Some Influences of Gravity Waves on Aviation Turbulence

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2016 SPARC Gravity Wave Symposium
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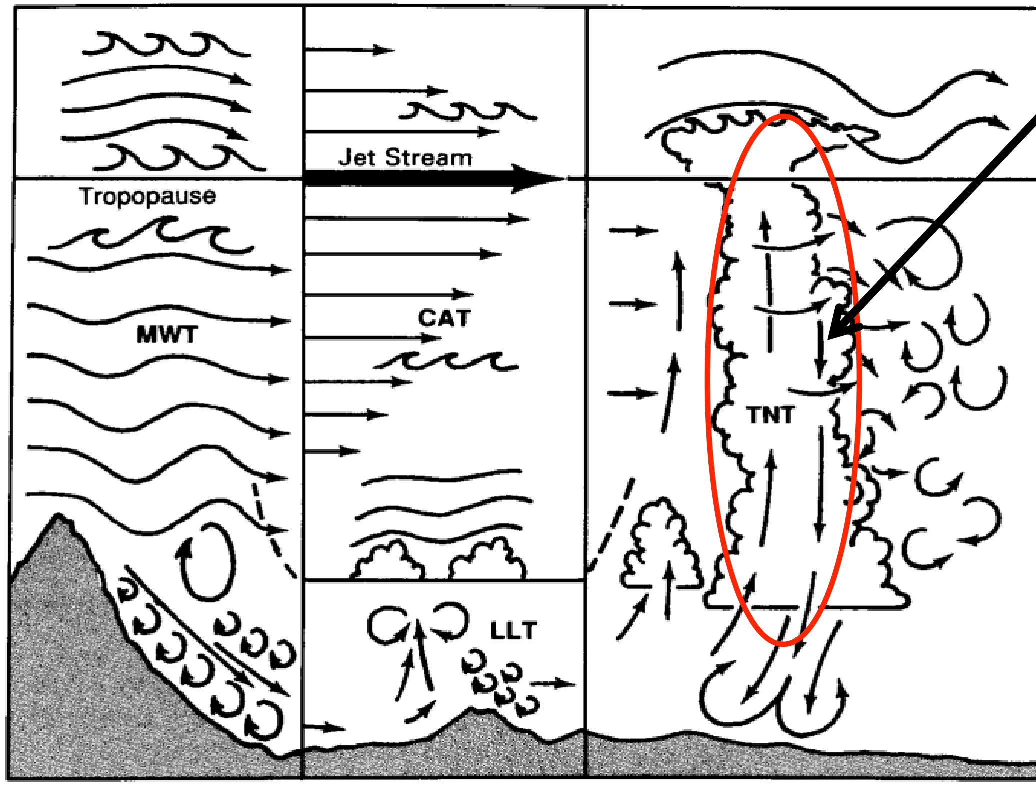
Background – known turbulence sources

Moist Convective Instability



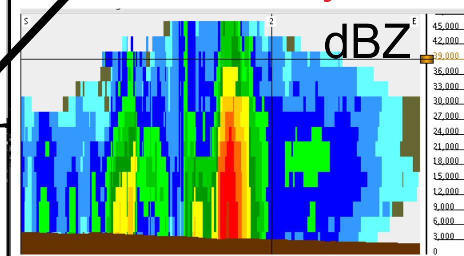
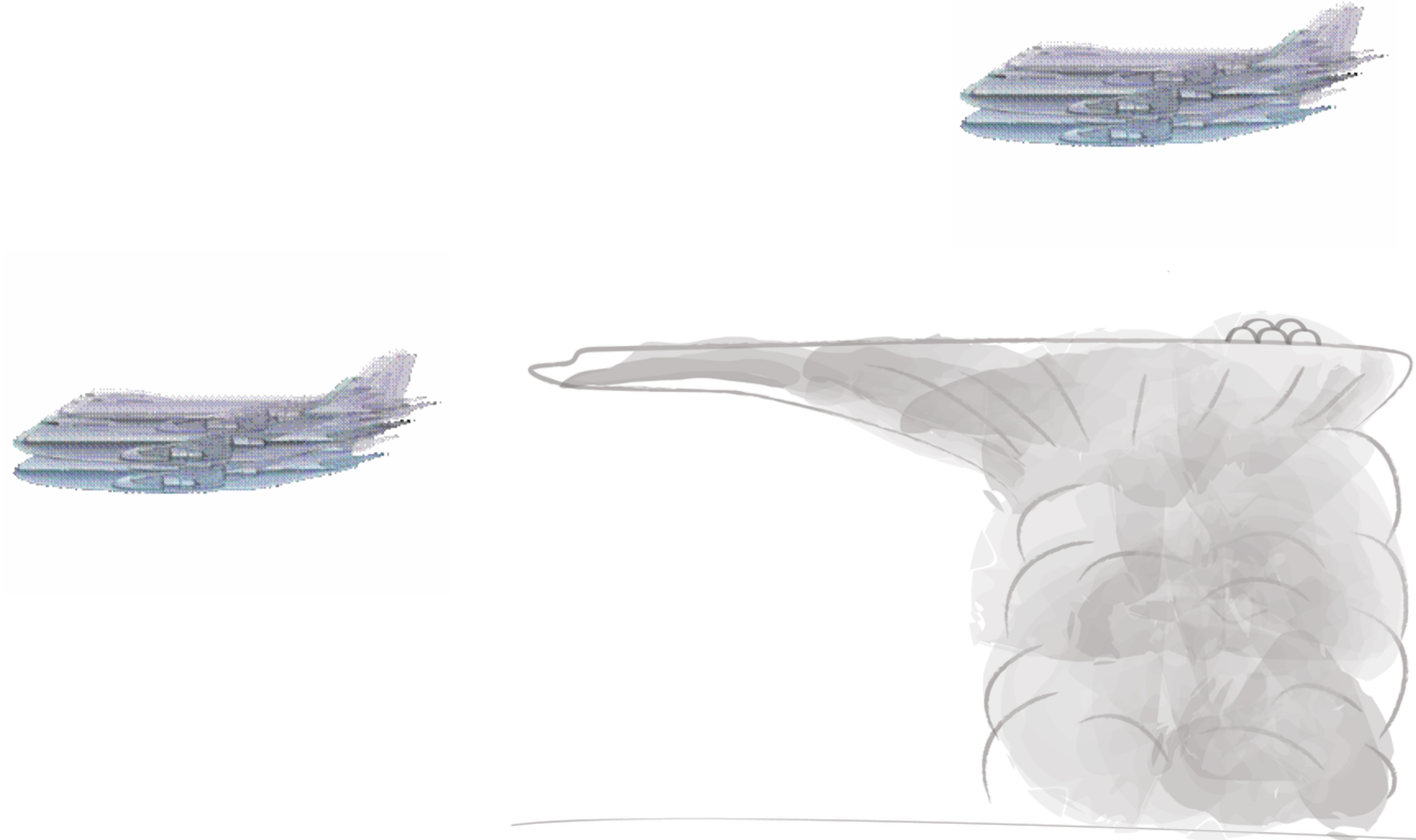


Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

Adapted From: P. Lester, “Turbulence – A new perspective for pilots,” Jeppesen, 1994

Convection Induced Turbulence (CIT) Occurring Outside of Storms



Outline

High-resolution simulations used to explore mechanisms directly responsible for the onset of turbulence near commercial aviation cruising altitudes (9-12 km MSL)

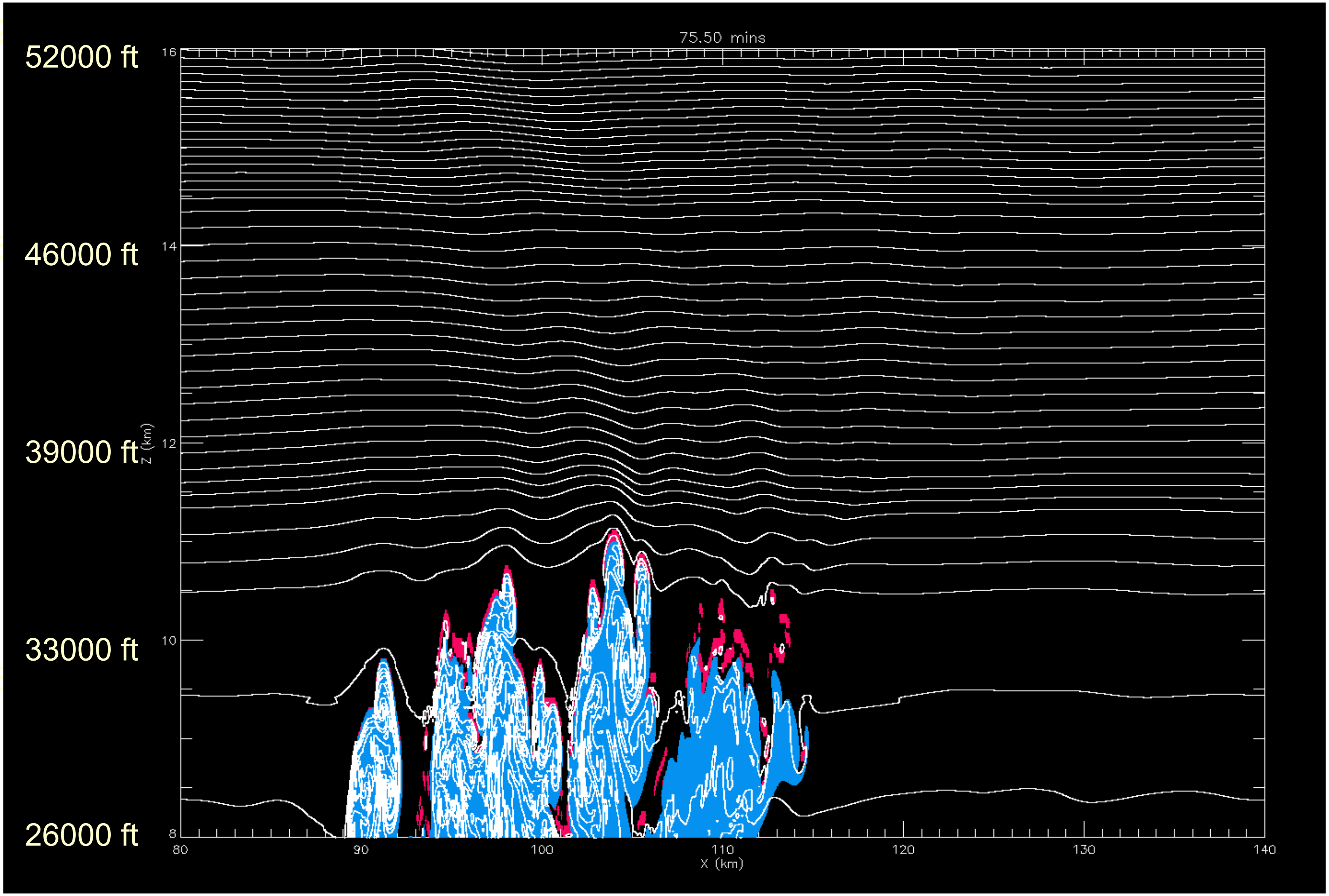
- Different roles of gravity waves induced by deep convection

1. Wave-breaking above deep convection (vertically propagating waves reaching a critical level)

2. Horizontally propagating gravity waves induced by deep convection

3. Mesoscale gravity waves leading to regions of shallow convective instability

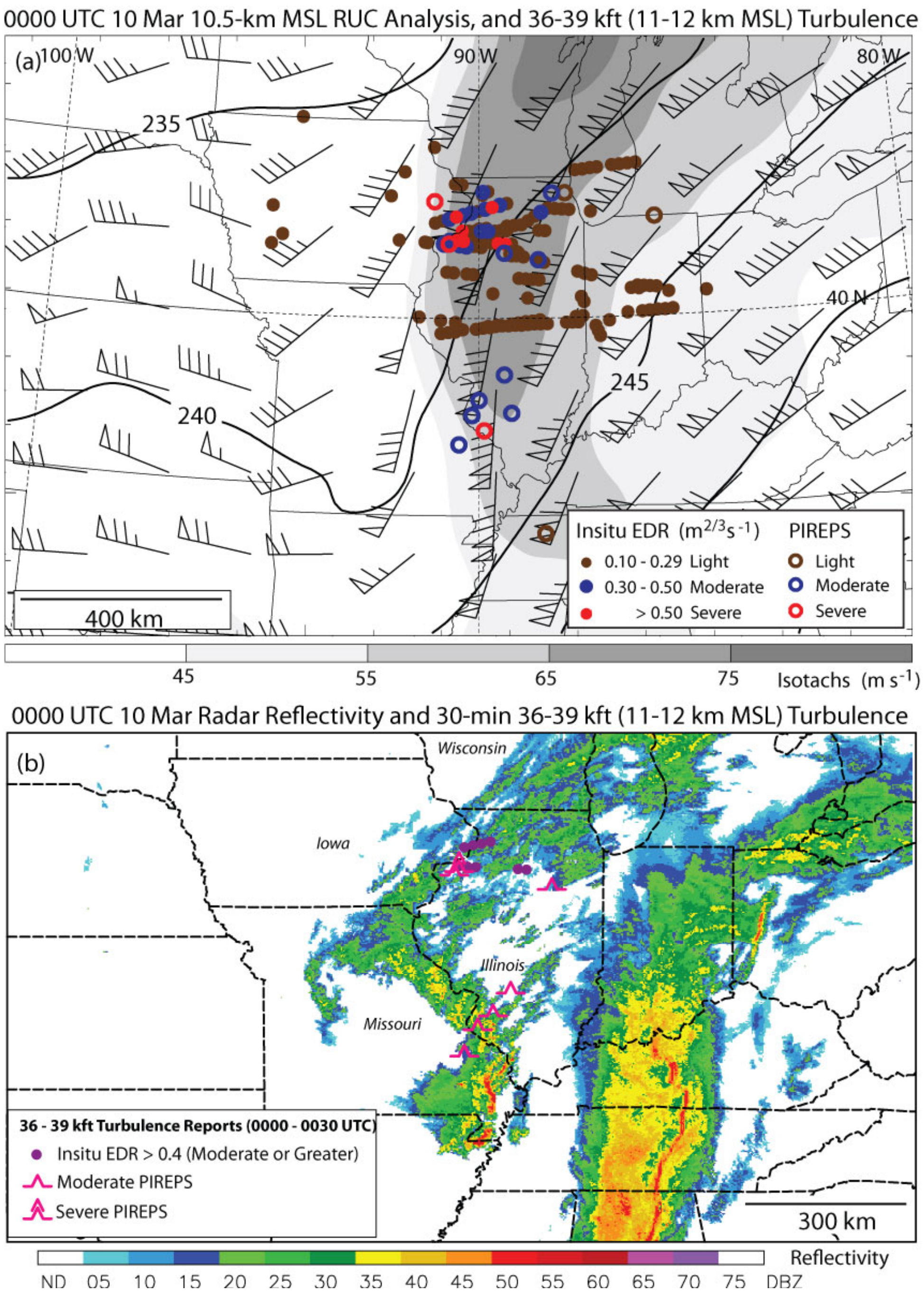
Numerical Simulation: Breaking Internal Gravity Waves and CIT



2-D simulation showing cloud, gravity waves, and turbulence (courtesy of Todd Lane)

Observed case (10 Jul 1997) where severe turbulence is encountered near tropopause at Dickinson, ND with 22 injuries

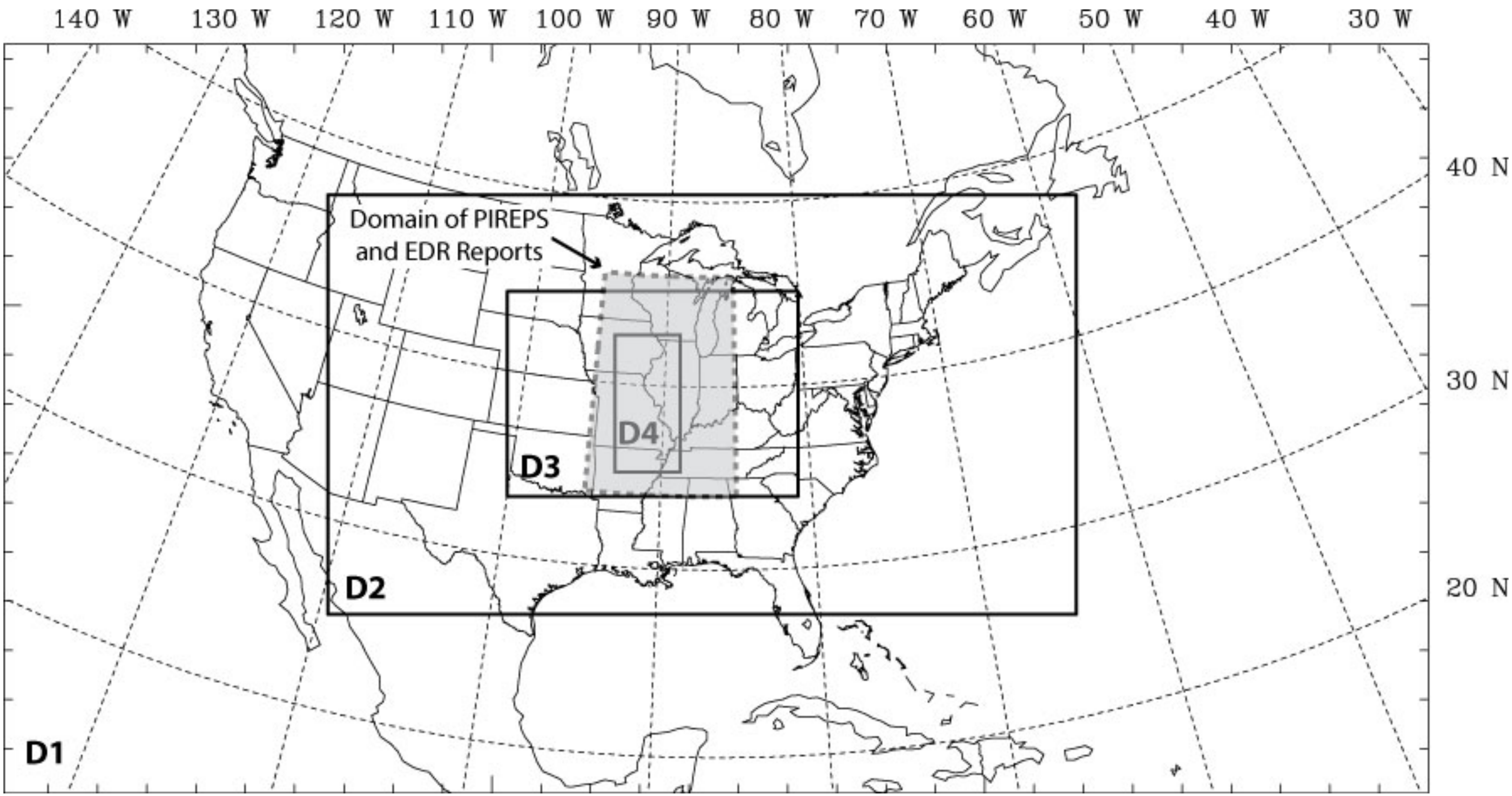
Lane, Sharman, Clark, and Hsu (J. Atmos. Sci., 2003)



Relationships Among Upper Winds Precipitation and Turbulence in 9-10 March 2006 Mississippi Valley Outbreak

Trier, Sharman, and Lane
(Mon. Wea. Rev., 2012)

Grid Set-Up for Simulations 9-10 March 2006 Turbulence Outbreak



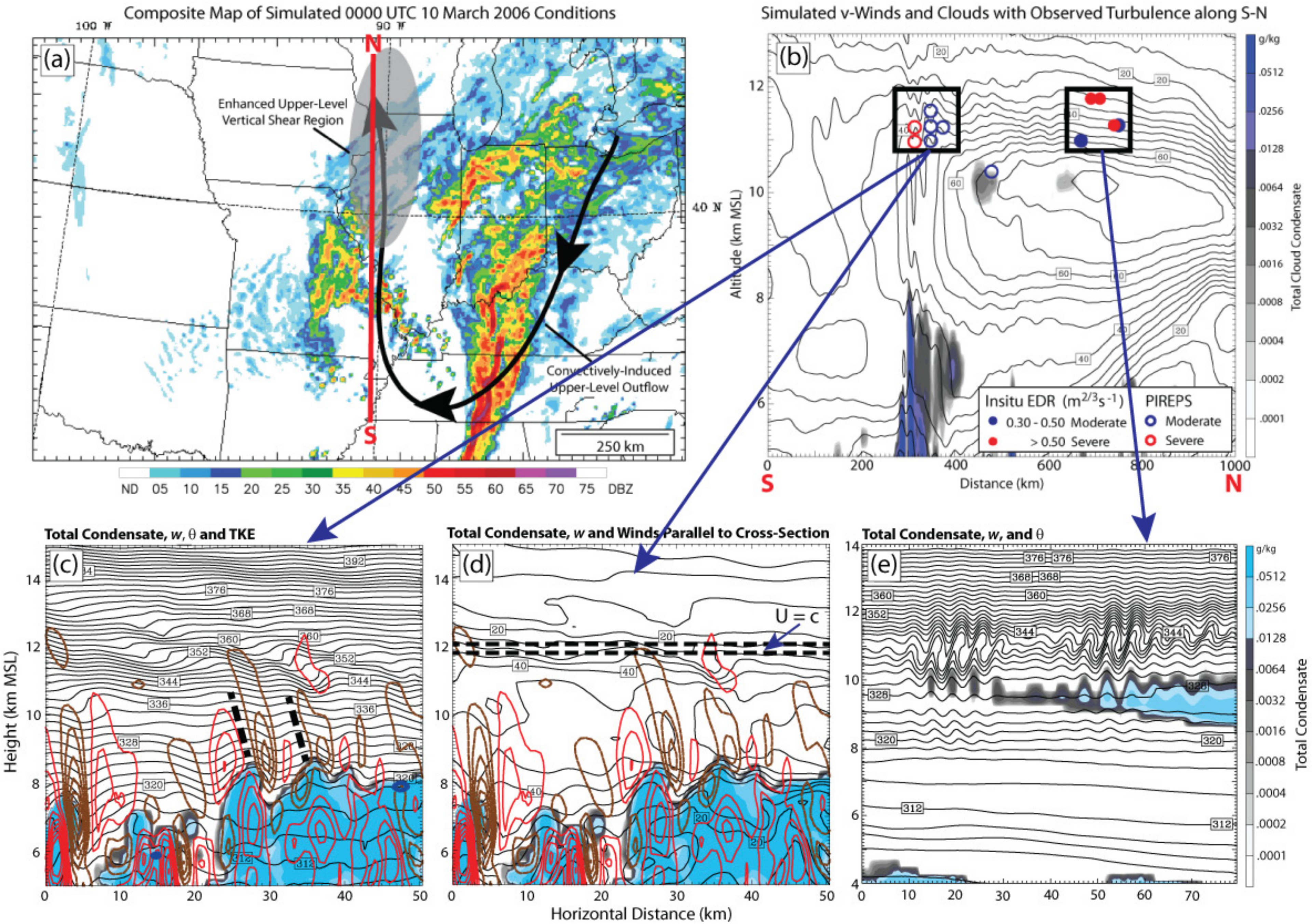
83 Vertical Levels

D1: Δ x,y = 30 km

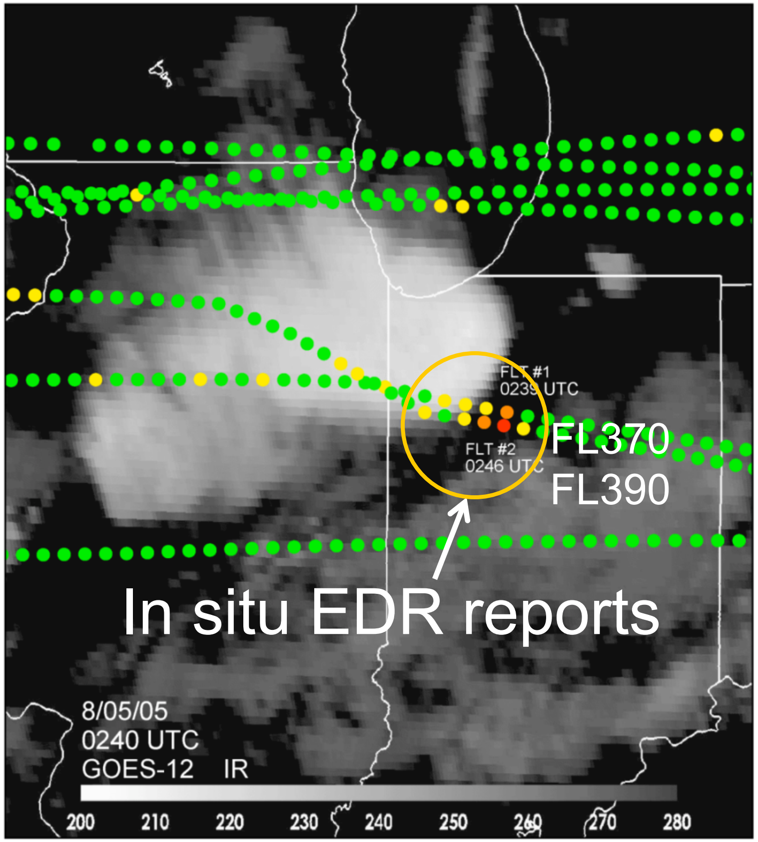
D2: Δ x,y = 10 km

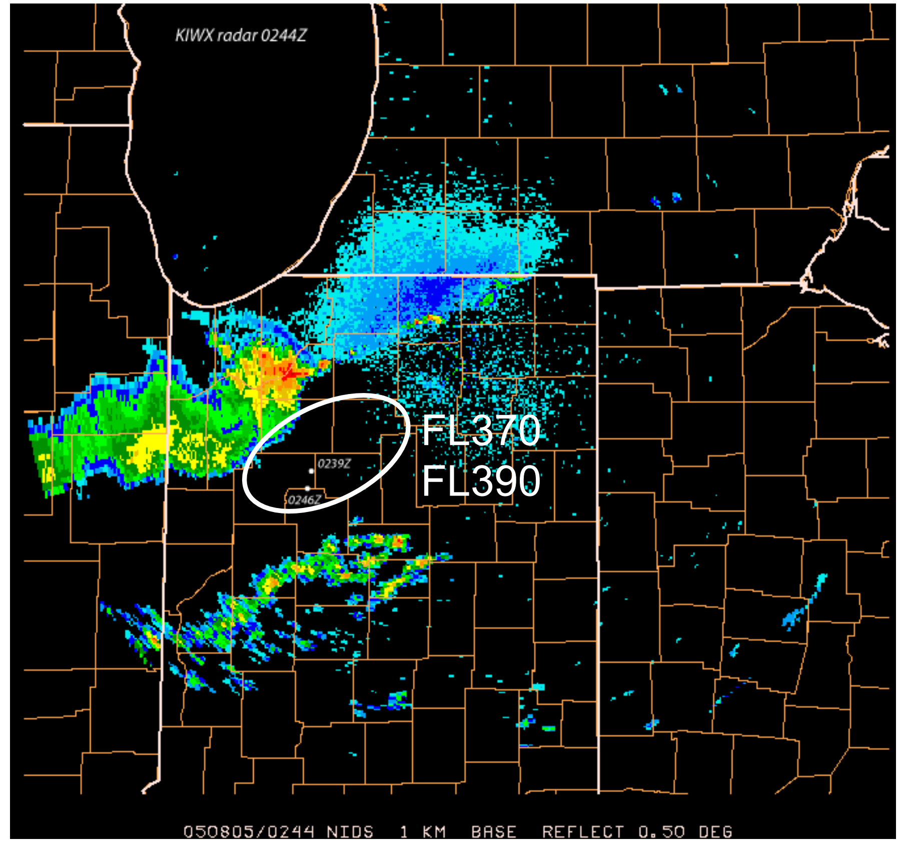
D3: Δ x,y = 3.3 km

D4: Δ x,y = 667 m


Composite Map of Simulated 0000 UTC 10 March 2006 Conditions
(a)
100 W
90 W
40 N
N
S
Enhanced Upper-Level Vertical Shear Region
Convectively-Induced Upper-Level Outflow
250 km
ND 05 10 15 20 25 30 35 40 45 50 55 60 65 70 75 DBZ
Simulated v-Winds and Clouds with Observed Turbulence along S-N
(b)
Altitude (km MSL)
Distance (km)
S
N
Total Cloud Condensate
g/kg
Insitu EDR (m2/3s-1)
0.30 - 0.50 Moderate
> 0.50 Severe
PIREPS
Moderate
Severe
Total Condensate, w, θ and TKE
(c)
Height (km MSL)
Total Condensate, w and Winds Parallel to Cross-Section
(d)
U = c
Horizontal Distance (km)
Total Condensate, w, and θ
(e)
Total Condensate
g/kg

Near-cloud turbulence associated with organized convection* (~0240Z 5 Aug 2005)





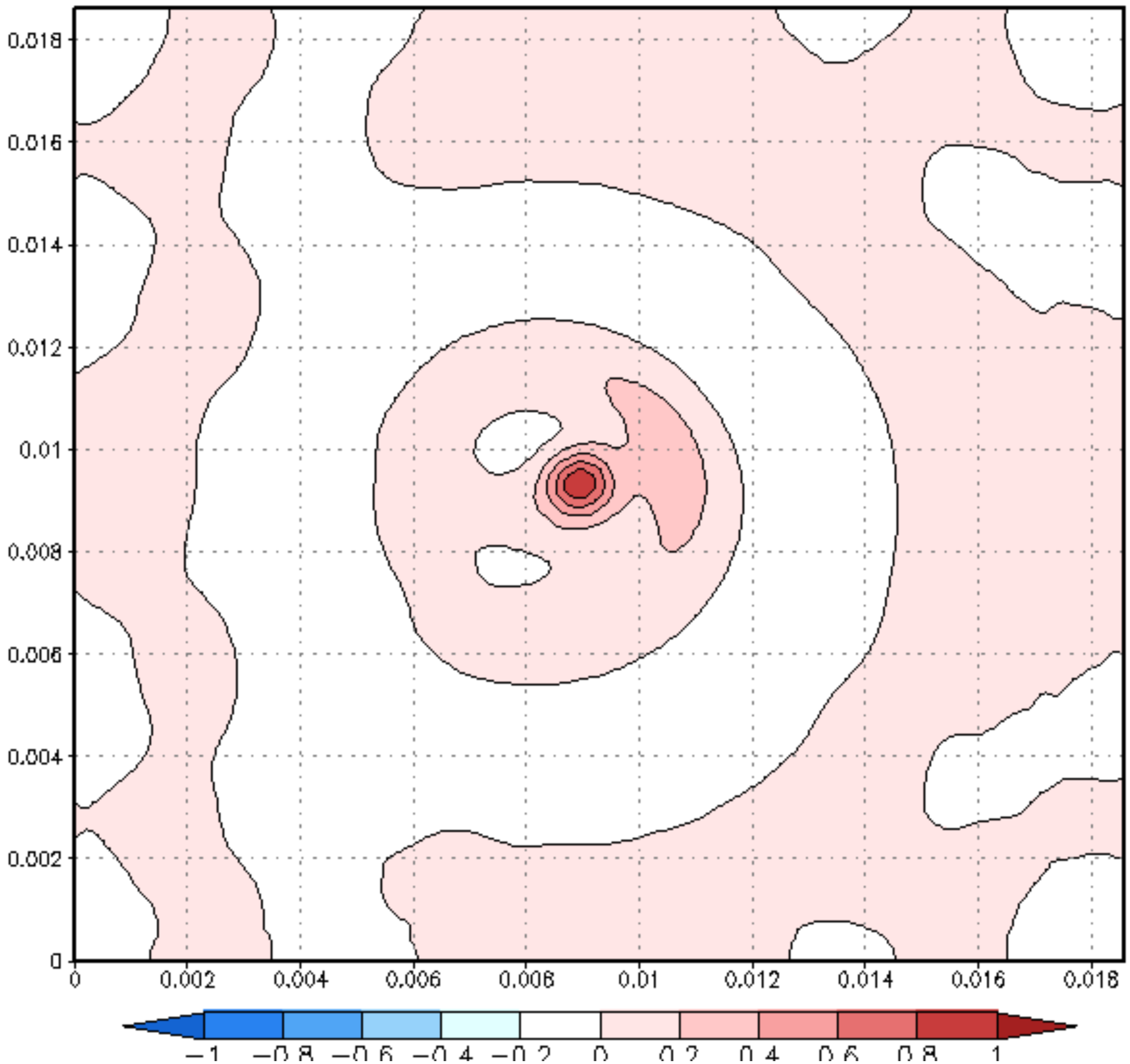
Turbulence intensities from in situ EDR:
Green = Smooth (EDR < 0.1)
Yellow = Light (0.1≤ EDR < 0.3)
Orange = Moderate (0.3 ≤ EDR < 0.5)
Red = Severe (EDR ≥ 0.5)

Reference: Lane et al. (2012; BAMS)

•EDR = $\varepsilon^{1/3}$ (Cornman et al. 1995, *J. Aircraft*)

•ε = Energy dissipation rate at the smallest scales (units of de/dt: m^2/s^3)

Simulated Horizontally Propagating Gravity Waves



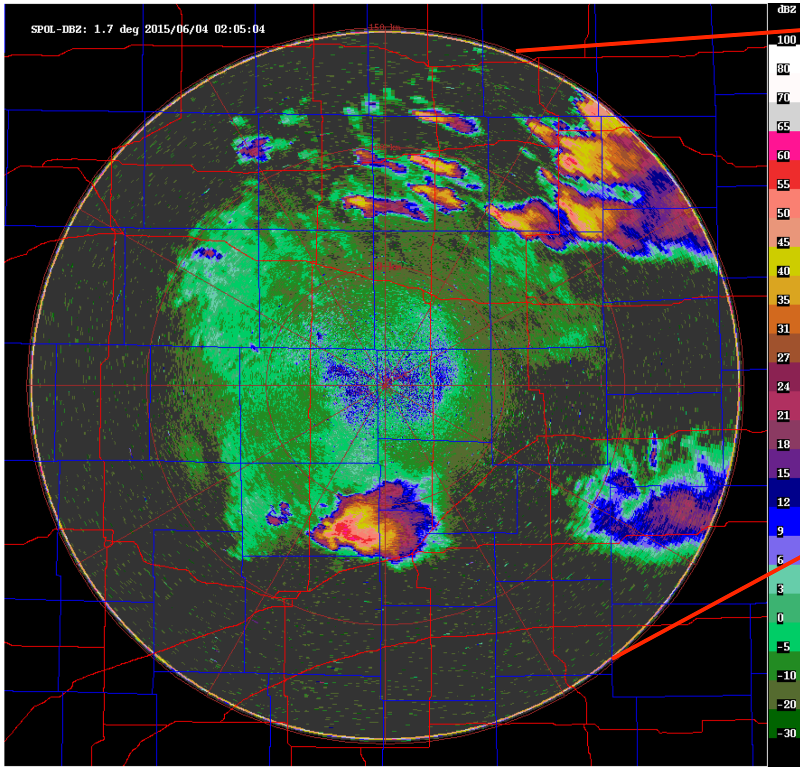
- WRFV212
- 94 km x 94 km x 30 km deep domain
- Δx = Δy = 500 m; Δz ~ 250 m
- Warm rain microphysics; rain off
- No subgrid mixing; damping above 22 km
- Sounding from ILX at 00Z, just ahead of cold front

ARWRF simulation using single sounding initialization – animation of w at z=12 km*

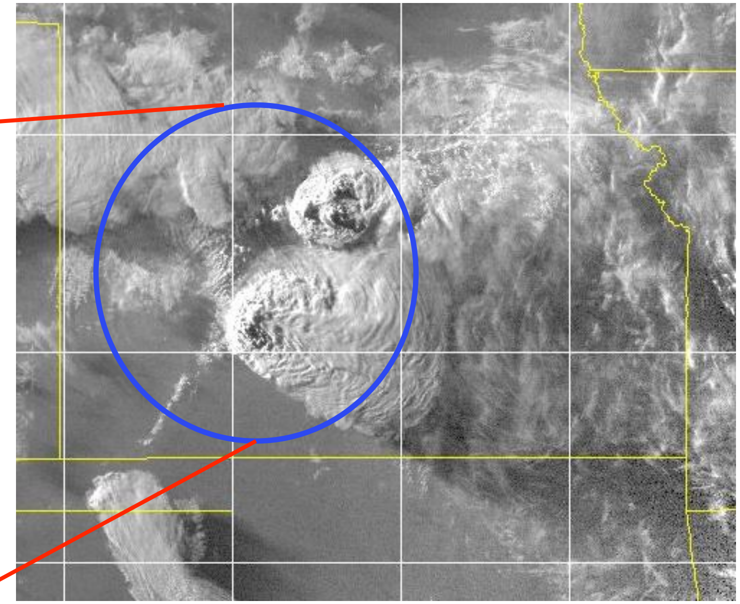
*Courtesy of Prof. Rob Fovell

Radar and Satellite Observations from PECAN

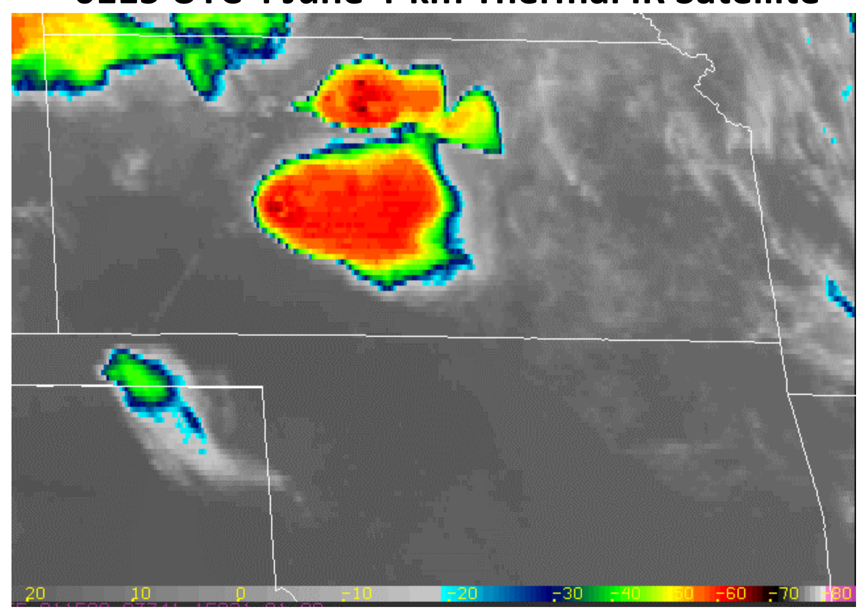
0205 UTC 4 June 2015 S-POL Radar Reflectivity



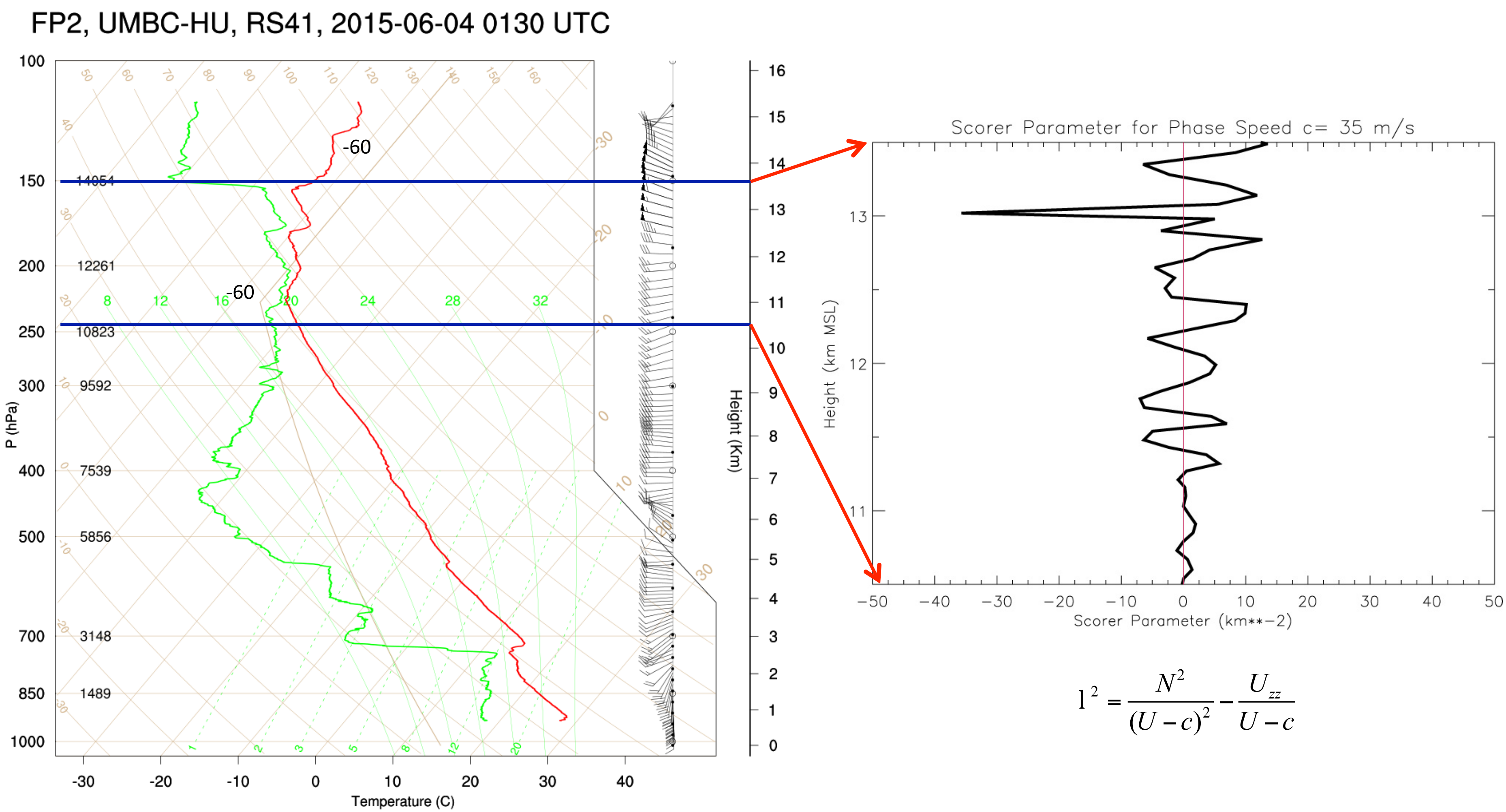
0115 UTC 4 June 1-km Visible Satellite



0115 UTC 4 June 4-km Thermal IR Satellite

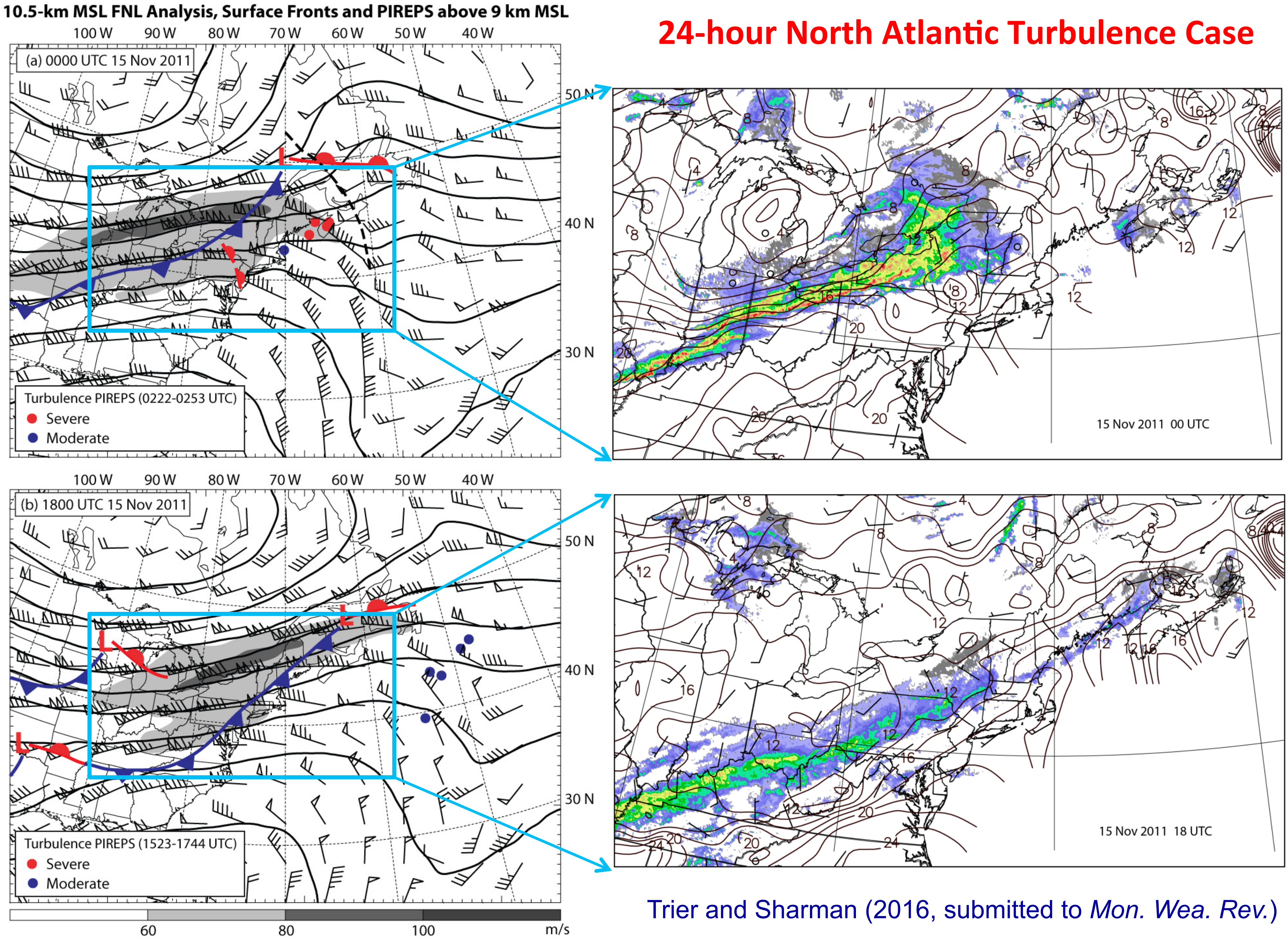


Environment for Horizontally-Propagating Gravity Waves During PECAN

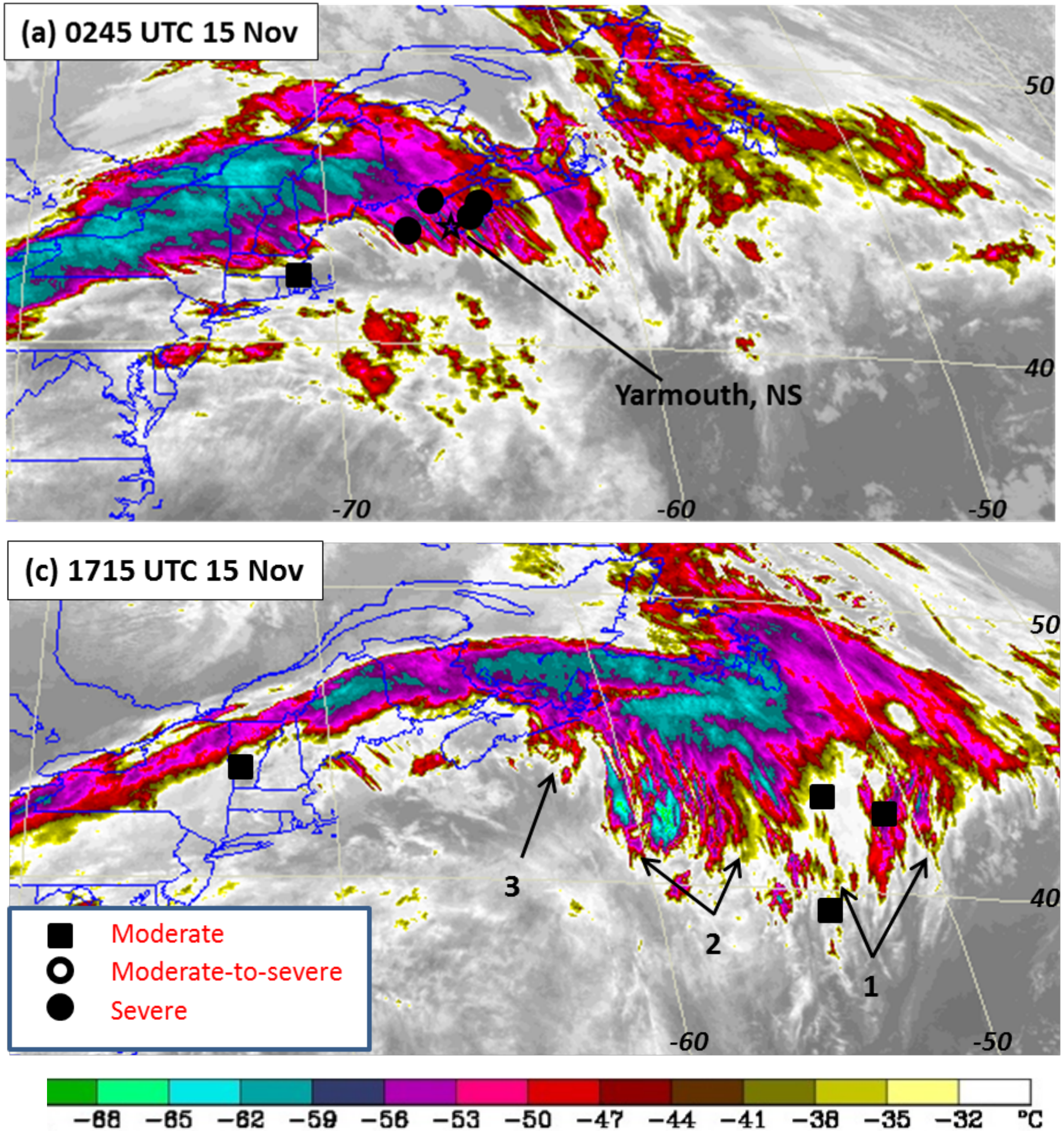


$$l^2 = \frac{N^2}{(U-c)^2} - \frac{U_{zz}}{U-c}$$

24-hour North Atlantic Turbulence Case



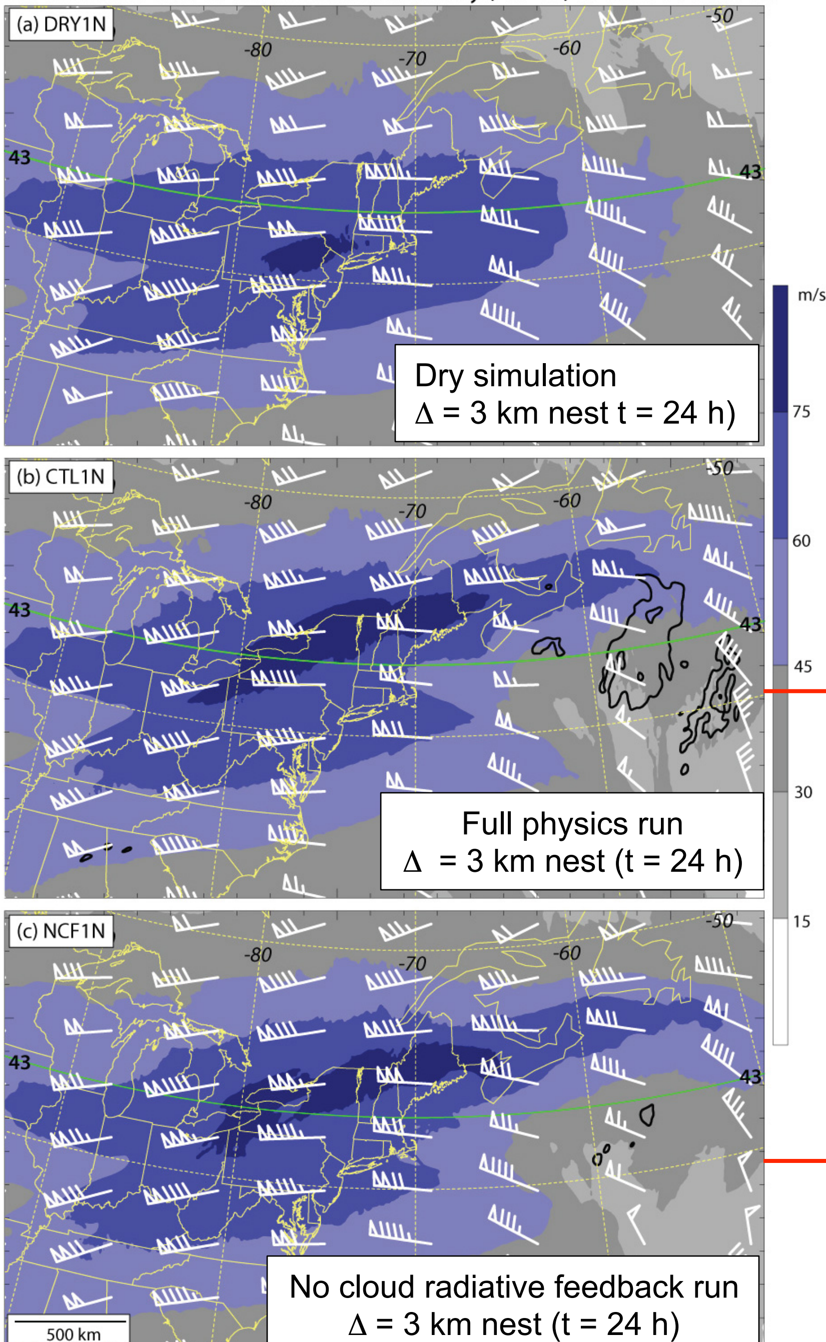
Trier and Sharman (2016, submitted to *Mon. Wea. Rev.*)



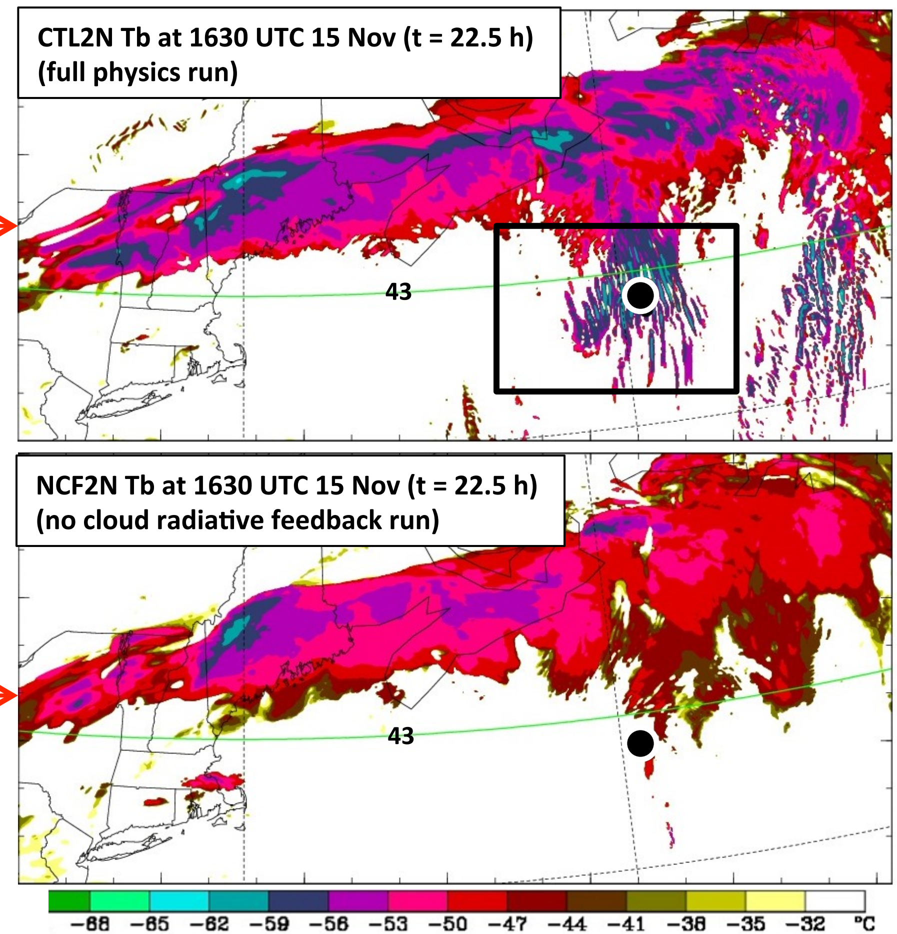
(a) 0245 UTC 15 Nov
Yarmouth, NS
50
40
-70
-60
-50
(c) 1715 UTC 15 Nov
50
40
-60
-50
1
2
3
Moderate
Moderate-to-severe
Severe
−68 −65 −62 −59 −56 −53 −50 −47 −44 −41 −38 −35 −32 °C

Simulations of N. Atlantic Turbulence Case

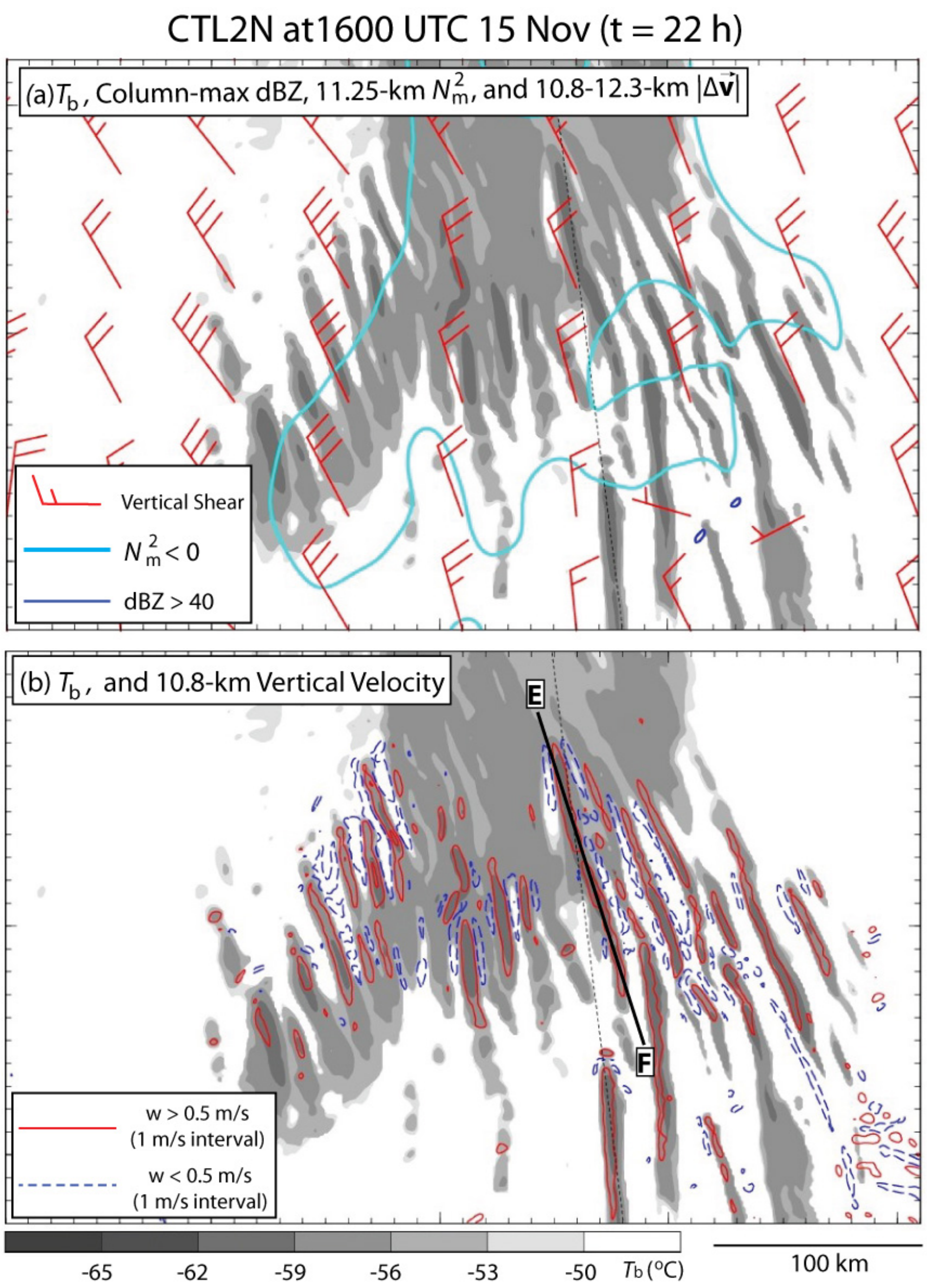
11.5 km Winds and 11-km Moist Static Stability ($N_m^2 < 0$) at 1800 UTC 15 Nov



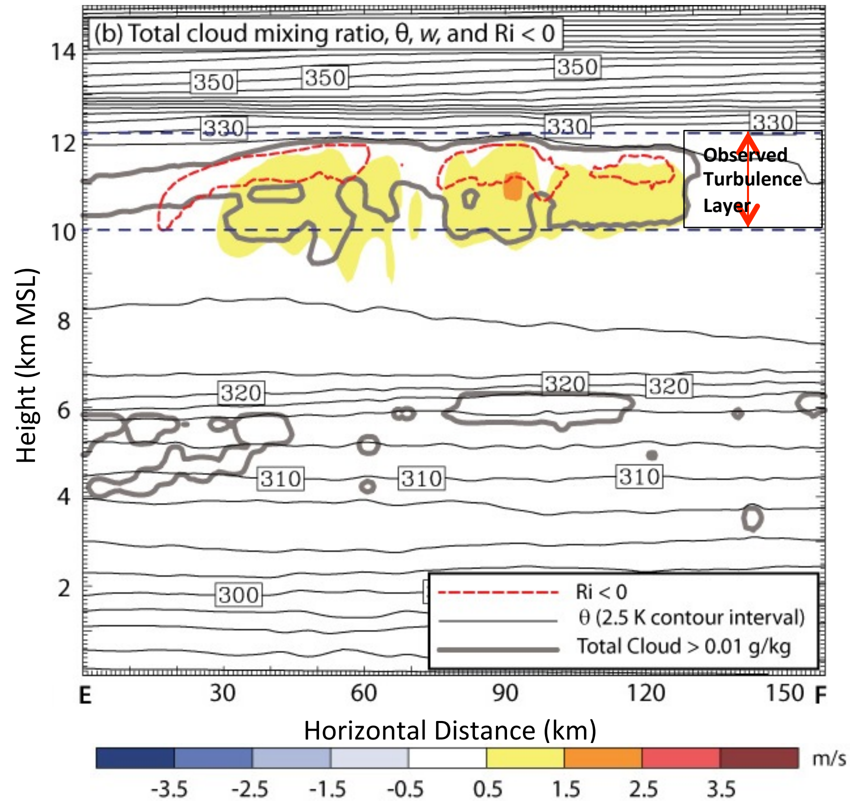
Δ x,y = 1 km, 83 vertical levels, Δ z = 230 m at z = 4-16 km MSL

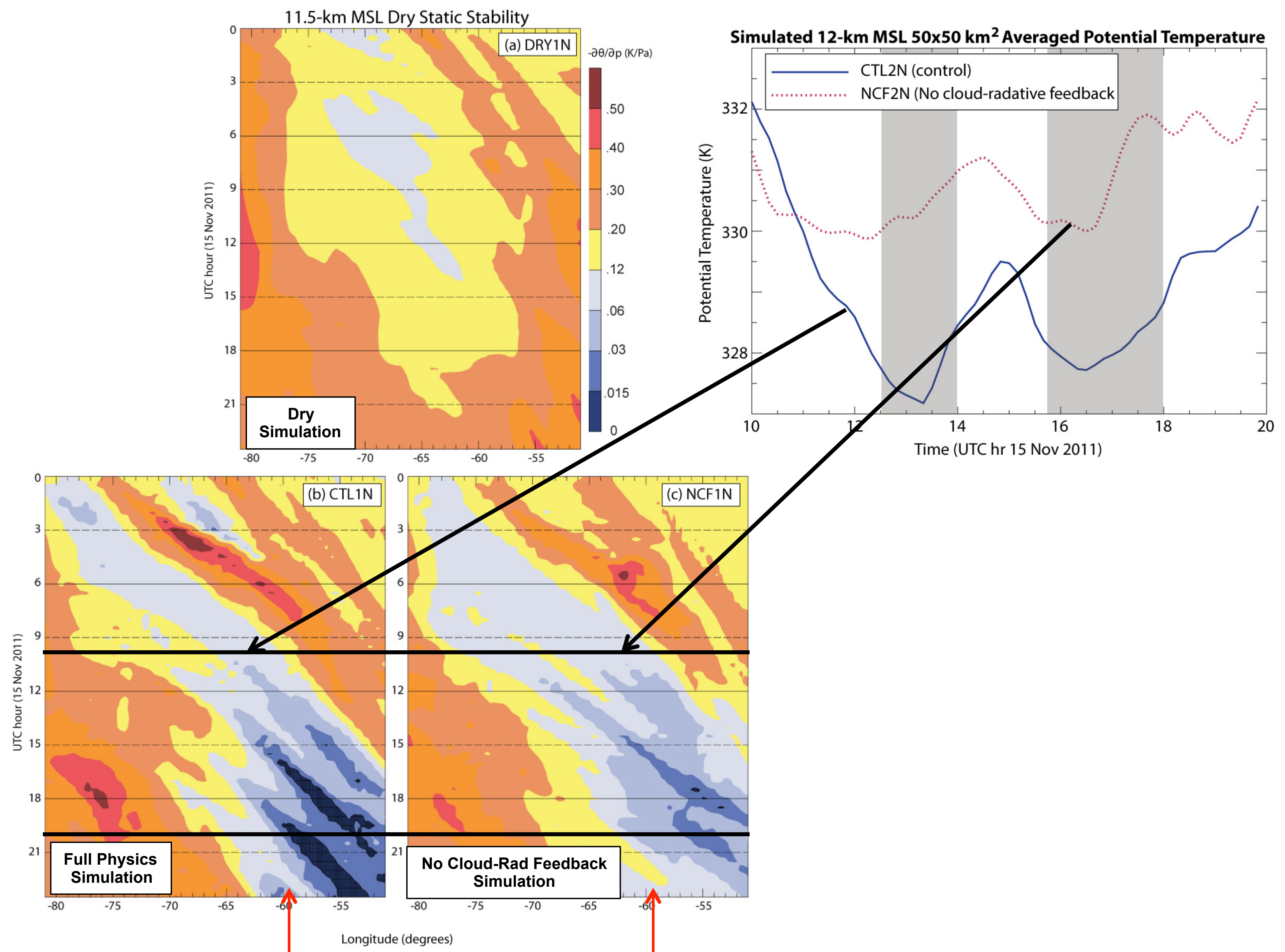


Full-Physics Run with Δ = 1 km Nest

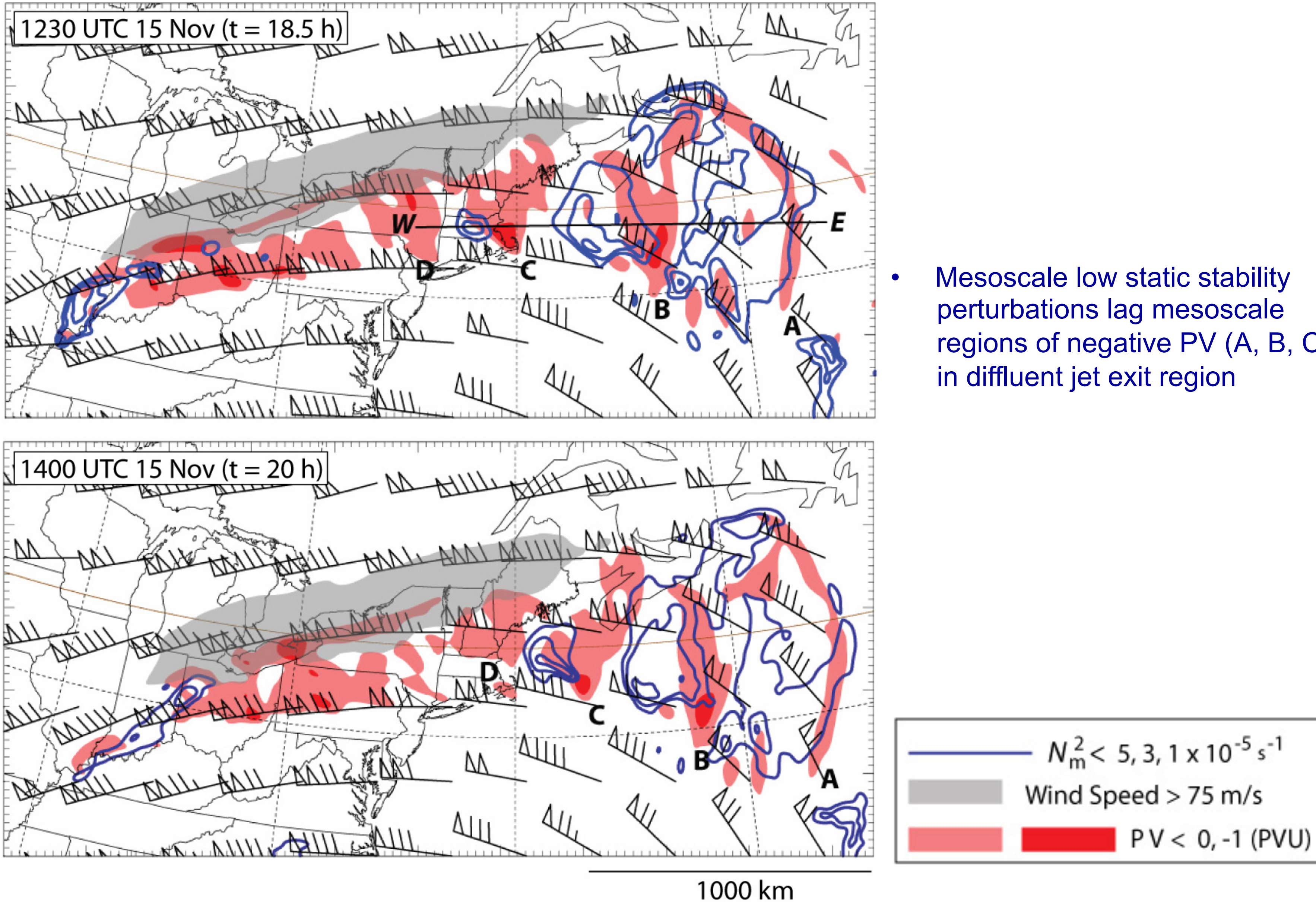


Along-Band Cross Section (EF) at 1600 UTC



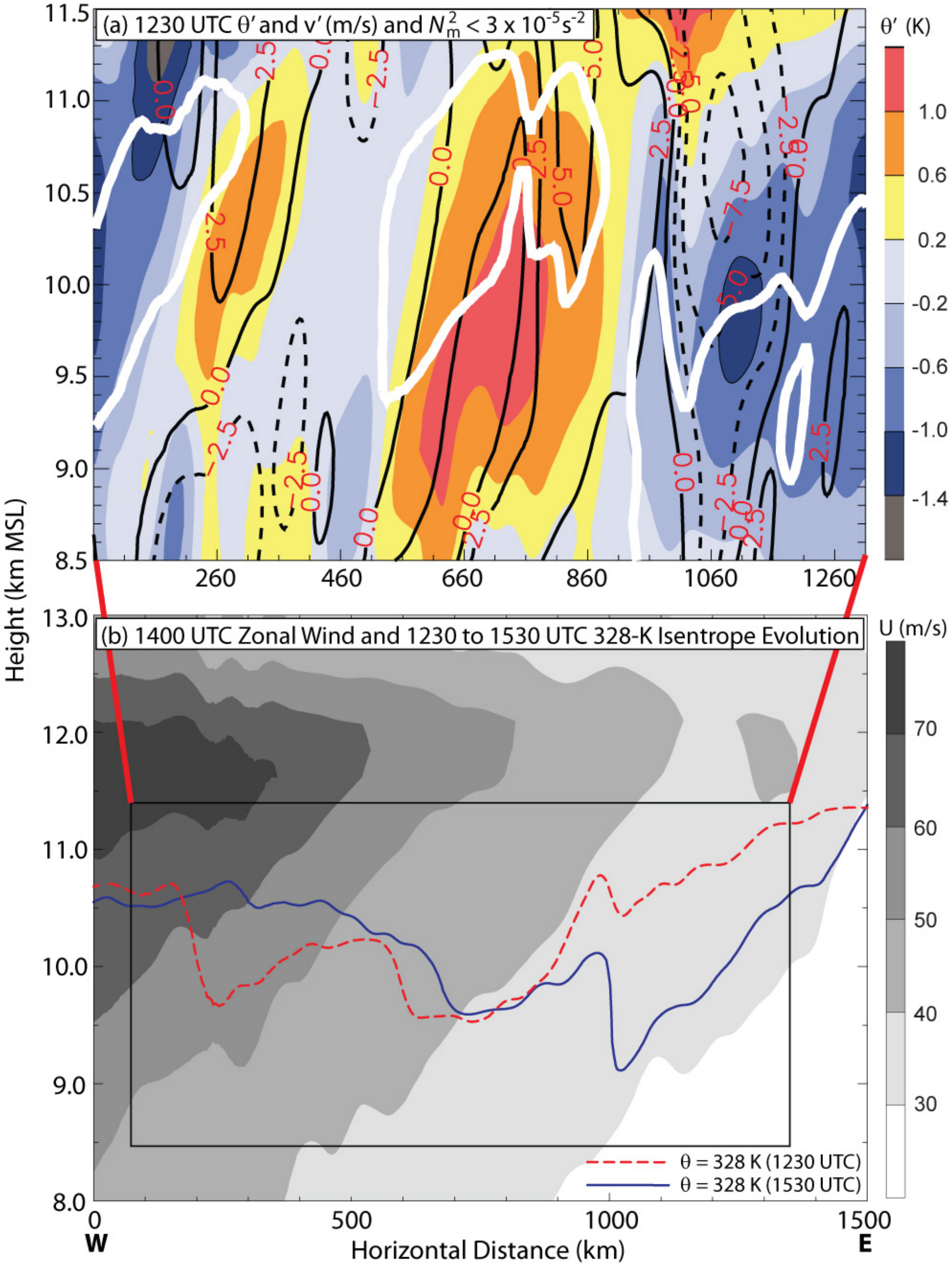

11.5-km MSL Dry Static Stability
(a) DRY1N
-∂θ/∂p (K/Pa)
.50
.40
.30
.20
.12
.06
.03
.015
0
UTC hour (15 Nov 2011)
Dry Simulation
(b) CTL1N
(c) NCF1N
Full Physics Simulation
No Cloud-Rad Feedback Simulation
Longitude (degrees)
Simulated 12-km MSL 50x50 km² Averaged Potential Temperature
CTL2N (control)
NCF2N (No cloud-radative feedback
Potential Temperature (K)
Time (UTC hr 15 Nov 2011)

11.25-km MSL Winds, PV and Static Stability in NCF1N (no cloud radiative feedbacks)

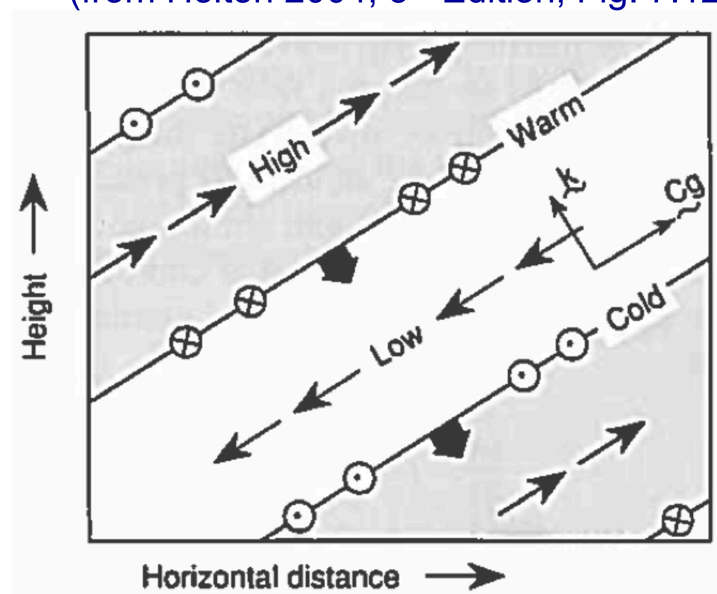


- Mesoscale low static stability perturbations lag mesoscale regions of negative PV (A, B, C) in diffluent jet exit region

Cross Section Through Negative PV and Low Static Stability Regions in No Cloud-Radiative Feedback Run

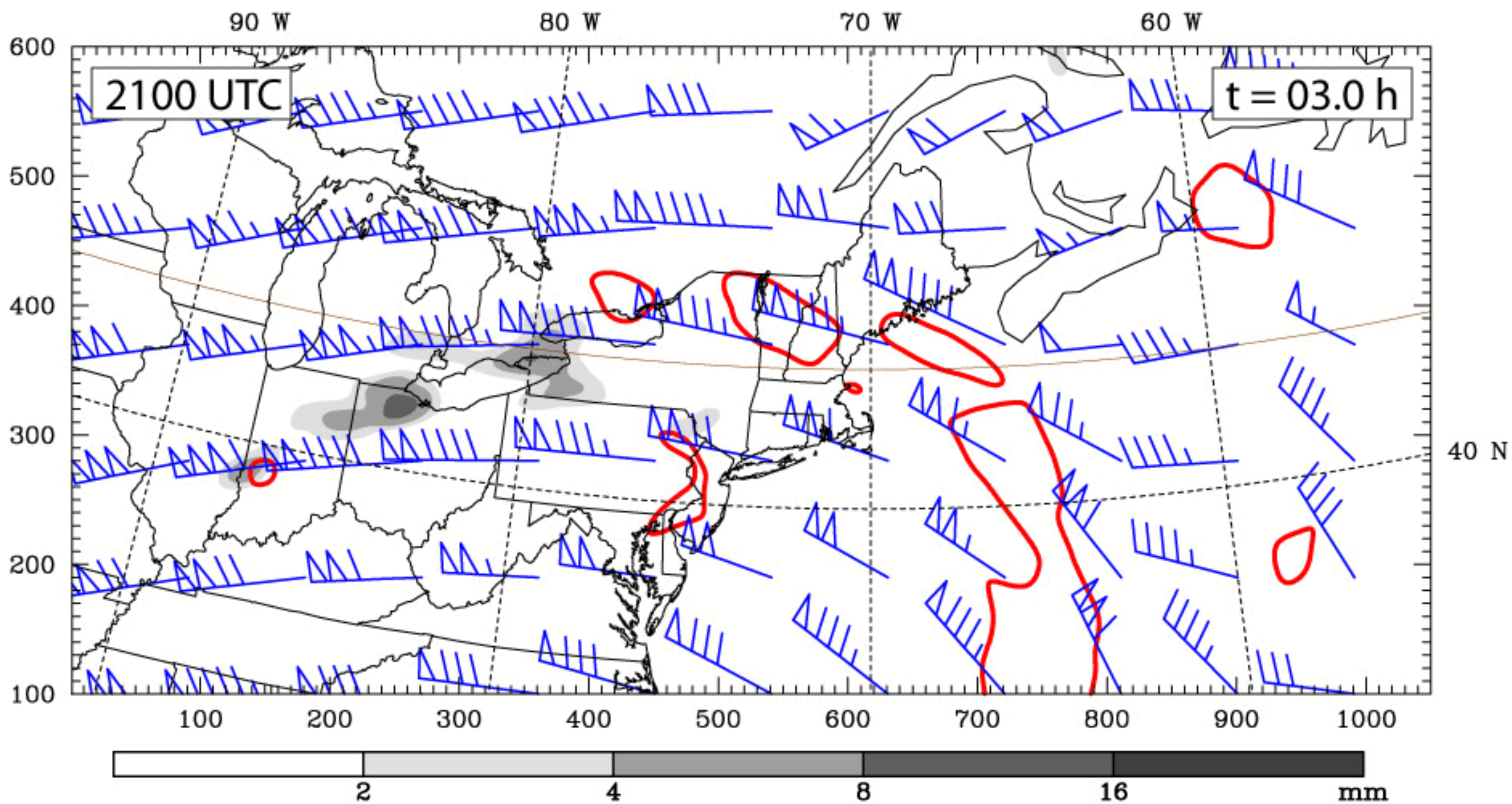


Schematic Diagram of Inertia-Gravity Wave (from Holton 2004, 3rd Edition, Fig. 7.12)



Southerly perturbations (v′ > 0) into page
Northerly perturbations (v′< 0) out of page

18-hr Loop of 11.25-km PV < 0 (1 PVU interval), Winds, and 1-h Rainfall for NCF1N (no cloud radiative feedback run)



In the absence of friction, $\frac{DP}{Dt} = \frac{1}{\rho}\left(\zeta_a \cdot \nabla \dot{\theta}\right)$, where P is Ertel's PV, ζ_a is 3-D absolute vector vorticity, $\dot{\theta}$ is the diabatic heating rate and ρ is density.

→ Negative PV (red contours) generated by vertical gradients of diabatic heating

Summary and Conclusions

- Convection-allowing simulations illustrate the crucial role of organized convection in several "clear-air turbulence" (CIT) cases spanning diverse meteorological settings

  - ARW-WRF provides accurate simulations of deep convection and illustrates plausible mechanisms directly responsible for the onset of UTLS turbulence outside of this convection

  - Large-scale upper-level anticyclonic outflows from deep convection key to modifying environment where widespread turbulence occurs

- Different types of gravity waves ranging from small-scale internal waves to mesoscale inertia-gravity waves may link convection to remote occurrences of turbulence

  - Directly through wave breaking near critical levels

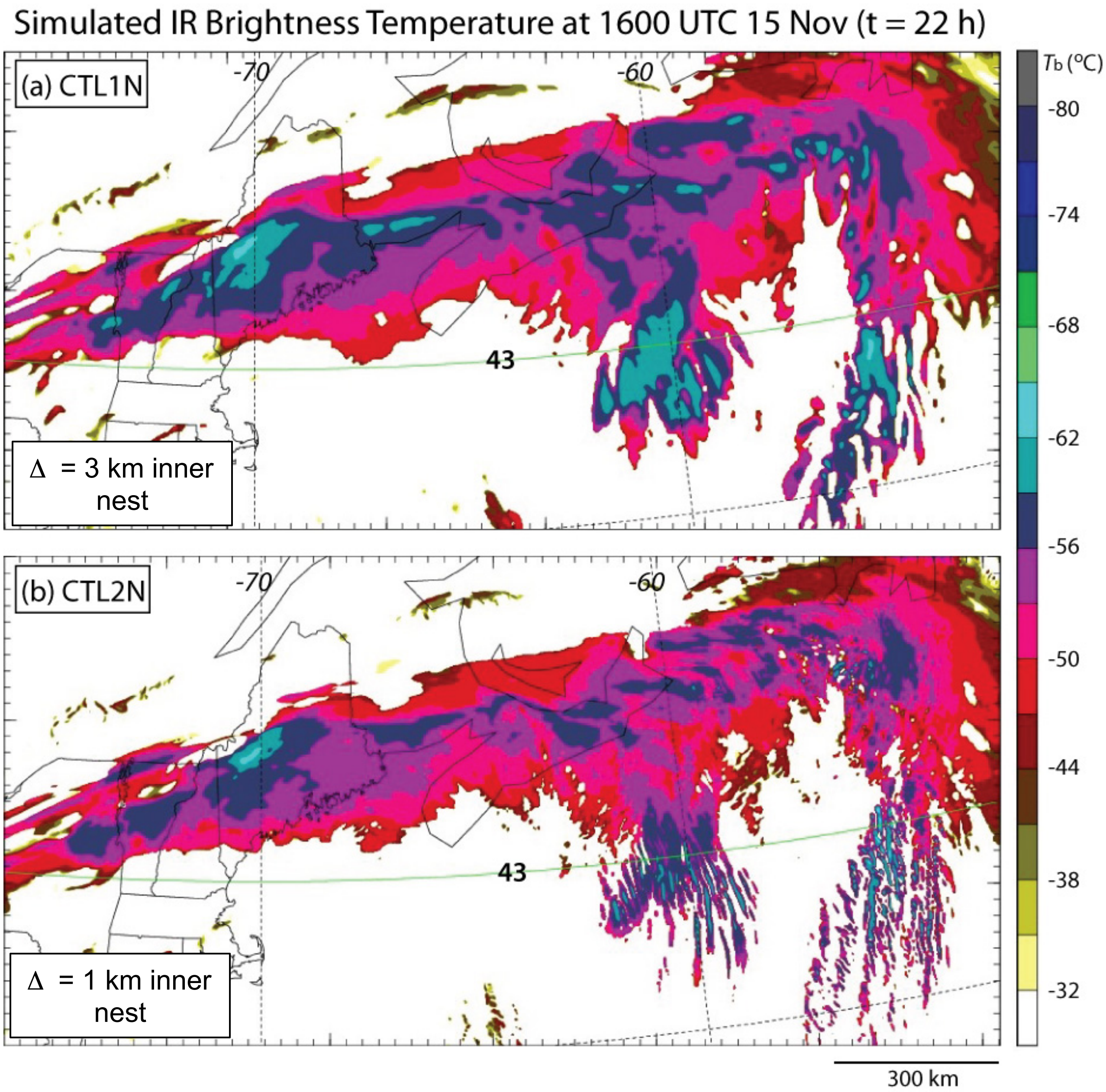
  - Indirectly by influencing environmental vertical shear and/or static stability

    Banded cirrus often linked to thermal-shear instability (like horizontal convective rolls in the PBL)

    Kelvin-Helmholtz instability (KHI)

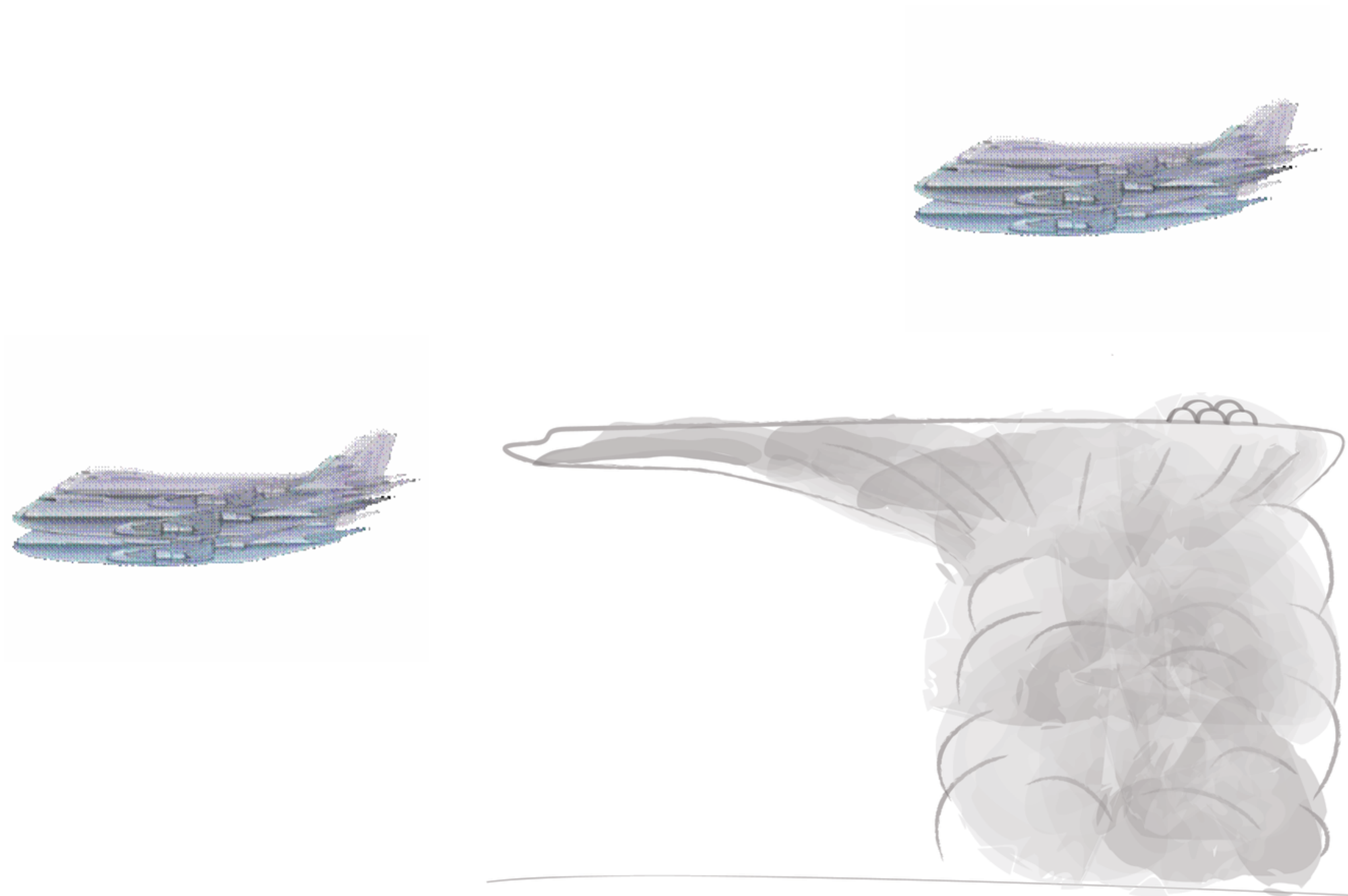
- Ability of NWP models to simulate mechanisms for onset of CIT outside of convection is sensitive to model resolution and situationally dependent

Sensitivity to Horizontal Grid Spacing in Full Physics Run



Simulation (top) at resolution of current experimental operational models (e.g., HRRR) give some indication of Day 2 cirrus banding

Also correct depiction of few hundreds of km spacing between band regions



Thank You!

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18-hr Loop of 11.25-km PV < 0 (1 PVU interval), Winds, and 1-h Rainfall for DRY1N (no moist physics run)