Non-hydrostatic Multi-scale Model on the B grid (NMMB)

Scientific Background

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Nonhydrostatic *Multiscale* Model on the B grid (NMMB)

- ✧ Built on NWP and regional climate experience (Janjic et al., 2001, MWR; Janjic, 2003, MAP)
- ✧ Further evolution of WRF Nonhydrostatic *Mesoscale* Model (WRF NMM, HWRF) (Janjic, 2005, EGU; Janjic & Black, 2007, EGU; Janjic & Gall 2012, NCAR)
- ✧ Add-on nonhydrostatic module
- ✧ Pressure based vertical coordinate, nondivergent flow remains on coordinate surfaces

Non-hydrostatic Multi-scale Model on the B grid (NMMB)

- Conservation of important properties of the continuous system aka “mimetic” approach in Comp. Math. (Arakawa 1966, 1972, …; Jacobson 2001; Janjic 1977, …; Sadourny, 1968, … ; Tripoli, 1992 …)
  - Nonlinear energy cascade controlled by energy and enstrophy conservation
  - No overspecification of *w* in the nonhydrostatic dynamics, Φ, w are not independent (see the nonhyhydrostatic continuity equation) ➔ no independent prognostic equation for *w*!
  - A number of first order (including momentum) and quadratic quantities (energy, enstrophy, temperature…) conserved
  - Conservative omega-alpha term, transformations between KE and PE
  - Errors associated with representation of orography minimized
  - Mass conserving positive definite monotone Eulerian tracer advection

Inviscid Adiabatic Equations

π Hydrostatic pressure

p Nonhydrostatic pressure

$\mu = \pi_{Sfc} - \pi_T$ Difference between hydrostatic pressures at surface and top

$$\pi(x,y,s,t) = \pi_T + \sigma_1(s)\Pi + \sigma_2(s)\mu(x,y,t)$$ General hybrid coordinate

Π Constant depth of hydrostatic pressure layer at the top

σ_1 Zero at top and bottom of model atmosphere

σ_2 Increases from 0 to 1 from top to bottom

$\alpha = RT/p$ Gas law

$$\frac{\partial \Phi}{\partial \pi} = -\alpha$$ Hypsometric (not "hydrostatic") Eq.

$$\left[\frac{\partial}{\partial t}\left(\frac{\partial \pi}{\partial s}\right)\right]_s + \nabla_s \cdot \left(\mathbf{v}\frac{\partial \pi}{\partial s}\right) + \frac{\partial}{\partial s}\left(\dot{s}\frac{\partial \pi}{\partial s}\right) = 0$$ Hydrostatic continuity Eq.

Continued ...

Inviscid Adiabatic Equations

$$w=\frac{1}{g}\left[\left(\frac{\partial\Phi}{\partial t}\right)_s+\mathbf{v}\cdot\nabla_s\Phi+\left(\dot{s}\frac{\partial\pi}{\partial s}\right)\frac{\partial\Phi}{\partial\pi}\right]+W(x,y,t)]$$

Integral of nonhydrostatic continuity Eq.

$$\varepsilon\equiv\frac{1}{g}\frac{dw}{dt}=\frac{1}{g}\left[\left(\frac{\partial w}{\partial t}\right)_s+\mathbf{v}\cdot\nabla_s w+\left(\dot{s}\frac{\partial\pi}{\partial s}\right)\frac{\partial w}{\partial\pi}\right]$$

Vertical acceleration

$$\frac{\partial p}{\partial\pi}=1+\varepsilon$$

Third Eq. of motion

$$\frac{d\mathbf{v}}{dt}=-(1+\varepsilon)\nabla_s\Phi-\alpha\nabla_s p+f\mathbf{k}\times\mathbf{v}$$

Momentum Eq.

$$\frac{\partial T}{\partial t}=-\mathbf{v}\cdot\nabla_s T-\left(\dot{s}\frac{\partial\pi}{\partial s}\right)\frac{\partial T}{\partial\pi}+\frac{\alpha}{c_p}\left[\frac{\partial p}{\partial t}+\mathbf{v}\cdot\nabla_s p+\left(\dot{s}\frac{\partial\pi}{\partial s}\right)\frac{\partial p}{\partial\pi}\right]$$

Thermodynamic Eq.

Nonhydrostatic Dynamics Specifics

- ✧ Φ, w, ε are not independent, no independent prognostic equation for w!
- ✧ More complex numerical algorithm, but no over-specification of w
- ✧ ε <<1 in meso and large scale atmospheric flows
- ✧ Impact of nonhydrostatic dynamics becomes detectable at resolutions <10km, important at 1km.

Nonhydrostatic Multiscale Model on the B grid (NMMB)

- ✧ Coordinate system and grid
  - ✧ Regional rotated lat-lon ➔ more uniform grid size
  - ✧ Arakawa B grid

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h       h       h
    v       v
h       h       h
    v       v
h       h       h
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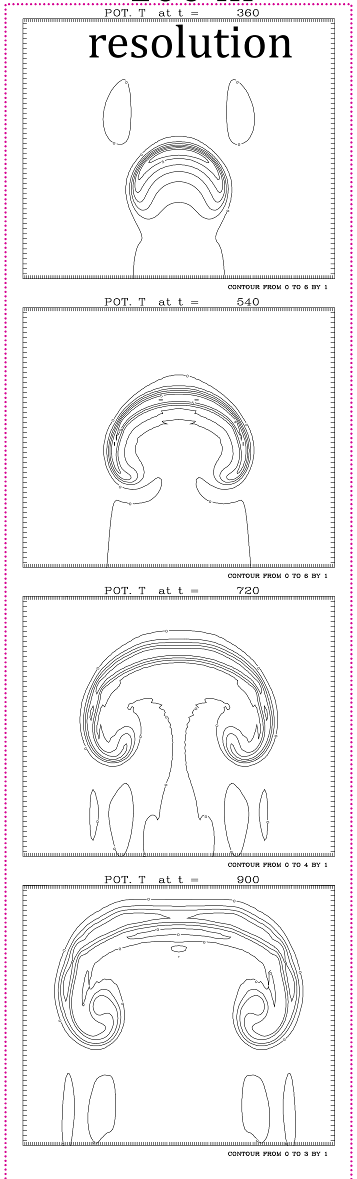
- ✧ No time splitting ➔ no iterative time differencing ➔ higher computational efficiency
- ✧ Global lat-lon, 2 way moving, telescoping nests

Nonhydrostatic Multiscale Model on the B grid (NMMB)

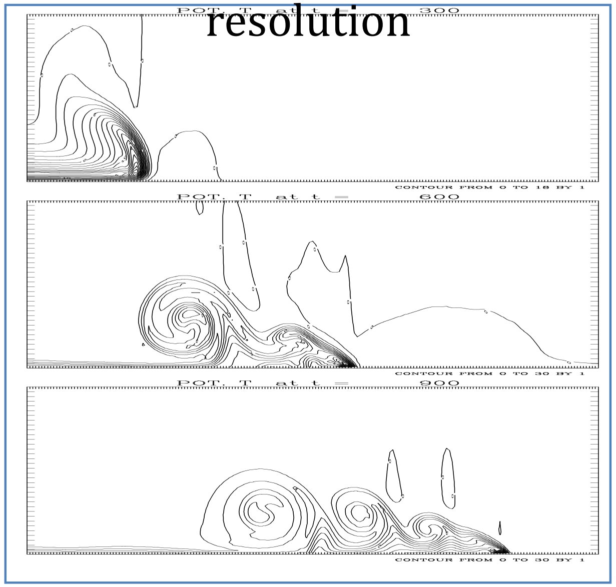
- ✧Regional domain lateral boundaries
  - ✧Narrow zone with upstream advection, no computational outflow BC for advection
  - ✧Blending zone
- ✧Conservative polar boundary conditions
- ✧Polar filter
  - ✧"Decelerator," tendencies filtered, waves slowed down, no effect on amplitudes

2D very high resolution non-hydrostatic tests

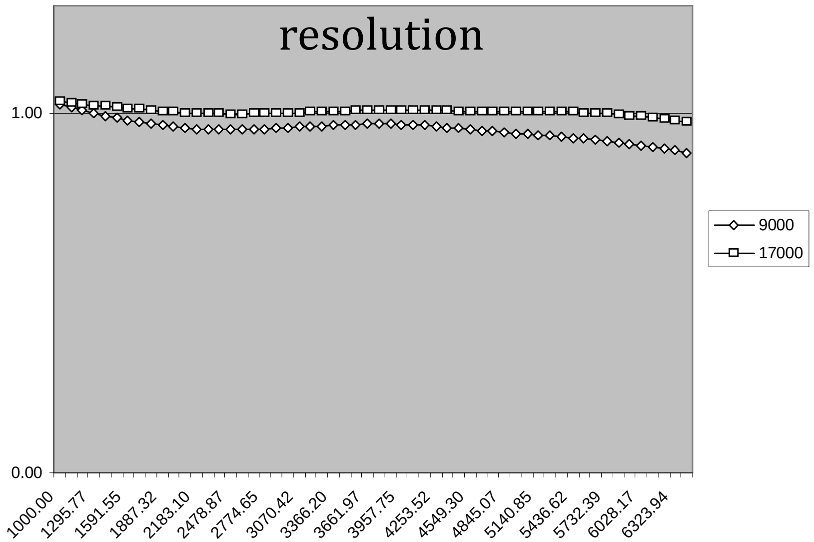
Warm bubble, 100 m resolution



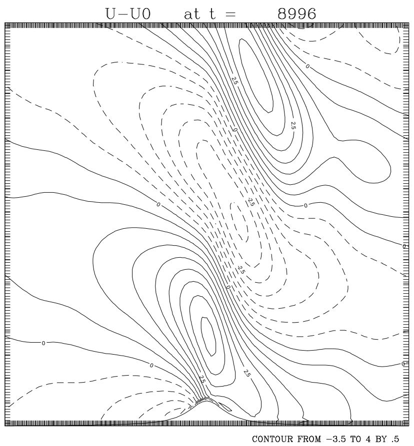
Cold bubble, 100 m resolution



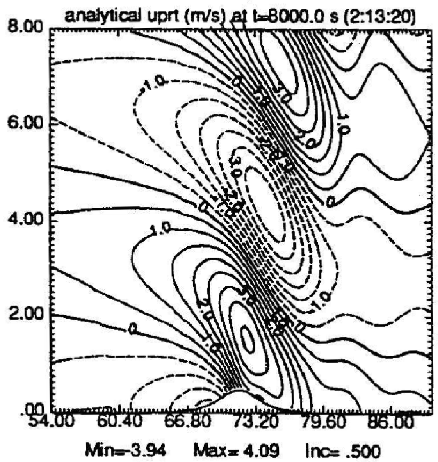
Normalized vertical momentum flux, 400 m resolution



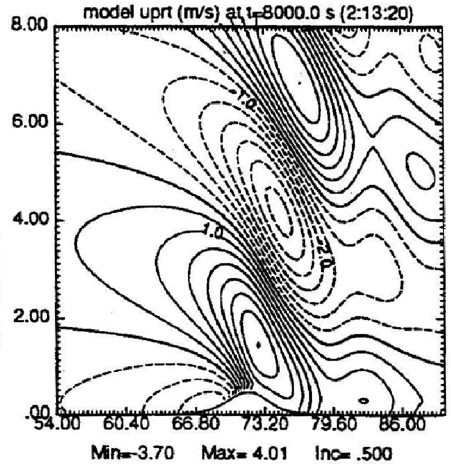
Nonlinear mountain wave 400 m resolution



Full compressible NMM (Boussinesque)

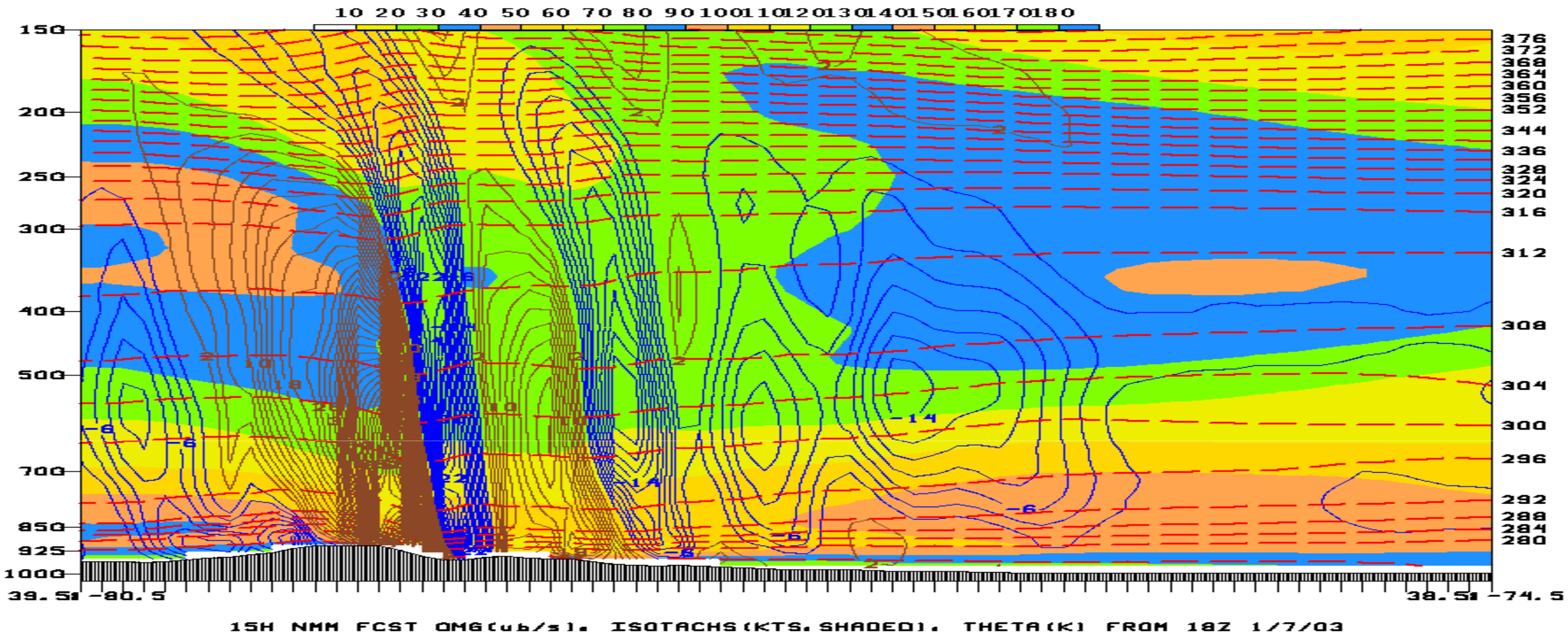


Analytical (Boussinesque)

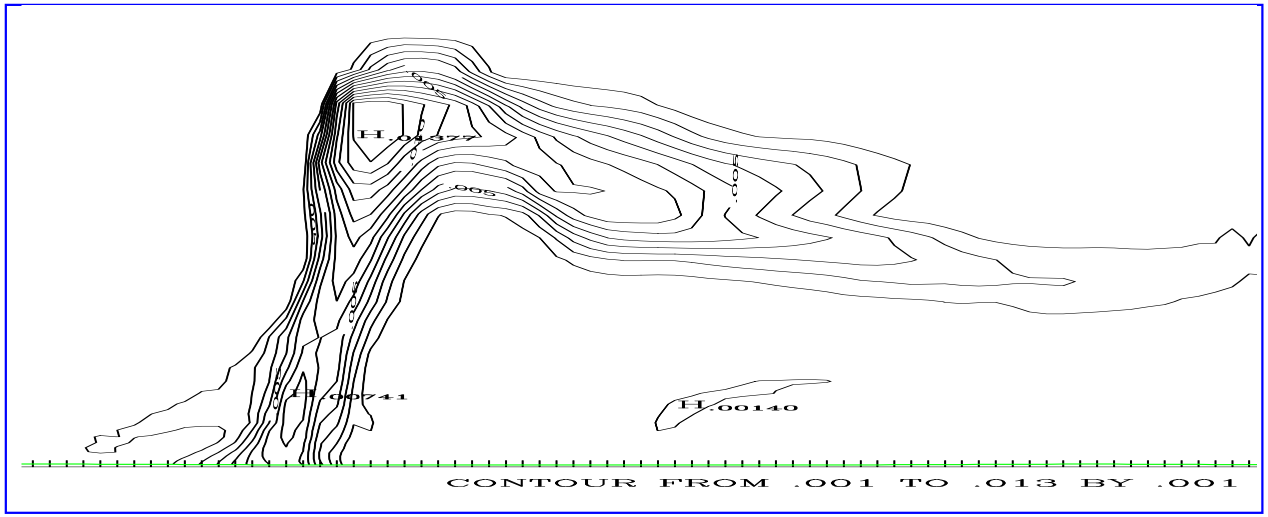


ARPS

Mountain waves, 8 km resolution



Convection, 1 km resolution



Atmospheric Spectrum

- Incorrect nonlinear energy cascade a major source of computational noise, classical paper by Sadourny, 1975, JAS:

> a correct energy spectrum for a numerical solution is not by itself a proof of the accuracy of the simulated energy transfers. In fact, it is always possible to force the energy distribution of any numerical solution to conform to a known spectral shape in the inertial range through ad-hoc assumptions, regarding, for instance, addition of artificial viscosity.

- **With filtering, one does not need an atmospheric model for "correct" atmospheric spectrum!**

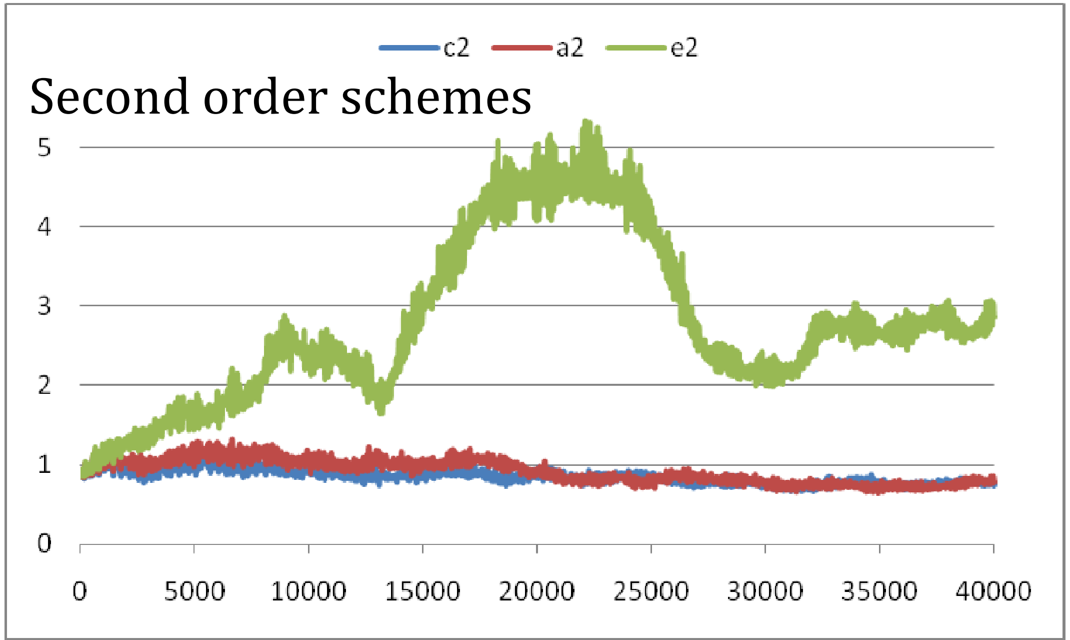
Atmospheric Spectrum

✧Instead (Sadourny, 1975, JAS):

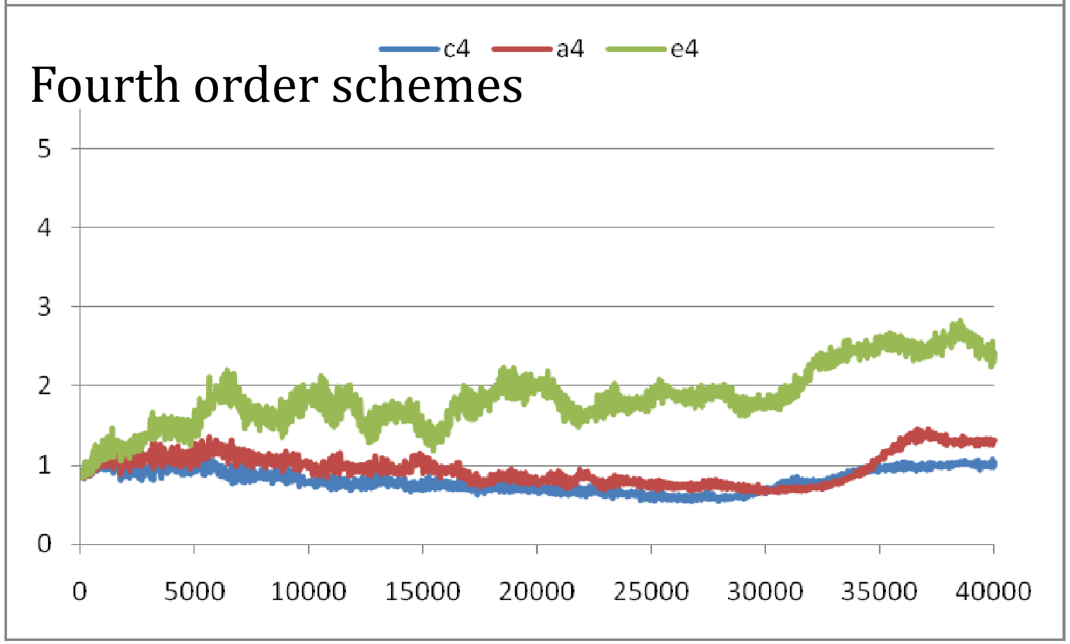
realistic energy spectrum should not be forced by artificial techniques, but should come instead as a by-product of the first principles only, via correct treatment of the non-linear interactions.

✧Philosophy built into the design of the compact nonlinear momentum advection schemes for semi-staggered grids (Janjic, 1984, MWR; Janjic, 2004, AMS; Janjic and Gall, 2012, NCAR)

Noise



Noise



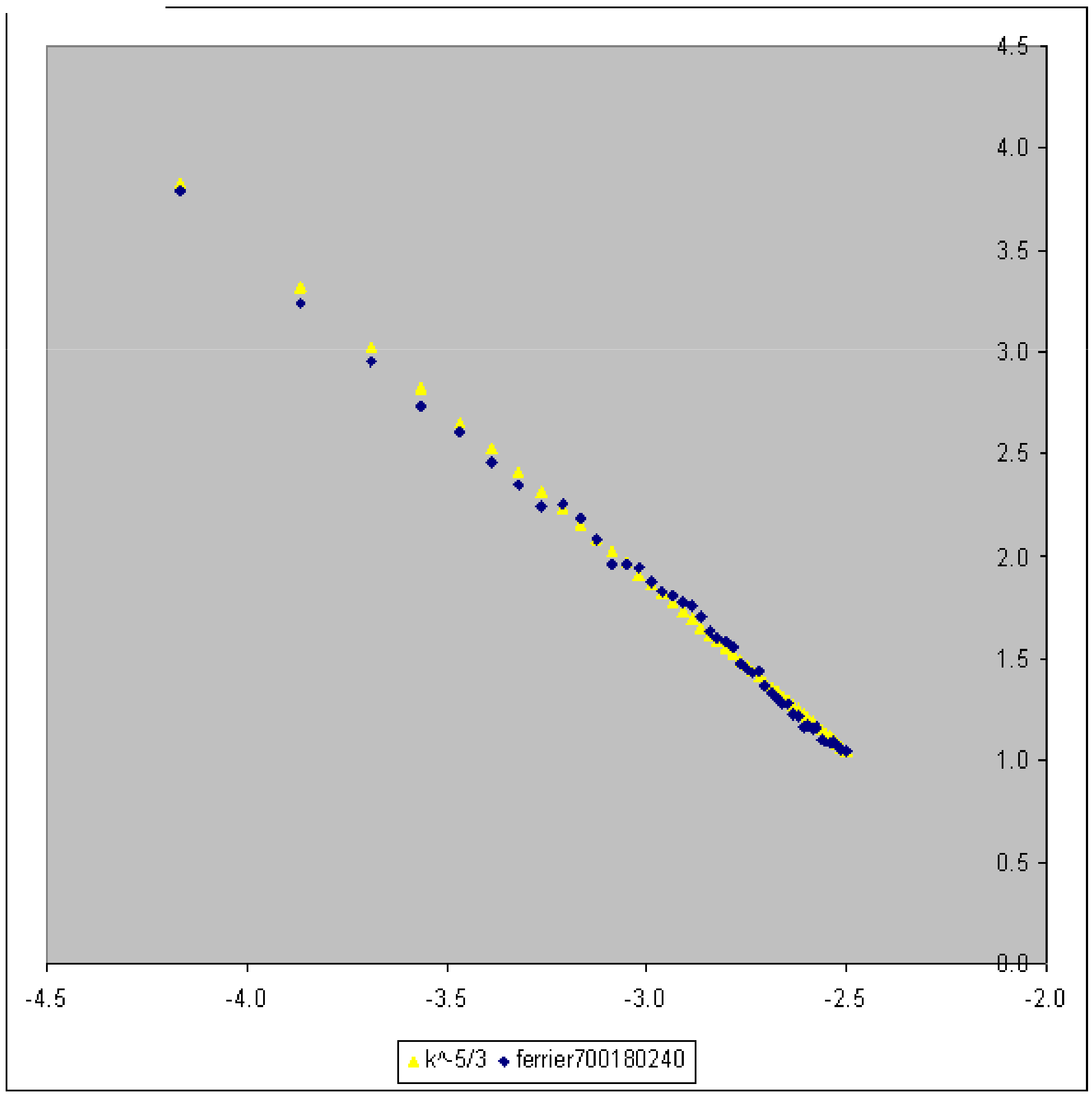
116 days

- Low resolution shallow water equations on flat square Earth
- Blue (Janjic, 1984, MWR) red, controlled energy cascade, but not enstrophy conserving, (Arakawa, 1972, UCLA) green, energy and x (alternative) enstrophy conserving (Janjic, 1984, MWR)
- Different nonlinear noise levels (green scheme) with identical formal accuracy and truncation error (Janjic et al. 2011, MWR)
- Enhanced formal accuracy of well behaved conservative nonlinear advection scheme did not add measurable value, also to global forecasts in terms of Anomaly Correlation Coefficient (Janjic et al. 2011, MWR)

Hours 3-4 average decaying 3D turbulence, Fort Sill storm, 05/20/77

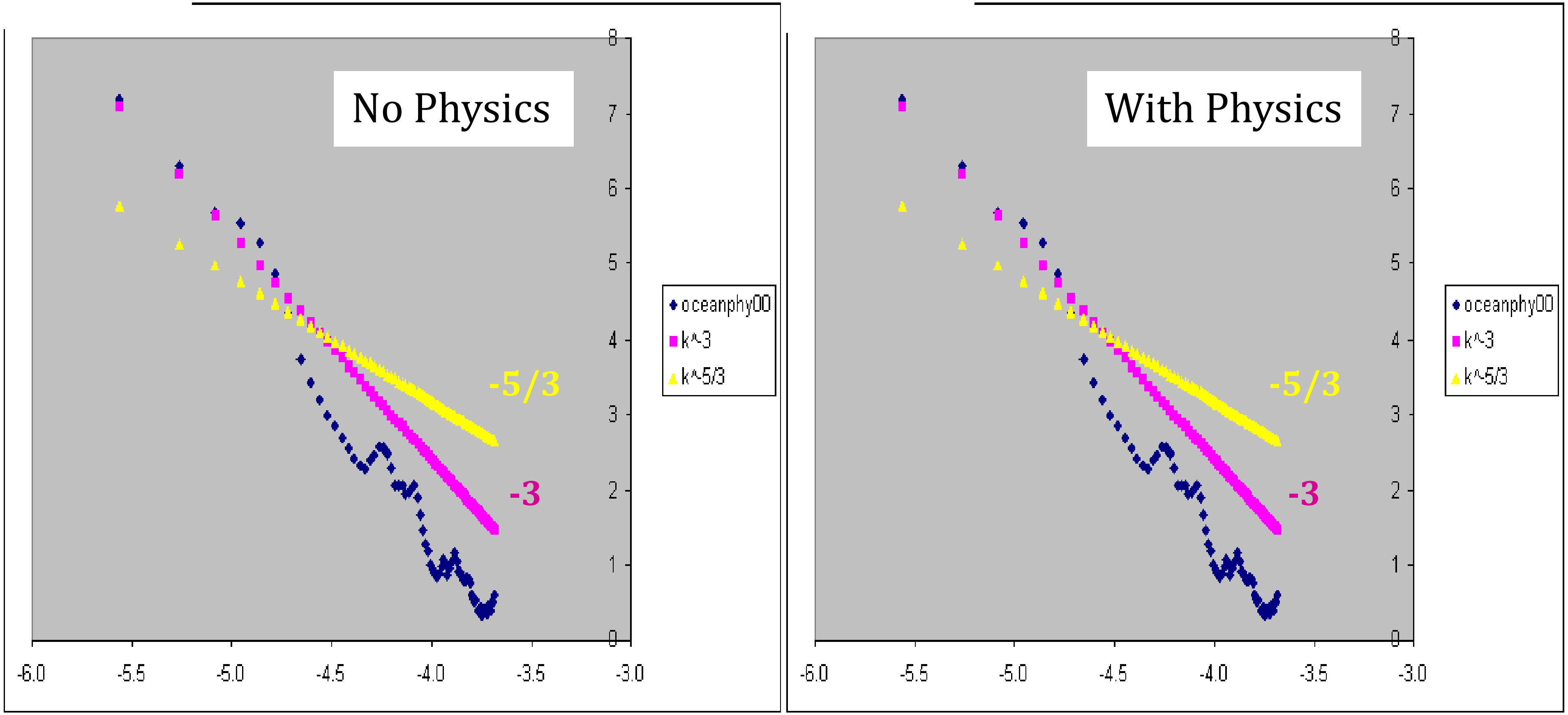
NMM-B,
Ferrier microphysics, 1km resolution, 32 levels,
112km by 112km by 16.4km, double periodic. Smagorinsky constant 0.32.

Mean spectrum of w^2 at 700 hPa.



- Small scale energy in short regional runs with controlled nonlinear cascade and controlled noise sources, where from?

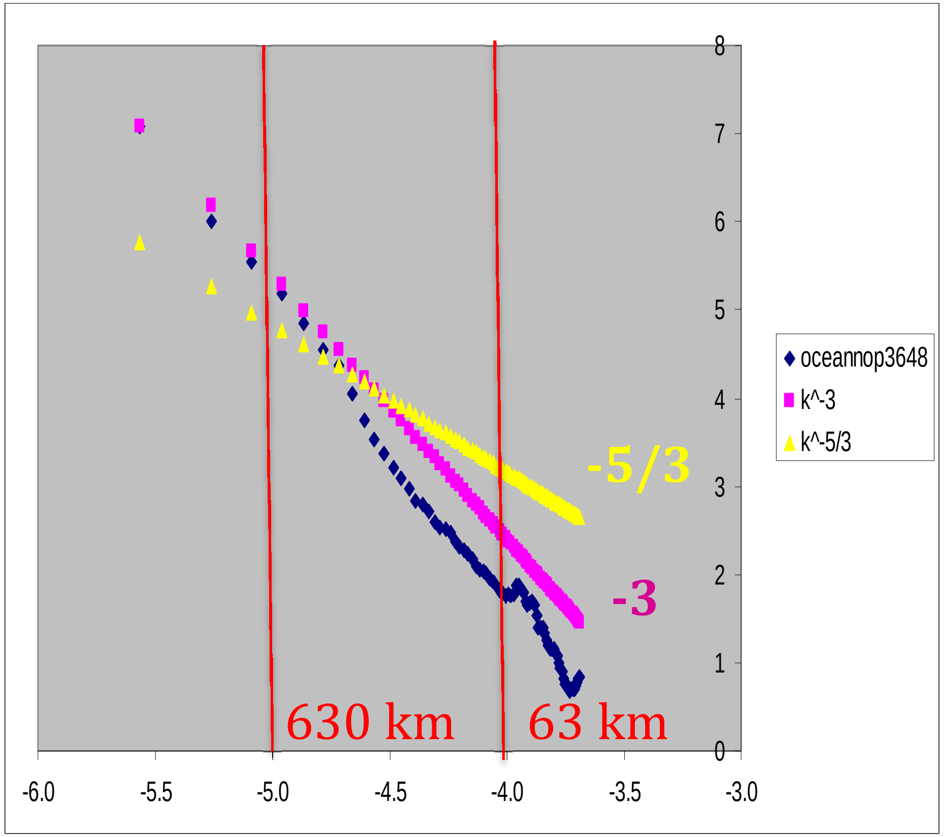
Flat bottom (Atlantic), NMMB, 15km, 32 levels, 48h run (Loops) Janjic, 2004, AMS



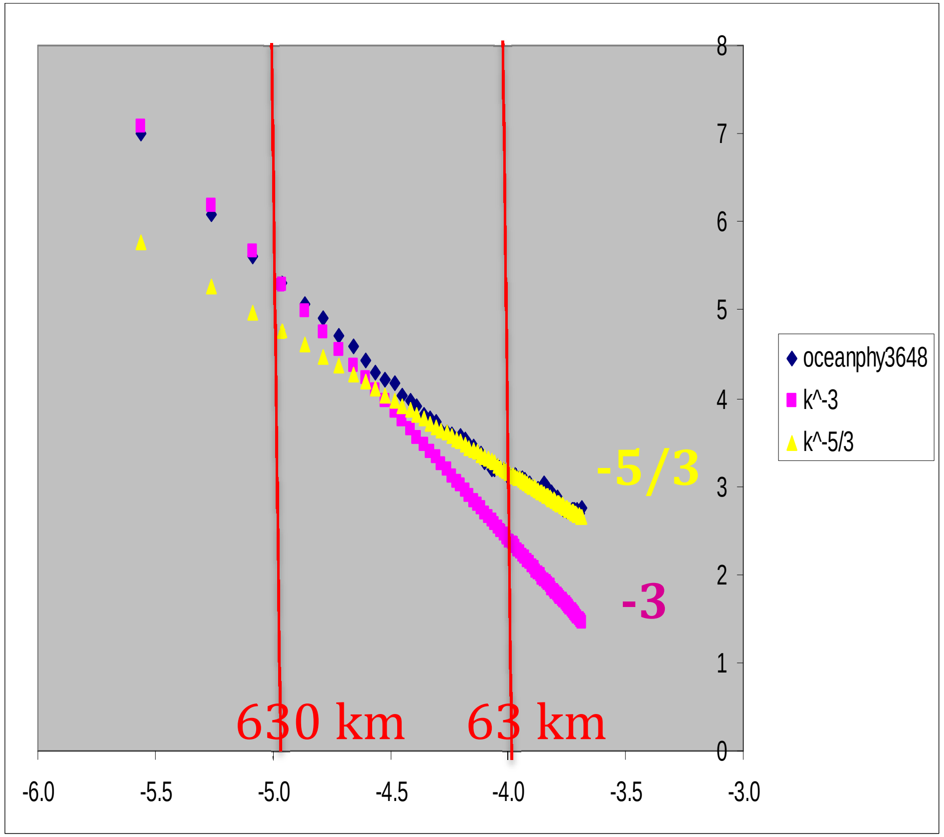
- Spectrum in agreement with observed (Nastrom-Gage, 1985, JAS) spun-up given physical (or spurious, e.g. sigma) sources on small scales

✧ Where is the small scale energy in the observed spectrum coming from?

Atlantic case, NMM-B, 15 km, 32 Levels, 36-48 hour average



No Physics



With Physics

Non-hydrostatic Dynamics

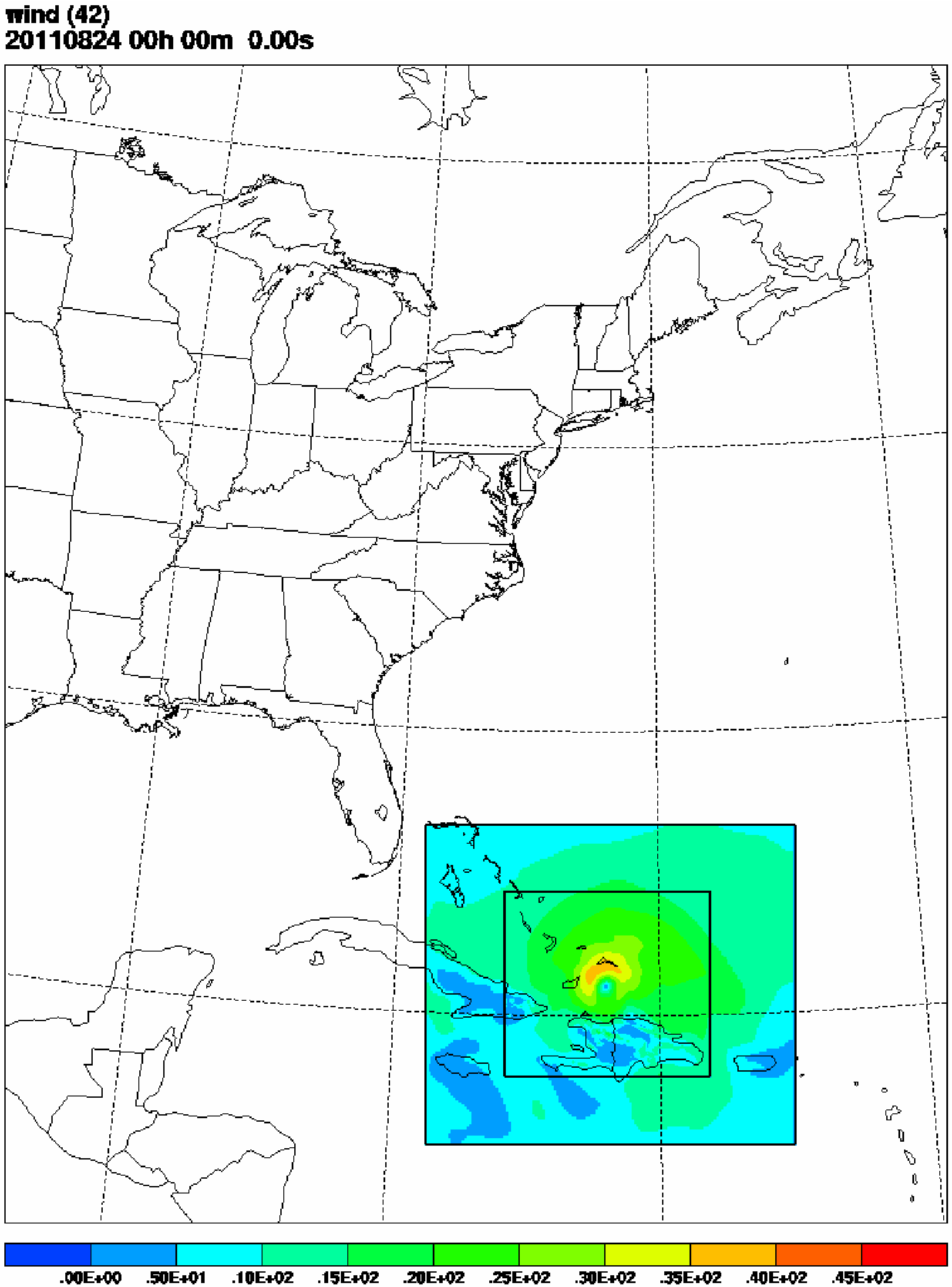
- ✧Differences between hydrostatic and non-hydrostatic solutions
  - ✧Detectable with horizontal resolutions < 10 km
  - ✧Significant with horizontal resolutions ≤ 1 km

Meso Scales

- Regional NMMB replaced WRF NMM in the NAM slot in 2011
- Hierarchy of nests running simultaneously, 12 km, 6 km, 4 km, 1.33 km (fire weather on the fly) resolutions (DiMego et al.)
- Work under way in cooperation with NOAA Hurricane Research Department (HRD) on transition of Hurricane WRF (HWRF) from WRF NMM to NMMB

IRENE 09L
2011/08/24 00Z

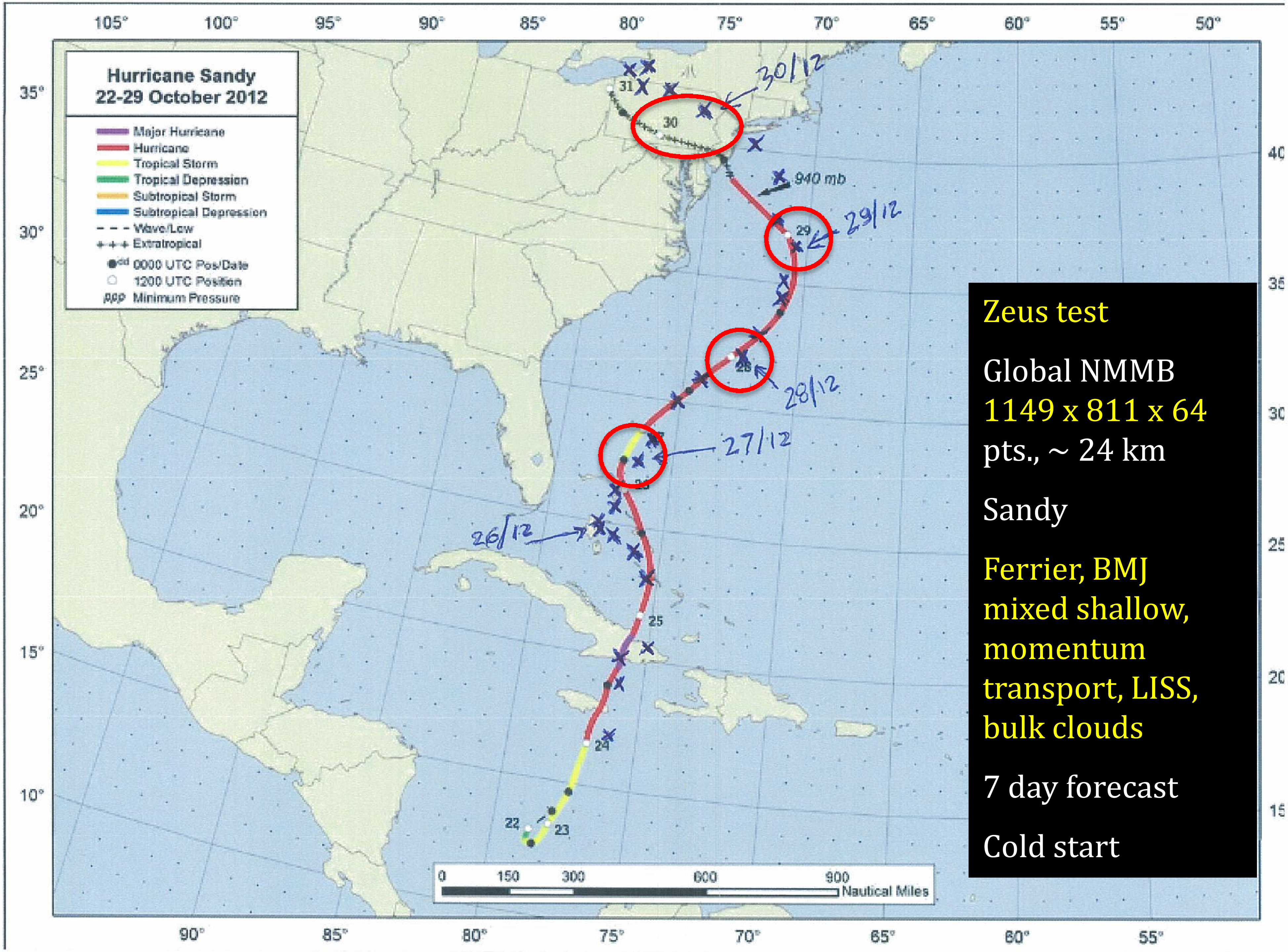
NMMB telescoping, 2-way interacting moving nests



Courtesy: Dusan Jovic, Tom Black, Qingfu Liu

Global Scales

- ✧Runs for testing and tuning at NCEP
- ✧Initialized from, and verified against spectral GFS analyses
- ✧Compatibility issues between grid-point and spectral data (Gibbs phenomenon)
- ✧Can run extended forecasts and drive nested models



Zeus test

Global NMMB
1149 x 811 x 64 pts., ~ 24 km

Sandy

Ferrier, BMJ mixed shallow, momentum transport, LISS, bulk clouds

7 day forecast

Cold start

Zeus test

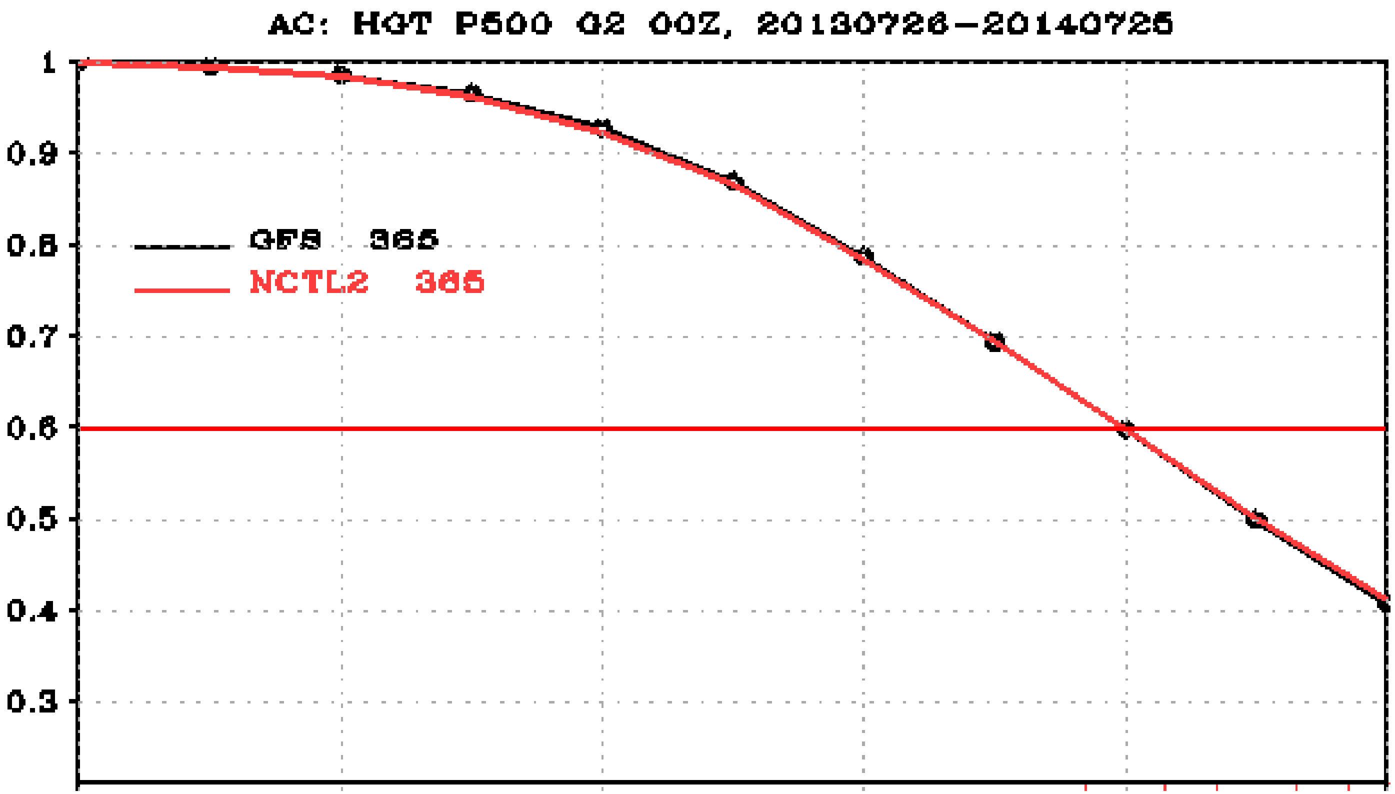
Global NMMB 1149 x 811 x 64 pts. vs. GFS T574 x 64

Recent near real time 00Z runs

Ferrier, BMJ mixed shallow, momentum transport, LISS, bulk clouds

1 year 500 hPa Height Anomaly Correlation vs. forecast time

Cold start, no cycling, initialized and verified using GFS analyses and climatology



Black – GFS

Red – NMMB

Global mean for 1 year 00Z parallel runs

Conclusions

- NMMB is a matured multiscale model
- Local, explicit and some vertically implicit time differencing, scales well
- NMMB tested on a wide range of scales
- 2 way moving, telescoping nests
- Competitive, reliable, robust, fast
- Similar performance of spectral and lat-lon NMMB on global scales, can drive its child nested models
- Unified model offers consistency in applications on various scales and reduced development and maintenance effort