# Les fréquences en-dessous de 10 Hz en mesure acoustique (et sismique) sous-marin

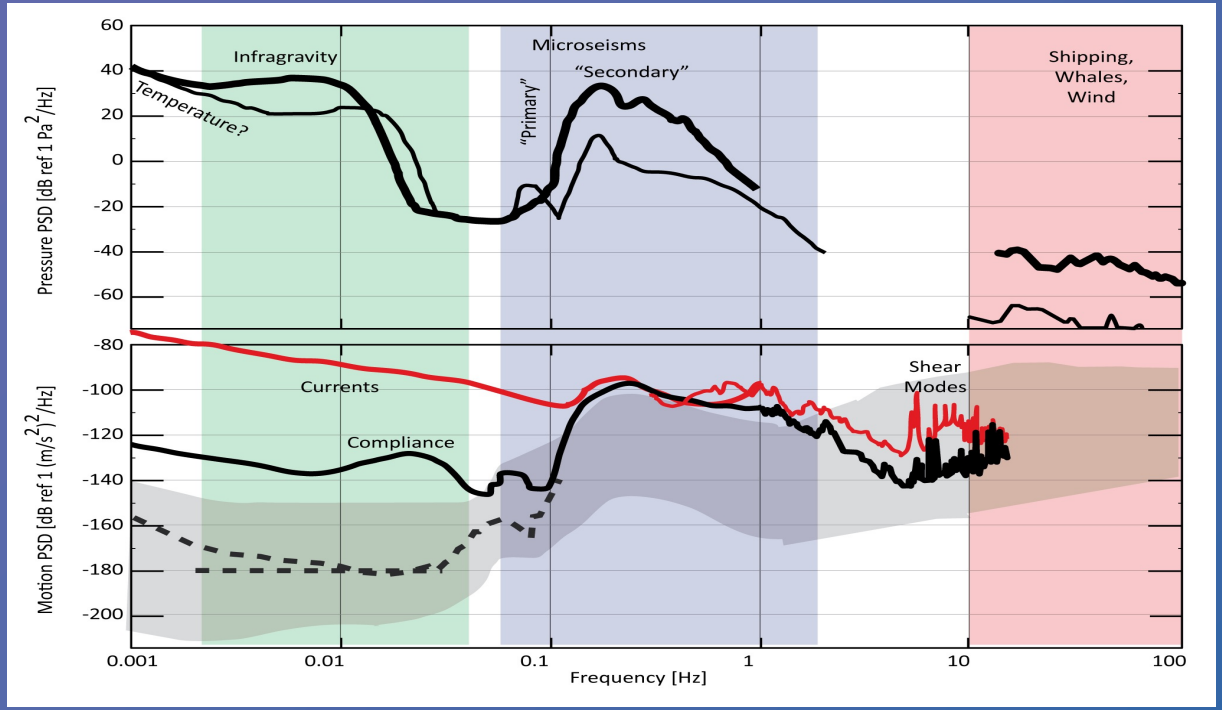
Wayne C Crawford

# Overview

- The marine “noise” spectrum (mostly) below 10 Hz
- A bestiary of sources and applications
  - The generation of global seismological noise
- Separating signal from signal (and noise)
- Seafloor seismology datasets
- The BRUIT-FM project

# The seafloor spectrum

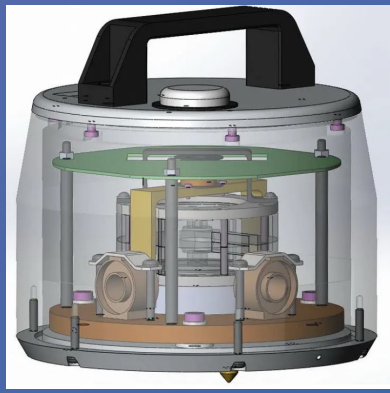
- Infragravity band (0.001-0.05 Hz)
  - Long period ocean waves
  - Seafloor currents
  - Whole-earth tremor/resonance
  - Large EQ surface waves
- Microseism band (0.05-2 Hz)
  - Highest noise levels
  - Interactions entre ”normal” ocean waves
  - ”Ambient noise” studies
  - Volcanic tremor
- Soundscape band (2-100 Hz)
  - Biosphere
  - Anthroposphere
  - Weather

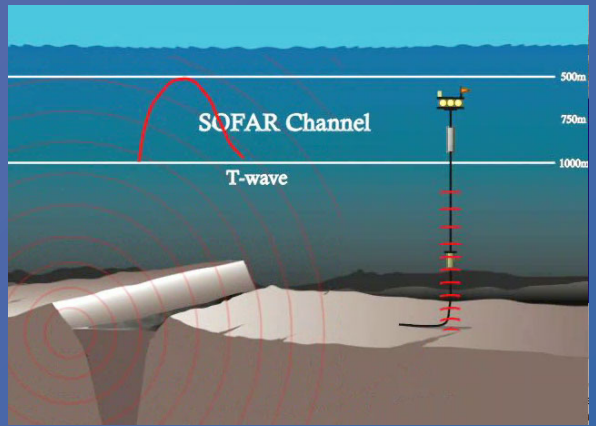


# Données/instruments utilisés

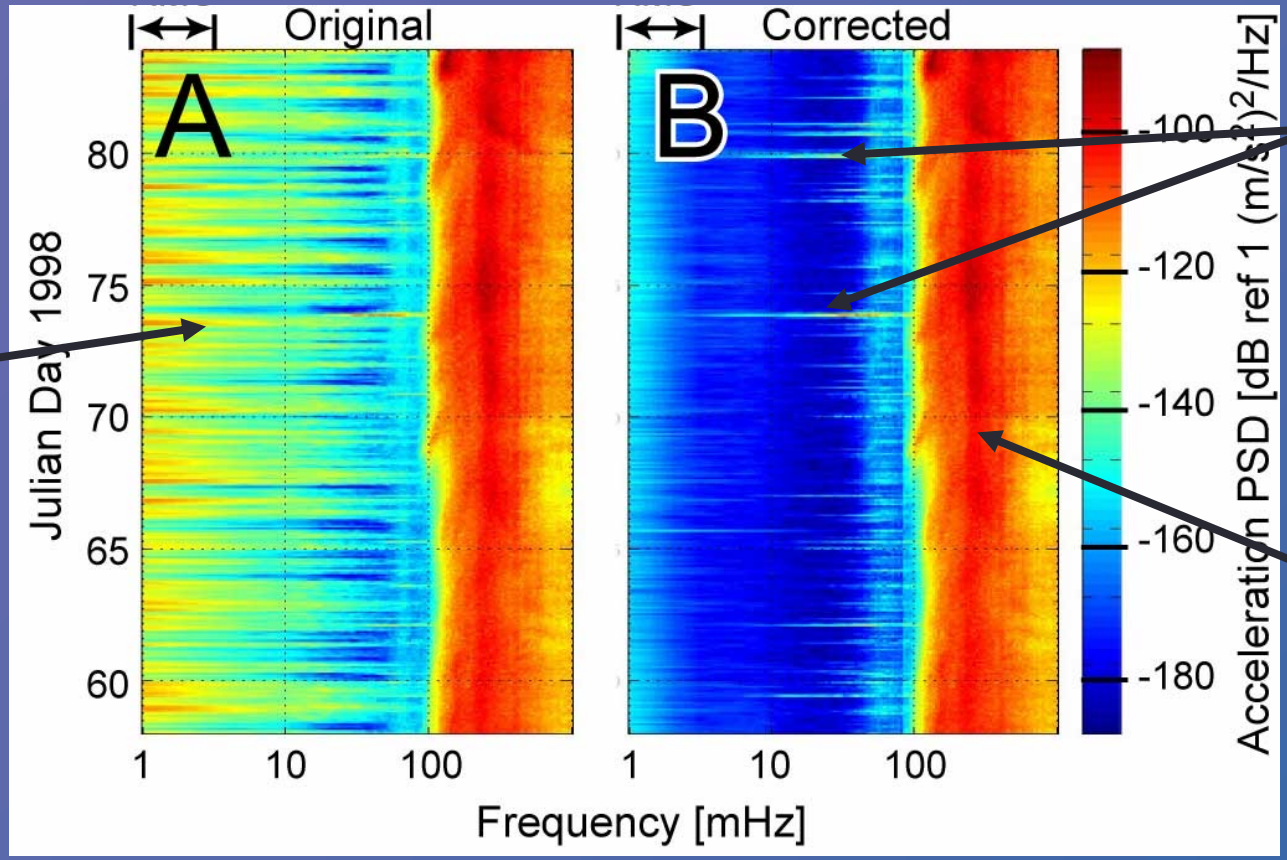
- Sismometres fond de mer 4 composants
  - Deploiements de plusieurs mois, voir 1+ ans
  - Beaucoup d'experiences
  - Données souvent ouvertes et accessibles, sous format standardisés
  - 1 composant de pression
    - Hydrophones large bandes ~ 0.01 – 10 000 Hz, ou
    - Jauge de pression differentielle, ou
    - Jauge de pression absolu
  - 3 composants mouvent du sol (sismologique)
    - Permet de calculer orientation (back-azimuth) de la source

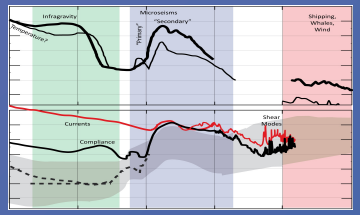
- Hydrophones dans la canale SOFAR
  - Tres longue porté de sensibilité





# Seafloor spectrograms



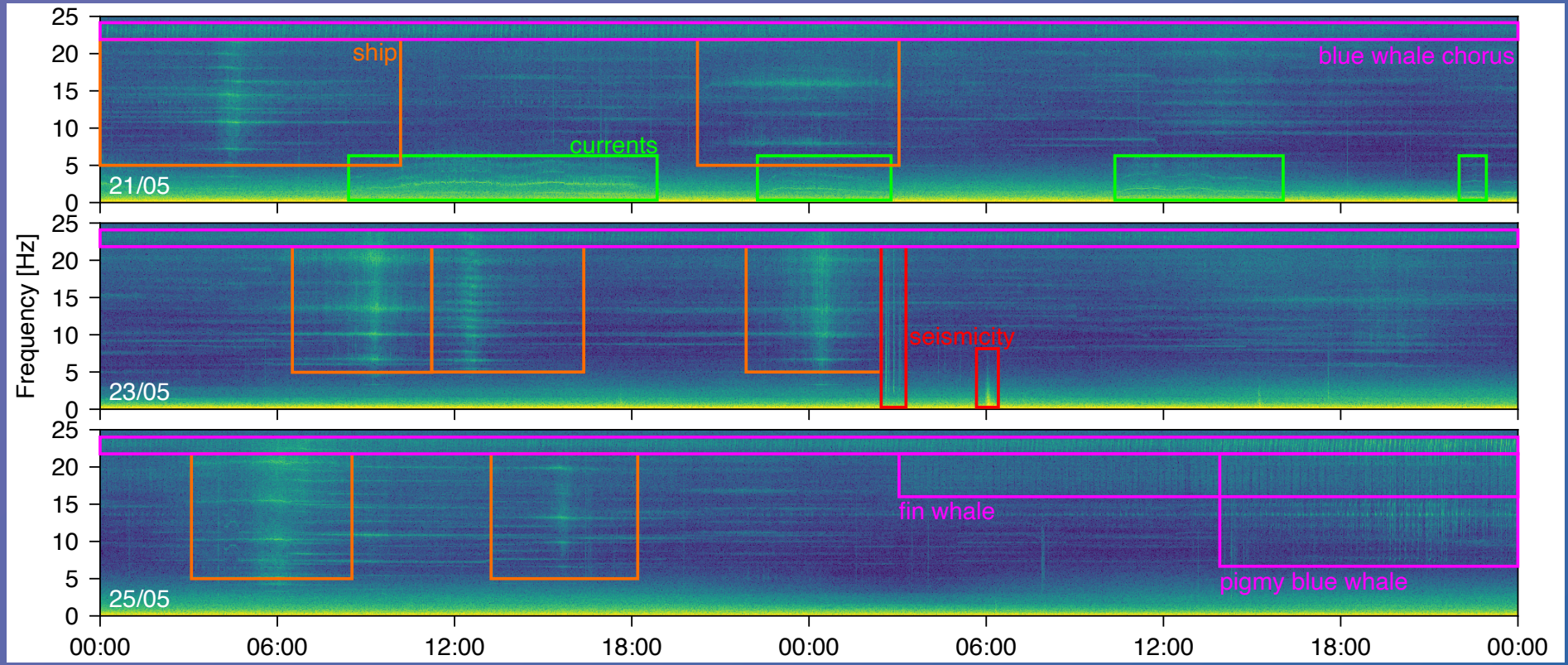
Earthquakes

Seafloor currents (tidal correlation)

Ocean waves (microseisms)

Crawford et al., 2007, BSSA

# Seafloor soundscape spectrogram

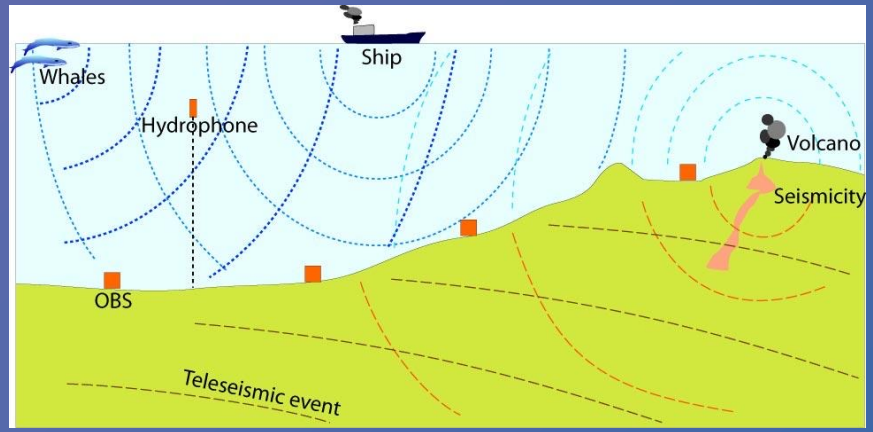


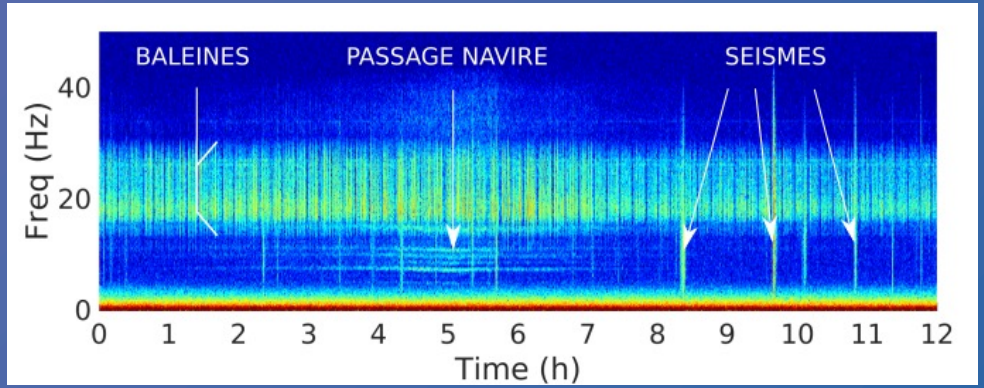

A Trabattoni 2021

# Seismological and hydroacoustic signals

- Natural events (Earthquakes, volcanoes, wind, rain, cyclones, currents, cryosphere)
- Bioacoustic noise (whales, …)
- Anthropogenic noise (ships, constructions, prospections, mining…)

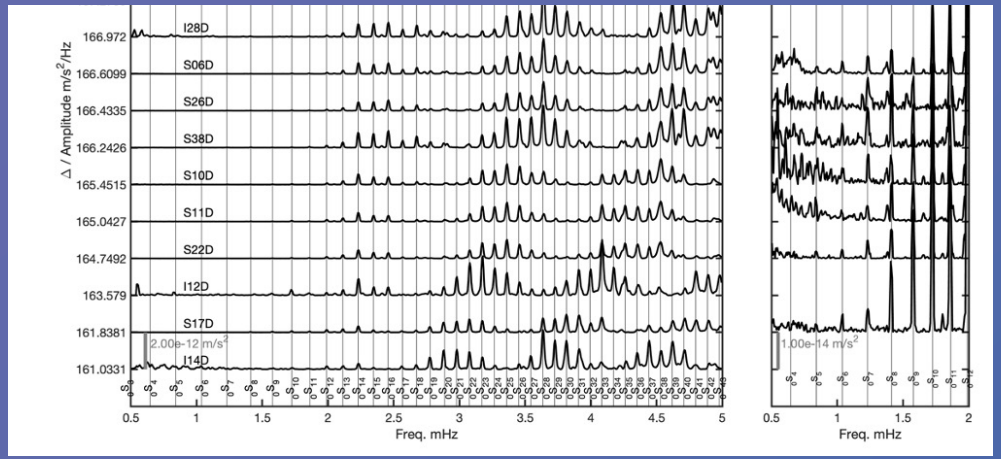
- → need some kind of systematic source cataloging



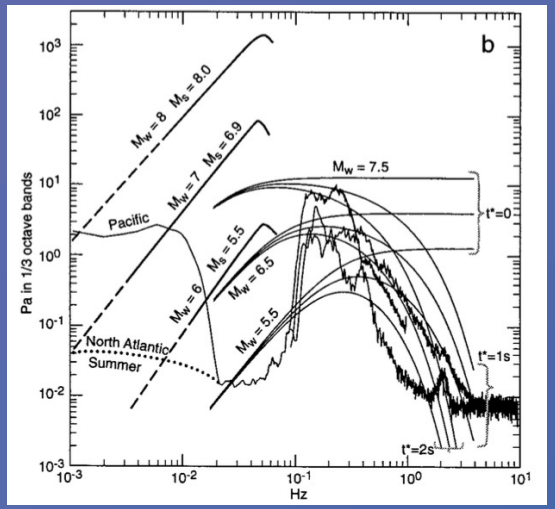
# Earthquakes

- Normal modes at frequencies of 0.002-0.01 Hz
- Surface waves at frequencies < 0.1 Hz
- Body waves at frequencies > 1 Hz (unless strong attenuation)



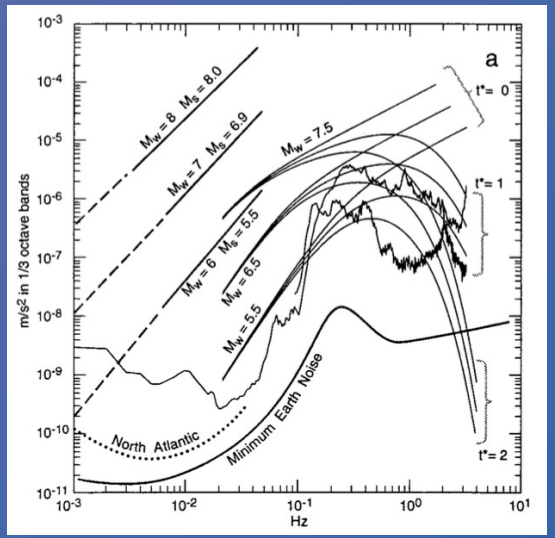

Harmon et al., *in prep*

Pressure



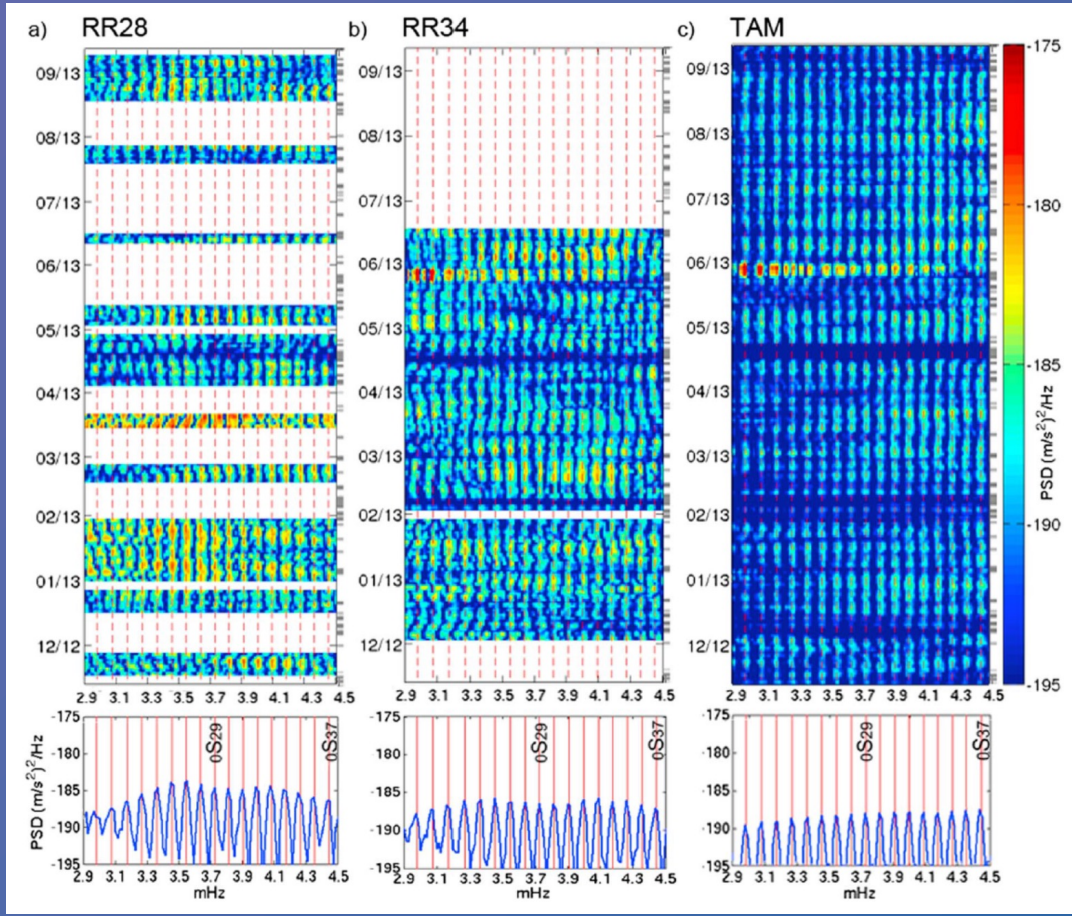

Webb, 1998, *Rev. Geophys.*

Acceleration



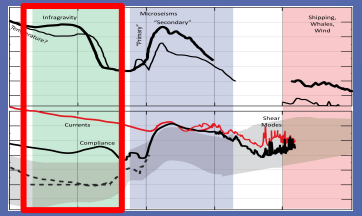
# Earth's normal modes

- Information about deep earth structure
- First detected on seafloor data ~year 2000
- Through noise reduction, can now detect "hum"

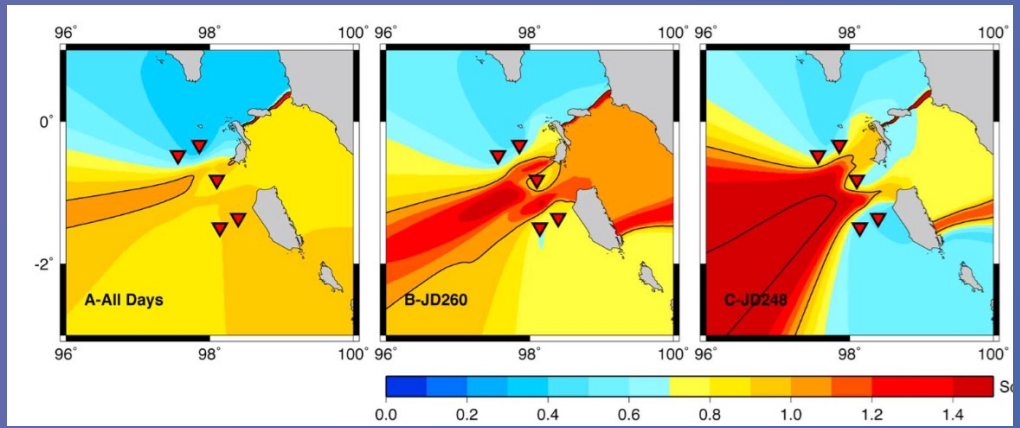



Deen et al., 2017

# Infragravity waves

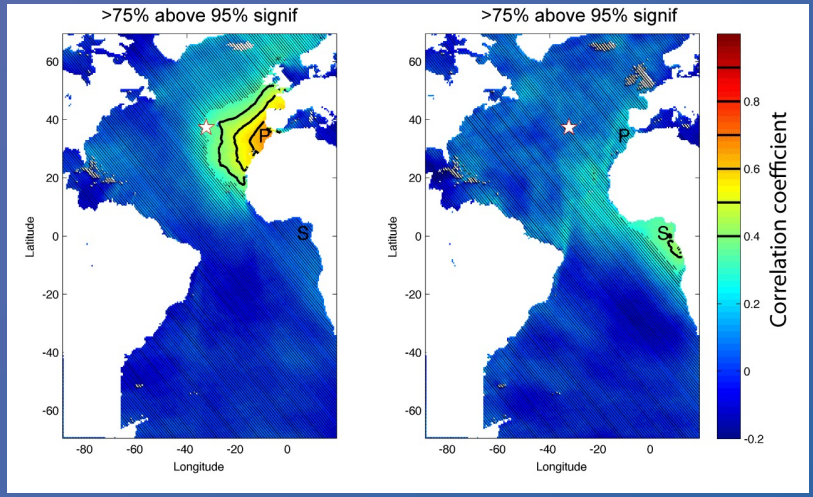



- Ondes de surface oceaniques a tres basse frequences (0.001-0.05Hz)
- Petits (<1cm) et longues (>1km)
- Capteurs de pression sur les OBS utilisés pour etudier leur niveaux, sources




Harmon et al., 2012

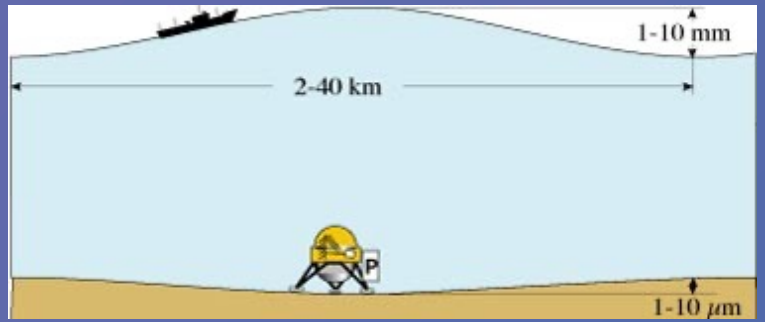
Été Hiver



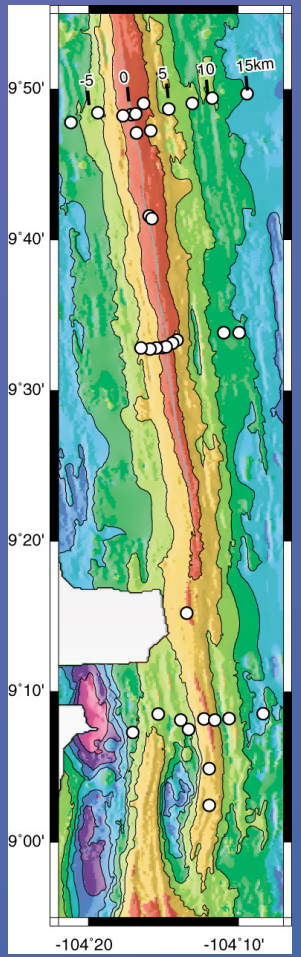

Crawford et al., 2015

# Seafloor Compliance

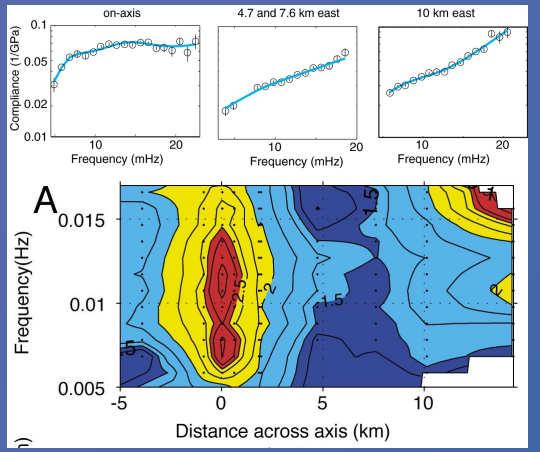
- Seafloor motion under infragravity waves
- Depends on subsurface shear modulus
- Need low frequency (<0.05Hz) pressure and acceleration measurements
- Now on Mars!



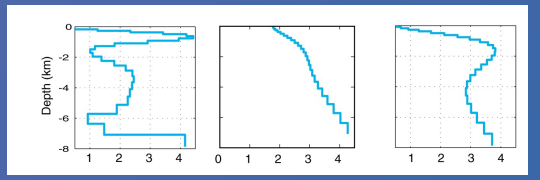

Crawford et al. (1998, *JGR)*



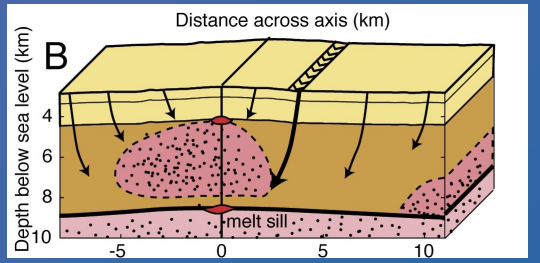

Données




Inversion



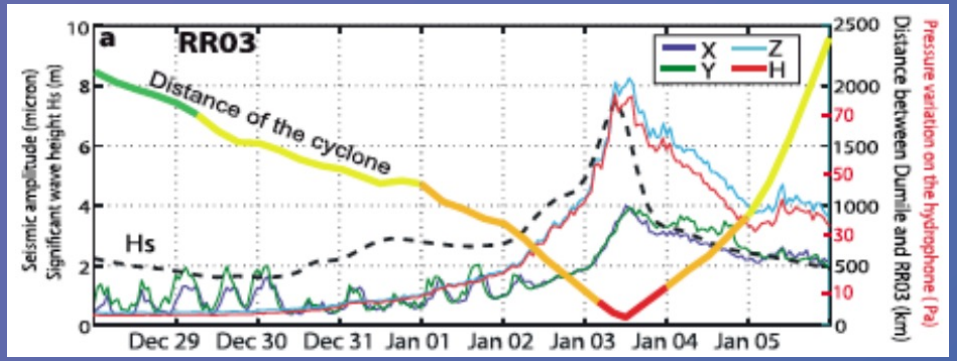

Interpretation

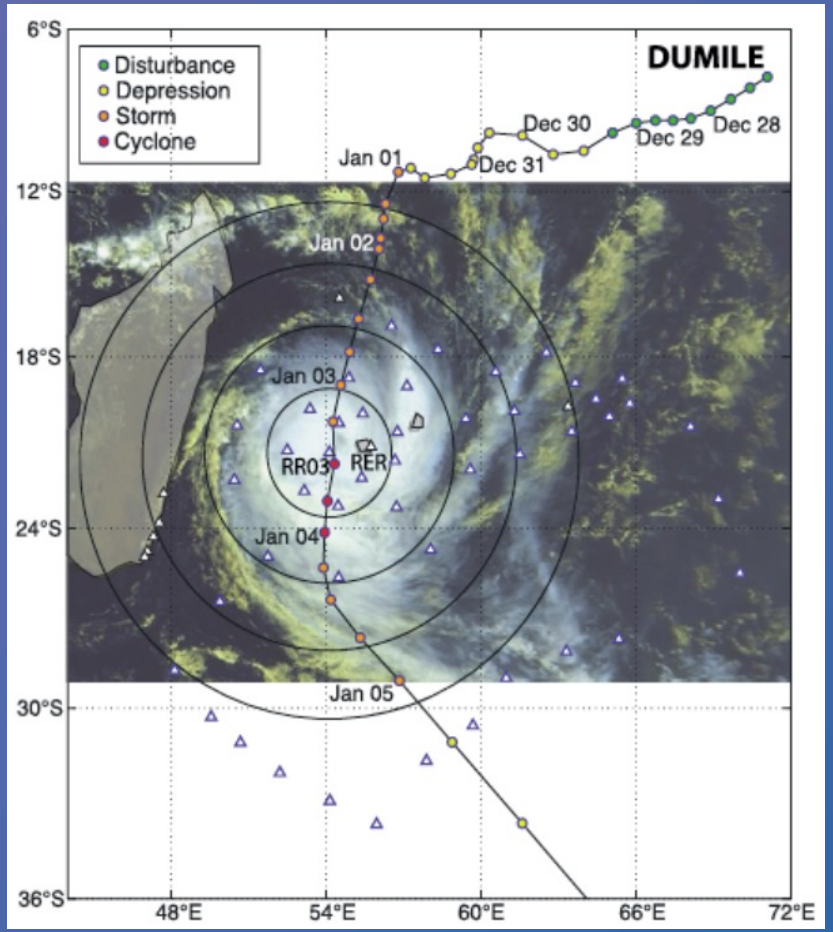



Crawford & Webb (2002, *BSSA)*

# Cyclones

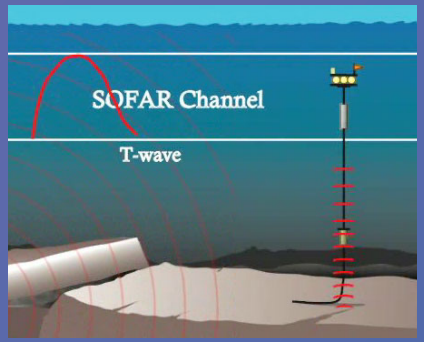
- Understanding the seismic signal:
  - Propagation/sources
  - Modelling noise in SM, PM and HF bands
- Structure/monitoring studies
- Use OBS as supplementary weather data
- Impact of cyclones on animal behevior

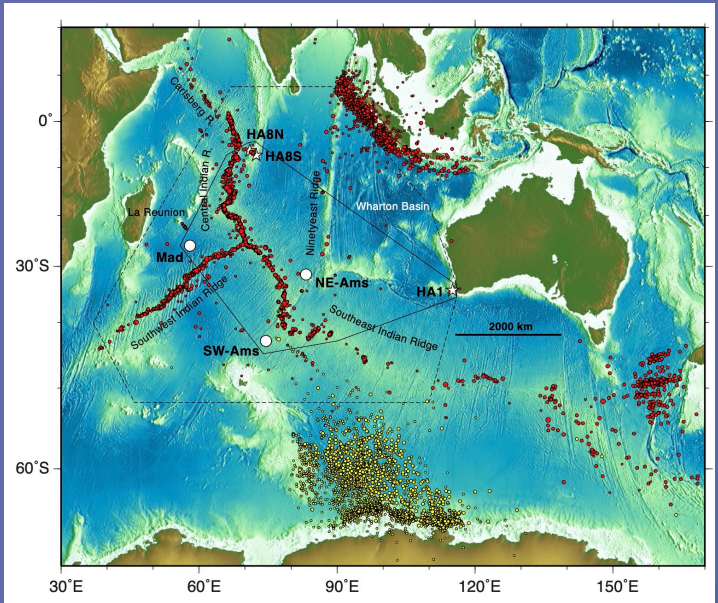


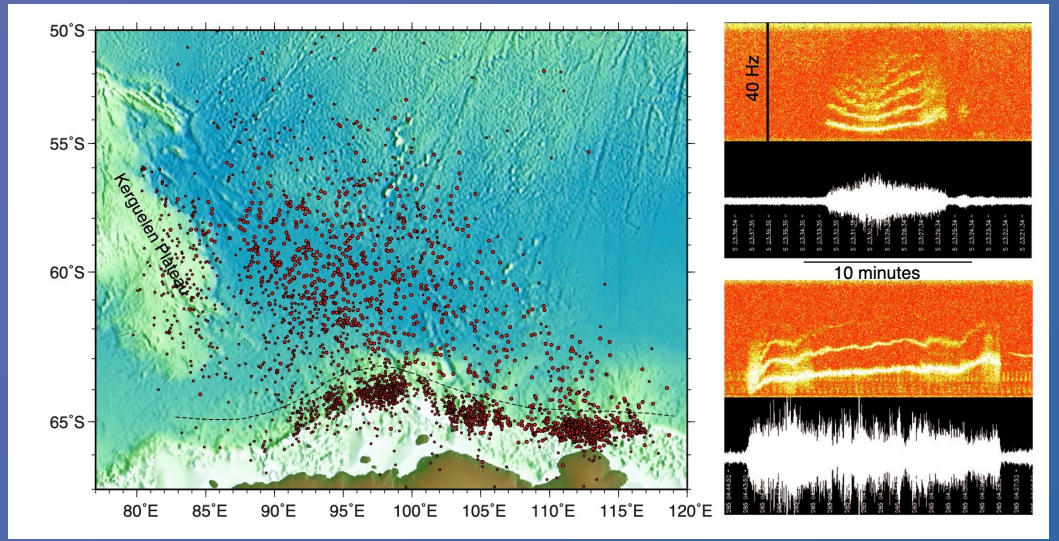



# Cryoseismology

- Far field: OHASIS-BIO network



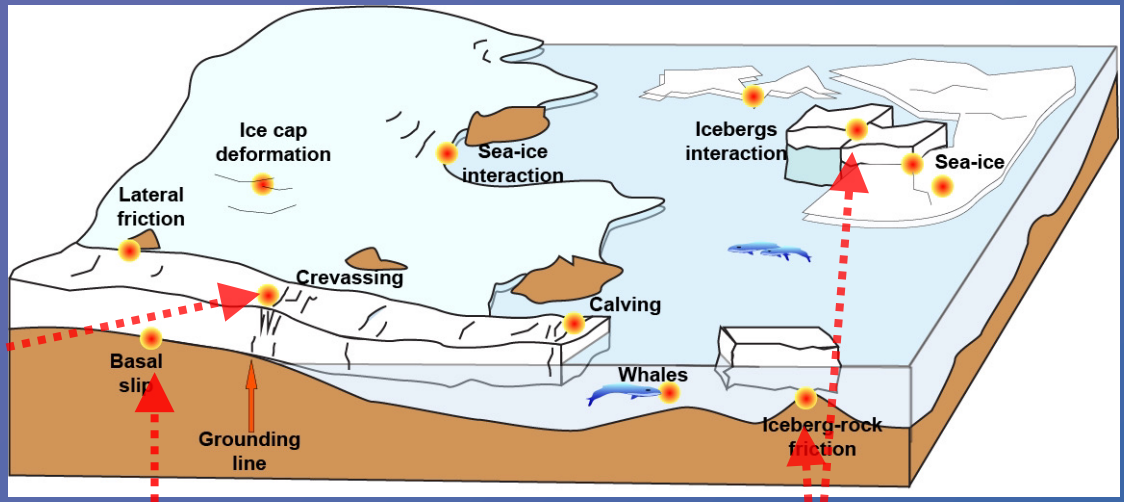



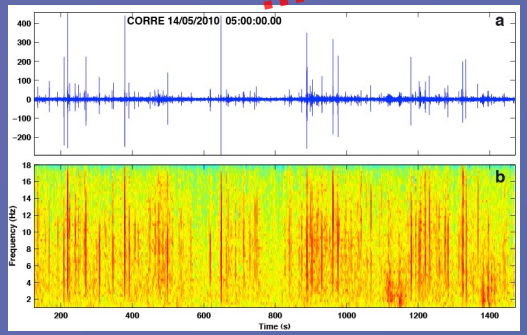

Royer et al., *GJI*, 2015

# Cryoseismology

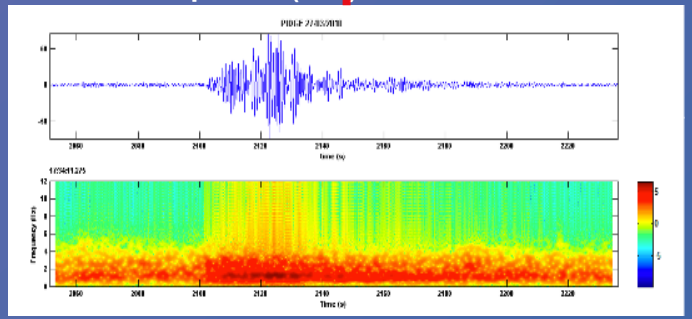
- Near field: SEIS-ADELICE expt (G Barruol)
  - Discriminate and locate sources
  - Subglacial bioacoustics
  - Subglacial hydrplogy
  - Calving signature



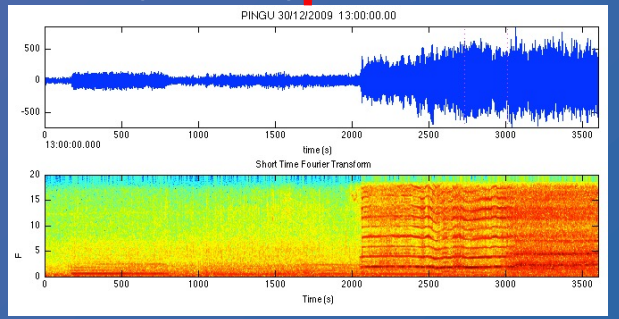

**Icequakes (1 s)**




**Glacial earthquakes (10s)**

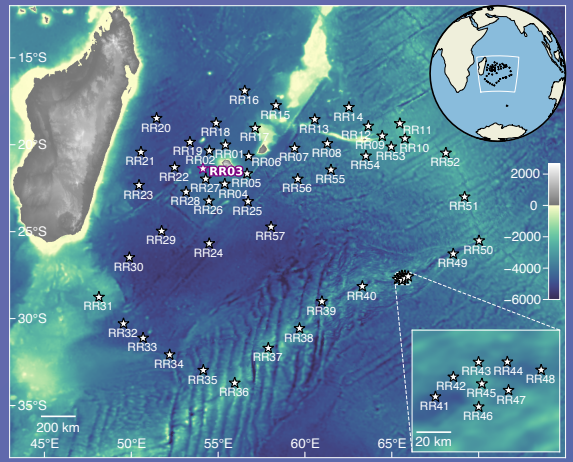


**Tremors (min to hrs)**

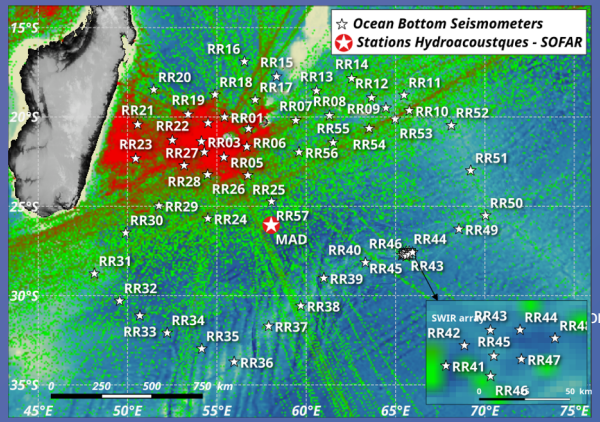


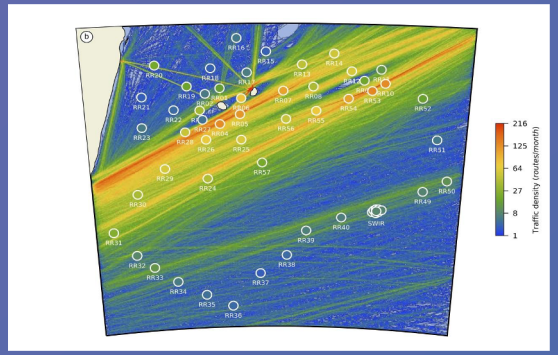
# Ship Noise

**RHUM-RUM (2012-13)**

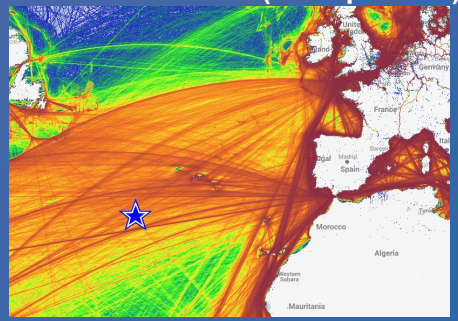



**RHUM-RUM + OHASIS-BIO**



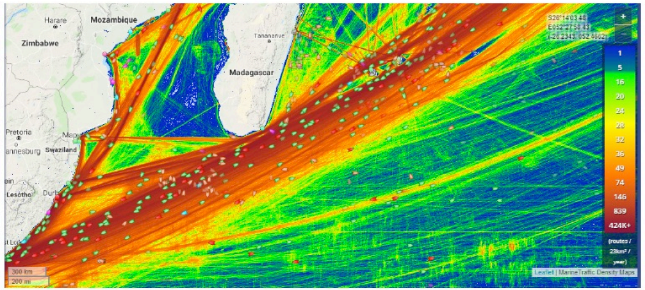



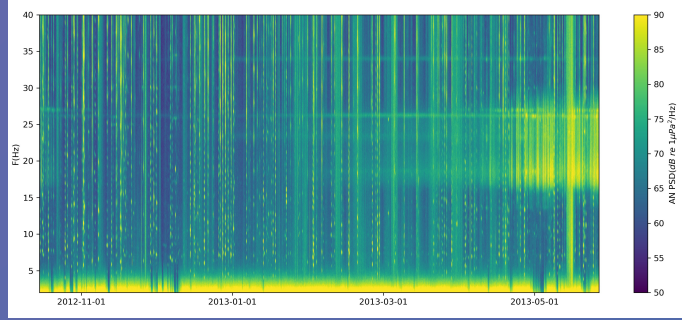

**MOMAR (2007-present)**



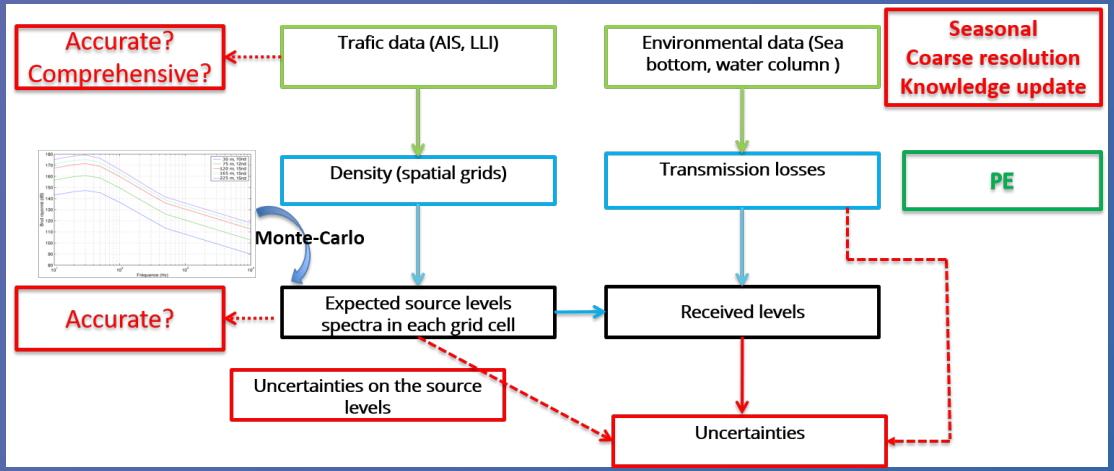
# Noise Pollution

- Validate numerical models at basin scale
- Characterize impact of noise on fauna behavior



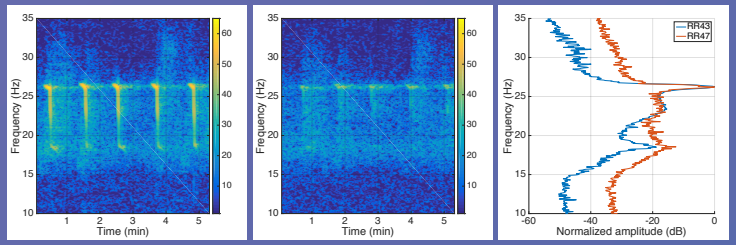

**Ambient noise modeling Framework**



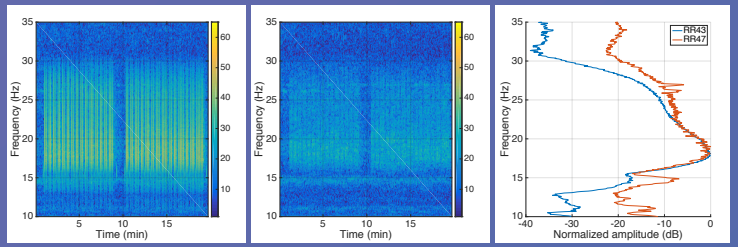

Kinda et al., JASA, 2018

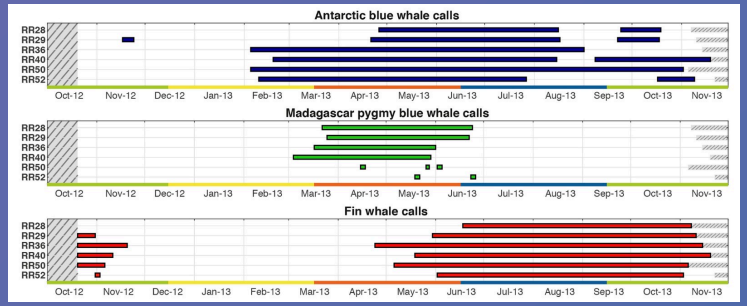
# Whale detection and tracking

Antarctic Blue Whale




Fin Whale




Seasonal occurrence of whales

CrossMark

**Passive stochastic matched filter for Antarctic blue whale call detection**[a)]

Léa Bouffaut,[1,b)] Richard Dréo,[1] Valérie Labat,[1] Abdel-O. Boudraa,[1] and Guilhem Barruol[2]

Contents lists available at ScienceDirect

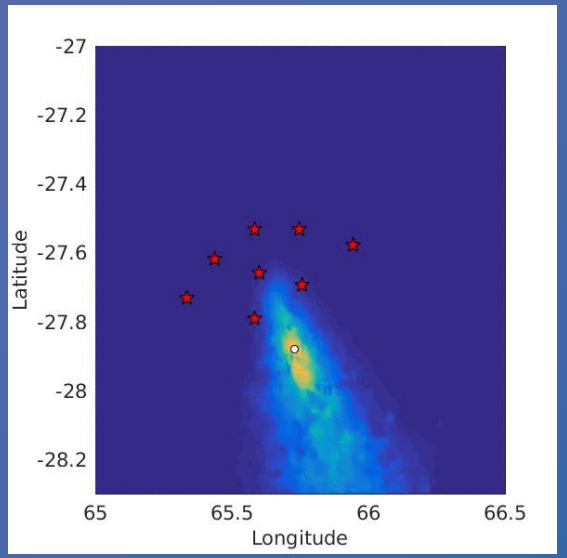
Deep-Sea Research Part II

journal homepage: www.elsevier.com/locate/dsr2

ELSEVIER

**Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean**

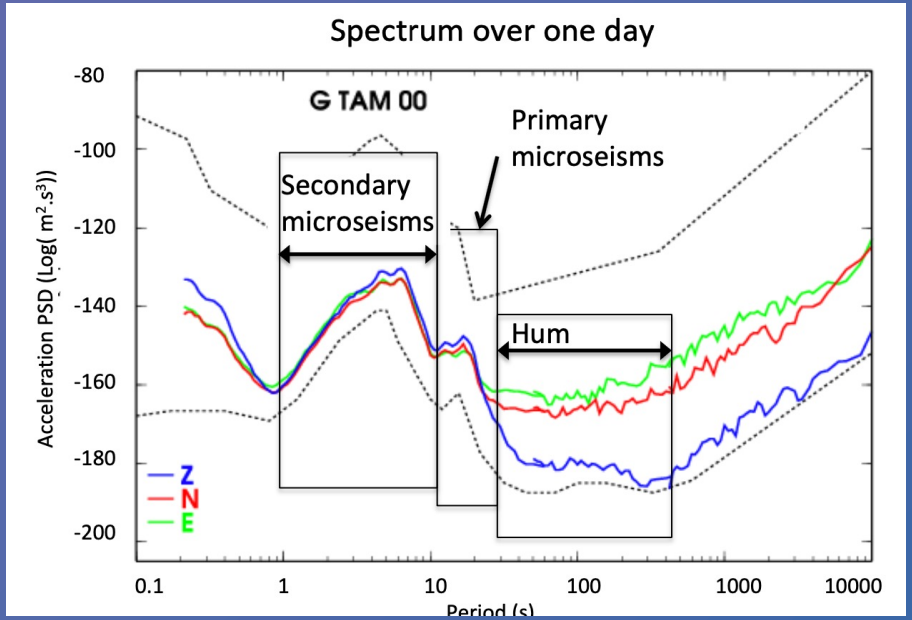
Richard Dréo[a,*], Léa Bouffaut[a], Emmanuelle Leroy[b,c], Guilhem Barruol[d], Flore Samaran[b]




Whale tracking by TDOA analysis (Dréo et al, 2019)

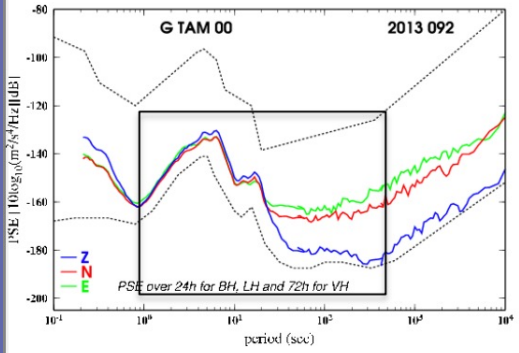
# Global Seismic noise

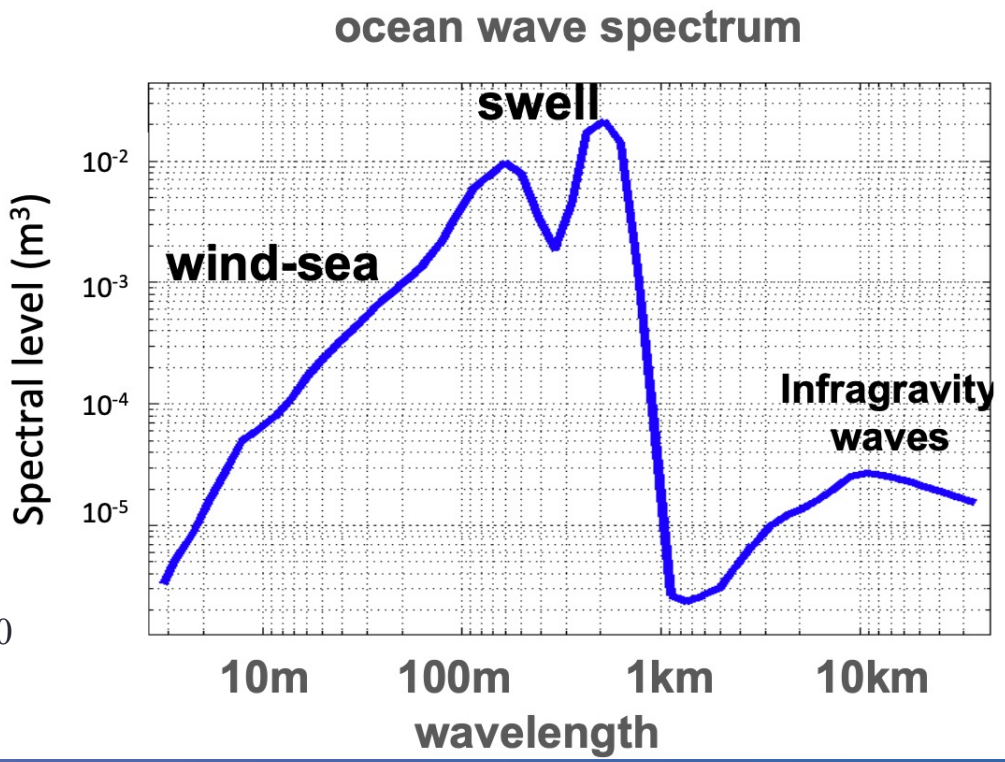
Strongest signal
= Rayleigh waves




Noise between 1 and 500 seconds is caused by ocean waves

# Ocean wave spectrum



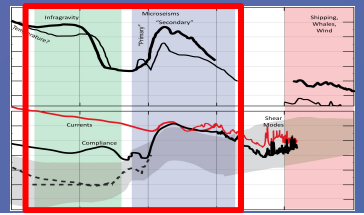




Longuet-Higgins, 1950
Hasselmann, 1963

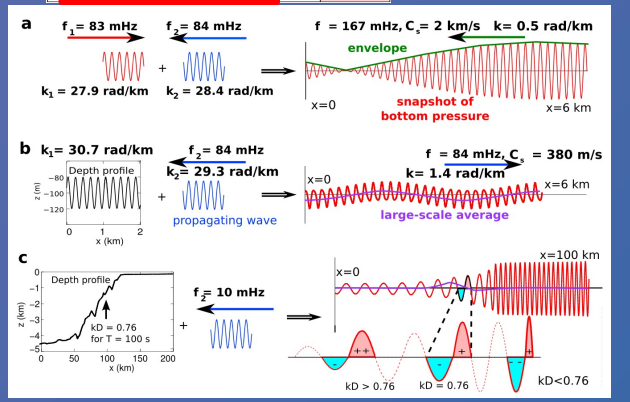
Wind sea and swell -> primary microseisms
Infragravity waves -> “hum"

# Generation of global seismological noise

- Sources:
  - Oceanic Infragravity waves
  - Oceanic microseisms
- Modeling
  - « Secondary Mechanism (SM ) »: wave-wave interaction
  - « Primary » Mechanism (PM) : wave-seafloor interaction
  - Predict noise levels using wave spectra and bathymetric maps
- Outputs
  - Better understanding of global noise
  - Measure oceanic storms and waves with land stations

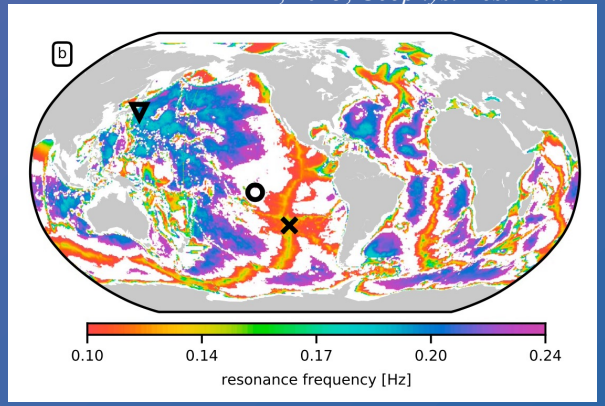



Theory




Ardhuin et al., 2015, *Geophys. Res. Lett.*

Mapping with storms




Meschede et al., 2017, *J. Geophys. Res.*

# Generation of global seismological noise

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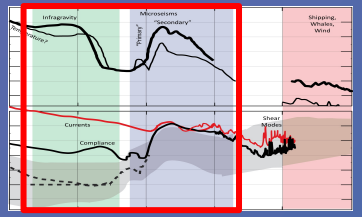
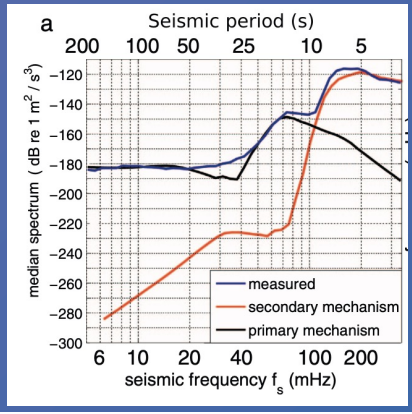
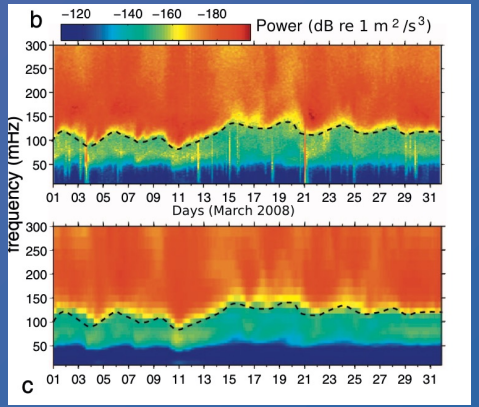
**Wave reflectivity coefficients at coastlines are the greatest model unknown**




Modeled vs observed spectra



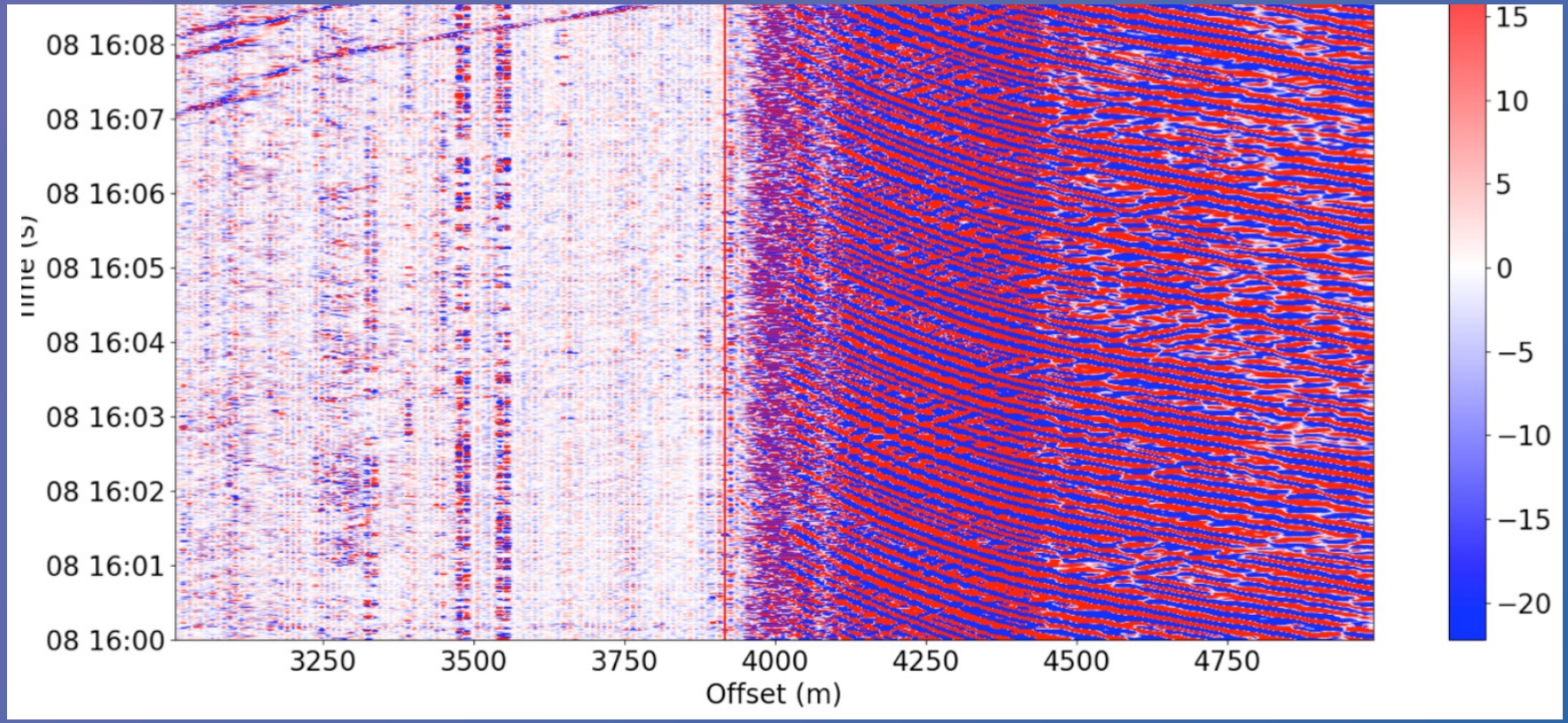

Modeled cvs observed spetrogram



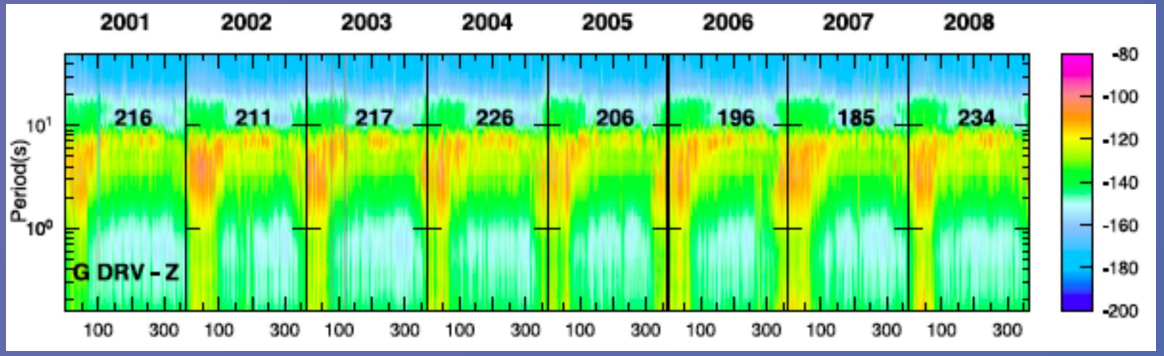

Bertin et al., 2018, *Earth Sci. Rev.*

# Link between ocean gravity waves and microseisms

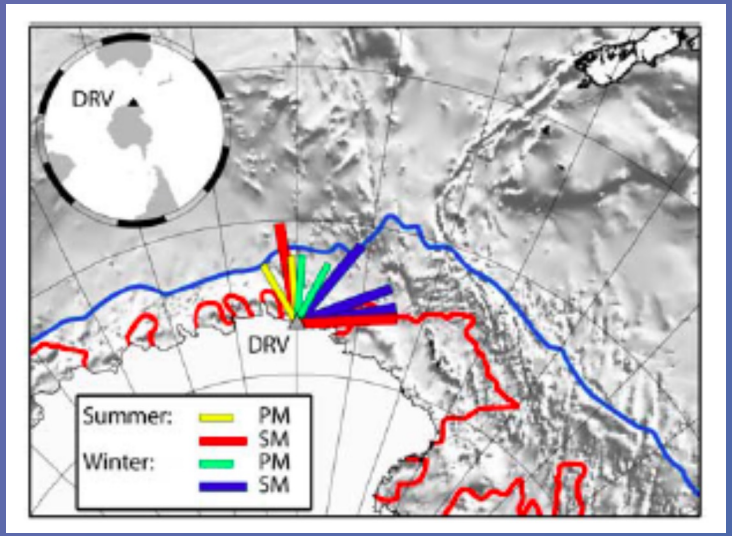
- Use of DAS to constrain ocean wave reflection coefficients



# Sea ice effect on seismic noise




Stutzmann, Schimmel et al. 2009
Grob et al., 2011

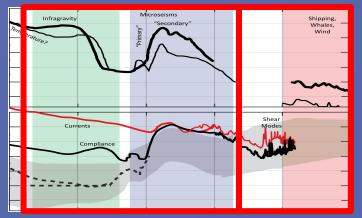


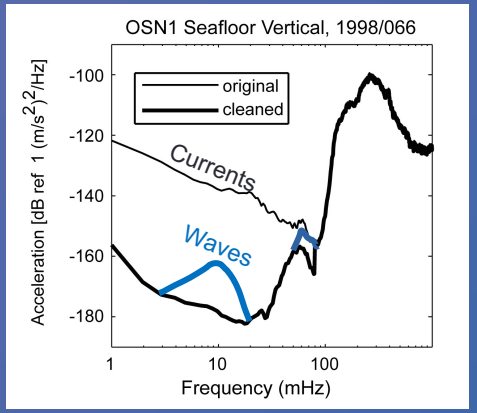

In winter, decrease of the amplitude of:

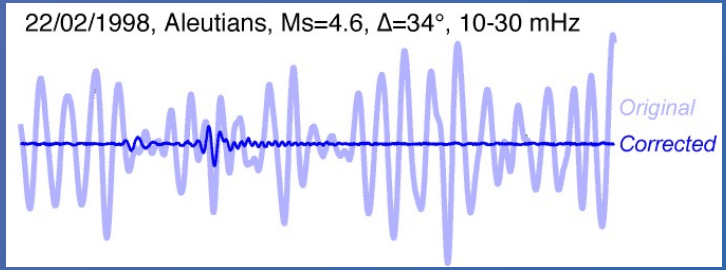
- The primary microseism (10-15 sec)
- The short-period secondary microseism

# Séparation des sources du bruit

- Sources
  - < 1Hz: bruit globale, ses sources, courants locaux, seismes…
  - > 1Hz: paysage sonore, shear modes, scattering, vents…
- Etudes principales:
  - traitement du signal
  - capteurs complementaires
- Resultat attendus
  - Meilleur identification et exploitation des differents signales
    - Basses frequences
    - Paysage sonore
    - Seismes
    - Modes propres de la terre
  - Decouverte d'autres signales?
  - Applications sur d'autres planetes



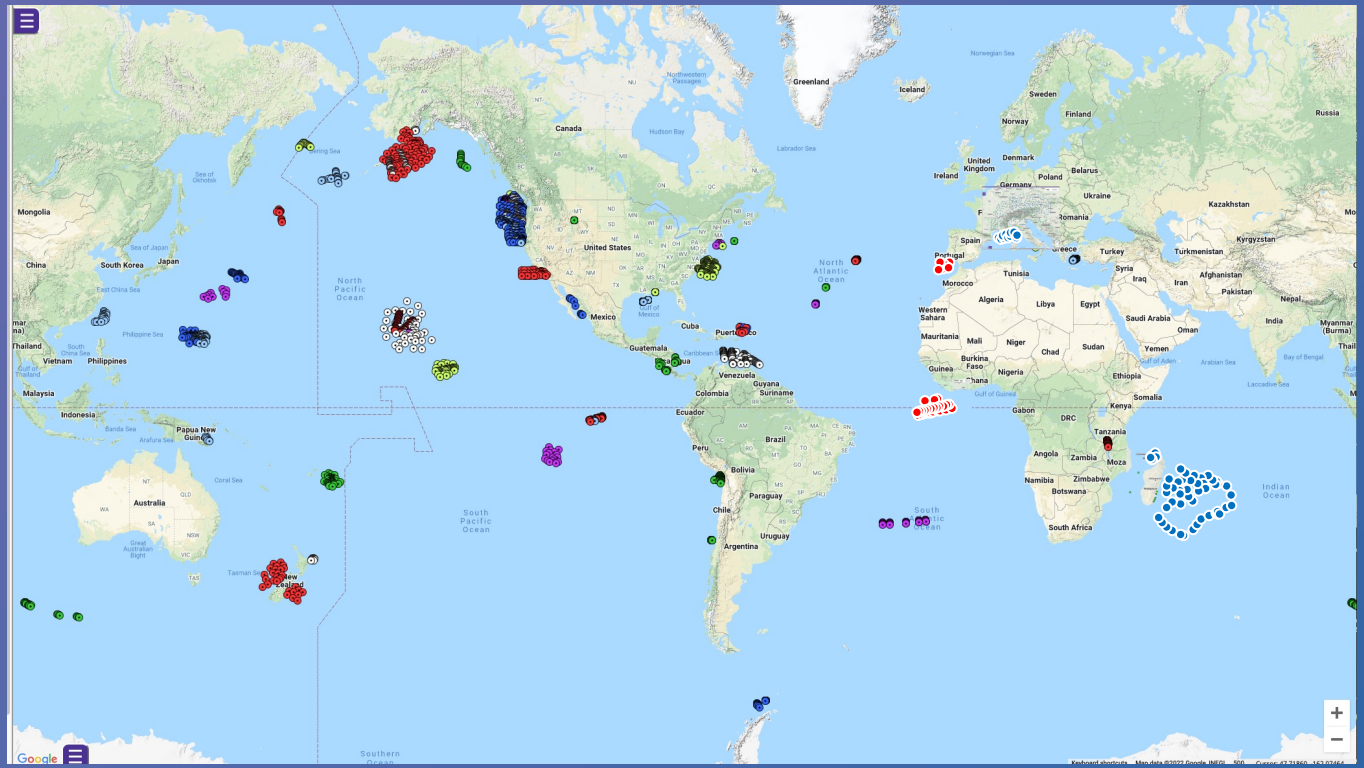




Crawford et al., 2006, *Bull. Seismo. Soc. Am.*

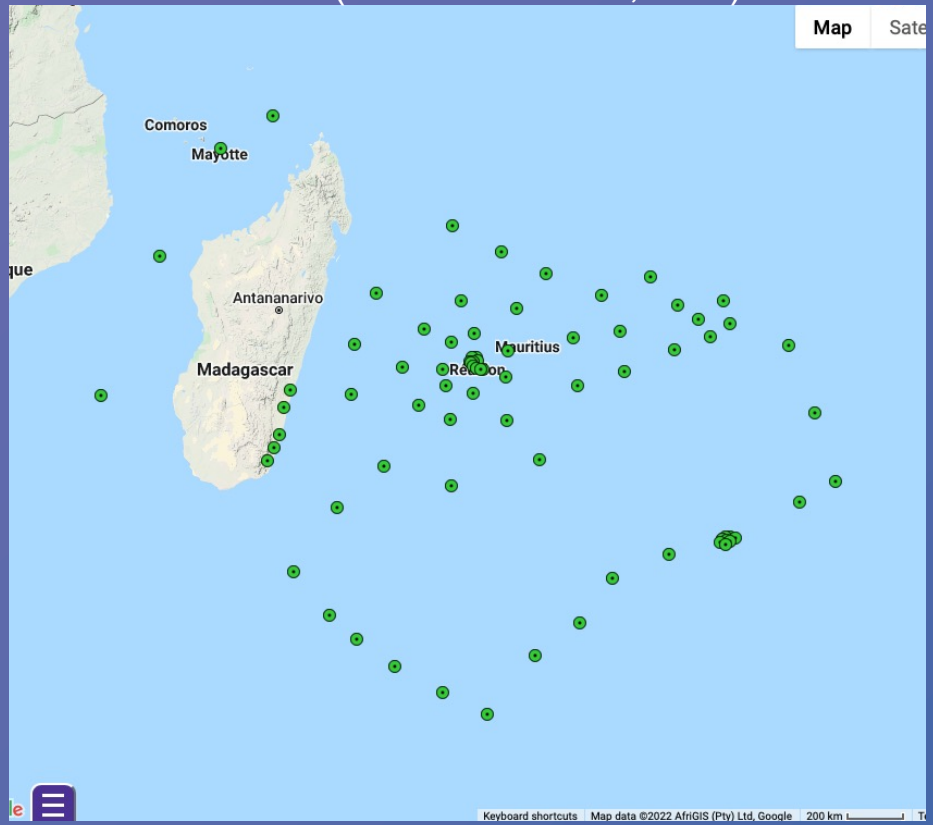
# Jeux de données

- Sur des serveurs ouvertes (US et France) et quelques autres jeux de données vouées à y etre (France, Portugal, Allemand)
- Beacoup de l'ordre d'un an

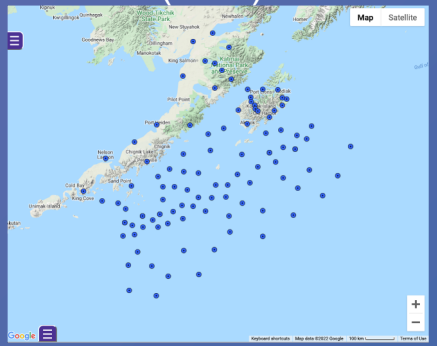


# Exemples de reseaux temporaires

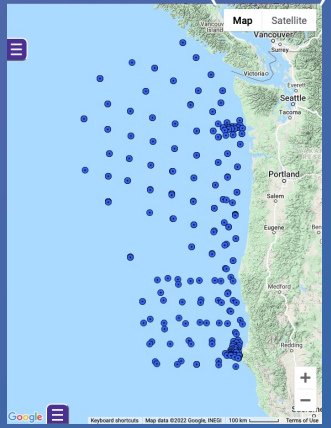
RHUM-RUM (Ocean Indienne, 1 an)




Alaska (1 an)




Cascadia (4 ans)



# Observatoires

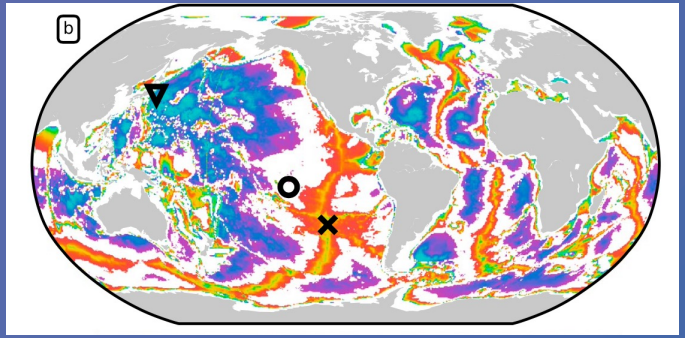
- Lucky Strike (15+ ans)
  - 5-6 stations, 7 km aperture, 2007+, network 4G
- Ocean Observatories Initiative (9+ ans)
  - 14 stations, 5 coastal and 9 mid-ocean, 2013+, open (network OO)
- Mayotte offshore volcanic observatory (3+ ans)
  - 6-18 stations, 50 km aperture, 2019+, network 1T

# Improving OBS data availability/access/usefullness

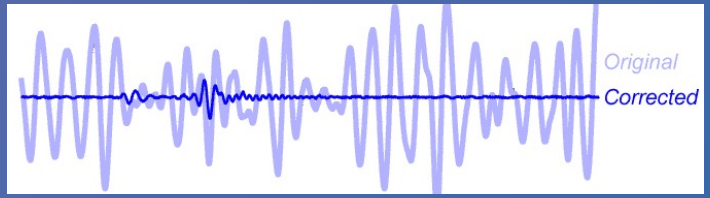
- Currently, only the US OBS facility systematically puts their deployment meta/data online
- France and Germany are working to do the same
  - The rest of Europe will follow ☺
- This is a good time to submit new suggestions (higher sampling rate, addition of moving platforms, …)
  - Rules and guidelines are being written
  - Environmental linkages are seen positively

# Le projet ANR BRUIT-FM (2022-2026)

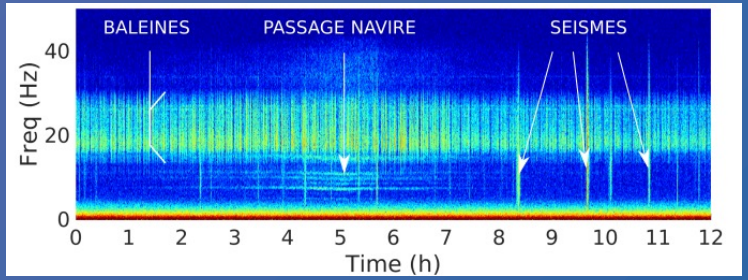
- WP2: The Generation of Global Seismological Noise
  - Sources and effects of spatio-temoral variations in seafloor noise
  - Sources of seafloor/global noise
  - An integrated seafloor/global noise model




- WP3: Seafloor Signal Separation and Noise Removal
  - Reducing horizontal noise using a rotational seismometer
  - Signal separation/removal techniques
  - Separating seismological and biological signals

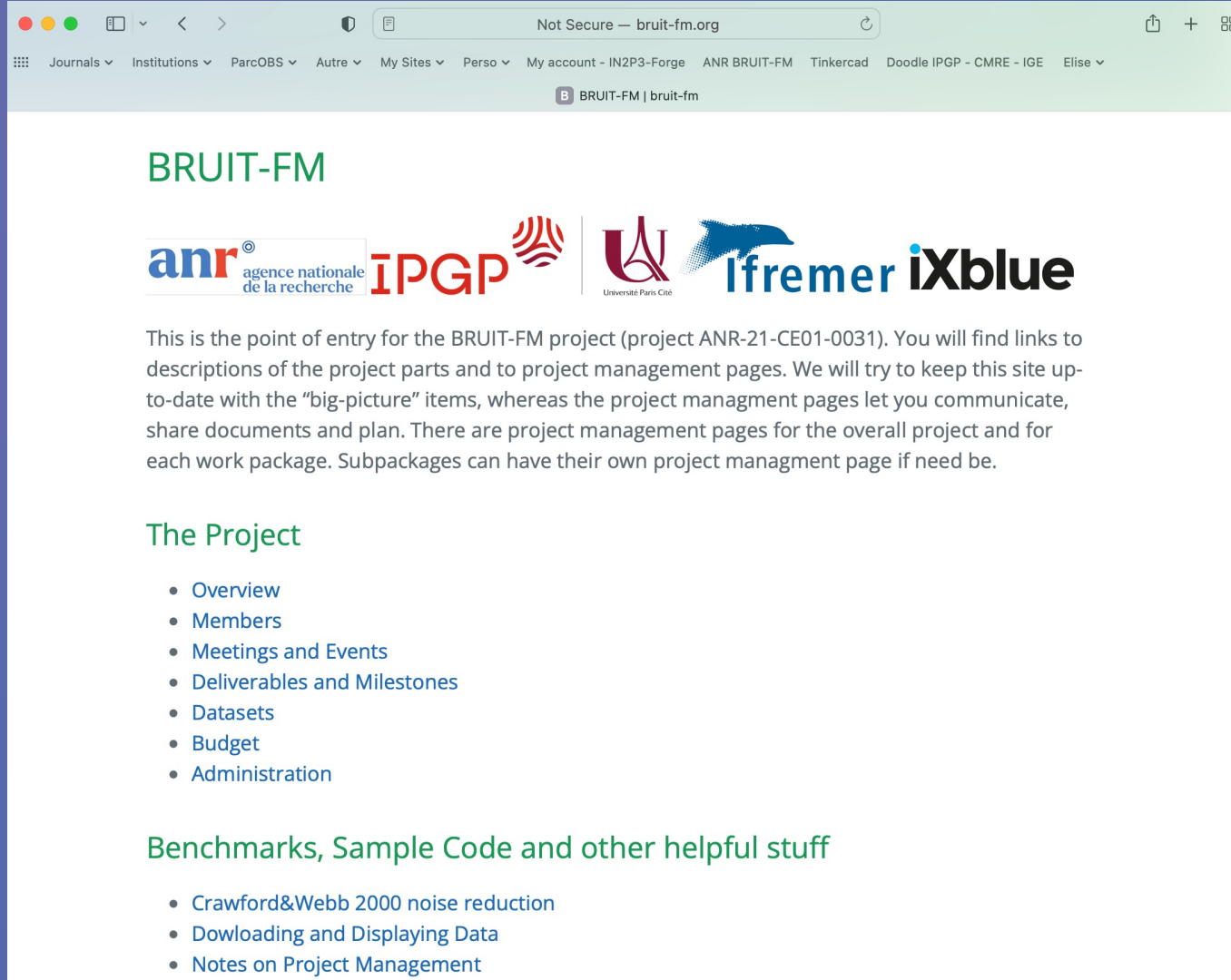



- WP5: Seafloor Soundscape
  - Whale sources
  - Noise Pollution
  - Ship Noise
  - Cryoseismic signals



# BRUIT-FM

- www.bruit-fm.org



# BRUIT-FM: Personnes impliqués

- WP3: Bruit globale
  - Eléonore STUTZMANN (IPGP), Fabrice ARDHUIN (IFREMER), Diane RIVET (Geoazur), Laurent STEHLY (EOST), Véronique FARRA (IPGP)

- WP4: Séparation des sources
  - Wayne Crawford (IPGP), Stephan KER (IFREMER), Jérôme MARS et Olivier MICHEL (GIPSA Grenoble), Laurent DUVAL (IFP), Fréderic GUATTARI (iXBlue), Martin SCHIMMEL (CSIC), Spahr WEBB (LDEO)

- WP5: Paysage sonore
  - Baleines: Flore SAMARAN (ENSTA), Richard DREO (IPGP)
  - Bruit anthropique: Bazile KINDA (SHOM)
  - Bruit environnementale: Guilhem BARRUOL (Grenoble)

# Summary

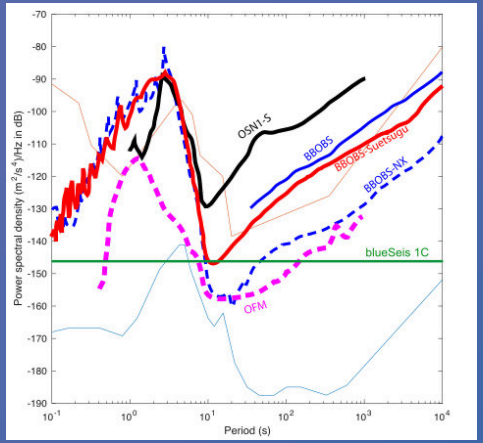
- Ocean Bottom Seismometer networks provide long, large aperture datasets
  - (more and more) open source and well-characterized
  - 4-component gives directivity, can be used to separate sources
  - A rich assortment of biological, envirnomental (storms, current, ocean waves…) and geodynamic (earthquakes, tremor) signal sources

- The high-frequency end is limited, mostly by limits of seismological interest
  - 500 sps is technologically ”simple”
  - The more requests/uses identified for higher frequency data, the more chance they will be collected

- Open source data centers could host some acoustic data
  - Might help standardize data access
  - Should increase use of a given dataset
  - Can’t (yet) handle variable sampling rates, drifting instruments

# Perspectives

- Rotational seismometers
  - To better characterize seismic arrivals, reduce horizontal channel noise
- The effect of internal waves
- High and low pressure noise reference models
  - Equivalent of existing models for seismology data
  - Help to determine what can be detected in your data (avoid false negatives, help to design experiments)
  - Basis for determining spatial and temporal variations
- Improved signal separation / noise removal



# State of the art in removing noise

**Codes**

- http://www.ipgp.fr/~crawford/software.html
  - Matlab codes using the methods of Crawford et al. (2000)
  - TiSKit toolbox with functions ts_data.clean_calc(), ts_data.clean() and ts_data.clean_rot()
- https://github.com/helenjanisz/ATaCR
  - Matlab codes implementing Bell et al's improvements
- https://nfsi-canada.github.io/OBStools/atacr.html
  - Python version of ATaCR codes
- https://github.com/WayneCrawford/rptransient
  - The rotate_clean() Python module reduces tilt noise through pure rotation (uses obspy, scipy.optimize)

# What's missing

- Better tilt and compliance noise removal on the vertical
  - Improve transfer function calculations
  - Other techniques (must minimize/quantify distortion)
  - Nothing to remove nonlinear tilt noise on vertical
- Tilt noise removal on horizontal: rotational sensor
- Soundscape signal understanding/separation
- Easy-to-apply open source codes
- Outside of proposed work
  - Can we do anything in the microseism band?
  - Can we do anything at > 300 s?