The NCEP WRF Core and Further Development of its Physical Package

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Instead of extending cloud models to synoptic scales and beyond, relax the hydrostatic approximation in a hydrostatic NWP model, build-on existing NWP experience by:

(a) extending the applicability of the model to nonhydrostatic motions, and

(b) preserving the favorable features of the hydrostatic NWP model formulation.

Janjic, Gerrity and Nickovic, 2001, *Monthly Weather Review*
Janjic, 2003, *Meteorology and Atmospheric Physics*

? Nonhydrostatic equations split into two parts:
- Hydrostatic part, except for higher order terms due to vertical acceleration,
- The part that allows computation of the corrections in the first part.

? No linearizations or additional approximations required.

? Separation of nonhydrostatic contributions shows in a transparent way how the hydrostatic approximation affects the model equations.

? Nonhydrostatic dynamics as an add–on module, can be turned on and off:
- Easy comparison of hydrostatic and nonhydrostatic solutions,
- Convenient for unified systems.

? Pressure based vertical coordinate:
- Exact mass (etc.) conservation
- Nondivergent flow on coordinate surfaces
- No problems with weak static stability

? Successfully reproduces classical 2D nonhydrostatic solutions, proof of concept.

Nonhydrostatic model equations, for simplicity, inviscid, adiabatic, sigma

$$s = (p - p_t)/(p_s - p_t), \; \mu = p_s - p_t$$

$$\frac{d\mathbf{v}}{dt} = -(1+e)\nabla_s F - a\nabla_s p + f\mathbf{k}\times\mathbf{v}$$

Horizontal equation of motion

$$\frac{\partial T}{\partial t} = -\mathbf{v}\bullet\nabla_s T - \dot{s}\frac{\partial T}{\partial s} + \frac{a}{c_p}\left[\frac{\partial p}{\partial t}\mathbf{v}\bullet\nabla_s p + \dot{s}\frac{\partial p}{\partial s}\right]$$

Thermodynamic equation

$$\frac{\partial \mu}{\partial t} + \nabla_s \bullet(\mu\mathbf{v}) + \frac{\partial(\mu\dot{s})}{\partial s} = 0$$

Mass continuity equation

$$\frac{\partial F}{\partial s} = -\mu\frac{RT}{p}$$

Hypsometric equation

$$a = RT/p$$

Gas law

$$w = \frac{1}{g}\left(\frac{\partial F}{\partial t_s} + \mathbf{v}\bullet\nabla_s F + \dot{s}\frac{\partial F}{\partial s}\right), \; e \equiv \frac{1}{g}\frac{dw}{dt}$$

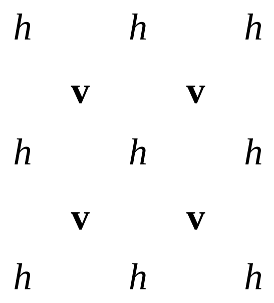
Compressible continuity equation

$$\frac{\partial p}{\partial p} = 1 + e$$

Vertical equation of motion

F, *w* and *e* not independent !

? Classical synoptic scale design, gravity-inertia wave frequencies on rectangular grids with 2nd order finite differencing (Winninghoff, 1968, UCLA PhD; Arakawa and Lamb 1977, MCP; Janjic 1984, MWR; Randall, 1994, MWR):



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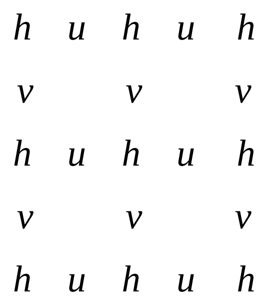
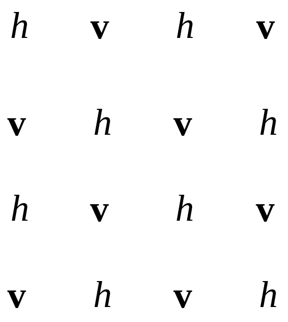
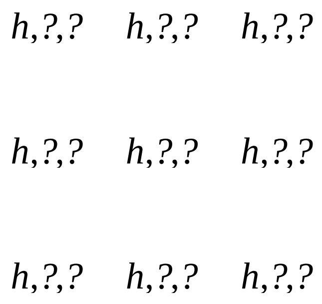


C



E



B’, (Z)

? Mesoscales, linearized anelastic nonhydrostatic system (Communicated by Klemp), different frequency equation (Janjic 2003, MAP).

? For historical reason, Arakawa E grid in the initial formulation, B grid formulation also exists (Janjic, 2003, MAP).

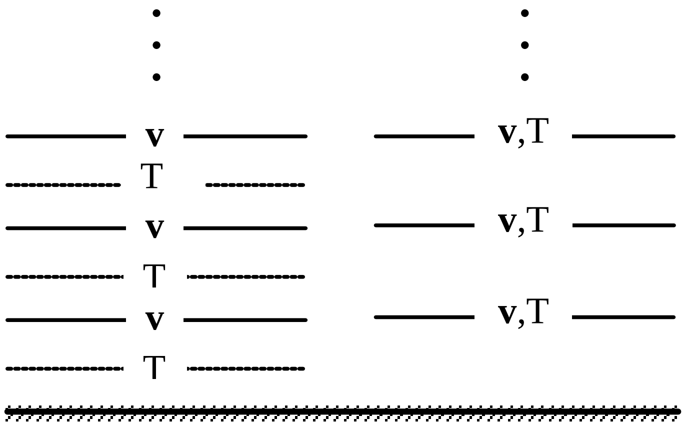
? Discretization principles unchanged since Janjic (1977, Beitrage), shared with HIBU and NCEP Meso (Eta) models:

- Controlled nonlinear energy cascade, Energy and Enstrophy conservation,

- Cancellation between contributions of the *? a* term and the PGF to KE, consistent transformations between KE and potential energy, cancellation of horizontal pressure advection in the thermodynamic equation with contribution of the second term of the pressure gradient force, otherwise computational stability problems,

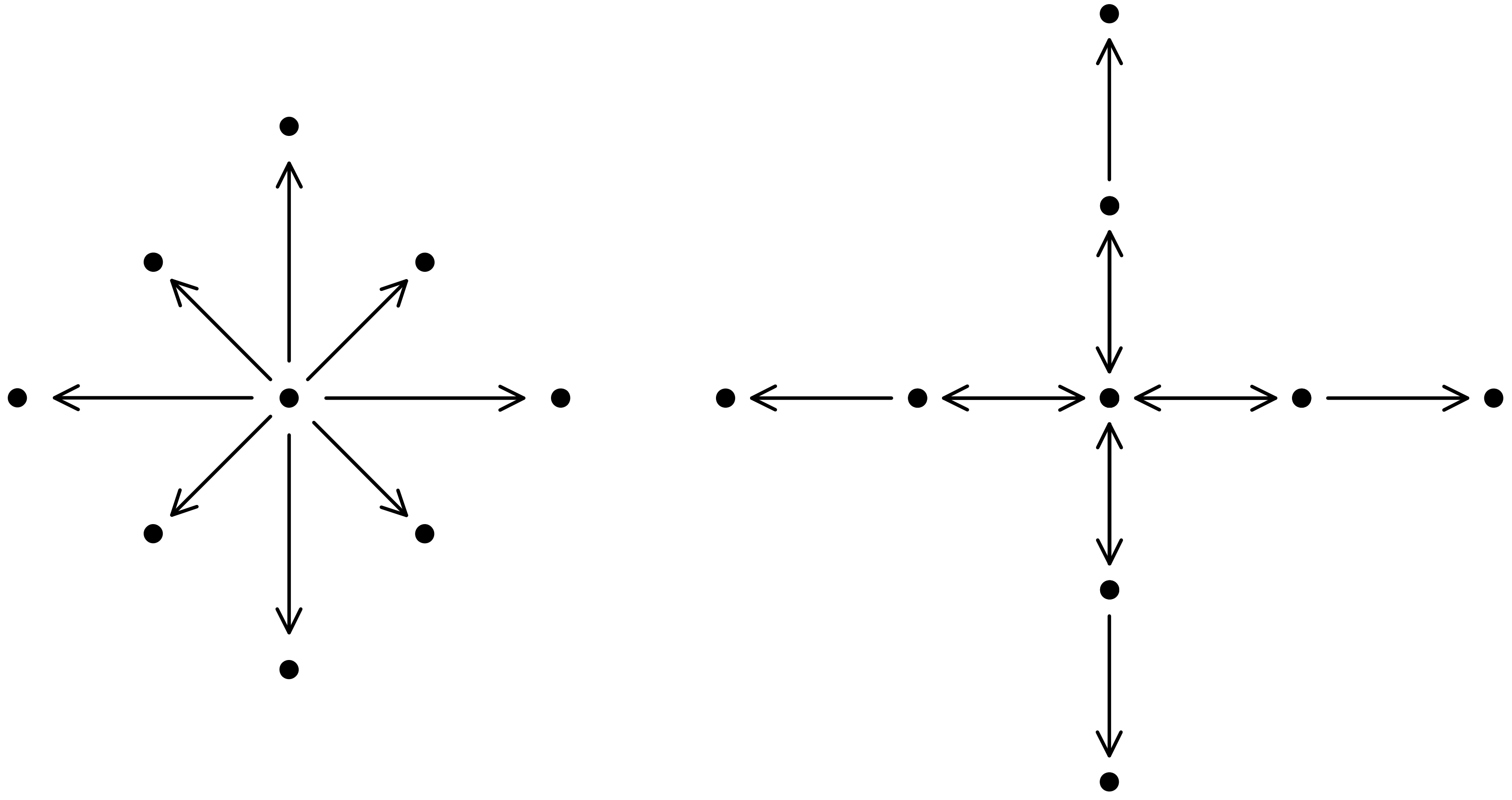
- Minimization of pressure gradient force error,

- Lorenz vertical distribution

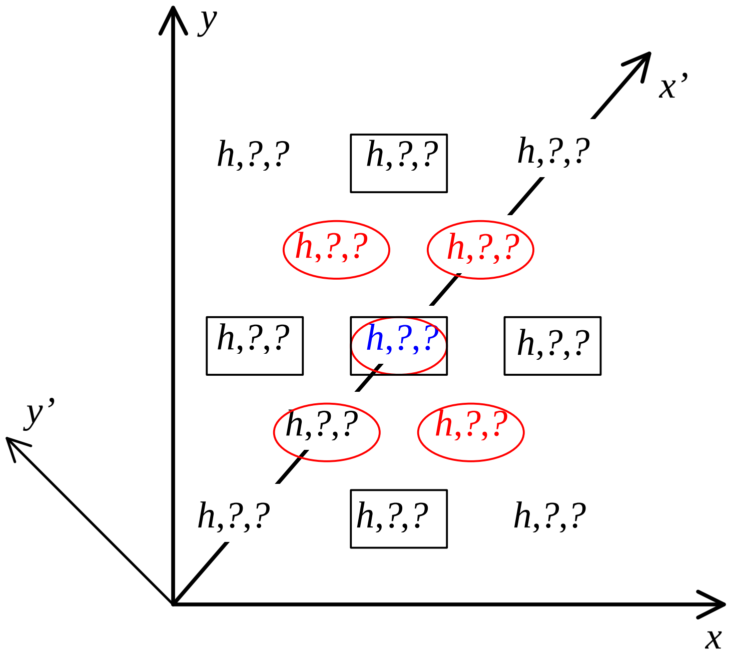


Charney-Phillips   Lorenz

? “Isotropicized” horizontal divergence & advection operators on 9-point Arakawa Jacobian stencils (Janjic, 1984, MWR).



? Interchangable flux/advective form in FD (Janjic 1984; Xue 2001, MWR).



For rotational flow and cyclic boundary conditions, the horizontal advection of momentum on the E grid conserves (Janjic 1984, MWR):

? Enstrophy as defined on the staggred grid C

$$\sum_{i,j}(d_{x'x'}y + d_{y'y'}y)^2 ? A,$$

? Rotational kinetic energy as defined on the staggered grid C

$$\sum_{i,j}\frac{1}{2}(d_{y'}y)^2 ? A + \sum_{i,j}\frac{1}{2}(d_{x'}y)^2 ? A.$$

2D turbulence on “Rotating Flat Square Earth” (Gavrilov & Janjic 1989, MAP)

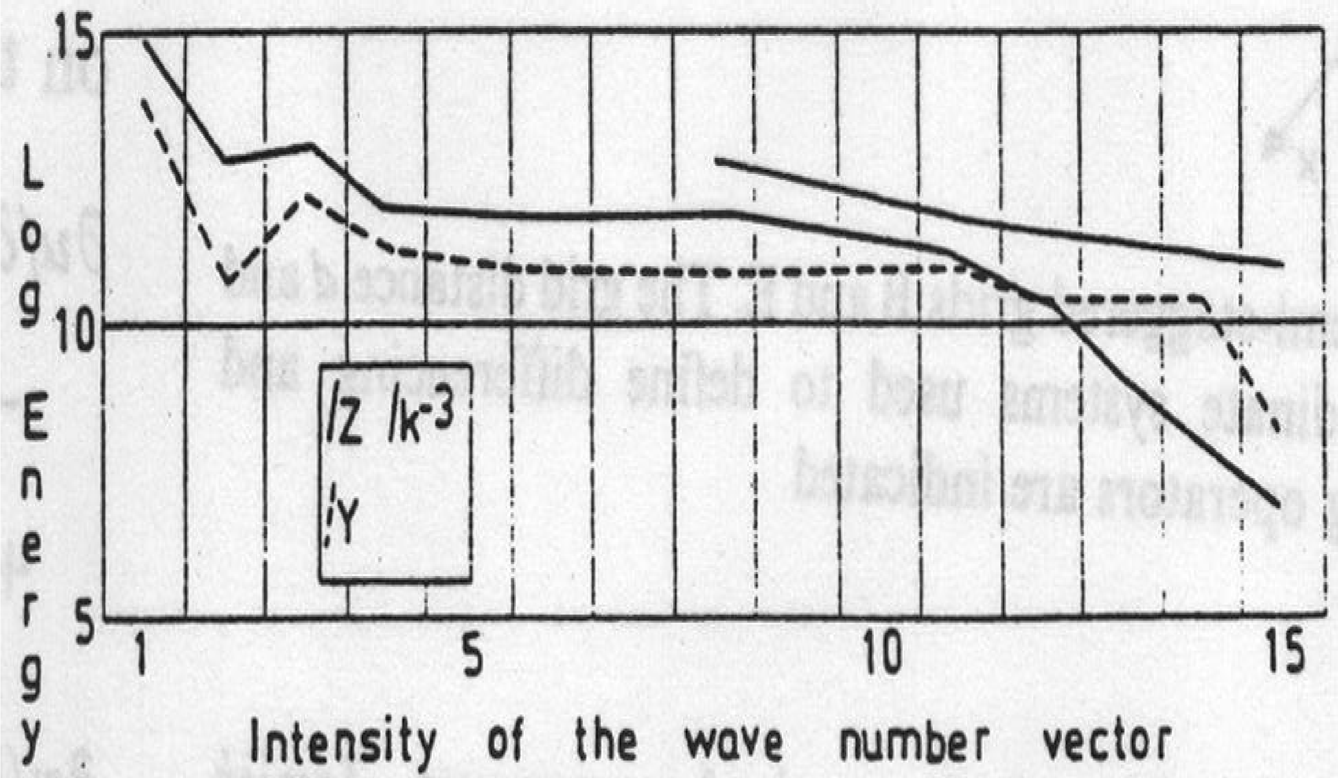


Fig. 2. Rotational energy content as a function of wave number range after averaging over the last 2 000 time steps of two 12 000 time step integrations. One integration was performed using Scheme Y (dashed line), and the other using Z Scheme (solid line). The natural logarithm scale was used for the ordinate axis. The k^{-3} curve is plotted for comparison (light solid line)

Arakawa: Energy and enstrophy conservation important for convergence at high resolutions.

? Rotational momentum as defined on staggered grid C.

? Rotational kinetic energy as defined on the semi-staggered grid E

$$\sum_{i,j}\frac{1}{2}[d_y y^{\ 2} + d_x y^{\ 2}]?A.$$

? Rotational momentum as defined on the semi-staggered grid E.

General flow:

? Kinetic energy as defined on the semi-staggered grid E

$$\sum\frac{1}{2}[(d_x f - d_y y)^2 + (d_y f + d_x y)^2]?V.$$

? Momentum as defined on the semi-staggered grid E.

? Mass.

? Advection of T conserves first and second moments.

E grid FD schemes also reformulated for, and used in a B grid model (SASA).

Vertical discretization, vertical coordinate, PGF error:

? Sigma (Phillips, 1957)?

- problems with sloping coordinate surfaces, worst at high altitudes.

? Step-mountains (Bryan, 1969, JCP; Mesinger, Janjic, Nickovic, Gavrilov, Deaven, 1988, MWR):

- problems with flow over topography (Adcroft et al, 1997, MWR; Galus, 2000 Wea & Fcst; Gallus and Klemp, 2000, MWR; Janjic and DiMego, 2001, AMS Albuquerque; Gavrilov 2002, JAM).

? Pressure-sigma hybrid (Arakawa and Lamb, 1977):

- flat coordinate surfaces at high altitudes where the sigma problems are worst;
- sloping surfaces at lower altitudes above topography
- high resolution over elevated terrain
- no discontinuities and internal boundary conditions

Time stepping:

? HIBU, Eta, RK2 additive splitting for advection of u, v, T, (Janjic, 1979, Beitrage):

- less memory
- good for synoptic scales with small Rossby #
- not good for high resolution, noise in time!

? Nonhydrostatic, NONSPLIT Adams-Bashforth for horizontal advection of u, v, T

- improved accuracy,
- no extra cost in operation count compared to Matsuno/RK2,
- no redundant computations, high computational efficiency.

? Forward-Backward (Ames, 1968; Janjic and Wiin-Nielsen, 1977; Janjic 1979, Beitrage) for gravity waves.

? Implicit for vertically propagating sound waves (Janjic et al., 2001, MWR).

Physics:

? Upgraded physical package of the NCEP Meso (Eta) model (Janjic 1990, 1994, MWR; Chen, Janjic and Mitchell, 1997, BLM; Janjic 2000, JAS; Janjic 2002, NCEP Office Note 437)

? The NMM model

- Computationally robust,
- Fast, can be further improved,
- NWP, convective cloud runs, PBL LES, with resolutions from 50 km to 100 m,
- No Rayleigh damping and associated extra computational boundary condition at the top with real data with resolutions down to 100 m.

? Operational at NCEP

- HiRes Windows, Fire Weather

? Weather Research and Forecasting (WRF) dynamical core

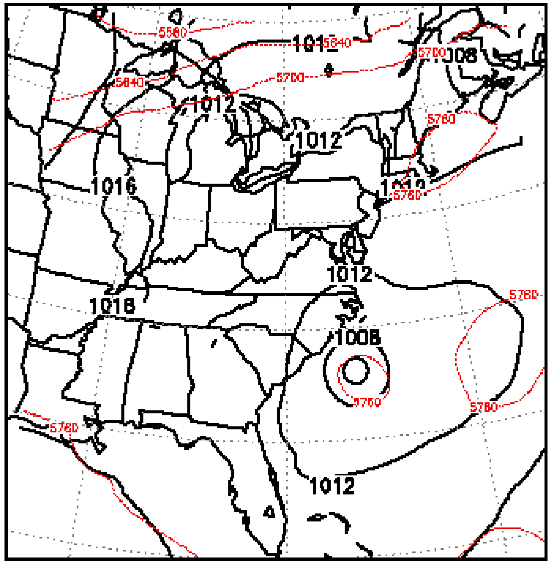
Fehler! Unbekanntes Schalterargument.

? 8 km (Alaska 10 km), 60 levels.

? Interpolated Eta 12 km initial and boundary conditions.

? Unfiltered gridbox mean USGS 30’’ mountains.

? Different domains for different cycles.



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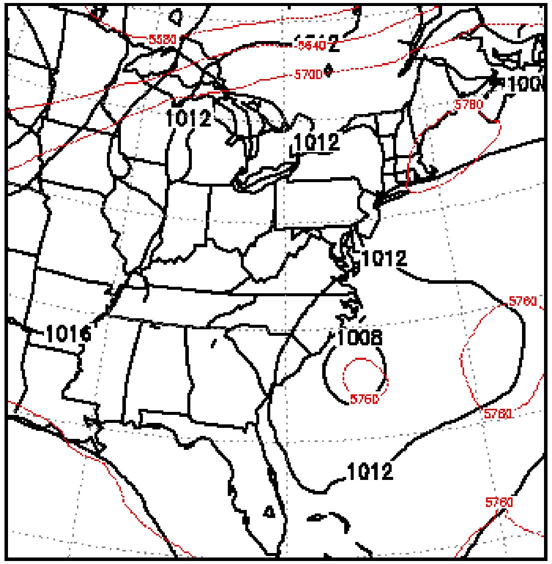

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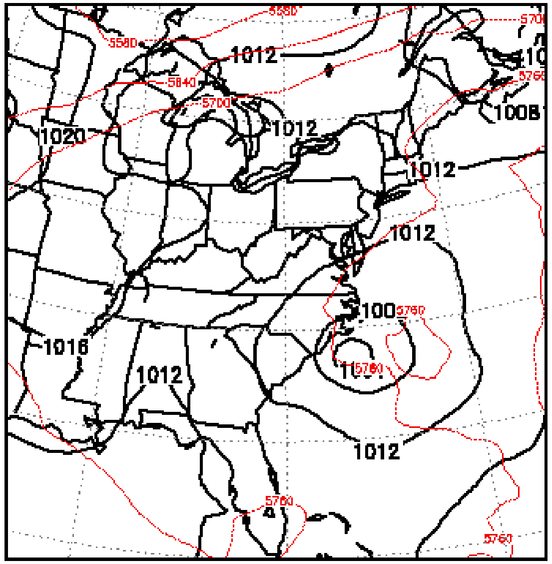

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? Betts-Miller-Janjic (BMJ) deep convection (Janjic, 1994, MWR; 2001, JAS), (simple dimensional formalism)

Determining parameters:

$$?S = \sum \frac{c_p ?T + L?q}{T} ?p$$

Entropy change

$$?P = \sum c_p ?T ?p$$

Precipitation

$$\bar{T} = \frac{\sum c_p (T + \frac{?T}{2}) ?p}{\sum ?p}$$

Mean temperature of the cloud

Nondimensional parameter:

$$E = const \frac{\bar{T} ?S}{?P}$$

“Cloud efficiency”

- Depending on *E*, equilibrium temperature and moisture profiles oscillate between “universal heavy convection profiles”, based on Betts (1986) profiles and moist-adiabatic profiles;

- Relaxation time depends on *E*

? Recent upgrades of the BMJ deep convection:

- Iterative computation of cloud efficiency,

- Iterative search for cloud top (reduces the number of pts. with aborted deep convection),

- Transition from convection to grid-scale precipitation depending on resolution?

Entropy change measures intensity of vertical transfers of heat and moisture

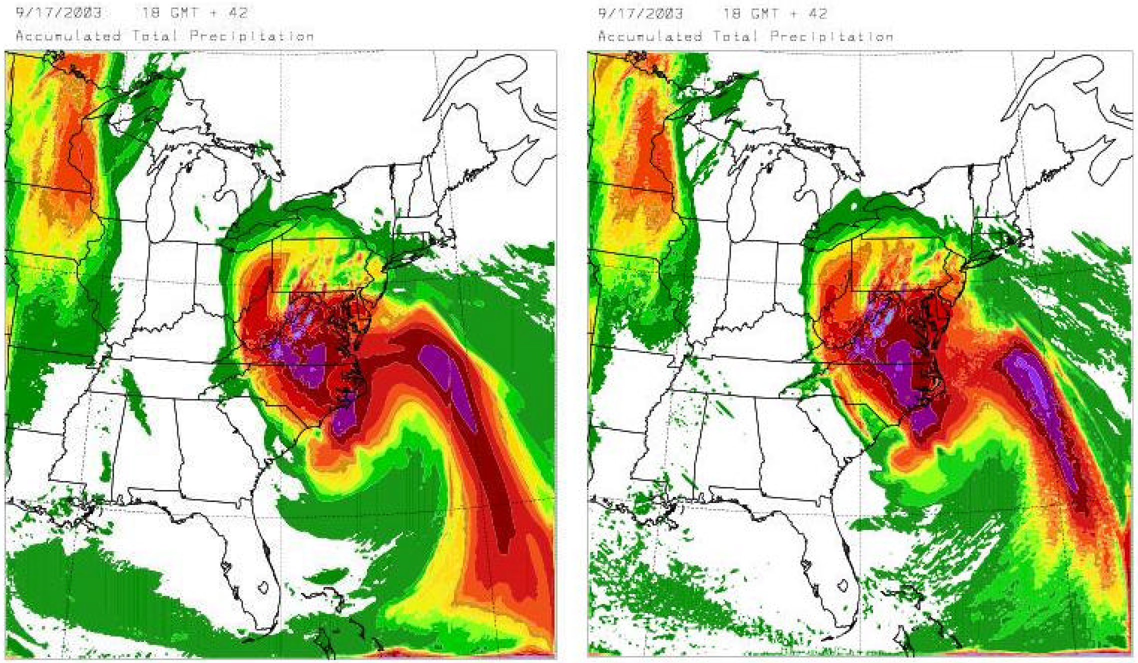
Increase the threshold of entropy change needed for the onset of deep convection depending on resolution, and thereby leave to the grid-scale precipitation to handle weaker instabilities that were handled by convection at coarser resolutions?

? BMJ shallow convection (Janjic, 1994, MWR, 2001, JAS) closure based on (1) enthalpy conservation and (2) requirement that entropy change must be positive

? Recent upgrades of the shallow convection

- Shallow clouds must not be too dry (prevents convection from inside convective mixed layer)

New convection



New convection and entropy constraint

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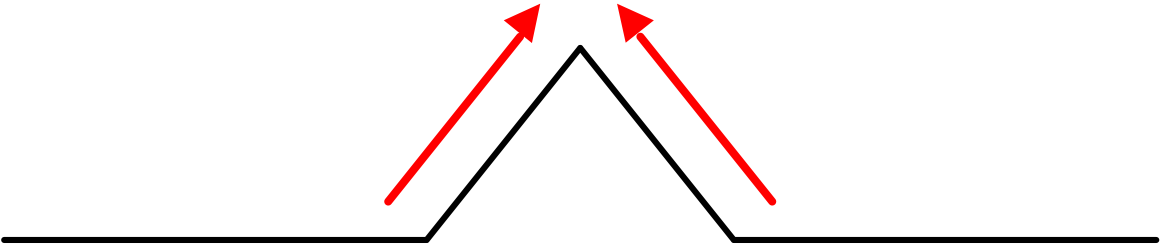
? Lateral diffusion on terrain following coordinate surfaces

Operational



Verification

- Spurious instability, spurious precipitation,

- Lateral diffusion of heat and moisture turned off if

$$\frac{?z}{?x} \leq 0.001$$

? Lateral diffusion

\- contribution of horizontal shear of *w* in deformation for high resolution.

? Effects of condensation in the turbulence closure model.

? Positive bias in geopotential height in Hi Res, Fire Weather domains with lateral boundaries running through mountainous areas, visible by eye

- Initial and boundary conditions interpolated from the Eta,

- Situation changes with synoptic situation,

- No sign of overheating.

? Imbalance between inflow and outflow of mass?

- Vertical integral of mass fluxes along the lateral boundaries must be the same before and after vertical interpolation

- Qubic spline vertical interpolation along lateral boundaries instead of local quadratic

- Improvements visible by eye

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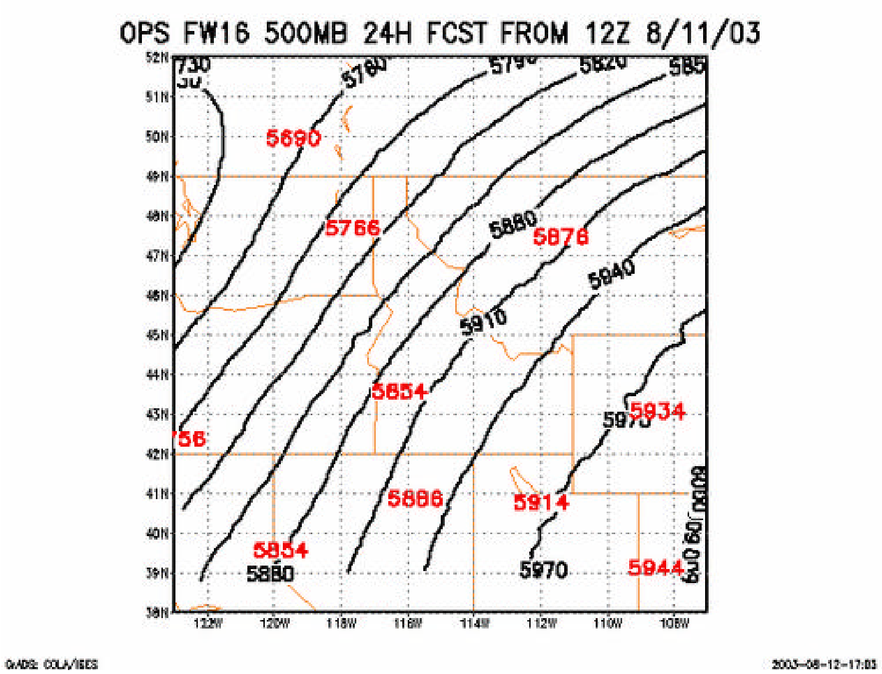
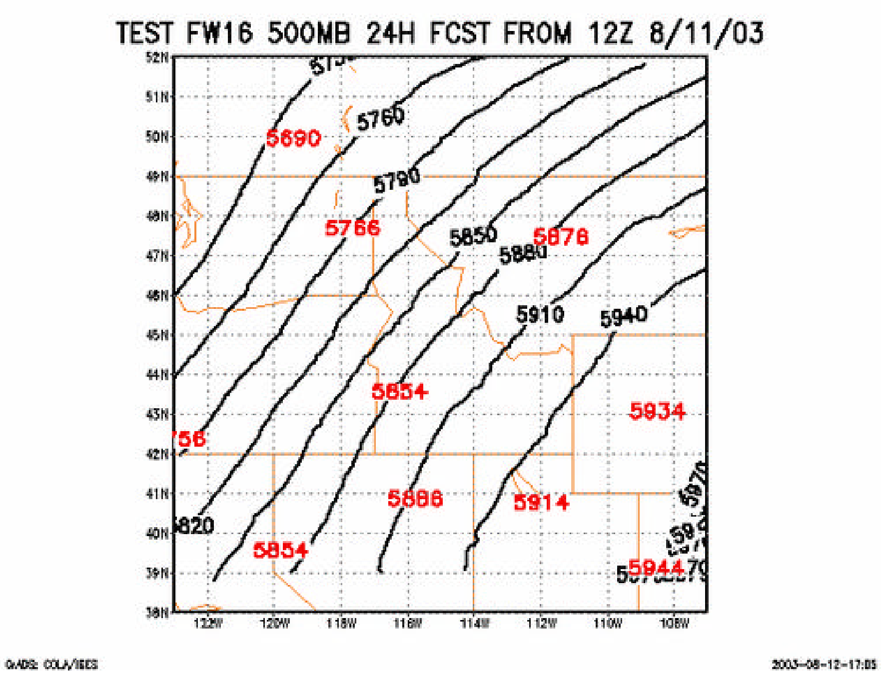
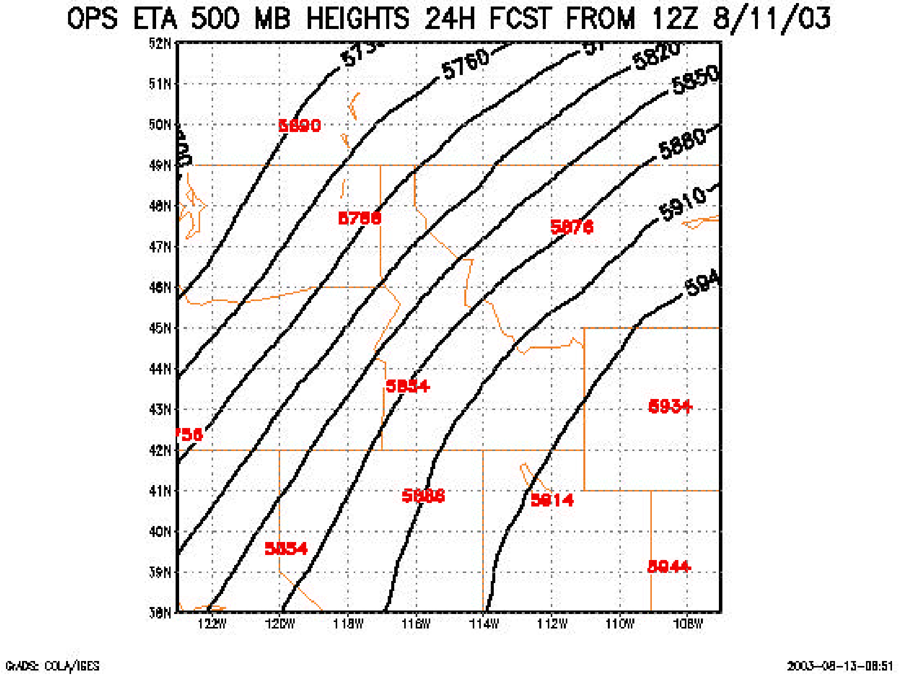


OPS FW16 500MB 24H FCST FROM 12Z 8/11/03

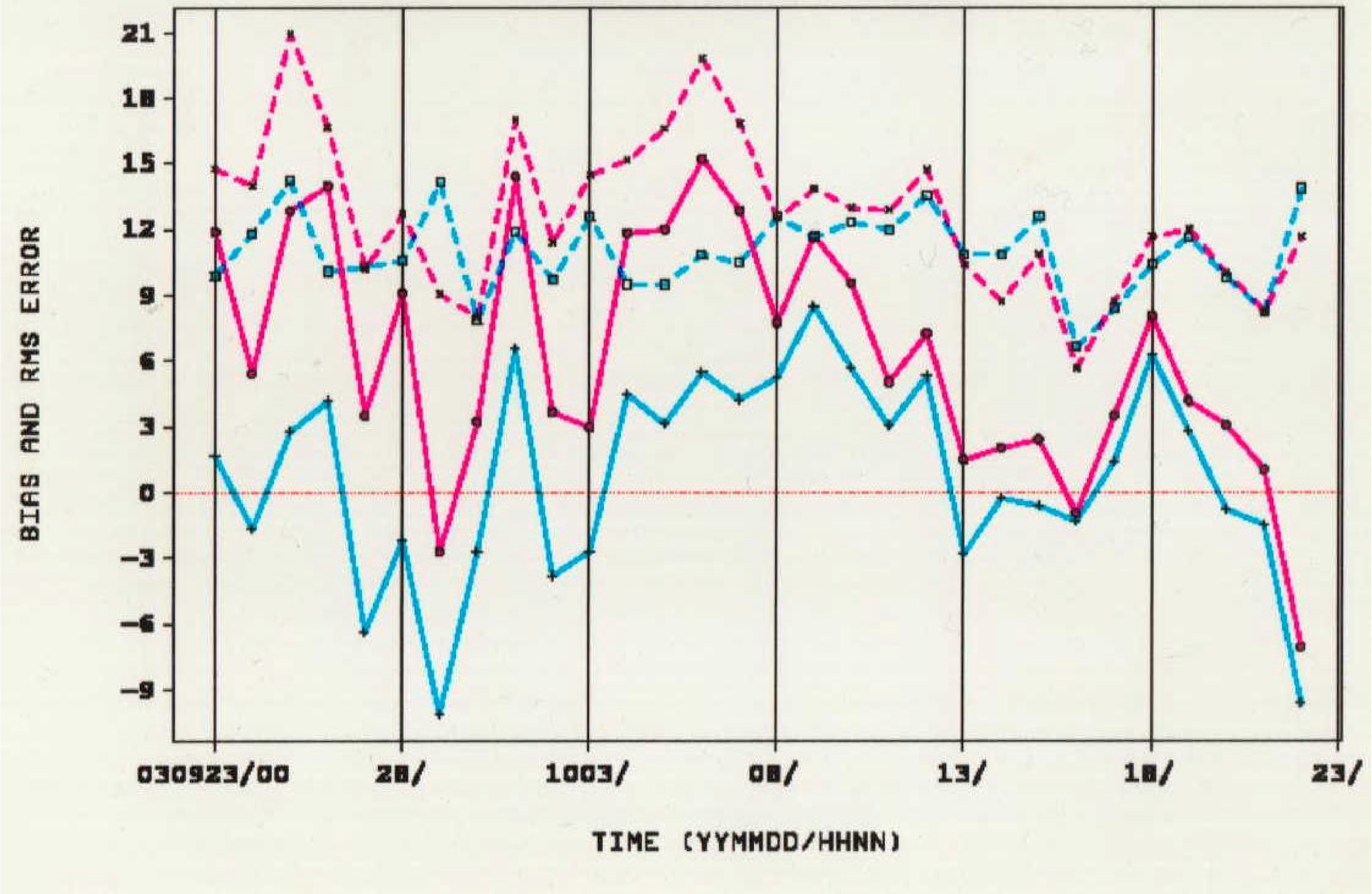


TEST FW16 500MB 24H FCST FROM 12Z 8/11/03



OPS ETA 500 MB HEIGHTS 24H FCST FROM 12Z 8/11/03

Dominated by the BC, domain to small to show big differences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TIME (YYMMDD/HHNN)

? Non-conventional verification, Nastrom-Gage (1985, JAS) spectrum.

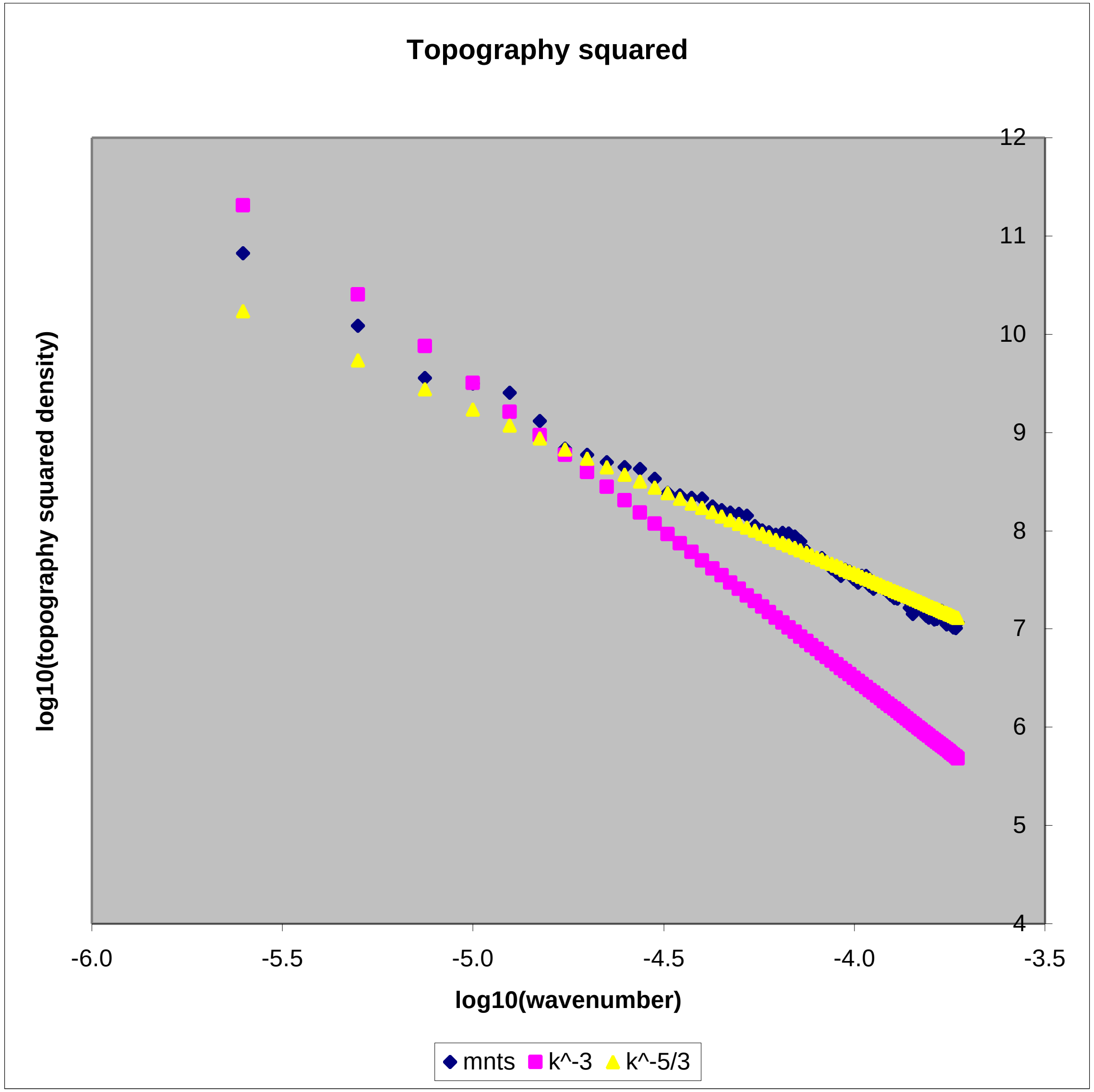
? The WRF-NMM and the NMM-B well qualified for investigating numerical spectra:

- Conservation of rotational energy and enstrophy, more accurate nonlinear energy cascade,

- Conservation of total energy provides stable integrations without excessive dissipation (either explicit or built-in finite-difference schemes) that could affect properties of model generated spectra,

- Hybrid pressure-sigma vertical coordinate system relatively free of errors associated with representation of mountains in the upper troposphere and in the stratosphere where the sigma coordinate errors are largest,

- Explicit formulation of dissipative processes allows precise “dosage” of dissipation.


Topography squared
log10(topography squared density)
12
11
10
9
8
7
6
5
4
-6.0
-5.5
-5.0
-4.5
-4.0
-3.5
log10(wavenumber)
◆ mnts ■ k^-3 ▲ k^-5/3

Central US

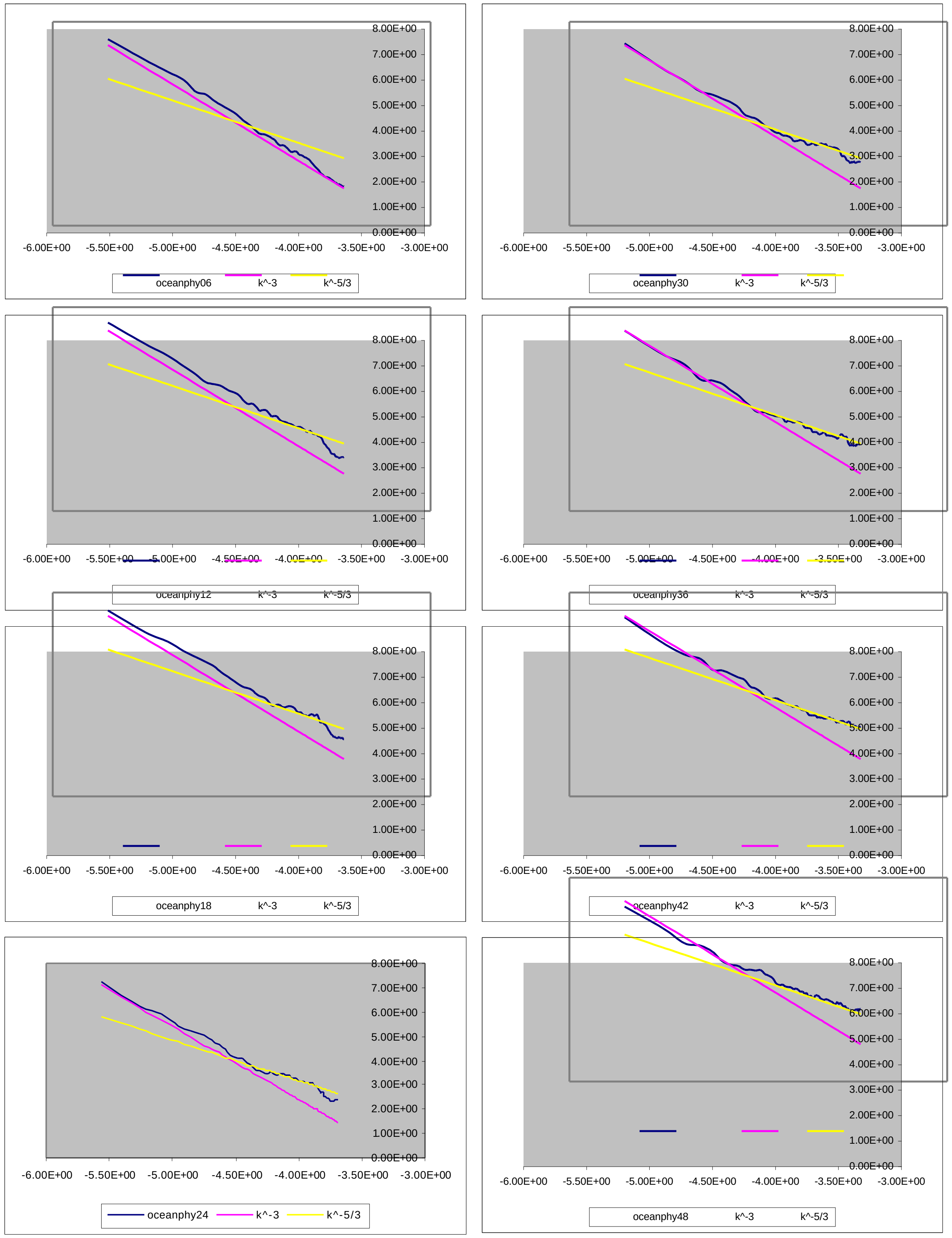


Fig. 4. Time evolution of the NMM-B spectra at 300 hPa over Atlantic Ocean. Run starting from 12 UTC, 09/07/2003, GFS data, 15 km, 32 levels resolution. No lateral diffusion, weak mass divergence damping. Plots every 6 hours, top to bottom, 6-24 left, 30-48 right.

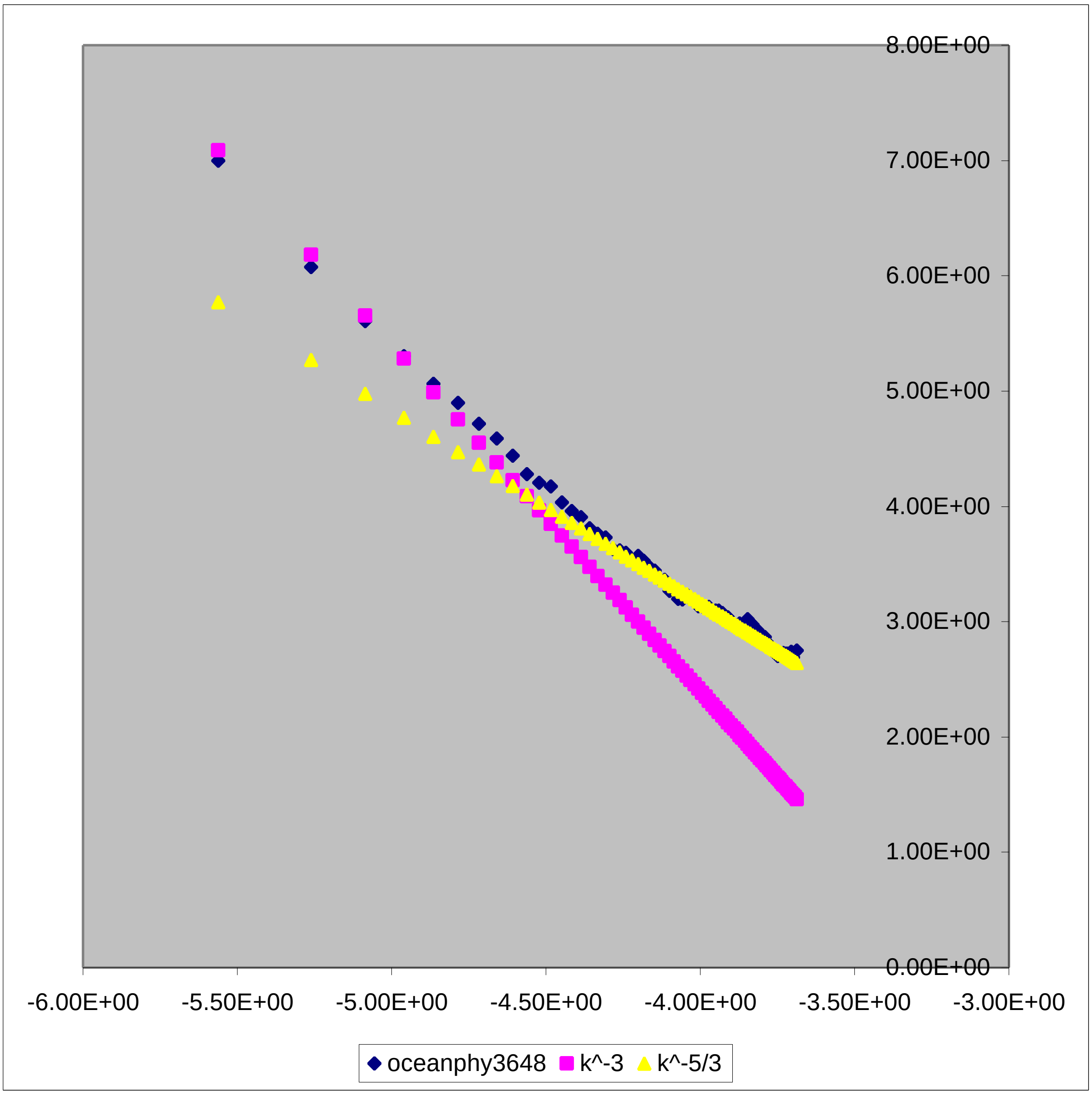


Fig. 5. Time average over 36-48 hours of the NMM-B spectra at 300 hPa over Atlantic Ocean. Run starting from 12 UTC, 09/07/2003, GFS data, 15 km, 32 levels resolution. No lateral diffusion, weak mass divergence damping.

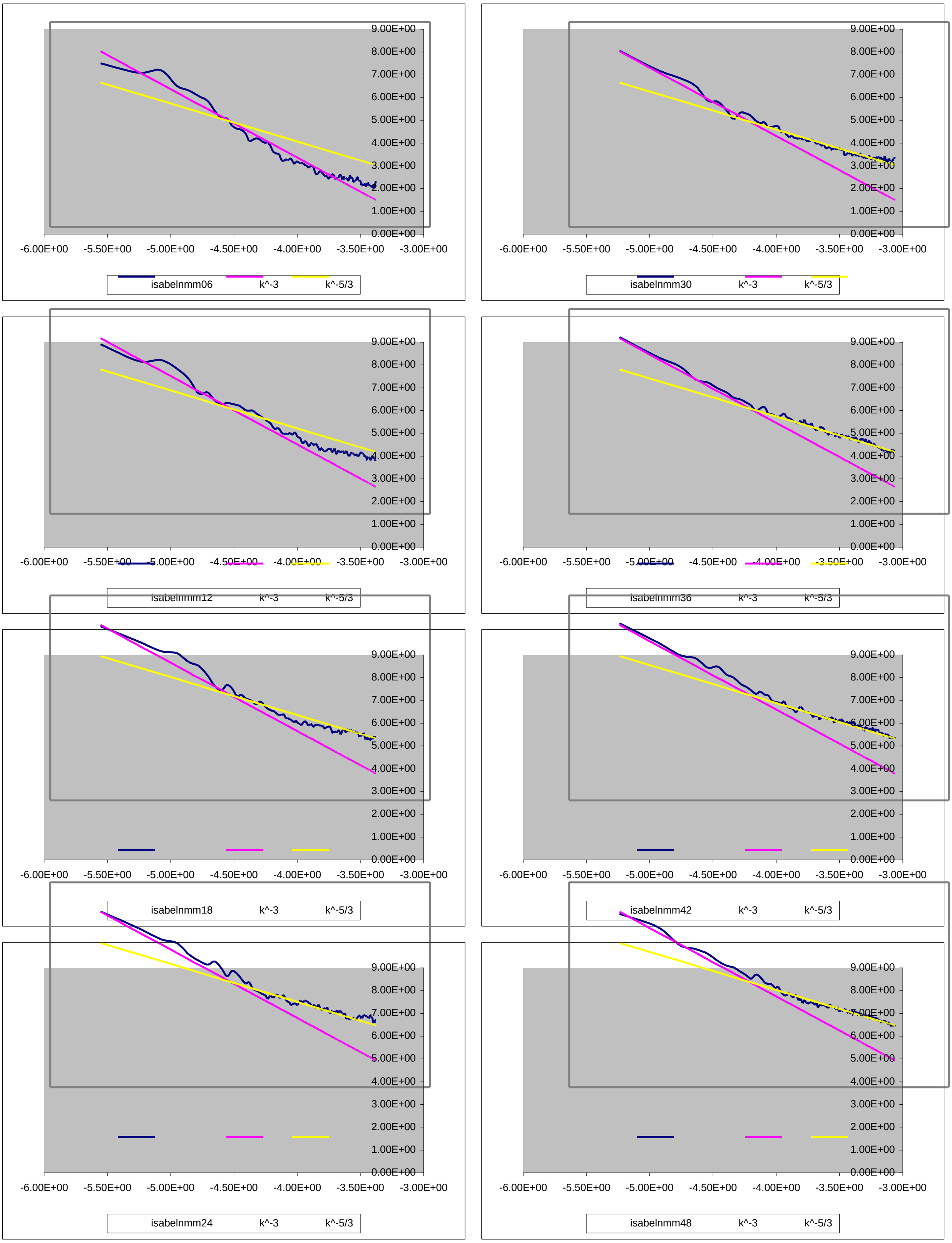


Fig. 6. Time evolution of the WRF-NMM spectra at 300 hPa in the Eastern Domain. Run starting from 18 UTC, 09/17/2003 (Isabel), Eta data, 8km, 60 levels. No lateral diffusion, weak mass divergence damping. Plots every 6 hours, top to bottom, 6-24 left, 30-48 right.

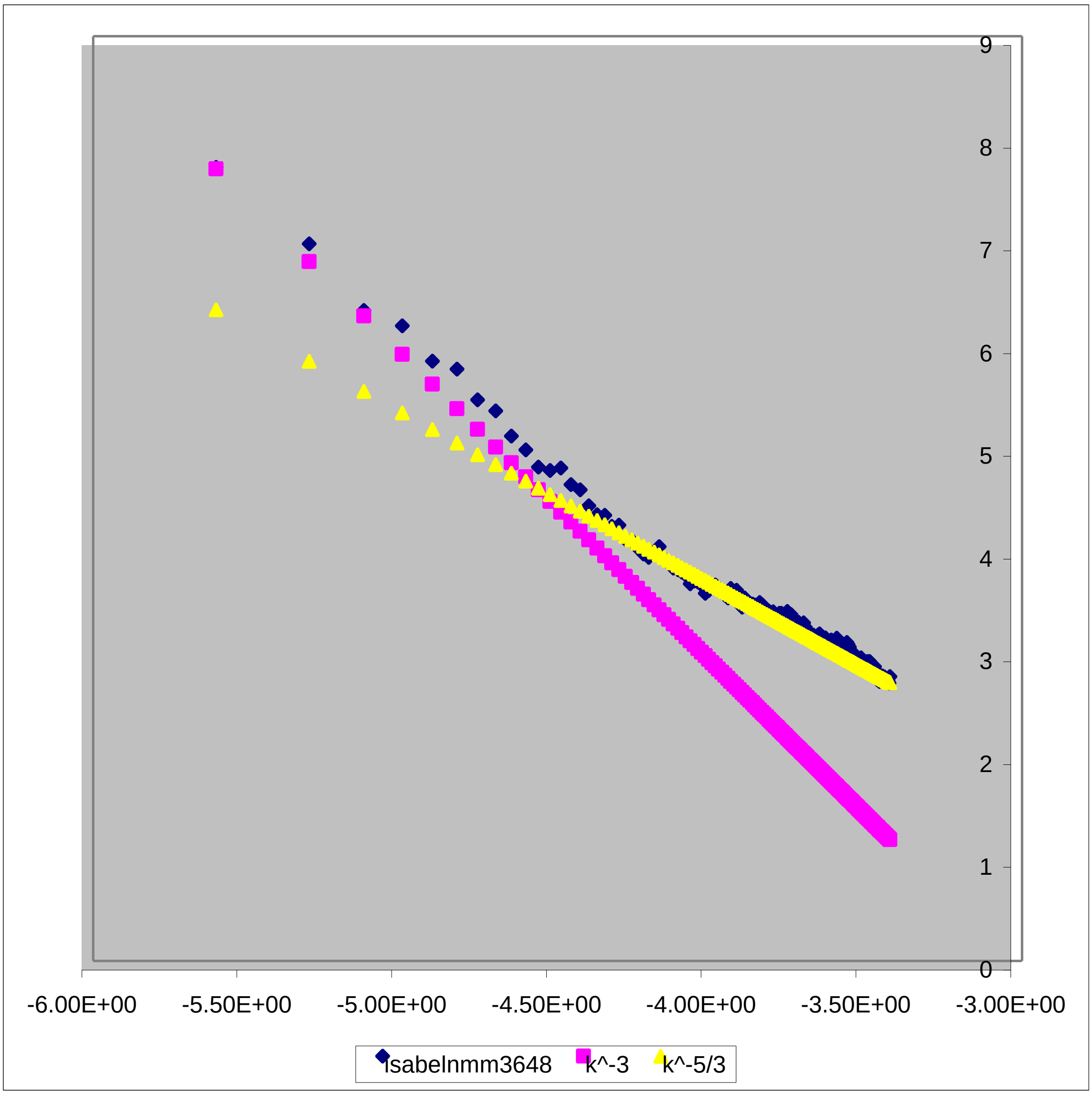


Fig. 7. Time average over 36-48 hours of the WRF-NMM spectra at 300 hPa in the Eastern Domain. Run starting from 18 UTC, 09/17/2003 (Isabel), Eta data, 8 km, 60 levels resolution.

- Can add value to the driving model
- Reliability 100%
- Very fast
- Higher resolution, more sophisticated physics (micophysics) affordable
- Needs much more work on retuning, very little has been done
- Mountain filtering, rounding of mountain tops?