Rotational and divergent kinetic energy in the mesoscale NCMRWF Unified Model

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Introduction

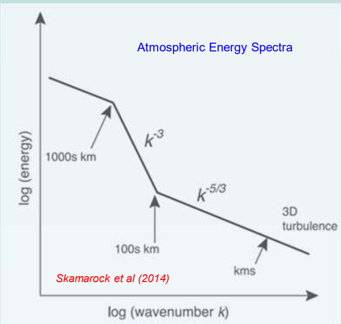


Figure 1: *Schematic of canonical atmospheric kinetic energy spectra [Fig. 1 of Skamarock et al (2014)]*

- ✓ Accurate representation of the Kinetic Energy(KE) wavenumber Spectrum is considered essential in weather and climate models, partly because it establishes the saturation bounds for forecast errors at each scale
- ✓ The atmospheric kinetic energy (KE) spectrum has a canonical structure depicted schematically
  - ❑ *The spectral magnitude decreases with scale.*
  - ❑ *shallow-sloped region at low wavenumbers and global scales*
  - ❑ *steeper-sloped power-law region (close to -3) at intermediate wavenumbers corresponding to wavelengths of baroclinic cyclones*
  - ❑ *shallower slope in mesoscale region, close to -5/3, that leads to fully three-dimensional turbulence at the smallest scales*
  - ❑ *These characteristics appear in many observational analyses*

- ✓ Spectrum constructed using 6900 commercial airplane flights during the Global Atmospheric Sampling Program (GASP) from 1975 and 1979.
- ✓ Salient features of the spectra:
  - ❑ *No systematic difference in the spectrum over land and oceans, or between winter and summer*
  - ❑ *Energy levels tend to be higher with increasing latitude, and the temperature variance appears to be higher in winter than in summer.*
  - ❑ *KE spectrum in the upper troposphere shows a -3 slope in macroscale (between ~5000-500km)*
  - ❑ *-5/3 slope in mesoscale below ~500km*

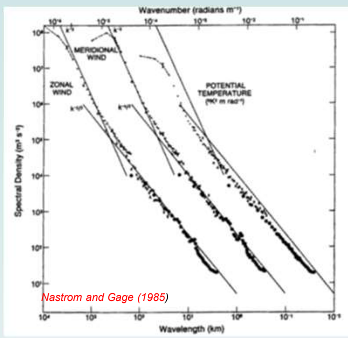


Figure 2: *Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. For more details refer Fig. 3 of Nastrom and Gage, 1985*

Motivation & Objectives

- ✓ An atmospheric model's ability to reproduce the canonical spectrum is often presented as evidence of the correctness of a model's formulation, implementation, and configuration.
- ✓ The KE spectrum also provides a direct measure of model filter effects and a model's effective resolution—that is, the filter scale of the model.

Therefore, the objectives of this work are:

- ✓ How good are the high-resolution NWP models running operationally at NCMRWF in representing the observed synoptic and mesoscale spectral characteristics?
- ✓ With respect to the goals of high-resolution NWP at NCMRWF, a critically important measure of an NWP model's accuracy is its ability to resolve features at the limits of its grid resolution.
- ✓ To see extent of spatial scales that NCUM Model resolve based on KE Spectra, commonly referred to as the effective resolution
- ✓ To understand the relative contribution of divergent and rotational energy to total kinetic energy that provides insights of main dynamical agent implicit in the mesoscale energy spectrum.

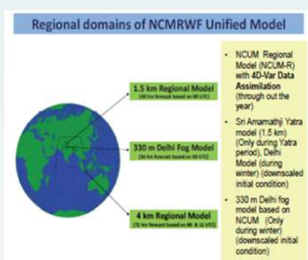


Figure 3: *Overview of regional configurations of NCUM Operational Model at NCMRWF*

Data and Methodology

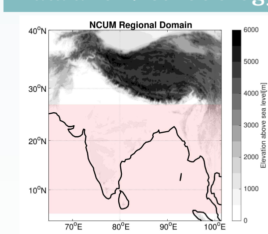


Figure 4: *The regional domain of mesoscale NCUM model overlayed with topography*

- ➢ A regional version of NCMRWF Unified Model (NCUM-R) is at 4 km resolution, covering entire Indian region, is run operationally and generates three-day forecasts based on 00 UTC and 12 UTC initial conditions.
- ➢ The NCUM-R adapted from the second Met Office Unified model/ Jules Regional Atmosphere and Land configuration, RAL2 (Bush et al., 2022), defines the dynamics and physics scheme of the atmosphere and land.
- ➢ Surface elevation and vegetation are derived from the 90m NASA Shuttle Radar Topographic Mission digital elevation map and 30 m Indian Space Research Organization land-use land cover map respectively
- ➢ NCUM-R still used 80 vertical levels with a top at 38.5 km and 14 model levels below 1 km instead of 90 levels defined in RAL2
- ➢ The operational forecast issued daily at 00UTC from NCUM-R were analyzed in this during the southwest monsoon period (June-September 2020).

The horizontal velocities from the model forecasts are split into divergent and rotational components from the Helmholtz decomposition. It is useful to write the horizontal velocity field on the sphere interms of the Helmholtz decomposition:

$$\vec{V} = \vec{V}_\psi + \vec{V}_\chi = \vec{V}_r + \vec{V}_d = -\hat{k} \times \vec{\nabla}_\psi + \vec{\nabla}_\chi$$

where

$\vec{V}_\psi = \vec{V}_r$ is called the *rotational component* ; $\vec{V}_\chi = \vec{V}_d$ is called the *divergent component*

$\hat{k}$ is the unit vector in the vertical, ψ is the *streamfunction* and χ the *velocity potential*. In cartesian components, we can write each component out:

$$\vec{V}_\psi = (u_r, v_r) = \left(-\frac{\partial\psi}{\partial y}, \frac{\partial\psi}{\partial x}\right); \qquad \vec{V}_\chi = (u_d, v_d) = \left(+\frac{\partial\chi}{\partial x}, \frac{\partial\chi}{\partial y}\right)$$

The rotational component describes swirling flow and has no divergence.

The horizontal KE ($E(k)$) spectrum is estimated based on spectra of zonal and meridional components using the following definition

$$E(k) = \frac{1}{2}\left(|U_k|^2 + |V_k|^2\right)$$

Results

General features of the energy spectra

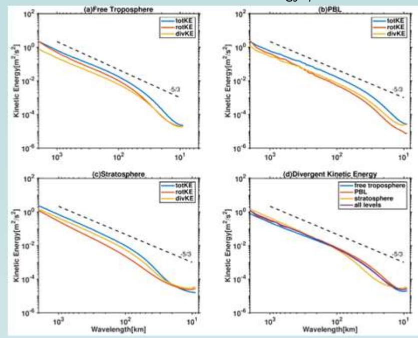


Figure 5: *Seasonally (JJA2020) and vertically averaged spectra of total (blue), rotational (red), divergent (yellow) in (a) the free troposphere, (b) the planetary boundary layer (PBL) and (c) the stratosphere. (d) Divergent kinetic energy in various layers.*

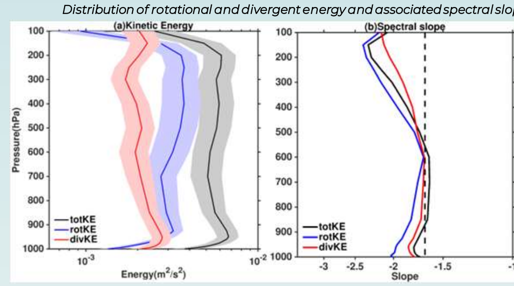
- ❑ Spectra averaged for three layers defined as the 'stratosphere' (11 pressure levels between 10 and 250 hPa), the 'free troposphere' (21 model levels between 250 and 850 hPa) and the 'planetary boundary layer' or 'PBL' (pressure levels below 850 hPa).
- ❑ On average, the spectra are shallowing towards the surface. A canonical spectrum with a slope -5/3 at the mesoscales is well predicted in the regional model
- ❑ In the free troposphere, the rotational KE(rotKE) dominates the divergent energy(divKE), and they merge at ~ 50km and below
- ❑ In the boundary layer, the rotKE dominates at larger scales while below ~500km the divKE is higher. In the stratosphere, the divKE dominates the roKE at all the scales.

Distribution of rotational and divergent energy and associated spectral slopes

Figure 6:

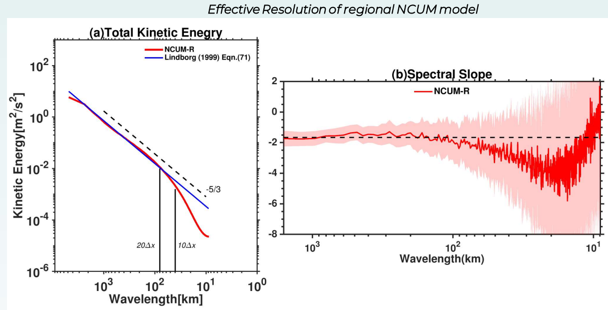
(a) Vertical distribution of the kinetic energy for the period Jun-August 2020. The averaging is done over the scales below 500 km.

(b) The slope of the spectra of rotational (blue), divergent (red) and total kinetic energy (black) as a function of pressure. Spectra were fitted in the range between 500 and 40 km. The thin grey line represents -5/3.



- ❑ The vertical distribution of energy indicates the flow within the PBL and in the upper levels is dominated by horizontal divergence rather vertical vorticity.
- ❑ The result above in (a) indicates the relative contribution of divergent and rotational energy to total kinetic energy which is a key to understanding the main dynamical agent underlying the mesoscale energy spectrum. Thus, to a first approximation, the result indicates the mesoscale spectrum follows mainly from gravity waves
- ❑ The mesoscale spectral slopes of NCUM-R (b) indicates a close fit to the -5/3 canonical slope (particularly in the free troposphere) as noted in many flight- track observations of GASP(Nastrom and Gage, 1985) and MOZAIC (Lindborg, 1999)

Effective Resolution of regional NCUM model



- ❑ **Figure 7:** *(a) The total energy spectrum is very well described by the analytical fit to the data derived by Lindborg (1999). The departure from the Lindborg model occurs around 50km scale between 20Δx and 10Δx (where Δx=4km).*
- ❑ *(b) The spectral slopes as a function of scale is given in (b) also suggests that the deviation from canonical mesoscale slope of -5/3 occurs between 20Δx and 10Δx . The standard deviation of the spectrum during June-August, 2020 is indicated by the shading.*

Conclusion

- ❑ The dynamical agent responsible for the mesoscale portion of the kinetic energy spectrum is a matter of ongoing debate and the spectral characteristics have significant implications for mesoscale and cloud-scale NWP. Hence, we examine the ability of a regional NCUM model to reproduce observed kinetic energy spectral characteristics. Further, relative contribution of divergent and rotational energy to total kinetic energy is also computed in understanding the main dynamical agent underlying the mesoscale energy spectrum.
- ❑ The general features of the model spectra follows observed mesoscale spectrum with slope close to -5/3. The divergent energy is dominant in the PBL and lower stratosphere relative to rotational energy suggesting the inertia-gravity waves dominate the forecast spectrum in the mesoscale .
- ❑ The NCUM-R model forecasts' kinetic energy spectra departs from their expected behaviors at high wavenumbers (short wavelengths) on the model grid that might be due to energy dissipation and numerical stability. These deviations are a direct measure of an NWP model's true resolution (effective resolution) capabilities..
- ❑ The effective resolution here is indicated by the departure from the Lindborg model that occurs around 50km scale. It suggests that the modes with wavenumbers higher than the effective resolution are dynamically suspect.

Bibliography

[1] *Blažica, V., Žagar, N., Strajnar, B., & Cedilnik, J. (2013) Rotational and divergent kinetic energy in the mesoscale model ALADIN, Tellus A: Dynamic Meteorology and Oceanography, 65:1, 18918, DOI:* https://doi.org/10.3402/tellusa.v65i0.18918

[2] *Skamarock, W. C., Park, S., Klemp, J. B., & Snyder, C. (2014). Atmospheric Kinetic Energy Spectra from Global High-Resolution Nonhydrostatic Simulations, Journal of the Atmospheric Sciences, 71(11), 4369-4381. DOI:* https://doi.org/10.1175/JAS-D-14-0114.1

[3] *Lindborg, E., 1999: Can the atmospheric kinetic energy spectrum be explained by two-dimensional turbulence? J. Fluid Mech., 388, 259–288, DOI:* https://doi.org/10.1017/S0022112099004851

[4] *Nastrom, G., and K. Gage, 1985: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft. J. Atmos. Sci., 42, 950–960, DOI:* https://doi.org/10.1175/1520-0469(1985)042<0950:ACOAWS>2.0.CO;2

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