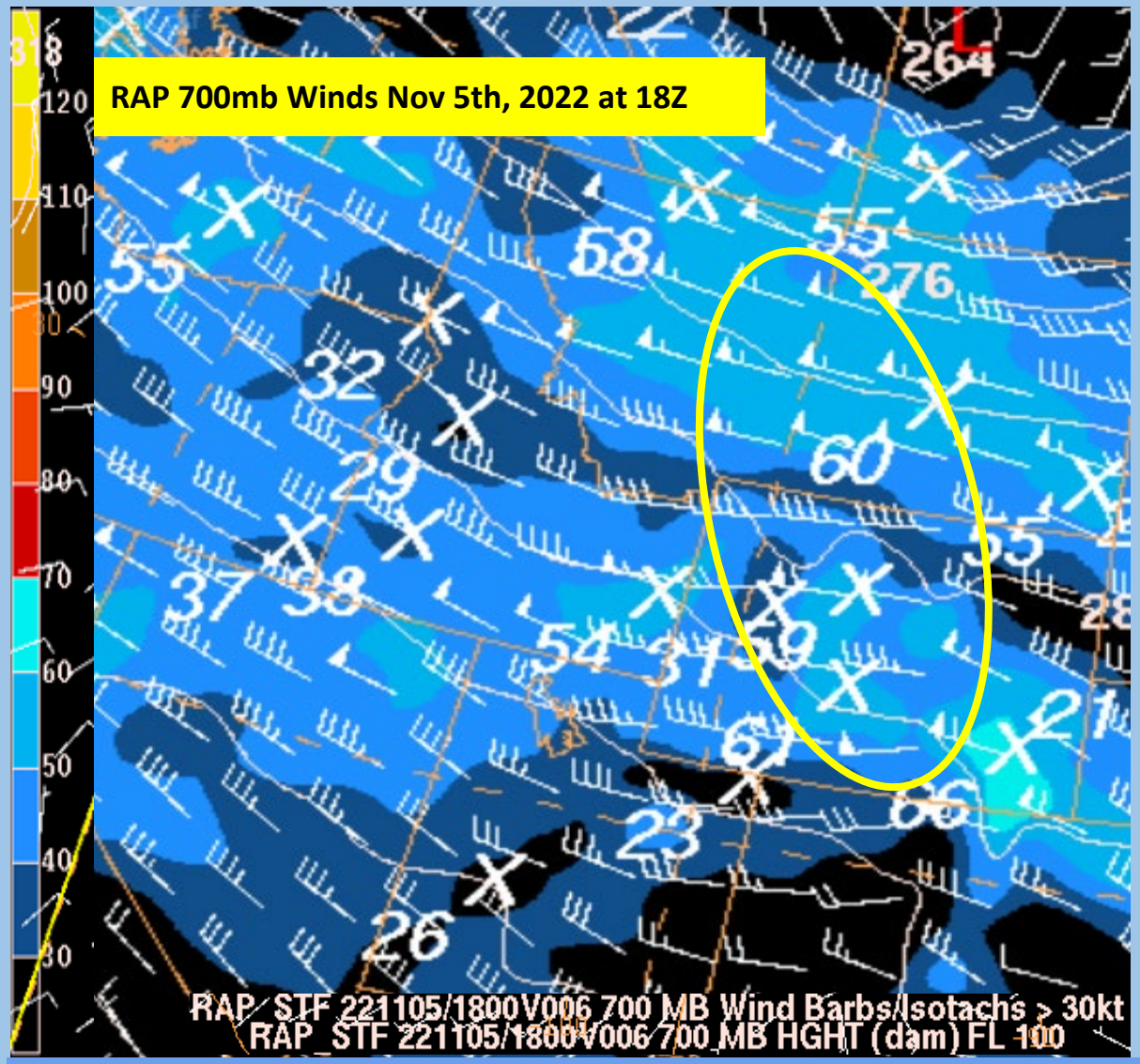


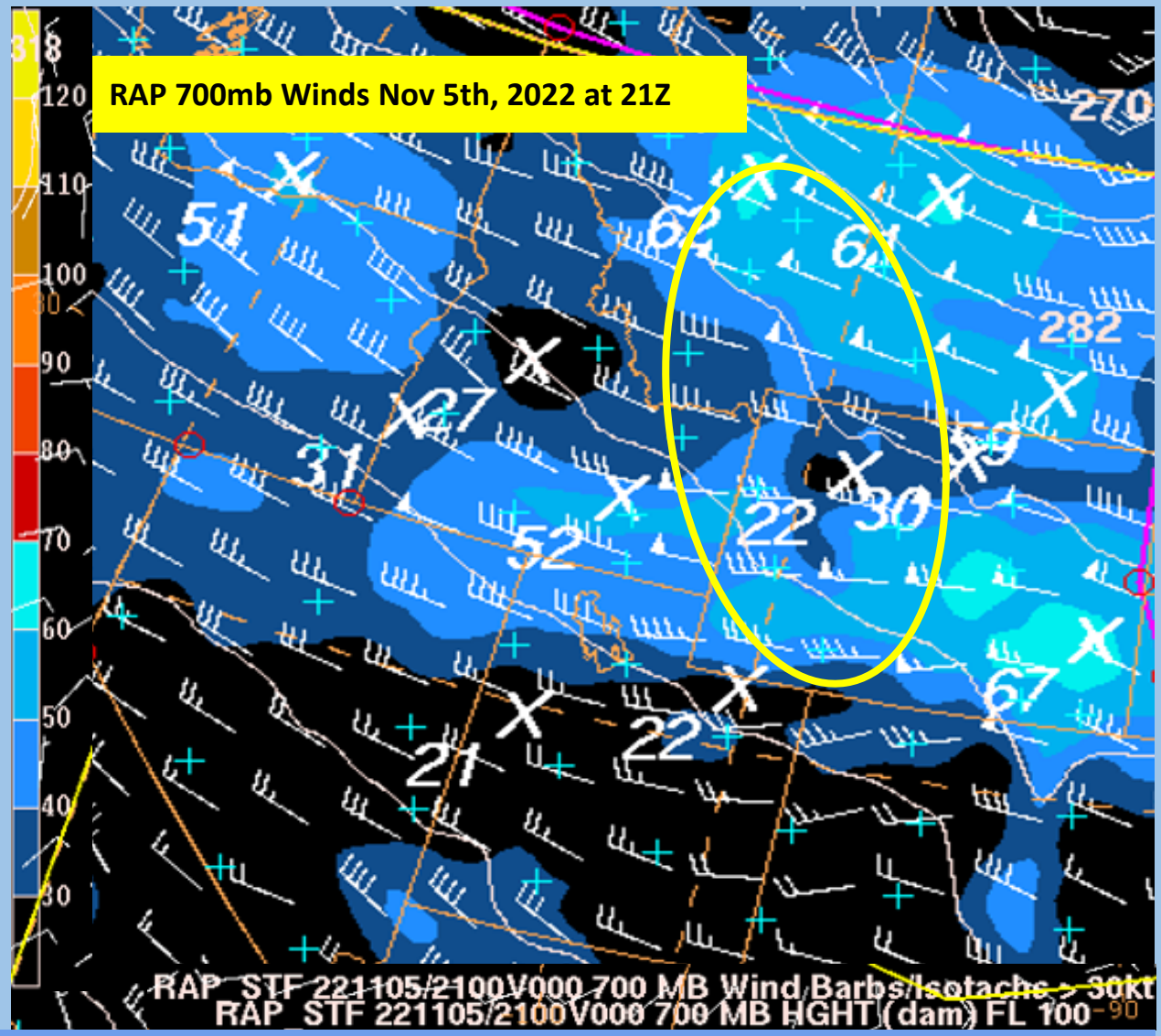
The RAP 2000 ft AGL winds in the yellow ovals continued with strong westerly cross barrier flow at 55-75 kts through the Tetons, Big Horn, Lewis Range and the Big Belt mountains through 11/06/00Z before beginning weakening by 11/06/03Z.



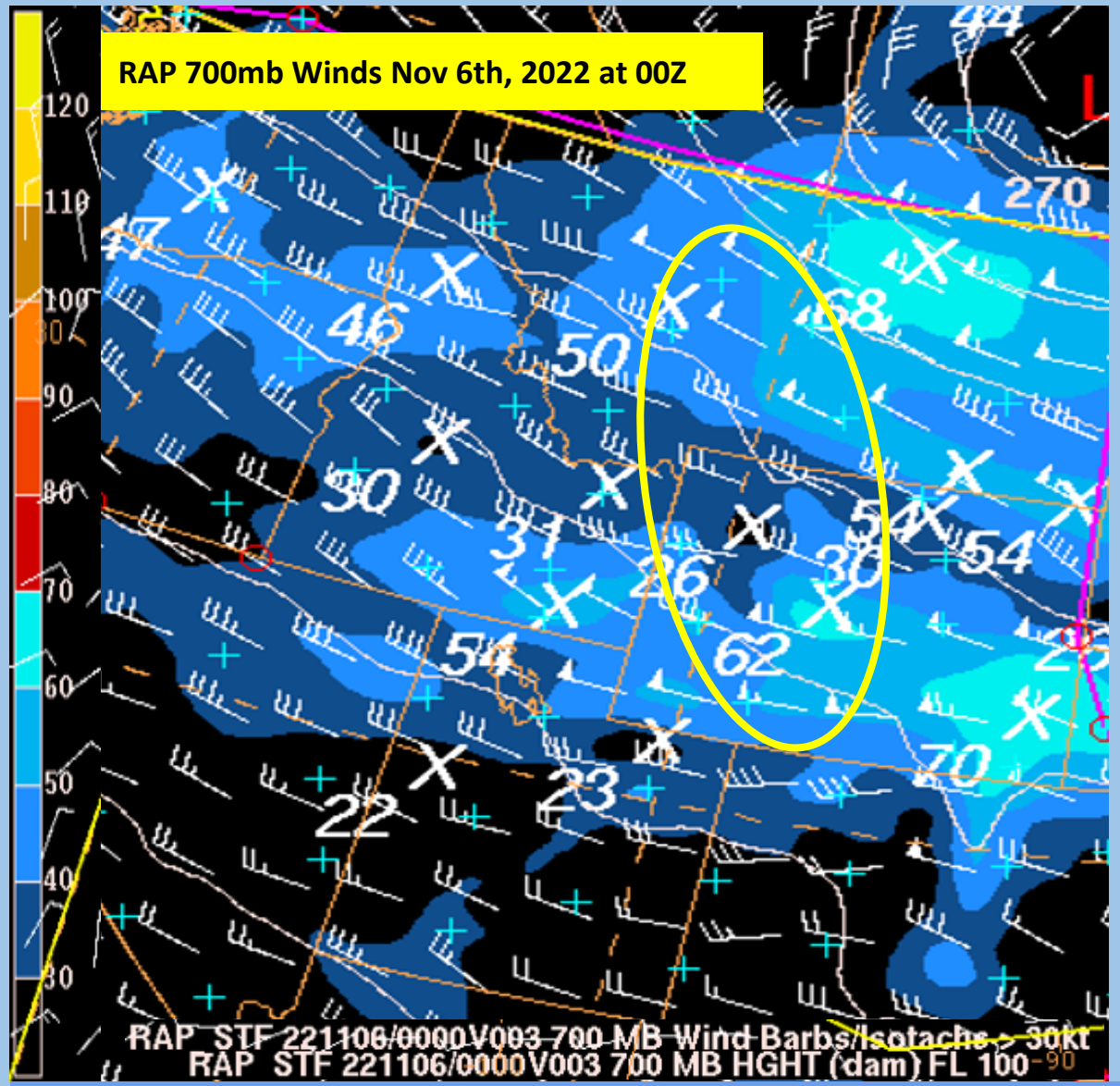


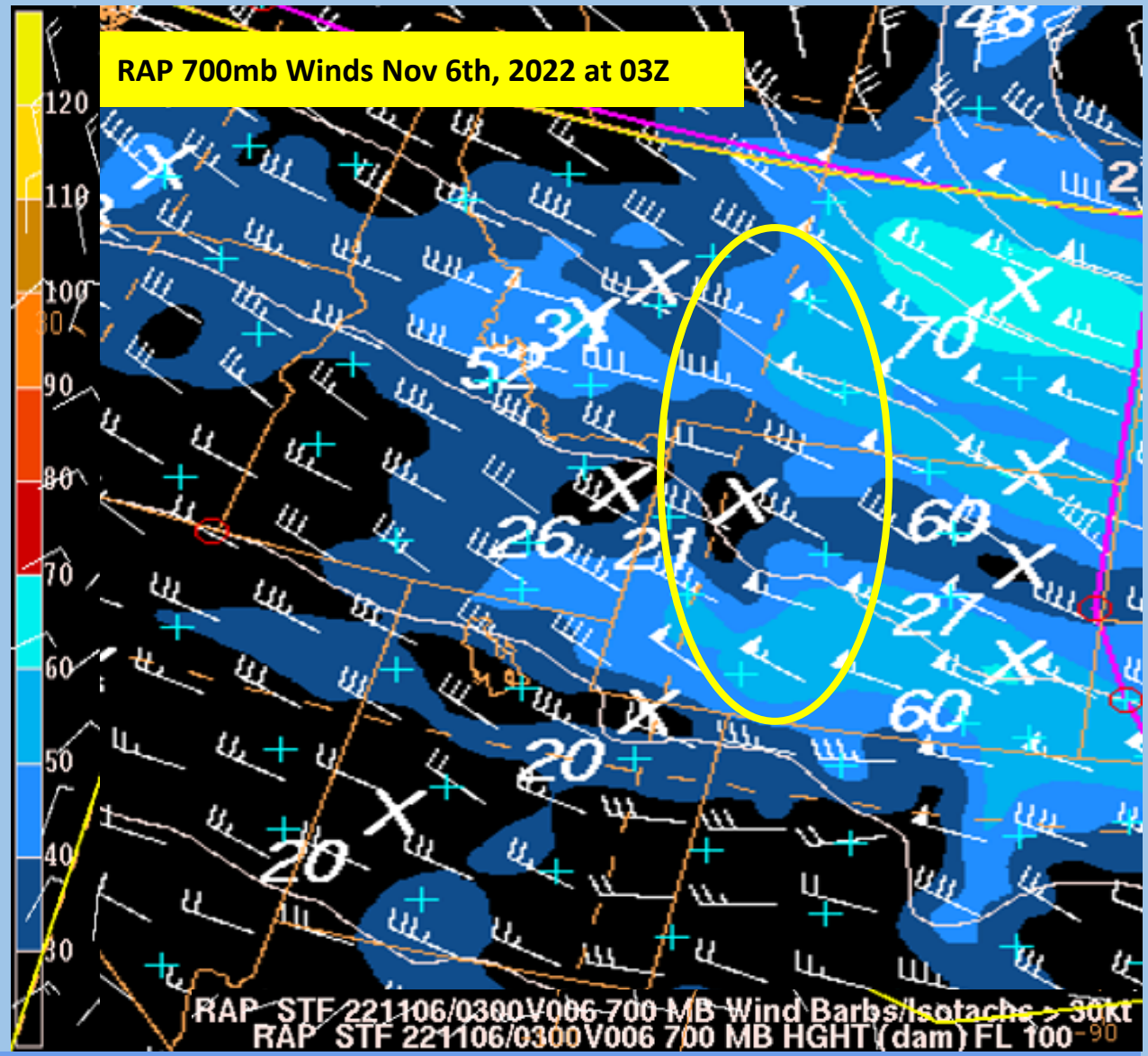
The RAP 700mb winds in the yellow ovals were showing strong westerly cross barrier flow at 60-70 kts from 11/05/12Z - 11/05/15Z through the Tetons, Big Horn, Lewis Range and the Big Belt mountains. I should of used 600mb winds for closer heights for more accurate height of ridge top winds.



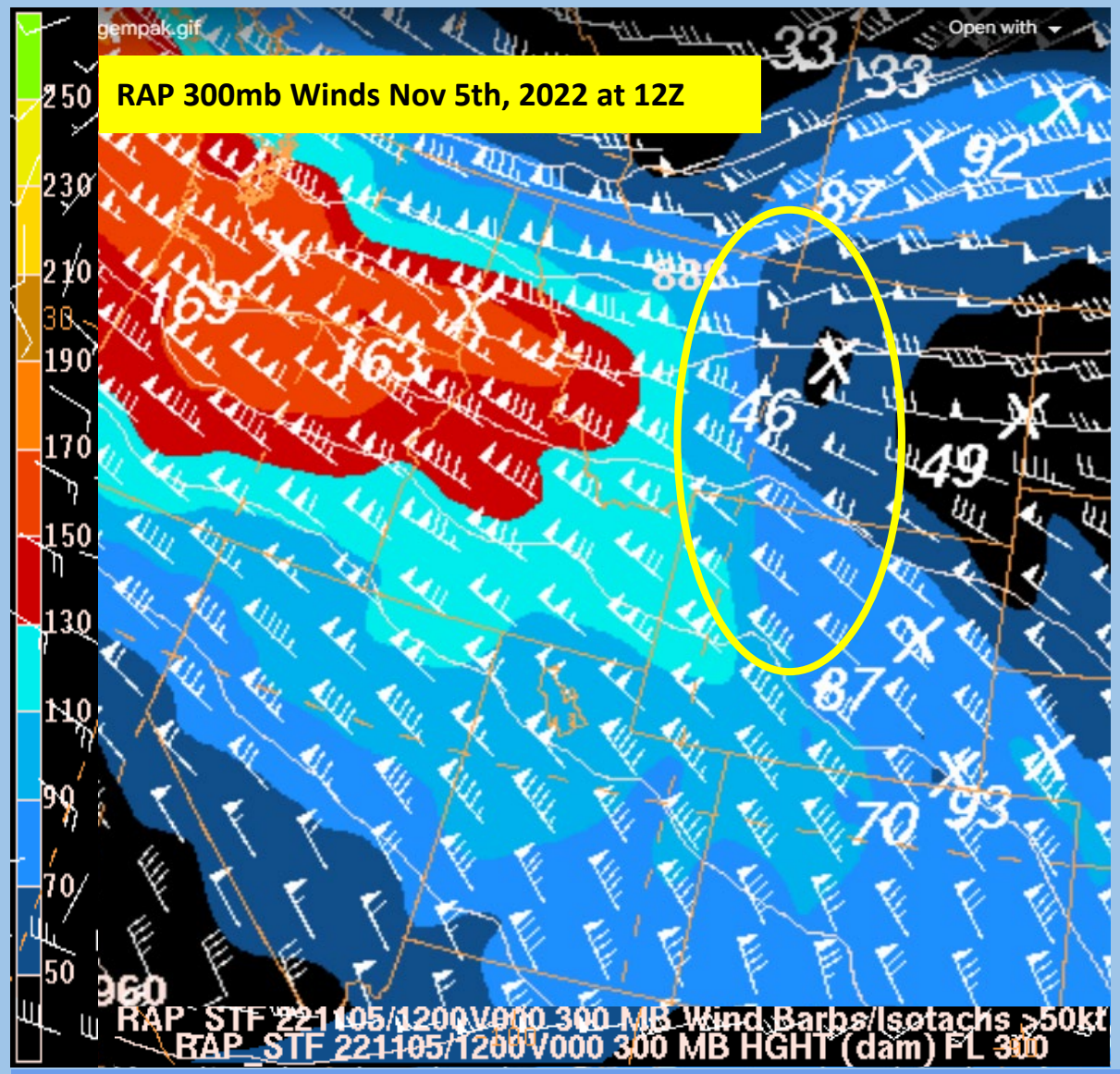


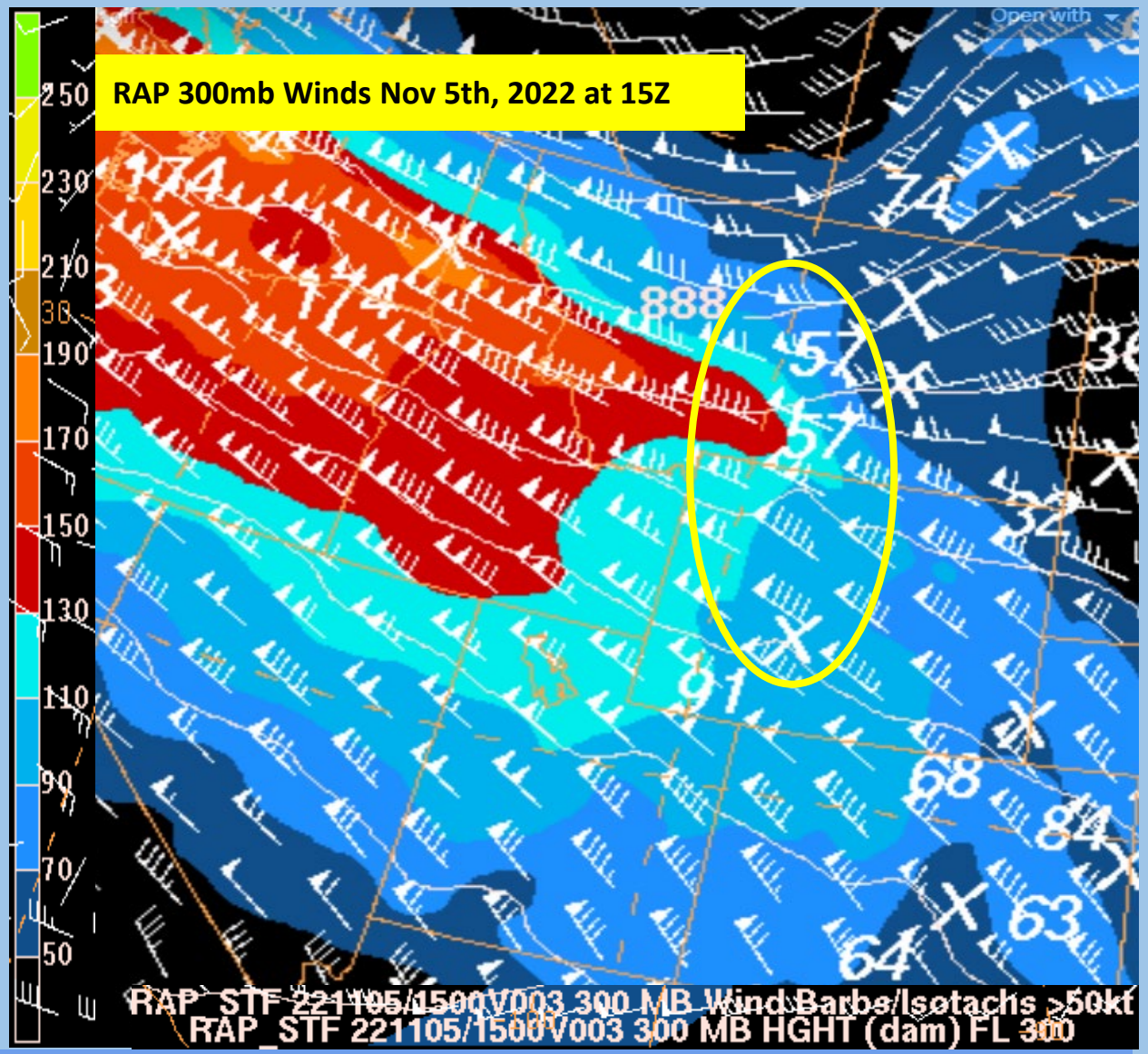
The RAP 700mb winds in the yellow ovals continued to show strong westerly cross barrier flow at 60-70 kts from 11/05/12Z - 11/05/15Z through the northern Rockies. While the northern Tetons the winds were diminishing but the southern Tetons and the Big Horn mountains remained with strong westerly cross barrier flow through 11/05/21Z.



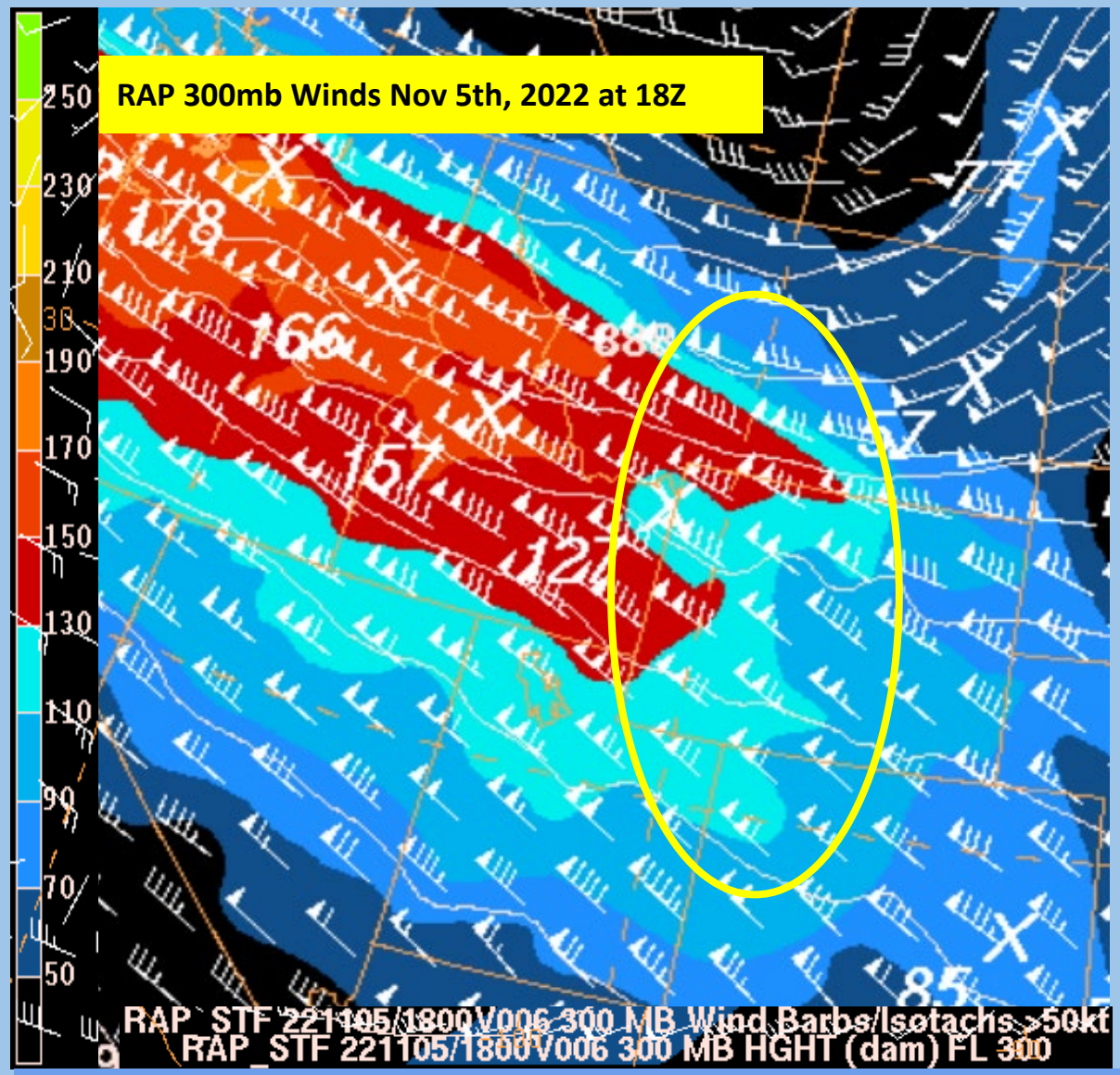


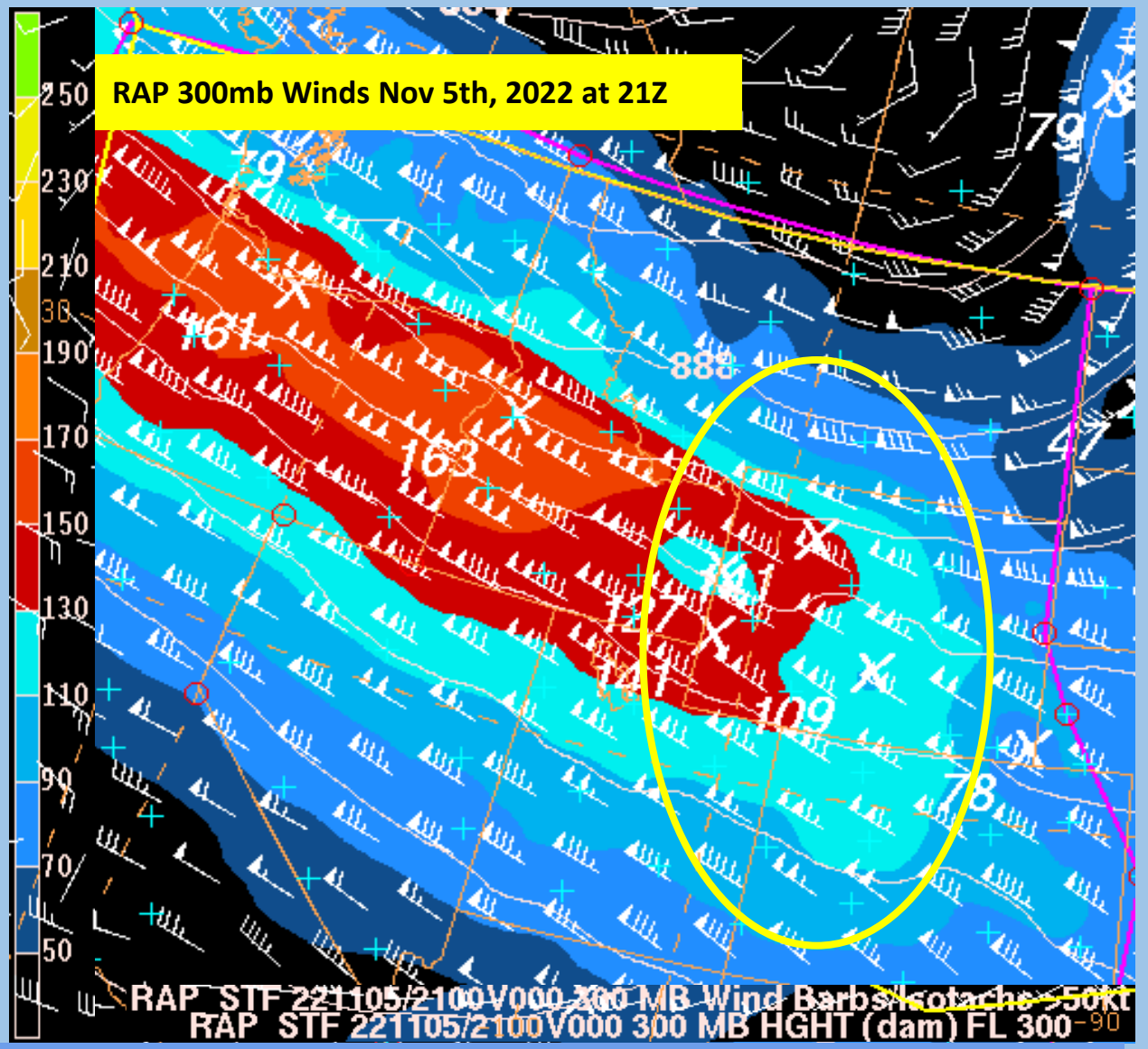
The RAP 700mb winds in the yellow ovals continued to show strong westerly cross barrier flow at 50-60 kts though 11/06/03Z through the northern Rockies. While the northern Tetons the winds continued to diminish but the southern Tetons and the Big Horn mountains remained with strong westerly cross barrier flow through 11/06/03Z.



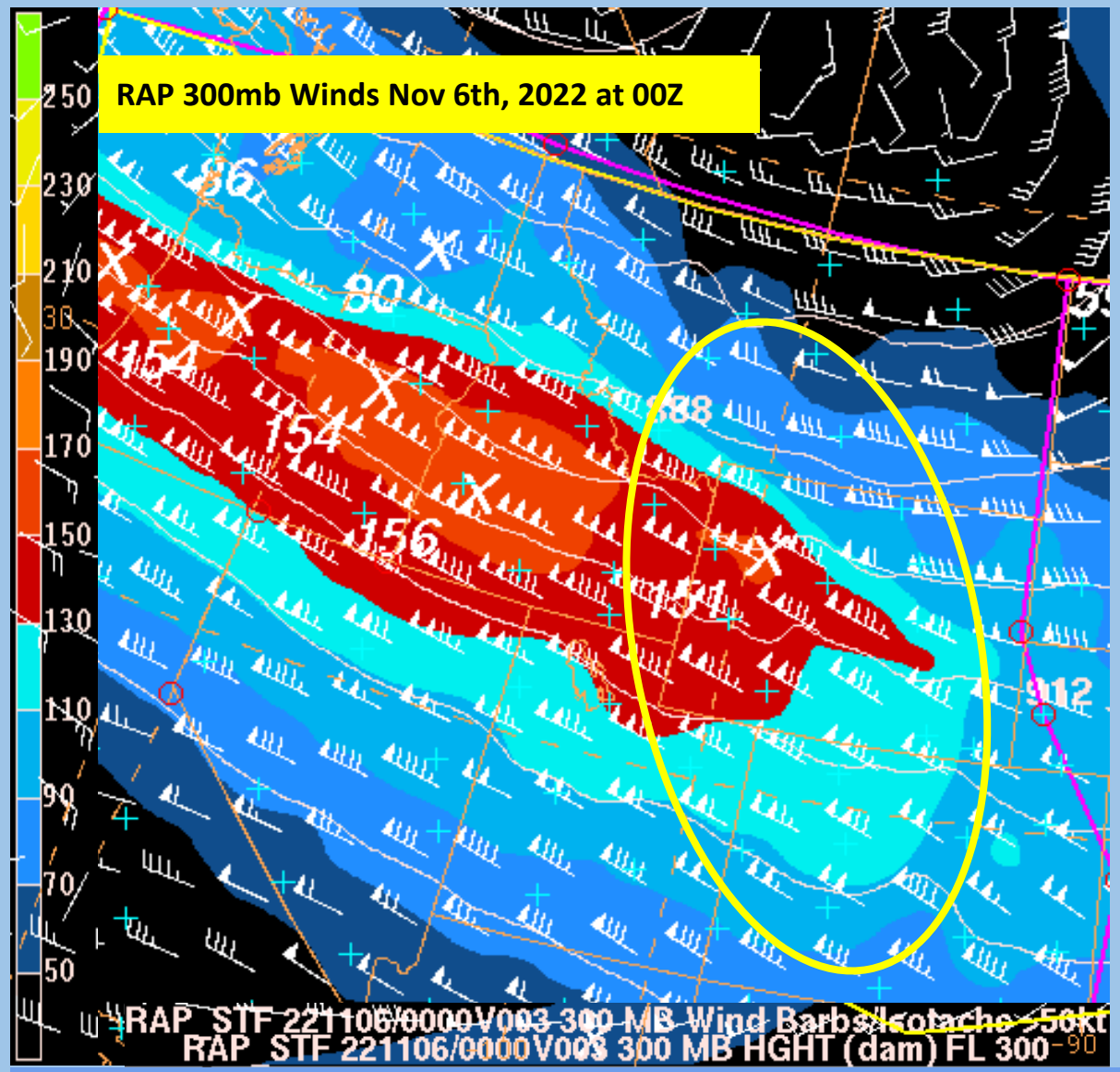


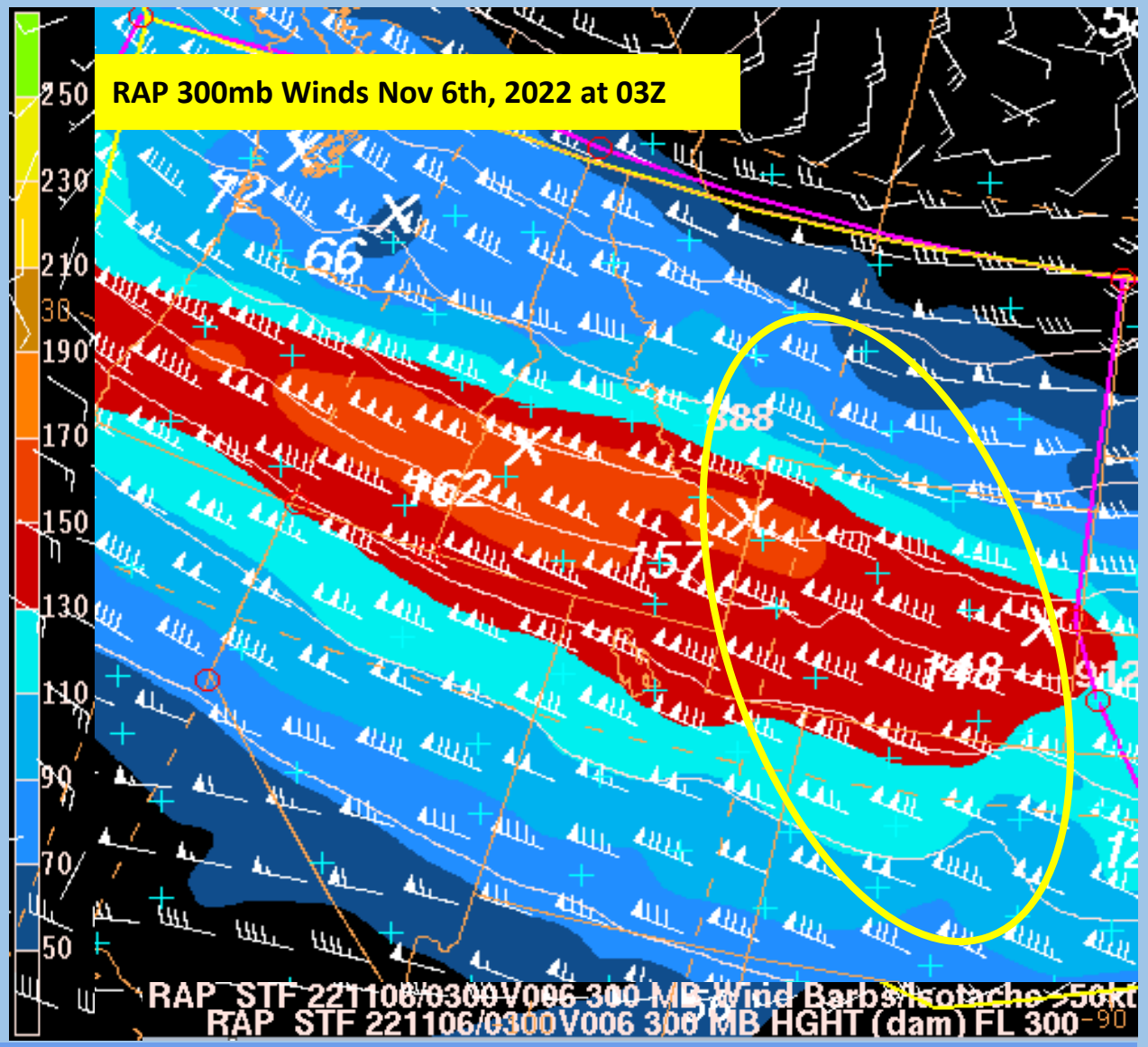
The yellow ovals were showing strong horizontal speed convergence intensifying by 15Z as the northwesterly to westerly nose of the jetcore entered the western to central MT region. While divergence occurred from central to eastern MT. These features were coupled with the left exit quadrant region of jetcore entering the central MT to northern WY region.



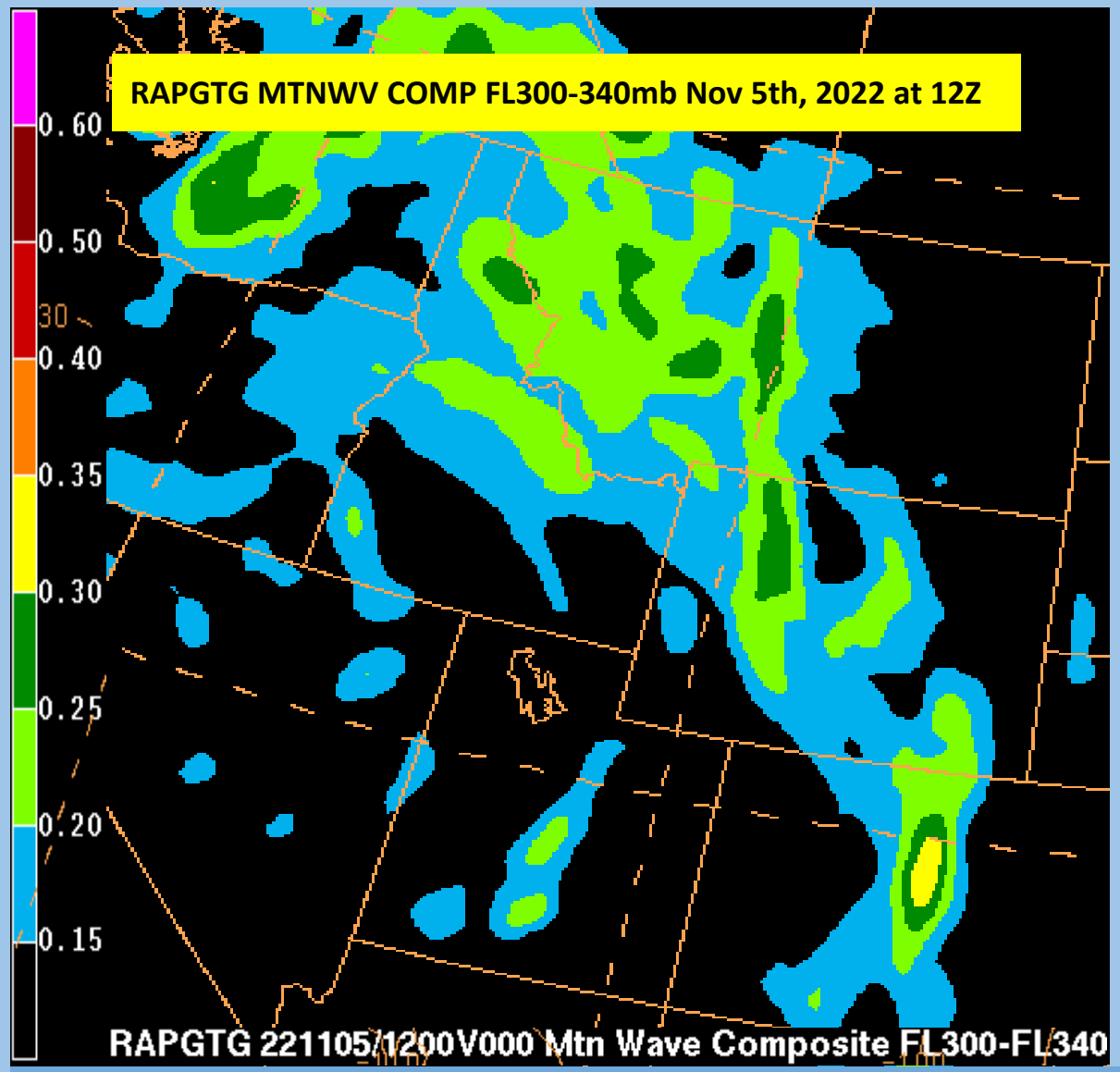


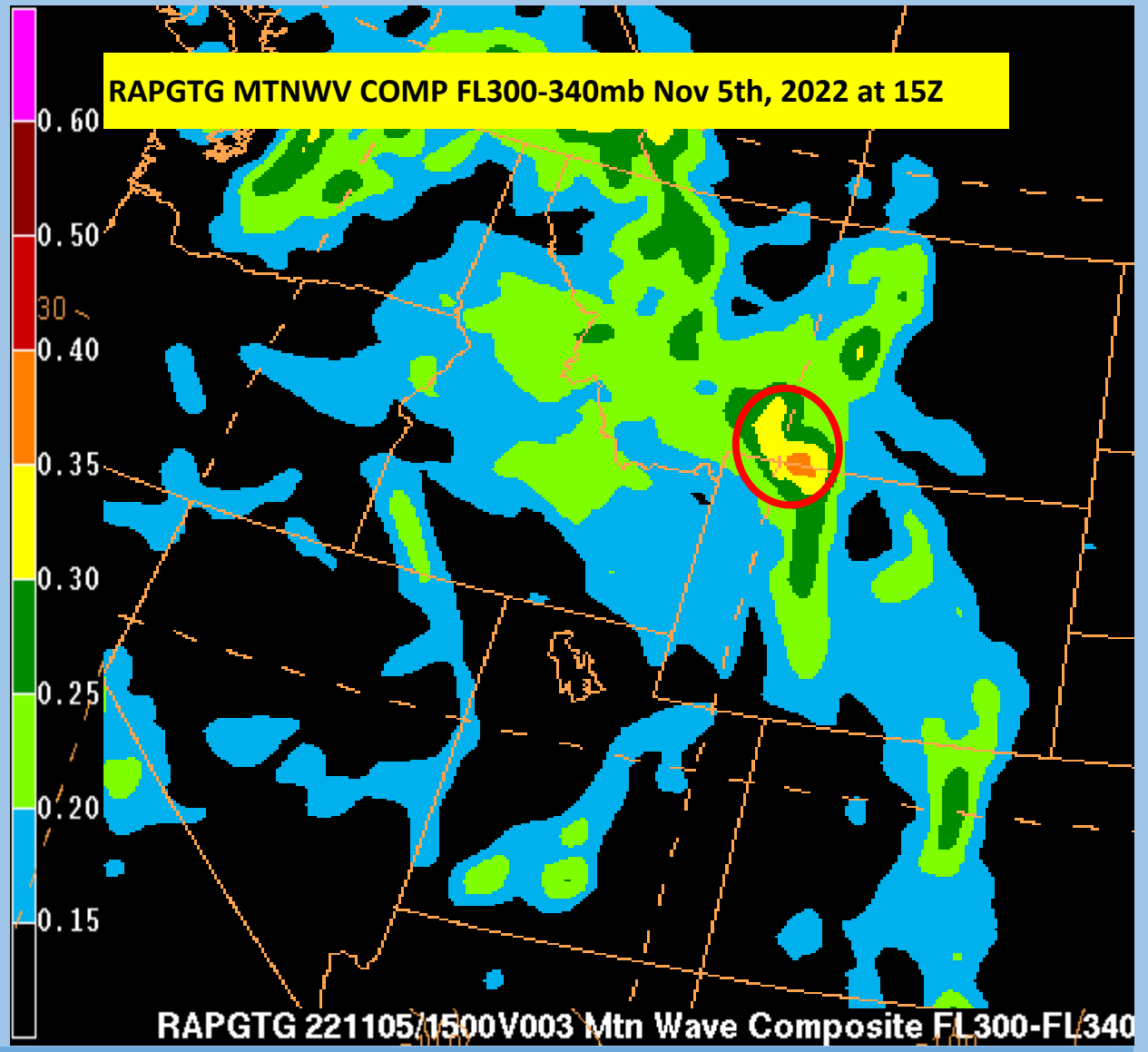
The yellow ovals show the northwesterly left front exit quadrant region of the 300mb jetcore as it continues to stream through the western to central MT & WY regions. While divergence has moved farther eastward into the ND/SD region.



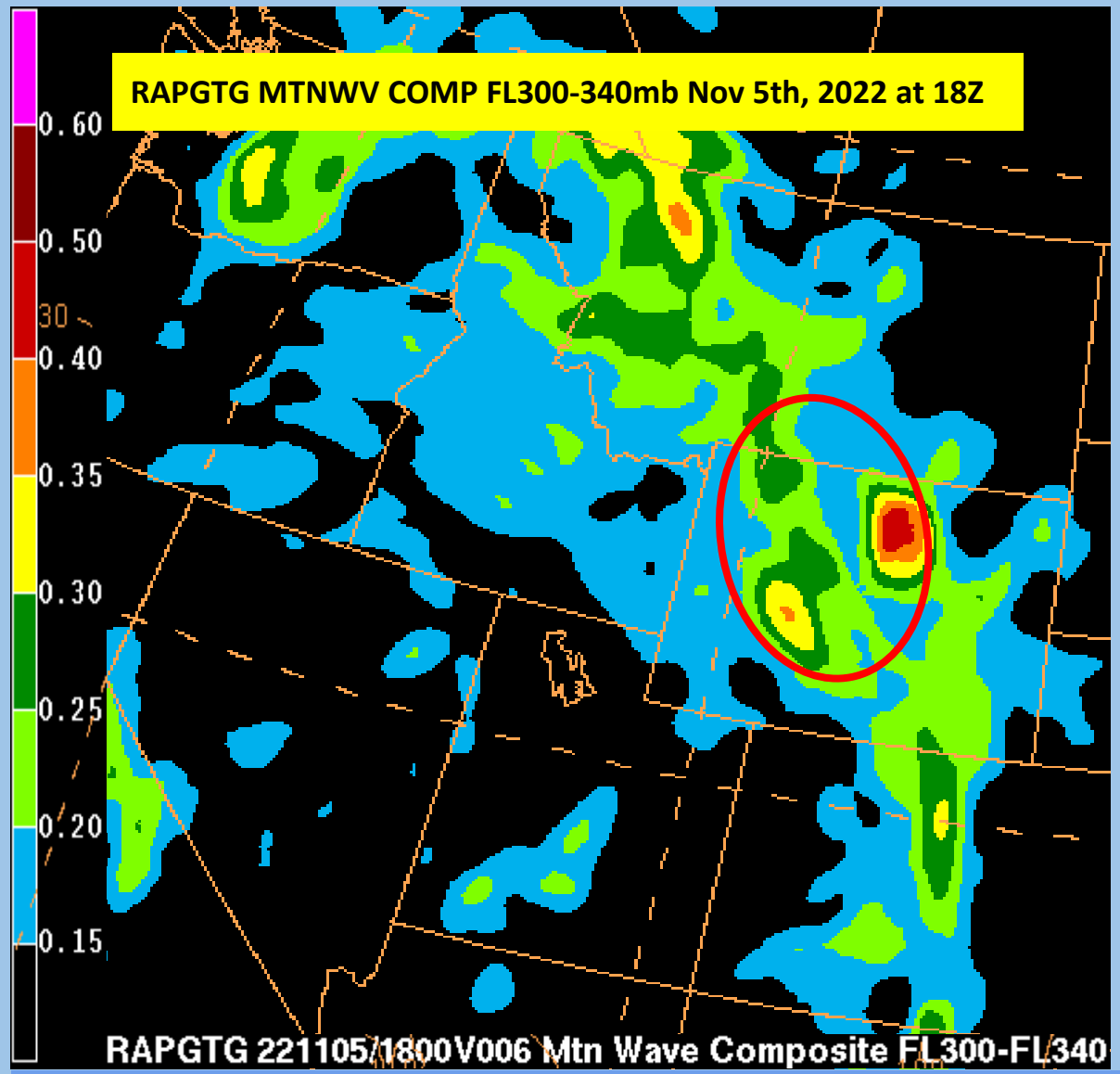


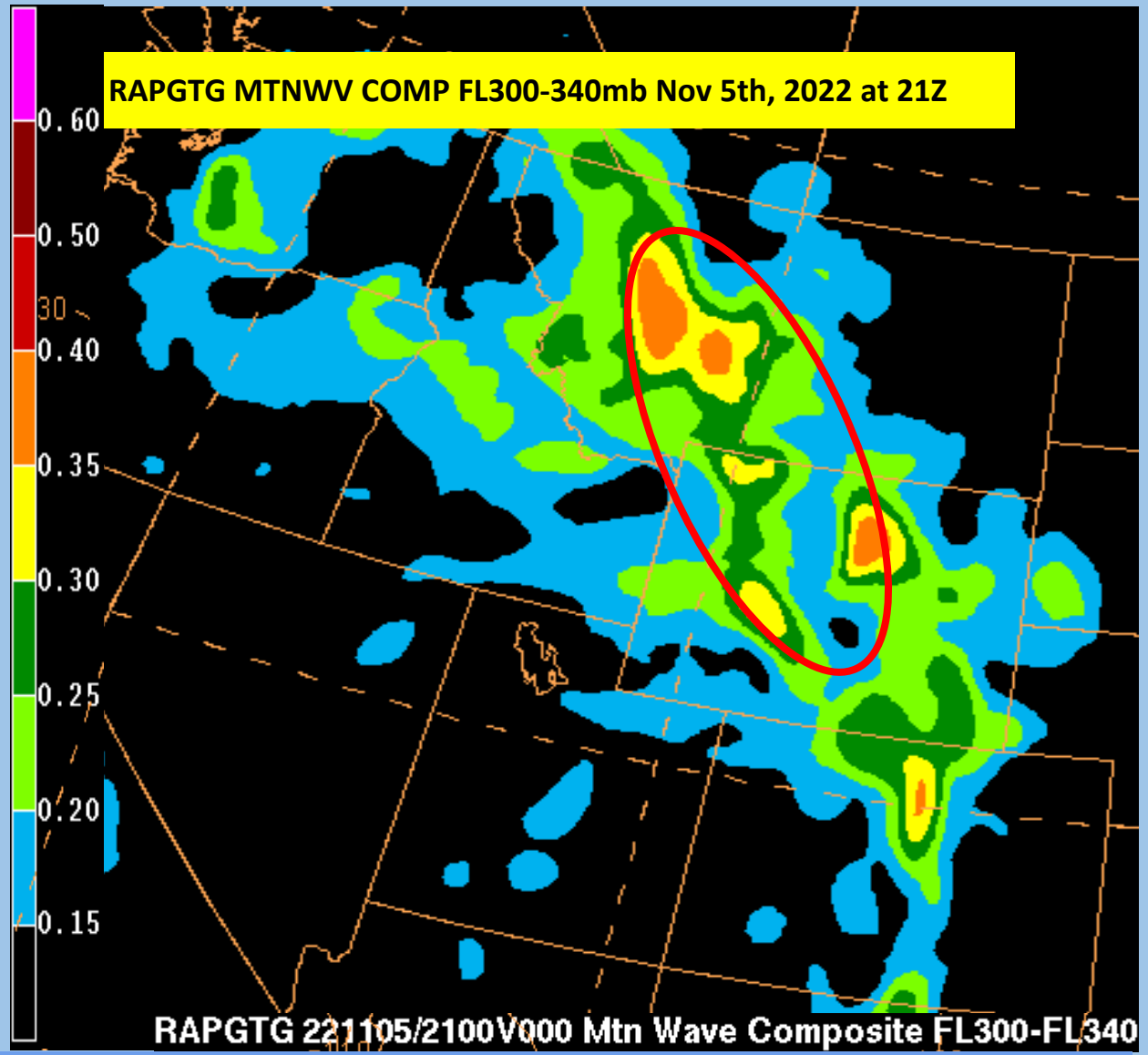
The yellow ovals show the continued northwesterly left front exit quadrant region of the 300mb jetcore as it streams through the western to central MT & WY regions through 11/06/03Z. While the right front exit quadrant region of the 300mb moves into the Denver region through 11/06/03Z.



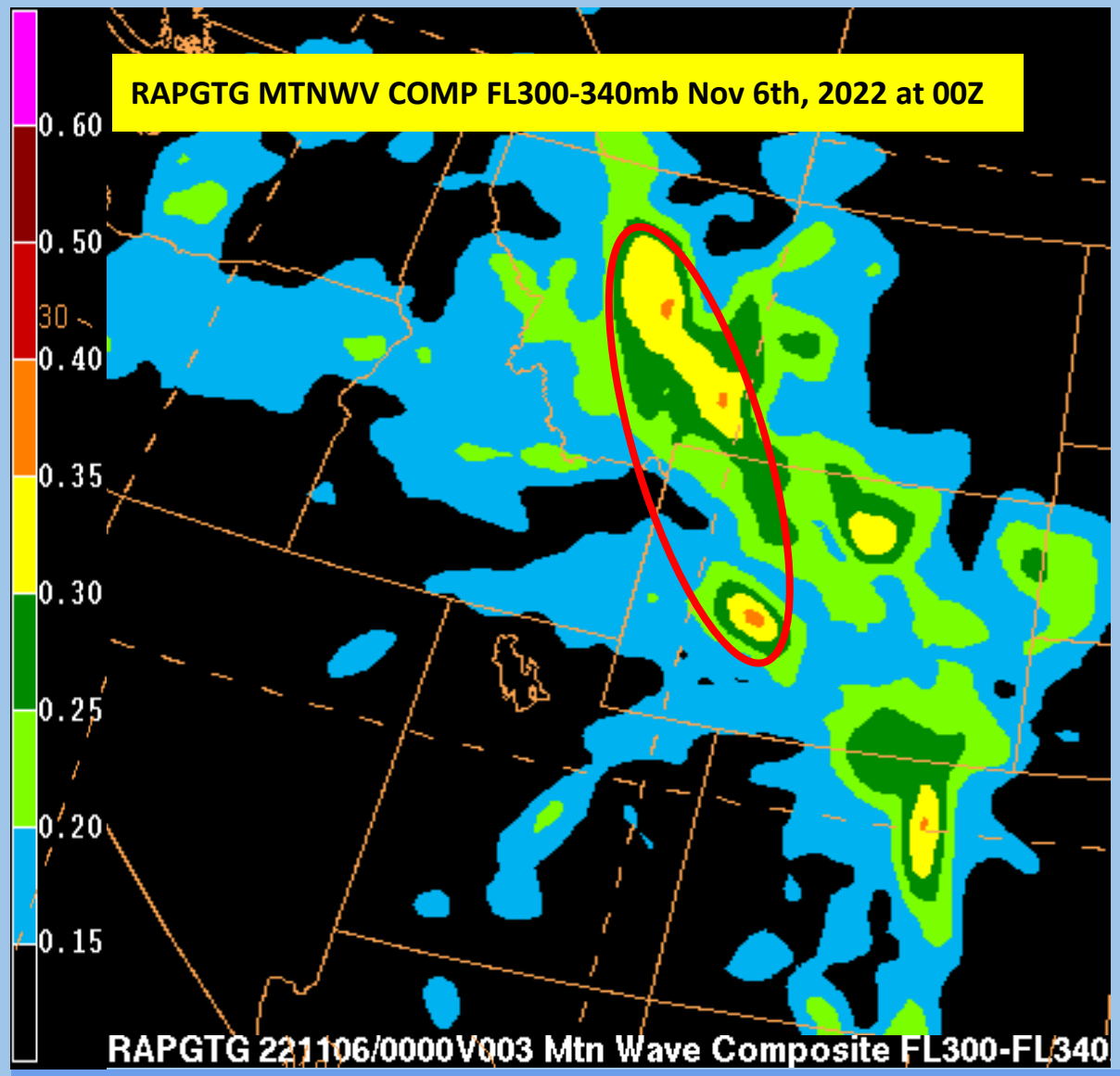


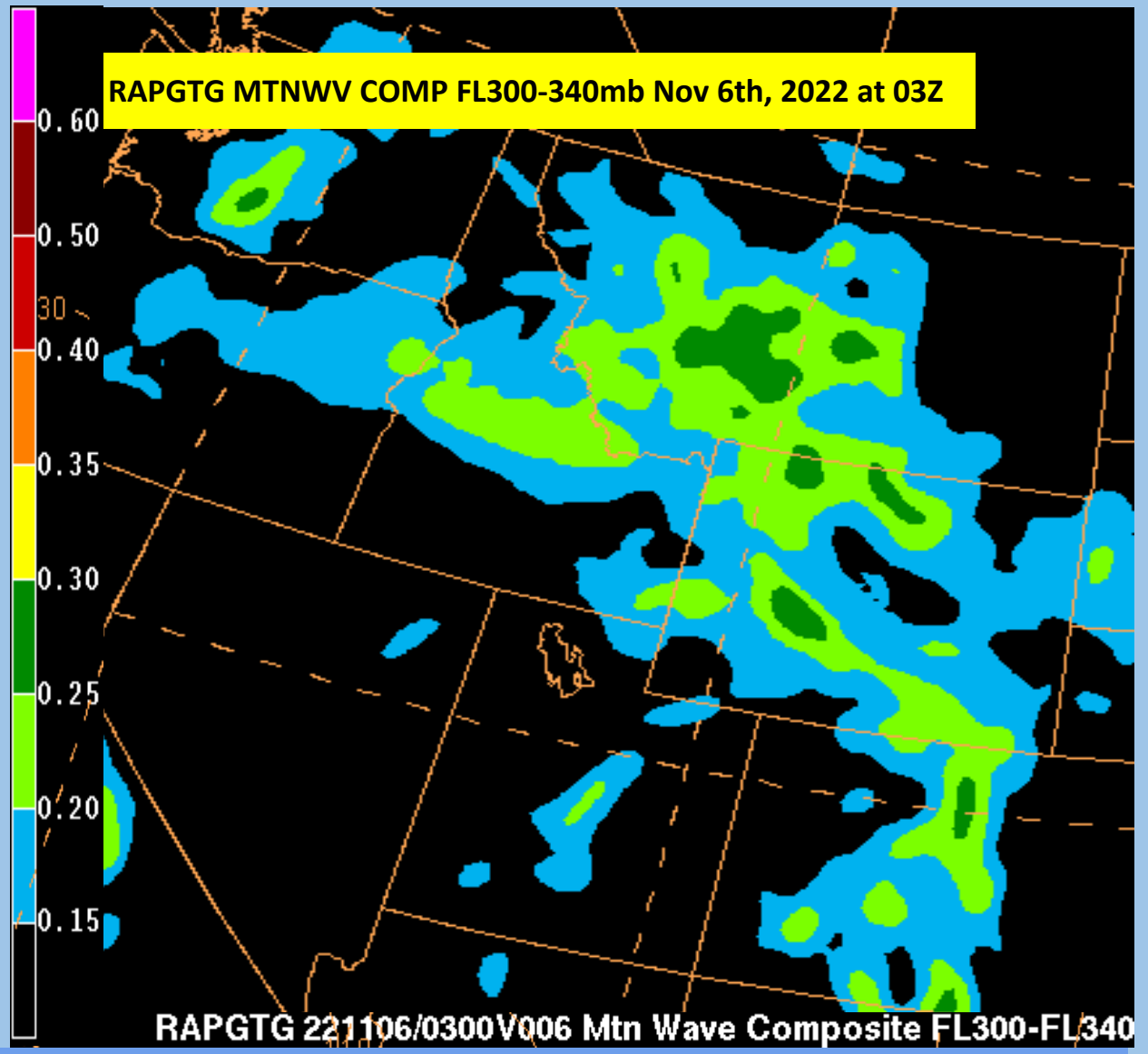
The RAPGTG Mountain Wave Composite shows possible moderate turbulence at FL300-340mb by 11/05/15Z through the lower southern Rockies or the Abasaroka mountains.



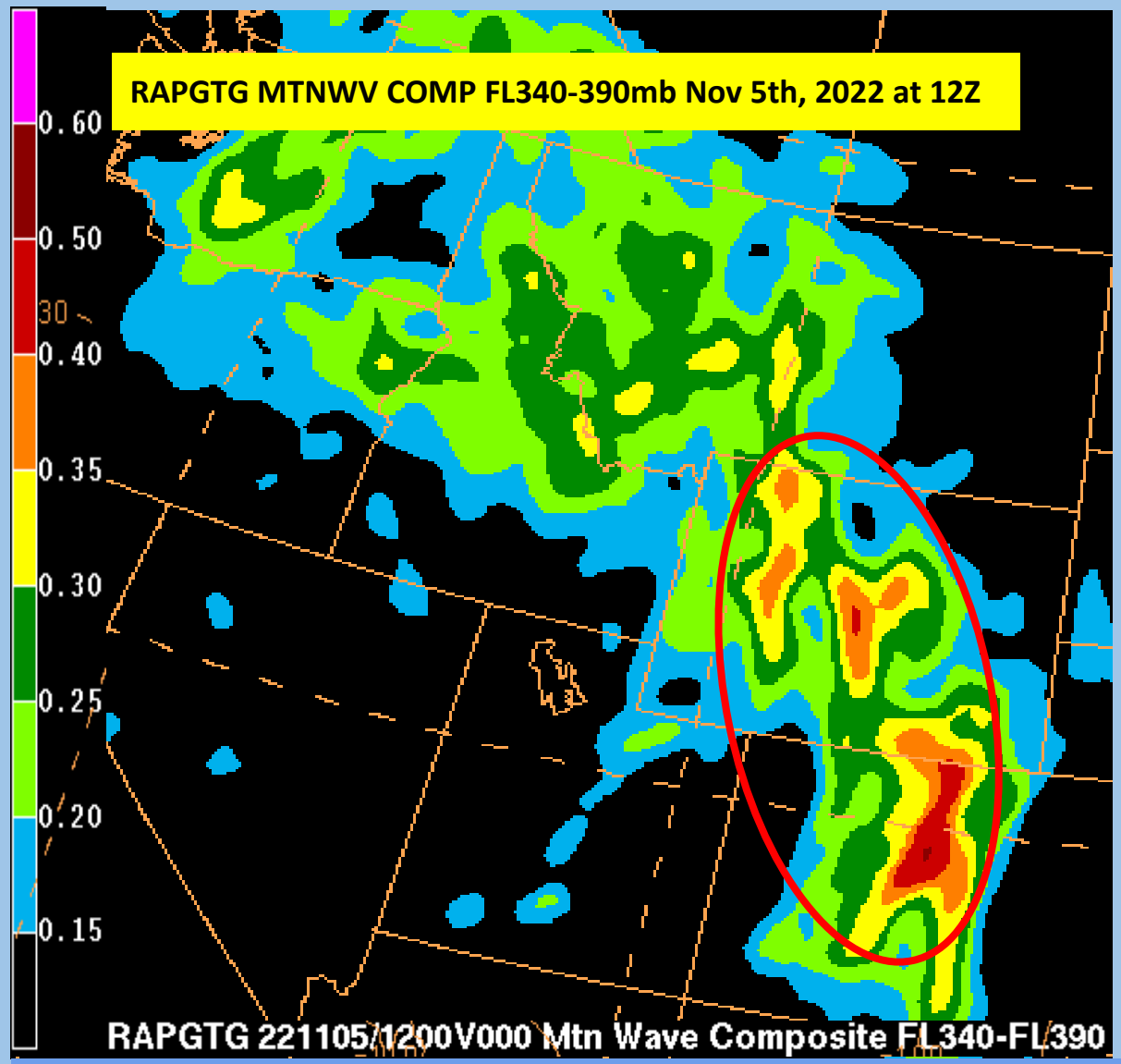


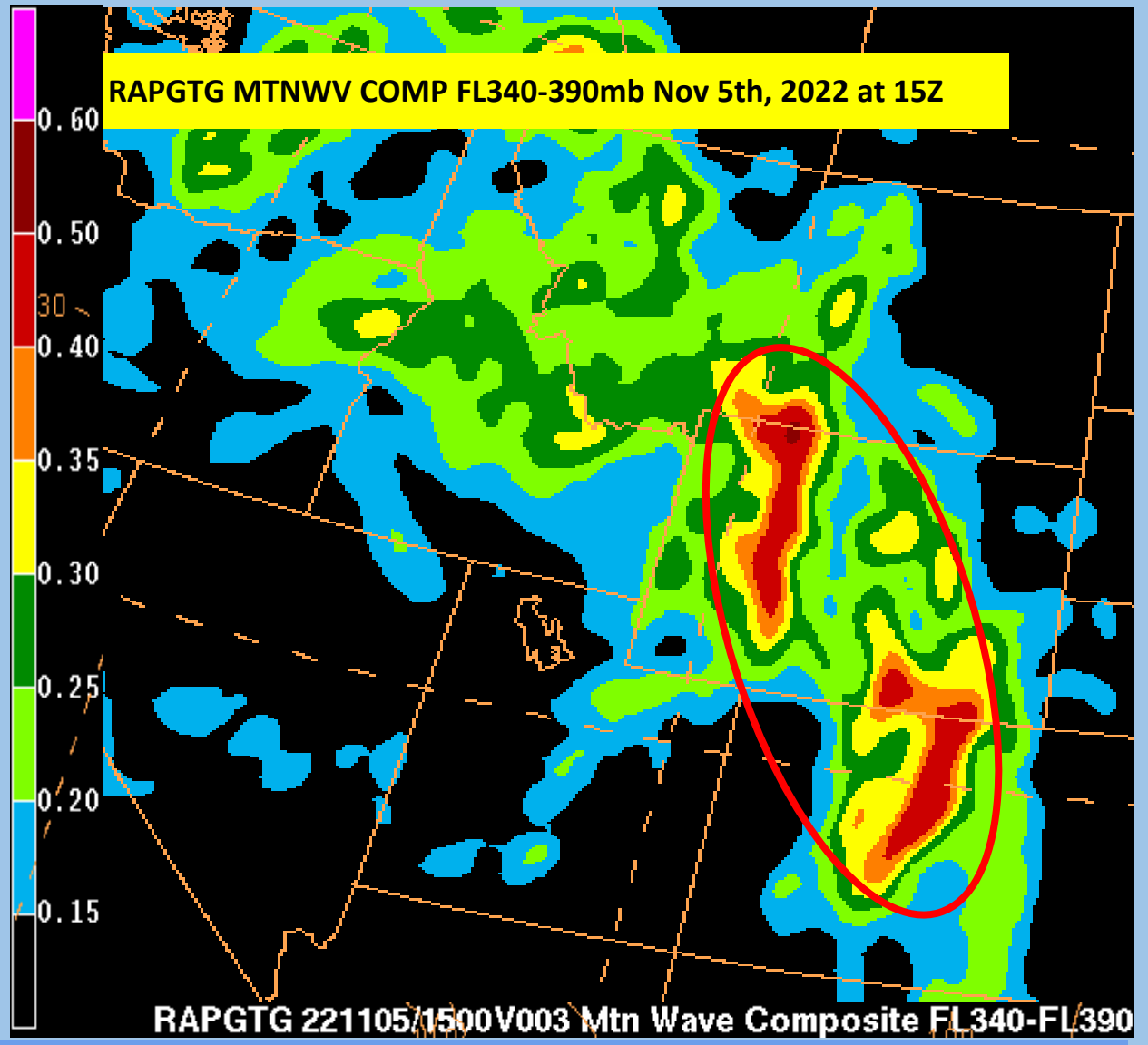
The RAPGTG Mountain Wave Composite at FL300-340mb starts to strengthen with stronger indices over the Big Belt mountains in MT and the Big Horn mountains in WY by 11/05/18Z.



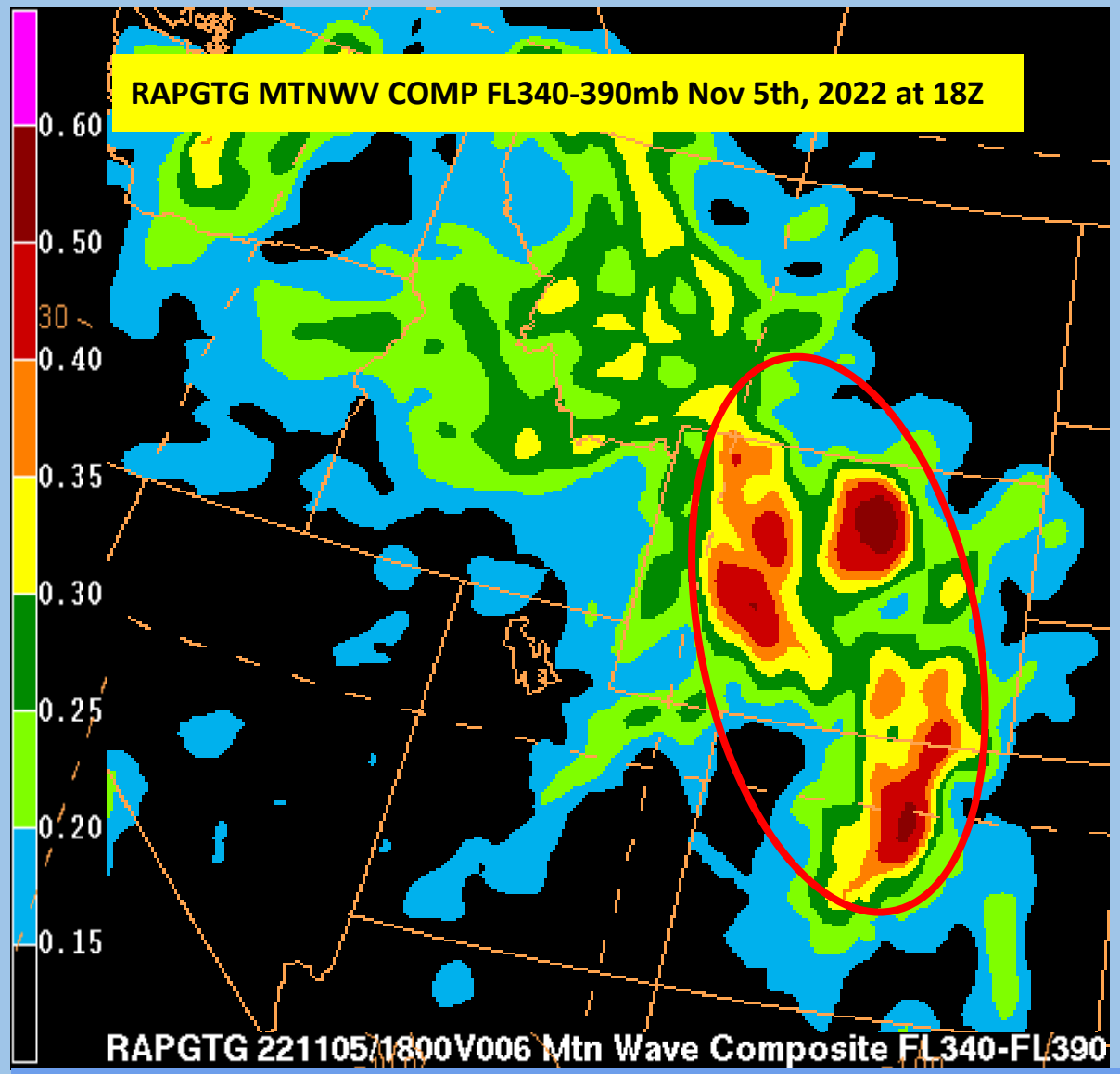


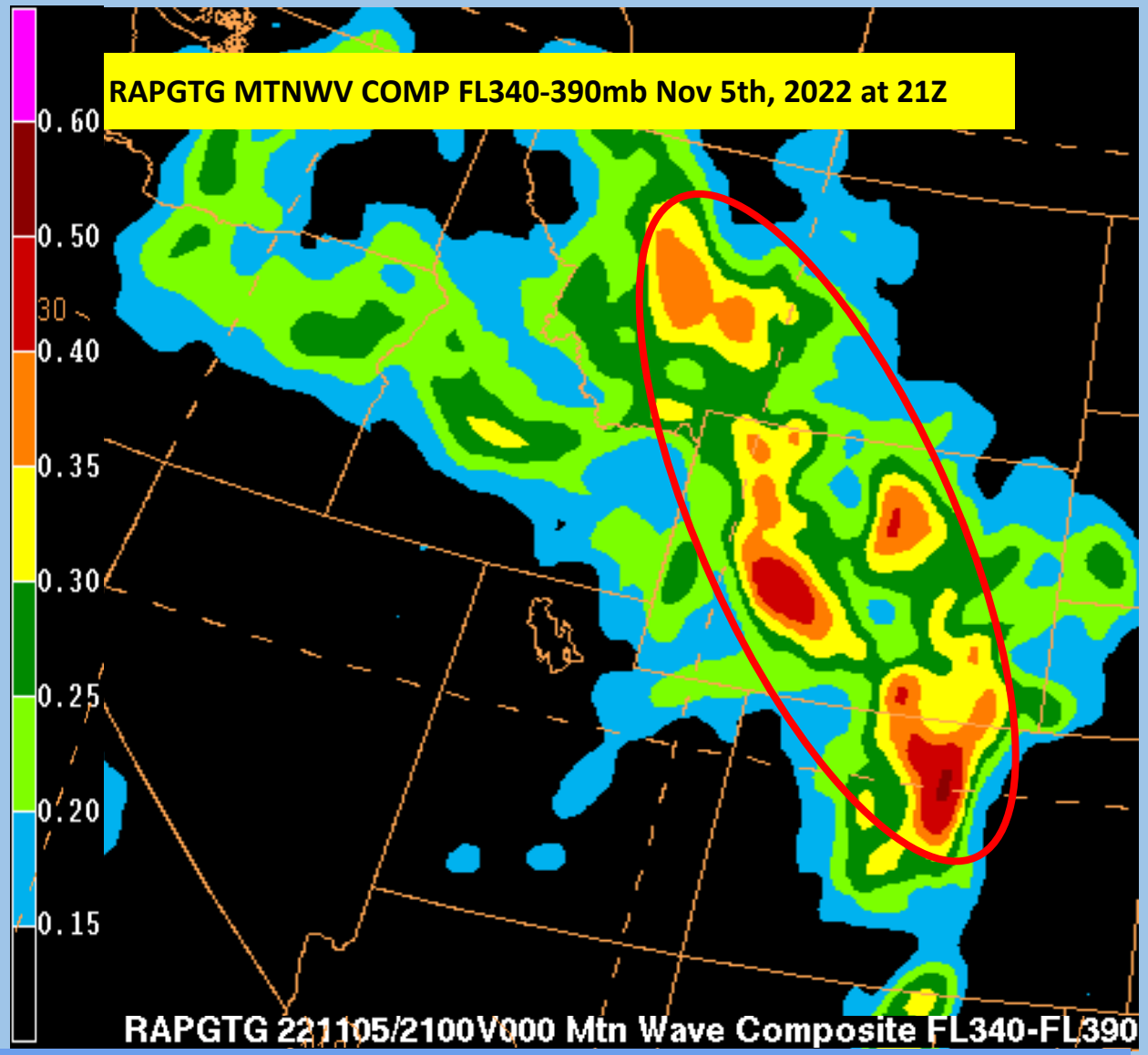
The RAPGTG Mountain Wave Composite at FL300-340mb has possible moderate turbulence during 11/06/00Z over the Tetons and northern Rockies. By 11/06/03Z the mountain wave indices totally diminishes for MT and WY regions.



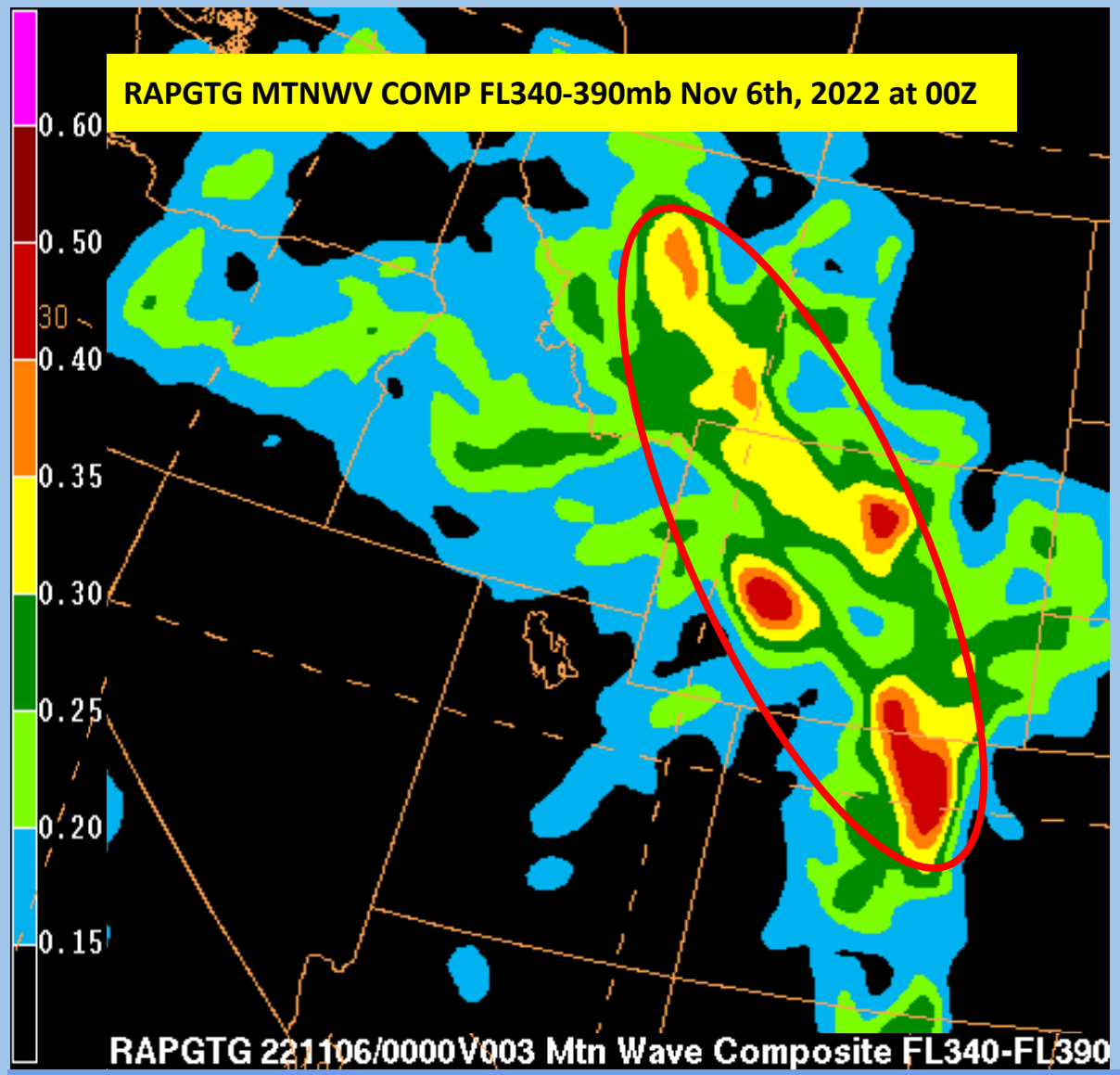


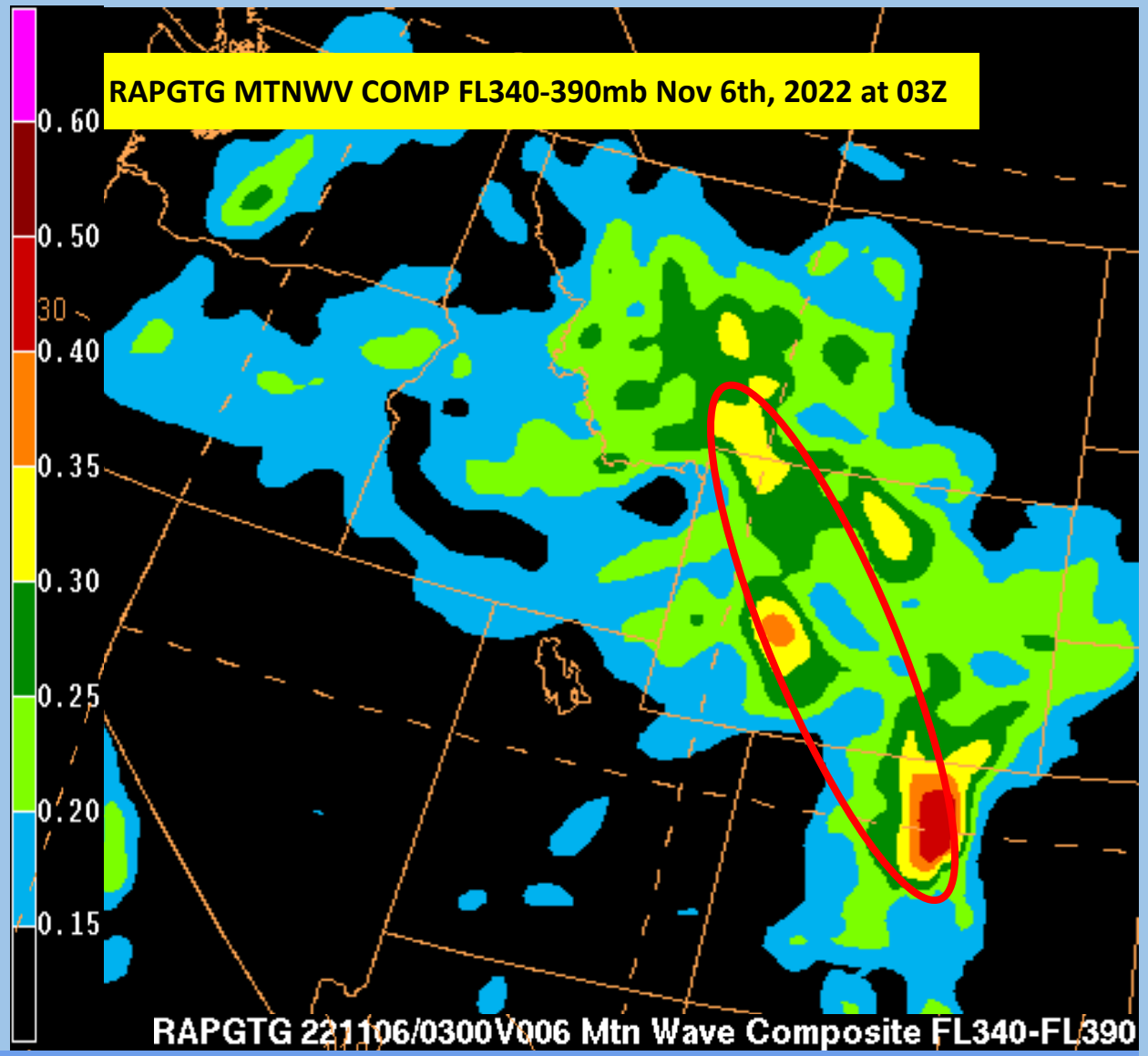
The RAPGTG Mountain Wave Composite at FL340-390mb has moderate to severe turbulence from 11/05/12Z over the Tetons and Big Horn and into the Rocky mountains in CO through 11/05/15Z.



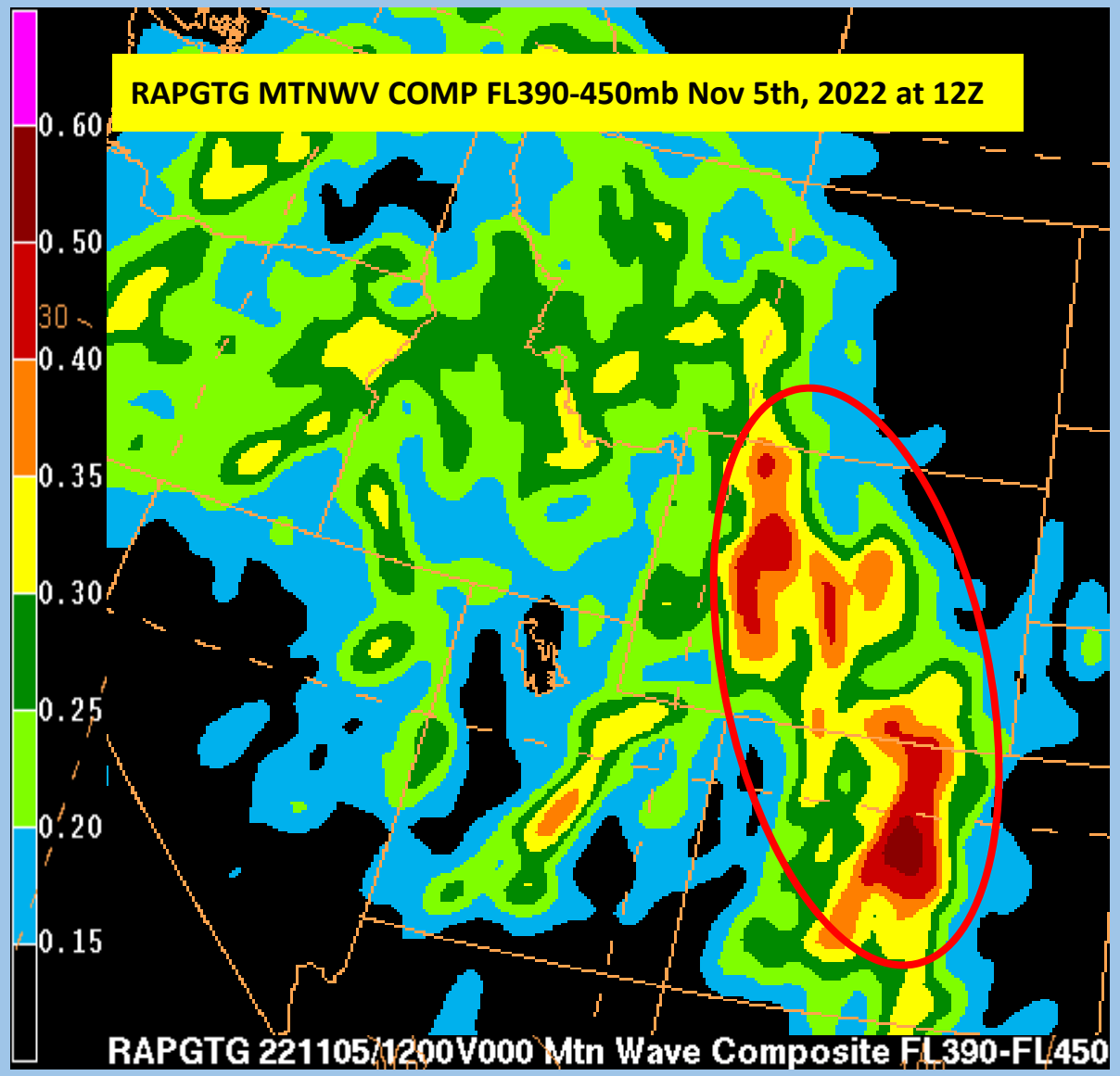


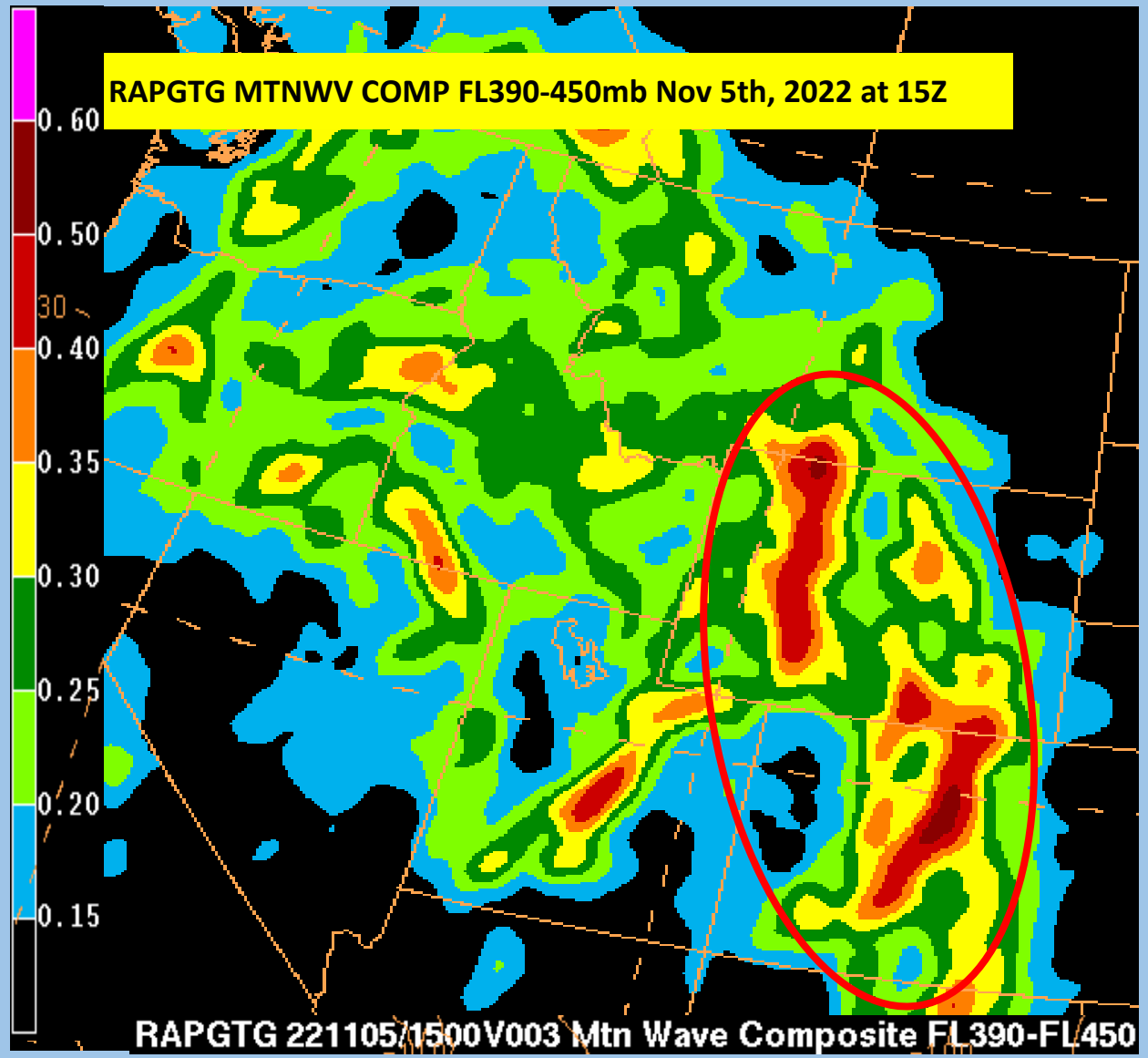
The RAPGTG Mountain Wave Composite at FL340-390mb continues showing potential for moderate to severe turbulence from 11/05/18Z over the Tetons and Big Horn and into the Rocky mountains in CO. The mountain wave indices stay strong through 11/05/21Z and spreads to northern Rockies or Big Belt mountains in MT.



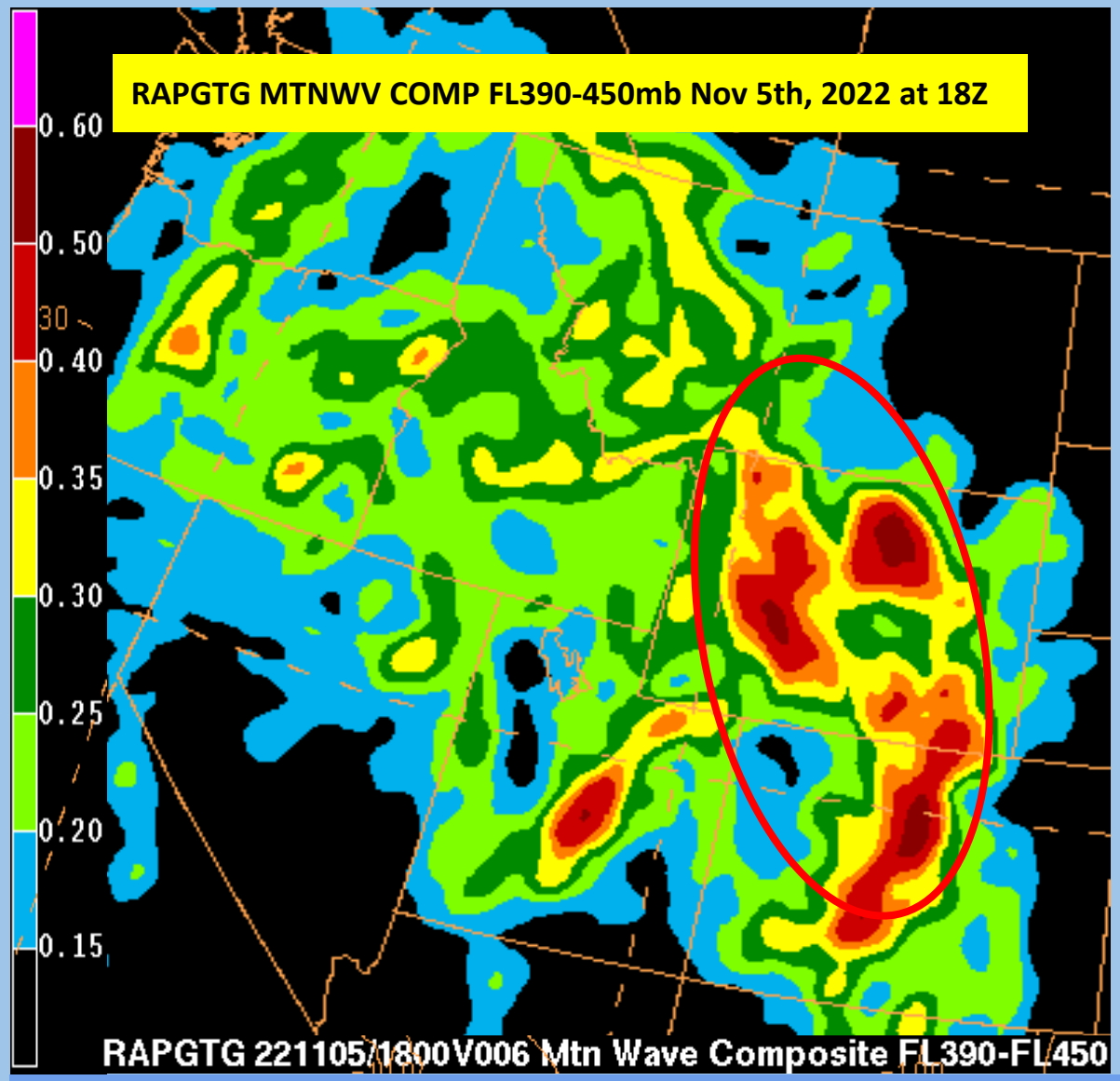


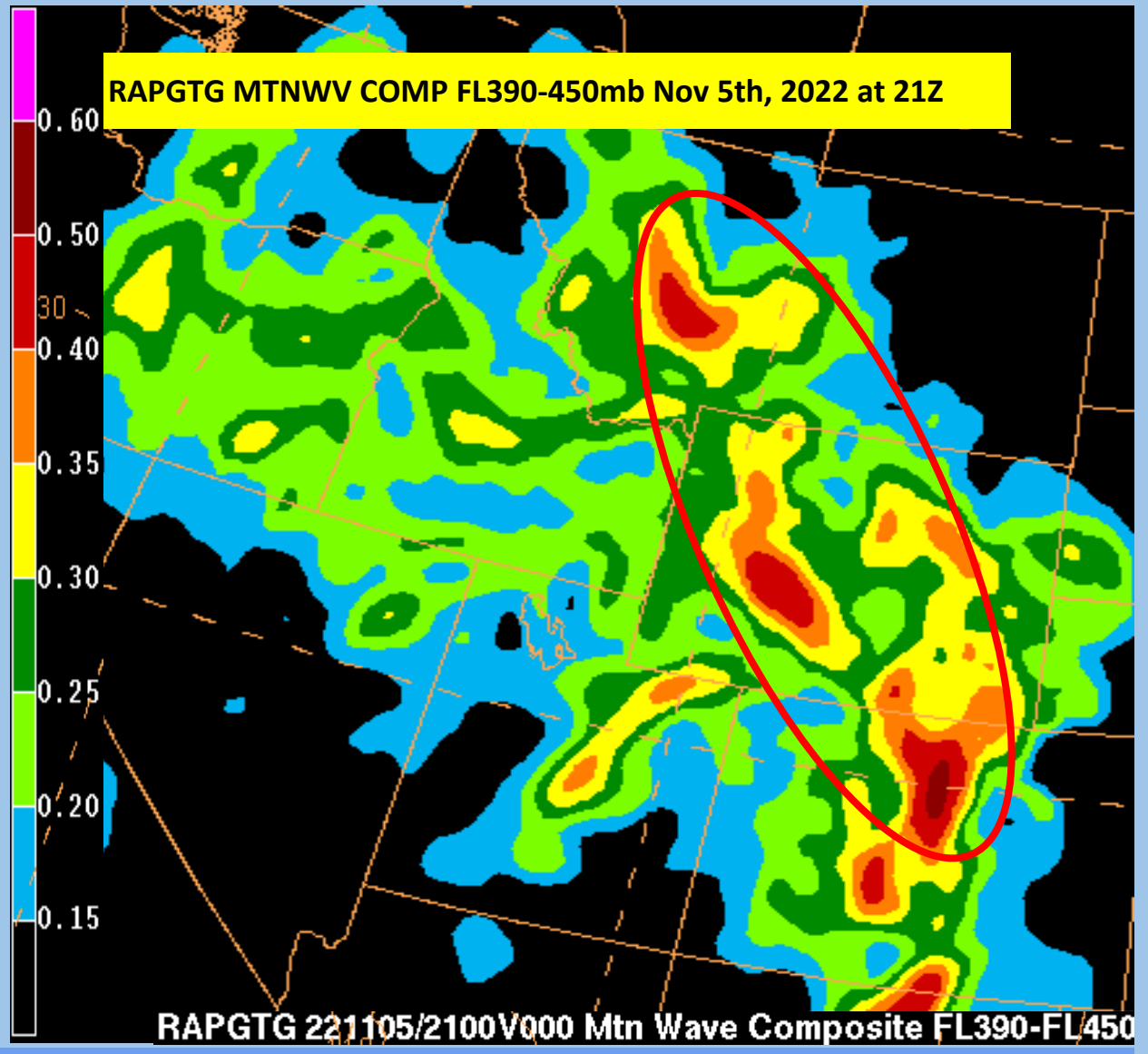
The RAPGTG Mountain Wave Composite at FL340-390mb continues showing potential for moderate to severe turbulence through 11/06/00Z over the Tetons and Big Horn and northern Rockies in MT. By 11/06/03Z the potential for moderate to severe turbulence is mainly over the Rocky mountains in CO.



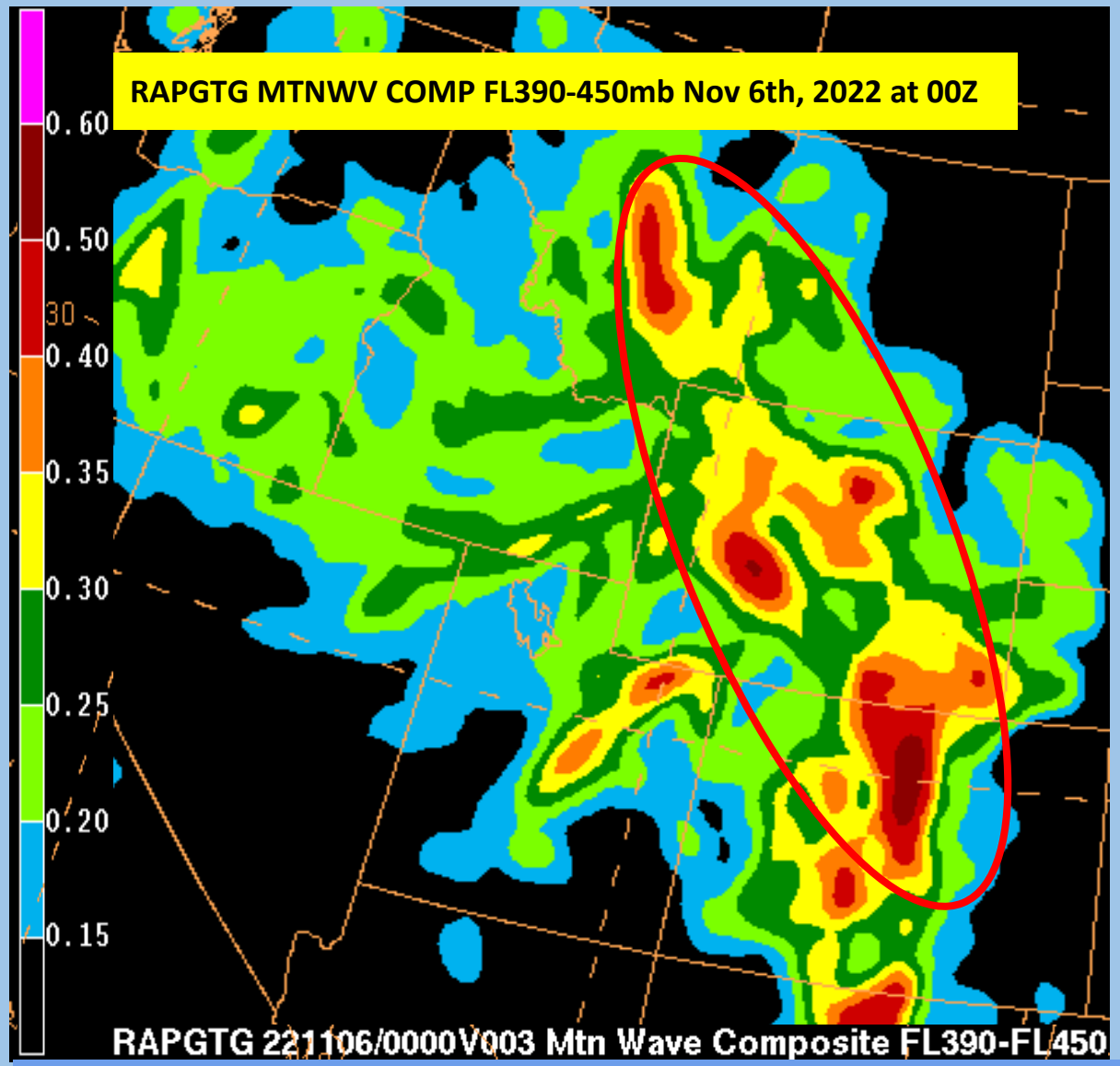


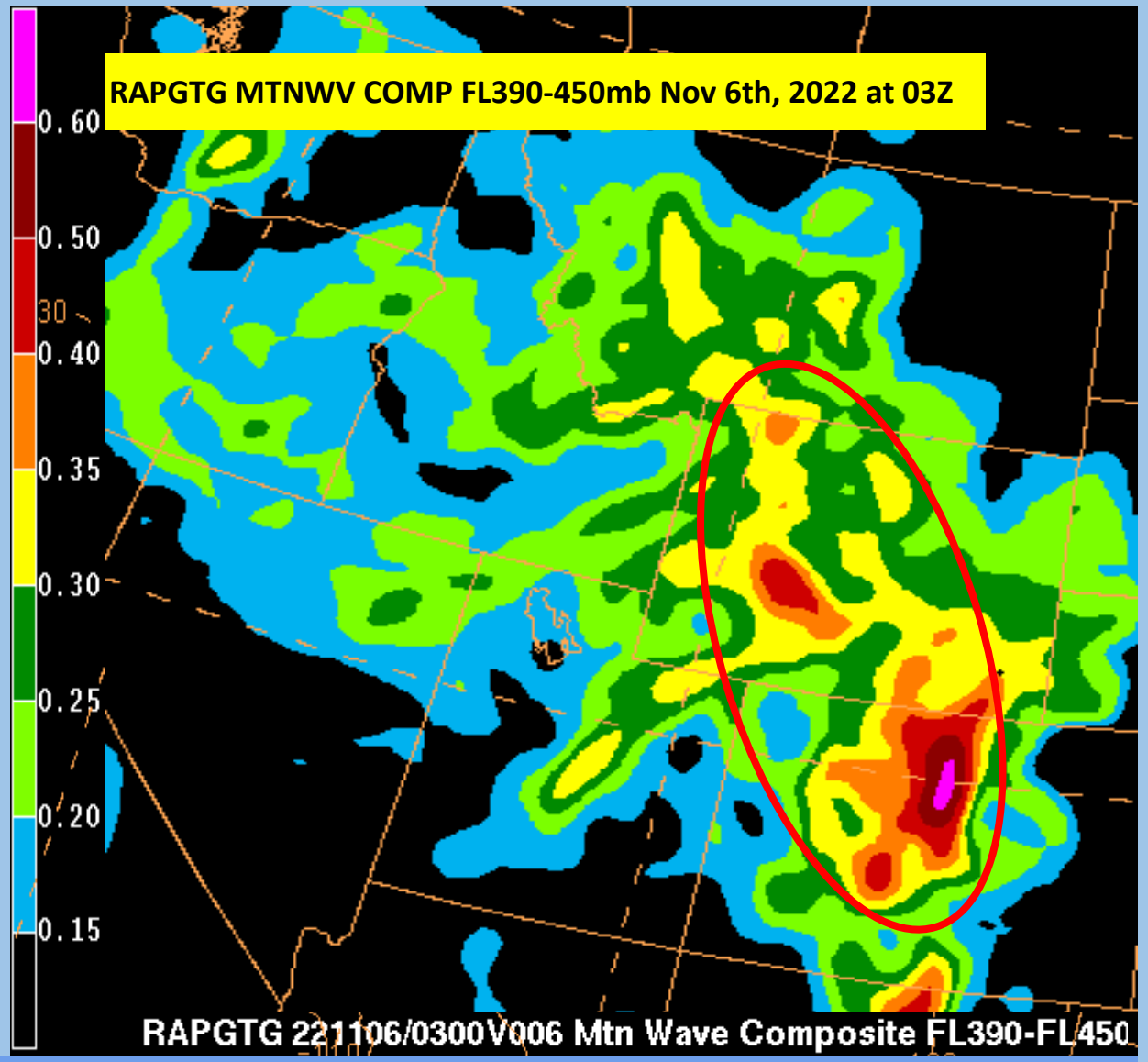
The RAPGTG Mountain Wave Composite at FL390-450mb showed good potential for moderate to severe turbulence from 11/05/12Z over the Tetons and Big Horn and southward into the Rocky mountains in CO. The mountain wave indices stayed strong through 11/05/15Z but there was only moderate turbulence pilot report in the CO region.





The RAPGTG Mountain Wave Composite at FL390-450mb continued to show good potential for moderate to severe turbulence from 11/05/18Z over the Tetons and Big Horn and southward into the Rocky mountains in CO. By 11/05/21Z the mountain wave indices intensified over the Big Belt mountains in MT region.





he RAPGTG Mountain Wave Composite at FL390-450mb continued to show good potential for moderate to severe turbulence from 11/06/00Z over the Tetons and Big Horn, Big Belt mountains and southward into the Rocky mountains in CO. By 11/06/03Z the strong mountain wave indices were mainly over the Tetons and the Rocky mountains in CO region.

MOUNTAIN WAVE INDUCED TURBULENCE DECISION TREE

Do you have perpendicular cross-barrier flow with surface wind speeds 35kts or greater? Do you have ridge top wind speeds 50kts or greater?

YES, keep going

NO, not likely

Does Satellite show Foehn gap or subsidence & any severe turbulence pilot reports?

YES, keep going

NO, not likely

Is there an inversion near the mountain tops?

(This allows for vertical propagating couplet to develop in stable region)

YES, keep going

NO, not likely

Do you have a sharp or tight strong updraft/downdraft couplet?

YES, keep going

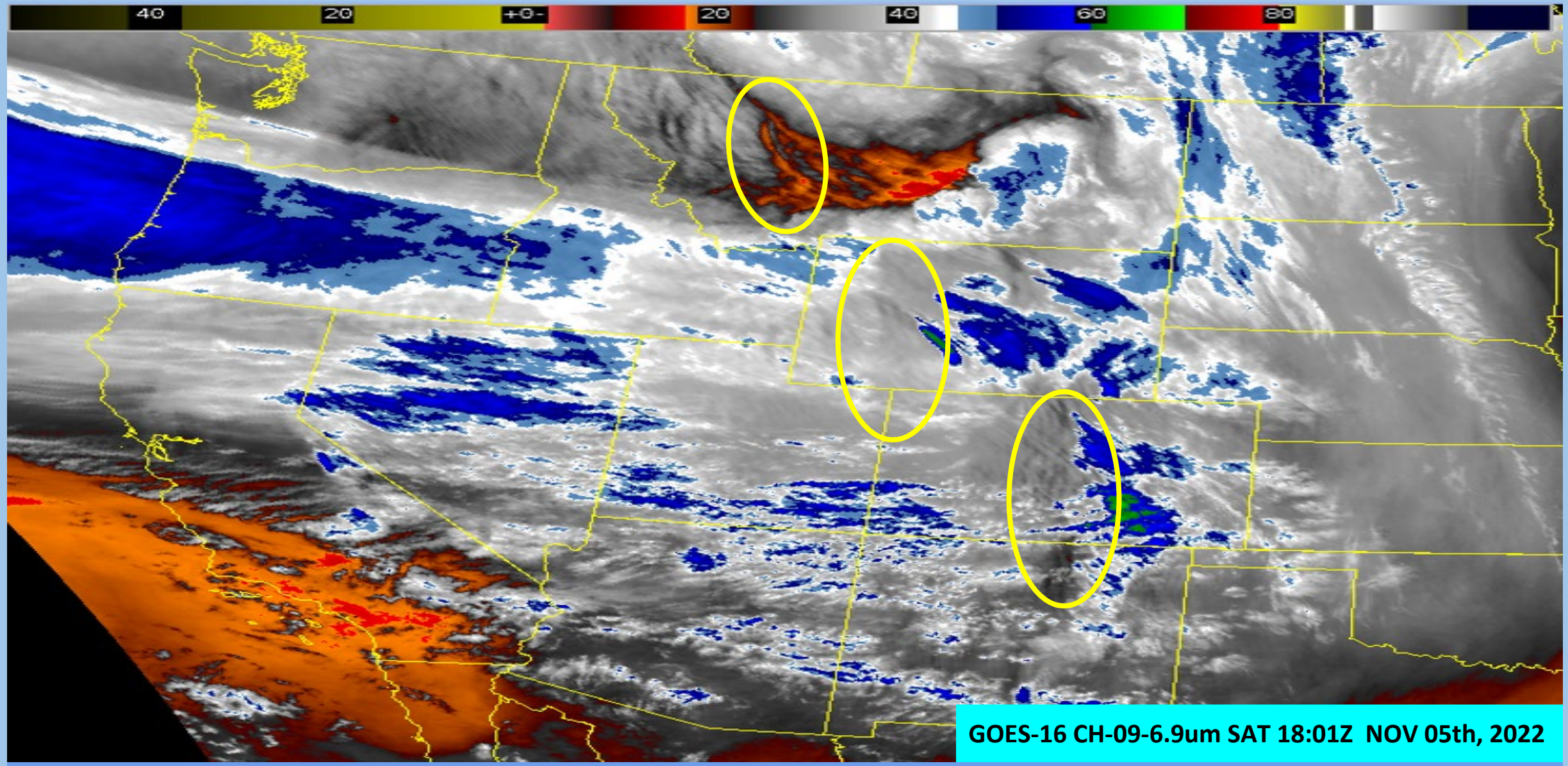
NO, monitor

Does the strong vertical propagating motion or couplet punch through the tropopause?

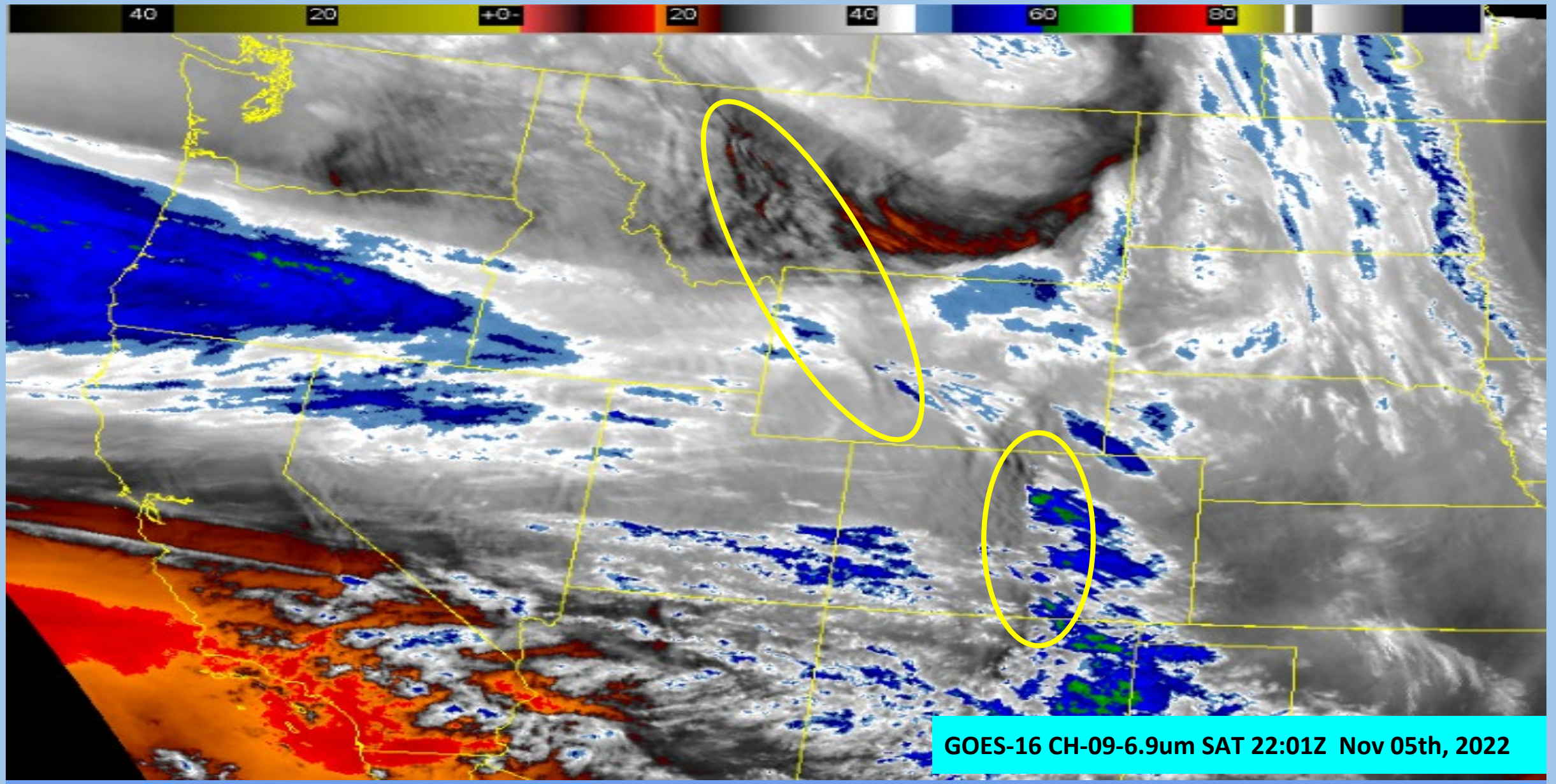
YES, keep going

NO, monitor

Issue the Low and/or High Severe Turbulence SIGMET



The yellow ovals showed the standing clouds and some had beginning of dry slots and MT region over northern Rockies had wide swath of subsidence and coupled with foehn gap.



The yellow ovals showed the standing clouds and transverse turbulence clouds. While WY had better developed dry slot through the Teton mountains.s

MOUNTAIN WAVE INDUCED TURBULENCE DECISION TREE

Do you have perpendicular cross-barrier flow with surface wind speeds 35kts or greater? Do you have ridge top wind speeds 50kts or greater?

YES, keep going

NO, not likely

Does Satellite show Foehn gap or subsidence & any severe turbulence pilot reports?

YES, keep going

NO, not likely

Is there an inversion near the mountain tops?

(This allows for vertical propagating couplet to develop in stable region)

YES, keep going

NO, not likely

Do you have a sharp or tight strong updraft/downdraft couplet?

YES, keep going

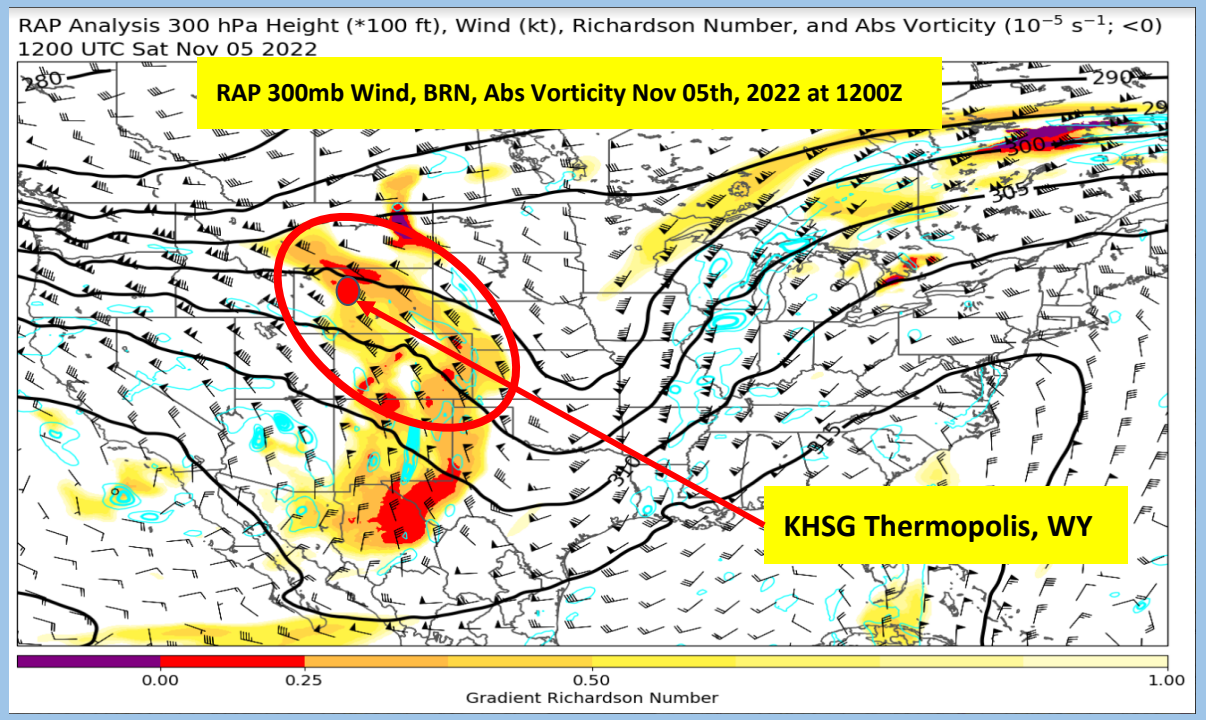
NO, monitor

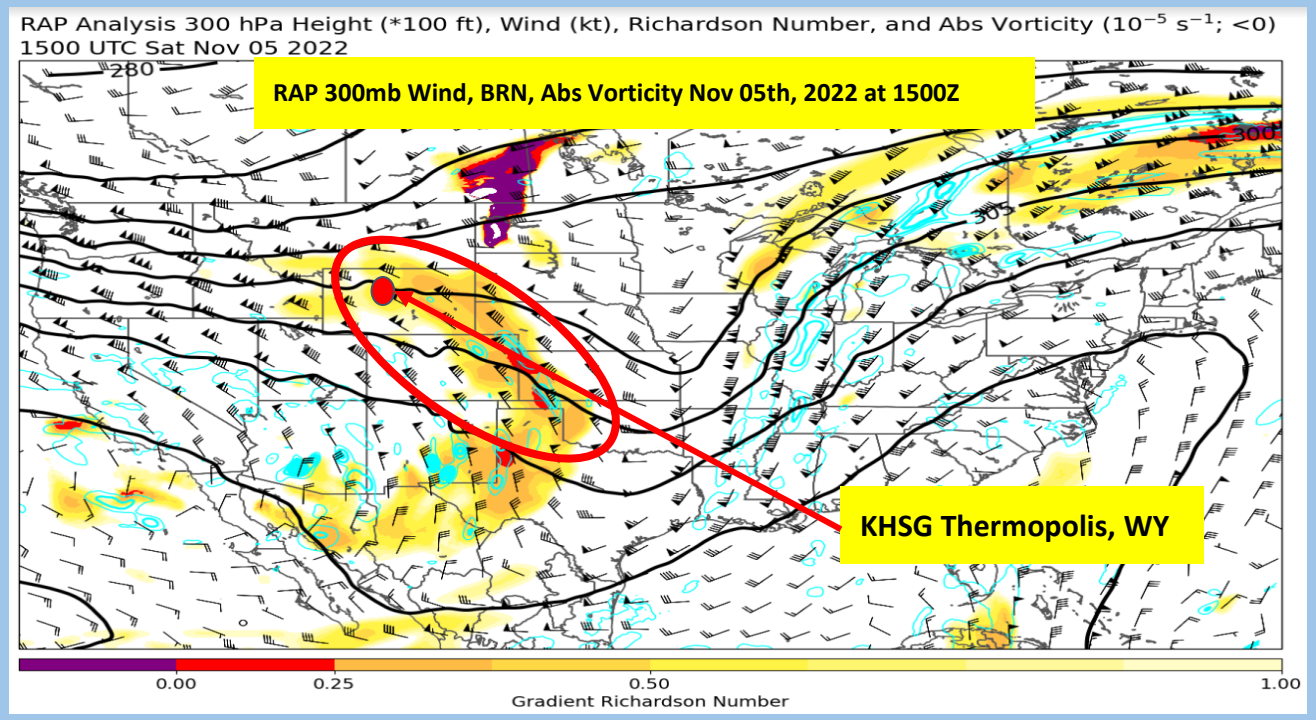
Does the strong vertical propagating motion or couplet punch through the tropopause?

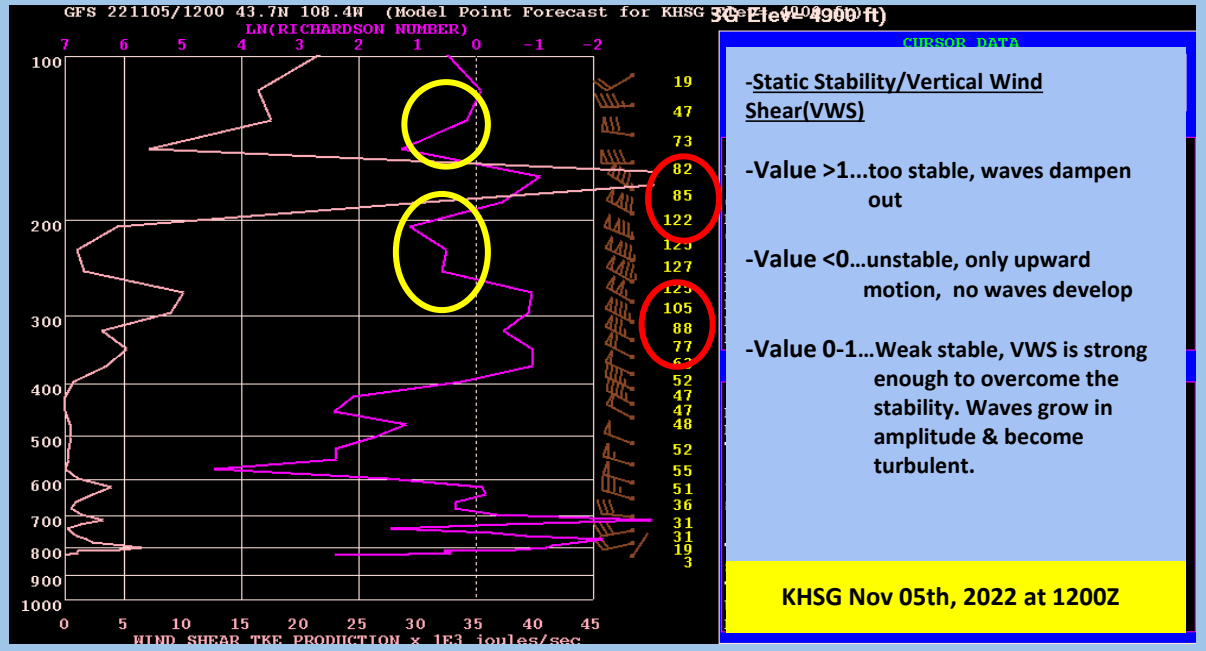
YES, keep going

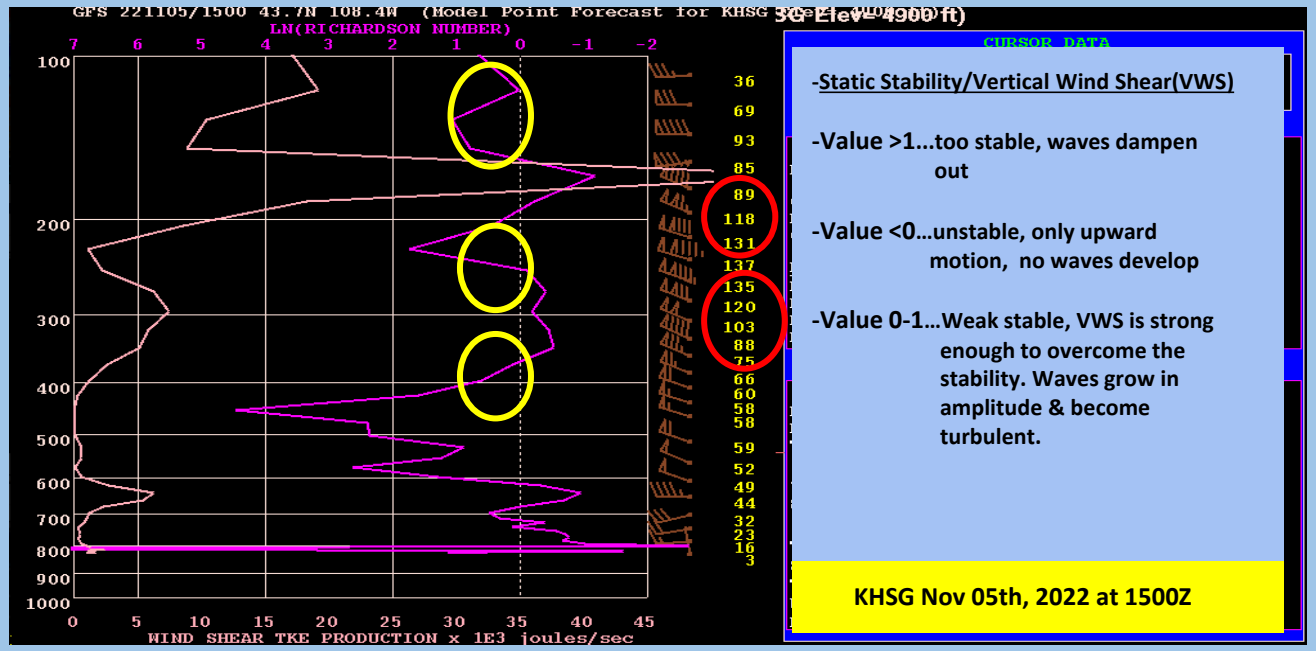
NO, monitor

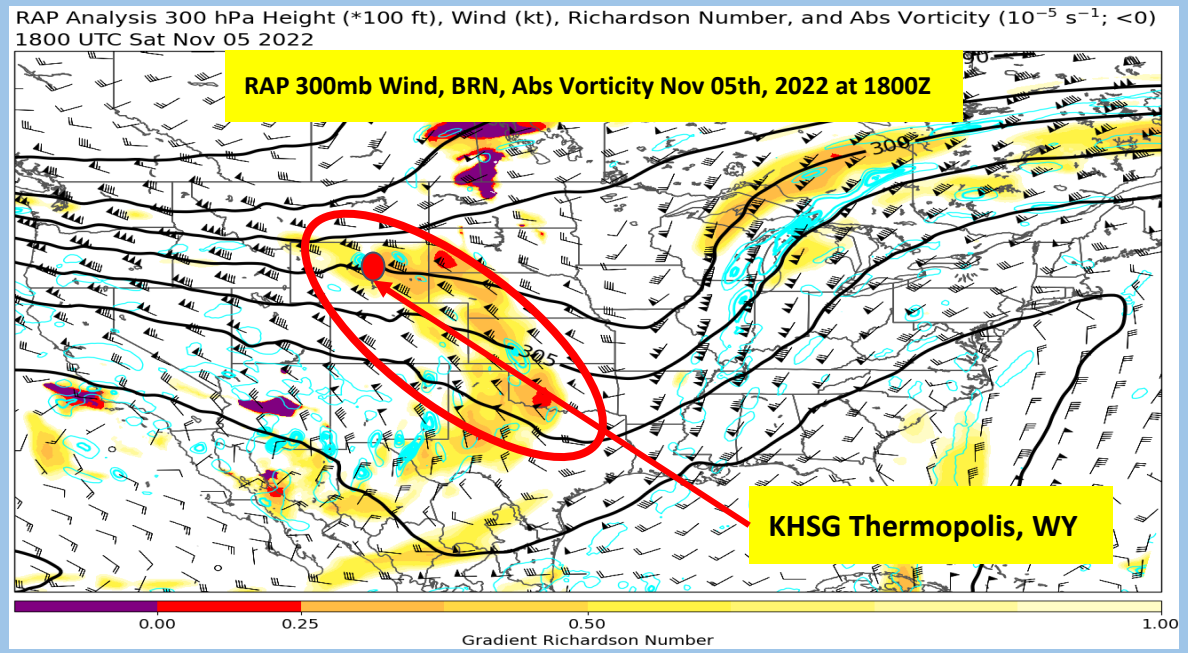
Issue the Low and/or High Severe Turbulence SIGMET

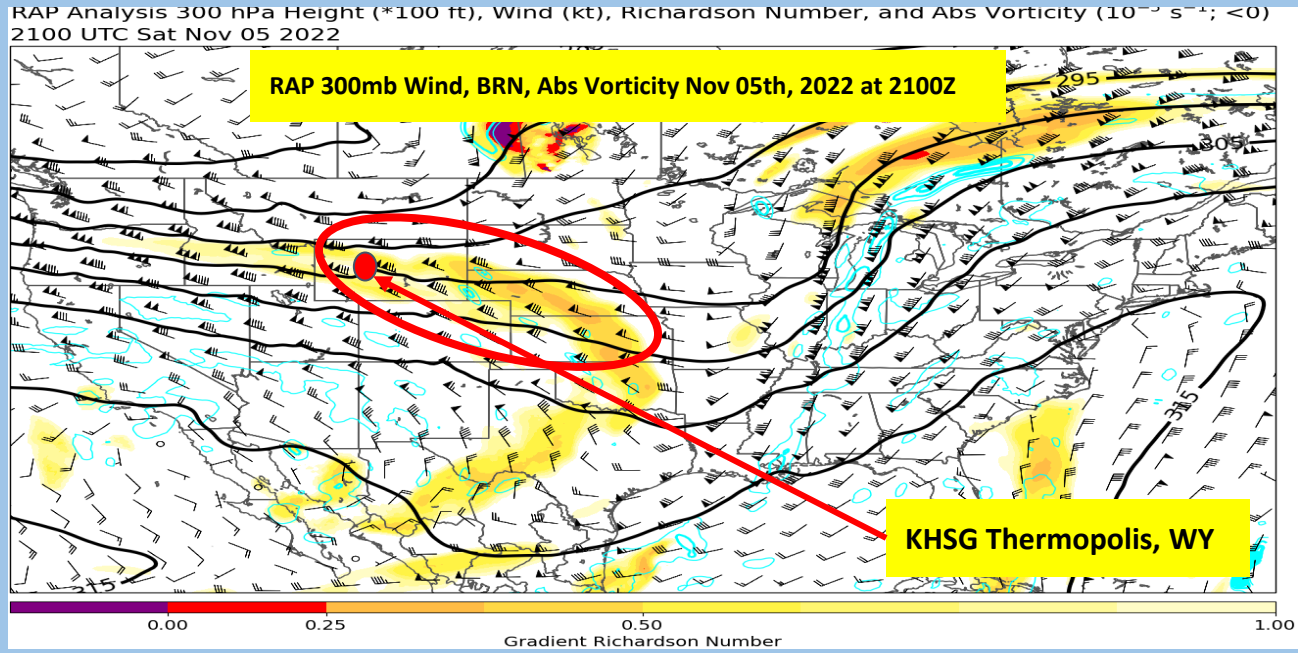

RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10^{-5} s^{-1}; <0)
1200 UTC Sat Nov 05 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 05th, 2022 at 1200Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number

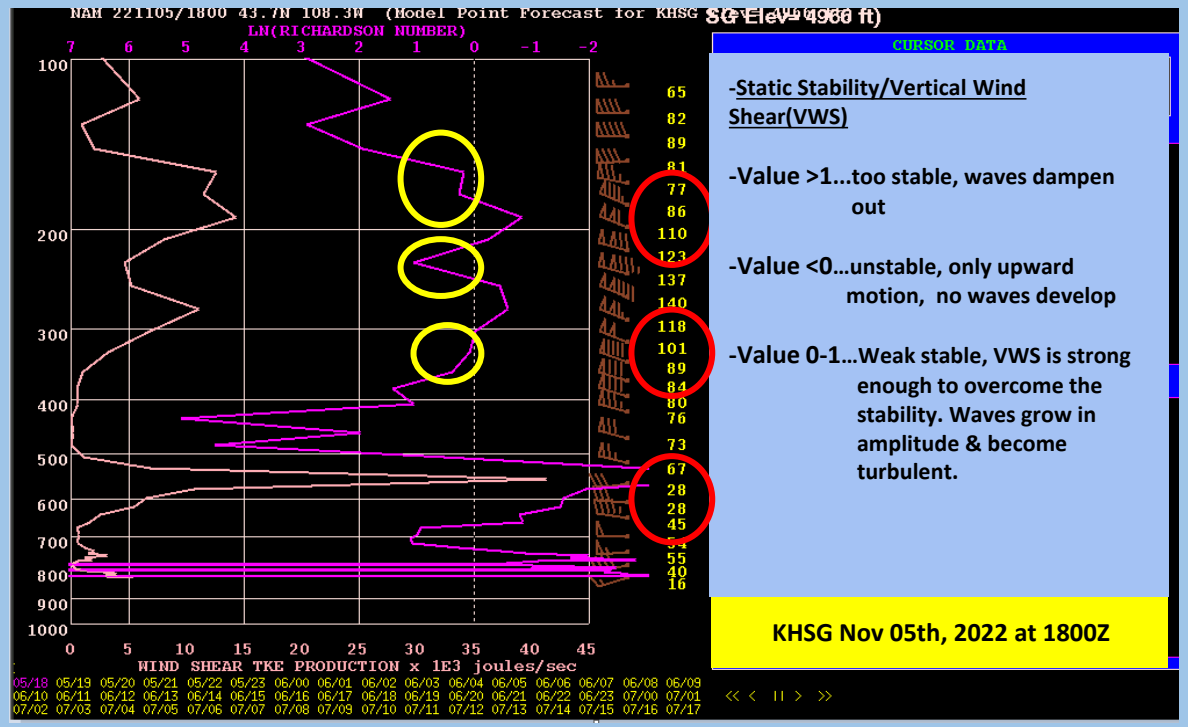

RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10^{-5} s^{-1}; <0)
1500 UTC Sat Nov 05 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 05th, 2022 at 1500Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number

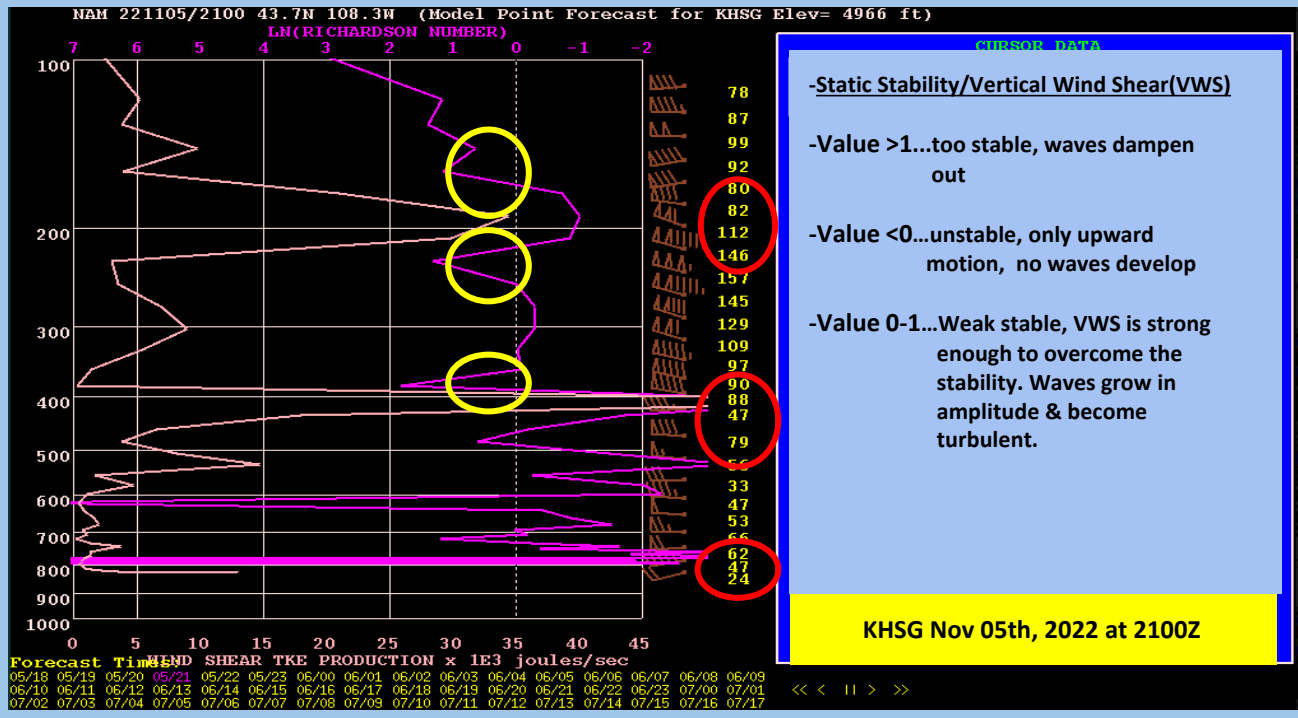

GFS 221105/1200 43.7N 108.4W (Model Point Forecast for KHSG 3G Elev=4900 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 05th, 2022 at 1200Z

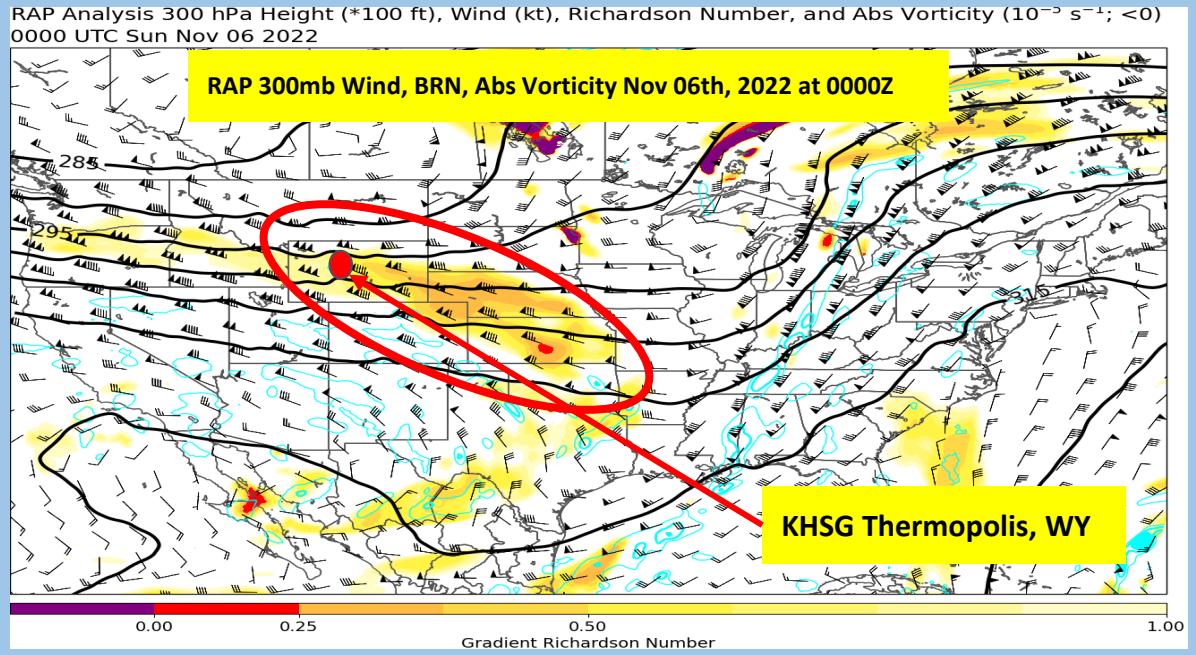

GFS 221105/1500 43.7N 108.4W (Model Point Forecast for KHSG 3G Elev=4900 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 05th, 2022 at 1500Z

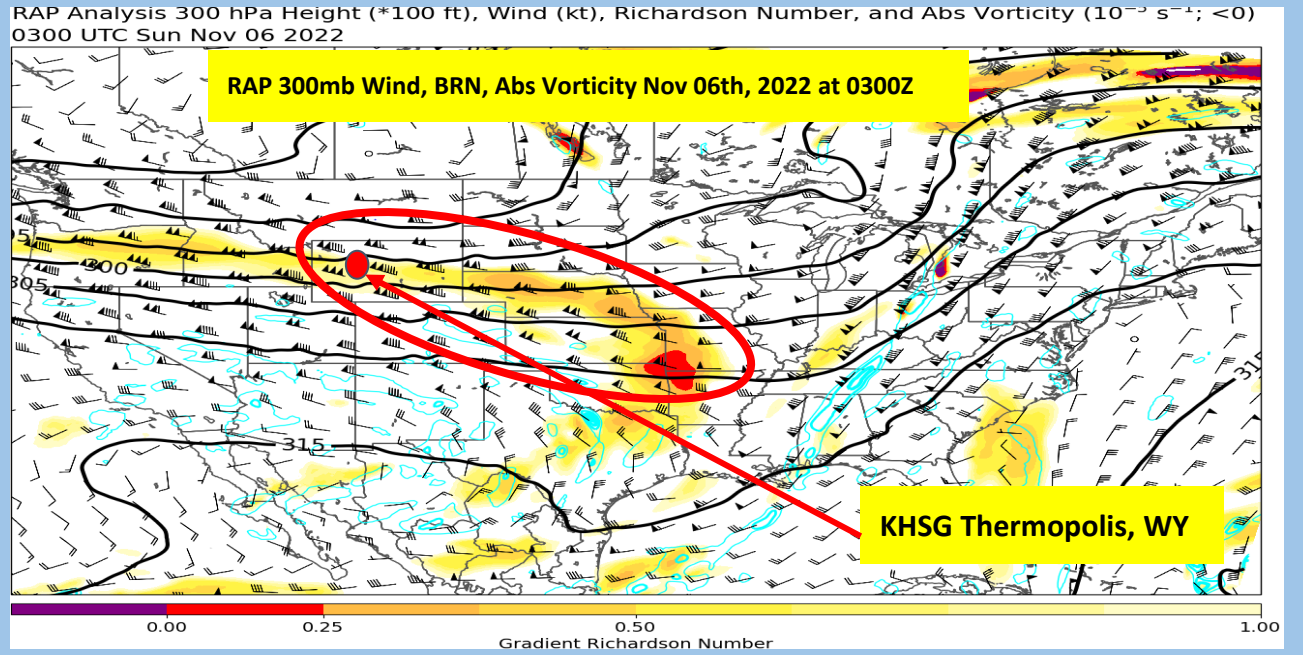

RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10^{-5} s^{-1}; <0)
1800 UTC Sat Nov 05 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 05th, 2022 at 1800Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number

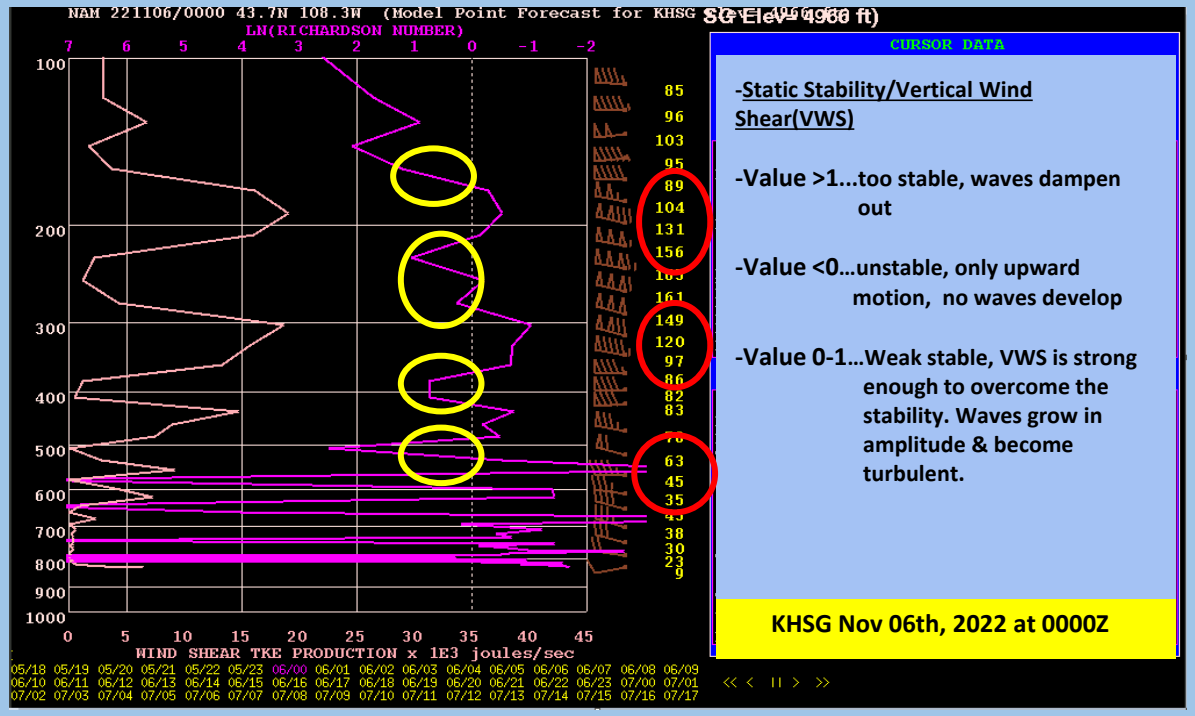

RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10^{-5} s^{-1}; <0)
2100 UTC Sat Nov 05 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 05th, 2022 at 2100Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number

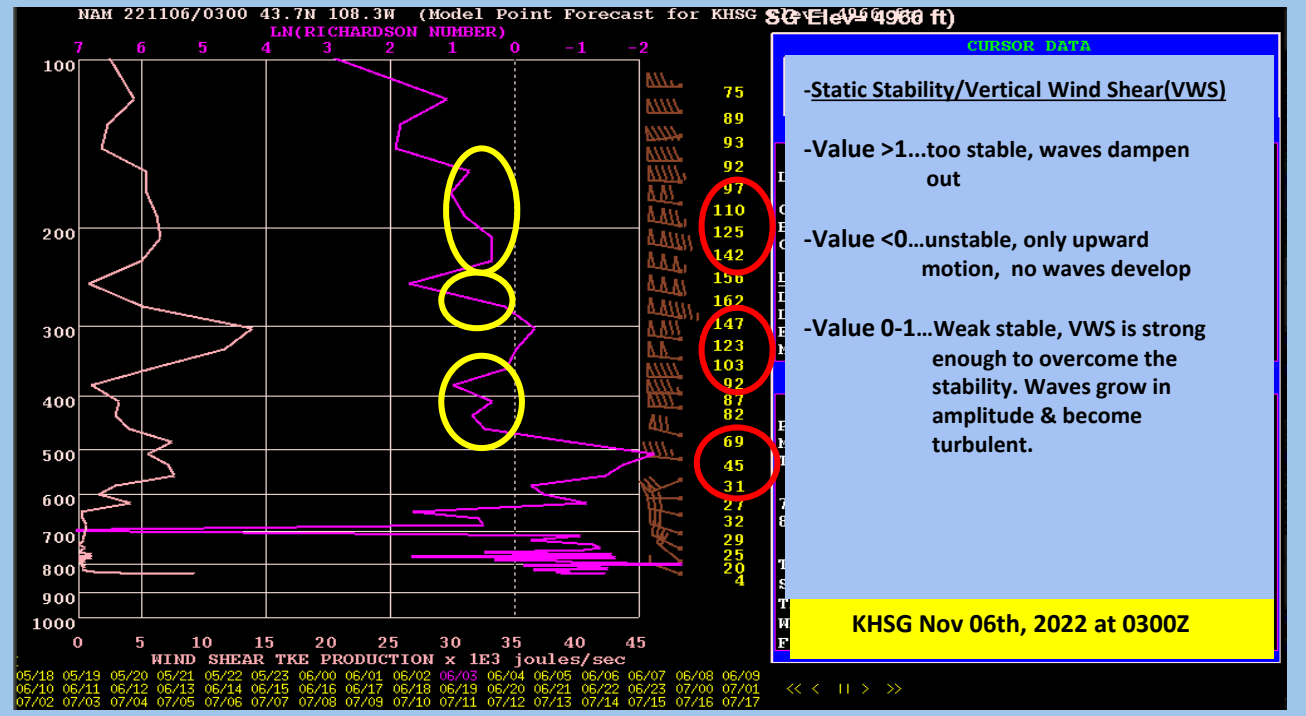

NAM 221105/1800 43.7N 108.3W (Model Point Forecast for KHSG Elev= 4966 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 05th, 2022 at 1800Z

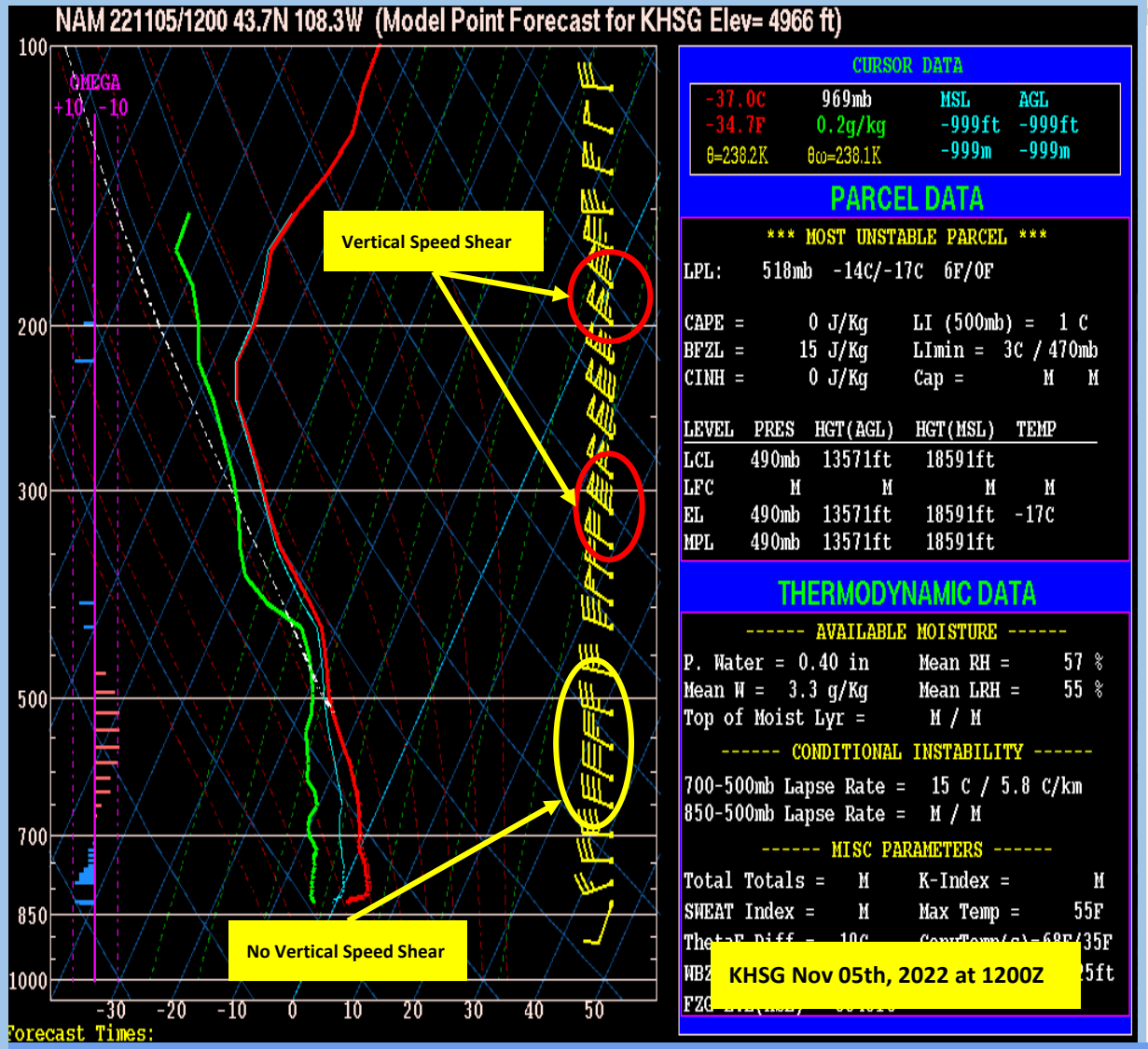

NAM 221105/2100 43.7N 108.3W (Model Point Forecast for KHSG Elev= 4966 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
Forecast Time
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 05th, 2022 at 2100Z

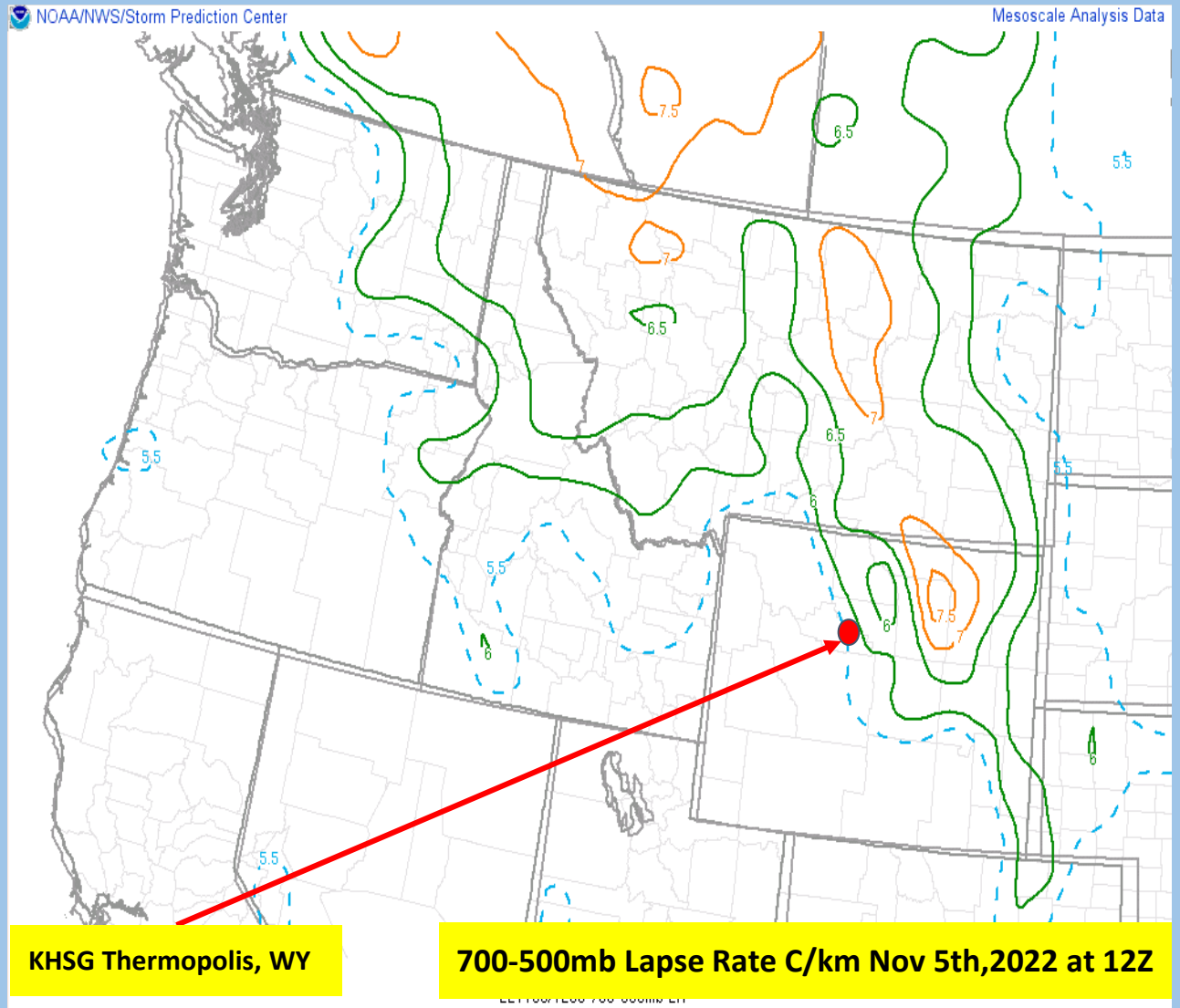

RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10⁻⁵ s⁻¹; <0)
0000 UTC Sun Nov 06 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 06th, 2022 at 0000Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number


RAP Analysis 300 hPa Height (*100 ft), Wind (kt), Richardson Number, and Abs Vorticity (10⁻⁵ s⁻¹; <0)
0300 UTC Sun Nov 06 2022
RAP 300mb Wind, BRN, Abs Vorticity Nov 06th, 2022 at 0300Z
KHSG Thermopolis, WY
0.00
0.25
0.50
1.00
Gradient Richardson Number

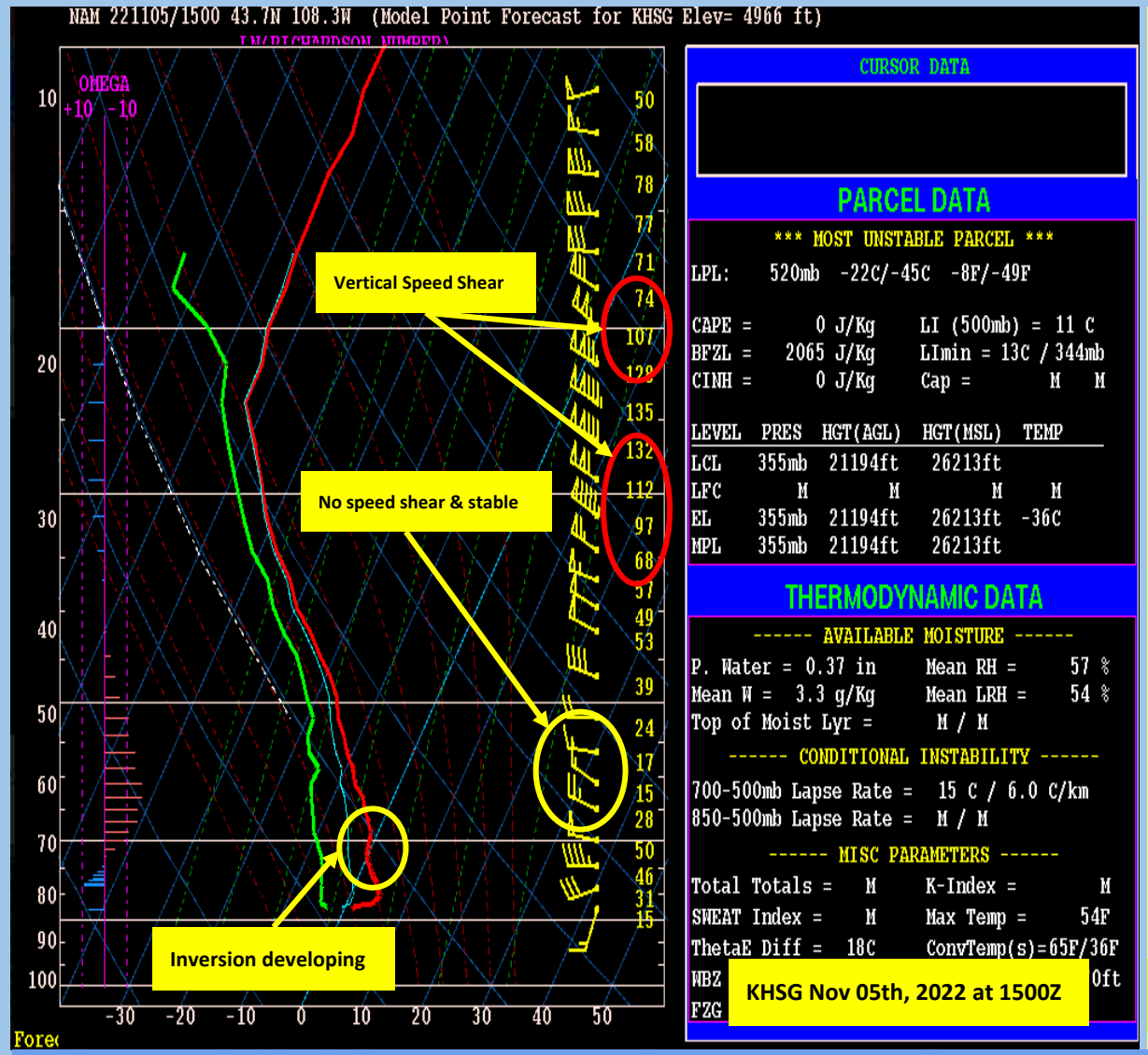

NAM 221106/0000 43.7N 108.3W (Model Point Forecast for KHSG
SG Elev= 4960 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 06th, 2022 at 0000Z

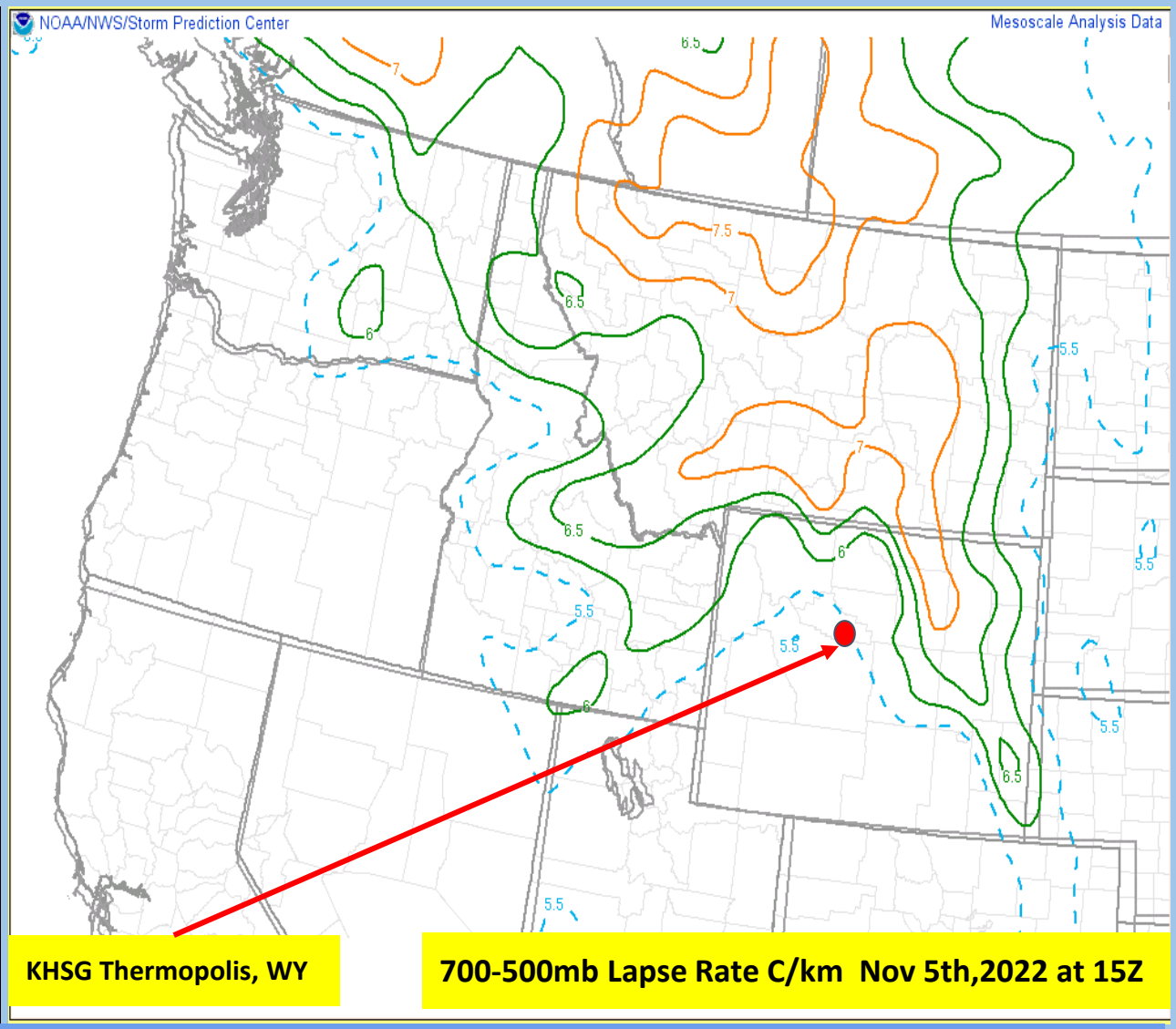

NAM 221106/0300 43.7N 108.3W (Model Point Forecast for KHSG
SG Elev= 4960 ft)
LN(RICHARDSON NUMBER)
WIND SHEAR TKE PRODUCTION x 1E3 joules/sec
CURSOR DATA
-Static Stability/Vertical Wind Shear(VWS)
-Value >1...too stable, waves dampen out
-Value <0...unstable, only upward motion, no waves develop
-Value 0-1...Weak stable, VWS is strong enough to overcome the stability. Waves grow in amplitude & become turbulent.
KHSG Nov 06th, 2022 at 0300Z



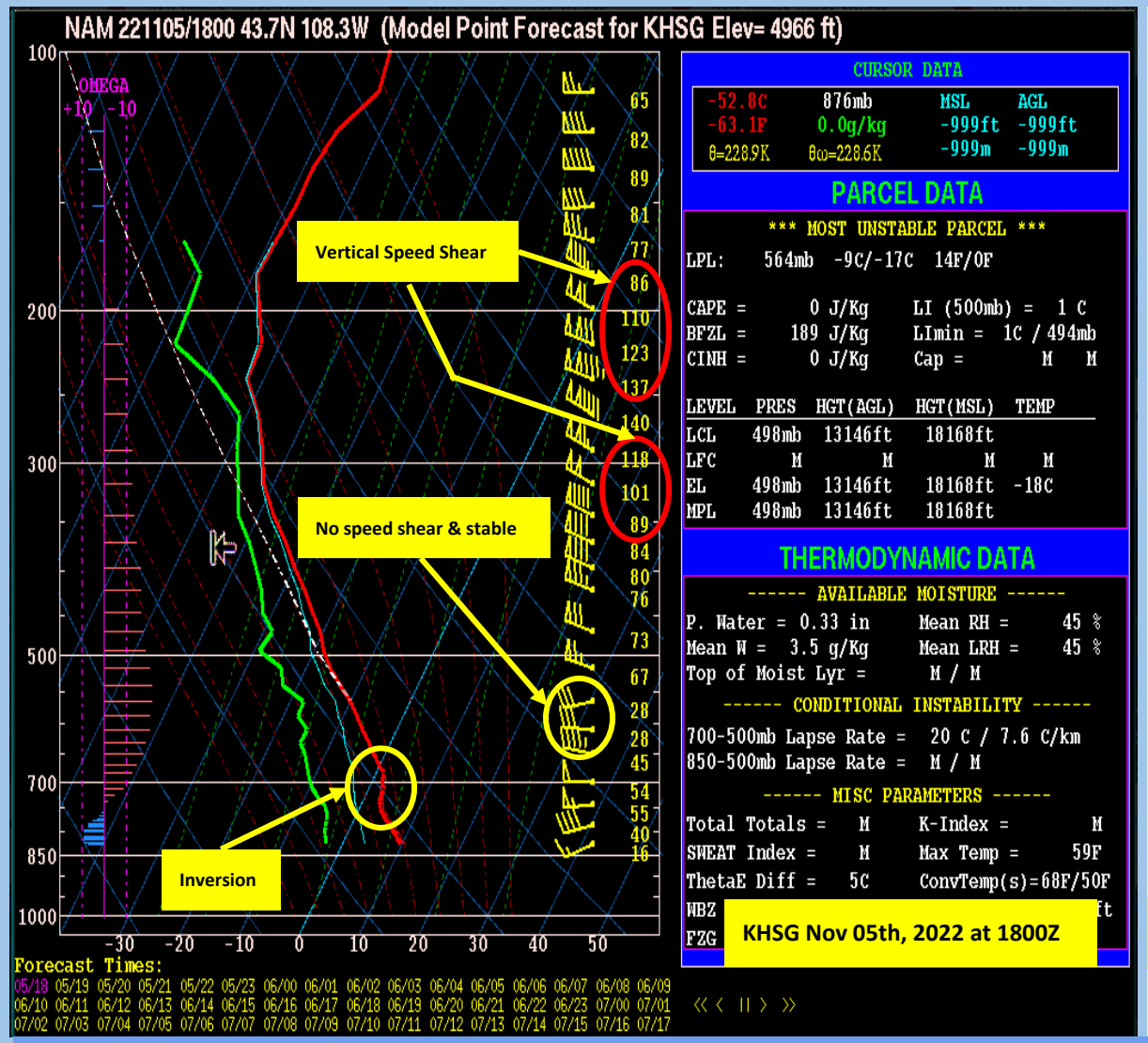


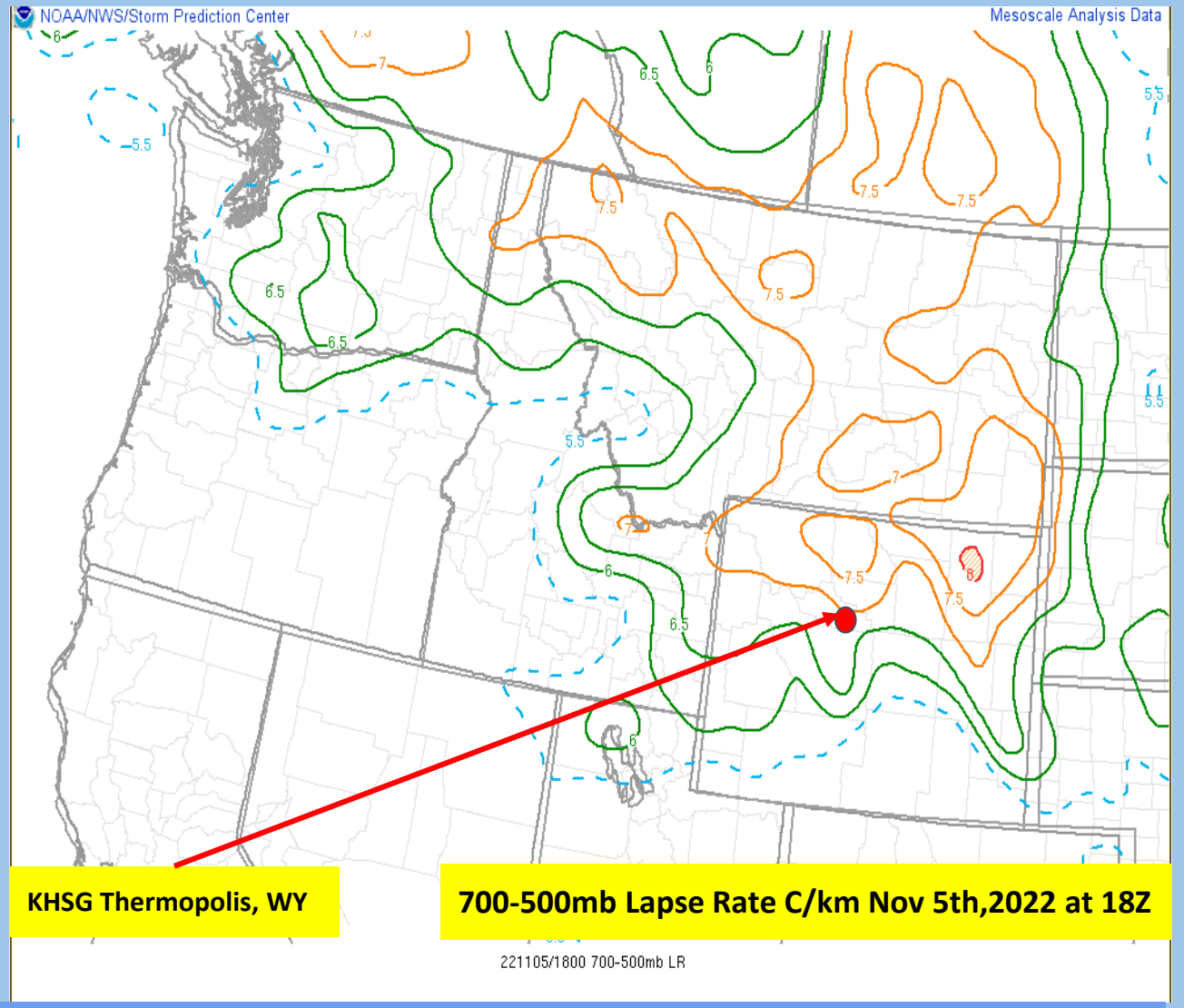
The KHSG skew-t at 12Z was showing forward wind shear profile. There looked to be vertical speed shear around 300mb and 200mb depicted with the red ovals. Looking at the Storm Prediction Center's 700-500mb lapse rates the Tetons and portions of the Big Horn mountains had stable conditions in the layer above the ridge tops. This feature as well extends to northern Rockies covering the Big Belt and the Abasaroka mountains. The importance of having stable lapse rate for 100-200mb above inversion or ridge tops it allows the possible development of couplet on lee side of mountains for hydraulic jump.



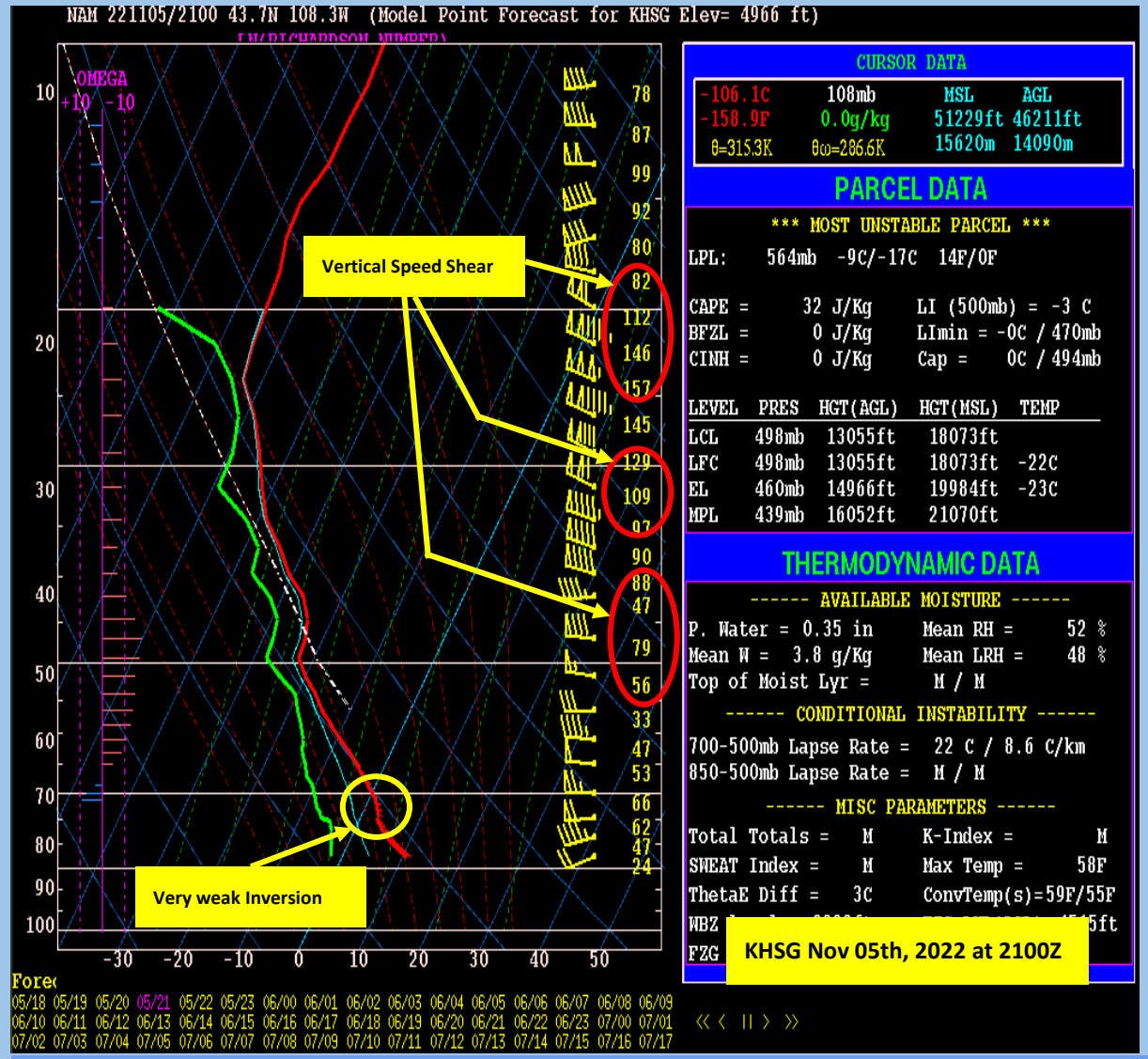


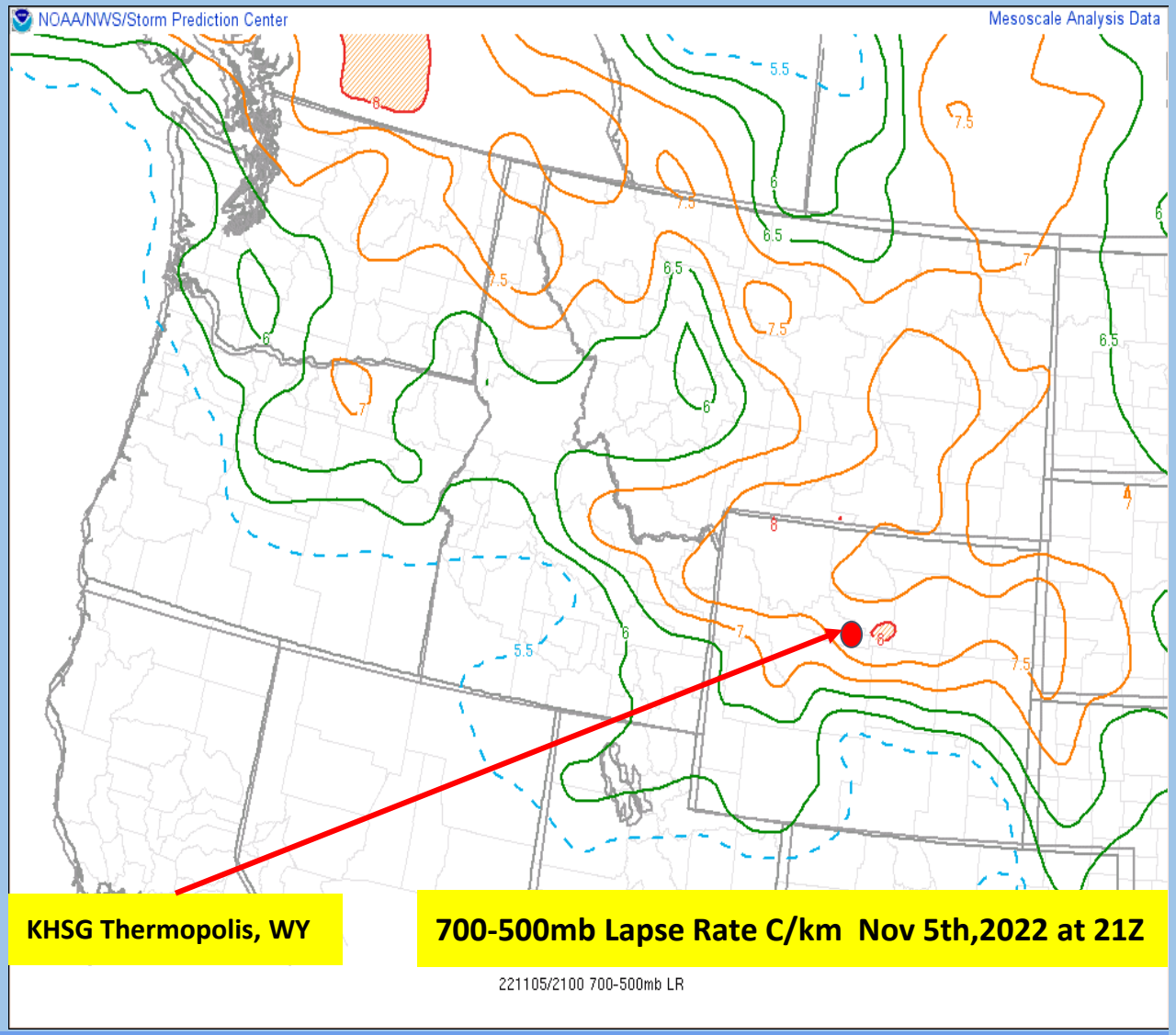
The KHSG skew-t at 15Z was showing a key feature with the development of inversion near the mountain ridge top. The 100-200mb layer above the inversion is then stable and the 700-500mb lapse rate over KHSG has a 5.5 C/Km which is another indicator of a stable layer near the mountain ridge top and will allow the development of a possible couplet on the lees side of the mountain. the upcoming cross-section slide (36) will show a strong upward vertical motion couplet that is shown easily punching through the tropopause. There looks to be vertical speed shear around 300mb and 200mb depicted with the red ovals.



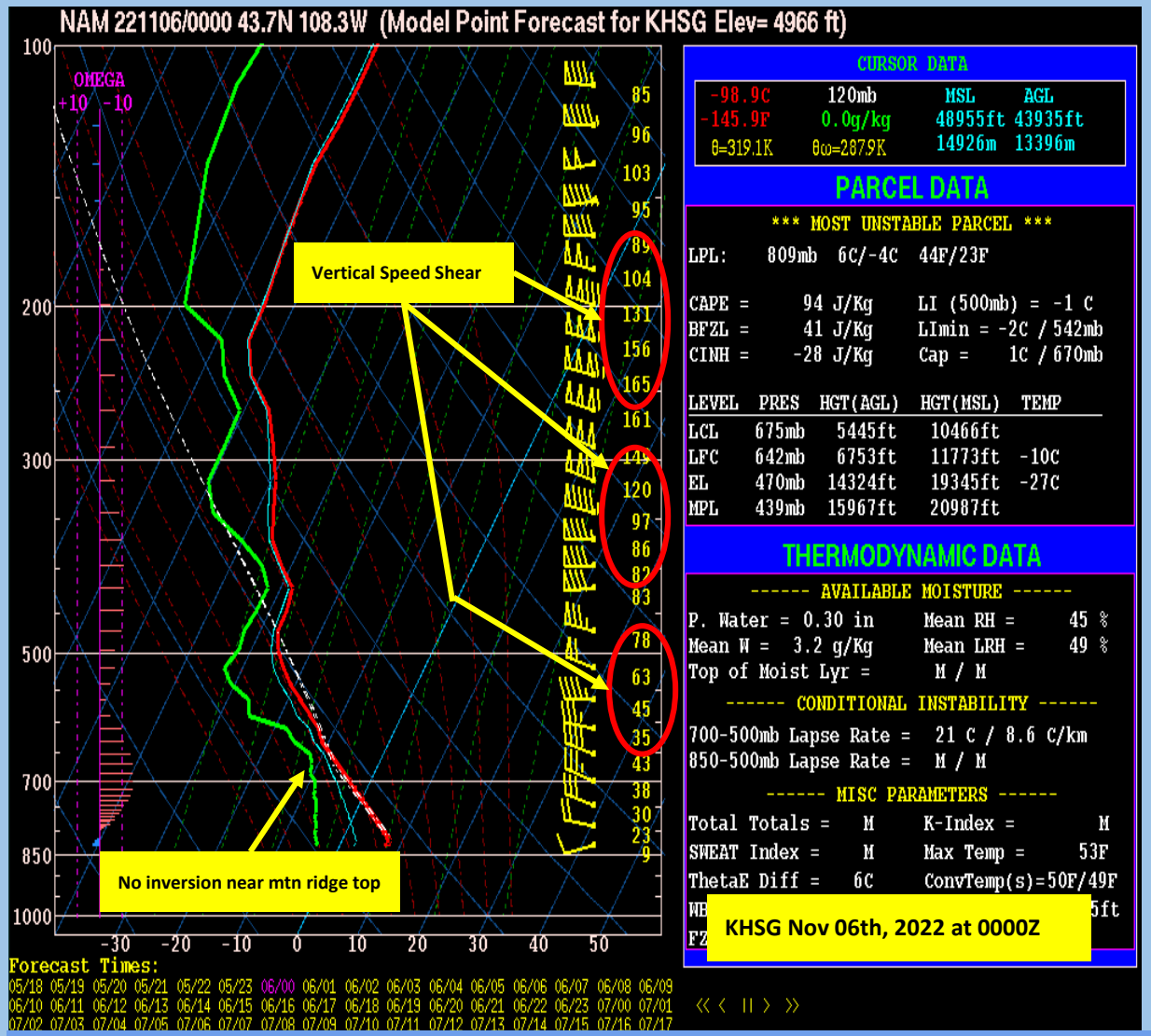


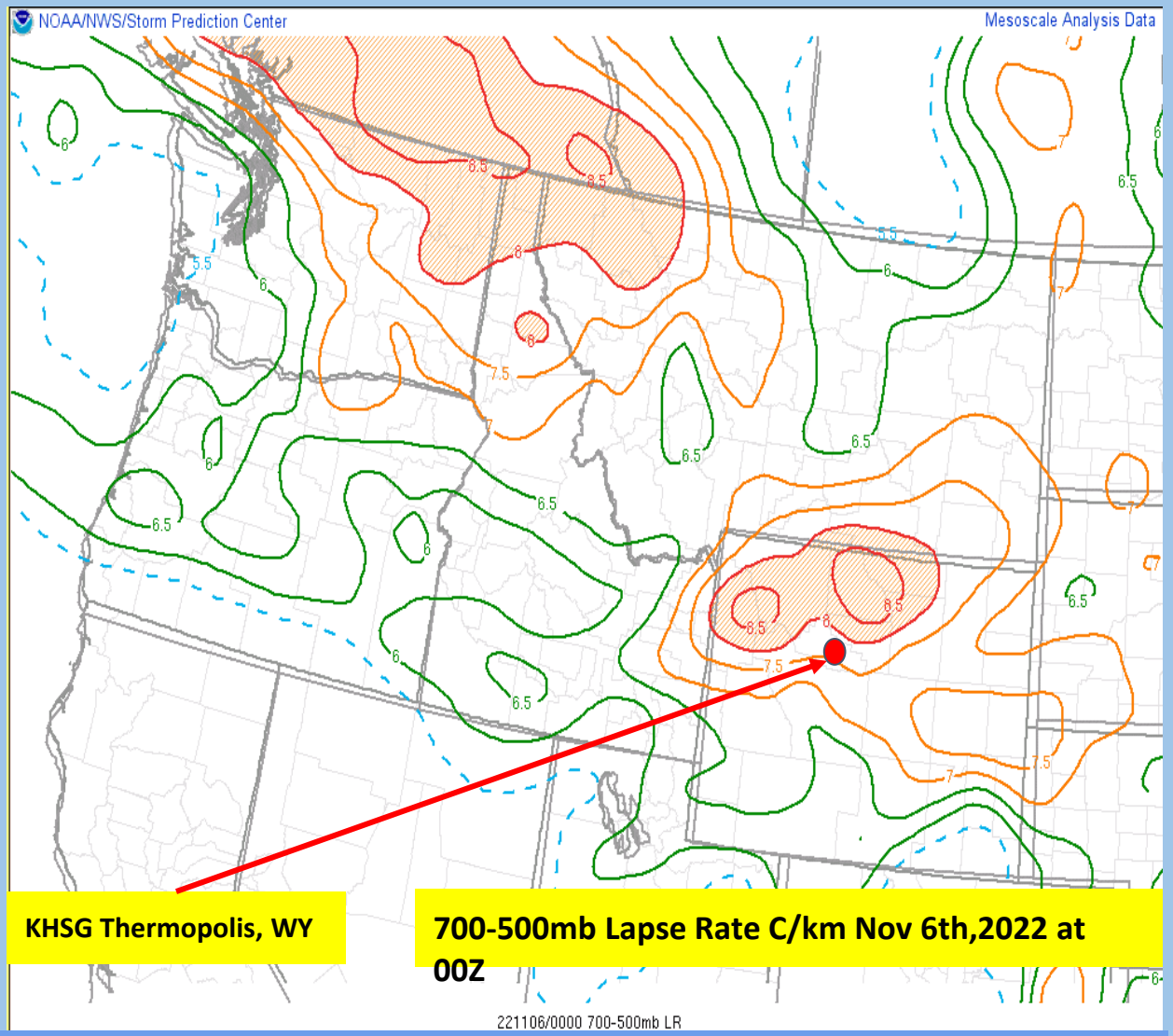
The KHSG skew-t at 18Z continues to show an inversion near the mountain ridge top near 680mb. The 100-200mb layer above the inversion still depicts stable conditions but had a higher 700-500mb lapse rate over KHSG around 6.8 C/Km. The cross-section on slide (36) shows a very strong upward vertical motion couplet propagating wave and punched through the tropopause. There looks to be vertical speed shear around 300mb and 200mb depicted with the red ovals. There were no severe mtn-wave pilot reports over the Tetons during this timeframe and not sure if it was due to the higher lapse rates.



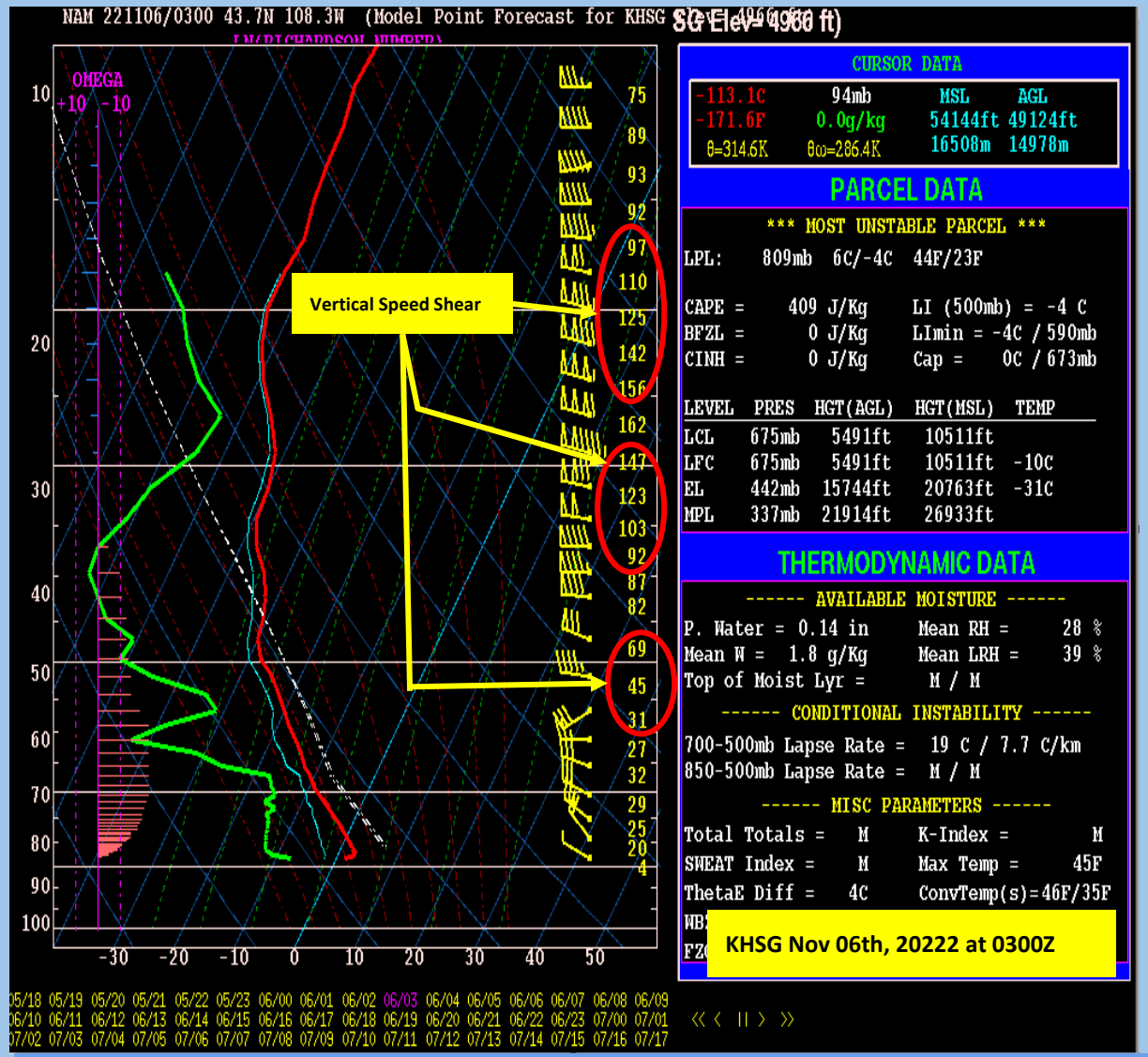


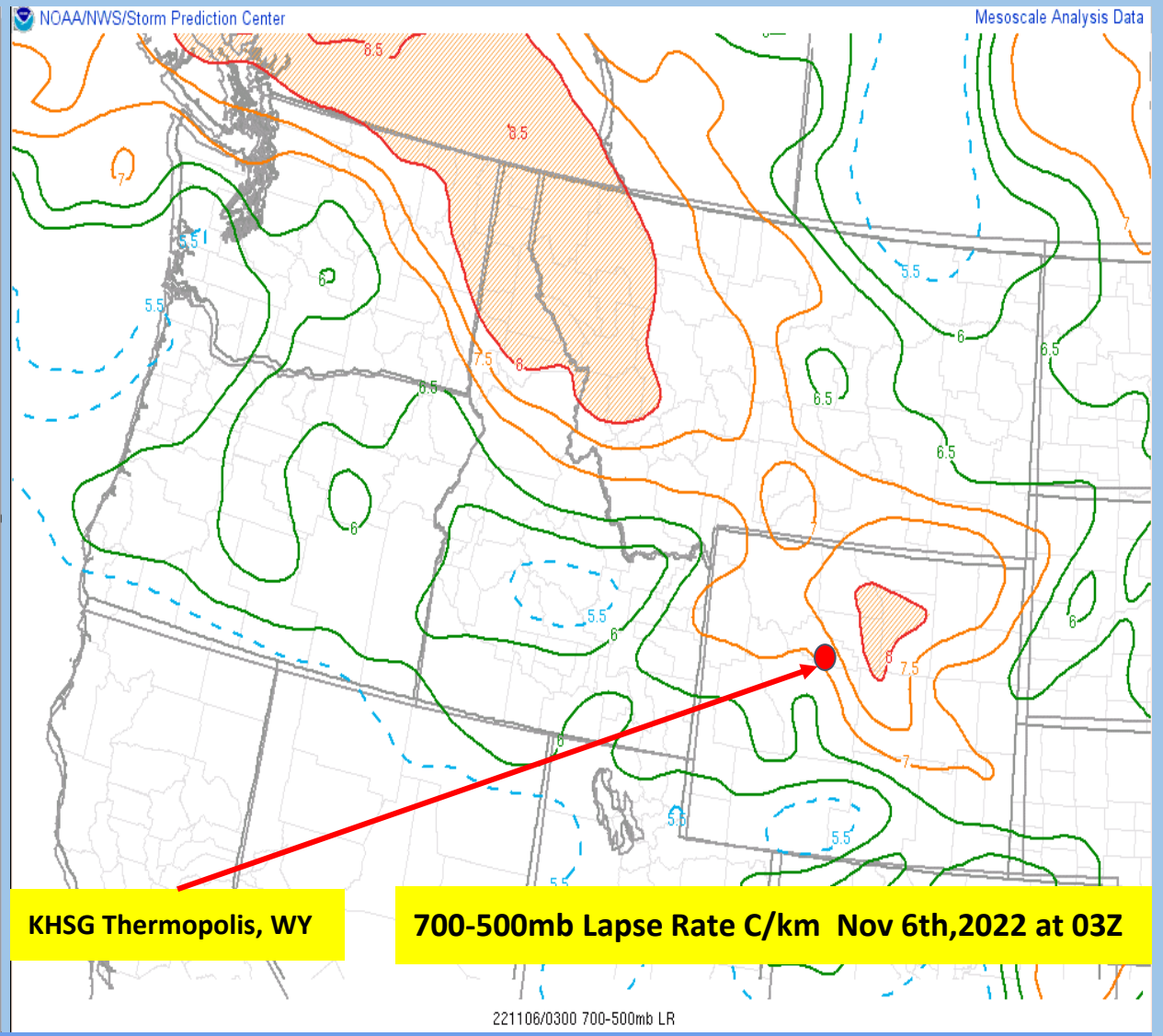
The KHSG skew-t at 21Z looks like the inversion has weakened and the 100-200mb layer above has stronger vertical speed shear. This coincides with the 700-500mb lapse rates near 8.0 C/km. Which inhibits mountain wave development but slide (37) shows the 11/05/21Z cross-section over KHSG still depicts a strong upward vertical motion couplet propagating wave and punching through the tropopause. There looks to be vertical speed shear around 300mb, 200mb, and 400mb depicted with the red ovals. There were only low level severe turbulence pilot reports over the Tetons during this timeframe.





The KHSG skew-t at 06/00Z shows no inversion near the mountain ridge top and the 100-200mb layer above has stronger vertical speed shear. This coincides with the 700-500mb lapse rates near 8.0 C/km. Which inhibits mountain wave development but slide (38) shows the 11/06/00Z cross-section over KHSG still has a strong upward vertical motion couplet propagating wave and punching through the tropopause. There looks to be vertical speed shear around 300mb, 200mb, and 500mb depicted with the red ovals. There were only low level severe turbulence pilot reports over the Tetons during this timeframe.





The KHSG skew-t at 06/03Z still shows no inversion near the mountain ridge top and the 100-200mb layer above has stronger vertical speed shear. This coincides with the 700-500mb lapse rates near 7.0 C/km. Which inhibits mountain wave development but slide (39) shows the 11/06/00Z cross-section over KHSG a slightly weaker upward vertical motion couplet propagating wave as it punches through the tropopause. There looks to be vertical speed shear around 300mb, 200mb, and 500mb depicted with the red ovals. There were only low level severe turbulence pilot reports over the Tetons during this timeframe.

MOUNTAIN WAVE INDUCED TURBULENCE DECISION TREE

Do you have perpendicular cross-barrier flow with surface wind speeds 35kts or greater? Do you have ridge top wind speeds 50kts or greater?

YES, keep going

NO, not likely

Does Satellite show Foehn gap or subsidence & any severe turbulence pilot reports?

YES, keep going

NO, not likely

Is there an inversion near the mountain tops?

(This allows for vertical propagating couplet to develop in stable region)

YES, keep going

NO, not likely

Do you have a sharp or tight strong updraft/downdraft couplet?

YES, keep going

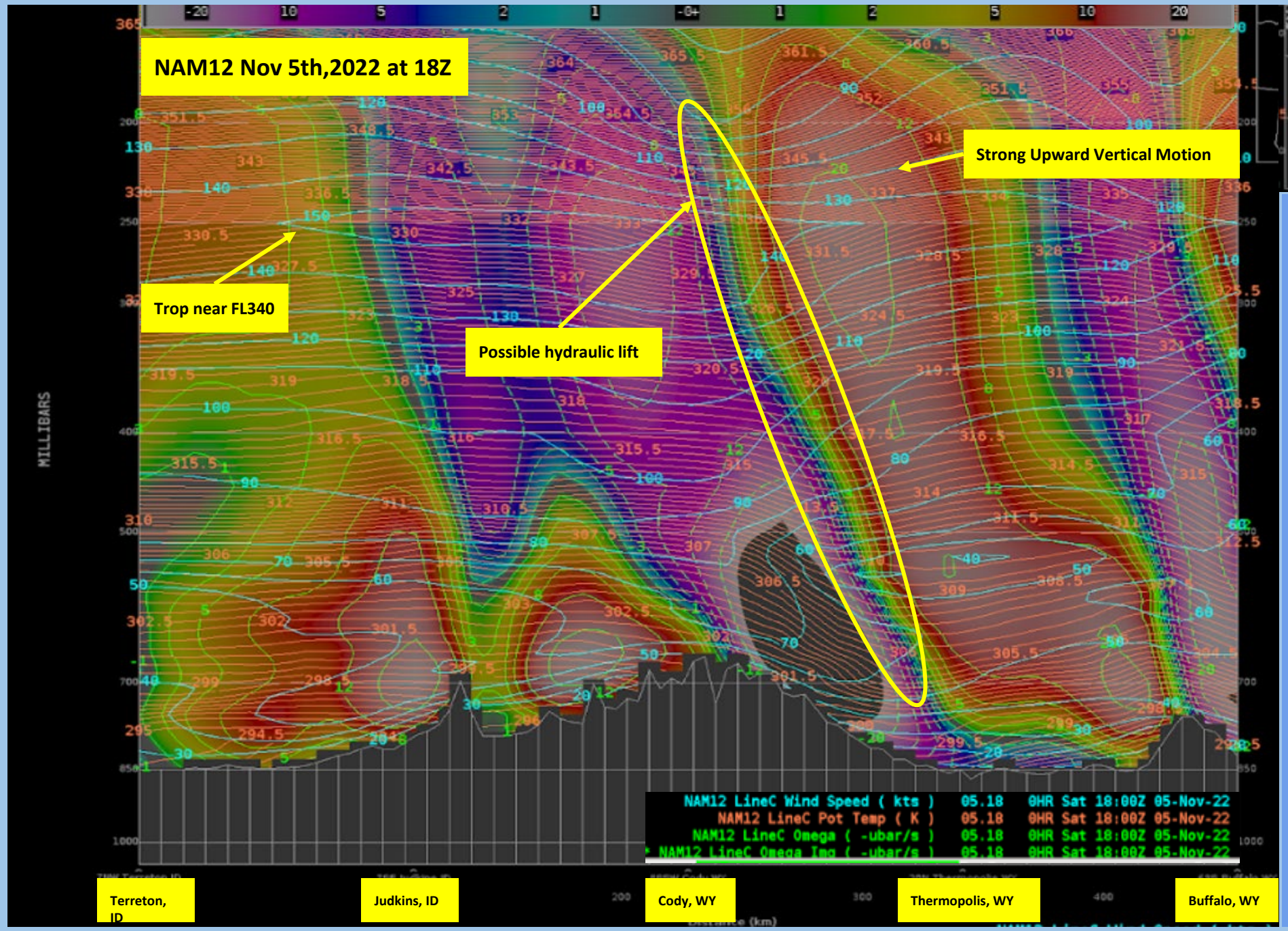
NO, monitor

Does the strong vertical propagating motion or couplet punch through the tropopause?

YES, keep going

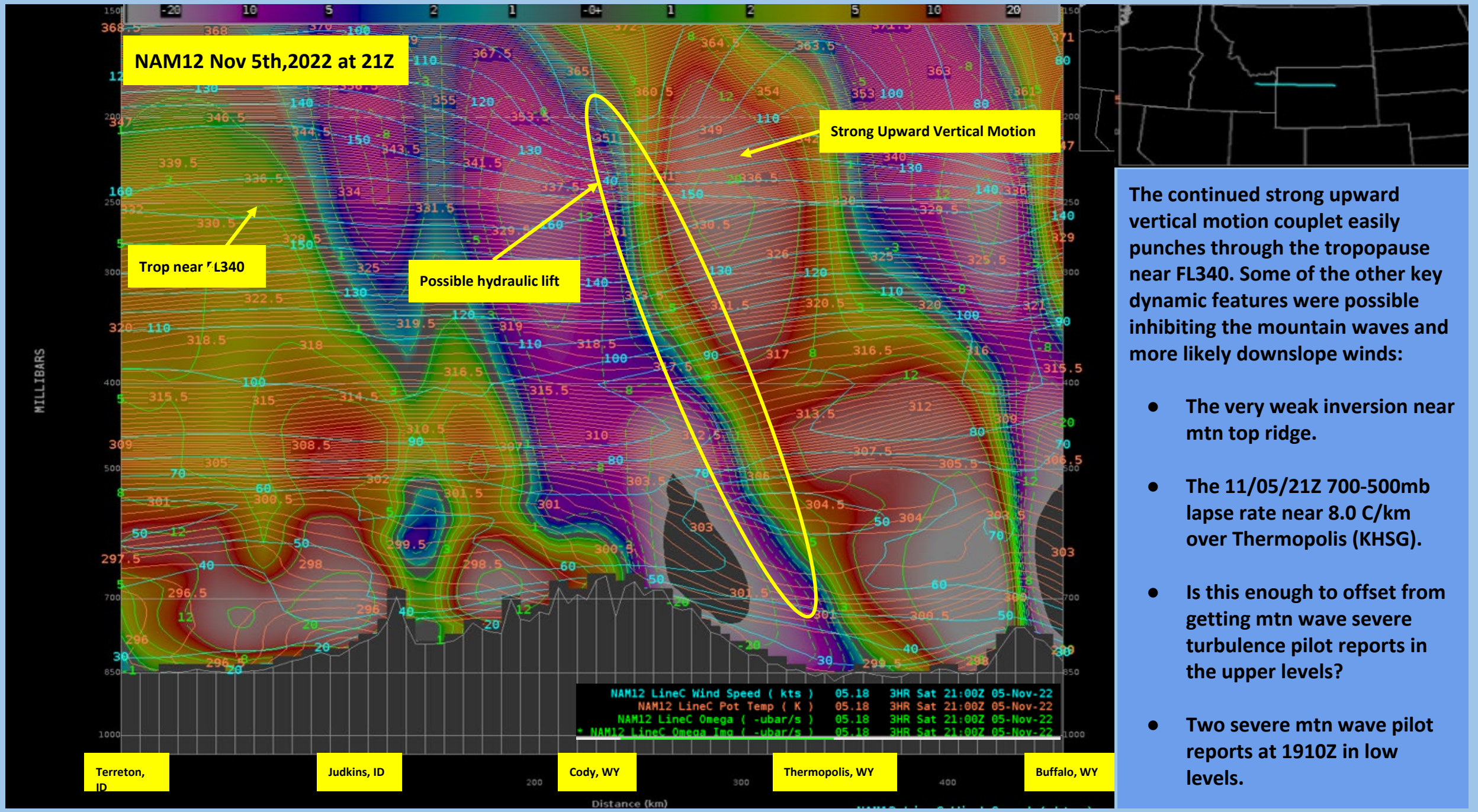
NO, monitor

Issue the Low and/or High Severe Turbulence SIGMET



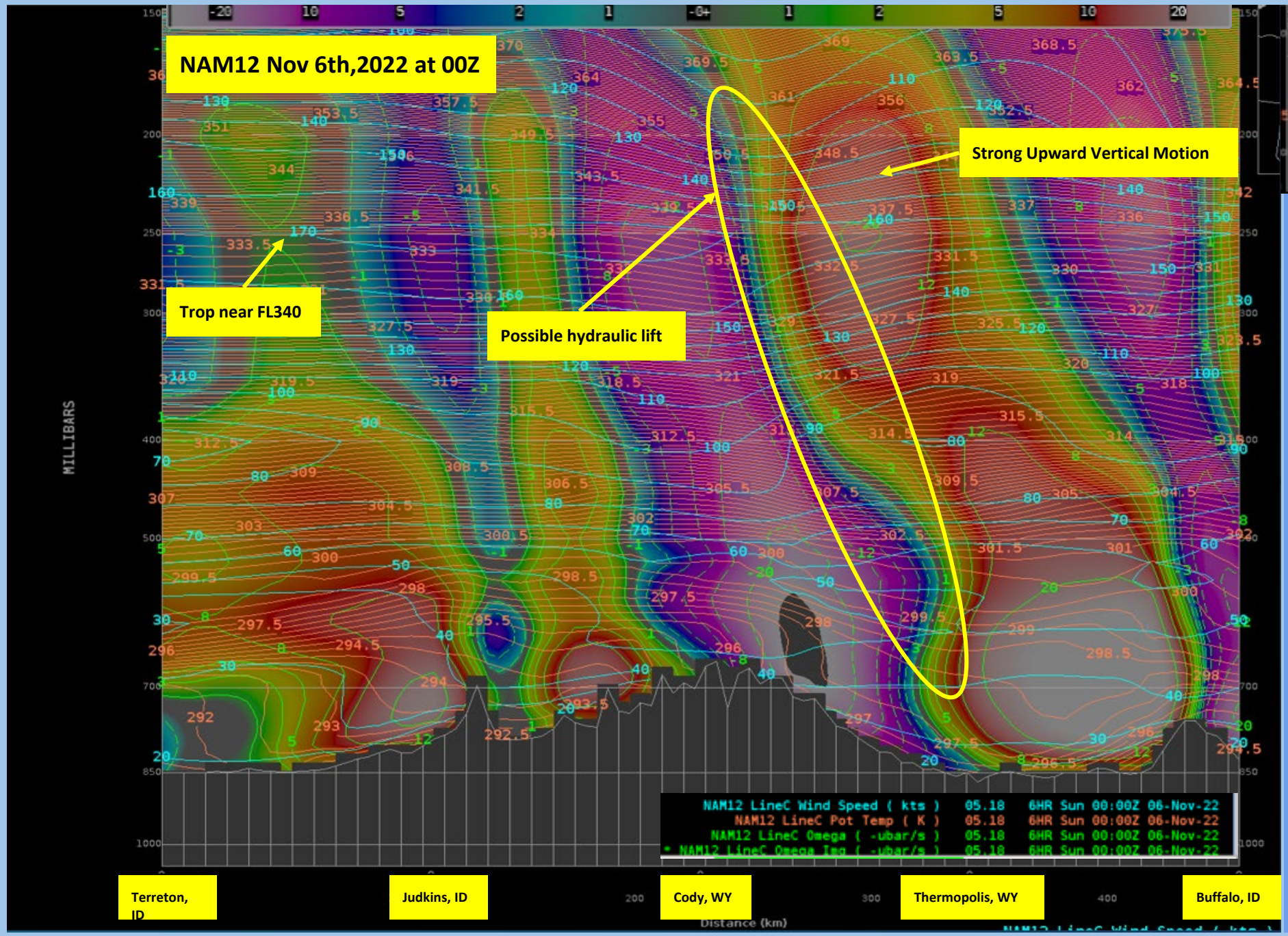
The strong upward vertical motion couplet easily punches through the tropopause near FL340. There were alot of other key dynamic features that aided in producing the potential for mountain waves:

- The RAPGTG Mtn wave composites from FL340 thru FL450 had strong bullseye indices over the Tetons.
- The 300mb nose of jetstreak over the Tetons.
- The RAP 2,000ft AGL had strong westerly 70kts winds.
- The 11/05/15Z 700-500mb lapse rate of 5.8 C/km over Thermopolis (KHSG).



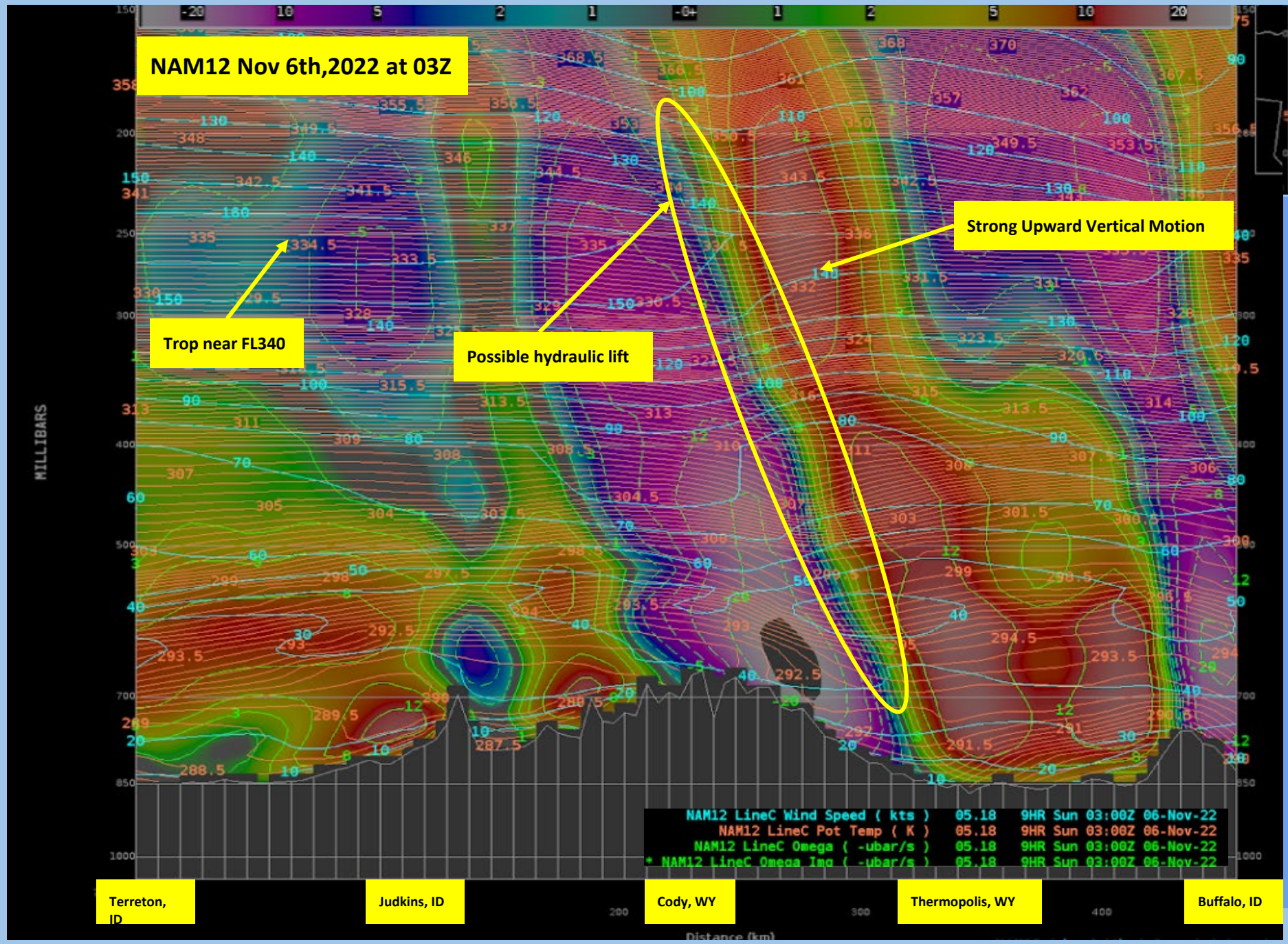
The continued strong upward vertical motion couplet easily punches through the tropopause near FL340. Some of the other key dynamic features were possible inhibiting the mountain waves and more likely downslope winds:

- The very weak inversion near mtn top ridge.
- The 11/05/21Z 700-500mb lapse rate near 8.0 C/km over Thermopolis (KHSG).
- Is this enough to offset from getting mtn wave severe turbulence pilot reports in the upper levels?
- Two severe mtn wave pilot reports at 1910Z in low levels.



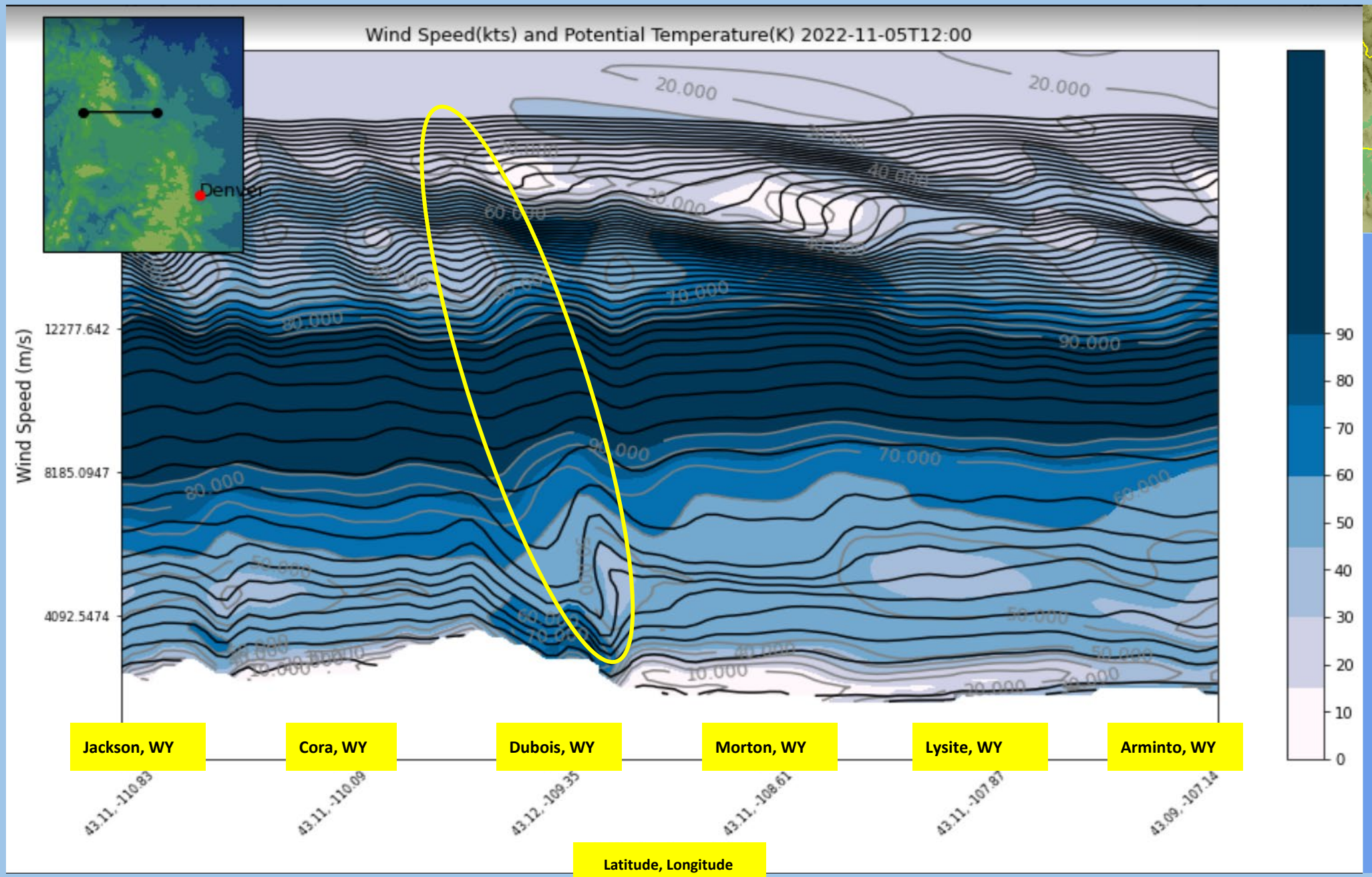
The continued strong upward vertical motion couplet easily punches through the tropopause near FL340. Some of the other key dynamic features were possible inhibiting the mountain waves and more likely downslope winds:

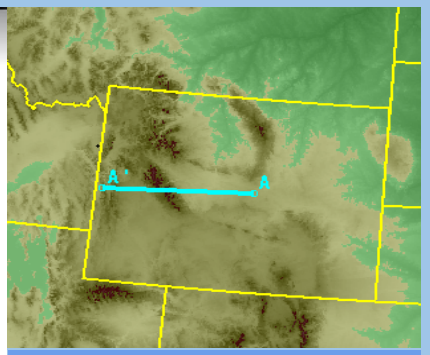
- No inversion near mtn top ridge.
- The 11/06/00Z 700-500mb lapse rate near 8.0 C/km over Thermopolis (KHSG).
- Is this enough to offset from getting mtn wave severe turbulence pilot reports in the upper levels?
- One severe mtn wave pilot reports at 2330Z in low levels.



The continued strong upward vertical motion couplet easily punches through the tropopause near FL340. Some of the other key dynamic features were possible inhibiting the mountain waves and more likely downslope winds:

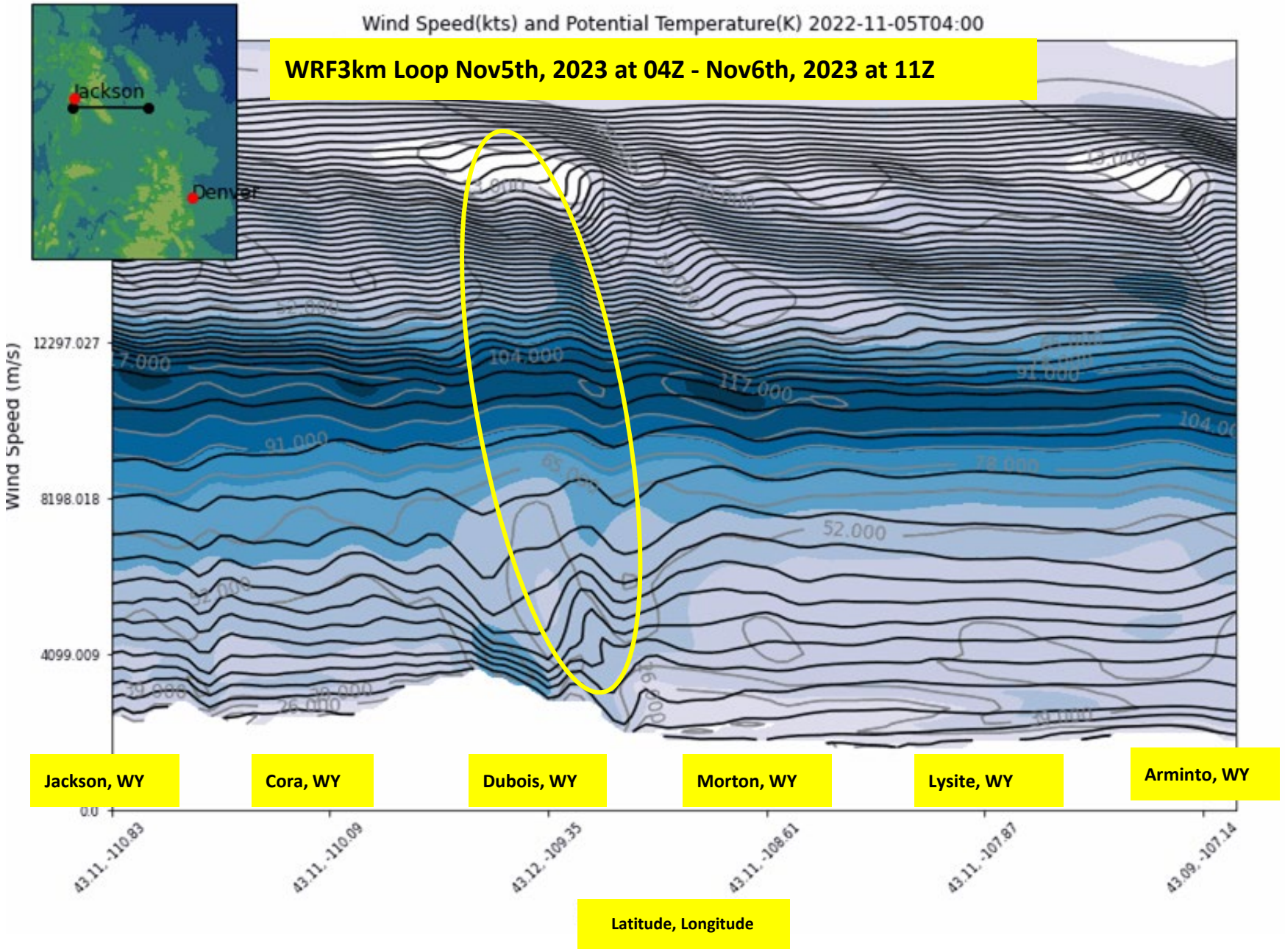
- No inversion near mtn top ridge.
- The 11/06/00Z 700-500mb lapse rate near 7.0 C/km over Thermopolis (KHSG).
- Is this enough to offset from getting mtn wave severe turbulence pilot reports in the upper levels?
- No severe mtn wave pilot reports.

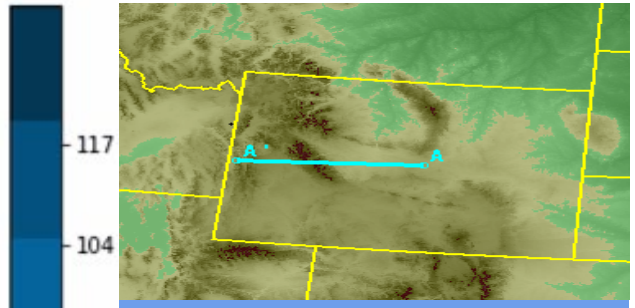




The yellow oval on the WRF-3km shows a breaking wave over the Dubois, WY area during the timeframe on Nov 5th, 2022 at 12Z. This disturbance coincides with:

- Nose of the 300mb jet streak entering the western WY region.
- The RAP 2,000 ft AGL wind were at 70-75kts with excellent cross barrier flow through the Teton mountains.





The yellow oval on the WRF-3km shows a breaking wave over the Dubois, WY area during the Nov 5th, 2022 occurring from 12Z - 18Z time-frame. This coincides with:

- Nose of the 300mb jet streak entering the western WY region.
- The RAP 2,000 ft AGL westerly wind were at 70-75kts with excellent cross barrier flow through the Teton mountains.
- RAPGTG Mtn Wave Composite having strong bullseye indices from FL340 to FL450.
- Strong upward vertical motion couplet punching through the tropopause.

CONCLUSION: There were several great dynamics for this severe turbulence event:

- Strong westerly cross-barrier flow across the Tetons, Big Horn and Rocky mountains.
- Right-front exit quadrant region jet-core over Tetons, but lapse rates too high and resulted in more downslope severe low turbulence.
- The 300mb RAP winds showed a strong northwesterly to westerly jet-core intensified by 11/05/18Z as the right-front exit quadrant region entered the western to central MT region. The 300mb speed convergence intensified with strong horizontal speed shear from 90kts at 11/05/12Z to 145kts by 11/05/15z.
- The NAM cross-sections thru western ID westward into the Tetons showed a vertically propagating wave punching through the Tropopause near 250mb. The WRF 3km showed a breaking mtn wave developed near Dubois, WY in the time-frame of 11/05/12Z to 11/05/18Z.
- The 700 to 500mb Lapse Rates values 5.5 - 6.5 C/km or less coincided in aiding in development of the vertically propagating couplets. There were severe mtn wave pilot reports over the Big Belt mountain in MT where the lapse rates were near 6.0 C/km. The left-rear entrance quadrant of jet was entering MT during those pilot reports.
- As this system moved into Denver later midday timeframe they had all the desired indices and resulted in several severe mtn wave turbulence pireps.

Future Goals:

- How to better analyze or understand cross-sections of propagating waves and incorporating the 600-500mb lapse rates and the 600-500mb QG forcing.

Thank You!

ICAO