

Global Internal Tides from Satellite Altimetry:

Next-Generation Internal Tide Model and Internal Tide Oceanic Tomography



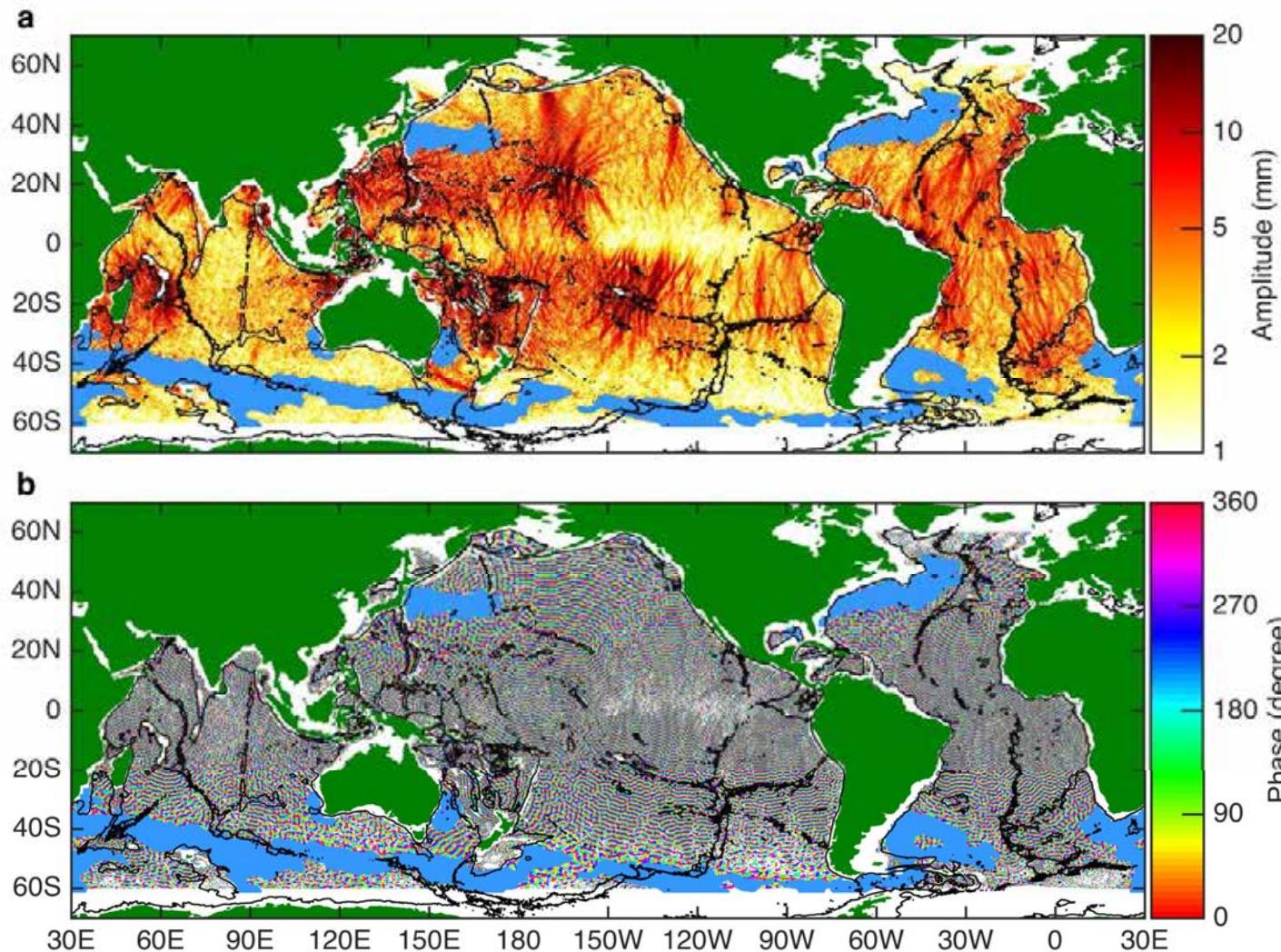
ZHONGXIANG ZHAO

APPLIED PHYSICS LABORATORY, UNIVERSITY OF WASHINGTON



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Coherent Mode-1 M2 Internal Tides 1993–2012



(Zhao et al. 2016 JPO)

Plane Wave Fit Method

Point-wise harmonic analysis (coherent in time)

$$A \cos(\omega t - \phi)$$

Single point $O(10^2)$ SSH record

Plane wave fit method (coherent in time and space)

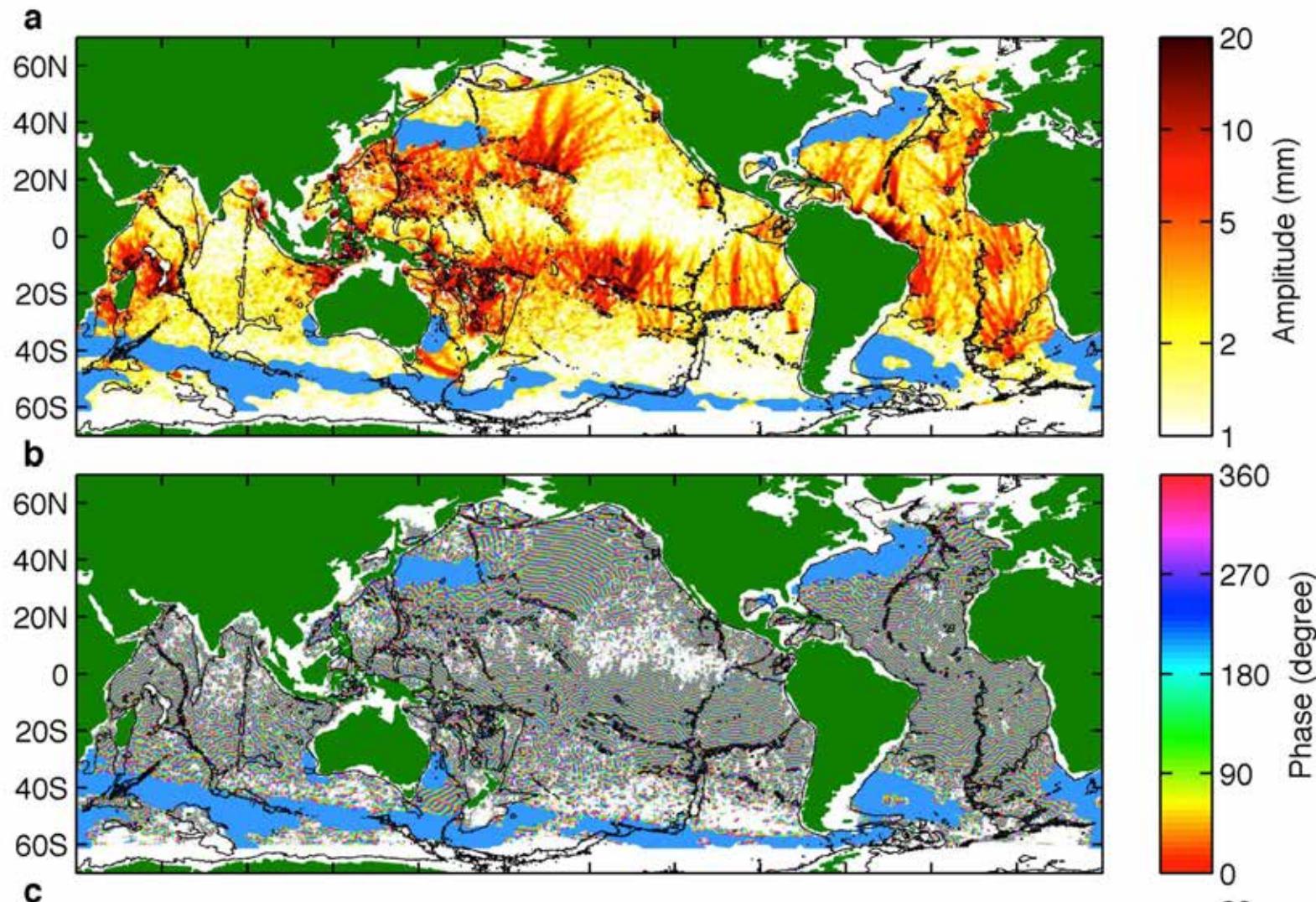
$$\sum_{m=1}^M A_m \cos(kx \cos \theta_m + ky \sin \theta_m - \omega t - \phi_m)$$

Fitting windows (160 km or larger), $O(10^4)$ space-time
SSH record, significantly reduce non-tidal noise

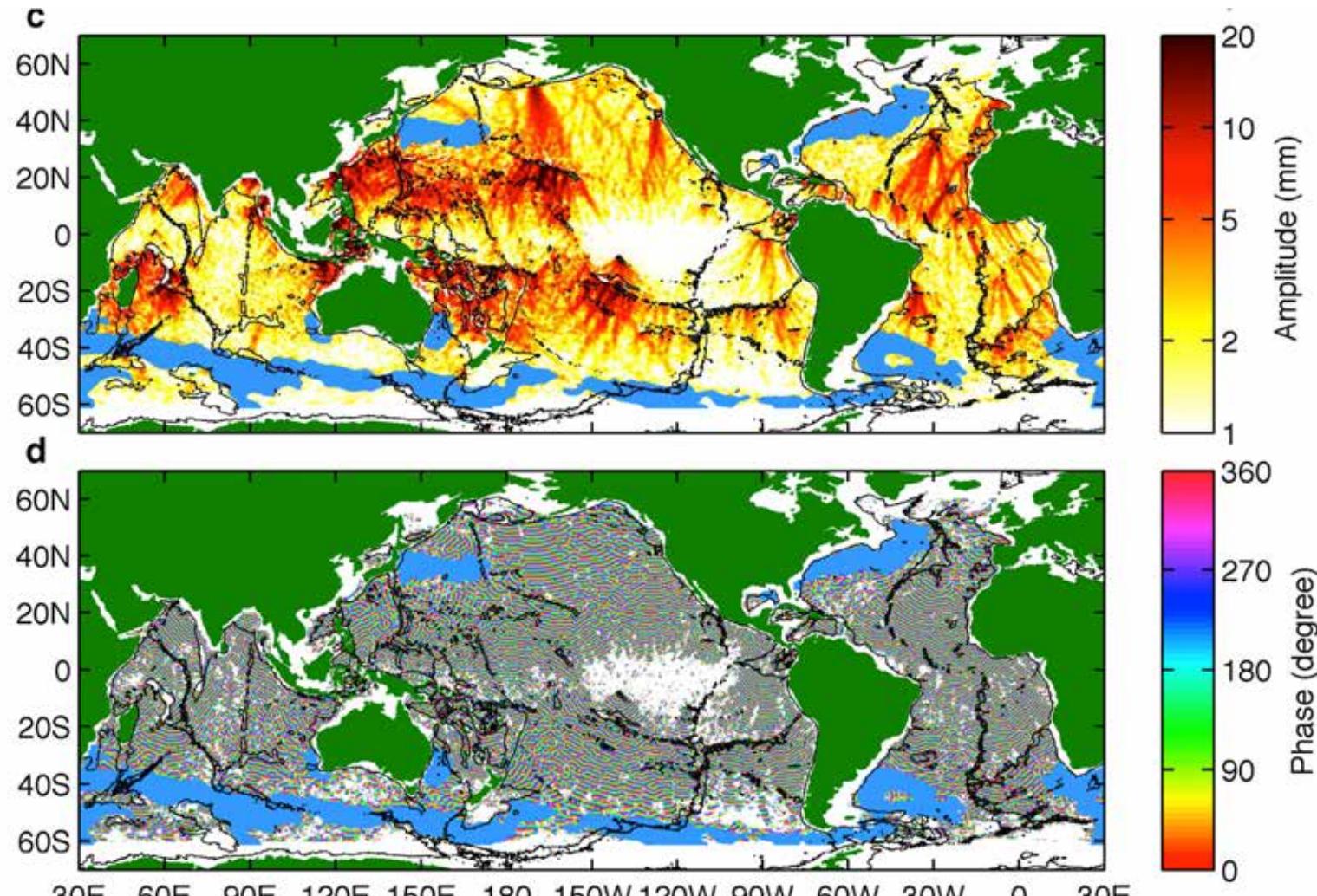
Advantage

Separately resolve internal tides of different
propagating directions
(to study their generation, propagation, destination)

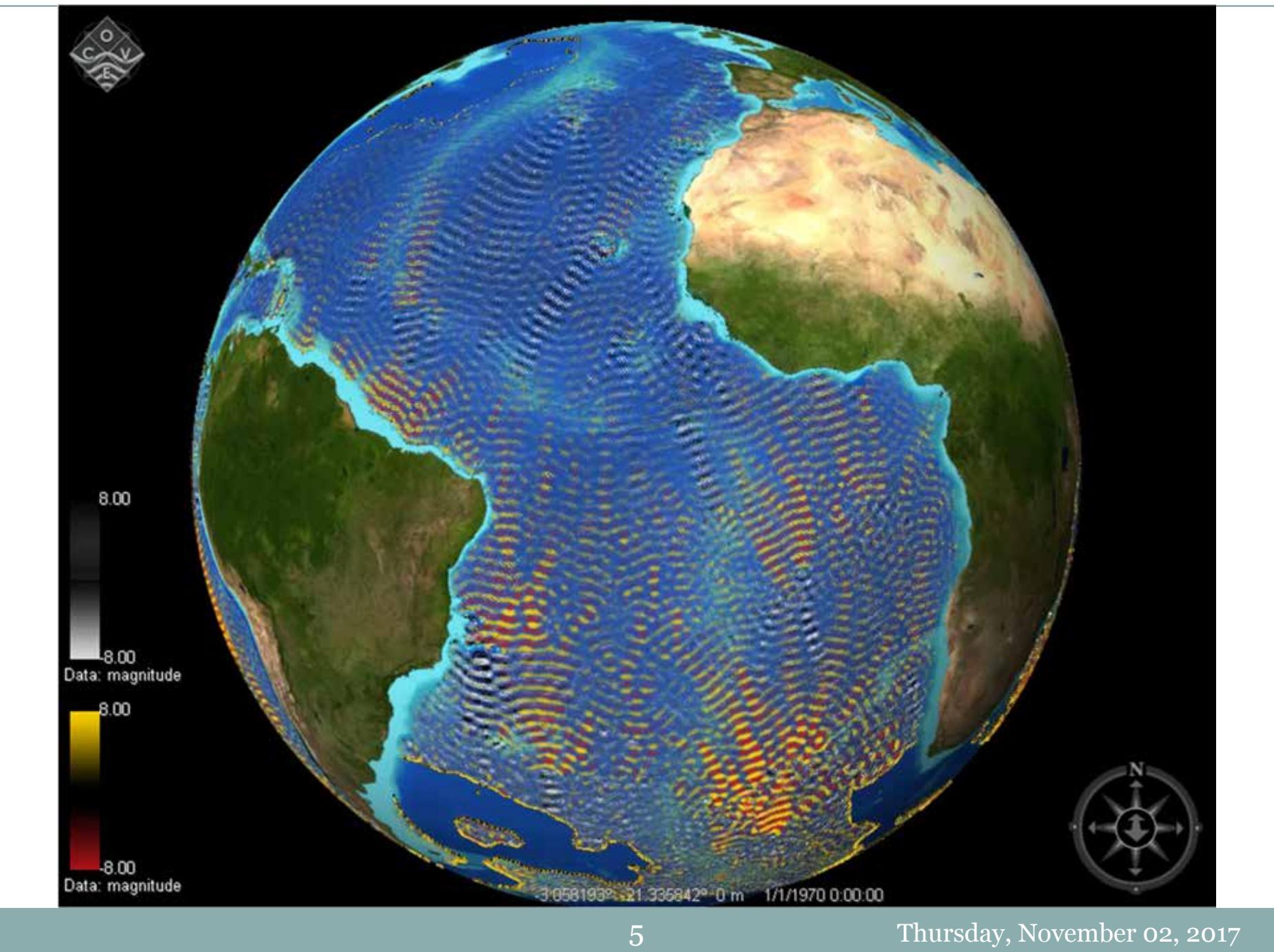
Northbound M2 Internal Tides



Southbound M2 Internal Tides



(southbound + northbound = the SUM map)



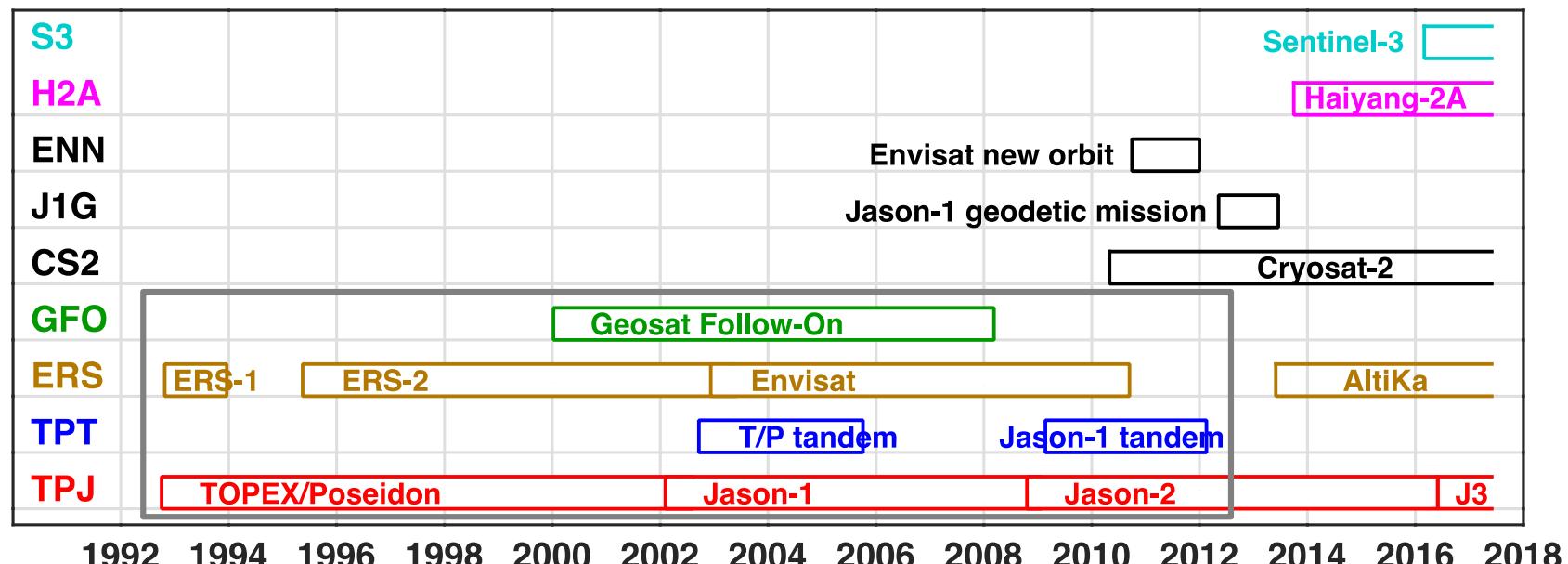
Next-Generation Internal Tide Model

Temporal variability of internal tides

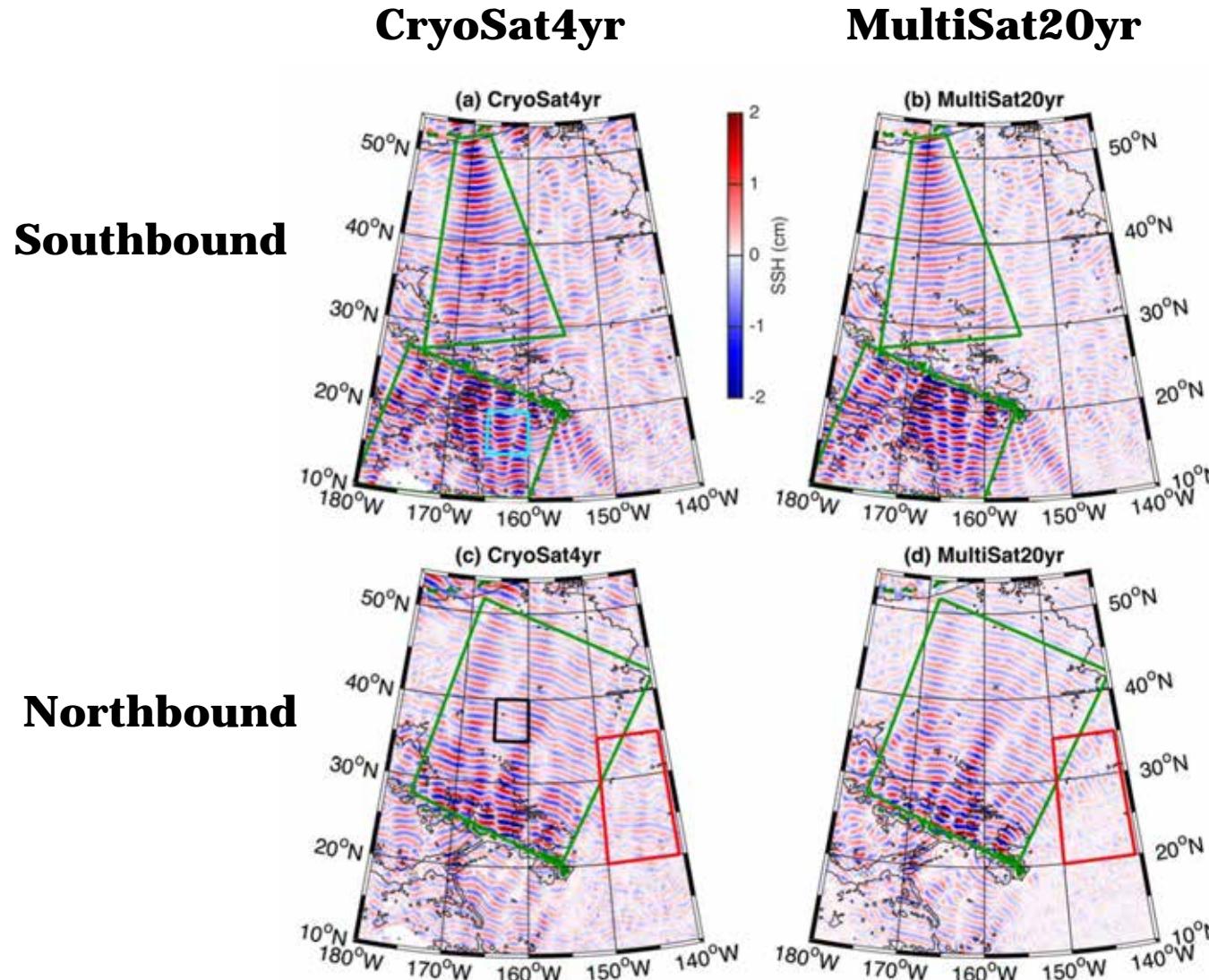
- Seasonal: 12 monthly internal tide fields
- Interannual: >20 yearly internal tide fields
- Eddies: NOT in this work

Current-generation model: **Constant** amplitude and phase

Next-generation model : **Time-variable** amplitude and phase



M2 Internal tides: CryoSat4yr and MultiSat20yr



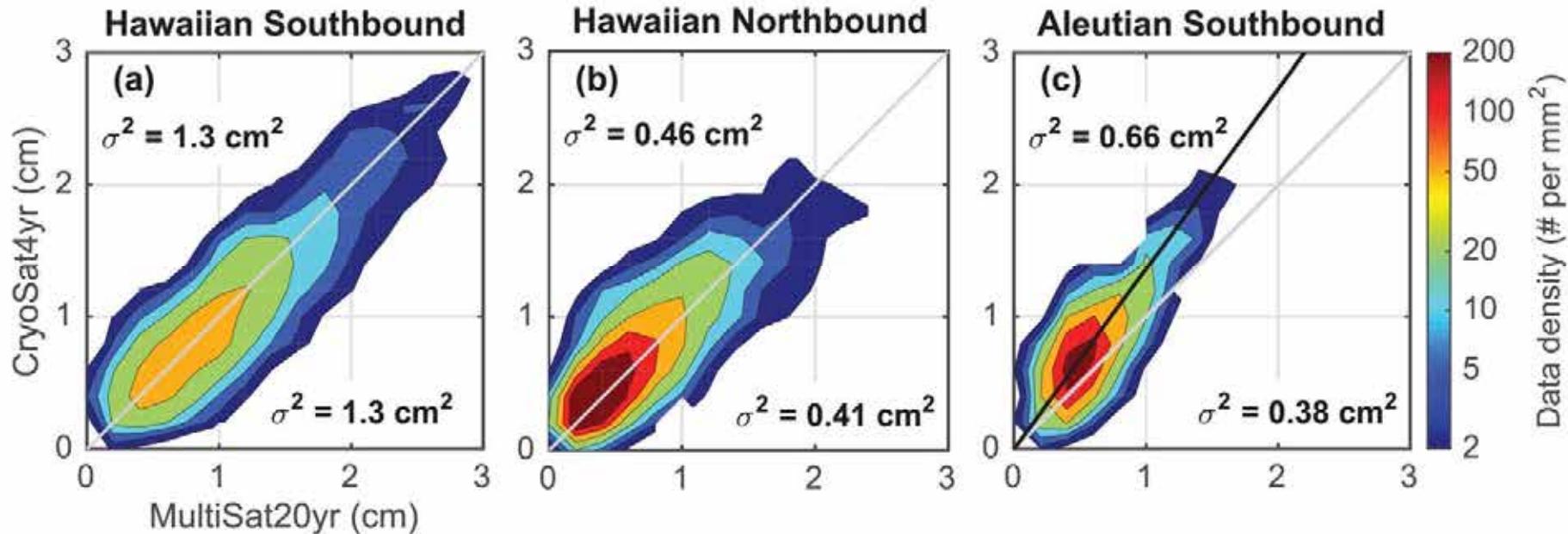
CryoSat-2:
~10,000 tracks

T/P-Jason:
254

GFO:
488

ERS:
1002

Comparison of M2 SSH Amplitudes



CryoSat4yr: 4 years (2011-2014)

MultiSat20yr: 20 years (1993-2012)

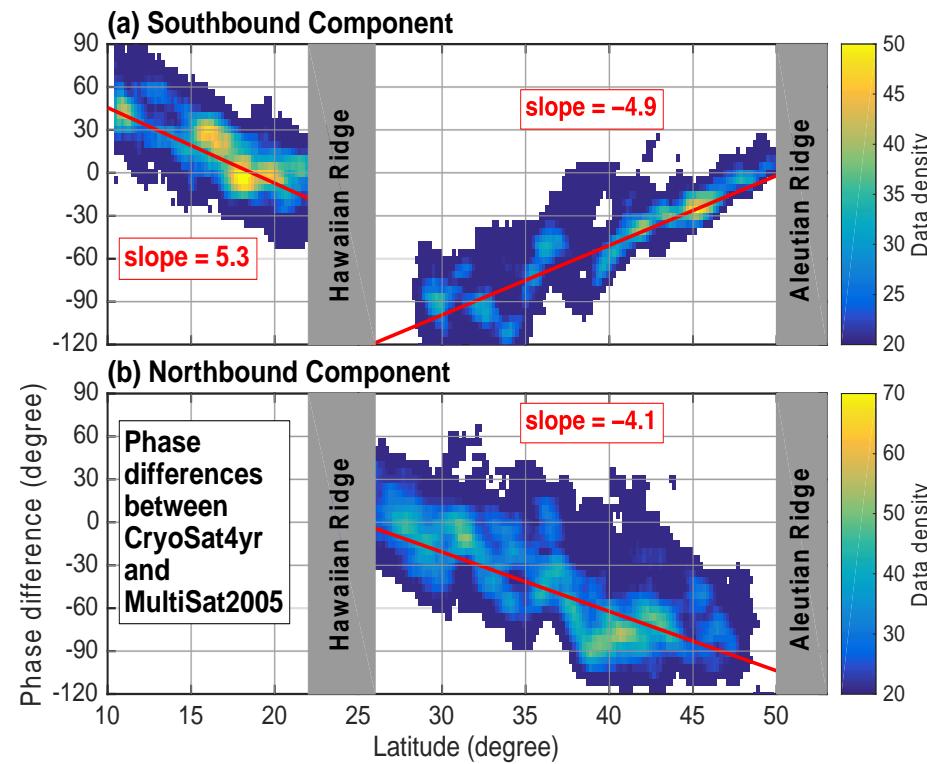
Hawaiian beams: Agree!

Aleutian Ridge: CryoSat4yr > MultiSat20yr

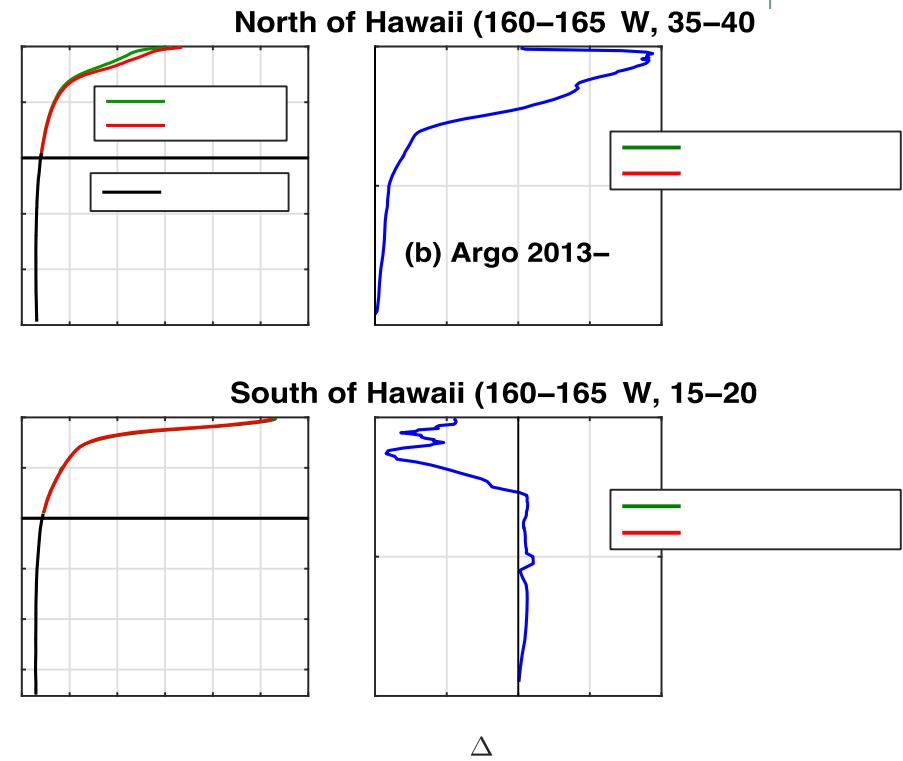
Reason? Aleutian a shallow generation source

Comparison of Phase: Ocean Warming/Cooling

CryoSat4yr – MultiSat2005



Argo measurements

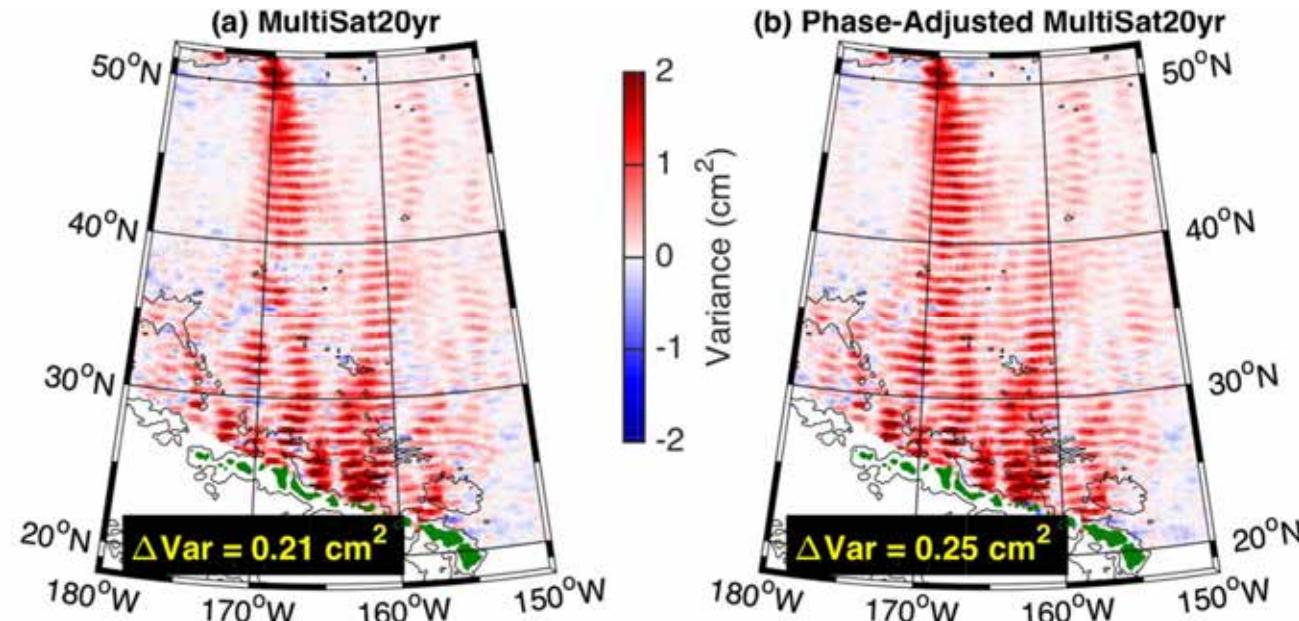


South of Hawaii: slower in CryoSat4yr—ocean cooling
North of Hawaii: faster in CryoSat4yr—ocean warming

Internal Tide Correction: Variance Reduction

Using the current ZHAO model

$$\begin{aligned}SSH(t) &= A \cos(\omega t + \phi) \\&= A_N \cos(\omega t + \phi_N) + A_S \cos(\omega t + \phi_S),\end{aligned}$$



Using the next-generation model

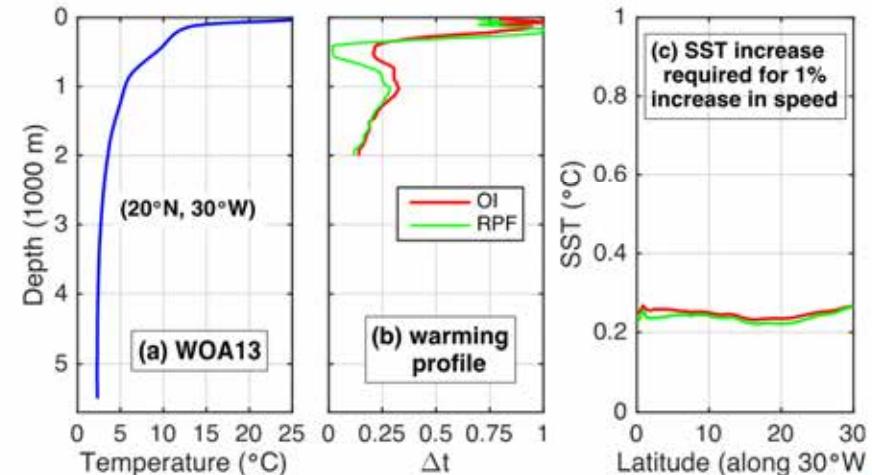
$$\begin{aligned}\phi_N^a(\text{latitude}) &= \phi_S - 2.0 \times (\text{latitude} - 25^\circ), \\ \phi_S^a(\text{latitude}) &= \phi_N - 2.6 \times (52^\circ - \text{latitude}),\end{aligned}$$

Using CryoSat-2 data to evaluate internal tide models in terms of variance reduction: The phase-adjusted model is improved by **20%!**
(Zhao 2016 JGR)

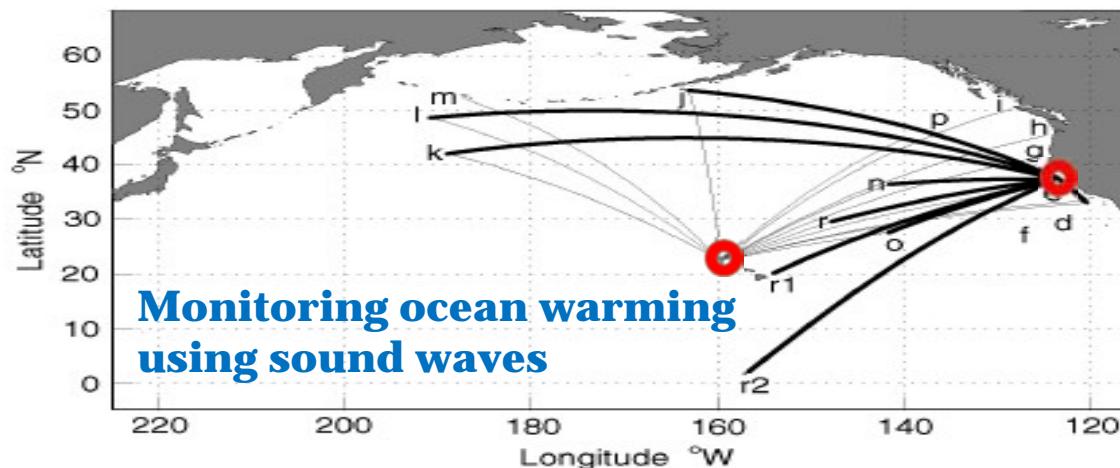
Internal Tide Oceanic Tomography

$$C = \frac{H N}{n \pi} \Leftrightarrow N = \sqrt{\frac{-g}{\rho_0} \frac{dp}{dz}} \Leftrightarrow \Delta\rho \propto \Delta T$$

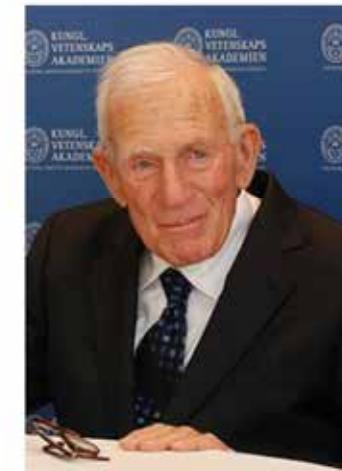
C: speed of internal tides
 N: ocean stratification
 ρ : ocean density
 T: ocean temperature
 [n, pi, g, rho₀]: constants



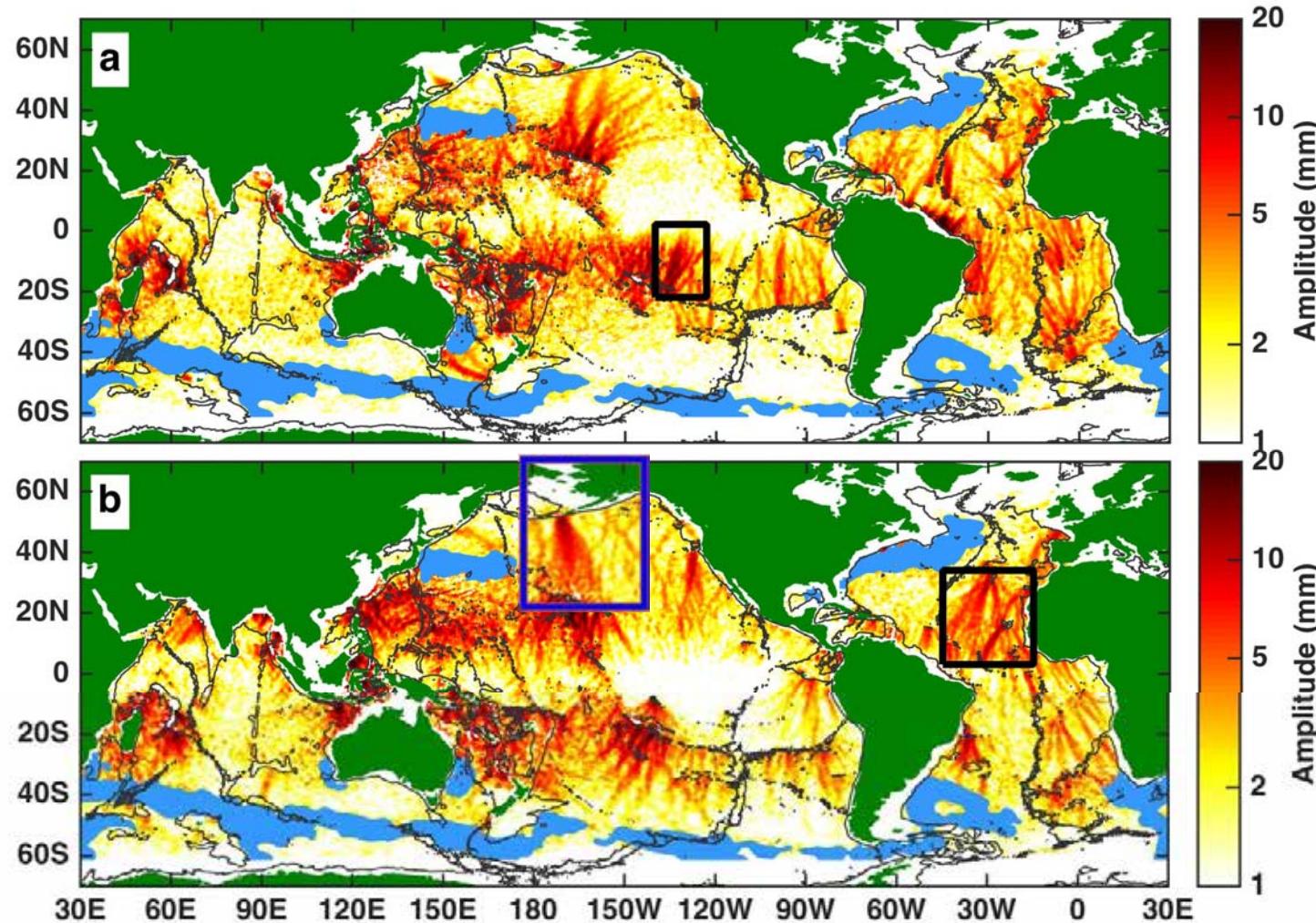
Acoustic Tomography (1976)



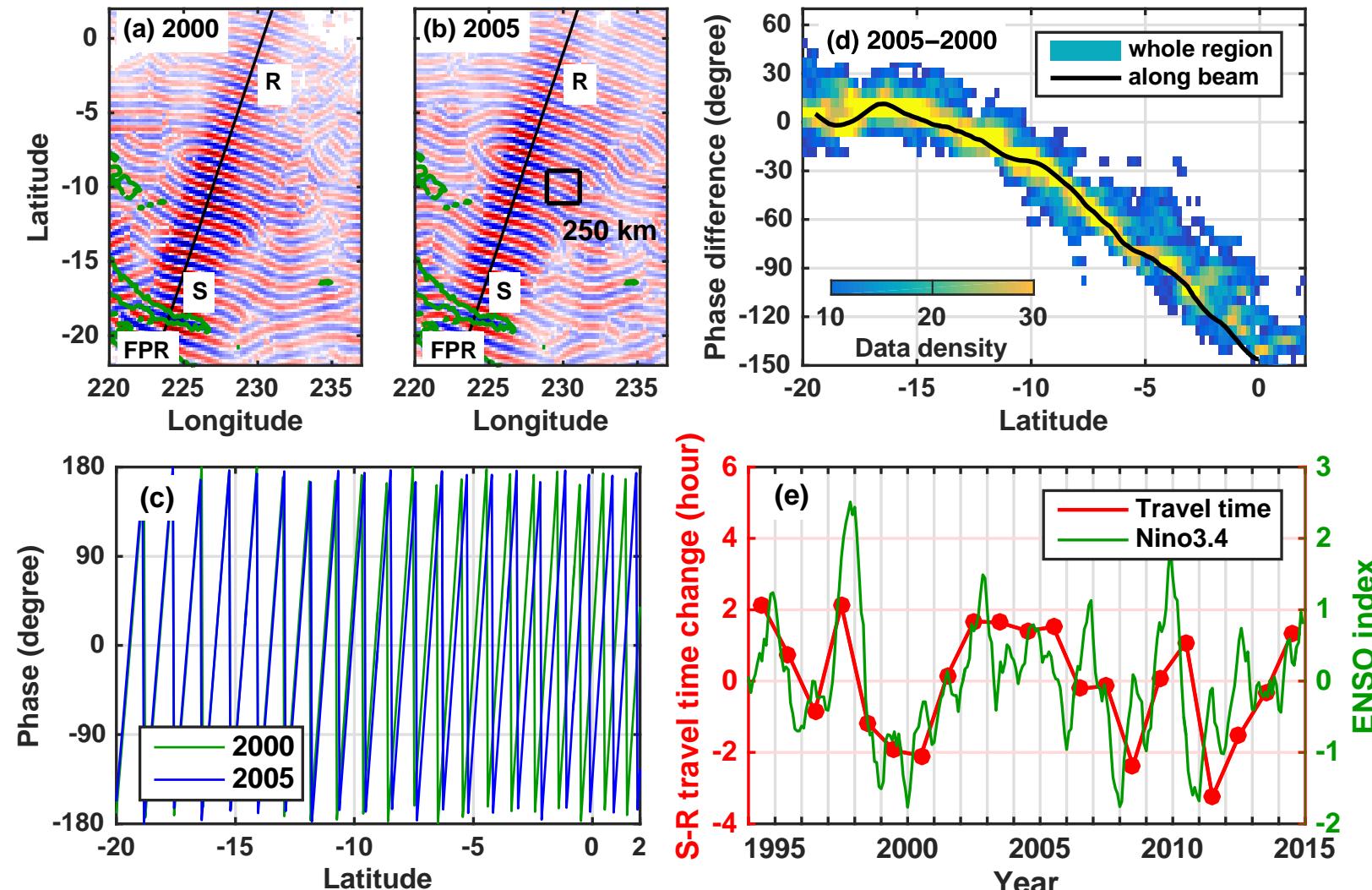
Walter Munk



ITOT: A Global Monitoring Network

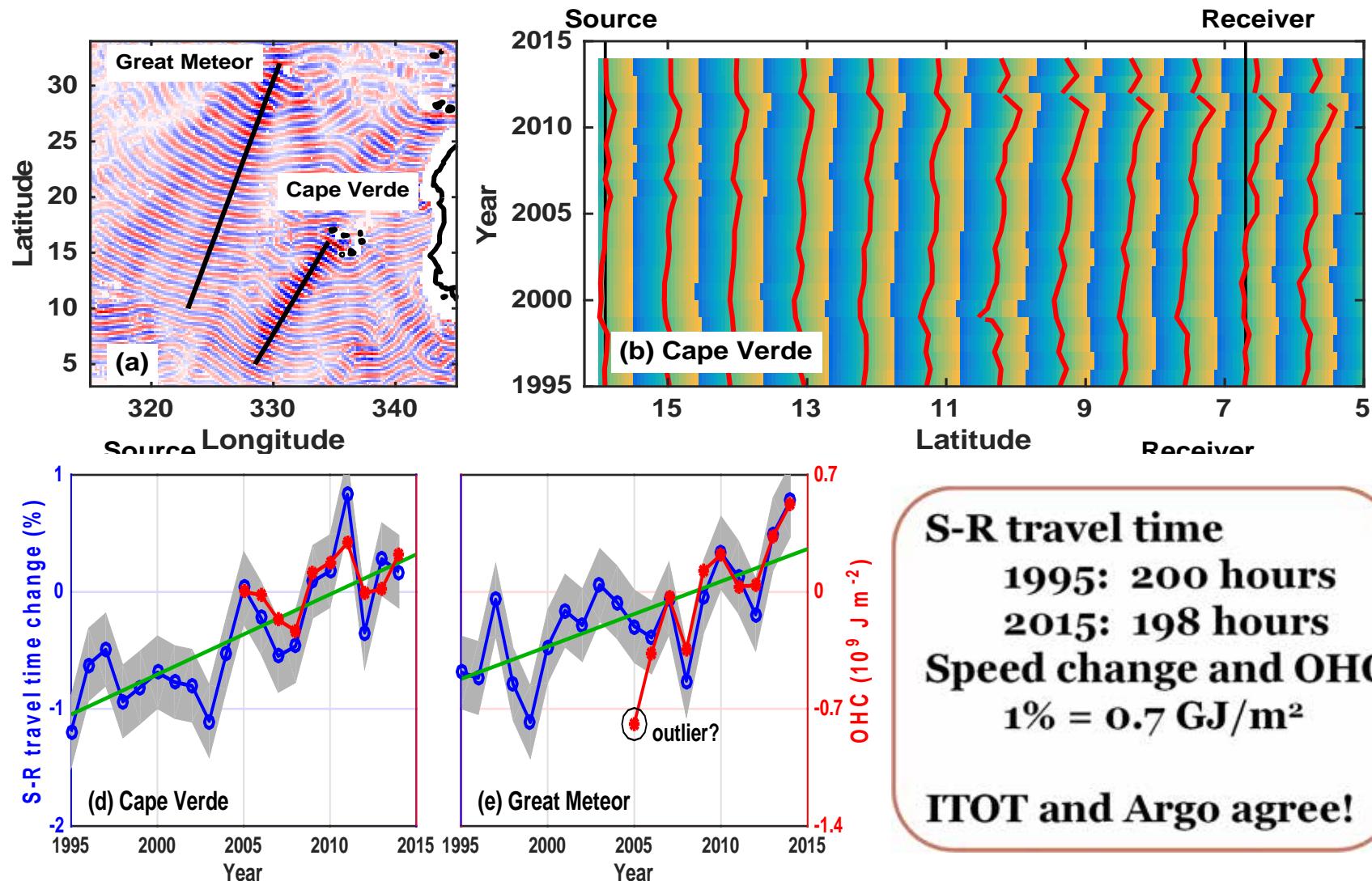


El Nino in the Pacific Detected by ITOT



(Zhao 2016 GRL)

North Atlantic Warming Detected by ITOT



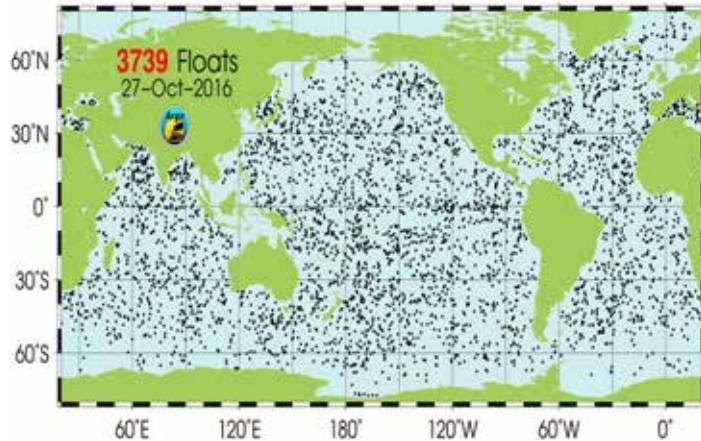
S-R travel time
1995: 200 hours
2015: 198 hours
Speed change and OHC
1% = 0.7 GJ/m²

ITOT and Argo agree!

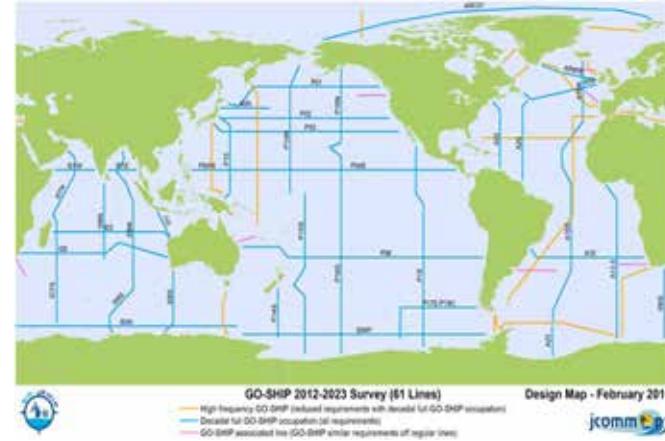
(Zhao 2016 GRL)

Global Ocean Warming Monitoring Networks

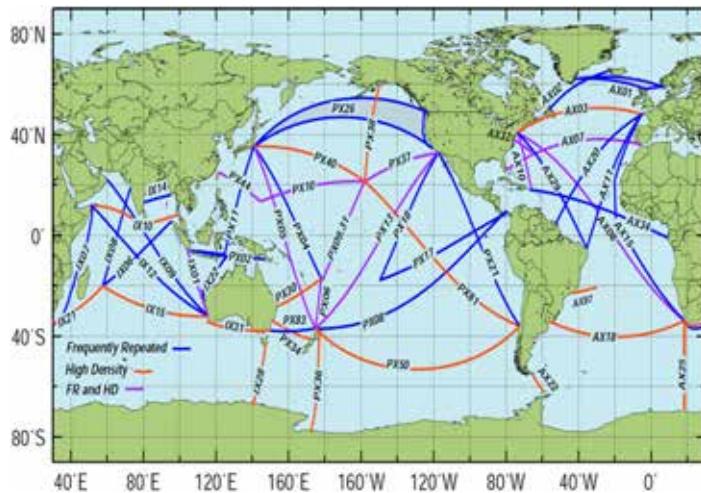
Argo (\$20M/yr)



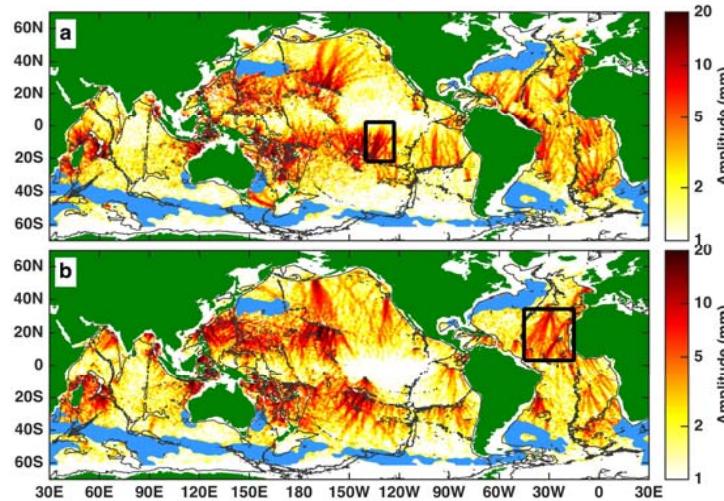
GO-SHIP



XBT



ITOT



Summary

Next-generation internal tide model

- ✓ Time-variable amplitude and phase
- ✓ Account for the incoherent internal tide caused by the seasonal and interannual variations
- ✓ Eddies are NOT addressed (3rd-generation?)

Internal tide oceanic tomography (ITOT)

- ✓ ITOT is a dual remote-sensing technique
- ✓ ITOT is feasible and useful (OHC, steric SLR, etc.)
- ✓ ITOT **may** offer a long-term, cost-effective, environmentally friendly technique for monitoring global ocean warming

Much work is underway ...