Wave–vortex decomposition of aircraft data: interpreting the Nastrom–Gage spectrum

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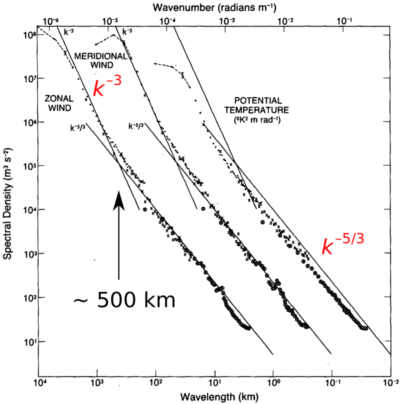
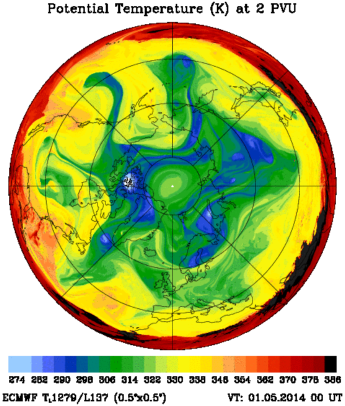
Nastrom–Gage: the synoptic-to-mesoscale transition





Geostrophic turbulence governs synoptic scales (enstrophy range), but what causes the transition in spectral slope at 500 km?

Nastrom and Gage (1985), Charney (1971)

The synoptic-to-mesoscale transition: contesting theories

1. Inverse energy cascade originating from small scales
   Energy injected by convective activity at small scales cascades to large scales in a quasi-two-dimensional cascade (Gage 1979, Lilly 1983).
2. Frontogenetic processes at the tropopause
   Surface quasi-geostrophic dynamics cause spectral transition (Tulloch and Smith 2006).
3. Ageostrophic stratified turbulence
   Mesoscale flow escapes rotational constraint; energy is cascaded down to small scales (Lindborg 2006).
4. Inertia–gravity waves
   Quasi-linear inertia–gravity waves dominate the mesoscale range (Dewan 1979, VanZandt 1982).

A theory of Jackson Pollock's art

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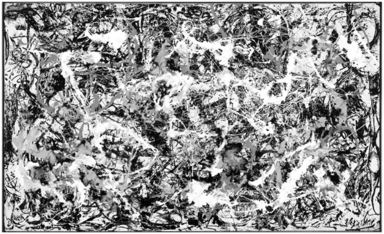

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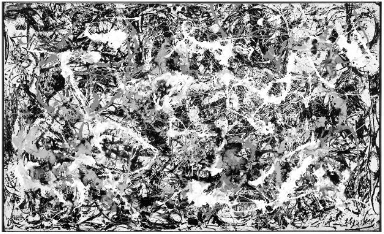

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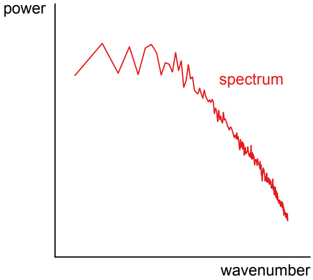

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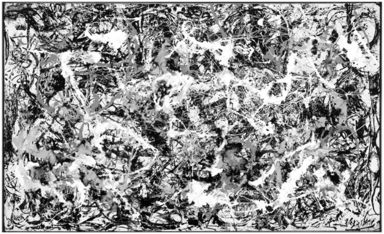

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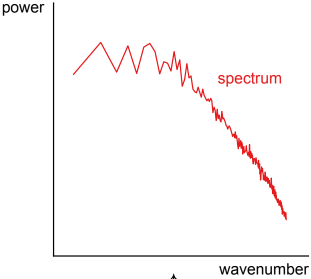

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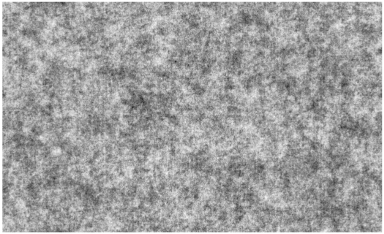
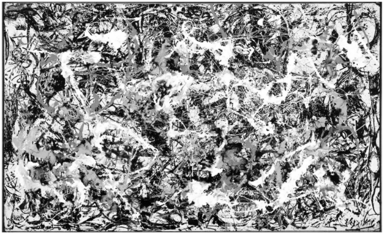


(randomized phase)

Different theories predict identical spectra.

A theory of Jackson Pollock's art



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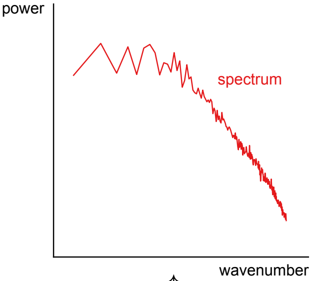

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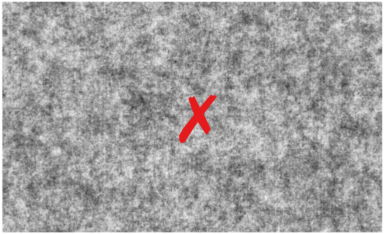

(randomized phase)

Different theories predict identical spectra.

Additional information in the data must be used to distinguish between theories.

cf. Armi and Flament (1985)

Helmholtz decomposition of MOZAIC data

$$S^u(k), S^v(k) \quad \rightarrow \quad K(k) = K^\psi(k) + K^\phi(k)$$

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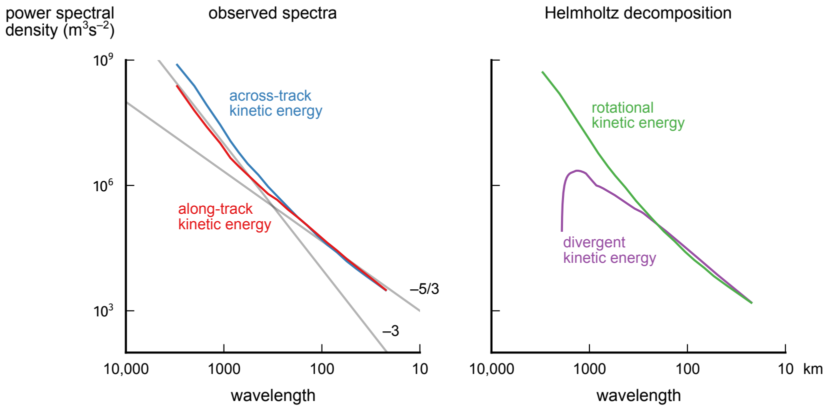

The synoptic scales are dominated by the rotational component.

The mesoscales have a significant divergent component.

The synoptic-to-mesoscale transition: contesting theories

1. Inverse energy cascade originating from small scales ✗

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2. Frontogenetic processes at the tropopause ✗

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   Quasi-linear inertia–gravity waves dominate the mesoscale range (Dewan 1979, VanZandt 1982).

Do linear waves dominate at mesoscales?

Check whether observations are consistent with polarization and dispersion relations of inertia–gravity waves.

Energy partition statement from linear wave theory:

$$E_\mathrm{w}(k) = 2K^\phi(k) \qquad \text{(hydrostatic)}$$

$$E_\mathrm{w}(k) = 2K^\phi(k) + S^w(k) \qquad \text{(nonhydrostatic)}$$

Does the diagnosed $E_\mathrm{w}(k)$ match the observed $E(k)$?

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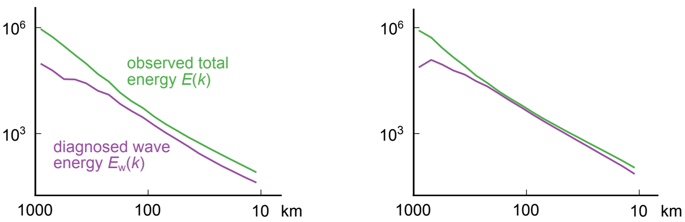
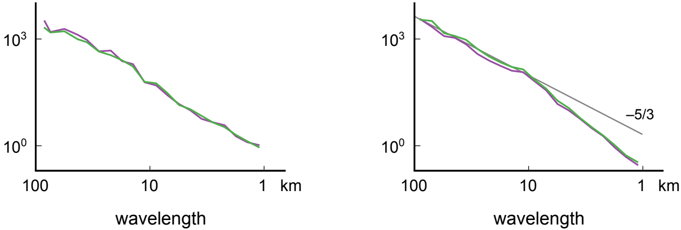
Vertical homogeneity assumption: density-weighted spectra, phase averaging by variable flight altitude

Wave–vortex decomposition

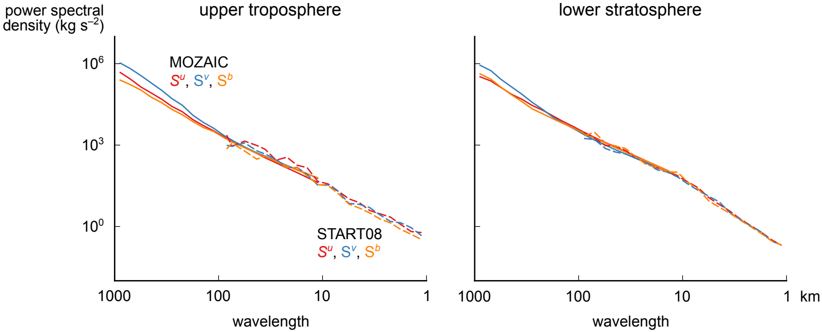


GV (START08)



cf. Zhang et al. (2015)

Source of inconsistency between the data sets



The two data sets disagree in the along-track velocity component at wavelengths 10–100 km in the upper troposphere.

Conclusions

Mesoscale flows have significant divergence, which excludes theories based on quasi-geostrophic dynamics.

The mesoscale spectra are consistent with linear inertia–gravity waves in both upper troposphere and lower stratosphere.

There is a mismatch in the MOZAIC upper-tropospheric diagnosis, where there is an inconsistency between data sets.

Stratified turbulence cannot explain the steepening of stratospheric spectra at wavelengths smaller than 10 km.

Bühler et al. (2014, JFM), Callies et al. (2014, PNAS), Callies et al. (submitted)