Simulations of Midlatitude and Tropical Out-of-Cloud Convectively-Induced Turbulence

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Motivation

- **Convectively-induced turbulence (CIT) can propagate more than 100 km (62 mi) away from convective sources**
  - Out of cloud
- **Forecasting of CIT is a challenge because convection must be accurately simulated**
  - CIT due to developing convection
  - Midlatitude continental convection versus tropical oceanic convection

Courtesy of A. Karboski

Research Questions

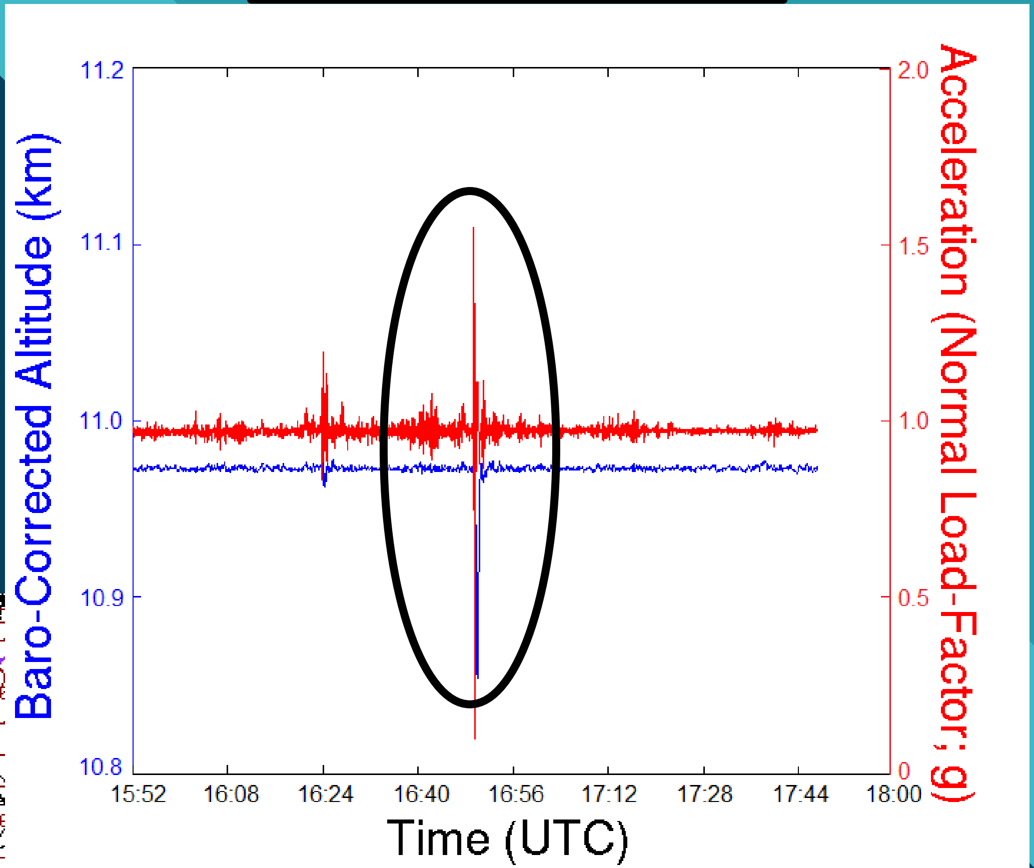
- **What is the role of developing convection in a severe turbulence case?**
  - Tropical oceanic convective simulation
- **How does resolution influence turbulence prediction?**
  - Midlatitude continental convective simulations

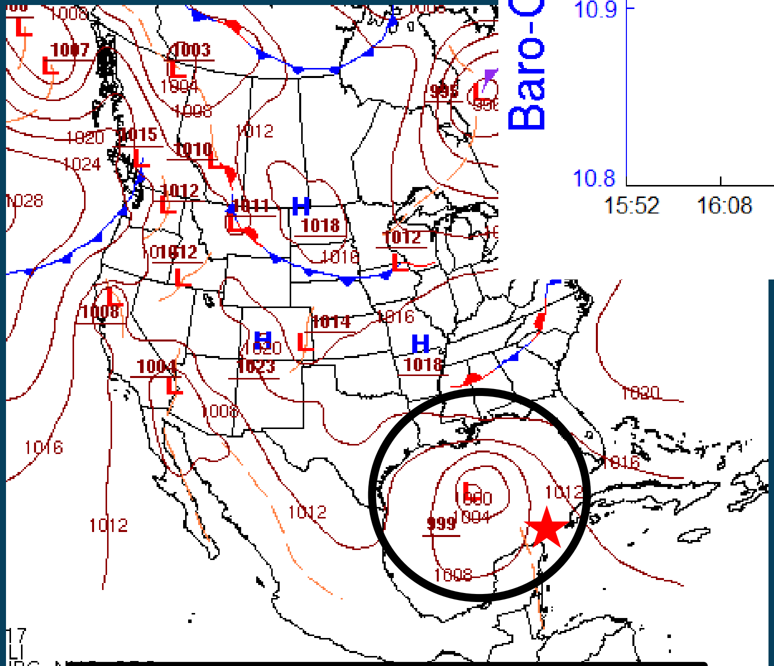
Courtesy of A. Karboski

What was the spatial coverage and intensity of turbulence near developing convection?

- **20 June, 2017**
  - Severe turbulence
    - 1651 UTC at 11 km (36 kft)
    - 80 nm NE of Cancun, MEX
    - 9 injuries
  - Active convection
    - Developing cells
  - Tropical oceanic region

In-Situ Observations





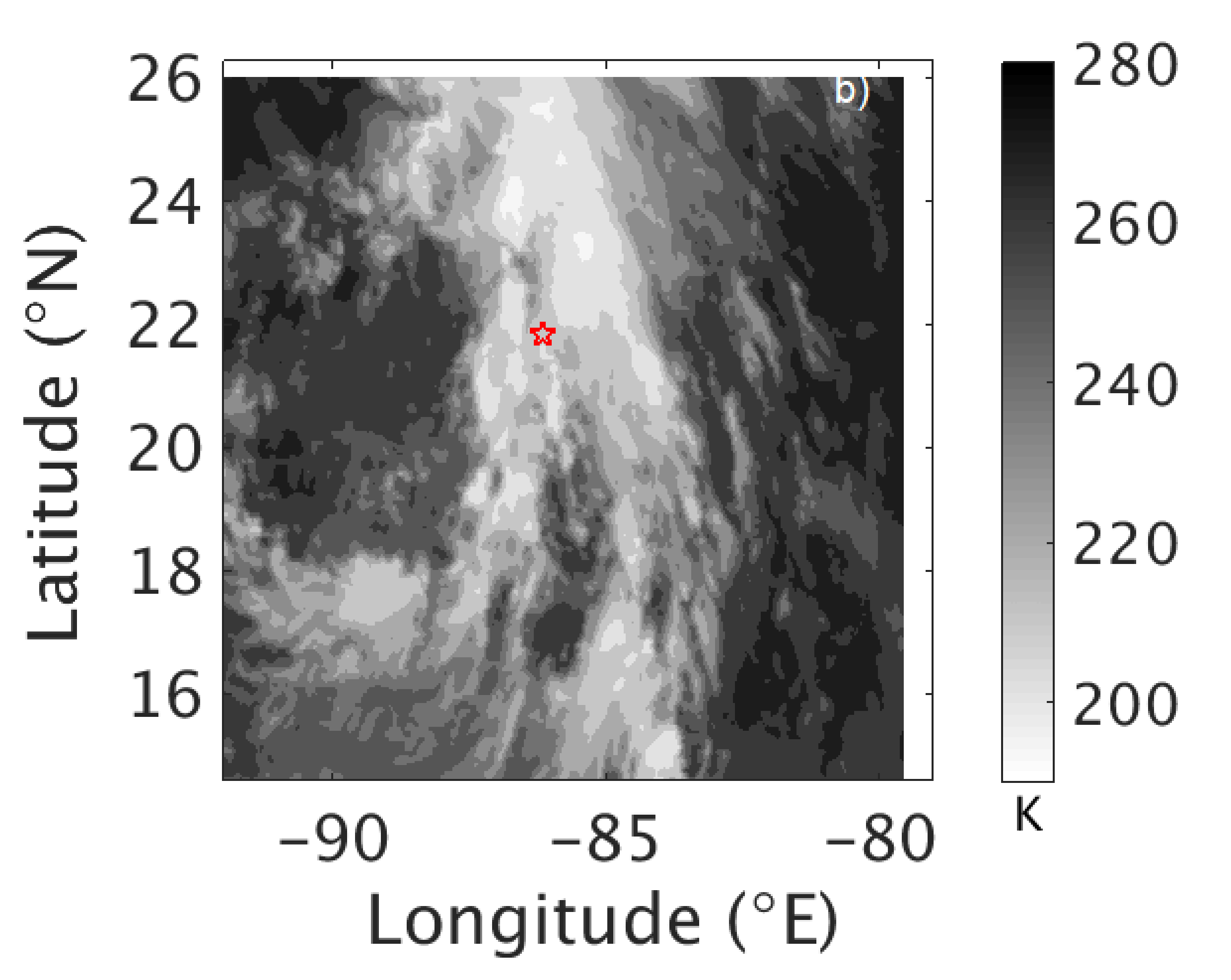
Surface Analysis 1500 UTC

Methodology

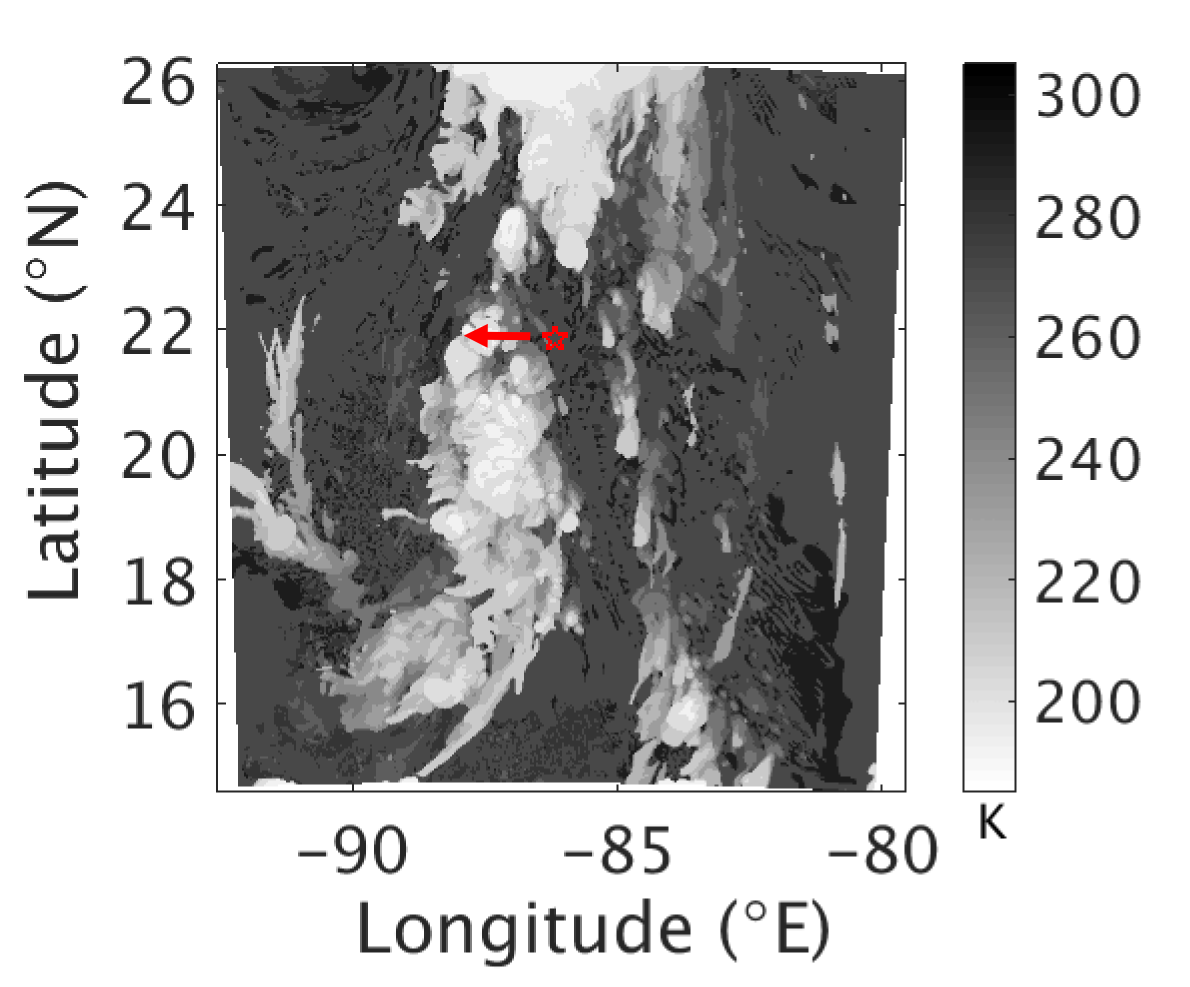
- **Weather Research and Forecast (WRF) v3.9**
  - 3 km horizontal grid spacing, 100 vertical levels
  - Initialized with ¼ degree GFS data
- **Turbulence diagnostics**
  - Richardson number (Ri)
    - Stability and shear
  - Model derived eddy dissipation rate ($\varepsilon^{1/3}$)
    - Turbulent kinetic energy
  - Second-order structure functions (SF)
    - u and v velocity components

Observations vs. Simulation

GOES-16 Cloud Top Temperatures

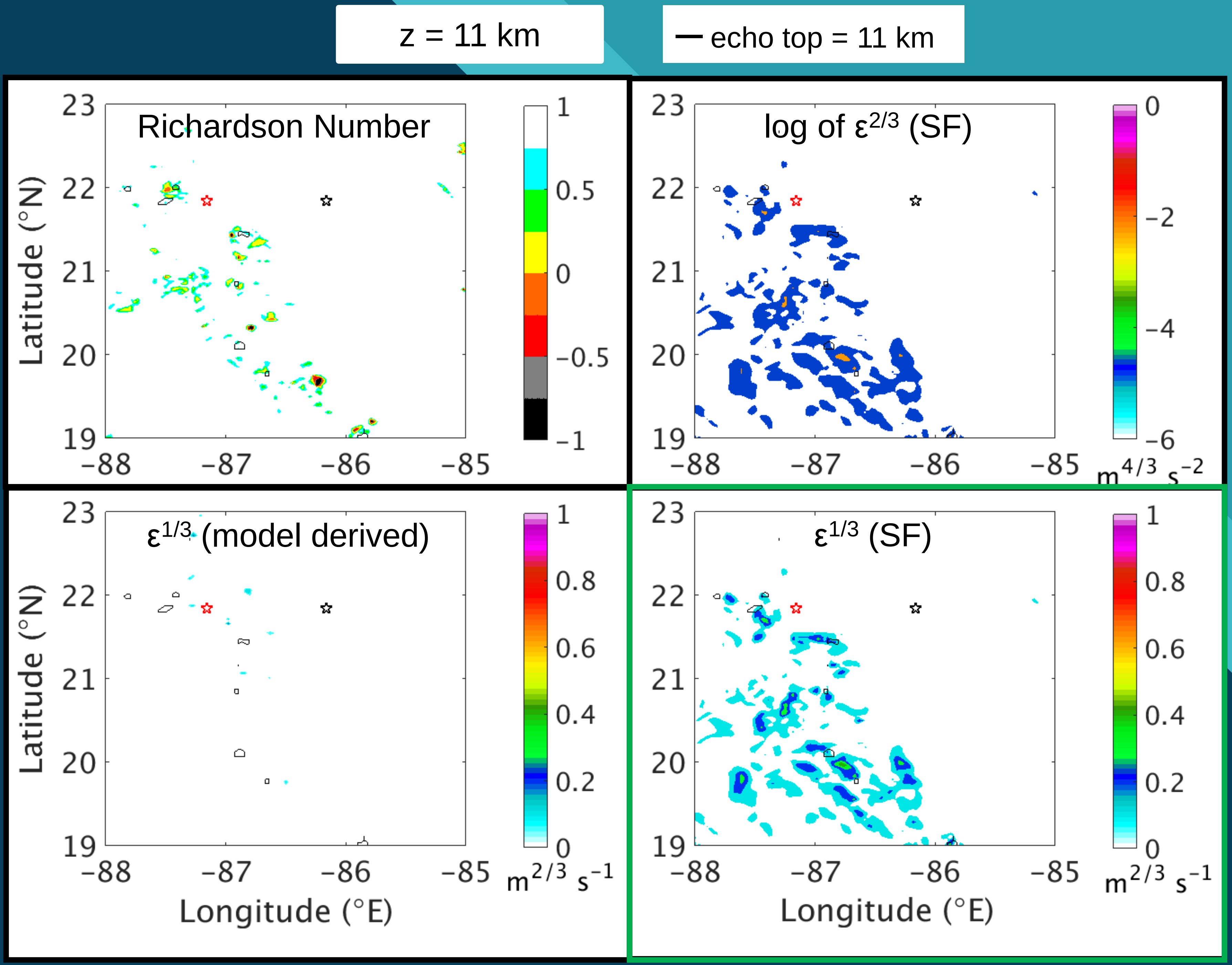


Simulated Cloud Top Temperatures



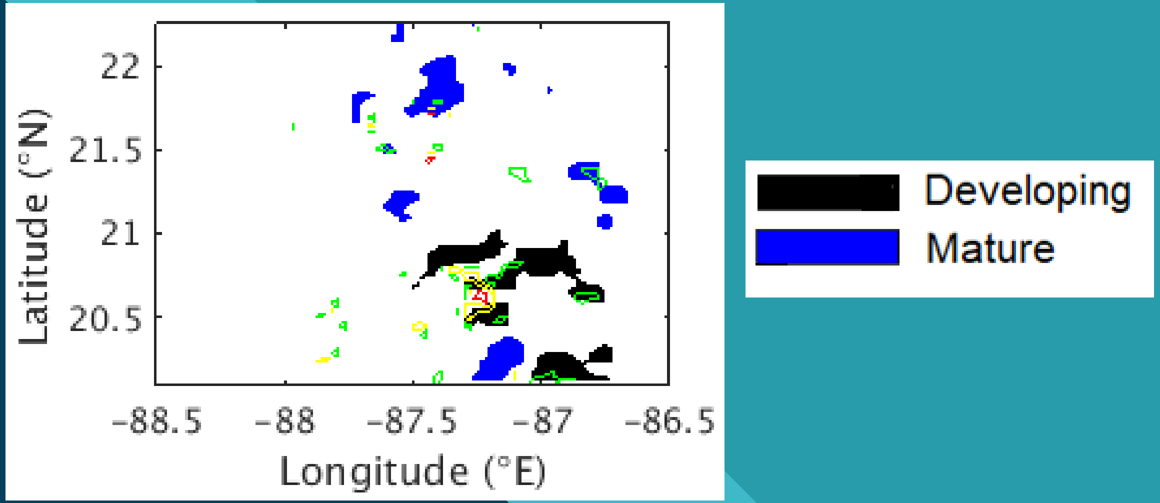
Tropical CIT

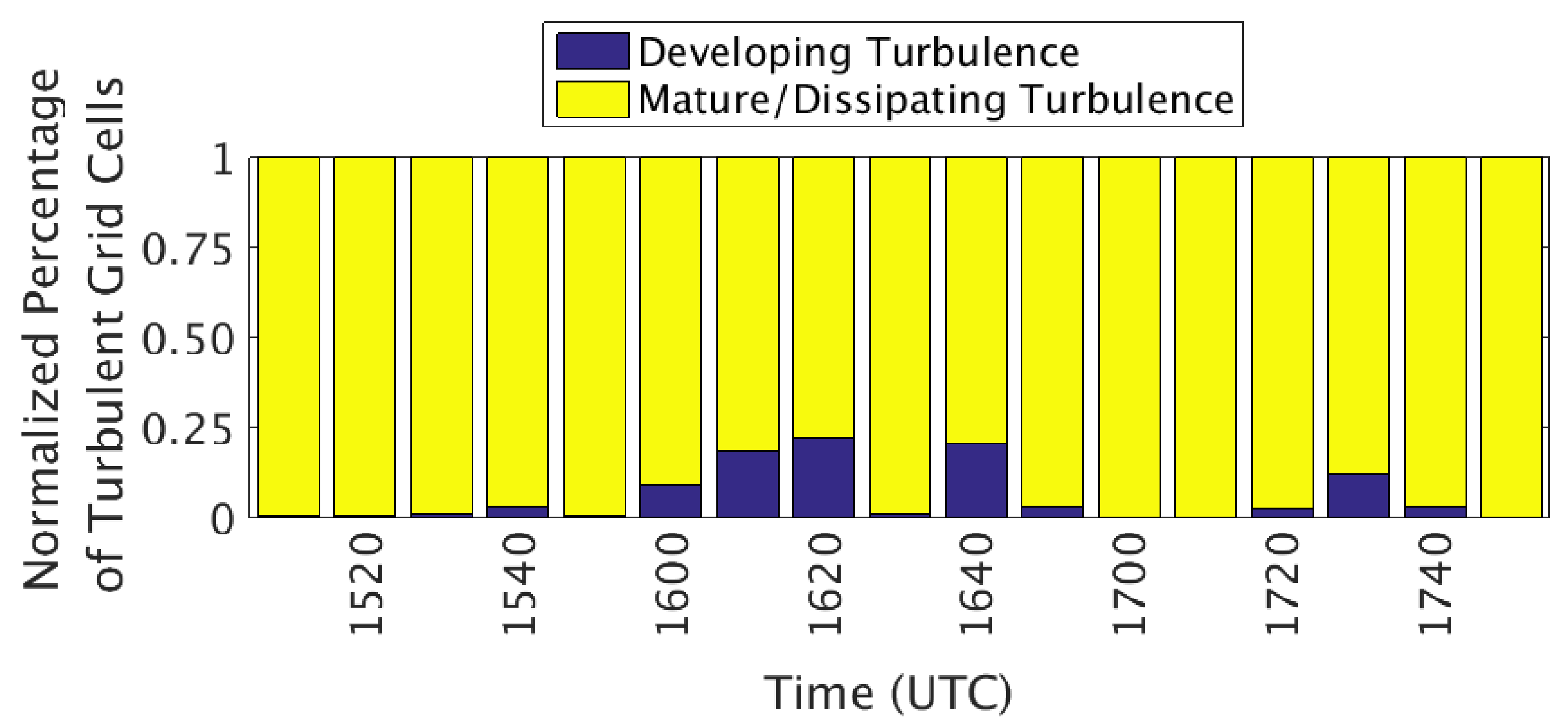
- **Ri**
  - Most turbulence is out-of-cloud
- **Log of $\varepsilon^{2/3}$ (SF) and $\varepsilon^{1/3}$ (SF)**
  - Most turbulence is out-of-cloud
  - Highest values are near convection
  - Moderate-severe
- **$\varepsilon^{1/3}$ model derived**
  - Under-predicted intensity and areal coverage



Developing Convection

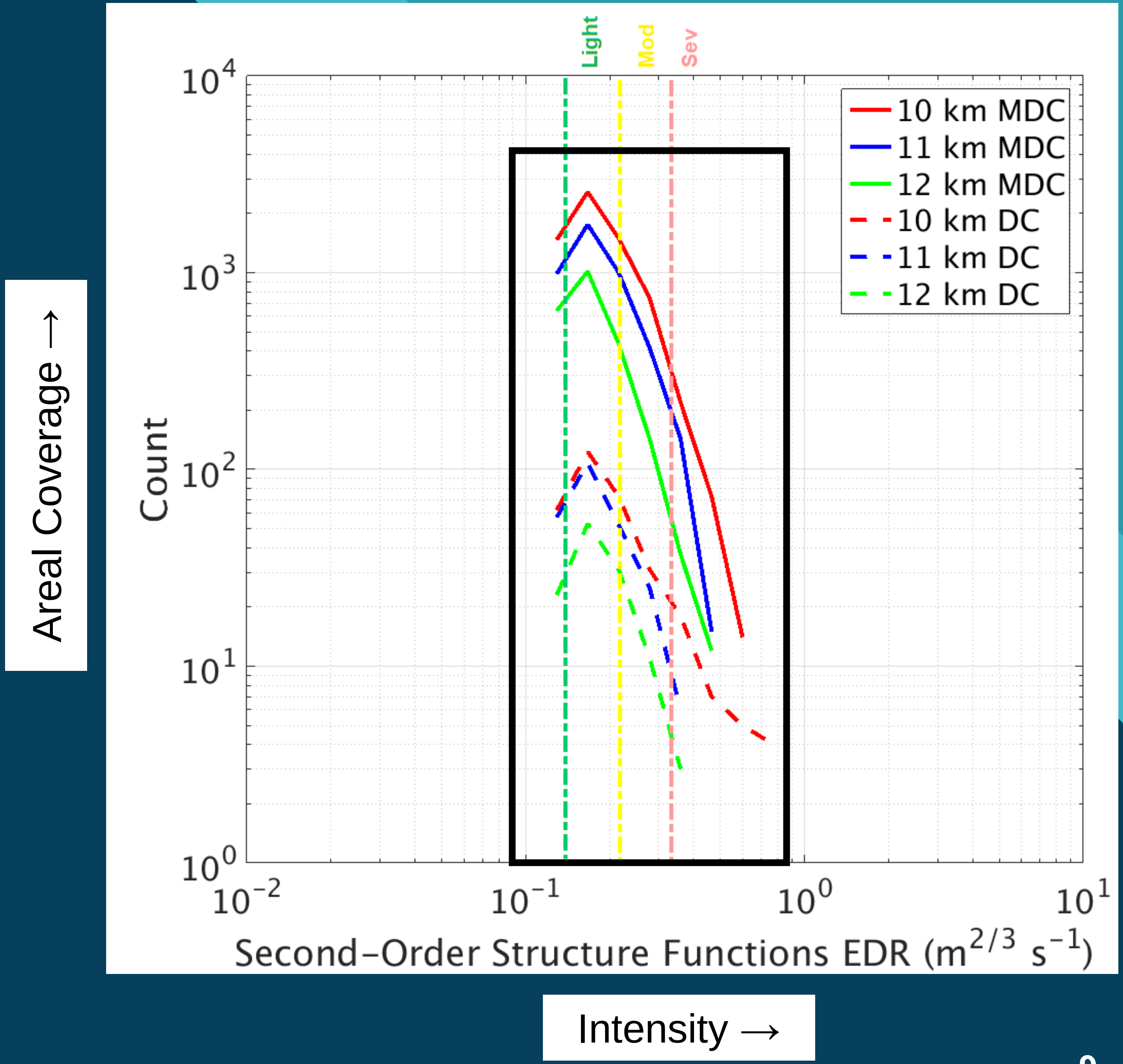
- Convective objects: Echo top heights ≥ 8 km (26 kft)
- Maximum vertical velocity increasing with time and < 90th percentile of vertical velocities
- Closest convective object to turbulent grid cell





Developing Convection

- **More turbulence is associated with mature and dissipating convection**
- **Highest intensity of turbulence is associated with developing convection at 10 km in altitude**
- **Convective object closest to severe turbulence had rapid development**
  - 9 m s^{-1} increase in vertical velocity
  - 3 km (~10 kft) increase in storm height



Discussion

- **Turbulence diagnostics (uncalibrated)**
  - Richardson number: Turbulence was predicted near convection
  - EDR: Under-predicted turbulence
  - Structure functions: Predicted severe turbulence near convection
- **Greatest areal coverage of turbulence is associated with mature/dissipating convection**
- **Most intense turbulence is associated with developing convection**
  - Increased hazard for aviation operations

More research on developing convection and turbulence is needed

Research Objective II

- **How does model resolution influence the distribution of turbulence?**
- **Current operational turbulence forecast systems are now running on a 3 km horizontal grid spacing**
  - Indices are being scaled for finer grid spacing
- **Turbulence that influences aviation occurs on scales of 10-1000 m**

Courtesy of A. Karboski

Ellrod and Knapp 1992; Ahmad and Proctor 2012

Methodology

- **Numerical simulations of convection in northern Great Plains using WRF**
  - 10-17 July 2015
- **Turbulence diagnostics**
  - Model derived eddy dissipation rate ($\varepsilon^{1/3}$)
    - Turbulent kinetic energy
  - Ellrod Index
    - Convergence, deformation, and vertical wind shear

Model	Horizontal grid spacing	Mean vertical grid spacing
S1	12 km	550 m
S2	3 km	550 m
S3	3 km	325 m
S4	500 m	325 m

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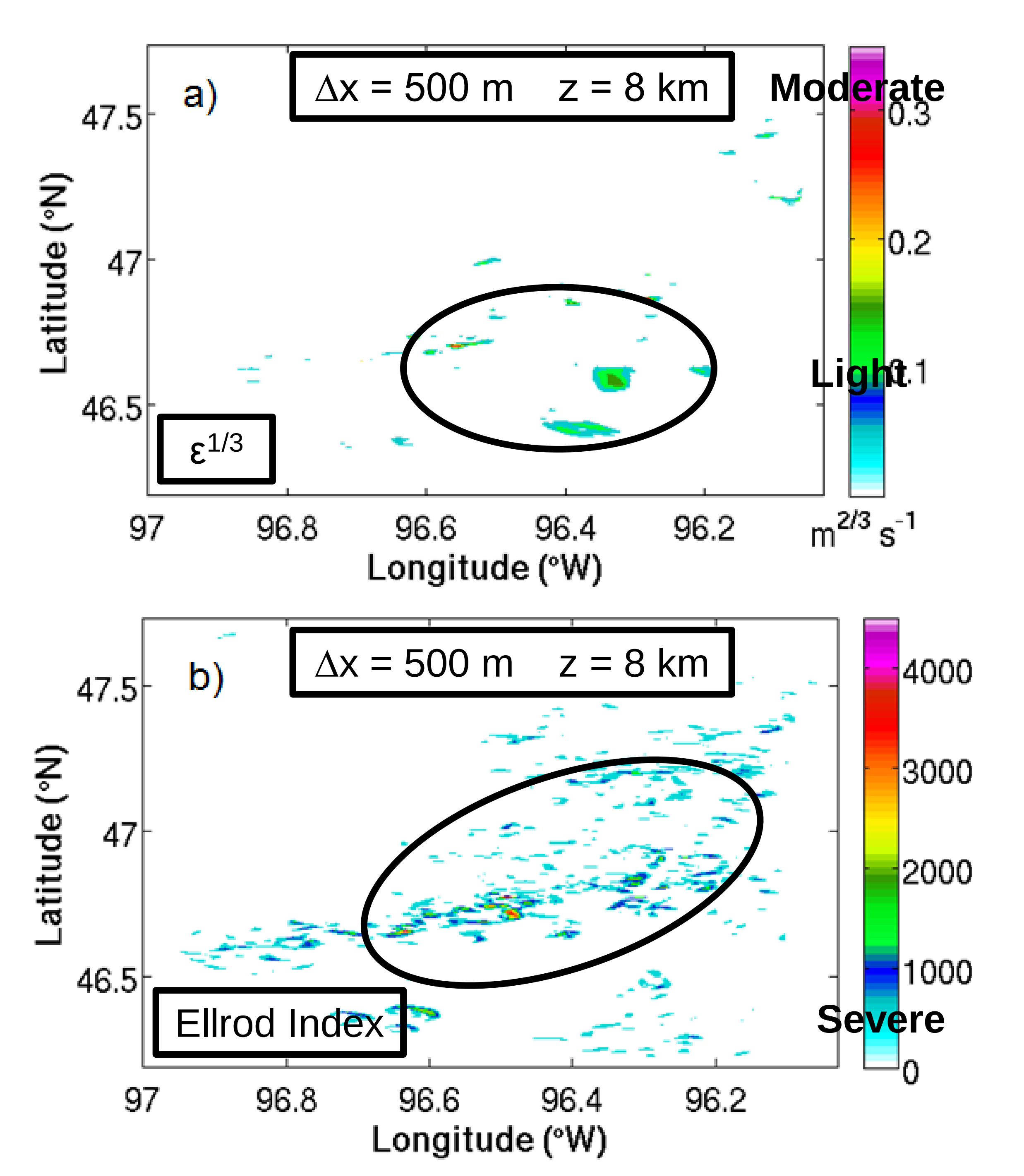
WRF: Weather Research and Forecasting model

Midlatitude CIT

- $\varepsilon^{1/3}$
  - Light to moderate turbulence
- **Ellrod Index**
  - Resolution sensitivity
    - Areal coverage of severe turbulence is much greater than $\varepsilon^{1/3}$
    - Magnitudes need to be scaled
    - Brown 1
- **Locations of maximum intensity vary between diagnostics**



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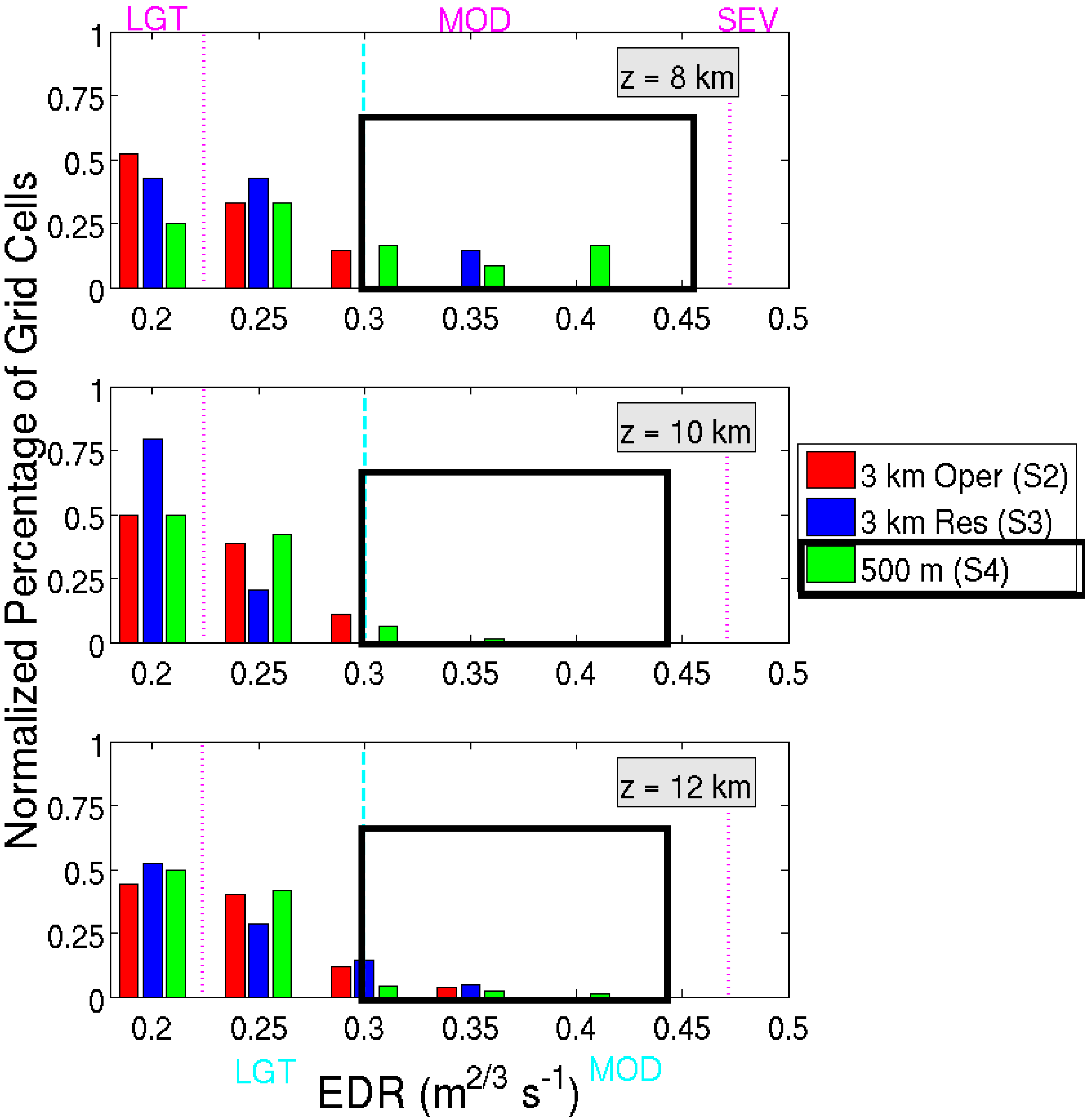
Midlatitude CIT

- **Coarser model resolution distributes the most turbulence towards lower thresholds**
- **Finer vertical and horizontal grid spacing is needed to predict extreme turbulence**

8 km = 26 kft
10 km = 33 kft
12 km = 39 kft



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Discussion

- Resolution influences the distribution of turbulence
- Increased horizontal and vertical resolution is important for turbulence prediction
- Moderate to severe turbulence was found more than 20 mi away from convection
- Turbulence prediction is sensitive to convective type and dynamical forcing (i.e. isolated convection and mesoscale convective systems)

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Conclusions

- **More research about CIT caused by developing convection is needed**
  - Midlatitudes and tropics
- **Storm type specific FAA guidelines**
  - Increase efficiency
- **Can convective parameters statistically be used as turbulence diagnostics?**


Courtesy of A. Karboski

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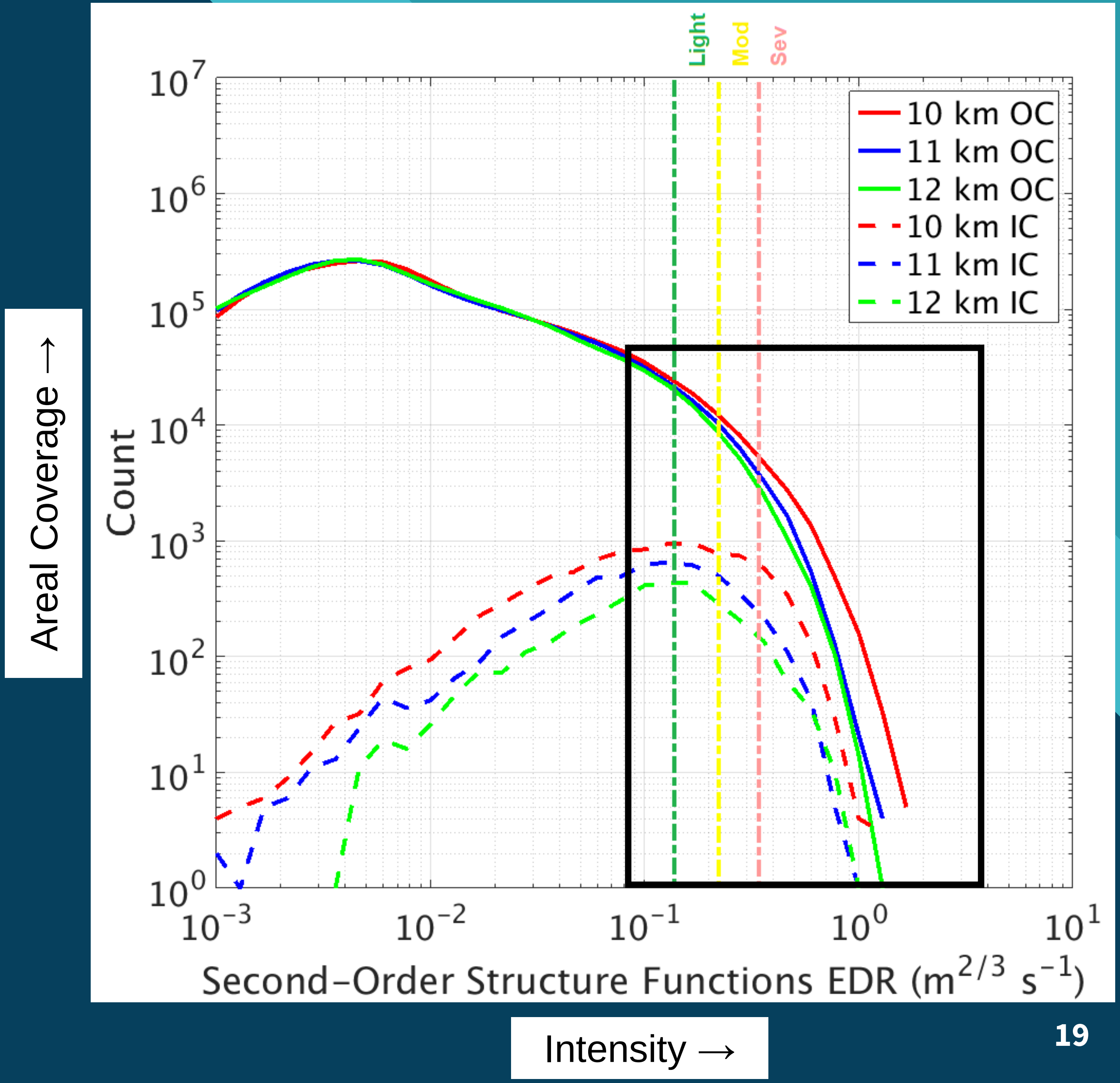
Extra Slides

Tropical CIT

- Out-of-cloud turbulence has the largest areal coverage
- Most severe turbulence is out of cloud
- 10 km in altitude has the greatest likelihood of experiencing severe turbulence (in and out of cloud)
- Majority of turbulence is above cloud



Model Physics

Model Physics	Model Setup
Microphysics	Thompson
Planetary Boundary Layer	YSU/MYJ
Surface Layer	MM5
Land Surface	Noah
Shortwave	RRTMG SW
Longwave	RRTMG LW
Cumulus	Tiedke (D01 and D02)

	Model setup			
Parameterizations	1	2	3	4
Microphysics	WDM6			
PBL	MYJ			
Surface layer	MM5 similarity			
Land surface	Noah			
Shortwave	Dudhia			
Longwave	RRTM			
Cumulus	Kain–Fritsch (D01 and D02)			—

Model Physics

- PBL:
  - **YSU**- no prognostic variables, diagnostic- diffusivity of heat
  - **MYJ**- prognostic variable- TKE, diagnostic- diffusivity of heat, length scale

YSU (diagnostic scheme) *imposes* this profile based on diagnosed PBL height *h*
MYJ (prognostic scheme) tries to *develop* it organically by predicting TKE
(Fovell 2018)

PBL scheme name, type, and reference	Description	Advantage(s)	Disadvantage(s)
YSU, nonlocal, Hong et al. (2006)	**First-order closure; similar to MRF, except YSU represents entrainment at the top of the PBL explicitly**	**More accurately simulates deeper vertical mixing in buoyancy-driven PBLs with shallower mixing in strong-wind regimes compared to MRF (Hong et al. 2006)**	**Has still been found to overdeepen the PBL for springtime deep convective environments, resulting in too much dry air near the surface and underestimation of MLCAPE related to environments of deep convection (Coniglio et al. 2013)**
MYJ, local, Janjić (1990, 1994)	*A 1.5-order closure scheme with an equation for prognosis of TKE*	*Improves upon Mellor–Yamada 1.5-order local scheme (Mellor and Yamada 1974, 1982) without particularly large computational expense*	*Undermixes PBL for locations upstream of spring convection (e.g., Coniglio et al. 2013)*