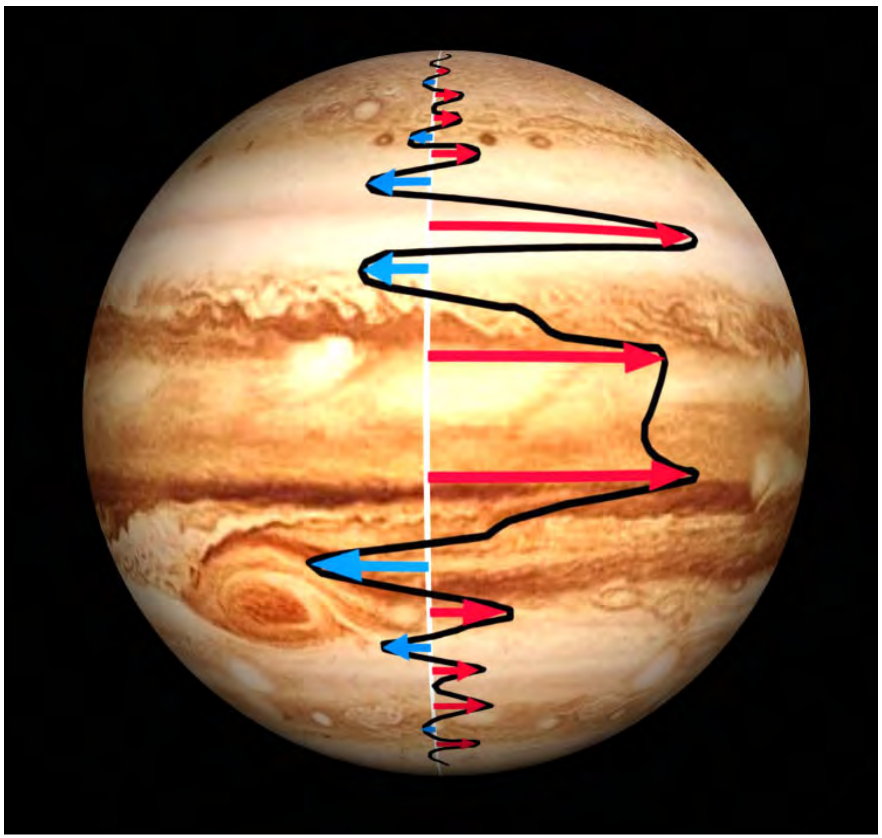
Magnetized Rossby waves and mean flow generation in the lower thermosphere

M. F. Larsen
Department of Physics & Astronomy
Clemson University
Clemson, South Carolina

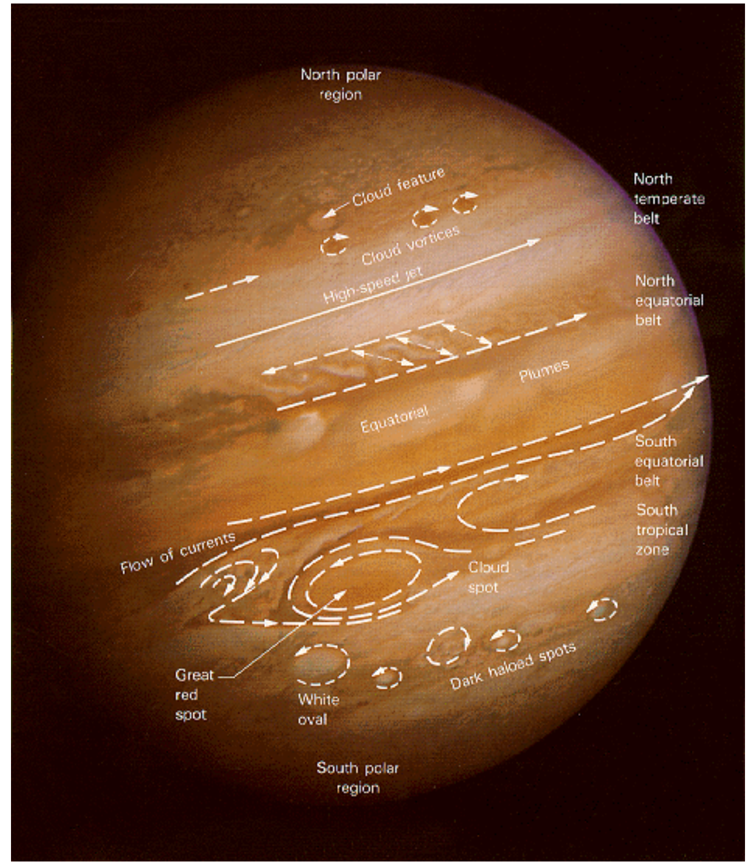
Student Workshop, CEDAR, June 24, 2012

Zonostrophic instability leading to zonation

What factors determine the specific distribution of mean flow in a planetary atmosphere?



MPI Planetary Dynamics Group



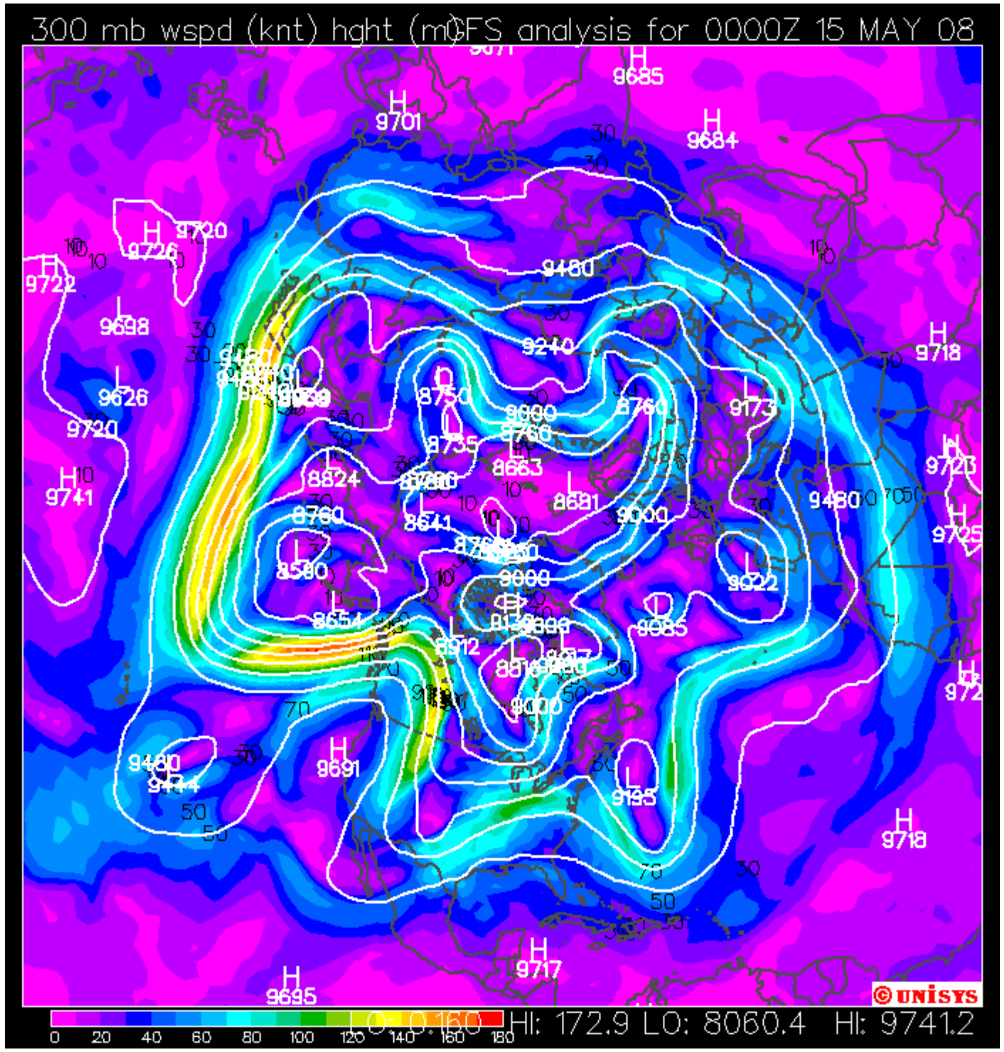
Mean flow with waves propagating along the fluid currents.

Rotating dishpan experiment

J. Gundlach, Clemson University

Rotating dishpan experiments use a rotating pan with a heat source at the outer rim of the pan and a heat sink (container with ice) at the center, as shown above. Although the system is simple, it can simulate the essential features of a large-scale planetary circulation.

The flow in the pan is initially highly structured with a large fraction of the energy in the small-scale structure. As time progresses, the vortices coalesce and produce large-scale coherent flow, indicative of a reverse cascade.



The map above is a typical 300-mb flow pattern that shows the large-scale Rossby wave pattern. Both laboratory experiments and numerical modeling studies show the tendency in geophysical flows for large-scale coherent flows of this type to develop in response to random, small-scale forcing in the fluid.

Large-scale jet structure generation by small-scale random forcing

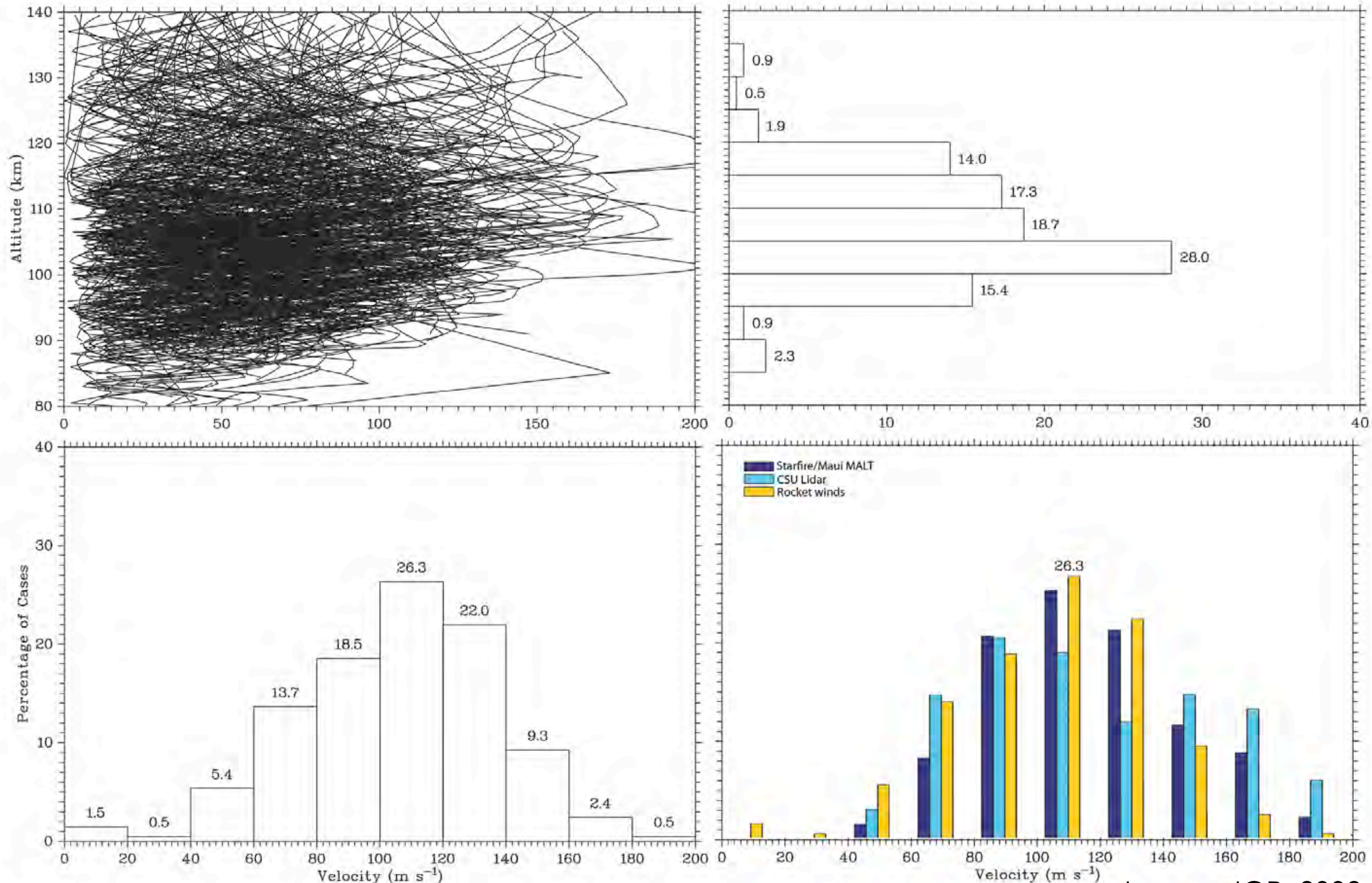
Zonation and zonostrophic instability:
Random small-scale forcing, due to convection for example, will generate large-scale coherent high-speed flows, i.e., jets or strong mean flows.

Large literature on the topic, including the following notable papers:

Lilly, Phys. Fluids,1969
Rhines, J. Fluid Mech.,1975
Farrell and Ioannou, J. Atmos Sci.,1993
Nozawa and Yoden, Phys. Fluids,1997
Huang et al., Nonlinear Processes Geophys.,1998
Manfroi and Young, J. Atmos. Sci.,1999
Danilov and Gryanik, J. Atmos. Sci., 2004
Danilov and Gurarie, Phys. Fluids, 2004
Diamond et al., Plasma Phys. Contr. Fusion, 2005
Galperin et al., Nonlinear Processes Geophys, 2006
Farrell and Ioannou, J. Atmos. Sci., 2007
Bakas and Ioannou, J. Fluid Mech., 2011
Srinivasan and Young, J. Atmos. Sci., 2012

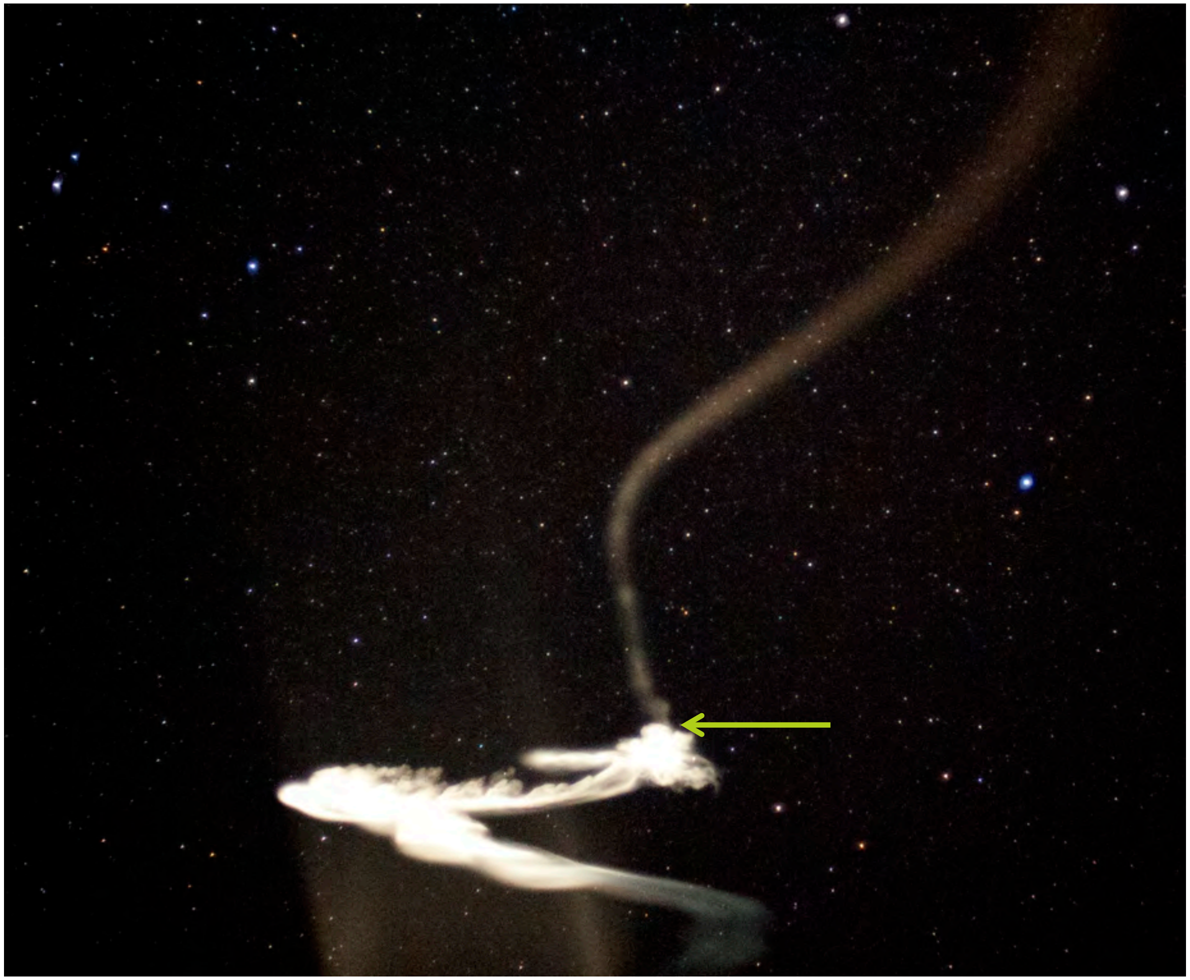
Combination of stratification and beta-plane effects lead to reverse cascade

Rocket wind observations and comparison to lidar wind measurements



Larsen, JGR, 2002

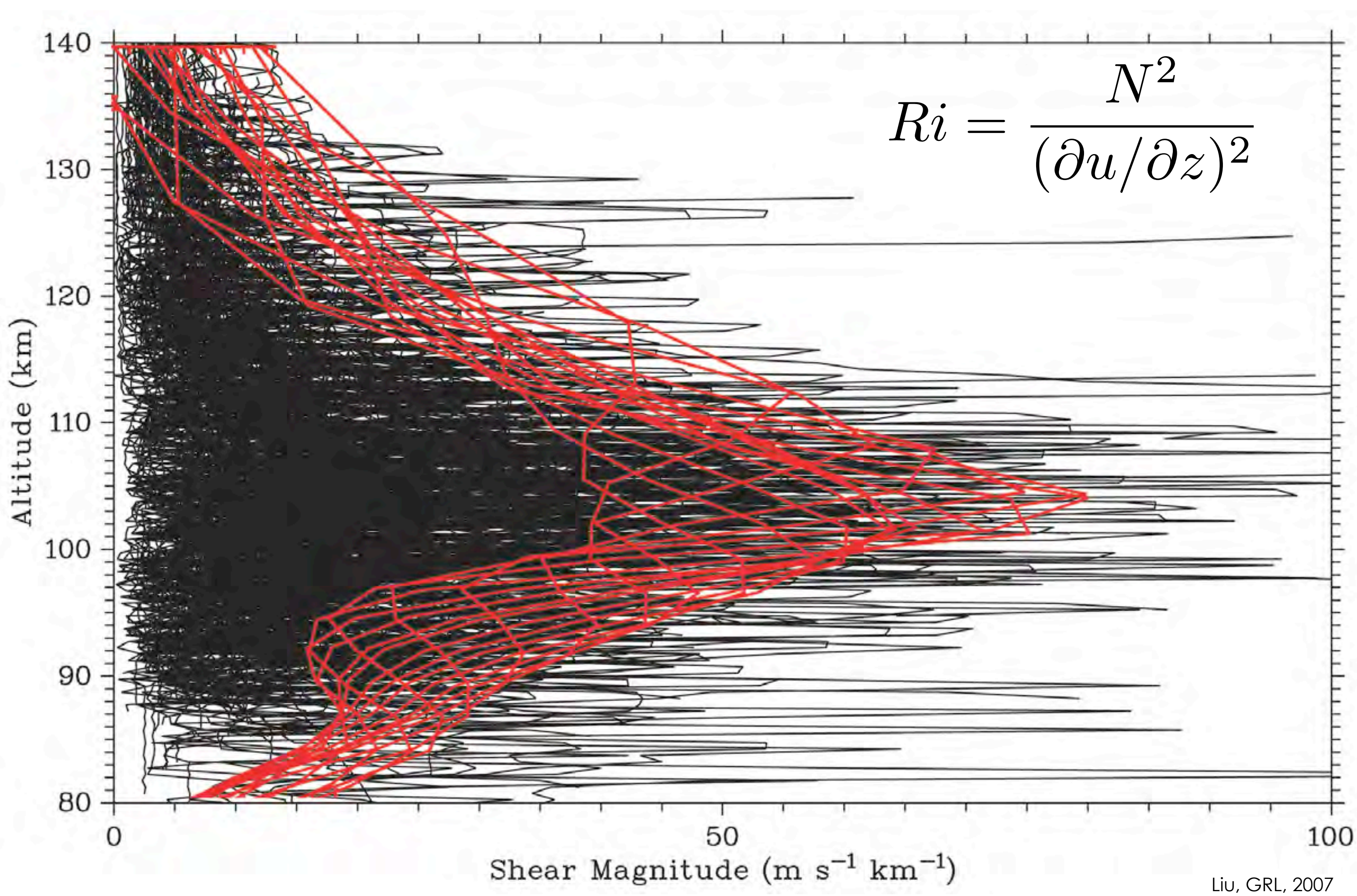
ATREX (Anomalous Transport Rocket Experiment)



• Wallops Flight Facility 0458 LT on Mar. 27, 2012

Chemical tracer trails released in the mesosphere/lower thermosphere region show the transition from turbulent flow to laminar flow near 100-km altitude.

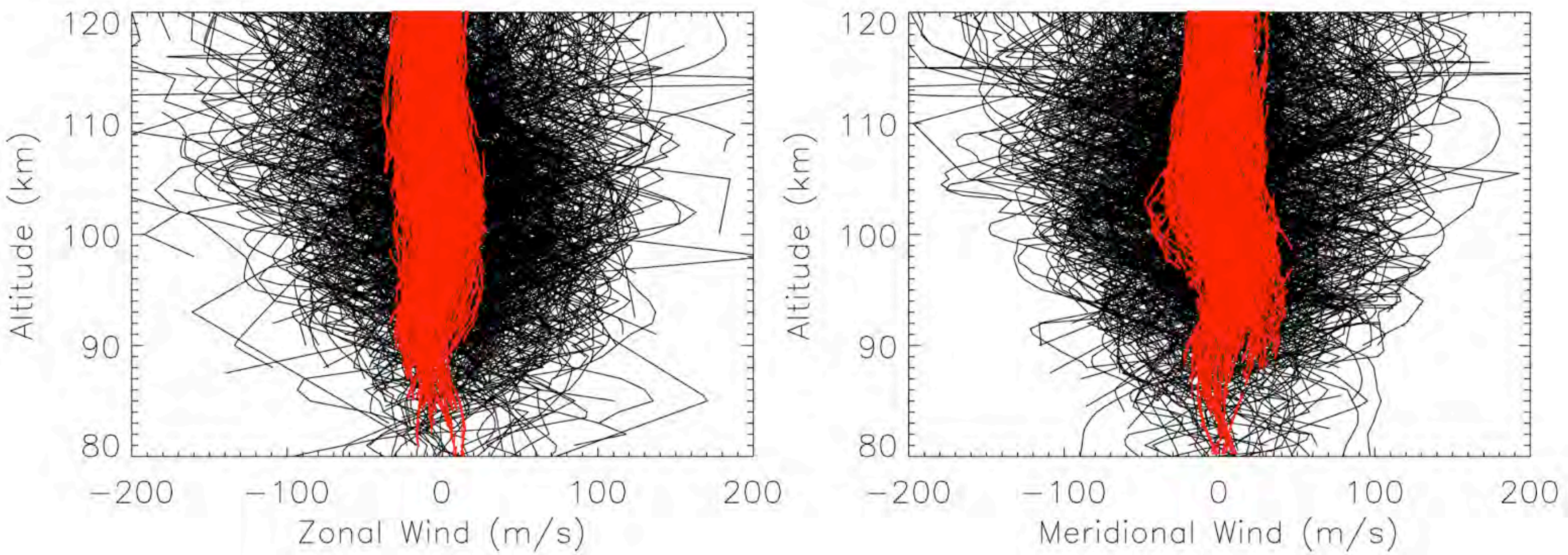
Observed shears compared to threshold stability values from model



Liu, GRL, 2007

+ Flow must be strongly forced to keep it at marginal stability over the long term

Observed winds compared to best estimate of tidal contribution plus mean

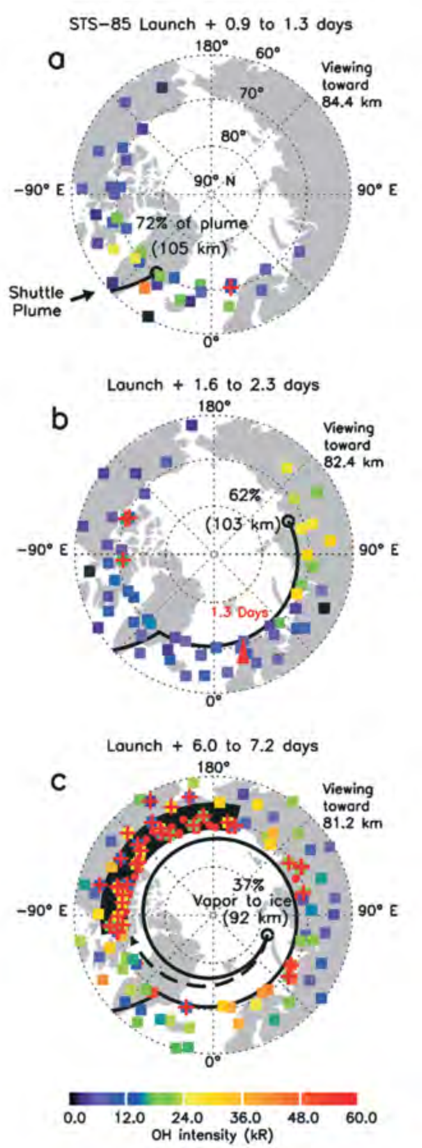


Larsen and Oberheide, GRL, in prep., 2012

+ Red curves show best estimate of winds for each rocket profile based on tidal climatology, using Hough mode extensions, and mean winds

+ If the red curves are the best estimates, then what is the rest?

Shuttle exhaust tracked with SABER on TIMED and ground-based instruments



- Tracking 6.8 um emission from water vapor released between 100 and 115 km by Shuttle engines
- Meridional transport speeds of 50 to 75 m/s
- Rapid motion from low latitudes to polar region

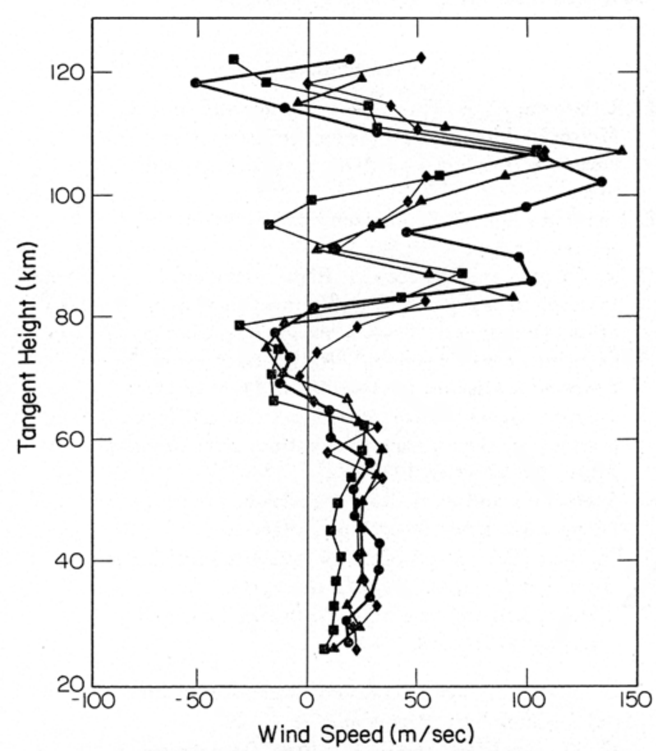
(See Siskind et al., GRL, 2003
Also Stevens et al., GRL, 2002, 2003), Niciejewski et al., JGR, 2011

Lithium release dispersal between dusk and dawn twilight (Feb 27-28, 1965)

- Lithium trail released between 100 and 200 km altitude in launch from Fort Churchill at dusk on Feb. 27,1965.
- Lithium enhancement detected by chain of spectro-photometers in Alaska at dawn on Feb. 28, 1965.
- Dispersion increases significantly at large scales with transition somewhere between separation scales of 10 and 100 km
- Sodium/lithium density enhancements detected at Saskatoon after atmospheric nuclear weapons tests at Johnston atoll (700 km w of Hawaii)

Deehr et al. JAS, 1966; Gault and Rundle, Can. J. Phys., 1966

Zonal winds obtained from Doppler shifts of solar occultation spectra obtained on Spacelab 3 (CO_2, CH_4, H_2O, and N_2O vibration lines)



Occultation	Date	GMT	Lat.	Long.
SR02 (sunrise)	4/30/85	11:30	48°.0 S	66°.3 W
SS06 (sunset)	4/30/85	23:07	31°.3 N	68°.1 E
SS09 (sunset)	5/ 1/85	17:27	27°.1 N	15°.9 W
SS11 (sunset)	5/ 1/85	20:30	27°.2 N	30°.2 E
SS13 (sunset)	5/ 1/85	23:33	26°.7 N	16°.2 W

van Cleef, G. W., J. H. Shaw, and C. B. Farmer (1987), Zonal winds between 25 and 120 km obtained from solar occultation spectra, Geophys. Res. Lett., 14, 1266–1268.

Measurements of the zonal winds over an extended range of longitudes show large-scale coherent circulation features with large wind speeds of 100 to 150 m/s in the MLT region.

Magnetized Rossby waves

- Rossby wave modes modified by the effects of the Hall ion drag term:

Kaladze et al., JGR, 2004 - Theory of magnetized Rossby waves

Kaladze et al., J. Plasma Phys., 2006 - Theory of mean-flow generation by magnetized Rossby waves

Aburjania et al., JGR, 2006 - Theory

Rasmussen et al., Phys. Scr. 2006 - Laboratory and modeling results

Also of interest:

Soomere, Phys. Rev. Lett., 1995

The neutral momentum equation in the ionosphere

$$\frac{d\vec{v}}{dt} = 2\vec{\Omega} \times \vec{v} - \frac{1}{\rho}\vec{\nabla} P + \frac{1}{\rho}\vec{J} \times \vec{B}$$

The y component and using geopotential height in place of pressure is

$$\frac{du}{dt} = (f - \nu_H)v - \frac{\partial \phi}{\partial x} - \nu_P u$$

$$\frac{dv}{dt} = -(f - \nu_H)u - \frac{\partial \phi}{\partial y} - \nu_P v$$

Here

$$\nu_P = \frac{\sigma_P B^2}{\rho} \qquad \nu_H = \frac{\sigma_H B^2}{\rho}$$

Consider the lower E region layer where the Hall conductivity is dominant.

For the simplified case with a purely vertical magnetic field and no Pedersen drag, linearizing the equations, cross-differentiating, and subtracting to get the vorticity equation gives a wave solution with the dispersion relation for Rossby waves:

$$c = U_o - \frac{\beta}{k^2}$$ without Hall drag

$$c = U_o - \frac{(\beta - \beta_H)}{k^2}$$ with Hall drag

Here the planetary vorticity gradient terms are given by

$$\beta = \frac{df}{dy} \qquad \beta_H = \frac{d\nu_H}{dy}$$

See Kaladze et al., JGR, 2004 for a detailed derivation that includes dip angle variation with latitude and both Hall and Pedersen drag terms

Mean flow generation by magnetized Rossby waves

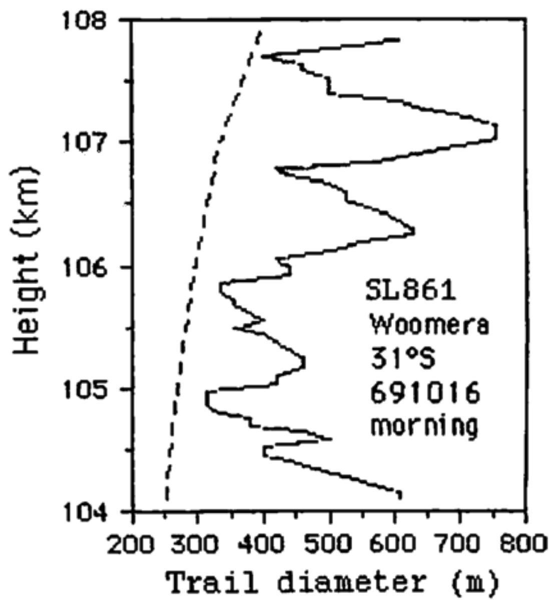
• An initial random distribution of Rossby waves will tend to move vorticity to larger scales via a reverse cascade, i.e., similar to a Kraichnan-Batchelor type two-dimensional enstrophy subrange process

• The energy transfer and wave component growth is enhanced in the region where the Hall conductivity (Hall drag terms) are important, with the growth rate for mean flow acceleration having the following proportionality

$$\gamma \propto (f - \nu_H)^{-2}$$

Kaladze et al., *J. Plasma Phys.*, 2006 - Theory of mean-flow generation by magnetized Rossby waves

Enhanced diffusion above the nominal turbopause



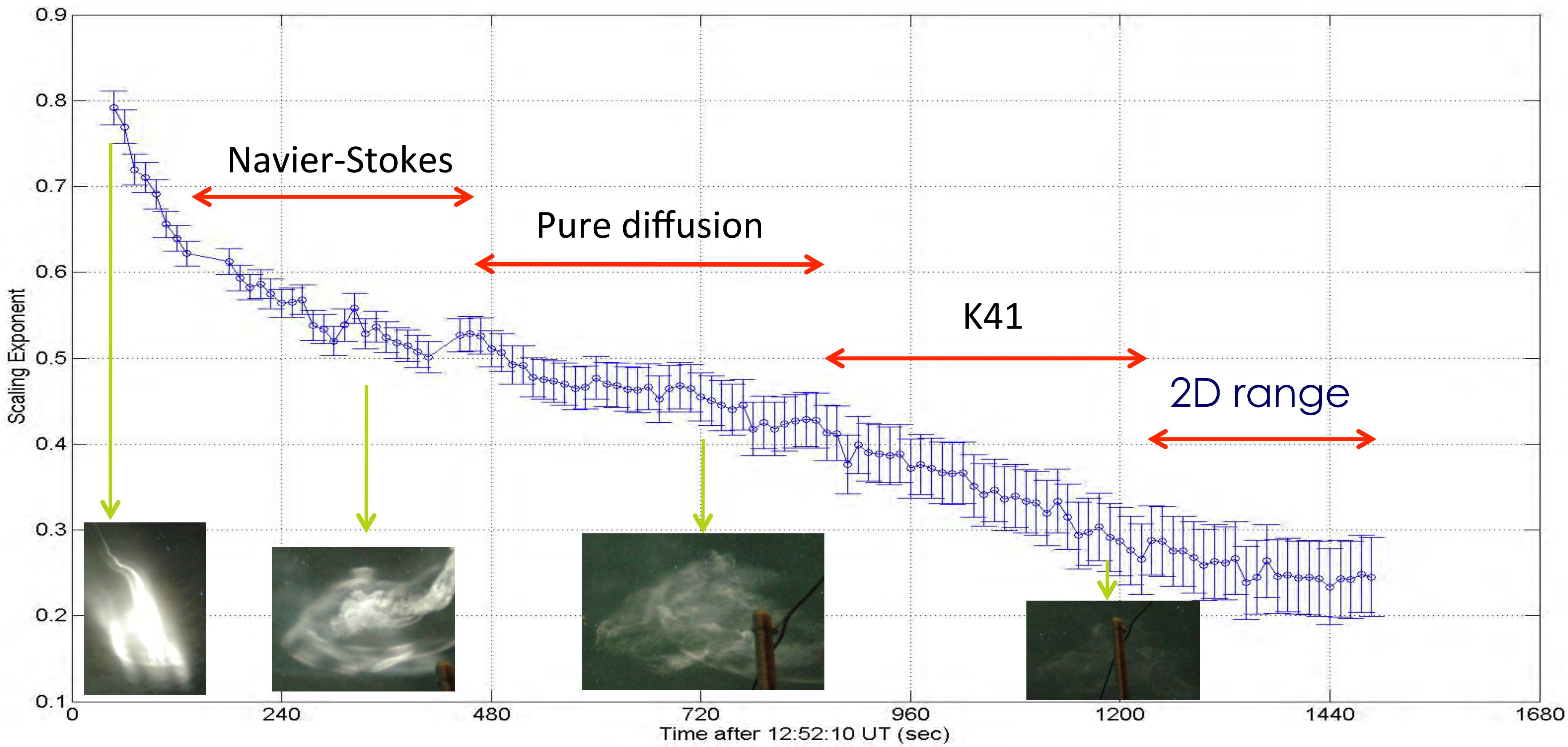
Roper, JGR, 1996

- Rees et al., Phil Trans Roy Soc, 1972
- Bishop et al., JGR, 2004

Both studies found diffusion rates significantly greater than the values expected for molecular diffusion alone in the 10-15 km altitude range above the transition height where the structure became laminar.

If the vertical structure disappears but the diffusion rates are enhanced, that suggests a transition from 3D to 2D turbulence!

Structure function analysis for long-lived TMA trail
Hurst exponent as a function of time



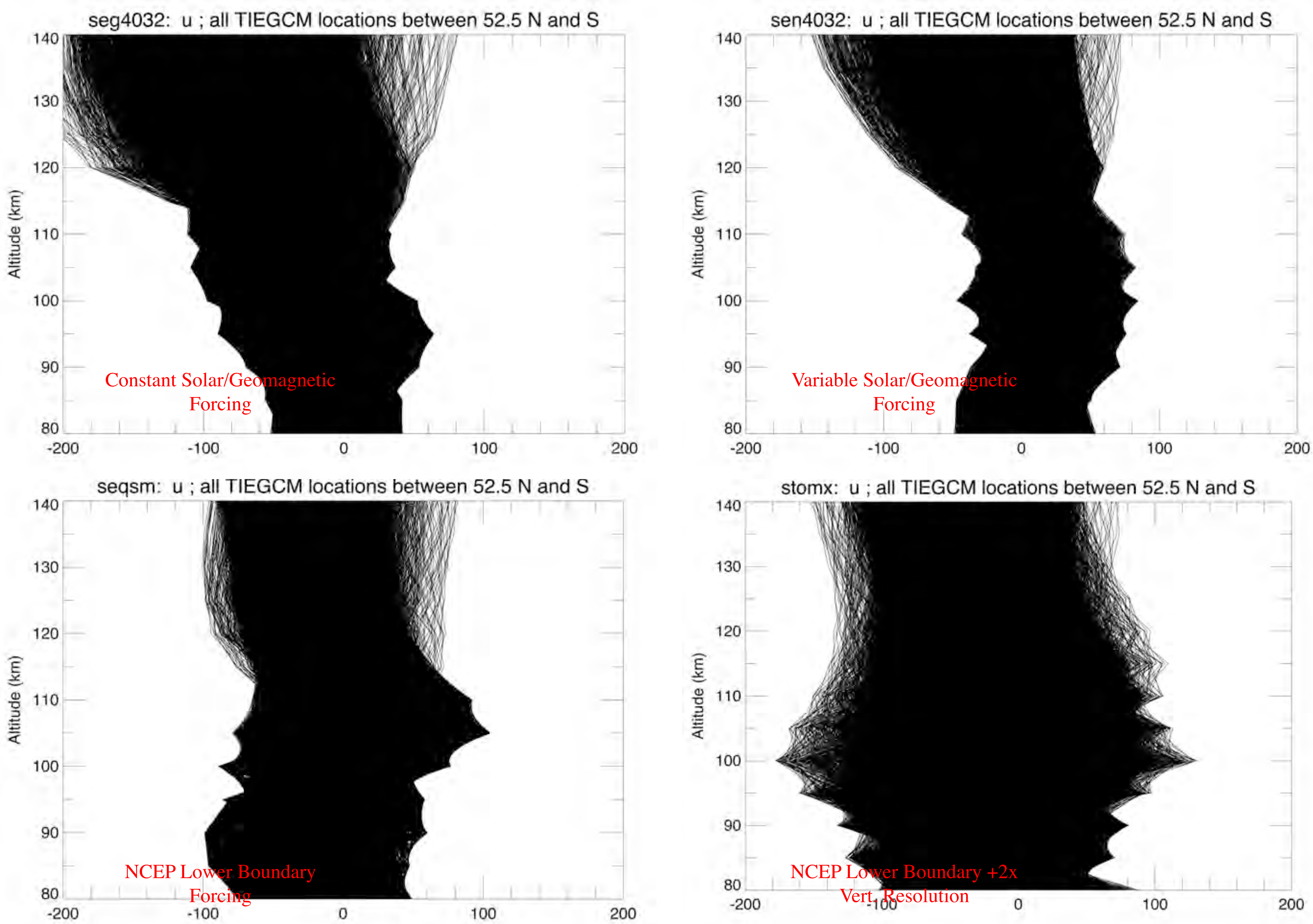
~1 km

~100 km

Total time interval 25 min

Wanliss and Larsen, Challenges in Nonlinear Plasma Phys. (2010)

Larsen and Fesen, Ann. Geophys., 2009



TIME-GCM model runs with improved height resolution appear to show the development of enhanced flow with a distribution similar to what is observed.

Summary

- There is evidence that a reverse cascade, and the associated mean flow generation, is especially important in the MLT region
- Critical to the dynamics is the effect of the Hall drag in modifying the Coriolis force and the large increase in the static stability associated with the rapid increase in temperature with height
- The small-scale forcing that drives the cascade is likely associated with breaking gravity waves and convective motion
- Very little is presently known about these processes! Relevant measurements are desperately needed…