Ocean waves as sources of seismic and acoustic noise

Fabrice Ardhuin

Laboratoire d'Océanographie Spatiale, Ifremer, Brest, France
http://wwz.ifremer.fr/iowaga

Ifremer

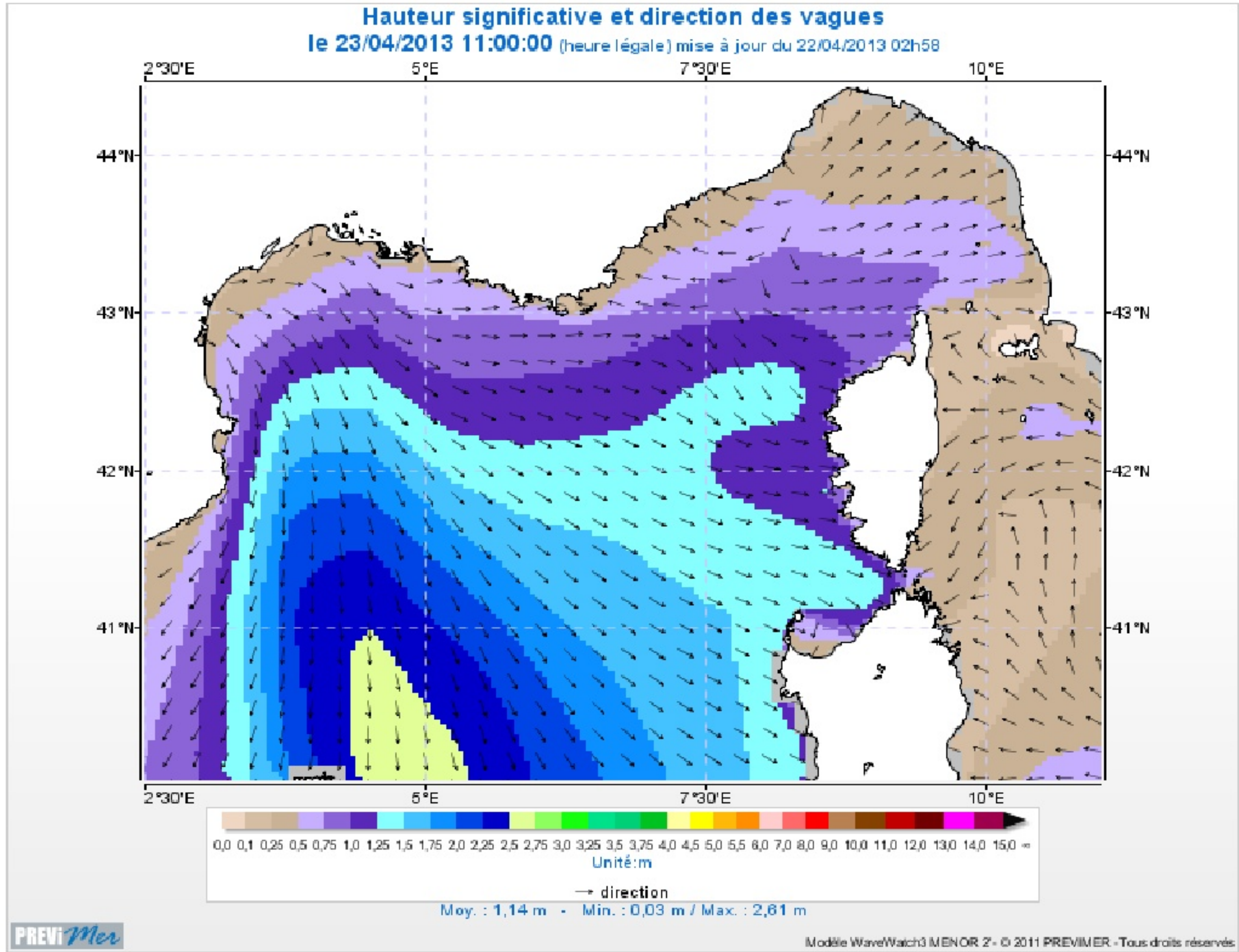
With the direct support of the European Research Council, the U.S. Office of Naval Research, CNES and Labex Mer

post-docs and research professorship now open

Ocean waves …

The forecast for today …
(issued Sunday)

(www.previmer.org)



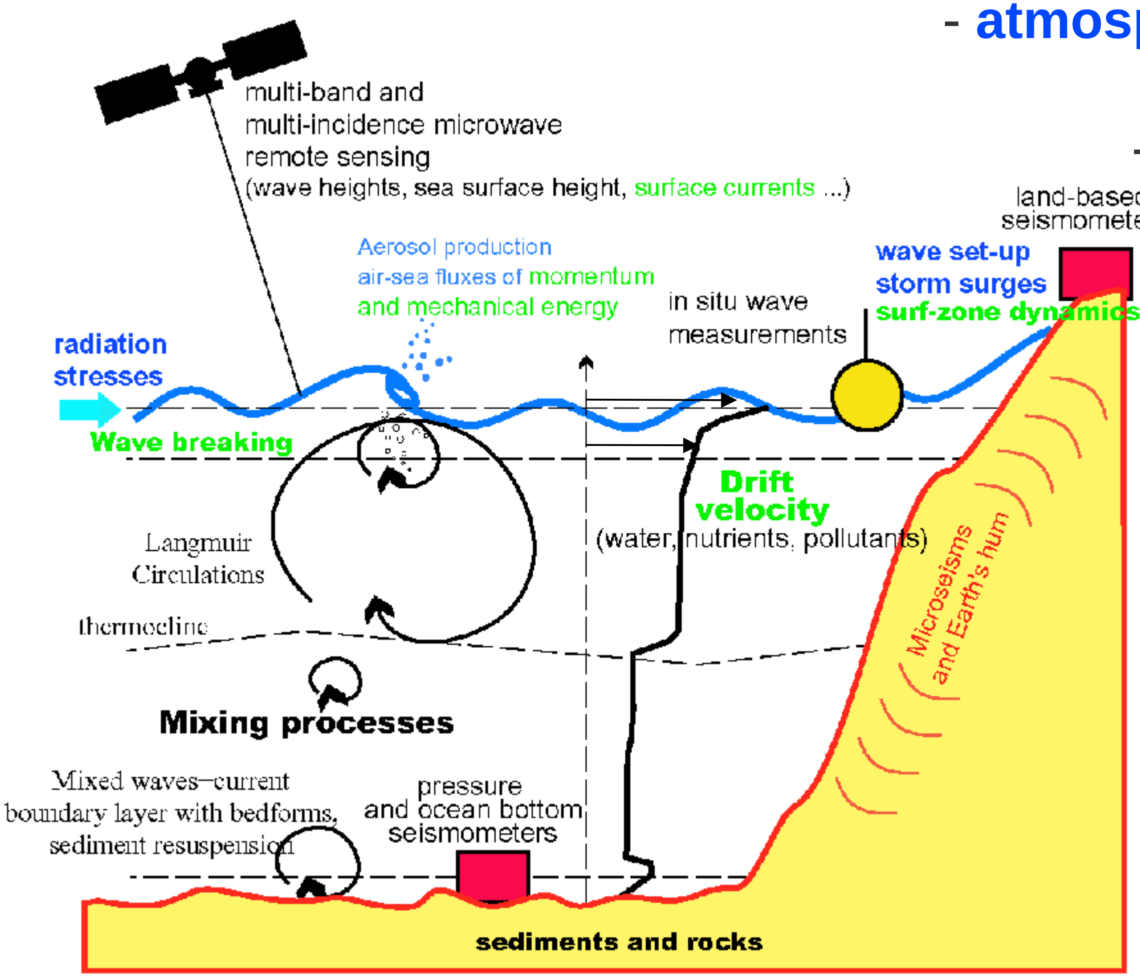
but there is more to waves than just wave heights …

Ocean waves …

Ocean waves uniquely connect Earth System components

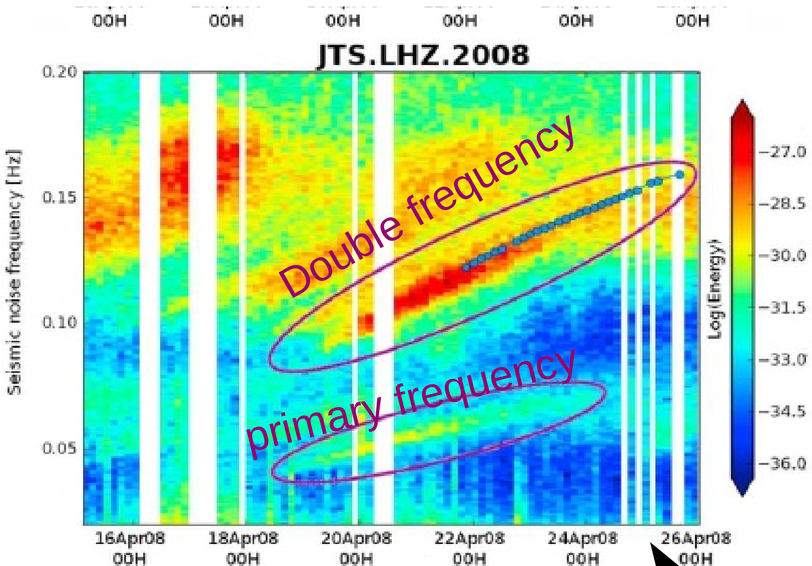
- **atmosphere** and **oceans**
- **oceans** and **land**
- **oceans** and **solid Earth**

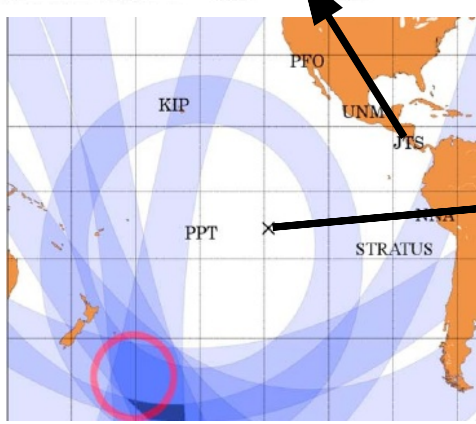
+ remote sensing
+ ocean engineering



Ocean waves …

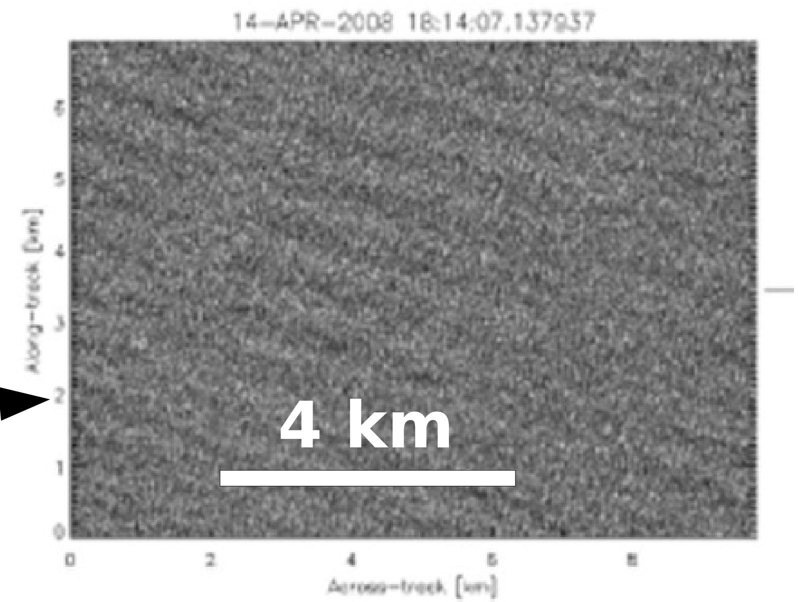
How I got into noise …: first the “climate chage paper” of Grevemeyer et al. (2000), then looking at some data …





Seismic record contain wonderful data about ocean waves, here a swell event...

Same swell field in radar imagery



(from Husson et al. GRL 2012)

Outline

1. **Ocean wave properties**
2. **From waves to acoustic and seismic noise : Sources**
3. **From waves to acoustic and seismic noise : Resulting noise**
4. **A few words on infragravity waves and hum**
5. **Perspectives & conclusions**

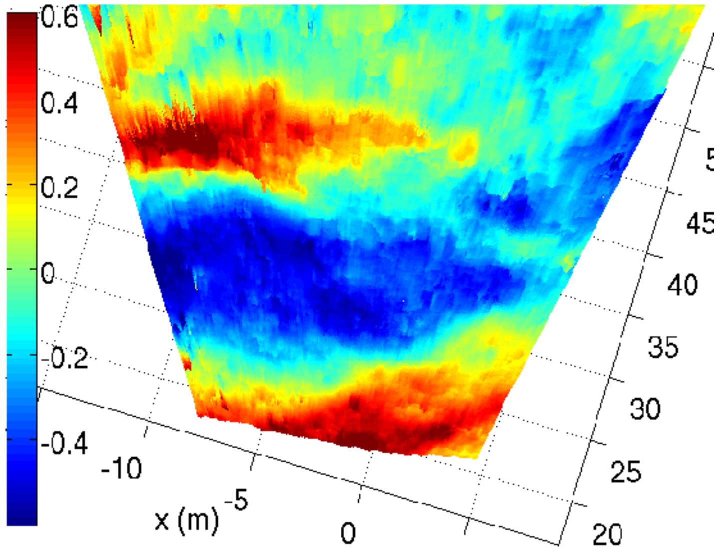
1

Ocean wave properties

1. Ocean wave properties

Winds generate waves that are irregular and broad-banded in frequency

Even if the wind is steady, the resulting waves have a wide range of propagation directions.



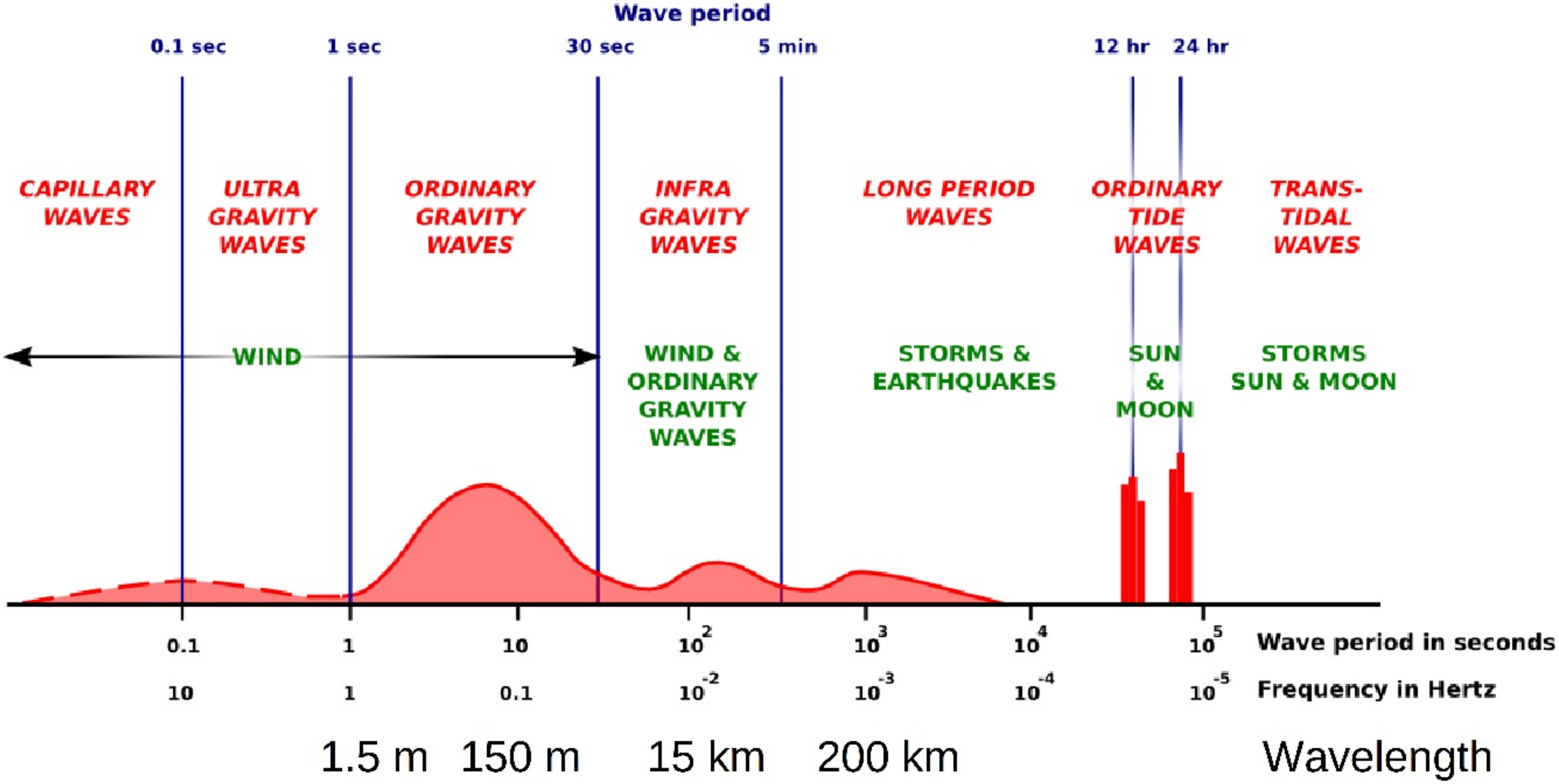
Sea surface elevation (from stereo video system)

One of the two images of the stereo pair

1. Ocean wave properties

Frequency spectra

Ocean waves in context : periods and wavelengths

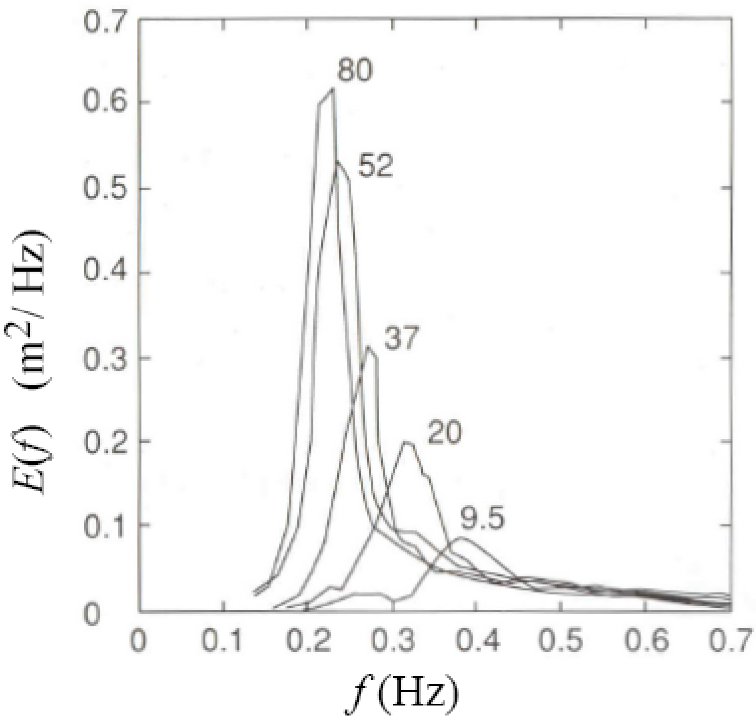


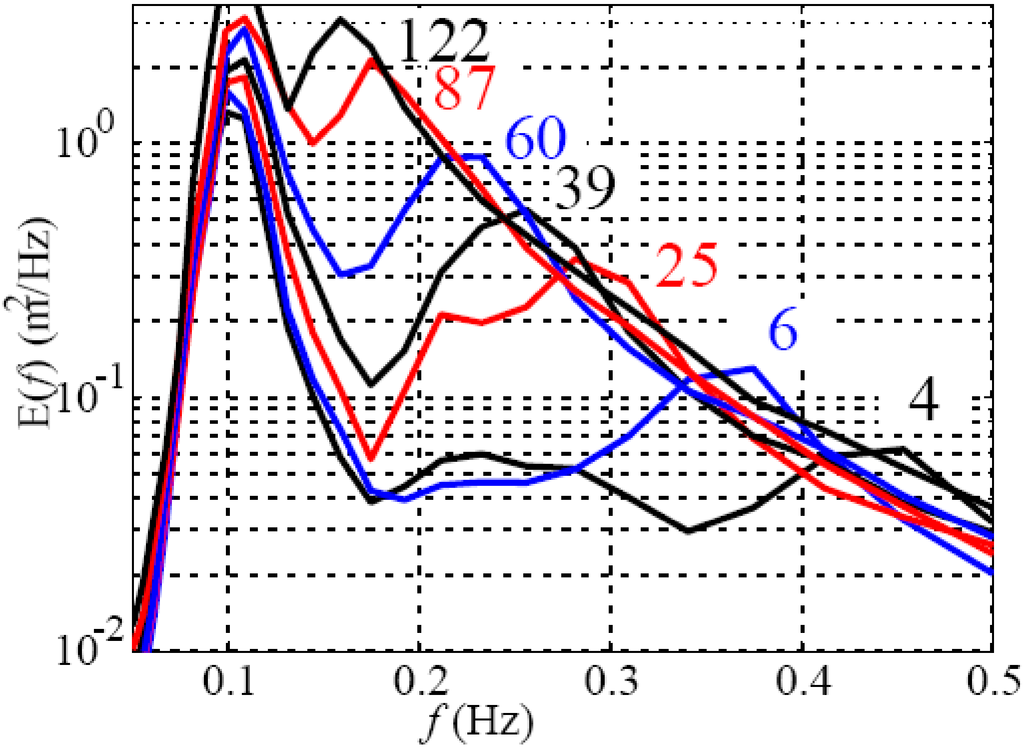
adapted from Walter Munk (1950)

1. Ocean wave properties

Frequency spectra

Example of wave spectra (Hasselmann 1973, Ardhuin et al. 2007)
development with fetch



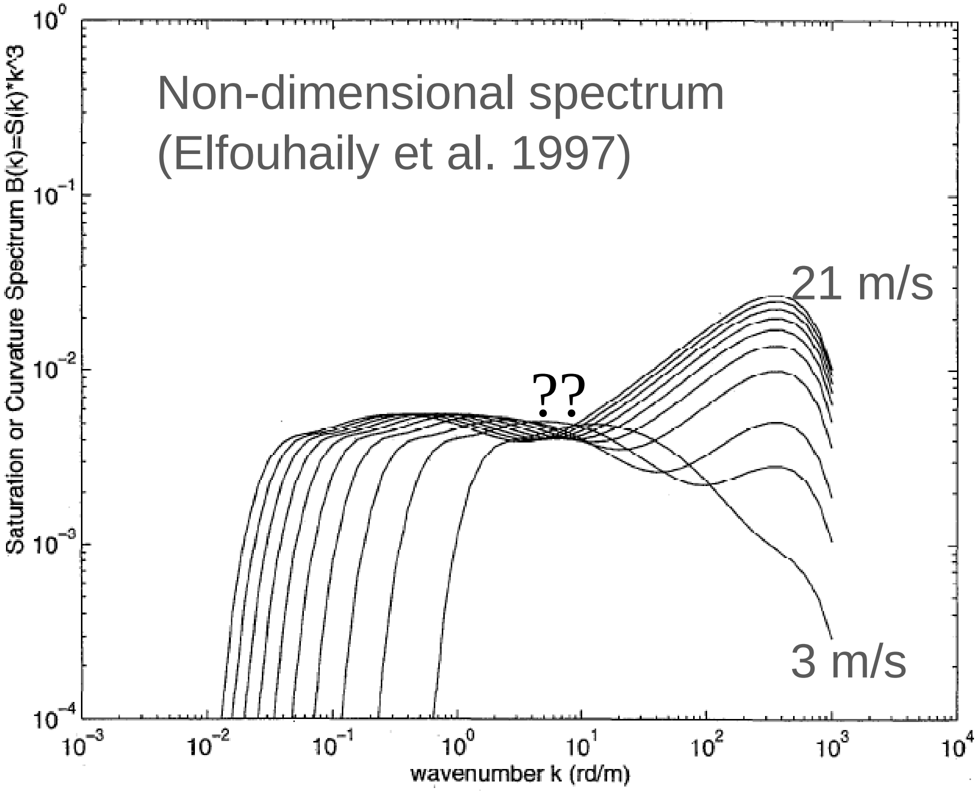


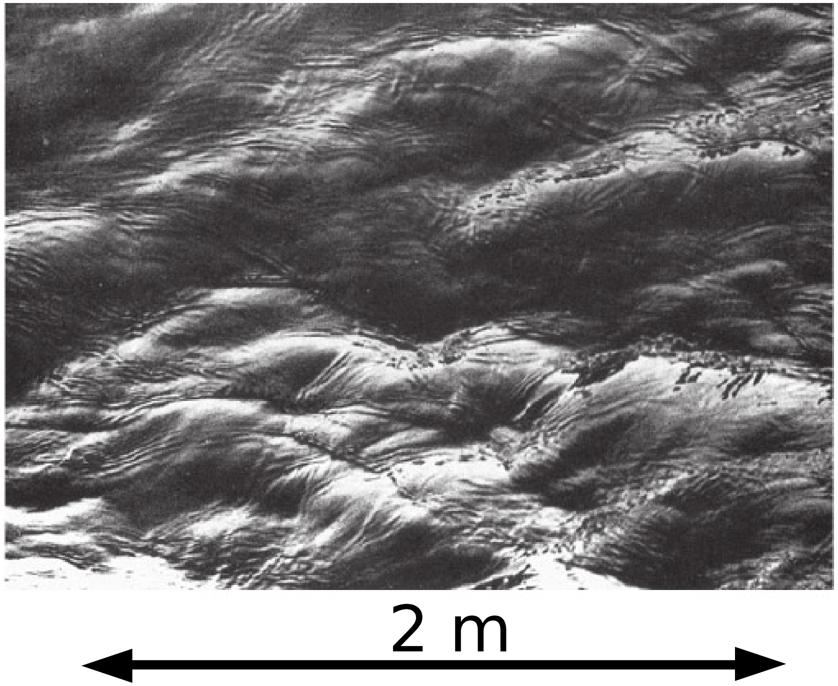
HF roll-off : f^-5 due to wave breaking (limited steepness)
LF roll-off : spectral peak corresponds to speed < 1.3 wind speed.
« Infragravity components » : results of nonlinear wave-wave interactions

1. Ocean wave properties

Frequency spectra

At high frequencies (f > 1 Hz) the shape of the wave spectrum is still a mystery (Munk 2009), despite its importance for remote sensing (wind …)





Can we use acoustic noise for this ? (Farrell & Munk 2008, 2010, 2013 …)

1. Ocean wave properties

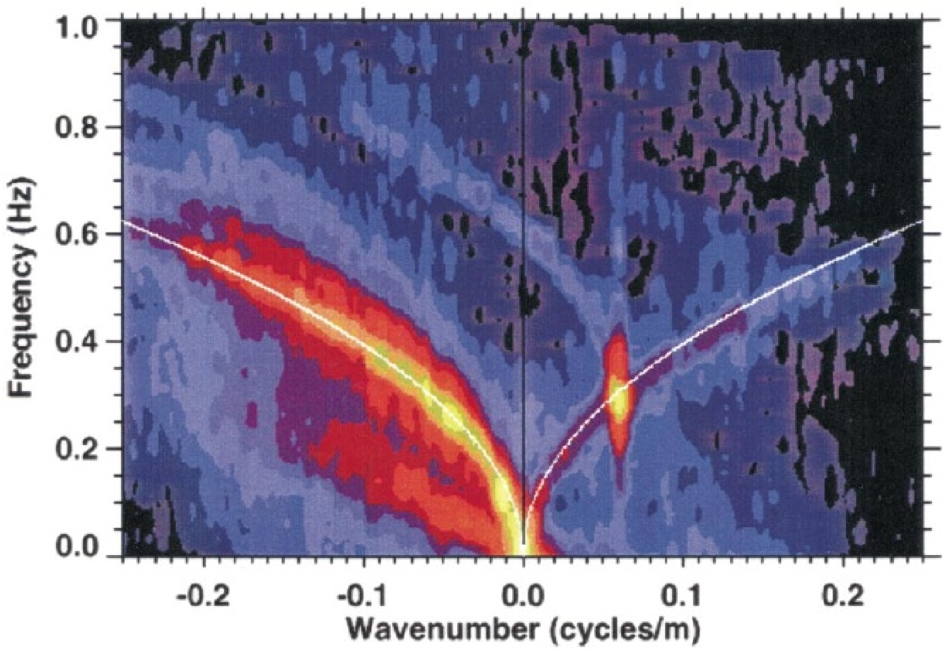
Frequency-wavenumber spectra

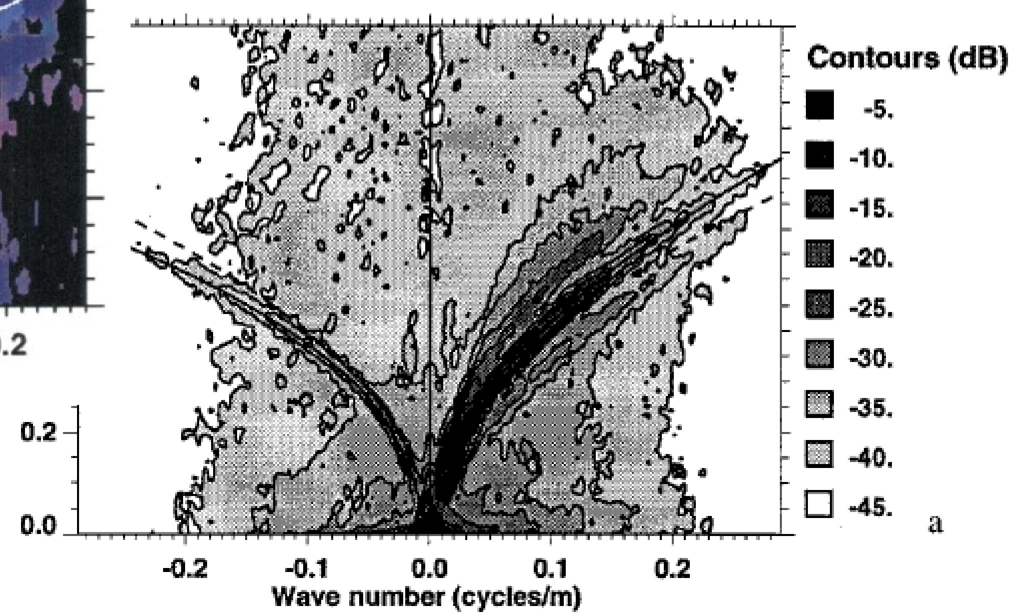
Most of the energy lies very close to the linear dispersion relation :

(2 pi /T)^2 = g (2 pi / L)
→ C = g T/ (2 pi)

valid for « deep water waves »
L/D < 0.5
and in **homogeneous** conditions

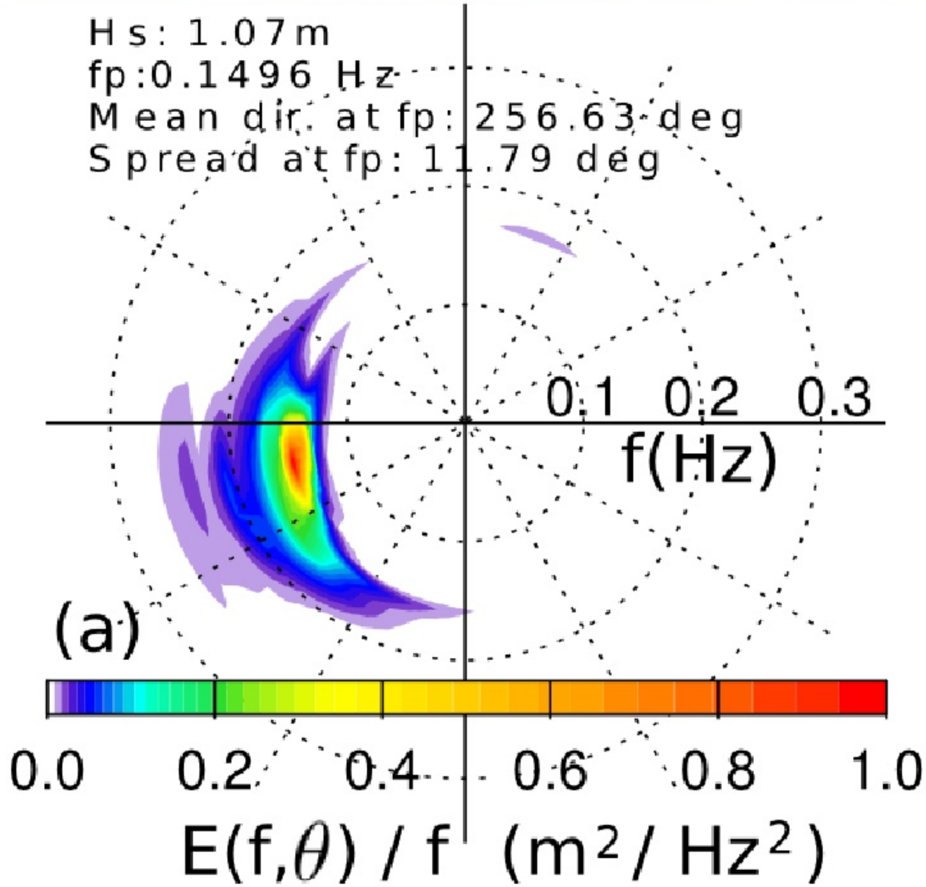
(pictures from Dugan et al. 2001)





→ we may use a 2D
wave spectrum for most applications

Frequency-wavenumber spectra



Example of a measured 2D wave spectrum (here using a stereo-video system mounted on a platform in the Black Sea)

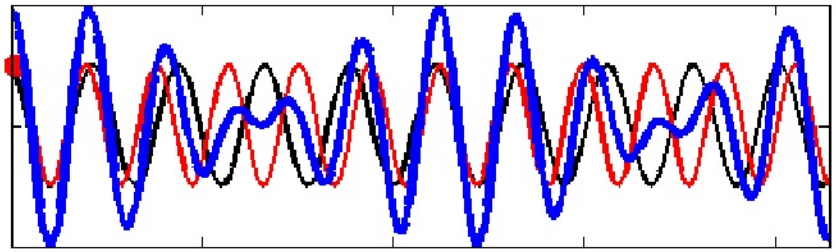
2

From waves to acoustic and seismic noise :

sources

a. a matter of phase speed

Hasselmann (1963) : nearly opposing waves generate seismic noise



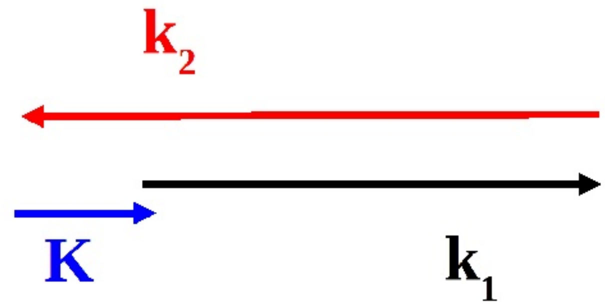
Movie of sea surface elevation

$Z = Z_1 + Z_2$

Any 2nd order quantity like Z^2 will thus contain

$\mathbf{K} = \mathbf{k_1} \pm \mathbf{k_2}$ and $\mathbf{f} = \mathbf{f_1} \pm \mathbf{f_2}$

Higher order interactions : $\mathbf{K} = \mathbf{k_1} \pm \mathbf{k_2} \pm \mathbf{k_3}$ and $\mathbf{f} = \mathbf{f_1} \pm \mathbf{f_2} \pm \mathbf{f_3}$ … *and so on* …



The interaction of $\mathbf{k_1}$ and $\mathbf{k_2}$ gives noise at $\mathbf{K} = \mathbf{k_1} + \mathbf{k_2}$ and $\mathbf{f} = \mathbf{f_1} + \mathbf{f_2}$

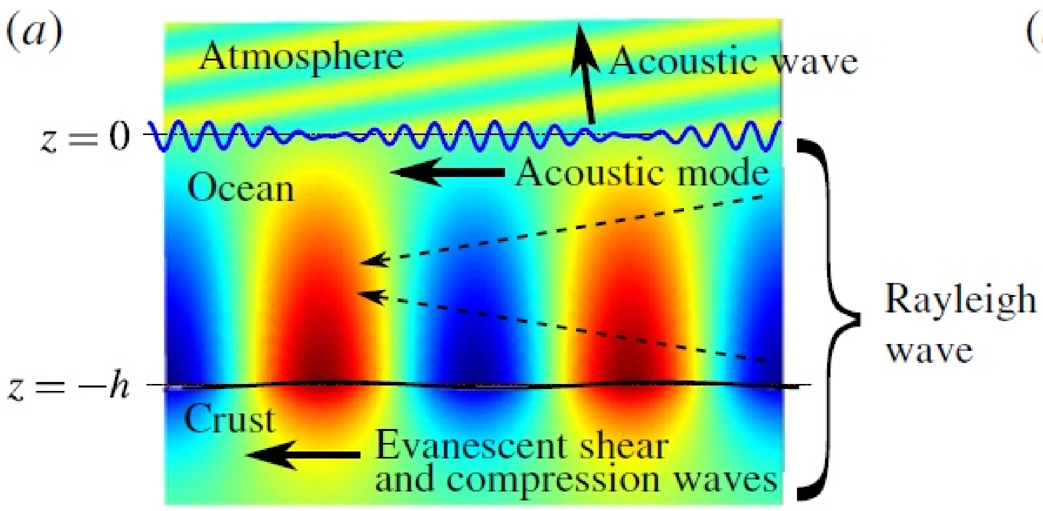
Resonant interaction if **2 pi f / K = C_s ,** the phase speed of one seismic mode.

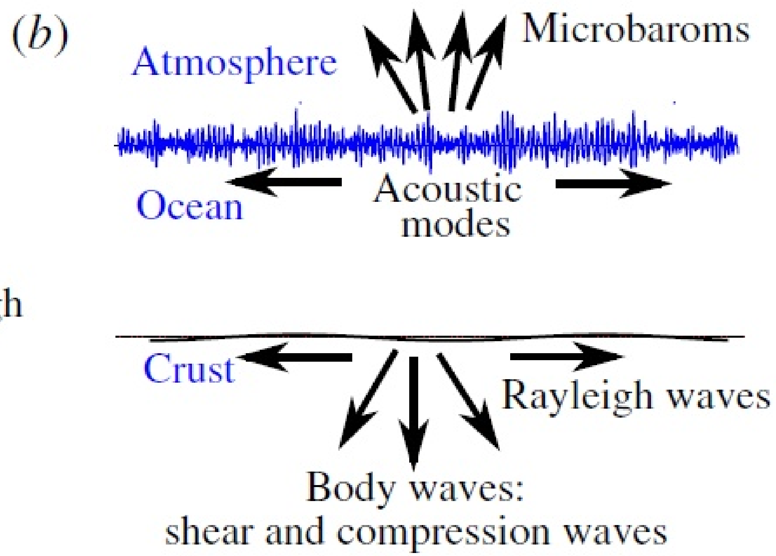
For any f, this selects K.

2. Noise generation theory

b. ocean waves with broad spectrum

From 2 wave trains … **to a full spectrum.**





2. Noise generation theory
c. point vs extended source

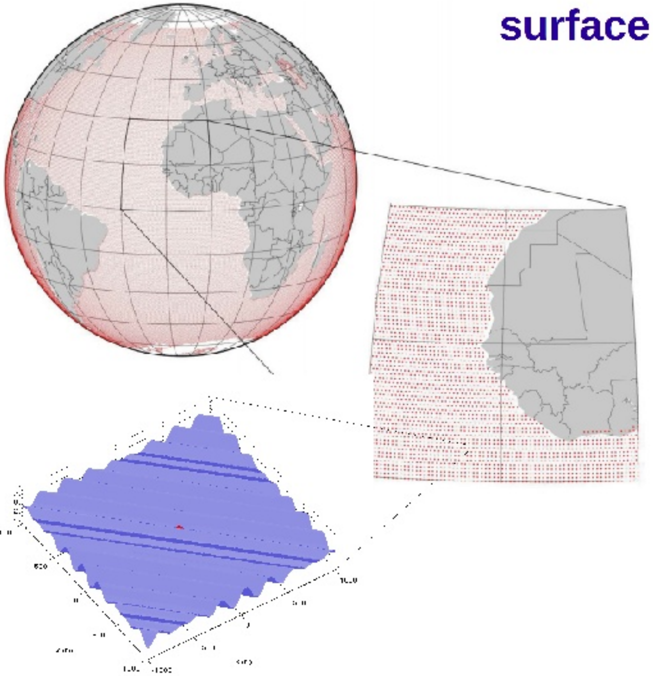
Because K << k , we may consider the equivalent point source that gives the same response :
(Longuet-Higgins 1950, Hasselmann 1963, Gualtieri et al., JGI 2013)

$$F_{\mathrm{rms}}(f_2, \mathrm{d}A, \mathrm{d}f_2) = 2\pi\sqrt{F_p(\mathbf{K} \simeq 0,\ f_2)\mathrm{d}A\mathrm{d}f_2}$$

rms amplitude of equivalent point force

Elementary area

Equivalent wave-induced Pressure spectrum at ocean surface



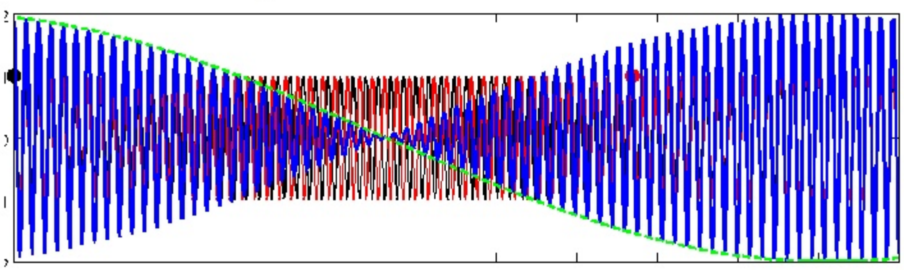
2. Noise generation theory

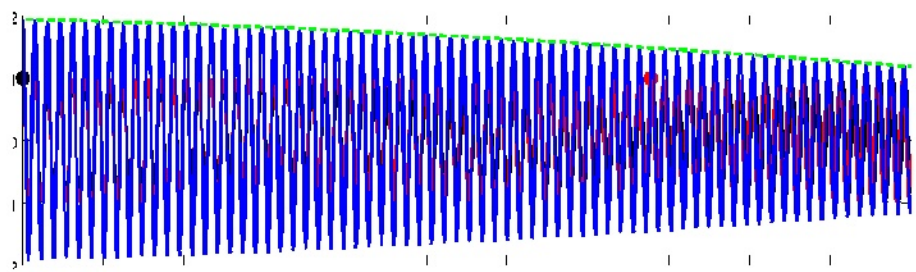
b. any speed is possible

Difference between Rayleigh and body waves : caused by horizontal phase speed of forcing.

For example, at f =0.2 Hz, in h=2000 m depth,

Rayleigh	Body waves
$k_2 = 0.0406$ rad/m	$k_2 = 0.04033$ rad/m
$k_1 = 0.04$ rad/m	$k_1 = 0.0402$ rad/m
K	K





$C_R = 2.2$ km/s

K = 0.00057 rad / m

$C = 10.4$ km/s ~ 2 C_P ~ 3.5 C_S

K = 0.00013 rad / m :

P wave with 30° take-off angle

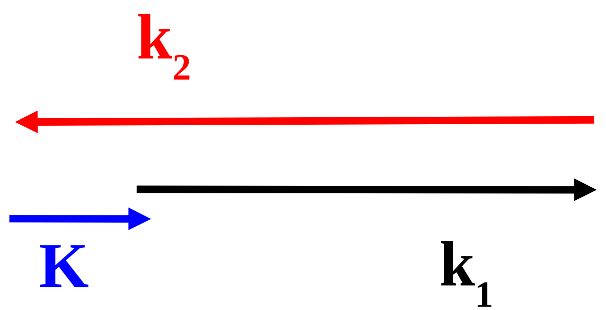
S wave with 17° take-off angle

2. Noise generation theory

c. « primary » generation

Waves may also interact with other things :

- Currents,
- Topography, in this case $\mathbf{f_2}$ = 0



This interaction of $\mathbf{k_1}$ and $\mathbf{k_2}$ gives noise at $\mathbf{K = k_1 + k_2}$ and $\mathbf{f = f_1}$

Again, resonant interaction if

2 pi f / K = C_s , the phase speed of one seismic mode.

For any f, this selects K.

2. Noise generation theory

d. relevant ocean wave properties

For seismic or ocean acoustic waves the double-frequency resonance imposes

K << k , meaning, for waves, K ~ 0

$$F_p(\mathbf{K} \simeq 0, f_s) = 2\pi F_p(\mathbf{K} \simeq 0, \omega) = \rho_w^2 g^2 f_s \int_0^{\pi} E(f,\theta) E(f,\theta+\pi) \mathrm{d}\theta$$

This is predicted in numerical wave models

Let's define the « overlap integral »

$$I(f) = \int_0^{2\pi} M(f,\theta) M(f,\theta+\pi) \mathrm{d}\theta$$

$$F_{p2,\mathrm{surf}}(\mathbf{K} \simeq 0, f_s) = \rho_w^2 g^2 f E^2(f) I(f)$$

1. Noise theory
Practical implications

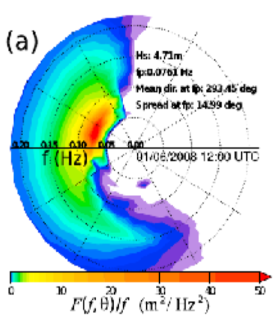
How well can we model $E(f,\theta) = E(f)M(f,\theta)$?

It depends. For wave frequencies 0.05 to 1 Hz, ***E(f)*** is usally pretty good, but noise is

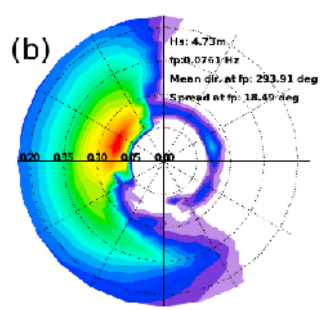
proportional to ***$E^2(f)$ I(f)*** with $I(f) = \int_0^{\pi} M(f,\theta)M(f,\theta+\pi)\,\mathrm{d}\theta$

3 broad classes

Difficult case (100% errors?)
Class I : broad spectrum typical of high frequencies (say $f_s > 0.4$ Hz)

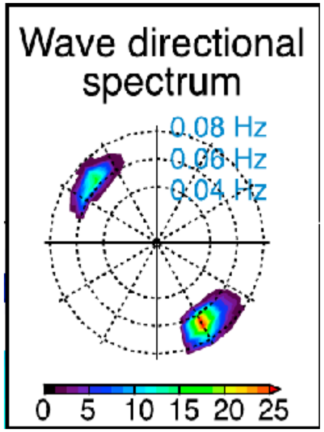


intermediate
Class II : coastal reflection



Example from Ardhuin & Roland (JGR 2012)

most easy
Class III : waves from different storms



Example from Obrebski et al. (GRL 2012)

2. Noise generation theory

d. relevant ocean wave properties

Because I(f) can be anything, the **wave height** is a **very bad proxy for the source** intensity.

I have computed for you 20 years of Fp(K=0,f), every 3 hours.

- http://tinyurl.com/iowagaftp

Or go to http://wwz.ifremer.fr/iowaga   Here are a few examples.

COMMENT ON DIFFERENT WAVE MODELS :

- forcing (winds, sea ice, currents, icebergs …)
- parameterizations
- numerical schemes

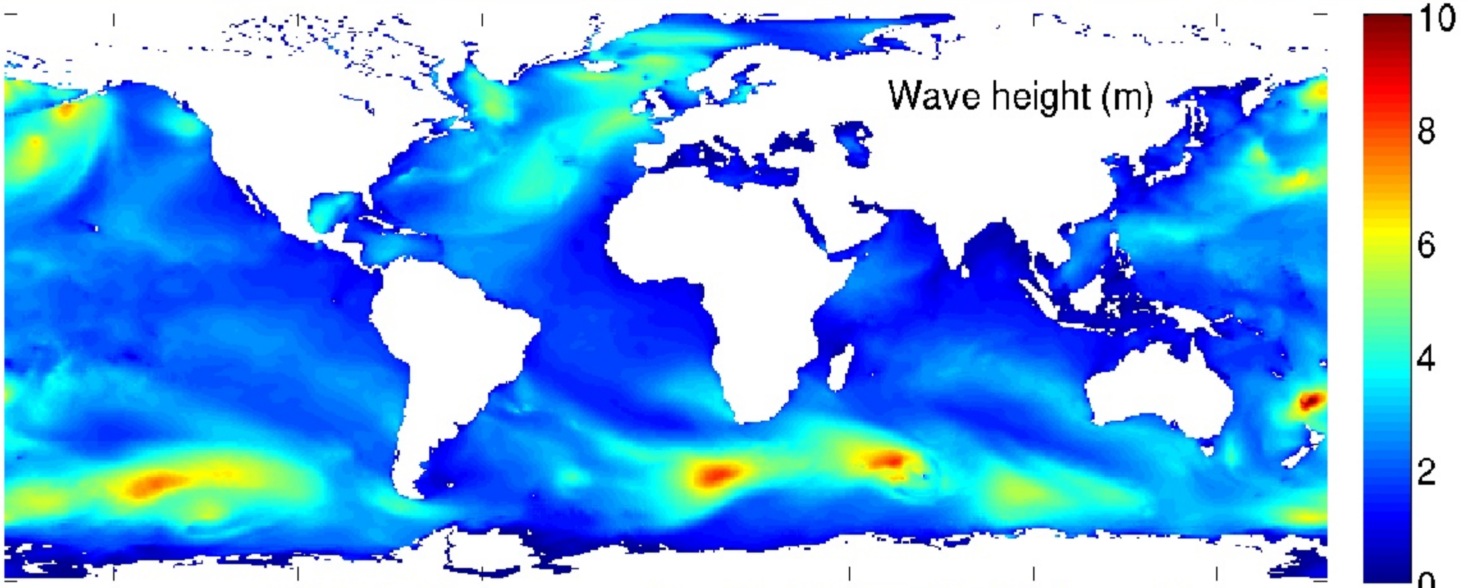
NB : One of the delicate issues is the coastal reflection (see Ardhuin & Roland, JGR 2012).
So, for the global 0.5° model, I did 2 runs :

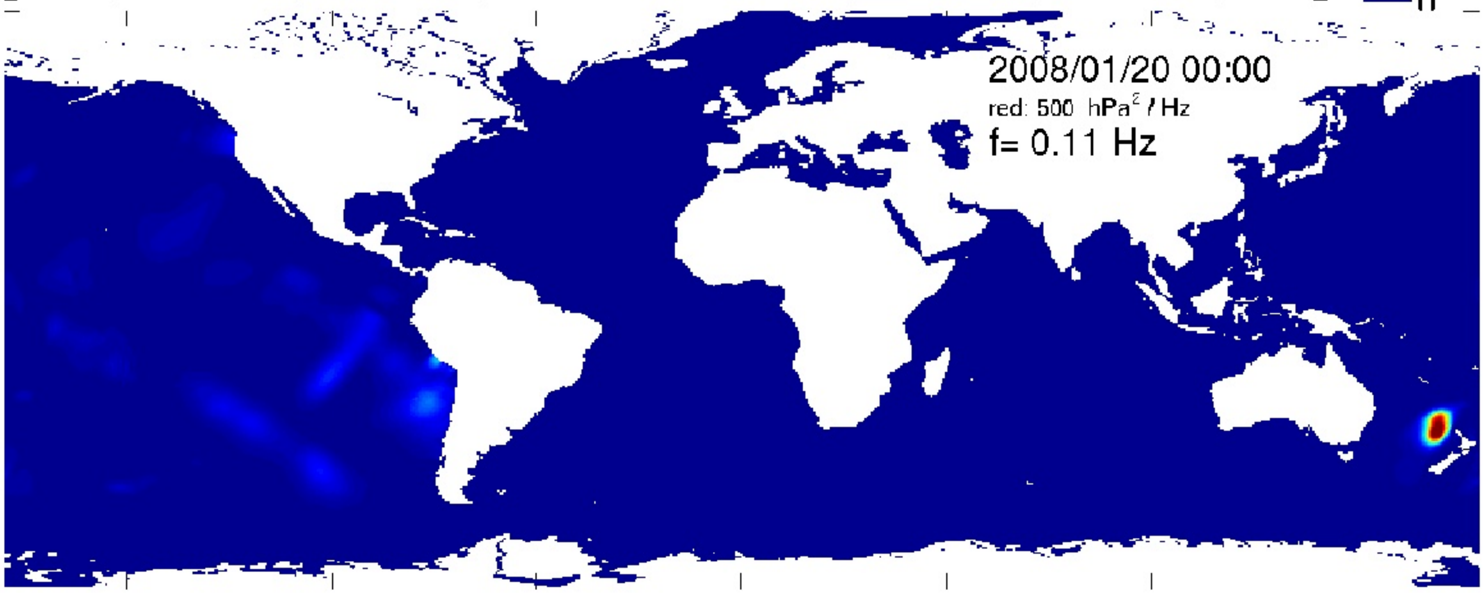
- One without reflection
- The other with $R^2 = 0.1$

Something more sophisticated should come this year.

2. Noise generation theory

a. a matter of phase speed

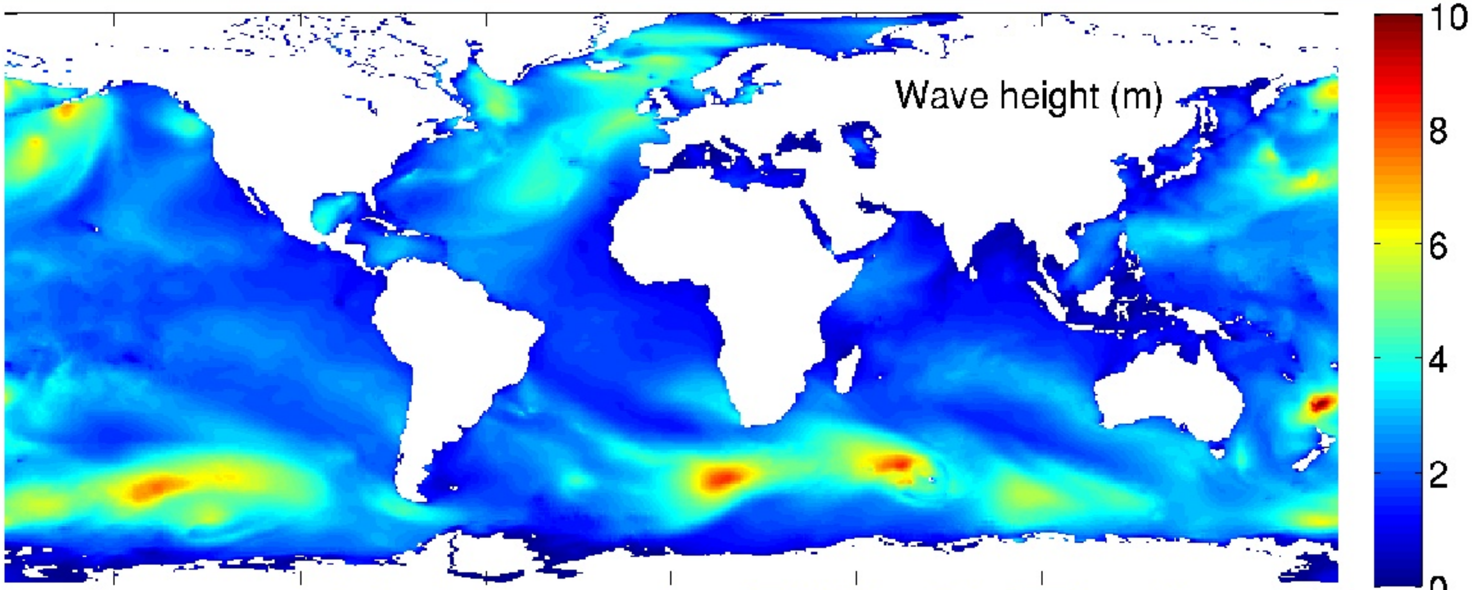


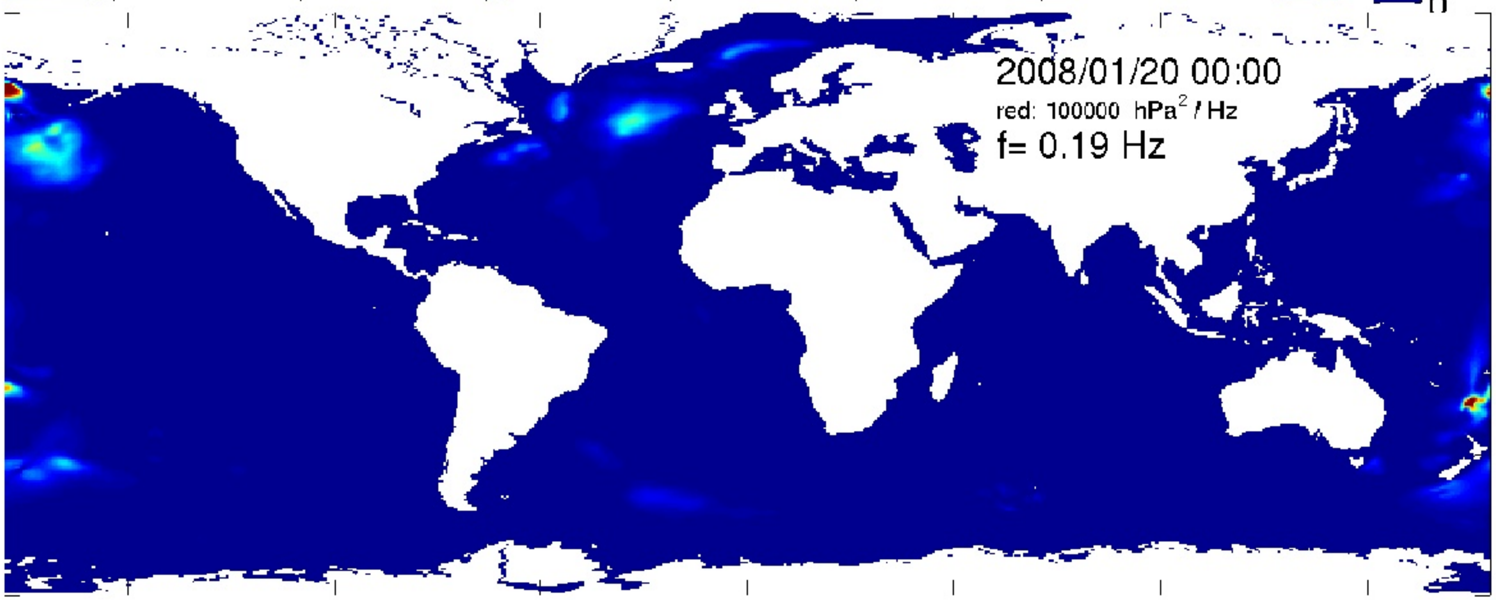


T=9s

2. Noise generation theory

a. a matter of phase speed

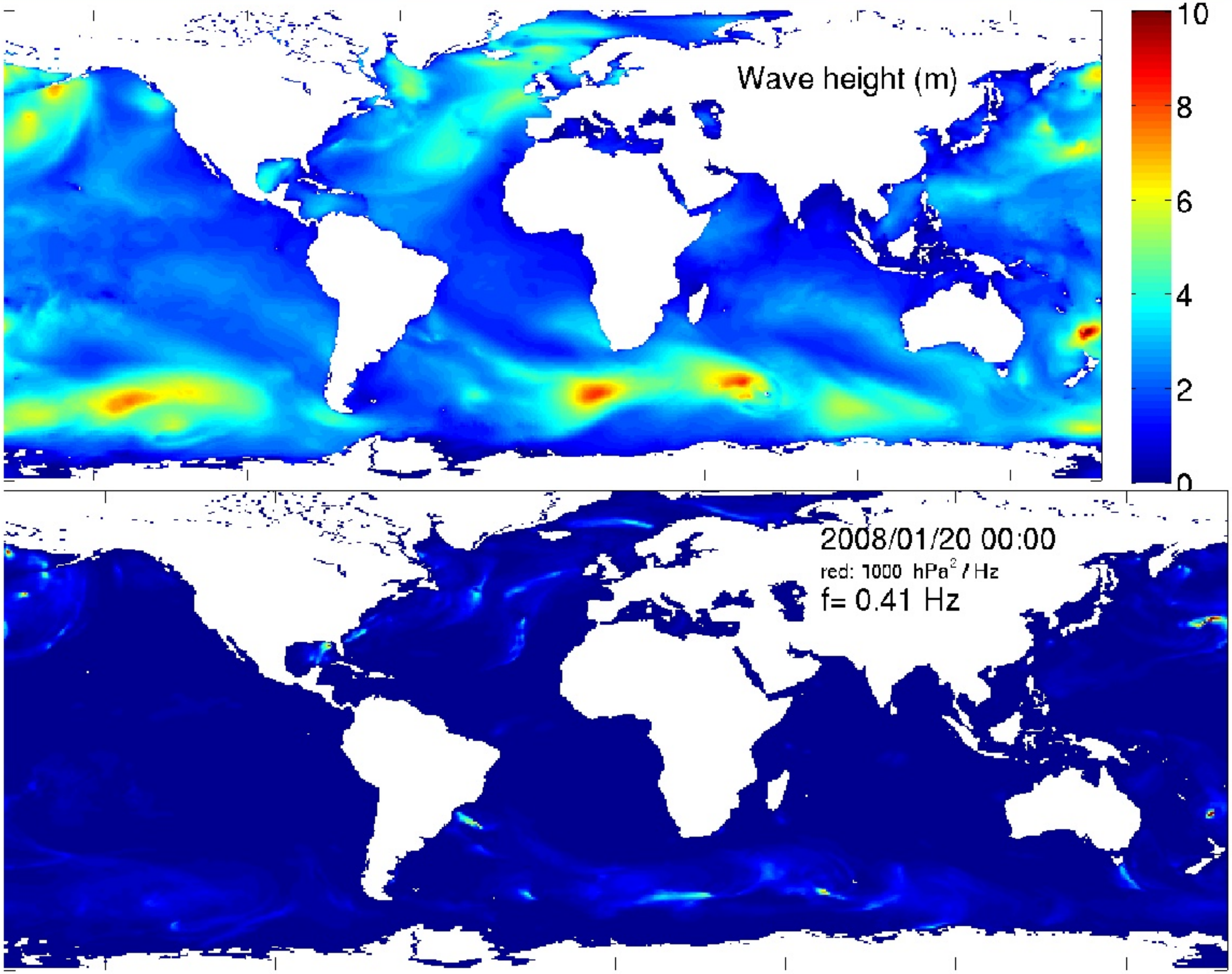




T=5s

2. Noise generation theory

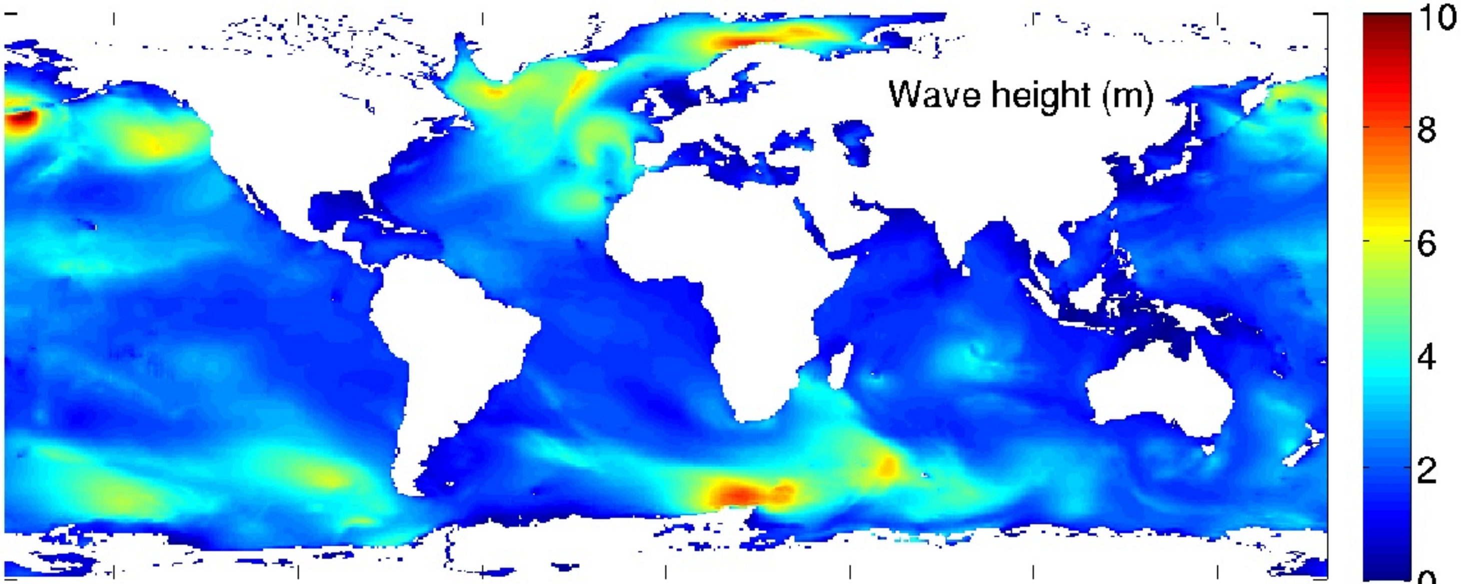
a. a matter of phase speed

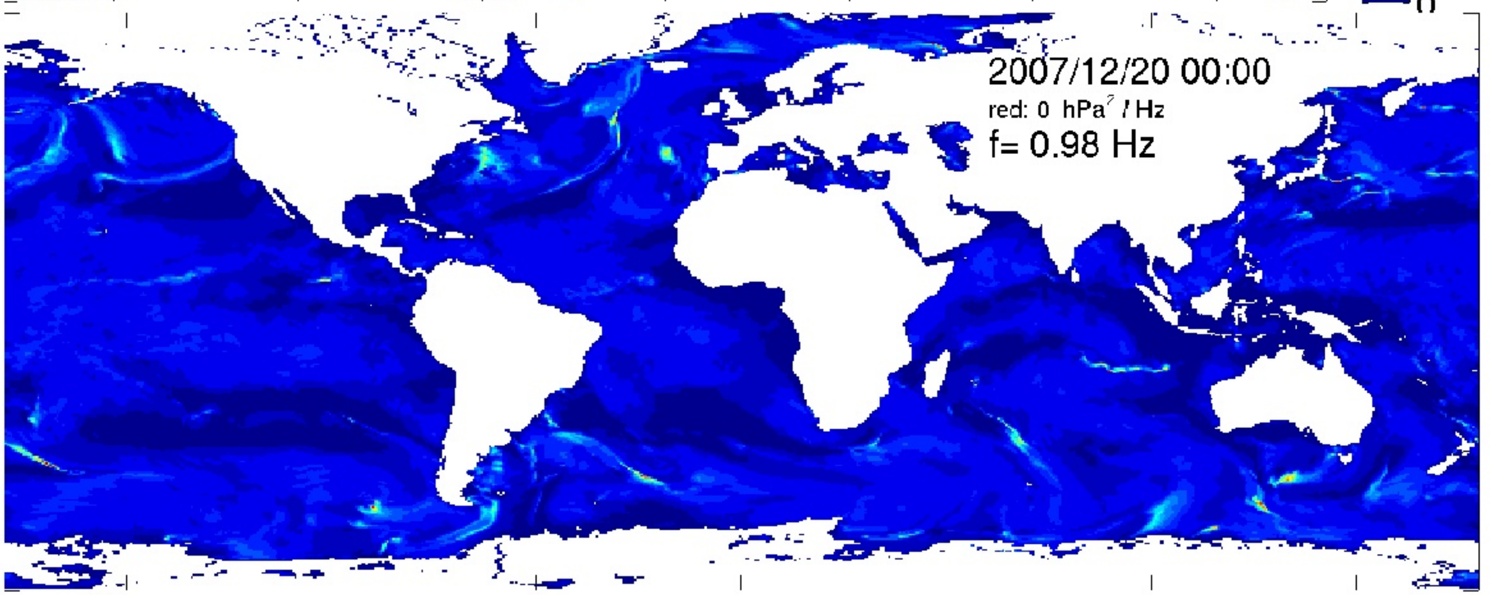


T=2.5s

2. Noise generation theory

a. a matter of phase speed





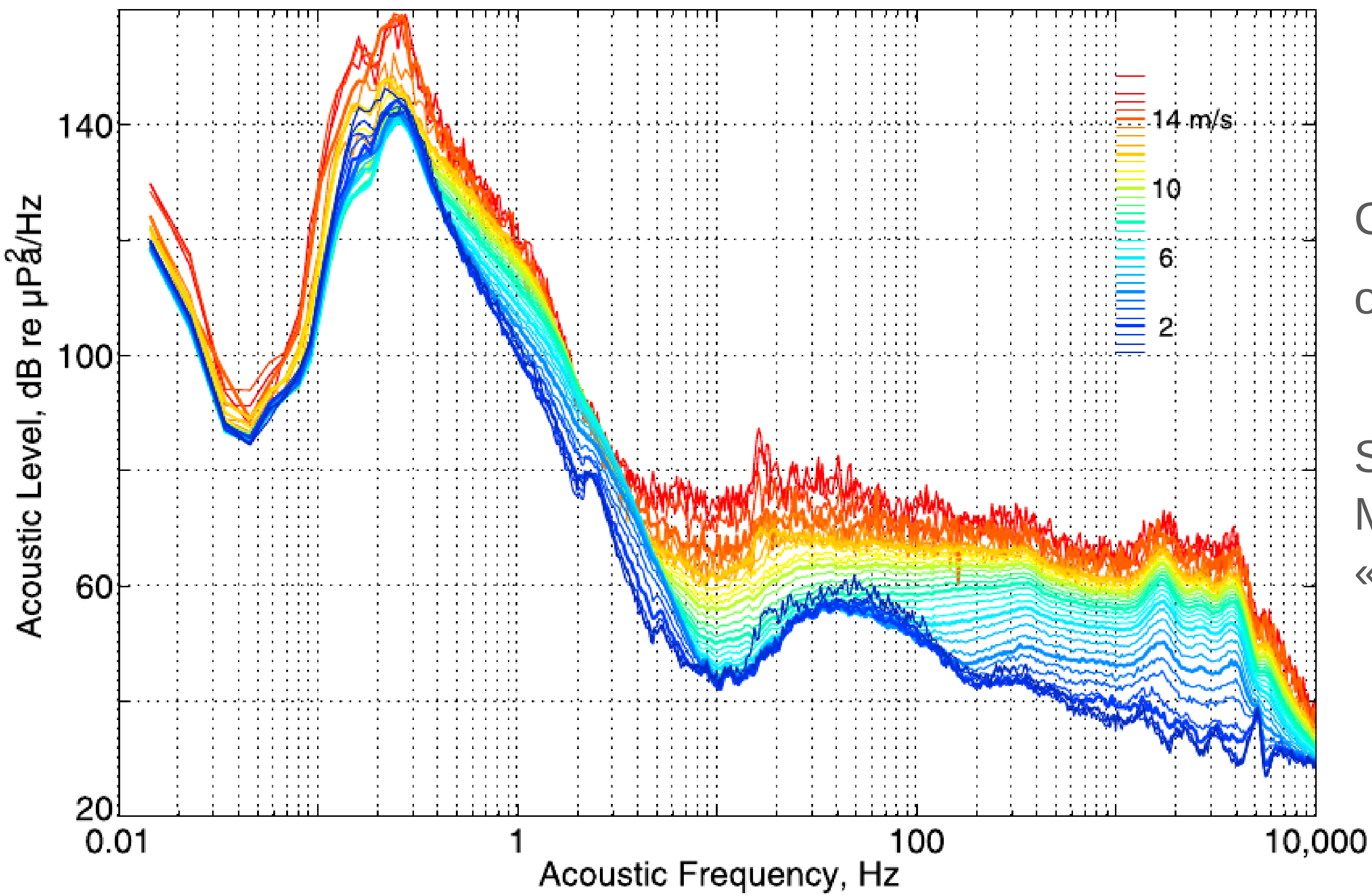
T=1 s

2. Noise generation theory

Moving on to measured noise

DUENNEBIER ET AL.: WIND AND SOUND AT STATION ALOHA

(JGR Oceans 2012)



Can we explain these observations ?

See also Farrell and Munk (2010) :
« booms and busts »

3

From waves to acoustic and seismic noise :

seismic response

3. Noise generation theory

a. getting the solution

1st order problem : linear ocean waves with compressibility correction (LH 1950) and possible bottom pressure (H 1963 → primary noise)

2nd order problem :

Laplace equation for water column with surface pressure (LH 1950, H 1963) coupled to a solid half space (or layered, Abramovici 1968) with possible wave-induced pressure on bottom (Ardhuin and Herbers 2013)

$$\phi_2 \propto \exp[\mathrm{i}(K_x x + K_y y + lz - \omega t)]$$

Linearized Laplace equation gives

$$\left\{-\omega^2 + \alpha_w^2 \left[K^2 + l^2\right]\right\} = 0 \qquad l = K\sqrt{\frac{\omega^2}{K^2\alpha_w^2} - 1}$$

Solutions are « homogeneous » (propagating) for small K and « inhomogeneous » (evanescent) for large K.

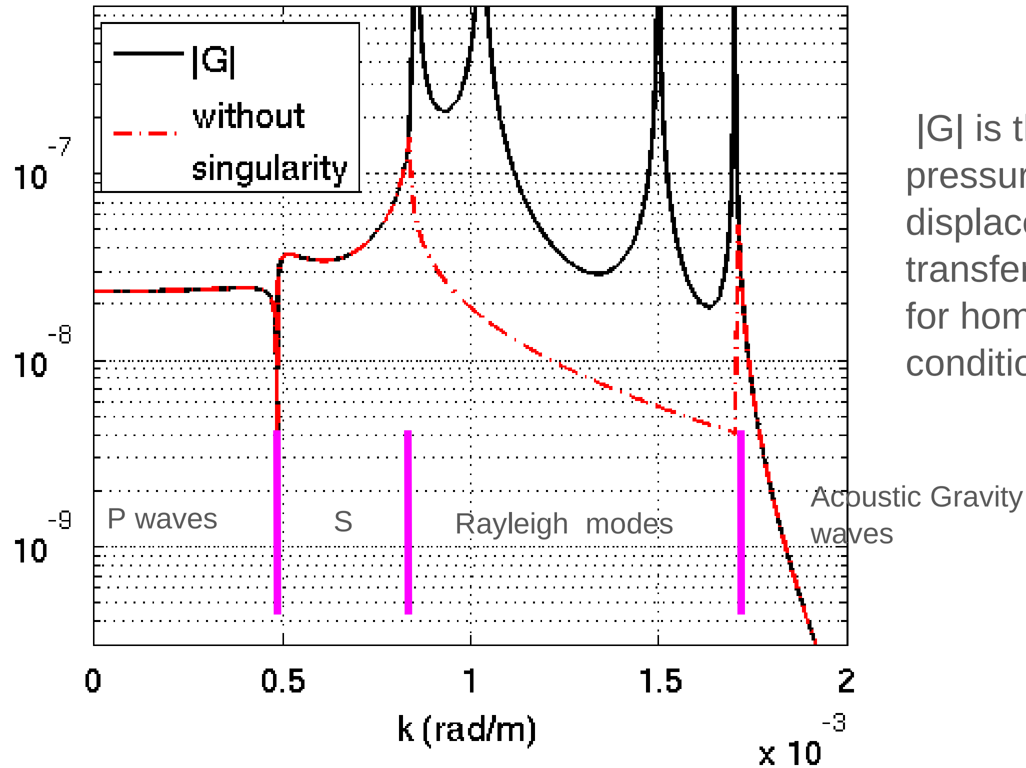
3. Noise generation theory

b. transfer functions

The amplitudes are given by coupling at interfaces (continuity of velocity and stresses)

Example with T=5 s, depth = 5600 m, **4 different types of waves** with different slowness.

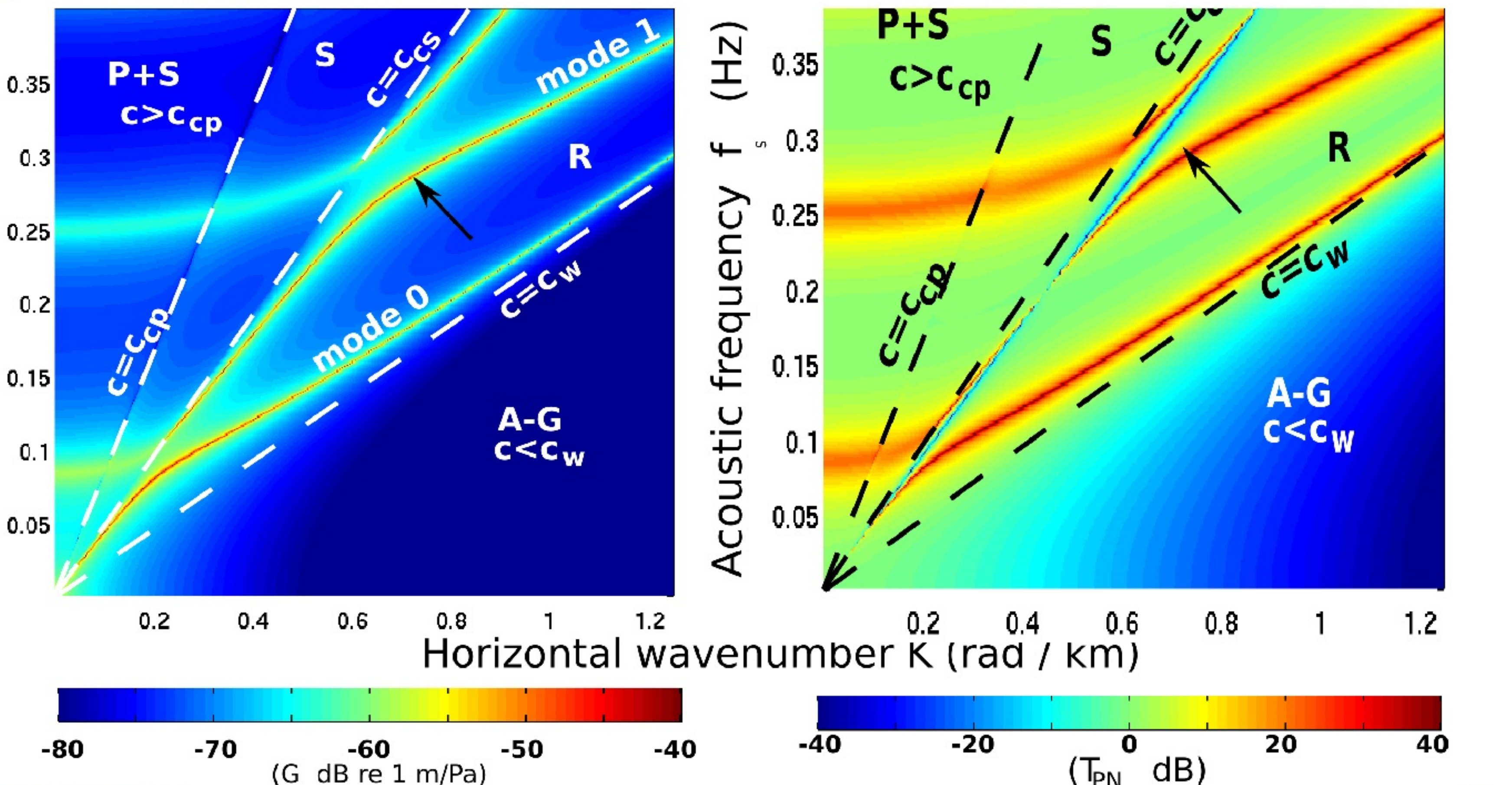
Their power are all prop. to the same wave forcing.



|G| is the ocean wave pressure to bottom displacement transfer function (m/Pa) for homogeneous conditions

G is the amplitude TF from surface pressure to vertical ground displacement. (h=4400 m, half space + water layer)

TPN is the spectral (variance) transfer function from surface to seabed pressure



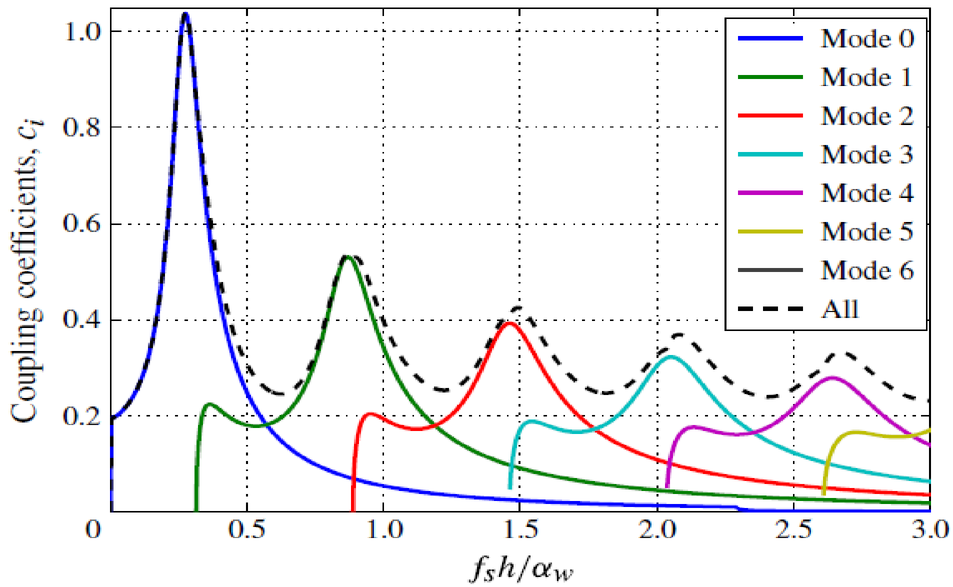
3. Noise generation theory

c. Rayleigh waves

Rayleigh wave response : local source of noise

Wave pressure to Rayleigh waves transfer function : given by properties of crust and water

$$S_{DF}(f_s) = \boxed{\frac{4\pi^2 f_s}{\beta^5 \rho_s^2}\left(\sum_{i=0}^{\infty} c_i^2\right)} F_p(\boldsymbol{K} \simeq 0, f_s)$$



(See Longuet-Higgins 1950)

Integral of S_{DF} x attenuation x propagation → noise spectrum at seismic station

(Hasselmann 1963, Szelwis 1982, Kedar et al. 2008, Ardhuin et al. 2011 ...)

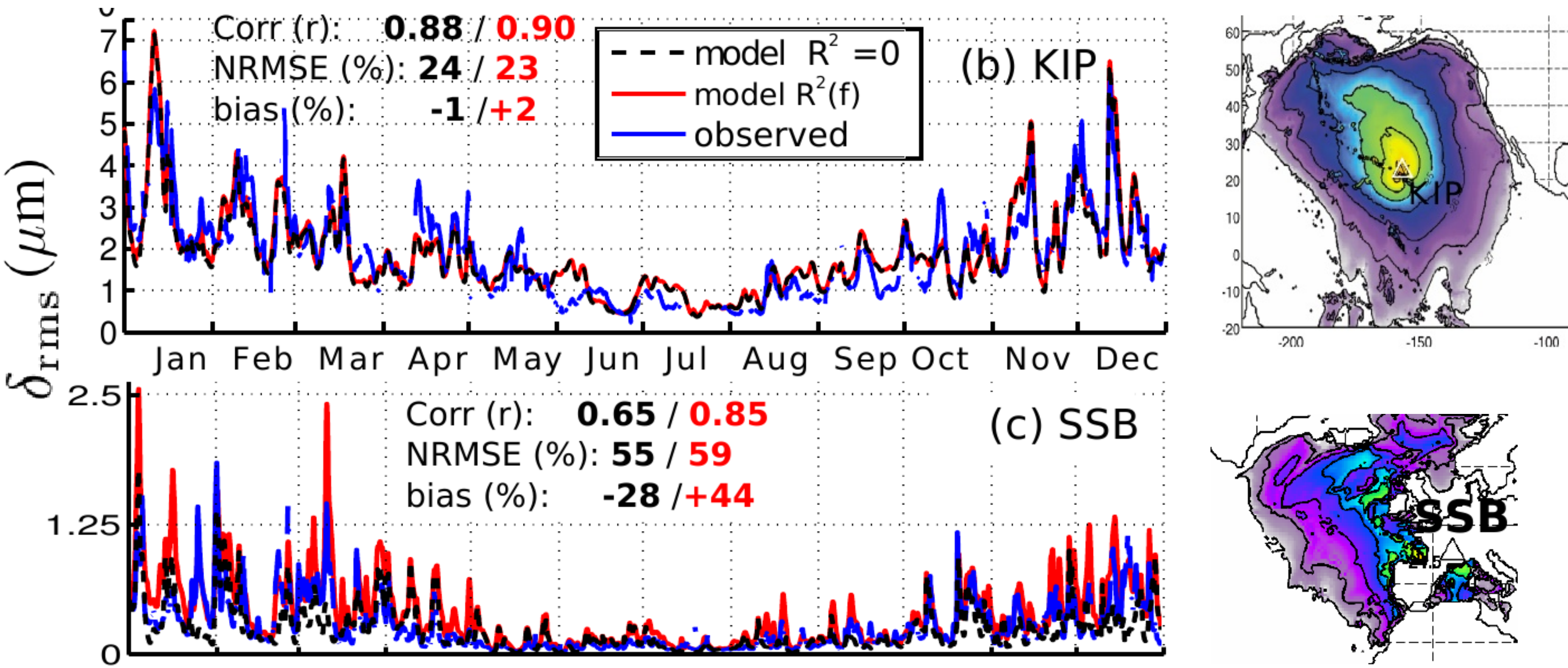
3. Noise generation theory

c. Rayleigh waves

With a simplistic propagation model + constant attenuation (200 < Q < 800) : it works !

Tuning knobs : shoreline reflection and Q.

Remaing issues : 3D seismic propagation effects...



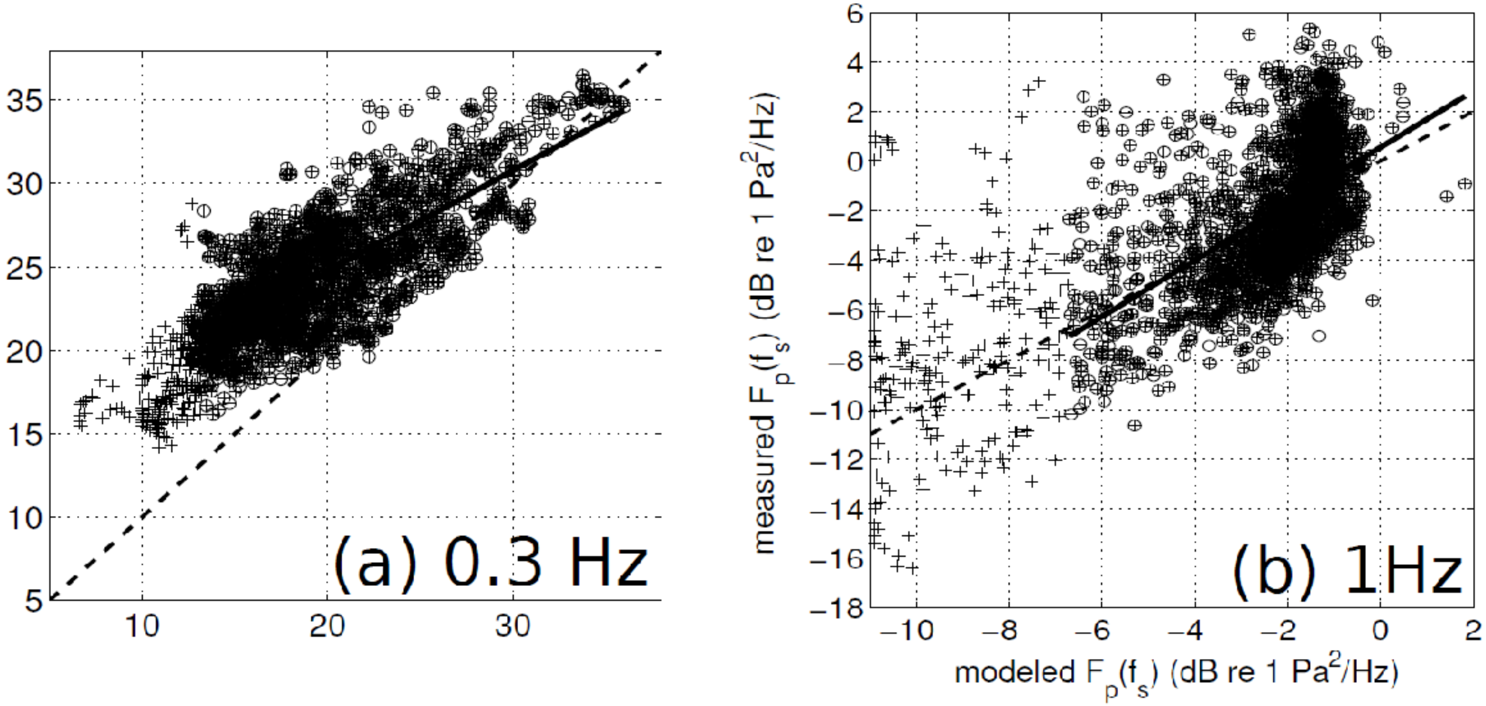
3. Noise generation theory

c. Rayleigh waves

We can also look at underwater measurements (Duennebier et al. 2012) :

Wave model + rayleigh wave theory explains the data very well from 0.1 to 0.8 Hz

But above 0.8 Hz, the model misses the high values → likely effect of wave breaking



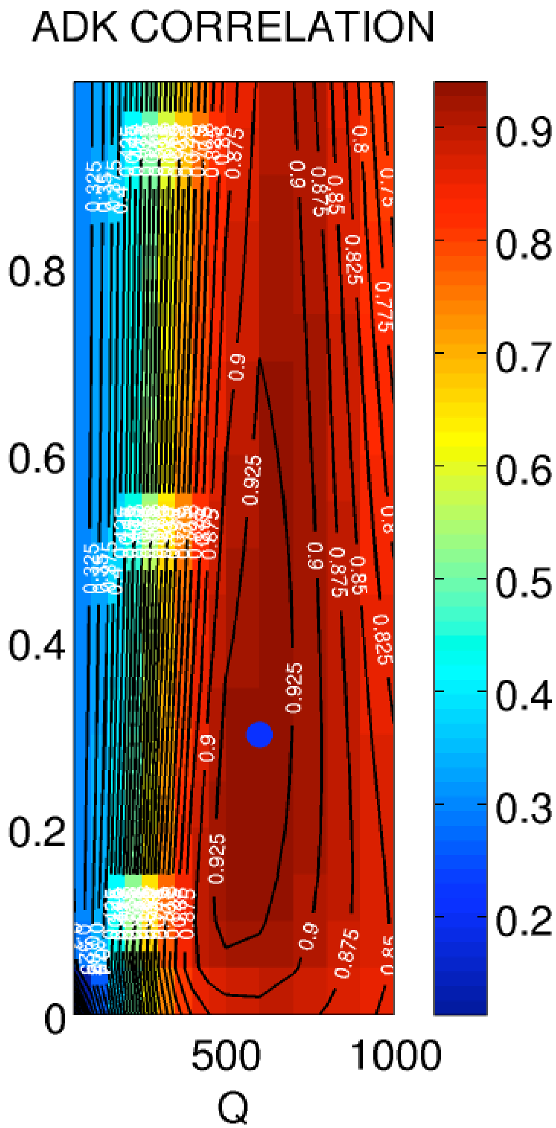
Ardhuin et al. (JASA, in press)

3. Noise generation theory

c. Rayleigh waves

Q is estimated by maximizing the correlaiton between model & observations

10 x R^2



Correlation r

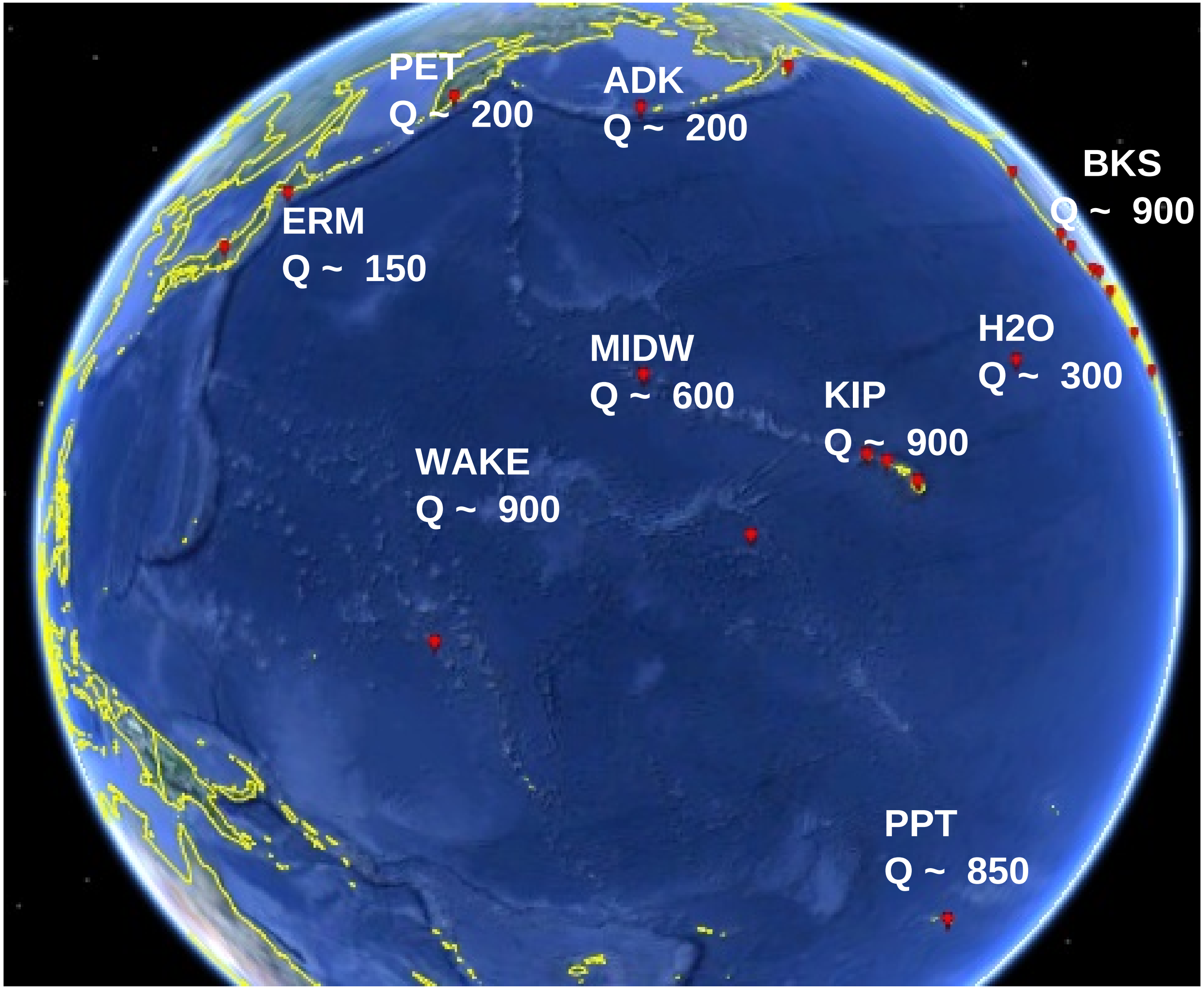
3. Noise generation theory

c. Rayleigh waves

Q cannot be homogeneous

Here for

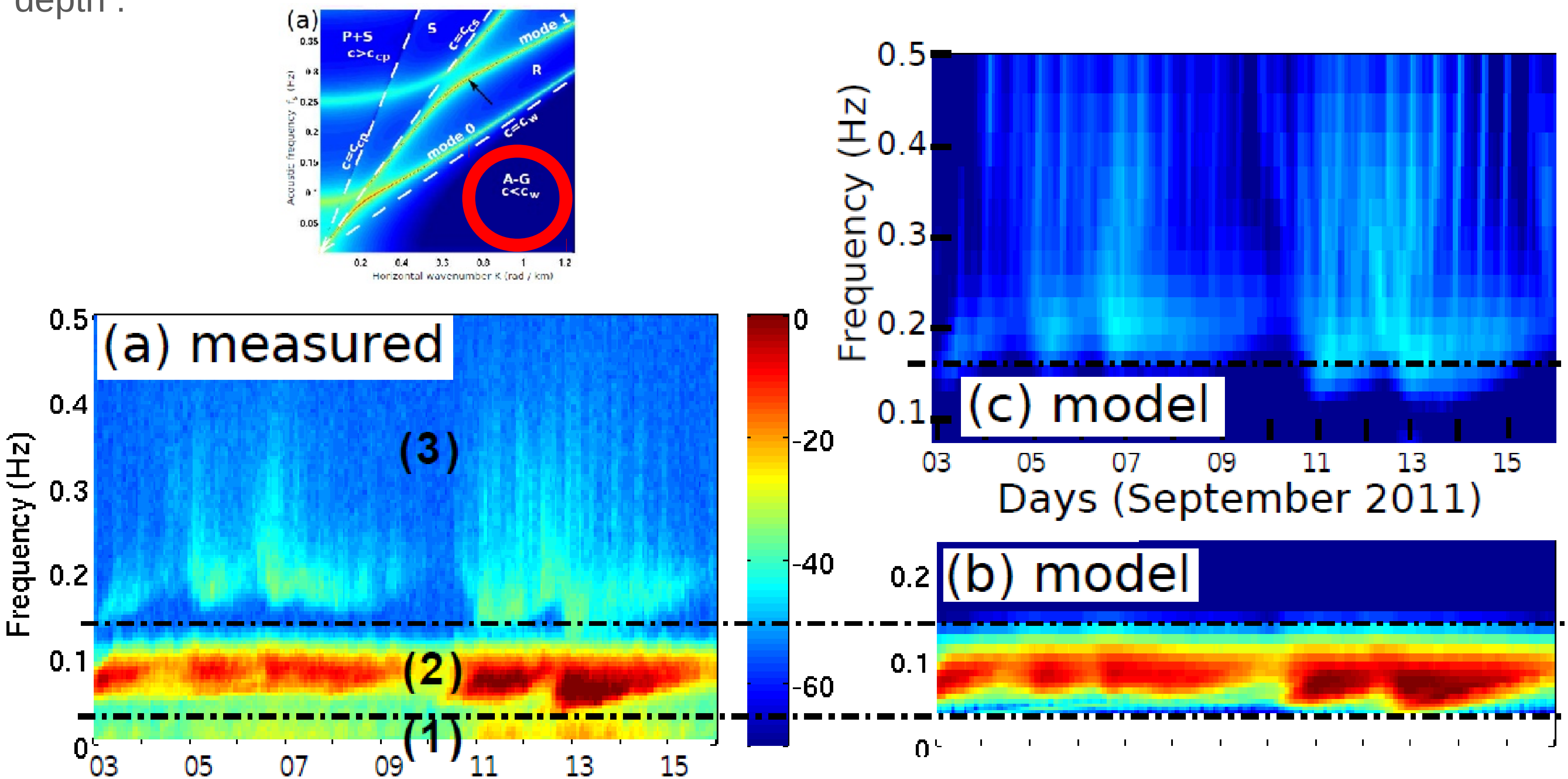
$f_s = 0.12$ Hz



3. Noise generation theory

d. Acoustic-gravity modes

In order to really verify the wave model, it is better to look at A-G modes : only a function of local sea state. Previous measurements from Cox & Jacobs (1989). Here data from 100 m depth :

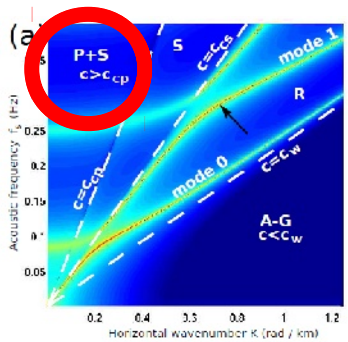


Ardhuin et al. (JASA, in press)

3. Noise generation theory

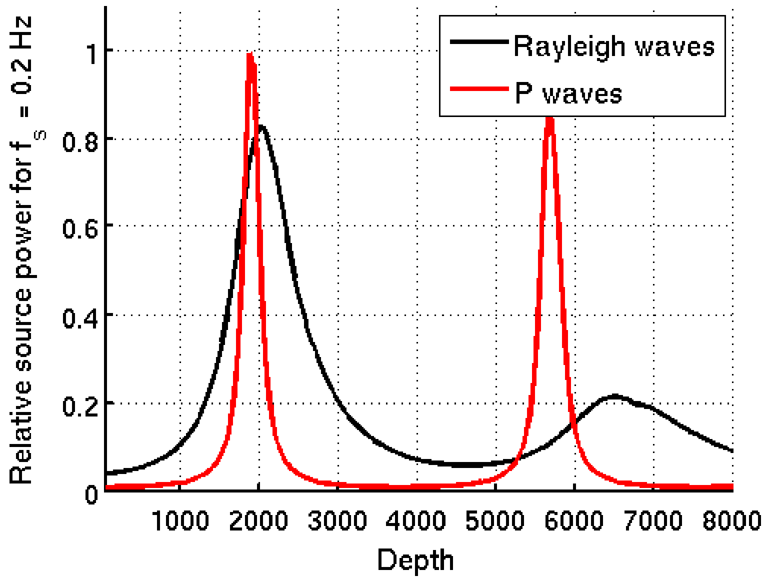
e. body waves

Once integrated over K we get the noise source

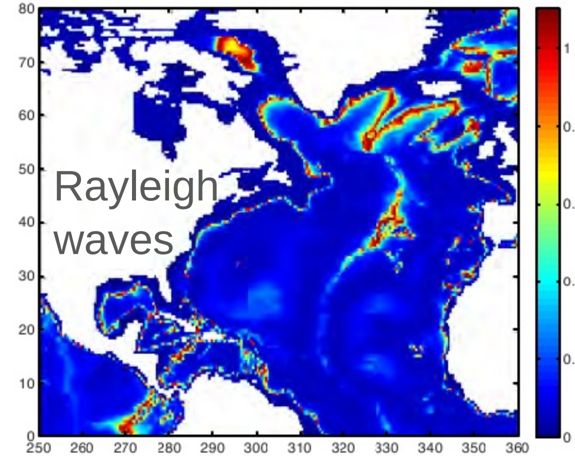


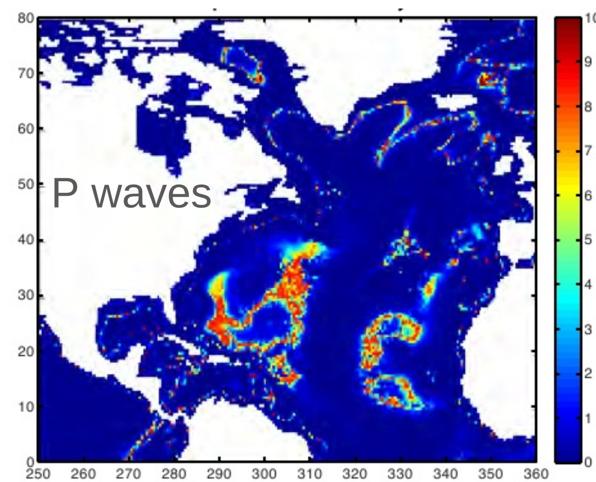
Different response from Rayleigh waves

→ different regions of the ocean



Amplification of sea surface pressure for T= 5 s





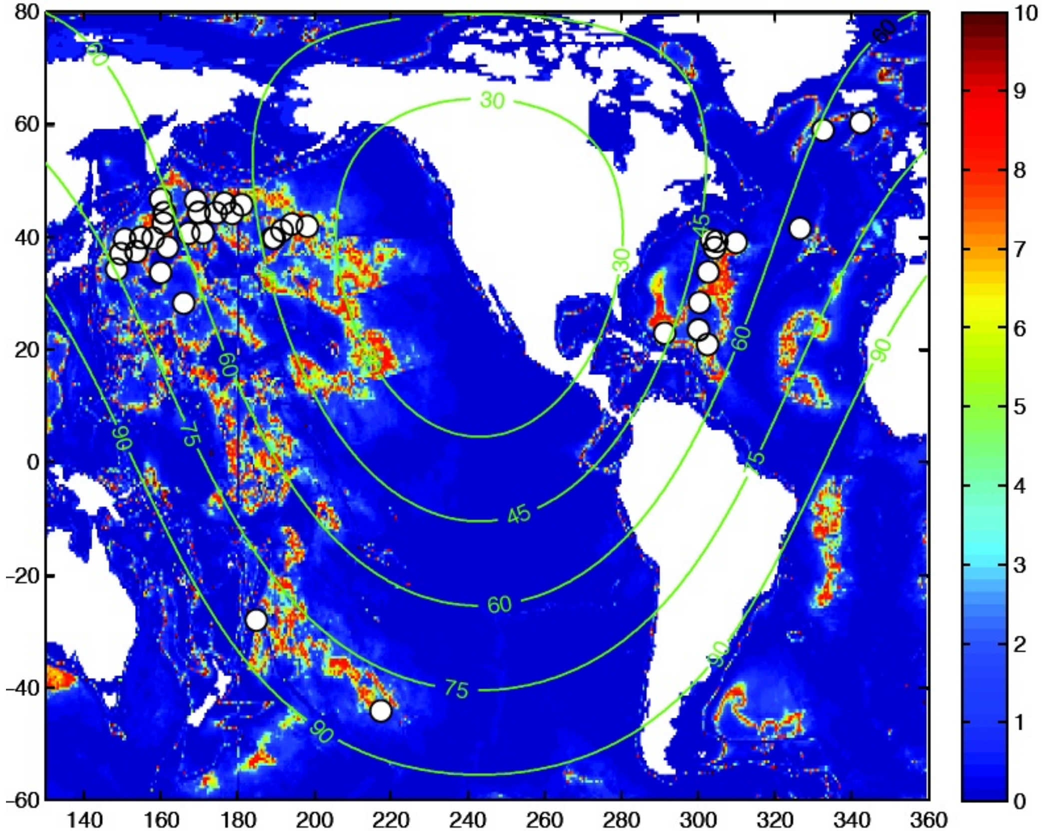
3. Noise generation theory

e. body waves

1 year of events at SCSN based on the noise model (at times of maximum source).

The P-waves do come from the areas of maximum transfer function.

(Obrebski et al., JGR, submitted)



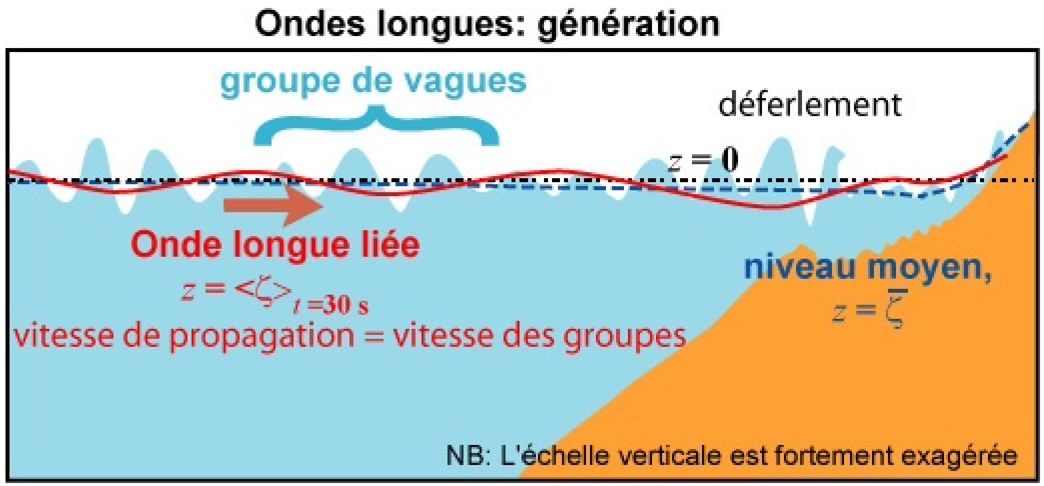
4

A few words on IG waves and hum

4. IG waves and hum

Long waves are associated to groups : generated as bound waves they are « released » in the surf zone and propagate back to the open ocean as free waves

Bound waves →



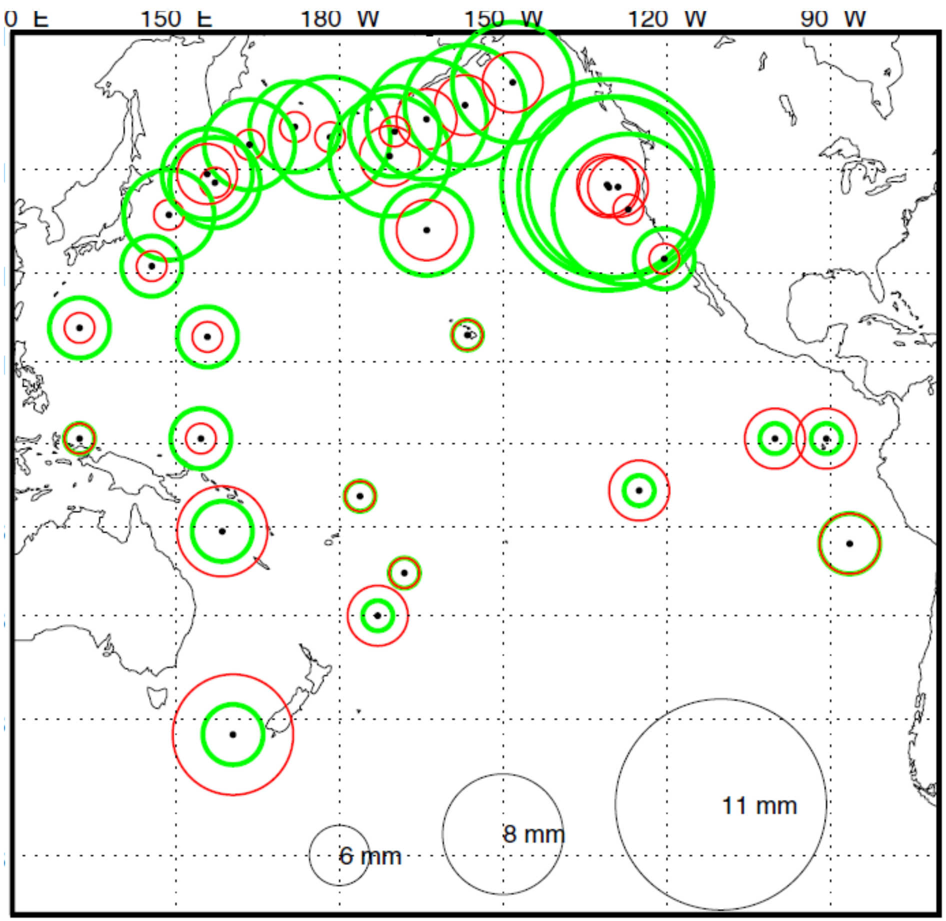
Free waves : these are long !! ←

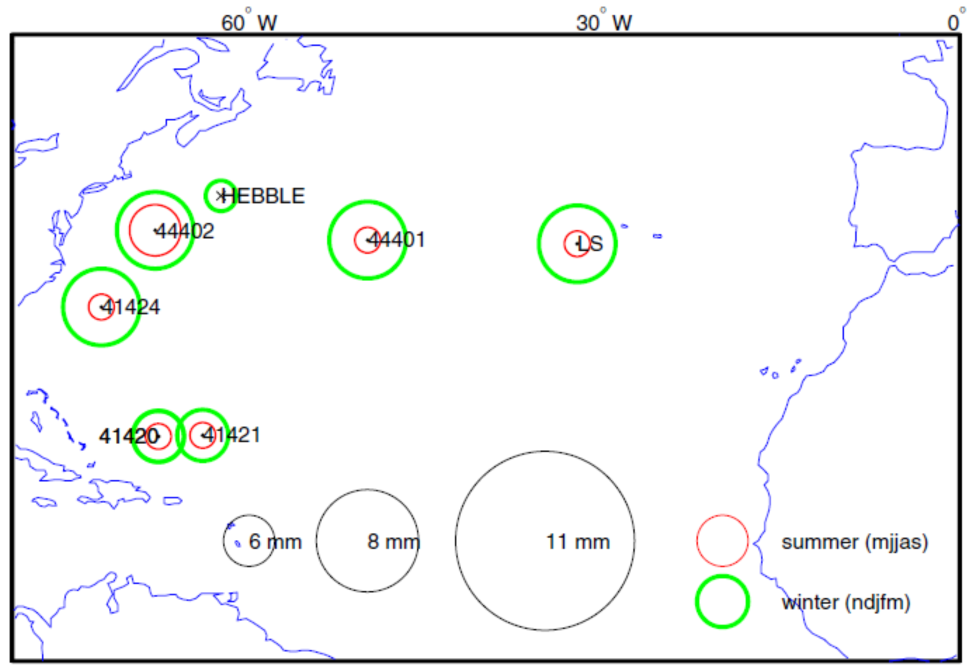
L ~ sqrt(D), height ~ 1/sqrt(D)

4. IG waves and hum

How high are these waves in the open ocean ?

A first answer from DART stations





Aucan and Ardhuin (GRL, in press)

Contribution of IG waves to elevation spectra : spectra from DART buoys

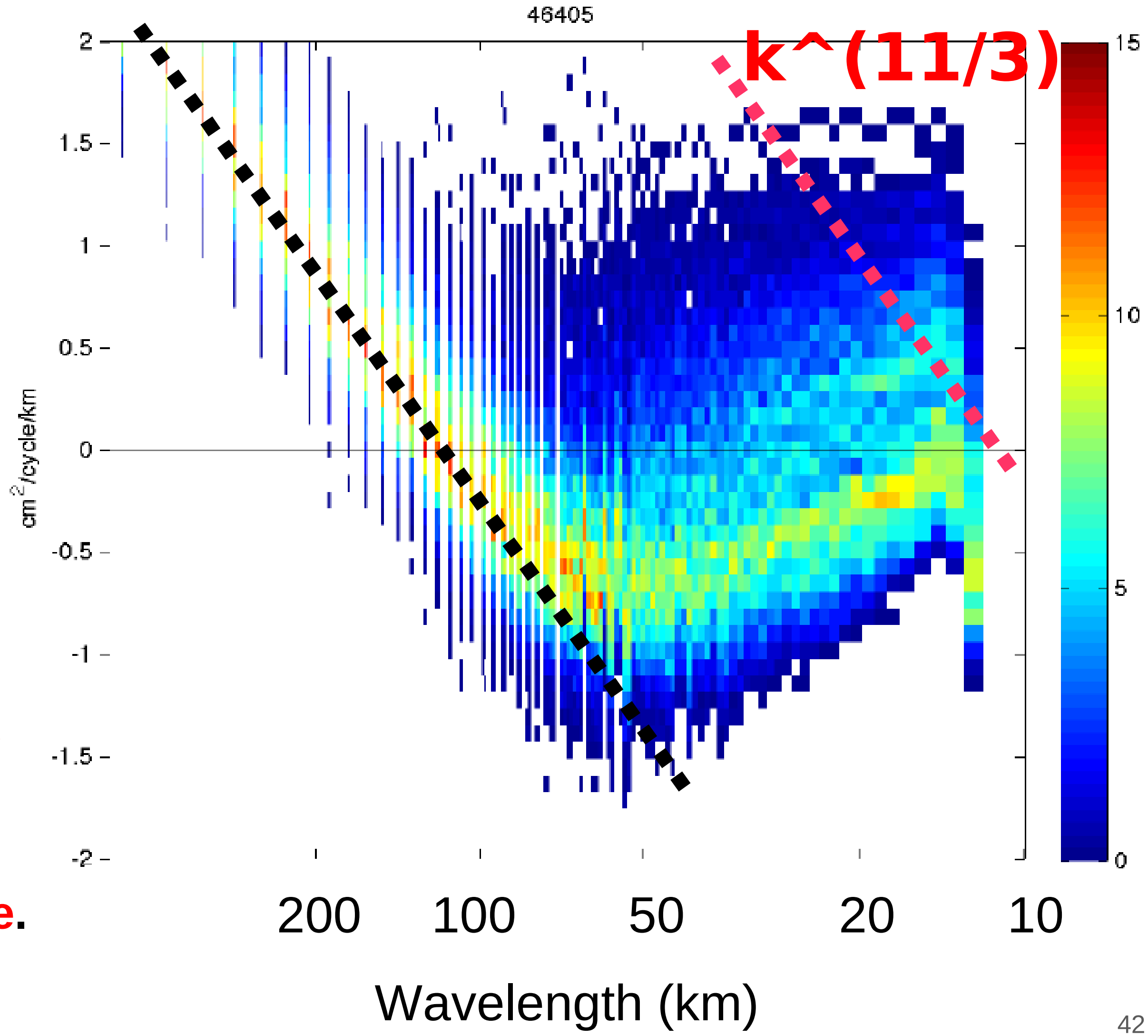
5 cm² / (cycle / km) →

0.5 cm² / (cycle / km) →

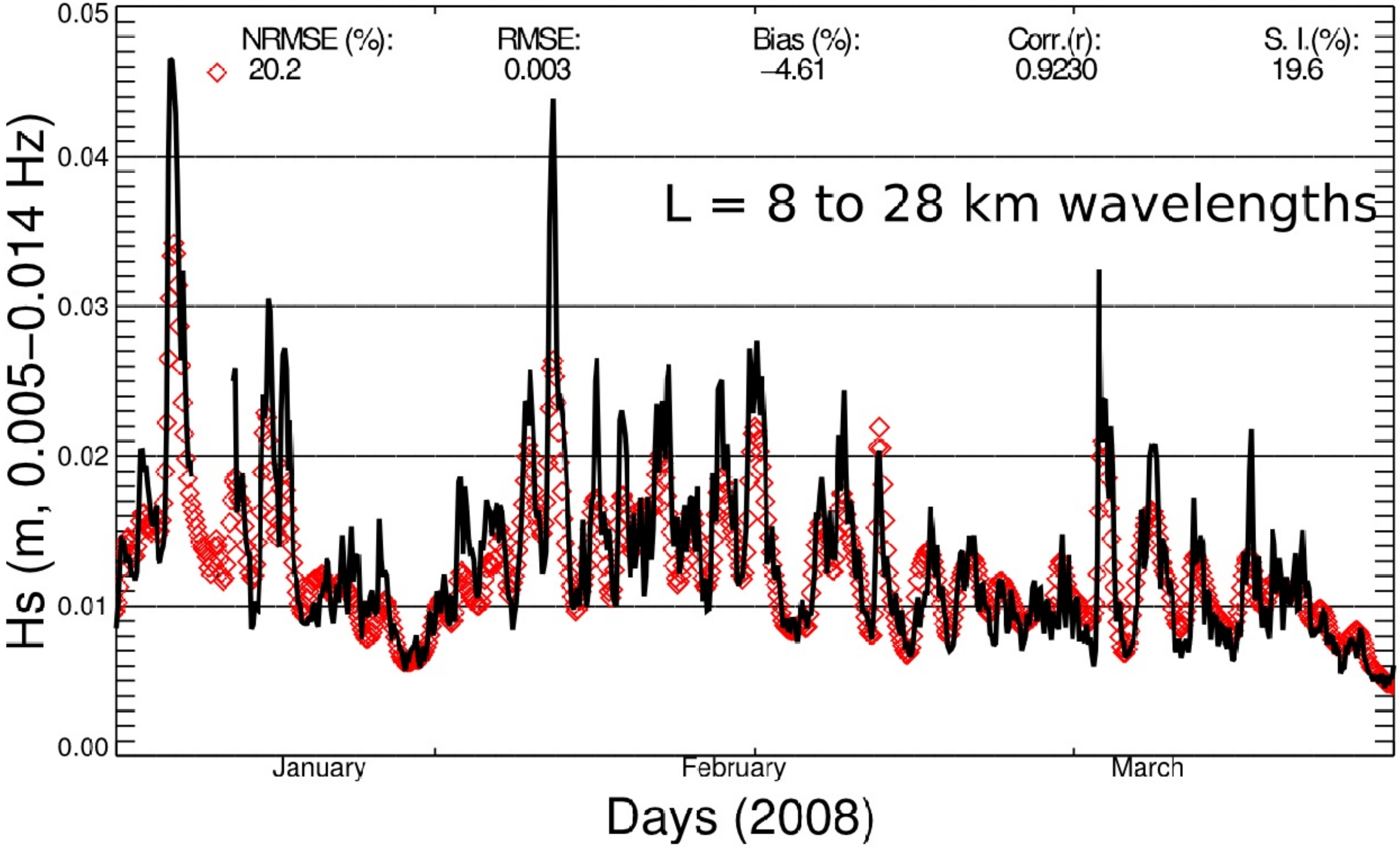
« noise level » at L=10 km

1 cm^2/ (cyc / km) exceeded **10% of the time**

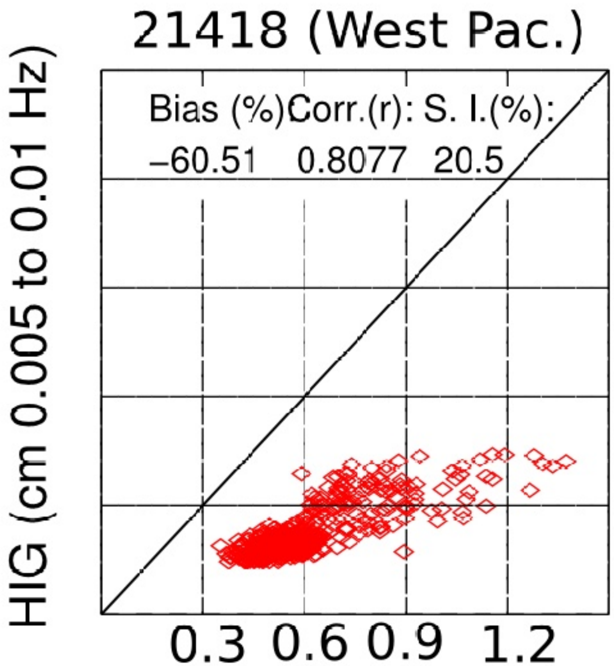
0.1 cm^2/ (cyc / km) exceeded **80% of the time.**

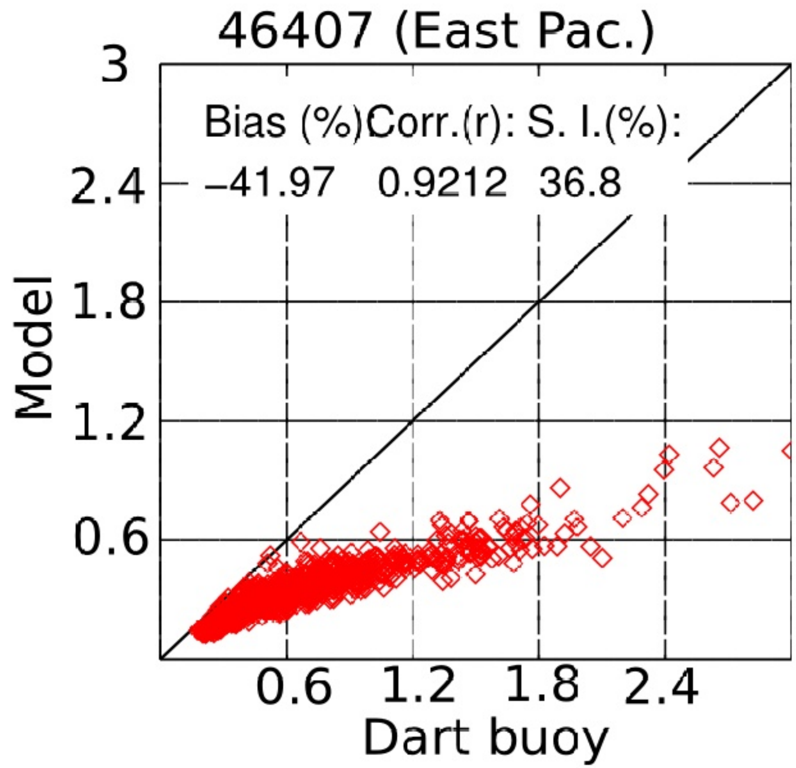


Model verification (off U.S. West Coast, 3200 m depth) … with bias correction...

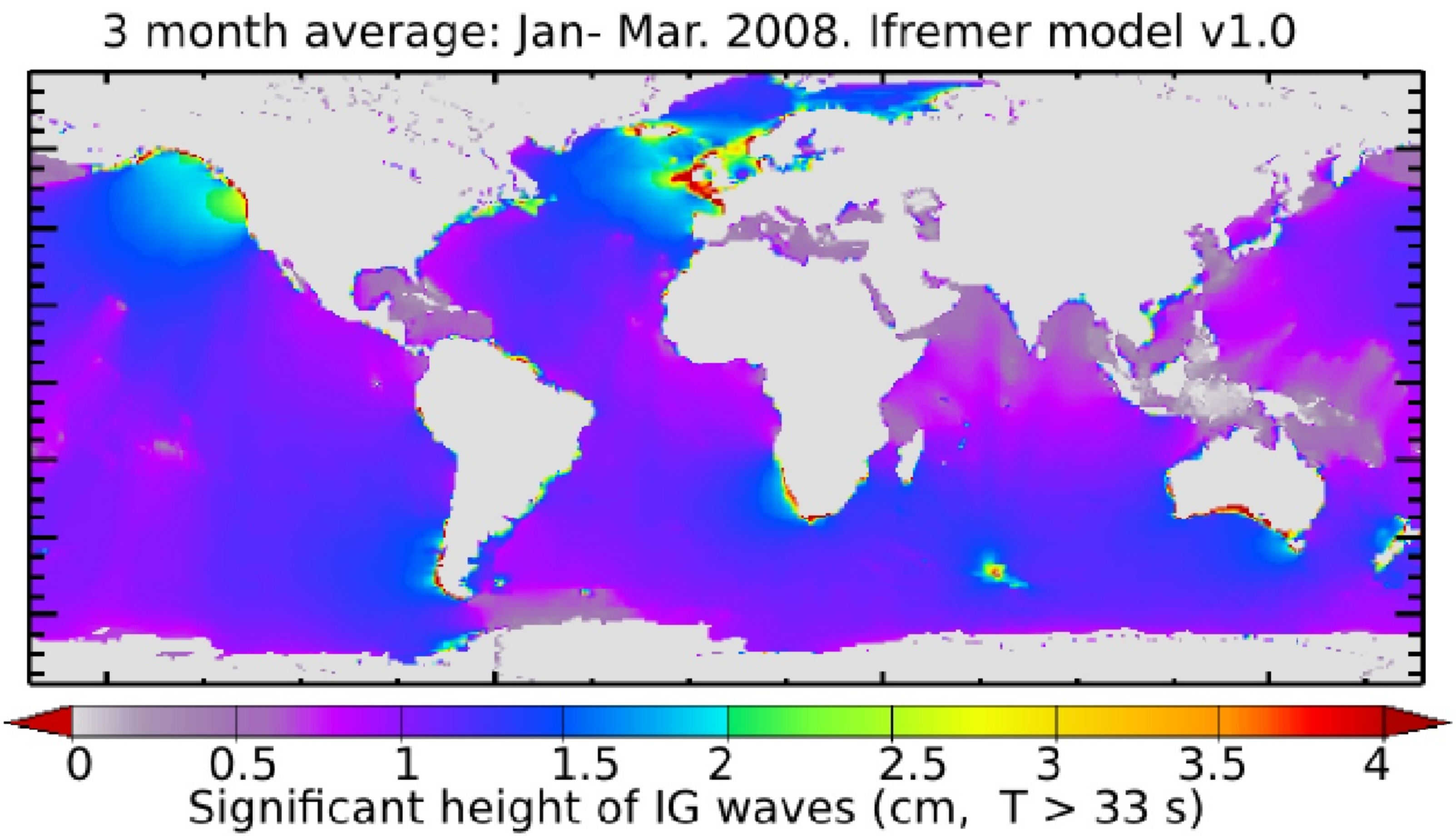


Is the bias the same at all stations ?



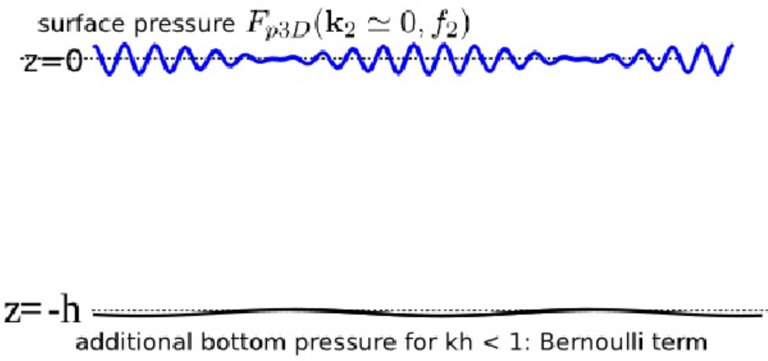


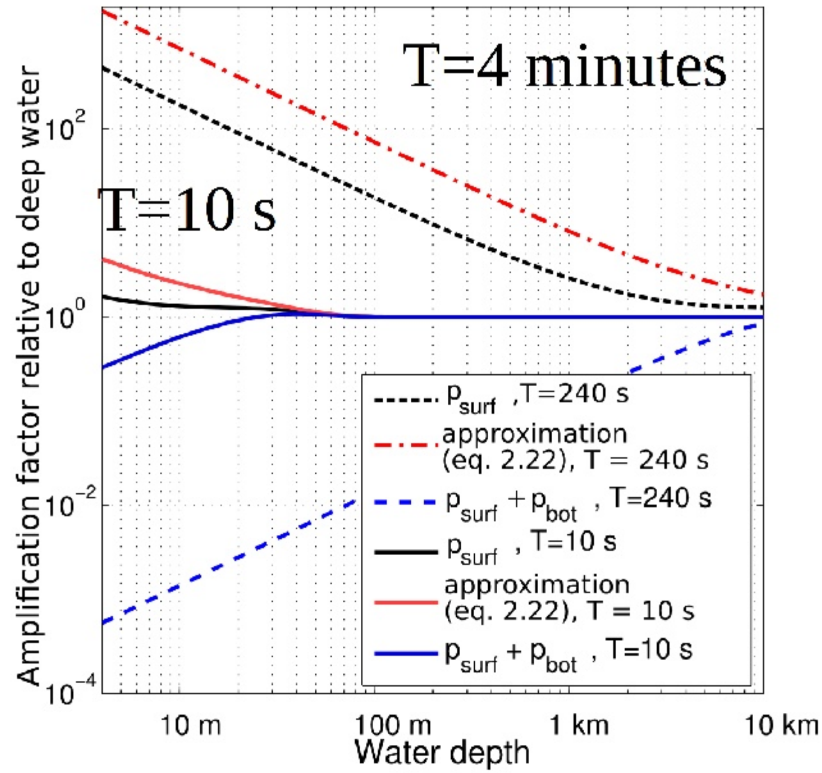
Global map of free IG amplitudes (further validation under way … large regional biases already detected, I'm looking for more data. Ph.D. work of Arshad Rawat for the further refinement of the model)



Can we explain the 50 – 200 s noise (the hum) with IG waves using secondary theory?

… hum … not quite yet ...





Amplification factors rel. to deep water waves : approximation used by Webb (2007) is 10,000 too big on the inner shelf.

Theory (Ardhuin & Herbers 2013) consitent with gravity wave limit (Herbers and Guza, JGR 1991).

First calculations: **noise levels that are too low by 20 dB or more**

5

Conclusions & Perspectives

Conclusions

1) The presence of different modes (Rayleigh, P & S, A-G, microbaroms) can be used to validate the noise source magnitude

2) Seismic noise sources for $0.1 < f_s < 0.6$ Hz are generally well modeled (warning : can be worse with other ocean wave models)

3) Attenuation of Rayleigh waves is loosely constrained by source distribution

4) Noise source database at **http://tinyurl.com/iowagaftp**

Work in pregress : validation of body wave source locations (Obrebski et al., submitted to JGR)
calculations with 0.01-0.06 Hz (hum) : Need a new theory?

Publications

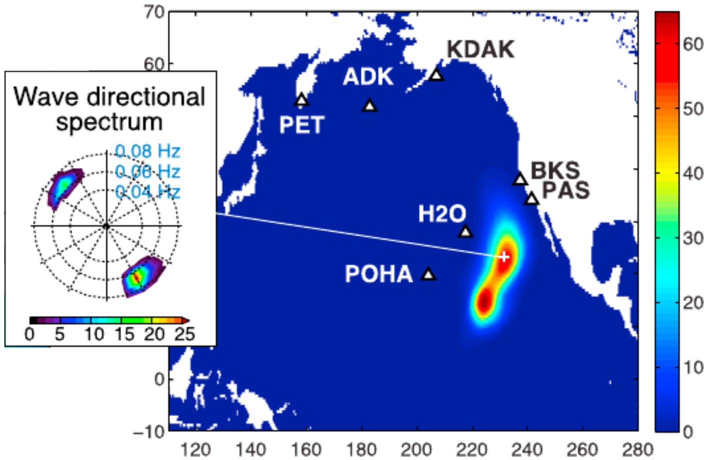
- Ardhuin et al. (JGR 2011), noise model
- Ardhuin and Roland (JGR 2012), refinement of coastal reflection
- Stutzmann et al. (GJI 2012), long-term validation of noise model
- Obrebski et al. (GRL 2012), particular case of loud noise with small waves (class III)
- Husson et al. (GRL 2012), combination of microseism with satellite data for swell analysis
- Ardhuin and Herbers (JFM,2013), theory extension for finite depth and body waves
- Gualtieri et al. (GJI 2013) : noise modeling with normal modes summation
- Ardhuin et al. (JASA, in press), effect of sediment layer, modes in underwater sound

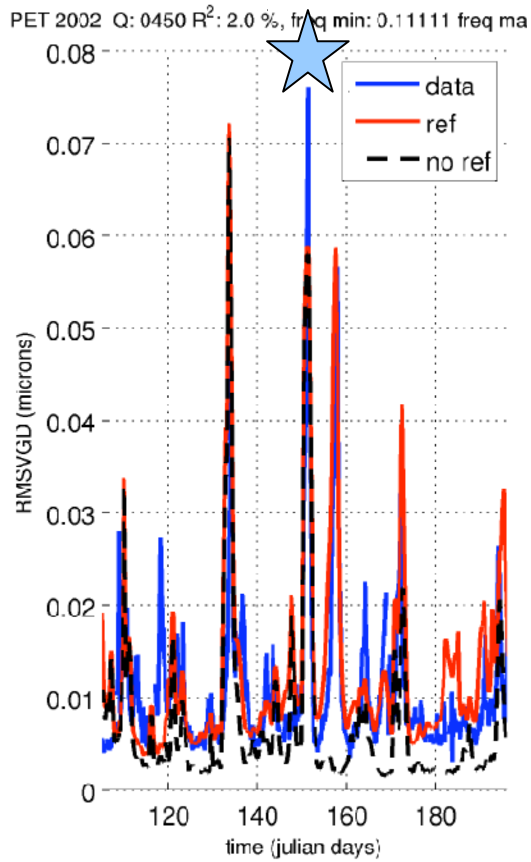
3. Possible constraints on attenuation at f < 0.3 Hz

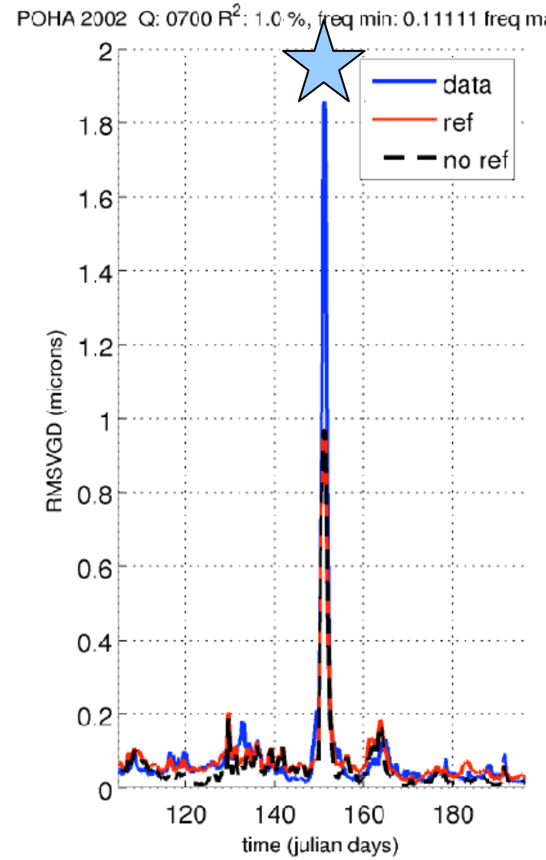
Clear anomaly along the West Pacific coasts with Q ~ 200

Compared to Q ~ 900 for mid-Pacific sites (Q ~ 400 in the North Atlantic).

→ **Rayleigh-wave noise from the Pacific is very difficult to detect in East Asia.**





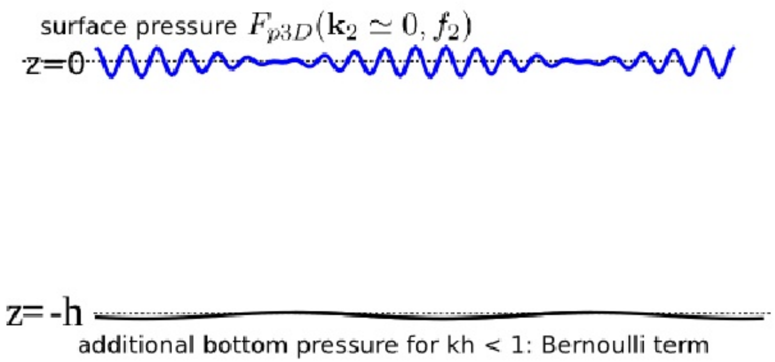


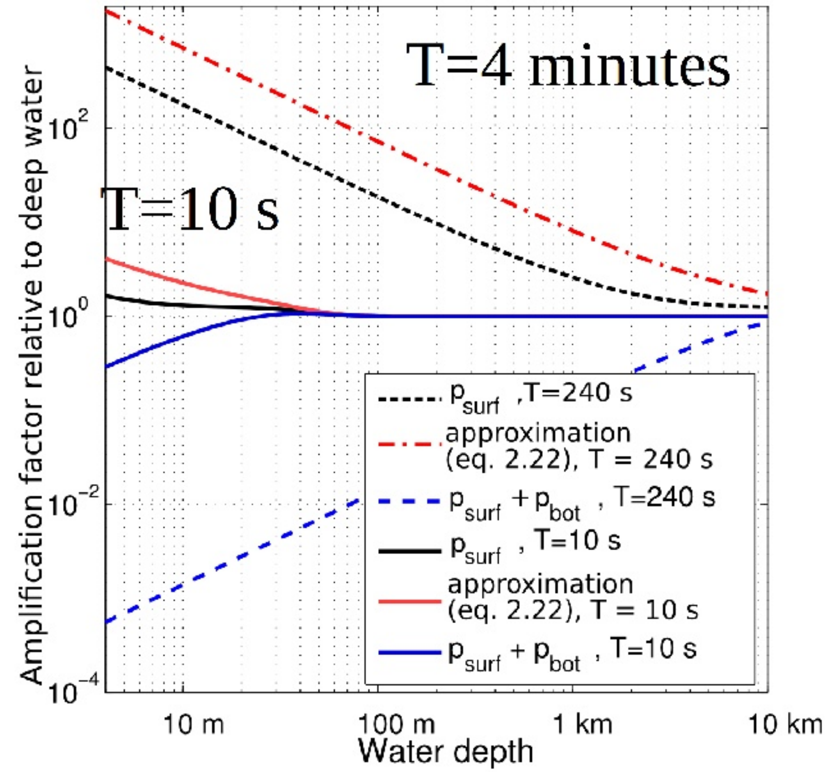
2. Theoretical developments :

Finite depth effects

For waves in finite depth, the wave kinematics are modified (up to a factor 4 correction) …

and we need to consider the
wave-induced pressure at the bottom



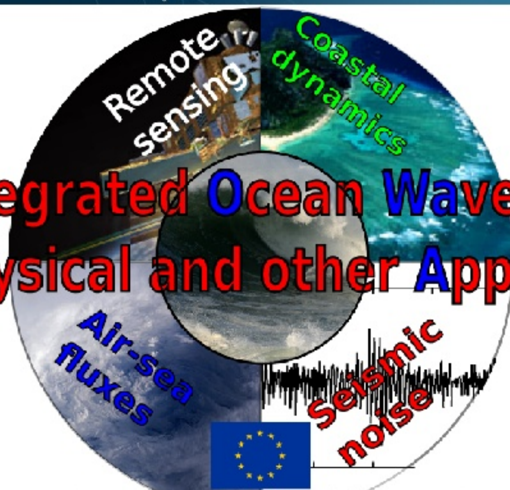


Amplification factors compared to deep water waves : approximation was used by Webb (2007) for the source of « hum » ... the error on the inner shelf is a factor 10000.

Our result is consitent with the gravity wave limit (Herbers and Guza, JGR 1991).

Some recent

wave work at Ifremer



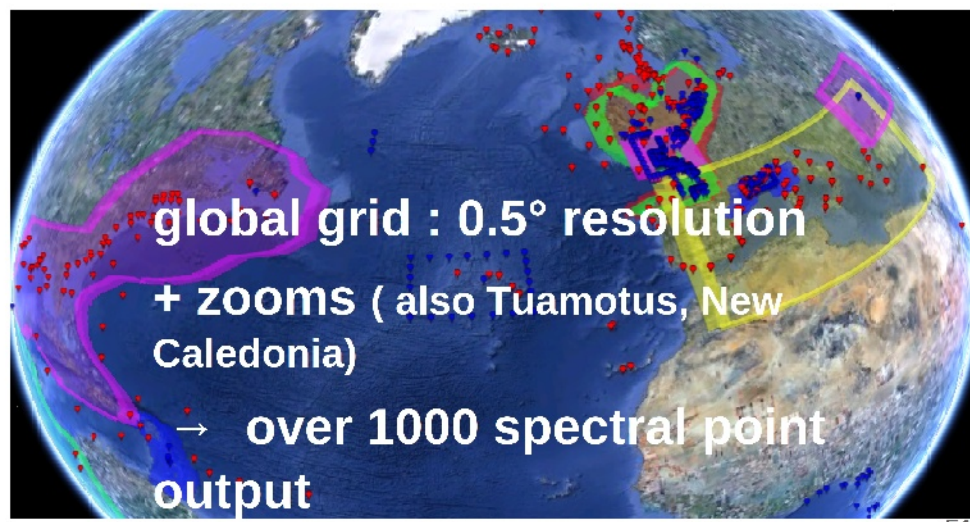
http://wwz.ifremer.fr/iowaga

« IOWAGA » integrates observations and models for a more comprehensive an accurate wave parameters for geosciences and engineering.
Supported by European Research Council

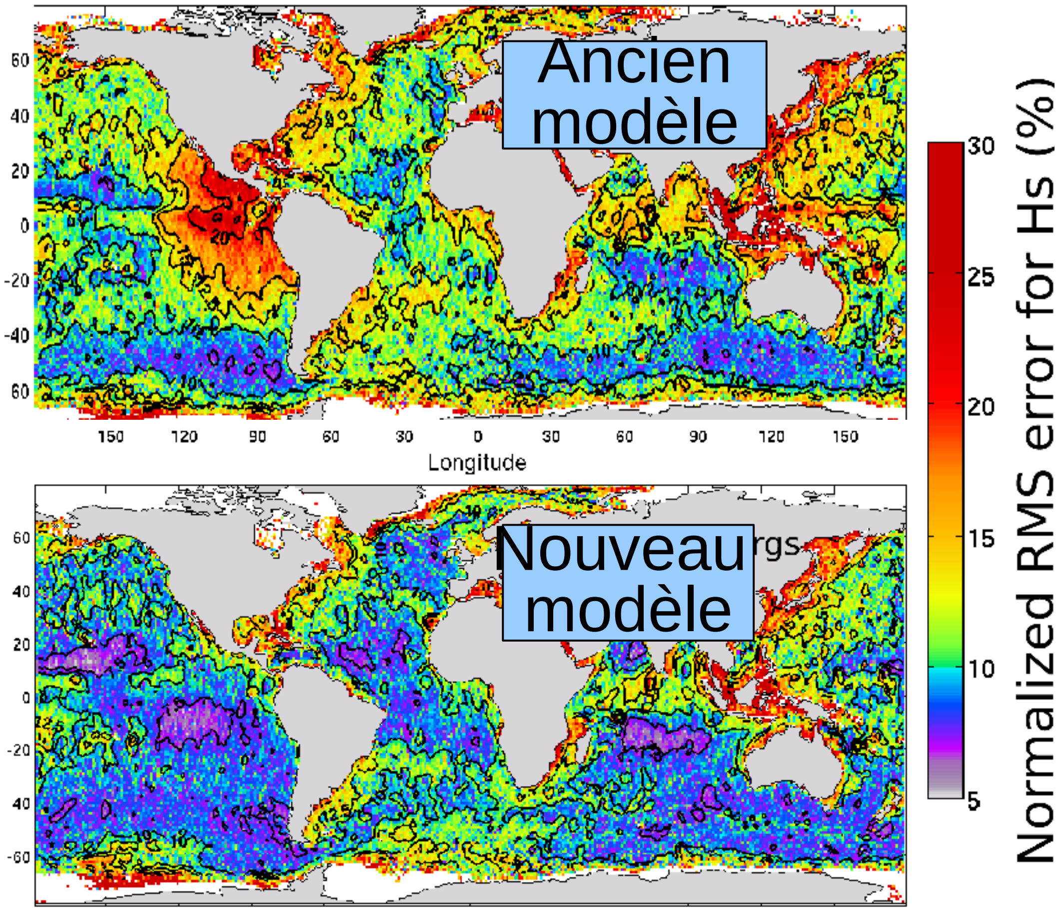
Zooms and spectral output
in the 1994-2012 hindcast

Output parameters include all
air-sea fluxes + sea and swells
data …

Global 1999-2012 already online



3. Observer les vagues depuis l'espace



Qualité du modèle pour la hauteur des vagues :

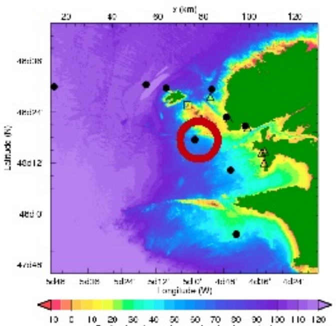
En rouge, **erreurs > 20 %**

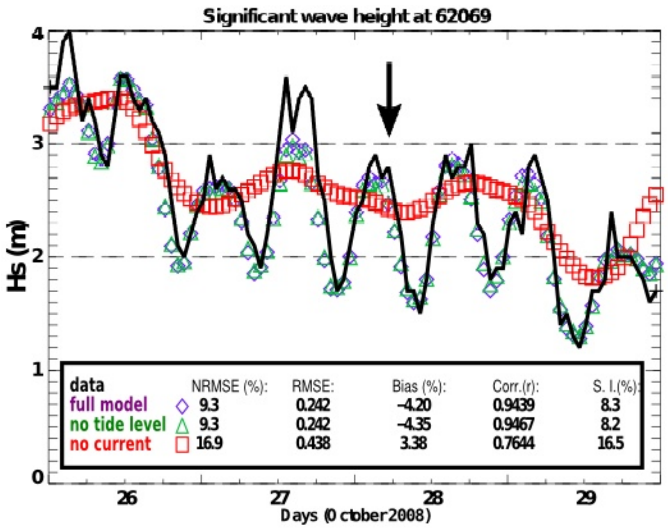
En bleu, **erreurs < 10 %**

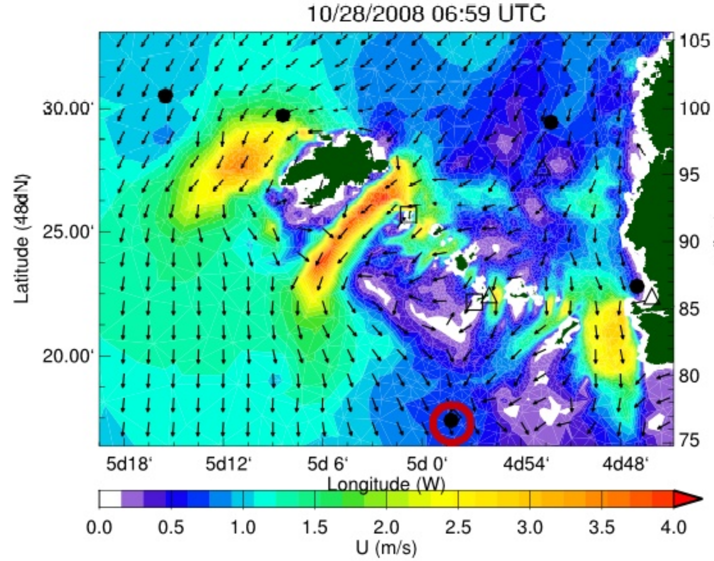
Ce nouveau calcul de la dissipation est utilisé pour Prévimer depuis 2008, par Météo-France depuis 2010, par le service météo des Etats-Unis depuis 2012 (NOAA/NCEP)

3. Observer les vagues depuis l'espace : du global au local

L'amélioration du modèle global permet aussi d'améliorer les prévisions locales.







Pour le Finistère, il convient en particulier de prendre en compte les courants de marée.

4. Le bruit des vagues

Et puis vérifier la théorie...