The Lower Thermosphere during the Northern Hemisphere Winter of 2009

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Stratosphere → Lower Thermosphere

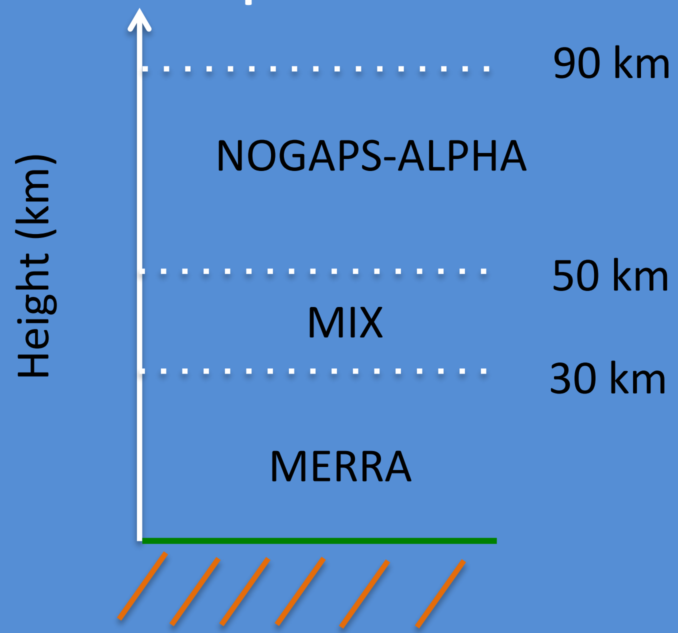
- *Fraser* (1977) found evidence of concurrent 5-day variability in ionospheric scatter and lower stratospheric temperature during various seasons.
- *Meyer* (1999) suggested that planetary-scale waves that survive dissipation may influence the ionosphere.
- *Liu and Roble* (2002) showed that the wintertime variability associated with a SSW can reach into the thermosphere.
- *Liu et al.* (2010) suggest that the presence of quasi-stationary PW in the thermosphere is necessary to couple the high latitudes with the tropical latitudes.

NH 2009 Winter: SSW

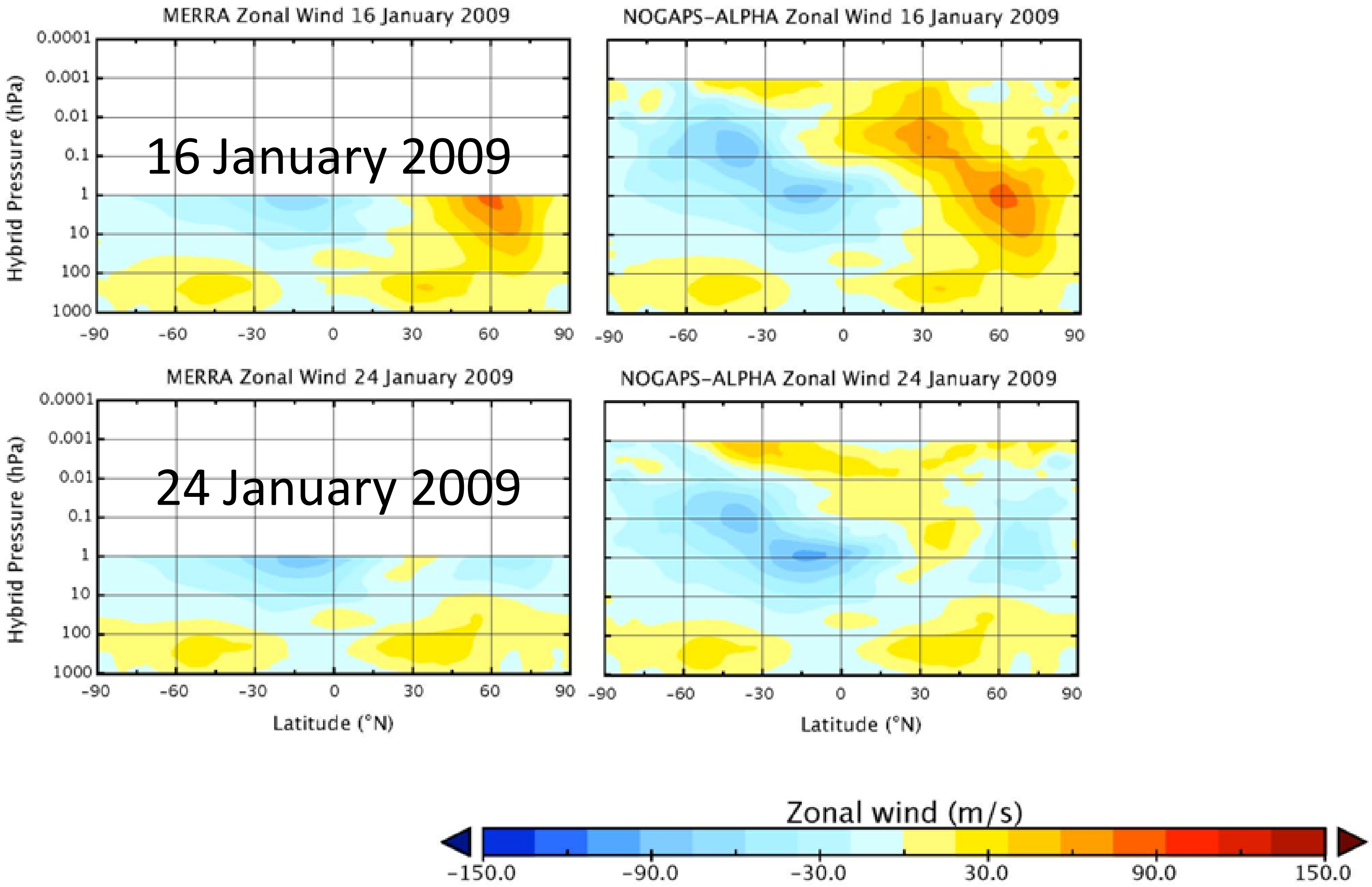
- Using WAM, *Wang et al.* (2011) show that the tidal amplitudes undergo substantial changes at times around the SSW of January 2009: resonant triads.
- Examining ERA-Interim data, *Goncharenko et al.* (2012) relate the tidal amplitude in the thermosphere with ozone changes in the stratosphere following a SSW.
- Using upper atmosphere data analysis products, *McCormack et al.* (2010) suggest that phase locking between tides and QTDW is another potential mechanism that can affect tidal amplitudes.

WACCMX-SD

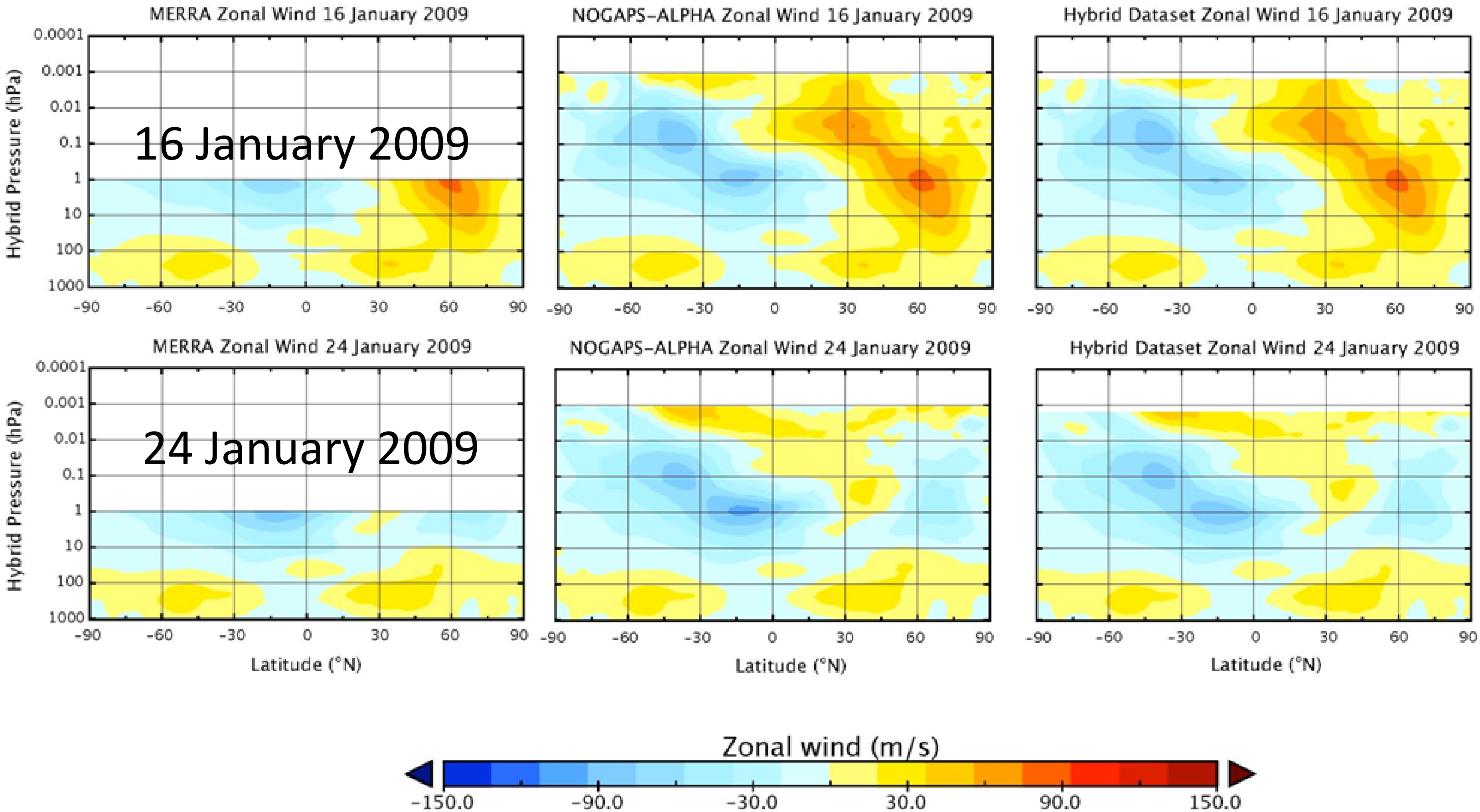
- WACCMX in SD configuration (lid at $3.3x10^{-9}$ hPa ~ 400 km).
- Data analysis products are obtained merging NASA/MERRA and NRL/NOGAPS-ALPHA.
- Focus period is January-February 2009.

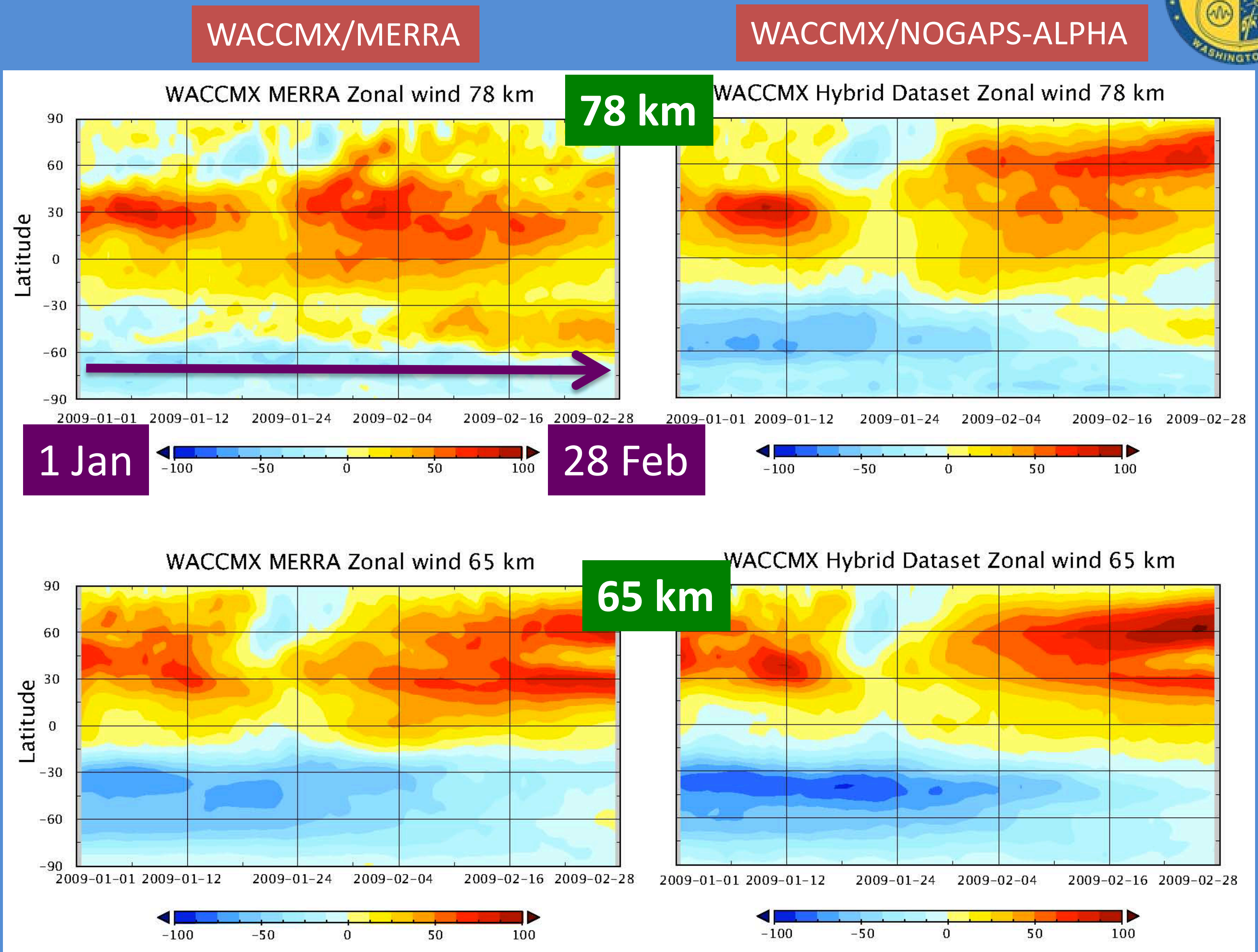


MERRA NOGAPS-ALPHA

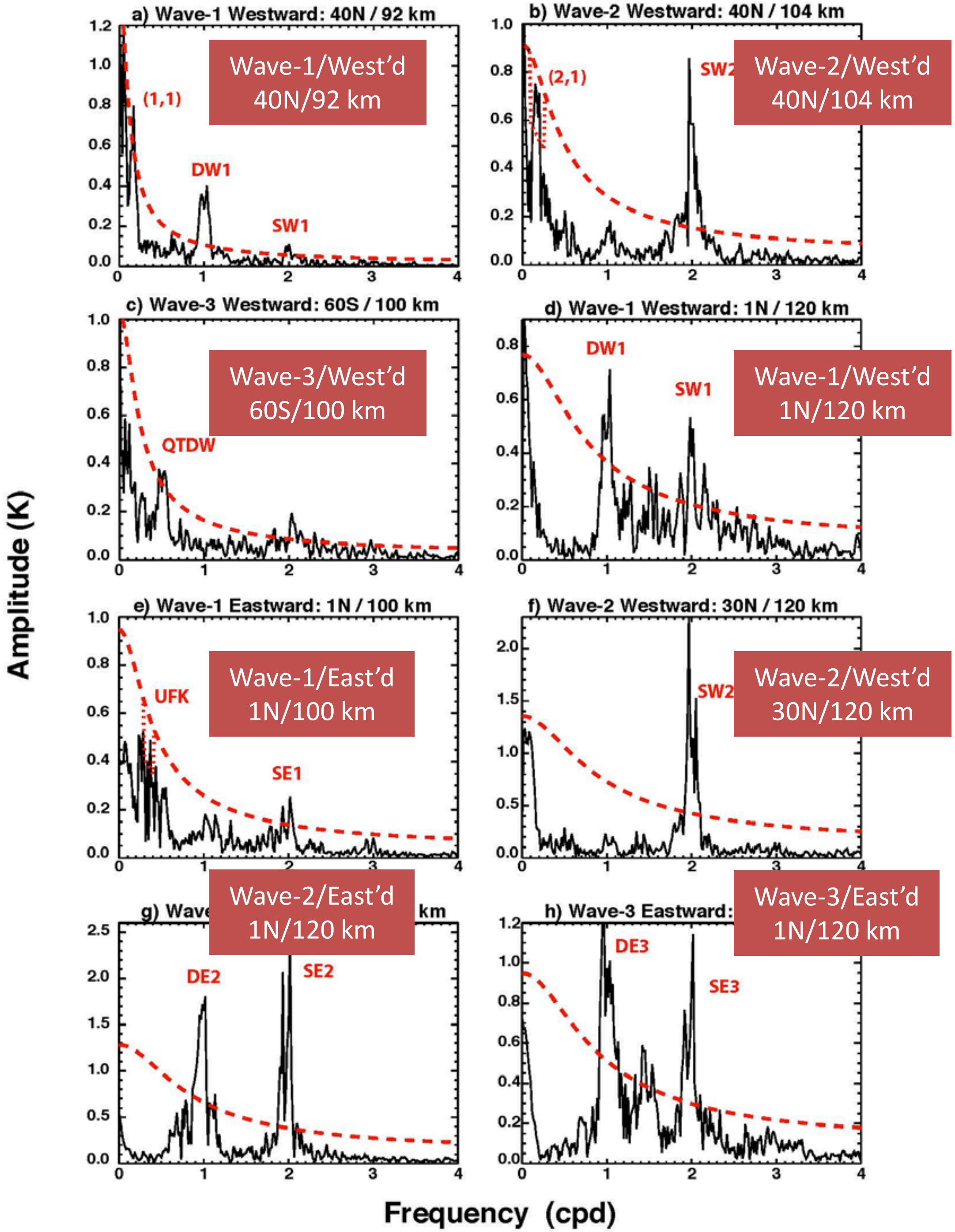


MERRA NOGAPS-ALPHA HYBRID



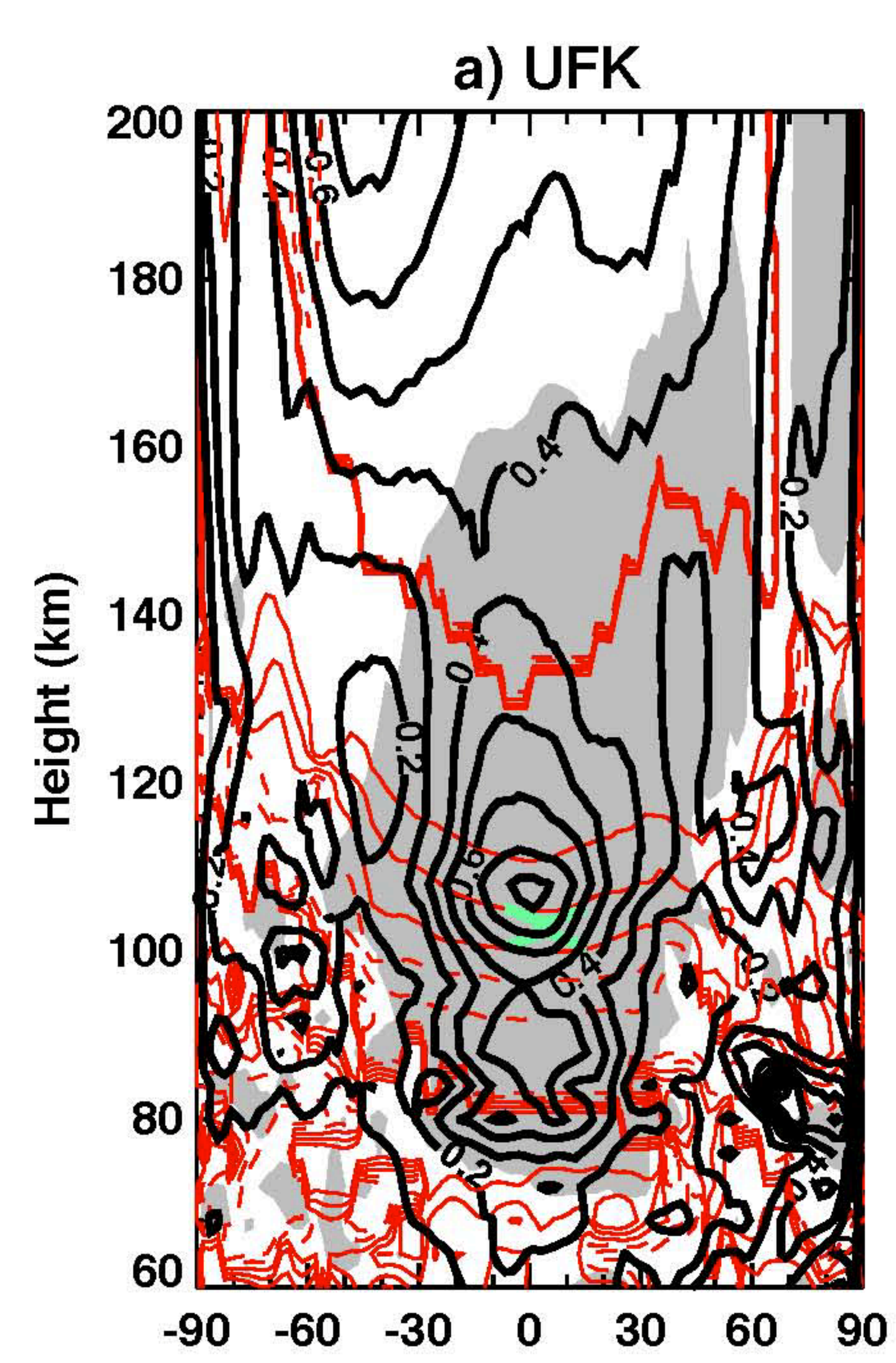

WACCMX/MERRA
WACCMX/NOGAPS-ALPHA
WACCMX MERRA Zonal wind 78 km
78 km
WACCMX Hybrid Dataset Zonal wind 78 km
Latitude
90
60
30
0
-30
-60
-90
2009-01-01
2009-01-12
2009-01-24
2009-02-04
2009-02-16
2009-02-28
1 Jan
28 Feb
-100
-50
0
50
100
WACCMX MERRA Zonal wind 65 km
65 km
WACCMX Hybrid Dataset Zonal wind 65 km

Spectral Analysis

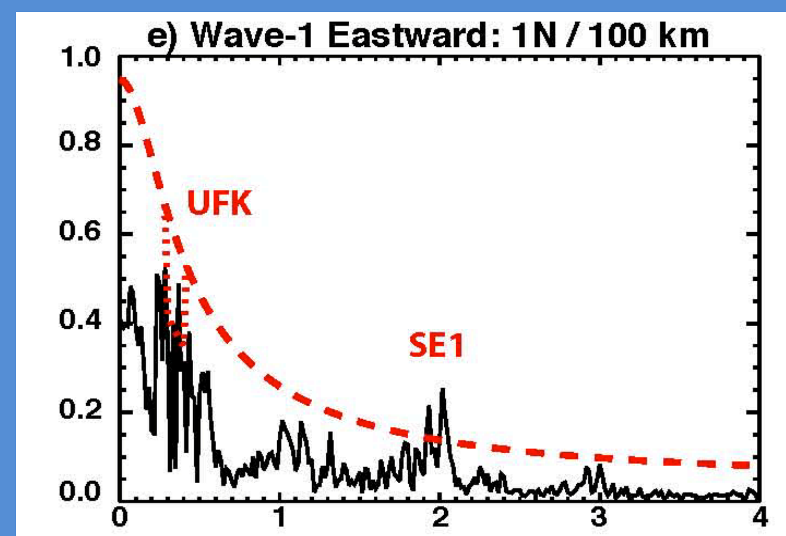


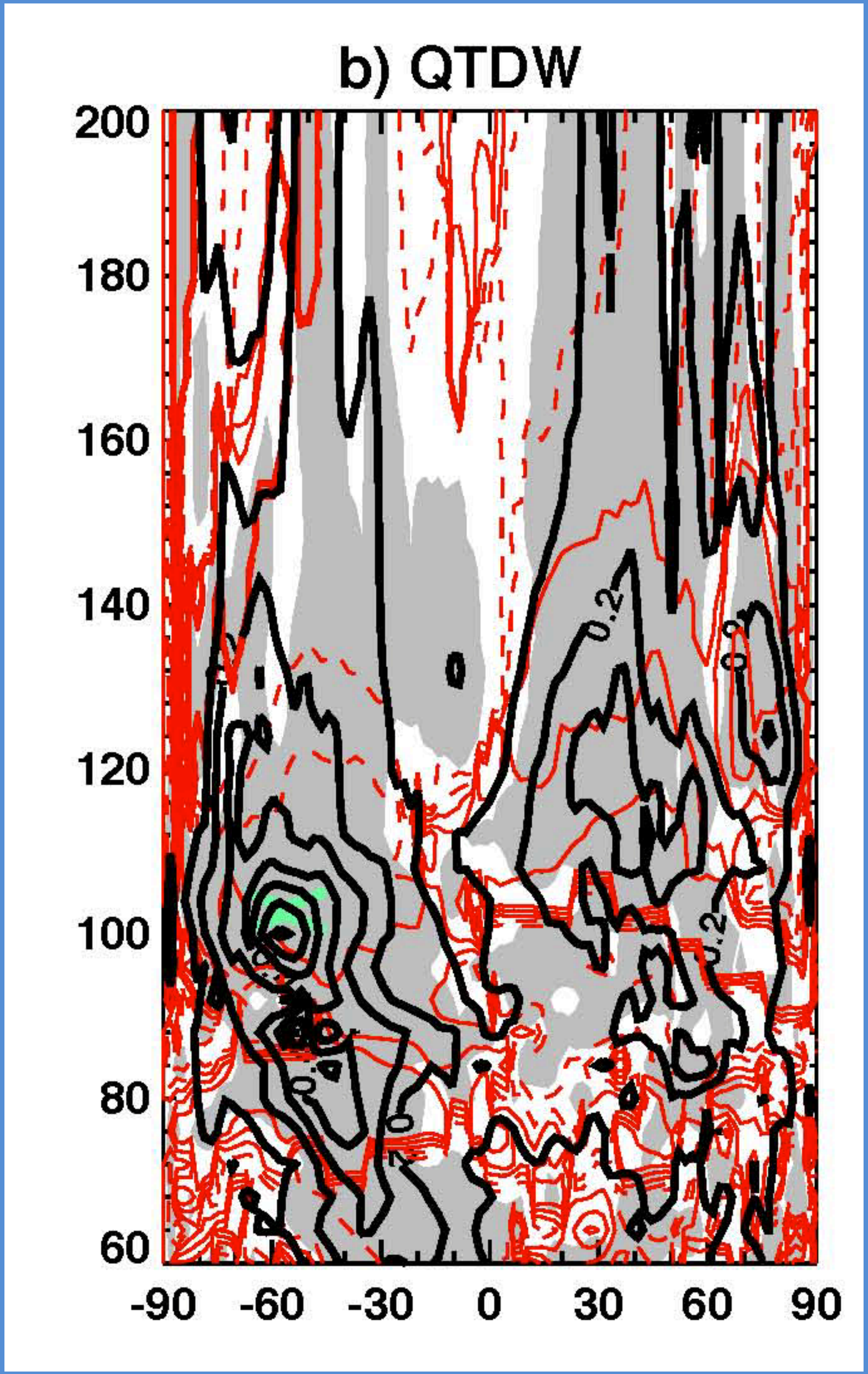
a) Wave-1 Westward: 40N / 92 km
Wave-1/West'd
40N/92 km
(1,1)
DW1
SW1
b) Wave-2 Westward: 40N / 104 km
Wave-2/West'd
40N/104 km
(2,1)
SW2
c) Wave-3 Westward: 60S / 100 km
Wave-3/West'd
60S/100 km
QTDW
d) Wave-1 Westward: 1N / 120 km
Wave-1/West'd
1N/120 km
DW1
SW1
e) Wave-1 Eastward: 1N / 100 km
Wave-1/East'd
1N/100 km
UFK
SE1
f) Wave-2 Westward: 30N / 120 km
Wave-2/West'd
30N/120 km
SW2
Wave-2/East'd
1N/120 km
DE2
SE2
h) Wave-3 Eastward:
Wave-3/East'd
1N/120 km
DE3
SE3
Amplitude (K)
Frequency (cpd)

Coherence Analysis: Spatial Structure

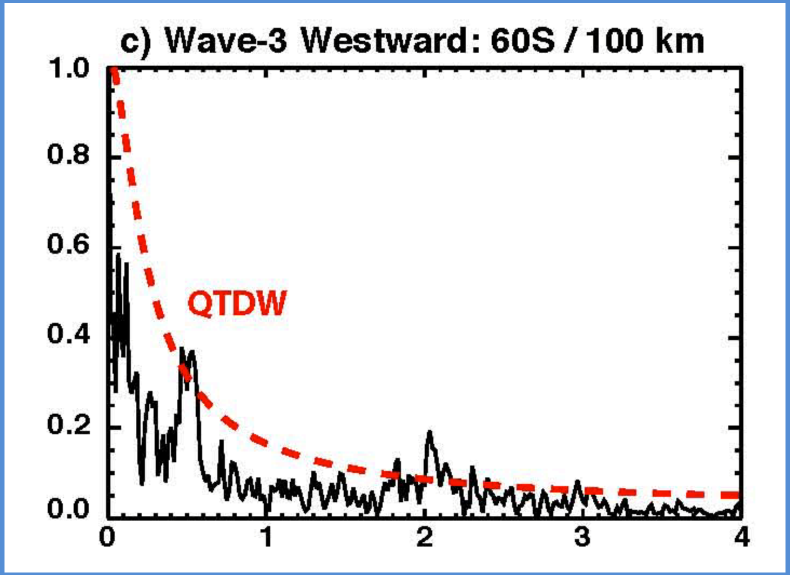


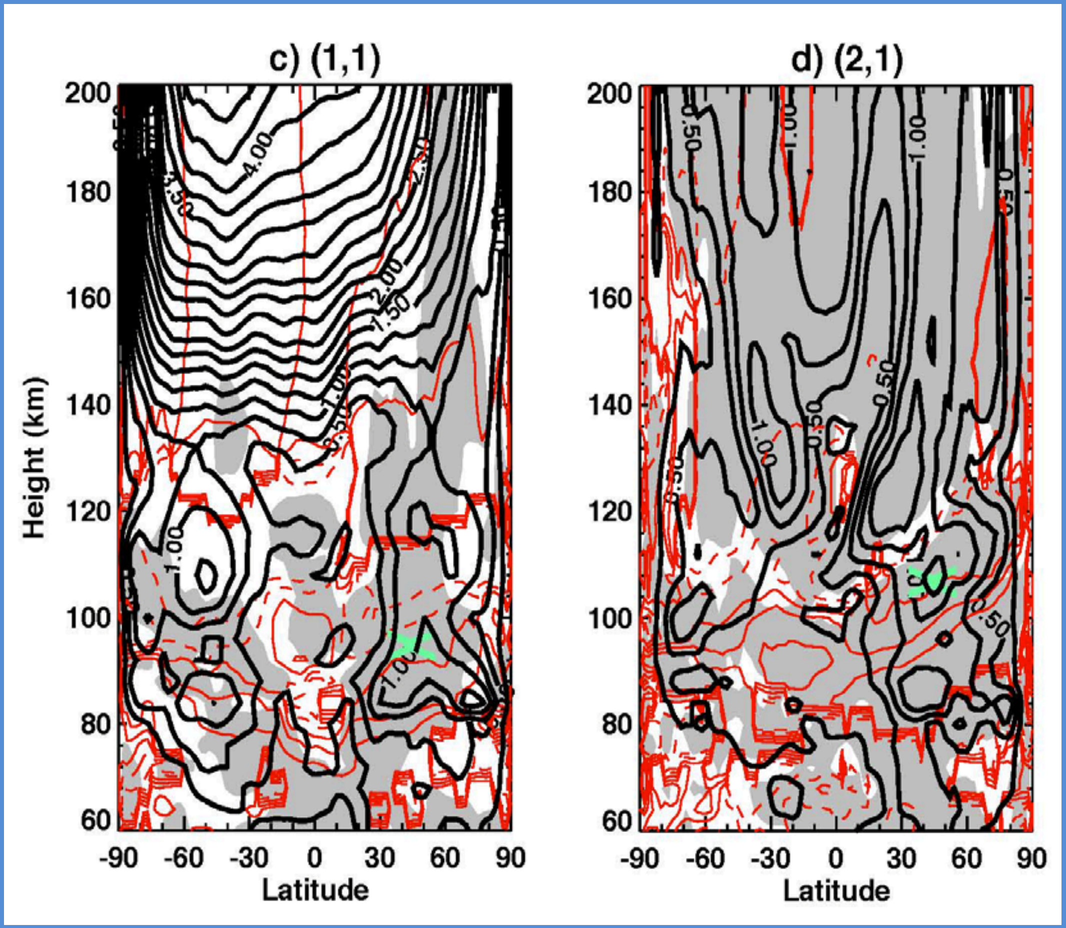
- Symmetric about the EQ
- Amplitude peaks ~110 km
- Vertical wavelength is ~30-40 km
- Amplitude decreases rapidly above 120 km with the phase becoming vertically uniform ➔ external mode.
- Consistent with an ultra-fast Kelvin mode.



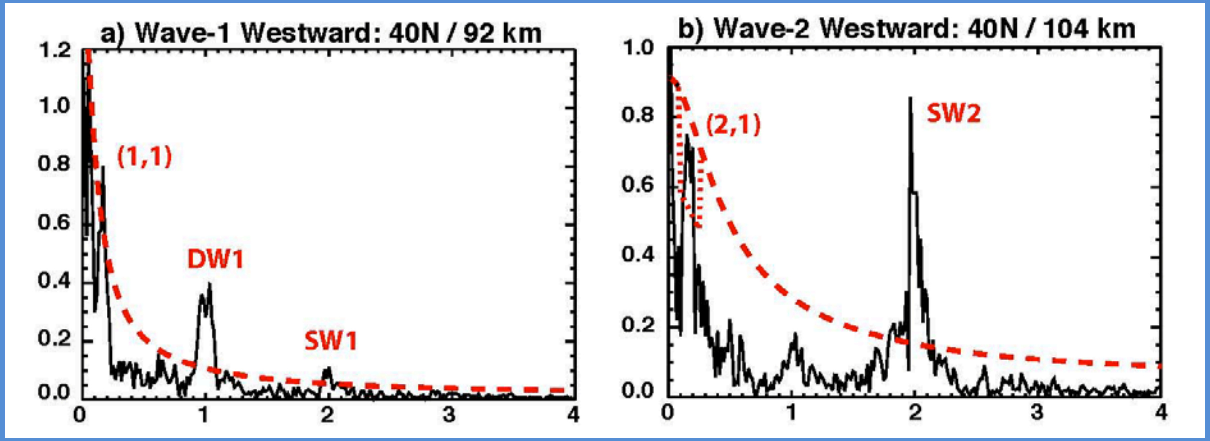


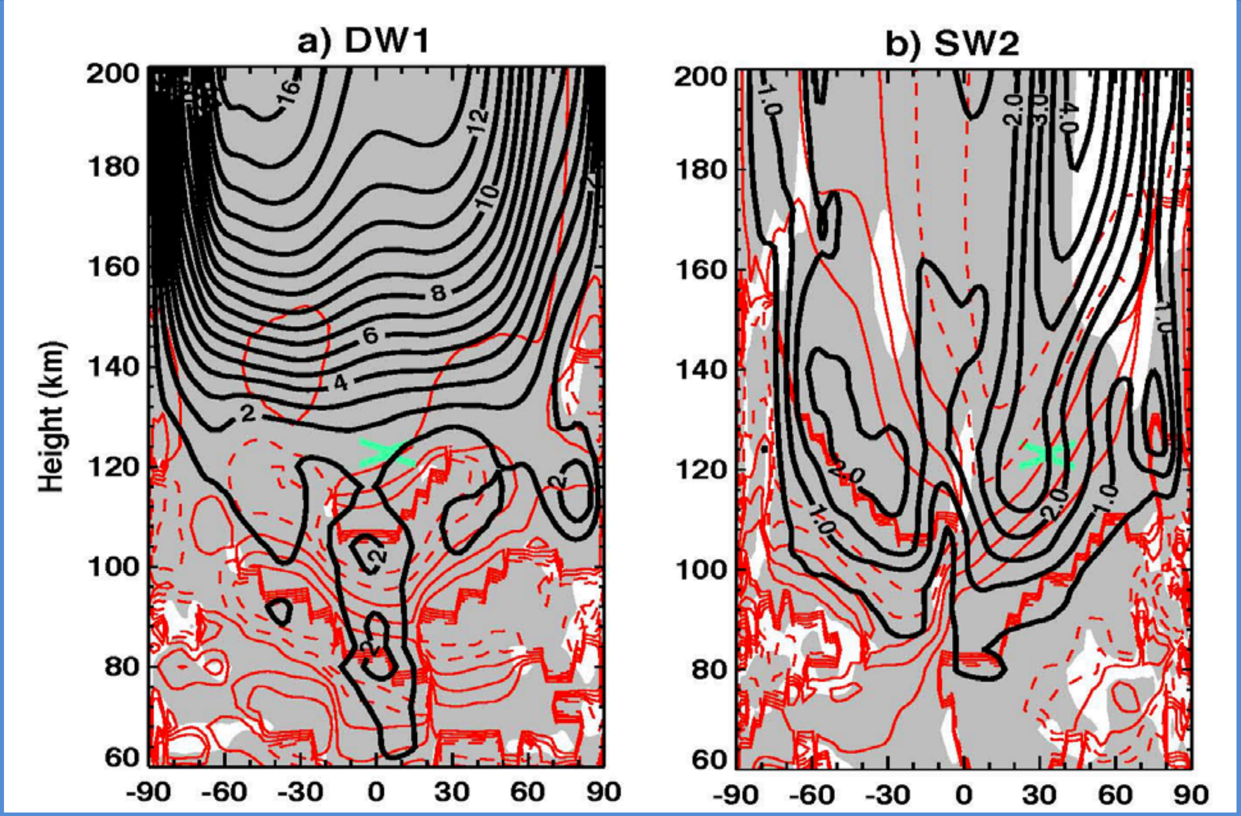
- Amplitude peaks in the SH at ~100 km and decreases rapidly above.
- Coherence is nearly global and extends above and below the base point.
- Mode becomes external above 140 km.
- Likely the Rossby-gravity quasi-two day wave.

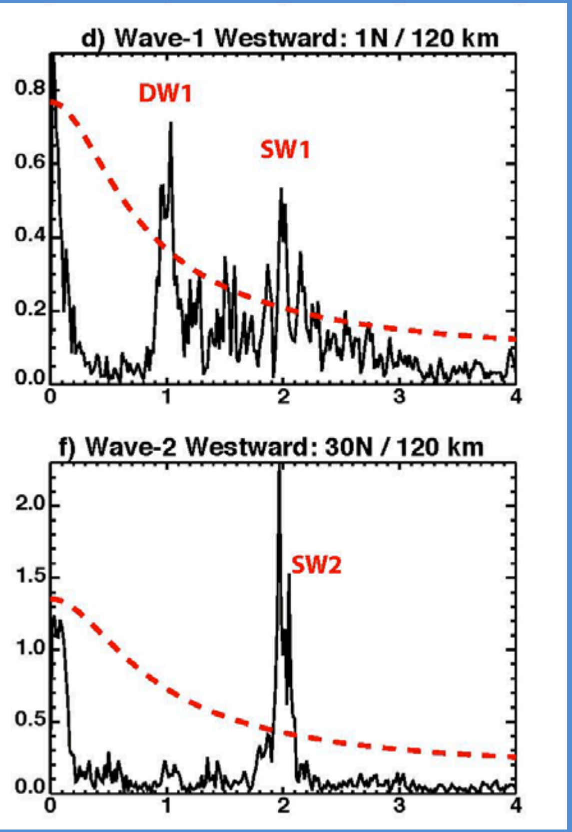




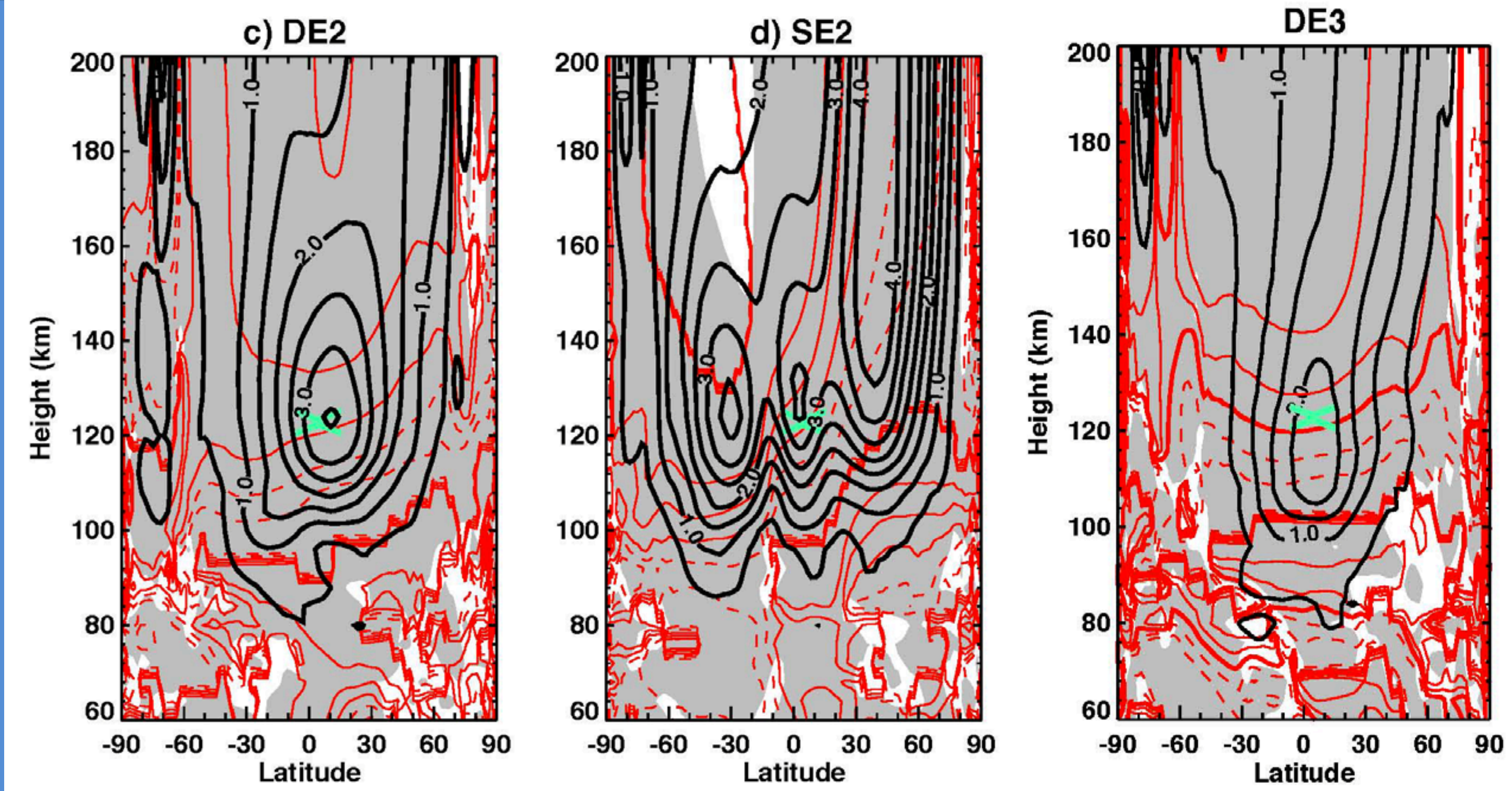
- These waves correspond to the fundamental Rossby modes at wave-1 and wave-2.
- It is curious that substantial amplitudes seem to emerge from the upper mesosphere.
- Both modes become external above 120 km but (1,1) shows larger amplitude in the summer hemisphere toward 200 km.

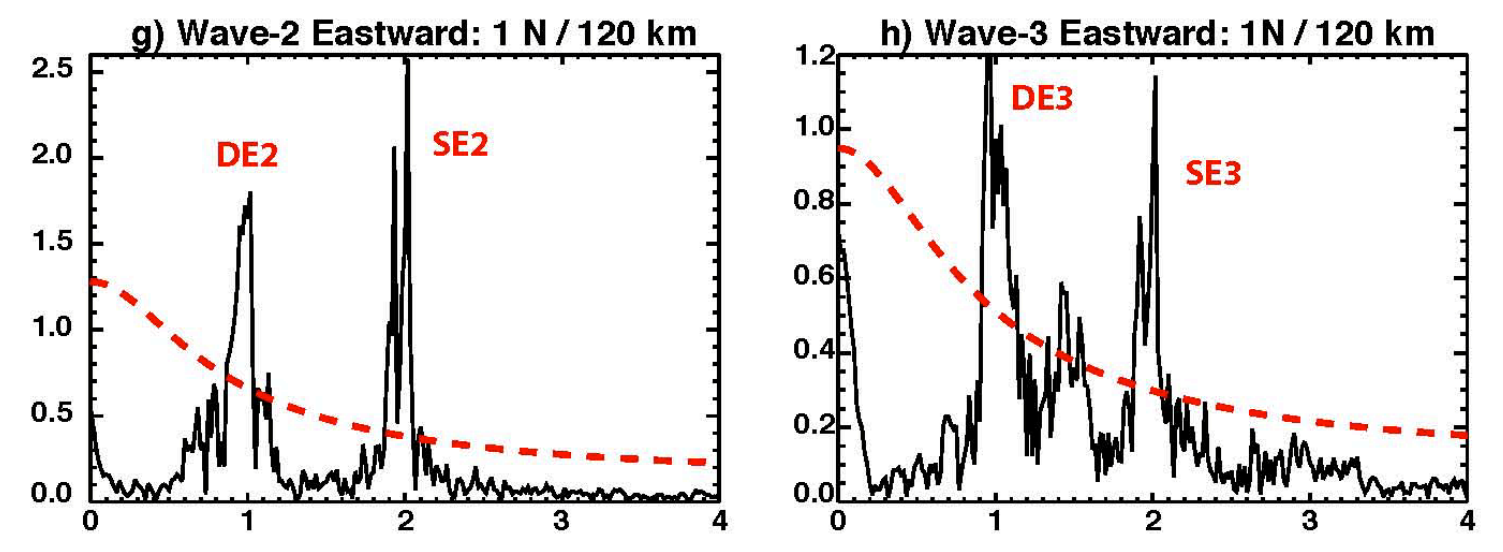






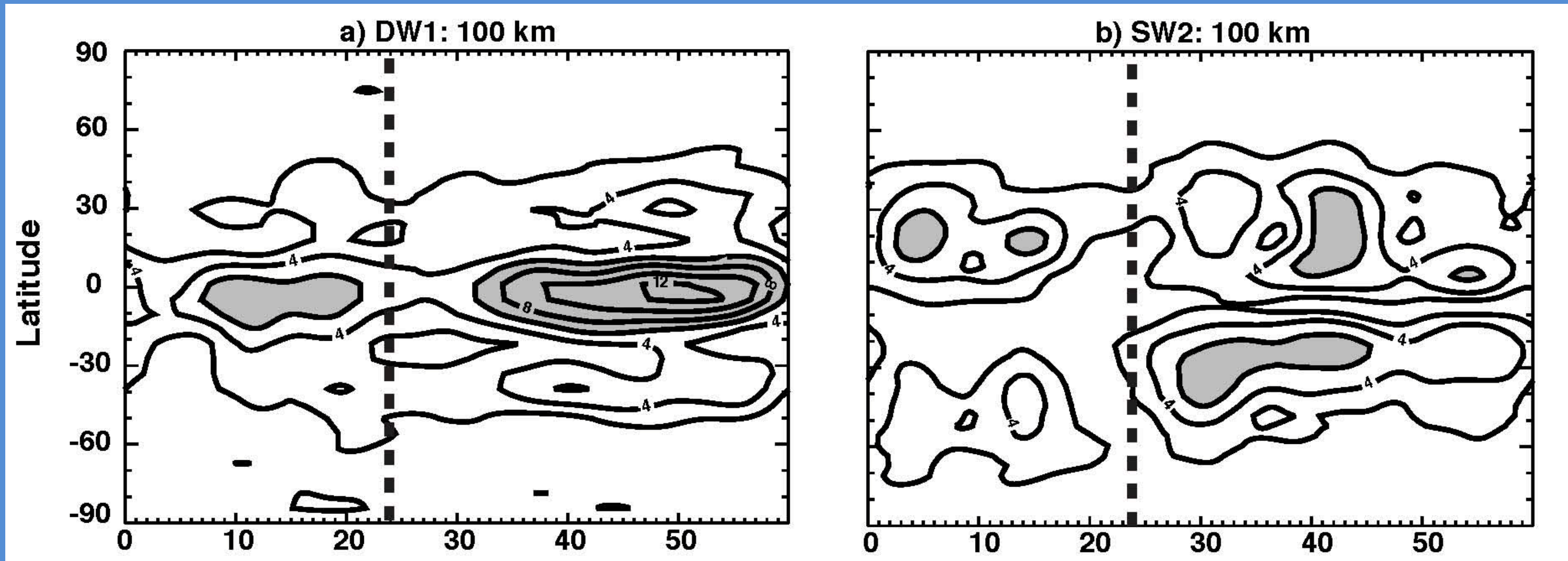
- The migrating tides show nearly global coherence.
- Below 120 km: DW1 is mostly equatorially trapped; SW2 is nearly anti-symmetric about the equator.
- Above 140 km both modes become external: DW1 shows increasingly larger amplitude in the summer hemisphere (likely due to EUV heating); SW2 shows increasingly larger amplitude in the winter hemisphere (possibly caused by zonal wind asymmetries).

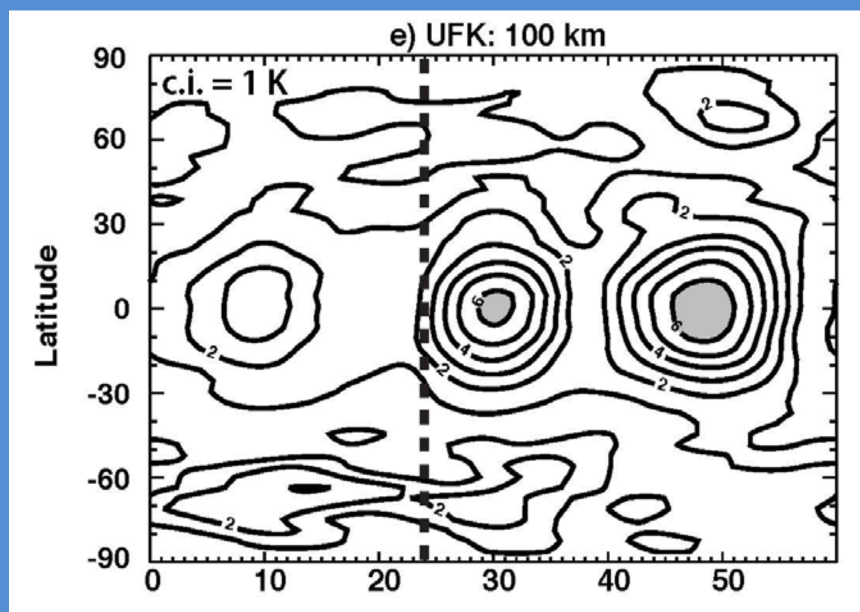

c) DE2
d) SE2
DE3
Height (km)
Latitude
200
180
160
140
120
100
80
60
-90 -60 -30 0 30 60 90
1.0
2.0
3.0
4.0


g) Wave-2 Eastward: 1 N / 120 km
h) Wave-3 Eastward: 1N / 120 km
DE2
SE2
DE3
SE3
2.5
2.0
1.5
1.0
0.5
0.0
1.2
0.8
0.6
0.4
0.2
0 1 2 3 4

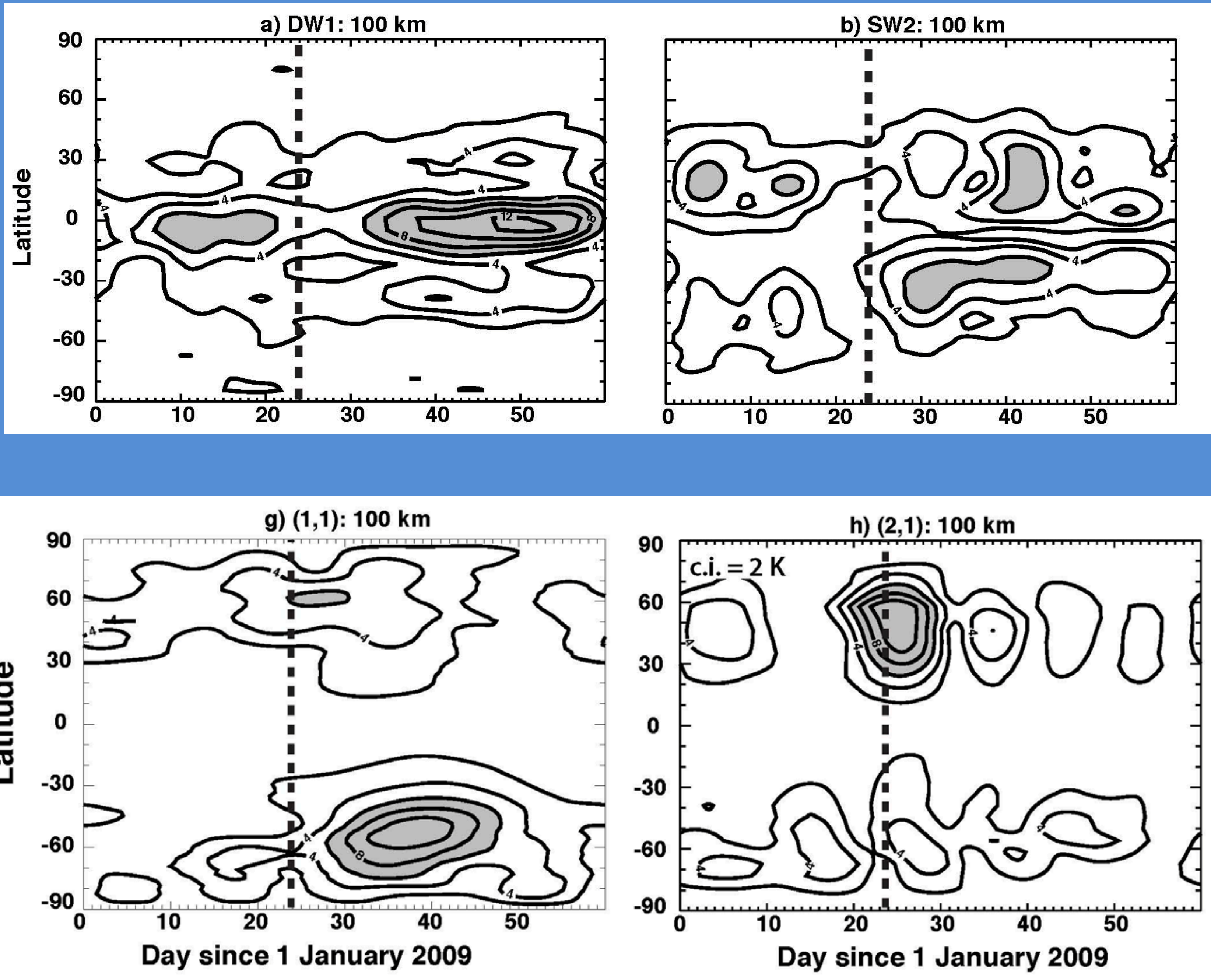
-
- at
-
- und

Temporal Behavior



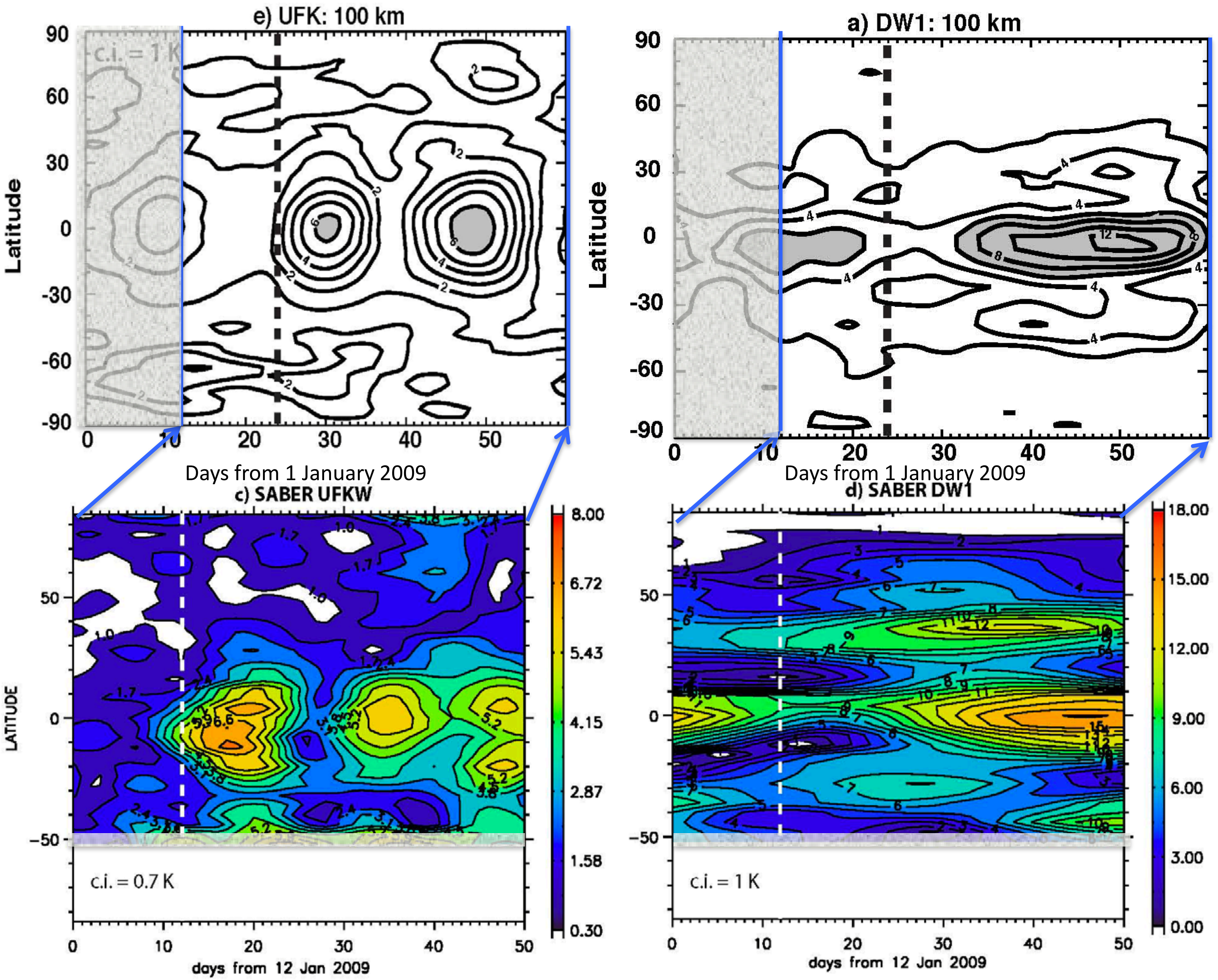


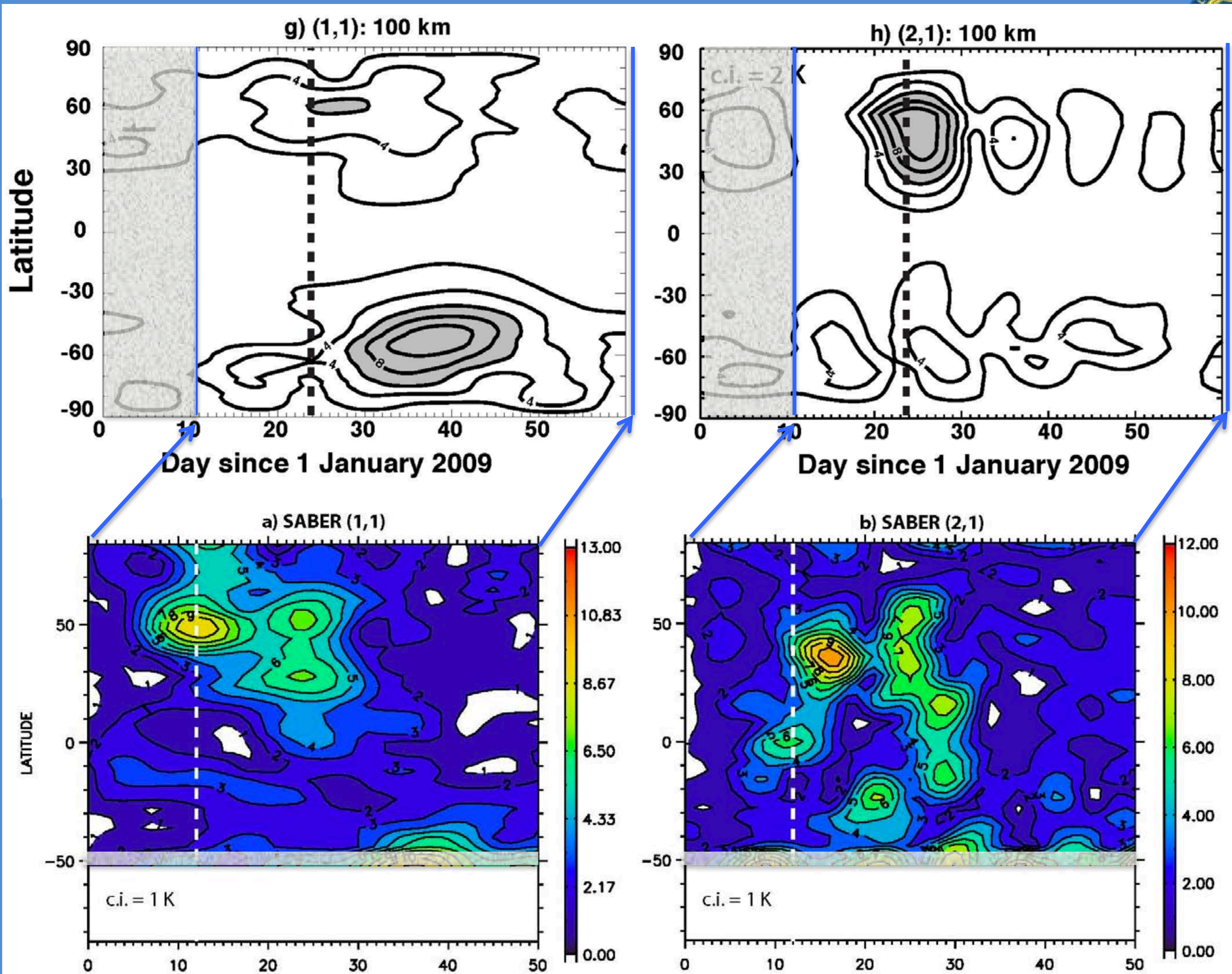
Day since 1 January 2009



Day since 1 January 2009

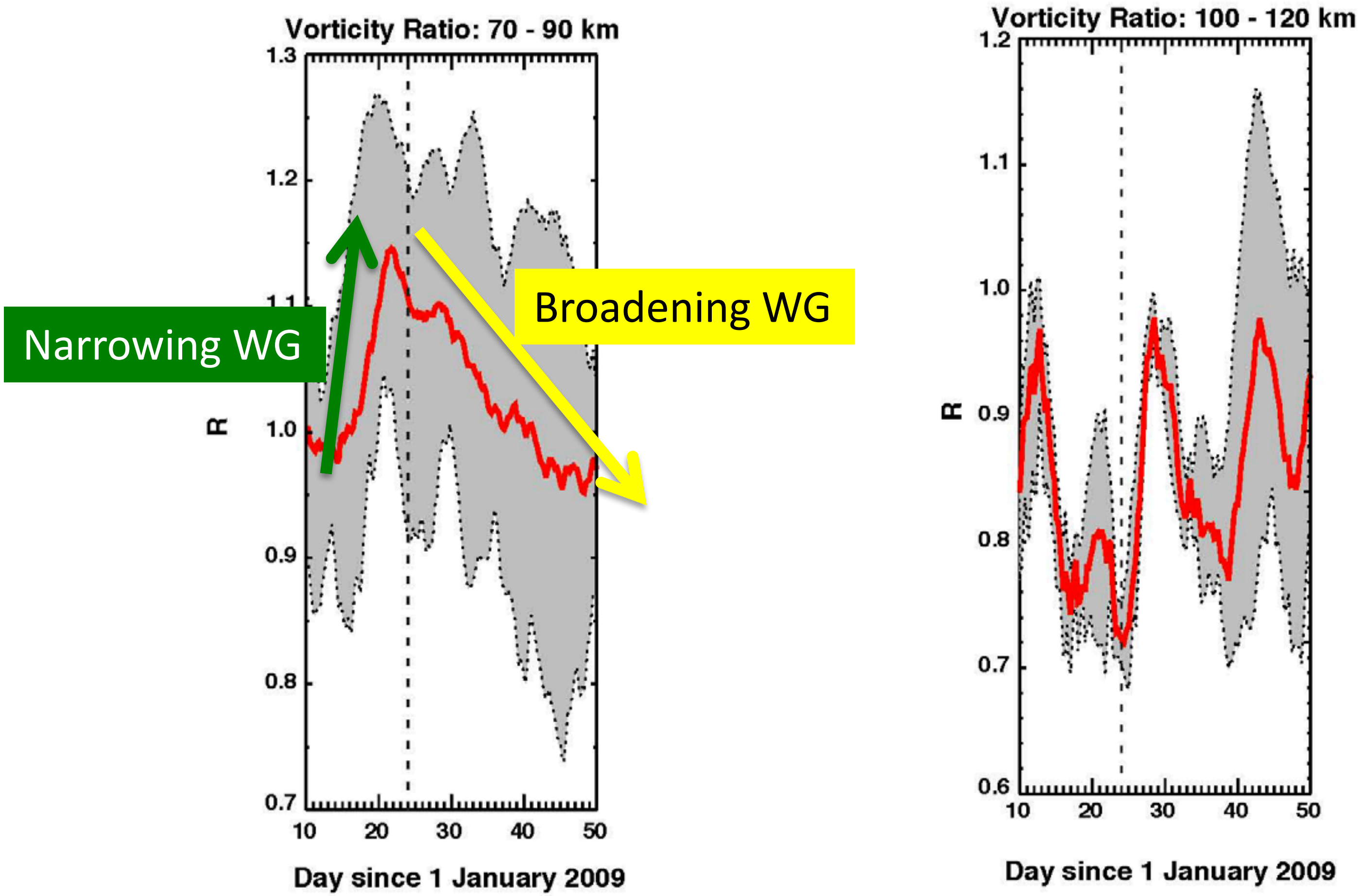
Comparison to SABER


e) UFK: 100 km
c.i. = 1 K
a) DW1: 100 km
Latitude
Days from 1 January 2009
c) SABER UFKW
c.i. = 0.7 K
d) SABER DW1
c.i. = 1 K
LATITUDE
days from 12 Jan 2009



g) (1,1): 100 km
h) (2,1): 100 km
Latitude
Day since 1 January 2009
Day since 1 January 2009
c.i. = 2 K
a) SABER (1,1)
b) SABER (2,1)
LATITUDE
c.i. = 1 K
c.i. = 1 K

- The presence of high-latitude vacillations at wave-1 and wave-2 in the upper mesosphere has been noted also by Meyer and Forbes (1997) and more recently by Chandran et al. (2013) following the 2012 SSW. These are *transient* planetary-scale, Rossby-like waves that are generated by barotropic/baroclinic instabilities of the zonal circulation.
- Tides are very fast waves (~ 460 m s^{-1}) and less likely to be affected *directly* by changing winds in the lower atmosphere.
- Tides can, however, be affected *indirectly* by changing winds through changes of the background vorticity: *McLandress* (2002) documented the inter-seasonal variability of tides in the upper mesosphere and lower thermosphere in a linear tidal model and showed it is controlled by changes of the background vorticity at lower levels.

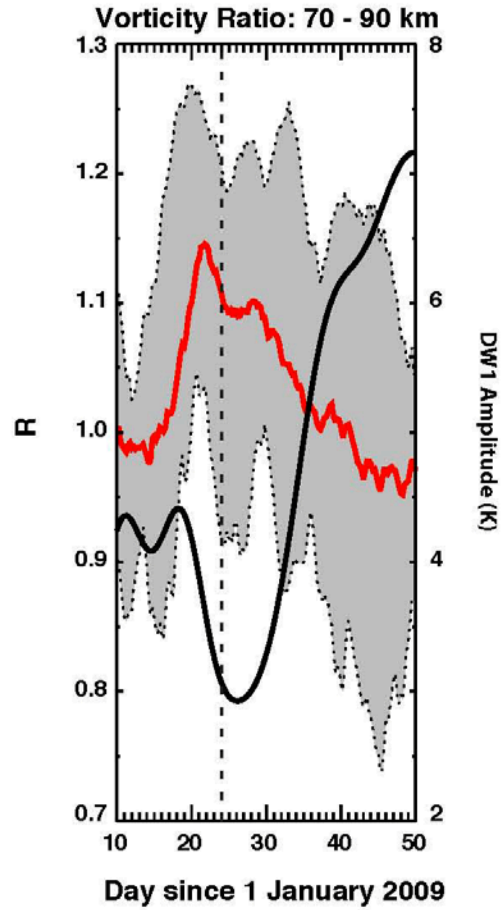


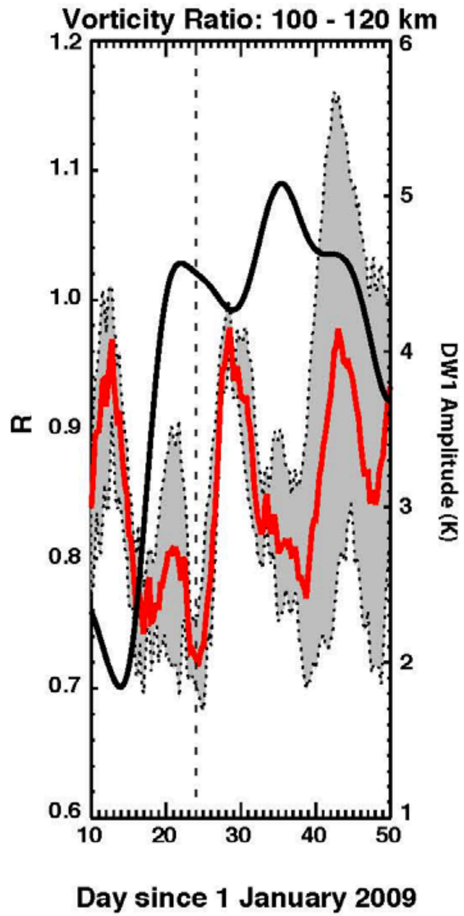
$$R = (f - Uy) / f \;;\; Uy = (Uy)_0 + \partial Uy$$

$\partial Uy = 0 \rightarrow R_0$

$\partial Uy > 0 \rightarrow R < R_0$; R decreases $\rightarrow$ *slower rotation / broad waveguide*

$\partial Uy < 0 \rightarrow R > R_0$; R increases $\rightarrow$ *faster rotation / narrow waveguide*



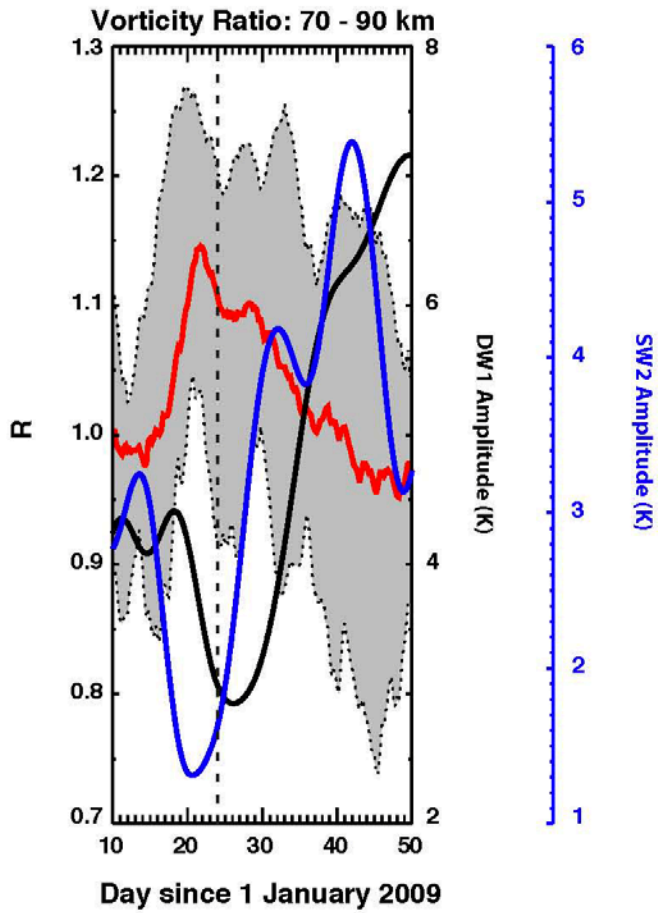


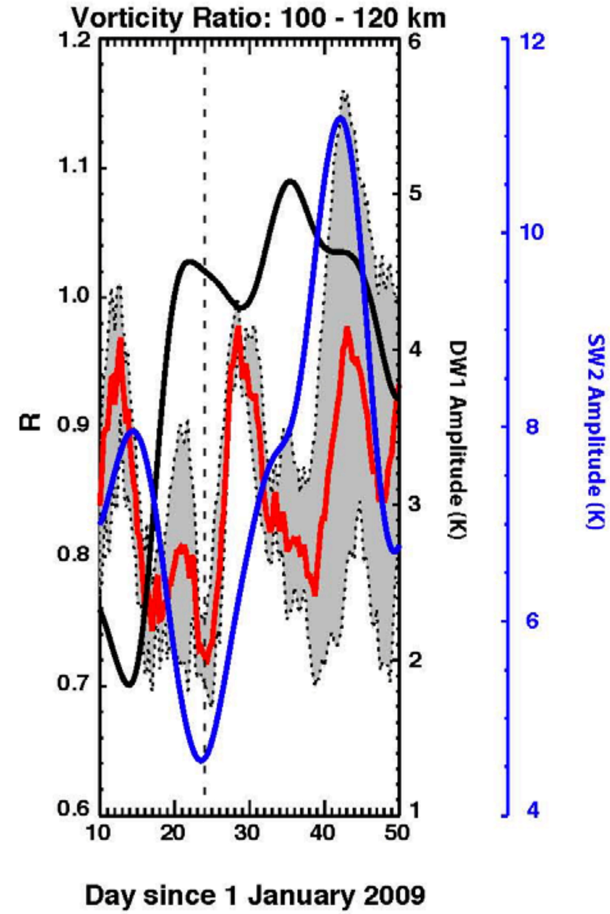
R = (f – Uy) / f

∂Uy = 0 ➔ R_0

∂Uy > 0 ➔ R < R_0; R decreases ➔ *slower rotation / broad waveguide*

∂Uy < 0 ➔ R > R_0; R increases ➔ *faster rotation / narrow waveguide*





$R = (f - U_y) / f$

$\partial U_y = 0$ → R_0

$\partial U_y > 0$ → $R < R_0$; R decreases → *slower rotation / broad waveguide*

$\partial U_y < 0$ → $R > R_0$; R increases → *faster rotation / narrow waveguide*

Closing remarks

- We have used WACCMX in SD configuration during the focus period January-February 2009.
- Using a combination of NASA/MERRA and NRL/NOGAPS-ALPHA atmospheric specification we have been able to nudge the WACCM meteorology from the ground to ~90 km, providing a realistic background state to study the meteorology that emerges in the lower thermosphere.
- Tides, ultra-fast Kelvin waves and Rossby waves are present with statistically significant amplitude.
- All modes become external (constant phase in height) in the thermosphere, with vanishing amplitude for most above 120-150 km as a result of dissipation due to molecular viscosity. A prominent exception is DW1 which becomes external above ~120 km but its amplitude *increases* in the thermosphere: this is likely the result of *in situ* forcing that is latitudinally broad and thus projects on modes with a negative equivalent depth (thus, external).
- Intra-seasonal variability of the tides in the upper mesosphere has been associated with concurrent changes of the background vorticity, as previously shown by *McLandress* (2002) for the inter-seasonal variations.
- This relationship is less effective at controlling the amplitude of tides at higher levels in the thermosphere.

Acknowledgments

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