Working Group on Space-based Lidar Winds, Monterey, 2008

The Scientific Value of Stratospheric Wind Measurements

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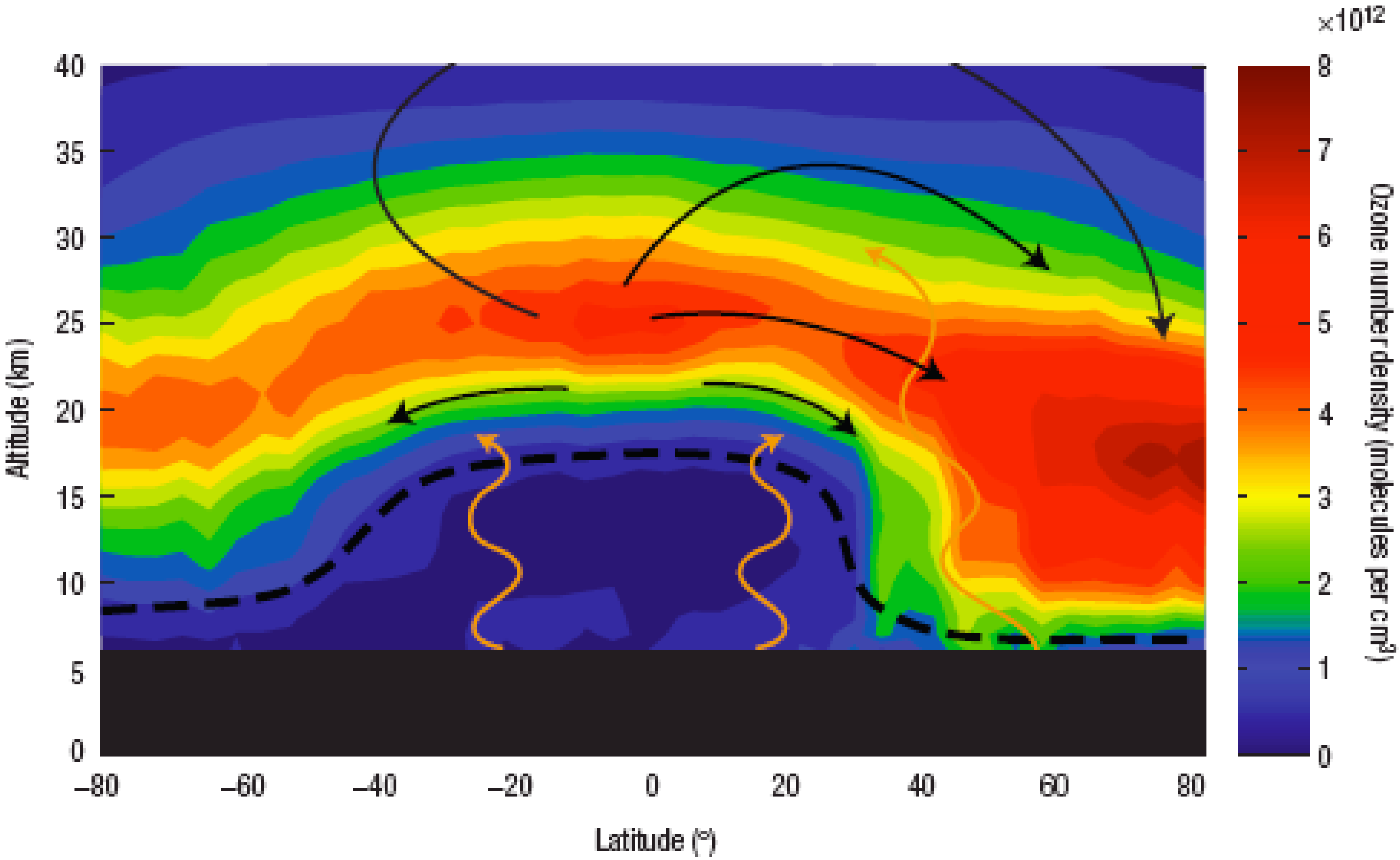
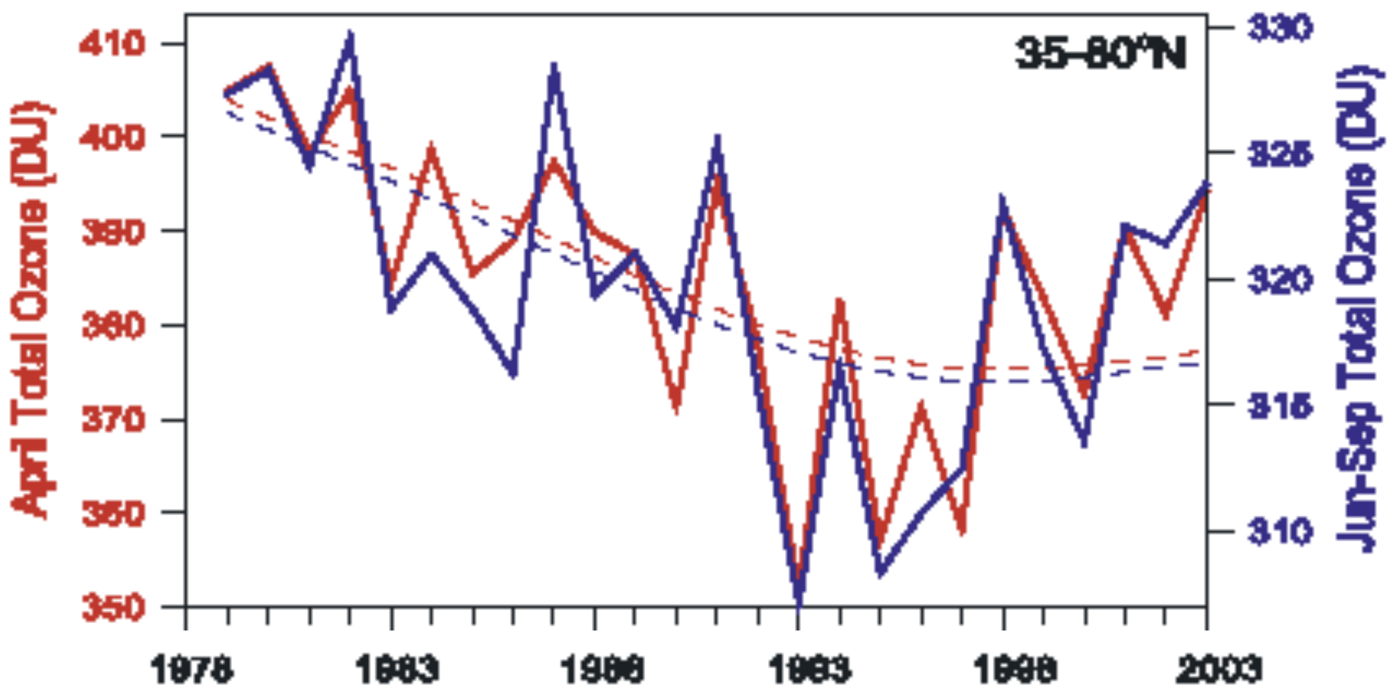
- The distribution of ozone (important for climate and health) is strongly shaped by transport (Brewer-Dobson circulation)



March 2004 OSIRIS ozone

Shaw & Shepherd (2008 Nature GeoScience)

- Decadal fluctuations of midlatitude total ozone arise from dynamical variability, and complicate the detection of ozone recovery
  - Important for policy reasons
  - We lack independent quantification of the contribution of transport to these changes



Fioletov & Shepherd (2005 GRL)

- Schematic of transport in the lower stratosphere
  - Brewer-Dobson circulation, tropical pipe, tropical transition region, lowermost stratosphere

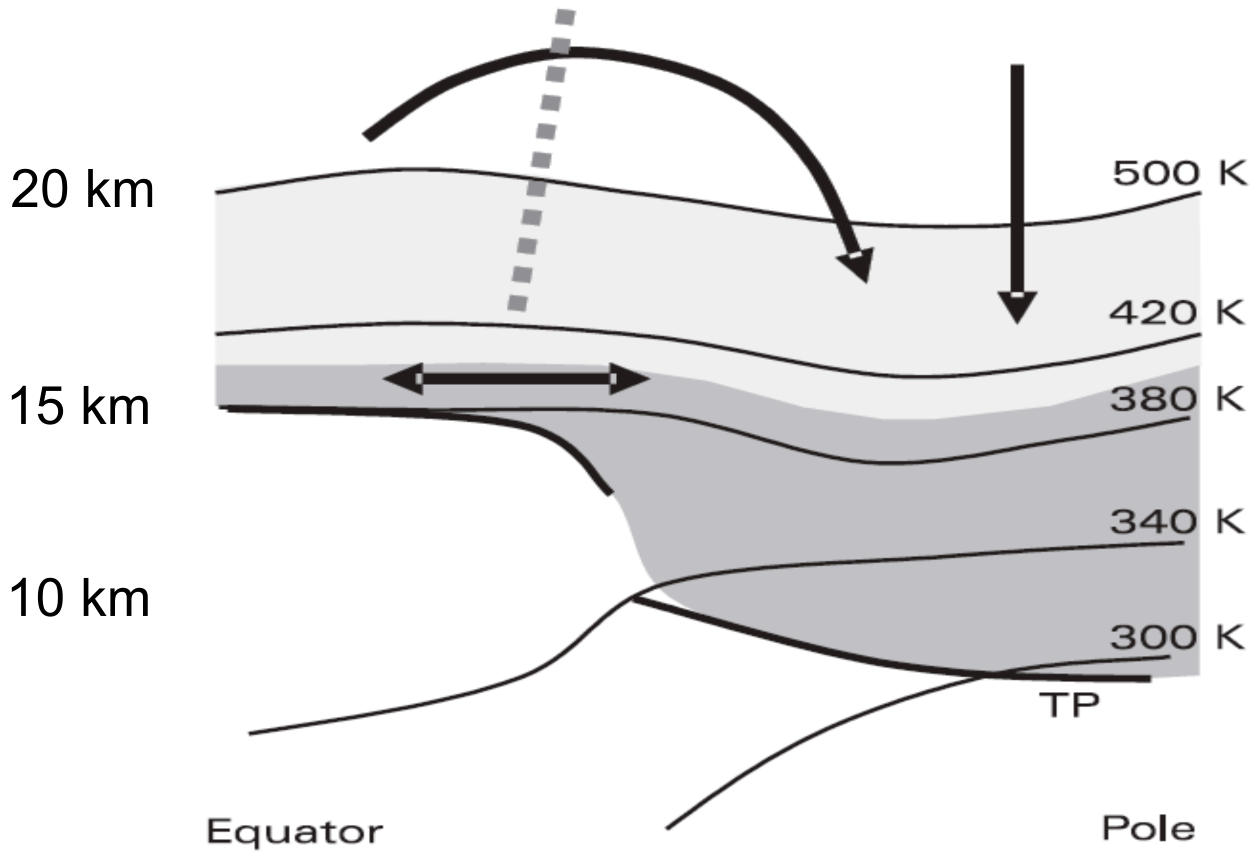
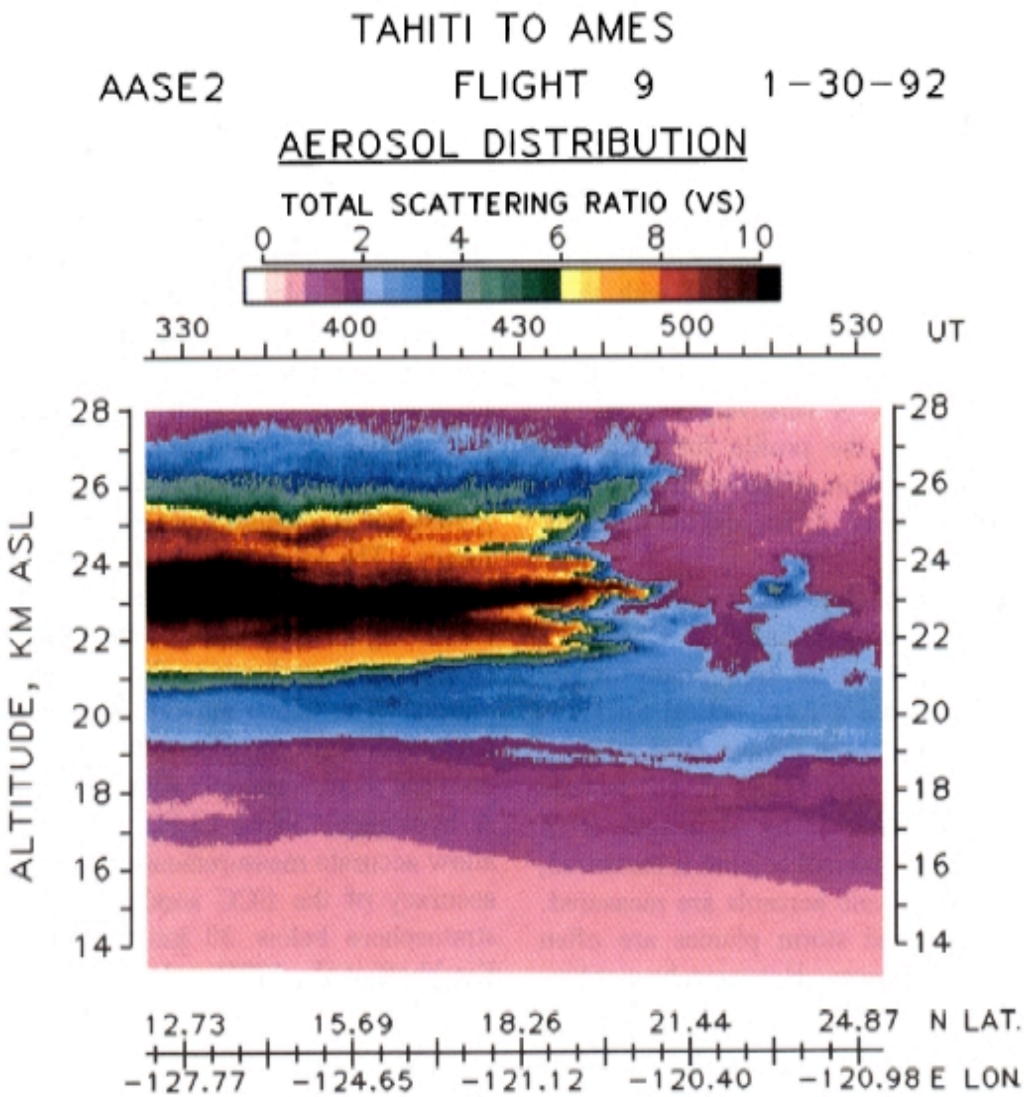


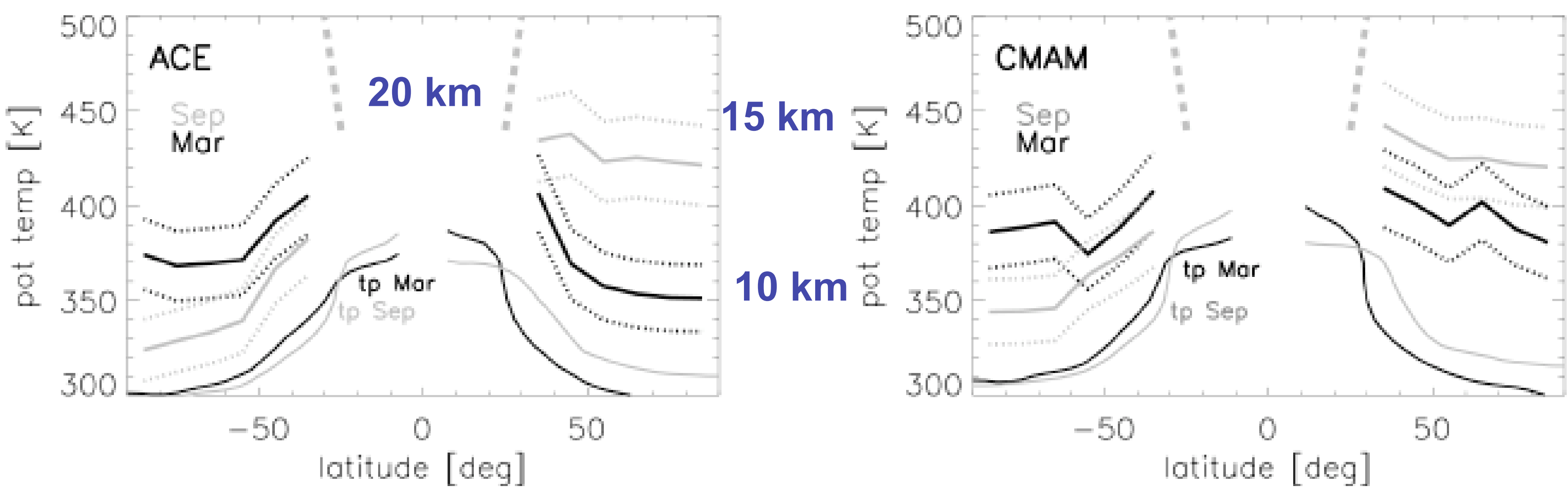
Figure courtesy of Michaela Hegglin, University of Toronto



Grant et al. (1994 JGR)

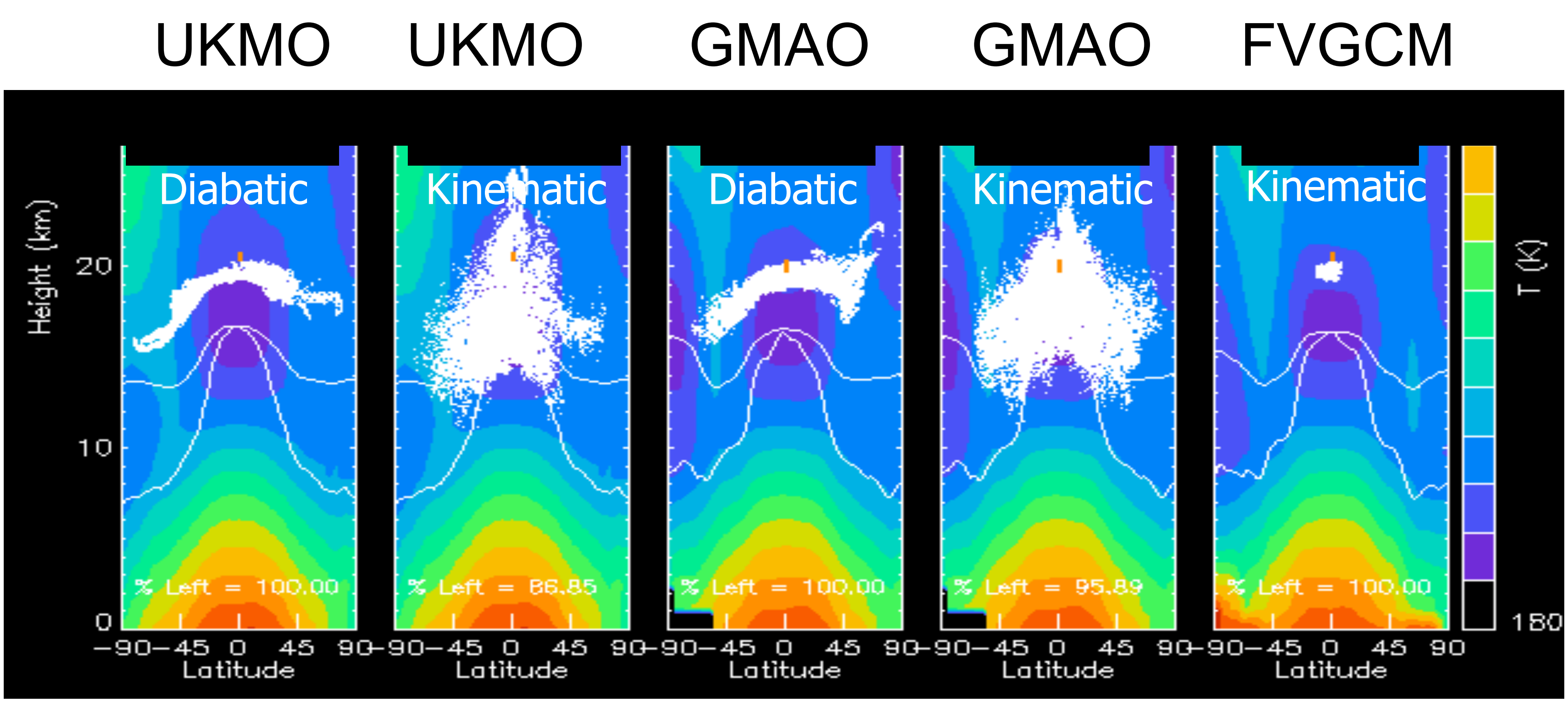
- Measurements of stratospheric aerosol after the Mt Pinatubo eruption show substantial transport below the base of the “tropical pipe”
- There is much current interest in this transport-defined upper troposphere/ lower stratosphere (UTLS), extending up to 22 km or so

- Figure shows top of “transport-defined UTLS” in September and March, from structure of O_3:N_2O correlations
  - Shows strong seasonal variability
  - Important for validation of chemistry-climate models such as CMAM



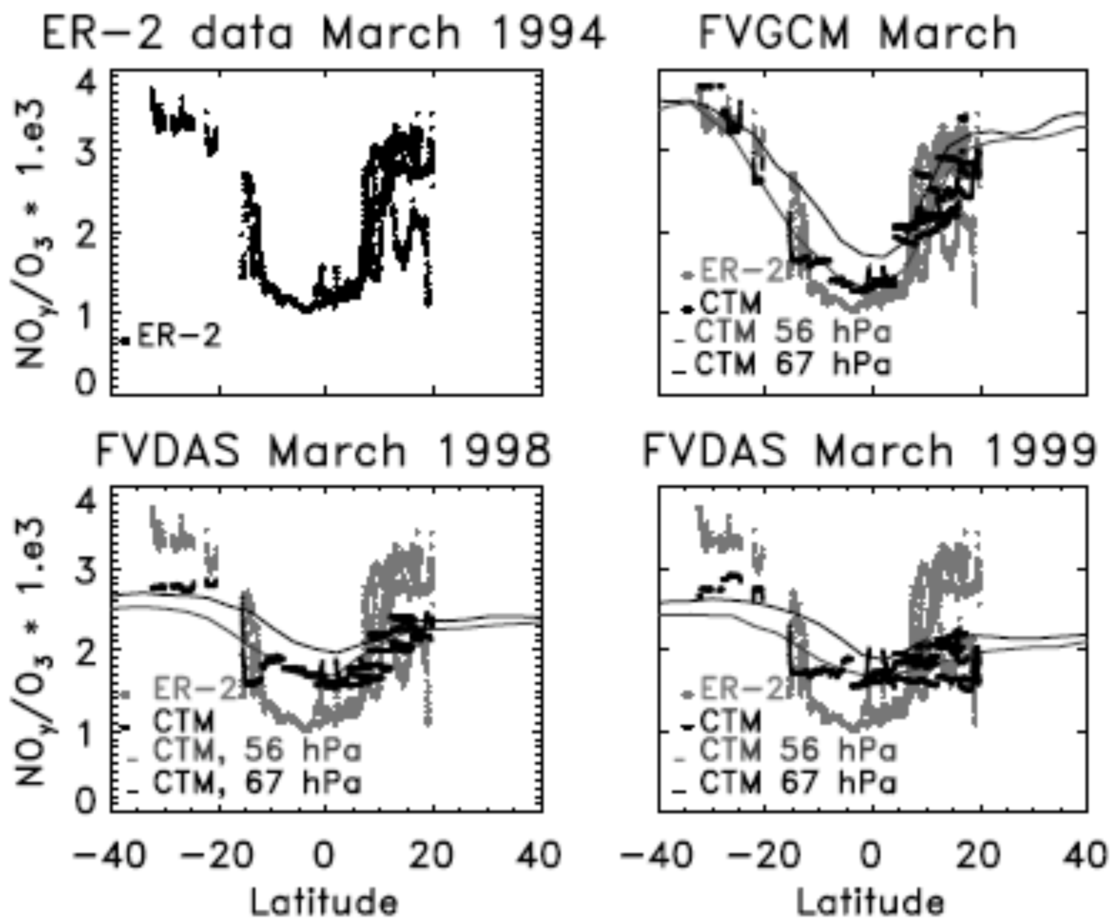
Hegglin & Shepherd (2007 JGR)

- Winds from data assimilation systems (DAS) tend to produce much more dispersion, both horizontally and vertically, than GCM winds
  - Figures show 50-day trajectory calculations
  - But is the isolation seen in the GCM correct?



Schoeberl et al. (2003 JGR)

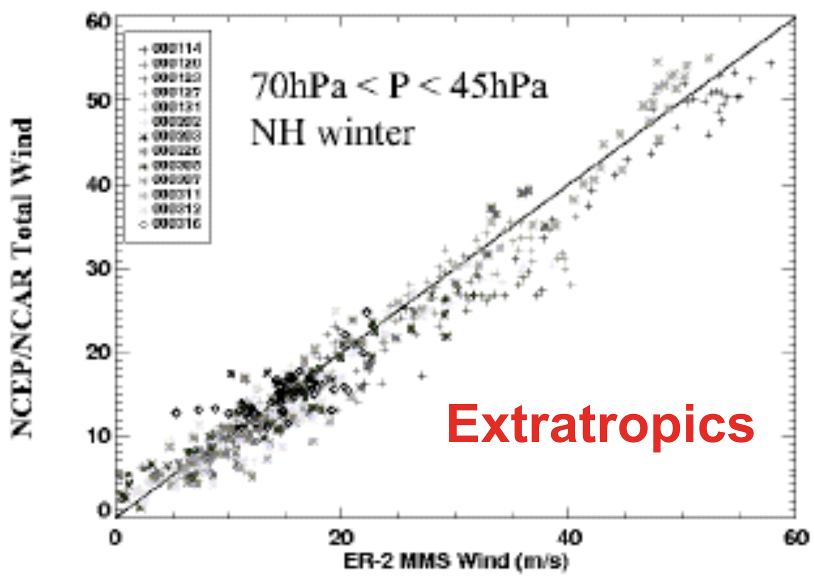
- Another example: NO_y/O_3 ratios at ER-2 altitudes (~20 km)
  - The DAS-driven chemistry transport model destroys the strong horizontal gradients



Douglass et al. (2003 JGR)

- The quality of analysed winds in the tropical stratosphere is known to be very poor
  - Figures show comparisons between ER-2 aircraft measurements around 21 km altitude, and NCEP/NCAR reanalysis winds

Rean. Wind vs. ER-2 MMS obs.



Rean. Vs. Obs. In the Tropics

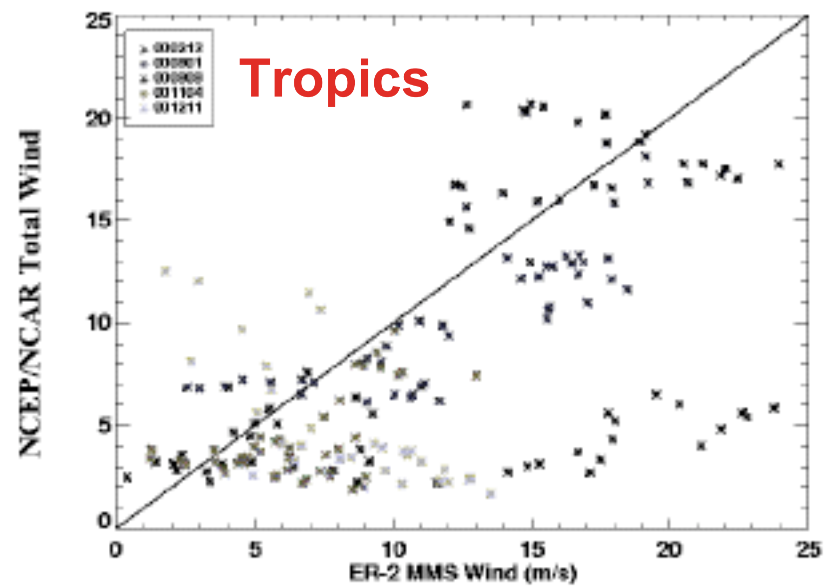
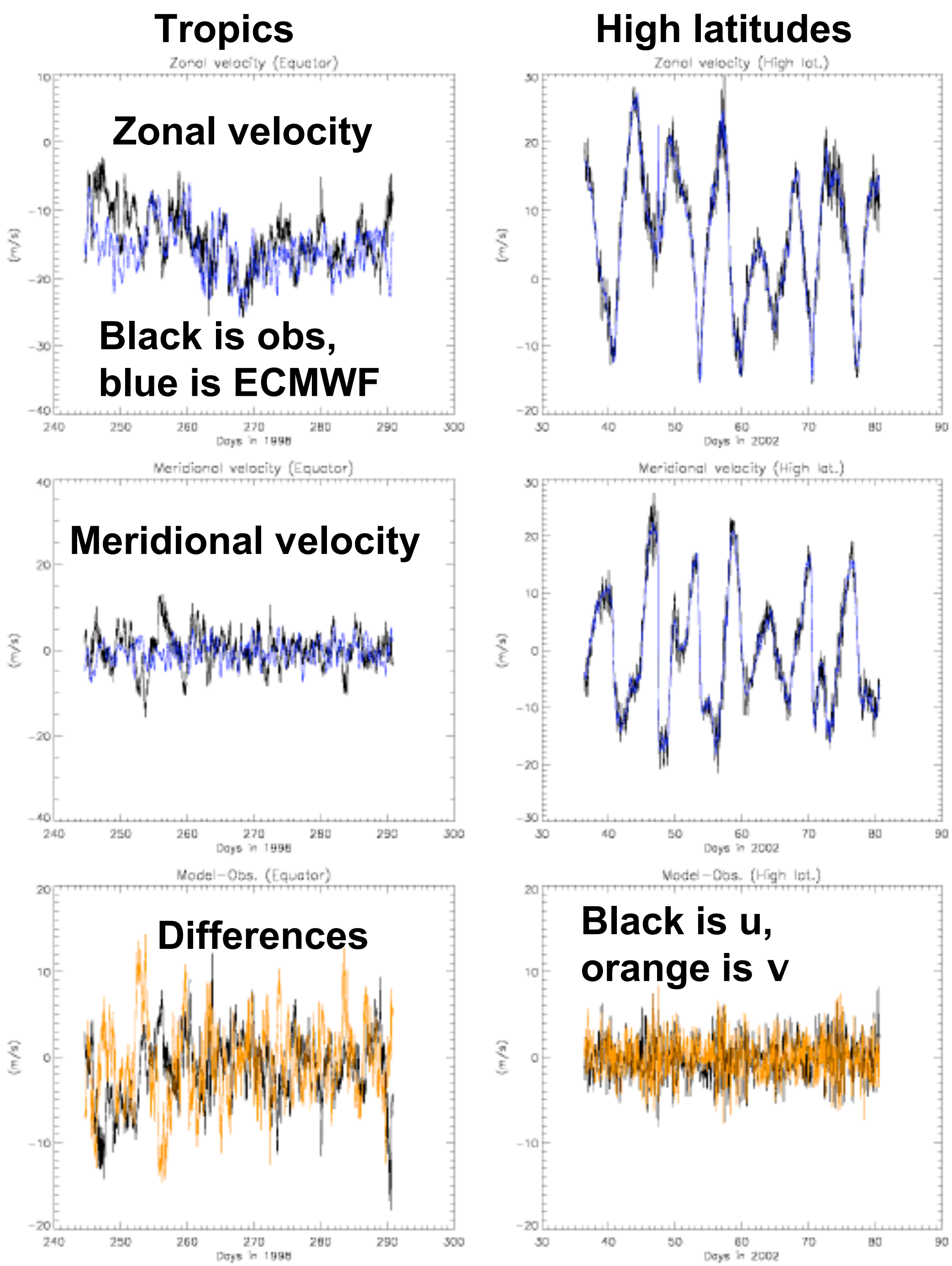
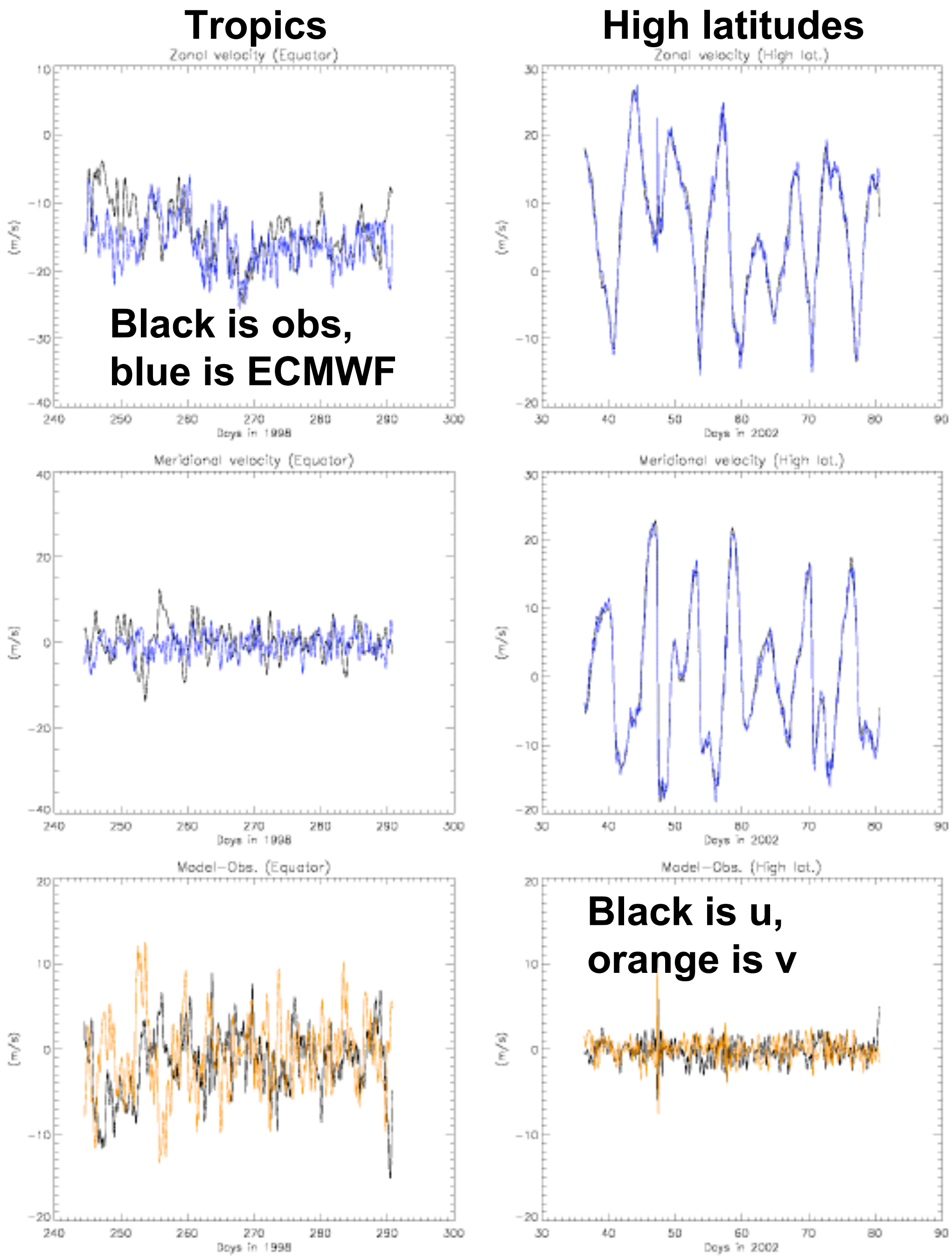


Figure courtesy of Paul Newman, NASA GSFC



Comparison of direct wind measurements with ECMWF analysed winds in long-duration stratospheric balloon flights (at 60 hPa) leads to the same conclusion

Figure courtesy of Albert Hertzog, LMD

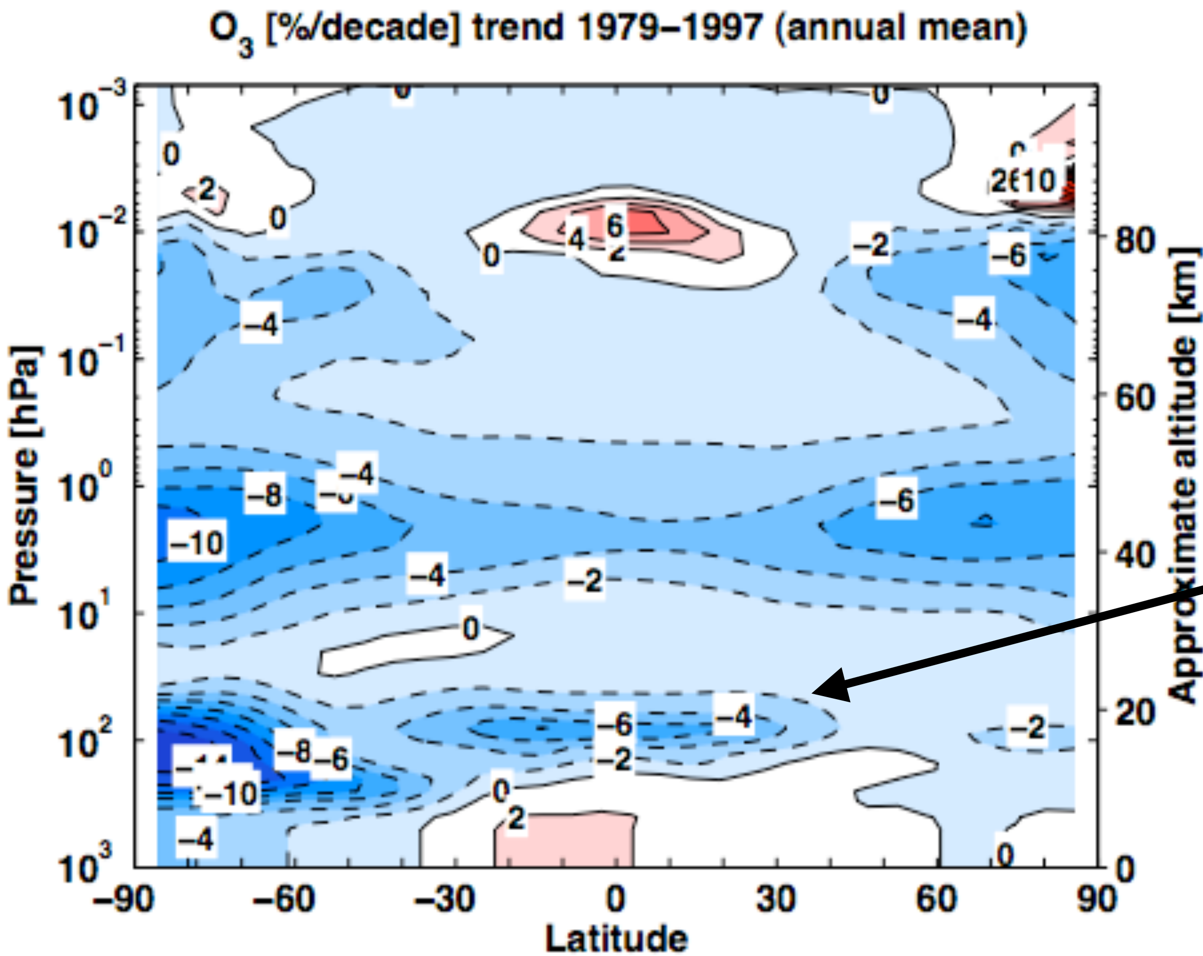


Filtering the directly measured winds to exclude periods shorter than 12 hr leads to excellent agreement at high latitudes, but has little impact in the tropics

Figure courtesy of Albert Hertzog, LMD

- The reasons for this are clear:
  - Mass-wind coupling is very weak in the tropics (especially for the meridional velocity)
  - Even the “balanced” component of the flow has only a weak signature in temperature
  - There is a rich spectrum of unbalanced motions
- Thus, on physical grounds, we know that we need direct wind measurements
  - In the stratosphere, this really has to be from space

- CMAM ozone trends over 1979-1997 show a strong decline in the tropical lower stratosphere

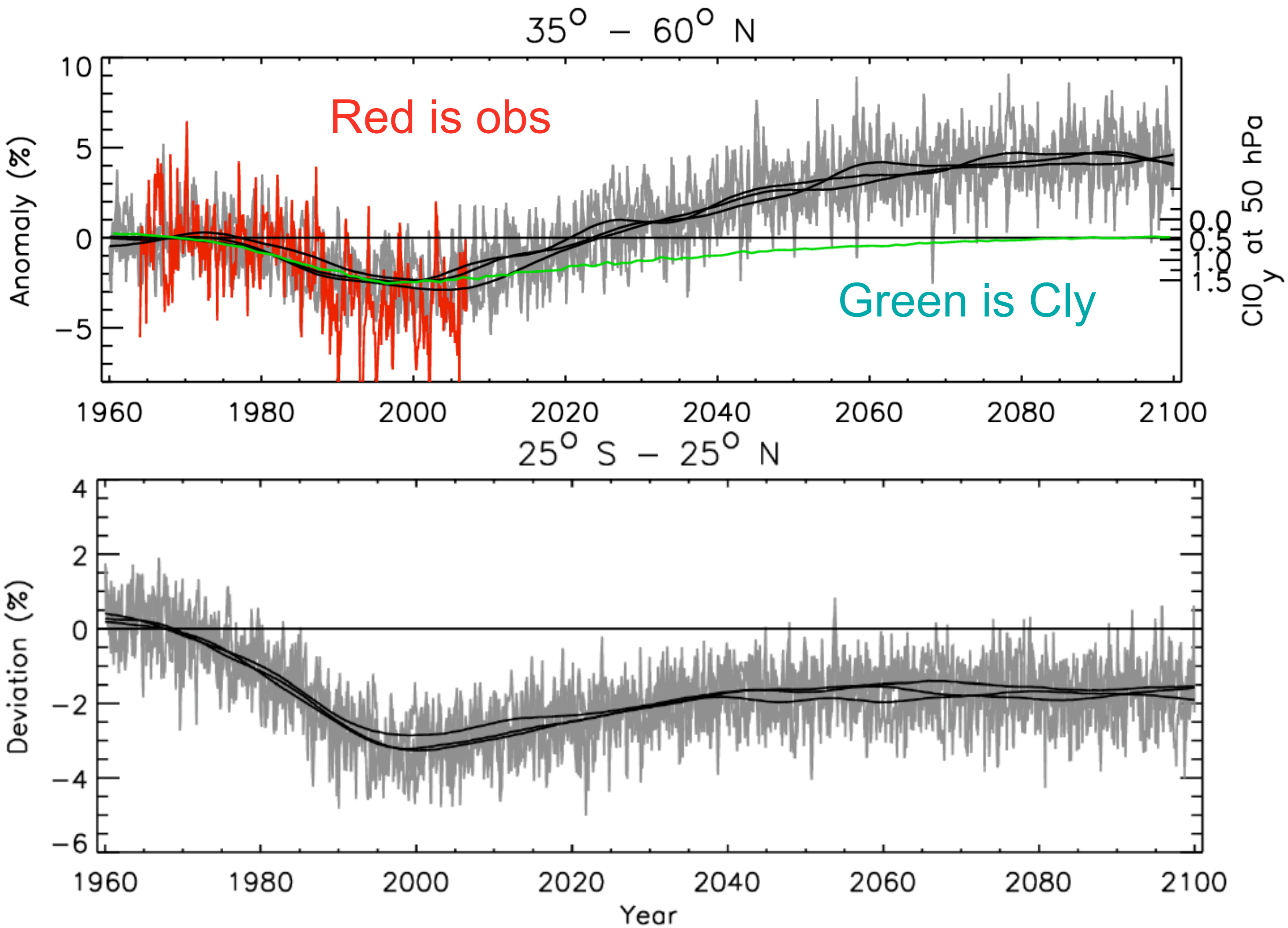


Implication is an increase in tropical upwelling (note also NH extratropics)

Similar changes are seen in SAGE observations

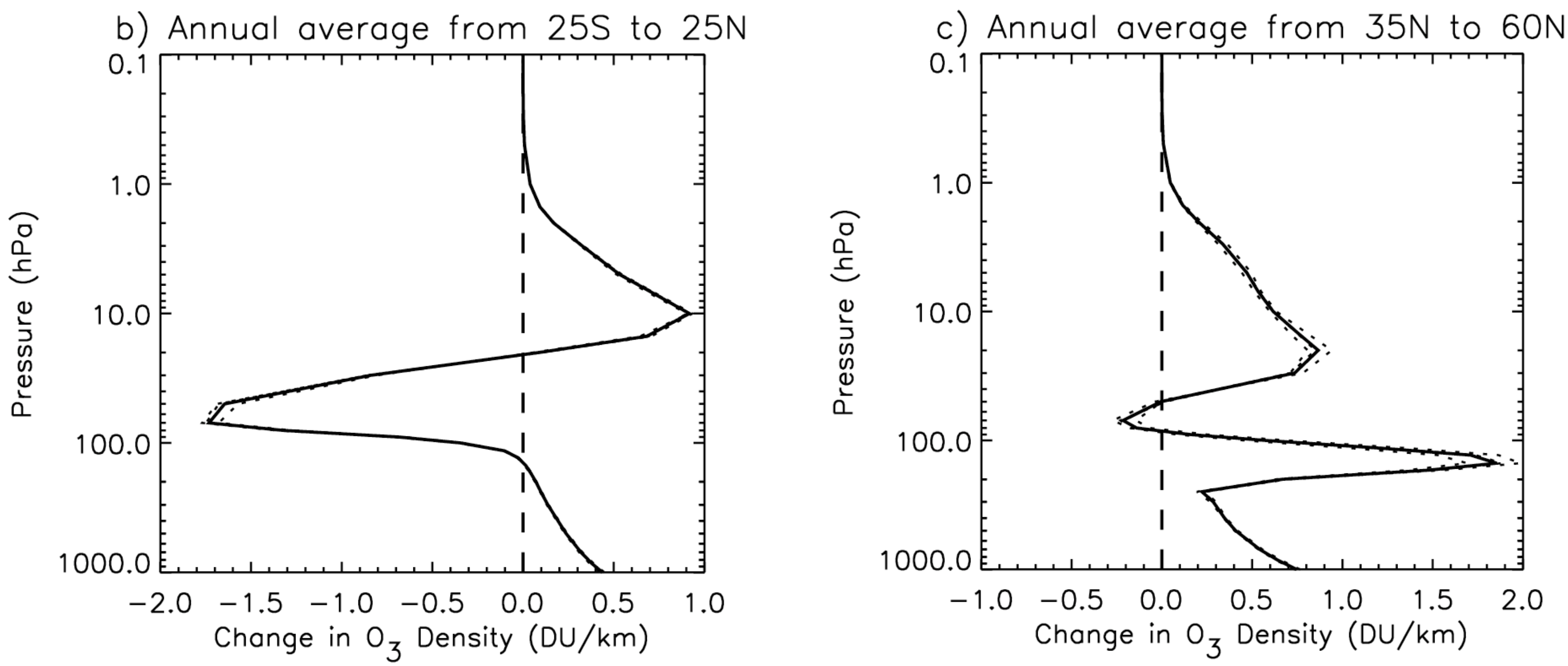
Figure courtesy of Andreas Jonsson, University of Toronto

- CCMs (here CMAM) suggest that a strengthened Brewer-Dobson circulation from climate change will lead to super-recovery of total ozone in NH midlatitudes



Shepherd (Atmos-Ocean, in press)

- The predicted changes (here 2070-2100 minus 1960-1975) come mainly from the lower stratosphere
  - Indicates role of transport, will need to be confirmed by direct measurements of winds



Shepherd (Atmos-Ocean, in press)

- As with many CCMs, CMAM's "age of air" decreases over time, by ~1 yr at 50 hPa from 1960 to 2100
- We need to understand, from wind measurements, how and why this is happening

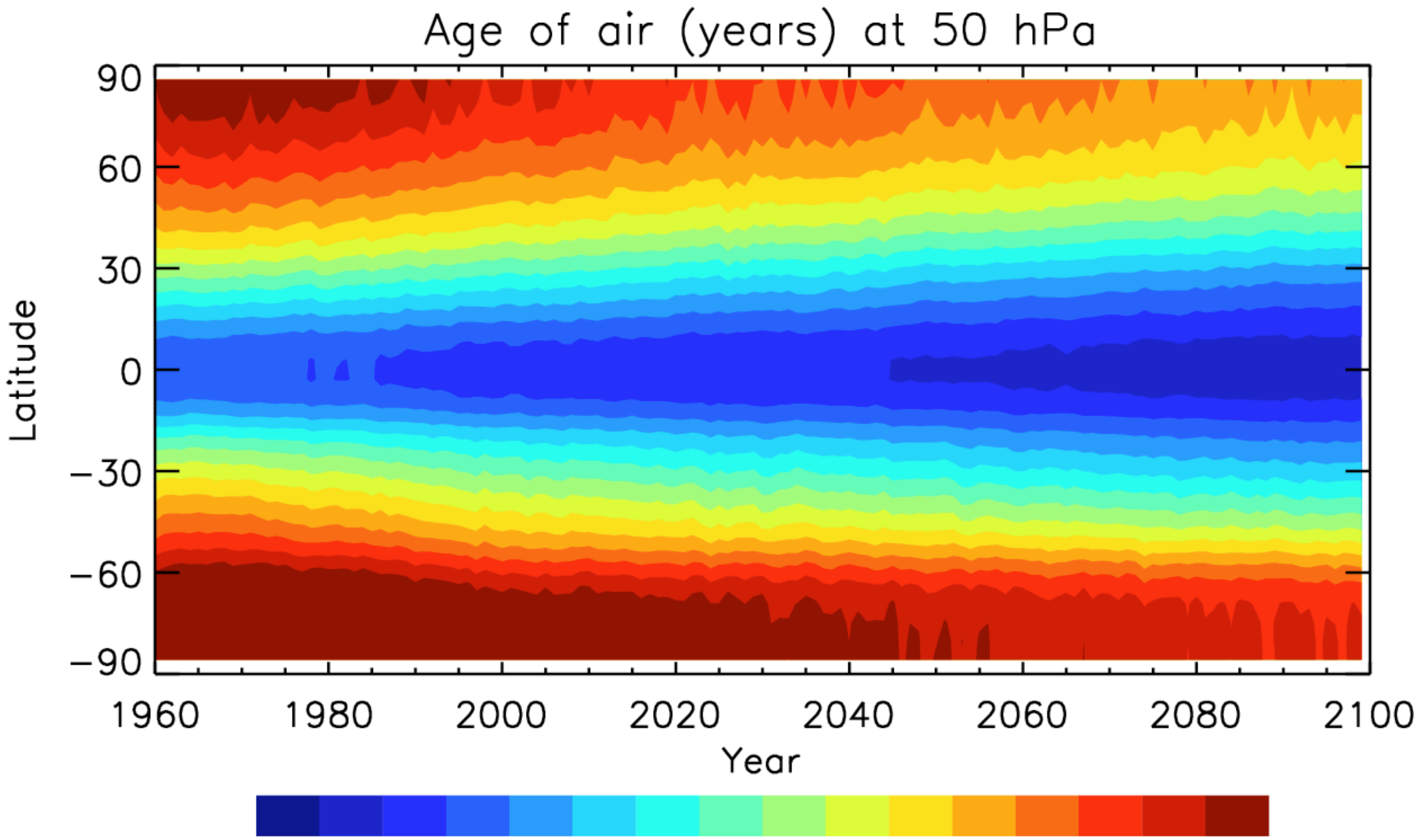
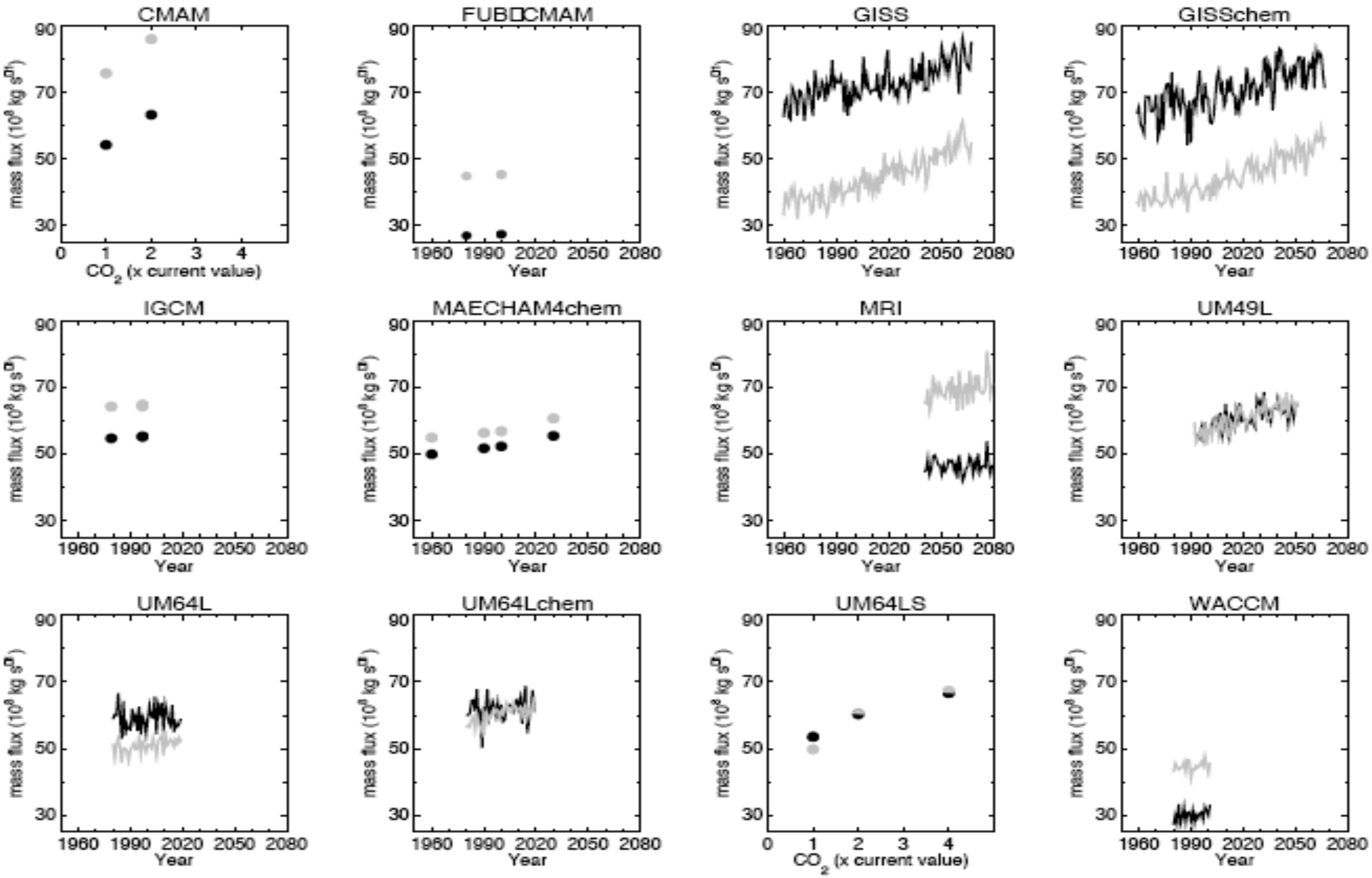


Figure courtesy of David Plummer, Environment Canada

- Models generally show a strengthened tropical upwelling from climate change
  - But the dynamical mechanisms for this are unclear



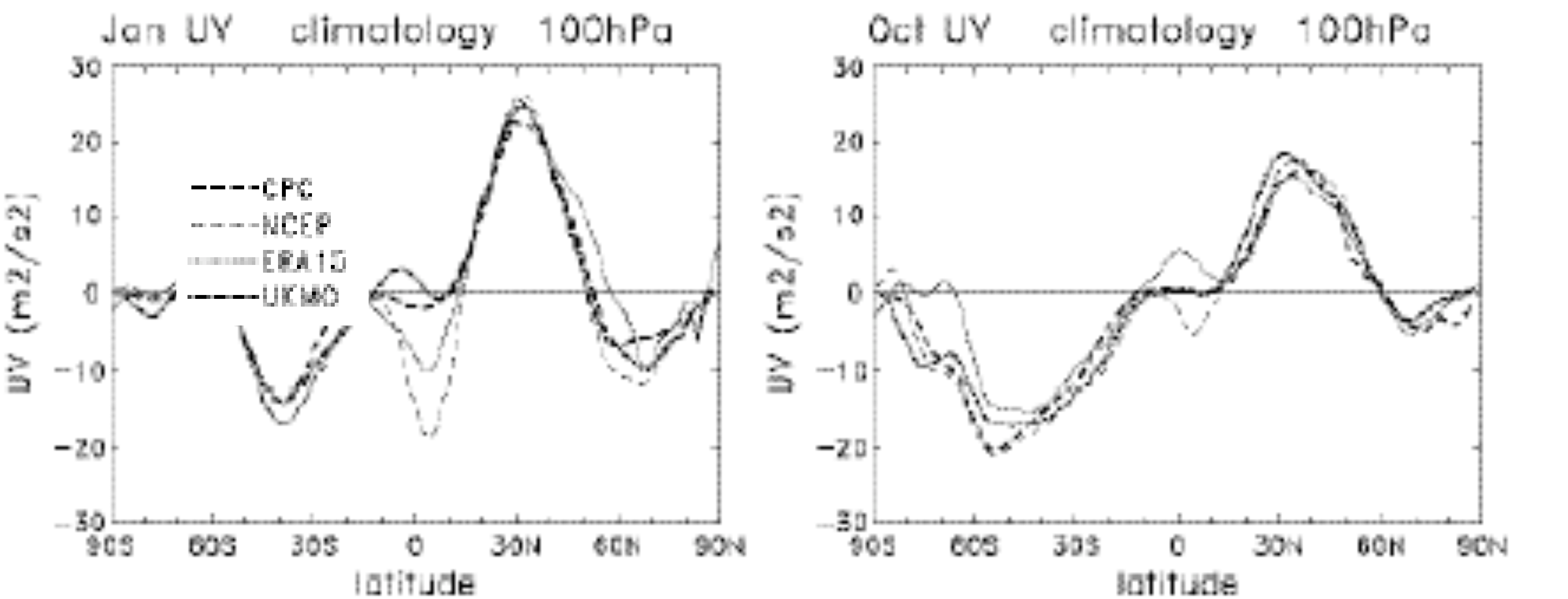
(mass flux at 70 hPa)

Butchart et al. (2006 Clim.Dyn.)

Tropical upwelling is driven by momentum fluxes, but these are not well quantified in this region

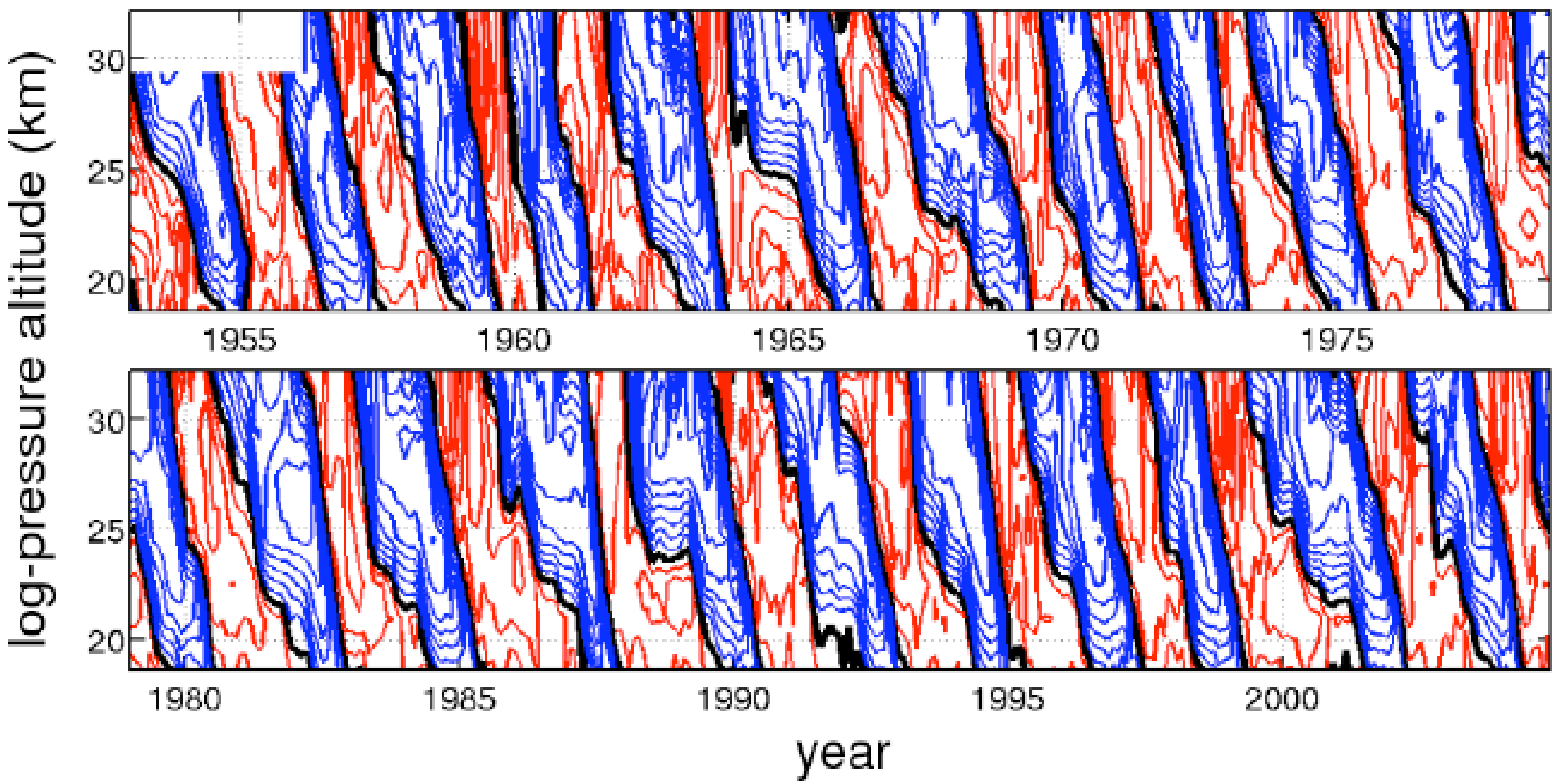
Figure shows horizontal momentum flux *u'v'* at 100 hPa

Reflects the same problem with analysed winds in the tropics seen in transport calculations



From SPARC Report No. 3 (2002)

- The quasi-biennial oscillation (QBO) in tropical zonal winds is a major source of variability
  - Here seen in Singapore radiosonde data
  - Red is eastward, blue is westward (5 m/s)



However the QBO is not well characterized by different meteorological analyses

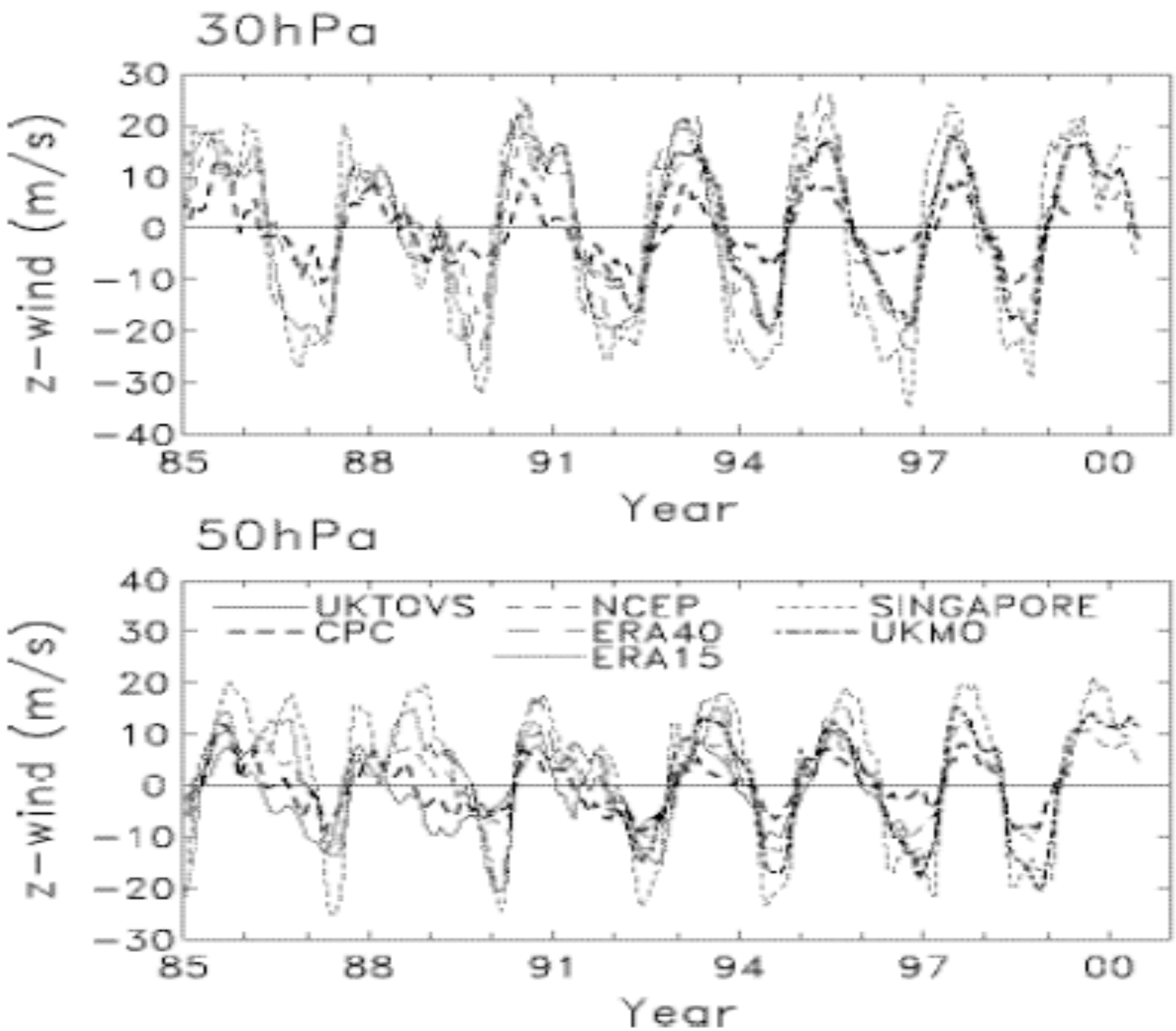


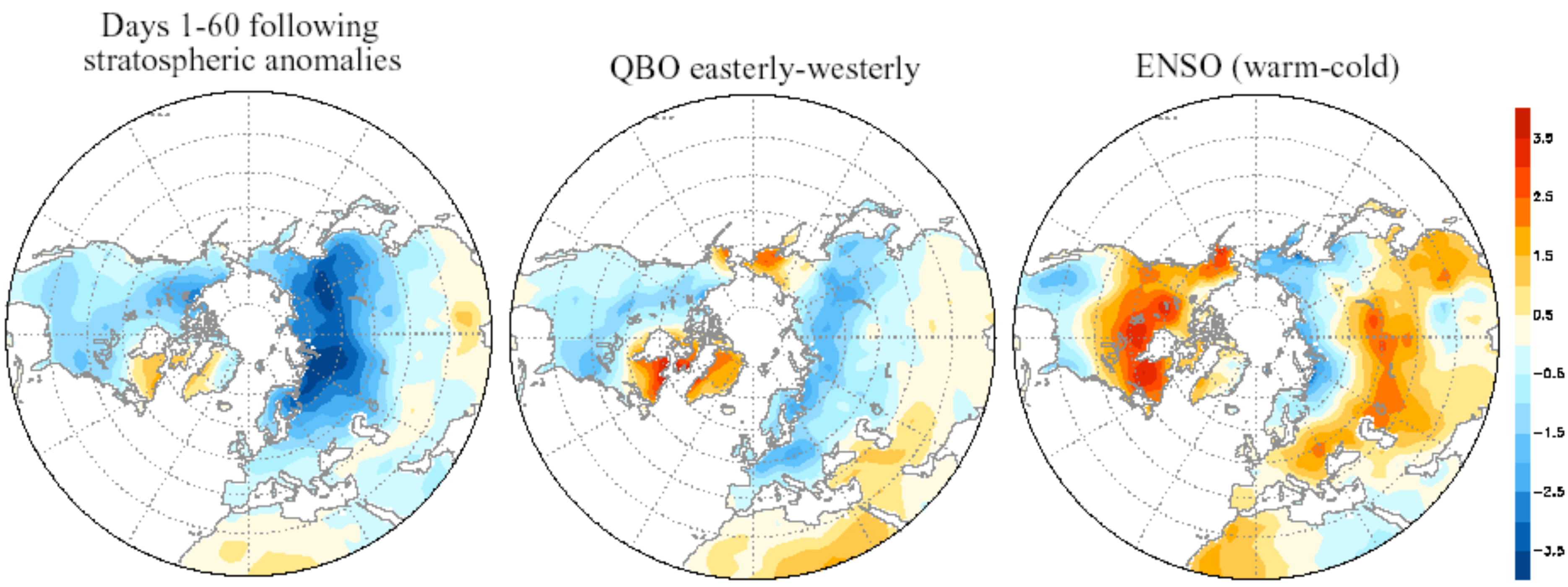
Figure shows zonal wind interannual anomalies at the equator

Meridional gradients are also very poorly characterized

From SPARC Report No. 3 (2002)

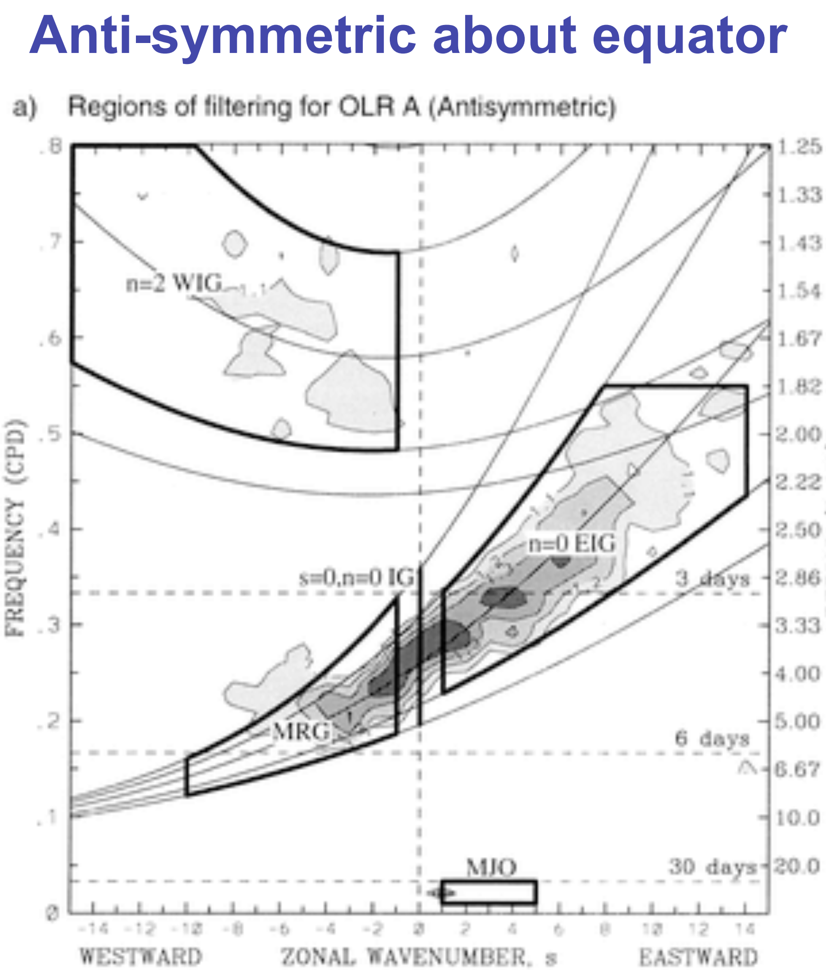
- The QBO has long been known to affect polar vortex conditions (Holton-Tan)
  - Recent research has shown that the tropical-polar coupling is actually two-way
- There is interannual memory in tropical stratospheric winds (‘flywheel’ effect of Scott & Haynes 1998 QJRMS)
  - The most compelling mechanisms for the influence of solar variability on the troposphere involve tropical winds in the upper stratosphere (e.g. Gray et al. 2006 Space Sci. Rev.)

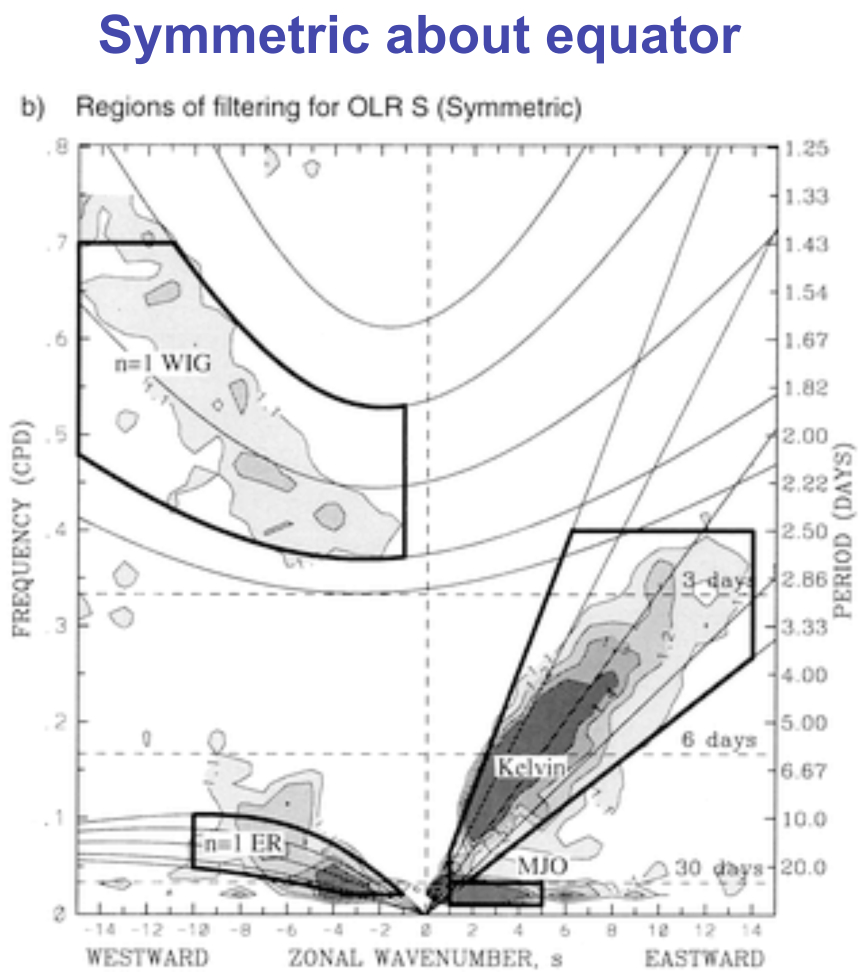
- The extratropical tropospheric impact associated with the QBO is comparable in magnitude to that associated with ENSO
- Figure shows wintertime surface air temperature differences (in K) between circulation regimes



Thompson, Baldwin & Wallace (2002 J.Clim.)

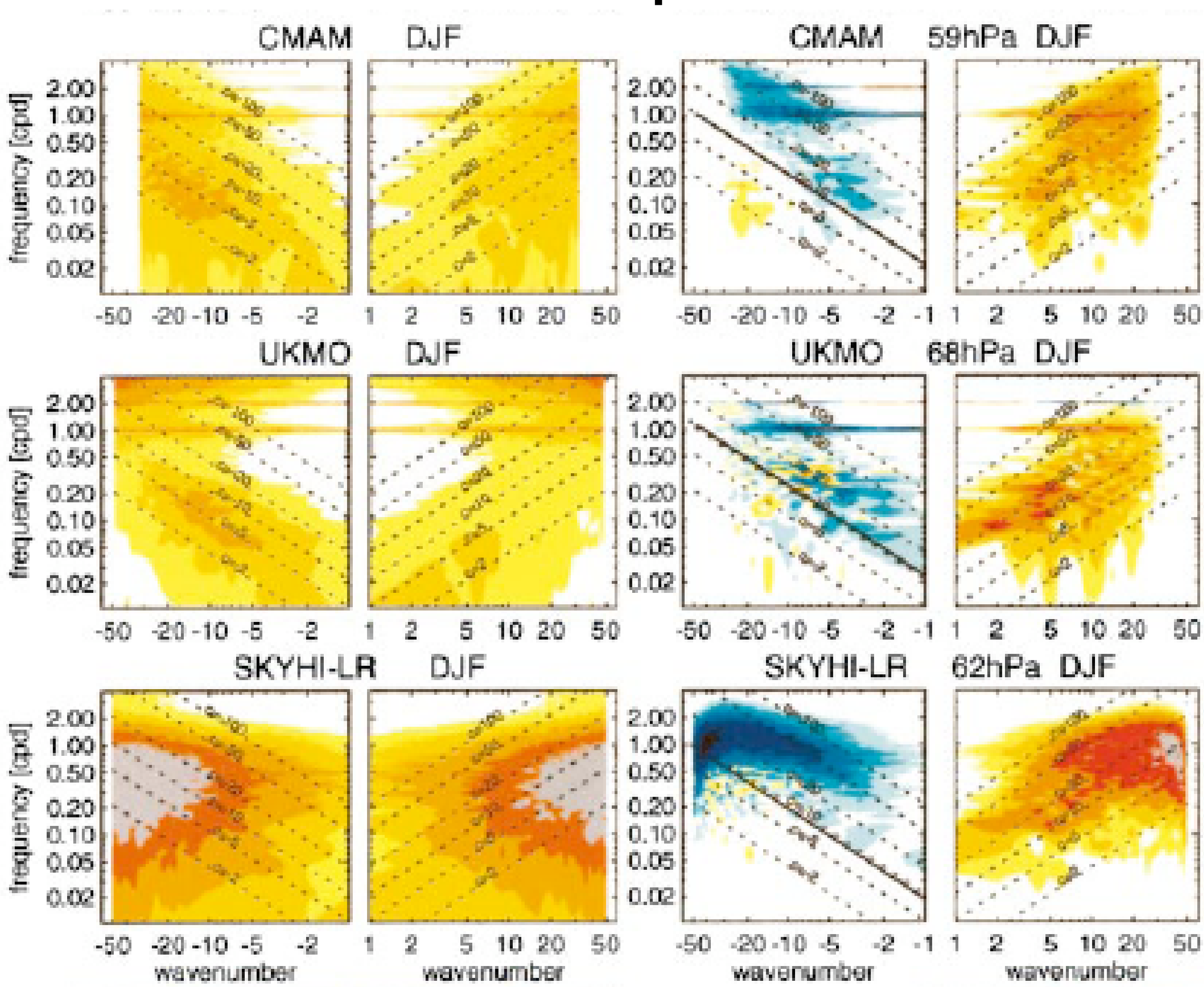
Equatorial waves seen in OLR frequency-wavenumber spectra: the tropics exhibits a rich spectrum of GWs, which are important for driving the QBO





Wheeler & Kiladis (2000 JAS)

- Resolved wavenumber-frequency spectra in GCMs show a strong dependence on the convective parameterization



Left is precip rate, right is vertical EP flux at 59 hPa (lower strat)

Model QBO would certainly depend on this

Horinouchi et al. (2003 JAS)

Summary

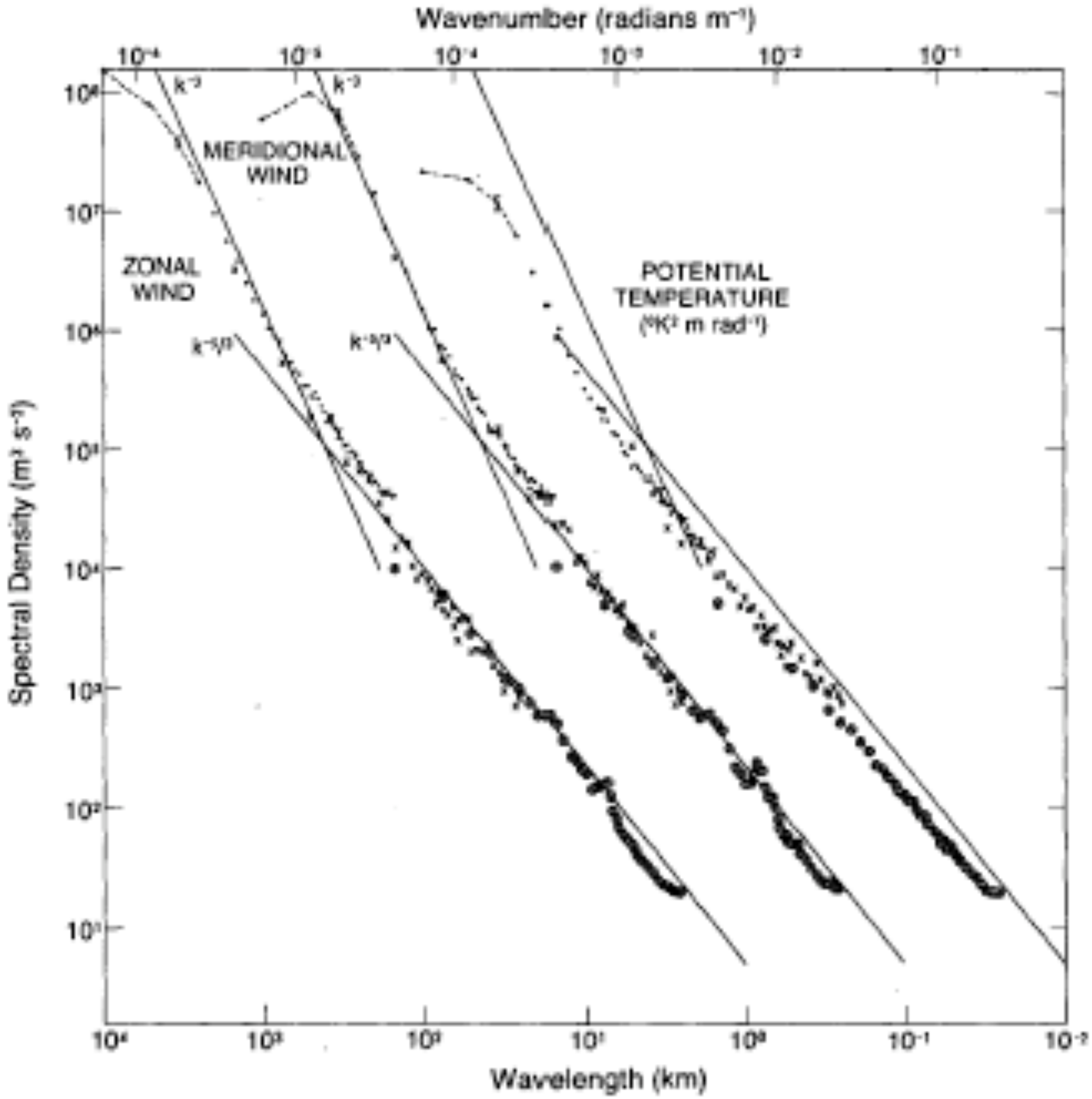
- The stratosphere is increasingly recognized to be an integral component of the climate system
  - Tropical winds play a central role in stratospheric dynamical variability and stratosphere-troposphere coupling
  - The interplay of ozone recovery and climate change involves stratospheric transport
  - For these reasons, the lids of both climate models and weather prediction models are being raised into the mesosphere

- Developments in data assimilation techniques are providing better estimates of winds in the tropical stratosphere
  - But they will need to be validated; this actually increases the value of direct measurements
  - There are fundamental limitations to what information can be obtained from tracers, especially in the tropics
- And for looking at long-term variability, there is no substitute for direct measurements, uncontaminated by assimilation
  - Even for stratospheric temperature, reanalyses are completely ignored in assessments of temperature trends!

References

- Polavarapu, S. and Shepherd, T.G., 2006. Report on the Joint SPARC Workshop on Data Assimilation and Stratospheric Winds. *SPARC Newsletter*, No. 26, pp. 20-27.
  – Downloadable from SPARC Office
- Shepherd, T.G., 2007. Transport in the middle atmosphere. *J. Meteor. Soc. Japan*, **85B**, 165-191.

Wind and potential temperature horizontal wavenumber spectra (offset by one decade) from commercial aircraft



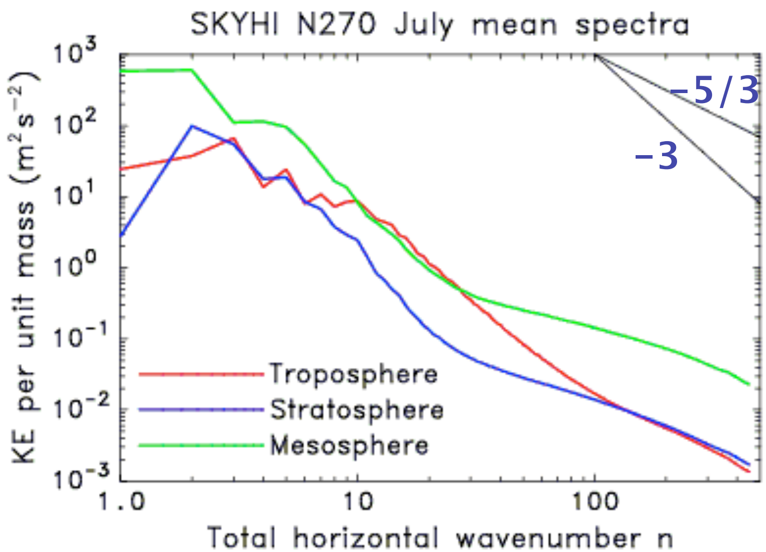
z ~ 10 km

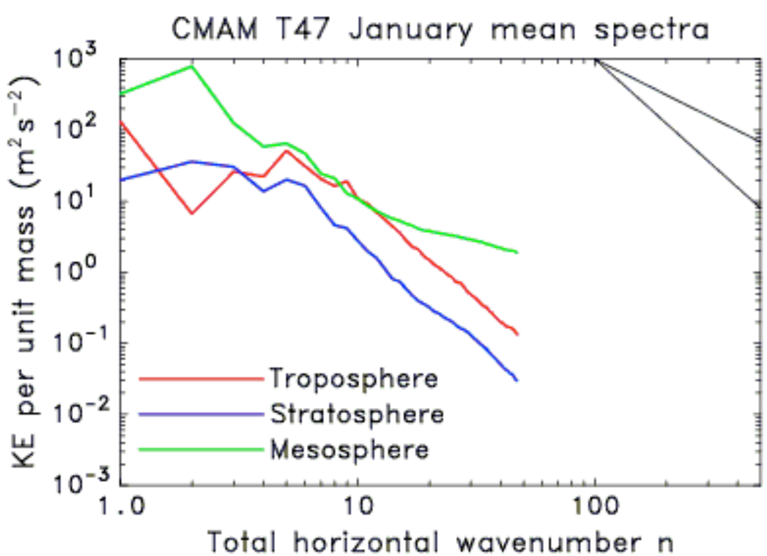
Approximate $k^{-5/3}$ spectra in mesoscale λ ~ 4-400 km

Contrast with approximate k^{-3} range at larger scales

Gage & Nastrom (1985 JAS)

KE spectra





- This can be seen in KE spectra
  - Steep spectra are balanced
  - Shallow spectra are unbalanced (GWs)
- Even in CMAM, at relatively low resolution, the GW spectrum emerges in the lower mesosphere

Figure courtesy of John Koshyk