# normal modes in the middle atmosphere observed by SABER

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# Outline

1. What is a normal mode?
2. SABER observations
   - The SABER dataset
   - Salby's Fast-Fourier Synoptic Mapping
3. Normal modes observed by SABER
   - Rossby modes
   - Rossby-gravity modes and the 2-day wave phenomenon
4. Conclusions

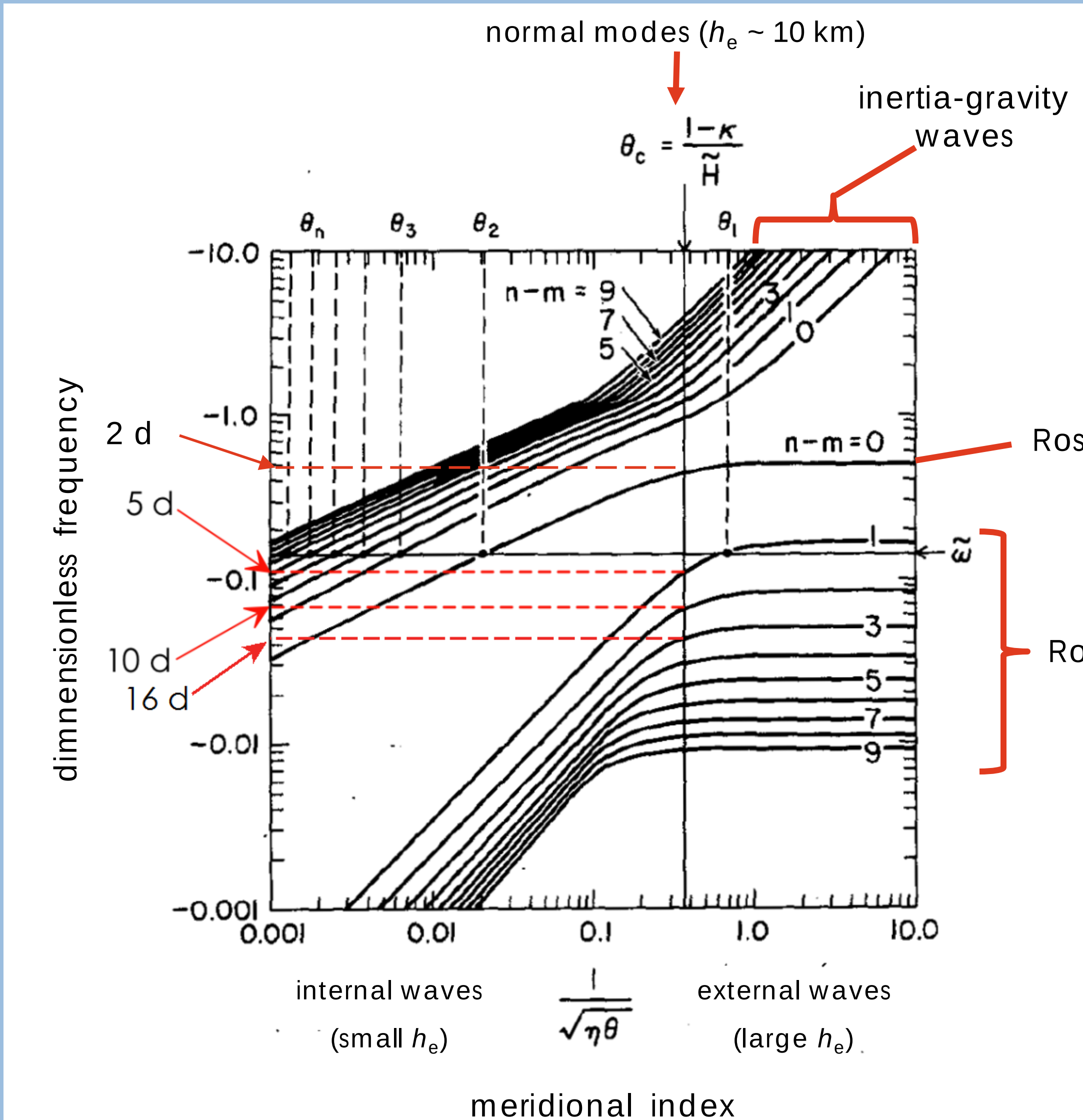
# atmospheric normal modes

- atmospheric normal modes are zonally-asymmetric (wave) **solutions to the primitive equations with a radiation upper boundary condition, and no internal or boundary forcing**

- approximate/asymptotic analytical solutions exist for a background atmosphere at rest (e.g., Hough, 1898; Longuet-Higgins, 1968; etc.)

- normal modes have structures that are global in latitude and “external” in altitude, with vertical structure ~ $\exp(\kappa z/2H)$

# dispersion relation for $s$ = 1



Salby (*JAS*, 1981)

- the dispersion relation curves correspond to eigensolutions of the horizontal structure (Laplace's) equation
- atmospheric normal modes correspond to solutions that also satisfy the homogeneous vertical structure equation

- we will look for westward-propagating Rossby and Rossby-gravity normal modes in T data from SABER

# The SABER instrument on TIMED

TIMED satellite: Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics

SABER instrument: Sounding of the Atmosphere Using Broadband Emission Radiometry

**SABER Measurements and Applications**

| Parameter | Wavelength ($\mu$m) | Application | Altitude Range (km) |
|---|---|---|---|
| $CO_2$ | 14.9 & 15.2 | T, density, IR cooling rates, P(z), non-LTE | 10–130 |
| $O_3$ | 9.6 | $O_3$ conc., cooling rates, solar heating, chemistry and dynamics studies | 15–100 |
| $O_2(^1\Delta)$ | 1.27 | $O_3$ conc. (day), inferred [O] at night, energy loss for solar heating efficiency | 50–105 |
| $CO_2$ | 4.3 | $CO_2$ conc., mesosphere solar heating, tracer | 85–150 |
| OH (v) | 2.0 & 1.6 | $HO_y$ chem., chemical heat source, dynamics, inference of [O] and [H], PMC studies | 80–100 |
| NO | 5.3 | Thermosphere cooling, $NO_x$ chemistry | 90–180 |
| $H_2O$ | 6.9 | $HO_y$ source gas, dynamical tracer | 15–80 |

The Johns Hopkins University Applied Physics Laboratory

- the results presented here use v.2.0 Temperature retrievals in the altitude range ~17–100 km
- data spans the period 2002-2015

# TIMED/SABER data

- TIMED is a high-inclination polar orbiter, with a precession period of ~120 days
- TIMED must "yaw" twice per precession cycle (~60 days) to keep the SABER radiometer from looking directly at the Sun
- latitudes observed are 52°S – 83°N and 52°N – 83°S in alternate yaw cycles; **latitudes in the range ±52° are observed continuously**
- process data for ±52° using **Salby's (1982) asynoptic mapping** technique, which **yields a synoptic spectrum with Nyquist limits $\sigma$ ~ ±1 cpd and *s* ~ 0 – 7**

# Viewing processed SABER data

The asynoptic mapping technique yields a synoptic wavenumber-frequency spectrum:

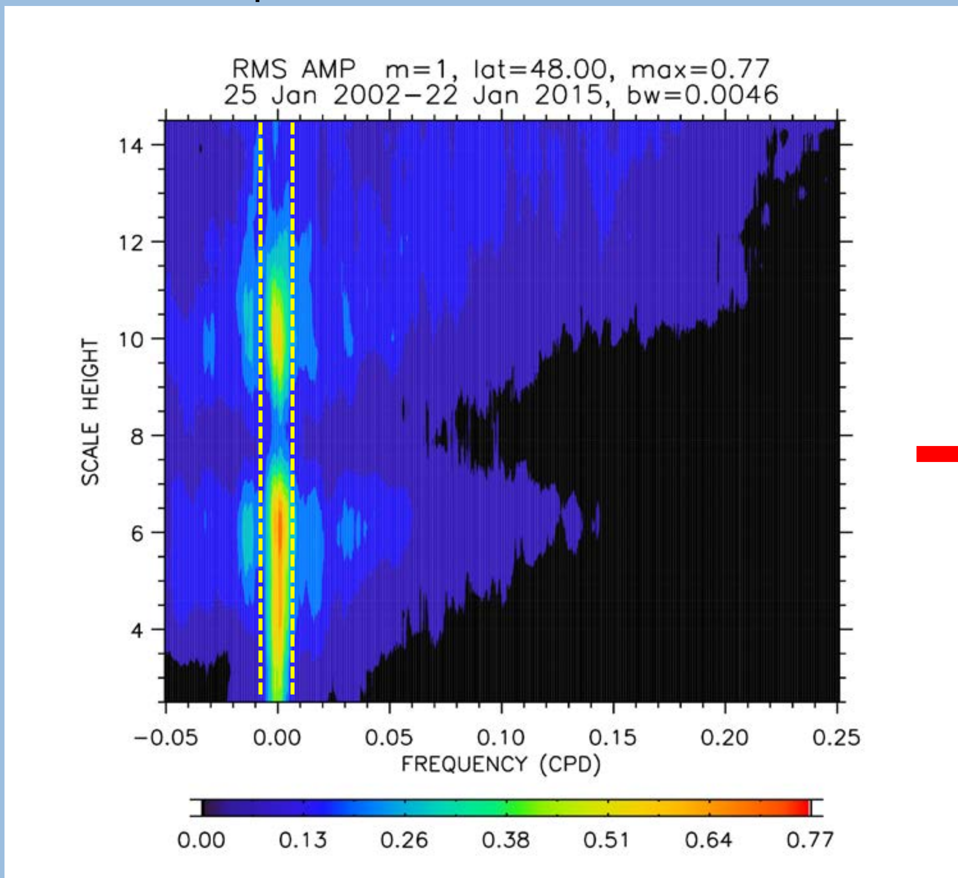
1. The **spectrum** can be viewed directly to identify variance associated with particular waves

2. The spectrum can be used to construct **amplitude/phase structures** for a given wavelength and frequency band using the squared coherence method (Hayashi, *JMSJ*, 1971)

3. The spectrum can be used to synthesize the **space-time evolution** of particular waves over specified wavenumber and/or frequency bands to examine their behavior in time, longitude, latitude and altitude

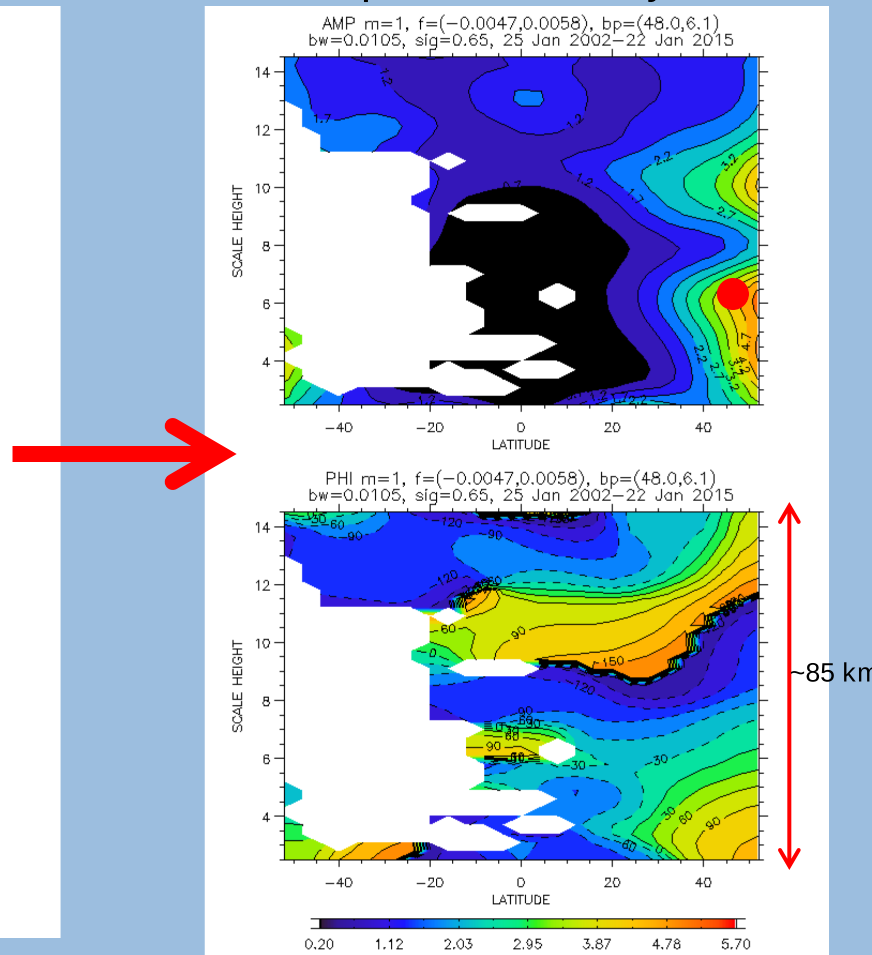
# Westward-propagating waves

spectrum for $s = 1$ @ 48°N




positive frequencies: westward propagating

coherent quasi-stationary structure



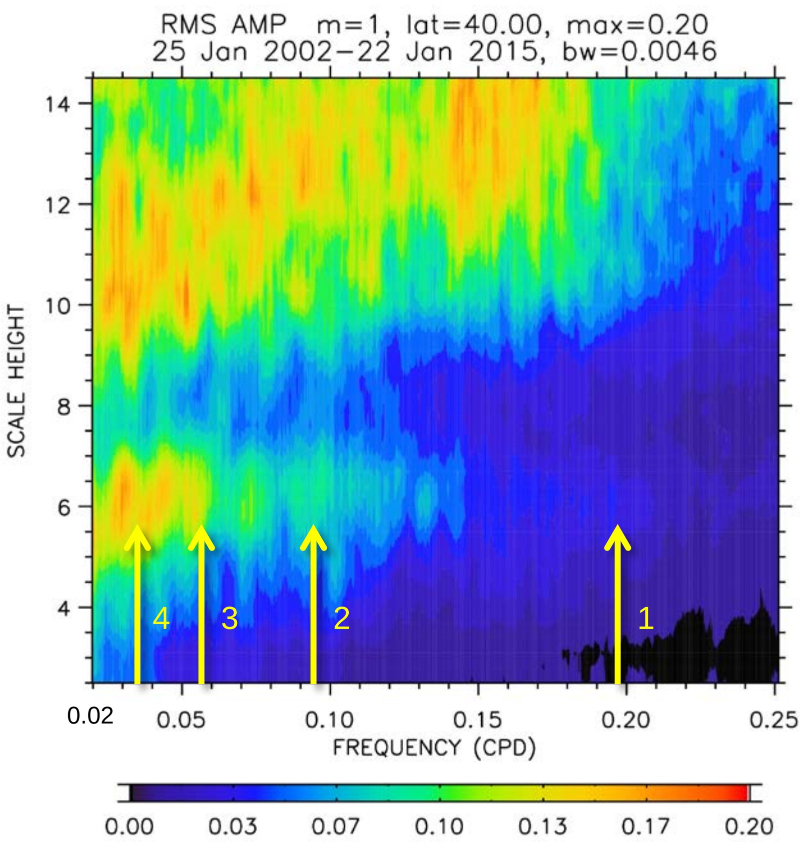

- westward spectrum is dominated by quasi-stationary waves of long wavelength ($\lambda_z$ ~ 55 km)

● denotes base point

data plotted only where Coh$^2$ is significant at 1-sigma level

# Rossby normal modes?

spectrum for *s* = 1 @ 48°N




s = 1 Rossby normal modes

Periods (d)

Divergent Rossby waves on a Sphere DJF winds (Kasahara, 1980: JAS)

| *s* \ $l - s$ | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | 1.20 | 4.85 | 9.91 | 18.39 | 28.08 |
| 2 | 1.71 | 3.84 | 7.27 | 14.23 | 21.47 |
| 3 | 2.30 | 4.28 | 7.40 | 13.65 | – |
| 4 | 2.90 | 5.21 | 8.20 | 13.55 | – |

*s* = zonal wavenumber *l* = meridional index.

Madden (*Tellus*, 2007)

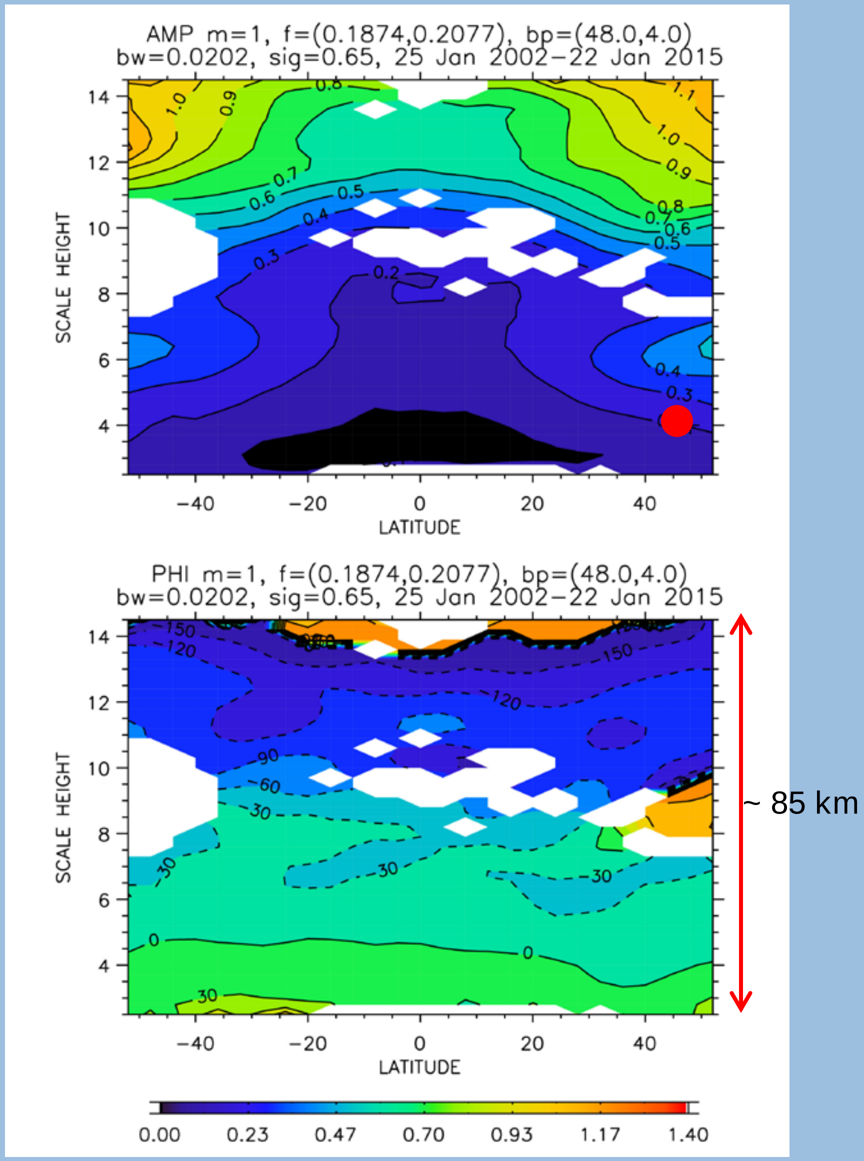
5-day wave

10-day wave

16-day wave

25-day wave

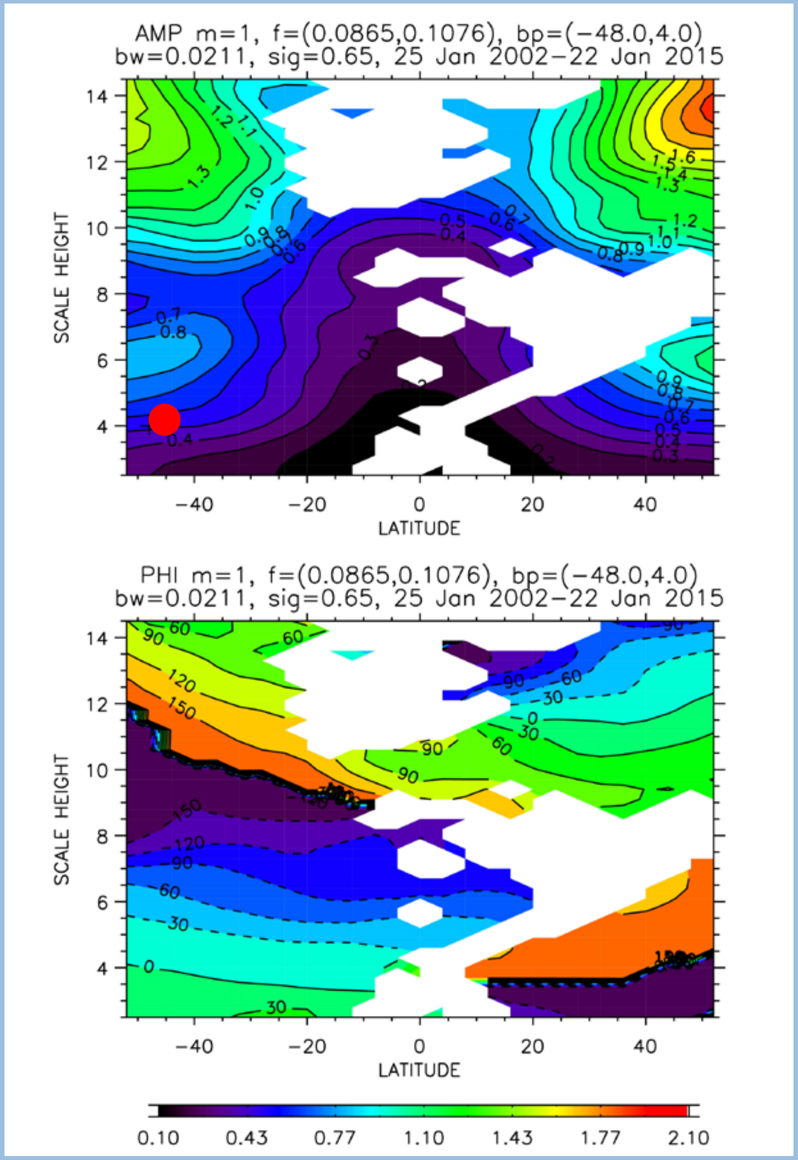
# Rossby normal modes, *s* = 1




*l* – *s* = 1 (5-day wave)

- period ~ 5 days
- globally coherent structure
- symmetric meridional structure, no nodes in latitude
- external vertical structure

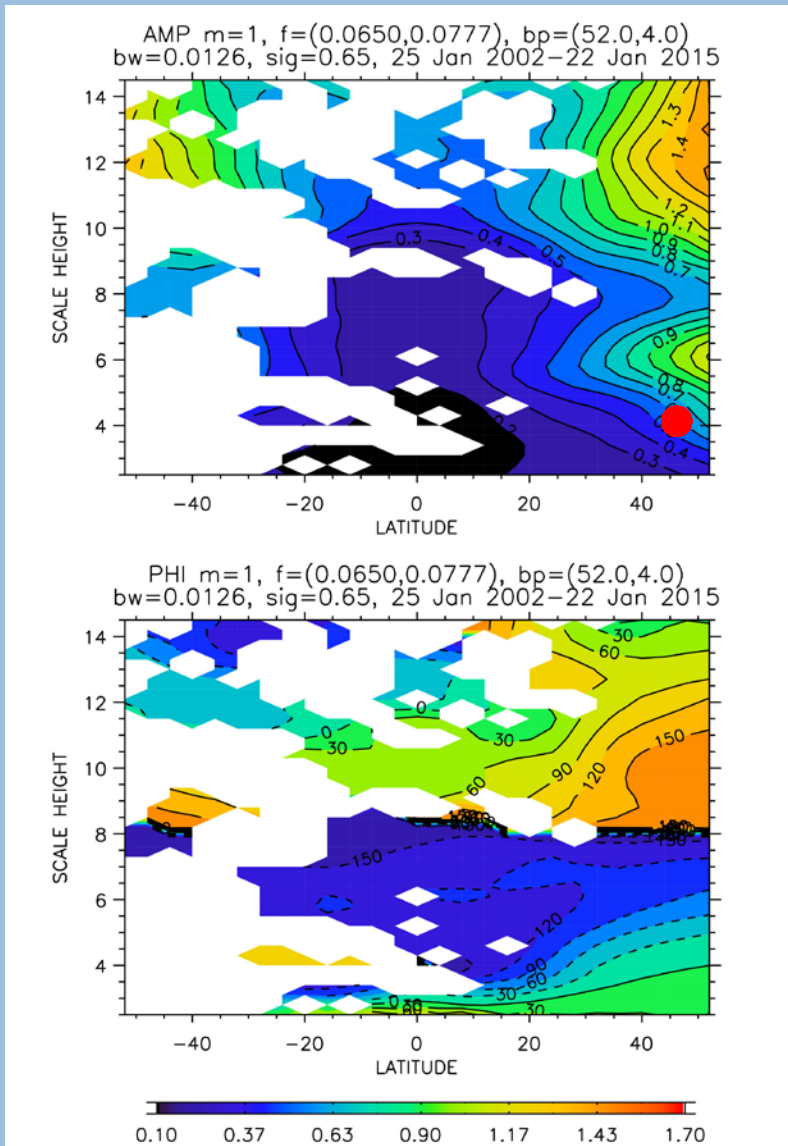
# Rossby normal modes, $s$ = 1




$l - s = 2$ (10-day wave)

- period ~ 10 days
- globally coherent structure
- asymmetric meridional structure, with node at the Equator
- (quasi) external vertical structure ($\lambda_z$ > 85 km)

# Rossby normal modes, $s$ = 1



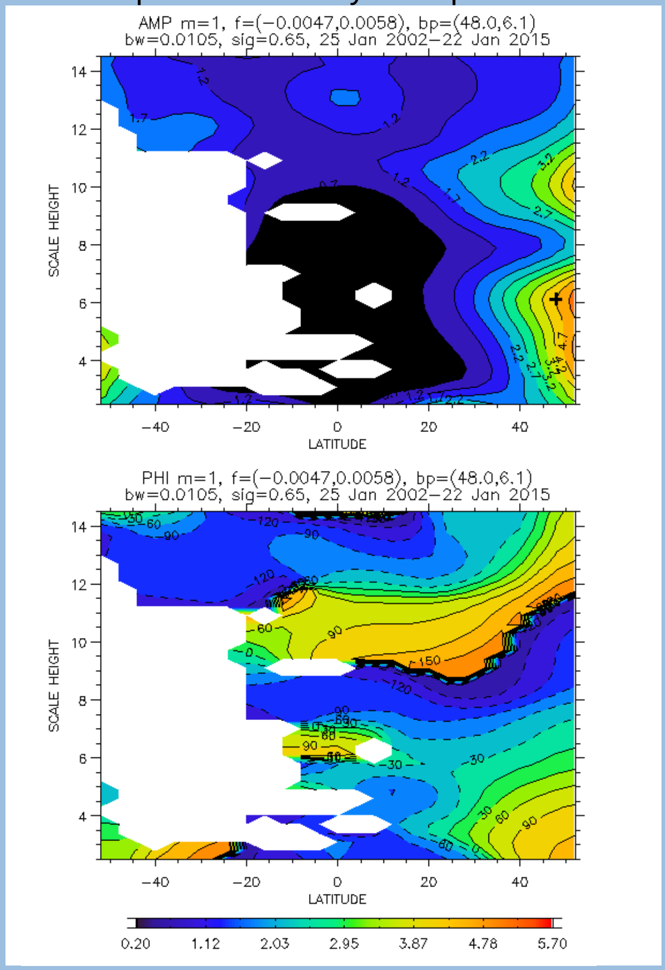

$l - s = 3$ (16-day wave?)

- period ~ 14.3 days
- globally coherent structure
- ? symmetric meridional structure, with nodes in the subtropics
- external vertical structure (but $\lambda_z$ is very long, ~ 80 km)

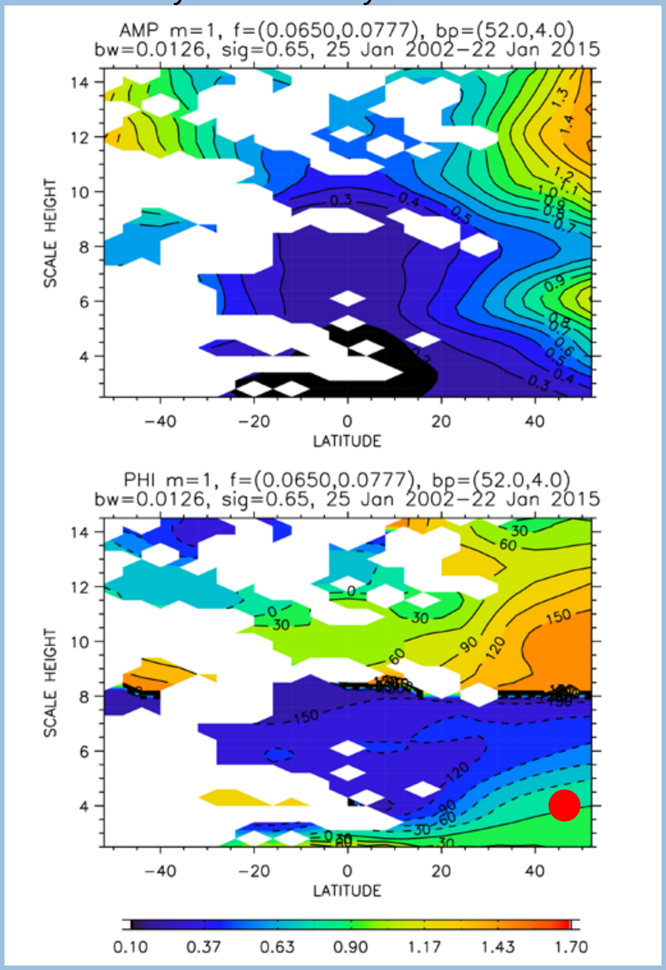
- *this and higher order modes are difficult to identify unambiguously because their structures are very similar to the background, quasi-stationary wave structure*

# 16-d vs. quasi-stationary structures

quasi-stationary component

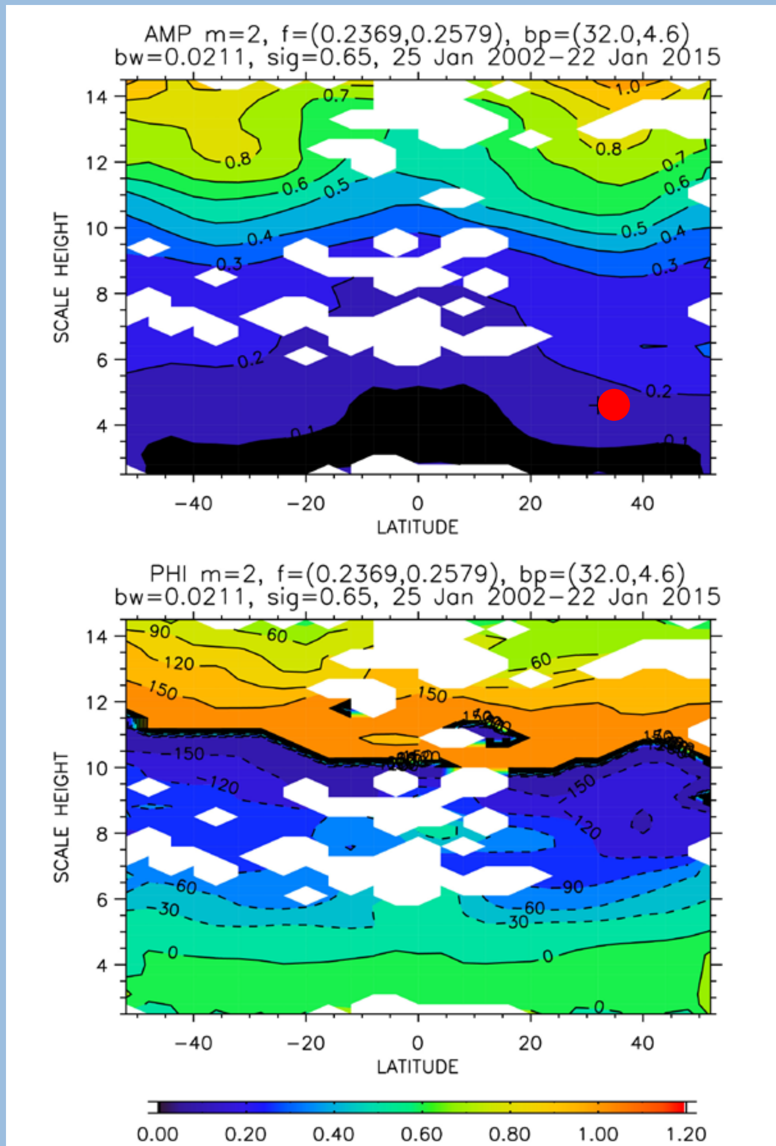



16-day $s$ = 1 Rossby normal mode




- 16-day wave has considerably longer $\lambda_z$
- otherwise, very similar structures

# Rossby normal modes, *s* = 2




*l* – *s* = 1 (4-day wave)

- period ~ 4 days
- globally coherent structure
- symmetric meridional structure,
- (quasi) external vertical structure ($\lambda_z$ > 85 km)

- *no other Rossby modes of s = 2 could be identified unambiguously (indistinguishable from low-frequency background)*
- *no Rossby modes of s > 2 could be identified unambiguously (no coherent structures found and/or indistinguishable from background)*

# Rossby-gravity normal modes?

Periods (d)
Divergent Rossby waves on a Sphere DJF winds (Kasahara, 1980: JAS)

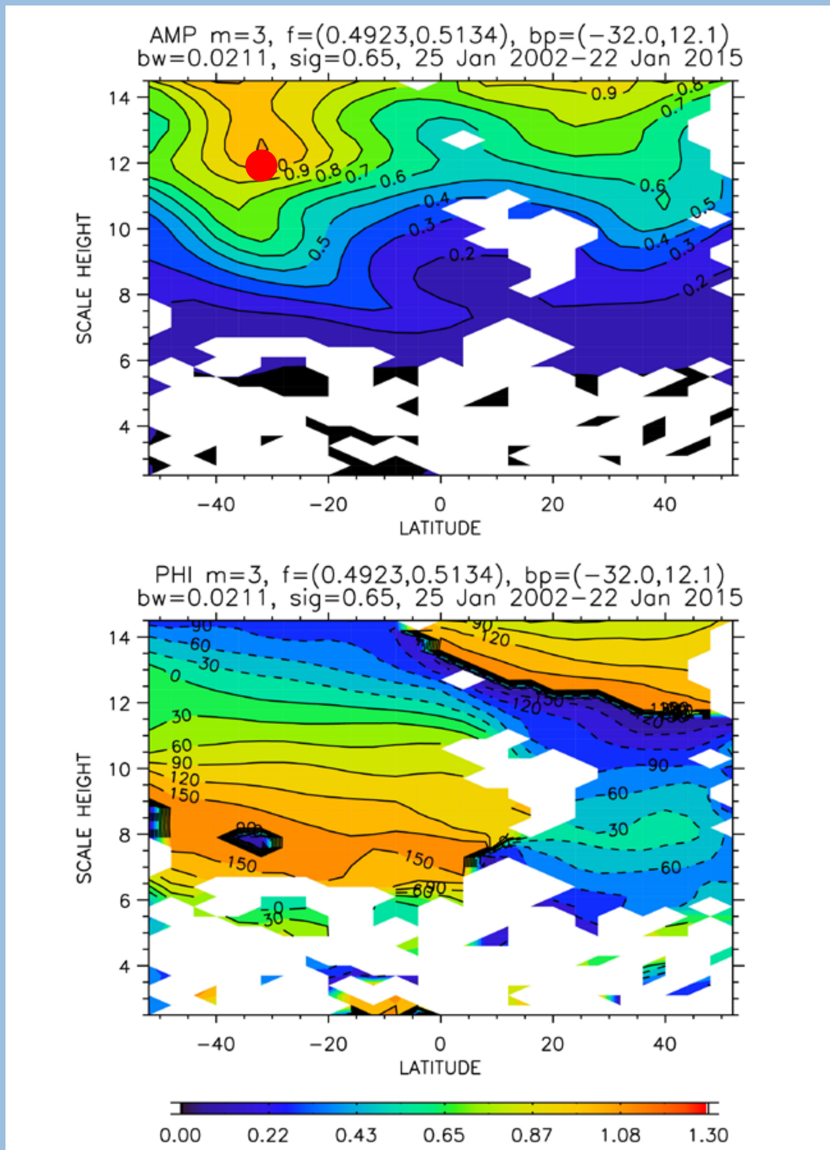
| | $l - s$ | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| $s$ | 1 | 1.20 | 4.85 | 9.91 | 18.39 | 28.08 |
| | 2 | 1.71 | 3.84 | 7.27 | 14.23 | 21.47 |
| | 3 | 2.30 | 4.28 | 7.40 | 13.65 | – |
| | 4 | 2.90 | 5.21 | 8.20 | 13.55 | – |

$s$ = zonal wavenumber $l$ = meridional index.

expected periods of RG normal modes

- three Rossby normal modes of $s = 1$ and one normal mode of $s = 2$ are identifiable in SABER data
- modes with $l - s = 0$ belong to the low-frequency (westward) branch of the Rossby-gravity manifold
- are any RG modes identifiable in SABER data?

# Rossby-gravity normal modes, $s = 3$




$l - s = 0$ (2-day wave)

- period ~ 2 days
- globally coherent structure (but not coherent below ~ 40 km)
- anti-symmetric meridional structure, node at Equator
- external vertical structure (but long $\lambda_z$ ~ 85 km)

- *note base point in upper mesosphere*
- *the lack of coherence below ~ 40 km suggests that this mode is uniquely forced at high altitude*

# baroclinic instability and the 2-d wave

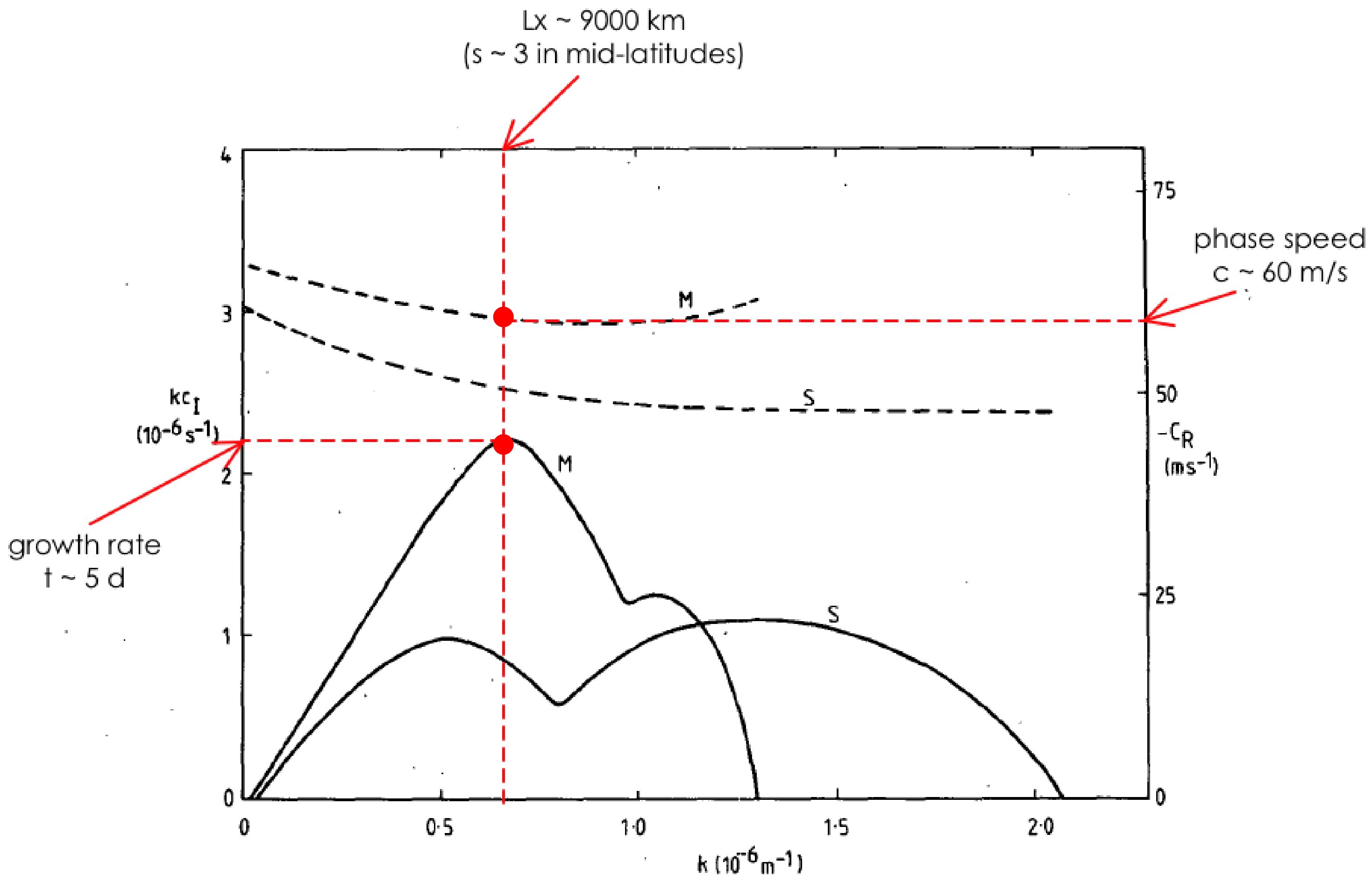
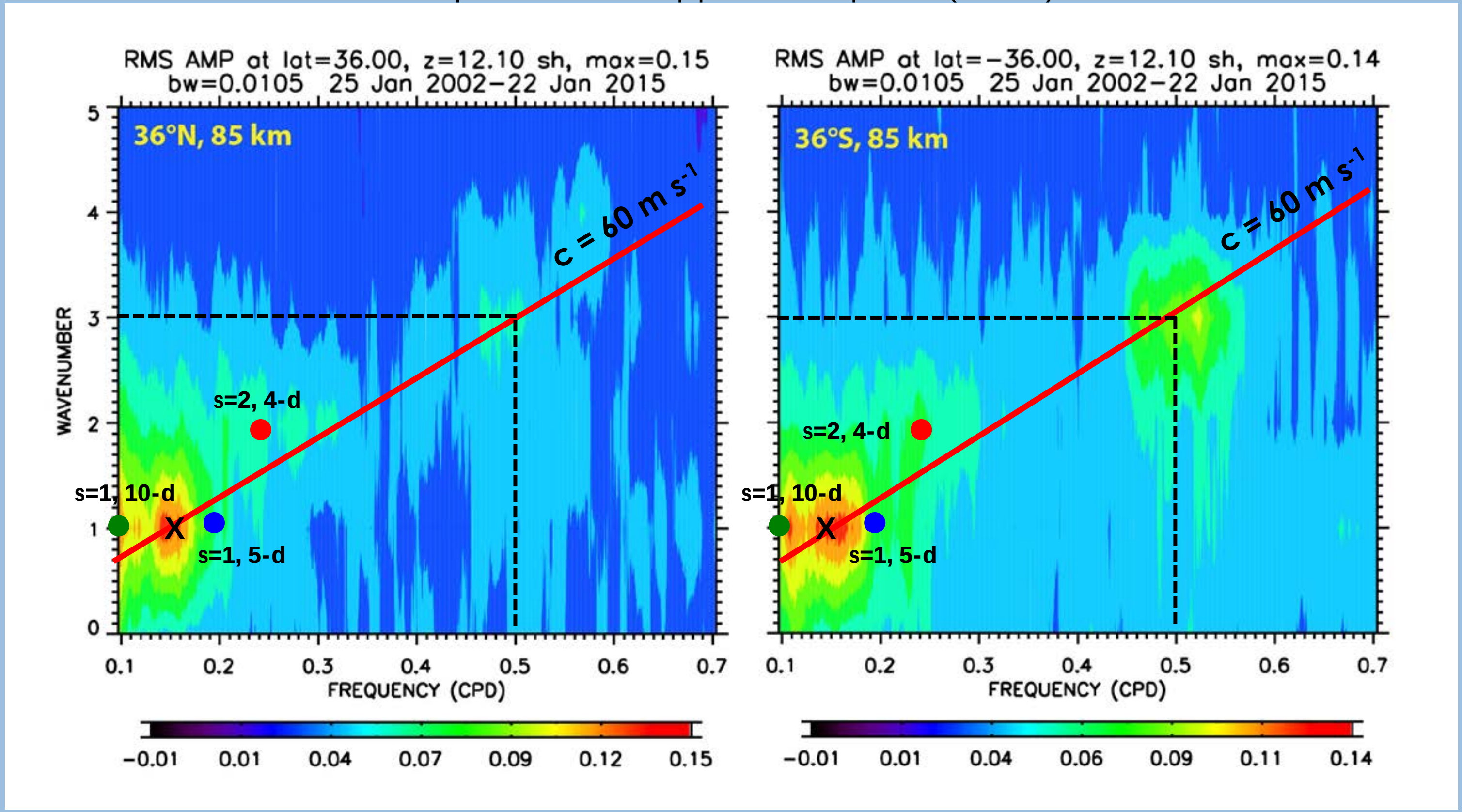



FIG. 2. Adiabatic growth rate $kc_I$ (solid) and phase speed $c_R$ (dashed) for the fastest growing wave perturbations to the flow of Fig. 1 as a function of zonal wavenumber $k$. M: mesospheric mode, S: stratopausal mode.

Plumb (JAS, 1983)

# (s,$\sigma$) spectrum of the "2-day wave"

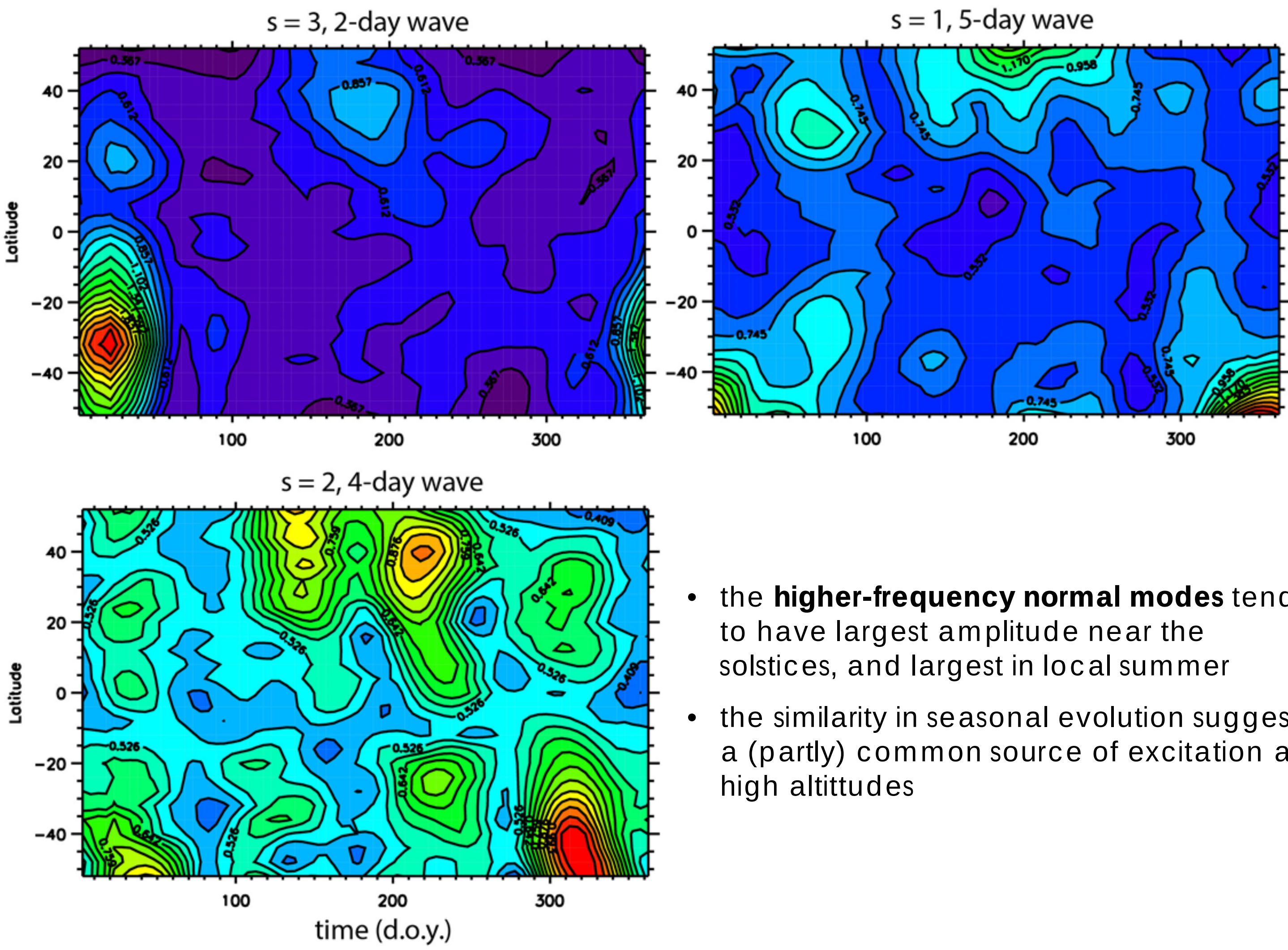
spectra in the upper mesosphere (85 km)




- the "classical" 2-day wave, ***s* = 3, $\sigma$ = 0.5 cpd**, coincides with the *s* = 3 **Rossby-gravity normal mode**
- there is also **power along *c* = 60 m s$^{-1}$ at other *s*, $\sigma$ that correspond to normal modes**
- large power at **s = 1, $\sigma$ = 0.15 cpd (marked with X) does not coincide with a normal mode**

# composite seasonal cycles

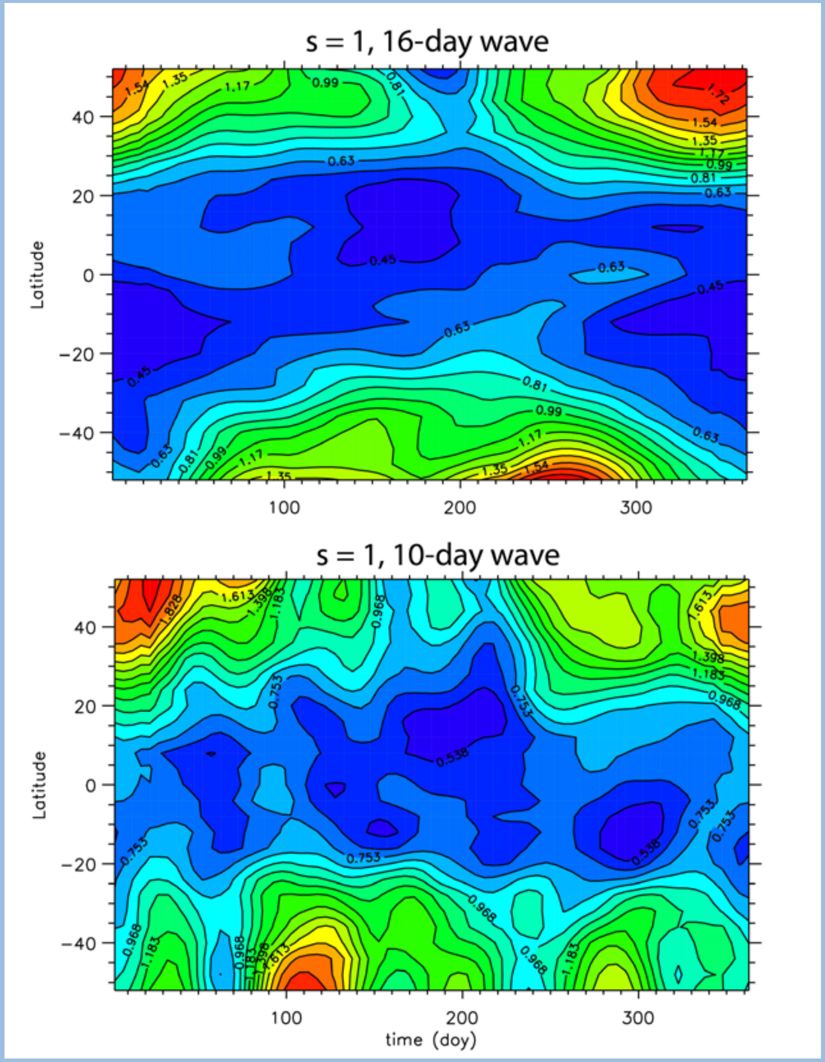
seasonal cycles at 12 SH (~85 km)




- the **higher-frequency normal modes** tend to have largest amplitude near the solstices, and largest in local summer
- the similarity in seasonal evolution suggests a (partly) common source of excitation at high altitudes

# composite seasonal cycles

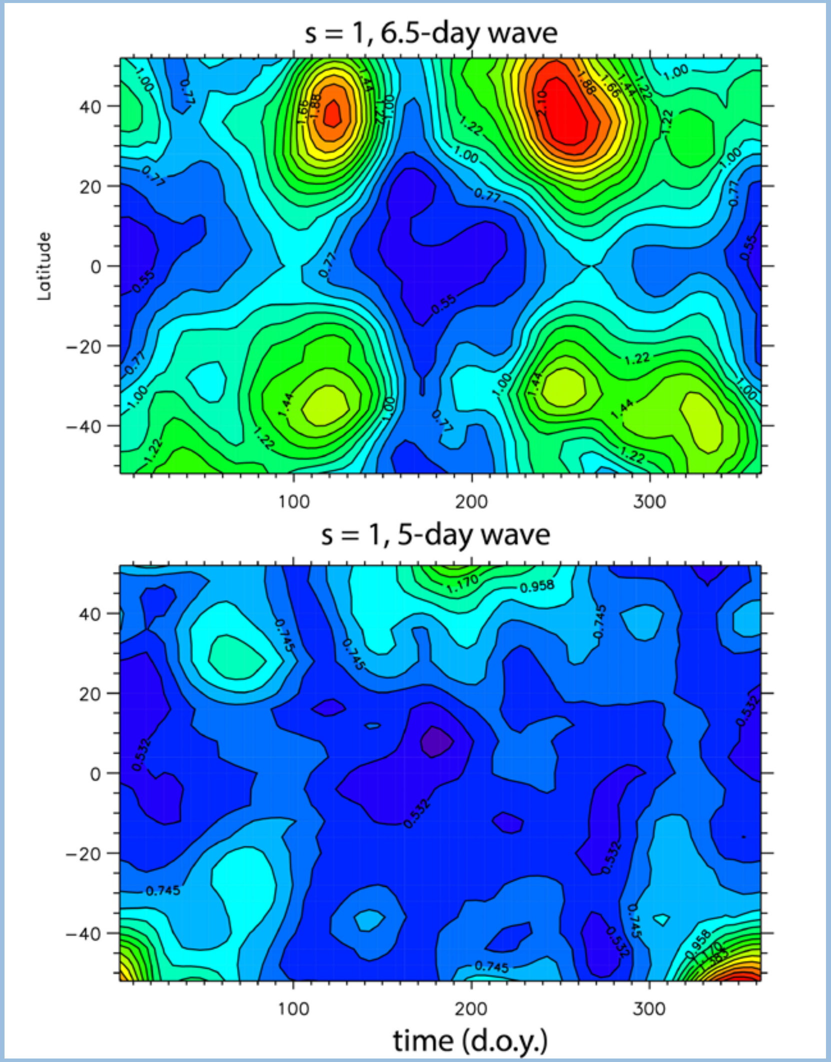
seasonal cycles at 12 SH (~85 km)




- the **lower-frequency Rossby normal modes** have seasonal cycles with largest amplitude in local winter
- they behave (and are forced?) like the quasi-stationary Rossby wave continuum

# seasonal cycles: 5-d vs. 6.5-d

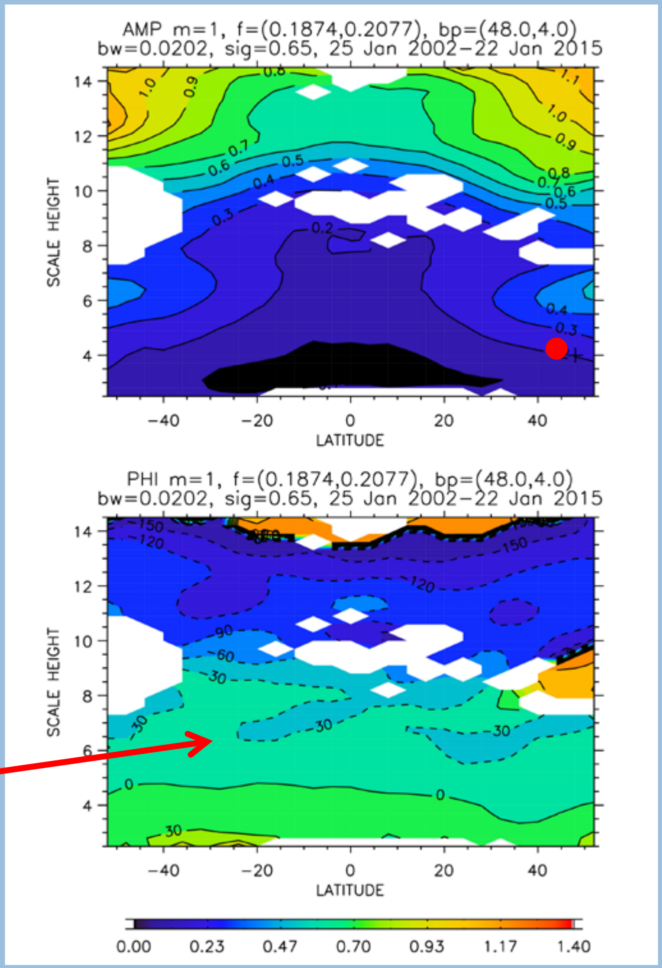
seasonal cycles at 12 SH (~85 km)




- the $s = 1$, 6.5-day wave has a distinctive seasonal cycle, with largest amplitude near the equinoxes
- the $s = 1$, 5-day normal mode has a different seasonal cycle, with maximum amplitude near the solstices, especially local summer

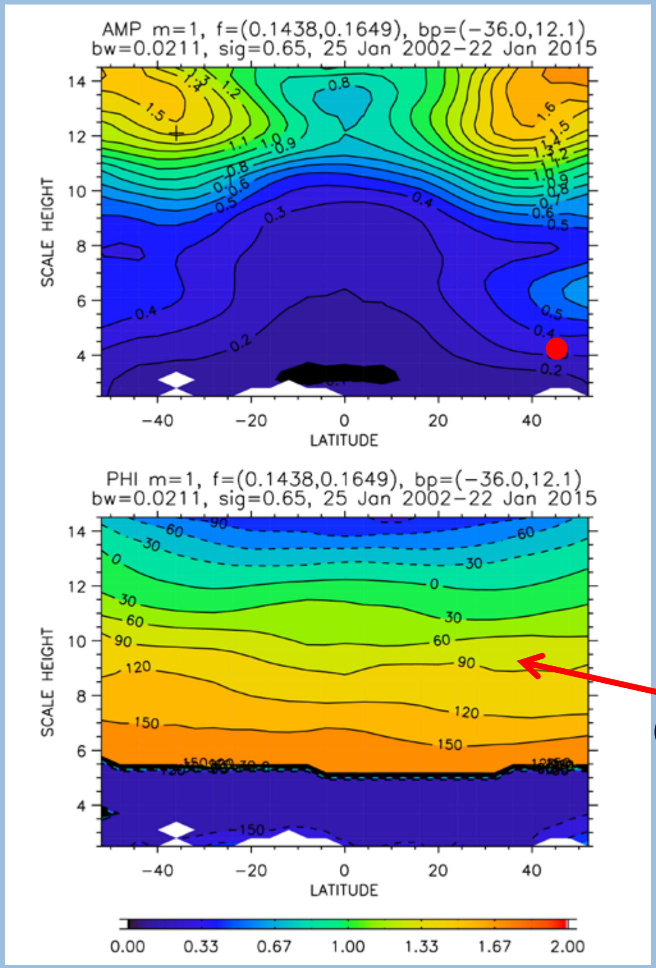
# $s$ = 1 structures near $\tau$ = 5 days

$s$ = 1, $\tau$ ~ 5 days




almost no phase tilt

$s$ = 1, $\tau$ ~ 6.5 days




clear phase tilt (although $\lambda_z$ is long)

- **the 5-day normal mode (left) is clearly distinct from 6.5-day wave (right)**
- the 6.5-day wave has the largest amplitude of the two and is more coherent throughout
- it would be difficult to distinguish these waves without adequate vertical and frequency resolution

# 5-day wave confusion?

a few studies from the last 20 years...

GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 24,
PAGES 2733-2736, DECEMBER 1, 1994

## Observations of the 5-day wave in the mesosphere and lower thermosphere

D. L. Wu,[1] P. B. Hays and W. R. Skinner

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor

**Abstract.** The 5-day planetary wave has been detected in the winds measured by the High Resolution Doppler Imager (HRDI) on the Upper Atmosphere Research Satellite (UARS) in the mesosphere and lower thermosphere (50-110 km).

The most significant amplitude response appears near the period of ~6 ±1.5 days at zonal wavenumber one for all the four latitudes. The observed period is consistent with the radar measurements in the same region (Massebeuf et al., 1981; Manson et al., 1982), which also suggested a longer period (5.5-6 days) for the 5-day wave. This 5-day wave signal is extracted in the

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D01109, doi:10.1029/2009JD012545, 2010

## The 5-day wave in the Arctic and Antarctic mesosphere and lower thermosphere

K. A. Day[1] and N. J. Mitchell[1]

Received 27 May 2009; revised 6 October 2009; accepted 15 October 2009; published 15 January 2010.

[1] The 5-day planetary wave in the polar mesosphere and lower thermosphere has been investigated using meteor radars at Esrange (68°N, 21°E) in the Arctic and Rothera (68°S, 68°W) in the Antarctic. The measurements span the 9-year interval from October 1999 to December 2008 and the 4-year interval from February 2005 to December 2008, respectively. The height range covered is approximately 80–100 km. Horizontal wind variance within a wave period range of 4–7 days is used as a proxy for the activity of the 5-day wave. Strong wave activity is seen in winter and late summer.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D20, 4640, doi:10.1029/2002JD003349, 2003

## The 6.5-day wave in the mesosphere and lower thermosphere: Evidence for baroclinic/barotropic instability

R. S. Lieberman,[1] D. M. Riggin,[1] S. J. Franke,[2] A. H. Manson,[3] C. Meek,[3] T. Nakamura,[4] T. Tsuda,[4] R. A. Vincent,[5] and I. Reid[5]

Received 21 December 2002; revised 11 May 2003; accepted 19 June 2003; published 24 October 2003.

[1] A westward propagating zonal wave number 1 wave with a period near 6.5 days was a prominent feature in the mesosphere and lower thermosphere (MLT) during the 1994 equinoxes. The meridional structure of the wave in the upper stratosphere and the MLT is consistent with the 5-day wave structure predicted by normal mode theory.

# Conclusions: Normal modes in SABER temperature observations

Periods (d)

Divergent Rossby waves on a Sphere DJF winds (Kasahara, 1980: JAS)

| $s$ \ $l - s$ | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
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| 3 | 2.30 | 4.28 | 7.40 | 13.65 | – |
| 4 | 2.90 | 5.21 | 8.20 | 13.55 | – |

$s$ = zonal wavenumber $l$ = meridional index.

- four Rossby and one Rossby-gravity normal modes are identifiable in SABER T data
- the higher-frequency Rossby modes ($s$ =1, 5-day and $s$ = 2, 4-day) may be excited at least in part by the instability associated with the Rossby-gravity $s$ = 3, "2-day wave"
- the slower Rossby modes ($s$ = 1, 10-day and 16-day) appear as part of the continuum of Rossby waves in local winter
- the prominent **Rossby *s* = 1, 6.5-day wave is distinct from the 5-day normal mode** and has largest amplitude near the solstices