Improving observations and interpretation of changes in Earth's shape: Present and future Contributions of the GGFC

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Goal: Answer the question: What can the GGFC do?

In order to reach to an answer, I will consider three questions related to positioning and displacements*:

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

Q2: What do we know (and thus can model) and what do we want to research?

Q3: Improvement: Where are key problems?

Conclusions: Potential GGFC products.

*) Displacement: difference between expected and computed position

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

Main operational products: reference frames ITRF & ICRF and the EOP.

I will focus on ITRF:

- increasingly important to have access to the ITRF anywhere, anytime with high accuracy and reliability;
- many application require 'fixed' coordinates: ability to relate coordinates measured at time t to reference epoch t_0;
- global approach to reference frame: contribution to sustainable development by providing equal access to resources;
- displacements with respect to ITRF are the difference between the expected ITRF position and the computed position.

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

Determination of ITRF:

- Currently described as polyhedron with regularized coordinates:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0)$$

- $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$: affected by station motion model, troposphere & ionosphere treatment, antenna model, analysis strategy, ...

Access to the ITRF:

- Through satellite orbits and clocks and EOP.
- These global parameters are affected by station motion model, ...
- Should be the same as used for the determination of the $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

Main task of the Services with respect to access to ITRF:

- Monitoring of ITRF (also EOP)

Experience shows: On the level of approximately 1 cm, the current ITRF definition (regularized coordinates) and determination not sufficient (i.e., displacements can be much larger than 1 cm).

Possible sources for uncertainties:

A: linear model (regularized coordinates) inadequate
B: station motion model inaccurate
C: other sources (troposphere, ionosphere, gravity field treatment, ...)

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

A: linear model (regularized coordinates) inadequate

- improvement: extension to non-linear models or time series;
- requirement: knowledge of non-linear velocity field;
- potential contribution of GGFC: models, time series analysis, velocity field.

B: station motion model inaccurate

- improve the station motion model (see Q2) both for determination of ITRF and for access to it;
- consider high-frequency and low-frequency part separately.

C: other sources (troposphere, ionosphere, gravity field treatment, ...)

- hopefully addressed by others, I will only address troposphere.

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

Models for describing reference point motion:

(0) Regularized coordinates:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0)$$

required: $\vec{V}_0^{(i)} = f(\vec{X})$

(1) Piecewise linear:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0) + \sum_{i=1}^{N^{(i)}} A_j^{(i)} H(t - t_j)$$

required: $A_j = g_j(\vec{X})$: earthquake displacement fields (GGFC?)

(2) Piecewise linear and harmonic:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0) + \sum_{i=1}^{N} A_j^{(i)} H(t - t_j) + \sum_{k=1}^{K} (\alpha_k^{(i)} \sin(\omega_k t) + \beta_k^{(i)} \cos(\omega_k t))$$

required: $\alpha_k,\ \beta_k = h(\vec{X})$: determined from observations and/or models (GGFC?)

(3) Geophysical models:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0) + \sum_{i=1}^{M} g_i(t, \vec{X}^{(i)})$$

required: g_i; $i = 1, M$: determined from observations and/or models (GGFC?)

(4) Observed polyhedron:

$$\vec{X}^{(i)}(t) = \vec{O}^{(i)}(t)$$

required:

(a) model for interpolation of $\vec{O}^{(i)}$ (GGFC?)

(b) approximation of $\vec{O}^{(i)}$ to improve station motion model for analysis (GGFC?)

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

B: station motion model inaccurate

- improve the station motion model (see Q2) both for determination of ITRF and for access to it;
- consider high-frequency and low-frequency part separately.

High-frequency part:

- "significant"*) variation during the analysis interval (for GNSS typically 1 day);
- needs to be taken into account during the analyses;
- necessary high-frequency station motion model from GGFC?

Low-frequency part:

- "nearly constant"*) during analysis interval;
- should be considered in aligning solution to ITRF;
- could be considered by using an extended non-linear model for the reference coordinates;
- necessary low-frequency station motion model from GGFC?

*) depends on target accuracy.

Q1: What are the operational geodetic products and what is needed to make them satisfy users' needs?

C: other sources (troposphere, ionosphere, gravity field treatment, ...)

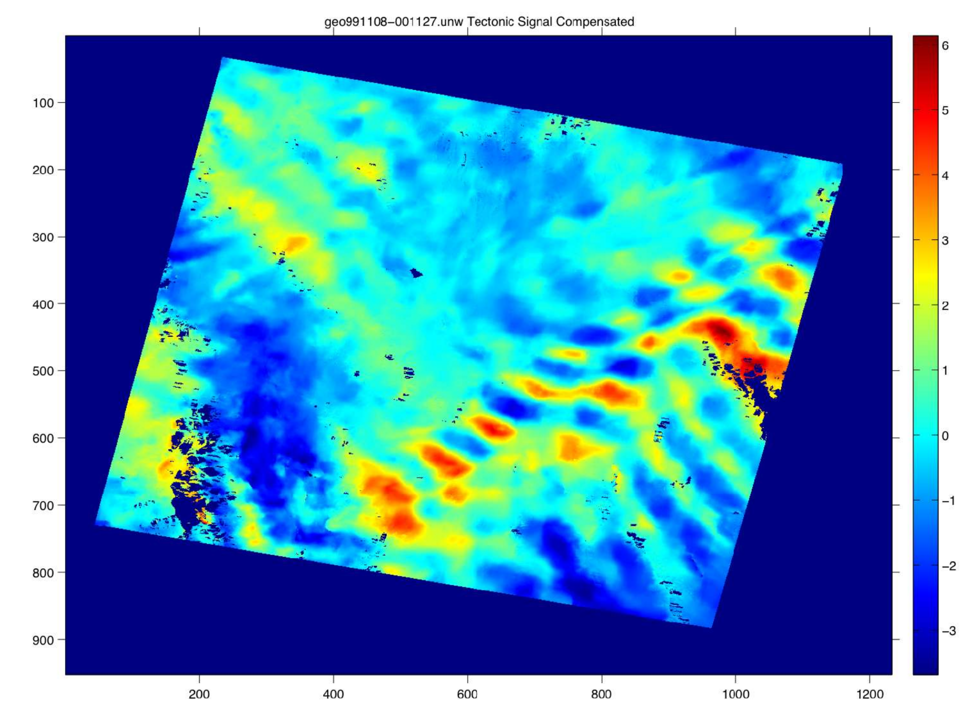
- hopefully addressed by others, I will only address troposphere.

Just one example: Determination of displacements with InSAR ...

Frame 2871: Yucca Mountain

Two example interferograms

991108-001127



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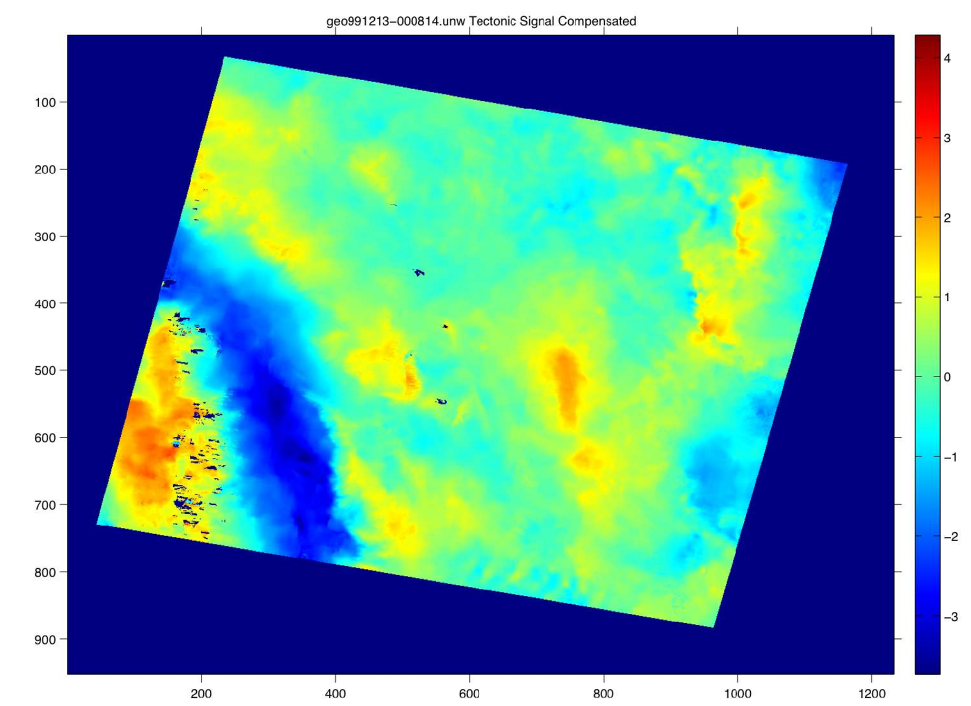


Hammond et al., 2006

Q2: What do we know and what do we want to research?

'Observed' displacements are the difference between expected and computed positions: How well do we know displacements?

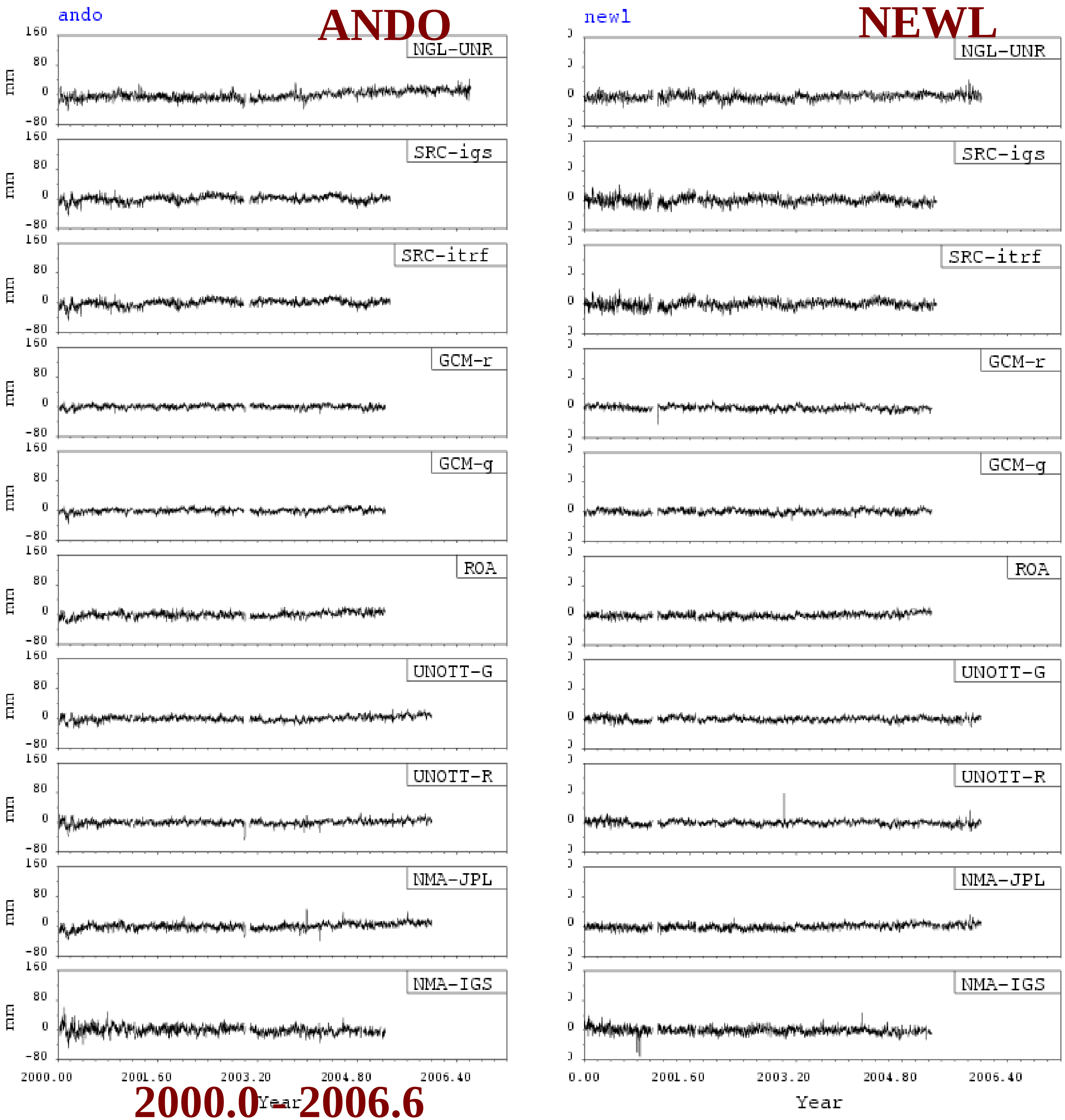
Modeled/derived phenomena include:

- static offsets (earthquakes)
- strong motion
- Earth tides
- ocean tidal loading
- surface loading
  * atmosphere
  * terrestrial hydrosphere
  * non-tidal ocean
  * grounded ice
- postglacial rebound
- tectonic secular motion

All phenomena affect Earth's shape, gravity field and rotation.

Some phenomena are quantitatively well known, others still in research state.

Q2: What do we know and what do we want to research?



Computed displacements

Example: ESEAS GPS Analysis Comparison

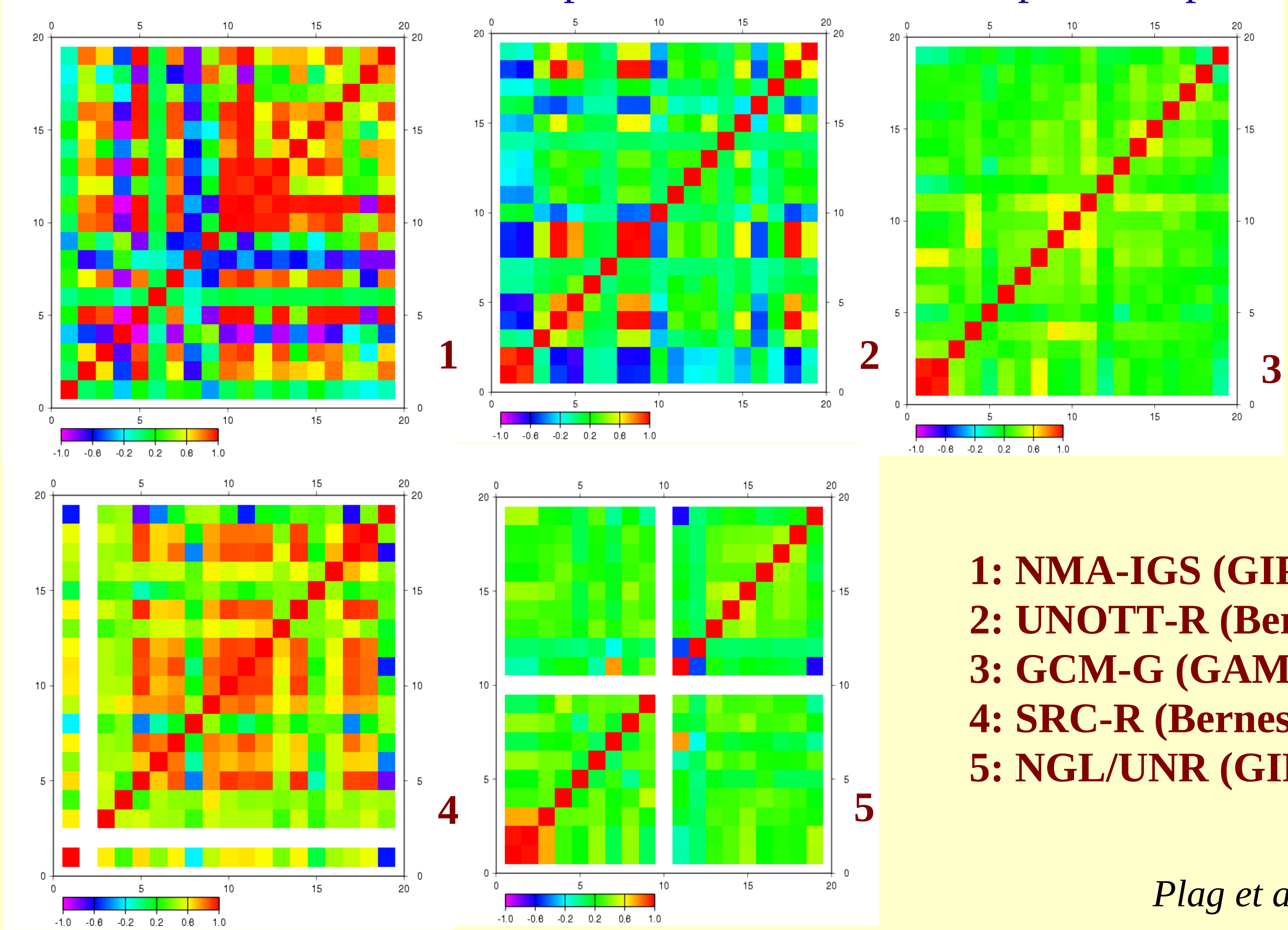
Analysis statistics:

- 7 groups
- 3 program packages
- 3 analysis strategies
- 2 orbits/clocks
- 5 alignments to ITRF2000

Plag et al., 2006

Q2: What do we know and what do we want to research?

Spatial correlation of computed displacements



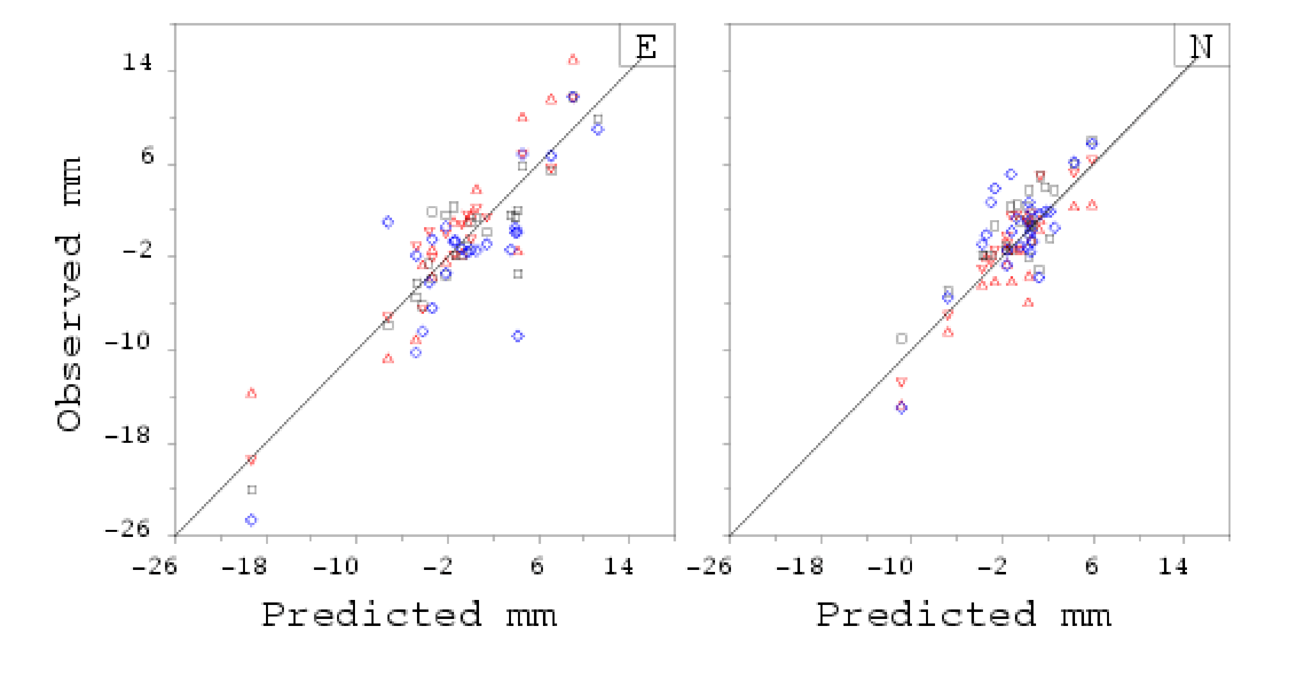
1: NMA-IGS (GIPSY/IGS)
2: UNOTT-R (Bernese)
3: GCM-G (GAMIT)
4: SRC-R (Bernese)
5: NGL/UNR (GIPSY/JPL)

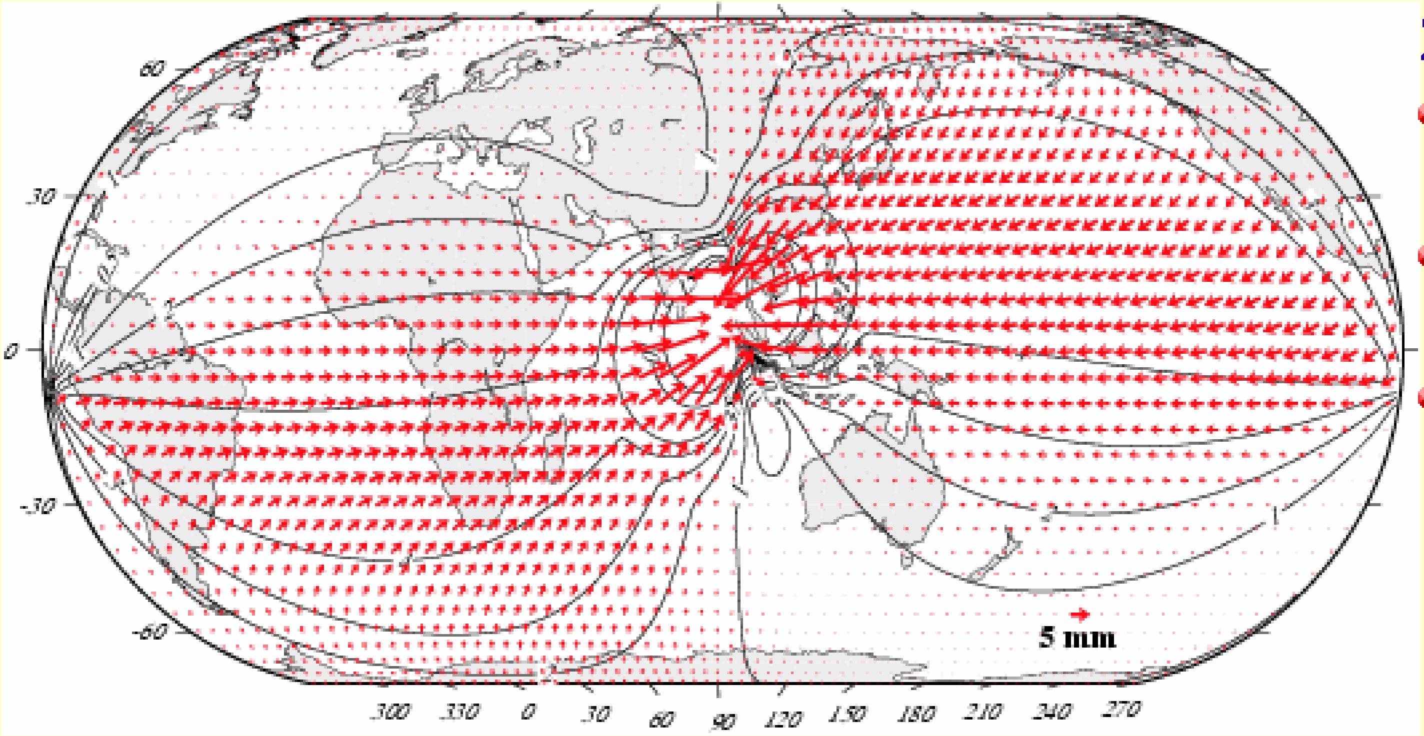
Plag et al., 2006

Q2: What do we know and what do we want to research?

Derived Phenomena:

- static offsets (earthquakes)





2004 Sumatra earthquake

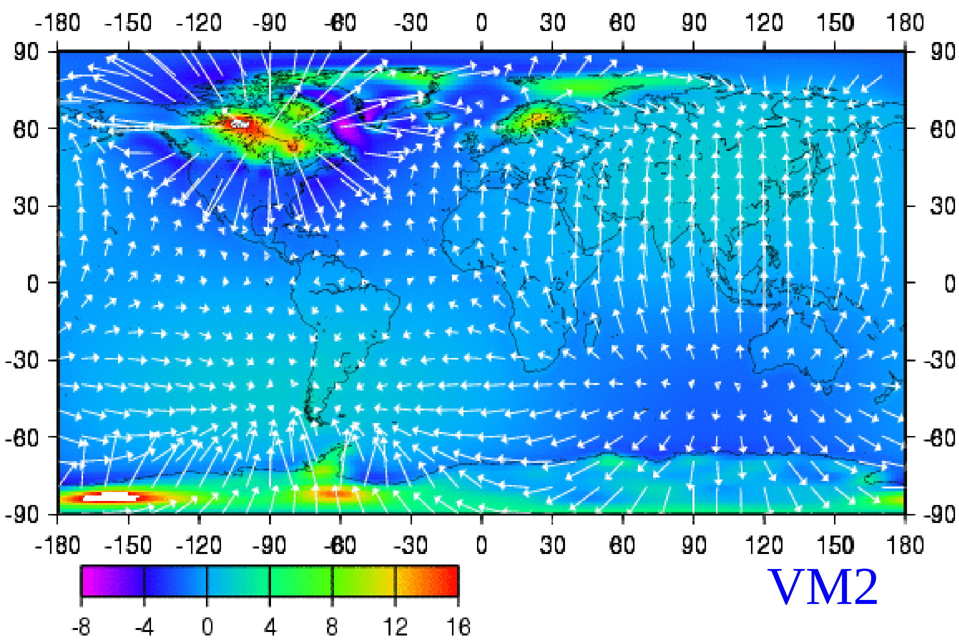
- Four different analysis of static offsets from GPS
- Different model predictions
- Task for GGFC?

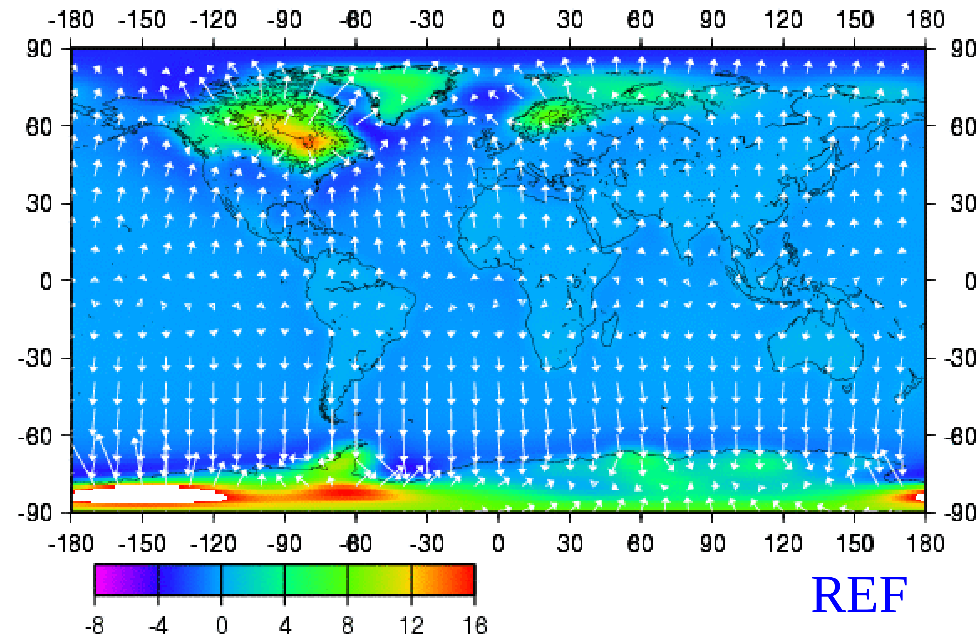
Plag et al., 2006

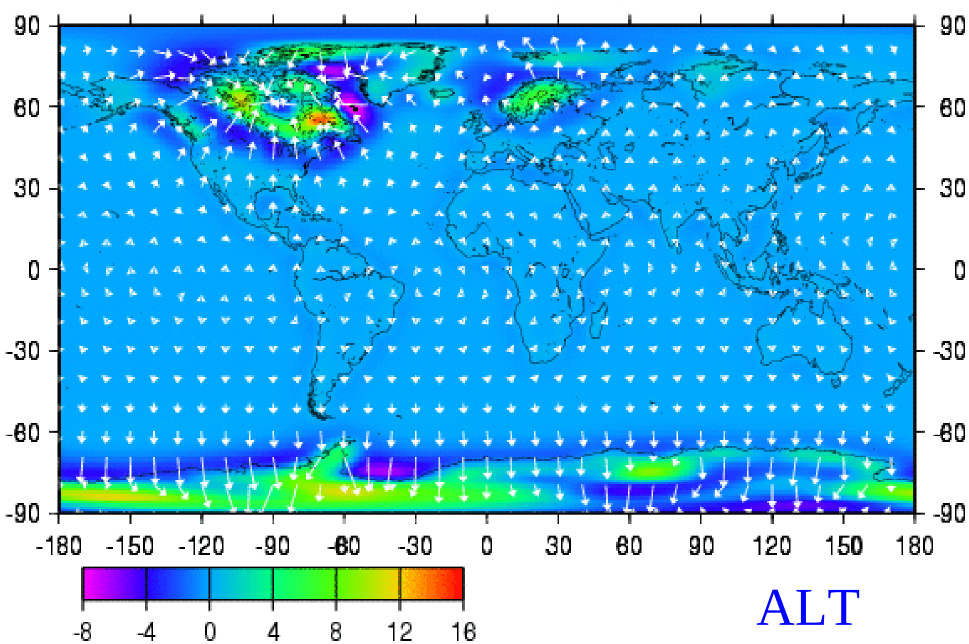
Q2: What do we know and what do we want to research?

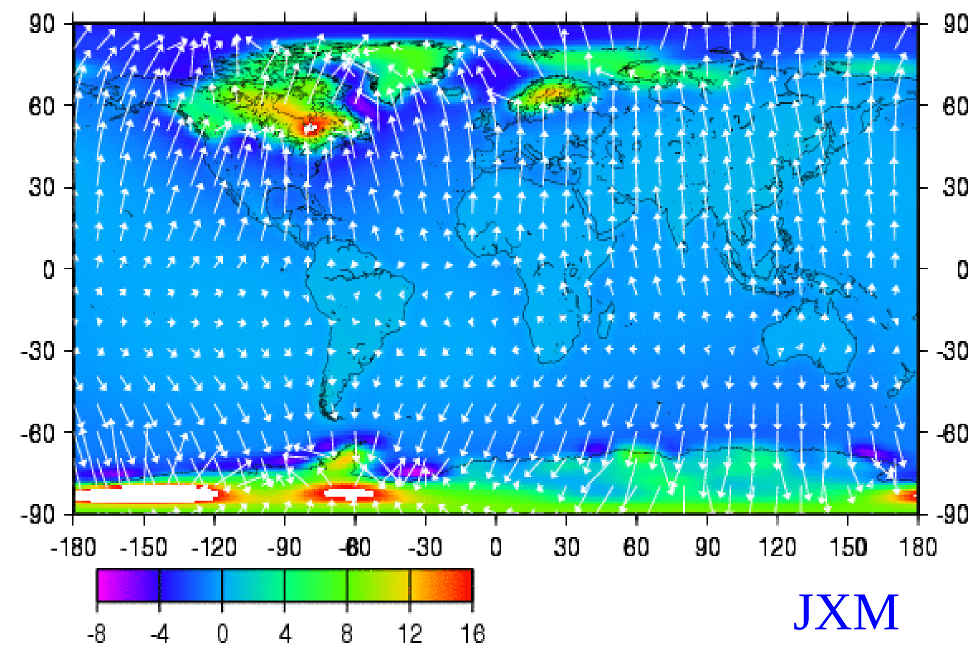
Modeled phenomena:

- postglacial rebound







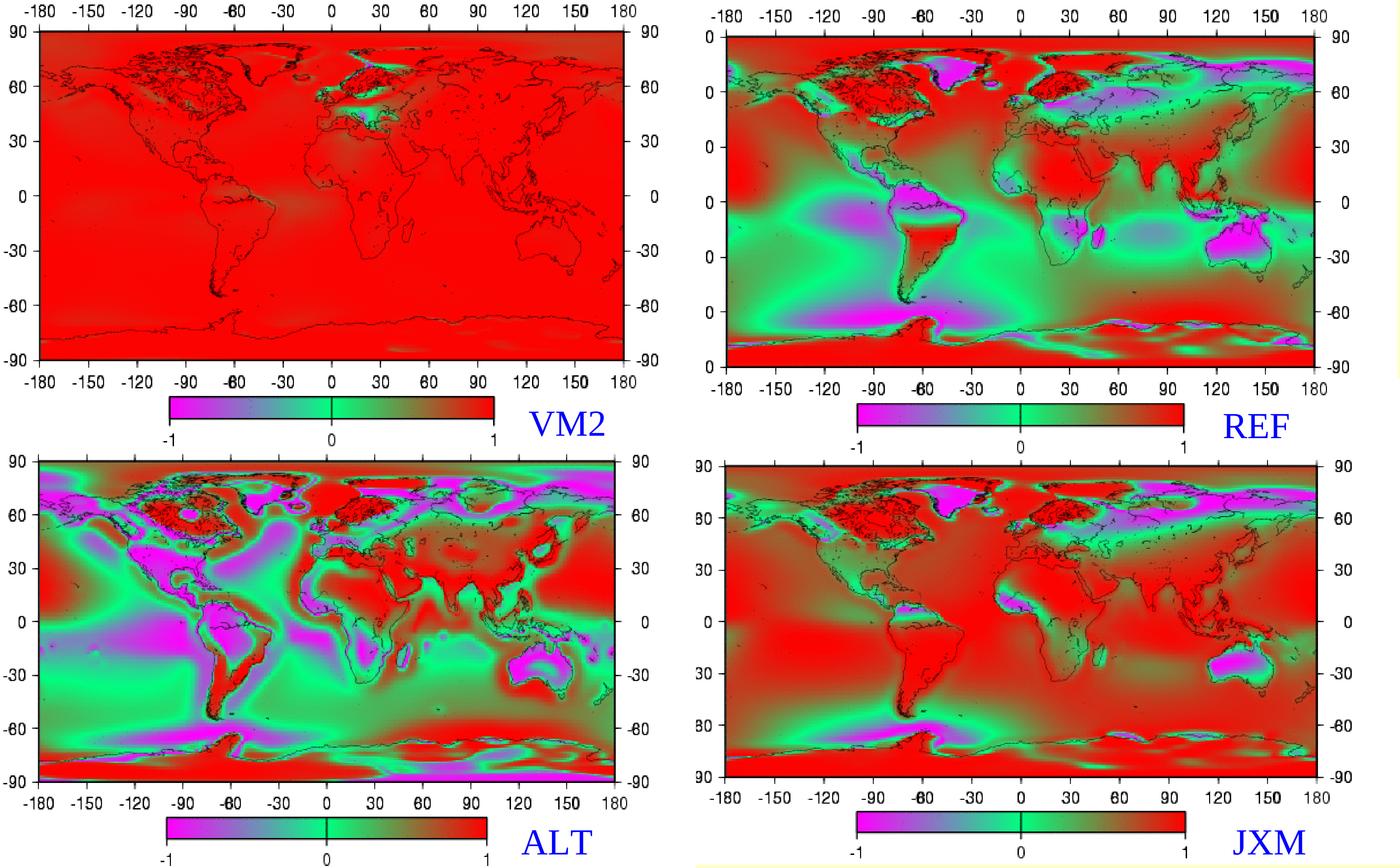


Q2: What do we know and what do we want to research?

Modeled phenomena:

- postglacial rebound

Normalized Scalar Product of 3-D Displacements for VM4 and the Other Models

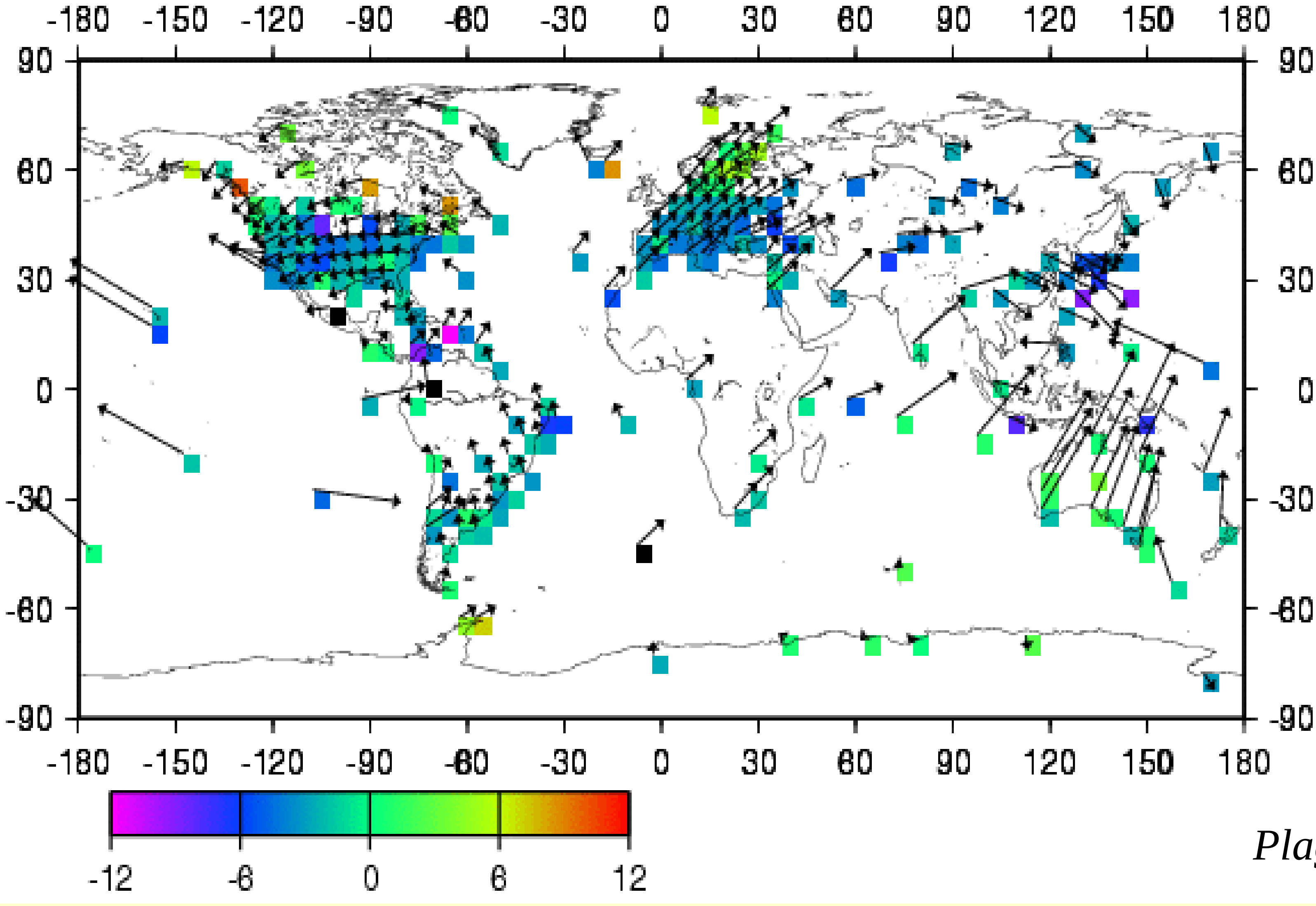


Q2: What do we know and what do we want to research?

Derived phenomena:

- tectonic secular motion

- 5 X 5 degrees
- Total of 222 grids elements
- 78 elements with multiple values

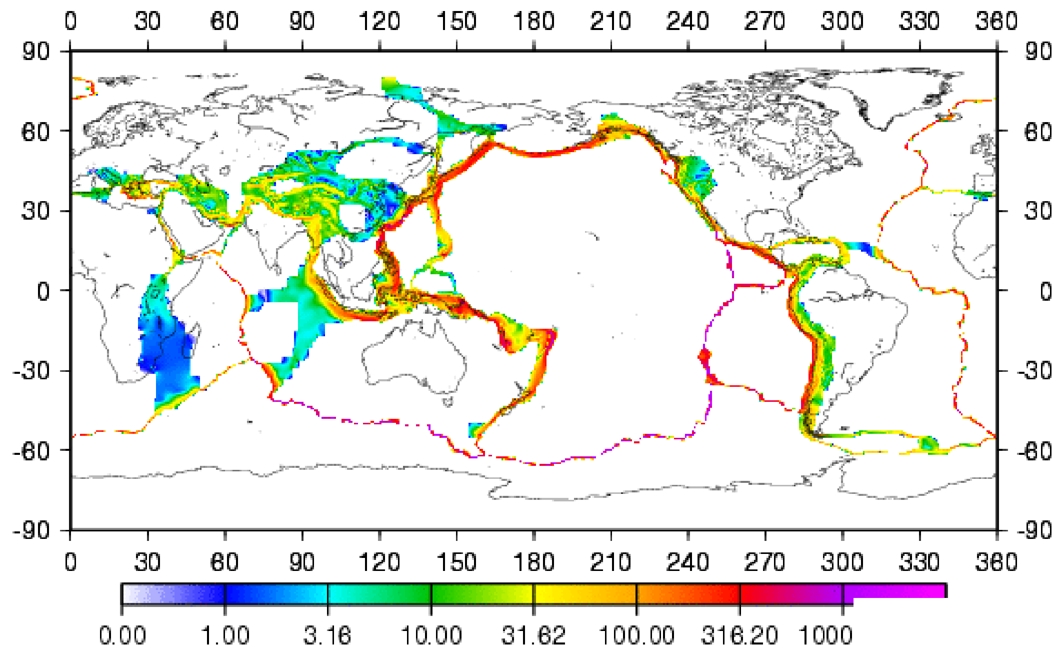


Plag et al., 2006

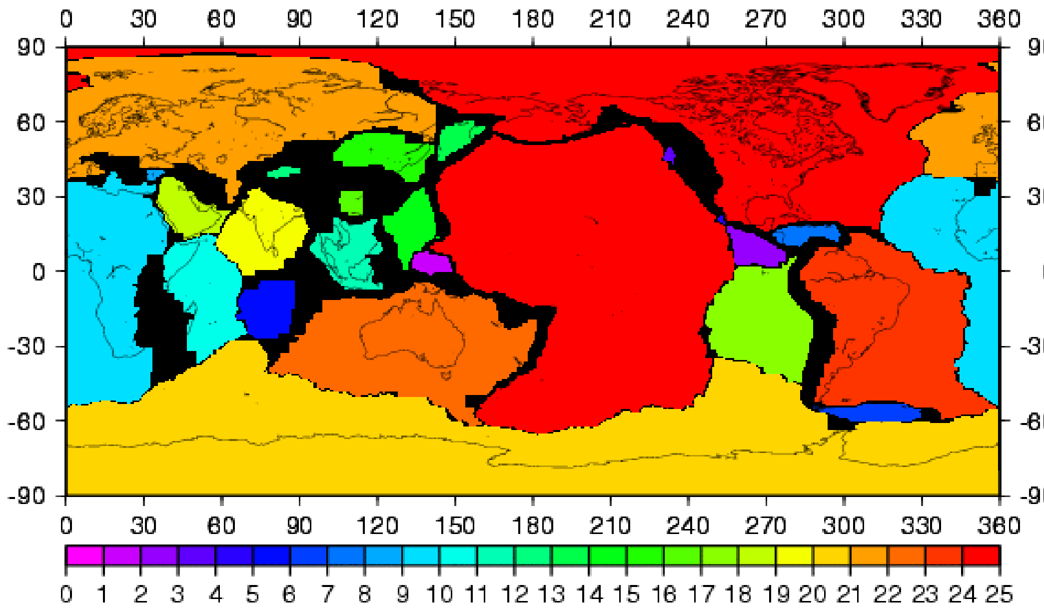
Q2: What do we know and what do we want to research?

Derived phenomena:

- tectonic secular motion



- Strain model: Kreemer et al., 2003
- Plate model: 25 Plates
- Deformation zone not allocated



Q2: What do we know and what do we want to research?

Summary:

- Computed displacements (*difference between expectation and results*):
  - Considerable inter-analysis differences at daily resolution.
  - Considerable inter-analysis differences at seasonal and secular time scales
- Modeled/derived phenomena:
  - static offsets (earthquakes): observations constrain models
  - strong motion, free oscillation, tsunami loading: short temporal scales
  - Earth tides: can be modeled with high accuracy
  - ocean tidal loading: ocean tide model is main uncertainty
  - polar motion: can be modeled
  - surface loading
    * atmosphere: pressure anomaly at Earth's surface main uncertainty
    * terrestrial hydrosphere: hydrological anomaly main uncertainty
    * non-tidal ocean: ocean bottom pressure anomaly main uncertainty
    * grounded ice: mass balance of ice sheets and glaciers uncertain
    * postglacial rebound: model predictions show large discrepancies
  - tectonic secular motion: insufficient spatial coverage with observations
- All phenomena affect shape, gravity field and rotation

Q3: Improvements: Where are key problems?

Ocean tidal loading:

- no standard ocean tide model for operational applications;
- no 'easy' access (fully automated) to loading coefficients; grid-based routines;

Atmosphere/Pressure field (*more during the SBL presentation*):

- what pressure field to use?
- what spatial and temporal resolution is necessary?
- sea surface pressure field has low quality;
- model topography pressure field has low resolution;
- inverted barometer is an insufficient approximation.

Terrestrial hydosphere:

- lack of operational model with low latency.

Non-tidal ocean loading:

- lack of operational model with low latency (including response to air pressure and wind).

Ice loads:

- no operational model;
- no model at inter-annual to sub-seasonal times scales.

Surface loads:

- no comprehensive, modular model; common problem: reference surfaces.

Potential GGFC Products

Station motion model:

- Offsets: earthquake-induced displacement fields
- High-frequency part:
  - ocean tidal loading:
    - improved access through grid-based routines
    - one standard ocean model for operational applications
  - surface loads:
    - atmospheric pressure loading (also for gravity)
    - non-tidal ocean loading (only in special cases?)
- Low-frequency part:
  - surface velocity field:
    - geophysical models for loading-induced displacements (including PGR)
    - empirical surface velocity field

Forcing:

- ocean tidal model (standard for operational applications)
- comprehensive, modular surface mass transport model (agile, see SBL presentation)

Others:

- Tropospheric water content (for InSAR), high temporal and spatial res.
- All predictions also for gravity field and PM/LOD