Robustness and singularity of pre-seismic signals in GRACE gravity solutions: application to the 2011 Tohoku M_w9.0 earthquake

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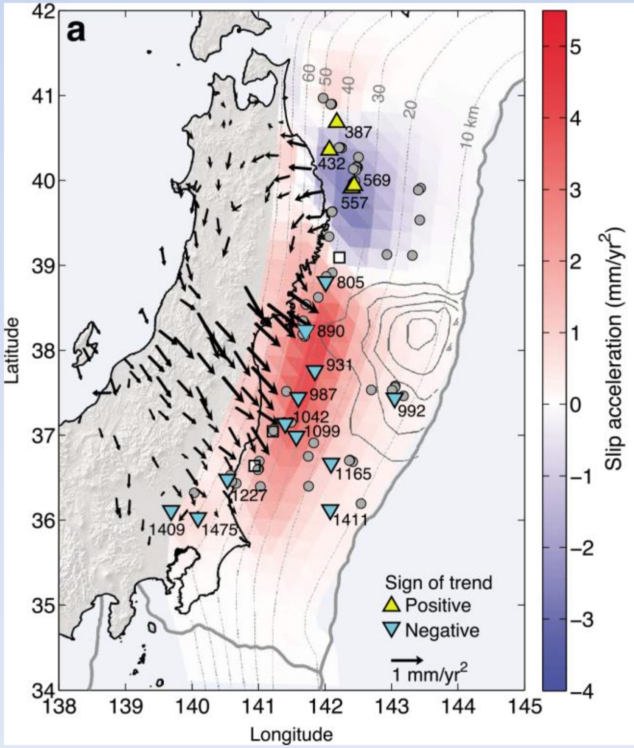
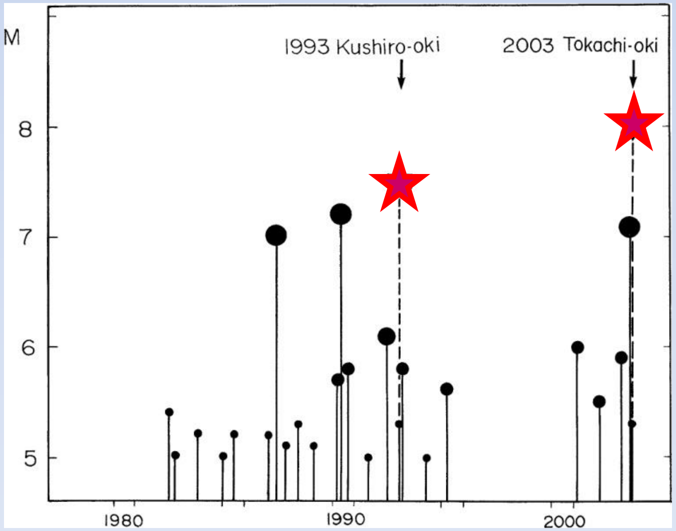
Documenting the preparation of great earthquakes

*Retrieving pre-seismic signals before the occurrence of a rupture:
a key, multi-disciplinary challenge of Earth Sciences.*

Geodesy and seismicity provide evidence for deep and shallow deformation transients at time scales from days to decade before great earthquakes



Mavrommatis et al. (2014), Yokota & Koketsu (2015). Decadal-scale deformation transient before the 2011 Tohoku earthquake

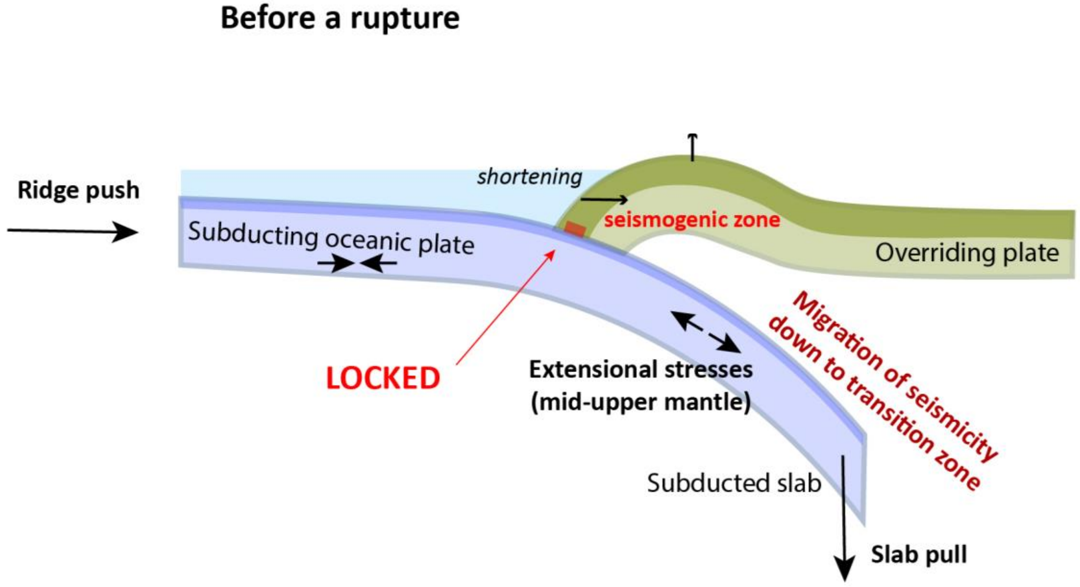


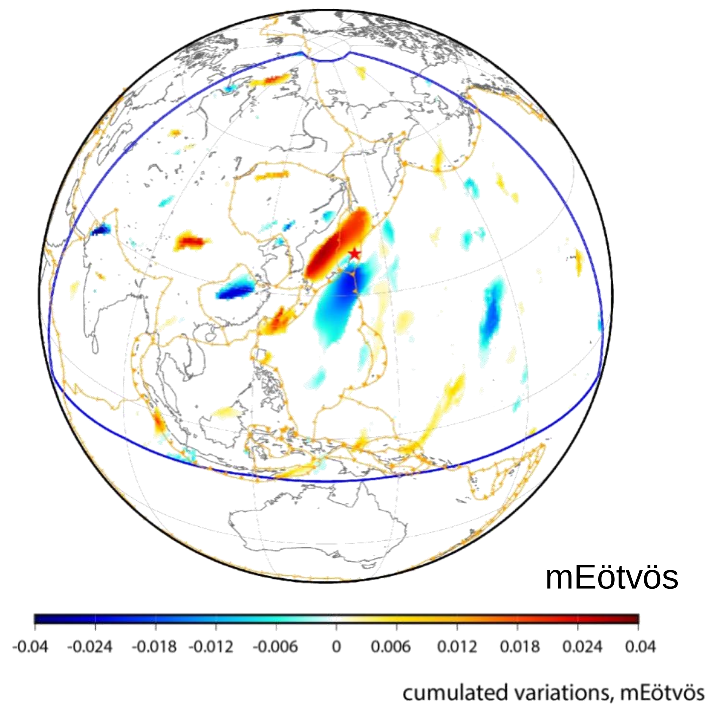
Mogi (2004): deep focus earthquakes (M>5, depth>200km) before the 1993 M7.5 Kushiro-oki and 2003 M8 Tokachi-oki events

→ *They suggest interactions between deeper and shallower deformation processes at different time scales before an earthquake*

Overcoming an observational gap using satellite gravity

An anomalous gravity gradient signal before the Tohoku earthquake, likely caused by deep slab deformation preceding the rupture.





Panet et al. (2018): pre-seismic horizontal gravity gradient signal before the 2011 Tohoku-Oki earthquake. See also Bouih et al. (2022) for the Maule earthquake.

- **Can we identify this pre-seismic signal as a unique feature in a global systematic analysis, before the rupture occurs?**

Global monitoring of subduction zones

Methodology

1. Developments in the space-time gravity gradient analysis

- An enhanced angular resolution using two overlapping ranges of azimutal sensitivity, to extract signals closely aligned with a subduction boundary as a geological constraint.

- Focus on the fast signals at sub-annual timescales before the event (sliding windows to remove low temporal frequencies)
  $\rightarrow$ global anomaly maps

2. A method to identify consistent solid Earth signals shared by different GRACE gravity models along plate boundaries

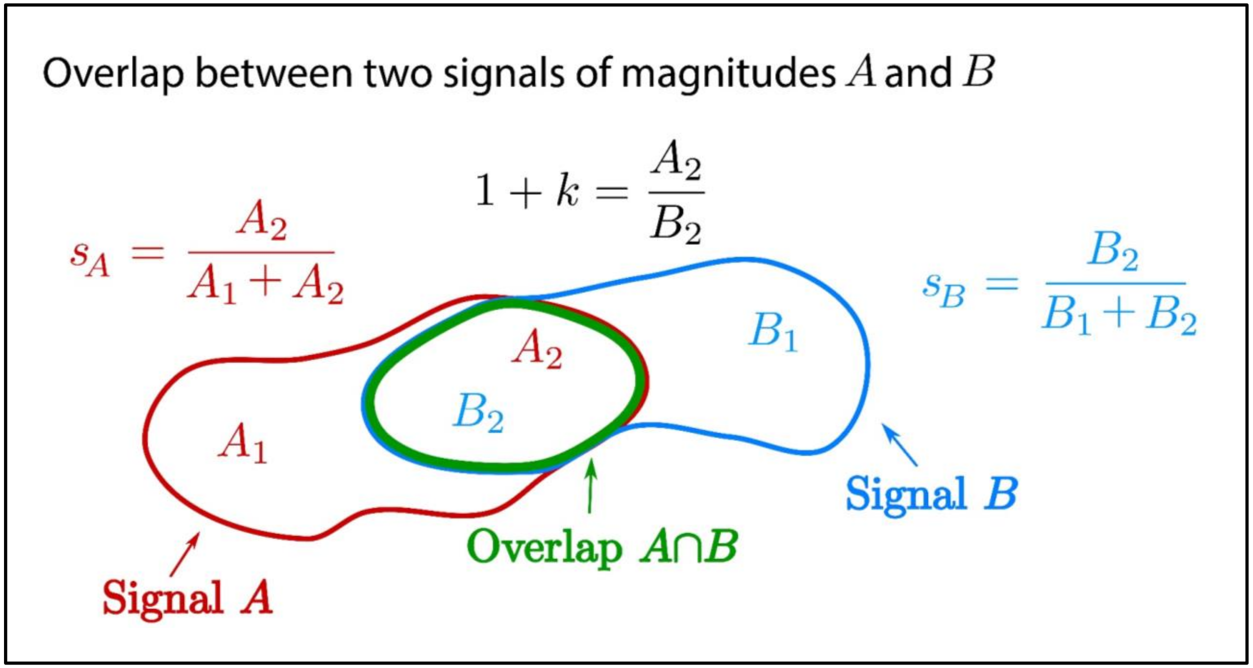
- Sensitivity of the signals to the ocean dealiasing model and the choice of a GRACE solution.

Consistent signals between different gravity models

Objective comparison of the signals geometry and amplitude in two gravity models

- k: relative intensity difference in the overlap of two signals

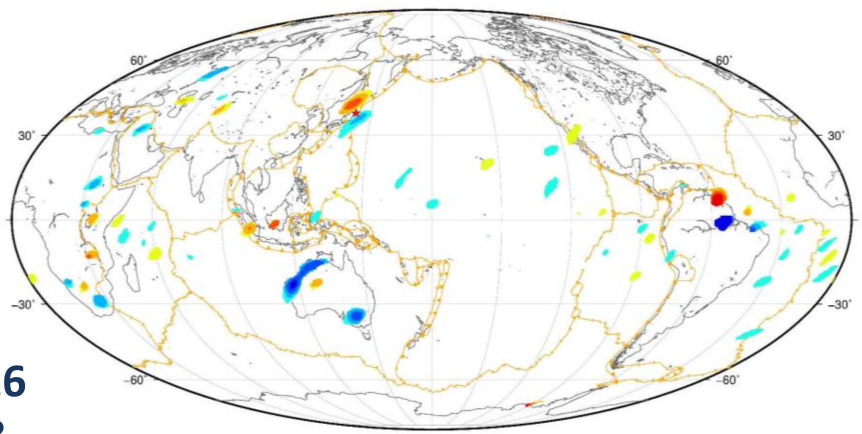
- S: fraction of the total magnitude of a signal A that overlaps with a signal B

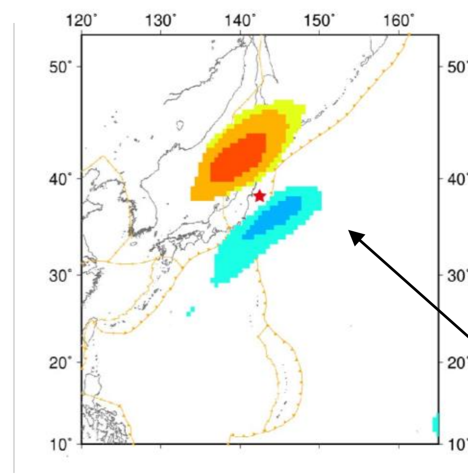


1. Consistent signals in two different GRACE solutions (GRGS03 vs CSR06)
2. Consistent signals, with or without restoring the dealiasing ocean model
3. Ocean & Solution: sequential combination of 1 and 2

Results: GRGS03 solution

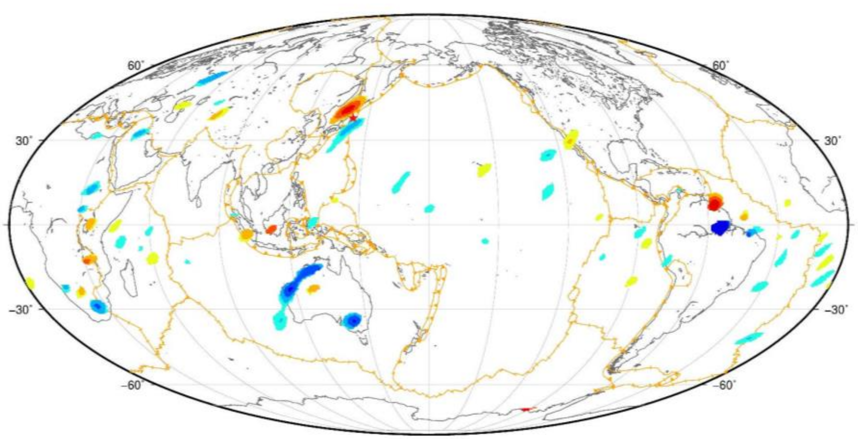
GRGS, ocean removed

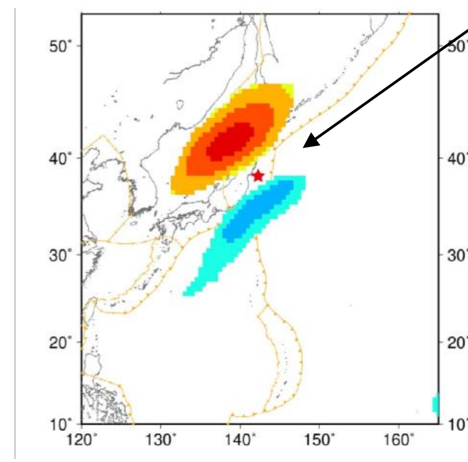




|k| < 0.26
S > 0.8

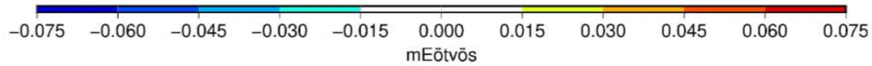
GRGS, ocean restored





Dipolar structure along the plate boundaries, typical of a solid Earth source

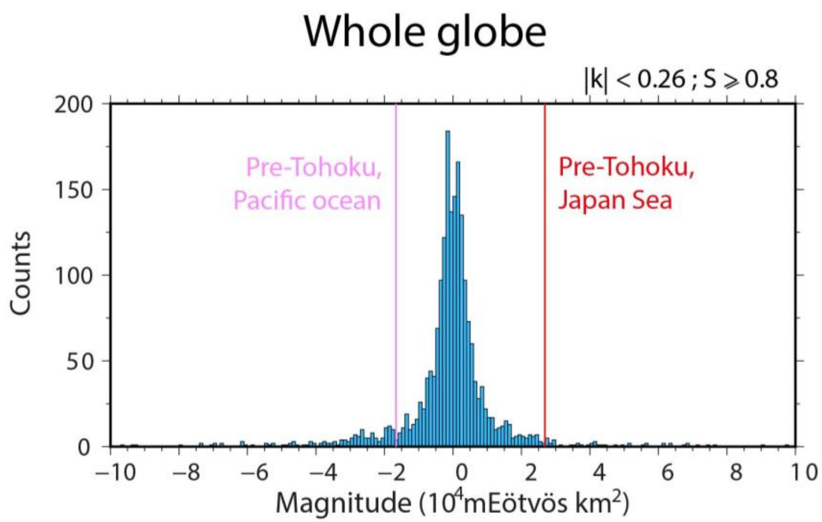
Scale 1400-km

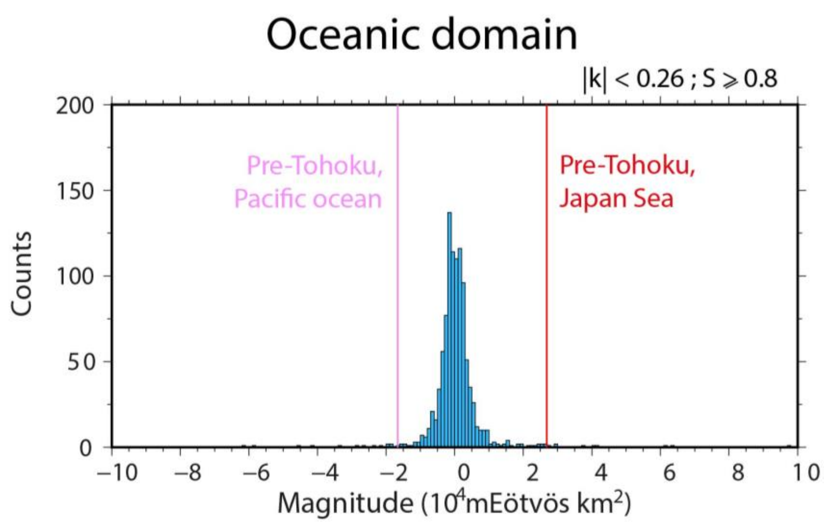


Anomalous signals in February 2011, enhanced azimutal sensitivity along the North Pacific subduction, poor sensitivity to the ocean model

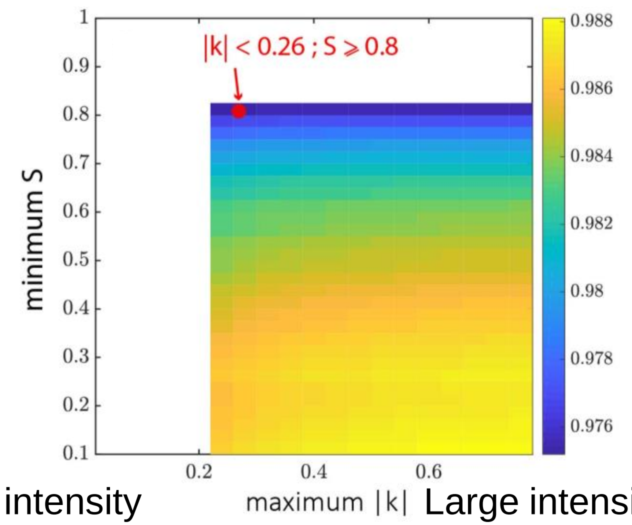
Uniqueness of the Tohoku pre-seismic signal in space and time (July 2004 – Feb 2011 period)

- *Statistics of the signals magnitudes*





- *Percentile of the pre-Tohoku positive anomaly in the distribution of magnitudes*

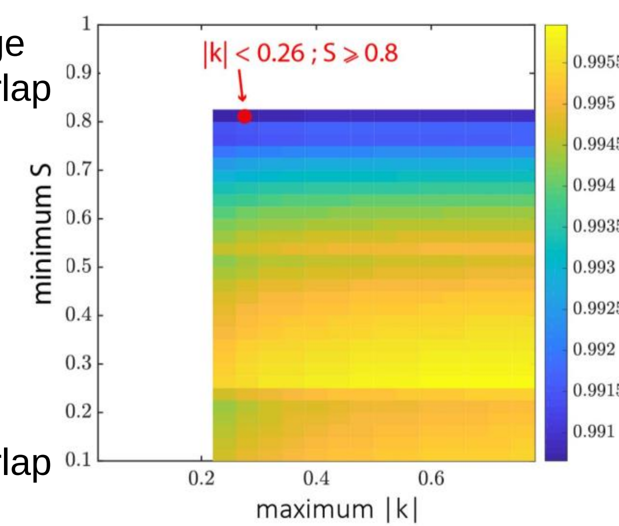


Low intensity difference

Large intensity difference

Large overlap

No overlap

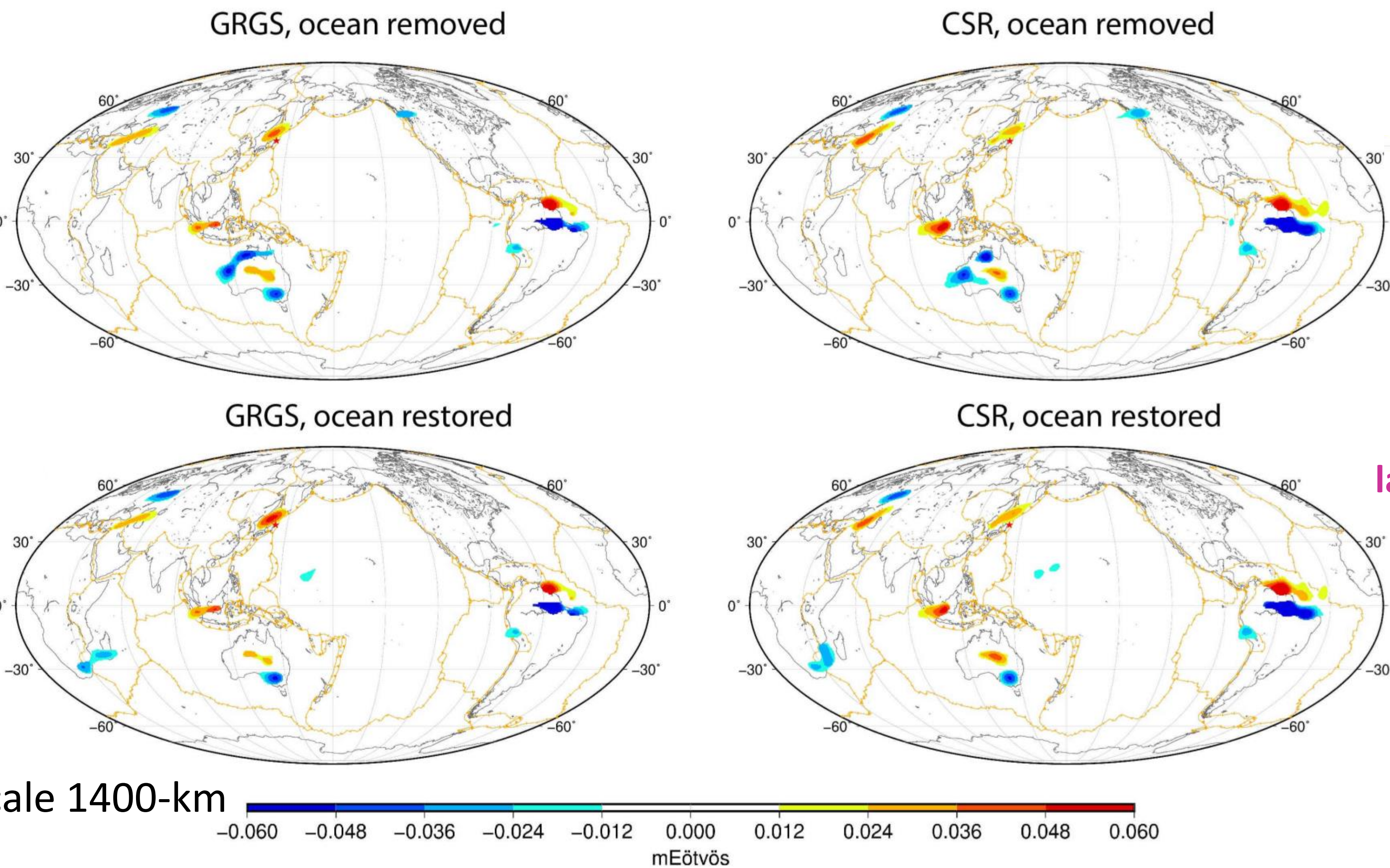


Percentiles above 97.5% (globally) or 99% (oceans) for all k and S values preserving the pre-Tohoku signal

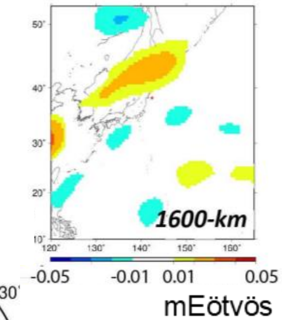
Comparison with the CSR06 solution

Anomalous signals in Feb. 2011, azimutal range Az_2 60-85°.

$|k| < 0.42 \,;\, S \geqslant 0.5$



Scale 1400-km

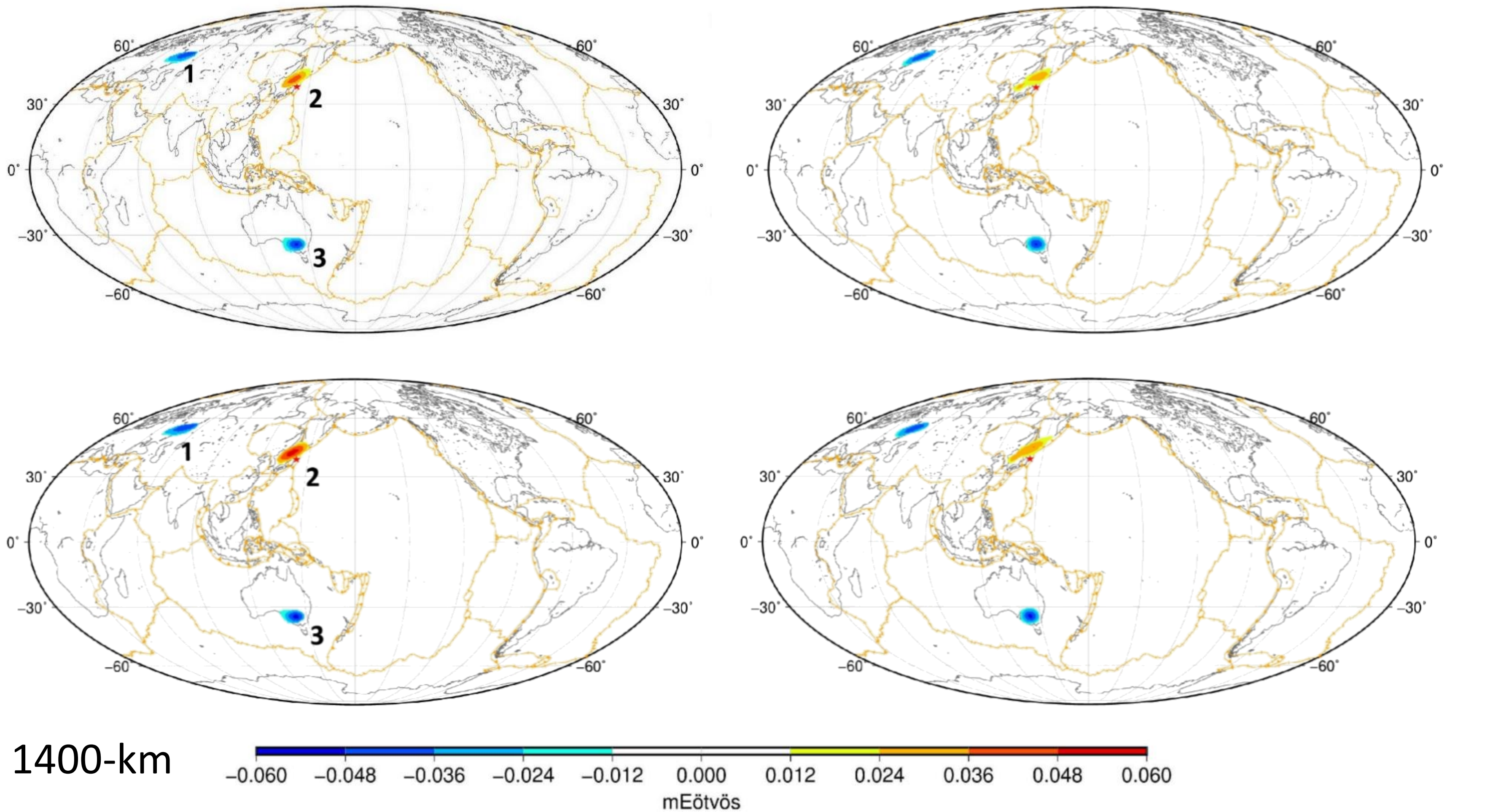


Except around Japan, the signs and locations of the signals are consistent with large water mass redistributions associated with an intense 2010-2011 La Niña event

Ocean & Solution consistency test: intermediate sensitivity to both the GRACE solutions and their dealiasing ocean model.

Most consistent signals between GRGS03 and CSR06

Pre-Tohoku positive signal: one of only 3 remaining anomalies

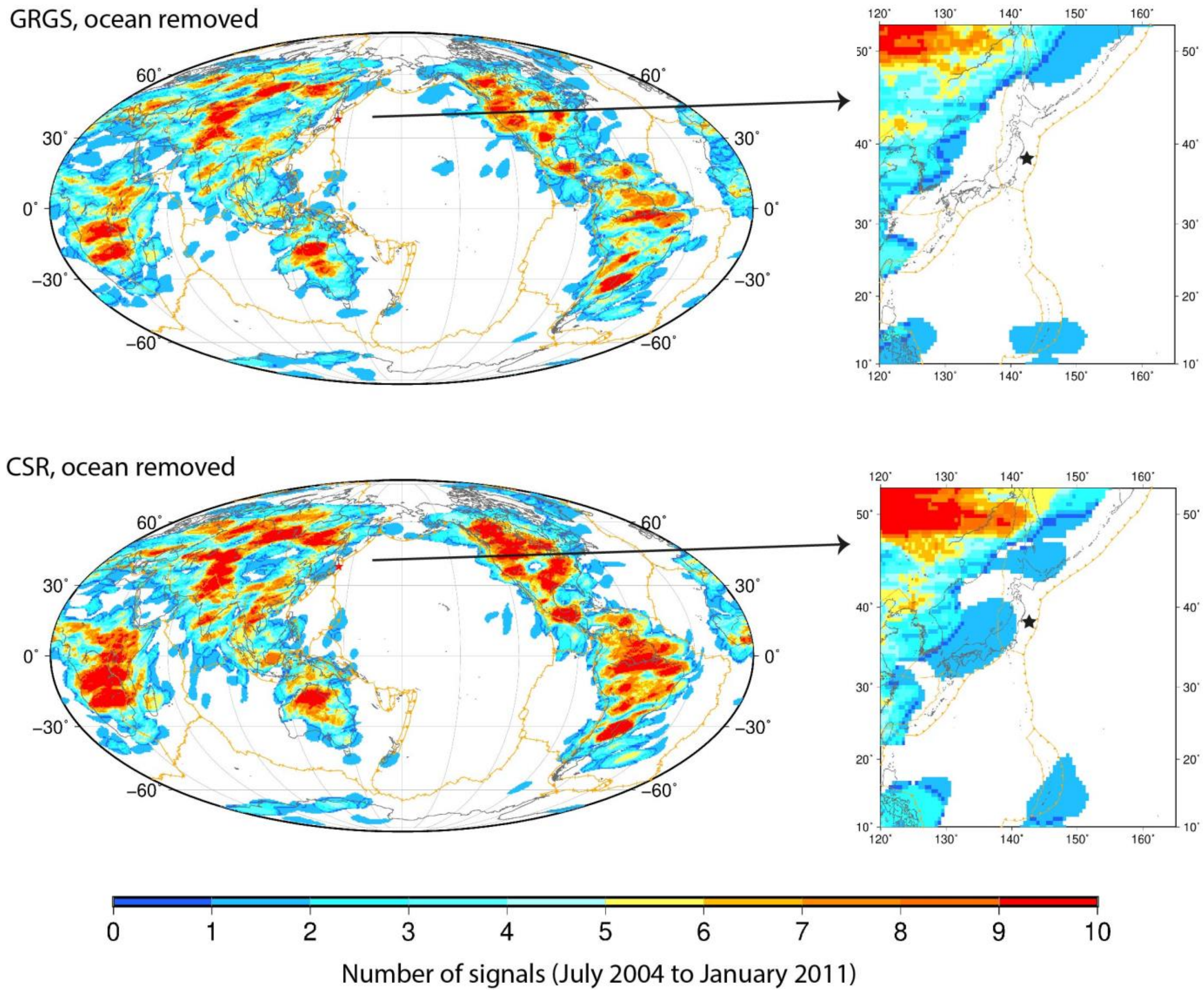


Scale 1400-km

Ocean & Solution consistency test:

- *GRGS* |k| < 0.34 ; S > 0.8
- *CSR* |k| < 0.42 ; S > 0.8

Temporal uniqueness of the pre-Tohoku signal
(July 2004 – Feb 2011 period)



Distribution of magnitudes:

Percentiles above 90% (globally) or 95% (oceans) for all k and S values preserving the pre-Tohoku signal (CSR06)

Number of anomalous signals at each location from July 2004 to February 2011
Azimutal range 60-85°, scale 1400-km.

Conclusions

• Our systematic analysis shows the uniqueness of the pre-Tohoku signal: 1) magnitude, 2) consistency between gravity models, 3) dipolar pattern, typical of dislocations within the Solid Earth.

→ Confirmation of the pre-seismic nature of the signal before the Tohoku earthquake.

• We can identify, before a giant earthquake, anomalous gravity gradient variations along a subduction boundary, likely to reflect processes associated with subducted slab deformation.

• Perspectives for a systematic monitoring of subduction zones worldwide, to detect transient motions deep in the slab, that might precede shallower deformations and foreshocks.

• A potential contribution of satellite gravimetry to alert systems in highly seismic zones (see also Bouih *et al*., EPSL 2022, for the Maule earthquake).