This poster participates in OSP

Outstanding Student Poster Contest

The troposphere-to-stratosphere transition in kinetic energy spectra and nonlinear spectral fluxes as seen in ECMWF analyses

Bel Helen Burgess, Andre R. Erler, and Theodore G. Shepherd

Atmospheric Physics, Department of Physics, University of Toronto

Atmospheric Physics
UNIVERSITY OF TORONTO

Introduction and motivating questions

We study synoptic and large-scale atmospheric circulation in the framework of 2D turbulence theory, using the modern high resolution ECMWF 'International Polar Year' operational analysis. We revisit open questions, such as whether there is a well-defined downscale enstrophy flux, and what spatial resolution is required to resolve the upscale energy flux. In the troposphere, this is equivalent to asking whether the baroclinic excitation range is spectrally confined, which has implications for required climate model resolution. The well-resolved stratosphere in the ECMWF IPY analysis allows us to compare stratospheric nonlinear spectral dynamics, driven primarily by planetary waves, with tropospheric dynamics, sourced by baroclinic excitation. Using change-point methods, we show that the IPY analysis resolves a break in the kinetic energy (KE) spectrum consistent with aircraft observations [5].

Data set

The ECMWF IPY winds are T799 forecast analysis data interpolated to a regular latitude-longitude grid. They are available on 91 hybrid model levels at 00 h, 06 h, 12 h, and 18 hr UTC, and resolve total spherical harmonic wavenumber $n = 721$. We use data from January 2008.

Rotational nonlinear KE interaction terms, KE and enstrophy fluxes

The KE interaction term at n represents energy transfer into n. Negative values indicate loss to other scales, positive values gain. The flux past n is the negative sum of terms up to $n-1$.

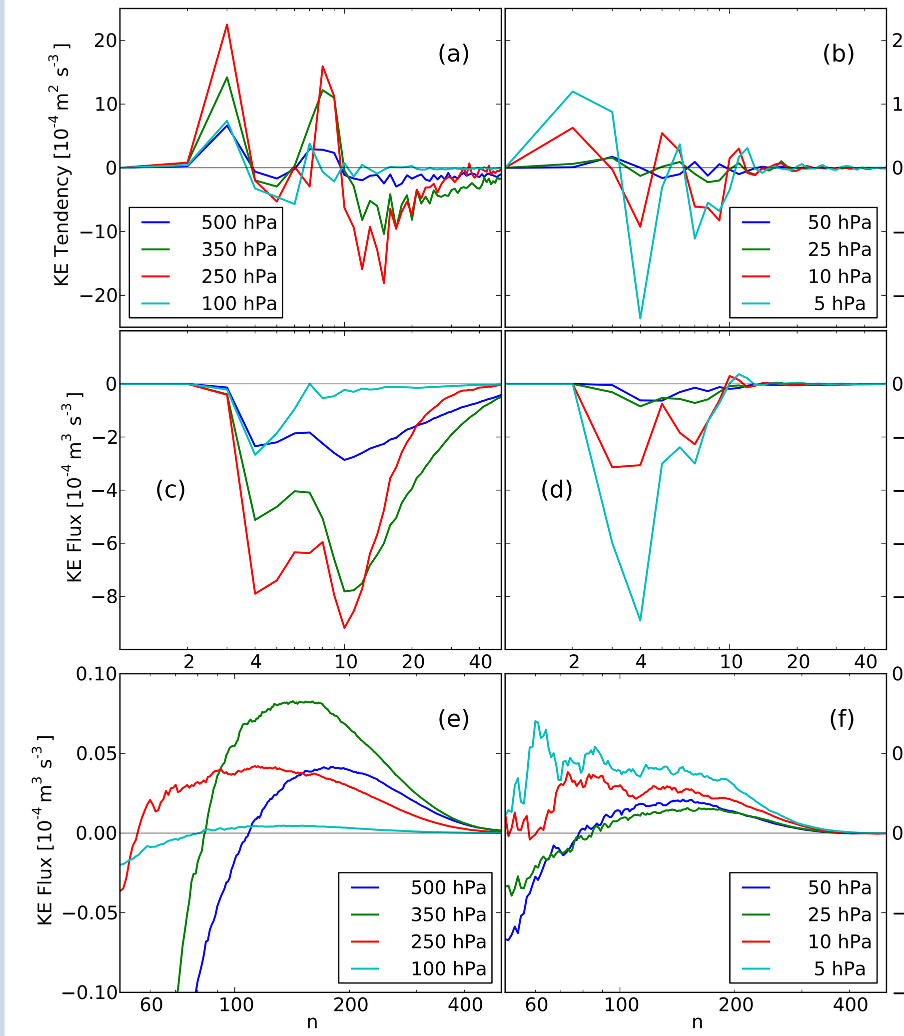

Fig. 1: Planetary and synoptic scale interaction terms (a)-(b) and KE fluxes (c)-(d); synoptic and mesoscale KE fluxes (e)-(f).

Interaction terms show KE loss from $n > 10$ and gain at $n = 3$ (zonal mean flow) and $n = 8$, Fig. 1(a), in the upper troposphere. Upscale KE transfer is at planetary scales $n < 10$ in the stratosphere, Fig. 1(b).

KE Fluxes are predominantly upscale, maximising in the upper troposphere, Fig. 1(c), and stratosphere, Fig. 1(d). Downscale fluxes, Fig. 1(e)-(f), are relatively small, in contrast to [1]- [2]: the KE source region is well-resolved.

Large-scale turbulence centers on the tropopause, Fig. 2, with a double-peaked flux structure, in contrast to the single peak found in [1].

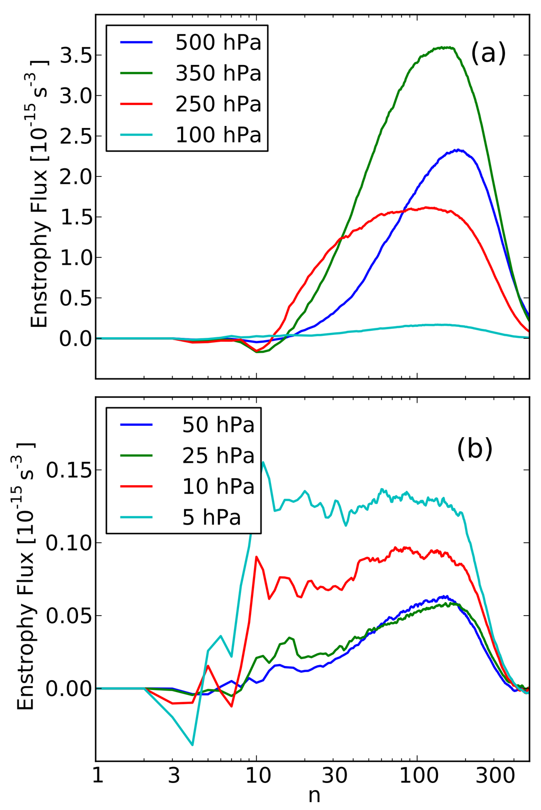

Fig. 3: Entropshy fluxes.

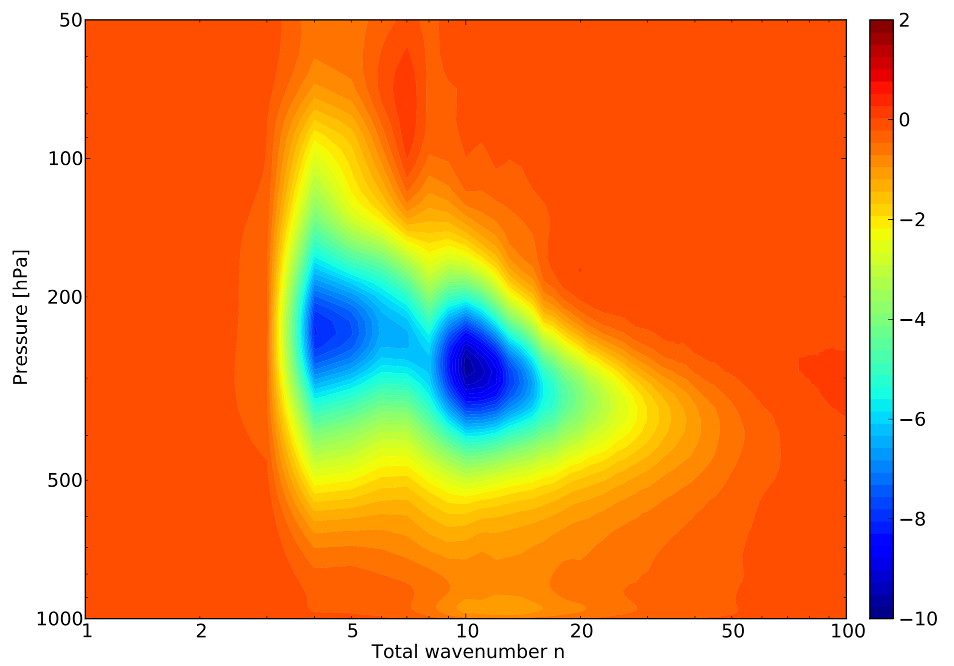

Fig. 2: Rotational kinetic energy fluxes ($m^3 s^{-3}$) scaled by 10^4.

Entrophy flux is downscale. A plateau at the tropopause, Fig. 3(a), suggests convergence and a turbulent inertial range, contrasting [1]-[2].

Zonal mean-eddy decompositions of interaction terms and fluxes

To study the role of the mean flow in inducing spectral transfers, we decompose the interaction terms and fluxes into zonal mean-eddy and eddy-eddy contributions.

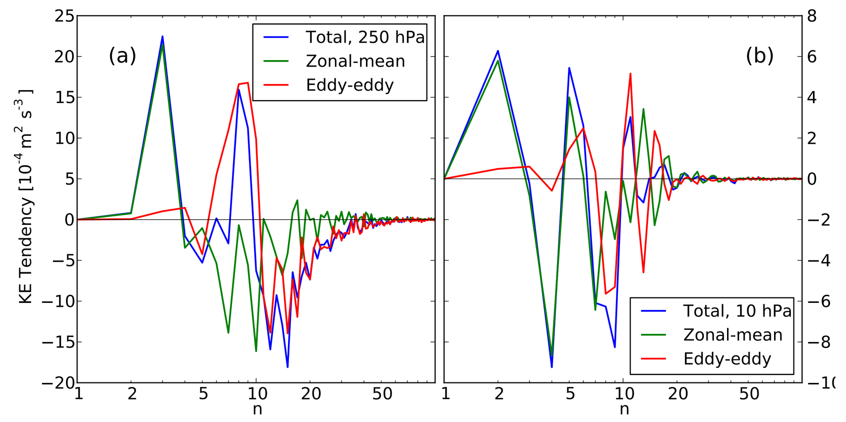

Fig. 4: Nonlinear KE interaction terms.

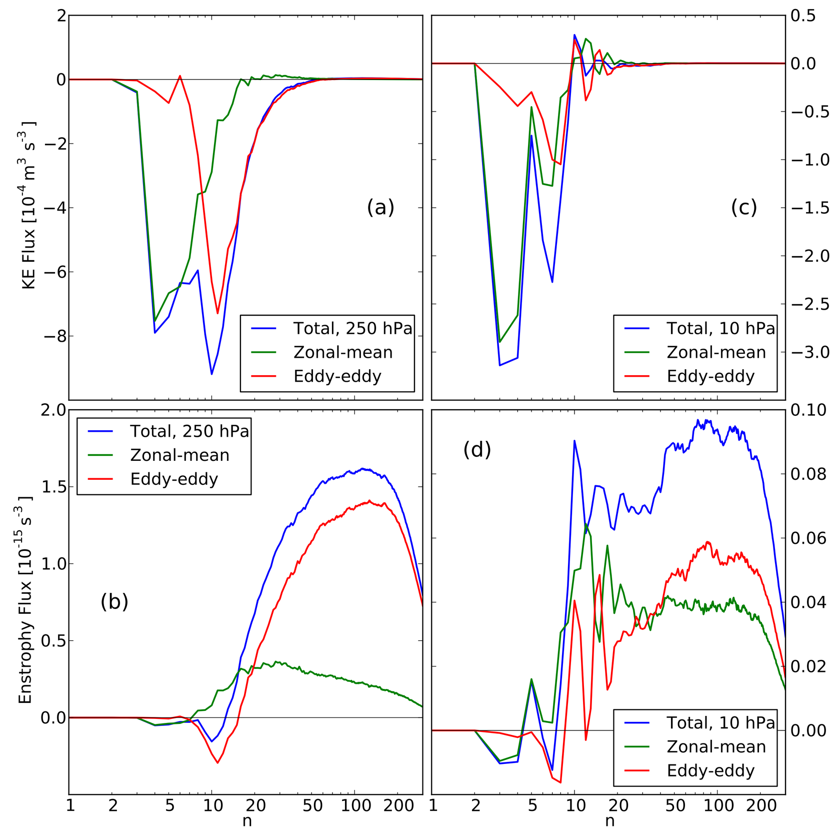

Fig. 5: KE fluxes (a)-(c) and enstrophy fluxes (b)-(d).

Tropospheric interaction terms, Fig. 4(a): Eddy-eddy interactions source the peak around $n = 8$ in the troposphere; zonal-eddy interactions carry KE up to $n = 3$.

Stratospheric interaction terms Fig. 4(b): Zonal-eddy interactions dominate and strengthen with altitude, consistent with a stronger polar jet, more active surf zone, and larger planetary wave amplitudes; dynamics are wave-mean-flow interaction.

Tropospheric fluxes: The two peaks in the KE flux, Fig. 2, have different origins, Fig. 5(a). Eddy-eddy interactions dominate downscale enstrophy flux in the upper troposphere, Fig. 5(b).

Stratospheric fluxes: Zonal mean-eddy interactions carry a downscale enstrophy cascade, Fig. 5(d). Eddy-eddy interactions contribute significantly: nonlinearity is important in surf zone wave breaking.

Kinetic energy spectra and change-point analysis

The KE spectral slope at 250 hPa is ~ -3, as found by [1] and [4]. In contrast to earlier studies, a spectral break emerges above 250 hPa, with a shallow mesoscale as seen in aircraft data [5].

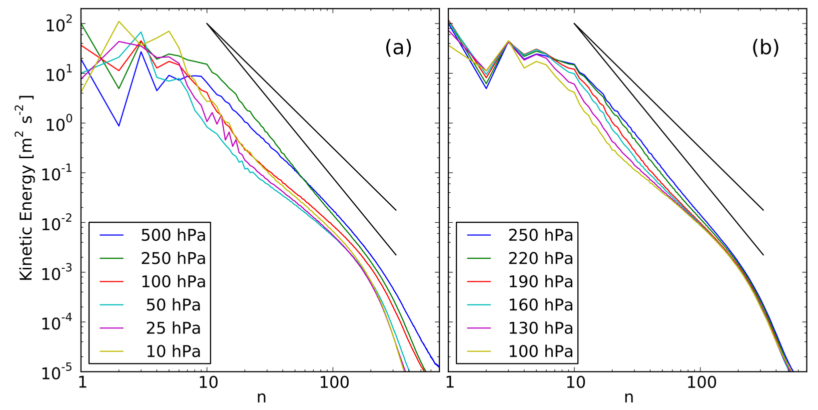

Fig. 6: KE spectra and slope lines -3.1 and -2.5.

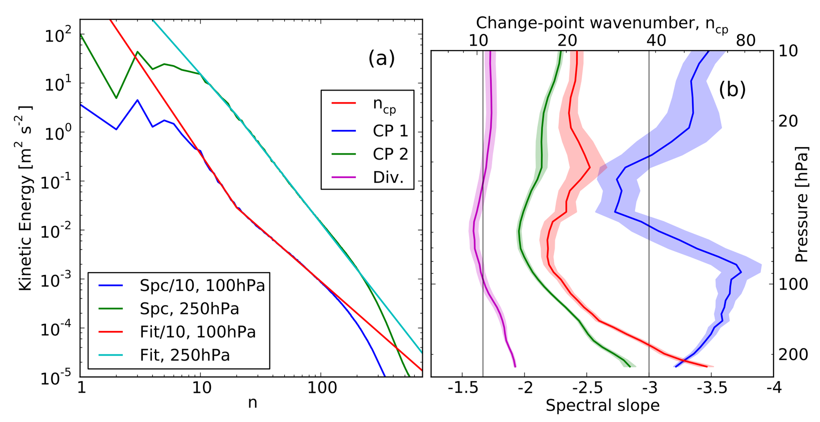

Fig. 7: (a) Spectra (Spc) and change-point fits. (b) Spectral break n_{cp}, slopes of the change-point segments (CP 1, CP 2) and divergent spectrum (Div.) vs. altitude.

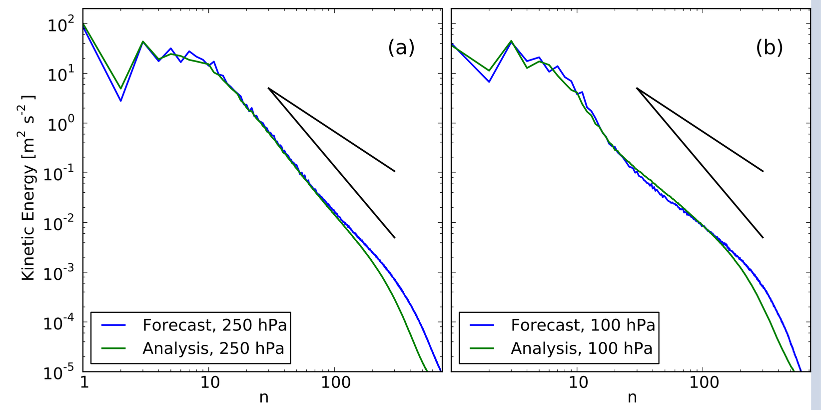

Fig. 8: IPY analysis and T1279 forecast model spectra, as well as lines of slope -3 and $-5/3$.

Change-point analysis (Fig. 7) identifies the sharp spectral break, which moves upscale from $n = 60$ to $n = 20$ between 250-100 hPa, Fig. 6(b), Fig. 7(b).

The Nastrom-Gage aircraft data (250 -100 hPa) show a smooth transition, not a sharp break, possibly due to averaging over pressure levels.

The IPY mesoscale slope is steeper than the observed $-5/3$; a new T1279 forecast model (Fig. 8) has slope closer to $-5/3$.

Rotational and divergent decompositions of KE spectra

Decomposing the KE spectra into rotational and divergent components (Fig. 9) reveals that the spectral break distinguishes a balanced (i.e. divergent KE $\ll$ rotational KE) synoptic-scale regime from an unbalanced mesoscale regime, Fig. 9(b).

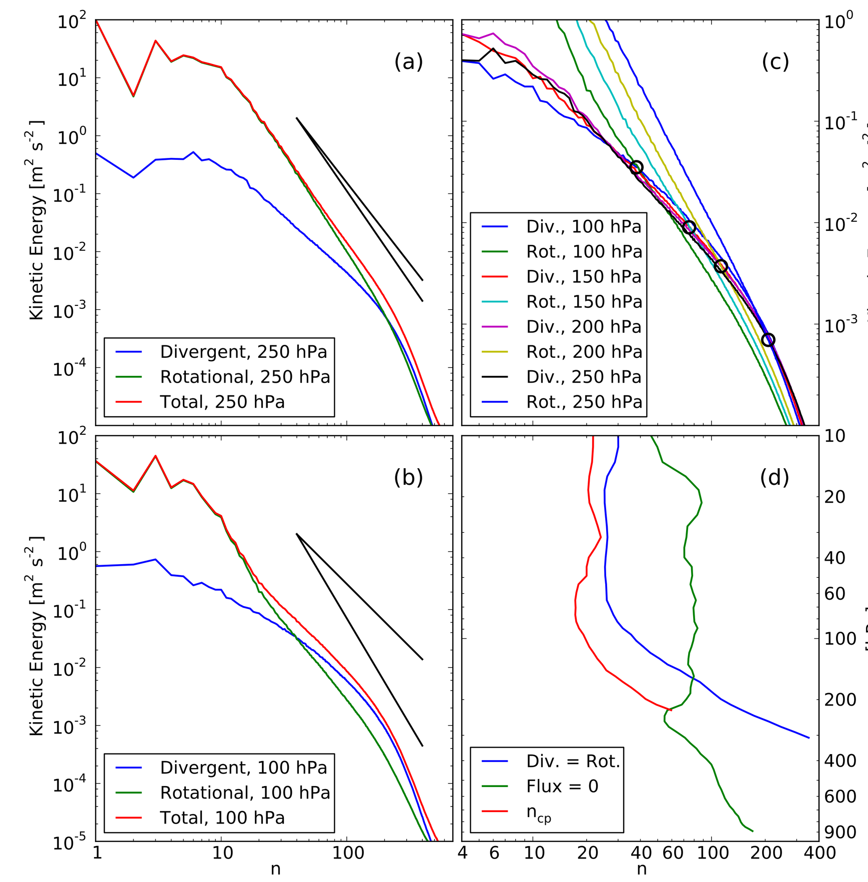

Fig. 9: KE spectra with (a) slope lines -2.79, -3.15, (b) -3.65, -2.16. (c) Transition region, spectral intersections circled. (d) Intersection, change-point, and wavenumber where KE flux becomes positive.

The intersection wavenumber of the divergent and rotational spectra parallels the break n_{cp}, Fig. 9(d).

The divergent spectrum has slope close to $-5/3$, Fig. 7(b); if extrapolated, the mesoscale spectrum would have slope closer to the observed value.

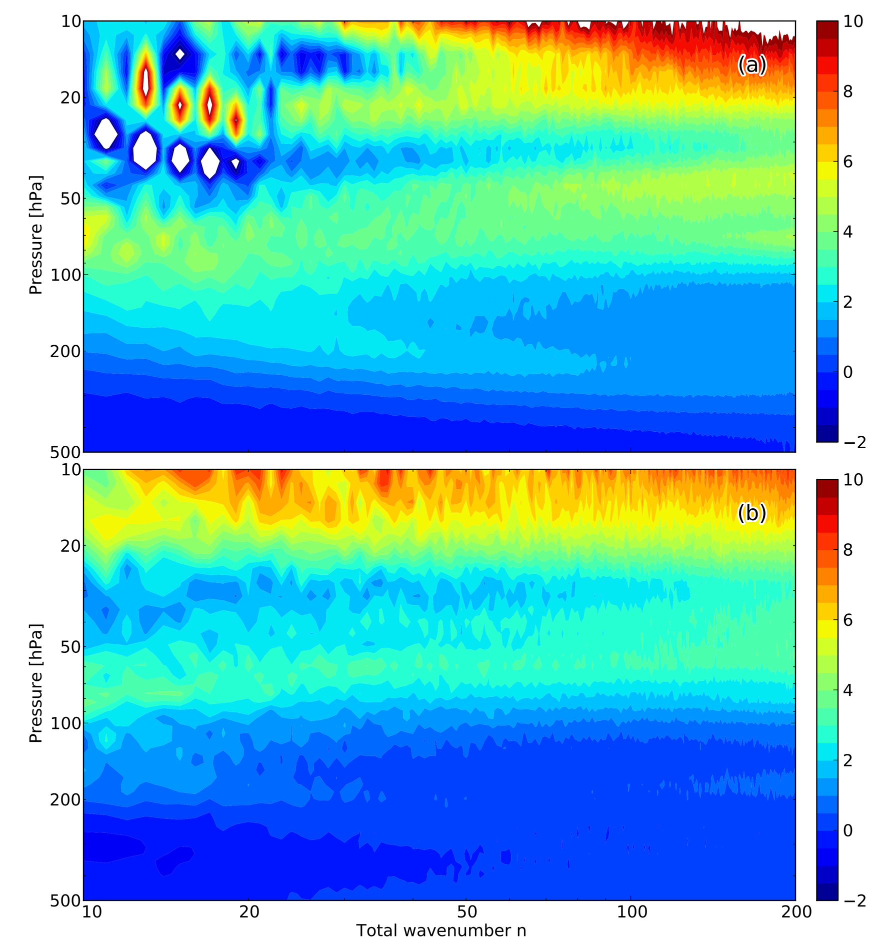

Fig. 10: The relative vertical derivative (i.e. the derivative scaled by the local value) of the logarithm of density-weighted (a) rotational and (b) divergent kinetic energy. This measures relative attenuation with height.

Preferential dissipation of synoptic-scale rotational KE with height, Fig. 9(c), Fig. 10, consistent with Charney-Drazin filtering, causes the shallow divergent spectrum to dominate the rotational spectrum in the mesoscale, and the break to move upscale.

Summary / Conclusions

- The baroclinic source region appears spectrally confined: upscale KE fluxes are well-resolved in the ECMWF IPY analysis, with comparatively small downscale KE fluxes.
- In the troposphere, eddy-eddy interactions dominate the downscale enstrophy flux. Around the tropopause, the flux plateaus, consistent with convergence and a 2D turbulent enstrophy-cascading inertial range.
- Eddy-eddy interactions carry KE to $n = 8$, and then zonal mean-eddy interactions carry it to $n = 3$.
- Stratospheric dynamics are primarily wave-mean-flow interaction, with a well-resolved downscale enstrophy cascade carried by zonal mean-eddy interactions.
- The break in the IPY KE spectra appears and moves to larger scales due to preferential dissipation of synoptic-scale rotational KE with altitude. The steep spectral regime at large scales is balanced, with rotational dominating divergent power, while the shallow mesoscale regime is unbalanced, with a downscale KE flux and small nonlinear interactions.

Acknowledgements

This work was supported by Natural Sciences and Engineering Research Council of Canada and a Zonta International Amelia Earhart Fellowship to ABHB.

References

[1] Boer, G. J. and T. G. Shepherd, 1983: Large-scale two-dimensional turbulence in the atmosphere. *J. Atmos. Sci.*, **40**, 164-184.
[2] Straus, D. M. and P. Ditlevsen 1999: Two-dimensional turbulence properties of the ECMWF reanalyses. *Tellus*, **51**, 751-772.
[3] Shepherd, T. G. 1987: A spectral view of nonlinear fluxes and stationary-transient interaction in the atmosphere. *J. Atmos. Sci.*, **44**, 1166-1178.
[4] Trenberth, K. E. andK. A. Solomon 1993: Implications of global atmospheric spectra for processing and displaying data. *J. Climate*, **6**, 531-545.
[5] Nastrom, G. D. andK. S. Gage 1985: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft. *J. Atmos. Sci.*, **42**, 950-960.