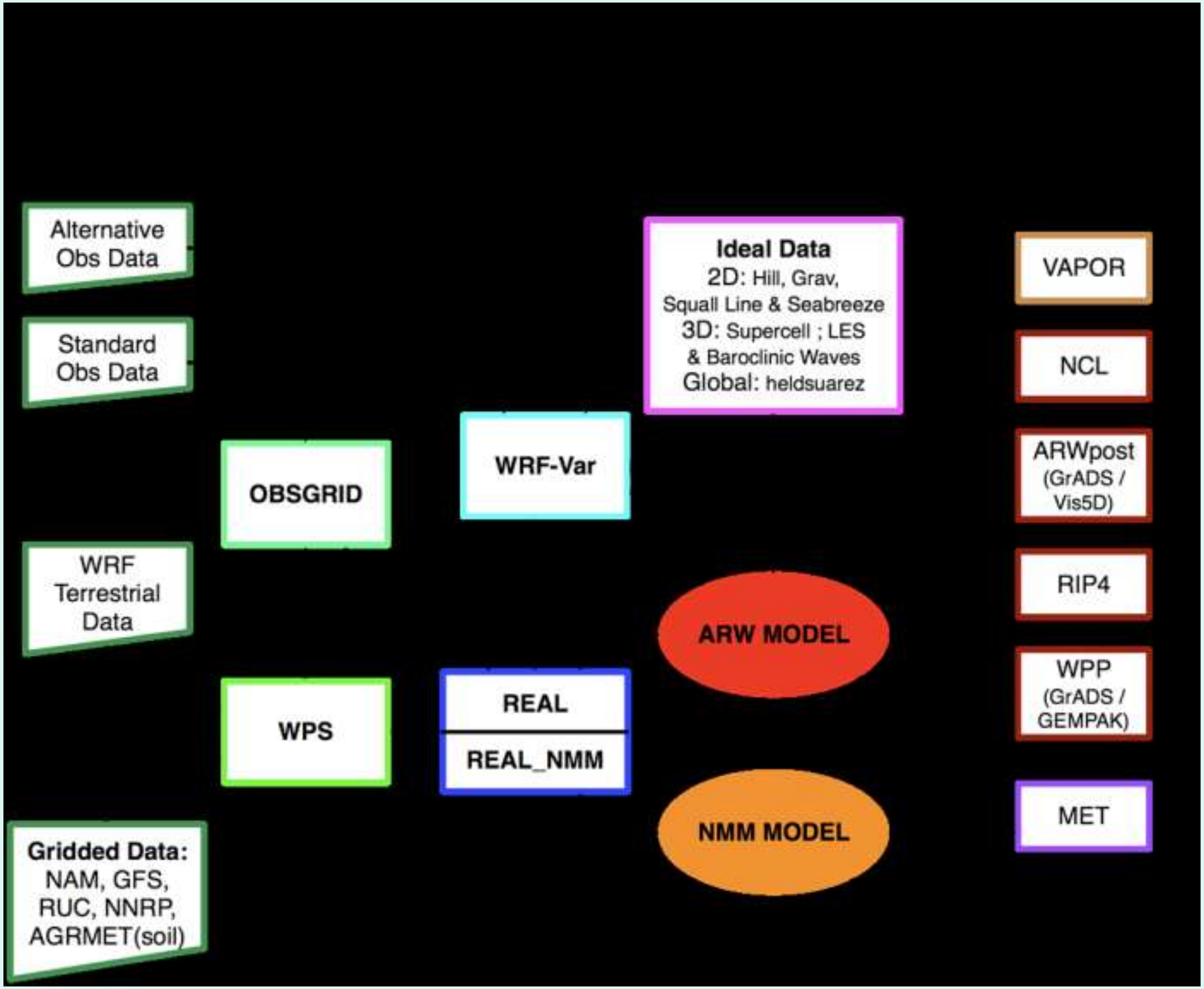
Regional Scale Modeling and Numerical Weather Prediction

Jimy Dudhia

NCAR/MMM

Overview of talk

- WRF Modeling System Overview
- WRF Model
  - Dynamics
  - Physics relevant to turbulence
    - PBL schemes and diffusion
- Regional Climate Modeling
- Numerical Weather Prediction
- WRF Examples
  - Convection forecasting
  - Energy spectrum in NWP models
  - Hurricane forecasting and sensitivity to physics
  - Idealized LES hurricane testing


Alternative Obs Data
Standard Obs Data
WRF Terrestrial Data
Gridded Data: NAM, GFS, RUC, NNRP, AGRMET(soil)
OBSGRID
WPS
WRF-Var
REAL
REAL_NMM
Ideal Data
2D: Hill, Grav, Squall Line & Seabreeze
3D: Supercell ; LES & Baroclinic Waves
Global: heldsuarez
ARW MODEL
NMM MODEL
VAPOR
NCL
ARWpost (GrADS / Vis5D)
RIP4
WPP (GrADS / GEMPAK)
MET

Modeling System Components

- WRF Pre-processing System (WPS)
  - Real-data interpolation for NWP runs
- WRF-Var (including 3d-Var)
  - Adding observations to improve initial conditions
- WRF Model (Eulerian mass dynamical core)
  - Initialization programs for real and idealized data (real.exe/ideal.exe)
  - Numerical integration program (wrf.exe)
- Graphics tools

WRF Preprocessing System

- GEOGRID program (time-independent data)
  - Define domain areas
  - Interpolate “static” fields to domain
    - Elevation, land-use, soil type, etc.
  - Calculate derived arrays of constants
    - Map factors, Coriolis parameter, etc.
- METGRID program (time-dependent data)
  - Interpolate gridded time-dependent data to domain
    - Pressure level data: geopotential height, temperature, winds, relative humidity
    - Surface and sea-level data
  - Multiple time periods needed
    - First time for initial conditions
    - Later times for lateral boundary conditions

WRF Model

- REAL program
  - Interpolate METGRID data vertically to model levels
    - Pressure-level data for atmosphere
    - Soil-level (below-ground) data for land-surface model
    - Balance initial conditions hydrostatically
    - Create lateral boundary file
- IDEAL program
  - Alternative to real-data to initialize WRF with 2d and 3d idealized cases
- WRF model runs with initial conditions from above programs

WRF Model

Key features:

- Fully compressible, non-hydrostatic (with hydrostatic option)
- Mass-based terrain following coordinate, η

$$\eta = \frac{\pi - \pi_t}{\mu}; \qquad \mu = \pi_s - \pi_t$$

where π is hydrostatic pressure, μ is column mass

- Arakawa C-grid staggering

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      v
  u   T   u
      v
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WRF Model

Key features:

- 3rd-order Runge-Kutta time integration scheme
- High-order advection scheme
- Scalar-conserving (positive definite option)
- Complete Coriolis, curvature and mapping terms
- Two-way and one-way nesting

Flux-Form Equations in Mass Coordinates

Hydrostatic pressure coordinate:

$$\eta = (\pi - \pi_t)/\mu, \qquad \mu = \pi_s - \pi_t$$

Conservative variables: $U = \mu u, \quad W = \mu w, \quad \Theta = \mu\theta, \quad \Omega = \mu\dot{\eta}$

Inviscid, 2-D equations without rotation:

$$\frac{\partial U}{\partial t} + \mu\alpha\frac{\partial p}{\partial x} + \frac{\partial p}{\partial \eta}\frac{\partial \phi}{\partial x} = -\frac{\partial U u}{\partial x} - \frac{\partial \Omega u}{\partial \eta}$$

$$\frac{\partial W}{\partial t} + g\left(\mu - \frac{\partial p}{\partial \eta}\right) = -\frac{\partial U w}{\partial x} - \frac{\partial \Omega w}{\partial \eta}$$

$$\frac{\partial \Theta}{\partial t} + \frac{\partial U\theta}{\partial x} + \frac{\partial \Omega\theta}{\partial \eta} = \mu Q$$

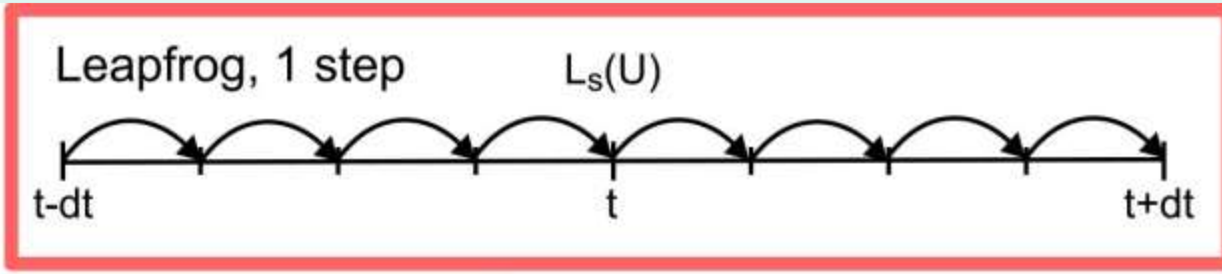
$$\frac{\partial \mu}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial \Omega}{\partial \eta} = 0$$

$$\frac{d\phi}{dt} = gw, \qquad \frac{\partial \phi}{\partial \eta} = -\mu\alpha, \qquad p = \left(\frac{R\theta}{p_0\alpha}\right)^{\gamma}$$

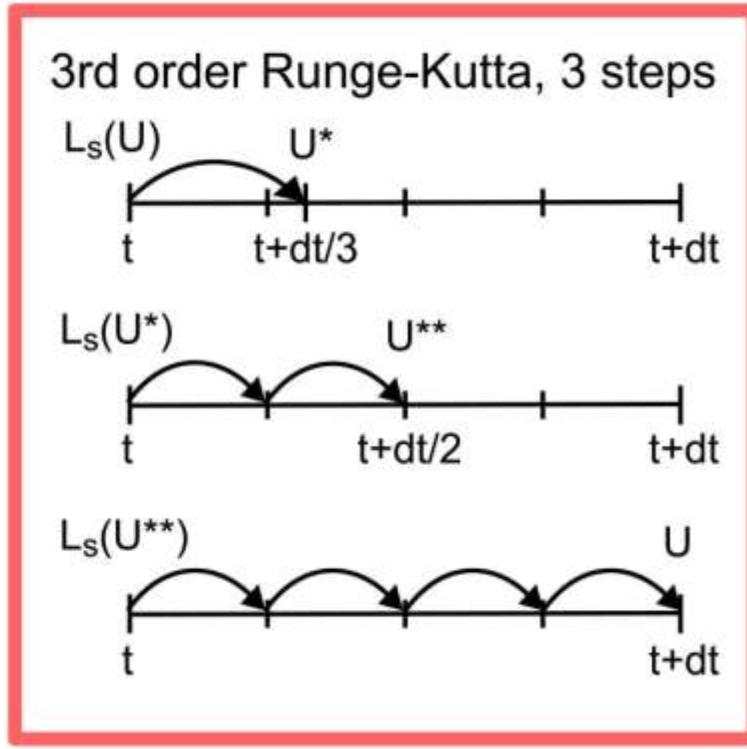
Time-Split Leapfrog and Runge-Kutta Integration Schemes

Integrate

$U_t = L_f(U) + L_s(U)$



- LF is formally 1st order accurate, RK3 is 3rd order accurate
- RK3 stable for centered and upwind advection schemes, LF only stable for centered schemes.
- RK3 is stable for timesteps 2 to 3 times larger than LF.
- LF requires only one advection evaluation per timestep, RK3 requires three per timestep.

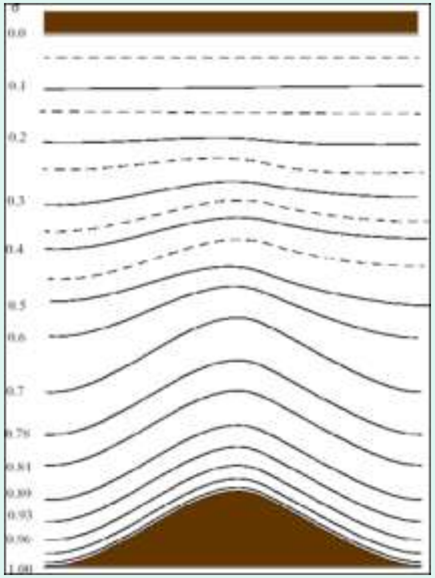


ARW Dynamics

Key features:

- Fully compressible, non-hydrostatic (with hydrostatic option)
- Mass-based terrain following coordinate, η

$$\eta = \frac{\pi - \pi_t}{\mu}, \qquad \mu = \pi_s - \pi_t$$



where π is hydrostatic pressure,
μ is column mass

- Arakawa C-grid staggering

$$\begin{array}{ccc} & v & \\ u & T & u \end{array}$$

WRF Model

Key features:

- Choices of lateral boundary conditions suitable for real-data and idealized simulations
  - Specified, Periodic, Open, Symmetric, Nested
- Full physics options to represent atmospheric radiation, surface and boundary layer, and cloud and precipitation processes
- Grid-nudging and obs-nudging (FDDA)

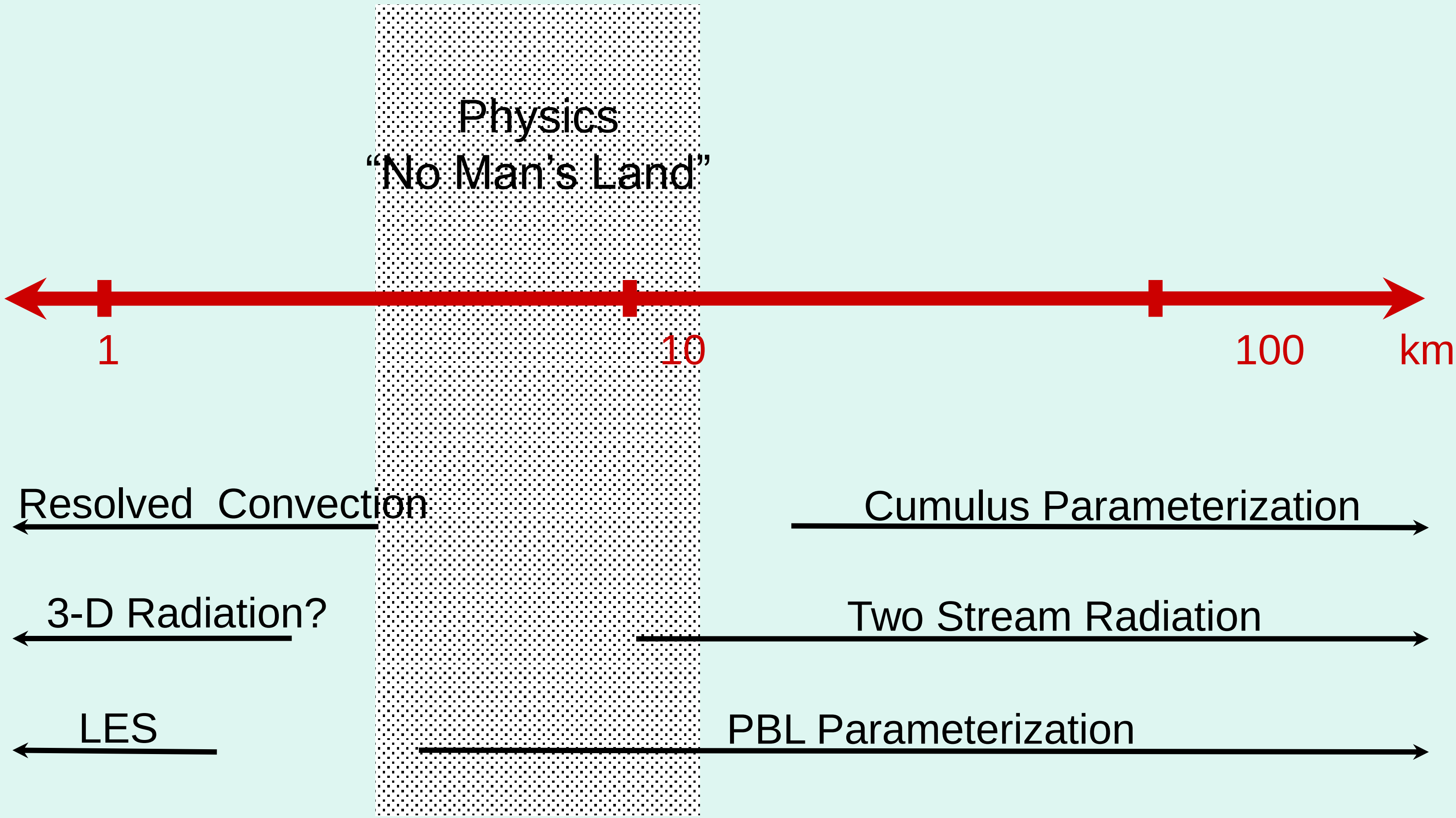
ARW Physics Options

- Turbulence/Diffusion
  - Constant K, 3d TKE, 3d Smagorinsky, 2d Smagorinsky
- Radiation
  - RRTM longwave, Goddard shortwave, Dudhia shortwave, CAM radiation, GFDL radiation
- Surface-layer/PBL/vertical mixing
  - Yonsei University (YSU), MRF, Mellor-Yamada-Janjic

ARW Physics Options

- Land Surface
  - Noah, RUC, 5-layer thermal soil
  - Water can be updated only through reading SST during run
- Cumulus Parameterization
  - Kain-Fritsch, Betts-Miller-Janjic, Grell-Devenyi ensemble
- Microphysics
  - Kessler, Lin et al., Ferrier, Thompson et al., WSM (Hong, Dudhia and Chen) schemes

Model Physics in High Resolution NWP



Sub-grid Turbulence Physics in NWP

- In NWP horizontal grid size >> vertical grid size (especially in boundary layer), therefore
  - Vertical mixing is done by a 1-d PBL scheme
  - Horizontal mixing is done by an independent horizontal diffusion

Role of PBL schemes in NWP

- PBL scheme receives surface fluxes of heat and moisture from land-surface model, and surface stress from surface-layer scheme
- Mixes heat, moisture and momentum in the atmospheric column providing rates of change for these quantities back to the NWP model
- Includes vertical diffusion in free atmosphere
- Schemes are mostly distinguished by various treatments of the unstable boundary layer
- Two popular schemes in WRF: YSU and MYJ

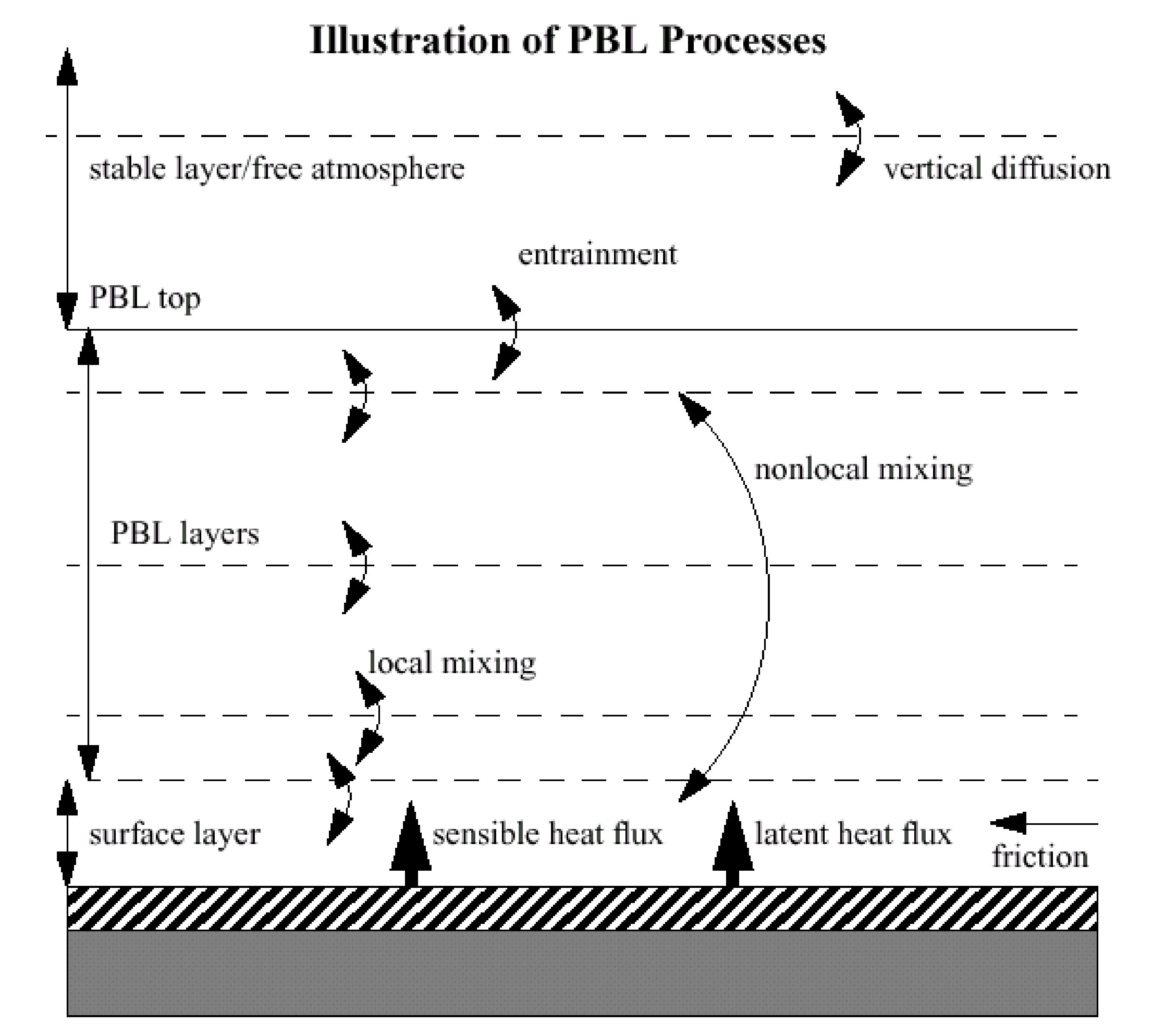


Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

YSU PBL

Yonsei University PBL scheme (Hong, Noh and Dudhia 2006)

- Parabolic non-local-K mixing in dry convective boundary layer
- Troen-Mahrt countergradient term (non-local flux)
- Depth of PBL determined from thermal profile
- Explicit treatment of entrainment
- Vertical diffusion depends on Ri in free atmosphere
- New stable surface BL mixing using bulk Ri

MYJ PBL

Mellor-Yamada-Janjic (Eta/NMM) PBL

- 1.5-order, level 2.5, TKE prediction
- Local TKE-based vertical mixing in boundary layer and free atmosphere
- TKE and diagnostic vertical mixing length scale provide K coefficient
- TKE may be advected or not

Horizontal Diffusion in NWP

- Separated from vertical diffusion
- Depends on horizontal gradients of wind (2d Smagorinsky deformation method)
- May also depend on TKE (NMM core)
- May also add numerical smoothing (NMM and MM5)

Other Filters and Dampers

- NWP models need to control energy build-up at shortest resolved scales
  - Filters and high-order smoothers may be used for this
- Also need to prevent noise due to unrealistic reflection at model top
  - Upper level dampers or radiative conditions may be used at the top

Applications of Regional Models

- Regional Climate
- NWP

Regional Climate Modeling

- For regional climate studies, a model's performance needs to be evaluated in the same way as global climate models
- This includes long-term radiative and surface statistical comparison with observations
- Typical runs are months to years in length
- Resolution is typically in the 10-50 km grid-size range
- The Nested Regional Climate Model is a WRF Version developed for such studies

Nested Regional Climate Model

WRFV2.1

Physics:

- CAM radiation: (30min calls, 6 hr LW emiss/abs calls)
- WSM-6 microphysics
- Noah LSM
- YSU boundary layer
- Kain-Fritsch convection (36 and 12 km domains)

Code modifications:

- Periodic lateral boundary conditions in East-West.
- Time-varying lower boundary condition: SST and Vegetation Fraction.
- Wide buffer zone of 10 grid points using a combined linear-exponential relaxation for North-South boundaries.
- Expanded diagnostic outputs including the ISCCP simulator and accumulated fluxes

Tropical Channel Simulations

Forcing Data:

- NCEP-NCAR reanalyses at north and south boundaries (6 hourly at 2.5°)
- Periodic lateral boundary conditions East-West.
- Lower boundary conditions: AMIP SST (0.5 degree) and interpolated monthly vegetation fraction (0.144 degree).

Vertical Levels:

- 35 sigma levels for all domains (5 in the lowest km).
- Terrain following coordinate.

Model Outputs:

- 3-hourly meteorological fields.
- Hourly accumulated surface and TOA fluxes.

Analysis and Evaluation:

- Climate diagnostics (Julie Caron and Jim Hack).
- Tropical cyclone statistics (Greg Holland).

Outgoing Longwave Radiation

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Regional Climate Applications

- Regional climate models may be driven by global climate models for future scenarios (downscaling)
- Emphasis on surface temperature and moisture means turbulence in the boundary layer is central to predictions
- Use of models for wind climate mapping (wind energy applications)
- Regional climate models also used for hydrology studies (water resource applications)

Air Quality Applications

- Long-term regional model outputs provide input to air-quality/chemistry models
- Input consists of winds and vertical mixing coefficients
- Vertical mixing is important for correct prediction of tracer concentrations near the surface (day-time and nocturnal mixing)

Numerical Weather Prediction

- Regional NWP models typically are run for a few days
- Boundary conditions come from other models
- For real-time forecasts, boundary conditions come from earlier larger-domain forecasts or ultimately global forecasts (which don't require boundary conditions) run at operational centers (NCEP global forecast data is freely available in real time on the Web)

Numerical Weather Prediction

- Time-to-solution is a critical factor in real-time forecasts
- Typically forecasts may be run up to 4 times per day, so each forecast should take only a couple of hours of wall-clock time
- Depending on the region to be covered, computing power constrains the grid size
- For a given region, cost goes as inverse cube of grid length (assuming no change in vertical levels) because time step is approximately proportional to grid length

Numerical Weather Prediction

- U.S. operational regional model (WRF-NMM) is currently on a 12 km grid
- Other smaller countries (e.g., U.K., Germany, Japan, South Korea) can use finer grid sizes to cover their areas of interest
- Real-time forecast models currently have grid sizes down to a few kilometers
  - Starting to resolve individual large thunderstorms (with no cumulus parameterization needed)
  - But, not yet at the LES scale for such models so PBL parameterizations still needed

Numerical Weather Prediction

- Deterministic versus Ensemble forecasts
  - Is it better to use given computing resources for
    - One high-resolution (deterministic) run, or
    - Multiple lower-resolution runs (ensemble)
  - Now reaching scales where resolution improvements do not necessarily improve forecasts
    - Added detail (e.g in rainfall) is not necessarily correctly located
    - Verification of detailed rainfall forecasts is a key problem
  - However, uncertainties in initial conditions are known to exist and to impact forecasts
  - Ensembles give an opportunity to explore the range of uncertainty in forecasts, can be used in data assimilation, and can provide probabilistic results

Real-time Forecasting at NCAR

- Twice-Daily US domains (20 and 30/10 km)
  - Run on MMM Division computers
  - Posted on Web
- Special Programs
  - Spring Programs (2003-2008)
    - 4 km daily over central US (3 km in 2008)
  - Atlantic Hurricanes (2004-2007)
    - 12 km and 4km moving nest for hurricane cases (1.33 km nest in 2007)

Spring Programs

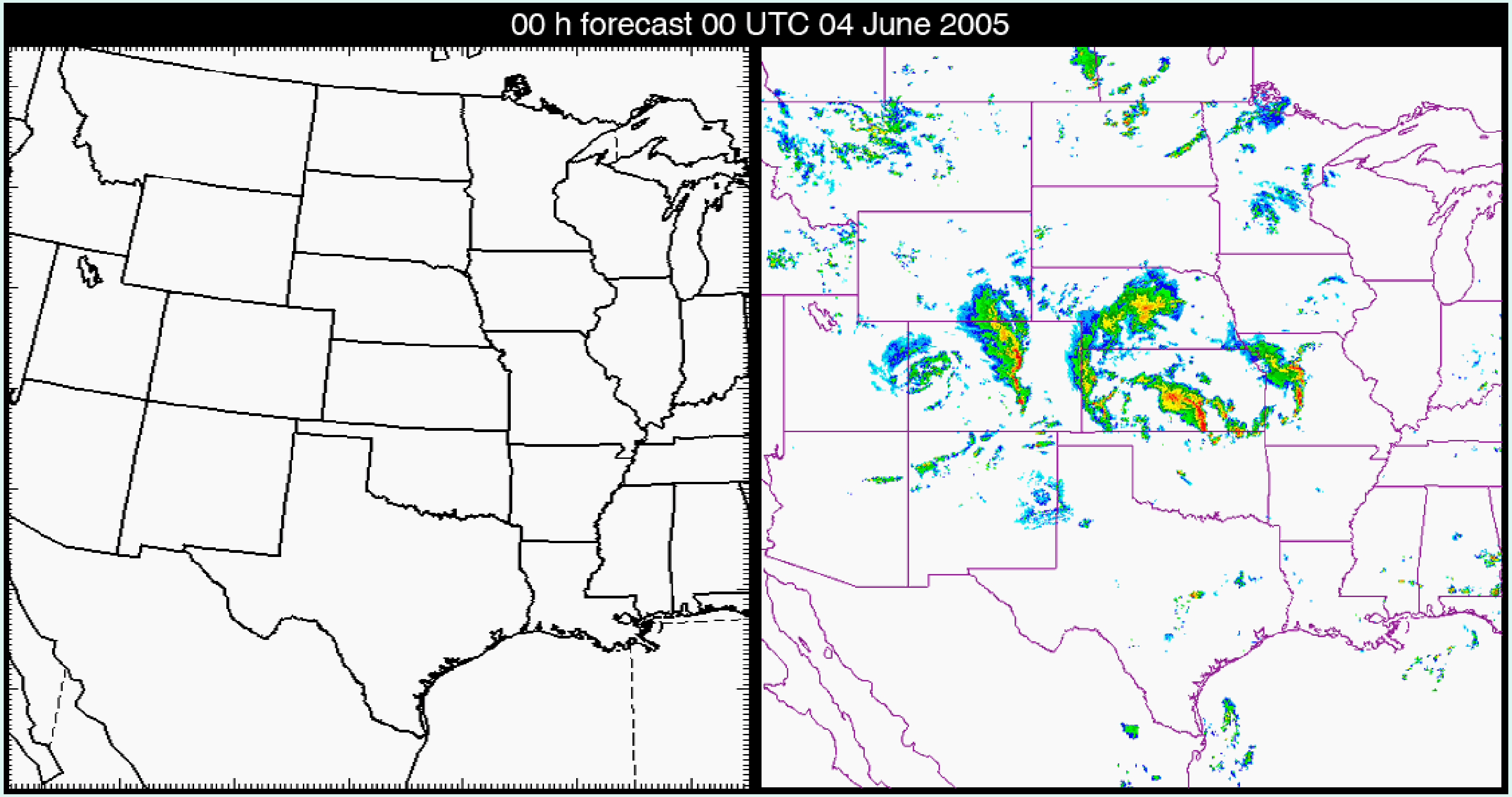
- Purpose is to evaluate benefits of convection-resolving real-time simulations to forecasters in an operational situation
- Single hi-res domain run daily from 00z for 36 hours to gauge next day's convective potential
- Sometimes (as with BAMEX 2003) done in conjunction with field program

WRF ARW model, 2003 BAMEX forecasts

BAMEX Goal: *Study the lifecycles of mesoscale convective vortices and bow echoes in and around the St. Louis MO area*

Field program conducted 20 May – 6 July 2003

Convective-scale Forecasting (4km)



Spring Program Results

- First-generation convection often is well forecast up to 24 hours
- Sometimes next generation is missed or over-forecast
- Forecasters find these products useful
- Give a good idea of convective mode (supercells vs squall lines)

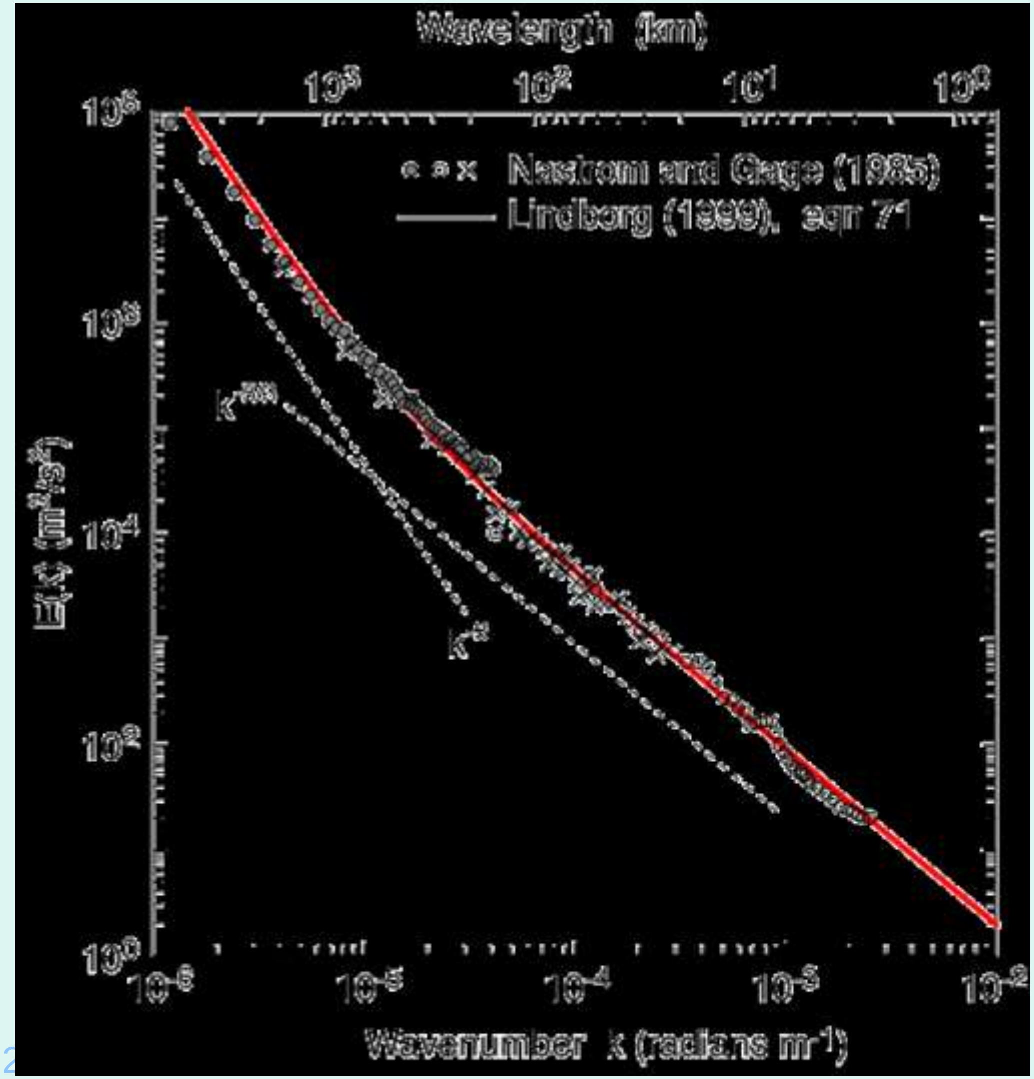
Study of Resolved Turbulence in NWP

- WRF Kinetic energy spectra study by Skamarock (2005)
  - How well does the model reproduce observed spectrum?
  - How does spectrum change with model resolution?
  - How does spectrum vary with meteorological situation?
  - How does spectrum develop in model?
  - How do different models do?

Kinetic Energy Spectra

Nastrom and Gage (1985) Spectra computed from GASP observations (commercial aircraft)

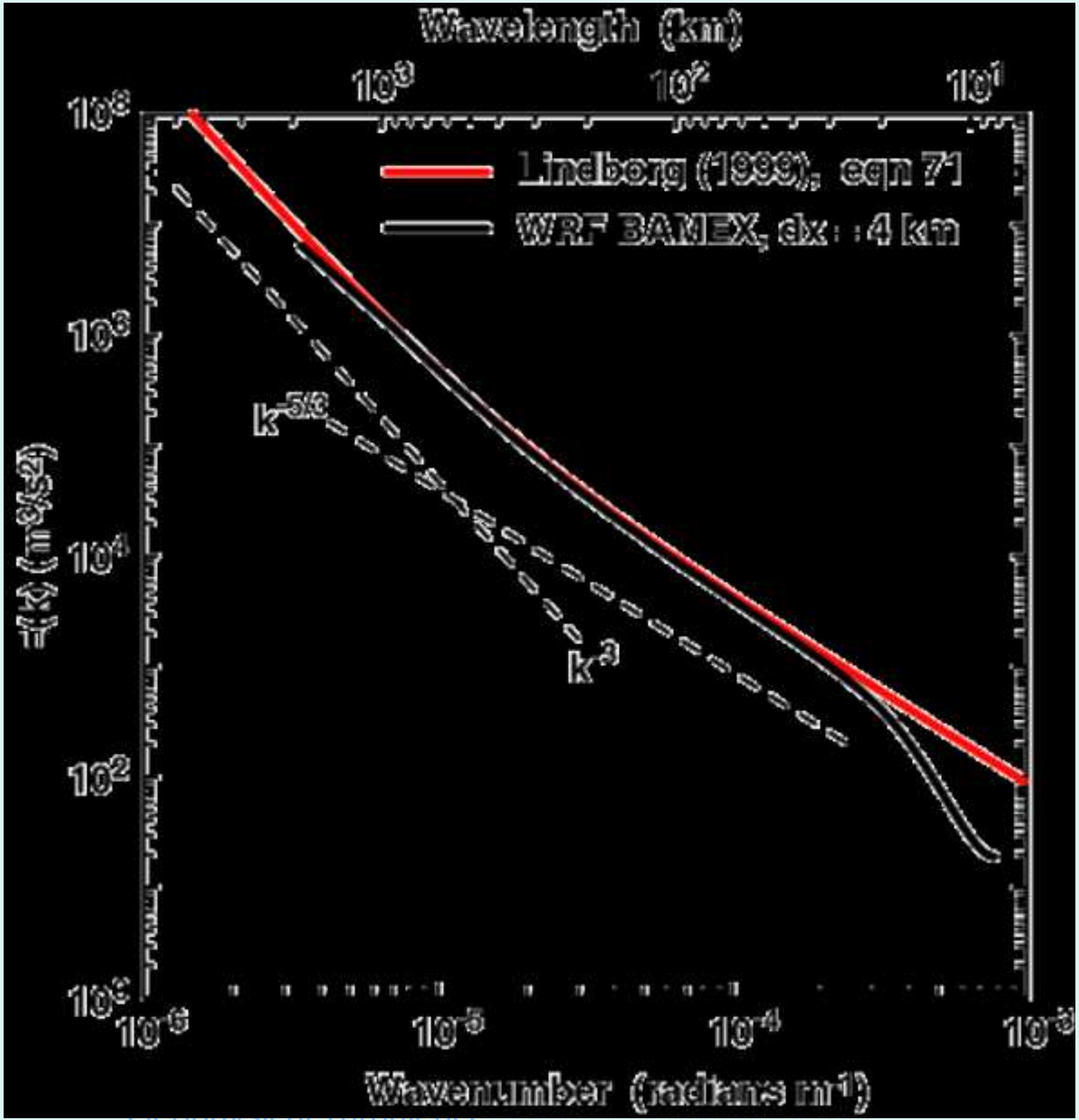
Lindborg (1999) functional fit from MOZAIC observations (aircraft)



Spectra for WRF-ARW BAMEX Forecasts, 5 May – 14 July 2003

Average over approx.
4 – 9 km height, on
model surfaces.

4 km WRF-ARW:
12 - 36 h forecast avg.

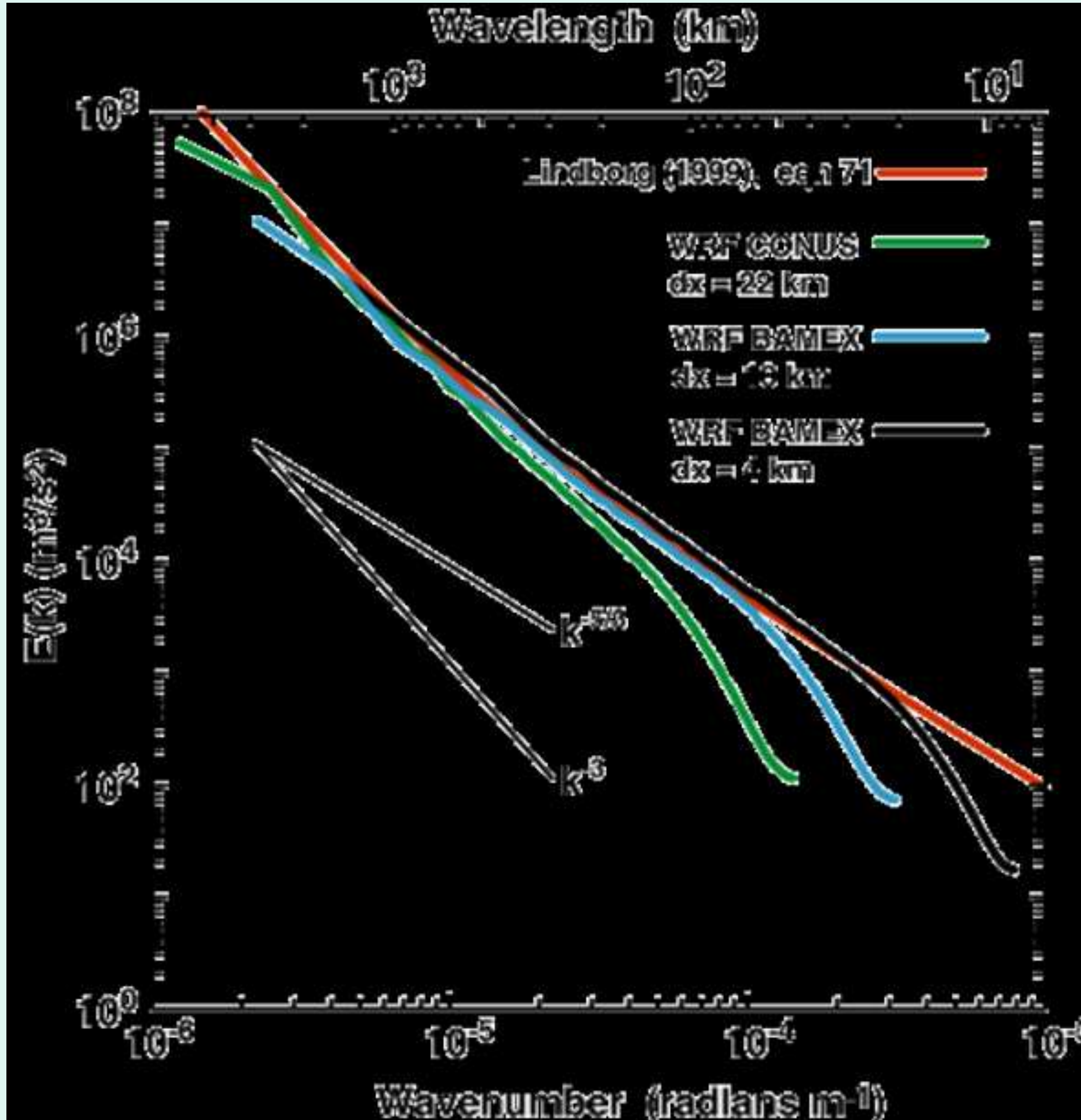


From Skamarock 2005

Spectra for WRF-ARW BAMEX Forecasts, 1 June – 3 June 2003

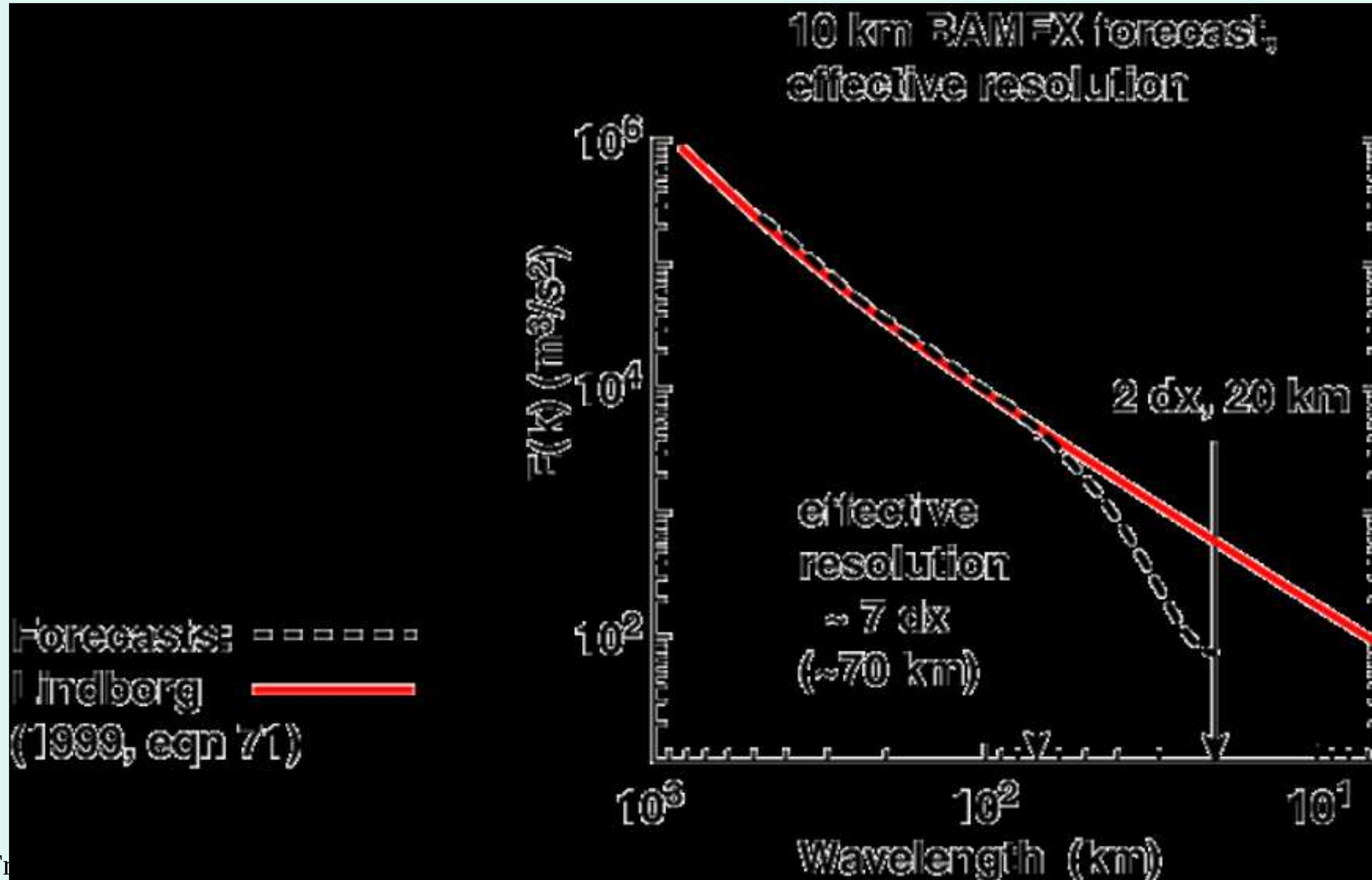
Average over approx. 4 – 9 km height, on model surfaces.

4, 10 and 22 km WRF-ARW:
12 - 36 h forecast avg.



From Skamarock 2005

WRF-ARW BAMEX Forecasts, 1 – 3 June 2003
Effective Resolution for the 10 km Forecast



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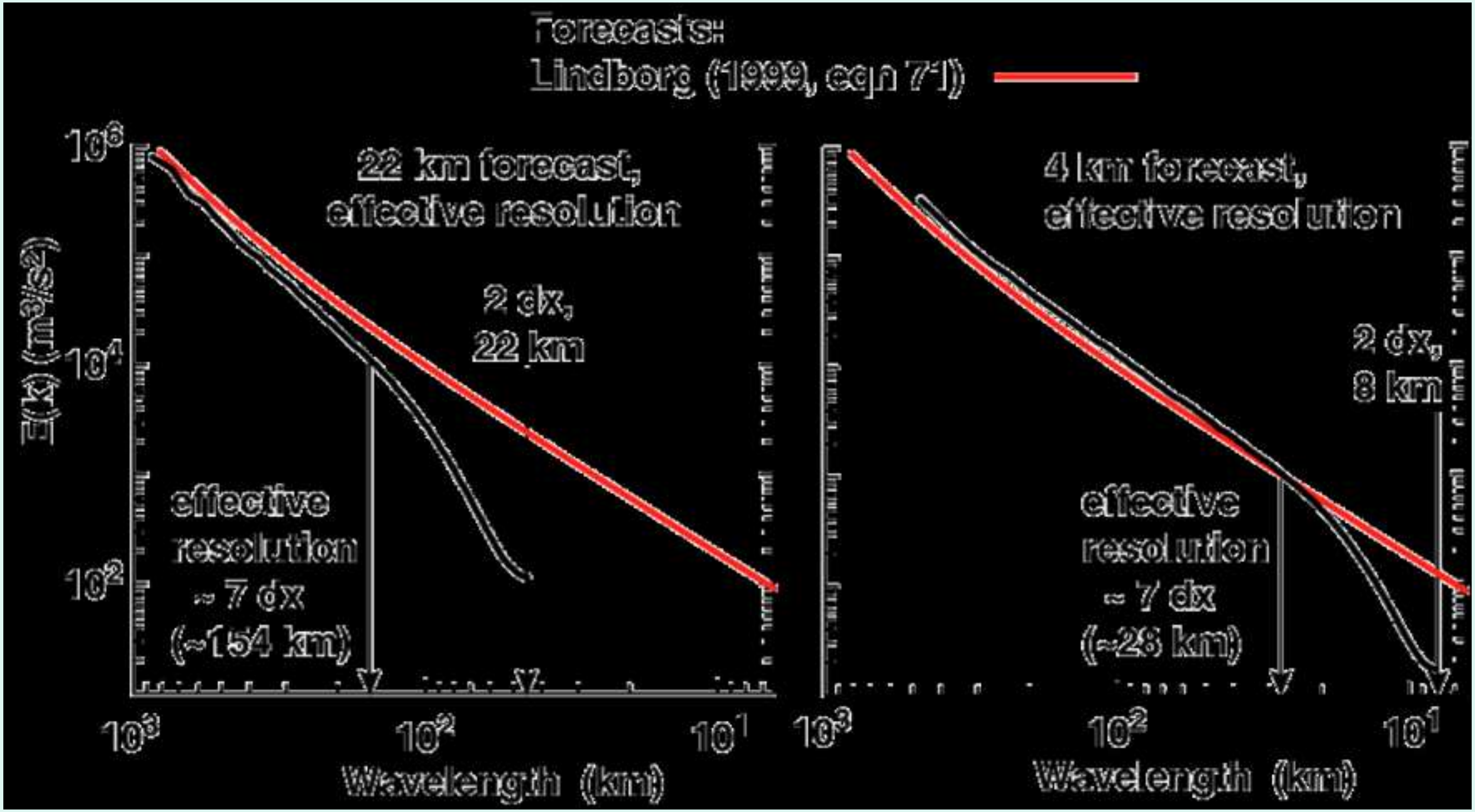
Geophysical Turbulence

WRF-ARW BAMEX Forecasts, 1 – 3 June 2003, Effective Resolutions for 22 and 4 km Forecasts

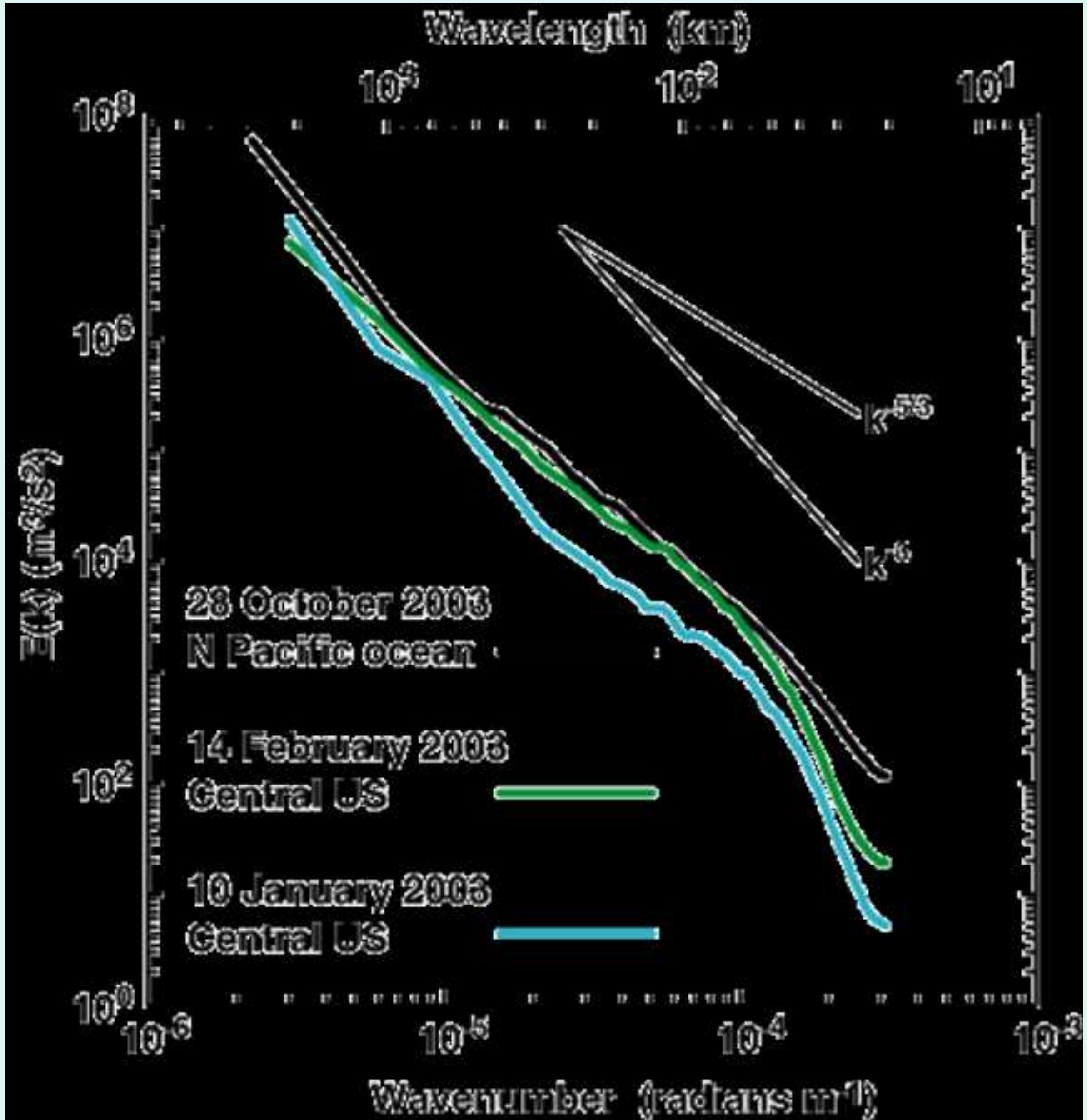


From Skamarock 2005

Spectra for WRF-ARW Forecasts, Ocean and Continental Cases

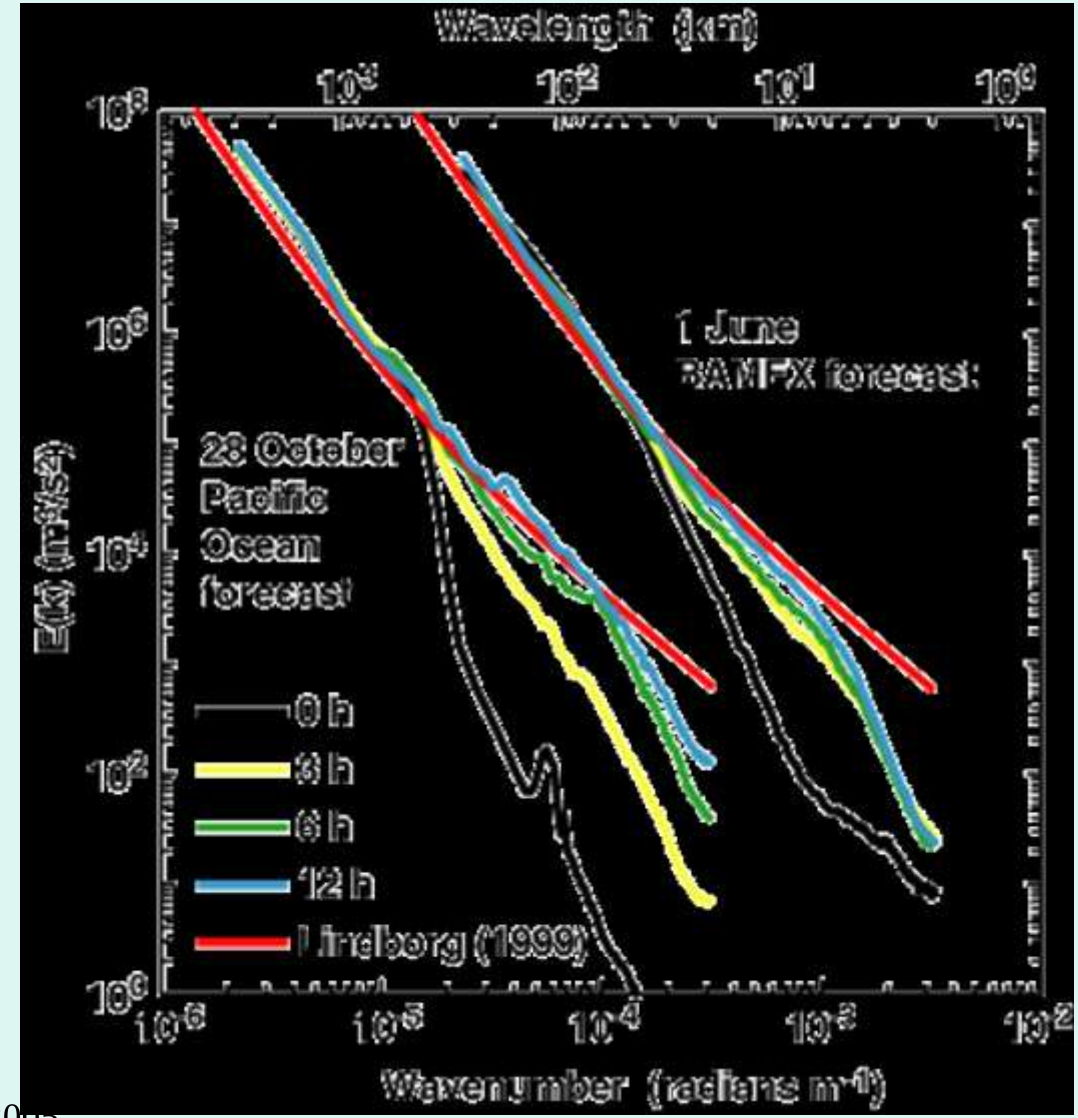
Average over approx.
4 – 9 km height, on
model surfaces.

10 km WRF-ARW:
12 - 36 h forecast avg.



From Skamarock 2005

WRF-ARW BAMEX Forecasts
10 km Forecast Spectra Evolution (model spin-up)



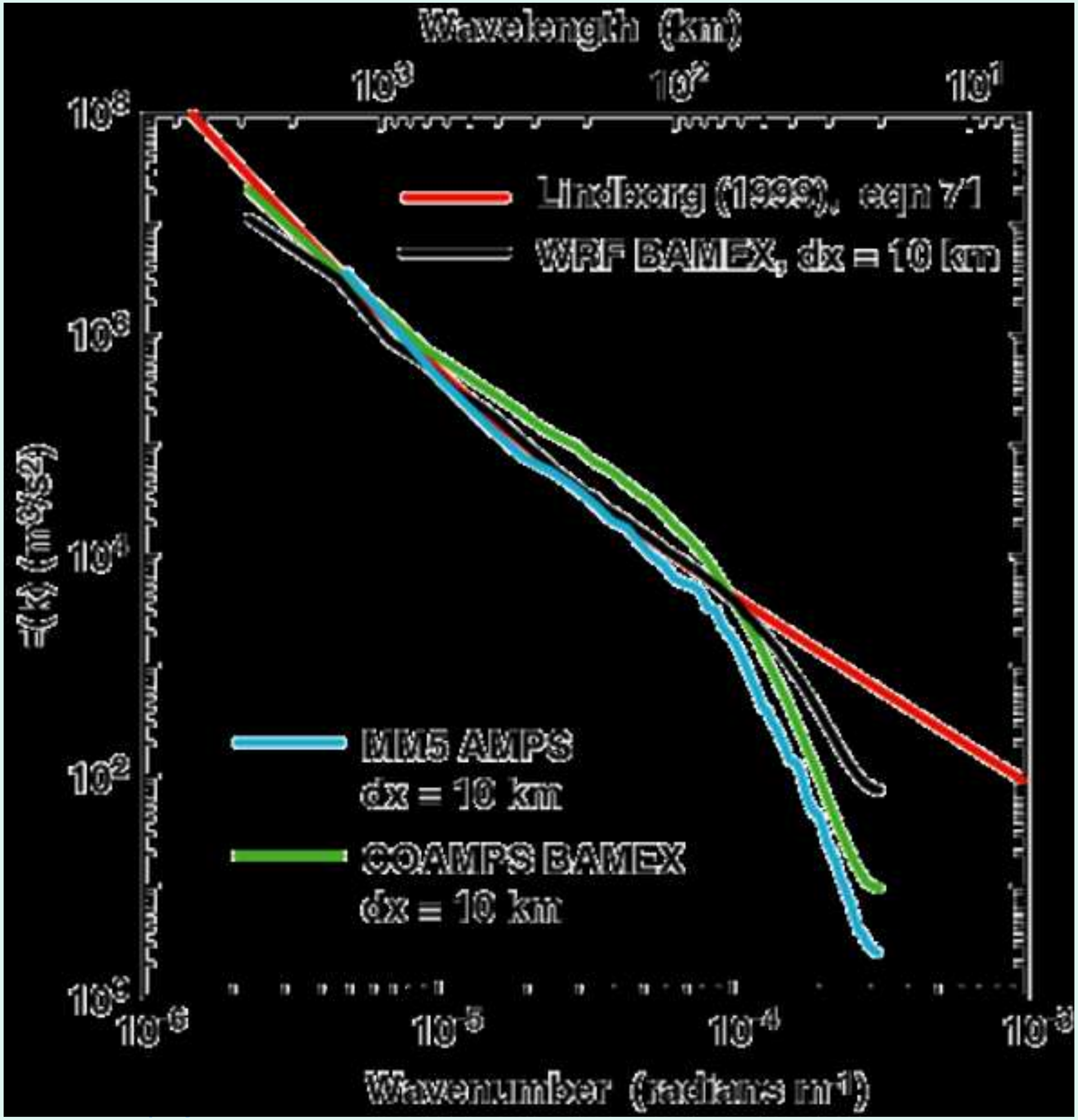
From Skamarock 2003

MM5, COAMPS and WRF-ARW Spectra

MM5 AMPS /Antarctica
20 Sept 2003, dx = 10 km

COAMPS BAMEX
2 June 2003, dx = 10 km

WRF-ARW BAMEX
1 – 3 June 2003, dx = 10 km



From Skamarock 2005

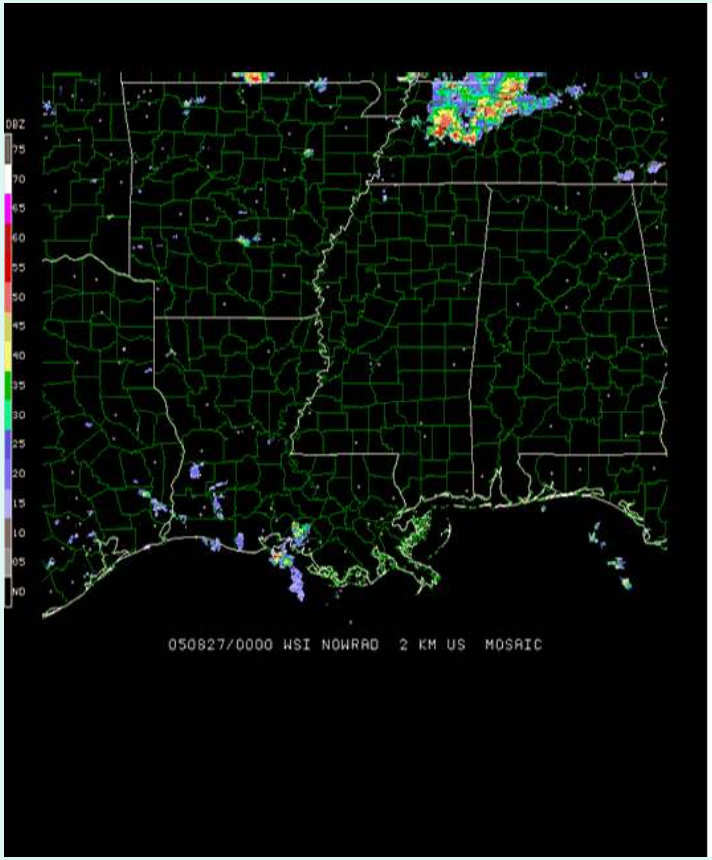
Spectra Results

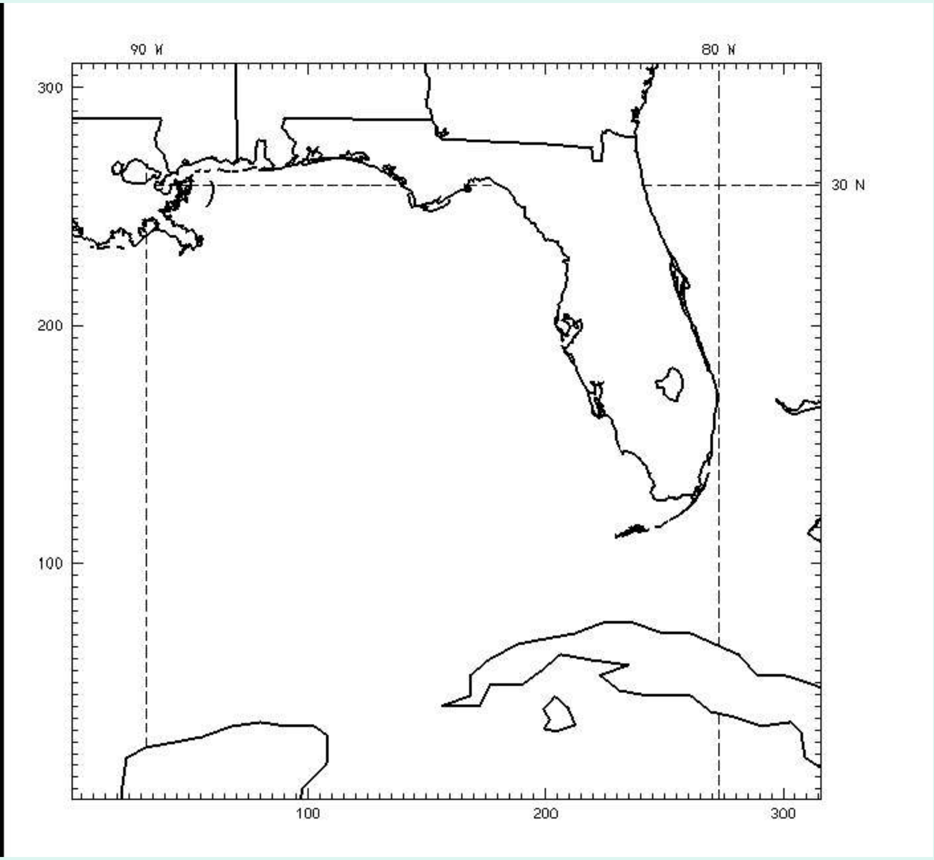
- ARW captures -3 to -5/3 transition at scales of a few hundred km
- ARW model spectrum resolution is effectively 7 grid lengths (damped below that)
- Different models have different effective resolutions for a given grid size
- Finer scales take ~6 hours to fully develop from coarse analyses

Hurricane Season Forecasts

- All hurricane cases have been run in real-time with a 4 km moving nest since 2004
- This includes the four Florida storms in 2004 and the major storms Katrina, Rita and Wilma in 2005

Hurricane Katrina Simulation (4km)

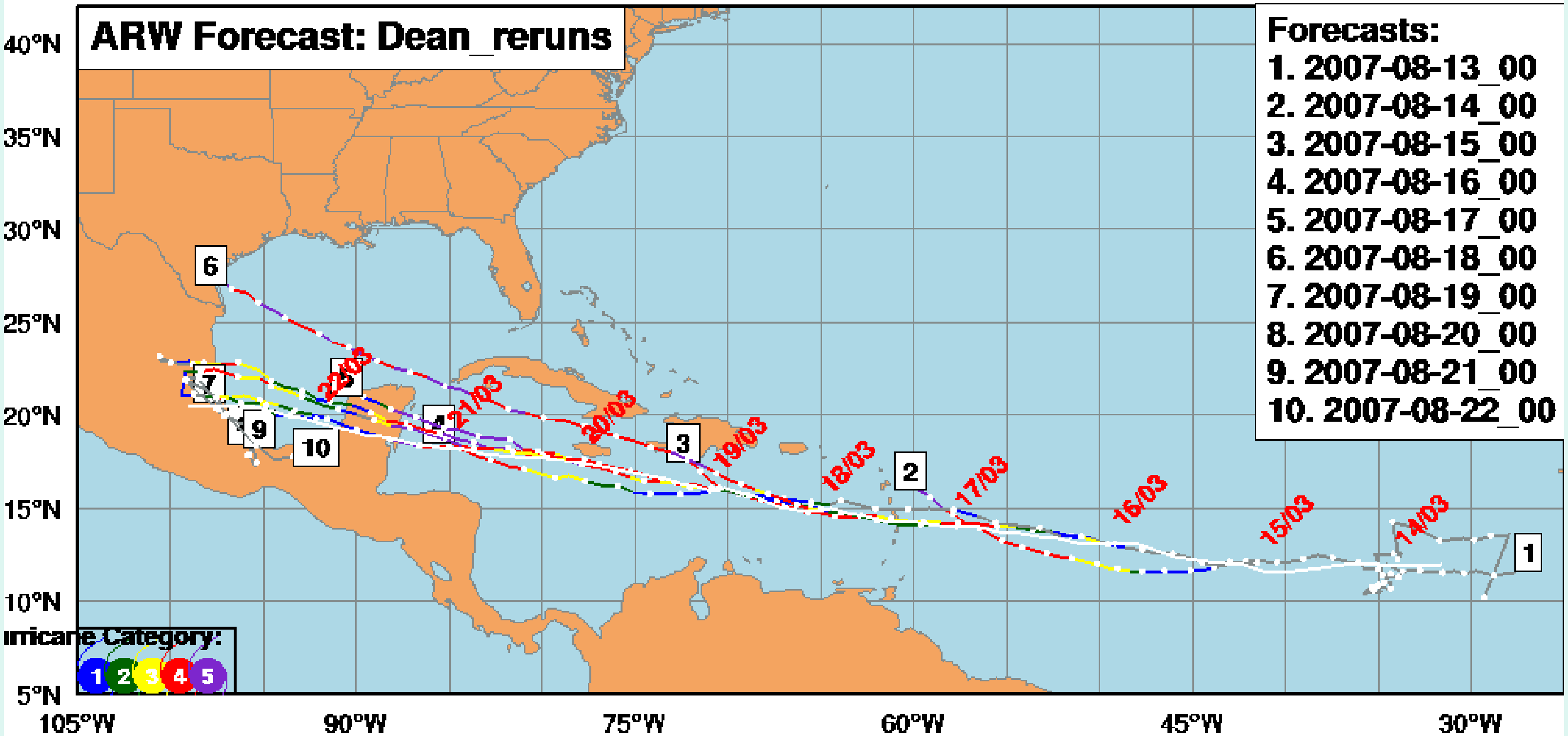




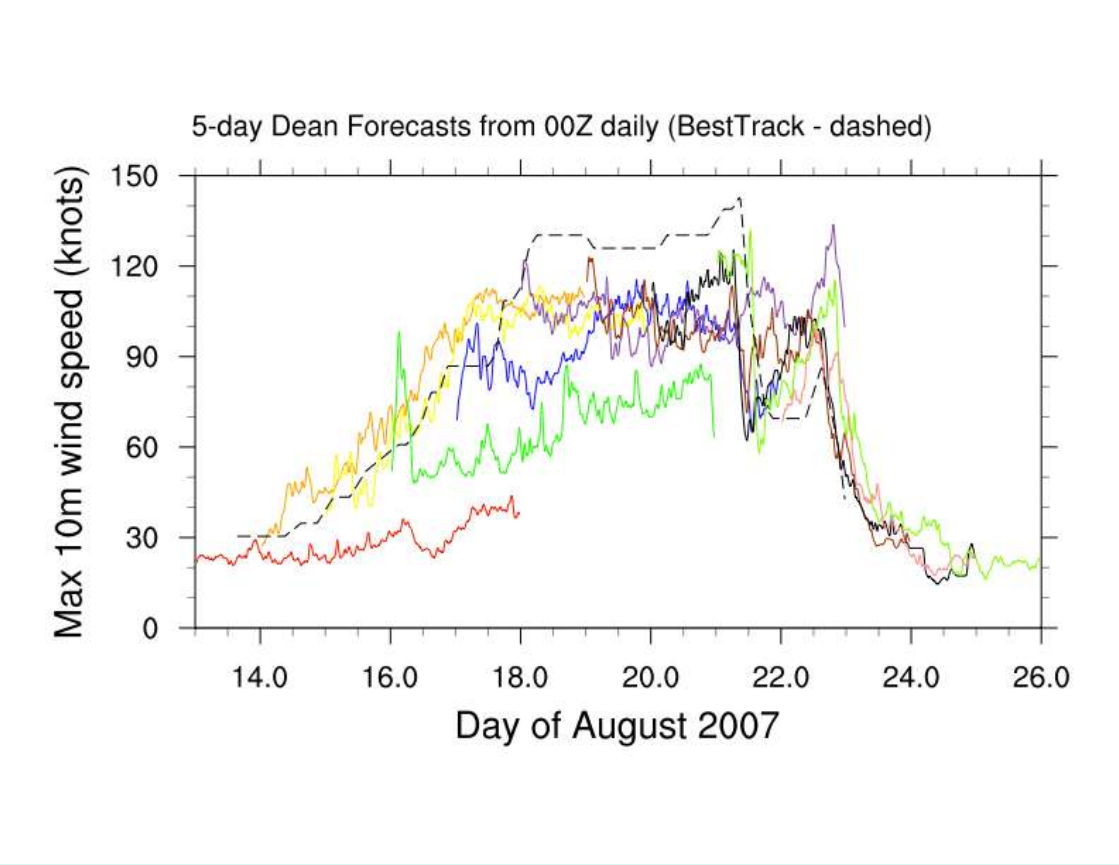
Hurricane Forecast Tests

- Statistical evaluation against operational models in 2005 showed WRF had better skill in track and intensity beyond 3 days (similar skill before that) (study by Mark DeMaria)
- Many re-runs have shown sensitivities to surface flux treatment (Cd and Ck), and grid size (example is Hurricane Dean of 2007)
- Also investigating 1d ocean-mixed layer feedback

Dean track forecasts

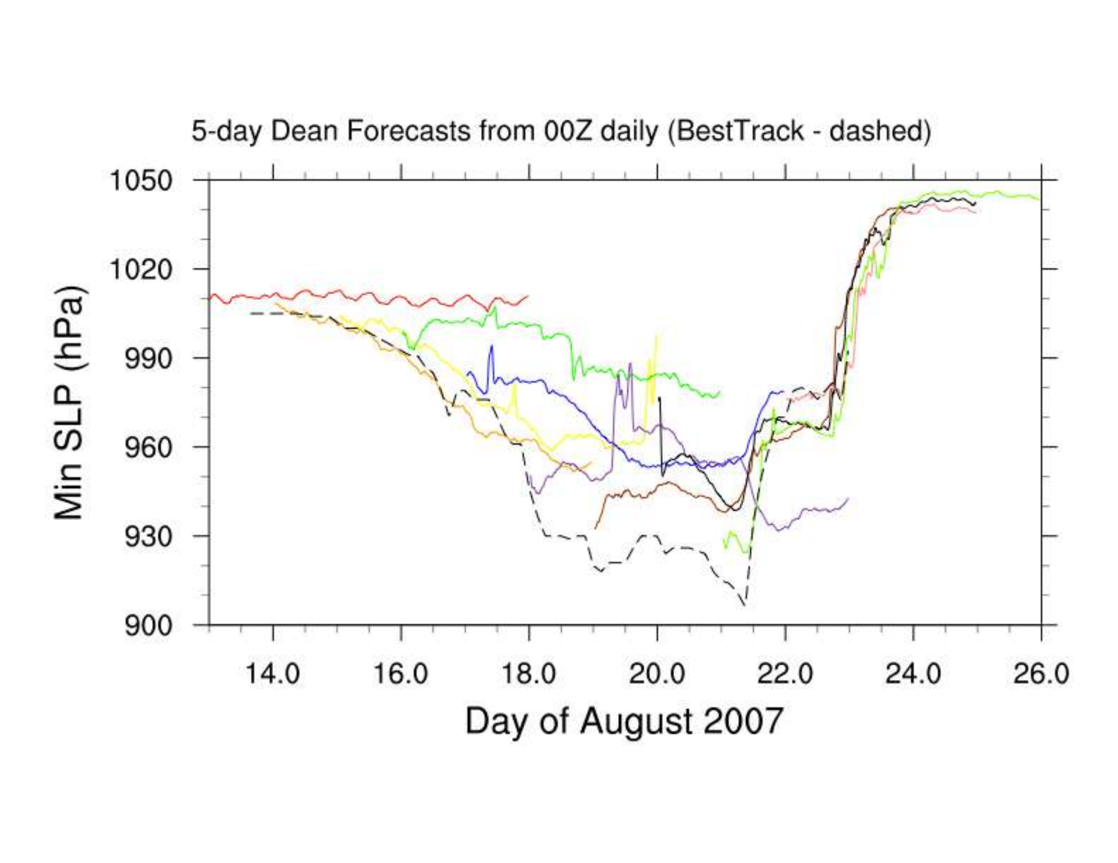


Hurricane Dean (2007)



Note that forecasts underestimate maximum windspeed

Hurricane Dean (2007)



Forecasts also underestimate pressure drop

Surface Fluxes

- Heat, moisture and momentum

$$H = \rho c_p u_* \theta_* \qquad E = \rho u_* q_* \qquad \tau = \rho u_* u_*$$

$$u_* = \frac{kV_r}{\ln(z_r / z_0) - \psi_m} \qquad \theta_* = \frac{k\Delta\theta}{\ln(z_r / z_{0h}) - \psi_h} \qquad q_* = \frac{k\Delta q}{\ln(z_r / z_{0q}) - \psi_h}$$

Subscript *r* is reference level (lowest model level, or 2 m or 10 m)

z_0 are the roughness lengths

Roughness Lengths

- Roughness lengths are a measure of the “initial” length scale of surface eddies, and generally differ for velocity and scalars
- In 2006 AHW $z_{0h}=z_{0q}$ are calculated based on Carlson-Boland (~10^{-4} m for water surfaces, weak variation with wind speed)
- z_0 for momentum is a function of wind speed following tank experiments of Donelan (this replaces the Charnock relation in WRF). This represents the effect of wave heights in a simple way.

Drag Coefficient

- C_{D10} is the 10 m drag coefficient, defined such that

$$\tau \equiv \rho C_{D10} V_{10}^2$$

It is related to the roughness length by (in neutral conditions)

$$C_{D10} = \left(\frac{k}{\ln(z_{10} / z_0)} \right)^2$$

Enthalpy Exchange Coefficient

- C_{E10} is the 10 m moisture exchange coefficient, defined such that

$$E \equiv \rho C_{E10} V_{10} \Delta q$$

It is related to the roughness lengths (assuming neutral conditions) by

$$C_{E10} = \left(\frac{k}{\ln(z_{10} / z_0)} \right) \left(\frac{k}{\ln(z_{10} / z_{0q})} \right)$$

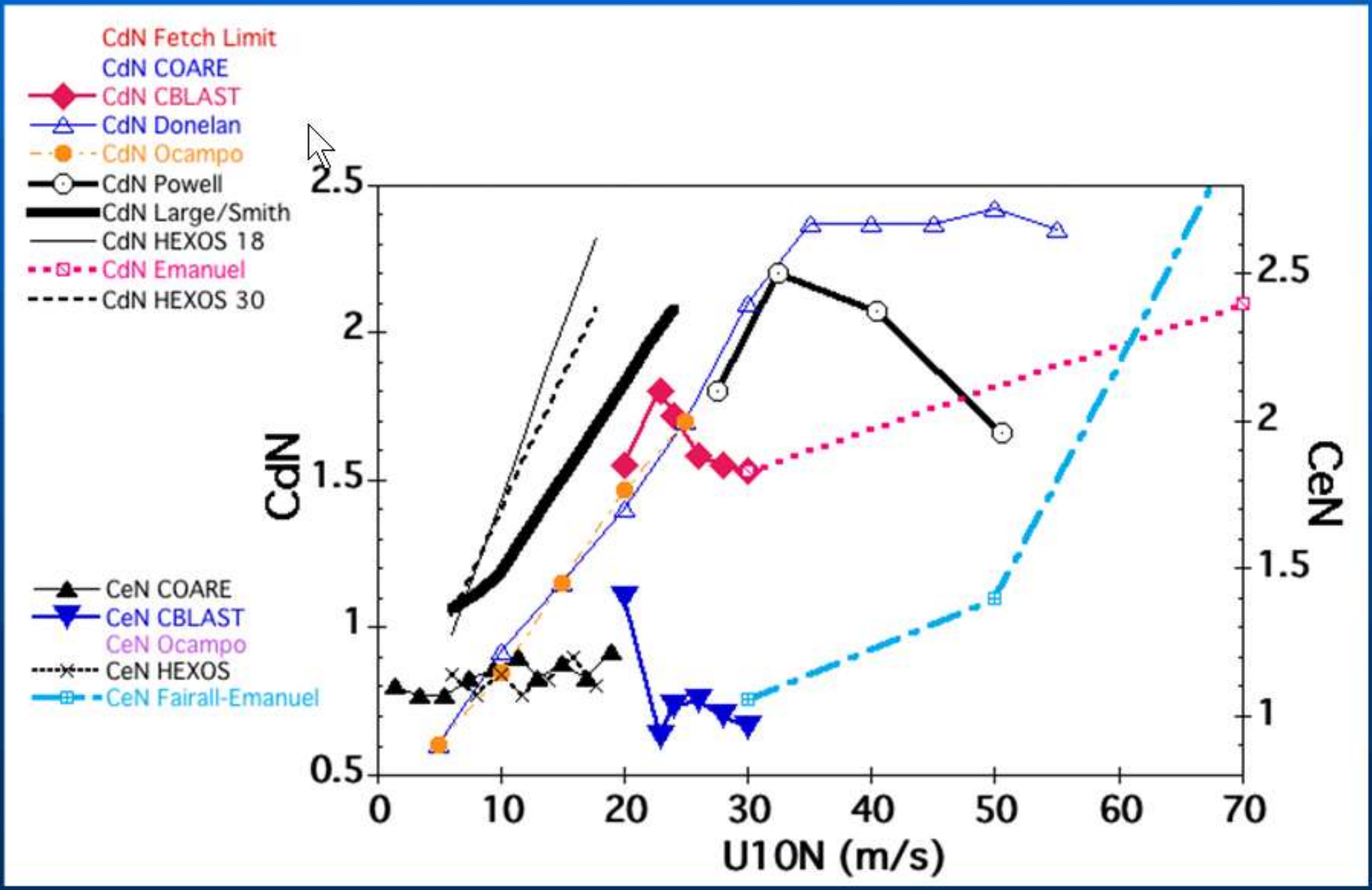
Often it is assumed that C_H=C_E=C_k where C_k is the enthalpy exchange coefficient. However, since 90% of the enthalpy flux is latent heat, the coefficient for sensible heat (C_H) matters less than that for moisture (C_E)

C_D and C_k

- From the works of Emanuel (1986), Braun and Tao (2001) and others the ratio of C_k to C_D is an important factor in hurricane intensity
- Observations give some idea of how these coefficients vary with wind speed but generally have not been made for hurricane intensity

27th AMS Hurricane conference

Black et al. (2006)

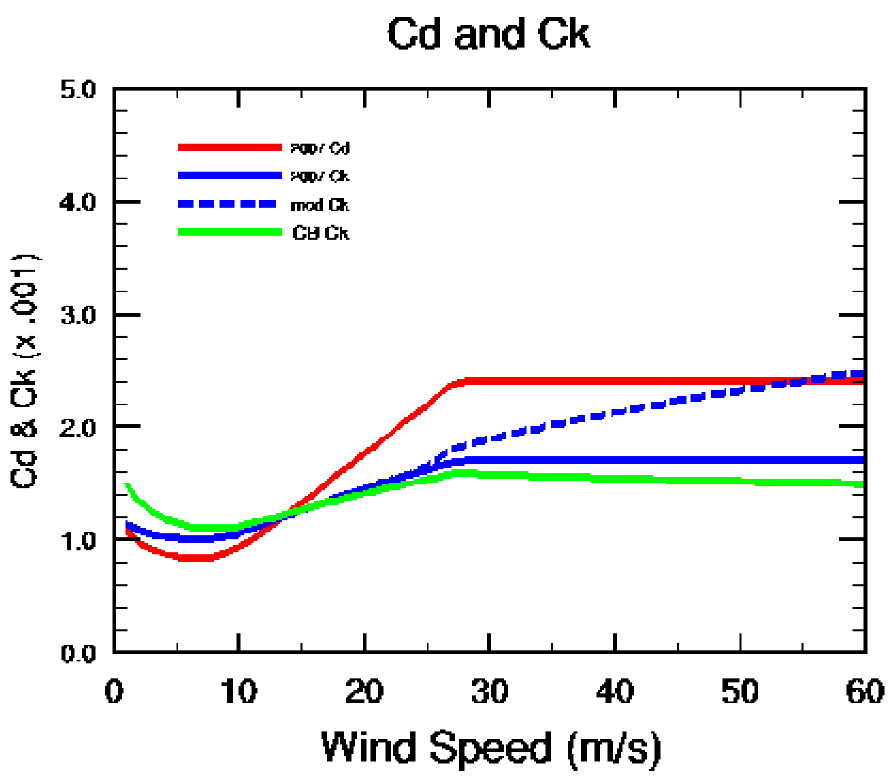


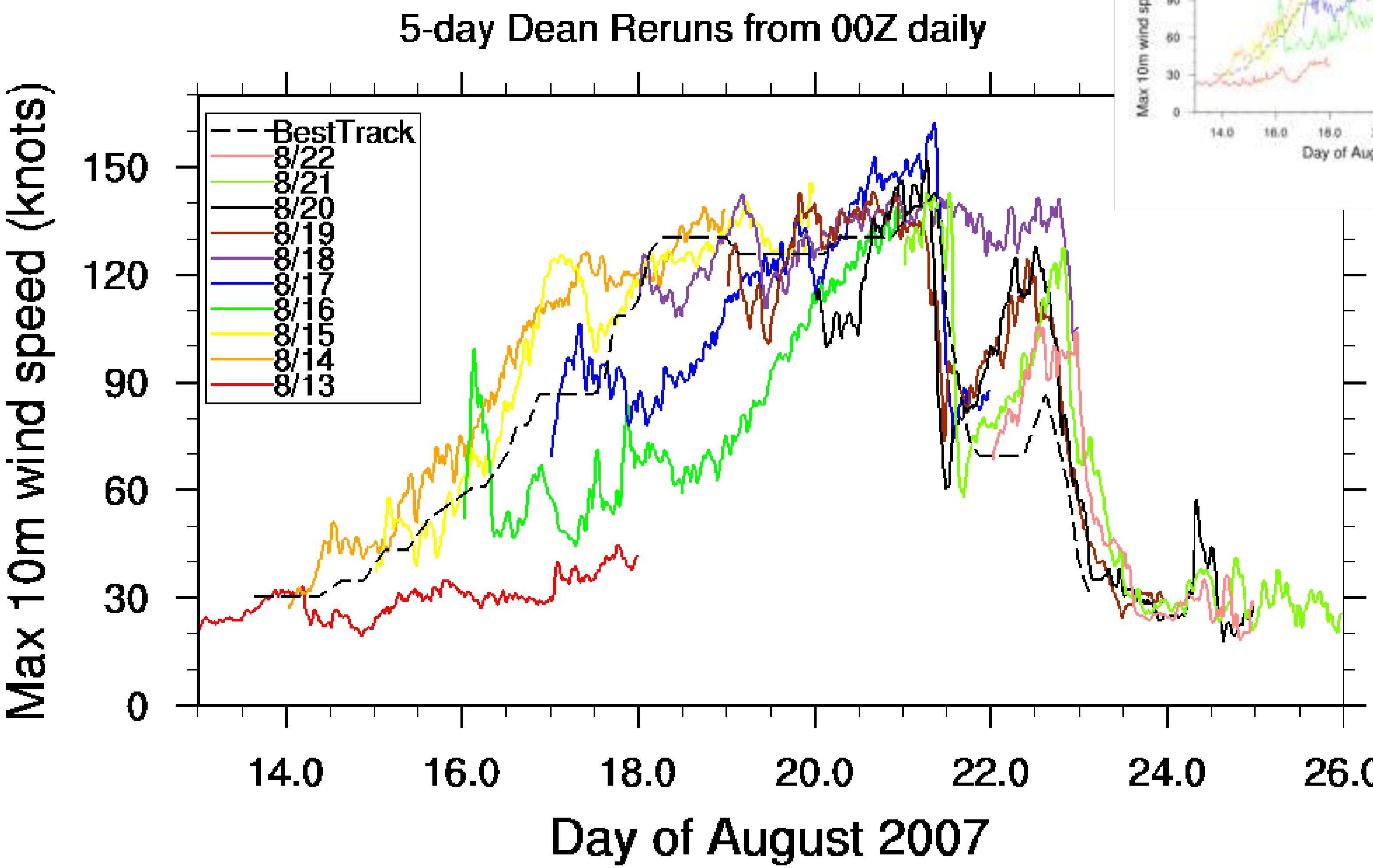
Modification to C_k in AHW

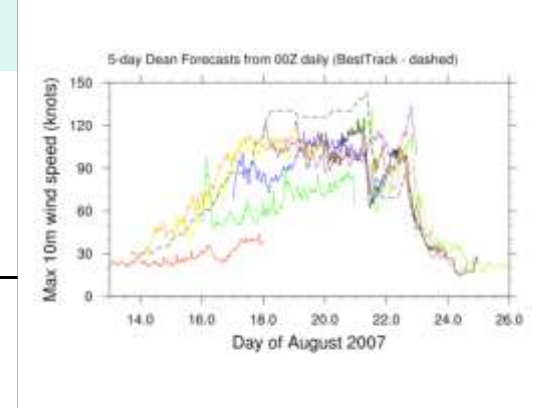
- Commonly z_{0q} is taken as a constant for all wind speeds
- However for winds greater than 25 m/s there is justification for increasing this to allow for sea-spray effects that may enhance the eddy length scales
- We modify z_{0q} in AHW to increase at wind speeds > ~25 m/s
- This impacts C_k as shown next

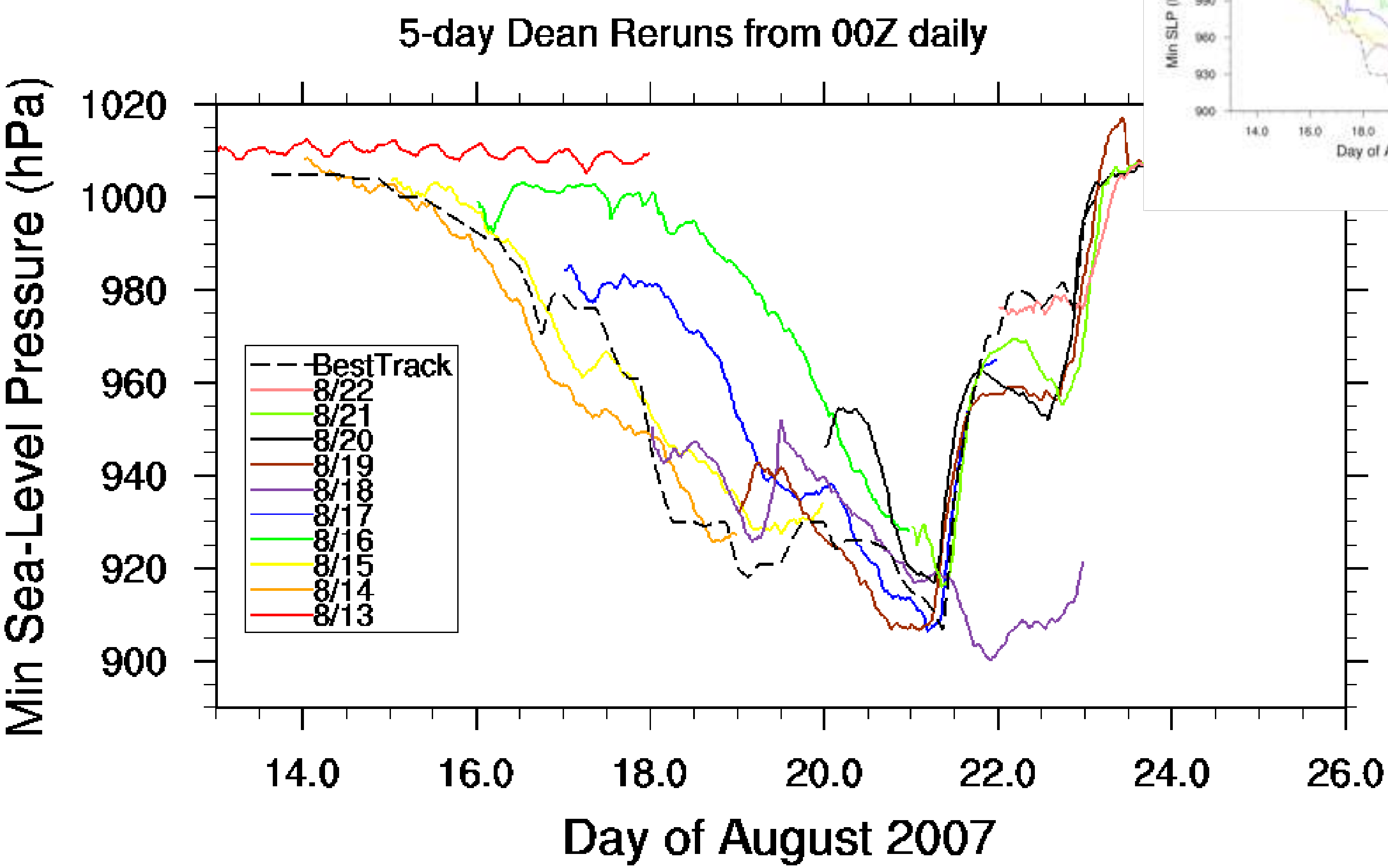
Modification to C_k in AHW

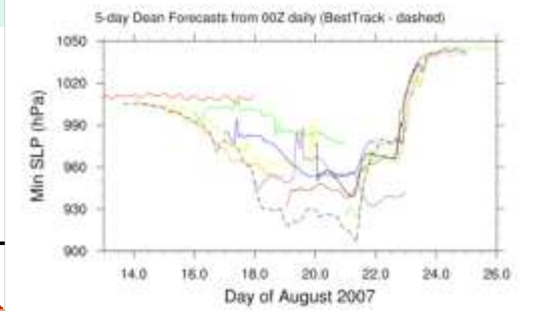
C_d - red
Old CB - green
New C_k - blue dashed
Z_{0q} const - blue solid




5-day Dean Reruns from 00Z daily
Max 10m wind speed (knots)
Day of August 2007
BestTrack
8/22
8/21
8/20
8/19
8/18
8/17
8/16
8/15
8/14
8/13
0
30
60
90
120
150
14.0
16.0
18.0
20.0
22.0
24.0
26.0


5-day Dean Forecasts from 00Z daily (BestTrack - dashed)
Max 10m wind speed (knots)
Day of August 2007


5-day Dean Reruns from 00Z daily
Min Sea-Level Pressure (hPa)
1020
1000
980
960
940
920
900
BestTrack
8/22
8/21
8/20
8/19
8/18
8/17
8/16
8/15
8/14
8/13
14.0
16.0
18.0
20.0
22.0
24.0
26.0
Day of August 2007


5-day Dean Forecasts from 00Z daily (BestTrack - dashed)
Min SLP (hPa)
Day of August 2007

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Hurricane Physics

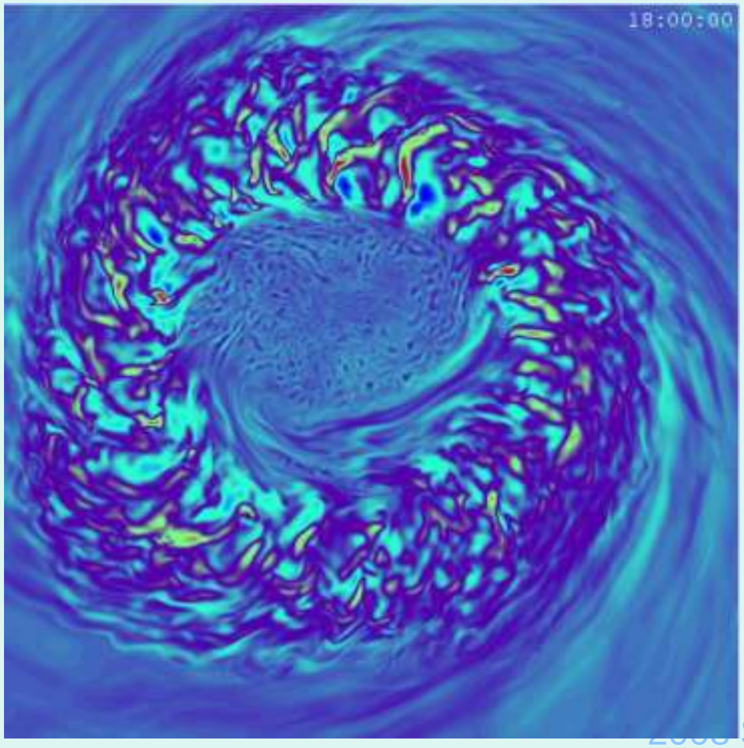
- Results here and elsewhere demonstrate sensitivity of simulated intensity to surface flux formulation
- Also need to add dissipative heating from friction (Bister and Emanuel)
- Other aspects of physics also affect hurricane structure (e.g. microphysics)

Towards LES Modeling

- LES scales (~100 m grids or less)
- NWP not yet at LES scales, but maybe in a decade or two it will be
- Need to evaluate how LES does for challenging situations like hurricanes
- Study by Yongsheng Chen et al. is an example of an early attempt using an idealized hurricane

Large Eddy Simulations of an Idealized Hurricane

Yongsheng Chen, Rich Rotunno, Wei Wang, Christopher Davis, Jimy Dudhia, Greg Holland
MMM/NCAR

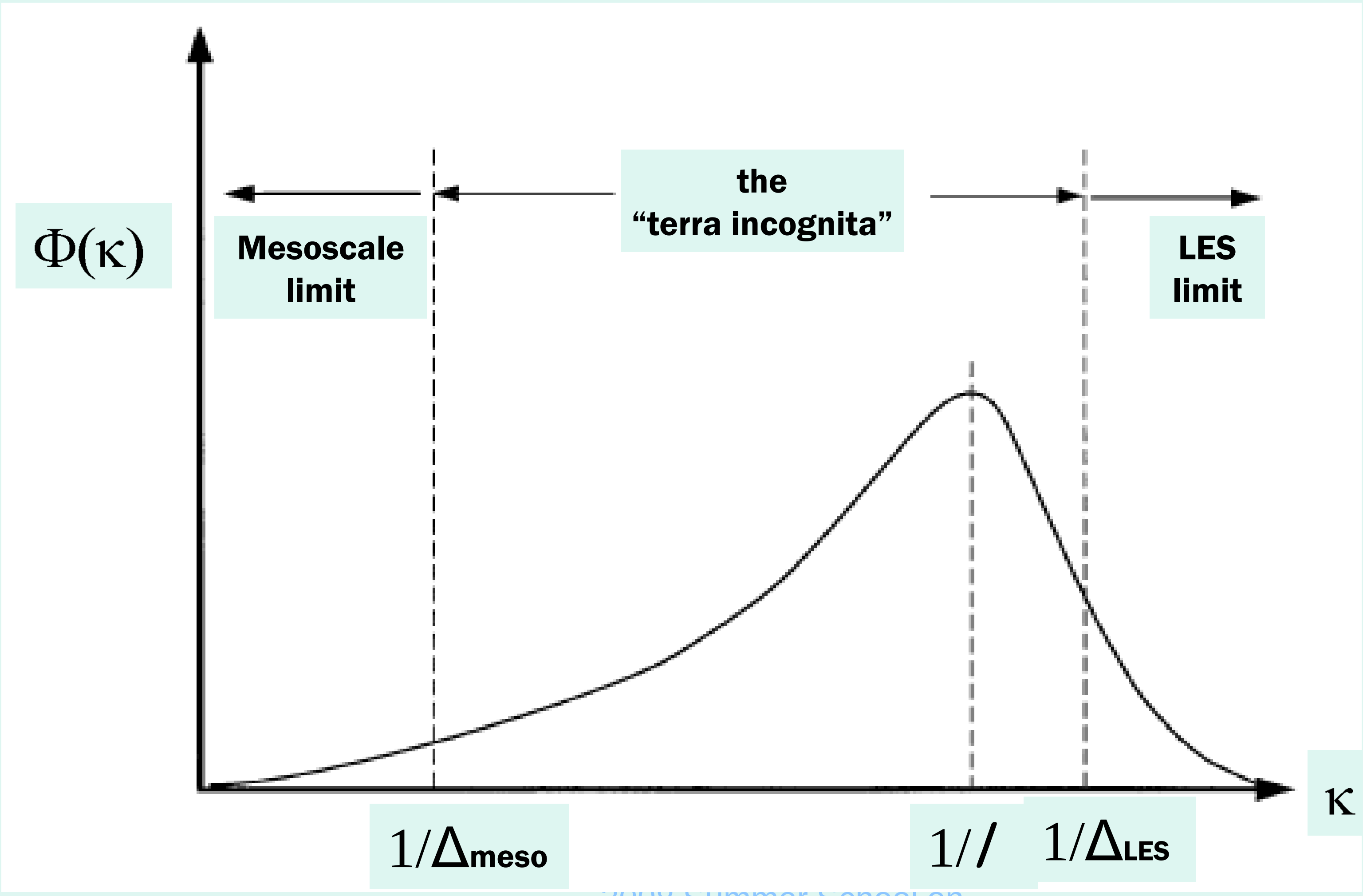


37km

Motivation

1. Intensity sensitivity to model resolution
2. Direct computation of effects of turbulence

Regimes of Numerical Modeling
(Wyngaard 2004)



From Y. Chen et al. 2008

Model Setup

Idealized TC

f-plane

zero env wind

fixed SST

Nested Grids

WRF Model Physics

WSM3 simple ice

No radiation

Relax to initial temp.

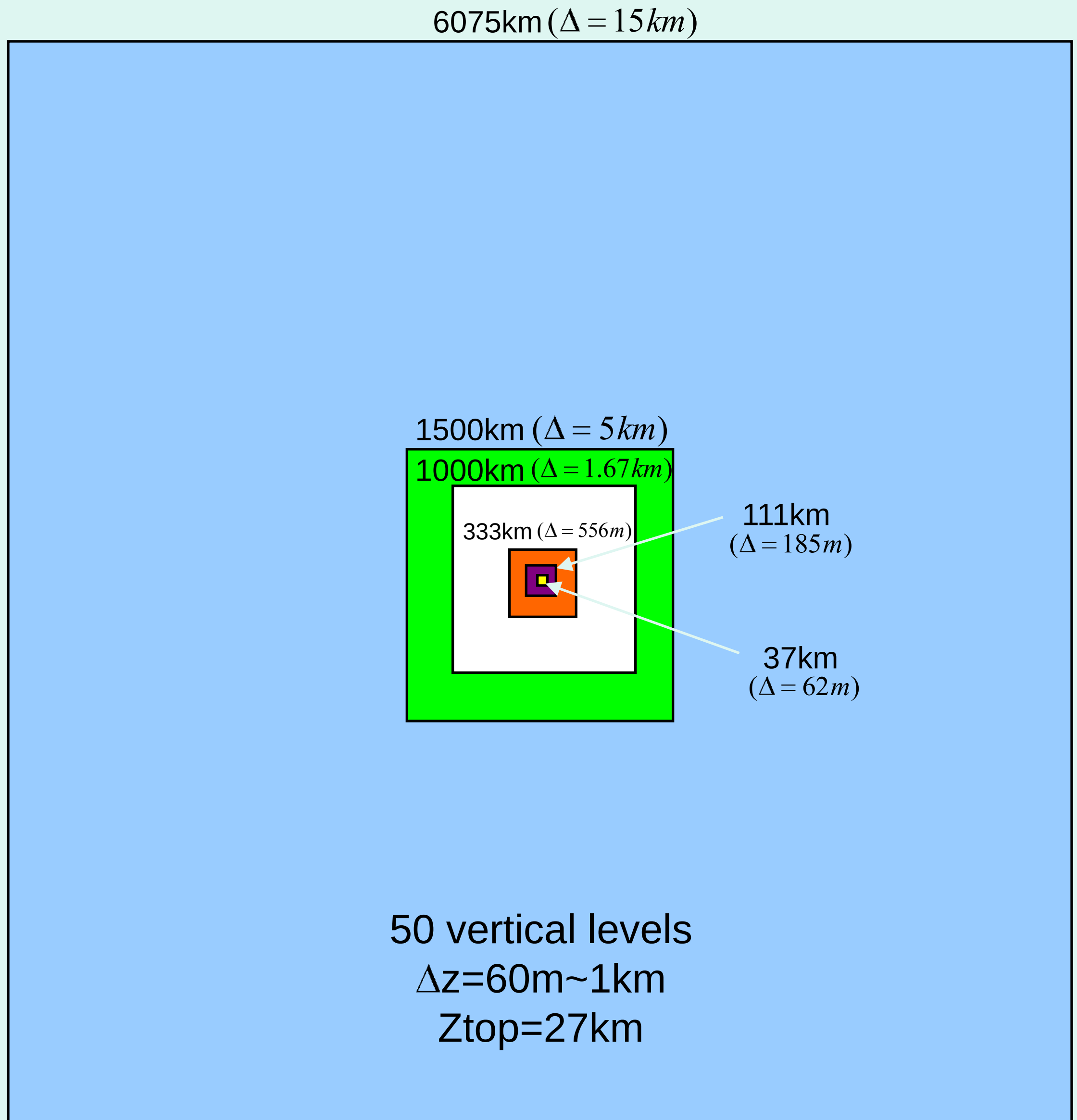
Cd (Donelan)

Ck (Carlson-Boland)

Ck/Cd ~ 0.65

YSU PBL $(\Delta \geq 1.67km)$

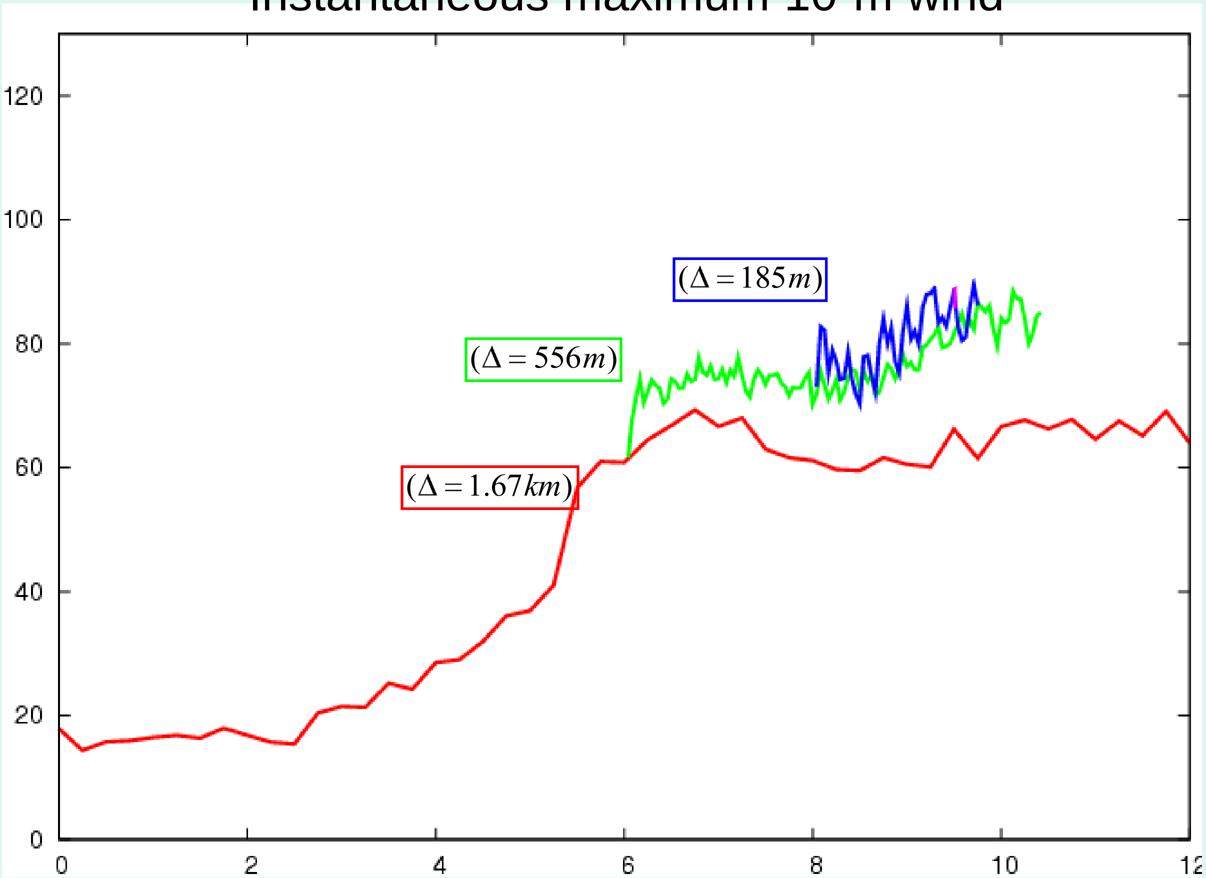
LES PBL $(\Delta < 1.67km)$



From Y. Chen et al. 2008

Intensity Evolution

Instantaneous maximum 10-m wind

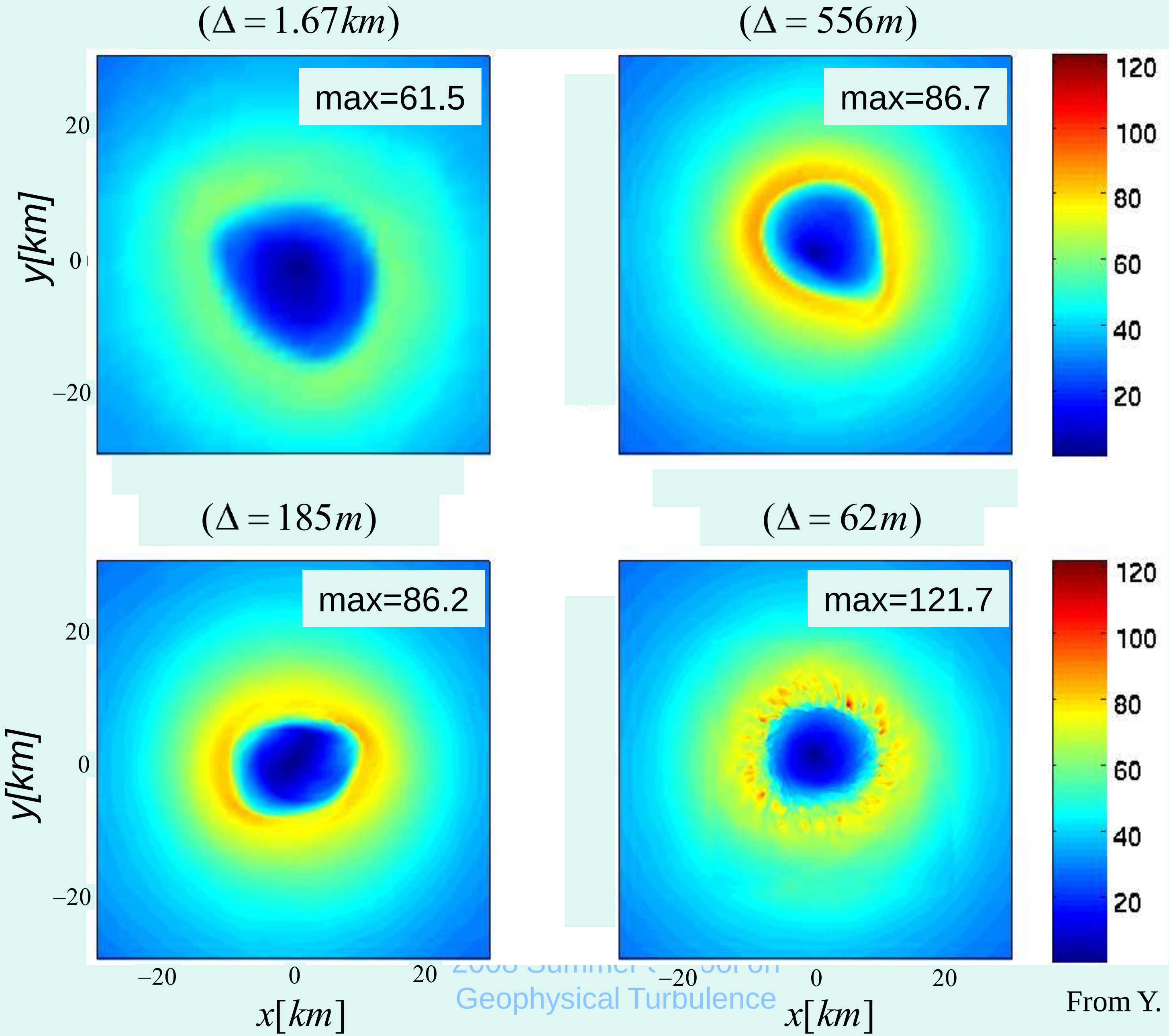


$t\,[d] \rightarrow$

From Y. Chen et al. 2008

LES

Surface Wind ~ Resolution

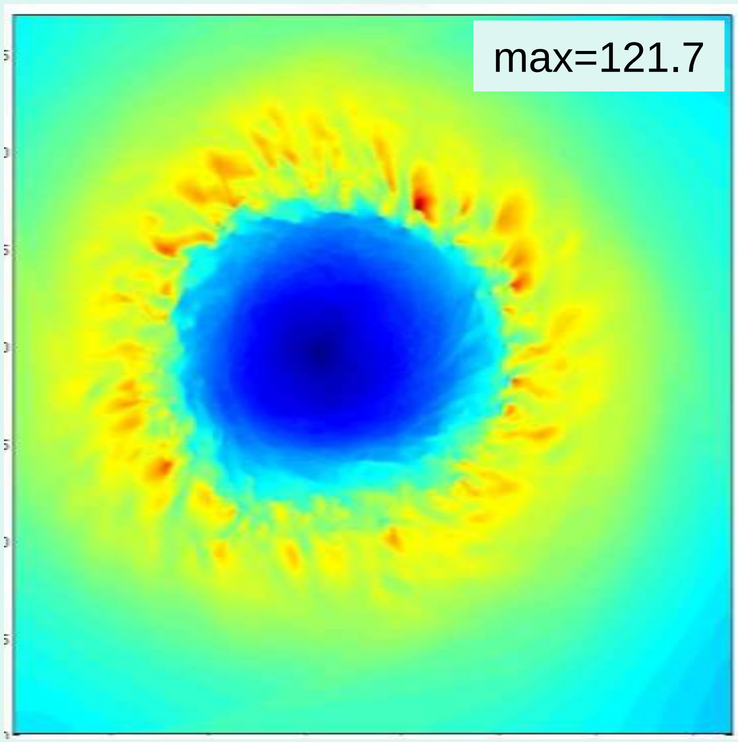


LES

From Y. Chen et al. 2008

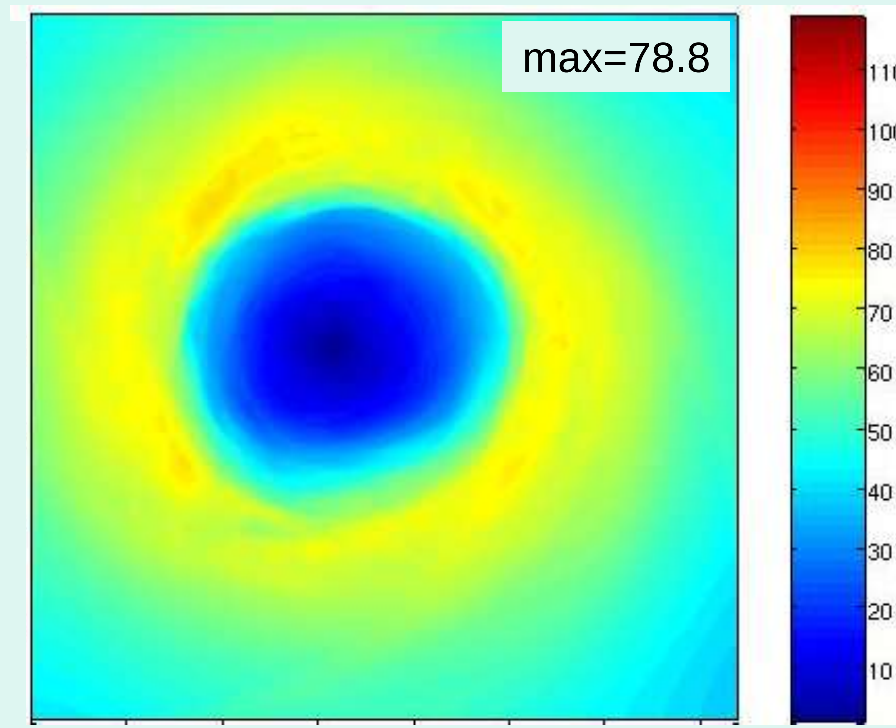
1-min Averaged Surface Wind

instantaneous



37km

1-min average

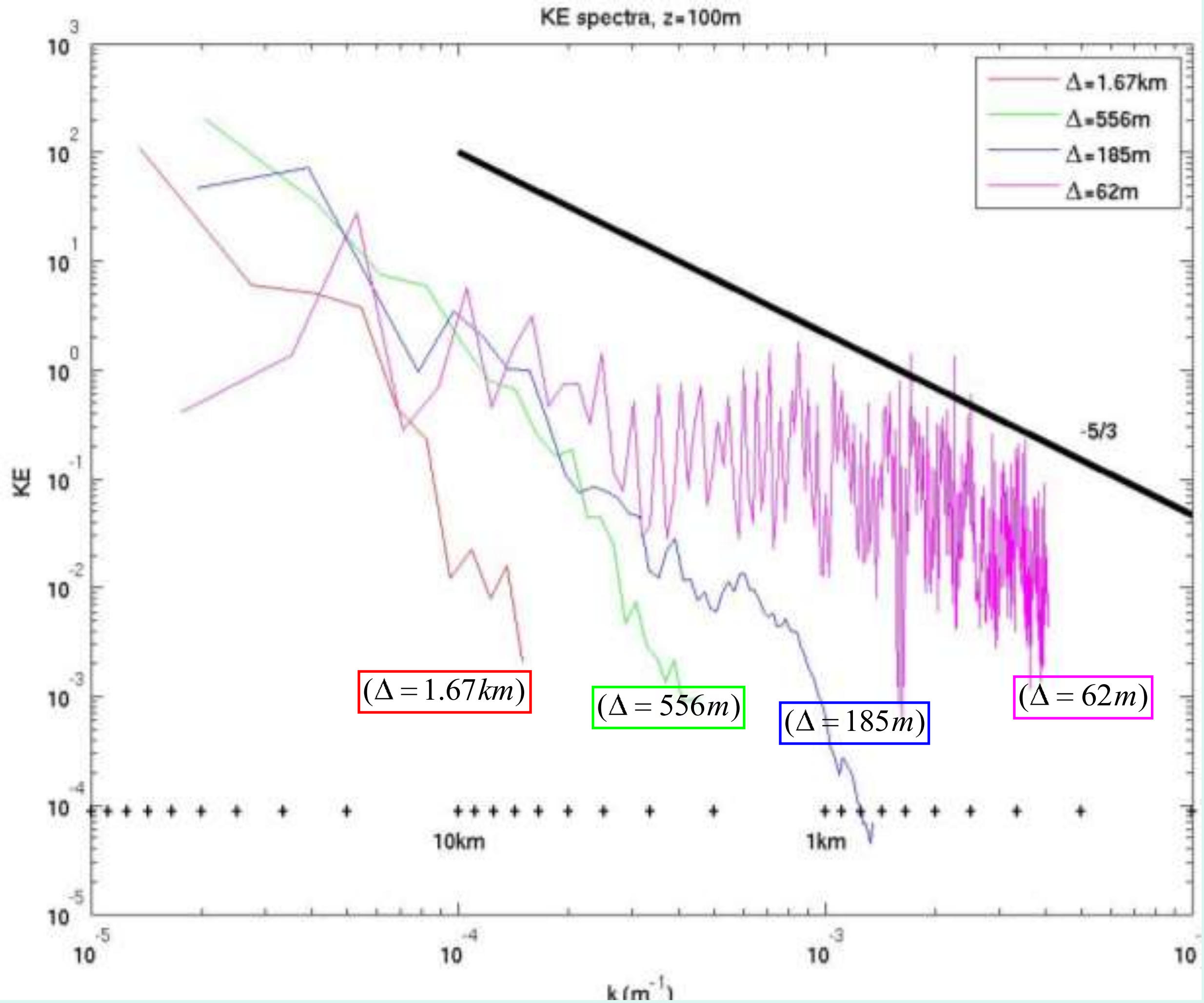


37 km

LES

From Y. Chen et al. 2008

Eddy Kinetic Energy Spectra



From Y. Chen et al. 2008

LES Hurricane Tests

- At 62 meter grid, eddies become resolved representing individual gusts
- Issues remain
  - Near ground LES schemes lack proper treatment of reduced eddy sizes, since much kinetic energy should remain in sub-grid-scale turbulence there
  - Therefore, never possible to fully resolve turbulence near surface

Summary and Conclusions

- Regional modeling and NWP rely on turbulence parameterizations
  - PBL schemes and vertical diffusion
  - Horizontal diffusion
  - Surface eddy transports
  - (also) Gravity-wave drag
- Forecast skill depends on methods used
- Better parameterizations for these processes are being developed in ongoing research