The ITRF and its scientific applications

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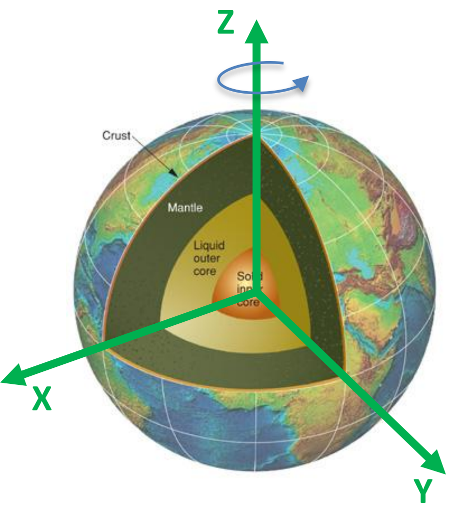
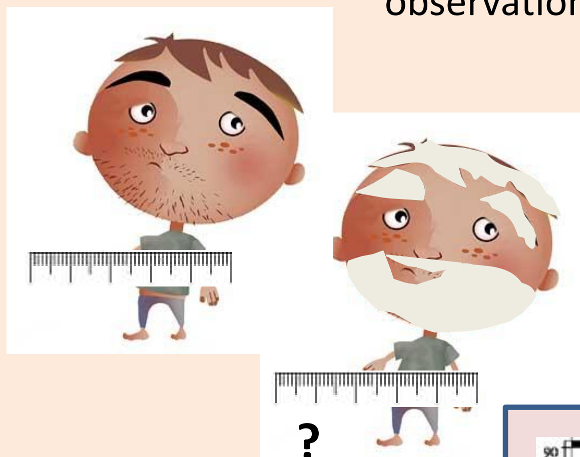
JOURNÉES 2013 SYSTÈMES DE RÉFÉRENCE SPATIO-TEMPORELS
Scientific developments from highly accurate
space-time reference systems

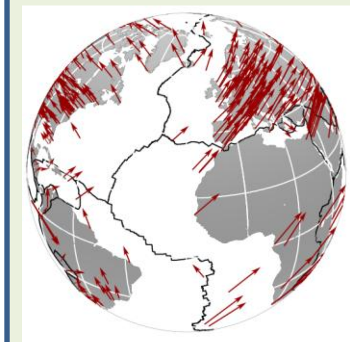
The International Terrestrial Reference Frame



Terrestrial Frame

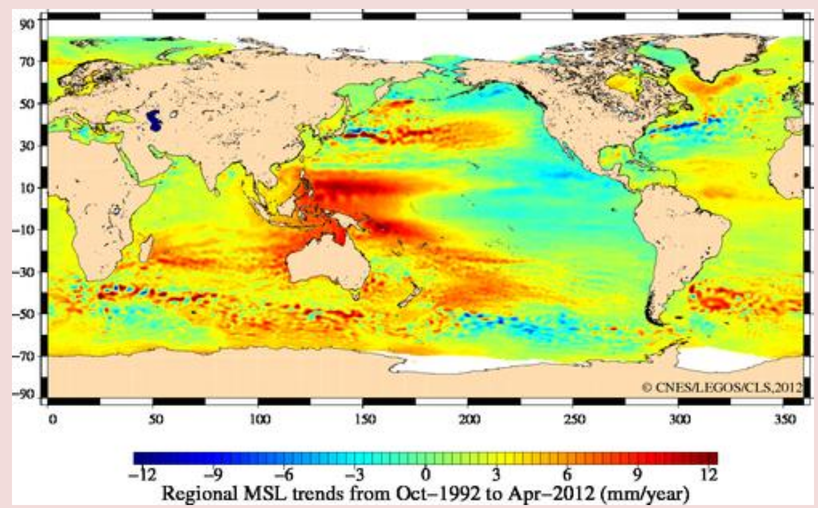
WHY? Accuracy, precision and stability for long term global observations





SOLID EARTH

Plate tectonic
Post Glacial Rebound
etc…



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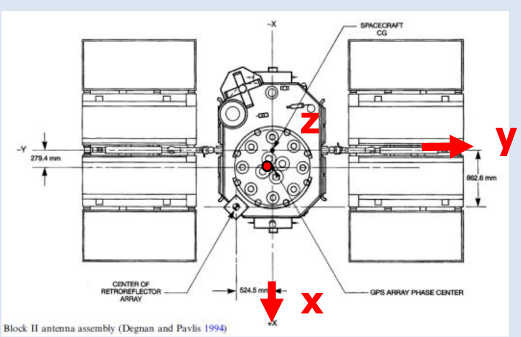
SURFACE FLUID DYNAMICS

Sea level rise
Climate changes
etc…

CALIBRATION

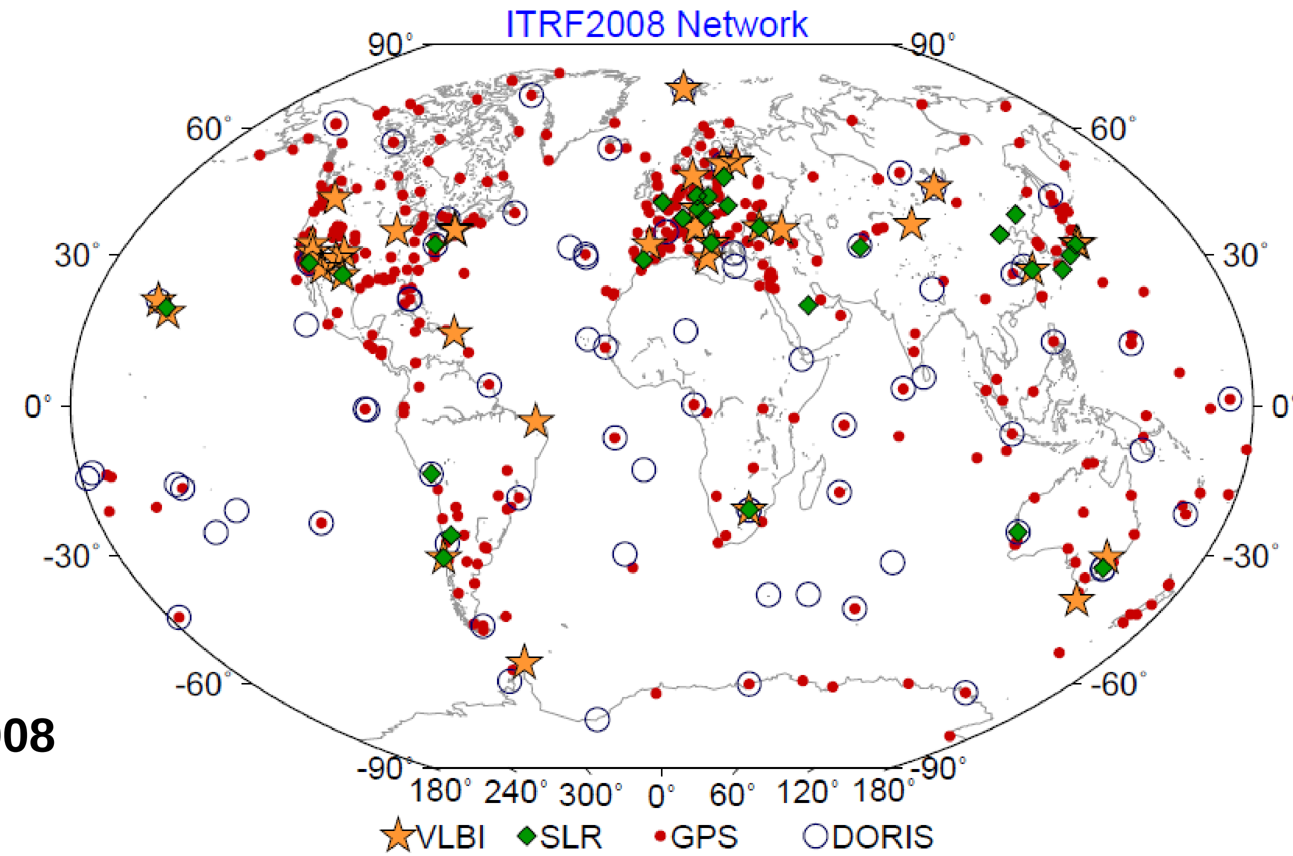
Space altimeter
GPS antenna phase center offsets
etc…



The ITRF adventure

- First combined reference frame was **BTS84**, published in 1985 (Boucher & Altamimi, 1985):
  - VLBI, LLR, SLR & Doppler: MERIT campaign
  - ~20 co-location sites
  - Precision : decimeter
- 12 ITRF versions: ITRF88 up to ITRF2008
  - 1992: GPS in the ITRF. First combined velocity field in (ITRF91)
  - 1995: DORIS in ITRF. Use of full variance-covariance information (ITRF94)
  - 2006: ITRF and EOP rigorous combination (ITRF2005)
- 2011: **ITRF2008** the up-to-date realization of the system
  - **Origine: Satellite Laser Ranging (SLR)**
  - **Scale: average of SLR and Very Long Baseline Interferometry (VLBI)**
  - **Orientation: aligned w.r.t. ITRF2005 over 131 sites**
  - **Precision: a few mm in position and ~1 mm/yr in velocity**
- **ITRF2013** coming soon (mid 2014)

International Terrestrial Reference Frame



580 sites

(935 stations)

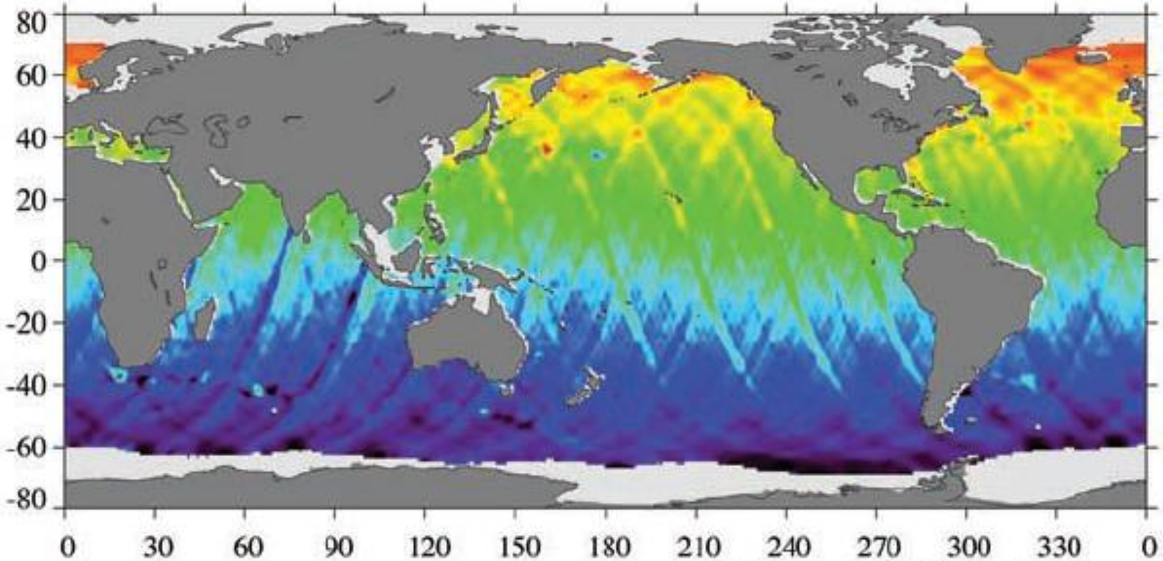
ITRF2008

```
SITE NAME          ID.          X/Vx          Y/Vy           Z/Vz            Sigmas        SOLN  DATA_START    DATA_END
                           -----------------------m/m/y---------------------
------------------------------------------------------------------------------------------------------------------------
Paris          OPMT   4202777.371    171367.999   4778660.203 0.001 0.001 0.001
                           -.0125        0.0178        0.0107 .0001 .0000 .0001
Grasse (OCA)   GRAS   4581690.901    556114.831   4389360.793 0.001 0.001 0.001  1 00:000:00000 03:113:00000
                           -.0133        0.0188        0.0120 .0001 .0000 .0001
Grasse (OCA)   GRAS   4581690.900    556114.837   4389360.793 0.001 0.001 0.001  2 03:113:00000 04:295:43200
                           -.0133        0.0188        0.0120 .0001 .0000 .0001
                                                 ….
```

Altamimi et al., 2011

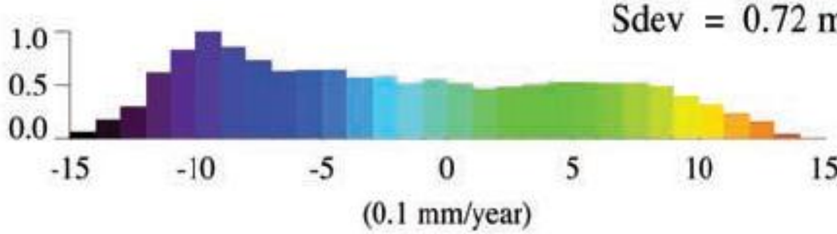
ITRF IMPACT ON MEASUREMENTS

Case of sea level estimations

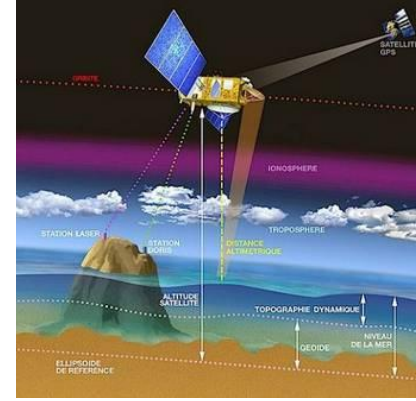


Beckley et al., 2007

Mean = -0.26 mm/year
Sdev = 0.72 mm/year



Sea level variation from space altimetry



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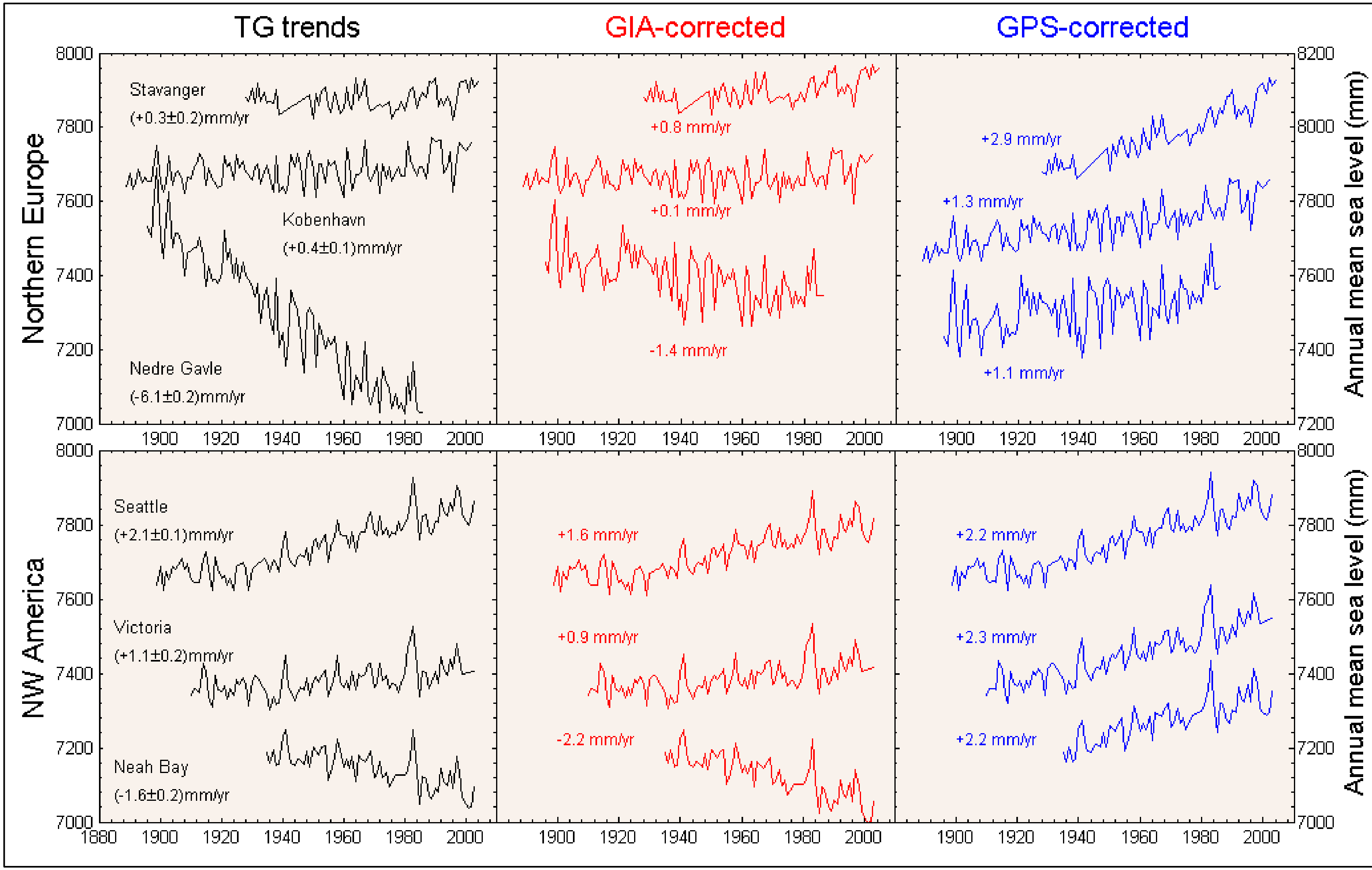
TOPEX (1993-2002): regional differences of sea level variations, via orbital parameters
(ITRF2005 minus CSR95/ITRF2000)

Sea level variability in space and time

- An origin Z-drift error of 2 mm/yr ==> errors in satellite altimetry data:
  - up to 0.3 mm/yr on global mean sea level
  - up to 1.8 mm/yr on regional sea level at high latitudes
- A scale drift error of 0.1 ppb/yr ==> drift up to 0.6 mm/yr in mean sea level determined by tide gauges records corrected with GPS expressed in ITRF.

GPS height velocities and Tide Gaude trends



Woppelmann et al., GRL (2009)

ITRF precision and requirements

- For sea level variations the reference frame error may be at the level of long term possible variations due to climate changes

(see e.g. IPCC Fourth assessment report, Bindoff et al., 2007)

➡ Users need a TRF with an accurate origin

- **Scientific Requirements** in terms of accuray and stability of the origin:
  - 1 mm in position
  - 0.1 mm/yr in velocity

(GGOS2020, Plag & Pearlman, 2009;
Blewitt et al., 2010;
US National Research Council report, 2010)

ITRF EVALUATION

How to evaluate TRF coordinate acuracy?

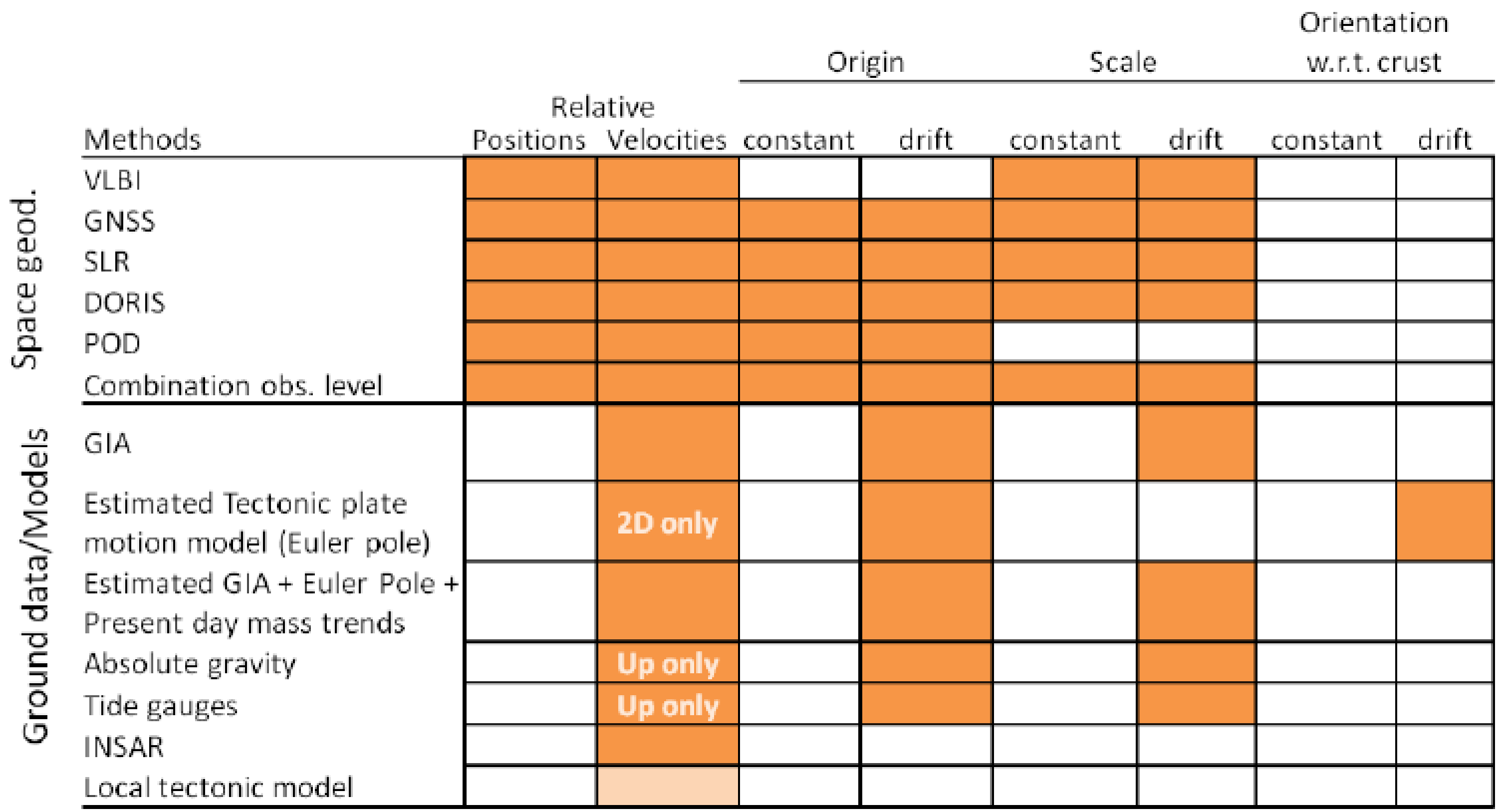
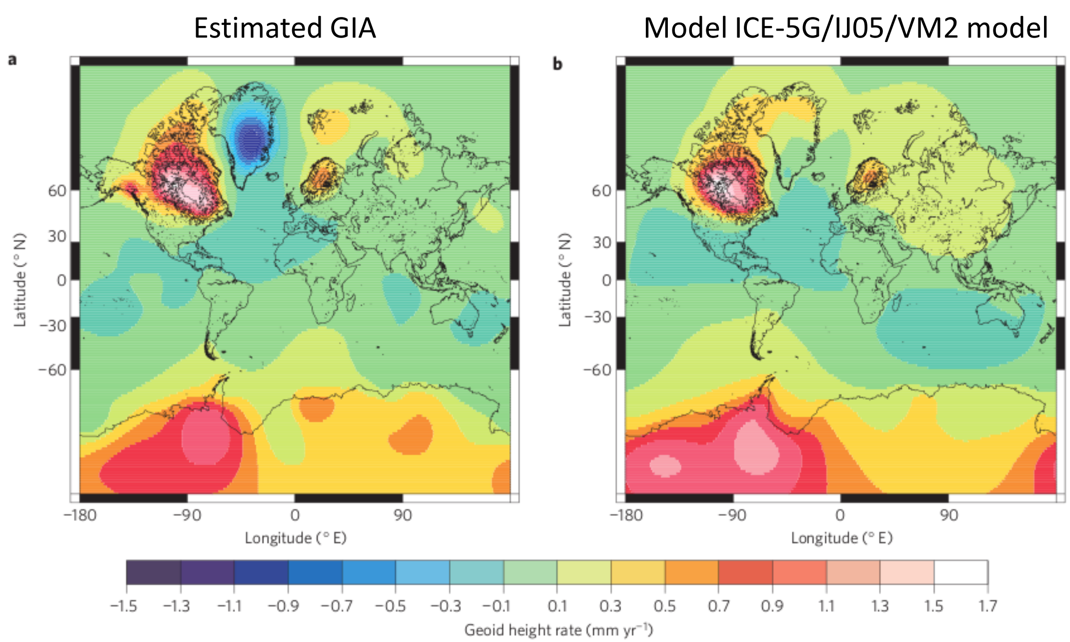


Fig. 2 Classification of the TRF evaluation methods and their contributions.

Collilieux et al., 2013, IUGG proceedings

Evaluation of ITRF origin

Wu et al. (2011) **have estimated simultaneously Glacial Isostatic Adjustment (GIA), present-day surface mass trend and tectonic plate motion from ITRF2008 velocities, GRACE gravity estimates and OBP models.**



Wu et al. 2010, nature geoscience

	Tx (mm/yr)	Ty (mm/yr)	Tz (mm/yr)	Scale (mm/yr)
ITRF2008 + GRACE + ECCO + OMCT	- 0.4 ± 0.1	- 0.2 ± 0.1	- 0.5 ± 0.2	- 0.1 ± 0.2

Consistent with Métivier et al. (EPSL 2010) results

Evaluation of ITRF origin

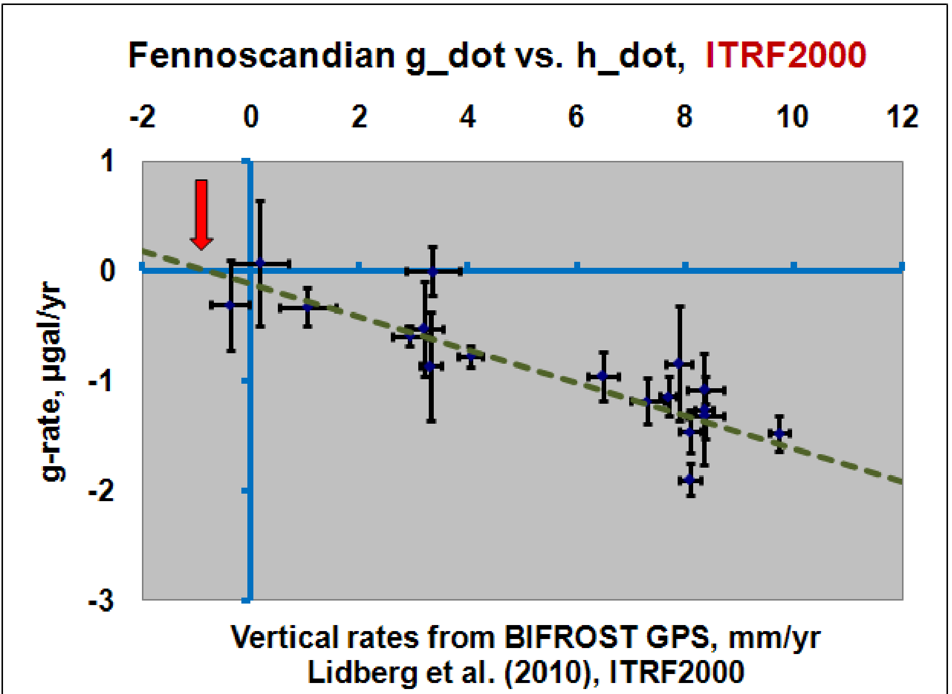
GPS height velocities and Absolute gravimeter trends

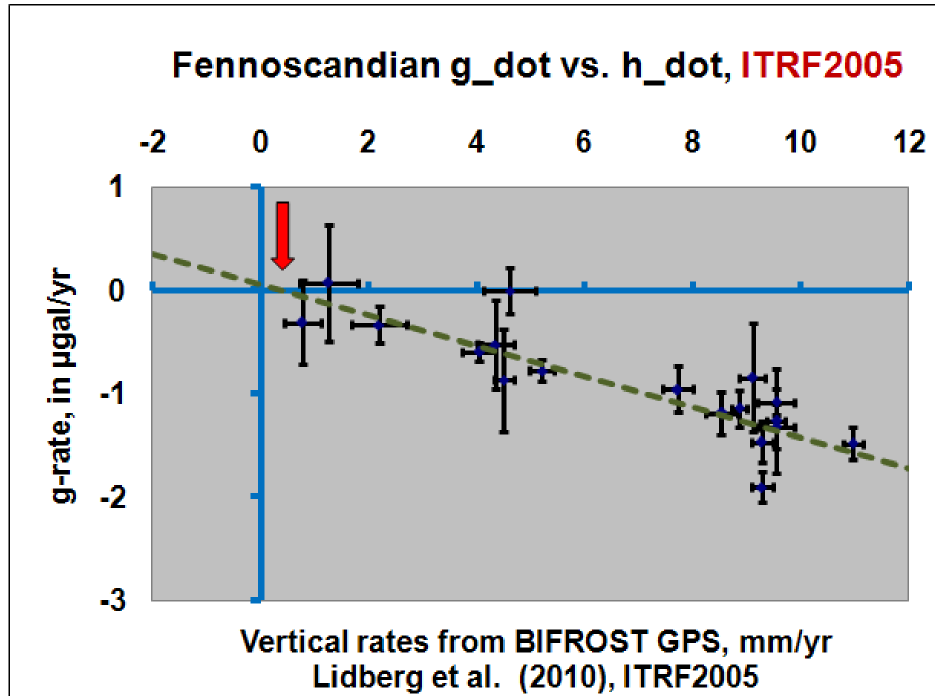
Vertical velocities = α(λ,ϕ) absolute gravimeter trends + TRF origin error

∈ [-6.66, -2.85] mm/µGal
(Richter et al., 2004)

Précision 0.1 µGal/yr w.r.t. Earth Center of Mass

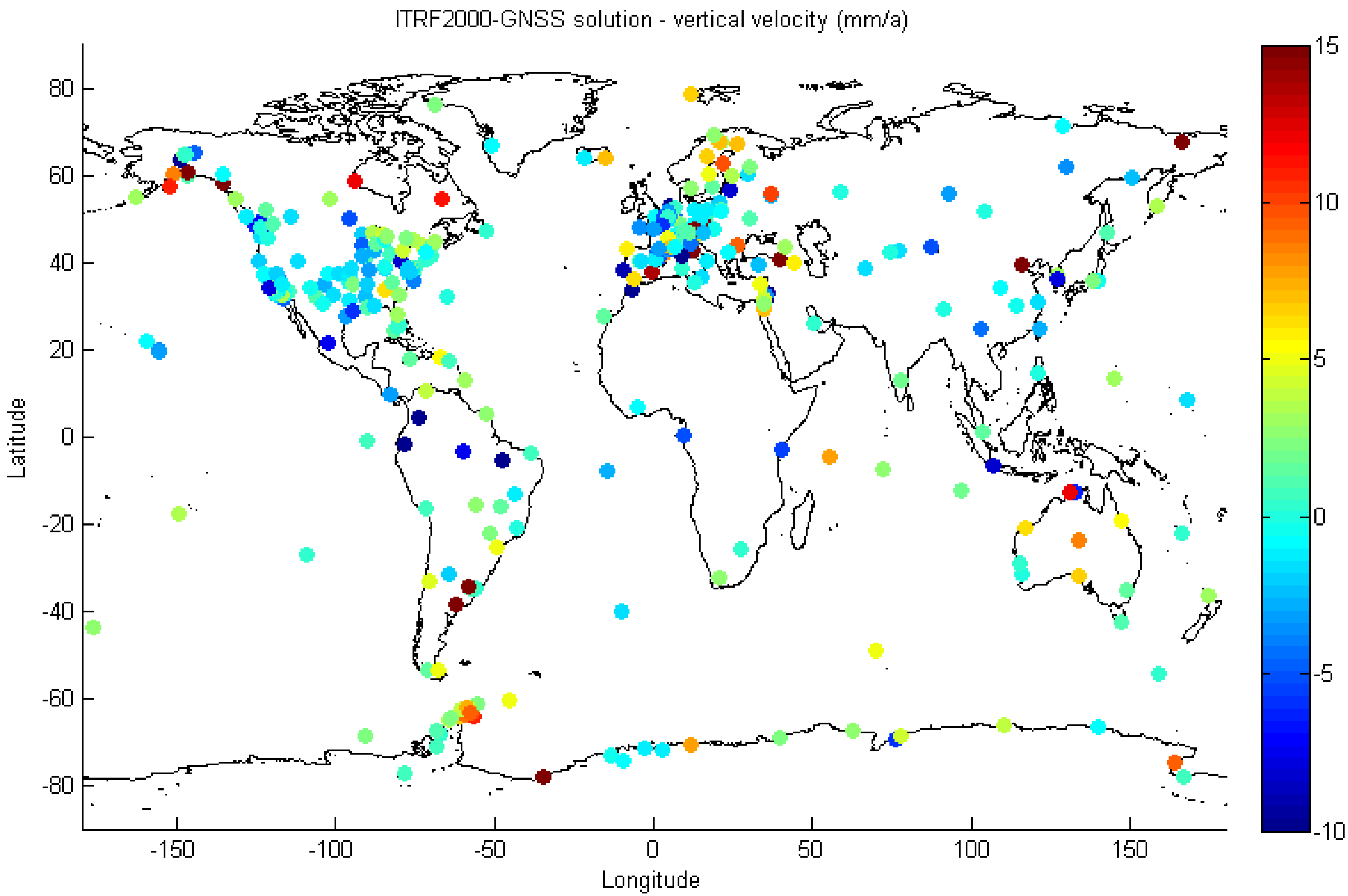
Nordic AG Project (coordinated by the Nordic Geodetic Commission) (Courtesy J. Mäkinen)



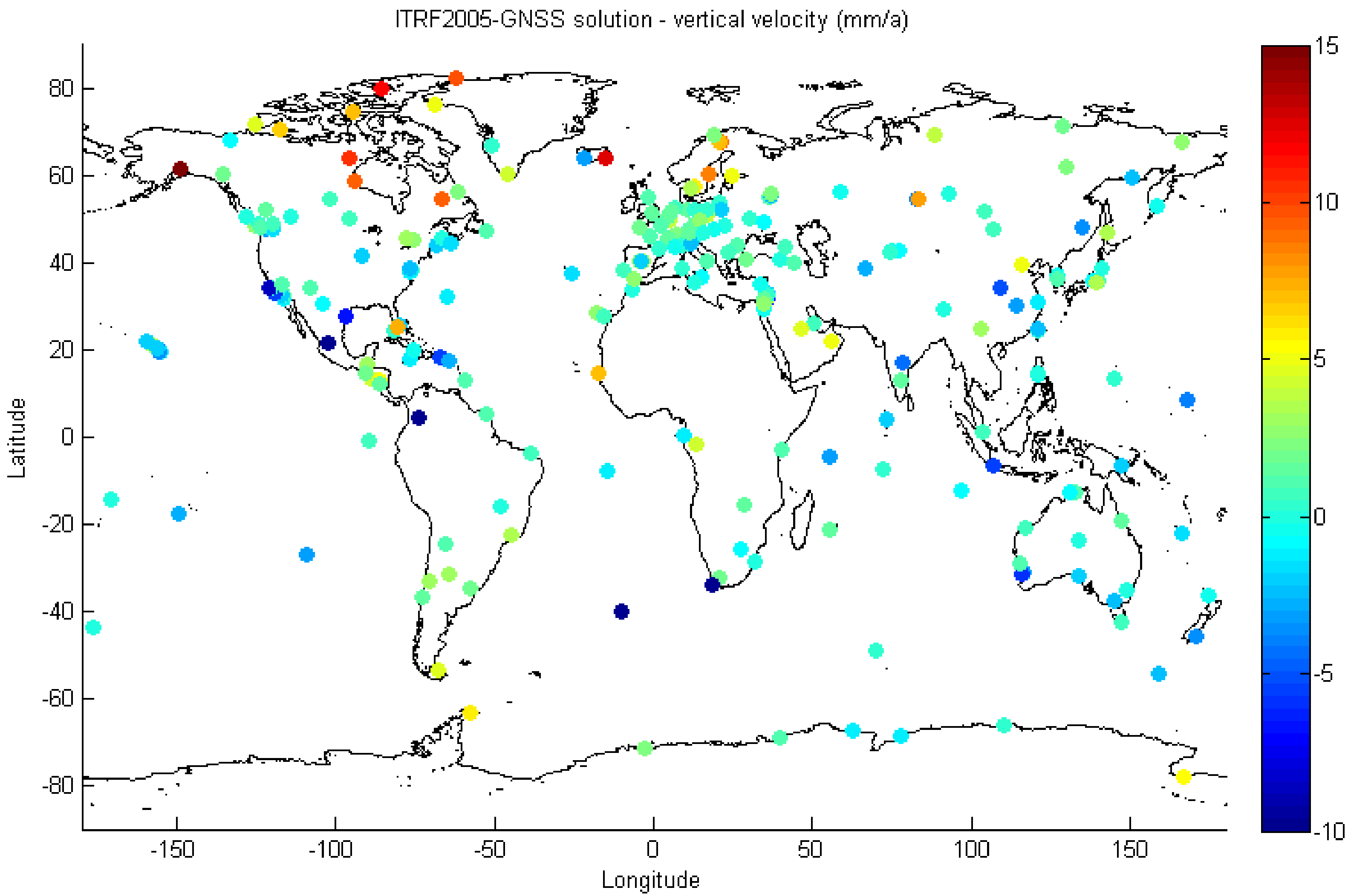


(Plag et al., 2007; Collilieux et al., 2013, proceedings UGGI; see also Mazzotti et al., 2011)

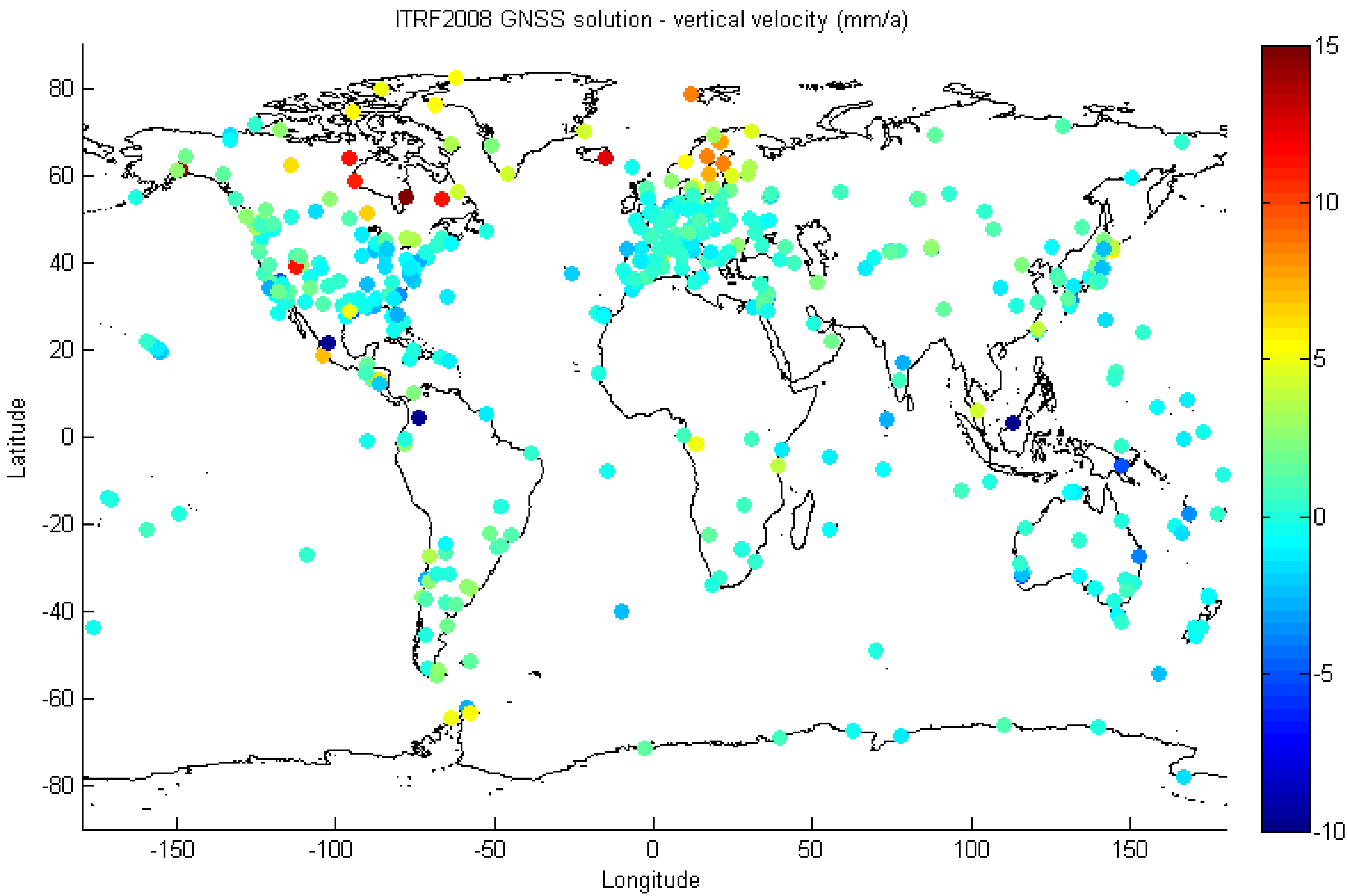
Evolution of the spatial consistency of vertical velocities: ITRF2000



Evolution of the spatial consistency of vertical velocities: ITRF2005



Evolution of the spatial consistency of vertical velocities: ITRF2008



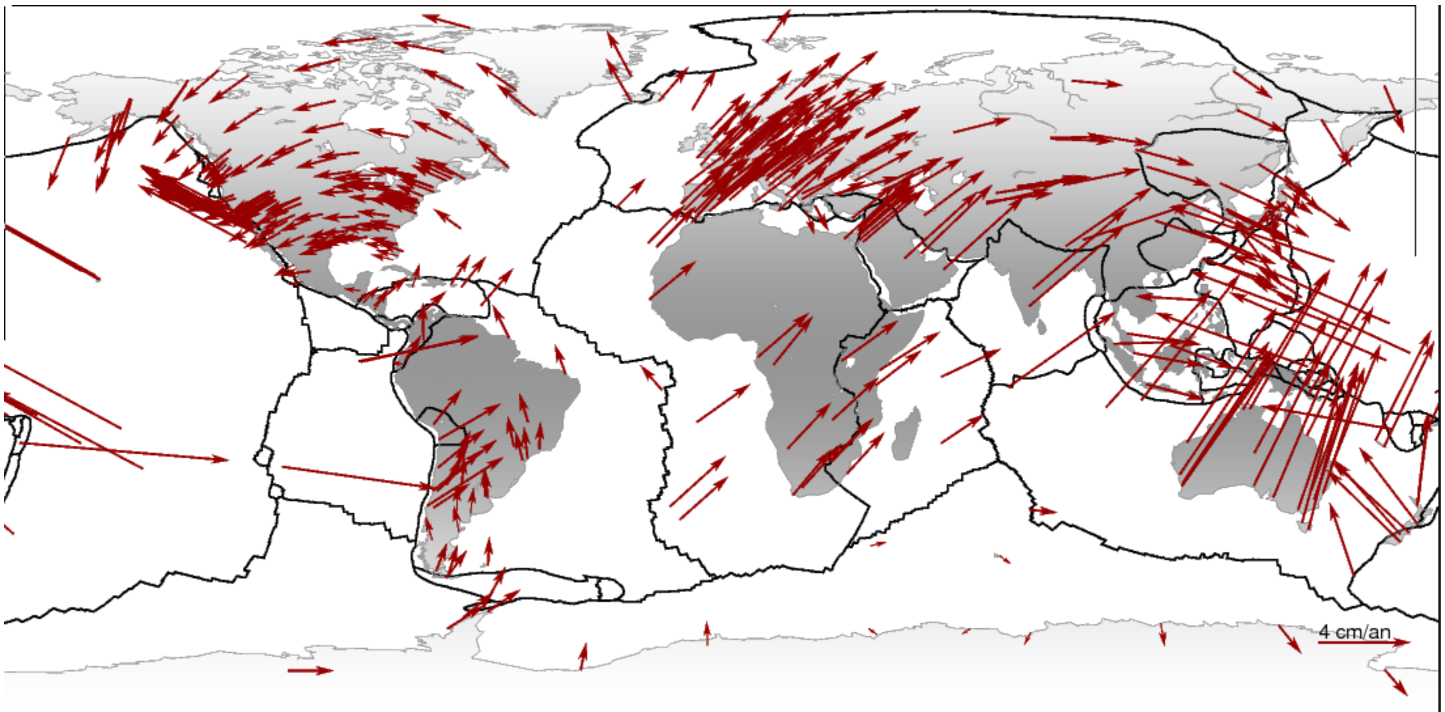
ITRF GEOPHYSICAL APPLICATIONS

Plate tectonic motion

Glacial Isostatic Adjustment (GIA) and recent ice melting

Plate tectonic motion

All ITRF2008 Site Horizontal Velocities:



ITRF2008: Rigid plates and deformation zones

- Plate boundary & deformation areas
- GIA
- Outliers: residuals > 3-sigma
- ITRF2008-PMM final selection

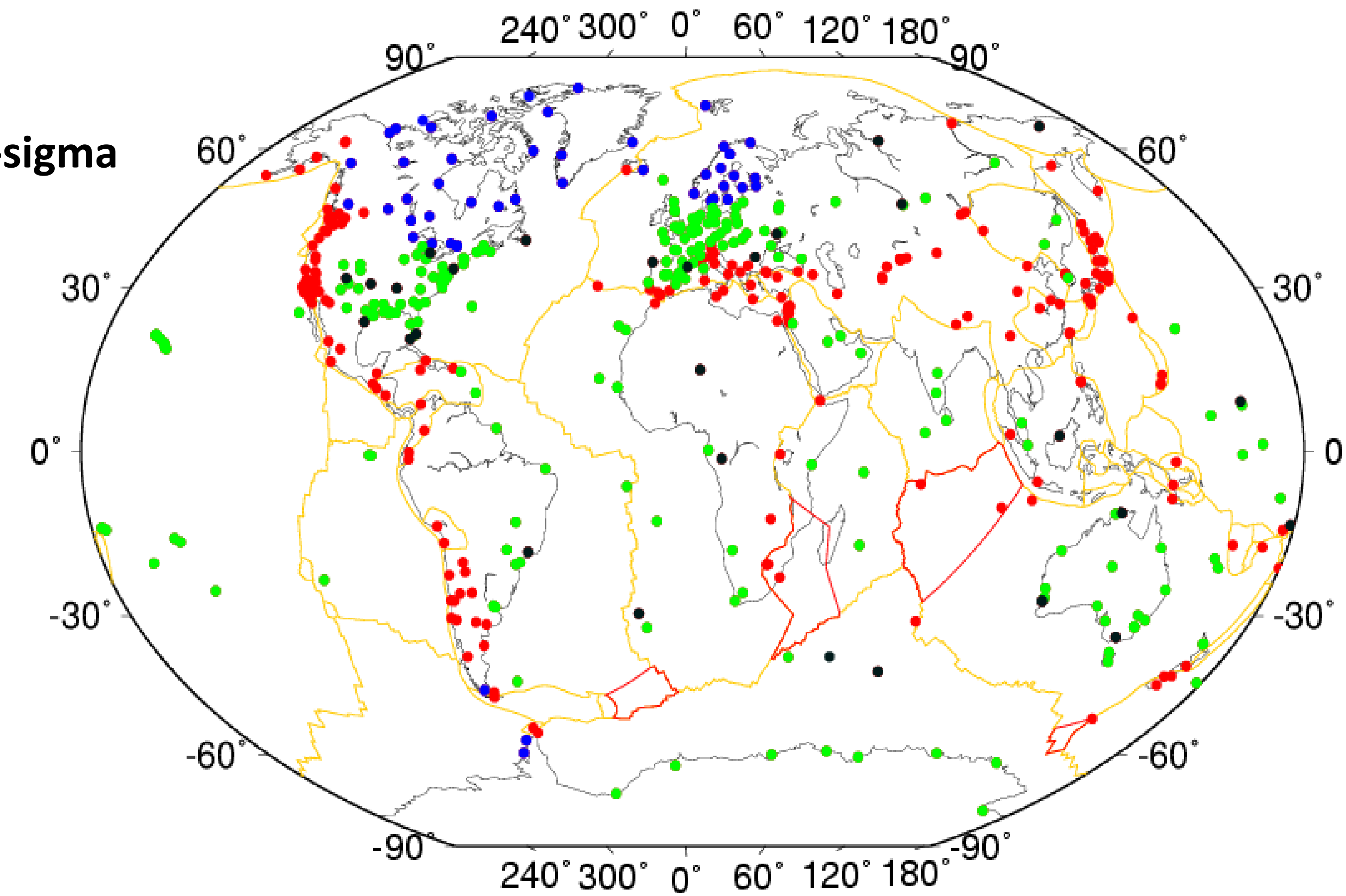
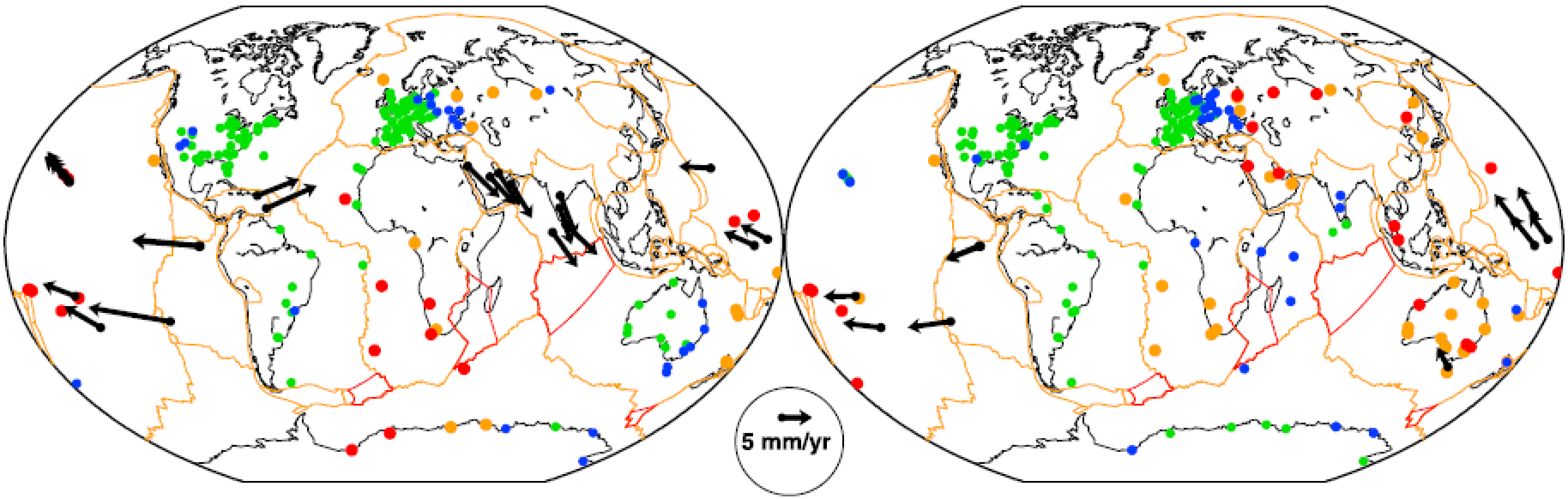


Plate motion model for 14 major tectonic plates.

Altamimi et al., 2012

Comparison btw ITRF2008 and
NNR-NUVEL-1 and NNR-MORVEL56

Velocity differences after rot. rate transformation



NNR-NUVEL-1A
RMS:
East : 2.5 mm/yr
North: 2.0 mm/yr

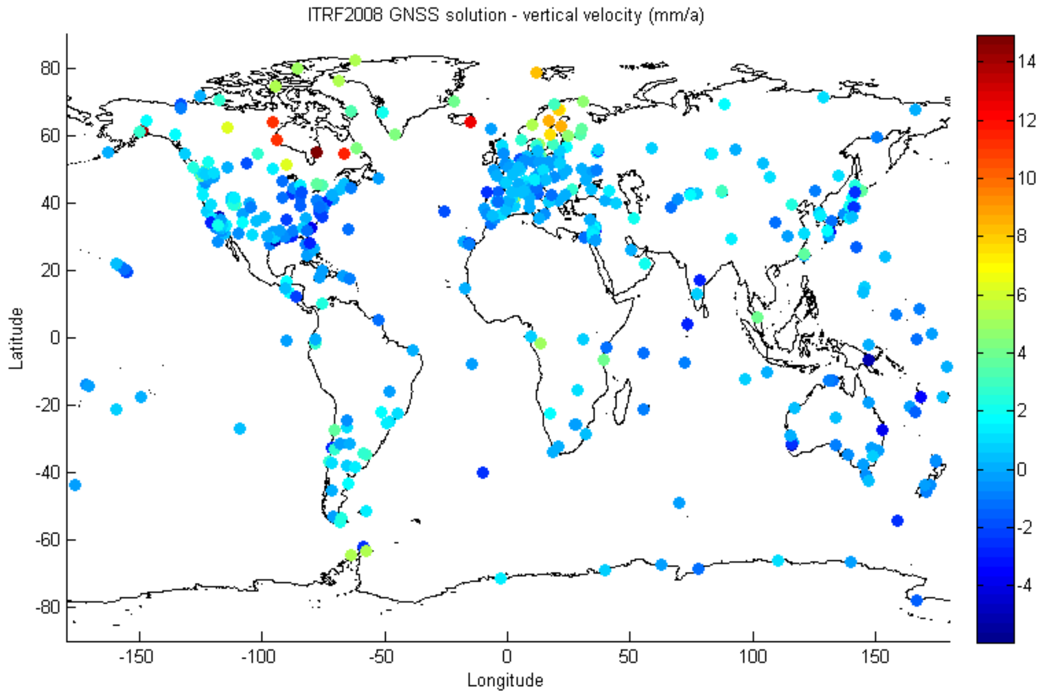
Ry = 0.025 mas/yr

Green: 1-2 mm/yr
Blue : 2-3 mm/yr
Orange: 3-4 mm/yr
Red : 4-5 mm/yr
Black : > 5 mm/yr

NNR-MORVEL56
RMS:
East : 1.7 mm/yr
North: 1.7 mm/yr

Rx = 0.084 mas/yr

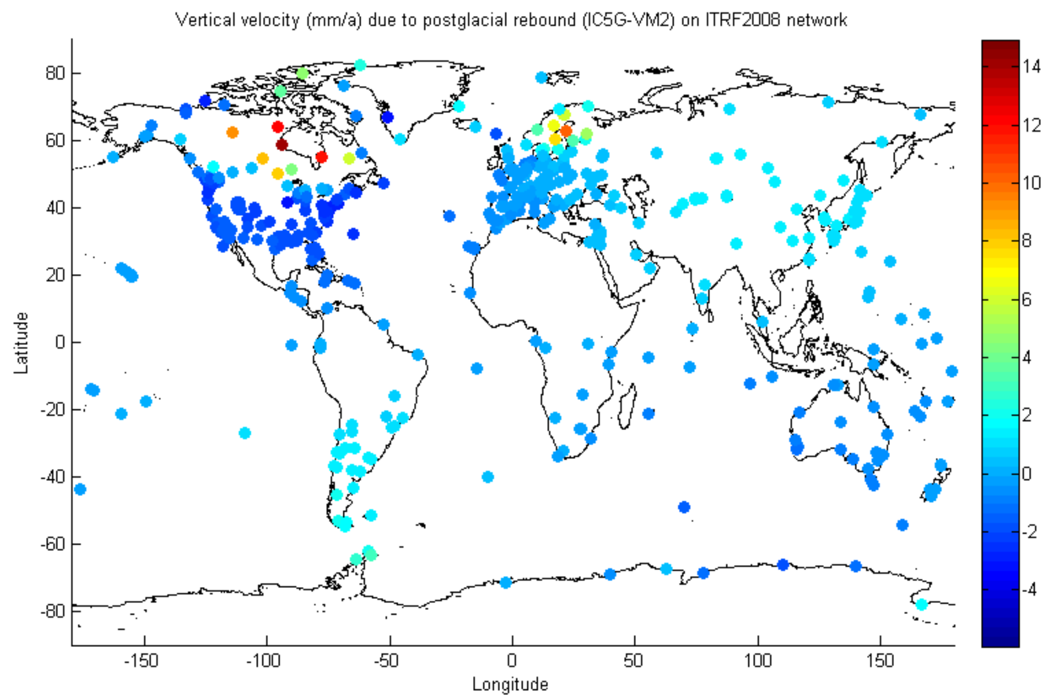
Vertical velocities and Glacial Isostatic Adjustment (GIA)



ITRF2008 GNSS vertical velocities

After exclusion of a few stations presenting large non-geophysical subsidence or a large error

Vertical velocities induced by the postglacial rebound (GIA) (ICE5G-VM2 model, Peltier 2004)

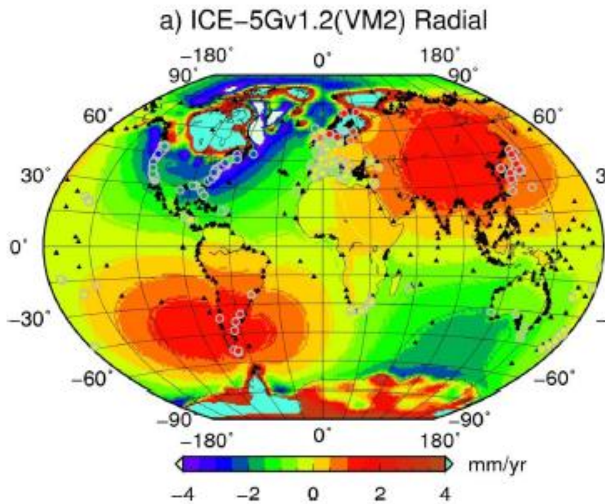


L. Métivier

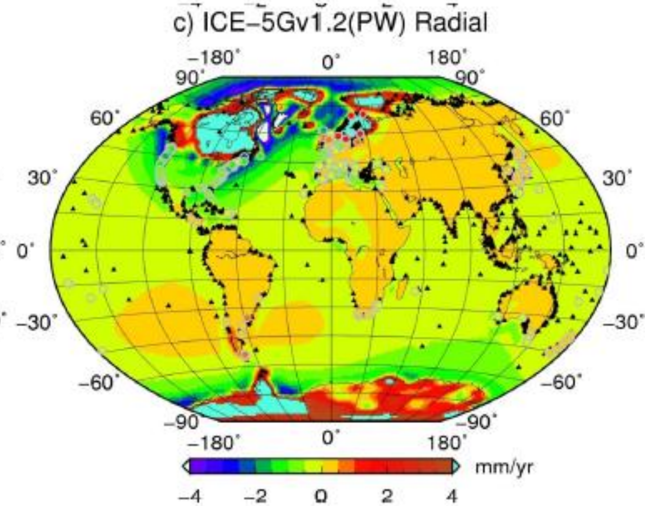
ITRF velocities and GIA

GIA models
(King et al., 2011, 2012)

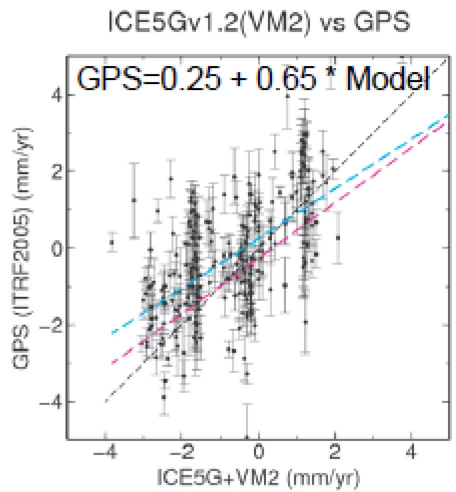
GIA Model (ICE-5G+VM2)

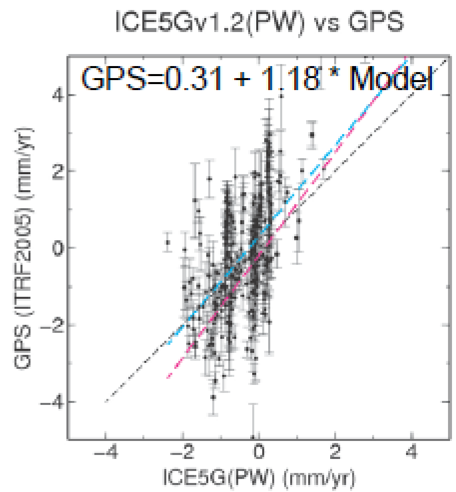


GIA model (ICE-5G+~VM2; PW comps)



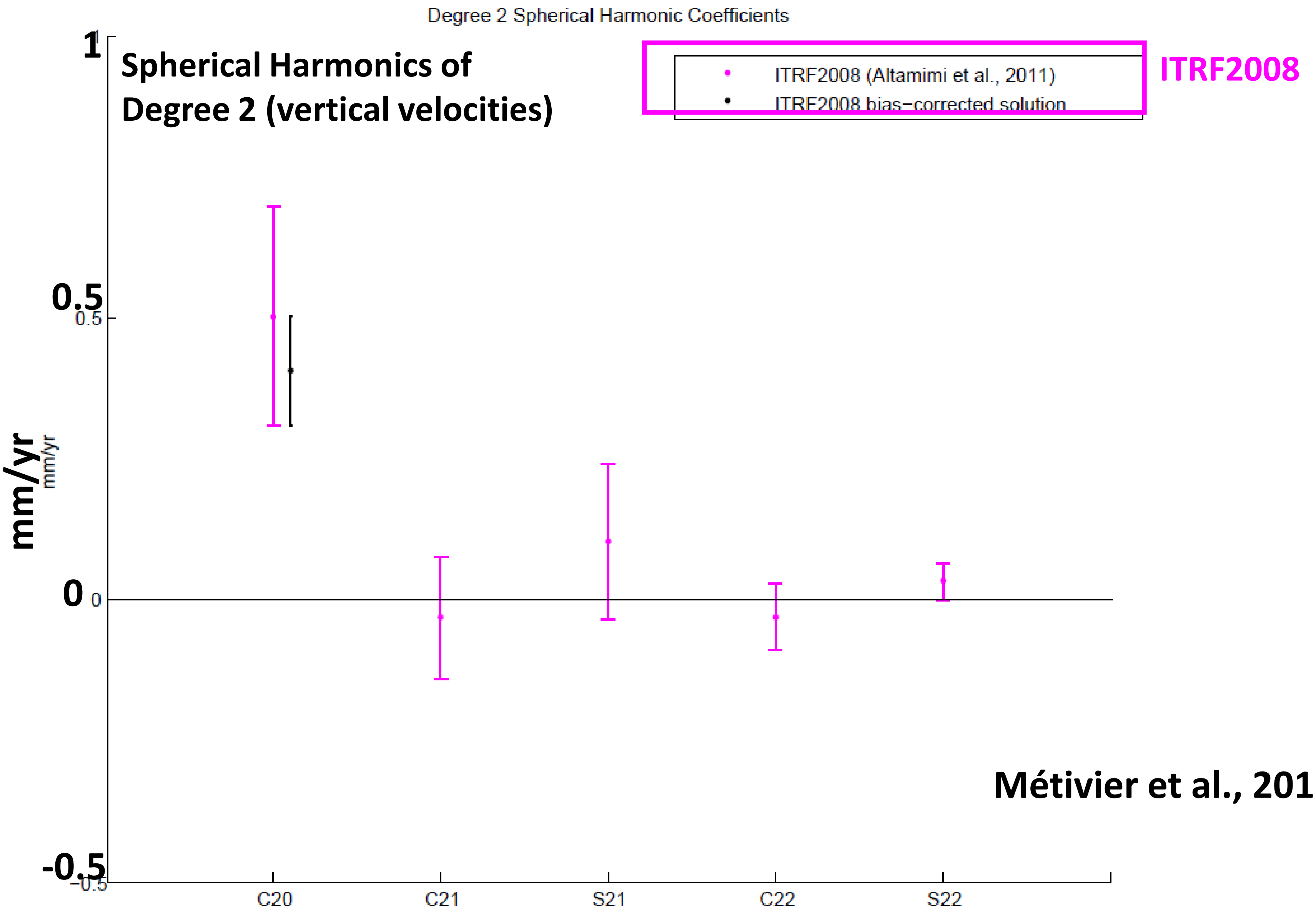
- Cyan = best fit
- Magenta = best fit after GPS Z-translation rate of -1.2mm/yr [c.f. Argus et al., 2007, 2010, 2011]





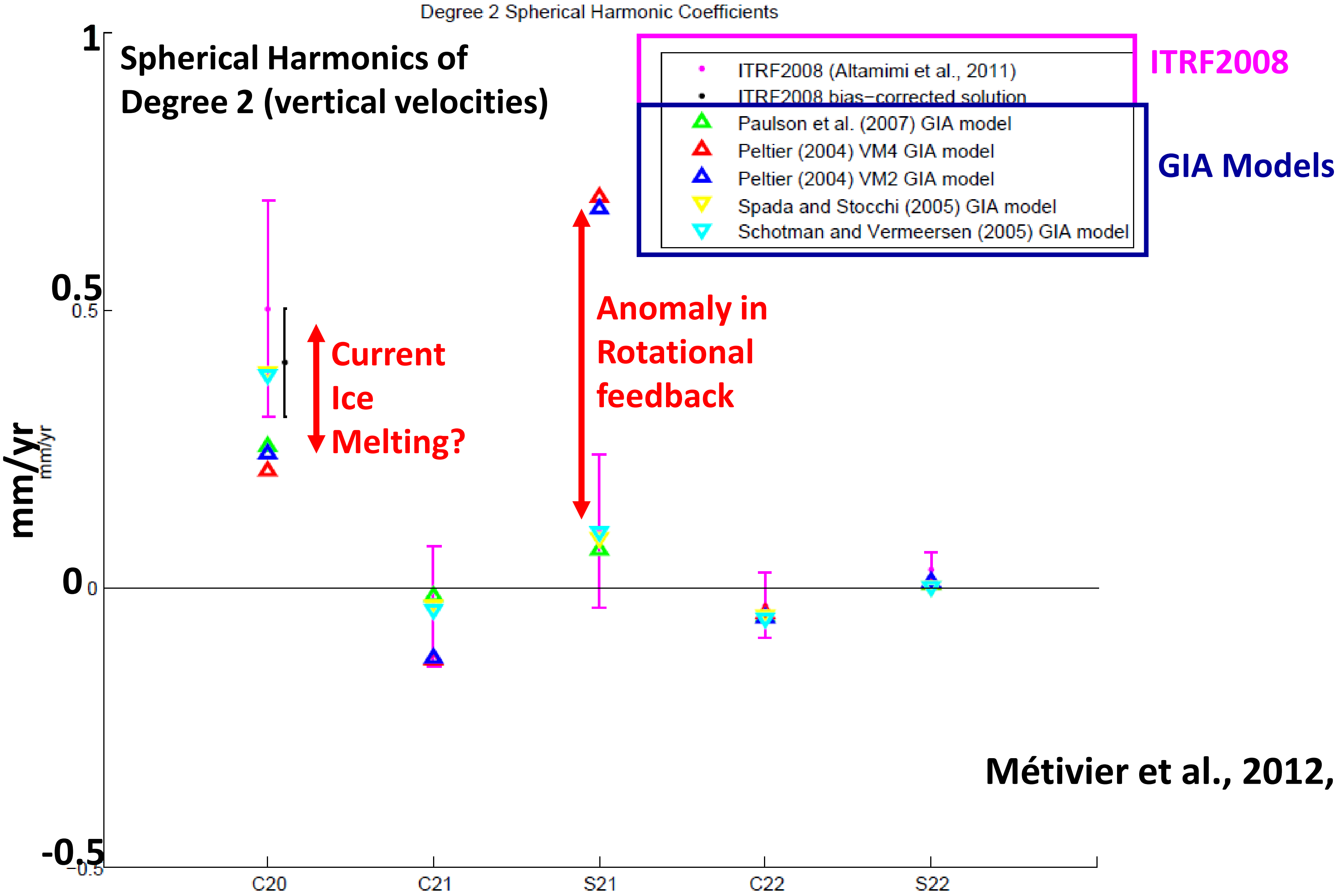
➡ Shifting ITRF origin does not drastically reconcile observed velocities with 2 GIA models

ITRF2008 & Post Glacial Rebound

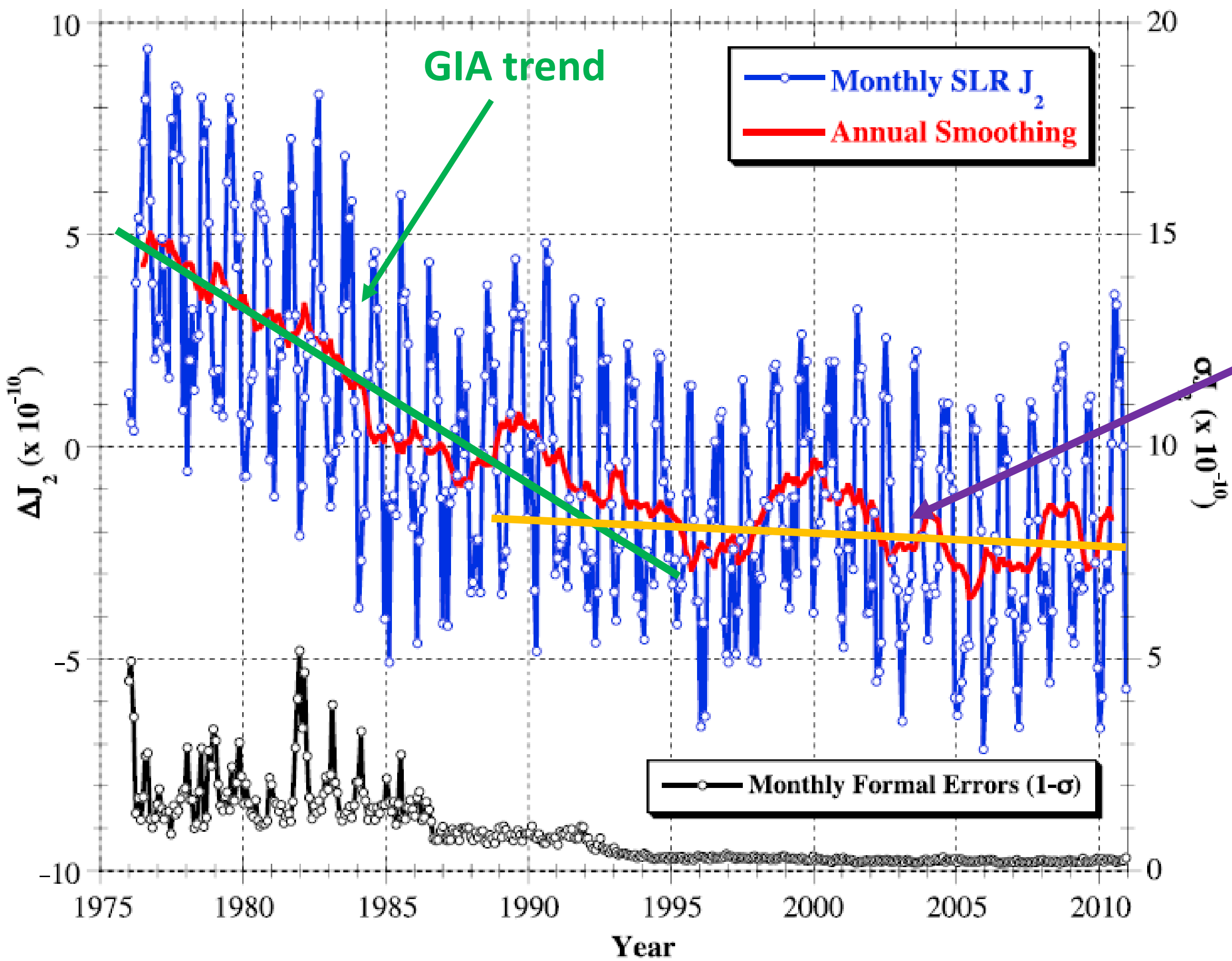


Métivier et al., 2012, GRL

ITRF2008 & Post Glacial Rebound



Métivier et al., 2012, GRL



ITRF2008 + prefered GIA model

Impact of climate changes due to recent ice melting?

Nerem & Wahr (2011) (see also Roy & Peltier, 2011)

FUTUR CHALLENGES

Non-linear behaviours

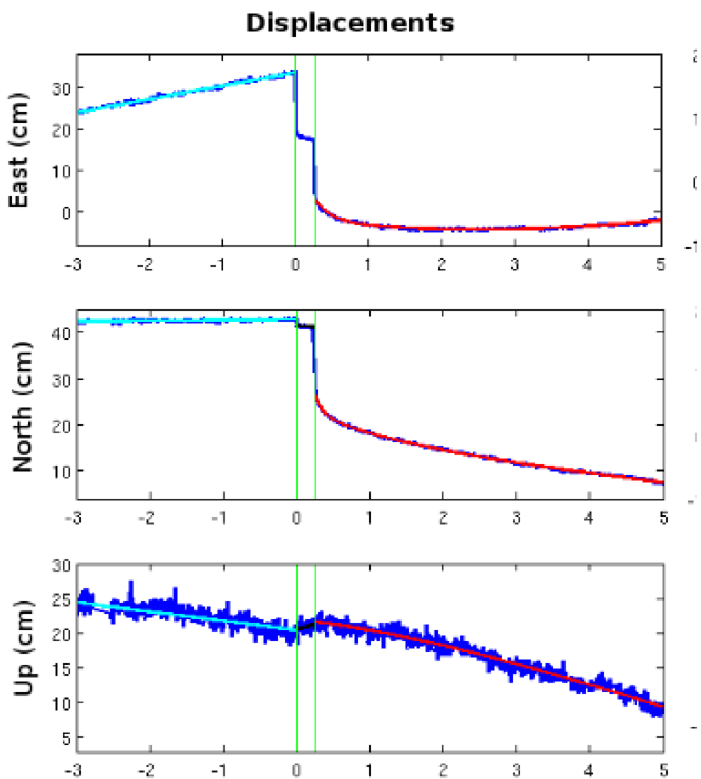
Co- and post-seismic deformations

$$X^{i}_{inst}(t) = X^{i}_{ITRF}(t) + \sum_{j} \Delta X^{i}_{j}(t)$$

(IERS conventions)

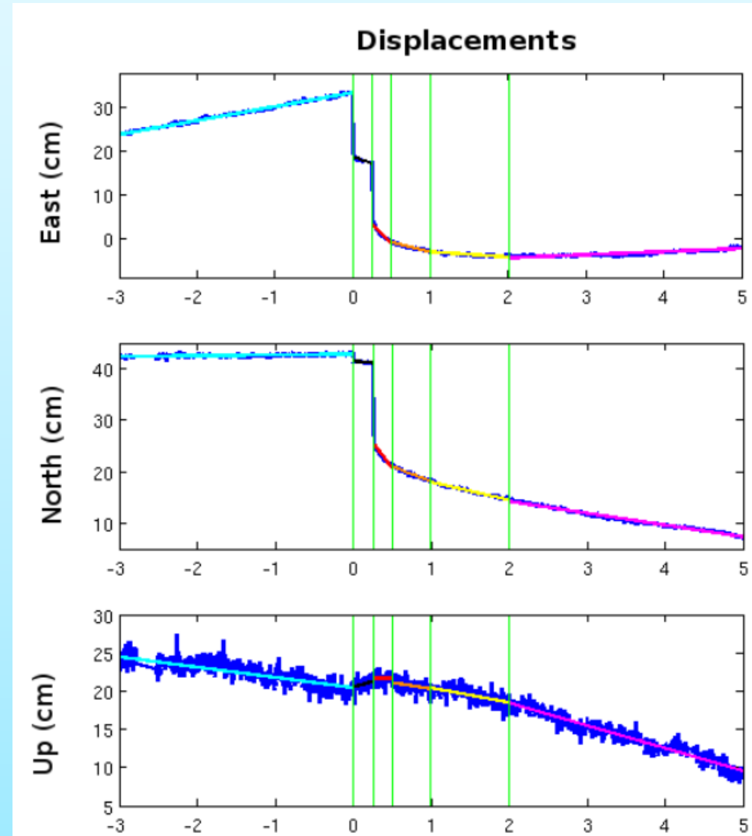
Geophysical model

Current handling of post-seismic motion in ITRF coordinates: many discontinuities are necessary!



Example of improved functional model

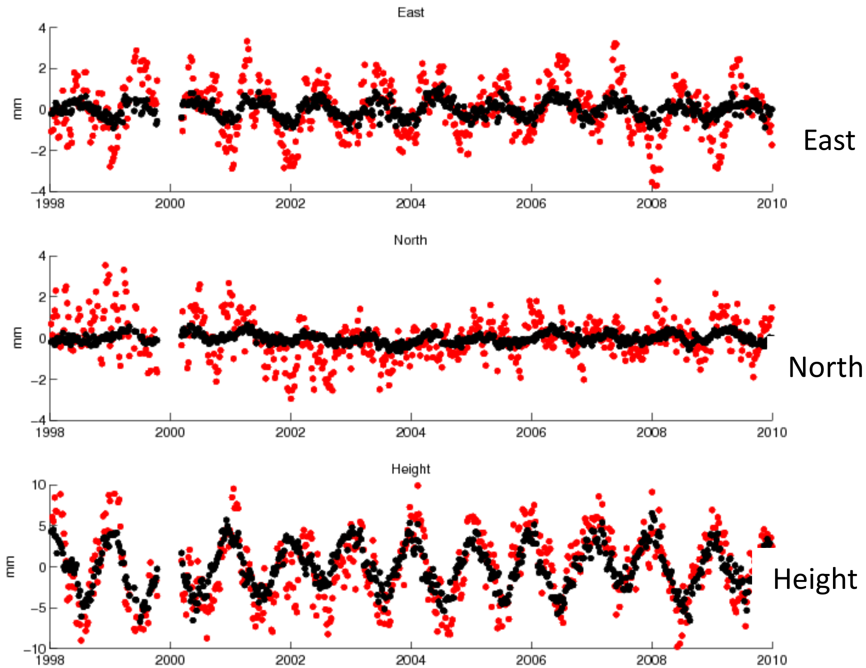
Piece-wise linear functions



What are the alternatives?

- Fit parametric models to stations before stacking.
- Add post-seismic parameters in the combination model.

Non-tidal loading effects



Collilieux et al. (2011)

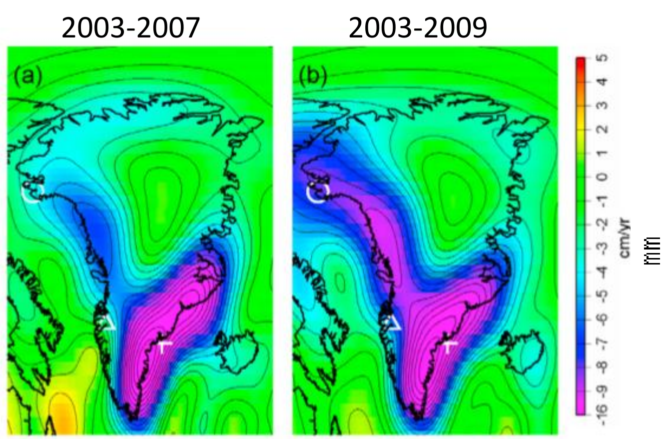
Fluid contributions are usually separated (hydrology, ocean, atmosphere) but exchanges between the « different layers » exist

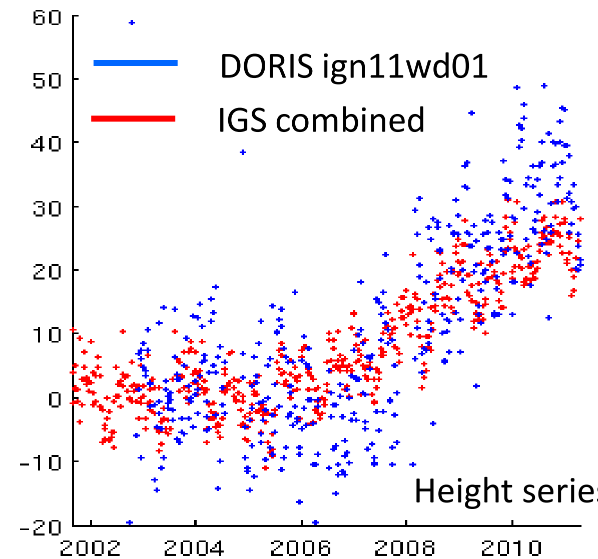
Raw GPS (IGS combined)
Load model (sum of the three main contributions)

Ex: YAR2 (Australia)

Acceleration processes?
Ex: ice melting

Khan et al., (2010)





Conclusions

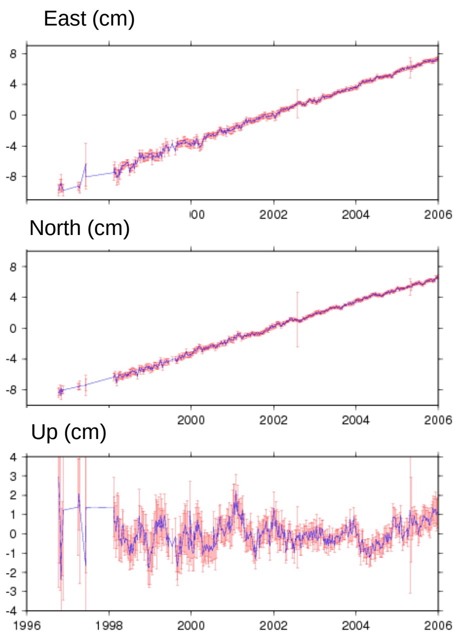
- The ITRF has improved in precision & accuracy over time. It is the most precise/accurate reference frame available today
- Its precision and stability make it adapted for the observation of long term evolution of numerous geophysical processes, for example here:
  - ITRF2008 Plate tectonic model
  - GIA models discrimination
  - Study of sea level rise and recent ice melting
  - Seasonal deformations
  - …
- The ITRF is still not at the level of science requirements. Needs to be improved by a factor of 10. This is critical at least for sea level estimations at global and local scales.
- Geophysical challenges for next ITRF realizations:
  - Detection of seismic discontinuities
  - Modeling of post-seismic deformations
  - Seasonal loading deformations
- Technical issues are not discussed here but are numerous:
  - The number of co-location sites, space geodesy and tie discrepancies are critical
  - Need to mitigate technique systematic errors

BACKUP

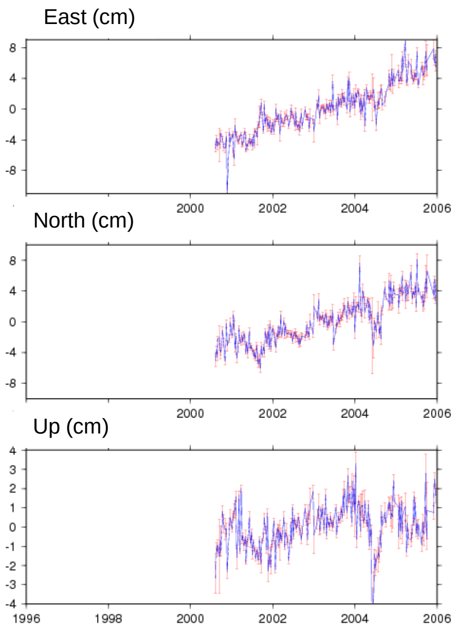
International Terrestrial Reference Frame

Input data

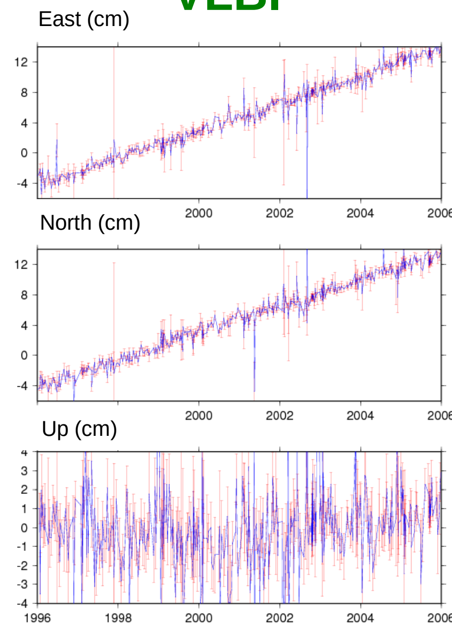
GPS



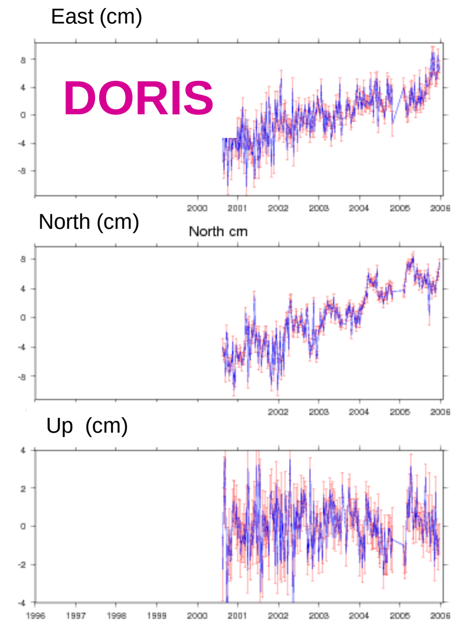
SLR

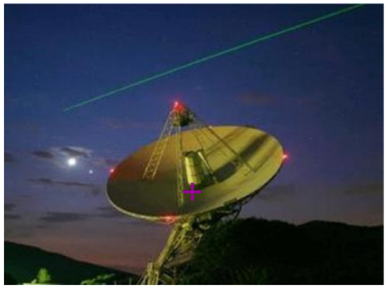


VLBI



DORIS

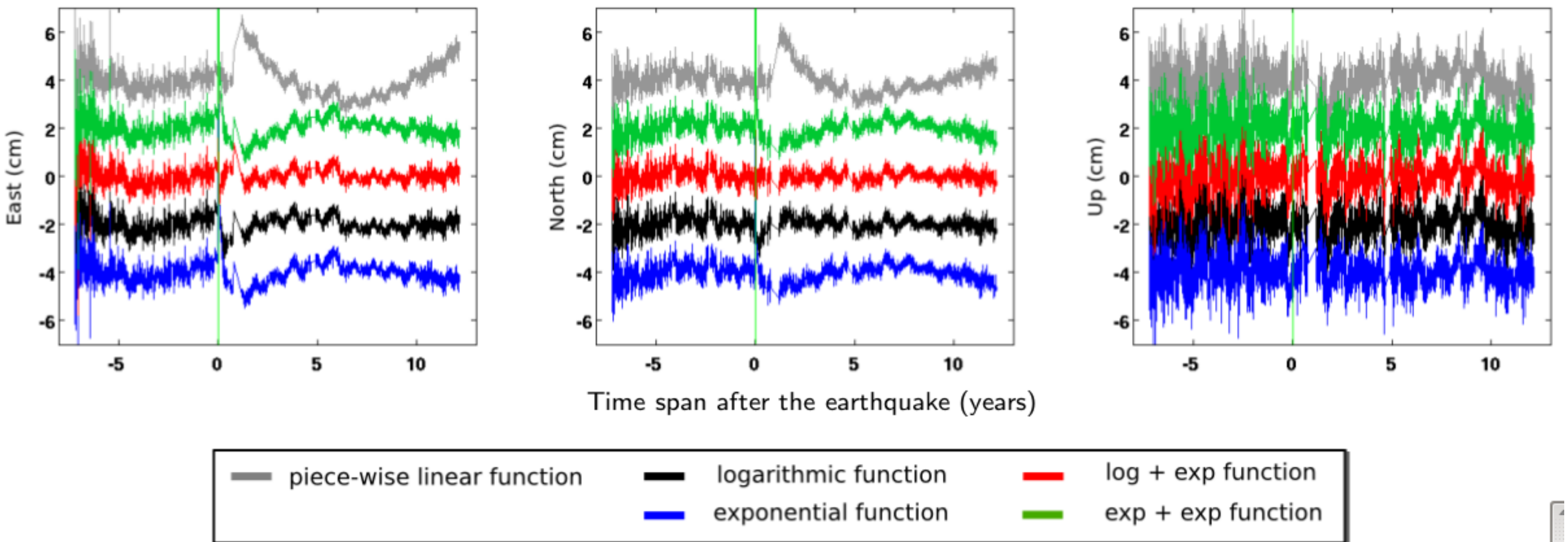




ITRF2008 computed from solutions processed by technique services: IGS, ILRS, IVS et IDS

Which parametric model?

Post-fit residuals for AREQ :

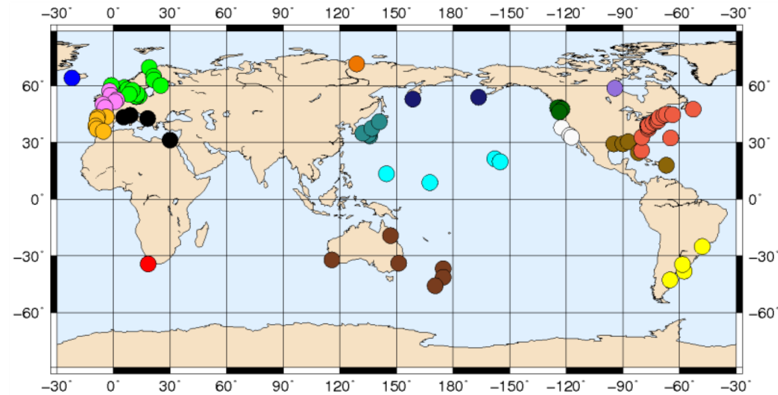


Lercier et al., 2013

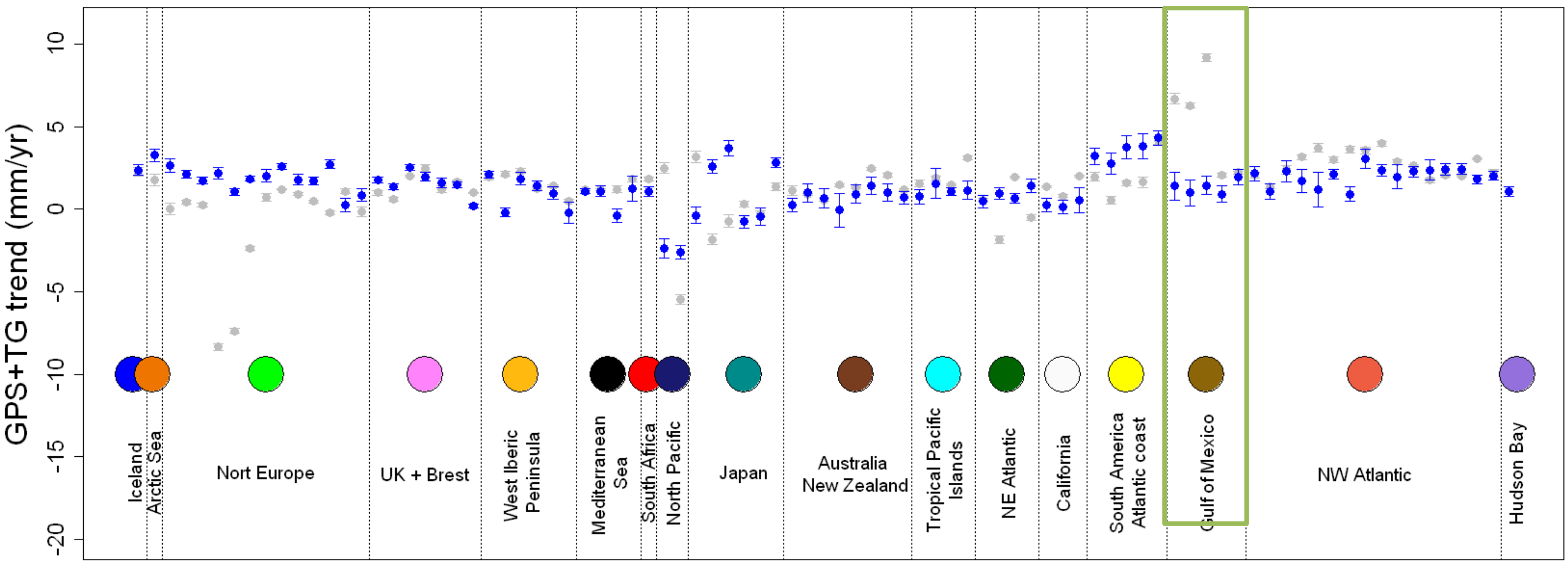
GPS height velocities and Tide Gaude trends

Gravelle et al., 2011; Santamaria et al., 2012

GPS+Tide gauge trends
RMS=1.2 mm/yr



Significant decrease in absolute sea level variability shows that GPS velocities are accurate



L. Métivier

Courtesy: University La Rochelle

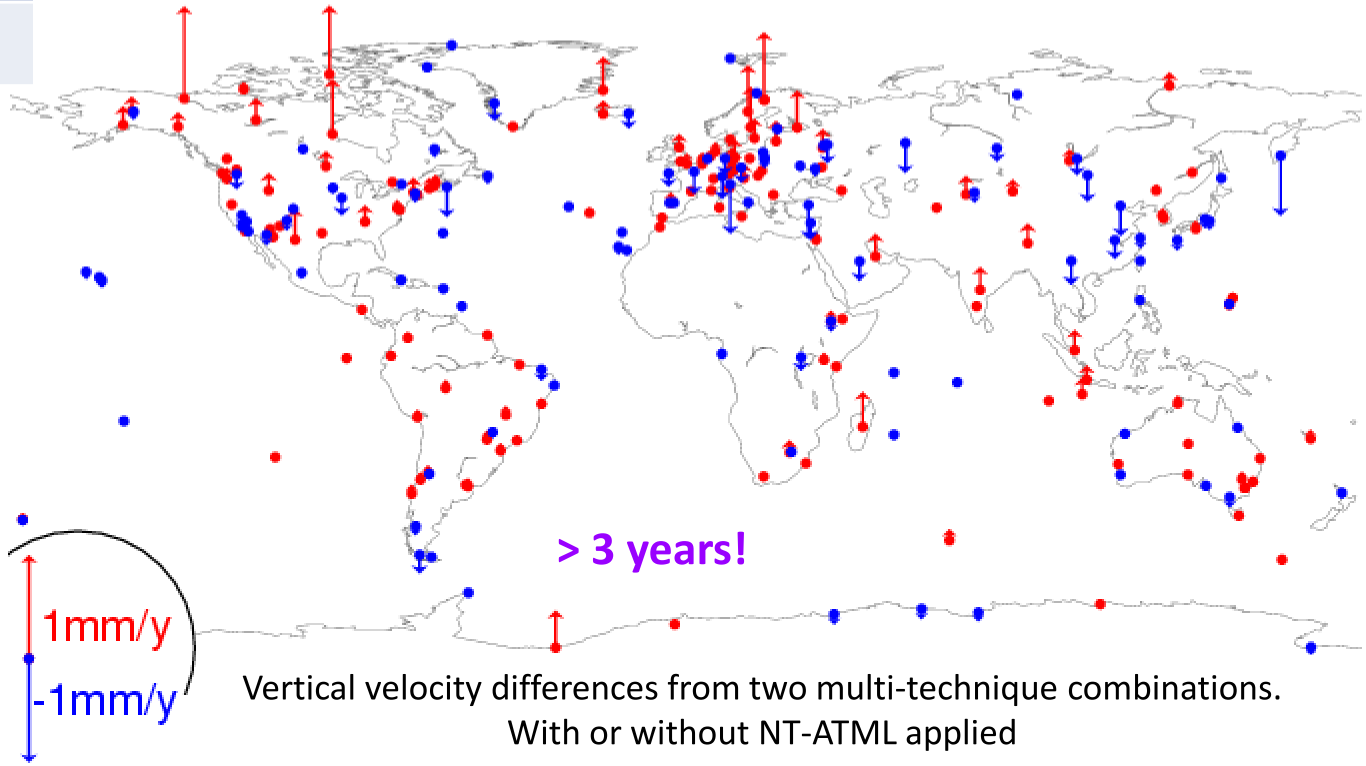
Non-tidal loading effects

Tech.	AC
SLR	GFZ
VLBI	GSFC
DORIS	GSFC
GPS	CODE

Result of the IERS campaign on non-tidal atmospheric loading corrections

- Selection of one solution per technique for combination tests
- Include local ties at co-location site
- ITRF2008 type combination (NB: 2006.0-2011.0)

Acknowledgments:
IERS campaign team (19 participants)
Collilieux et al., 2013



Vertical velocity differences from two multi-technique combinations.
With or without NT-ATML applied