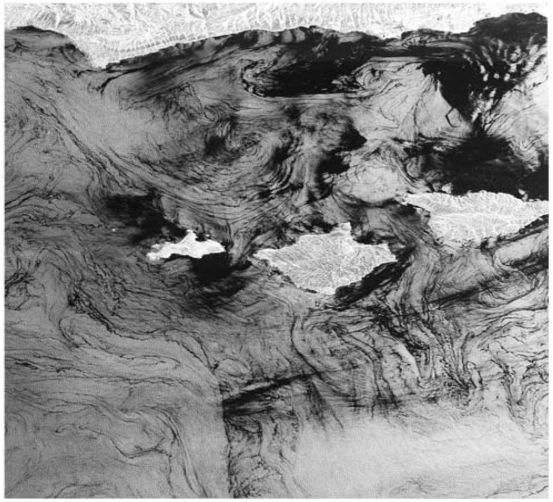
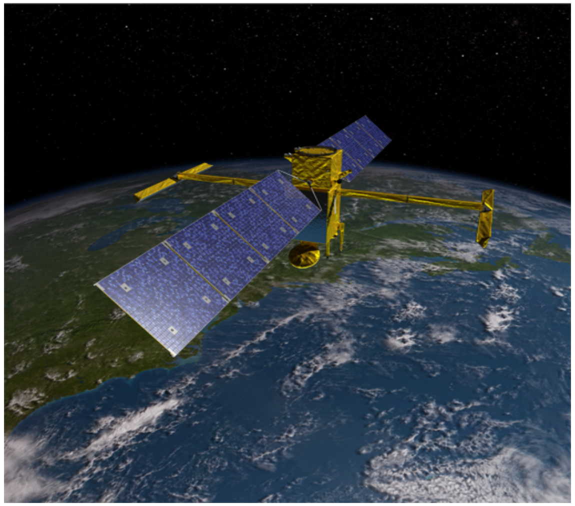
“Wave-Turbulence Interactions in the Oceans”

Patrice Klein (Caltech/JPL/Ifremer)

(II) Introduction (b): Waves





Textbooks:

- **Cushman-Roisin B. & J.M. Beckers (2011): Introduction to Geophysical Fluid Dynamics. Academic Press.**

- **Gill A.E. (1982): Atmosphere-Ocean Dynamics. Academic Press.**

- **Pedlosky J. (2003): Waves in the Ocean and Atmosphere: Introduction to Waves Dynamics. Springer.**

- **Kundu P. (2015): Fluid Mechanics, Academic press**

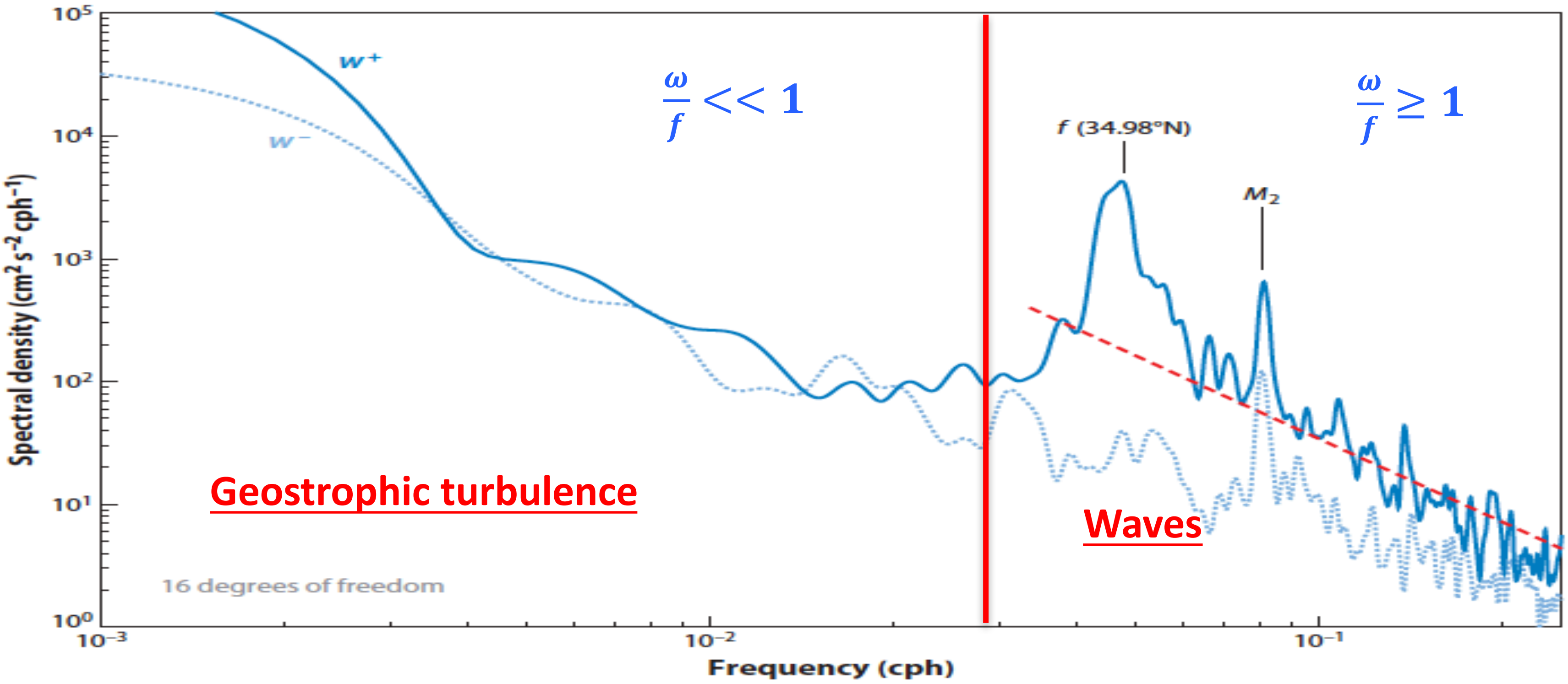


Figure 1

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

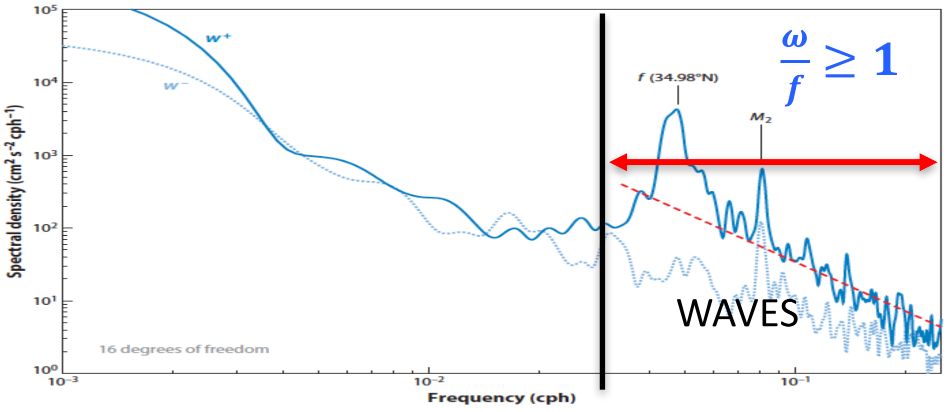
What is the motivation of this course ?

Geostrophic turbulence [10-500 km]:

- explains **most of the kinetic energy in the oceans,** well captured by satellite observations on a global scale [SSH (> 100 km), SST, Ocean Color, …]

Waves (near-inertial, tidal, internal gravity waves):

- assumed to explain **most of the mixing** (at small-scale) **in the ocean interior**
- strong signature in in-situ (moorings, gliders, ADCP, surface drifters) and satellite observations [SAR, SWOT] mostly at high-resolution.



PROPERTIES OF WAVES: FREQUENCY SPECTRUM

- FREQUENCIES BETWEEN F AND N
- DISPLAYS SEVERAL PEAKS [F, TIDES (O1, K1, M2) + HARMONIQUES]
- U / L IS SMALLER THAN THEIR PROPAGATION (OMEGA) $[c = \frac{\omega}{k} \gg U]$

We focus today on near-inertial waves and tidal waves:
the most energetic waves in the high-frequency band

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

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

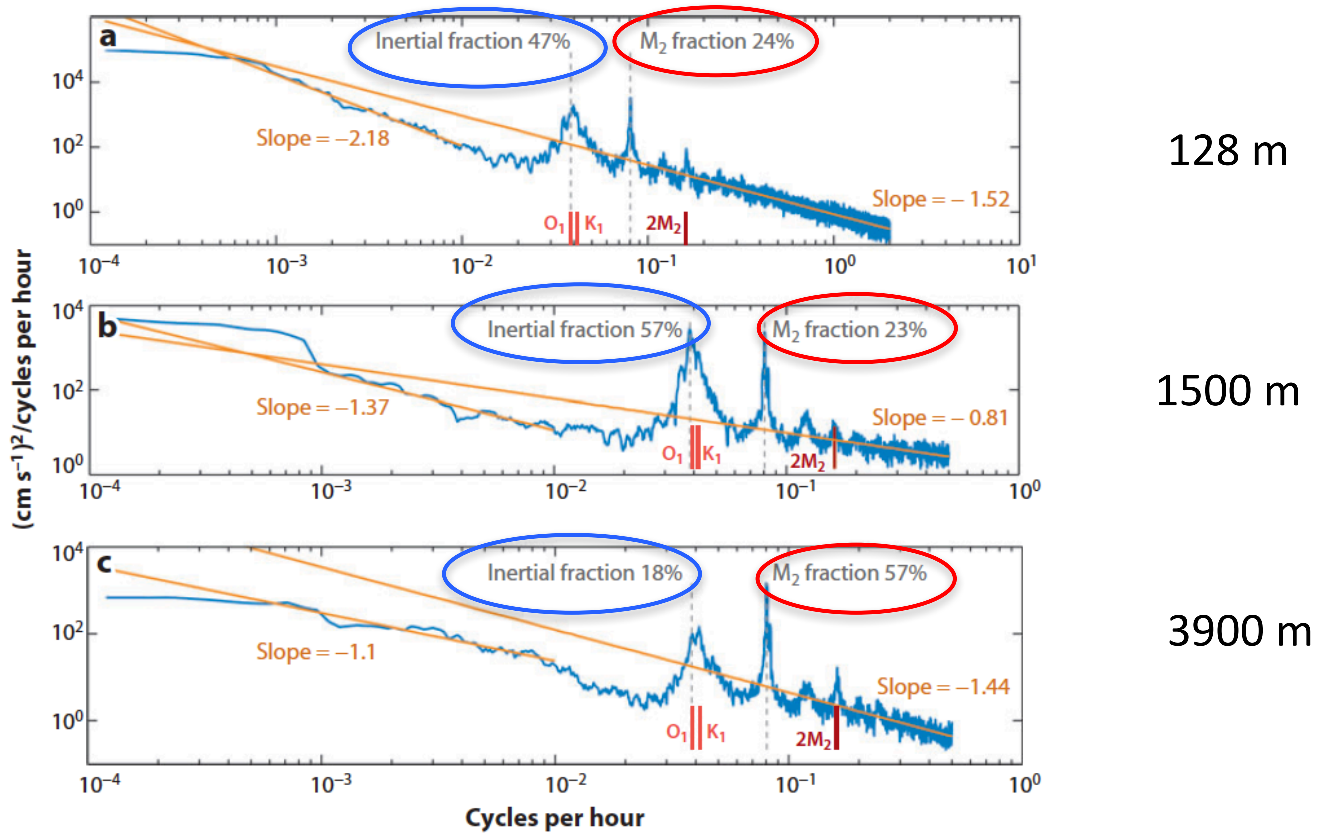


Figure 1

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.

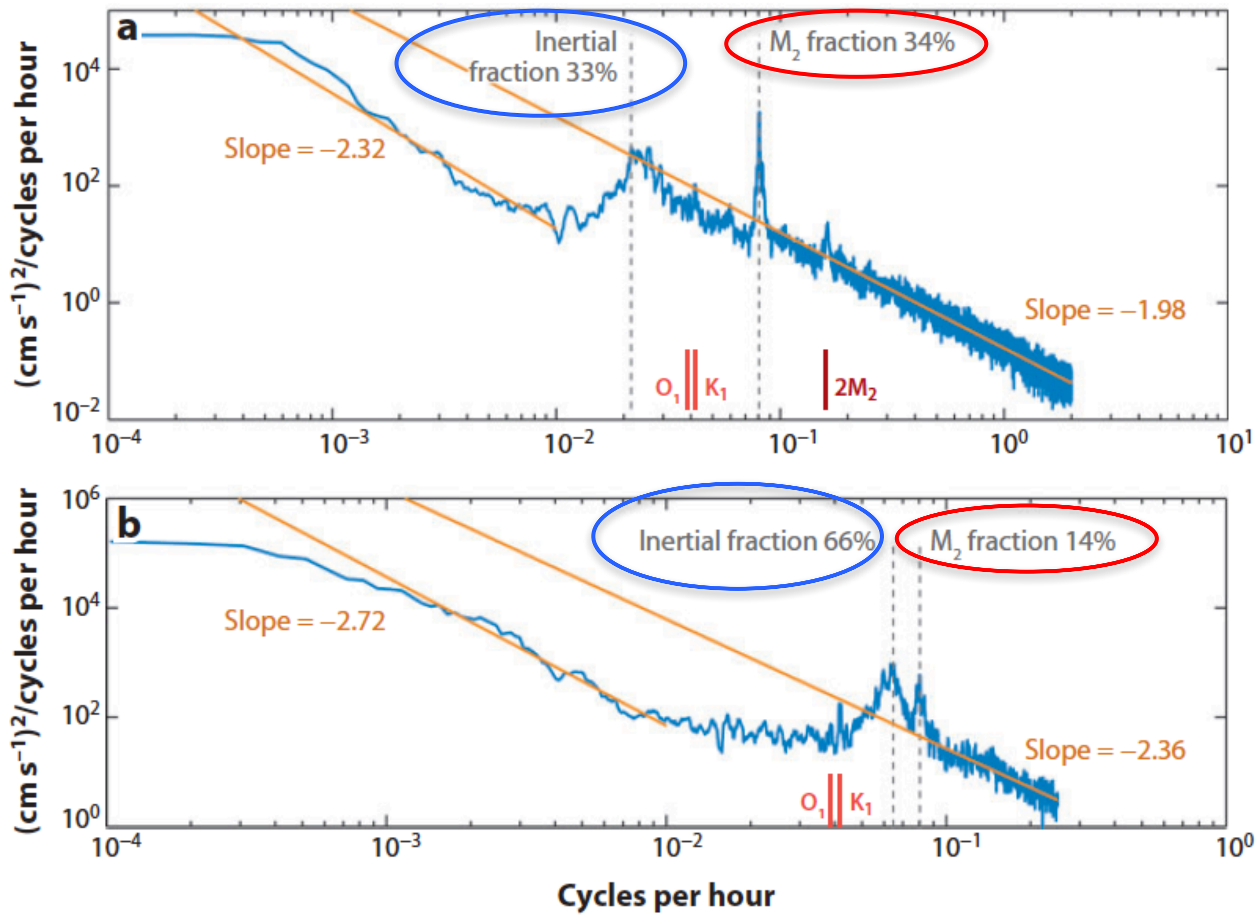


Figure 2

(*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.

WAVES:

NEAR-INERTIAL WAVES AND INTERNAL TIDES:

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

BUT **NEAR-INERTIAL WAVES** ARE **FAR MORE INTERMITTENT**, MOSTLY WIND-DRIVEN (NEAR THE SURFACE) (TYPHOONS, CYCLONE), ARE GENERALLY **HIGHER VERTICAL MODES** (VERTICAL SHEAR)**, WITH A STRONG SEASONALITY,**
AND HAVE **SMALLER VERTICAL DISPLACEMENTS** (ALMOST NOT IMPACT ON SSH) FOR THE SAME TOTAL ENERGY **THAN INTERNAL TIDES**.

THIS MAKES NEAR-INERTIAL WAVES TO BE MORE DIFFICULT TO OBSERVE (IN PARTICULAR FROM SPACE) THAN INTERNAL TIDES

NEAR-INERTIAL WAVES (FREQUENCY CLOSE TO F)

- THE OCEAN IS AN OSCILLATOR WITH A FREQUENCY *F* !
- MOSTLY FORCED BY THE INTERMITTENT WINDSTRESS AT THE OCEAN SURFACE
- NEAR-INERTIAL OSCILLATIONS ARE MOSTLY CLOCKWISE

USING WIND OBSERVED EVERY 3 H ON A WEATHERSHIP (KILO) FOR 540 DAYS:
STRONG INTERMITTENCY!

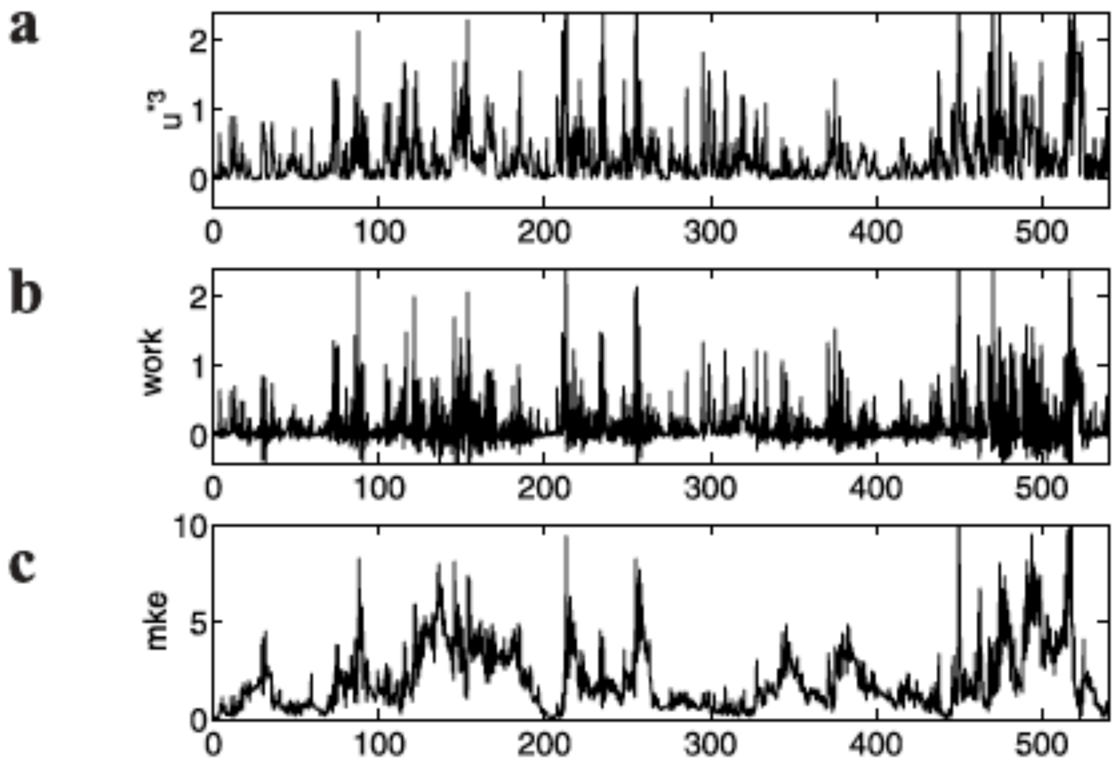


Figure 1. Results of a 3-hourly simulation: (a) $u^{*3} = |\tau|^{\frac{3}{2}}$ (in $m^3\ s^{-3} \times 1.5.10^5$), (b) wind energy flux ($[\boldsymbol{\tau}\ .\mathbf{u}]$(in $m^3\ s^{-3} \times 10^4$)), (c) inertial energy integrated over the water column (in $m^3\ s^{-2}$). Abscissa units are days.

INTERMITTENCY IS DUE THE CHANGE OF MAGNITUDE AND ALSO OF ROTATION OF $\vec{\tau}$

WHAT HAPPENS NORTH AND SOUTH OF A LOW PRESSURE A ATMOSPHERIC SYSTEM MOVINGTO THE EAST ?

ROTATION OF THE WIND VECTOR:

- IN THE NORTH (ANTICLOCKWISE) WILL GENERATE WEAK INERTIAL MOTIONS
- IN THE SOUTH (CLOCKWISE) WILL PRODUCE STRONG INERTIAL MOTIONS

INTERMITTENCY OF THE WINDSTRESS: NOT PRESENT IN NCEP OR ECWMF DATA! BUT WIND DIRECTION CAN CHANGE QUICKLY (FROM SCATTEROMETER DATA)

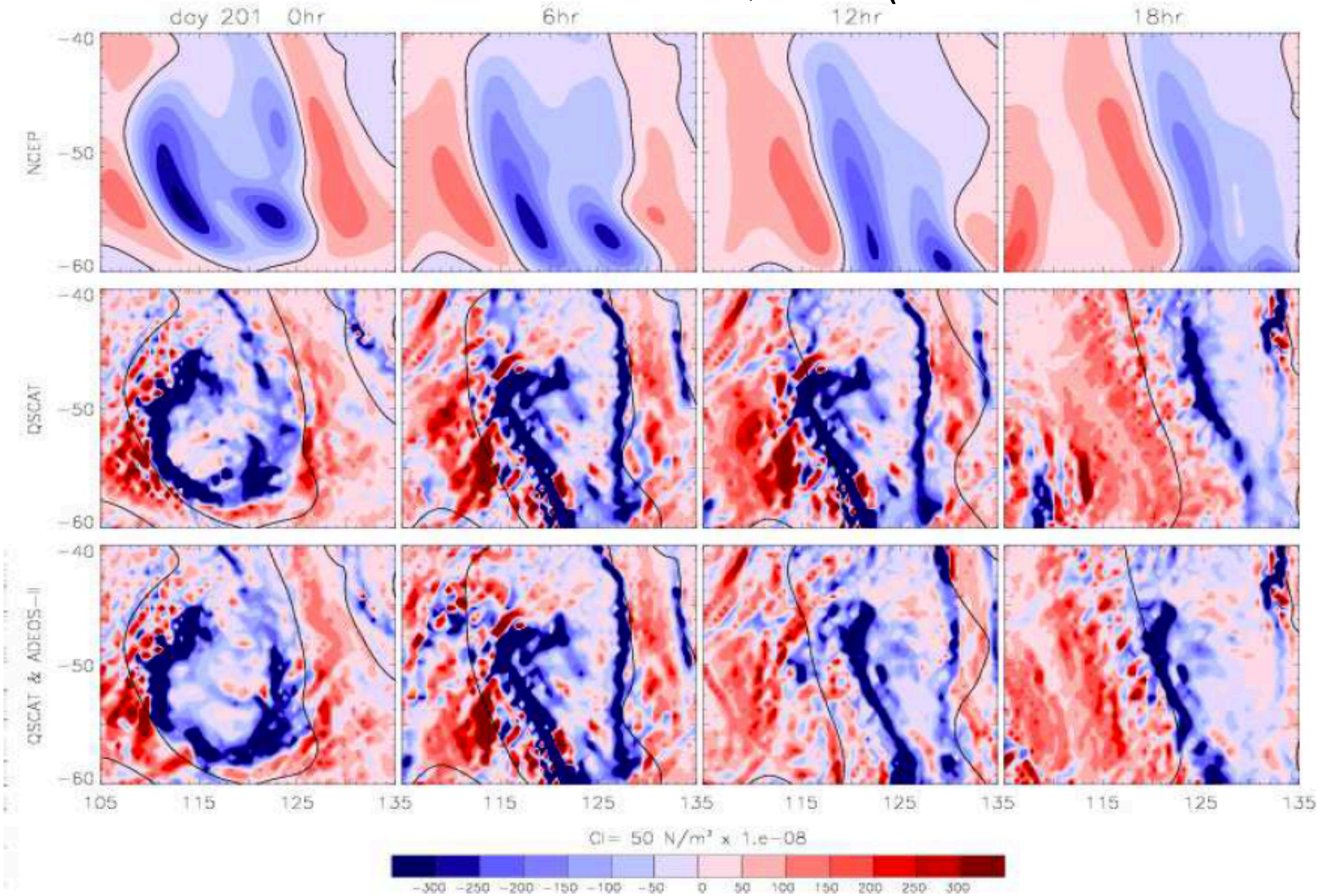
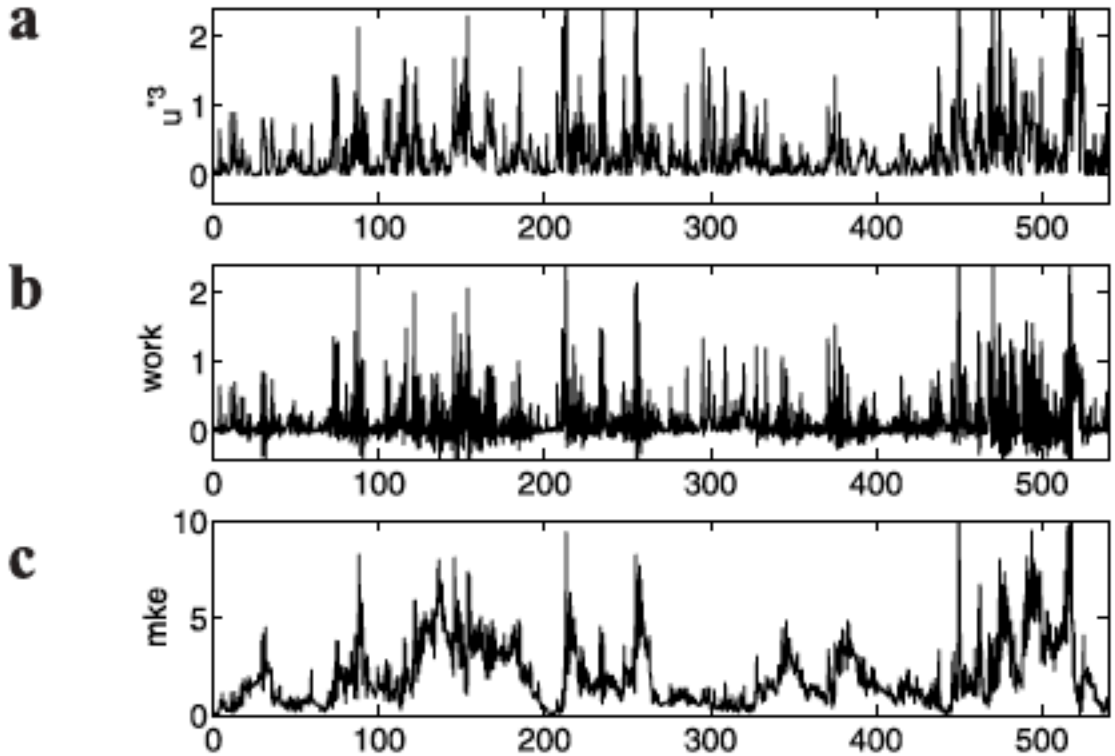


Figure 11. 6 hourly time sequence of the windstress curl (at 40° - 60° S, 75° - 135° E) estimated from only the NCEP data (upper panel), from blended winds generated with QSCAT only (middle panel) and with both QSCAT and ADEOS-II data (lower panel). [see http://www.cora.nwra.com/ morzel/blendedwinds.qscat.swsa2.html]. The dual blended winds agree very well with the location in NCEP, whereas the single blended winds are already 6hr ahead, placing the curl front too far to the East [e.g. *Milliff et al.*, 2004; *Chelton et al.*, 2004].

USING WIND OBSERVED EVERY 3 H ON A WEATHERSHIP (KILO) FOR MORE 530 DAYS:
STRONG INTERMITTENCY!



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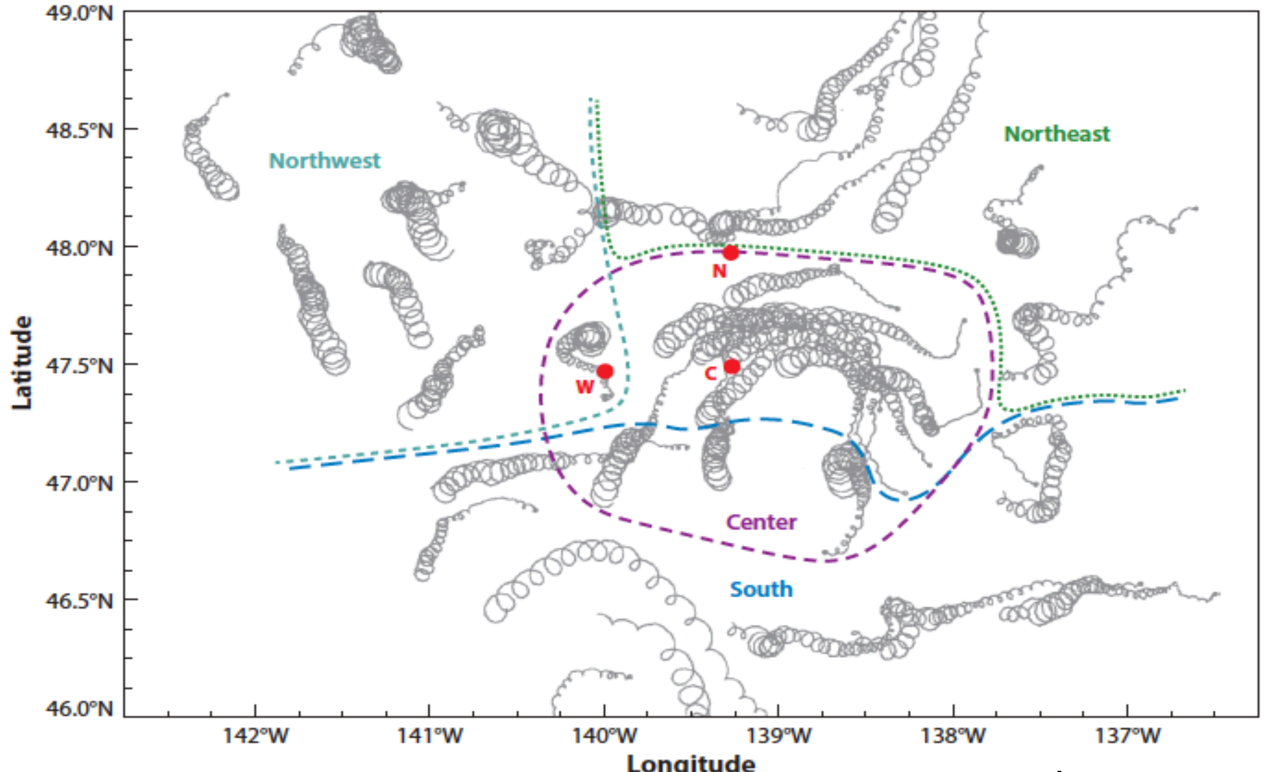
WHAT HAPPENS IF WE DO NOT TAKE INTO ACCOUNT PROPERLY THIS INTERMITTENCY?

Table 1. Statistics Over 540 Days of the Inertial Energy Integrated Over the Water Column (in $m^3\ s^{-2}$) Obtained With the 1-D Model

Simulations	Mean Inertial Energy	RMS Inertial Energy
3 hourly winds	2.03	1.70
6 hourly winds	1.65	1.38
12 hourly winds	0.62	0.56
24 hourly winds	0.28	0.28

NEAR-INERTIAL OSCILLATIONS: TRAJECTORIES DIFFER DEPENDING ON THEIR LOCATION RELATIVELY TO THE STORM



D'ASARO ET AL. JPO 1995

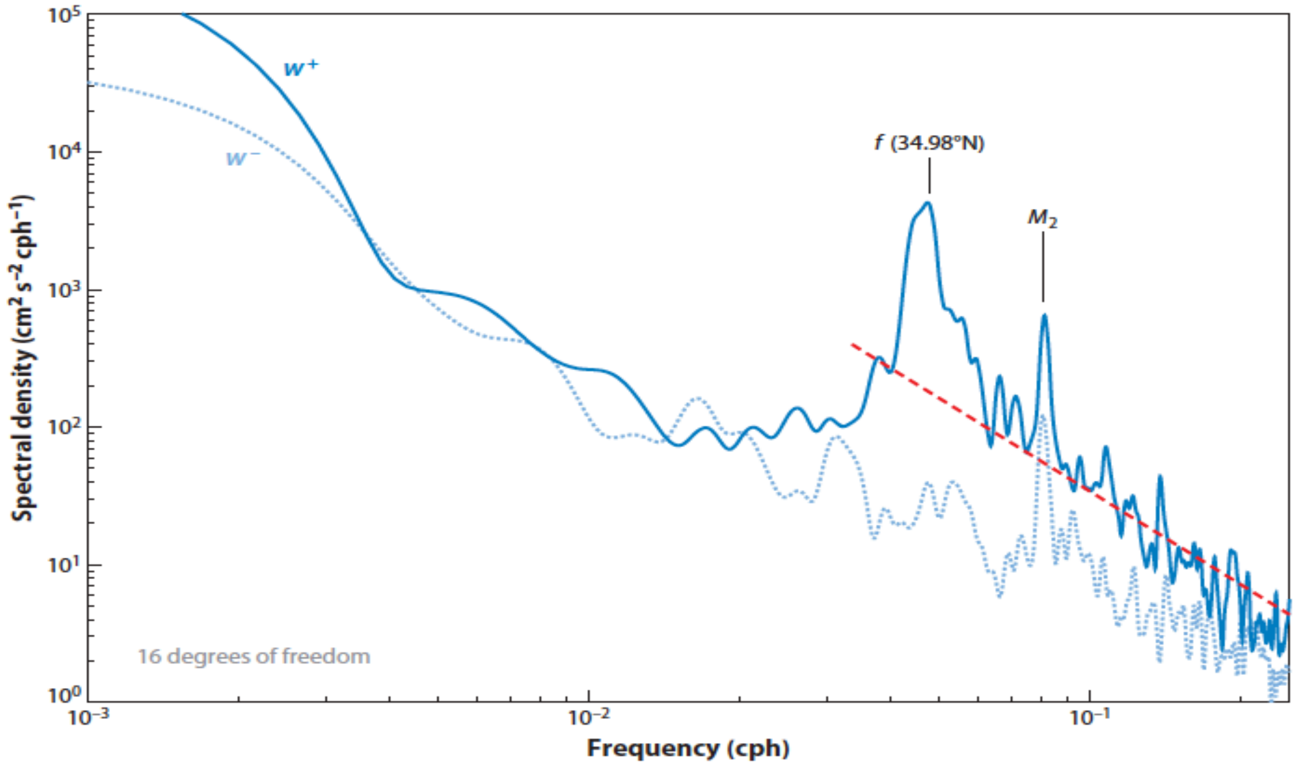
Figure 2

Drifter tracks in the Ocean Storms Experiment, showing near-inertial trajectories following a midlatitude storm. The dashed lines represent geographic regions: center (*purple*), northeast (*green*), northwest (*teal*), and south (*blue*). The red dots are moorings (C, center; N, north; W, west). Modified from D'Asaro et al. (1995).

THE WIND INTERMITTENCY EXPLAINS THE INHOMOGENEITY OF THE SURFACE DRIFTER TRAJECTORIES DURING THE OCEAN STORM EXPERIMENT. **MOST TRAJECTORIES ARE CLOCKWISE.**

CLOCKWISE MOTIONS ARE MORE ENERGETIC THAN ANTICLOCKWISE MOTIONS

INTERNAL WAVE ENERGY IS PROPAGATING DOWNWARD (why? see next classes)



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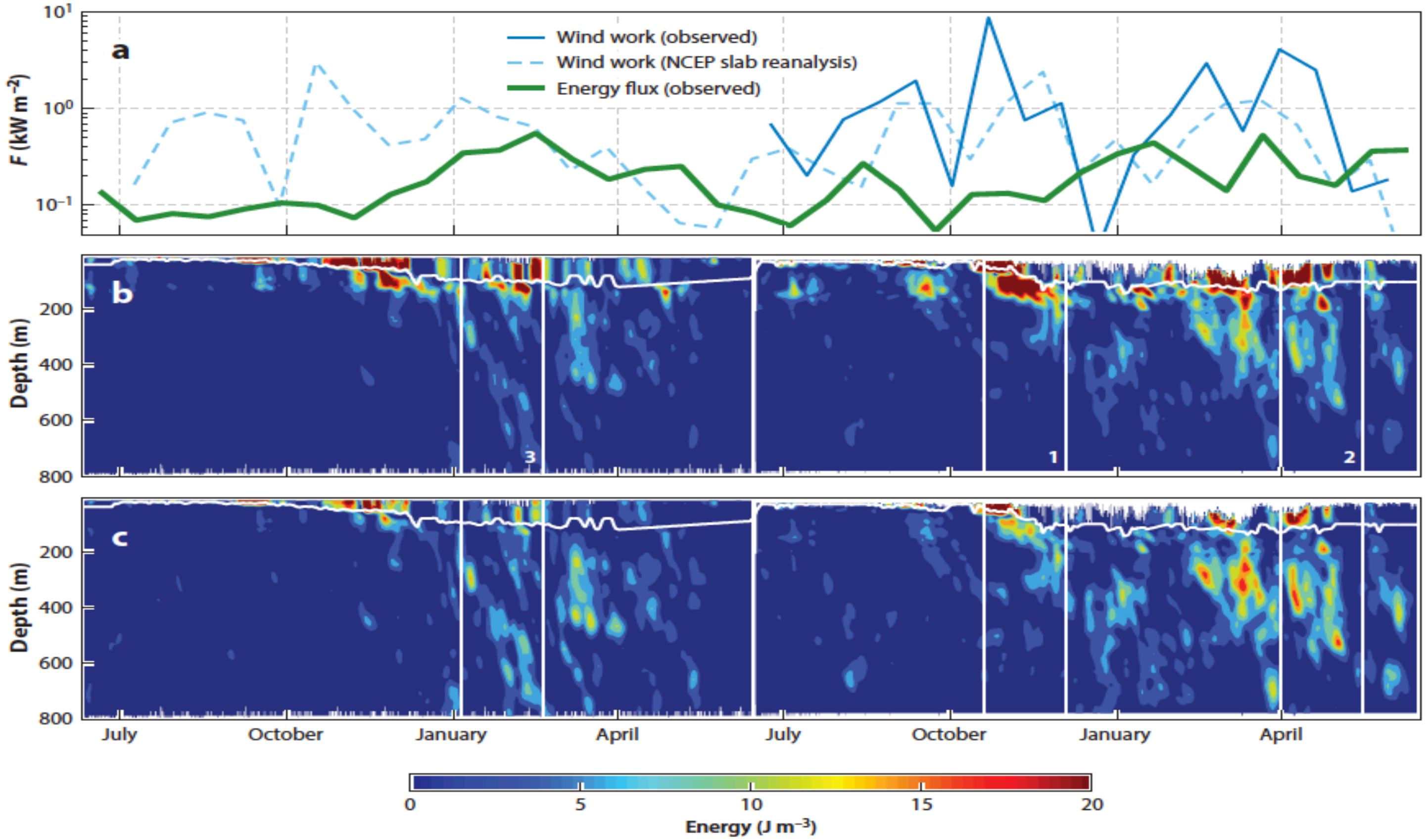


Figure 5

Near-inertial waves at Ocean Station Papa. (*a*) Wind work from observations (*solid blue line*) and from Equation 2 forced with reanalysis winds (*dashed blue line*), along with observed energy flux computed as the mean of energy from 600 to 800 m multiplied by $c_{gz} = 1.03 \times 10^{-4}$ m s^{-1} (9 m d^{-1}; *thick green line*). All three lines have been smoothed over 20 days. (*b*) Near-inertial kinetic energy for the whole two-year record. (*c*) The same as panel *b* but additionally accounting for WKB refraction. In panels *b* and *c*, the mixed-layer depth is overplotted in white. Abbreviations: NCEP, National Centers for Environmental Prediction; WKB, Wentzel, Kramers, Brillouin. Modified from Alford et al. (2012).

NEAR-INERTIAL WAVES: STRONG VERTICAL SHEAR (HIGH BAROCLINIC MODES)

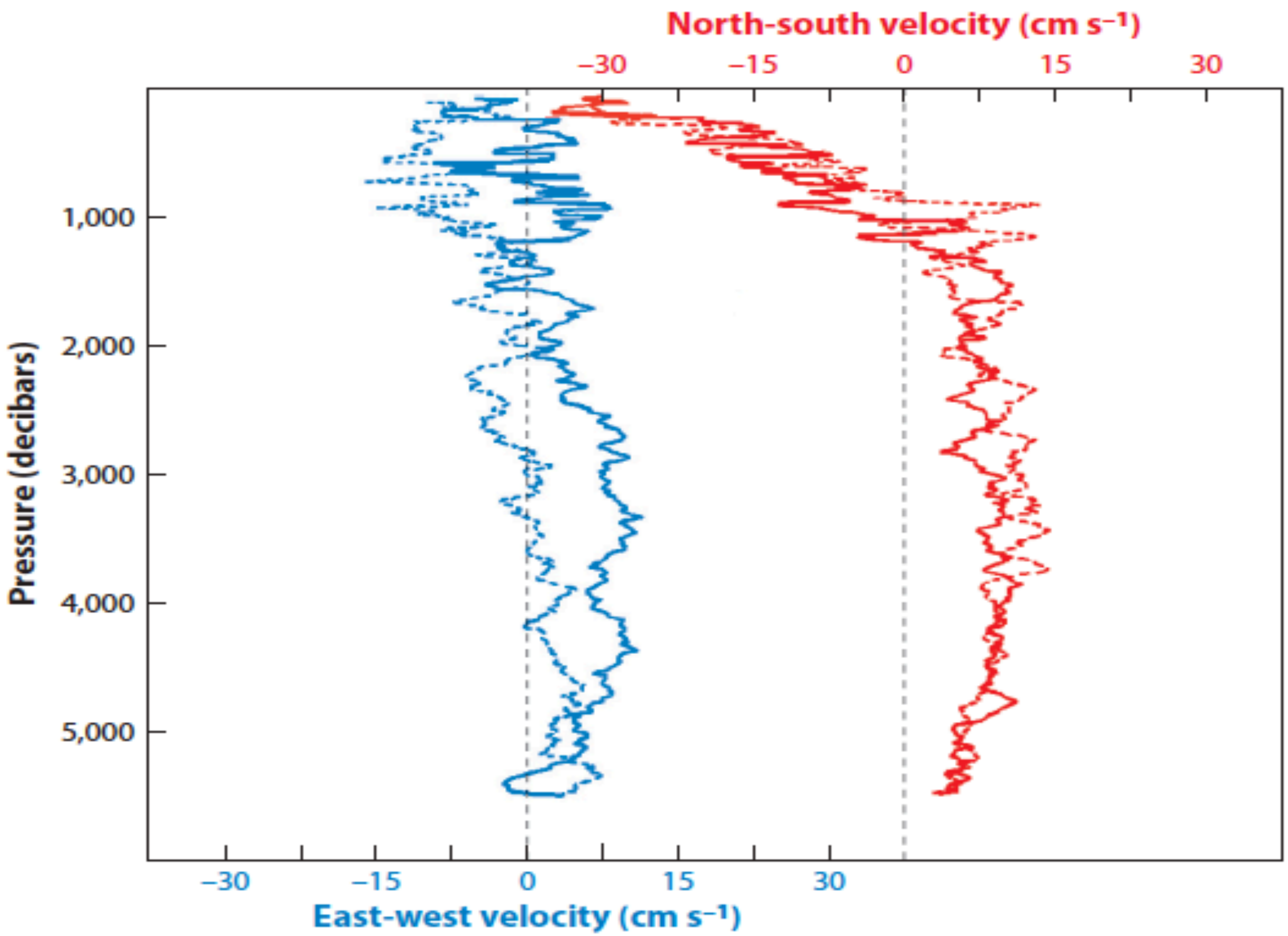


Figure 3

Two profiles (*dashed* and *solid lines*) of east-west (*blue*) and north-south (*red*) velocity taken at an interval of half an inertial period, showing high-wavenumber near-inertial motions. Modified from Leaman & Sanford (1975).

NEAR-INERTIAL WAVES: STRONG SEASONALITY

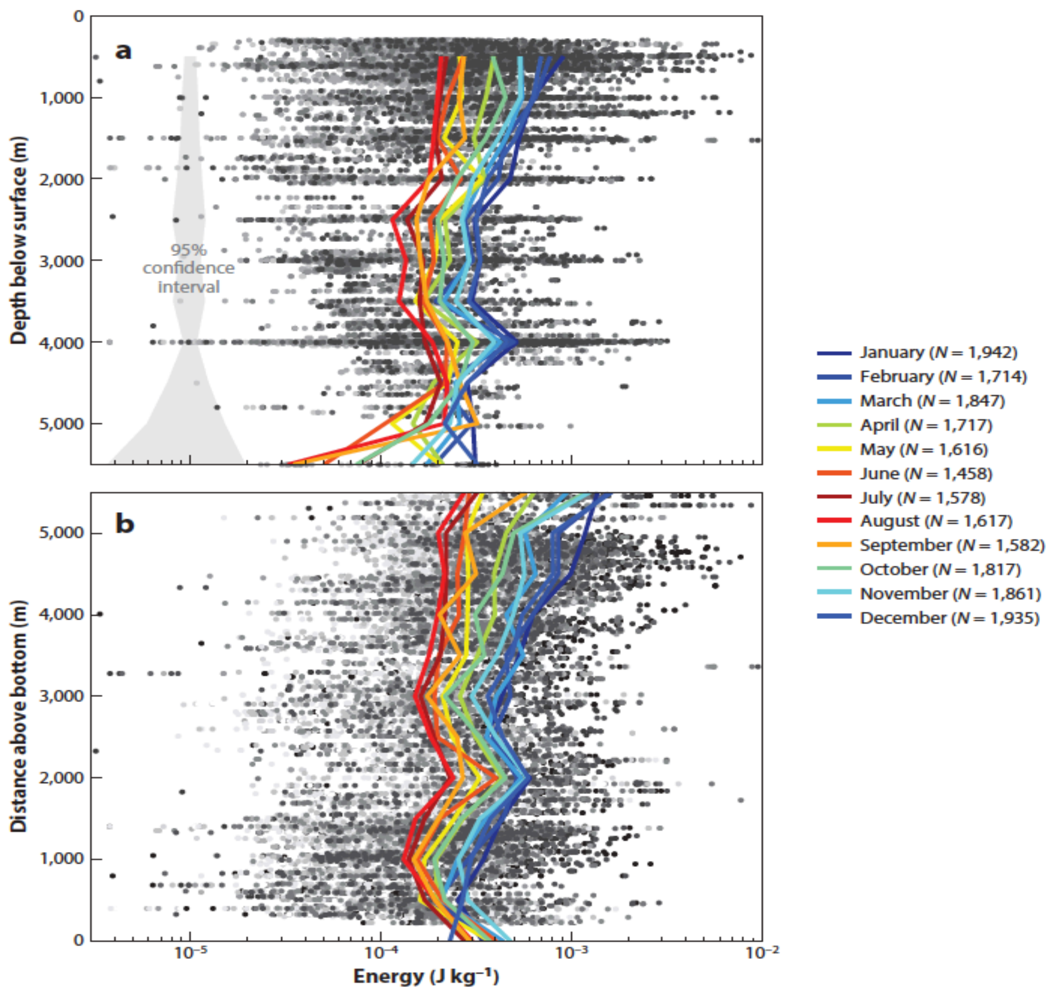


Figure 6

Northern Hemisphere WKB-scaled near-inertial kinetic energy plotted versus (*a*) depth below the surface and (*b*) distance above the bottom. Individual 30-day estimates are plotted with dots, with lighter shades for summer months. Colored lines indicate the 500-m boxcar average for each month; the legend additionally indicates the number of observations in each month. The gray area on the left side of panel *a* shows the 95% confidence intervals on the mean computed using the number of observations in each depth range. Abbreviation: WKB, Wentzel, Kramers, Brillouin. Modified from Alford & Whitmont (2007).

WATANABE AND HIBIYA GRL 2002

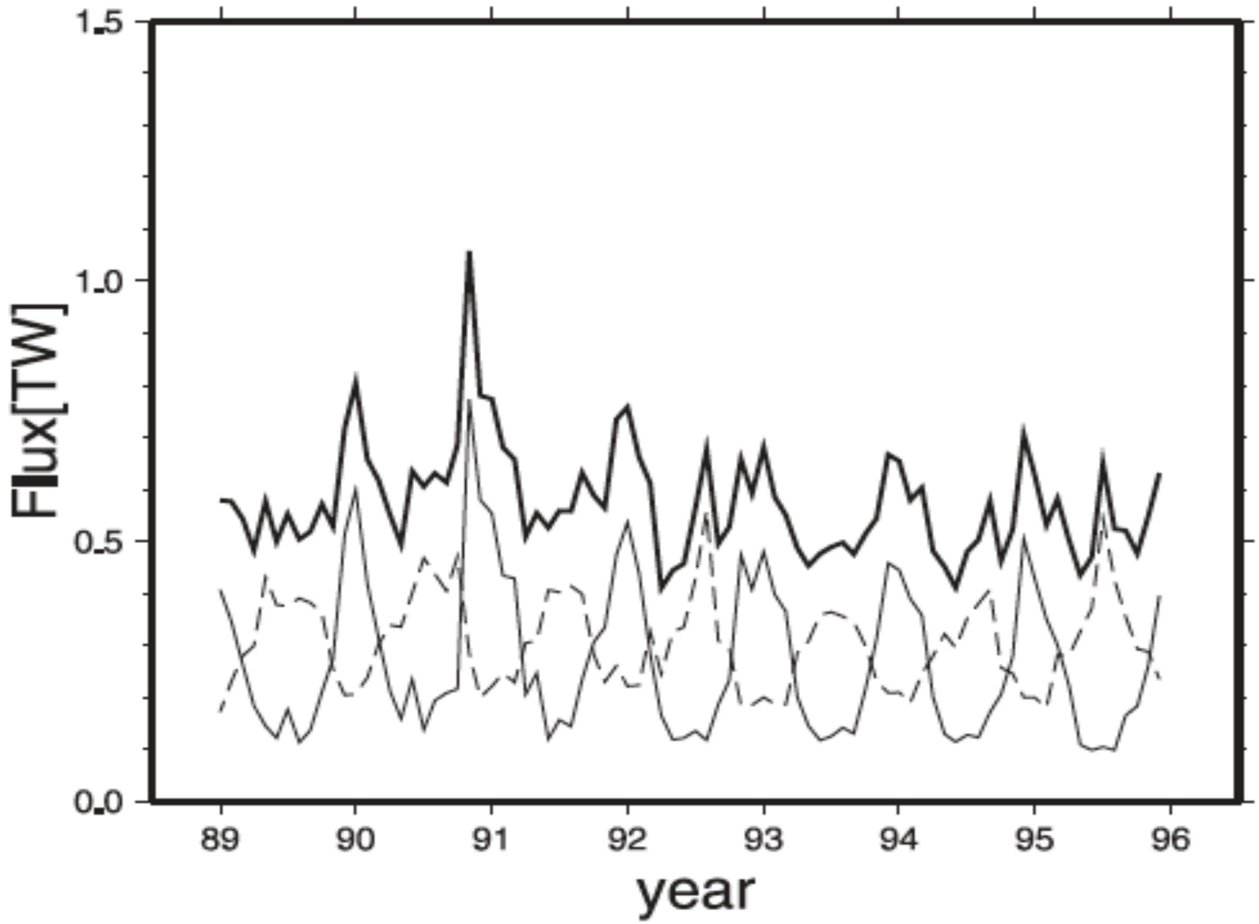


Figure 2. The time variation of the global inertial energy flux (heavy solid line) over the period of 1989–1995 for the case corresponding to Figure 1. The time variation of inertial energy flux in the northern hemisphere (light solid line) and that in the southern hemisphere (dashed line) are also shown.

DO NEAR-INERTIAL WAVES INTERACT WITH THE MESOSCALE/SUBMESOSCALE TURBULENCE ?

YES !

A near-inertial mode observed within a Gulf Stream Warm-Core Ring (anticyclonic): Joyce et al. JGR 2013

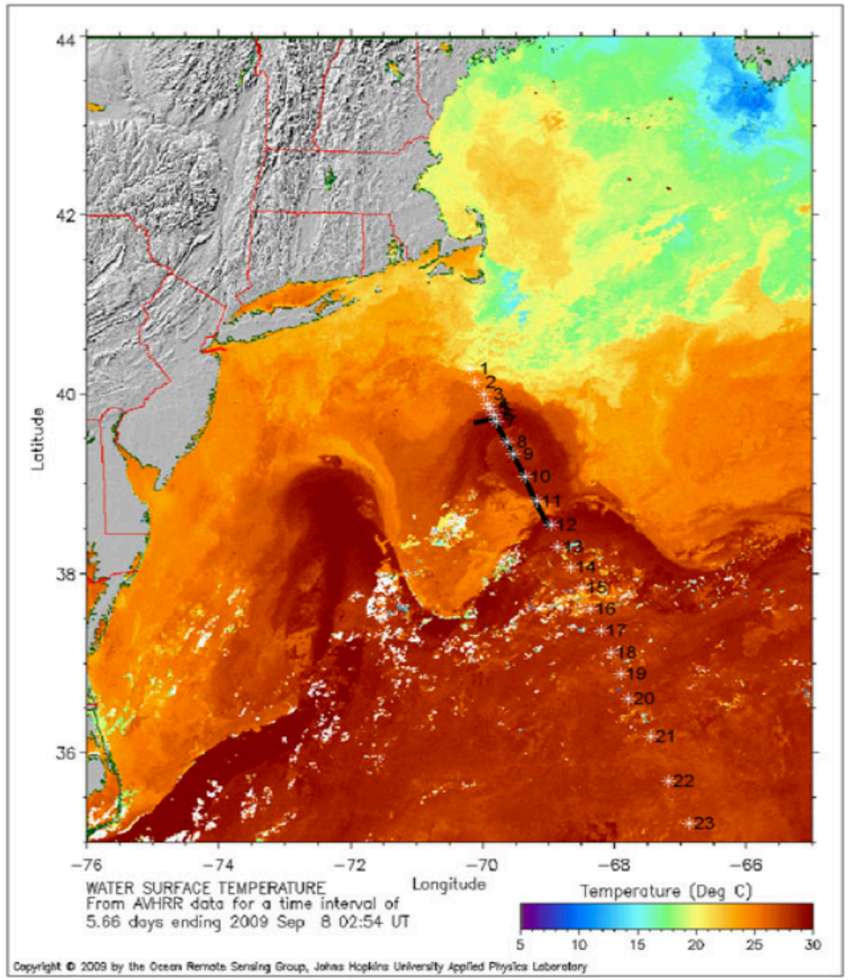


Figure 1. Stations (white asterisks with black numbers) were taken on the way south toward Bermuda (stations 24–26, off page). The return section through the WCR (mostly on 9 September 2009, about 1 week after the CTD stations in the WCR on the way south; black line) is indicated. Infrared sea surface temperature (SST) data (in color) are from *Fermi.JHUAPL*. While SST contrasts at this time of year are usually masked by broadscale warming, one can easily see the north wall of the Gulf Stream and two mostly separated warm-core rings at the crest of adjacent GS meanders. Our Line W section passed through the middle of the easternmost WCR on both legs.

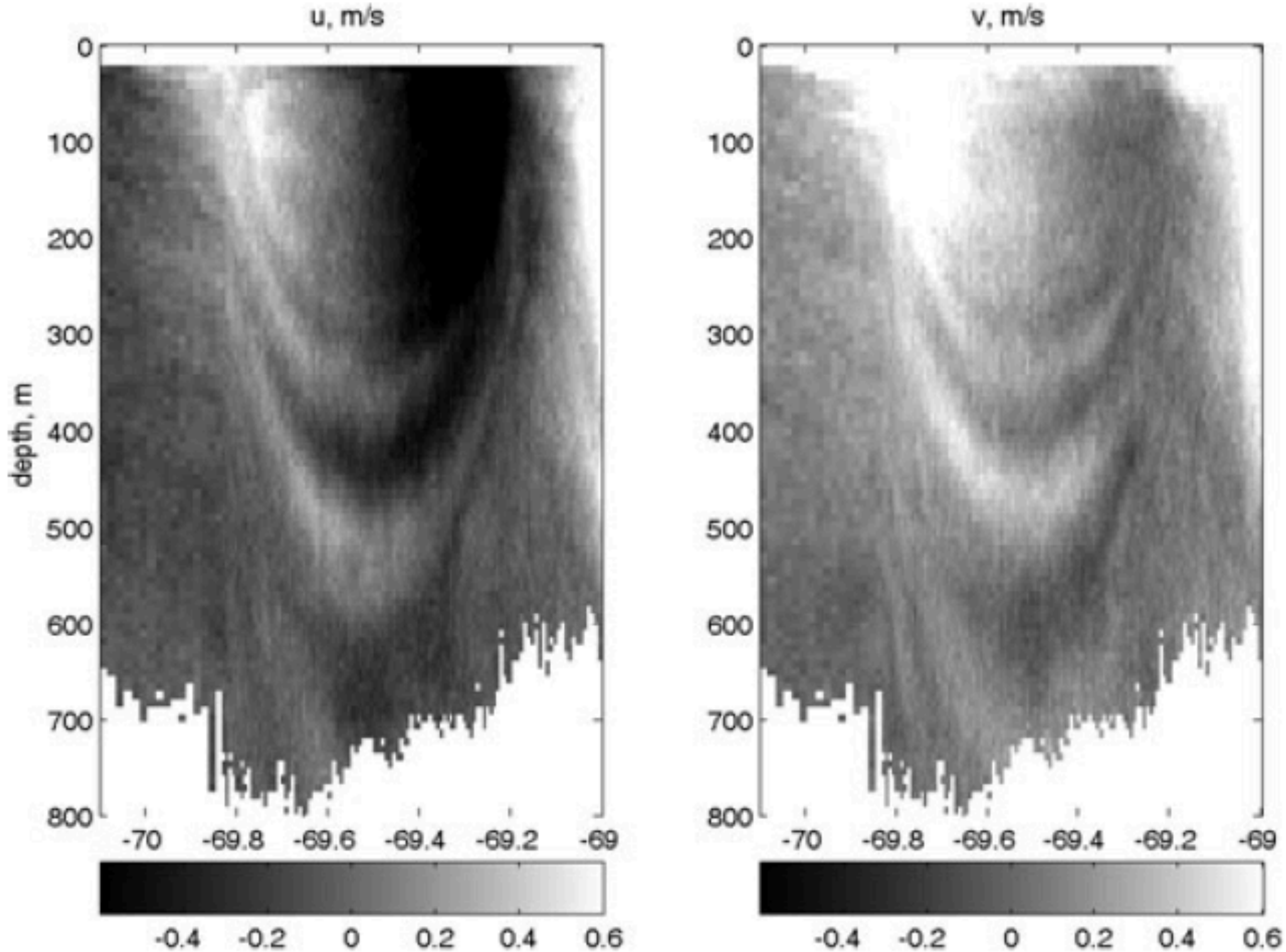


Figure 2. Grey-scale images of SADCP velocity data (zonal component on the left panel and meridional component on the right panel) plotted against longitude showing vertical banding of 100–200 m wavelength within the center of the WCR (Figure 1) with strong WSW flow on the seaward side (69.3°W) and NNW flow on the shoreward side (69.8°W). The phase of the vertical banding slopes up on both flanks of the WCR.

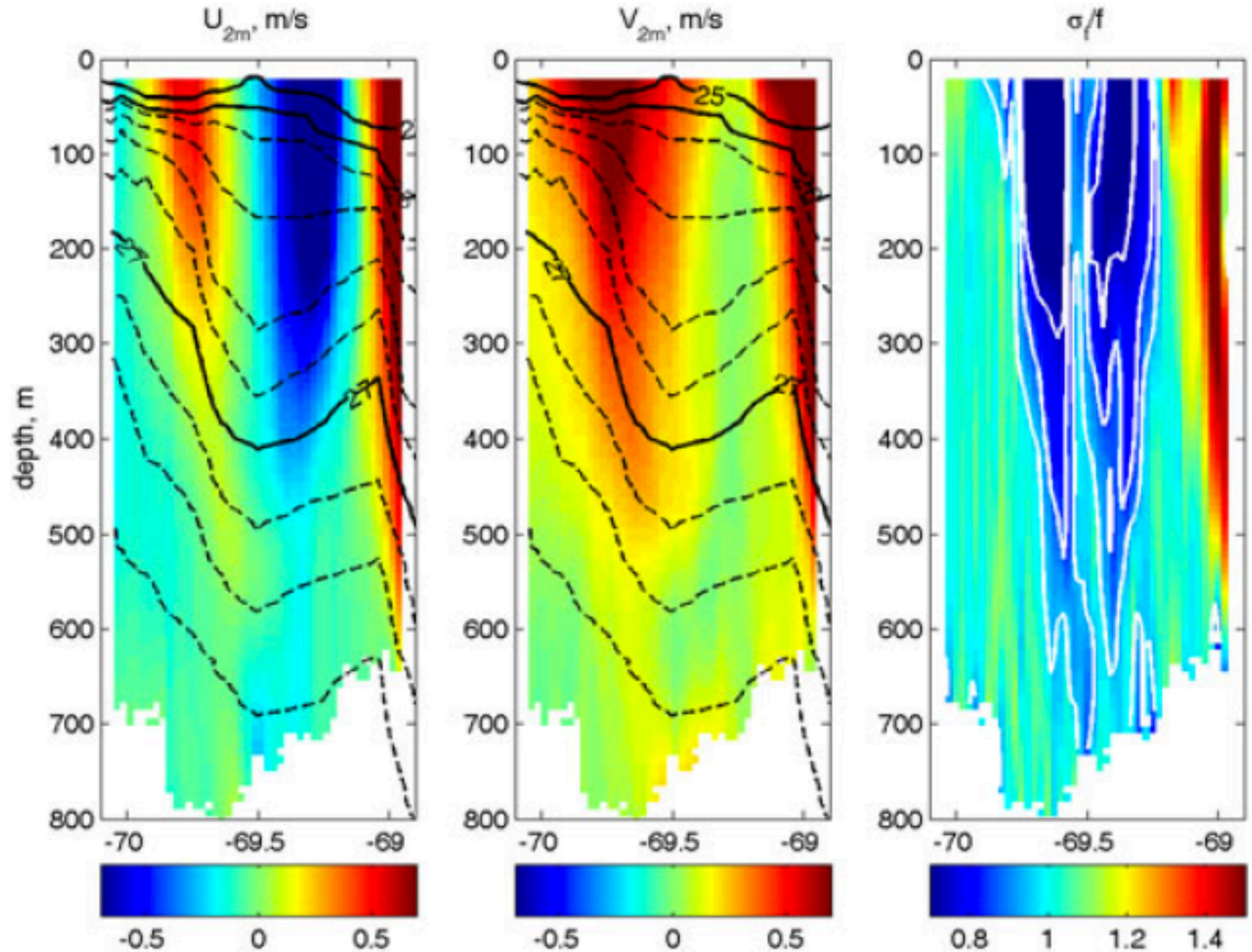


Figure 4. Smoothed velocity components and vortex-modified inertial frequency associated with the circulation of the WCR. In the latter, the white contours illustrate the sub-inertial structure of σ_f/f (equation (B10), contours of 0.75, 0.85, and 0.95), and this can be seen to encompass the region of anomalous velocities and spice (see Figure 5) within the WCR.

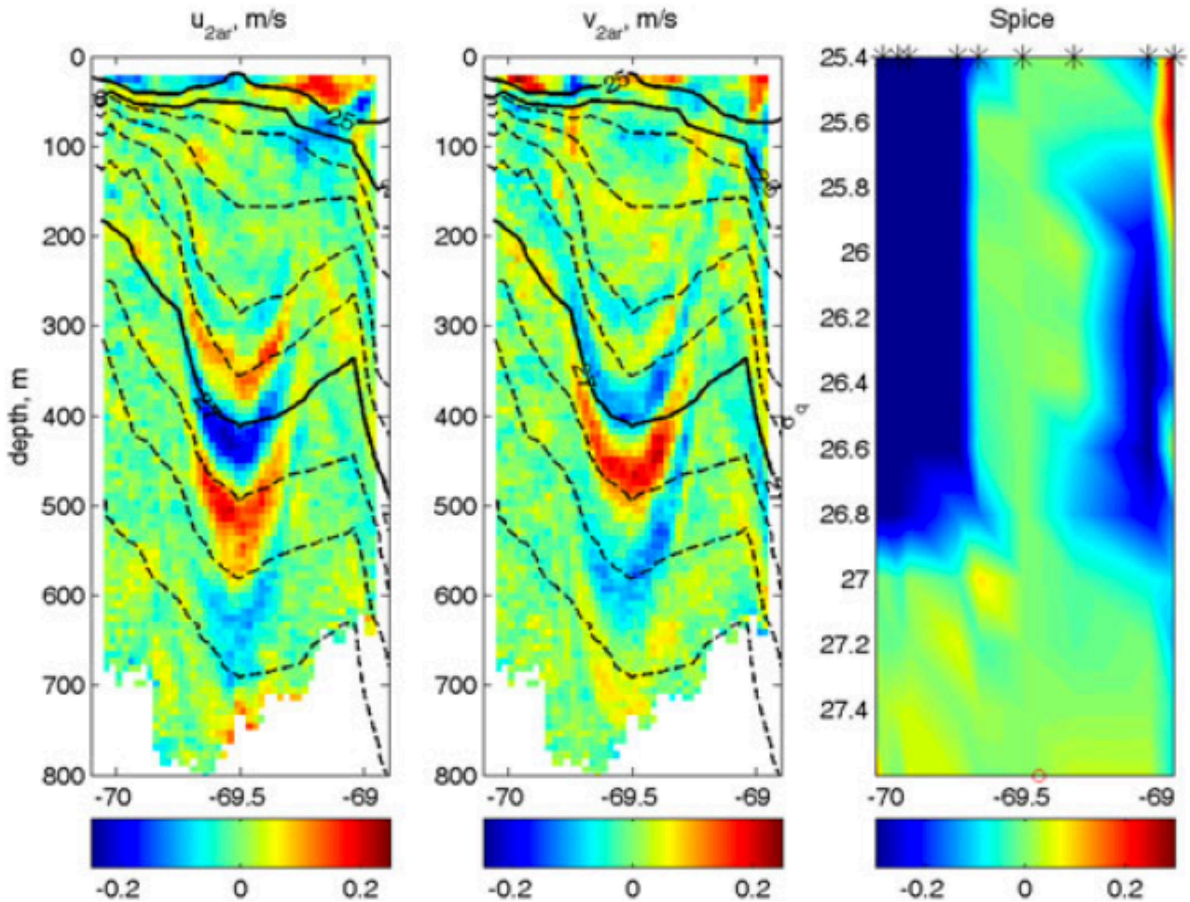


Figure 5. Phase-adjusted anomalies of velocity and spice (relative to ring center; right panel). During the velocity anomaly phase adjustment, the upward phase propagation altered the rotated velocity anomalies, and the constant phase lines (Figure 2) moved slightly upward on the right and downward on the left of ring center. Also plotted are constant σ_θ surfaces at a 0.2 kg m^{-3} contour interval. Solid lines denote the 25, 26, and 27 σ_θ surfaces. These are from the CTD stations taken on the seaward leg and have been shifted westward in longitude an amount of 0.13° to account for translation of the WCR between the two legs of the cruise. The Gulf Stream north wall can be seen intruding at the far right of all panels, consistent with the contact between the Gulf Stream and WCR indicated in Figure 1. The vertical axis is depth for the left and middle panels and σ_θ for the right panel. Longitude of the mooring W2 is indicated by the open circle at the bottom of the right panel.

NEAR-INERTIAL WAVES OBSERVED ON A GLOBAL SCALE WITH SURFACE DRIFTERS

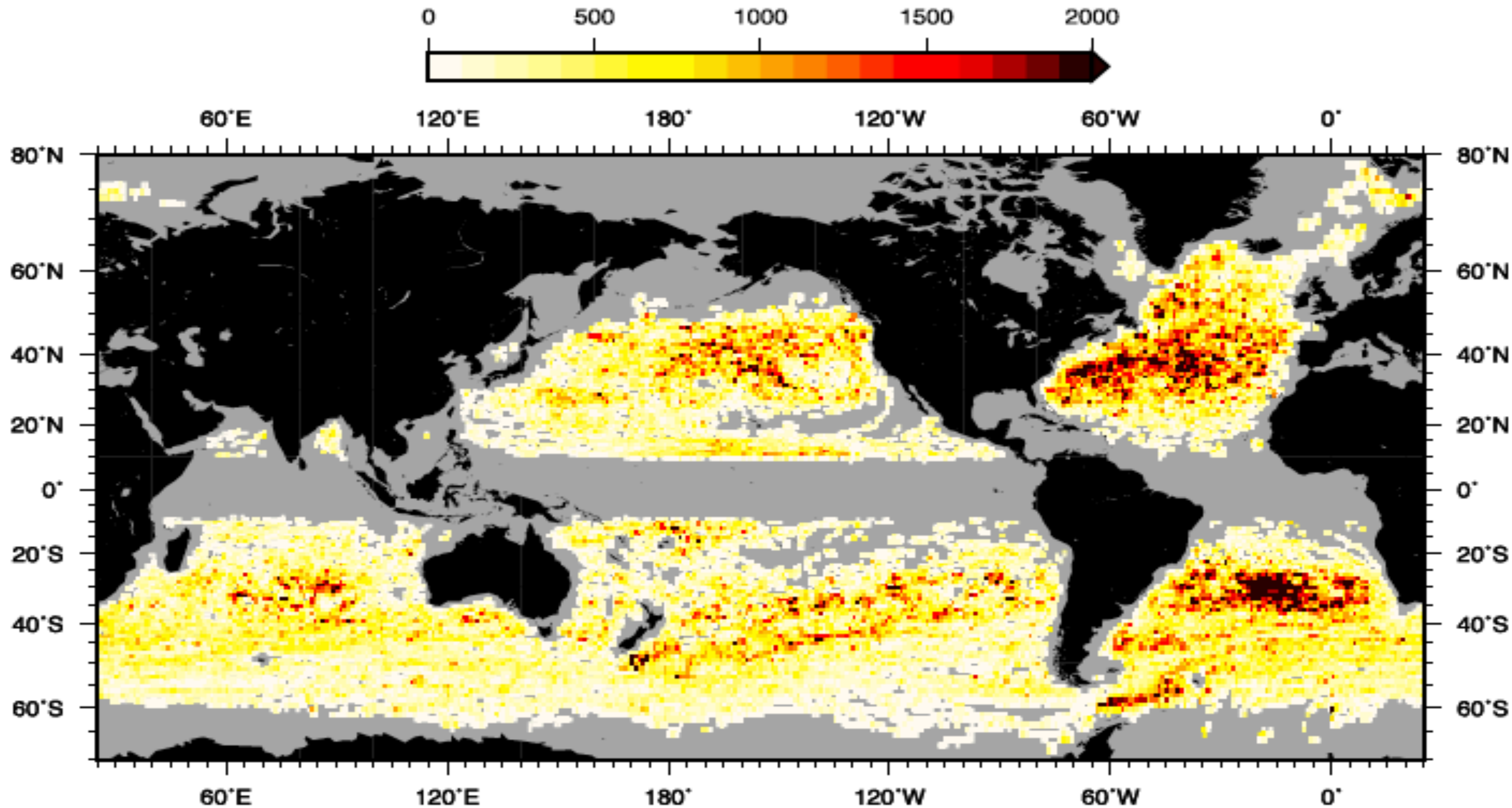
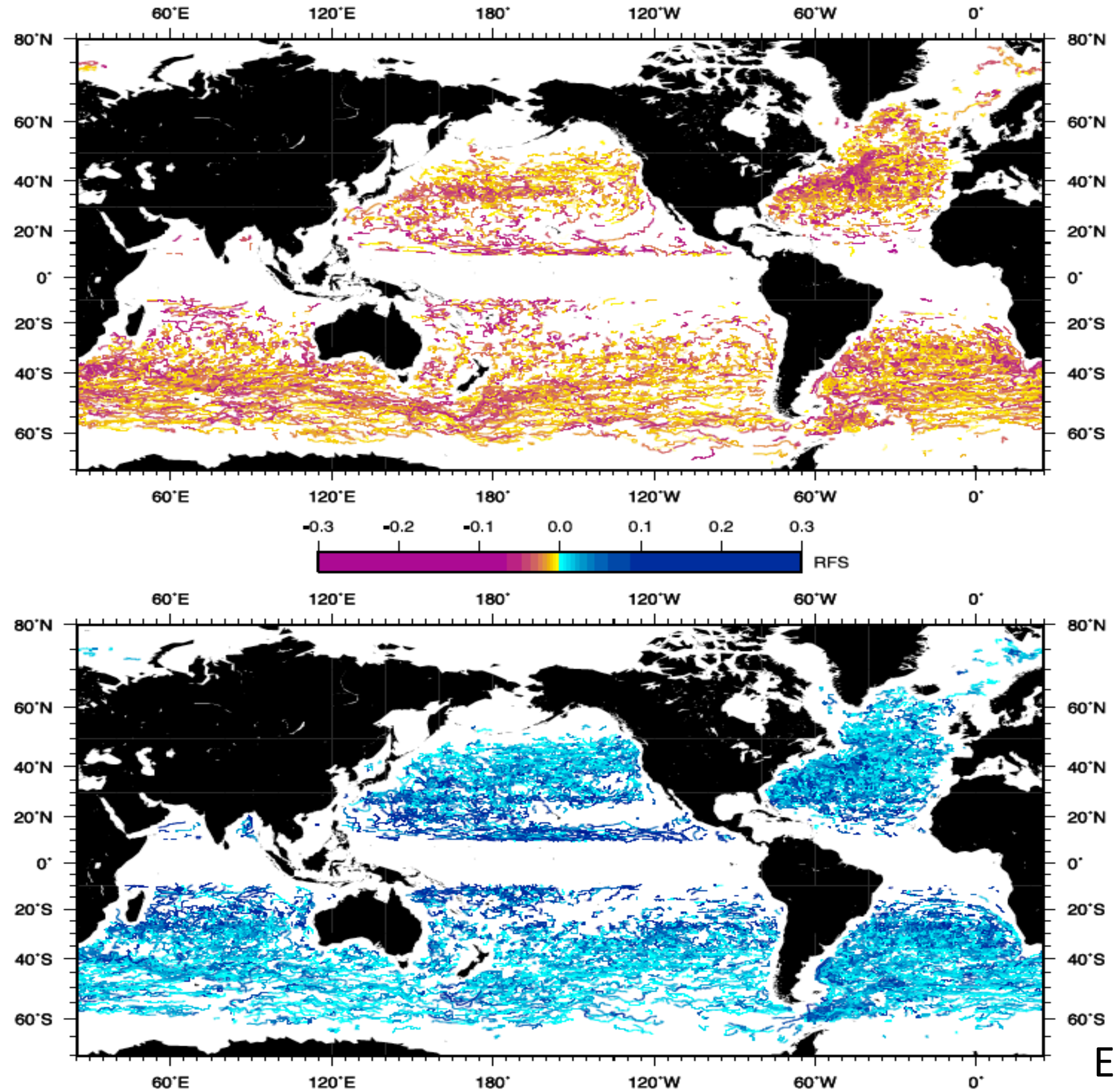


Figure 1. Number of hourly velocity observations in 1° bins. Gray indicates absence of data or areas were no data were selected for the analysis.

Elipot et al. 2010

NEAR-INERTIAL WAVES OBSERVED WITH SURFACE DRIFTERS ON A GLOBAL SCALE: THESE WAVES ARE AFFECTED BY THE RELATIVE VORTICITY OF MESOSCALE EDDIES (see next classes)



Elipot et al. 2010

Figure 7. The 20 day trajectory segments color coded for their RFS. (top) Negative relative frequency shift and (bottom) positive relative frequency shift.

TIDAL MOTIONS

(NEXT CLASS …)