Intrinsic Middle Atmosphere Predictability

Keith Ngan and Giles Eperon
Data Assimilation and Ensembles

Contents

This presentation covers the following areas

Background

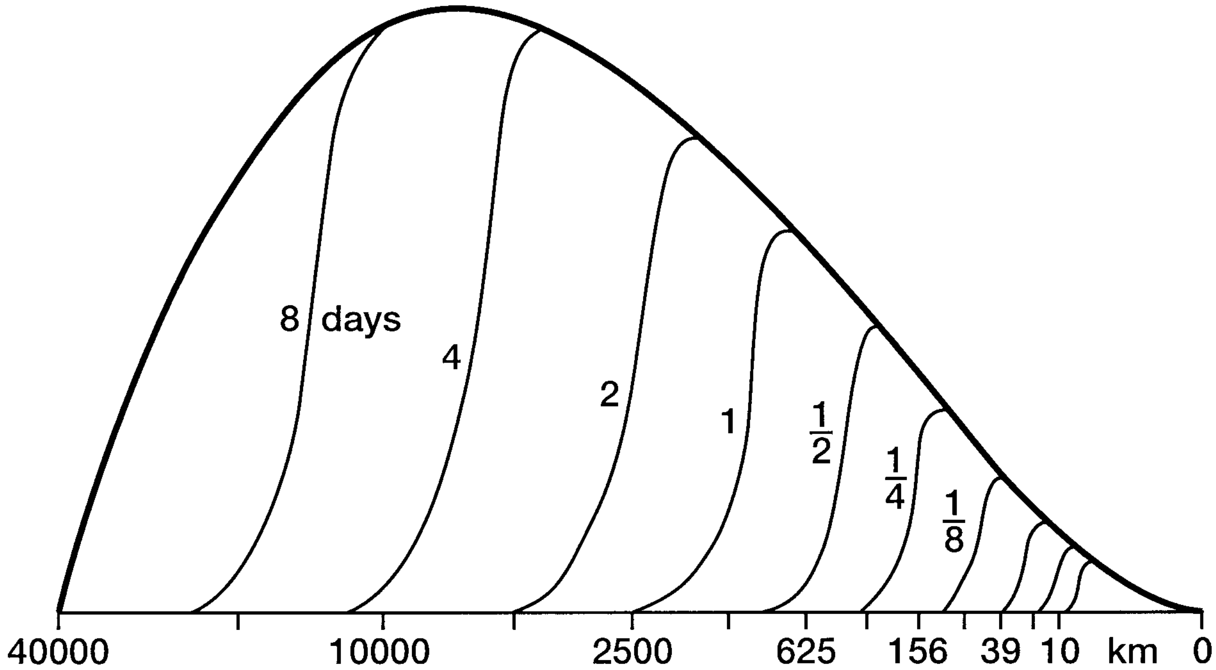
Definitions

Many different aspects (and definitions) of predictability.

This talk is concerned with the growth and propagation of small-scale, small-amplitude errors in spectral space.

Approach is embodied in the classical picture of predictability due to Lorenz, Leith & Kraichnan.

Lorenz (1969)



Predictability is measured by relative errors (i.e. relative KE)

There is an inverse error cascade from small to large scales

Key assumption: homogeneous, isotropic turbulence.

Applicability to the real atmosphere

The real atmosphere cannot be described exactly by 2-D or quasi-geostrophic turbulence.

Conventional view is that the classical picture carries over straightforwardly to the real atmosphere.

Key quantity: eddy turnover time

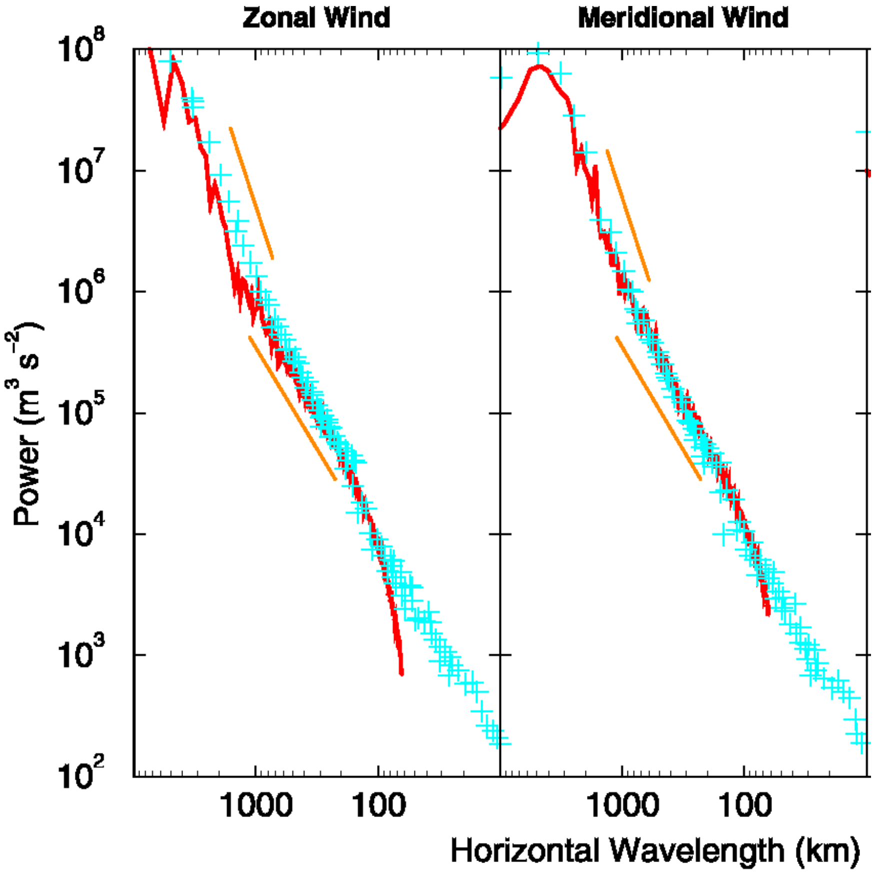
$$\tau(k;k_1) = \left(\int_{k_1}^{k} k'^2 E(k')dk' \right)^{-\frac{1}{2}}$$

For $E(k) \sim k^{-p}$ and $k \to \infty$

$$\tau(k;k_1) \sim \begin{cases} \text{constant}, & p > 3 \\ k^{(p-3)/2}, & p < 3 \end{cases}$$

Upshot: predictability behaviour depends crucially on the atmospheric energy spectrum.

GCM simulations



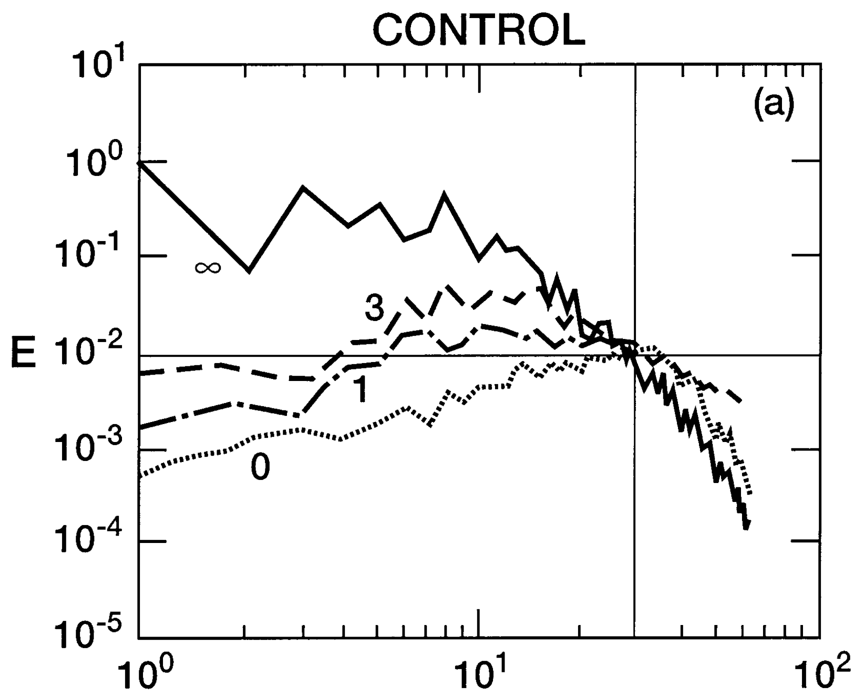
Hamilton et al. (2008)

Mesoscale energy spectrum remains controversial.

One possible explanation: downscale propagation of wave energy

(e.g. Bartello 1995).

NWP Predictability



Tribbia & Baumhefner(2004)

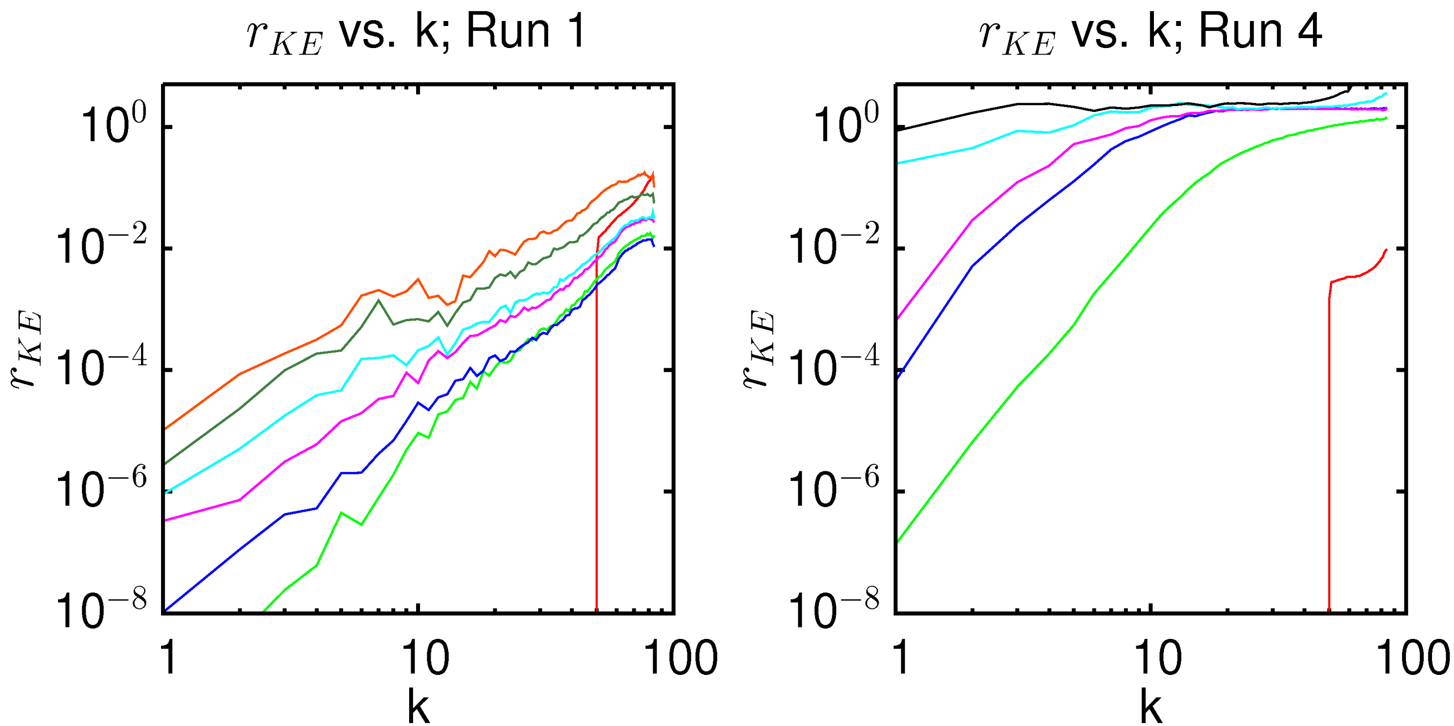
NWP predictability departs from the classical picture:

- Rapid saturation of small scales; exponential growth of synoptic scales.

- Don’t have simple inverse error cascade: predictability regimes (Boer 1994).

Rotating stratified turbulence

subsynoptic [$L_d/L_0 = 10$] (super)synoptic [$L_d/L_0 = 0.1$]



Predictability decay for subsynoptic flow is significantly slower.

Implication: gravity waves *increase* predictability.

Reference: Ngan, Bartello & Straub, JAS 2009.

Middle atmosphere predictability

Middle atmosphere predictability

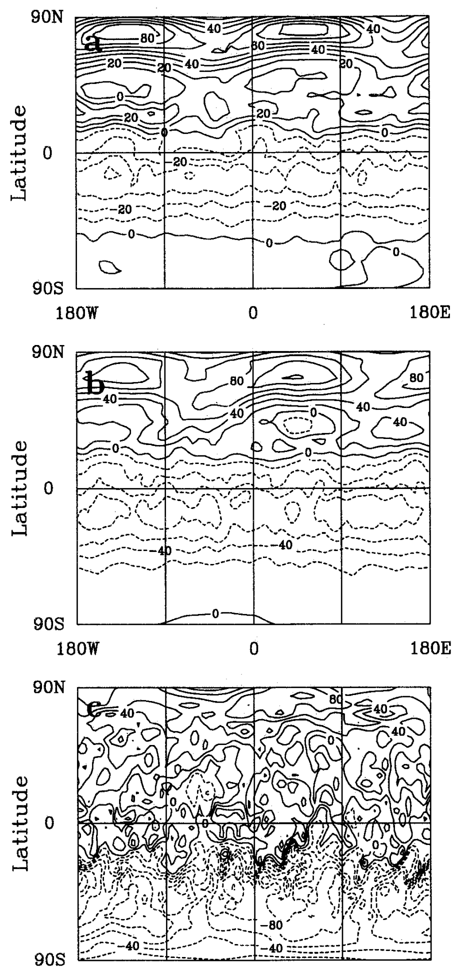
Most studies of NWP predictability have been restricted to the troposphere.

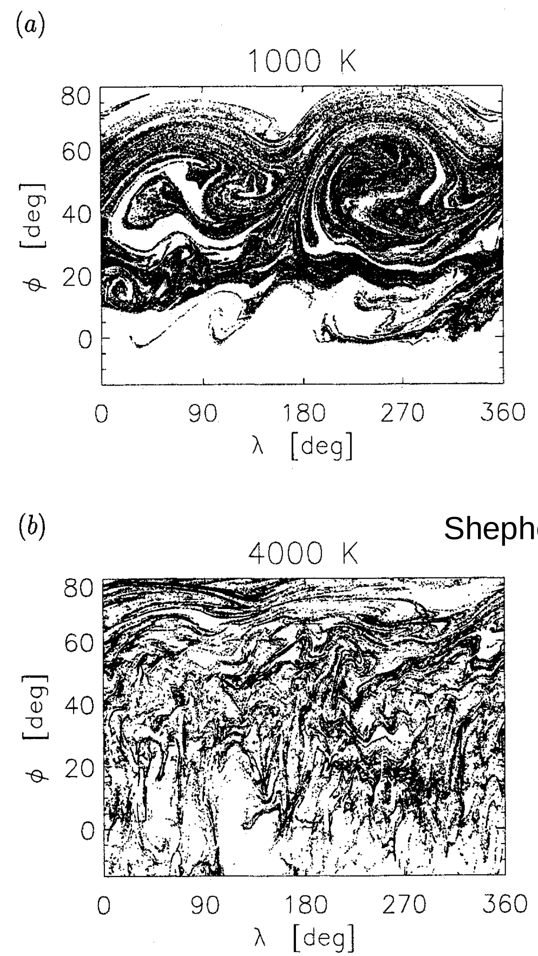
One might expect differences in the middle atmosphere, where small-scale gravity waves play an important role.

Troposphere

Stratosphere

Mesosphere





Shepherd et al. (2000)

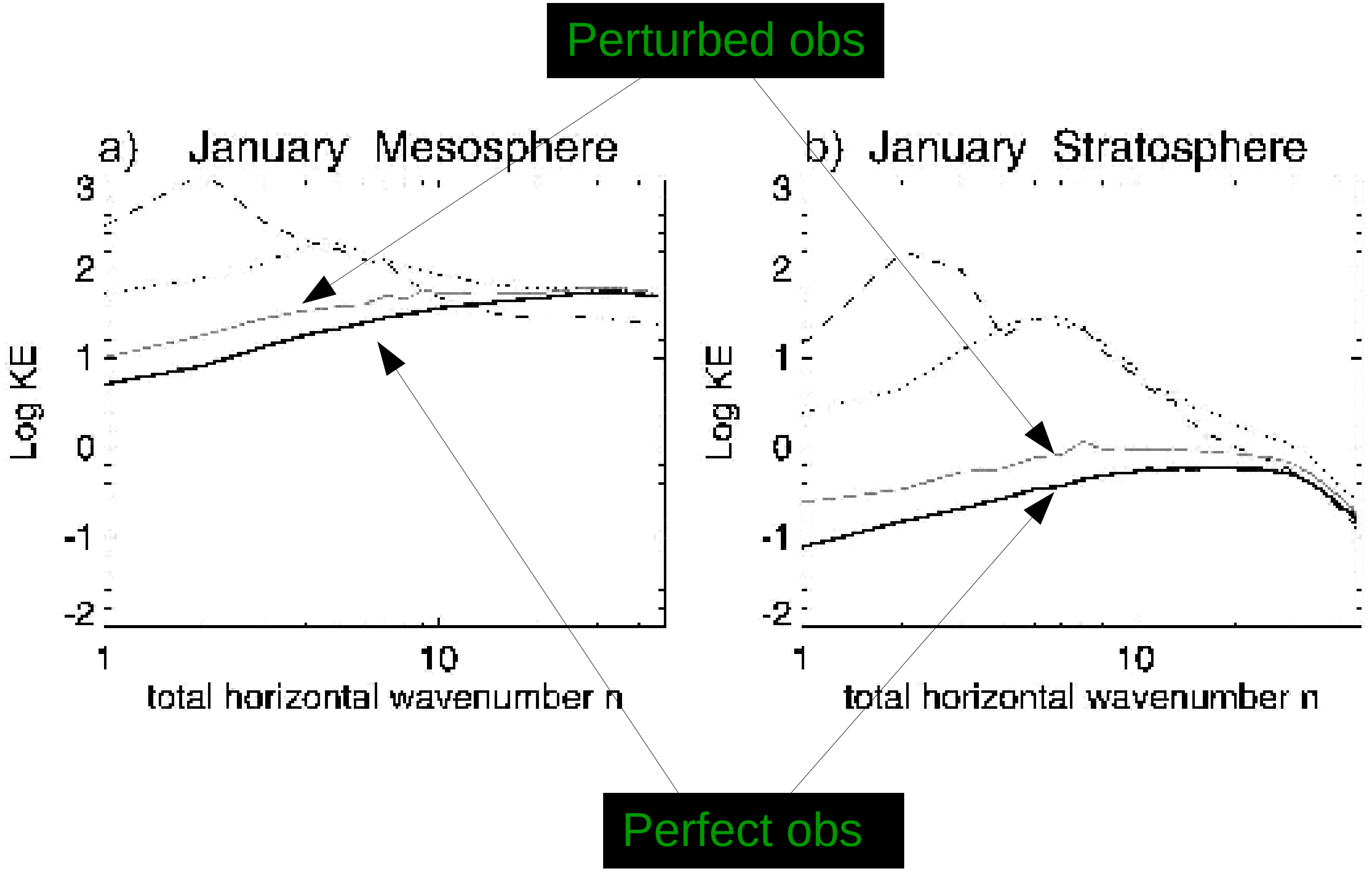
strat

mes

Nezlin et al. (2008)

Examined predictability of the CMAM DAS.

Key result: large-scale stratospheric information can be assimilated in the mesosphere.



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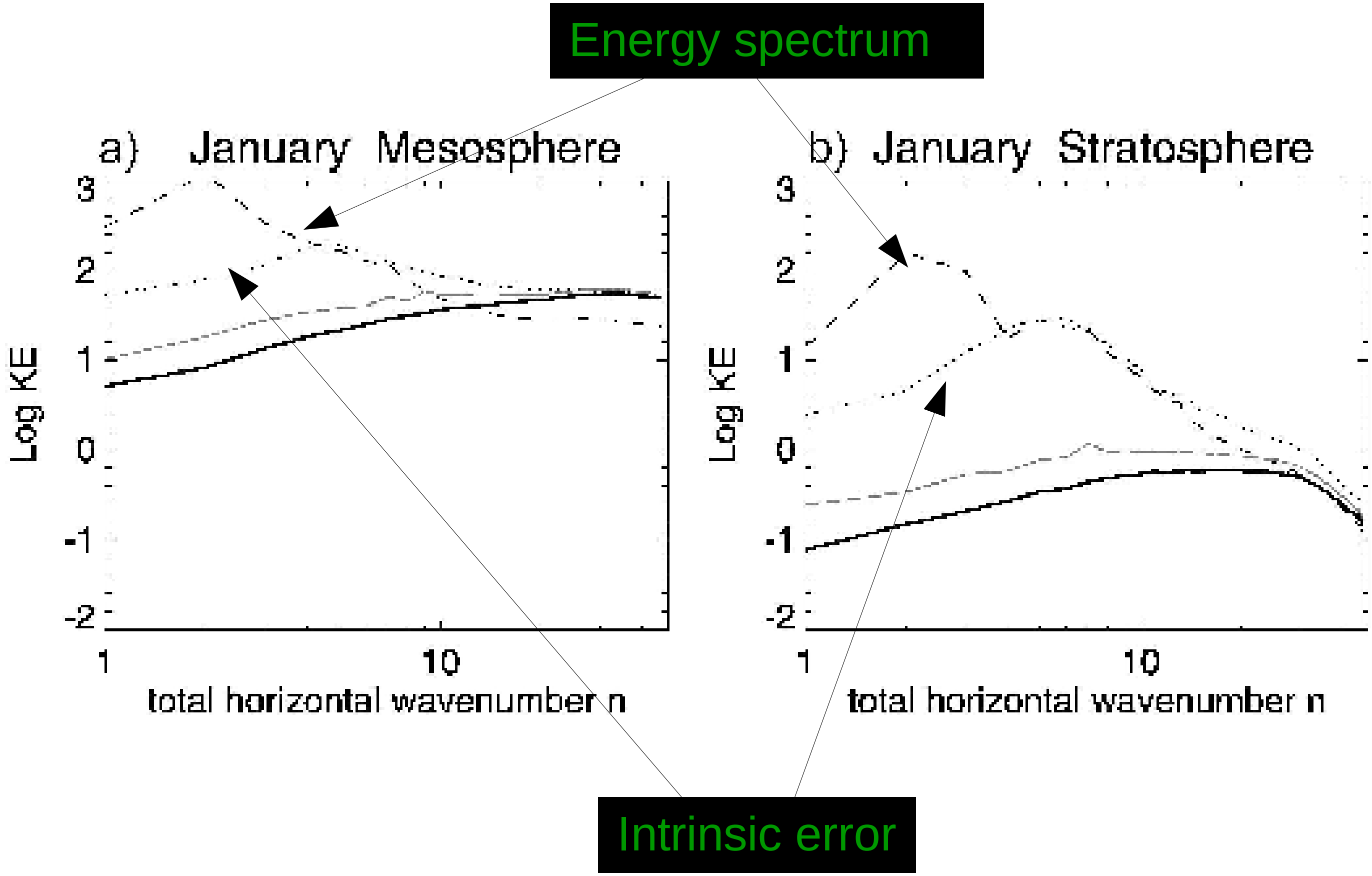

Liu et al. (2009)

Examed predictability of a whole-atmosphere model (NCAR WACCM: lid at ~ 140 km).

Key result: vertical coupling due to gravity waves

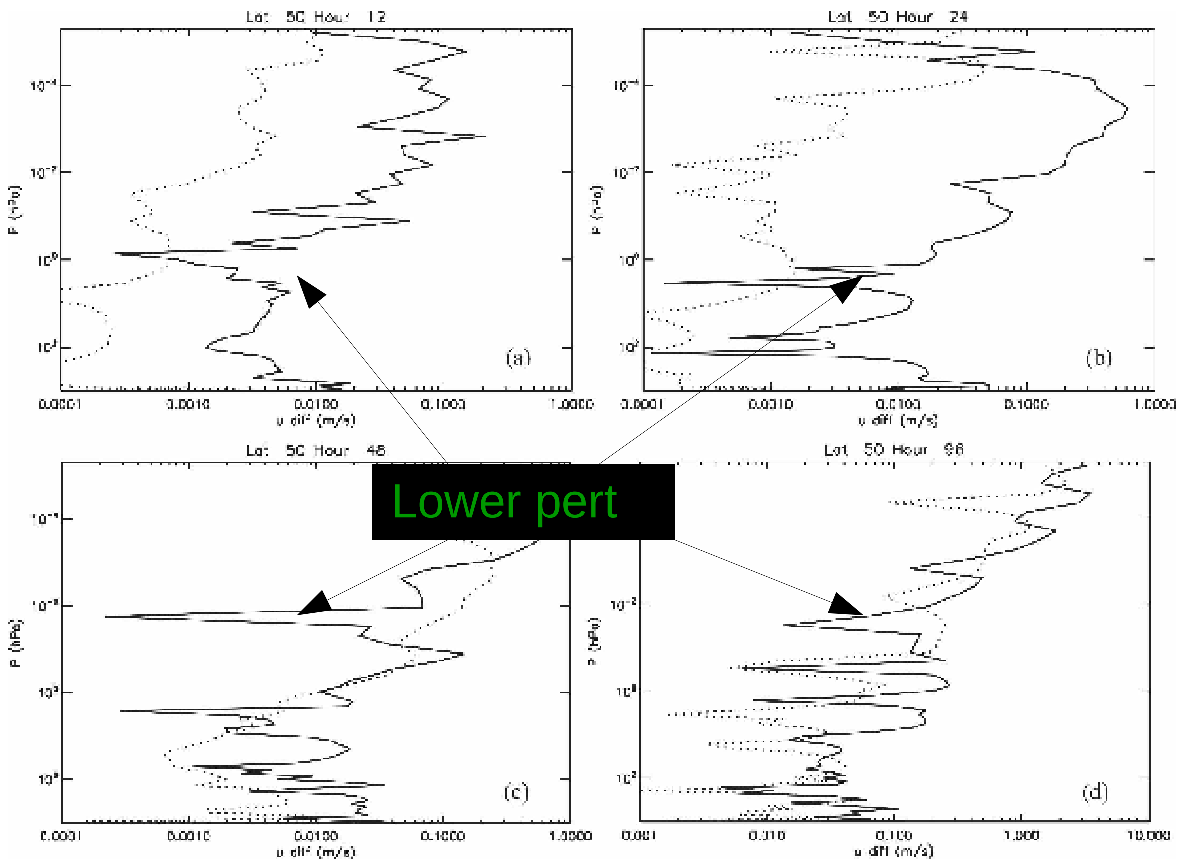

FIG. 7. Vertical profiles of rms zonal wind error in case L (solid line) and case U (dotted line) (a) 0.5 day, (b) 1 day, (c) 2 days, and (d) 4 days after the simulation starts.

Met Office

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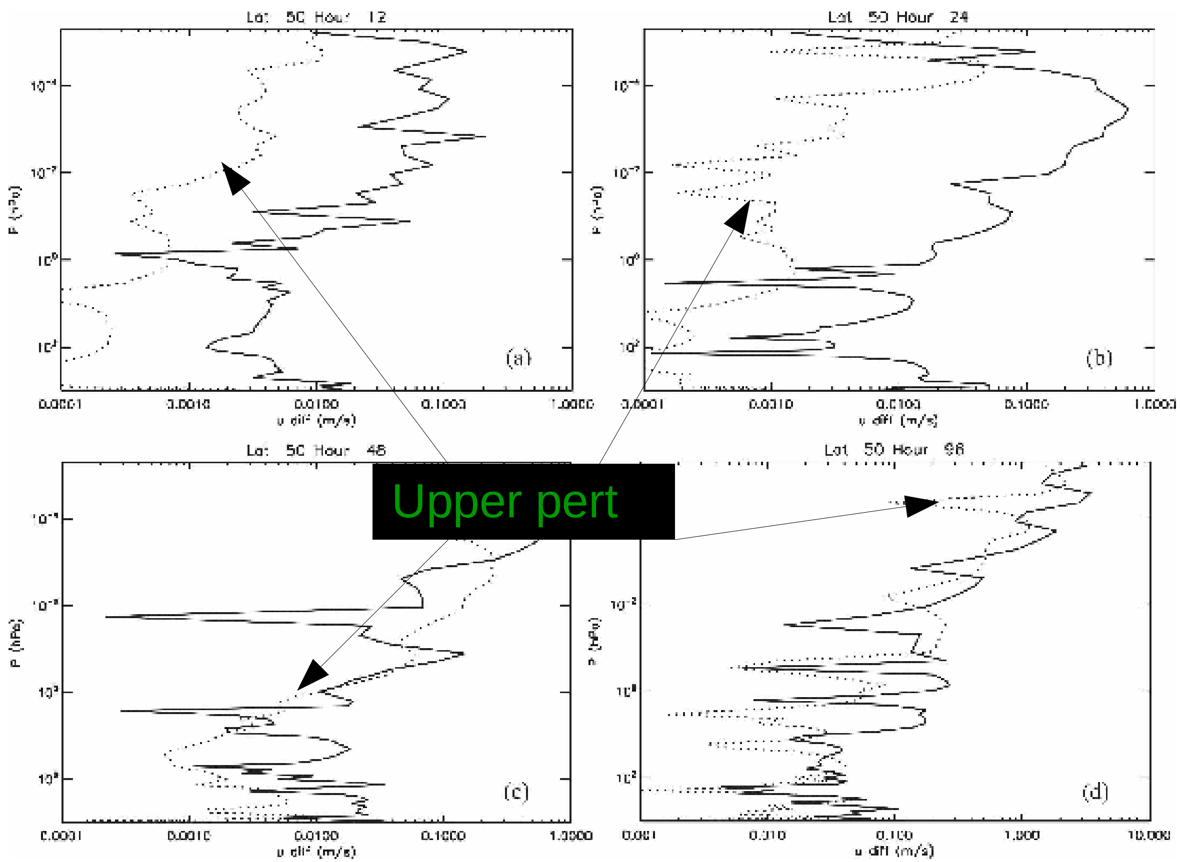


FIG. 7. Vertical profiles of rms zonal wind error in case L (solid line) and case U (dotted line) (a) 0.5 day, (b) 1 day, (c) 2 days, and (d) 4 days after the simulation starts.

A few questions

Focusing on the intrinsic error:

• What is the role played by gravity waves? For a shallow spectrum, Ro and Fr increase towards small scales.

• What happens in the stratosphere and mesosphere? Expect them to be more predictable.

• Is rapid vertical coupling robust?

NWP model

NWP Model (Met Office Unified Model)

Key features:

- Based on compressible Navier-Stokes
- Comprehensive model physics (e.g. convection, radiation, microphysics)
- Semi-Lagrangian/semi-implicit timestepping

Overview of simulations:

- 432 x325 grid (spacing ~ 50 km)
- 50 levels (lid at ~ 60 km)
- 30-day forecasts
- Initial conditions taken from winter 2006 analysis

Procedure

Perturbations are constructed by decomposing horizontal velocity field into spherical harmonics and randomising phase.

Two cases

– Small scale: $70 \leq n_f \leq 216$

– Large scale: $1 \leq n_f \leq 3$

No initialisation (e.g. horizontal non-divergence or geostrophy) or data assimilation: "intrinsic predictability".

Diagnostics

Error spectra:

$$\Delta_{KE}(k) = \sum_{|\boldsymbol{k}|=k} \frac{(\Delta\boldsymbol{\omega})^2}{k^2}, \quad \Delta\boldsymbol{\omega}(k) = \boldsymbol{\omega}^{(p)} - \boldsymbol{\omega}^{(c)}$$

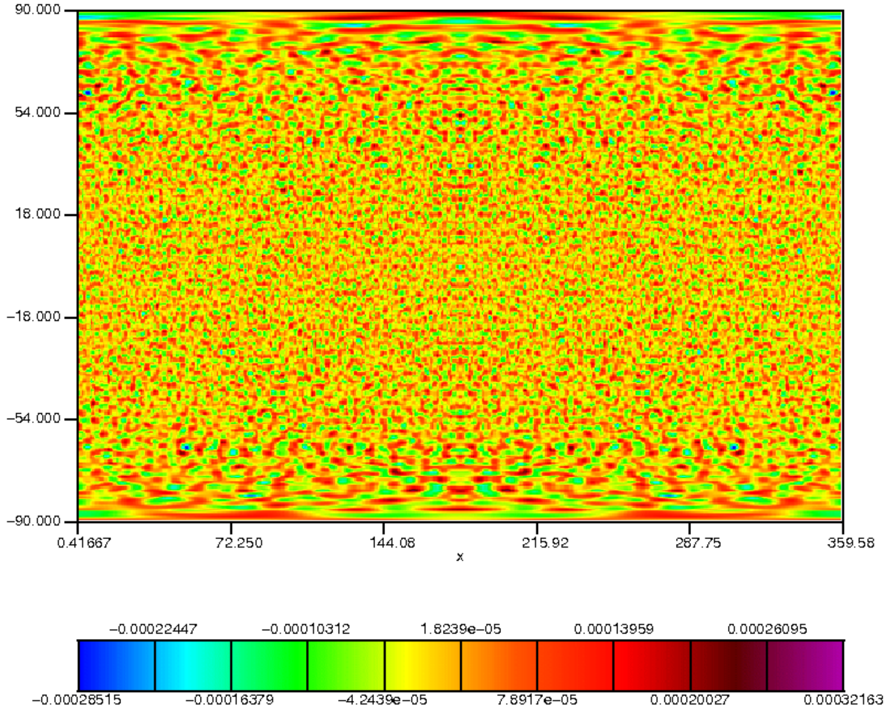
Relative error:

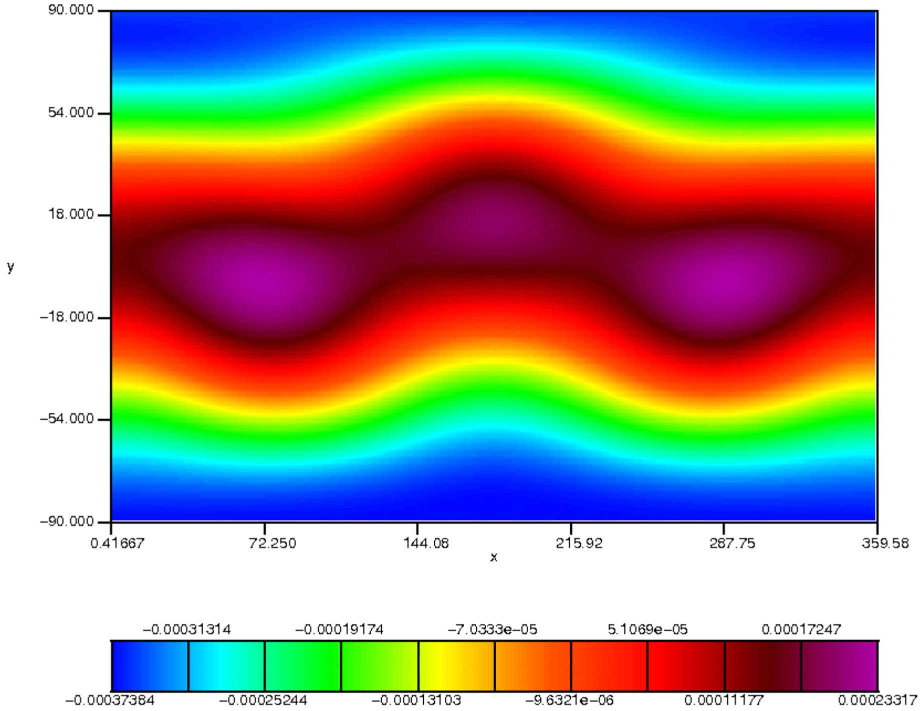
$$r_{KE}(k) = \frac{\Delta_{KE}(k)}{E_K(k)}$$

Mean relative error:

$$\overline{r_{KE}}(\tau) = \frac{\sum_k \Delta_{KE}(k)}{E_K}$$

Perturbations

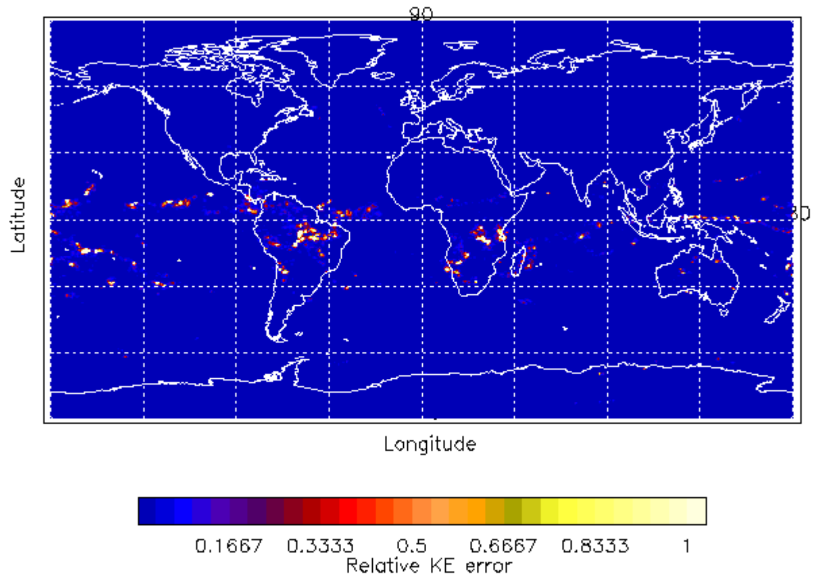


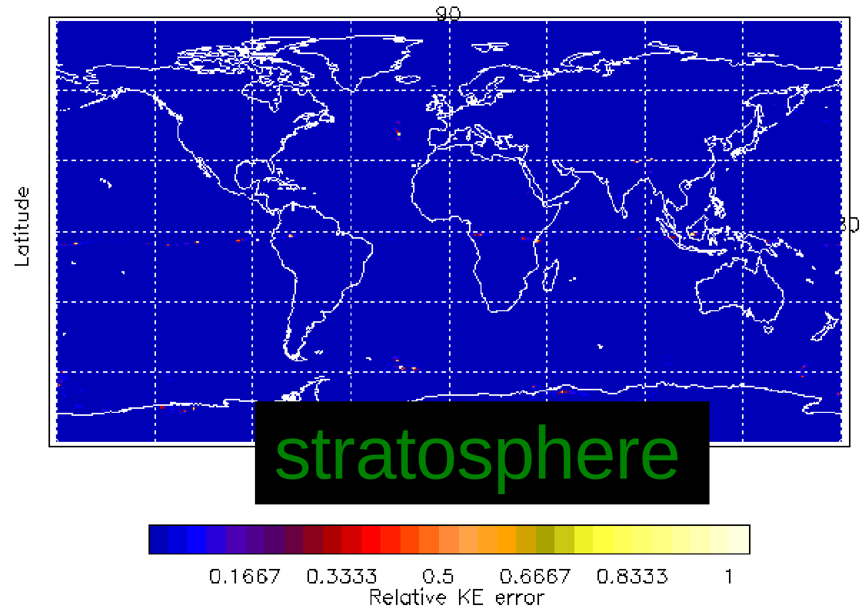


small scale

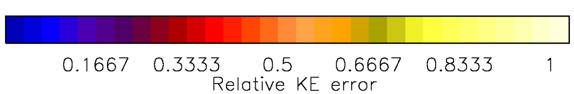
large scale

Spatial error (t=24hours)

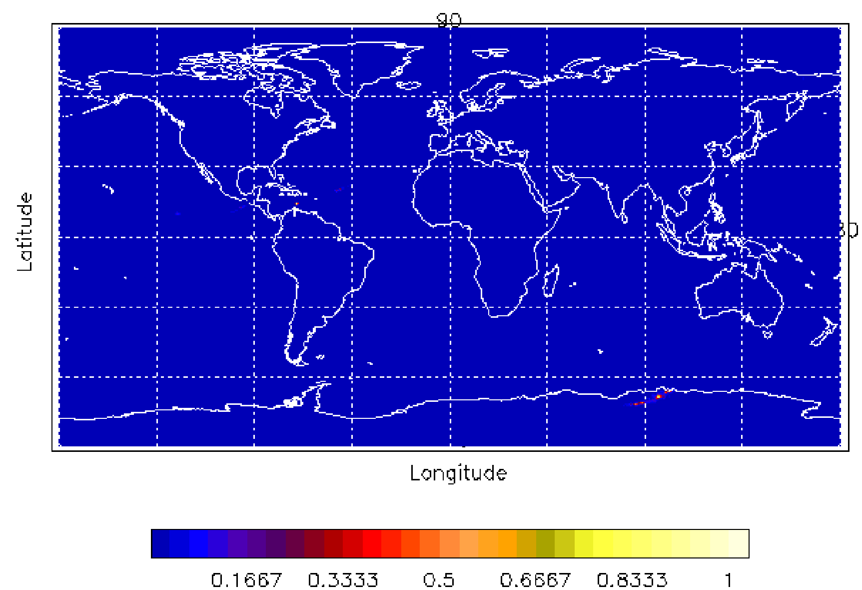




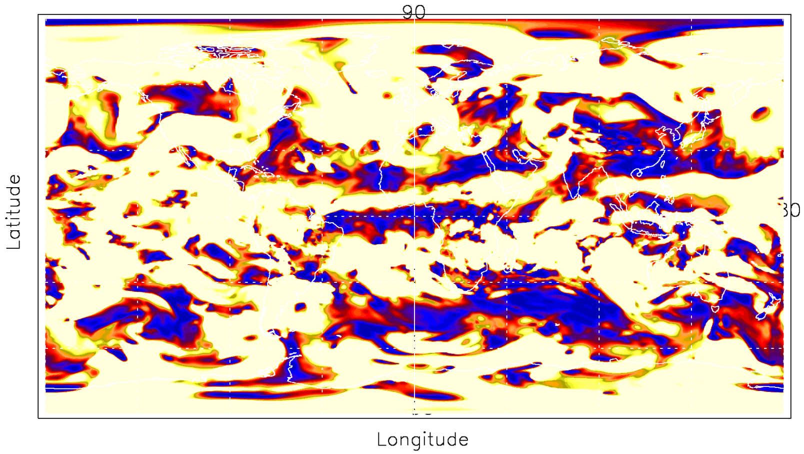
Troposphere



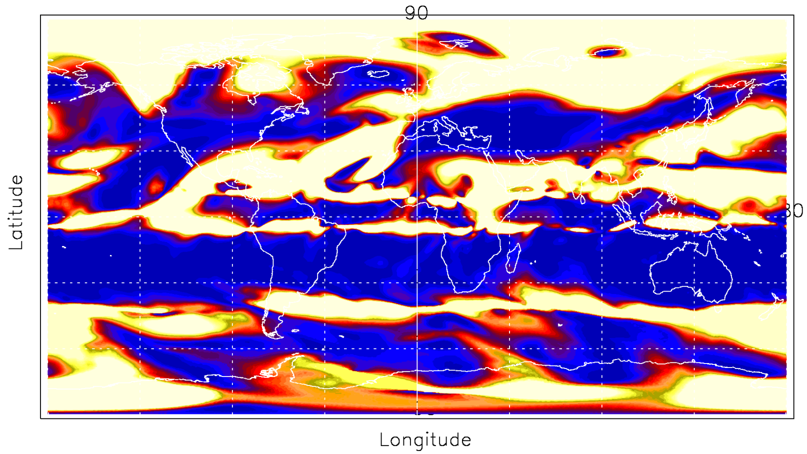
Mesosphere



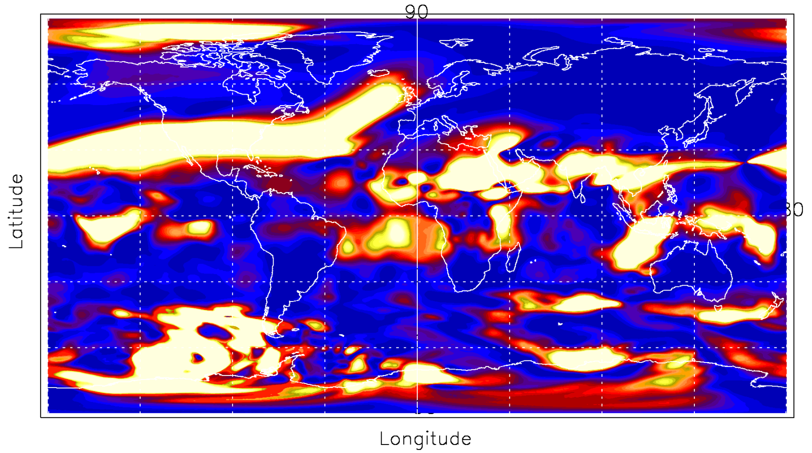
Spatial error (t=720hours)



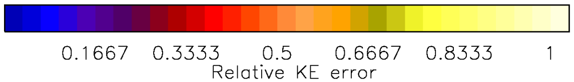
Troposphere



Stratosphere



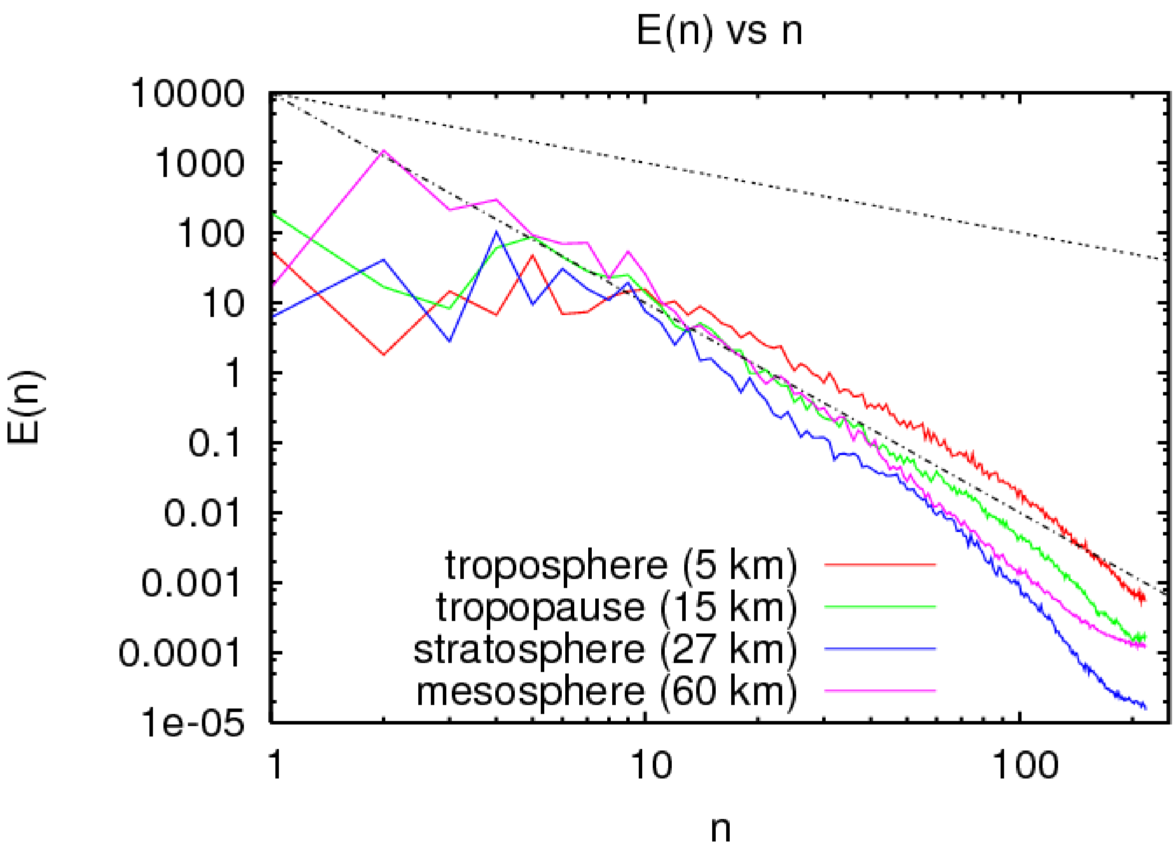
Mesosphere



Errors are much smaller in the mesosphere.

Slower error growth in tropics.

Energy Spectra

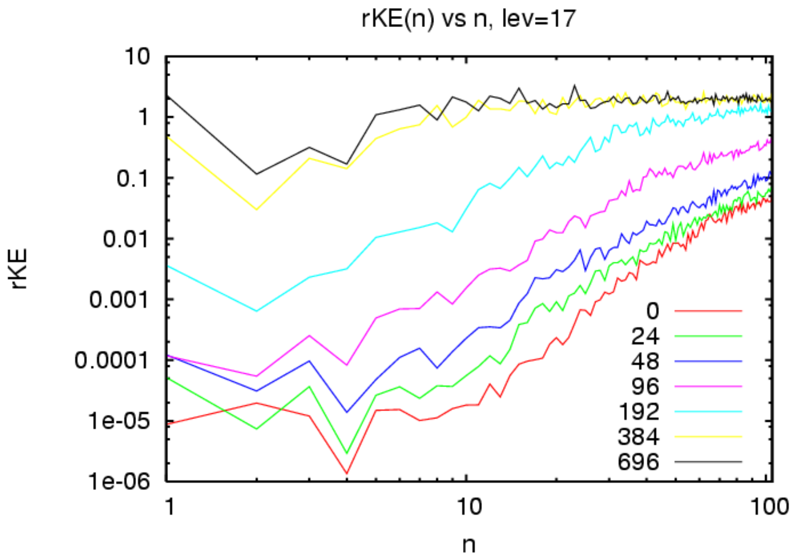


Mesospheric spectra of middle-atmosphere GCMs show evidence of shallowing (Koshyk et al. 1999).

Similar results are obtained with a 1-minute timestep.

Relative error spectra (small-scale pert)

trop



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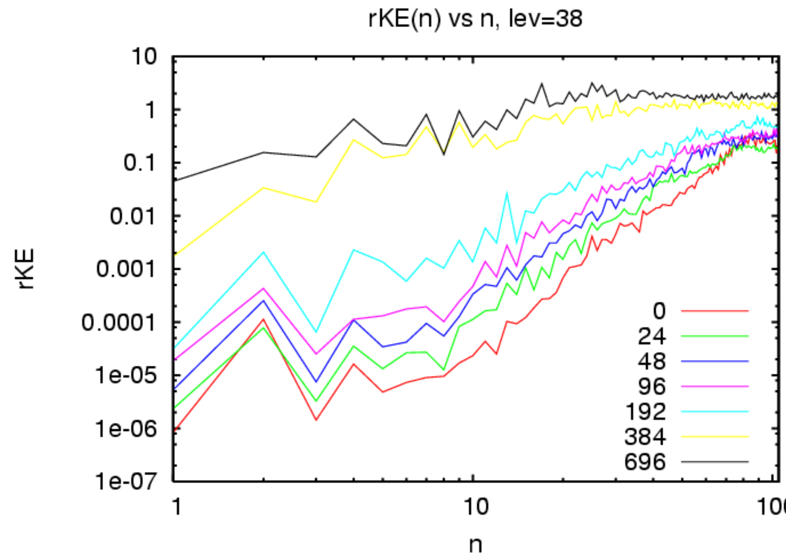
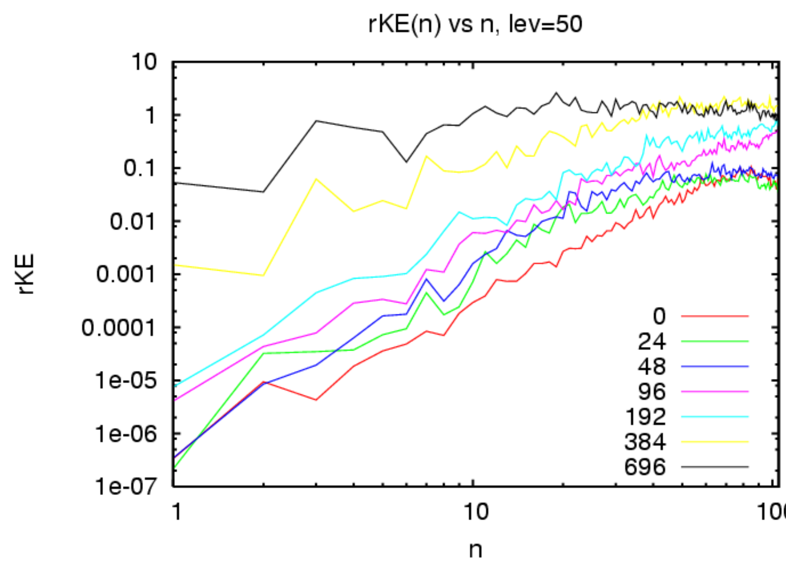


mes

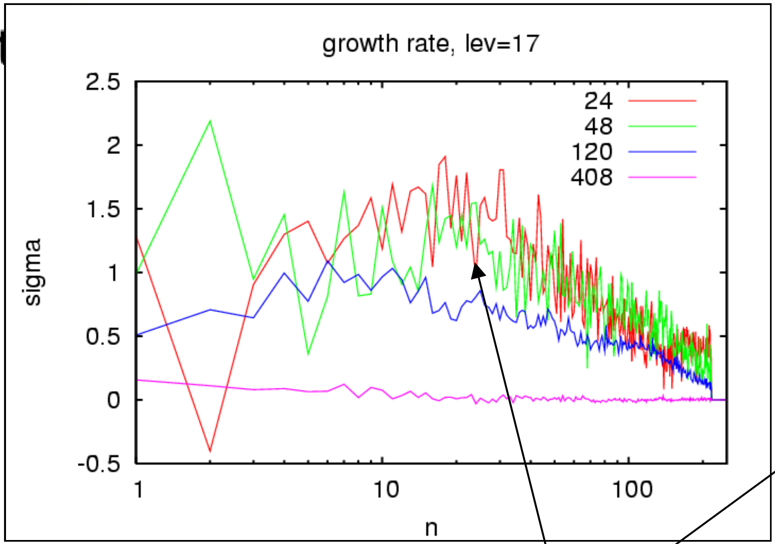


- Stratosphere and mesosphere are more predictable.

- Structure of evolution is broadly similar from troposphere to mesosphere.

Spectral growth rates

trop



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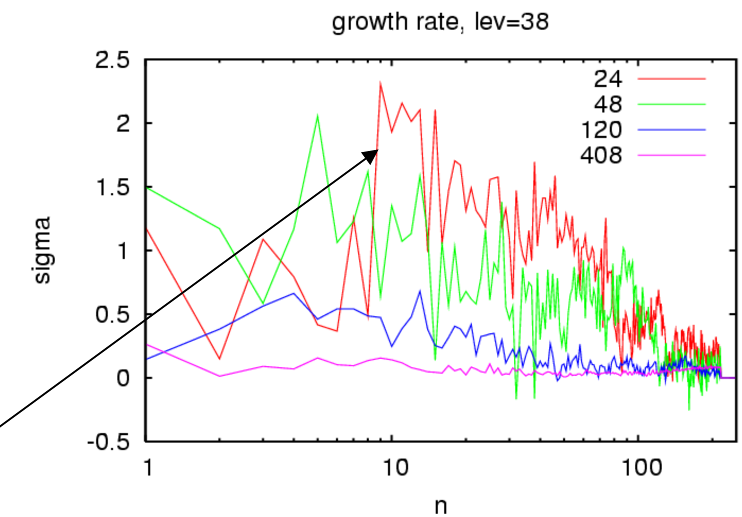
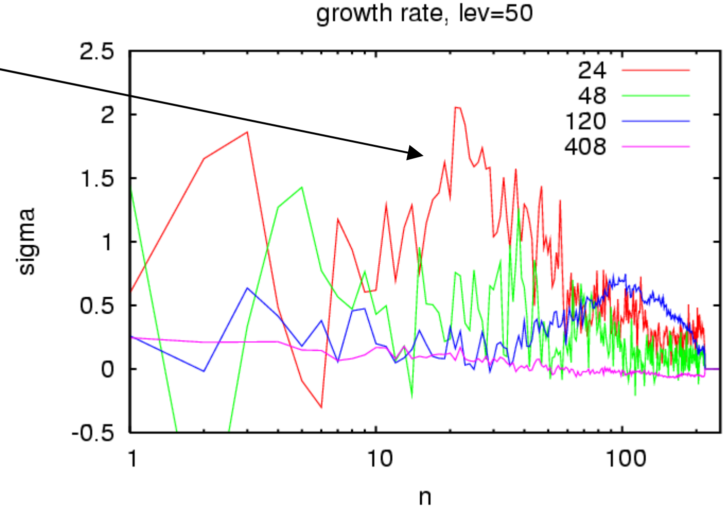


intermediate

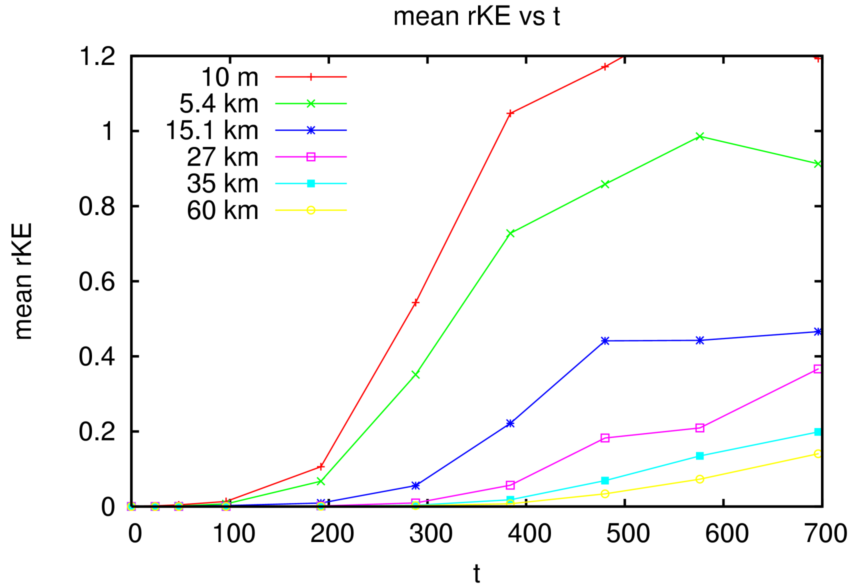
mes



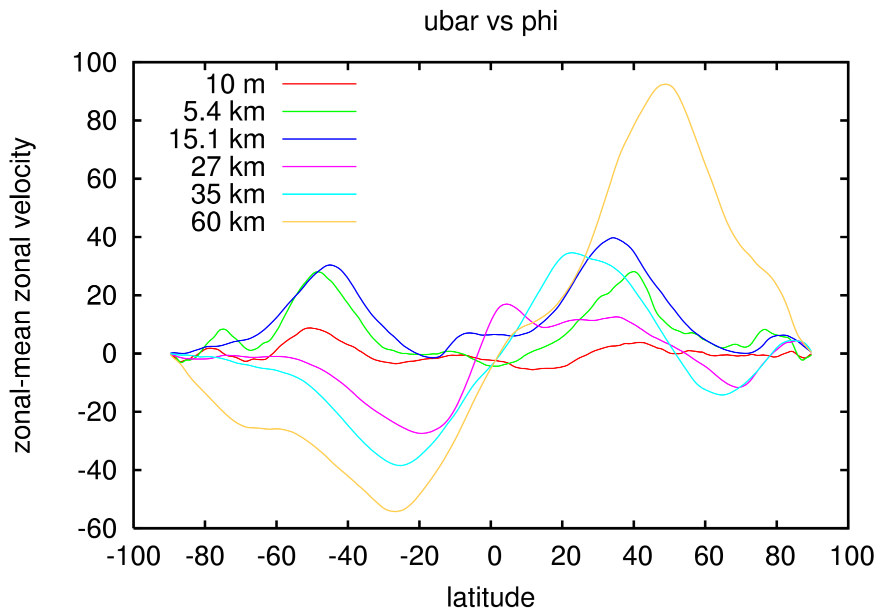
Initially there is preferential growth on intermediate, baroclinically-active scales (Tribbia & Baumhefner 2004).

Enhanced mesospheric predictability

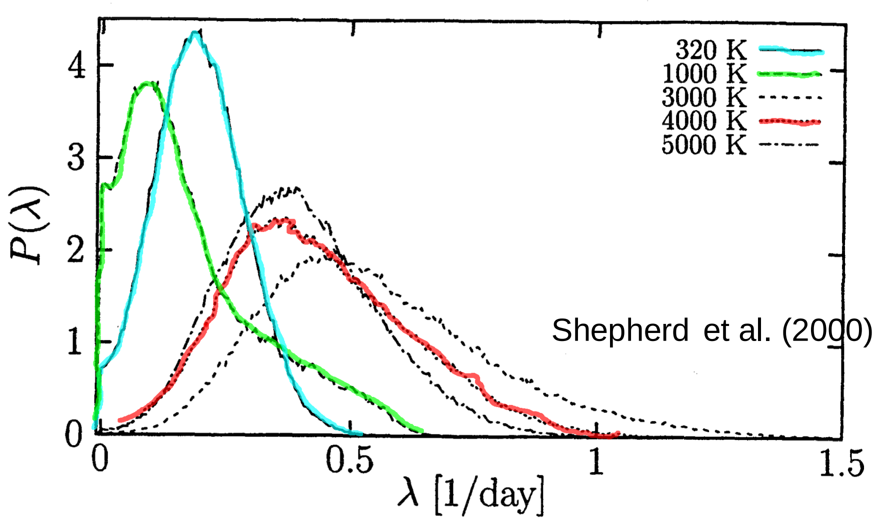
mean relative error



zonal wind

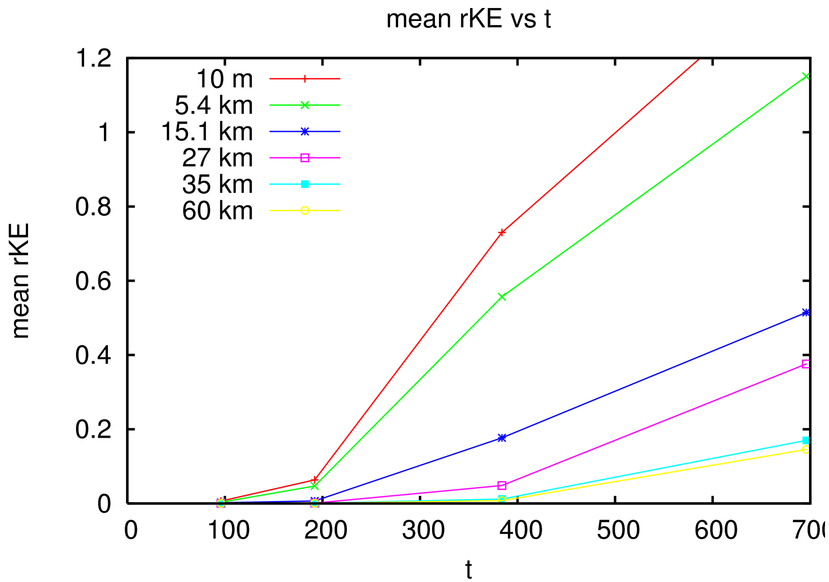


lyap exp's



Vertical localisation

trop



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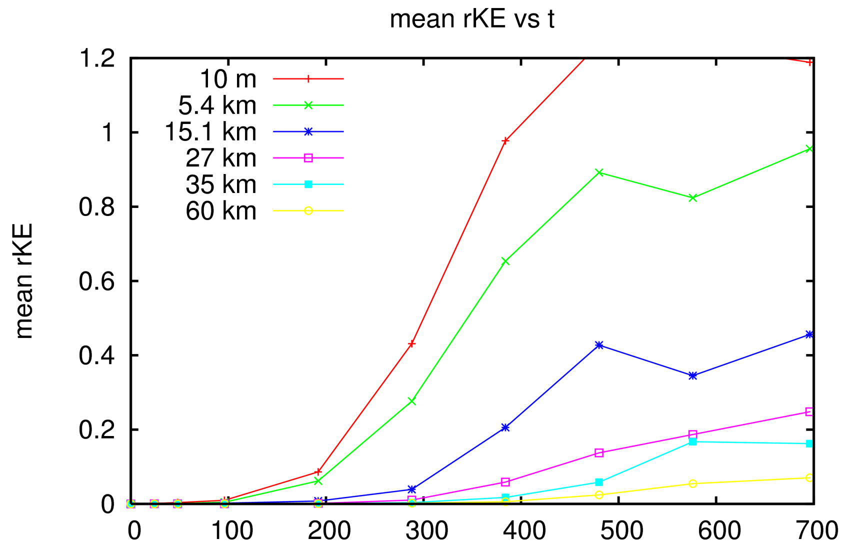
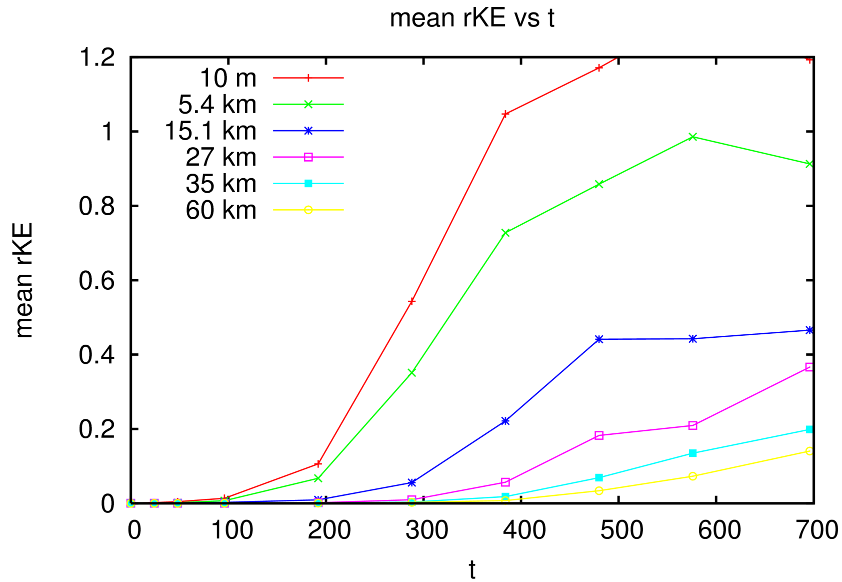


rig



- Results closely resemble those for whole-atmosphere perturbation (cf. Liu et al. 2009).

- Mechanism: vertically-propagating waves

Resolved gravity waves

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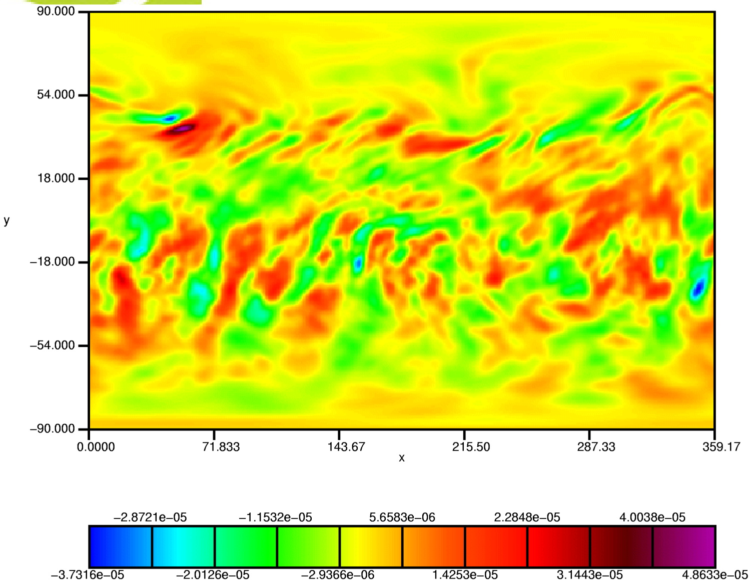
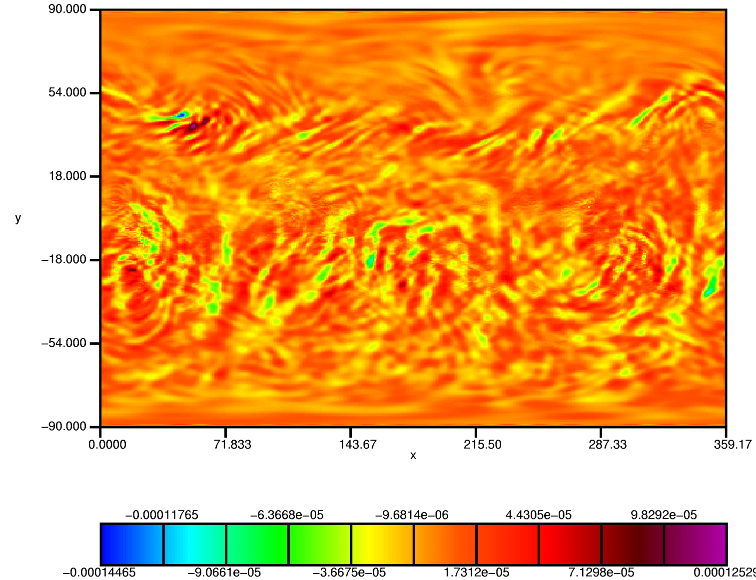
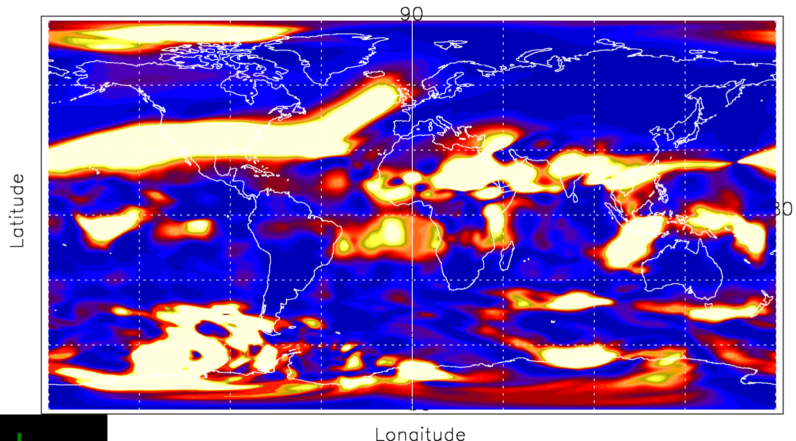
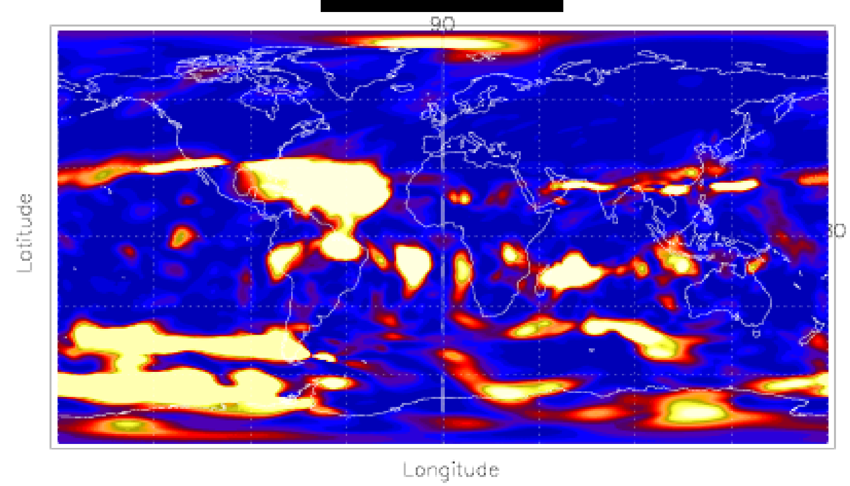




Δt = 20 min

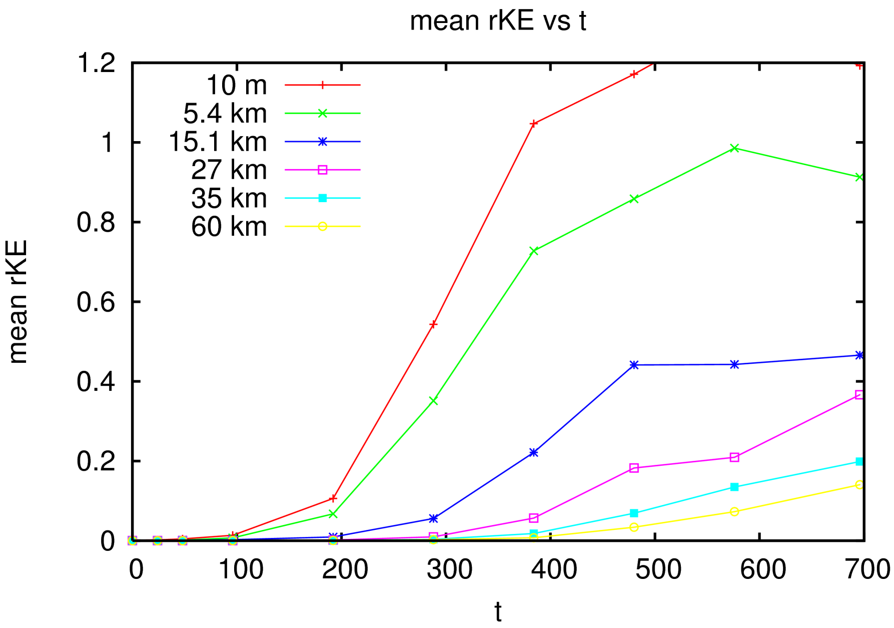
Δt = 1 min



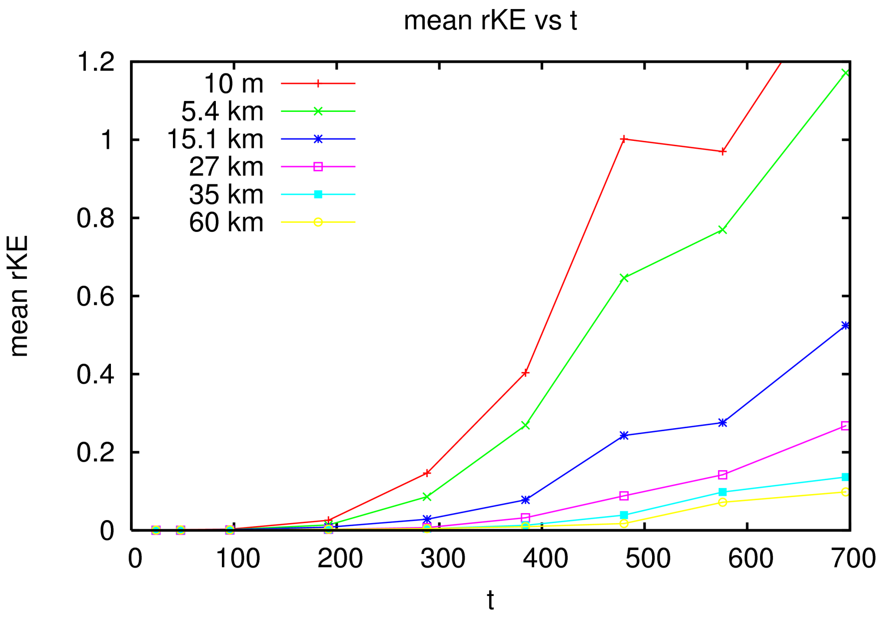


Rel err

1-minute timestep



Δt = 20 min



Δt = 1 min

- Operational NWP model is run with a fairly large timestep. In the mesosphere, Courant number > 1.
- With Δt = 1 min, advective Courant number < 1, but wave Courant number is large.
- Fast waves are not being resolved properly. Implications for predictability?

Discussion

Open questions

- Influence of increased resolution (more resolved gravity waves, shallower spectrum)
- Influence of initialisation/ data assimilation.

Summary

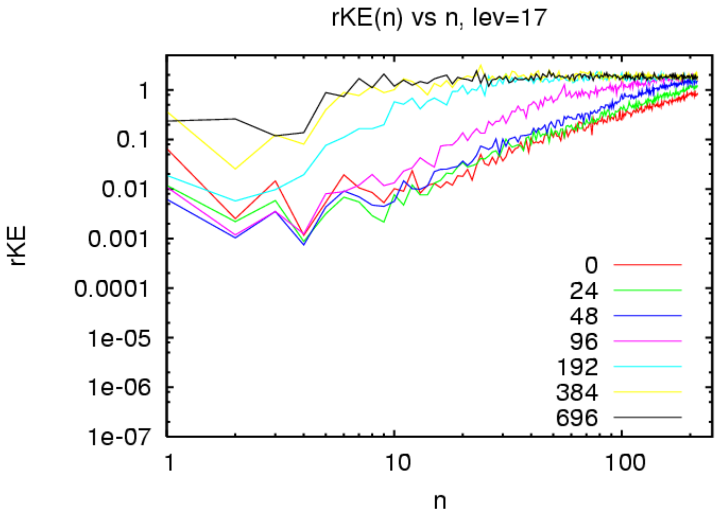
- Predictability decay is significantly slower for small-scale, strongly stratified flow.

- Predictability decay is slower in the mesosphere than in the troposphere. But difference is modest: numerics (e.g. resolving gravity waves) could be an issue.

Questions and answers

Relative error spectra (O(1) large-scale pert)

trop



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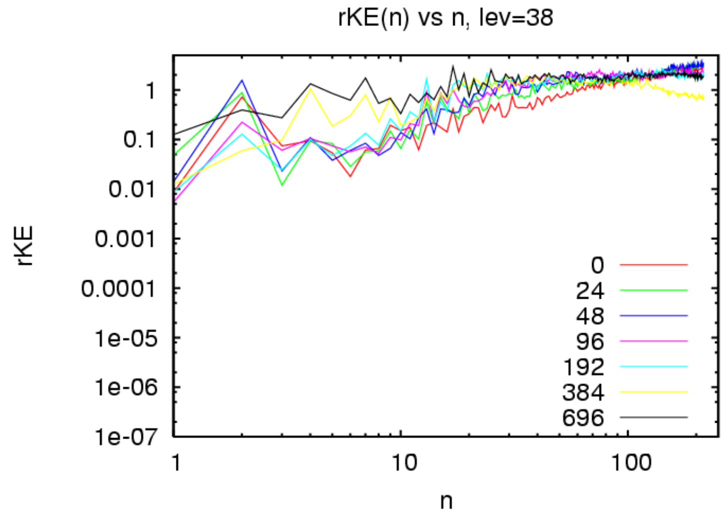

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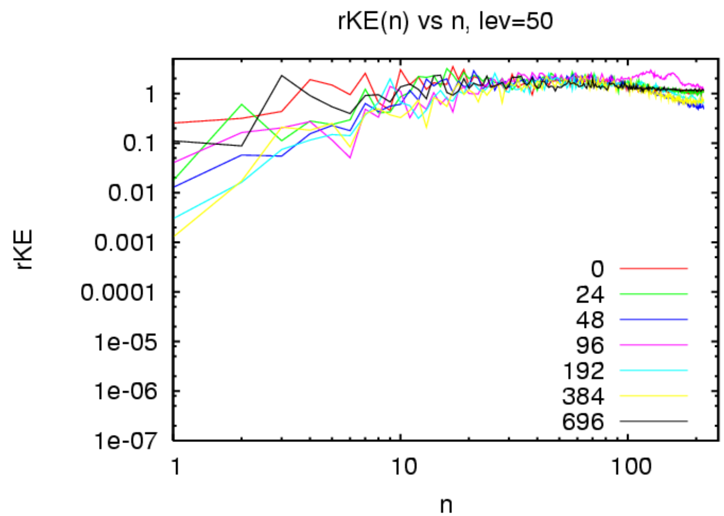
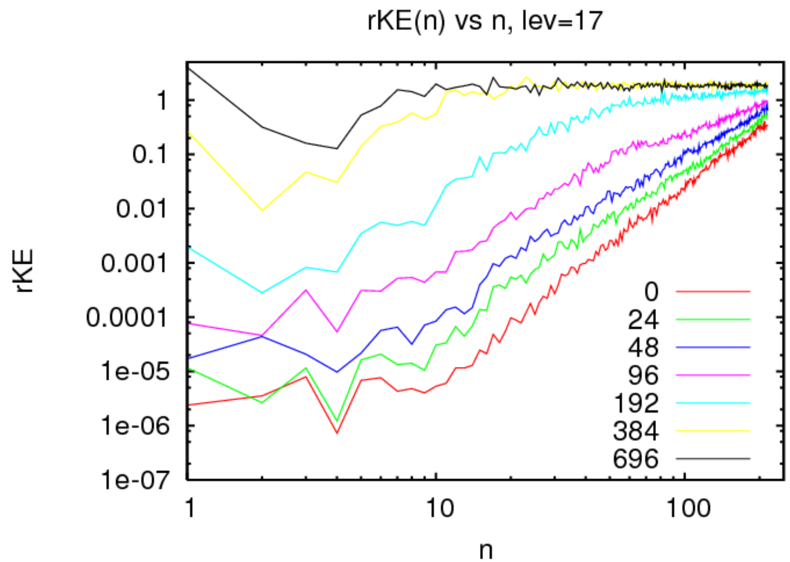


tion of a large-amplitude, large-scale pertur

bility loss at large scales.

Relative error spectra (large-scale pert)

trop



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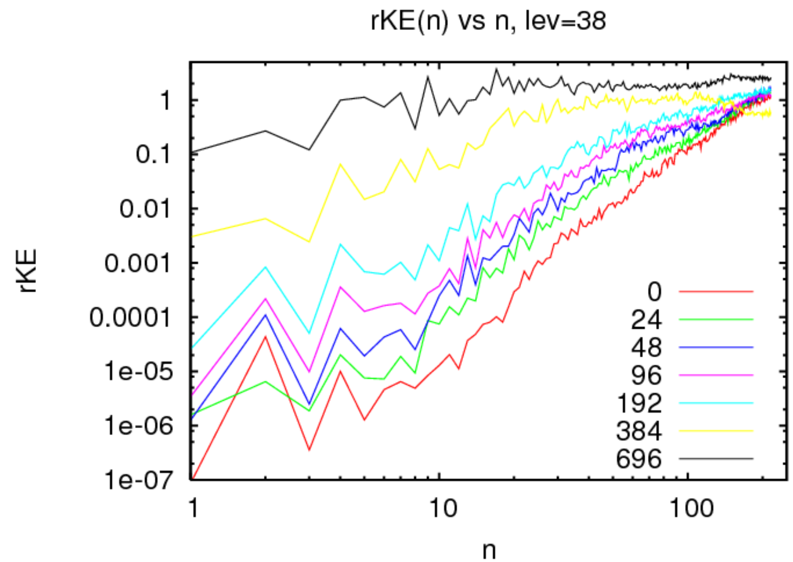

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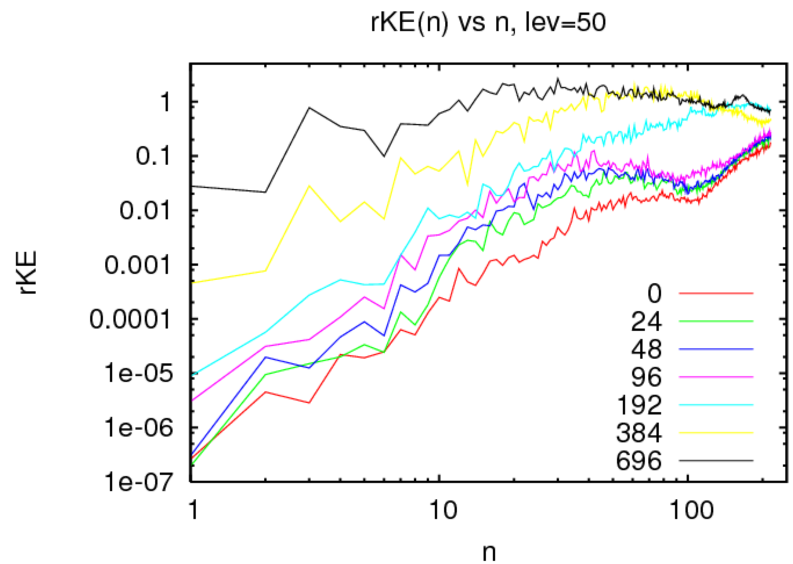

- Results are essentially identical to those for the small-scale perturbation.
- Spectral filtering is not exact: residual small-scale noise (energy is ~10^6 smaller).

Classical picture of predictability

Much of our intuition about atmospheric predictability derives from the pioneering work of Lorenz, Leith & Kraichnan.

Using a stochastic model of the barotropic vorticity equation, Lorenz (1969) showed that there is finite atmospheric predictability: infinitesimal small-scale errors contaminate the largest scales within a finite period of time.

Lorenz's analysis was later corrected and extended by Leith & Kraichnan (1972).

This is the so-called atmospheric butterfly effect.

Dynamical regimes

Nature of the dynamics is controlled by Ro and Fr. Expand in Ro:

O(1): geostrophy

O(Ro), Ro ~Fr, quasi-geostrophy

Hierarchy of balanced models.

Want to examine contrast between (super)synoptic (large-scale) and subsynoptic (small-scale) flows.

Energy spectra in turbulence

Navier-Stokes equations for a constant-density fluid:

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u} = -\frac{1}{\rho_0} \boldsymbol{\nabla} p + \nu \nabla^2 \boldsymbol{u}, \quad \boldsymbol{\nabla} \cdot \boldsymbol{u} = 0,$$

in T^2 or T^3. Turbulence for Re = UL/ ν >> 1.

Kinetic energy spectrum

$$E(k) = \sum_{\boldsymbol{k}=|k|} \frac{1}{2} \boldsymbol{u}(\boldsymbol{k}) \boldsymbol{u}(\boldsymbol{k})^*$$

3-D (Kolmogorov)

E(k) ~ $k^{-5/3}$ [inertial range]

2-D (Batchelor-Leith-Kraichnan

E(k) ~ k^{-3} [small scales; enstrophy range]

E(k) ~ $k^{-5/3}$ [large scales; energy range]

Quasi-geostrophic turbulence is essentially identical.

Applicability to the real atmosphere

The real atmosphere cannot be described exactly by 2-D or quasi-geostrophic turbulence.

Conventional view is that the classical picture carries over straightforwardly to the real atmosphere.

Key quantity: eddy turnover time

$$\tau(k;k_1) = \left(\int_{k_1}^{k} k'^2 E(k')dk'\right)^{-\frac{1}{2}}$$

For $E(k) \sim k^{-p}$ and $k \to \infty$

$$\tau(k;k_1) \sim \begin{cases} \text{constant}, & p < 3 \\ k^{(p-3)/2}, & p > 3 \end{cases}$$

Upshot: predictability behaviour depends crucially on the atmospheric energy spectrum.