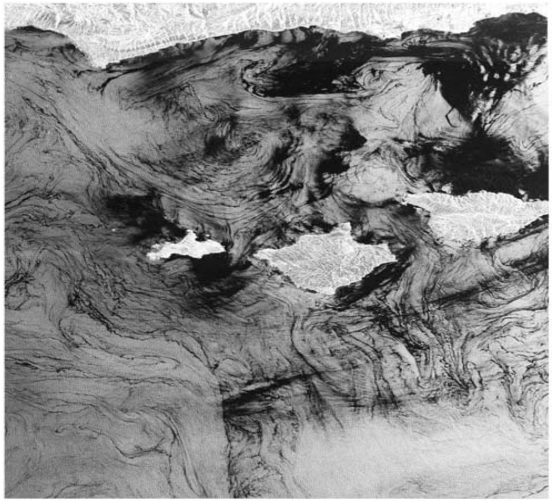
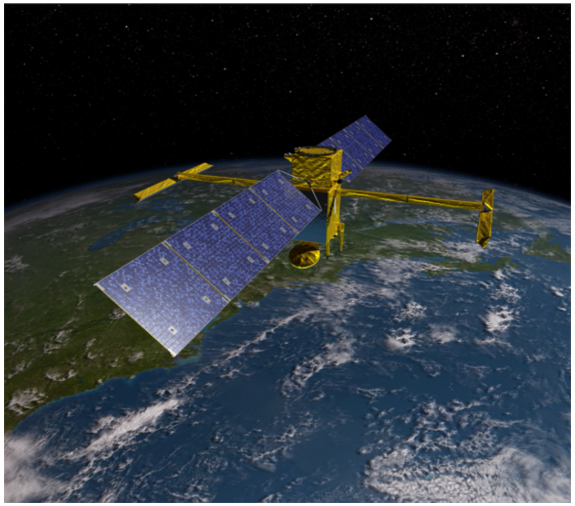
“Wave-Turbulence Interactions in the Oceans”

Patrice Klein (Caltech/JPL/Ifremer)

(III) Introduction (c): Tidal waves





NEAR-INERTIAL WAVES AND TIDAL WAVES

- Matthew H. Alford, Jennifer A. MacKinnon, Harper L. Simmons, and Jonathan D. Nash**: Near-Inertial Internal Gravity Waves in the Ocean.** ARMS, 2016, 8, 95-123.

- **Chris Garrett and Eric Kunze: Internal Tide Generation in the Deep Ocean. ARFM, 2007, 39:57-87**

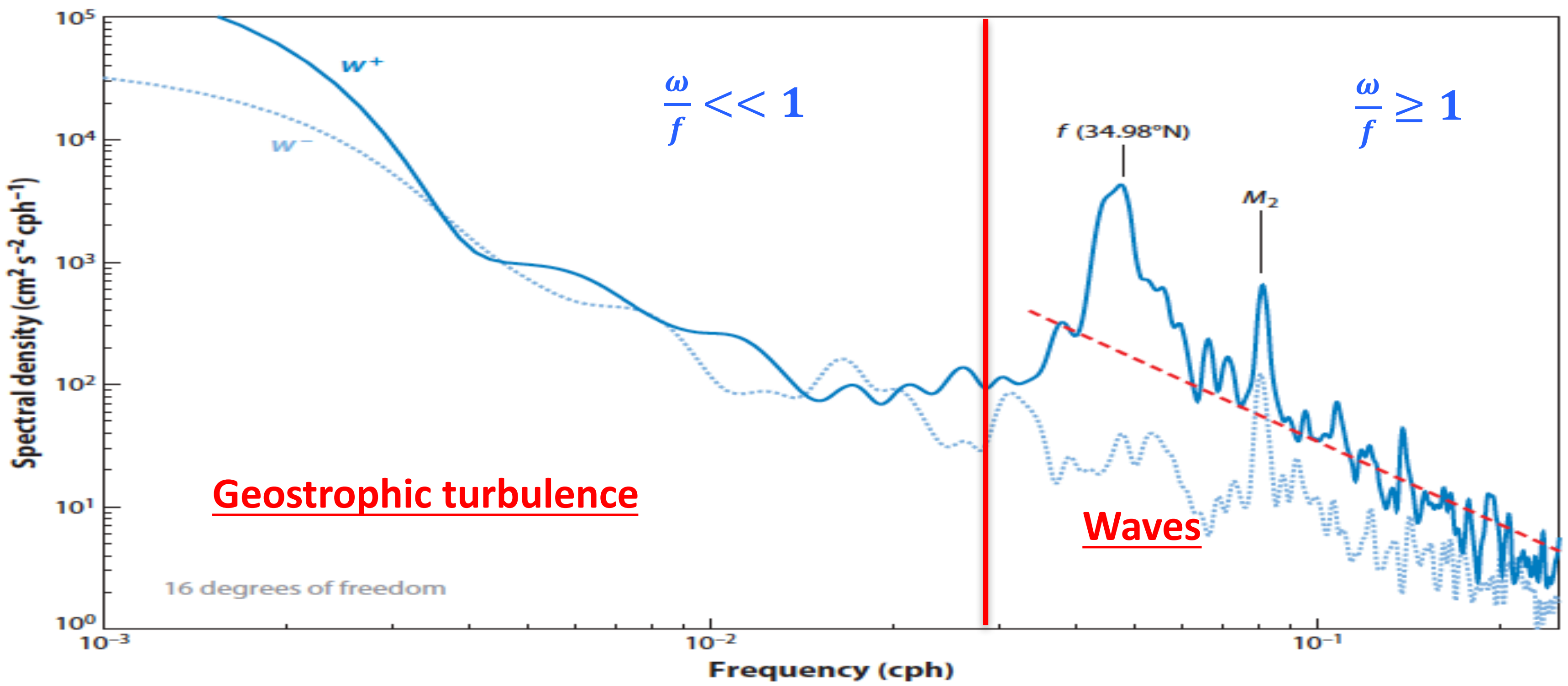
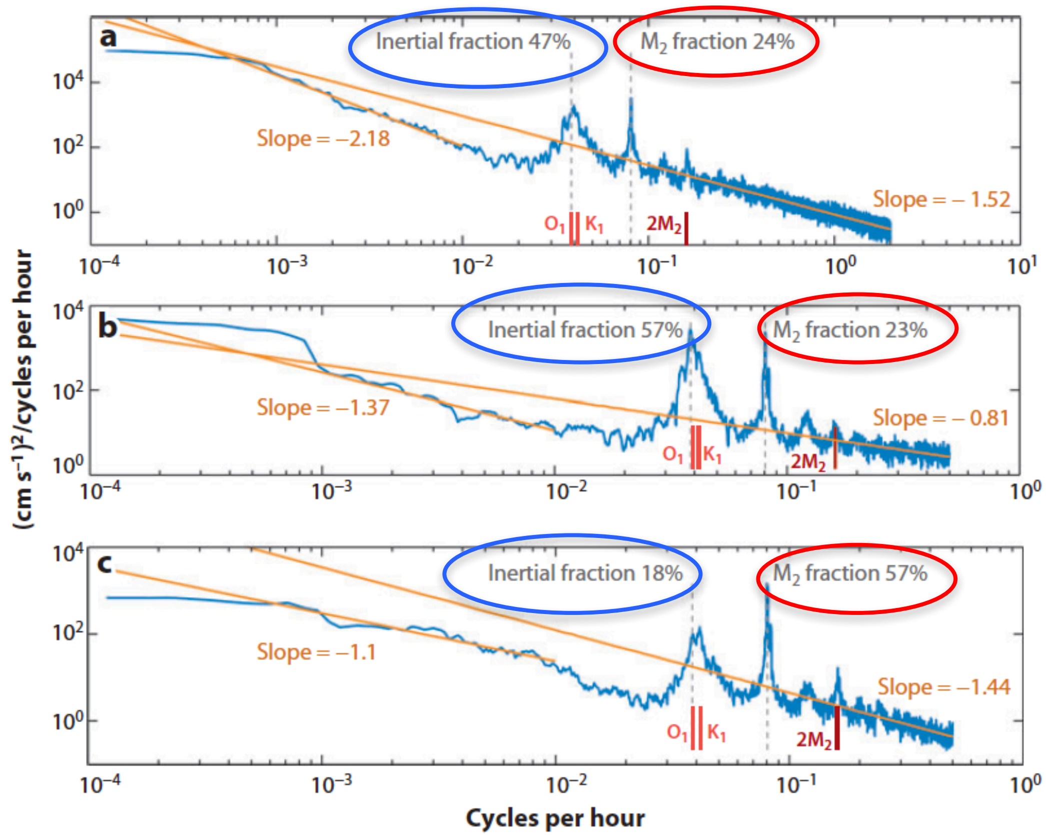


Figure 1

Rotary velocity spectrum at 261-m depth from current-meter data from the WHOI699 mooring gathered during the WESTPAC1 experiment (mooring at 6,149-m depth.) The solid blue line (w^+) is clockwise motion, and the dashed blue line (w^-) is counterclockwise motion; the differences between these emphasize the downward energy propagation that often dominates the near-inertial band. The dashed red line is the line $E_0 N \omega^{-p}$ with $N = 2.0$ cycles per hour (cph), $E_0 = 0.096$ cm^2 s^{-2} cph^{-2}, and $p = 2.25$, which is quantitatively similar to levels in the Cartesian spectra presented by Fu (1981) for station 5 of the Polygon Mid-Ocean Experiment (POLYMODE) II array.

A frequency spectrum displays different properties between fast and slow motions

PARTITION OF KE NEAR-INERTIAL WAVES/TIDES (BAROTROPIC AND INTERNAL)/INTERNAL GRAVITY WAVES



128 m

1500 m

3900 m

Figure 1

Kinetic energy spectral estimates for instruments on a mooring over the Mid-Atlantic Ridge near 27°N (Fu et al. 1982). The inertial, principal lunar semidiurnal M_2, and diurnal O_1, K_1 tidal peaks are marked, along with the percentage of kinetic energy in them and the kinetic energy lying between f and the highest frequency estimate. Least-squares power-law fits for periods between 10 and 2 h and for periods lying between 100 and 1000 h are shown. The approximate percentage of energy of the internal wave band lying in the inertial peak and the M_2 peak is noted. In most records, the peak centered near f is broader and higher than the one appearing at the M_2 frequency. When f is close to the diurnal frequency, it is also close to one-half the frequency of M_2, when the parametric subharmonic instability can operate. Some spectra show the first overtone, 2 M_2 of the semidiurnal tide. Instrument at (*a*) 128 m, (*b*) 1500 m, and (*c*) 3900 m (near the bottom). The geostrophic eddy band is greatly reduced in energy near the bottom, as is the inertial band, presumably because of the proximity of steep topography. Note the differing axis scales.

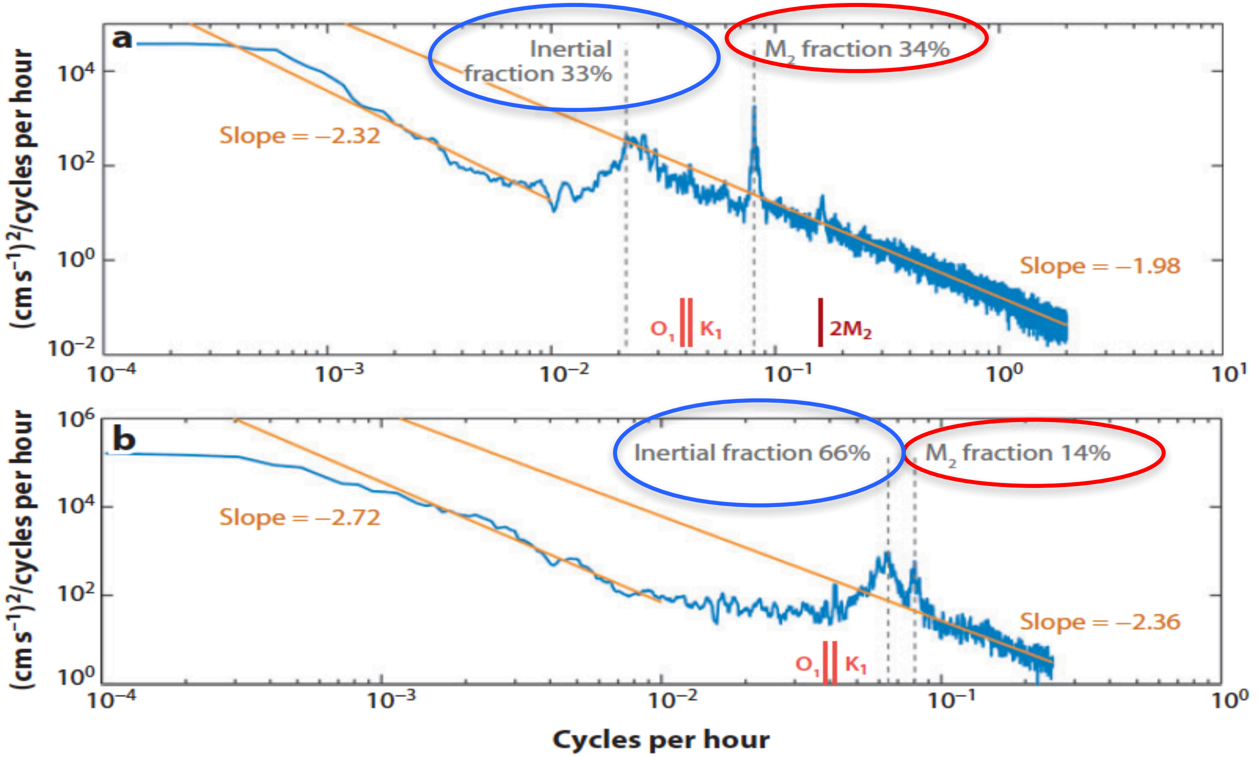


Figure 2

(*a*) Kinetic energy estimate for an instrument in the western North Atlantic near 15°N at 500 m. In this record, the diurnal tides are well separated from the inertial frequency. This record was described by Fu et al. (1982). (*b*) Power density spectral estimate from a record at 1000 m at 50.7°S, 143°W, south of Tasmania in the Southern Ocean (Phillips & Rintoul 2000). Now the diurnal tides are below f in frequency, but whether the apparent peaks represent dominantly barotropic or baroclinic motions is not known.

Tidal motions explain 20% to 50% of the high-frequency motions
THIS PARTITION DEPENDS ON THE REGION (SEE LATER)
and tidal motions have properties quite different from the near-inertial waves

What are these properties …

NEAR-INERTIAL WAVES AND TIDES:

- HAVE SIMILAR POWER INPUT ON A GLOBAL SCALE;
- SAME POTENTIAL TO CONTRIBUTE TO MIXING;
- CAN PROPAGATE FAR FROM THEIR SOURCES

NEAR-INERTIAL WAVES ARE **INTERMITTENT**, MOSTLY WIND-DRIVEN (NEAR THE SURFACE) (TYPHOONS, CYCLONE), **, WITH A STRONG SEASONALITY** AND ARE GENERALLY **HIGHER VERTICAL MODES** (VERTICAL SHEAR)**.**

THEY HAVE **SMALL VERTICAL DISPLACEMENTS** (ALMOST NOT IMPACT ON SSH, SEE LATER). THIS MAKES NEAR-INERTIAL WAVES TO BE DIFFICULT TO OBSERVE (IN PARTICULAR FROM SPACE).

TIDES (BAROTROPIC AND BAROCLINIC)

BAROTROPIC TIDES (MOTIONS ARE HOMOGENEOUS ON THE VERTICAL) ARE FORCED GRAVITY WAVES (KELVIN WAVES, see next class), CAUSED **BY THE GRAVITATIONAL ATTRACTION OF THE MOON (M) AND THE SUN (S).** THIS LEADS TO DIFFERENT TIDAL COMPONENTS, THE LARGEST ONE IS $\mathbf{M_2}$ (SEMI-DIURNAL). **THE FORCING HAS NO SEASONALITY, NO INTERMITTENCY.**

THEY ARE GENERATED IN THE DEEPER PARTS OF THE OCEANS, CREATING CONVERGENCE AND DIVERGENCE THAT LOCALLY MODIFIES THE SSH.

SSH IS THEN PROPAGATING AS A SET OF KELVIN WAVES IN OCEAN BASINS WITH LARGE WAVELENGTHS (6000-10000 KM). STRUCTURE OF THESE WAVES IS CONSTRAINED BY THE BASIN GEOMETRIES.

AS AN ILLUSTRATION: MAP OF M_2 SSH IN THE GLOBAL OCEAN…

SSH FROM M_2 BAROTROPIC TIDES (Richman et al. 2012)

SSH FROM M_2 IS BASIN-SCALE! IT BEHAVES AS KELVIN WAVES (6000 KM) PROPAGATING CYCLONICALLY AROUND A BASIN WITH A PERIOD OF ~12 H (see next class)..

USING $\eta = \eta_o . \sin\alpha$ WITH $\alpha = k_x x + k_y y - \omega t$ THE PHASE. THIS FIGURE SHOWS:

η_o in colour and α lines, the white lines

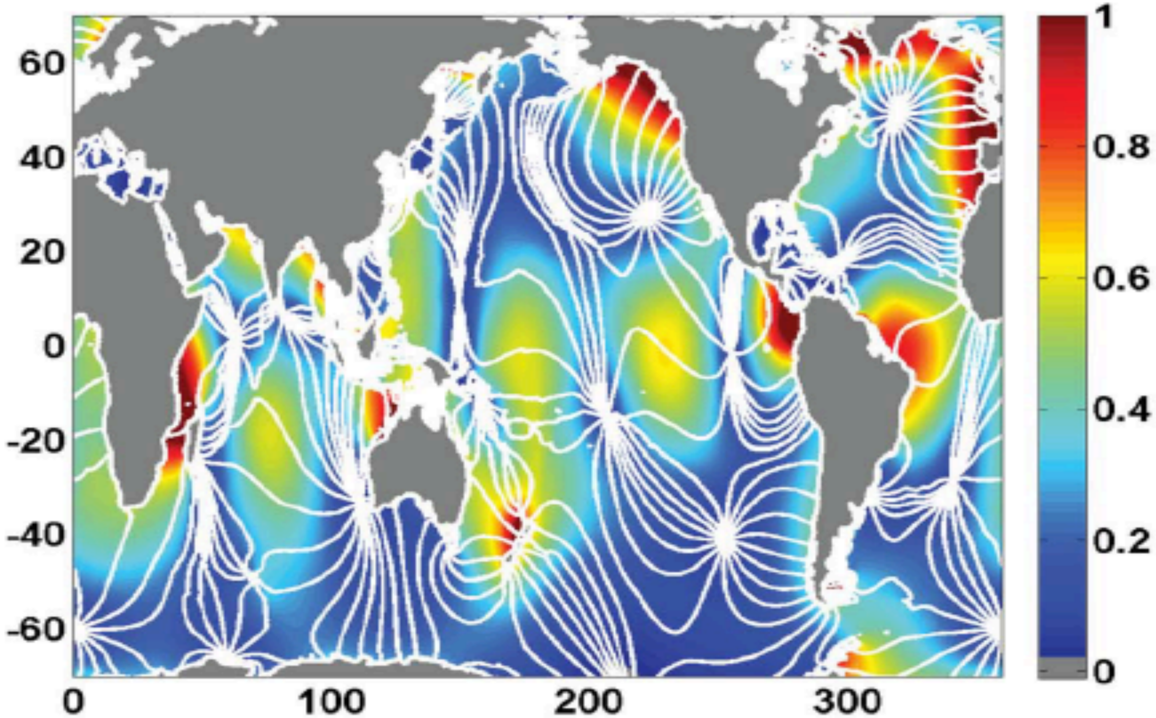
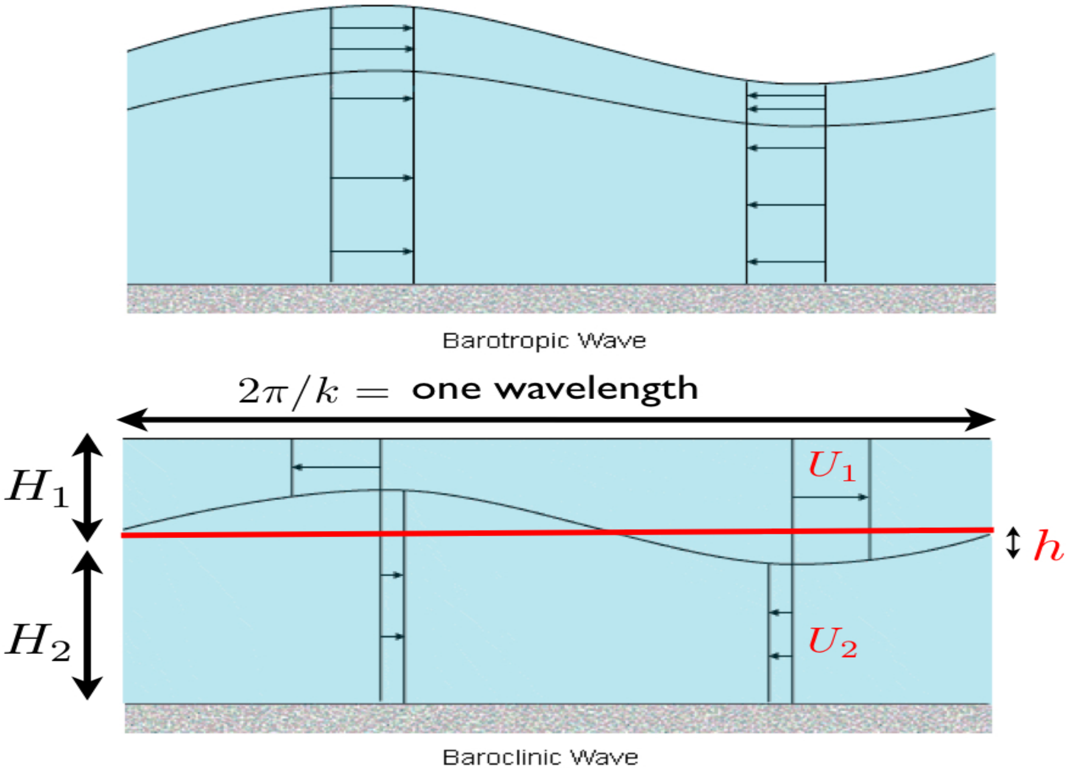


Figure 1. M_2 sea surface elevation amplitudes (m) and phase for (a) HYCOM and (b) TPXO7.2 [*Egbert et al.*, 1994], a highly accurate altimetry-constrained model of the barotropic tides. White lines indicate phase, drawn 20° apart.



BAROTROPIC TIDE

BAROCLINIC TIDE

INTERNAL (OR BAROCLINIC) TIDES RESULT FROM THE INTERACTION OF BAROTROPIC TIDAL CURRENTS (0.1 M/S) WITH THE BOTTOM TOPOGRAPHY IN PRESENCE OF STRATIFICATION. SO **INTERNAL TIDES ARE INTERNAL WAVES AT A TIDAL FREQUENCY.**

INTERNAL TIDES

INTERNAL TIDES RESULT FROM THE INTERACTION OF BAROTROPIC TIDAL CURRENTS (0.1 M/S) WITH THE BOTTOM TOPOGRAPHY IN THE PRESENCE OF STRATIFCATION.

THEY HAVE A STRONG COHERENCE (AND NO INTERMITTENCY AND SEASONALITY) AS BAROTROPIC TIDES

THEY CAN PROPAGATE FOR O(1000 KM) AWAY FROM THEIR SOURCE REGION.

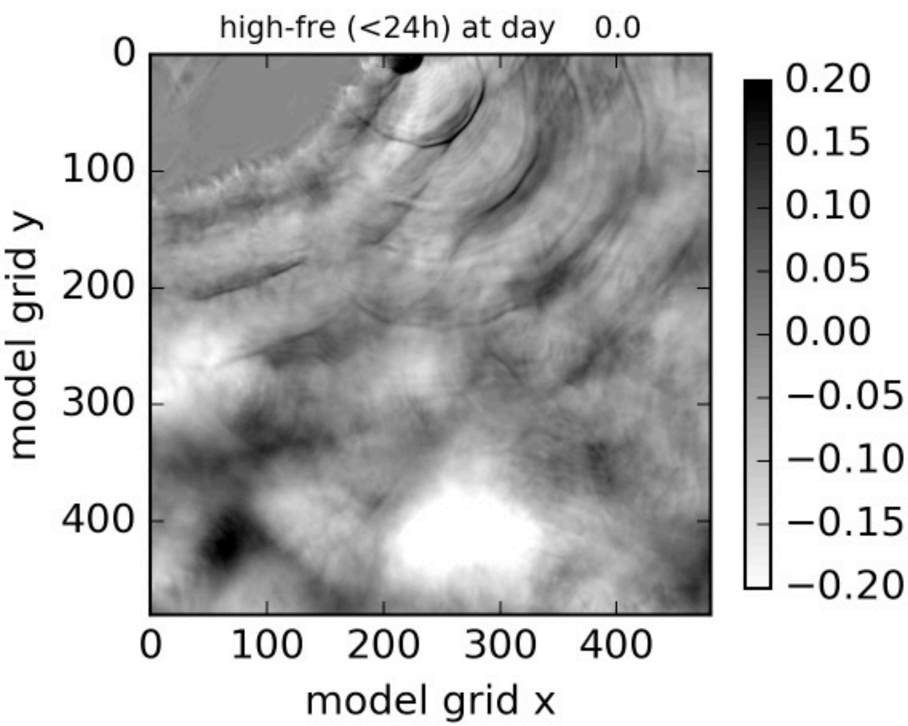
INTERNAL TIDES HAVE A MUCH LARGER IMPRINT ON SSH THAN NEAR-INERTIAL (INTERNAL) WAVES (see next classes). THEIR SIGNATURE ON SSH IS O(1 CM),THEIR WAVELENGTHS, O(100 KM) AND VELOCITY MOTIONS O (0.1 M/S).

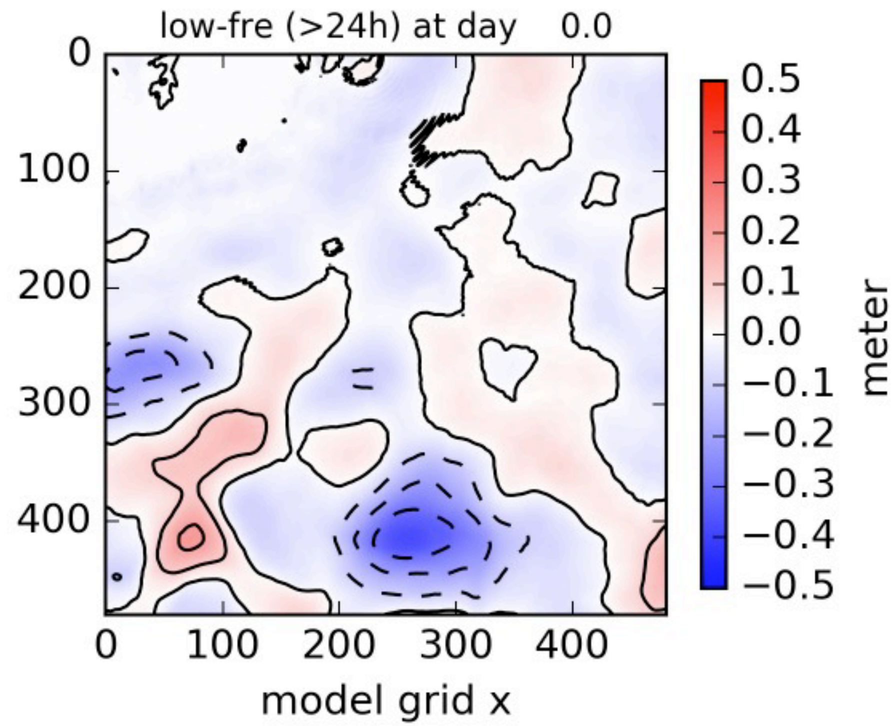
THEIR DYNAMICS IS EXPLAINED BY THE THEORY OF IGW (SEE NEXT WEEK).

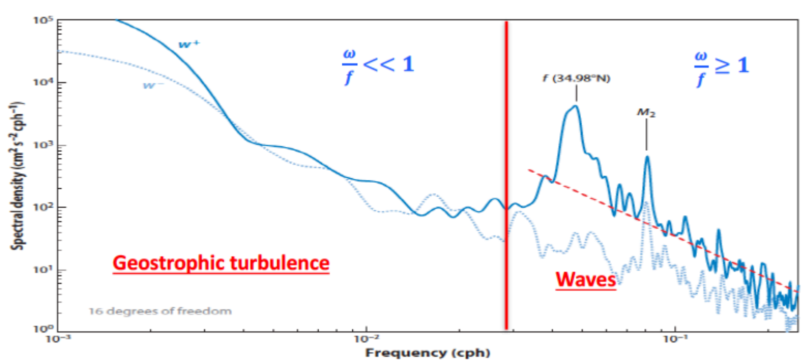
THEIR IMPRINT ON SSH AND THEIR COHERENCE ALLOW THEIR OBSERVATIONS ON A GLOBAL SCALE USING LONG TIME SERIES OF ALTIMETER DATA (SEE JINBO'S TALK).

THIS HAS ALLOWED TO BUILD UP NUMERICAL MODELS TO PREDICT THE COHERENT INTERNAL TIDES.

Global simulation using MITgcm 1/48° (with 90 vert. levels) including tides: Gulf Stream region (from Jinbo Wang, JPL 2016)







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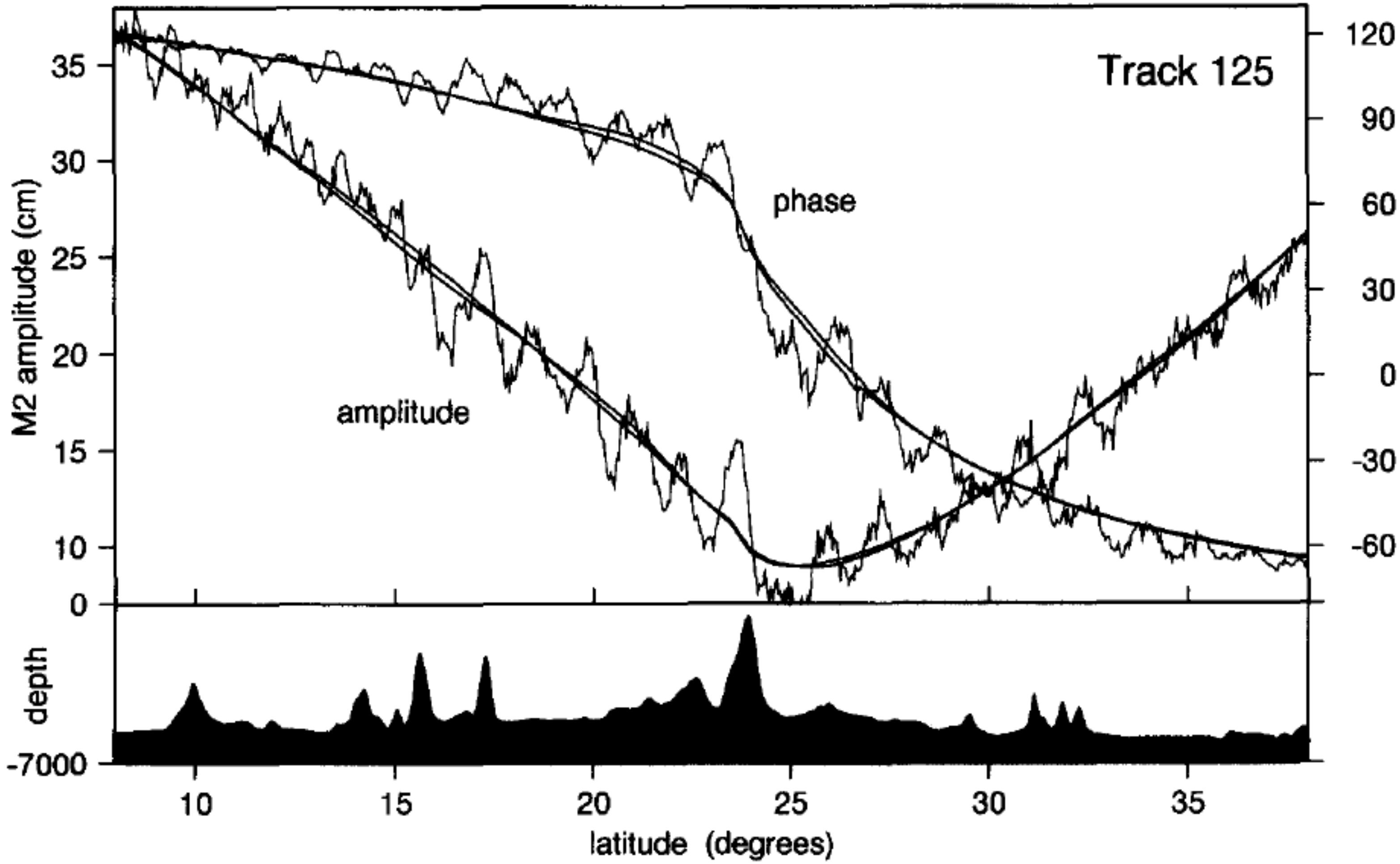

Fig. 10. M_2 amplitudes and Greenwich phase lags along T/P track 125. Ragged lines are estimates independently computed every 5.75 km along the track, from approx. 3.5 years of T/P data. Standard errors for the amplitudes vary, but are always between 5 and 10 mm; standard errors for the phases, taking a nominal amplitude of 20 cm, are therefore roughly 3°, and twice that near the Hawaiian Ridge. Smooth lines are from the recent T/P global models of Richard Eanes (version CSR 3.0) and Schrama and Ray (1994; version 960104). Strictly, these data include the radial-displacement load tide, so they are not exactly comparable to the cotidal chart of Fig. 2. Track location can be found from Fig. 12 (top).

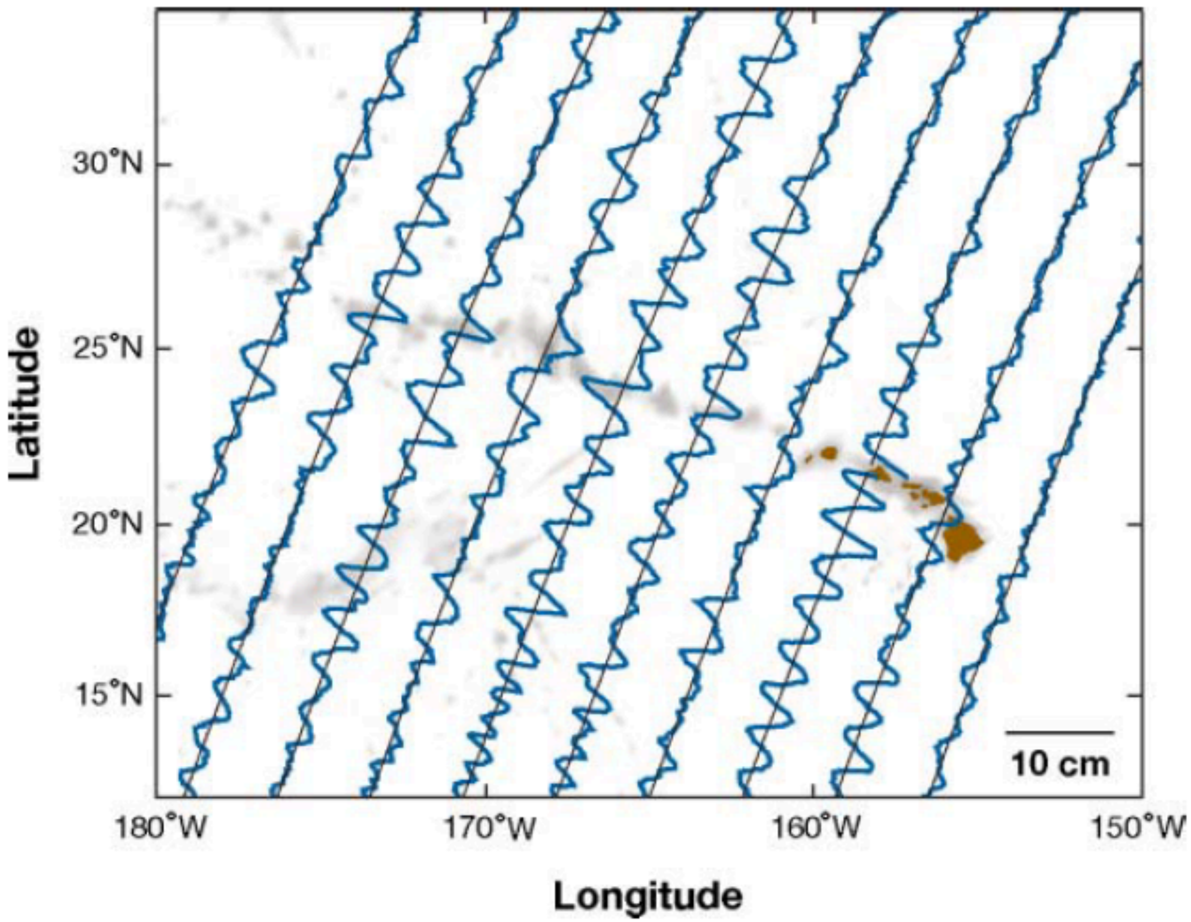

Figure 1

The amplitude near Hawaii of the surface displacement at the M_2 frequency (*blue lines* with the 10 cm scale shown), plotted normal to the TOPEX/Poseidon track (*smooth gray lines*) and high-passed with a cut-off scale of approximately 400 km. The large-scale pattern expected for the barotropic tide is alternately reinforced and reduced by motions with a much shorter wavelength (updated from Ray & Mitchum 1997, courtesy of Richard Ray, 2006).

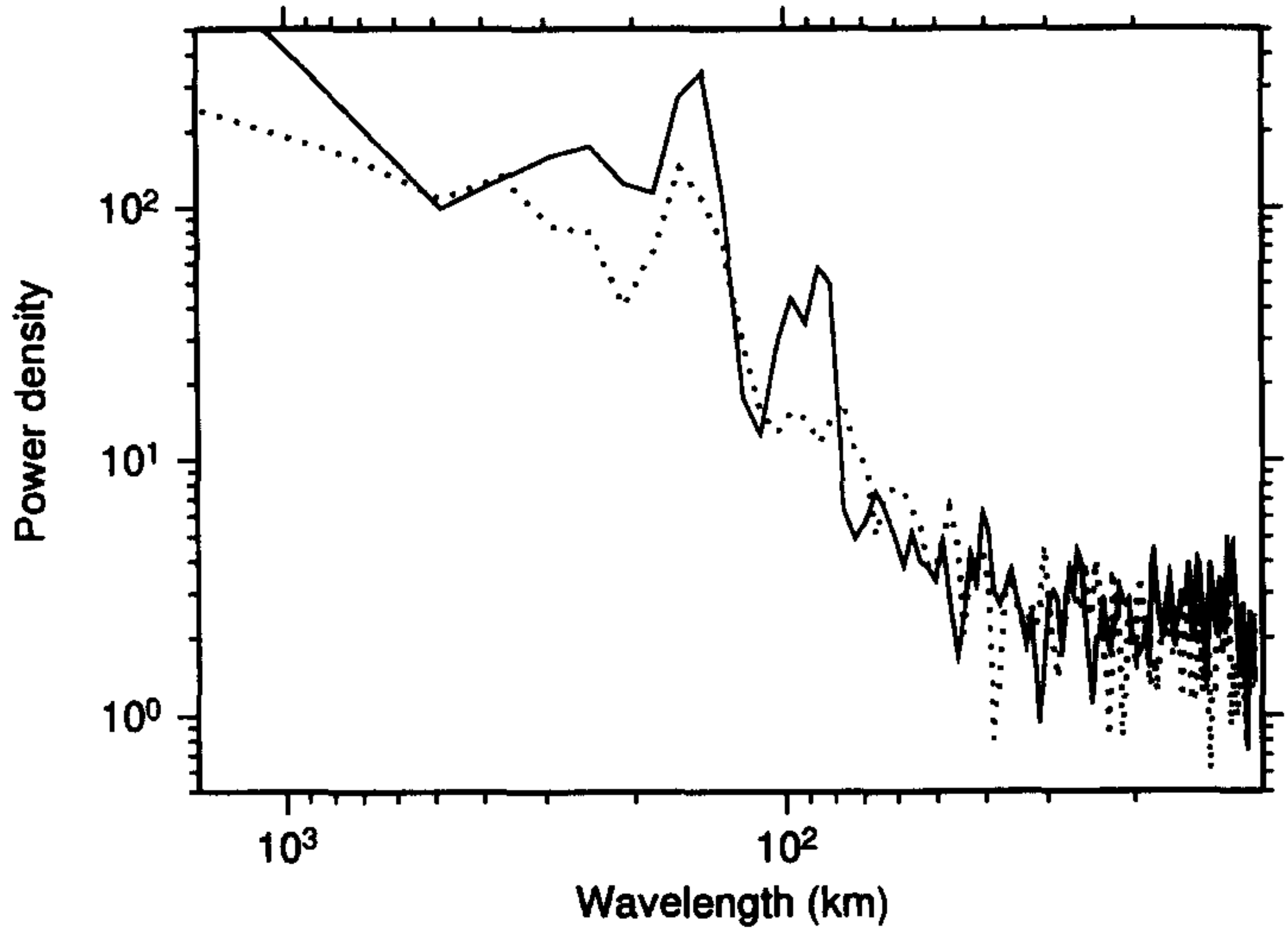

Fig. 13. Power spectrum of the amplitude data shown in Fig. 10 for track 125. Solid line for M_2; dashed line for S_2. The peak near 150 km is near the expected wavelength for the first baroclinic mode. Adapted from RAY and MITCHUM (1996). The spectrum for track 92 (a descending track) shows a similar peak near 190 km; elementary trigonometry confirms that this is consistent with internal waves propagating essentially in the direction of the ascending tracks.

SSH FROM M_2 BAROTROPIC TIDES (Richman et al. 2012)

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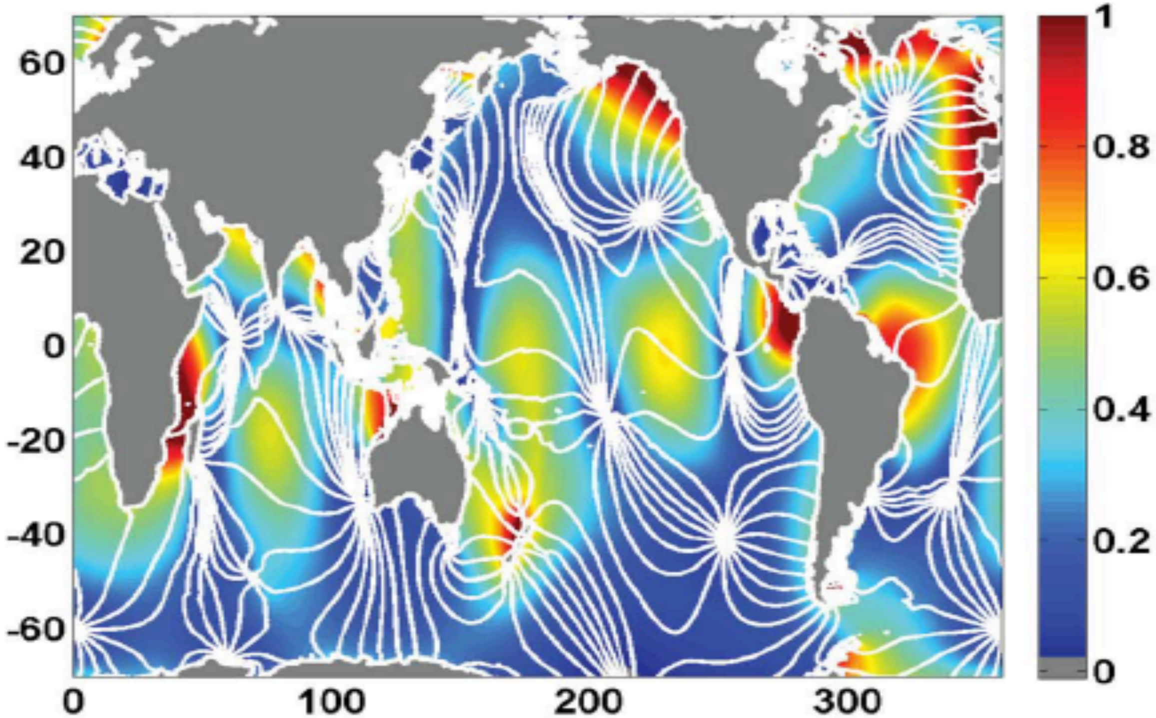

meters

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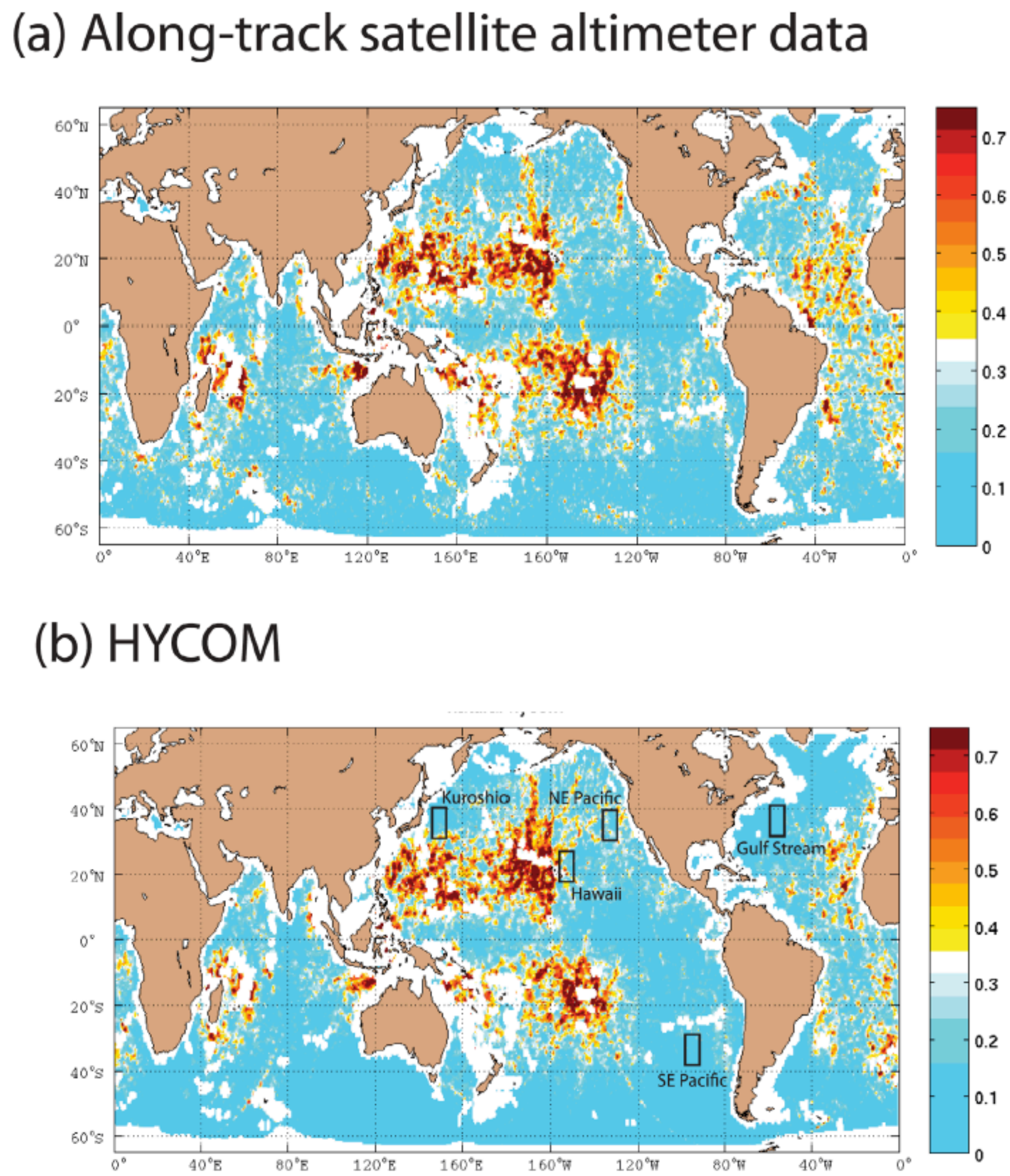
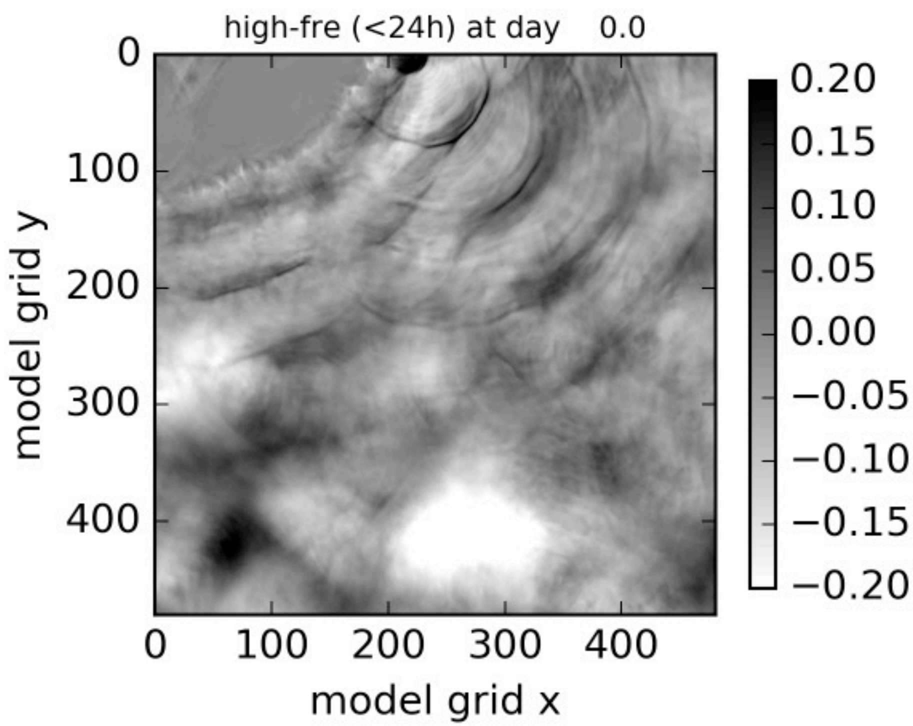


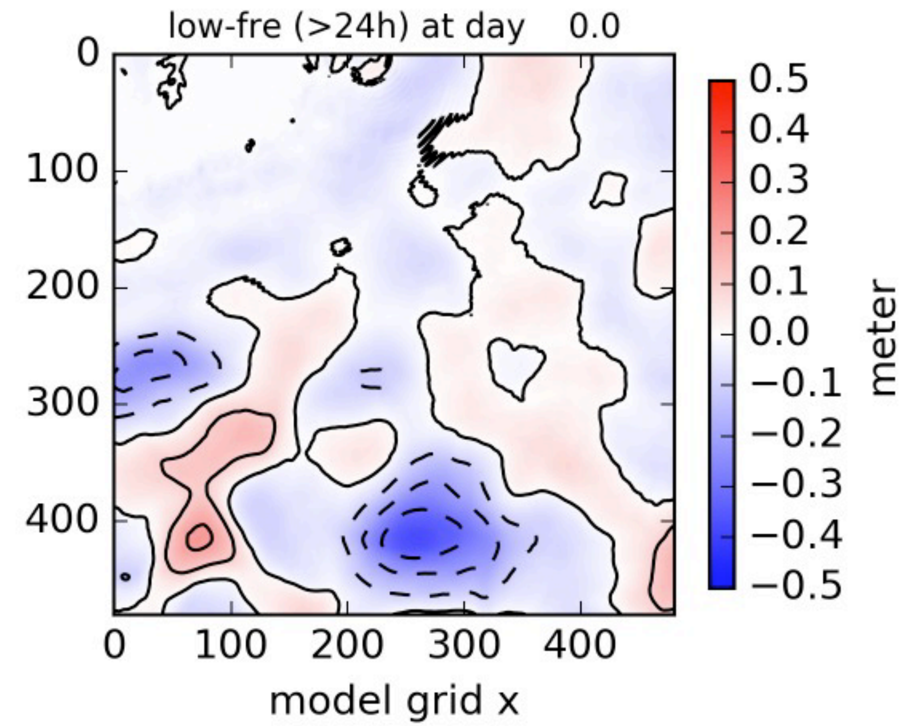
Figure 2. Internal tide signature in M_2 sea surface elevation amplitudes (cm) in (a) along-track altimeter data [*Ray and Mitchum*, 1996, 1997; *Ray and Byrne*, 2010] and in (b) HYCOM. The internal tide signature is determined from band-passing 50–400 km wavelengths in the M_2 sea surface elevations; absolute values of the band-passed results are shown. Boxes indicate regions over which wavenumber spectra are computed in Figures 3–5.

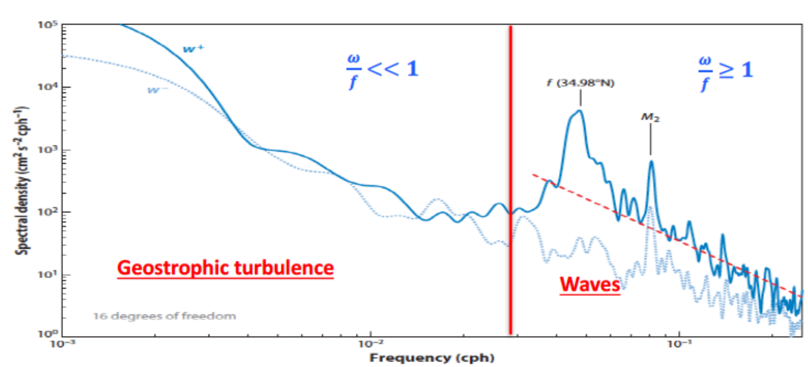
WHAT IS THE RELATIVE IMPORTANCE OF INTERNAL WAVES

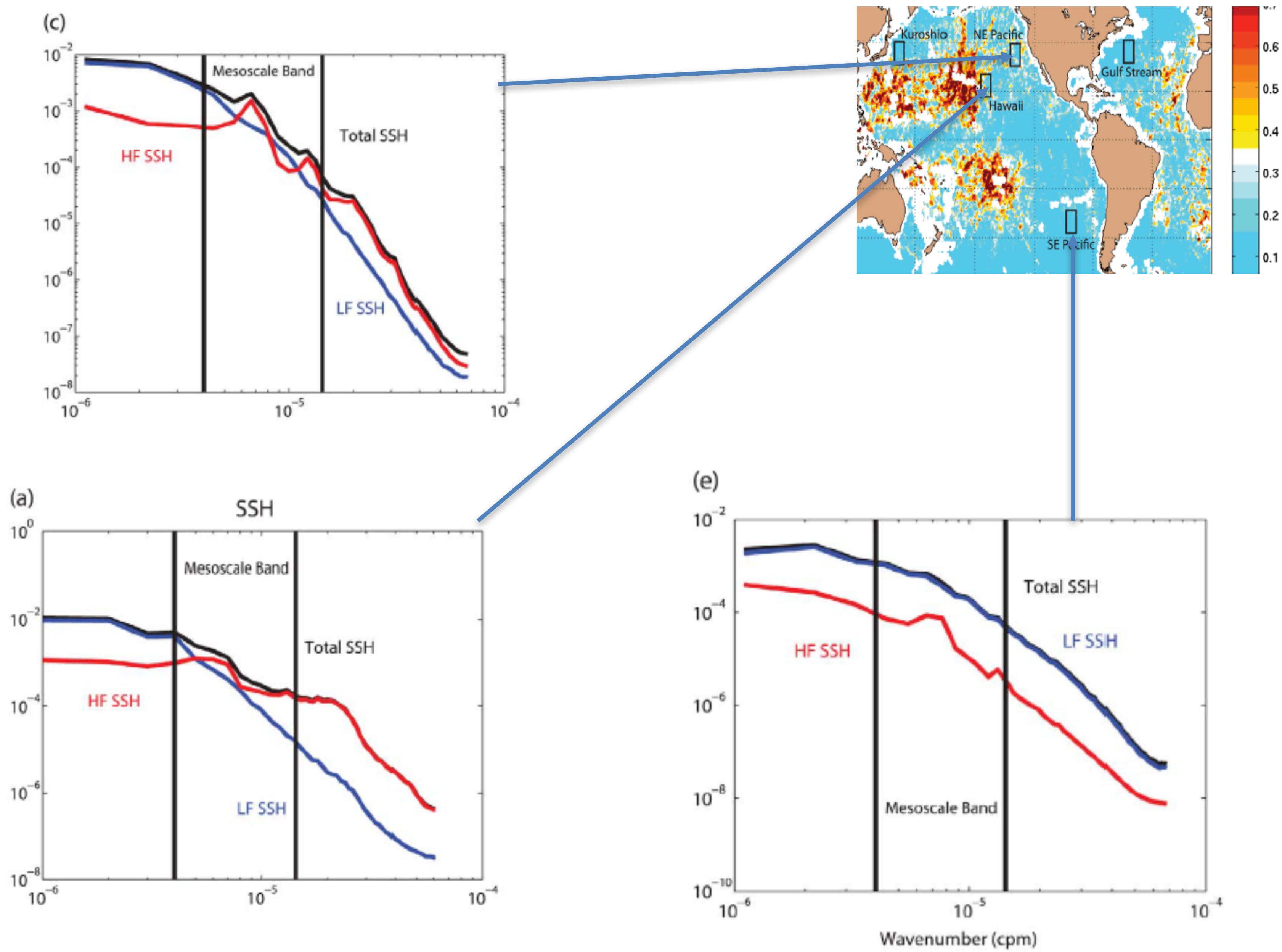
AND OF MESOSCALE TURBULENCE ON SSH?

**Global simulation using MITgcm 1/48° (with 90 vert. levels) including tides:
Gulf Stream region (from Jinbo Wang, JPL 2016)**









RICHMAN ET AL. JGR 2012

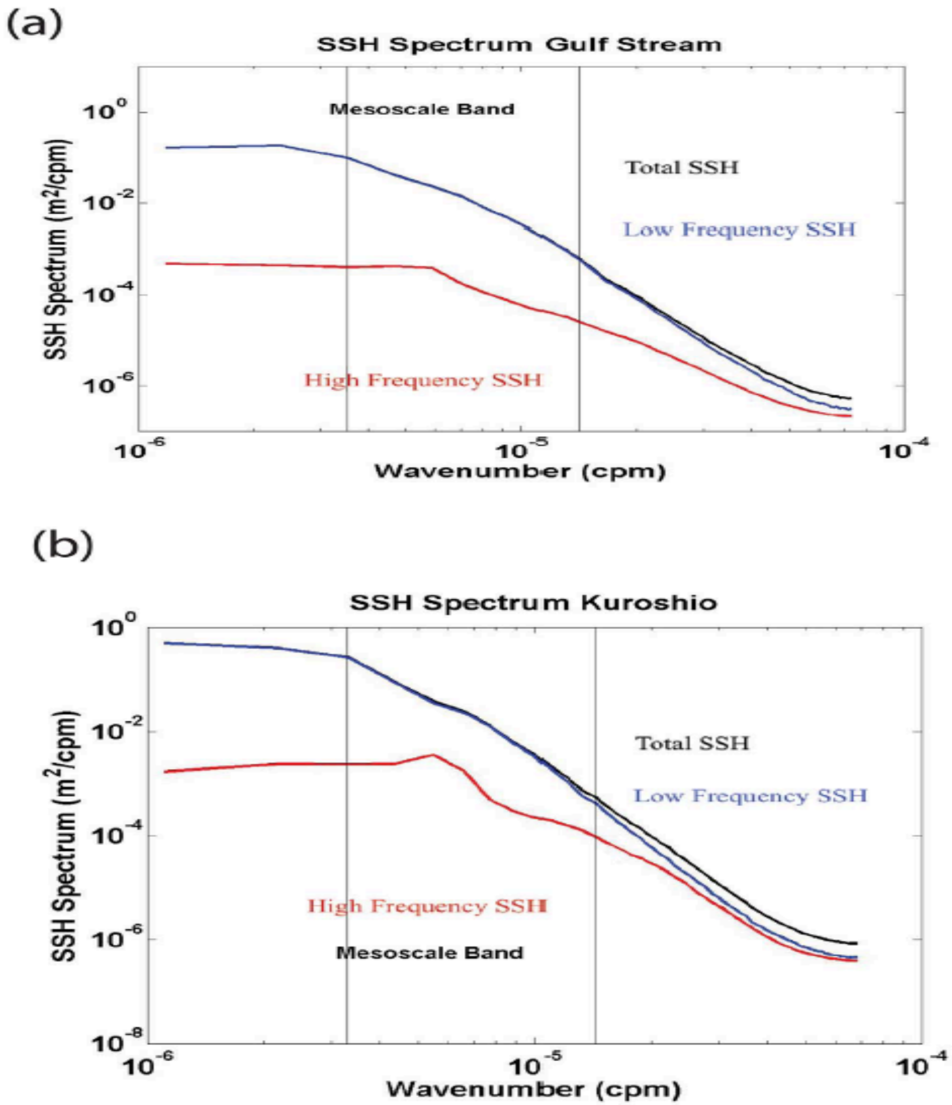
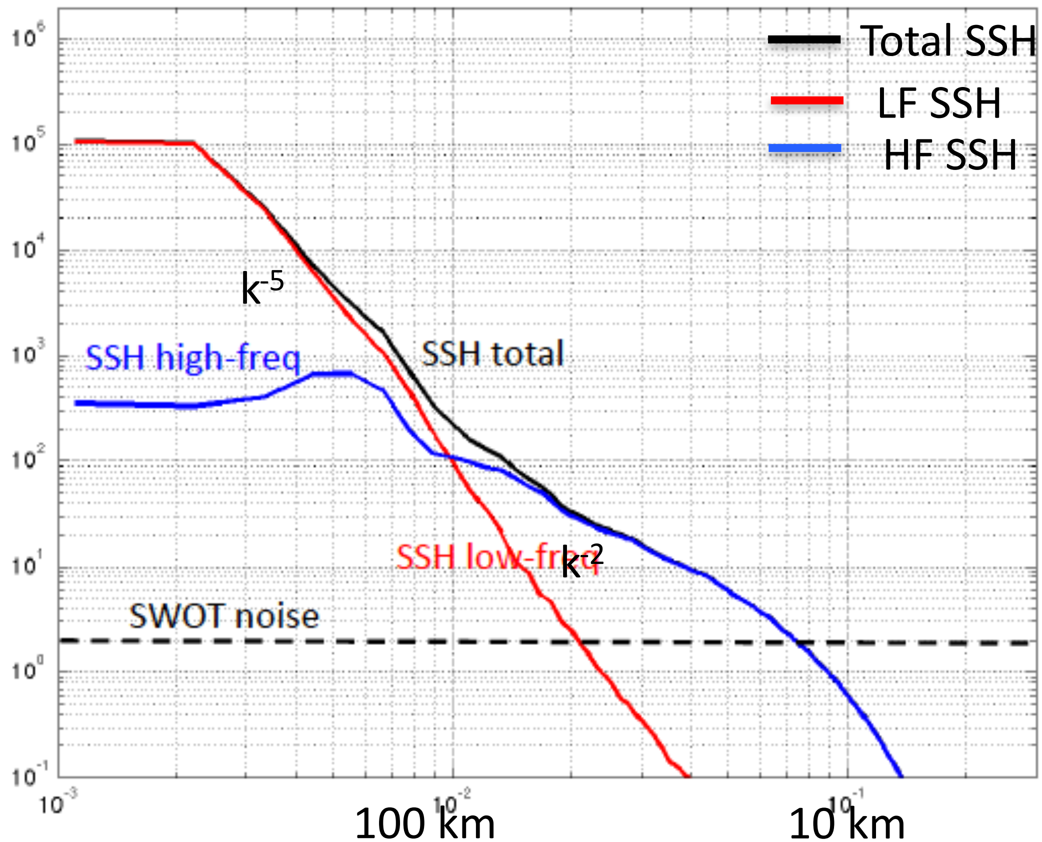


Figure 3. Wavenumber spectrum of sea surface height in high EKE regions of (a) the Gulf Stream (35°N, 305°E) and (b) the Kuroshio (35°N, 155°E) from the marked boxes in Figure 2b. Spectra of total (black), low frequency (blue), and high frequency (red) SSH are shown. In this figure, as in the rest of this paper, the mesoscale band is defined from 70 to 250 km as in *Xu and Fu* [2011]. In this band the least squares slopes of the total SSH spectra for the mesoscale band are -4.0 ± 0.5 and -4.4 ± 0.4 in the Gulf Stream and Kuroshio, respectively.

RICHMAN ET AL. JGR 2012

BUT INTERNAL WAVE SPECTRUM IS POORLY REPRESENTED IN THIS MODELLING STUDY

High-frequency internal waves have an impact on SSH !



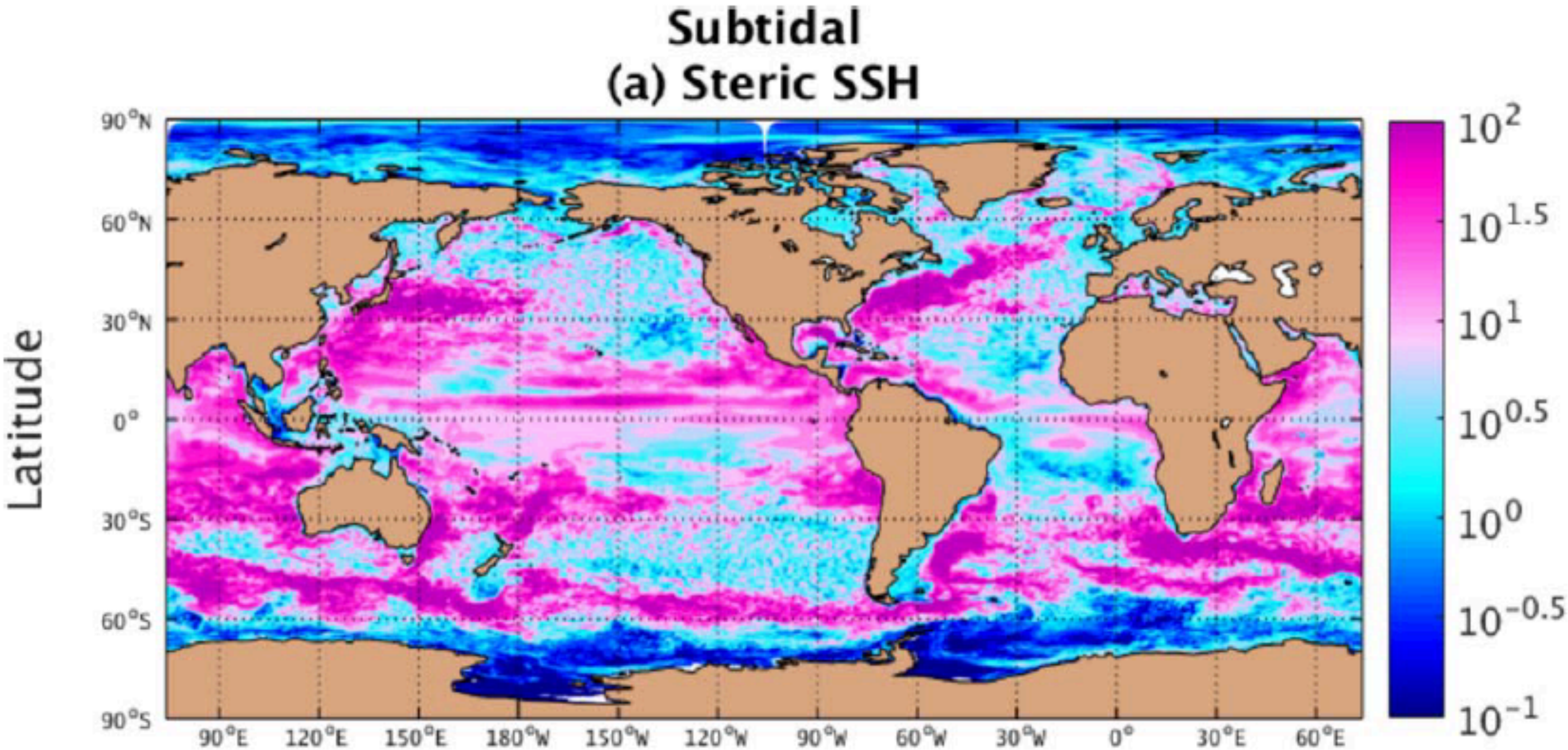
Problem at small scales: $\mathbf{RV} = \Delta\, \boldsymbol{SSH}$ is noisy !

LF SSH (T> 1 day) leads to a classical k^{-5} slope

HF SSH (T< 1 day) explains the k^{-2} slope.

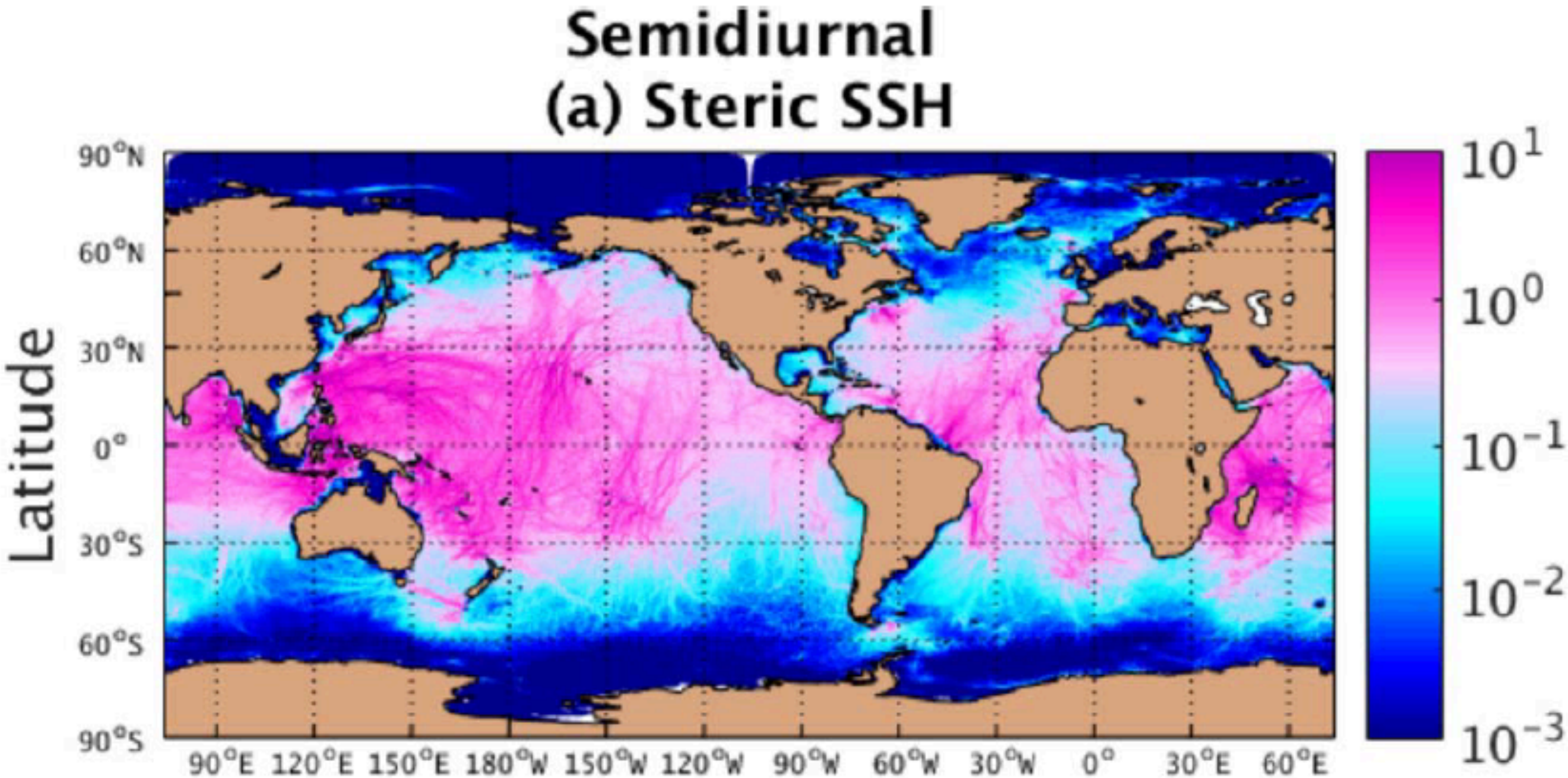
Clément Ubelmann JPL 2015 **in the Gulf Stream…**

Savage et al. 2017



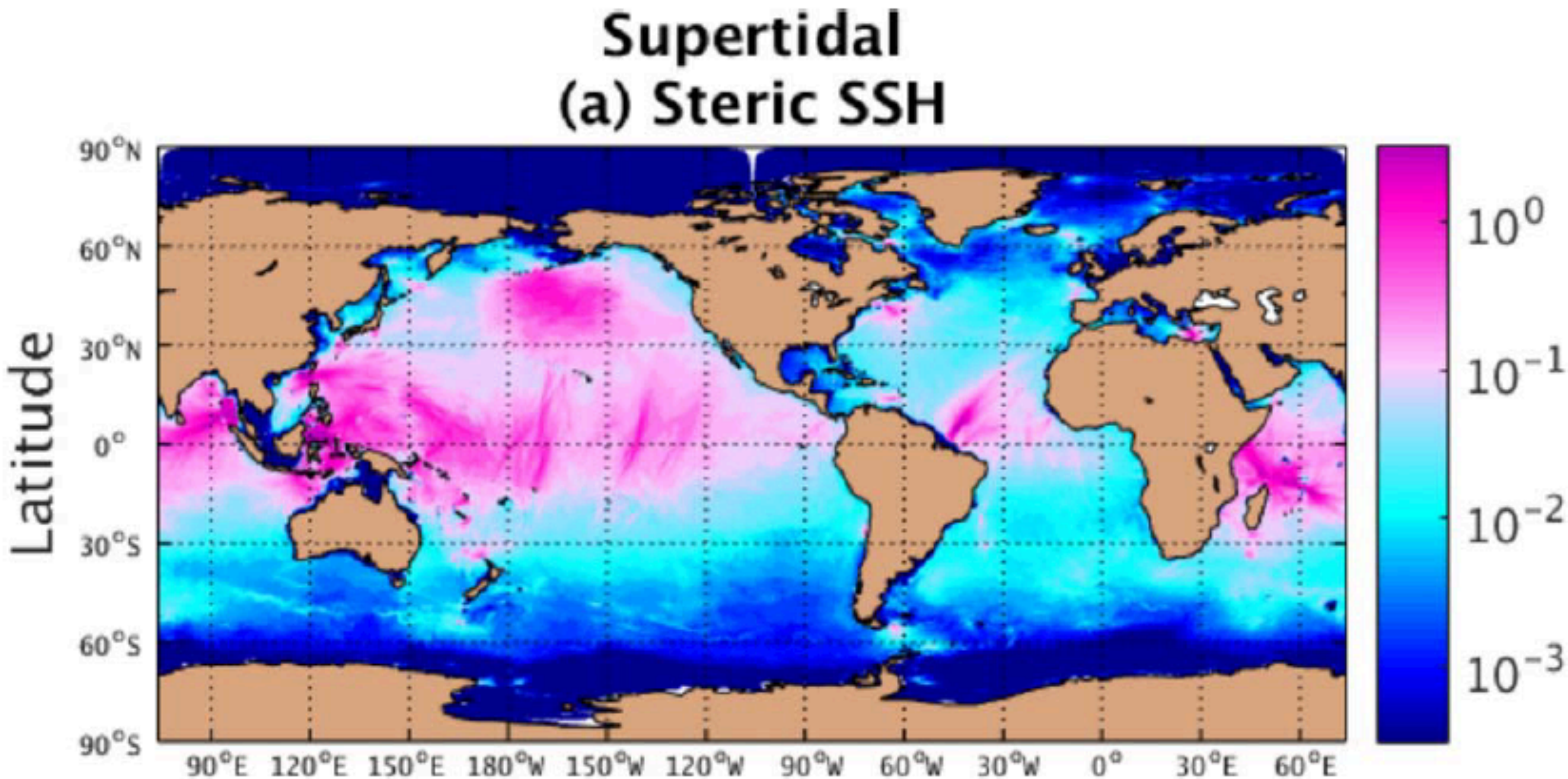
IMPACT OF MESOSCALE TURBULENCE ON THE SSH IN THE GLOBAL OCEAN
[GLOBAL SSH VARIANCE IN CM^2]

Savage et al. 2017



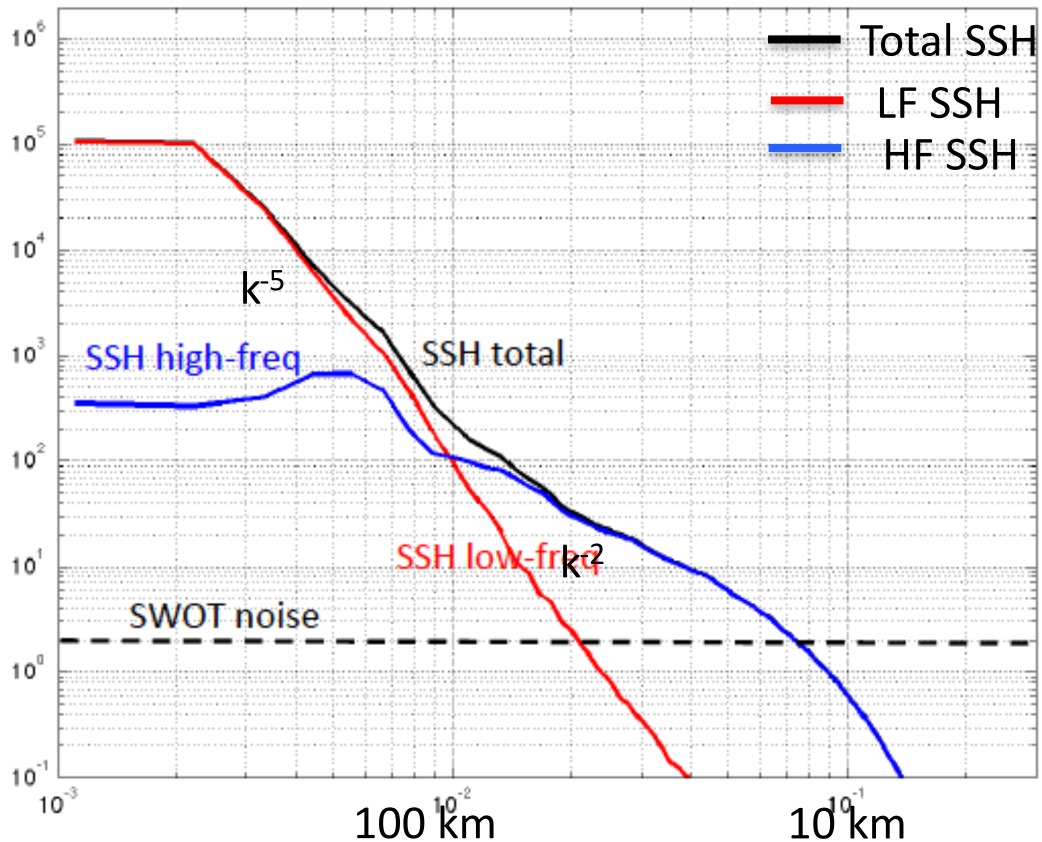
IMPACT OF THE INTERNAL (M2) TIDE ON THE SSH IN THE GLOBAL OCEAN
[GLOBAL SSH VARIANCE IN CM^2]

Savage et al. 2017



IMPACT THE HIGHER-FREQUENCY INTERNAL WAVES ON THE SSH IN THE GLOBAL OCEAN
[GLOBAL SSH VARIANCE IN CM^2]

High-frequency internal waves have an impact on SSH !



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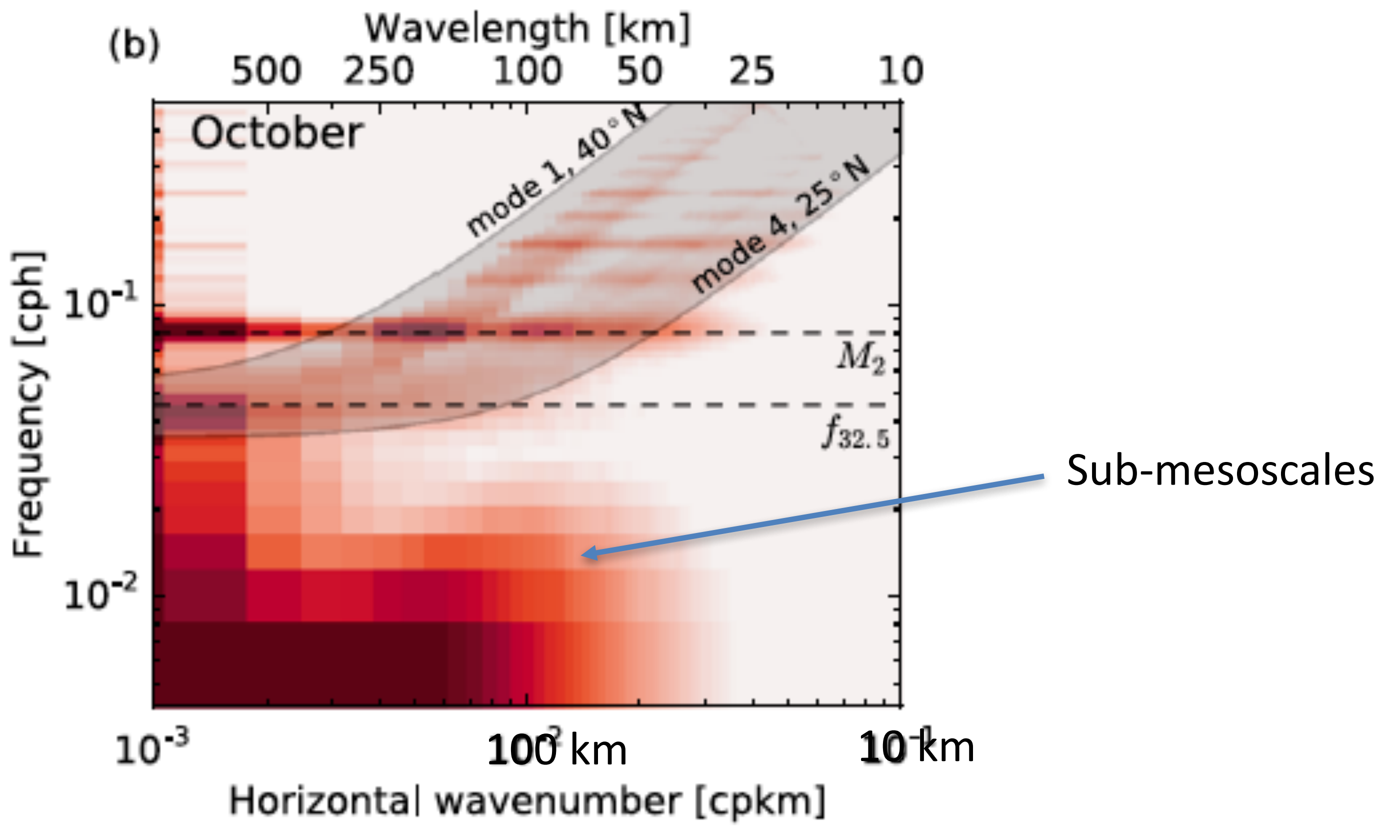
Clément Ubelmann JPL 2015 **in the Gulf Stream…**

High-frequency/high-wavenumber spectrum in the Kuroshio



HF SSH is captured by

- **internal tides** **[coherent (150 km) and incoherent tidal motions]**
- **internal gravity waves at higher wavenumbers (following the dispersion relation) with mode 2**

From Cesar Rocha GRL 2016

… and in the Kuroshio Extension [Rocha et al. GRL 2016]

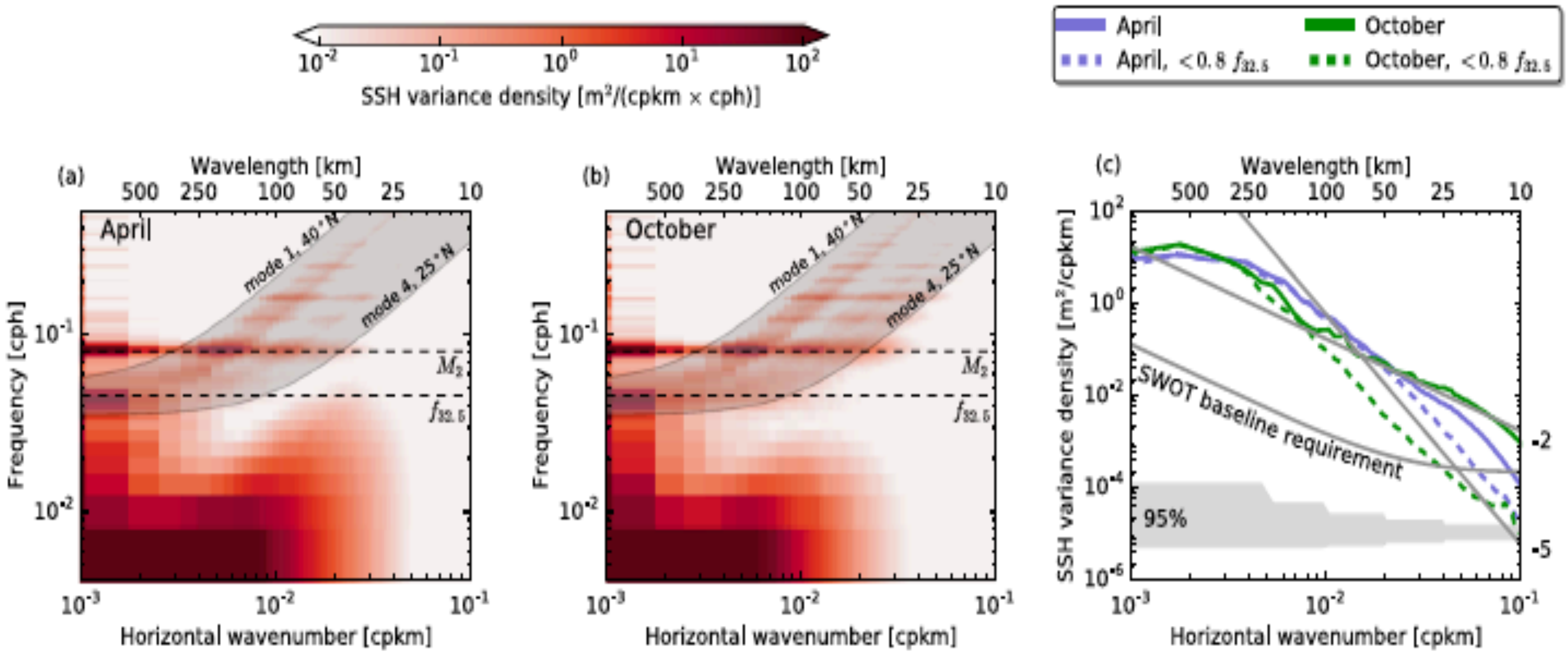


Figure 4. LLC4320 wave number-frequency spectrum of SSH variance in (a) April and (b) October. (c) Wave number spectrum of SSH variance—the integral of Figures 4a and 4b over frequency. In Figures 4a and 4b, the light gray shaded region depicts the dispersion relations for inertia-gravity waves from mode 1 through mode 4 across the latitudinal

- **Both, internal tides and higher frequency internal gravity waves impact SSH;**
- **Higher impact in summer than in winter.**