Analysis and Automated Detection of Turbulence Signatures in Visible and Infrared Satellite Imagery

Kristopher Bedka
Science Directorate, NASA Langley Research Center

Anthony Wimmers
Cooperative Institute For Meteorological Satellite Studies (CIMSS)
University of Wisconsin – Madison

Work Supported By
Konstantin Khlopenkov and Benjamin Scarino
Science Systems and Applications, Inc.

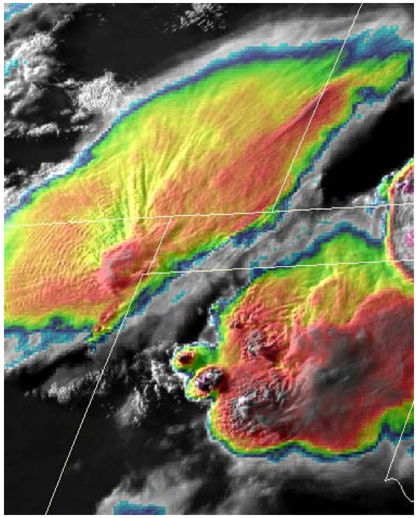
Sarah Griffin, Scott Bachmeier, Jordan Gerth, and Scott Lindstrom
UW-CIMSS

Introduction

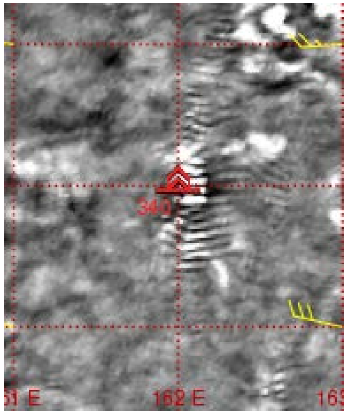
- **Many atmospheric processes and phenomena linked to aviation turbulence generate unique patterns in visible and IR satellite imagery, now being collected at increasingly high spatio-temporal resolution across the globe**

- **These phenomena include, but are not limited to:**

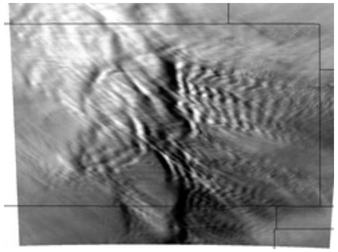
1) Anvil-penetrating updrafts and surrounding concentric gravity waves
2) Above-anvil cirrus plumes indicative of gravity wave breaking
3) Transverse bands along the periphery of storm anvils and within jet streams



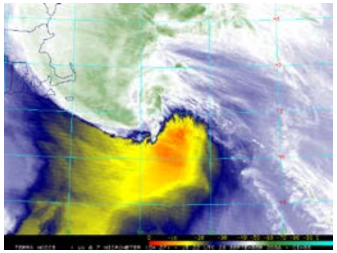
4) Gravity waves evident in "clear air”



5) Mountain waves



6) Tropopause folds



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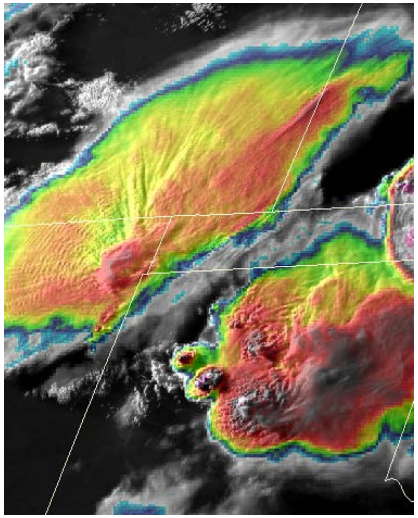

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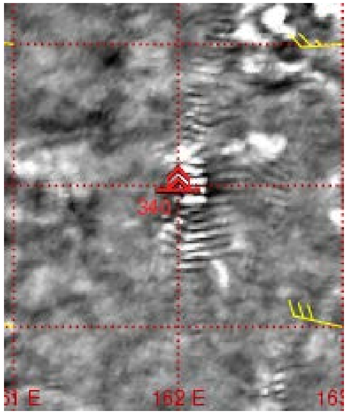

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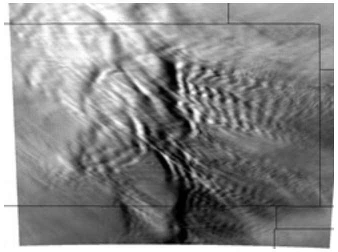

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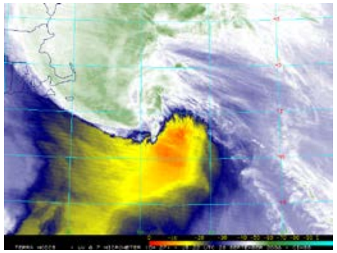


Topics Featured In This Talk

Detection Algorithm For Trop Folds Already Developed
Transverse Bands and Mountain Waves
Are Areas Of Active Research

Introduction

- **New imagery such as that from GOES-16/17, Himawari-8/9, and VIIRS can better resolve turbulence signatures, enabling development of new detection methods / “products”**

- **This talk will summarize recent efforts at UW-CIMSS and NASA LaRC toward satellite-based analysis and detection of aviation turbulence signatures**

RESEARCH PRESENTED IN THIS TALK SUPPORTED BY:

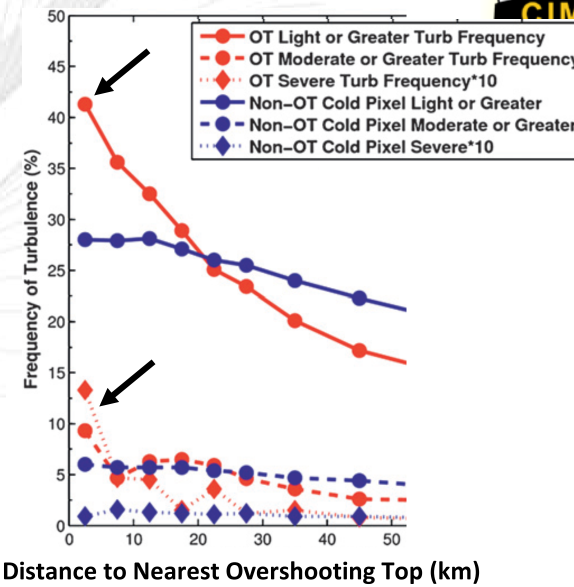
NASA ROSES A.25 Severe Weather (LaRC)
NASA ROSES A.40 NASA Data For Operations and Assessment (LaRC)
NOAA GOES-R Risk Reduction Research Program (CIMSS, LaRC)
NOAA GOES-R Aviation Algorithm Working Group (LaRC)
Federal Aviation Administration Aviation Weather Research Program (LaRC)

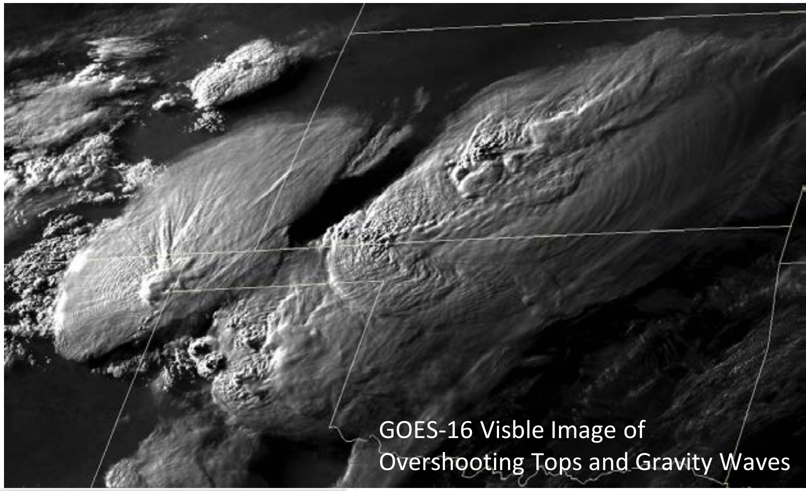
Automated Overshooting Top and Convectively-Generated Gravity Wave Detection

- **Turbulence is concentrated in the updraft region of deep convection**
- **Updrafts are evident in satellite imagery via cold temperatures and visible channel texture**
- **Pilots avoid ”red echoes” (> 40 dBZ) identified via onboard radar**
- **Flight through cold cores in IR imagery, indicative of vertical motions / overshooting cloud tops, does occur**
- **Comparison between United EDR data from 2005-2008 and an automated GOES IR-based overshooting top detection product showed** **(Bedka et al. (JAMC, 2010))**:

1) Light turbulence is 45% more frequent during flight near to overshooting regions (red solid line, upper left) than flight through spatially uniform but cold cloud (blue solid line)

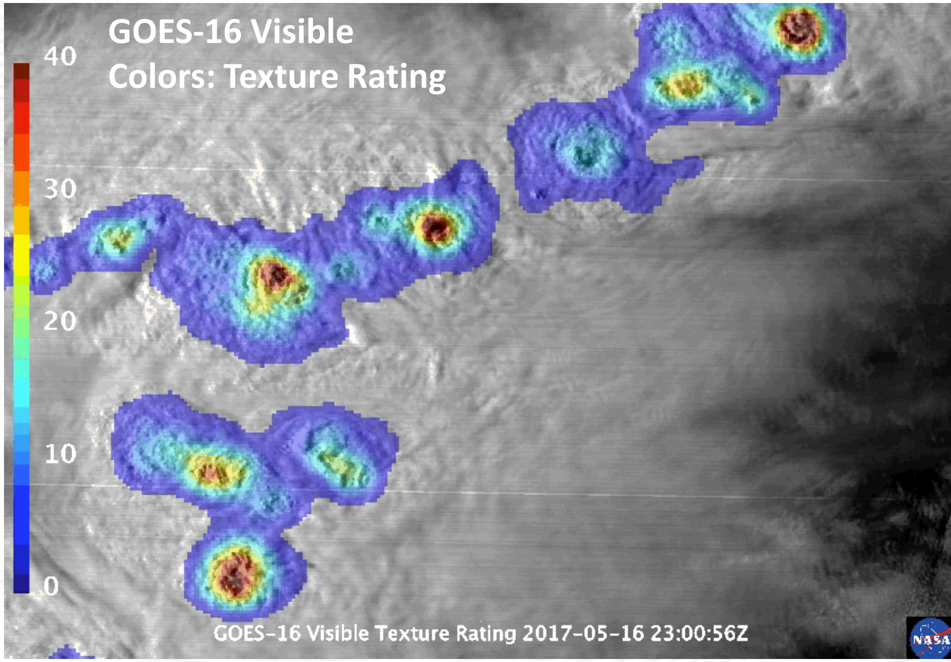
2) MOG turbulence is 58% more frequent during flight near to overshooting regions (dashed lines)

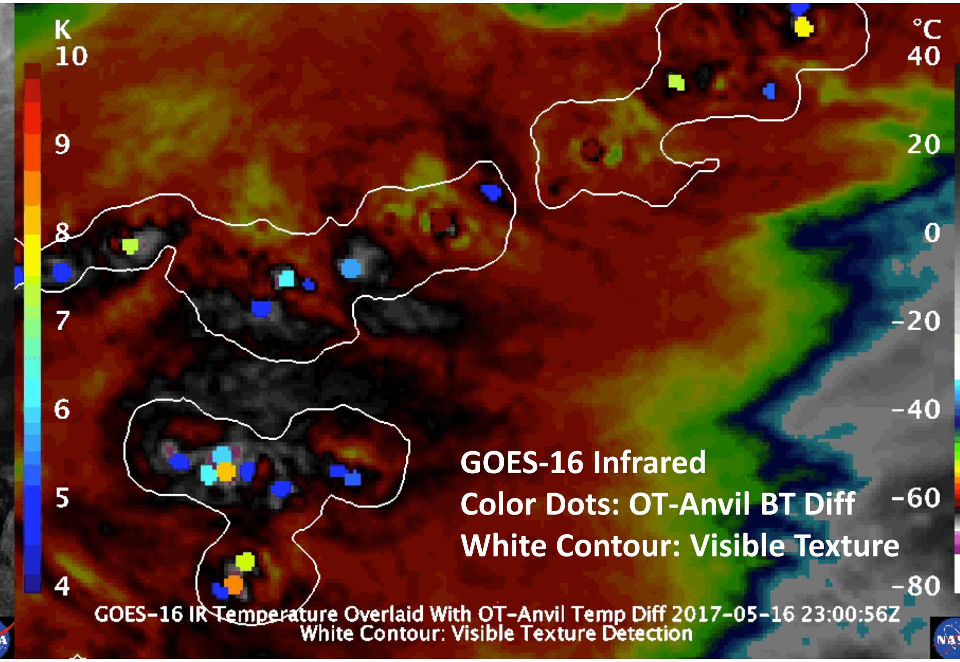




GOES-16 Visble Image of Overshooting Tops and Gravity Waves

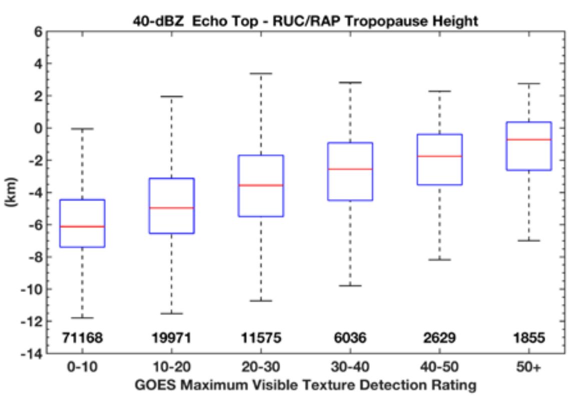
Automated Overshooting Top and Convectively-Generated Gravity Wave Detection





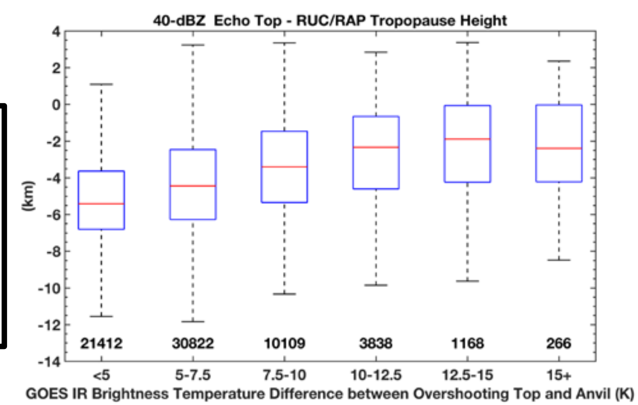
GOAL: Develop automated, pattern recognition methods for identifying embedded cold and textured areas within anvils using IR and visible imagery

WHY?: Thunderstorm updrafts indicate where aviation weather hazards (turbulence, ice crystal icing) and severe weather occur. An automated product can map locations impacted by these hazards anywhere and any time

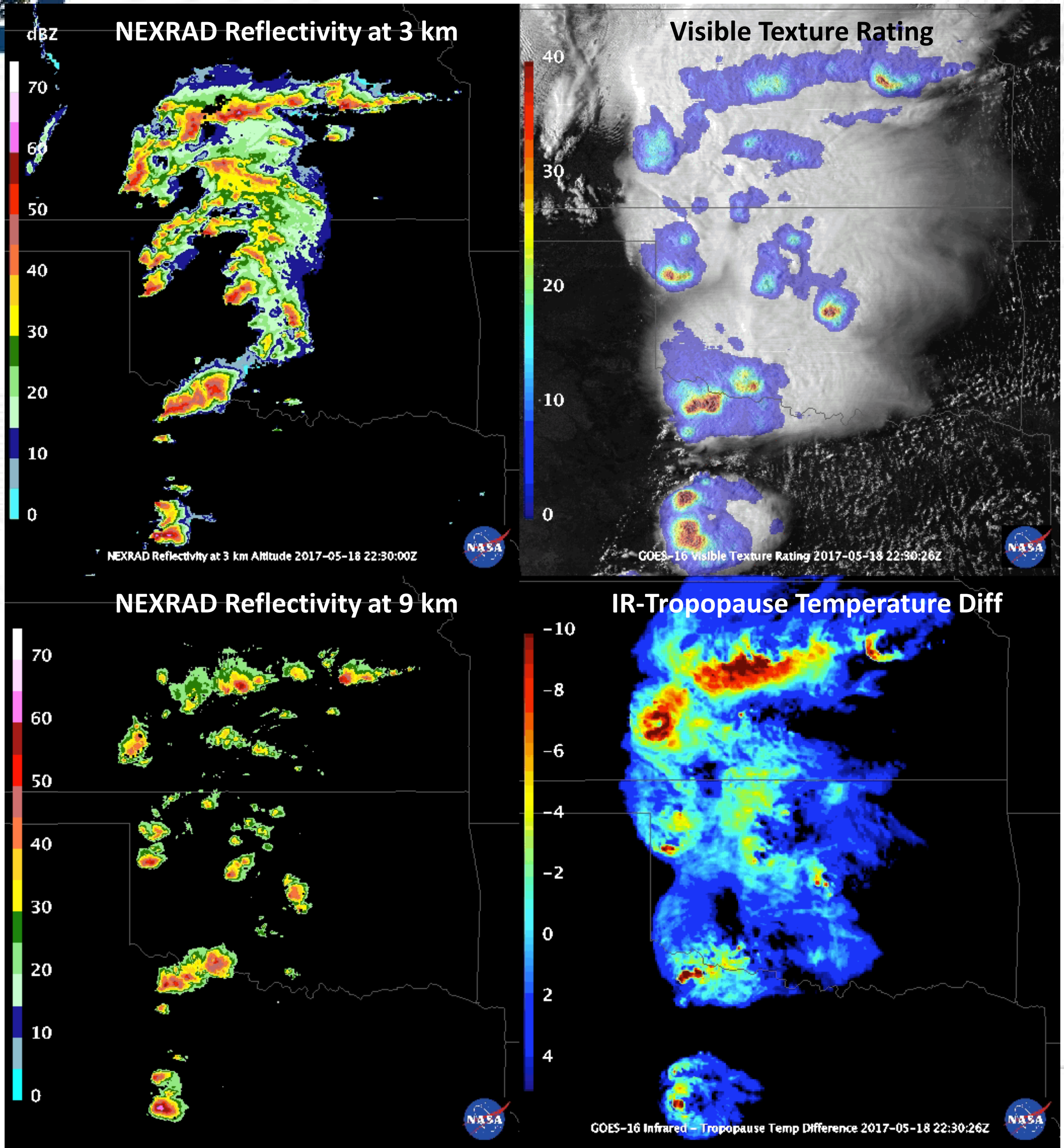


Analysis of 2000+ radar object tracks and 1-min GOES-16 data shows:

Increasing visible texture (left) and IR temperature contrast from anvil (right) indicates increasingly high 40 dBZ echo top



GOES Visible and Infrared Relationships With Radar Reflectivity



Neither GOES visible texture nor IR temperature correspond well with 3 km altitude NEXRAD reflectivity patterns

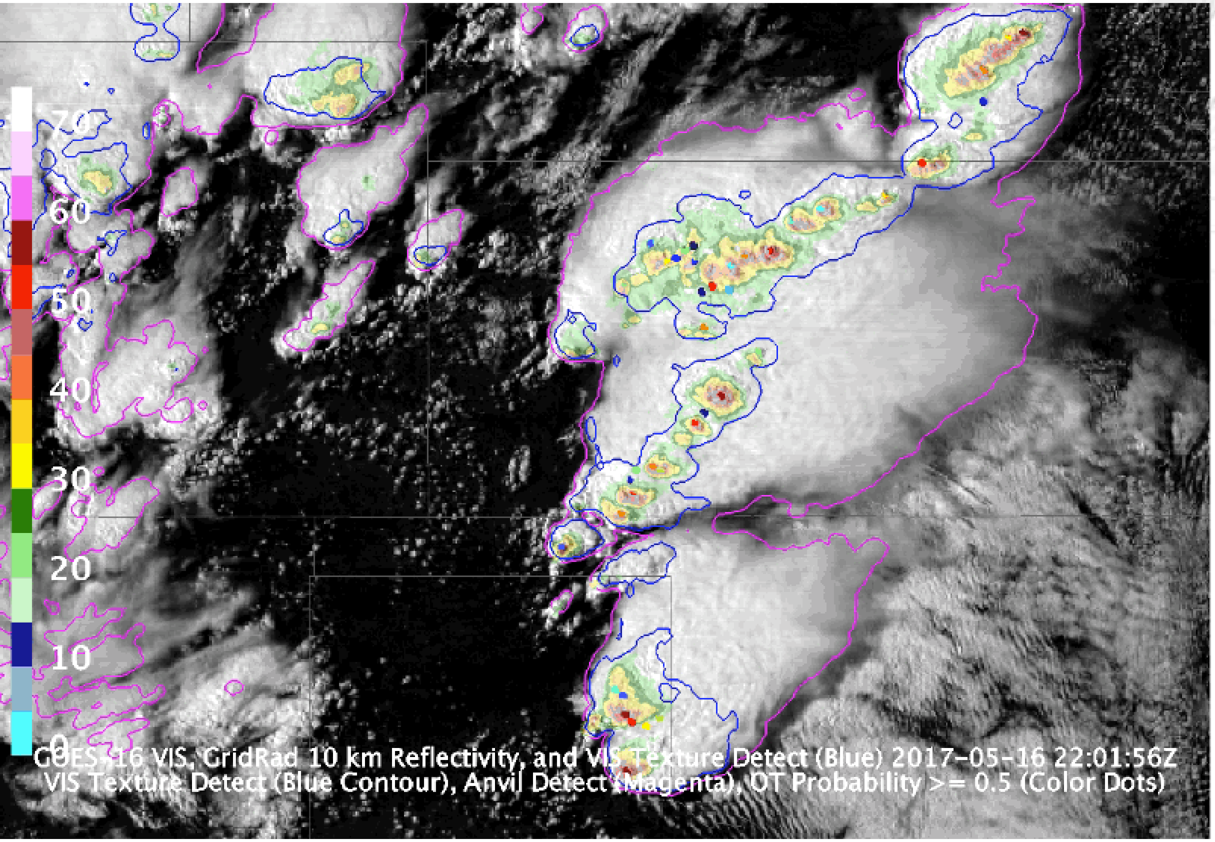
9 km reflectivity patterns corresponds better with texture. Updrafts that carry large ice particles to high levels deform the cloud top and produce texture

Moderate correlation between texture rating and 9 km reflectivity values, given the time differential between 1-min GOES imagery and 5-min NEXRAD scans

IR temperature very weakly correlated with 9 km reflectivity. Cold outflow from updrafts covers a broad area. Changes in NWP tropopause analyses across model runs can also bias IR temperature normalization

Cold temperatures alone are not necessarily a good indicator of turbulent clouds

Automated Overshooting Top and Convectively-Generated Gravity Wave Detection



NEXRAD data courtesy of Cameron Homeyer (OU)

VIS texture and IR OT detections are defining regions where precipitation is reaching aircraft cruise level (~9 km)

These satellite-based products can be used to consistently map hazardous storms anywhere across the world, which is especially valuable over ocean or in nations without weather radars

GOES-16 OT products are currently available in AWIPS-II at 5-min resolution over CONUS and are being evaluated by NOAA Southern Region CWSUs and National Centers such as AWC, OPC, and WPC

Products being used by NOAA ESRL to validate the NWP-based NCAR Ensemble Prediction of Oceanic Convective Hazards

NASA LaRC seeks to compare GOES-16 visible texture / IR OT detections with EDR observations to quantify product utility for turbulence nowcasting

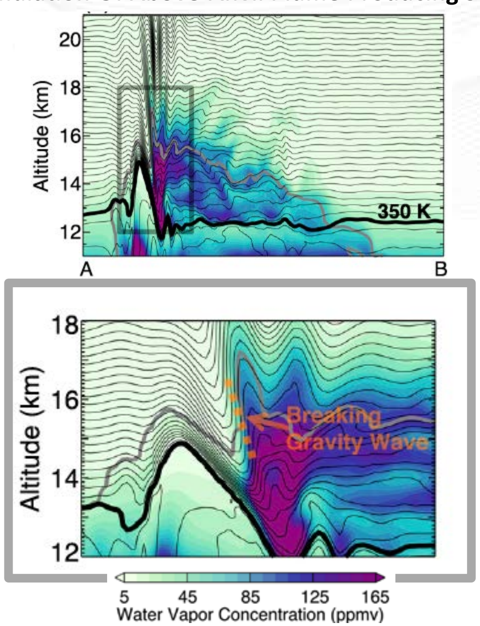
Bedka, K. M. and K. Khlopenkov, 2016: A probabilistic multispectral pattern recognition method for detection of overshooting cloud tops using passive satellite imager observations. J. Appl. Meteor. Climatol., 55, 1983–2005, https://doi.org/10.1175/JAMC-D-15-0249.1

Above Anvil Cirrus Plumes

An Indicator of Gravity Wave Breaking and Turbulence

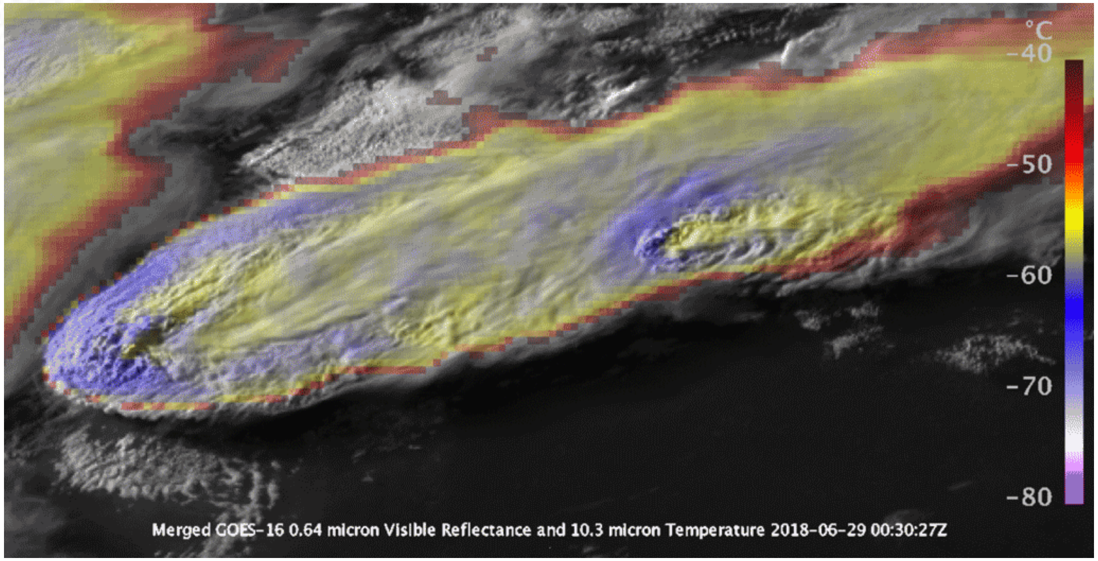
- **Above anvil plumes are typically generated by intense tropopause-penetrating updrafts, often in environments with strong storm-relative wind shear**
- **Updraft – shear combination generates unstable layers, enabling gravity wave breaking and injection of ice several kilometers into the stratosphere (See works by Sharman and Trier, Pao Wang, Martin Setvak, Cameron Homeyer, et al.)**
    - Gravity wave breaking atop convection has been linked to aviation turbulence (e.g. Lane and Sharman (JAMC, 2008))
- **The stratosphere is generally warmer than the anvil, causing plumes to be anomalously warm. This causes IR-based cloud top height retrievals to be biased low by 5+ kilometers in some cases**

Water Vapor Mixing Ratio Cross Section Through Numerical Model Simulation Of Above-Anvil Plume Producing Storm



Adapted From Figure 10 Of Homeyer et al. (JAS, 2017)

1-Minute Resolution GOES-16 Merged Visible and IR Animation of Above Anvil Producing Storms Over North Dakota

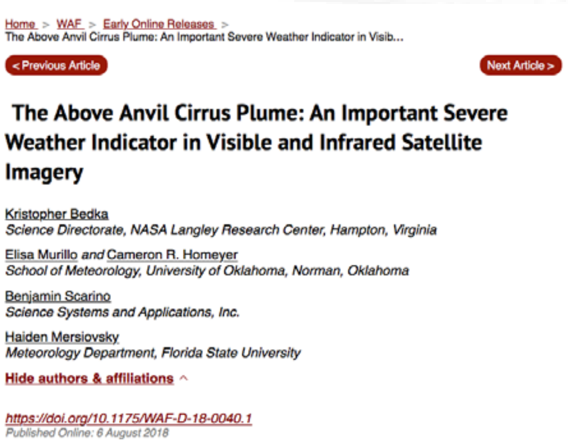


Above Anvil Cirrus Plumes

An Indicator of Gravity Wave Breaking and Turbulence

- Storms with above anvil plumes are an especially intense subset of deep convection and occur throughout the world
- On average, plume storms produce the highest echo tops, strongest updrafts, most lightning, a high frequency of severe weather, and often characteristics similar to a supercell storm
- One would expect these storms to generate aviation turbulence, but how far does the turbulent region extend?
- Turbulence relationships can be quantified through comparison with EDR reports. NASA LaRC has assembled a database of 1000+ plume storms that could be used for this analysis
- An automated plume detection algorithm is under development at NASA LaRC, but this pattern is quite challenging to detect with high accuracy (i.e. 90+% POD with <10% FAR)

Background and references on Above Anvil Plumes provided by Bedka et al. (WAF, 2018)



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The Above Anvil Cirrus Plume: An Important Severe Weather Indicator in Visib...

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The Above Anvil Cirrus Plume: An Important Severe Weather Indicator in Visible and Infrared Satellite Imagery

Kristopher Bedka
Science Directorate, NASA Langley Research Center, Hampton, Virginia

Elisa Murillo and Cameron R. Homeyer
School of Meteorology, University of Oklahoma, Norman, Oklahoma

Benjamin Scarino
Science Systems and Applications, Inc.

Haiden Mersiovsky
Meteorology Department, Florida State University

Hide authors & affiliations ^

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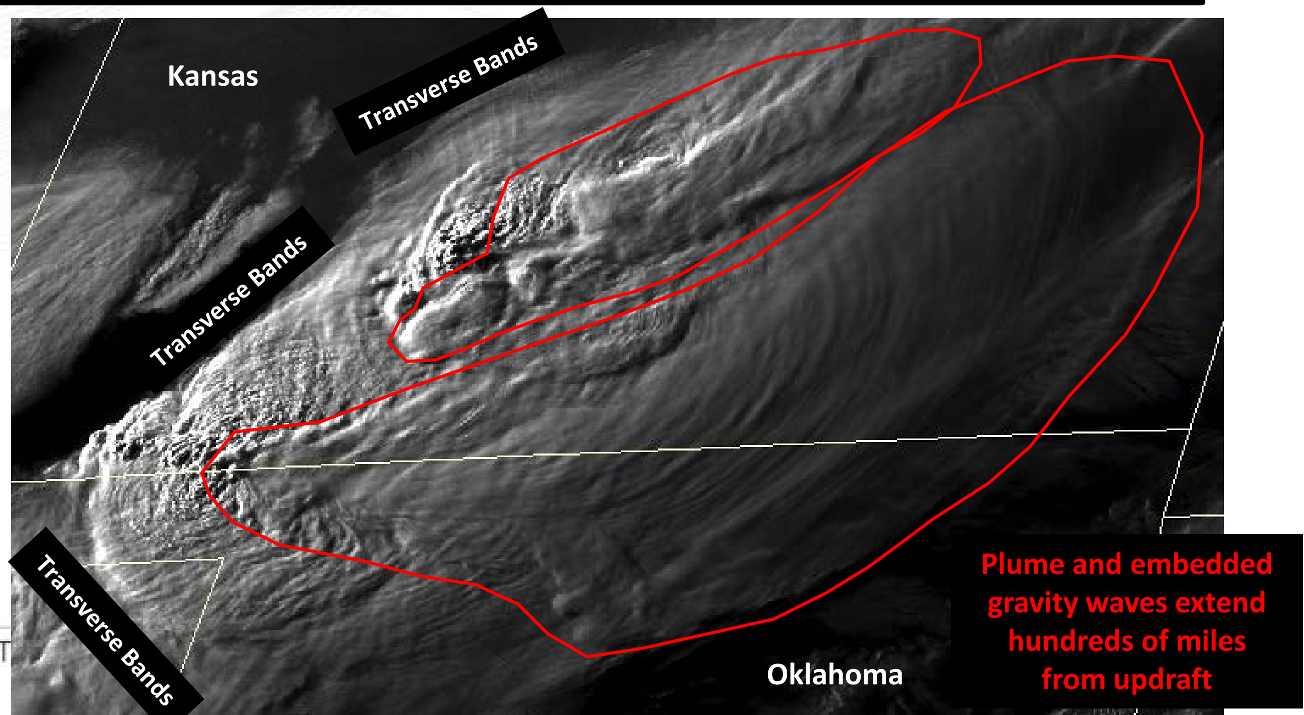


Resolving gravity waves with Himawari-8 at the new limit of resolution, and the application to aircraft-scale turbulence

Tony Wimmers, Scott Bachmeier, Jordan Gerth,

Sarah Griffin, Scott Lindstrom

Cooperative Institute for Meteorological Satellite Studies

University of Wisconsin - Madison

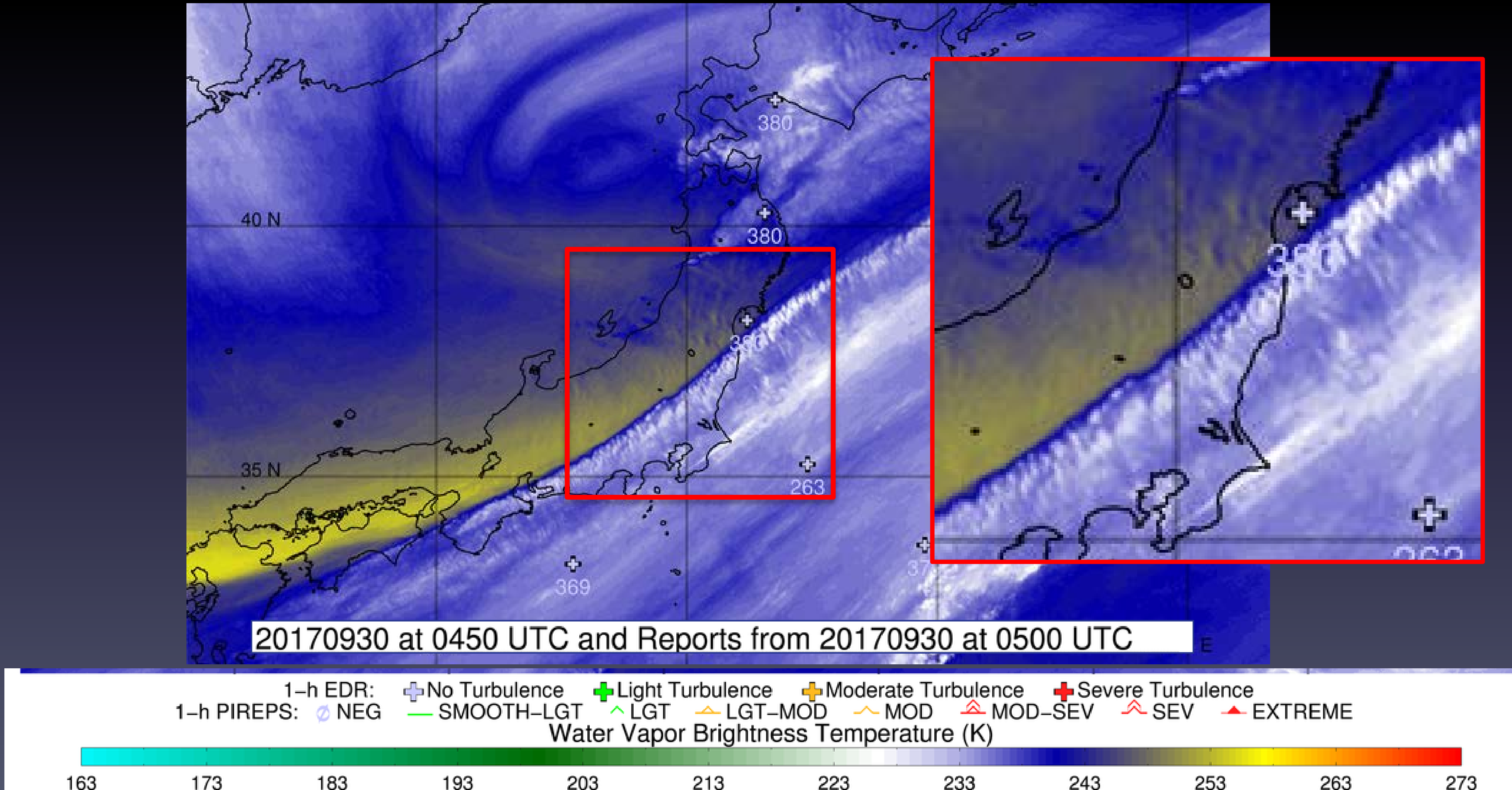
Sponsored by GOES-R Risk Reduction - Turbulence

Motivation

- Clear air turbulence is often not captured in forecast models.
- Geostationary weather satellites are used to observe events that are not modeled well (for example, rapidly evolving convection and shear)
- Clear air turbulence is sometimes also found around gravity waves in the satellite imagery …
- … but this pushes the limit of resolution.
- So, what can the higher resolution of AHI/ABI tell us?
- (Previous GOES: 4 km, 0.5 K. AHI/ABI: 2 km, 0.1 K.)

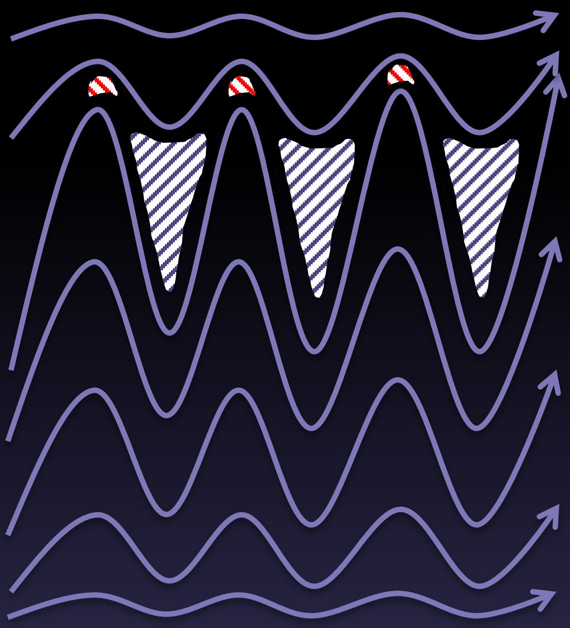
Matching Gravity waves and turbulence: Why is this so difficult?

Most gravity waves are not turbulent: Gravity waves propagate because of *stability*, and are usually not hazardous to fly through

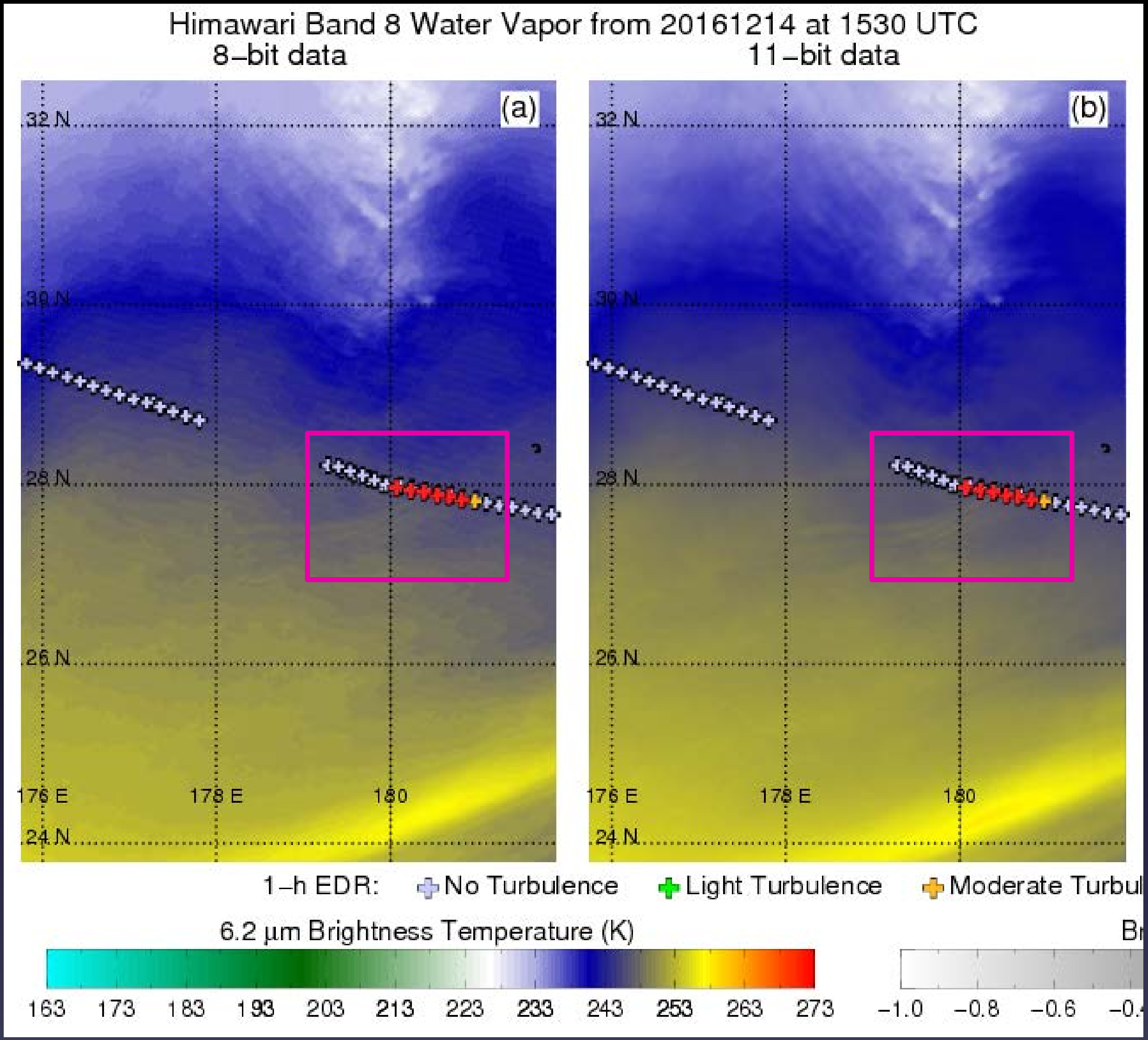


Then how are gravity waves ever associated with turbulence?

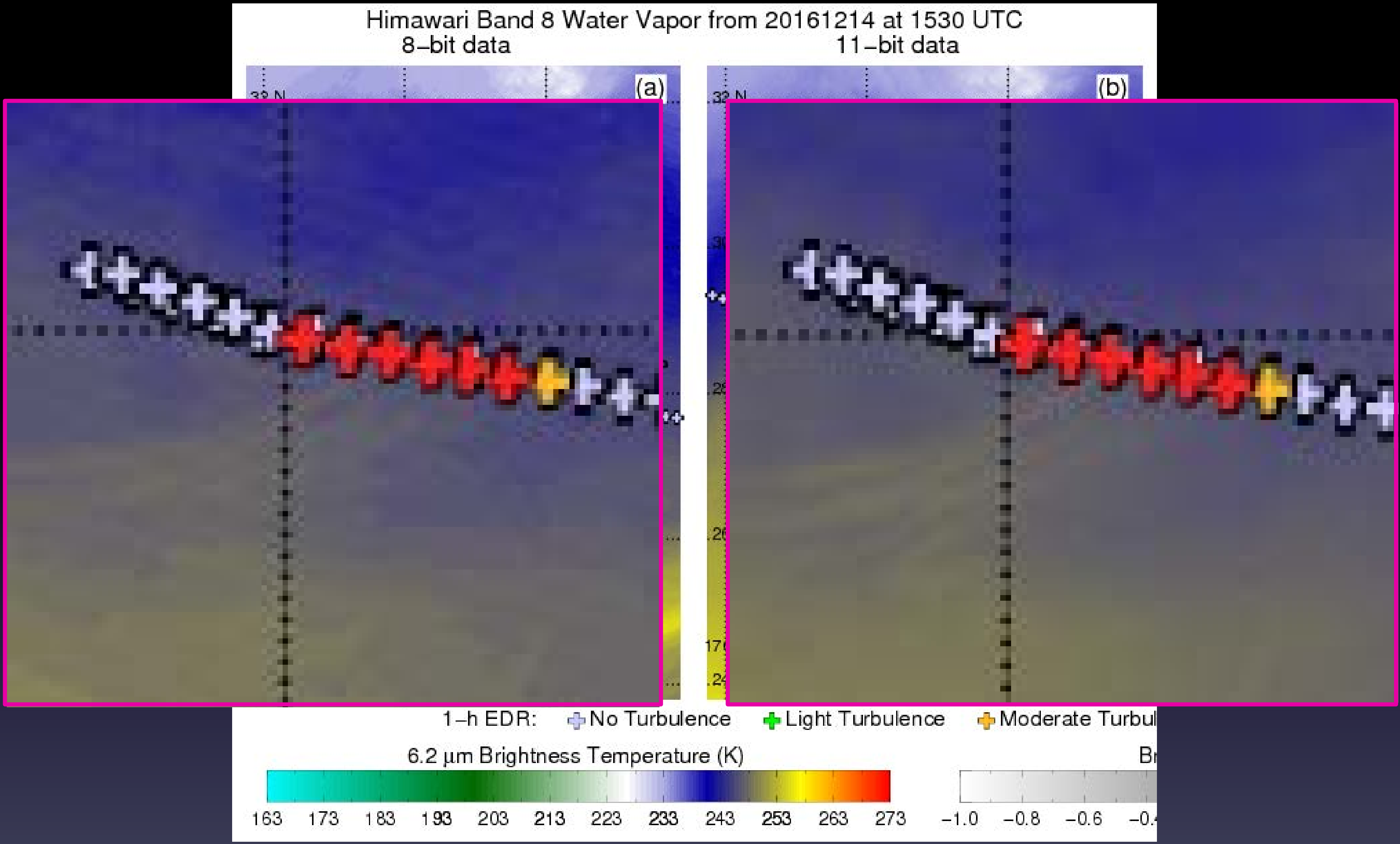
$$Ri = \frac{static\ stability}{vertical\ shear} = \frac{\frac{g}{T_v}\frac{\partial \theta_v}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2}$$



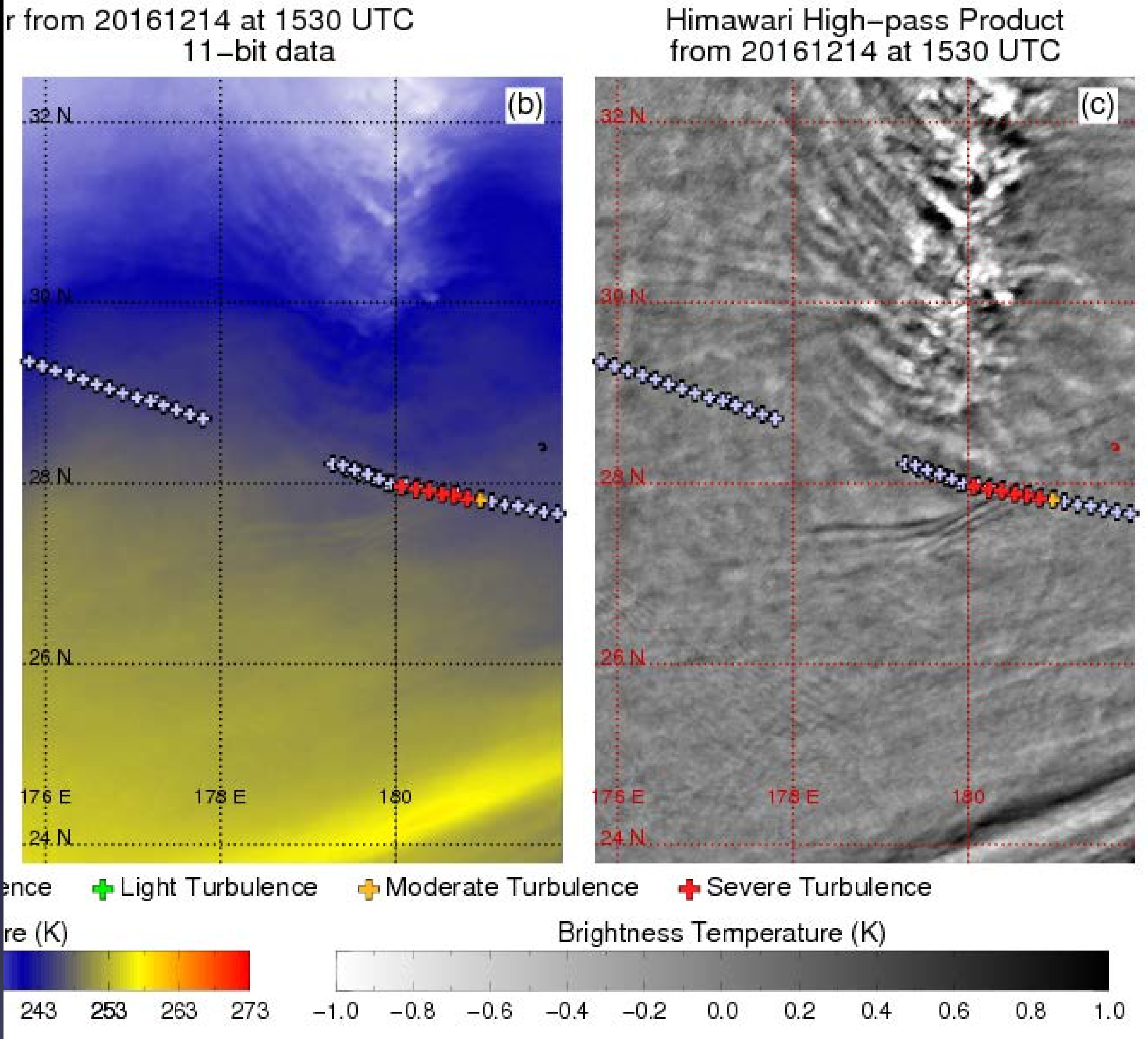
- Flow becomes turbulent when Ri < ~ 0.25
- If a layer is already close to Ri = 0.25, adding a gravity wave can create locally unstable areas



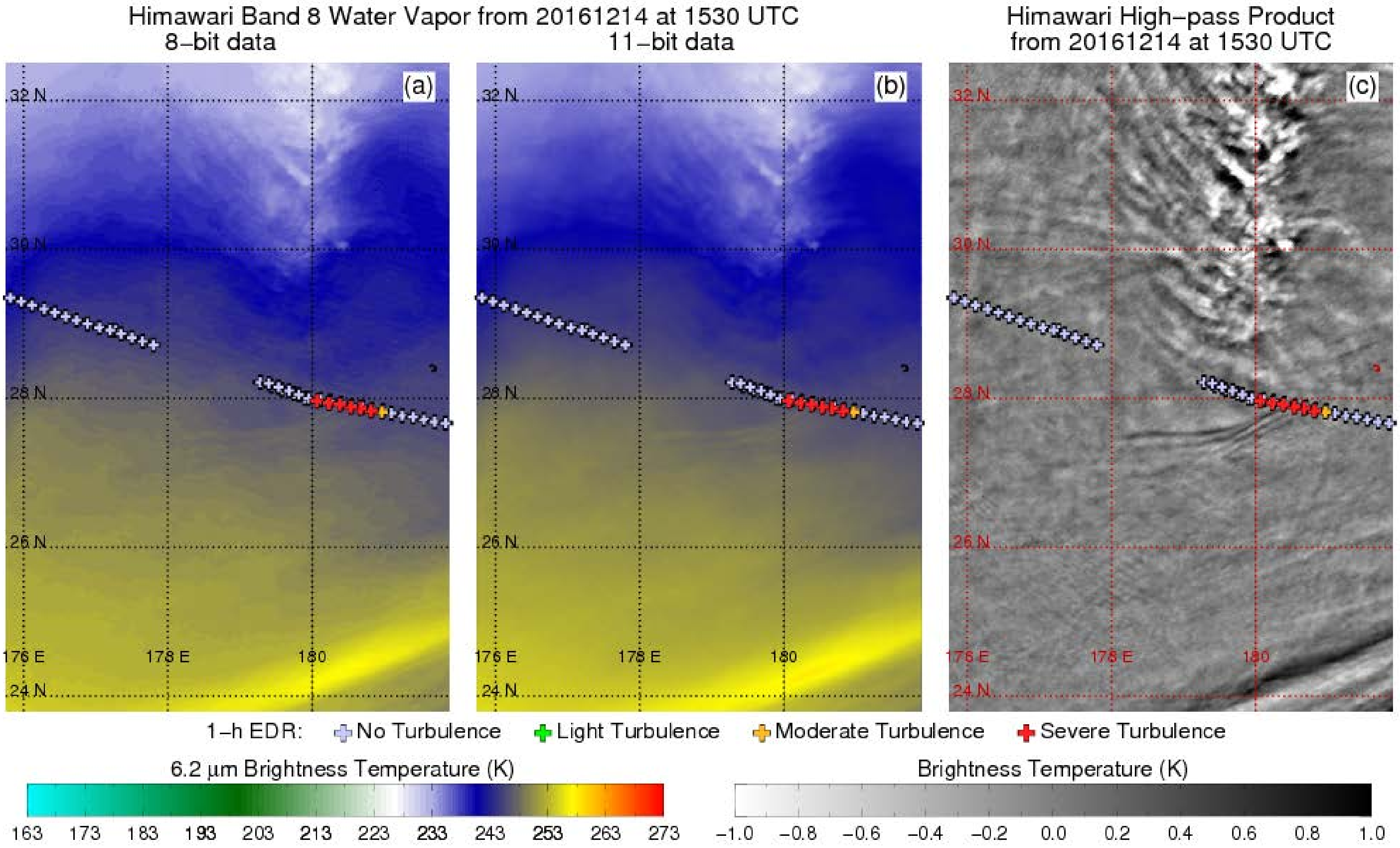
Himawari Band 8 Water Vapor from 20161214 at 1530 UTC
8−bit data
11−bit data
(a)
(b)
32 N
30 N
28 N
26 N
24 N
176 E
178 E
180
1−h EDR:
No Turbulence
Light Turbulence
Moderate Turbul
6.2 μm Brightness Temperature (K)
163
173
183
193
203
213
223
233
243
253
263
273
−1.0
−0.8
−0.6



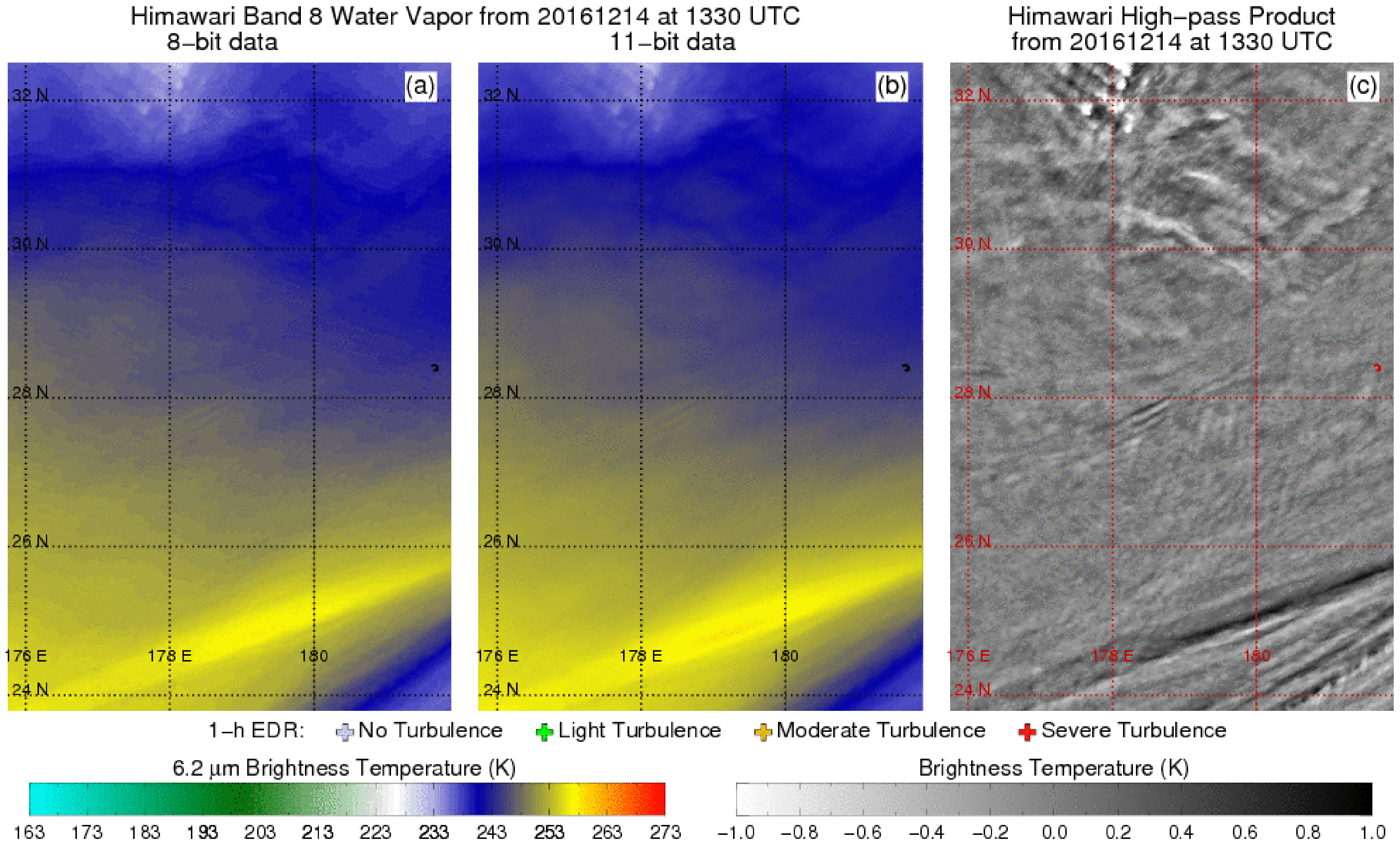
AHI shows more detail than some of our displays are designed for!



Right: High-pass filter applied to the image



Himawari Band 8 Water Vapor from 20161214 at 1530 UTC
8−bit data
11−bit data
Himawari High−pass Product
from 20161214 at 1530 UTC
(a)
(b)
(c)
32 N
30 N
28 N
26 N
24 N
176 E
178 E
180
1−h EDR: No Turbulence Light Turbulence Moderate Turbulence Severe Turbulence
6.2 µm Brightness Temperature (K)
163 173 183 193 203 213 223 233 243 253 263 273
Brightness Temperature (K)
−1.0 −0.8 −0.6 −0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0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8–bit data
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Himawari High–pass Product
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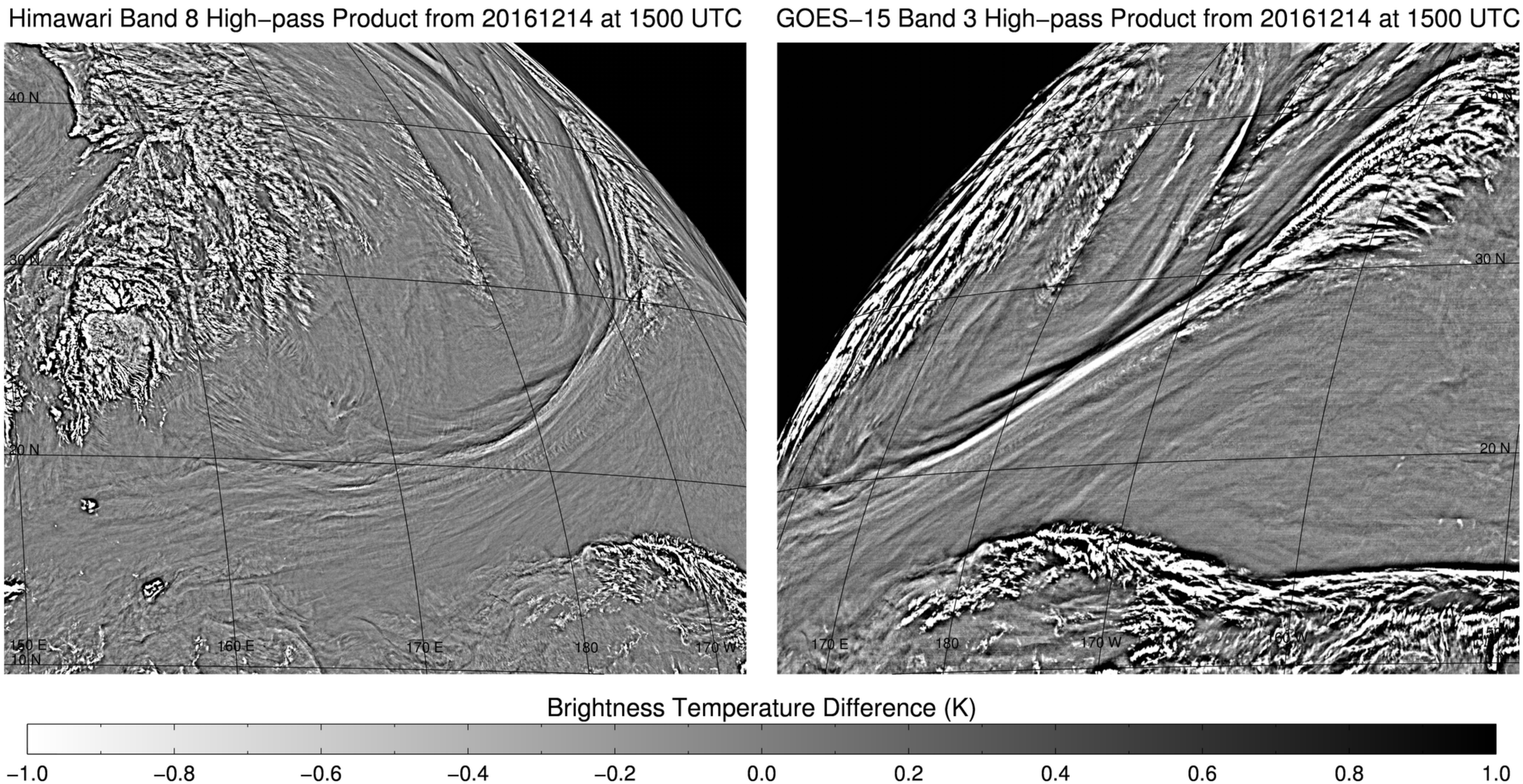
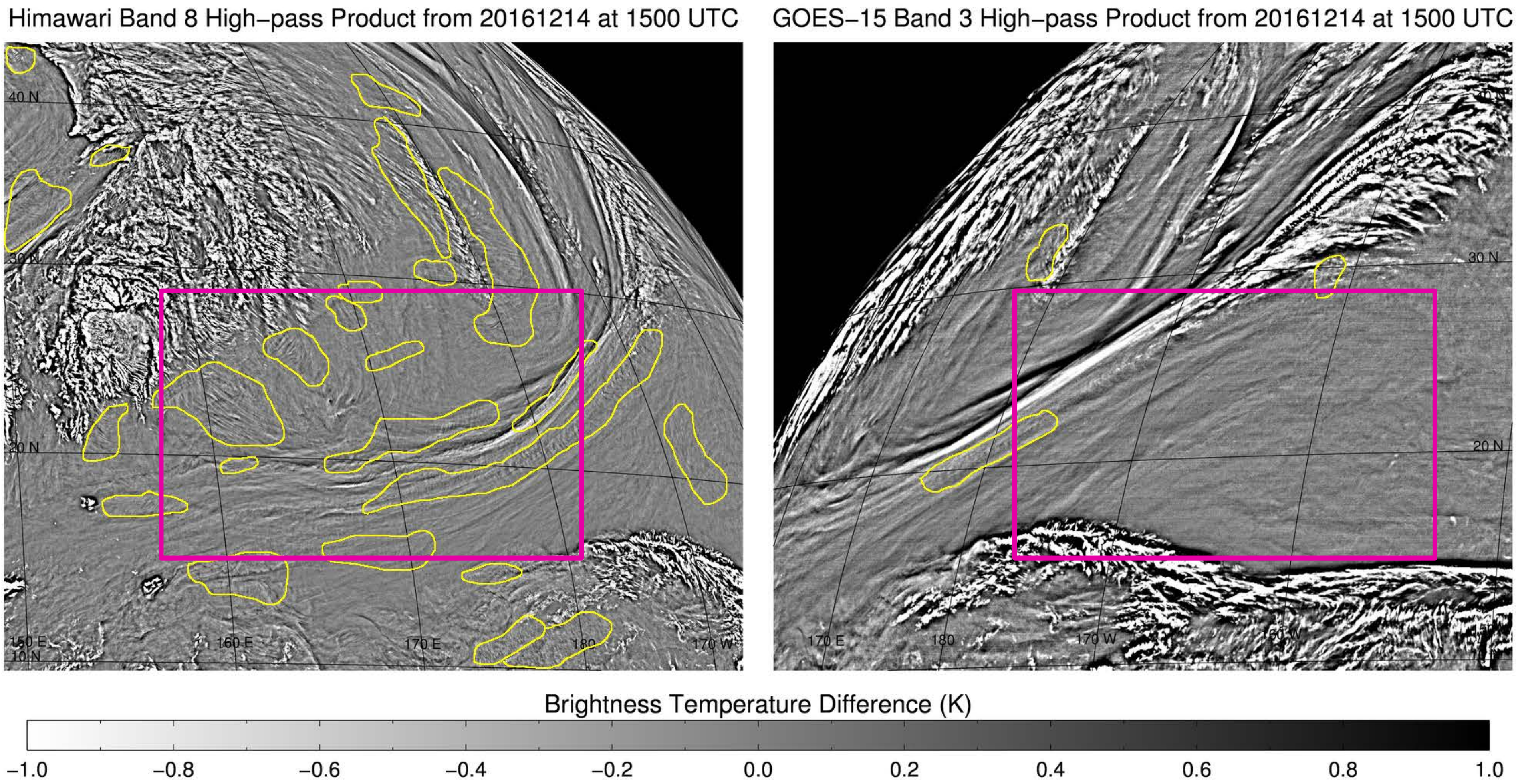
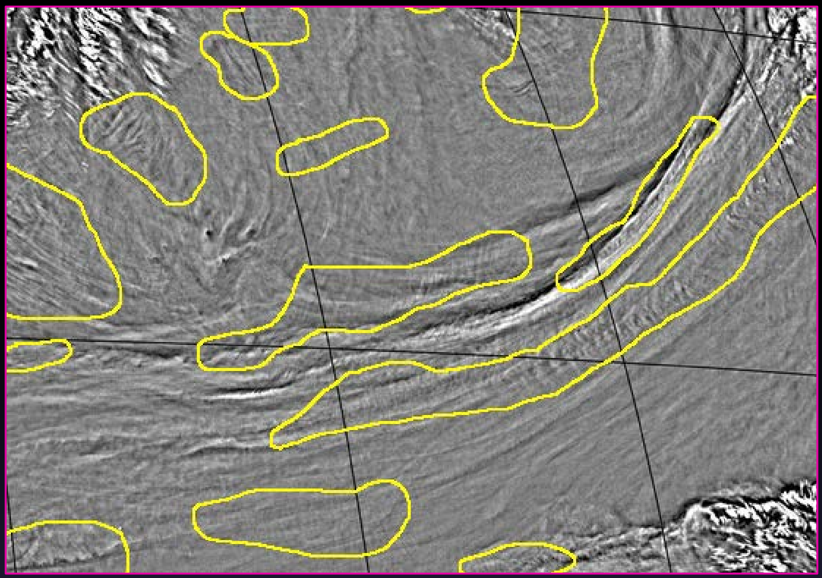

Himawari Band 8 High−pass Product from 20161214 at 1500 UTC
GOES−15 Band 3 High−pass Product from 20161214 at 1500 UTC
40 N
30 N
20 N
10 N
150 E
160 E
170 E
180
170 W
Brightness Temperature Difference (K)
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

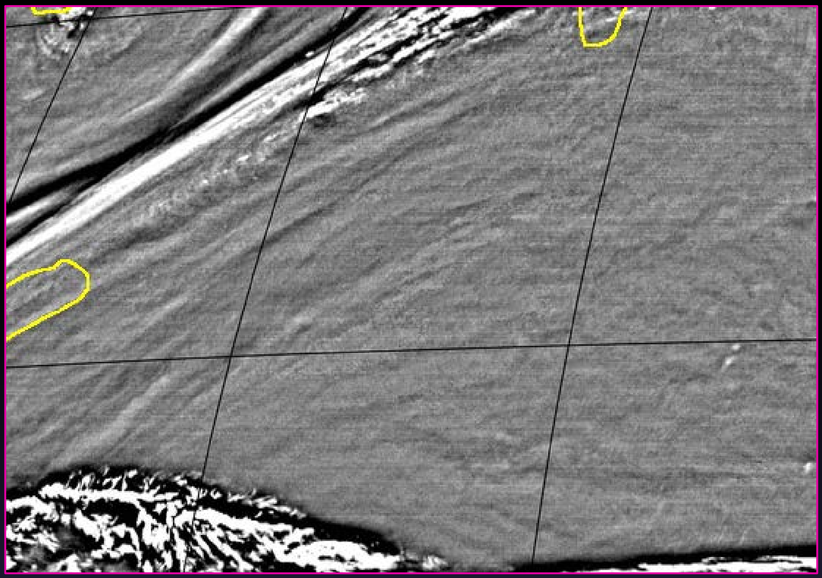


Himawari Band 8 High−pass Product from 20161214 at 1500 UTC
GOES−15 Band 3 High−pass Product from 20161214 at 1500 UTC
40 N
30 N
20 N
10 N
150 E
160 E
170 E
180
170 W
Brightness Temperature Difference (K)
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

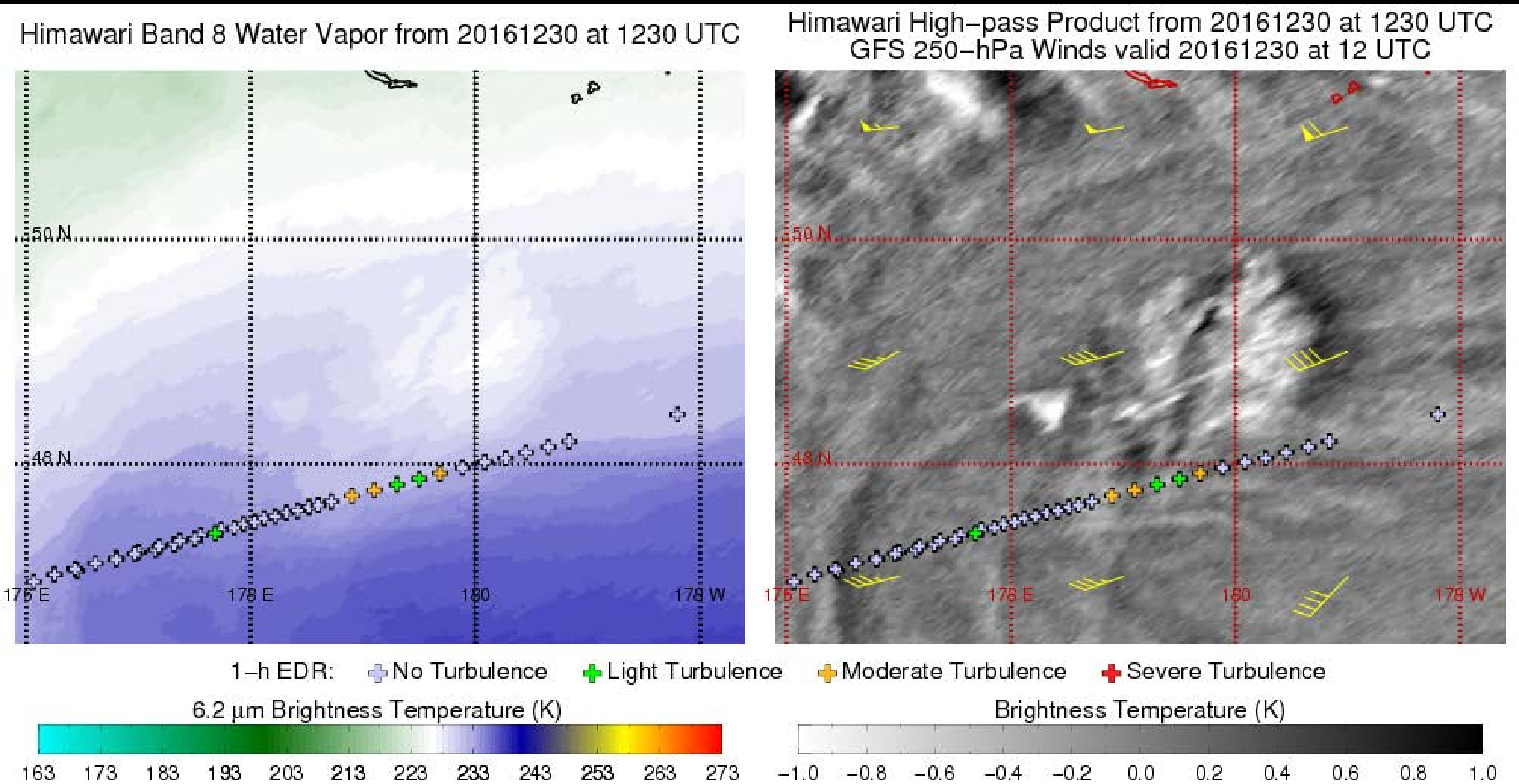
AHI

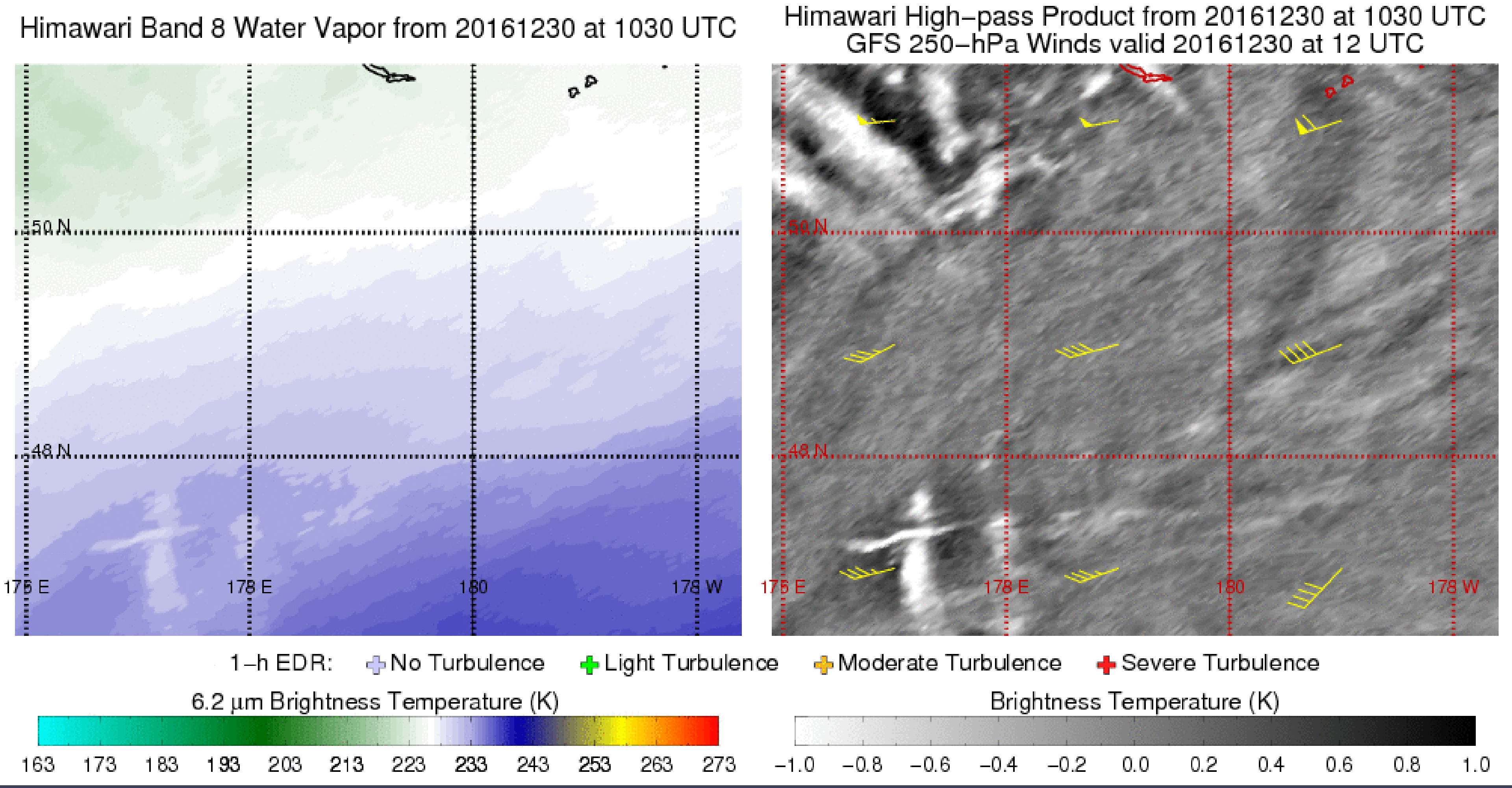


GOES-15



- Gravity waves are *very* common at the AHI/ABI resolution.
- Then how do we find the *minority* of cases that are turbulent and a problem for aircraft?


Himawari Band 8 Water Vapor from 20161230 at 1230 UTC
Himawari High−pass Product from 20161230 at 1230 UTC
GFS 250−hPa Winds valid 20161230 at 12 UTC
50 N
48 N
176 E
178 E
180
178 W
1−h EDR: No Turbulence Light Turbulence Moderate Turbulence Severe Turbulence
6.2 μm Brightness Temperature (K)
163 173 183 193 203 213 223 233 243 253 263 273
Brightness Temperature (K)
−1.0 −0.8 −0.6 −0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0


Himawari Band 8 Water Vapor from 20161230 at 1030 UTC
Himawari High−pass Product from 20161230 at 1030 UTC
GFS 250−hPa Winds valid 20161230 at 12 UTC
50 N
48 N
176 E
178 E
180
178 W
1−h EDR: No Turbulence Light Turbulence Moderate Turbulence Severe Turbulence
6.2 µm Brightness Temperature (K)
163 173 183 193 203 213 223 233 243 253 263 273
Brightness Temperature (K)
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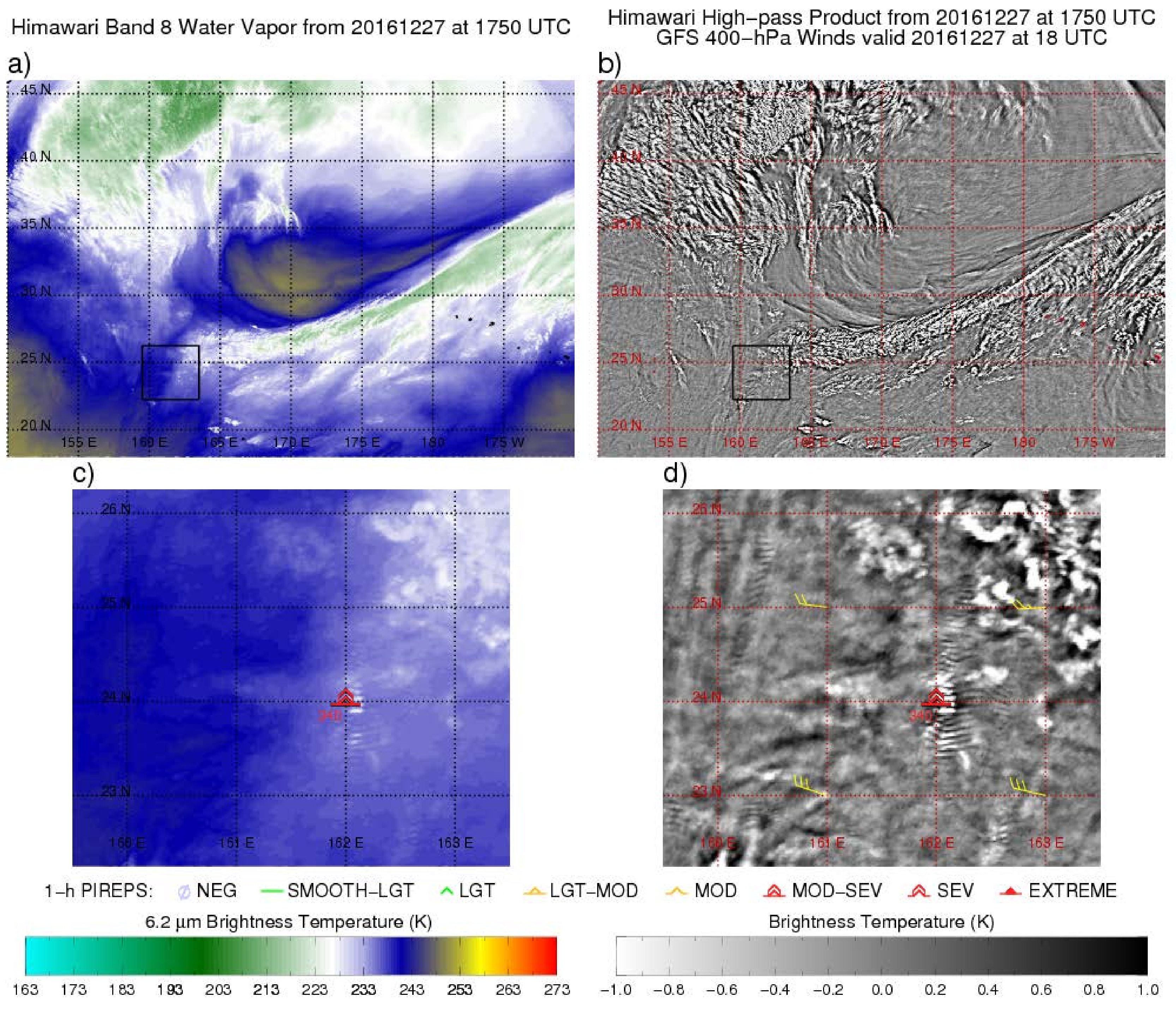
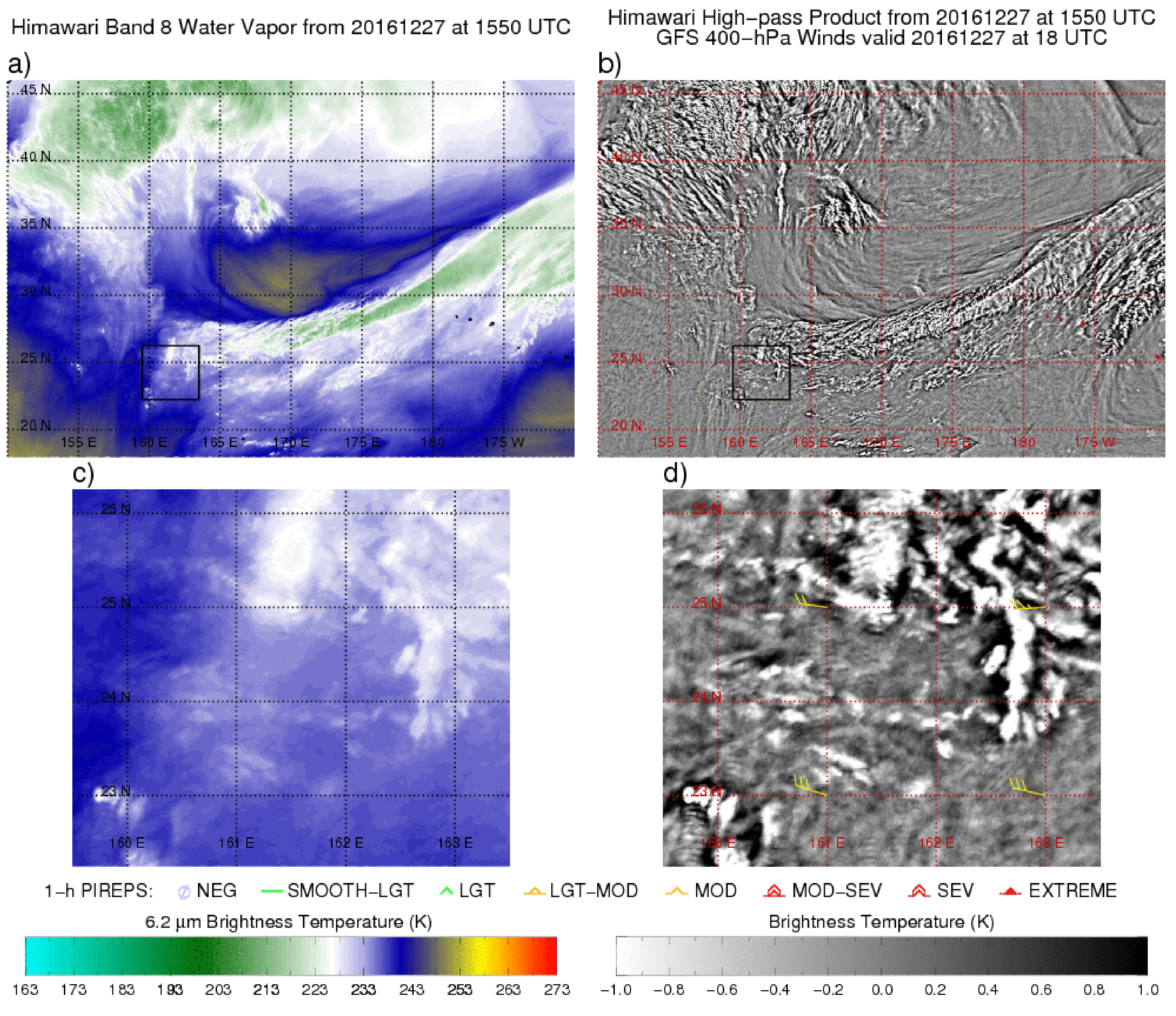
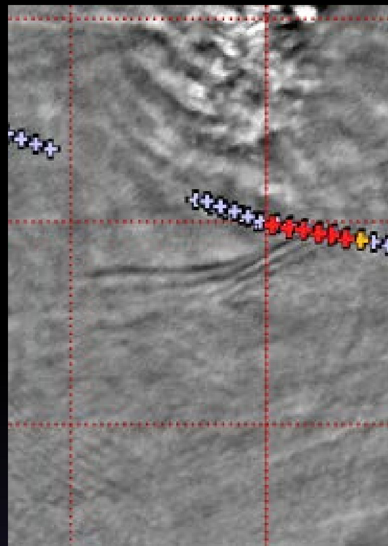


Himawari Band 8 Water Vapor from 20161227 at 1750 UTC
Himawari High-pass Product from 20161227 at 1750 UTC
GFS 400-hPa Winds valid 20161227 at 18 UTC
a)
b)
c)
d)
45 N
40 N
35 N
30 N
25 N
20 N
155 E
160 E
165 E
170 E
175 E
180
175 W
26 N
25 N
24 N
23 N
160 E
161 E
162 E
163 E
340
1-h PIREPS:
NEG
SMOOTH-LGT
LGT
LGT-MOD
MOD
MOD-SEV
SEV
EXTREME
6.2 µm Brightness Temperature (K)
163 173 183 193 203 213 223 233 243 253 263 273
Brightness Temperature (K)
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0

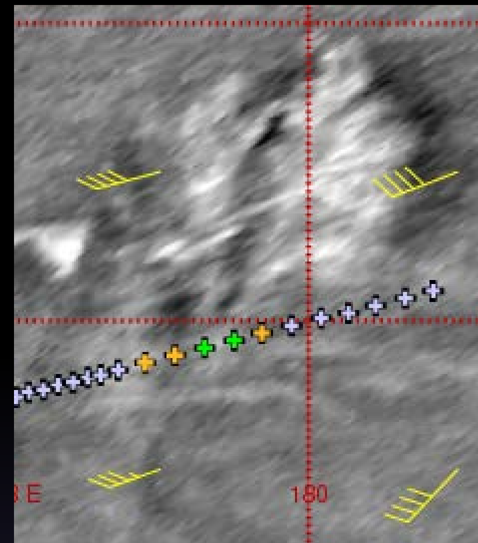


Himawari Band 8 Water Vapor from 20161227 at 1550 UTC
Himawari High-pass Product from 20161227 at 1550 UTC
GFS 400-hPa Winds valid 20161227 at 18 UTC
a)
b)
c)
d)
45 N
40 N
35 N
30 N
25 N
20 N
155 E
160 E
165 E
170 E
175 E
180
175 W
26 N
25 N
24 N
23 N
160 E
161 E
162 E
163 E
1-h PIREPS:
NEG
SMOOTH-LGT
LGT
LGT-MOD
MOD
MOD-SEV
SEV
EXTREME
6.2 µm Brightness Temperature (K)
163
173
183
193
203
213
223
233
243
253
263
273
Brightness Temperature (K)
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

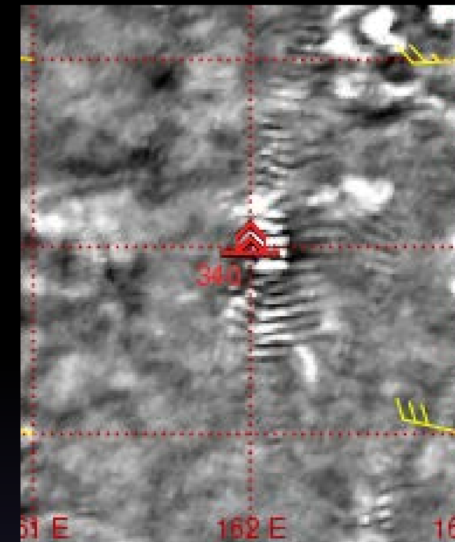
1) Dec 14



2) Dec 30



3) Dec 27



Background flow:

Wave propagation:

Possible indicators for nowcasting/forecasting of turbulence:

- Waves propagate orthogonally to the background flow (showing either more shear or convective outflow), and gravity waves appear to push this into *critically unstable flow*
- Perhaps turbulence is also worsened by interfering waves or wave heterogeneity

Weather and Forecasting, 2018

Observations of gravity waves with high-pass filtering in the new generation of geostationary imagers and their relation to aircraft turbulence

Anthony Wimmers, Sarah Griffin, Jordan Gerth, Scott Bachmeier, *and* Scott Lindstrom
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin – Madison, Madison, Wisconsin

https://doi.org/10.1175/WAF-D-17-0080.1
Published Online: 30 October 2017

Recent developments

- Met with NWS aviation forecasters, esp. the Honolulu office, to share ways to identify these signatures for turbulence nowcasting
- Expanded the real-time product to apply this to GOES-16, SEVIRI, soon GOES-17*
- Add the product to SSEC RealEarth application (re.ssec.wisc.edu)

* The real-time product has restricted access for online viewing. For (possible) access and updates, email: wimmers@ssec.wisc.edu.

Next steps

- Add the product to AWIPS2 for NWS aviation forecasters
- Develop a probabilistic gravity-wave turbulence detection tool for rapid clear-air turbulence warning
    - We are exploring a Deep Learning model to identify sections of the gravity wave product that match independent turbulence observations.

Summary

- **New satellite imagery with improved spatio-temporal detail, coupled with better knowledge of turbulence signatures and advanced pattern recognition techniques, has resulted in a new products that identify where turbulence is likely**
- **Output from these methods can be used:**
  - Directly by aviation weather forecasters for tactical aircraft routing and hazard avoidance
  - As interest fields in turbulence nowcasting expert systems (DCIT, GTG-N?)
  - To understand NWP fields correlated with the satellite-observed signatures for improved process understanding and advanced prediction
- **We seek to determine the utility of these satellite-derived products for turbulence nowcasting.**
  - Datasets such as EDR that detail where turbulence is (and isn't) occurring are essential to quantify turbulence relationships
  - Real-time demonstrations in an operational forecast environment help developers better understand user requirements/expectations, resulting in more useful products
- **Collaborations on any topics/products described in this talk are welcomed**

Contact Us

Kristopher Bedka: kristopher.m.bedka@nasa.gov

Anthony Wimmers: wimmers@ssec.wisc.edu