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SATELLITE GEODESY FOR TSUNAMIGENIC EARTHQUAKE MONITORING

STATUS AND DEVELOPMENT OF RUSSIAN TSUNAMI WARNING SYSTEM

Seismic-based tsunami early warning systems: reasons to upgrade

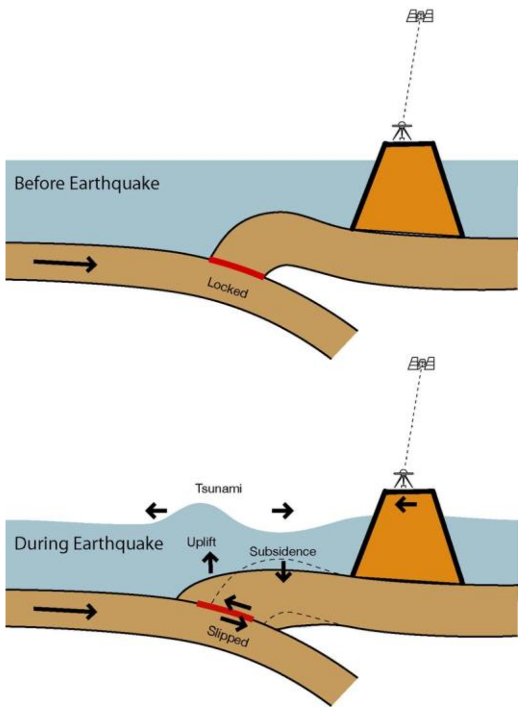
Russian tsunami warning system based on seismological observations at the dedicated stations located at the Far East of Russia have shown its effectiveness for the years of its implementation. For example, when the Great Tohoku-oki earthquake occurred on March 11, 2011, the alarm was issued in a few minutes. The system based on detecting undersea earthquake with the magnitude exceeding specific threshold, designated for each particular coastal zone is robust, but it does not accounts for the depth of the event and its displacement characteristics along the rupture zone (source mechanism), that is so essential to describing tsunami risk for the length of the coastal zone. For example, for the Sea of Okhotsk event, May 24, 2013, 611 km depth, the false alarm was issued and later cancelled.

Analysis of the devastating earthquake on December 26, 2004 have shown that timely moment magnitude estimates of mega-thrust earthquakes is complicated by the long rupture times, instrument saturation, and limitations on surface wave analysis above Mw8.

An attempt to improve the seismological inversion for the source characteristics was made by using the Earth normal mode analysis, also called W-phase analysis [Stein and Okal, 2005]. The W-phase source inversion algorithm was initially developed to provide rapid characterization of the seismic source for tsunami warning purposes and is a reliable and straightforward method to resolve the first order attributes of large earthquakes. Unfortunately the technique requires at least 20 minutes for the acquisition of the long wavelength teleseismic data. But the near field forecast of a tsunami is effective when it is broadcasted within 5 to 10 minutes of initial rupture.

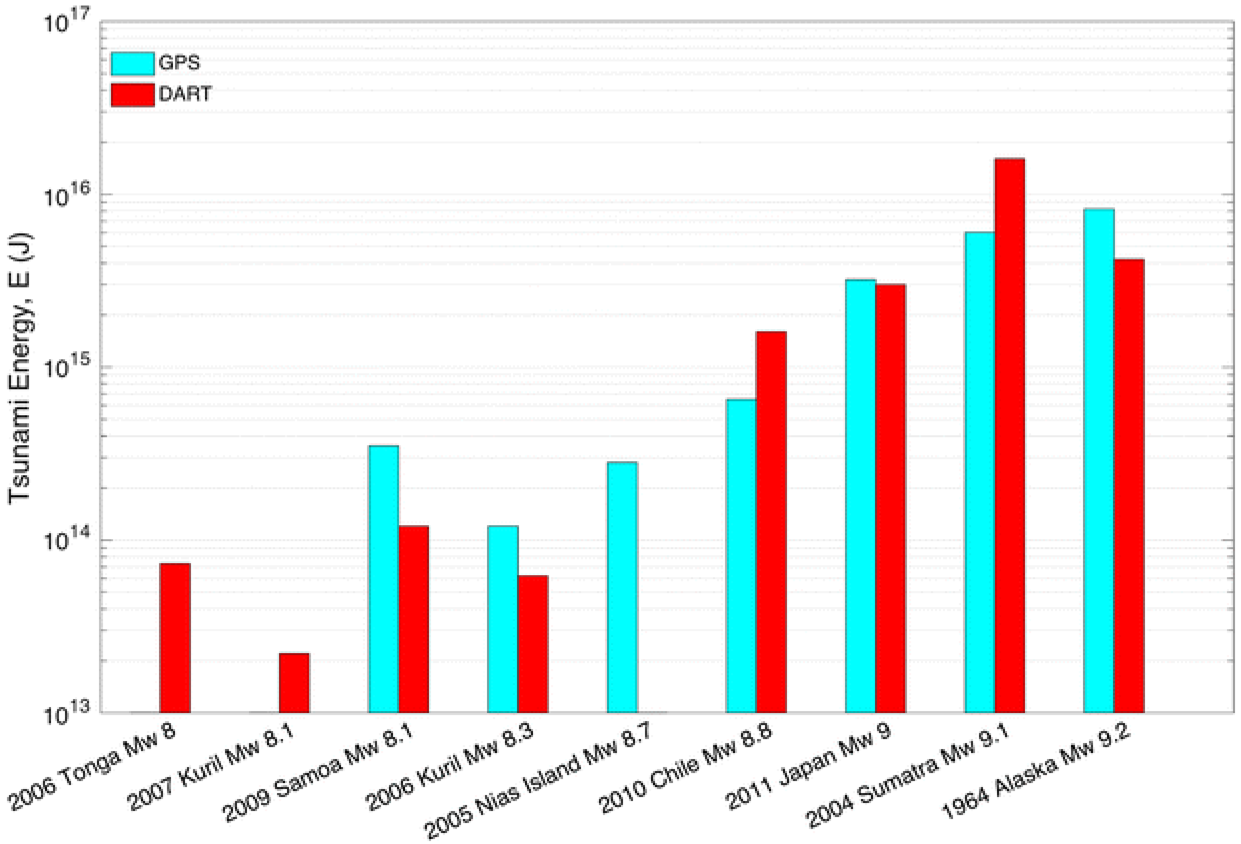
Numerus studies since December 26, 2004 demonstrated ability of the GNSS network to provide seismic source parameters with acceptable resolution, as quick as 3-5 min.

Blewitt, G., C. Kreemer, W. C. Hammond, H.-P. Plag, S. Stein, and E. Okal, Rapid determination of earthquake magnitude using GPS for tsunami warning systems, Geophys. Res. Lett., 33, L11309, doi:10.1029/ 2006GL026145, 2006.
Sobolev, S.V., A. Y. Babeyko, R. Wang, A. Hoechner, R. Galas, M. Rothacher, D. V. Sein, J. Schroter, J. Lauterjung,C. Subarya, Tsunami early warning using GPS Shield arrays, JGR, V. 112, B08415, doi:10.1029/2006JB004640, 2007.
Song, Y. Tony, Detecting tsunami genesis and scales directly from coastal GPS stations, Geophys. Res. Lett., 34, L19602, doi:10.1029/2007GL031681, 2007.



Recent studies demonstrated good agreement between GNSS-based and DART-based estimates.

Titov, V., Y. Tony Song, L. Tang, E. N. Bernard. Y. Bar-Sever, Y. Wei, Consistent Estimates of Tsunami Energy Show Promise for Improved Early Warning, Pure Appl. Geophys., 173, P. 3863–3880, doi:10.1007/s00024-016-1312-1, 2016.



Seismic-based tsunami early warning systems: reasons to upgrade

In accordance with 2 previous IOC reports:

1) Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS)
Twenty-sixth Session
Honolulu, United States of America, 22–24 April 2015
Intergovernmental Oceanographic Commission
Reports of Governing and Major Subsidiary Bodies (Annex II):

- **Noting** the importance of clarifying the earthquake and tsunami potential in the Pacific Ocean region, **encourages** Member States to acquire and share new datasets such as GNSS, seismic and other geological data;

2) Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS)
Twenty-seventh Session
Tahiti, French Polynesia, 28–31 March 2017
Intergovernmental Oceanographic Commission
Reports of Governing and Major Subsidiary Bodies (Annex II):

- **Noting** the importance of clarifying the earthquake characteristics and tsunami potential in the Pacific Ocean region, **encourages** Member States to acquire and share new datasets such as GNSS, seismic and other geological data;

validation of GNSS augmentation for tsunami warning systems was performed.

To estimate tsunamis source energy both potential and kinetic components of the seafloor displacements are needed: vertical uplift and continental slope horizontal motion.
The existing approach, proposed by T.Song [2008] to detect the seafloor displacements along the cross-shelf section is based on an empirical profile relating these displacements with the observable GNSS displacements:

$$\Delta E(r) = \Delta E_j \exp\left(r_j^2 - r^2\right) + \Delta e_{j2}$$

$$\Delta N(r) = \Delta N_j \exp\left(r_j^2 - r^2\right) + \Delta n_{j2}$$

$$\Delta U(r) = \alpha\sqrt{\Delta E(0)^2 + \Delta N(0)^2}\left\{\exp(-ar^2) - \sqrt{\frac{\pi}{4a}}\exp(-r)\right\},\ \ r = d/W$$

$$\Delta\eta \approx \Delta h = \Delta U + \Delta E\, h_x + \Delta N\, h_y$$

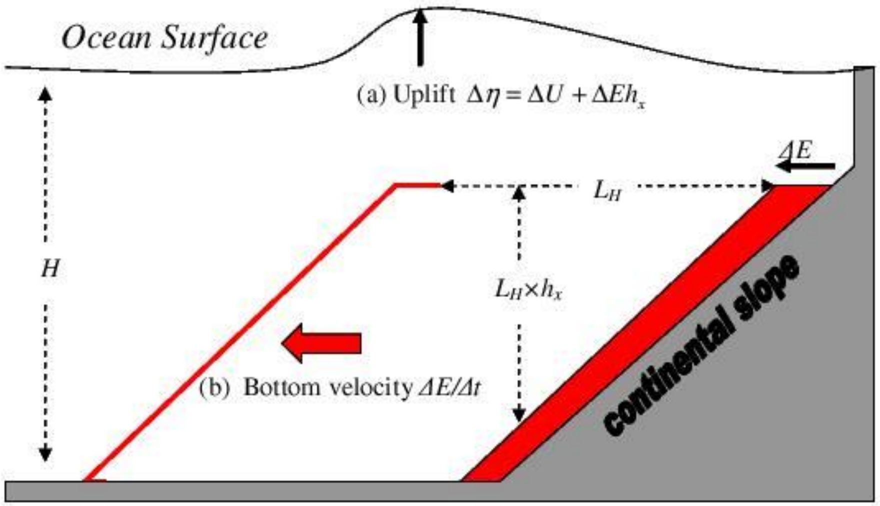
Potential energy: $\Delta PE = g\varrho \frac{\Delta\eta^2}{2}\Delta x \Delta y$

$$\Delta u_b(z) = \begin{cases} \Delta E/\Delta t, & -h \le z \le -R_x = h - \min\{h, L|h_x|\} \\ 0, & \text{otherwise} \end{cases}$$

$$\Delta v_b(z) = \begin{cases} \Delta N/\Delta t, & -h \le z \le -R_x = h - \min\{h, L|h_x|\} \\ 0, & \text{otherwise} \end{cases}$$

Kinetic energy: $\Delta KE = \varrho\frac{1}{2}\left(\Delta u_b^2 + \Delta v_b^2\right)\Delta z \Delta x \Delta y$

Total energy: $E_{\mathrm{T}} = \sum_{i,j} \Delta PE + \sum_{i,j,k} \Delta KE$

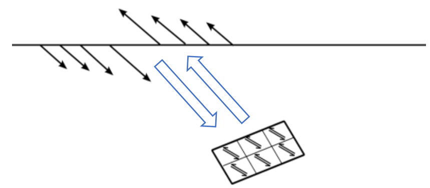


Y. Tony Song, L.-L. Fu, Victor Zlotnicki, Chen Ji, Vala Hjorleifsdottir, C.K. Shum, Yuchan Yi. The role of horizontal impulses of the faulting continental slope in generating the 26 December 2004 tsunami. Ocean Modelling, V. 20, Iss. 4, 2008, Pages 362-379, doi:10.1016/j.ocemod.2007.10.007

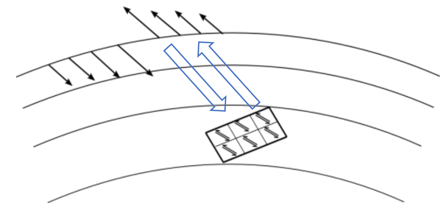
The empirical approach for seafloor displacements detection can be improved by physical modelling on the basis of dislocation theory in 2 steps:

1) resolving source mechanism from the land surface observable motion,
2) calculating uplift and horizontal

motion from the resolved slip distribution.



Yo. Okada. Surface deformation due to shear and tensile faults in a half-space // Bulletin of the Seismological Society of America, 1985, Vol. 75, No. 4, pp. 1135-1154.



F.F. Pollitz. Coseismic deformation from earthquake faulting on a layered spherical earth // Geophys J. Int., 1996, Vol. 125, N.1, pp. 1-14

Observation model:

$$\vec{u}(\vec{r}) = \iint_S G(\vec{r},\vec{r}_s)\bar{U}(\vec{r}_s)dS$$

$$S = \bigcup_j S_j \qquad S_p \cap S_q = \emptyset\Big|_{p\neq q}$$

$$\bar{U}(\vec{r}_s) = \bar{U}_j\Big|_{\vec{r}_s\in S_j} \qquad \bar{U}_j = k_{2j-1}\vec{e}_{2j-1} + k_{2j}\vec{e}_{2j}$$

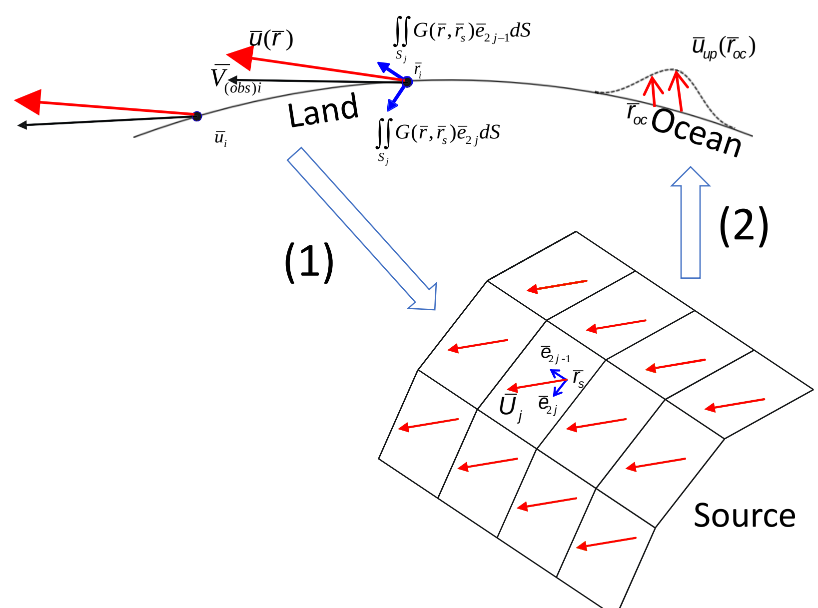
$$\vec{u}(\vec{r}) = \sum_j \left[k_{2j-1}\iint_{S_j} G(\vec{r},\vec{r}_s)\vec{e}_{2j-1}dS + k_{2j}\iint_{S_j} G(\vec{r},\vec{r}_s)\vec{e}_{2j}dS\right]$$

Observation equations:

$$\sum_j \left[k_{2j-1}\iint_{S_j} G(\vec{r}_i,\vec{r}_s)\vec{e}_{2j-1}dS + k_{2j}\iint_{S_j} G(\vec{r}_i,\vec{r}_s)\vec{e}_{2j}dS\right] = \bar{V}_{(obs)i}$$

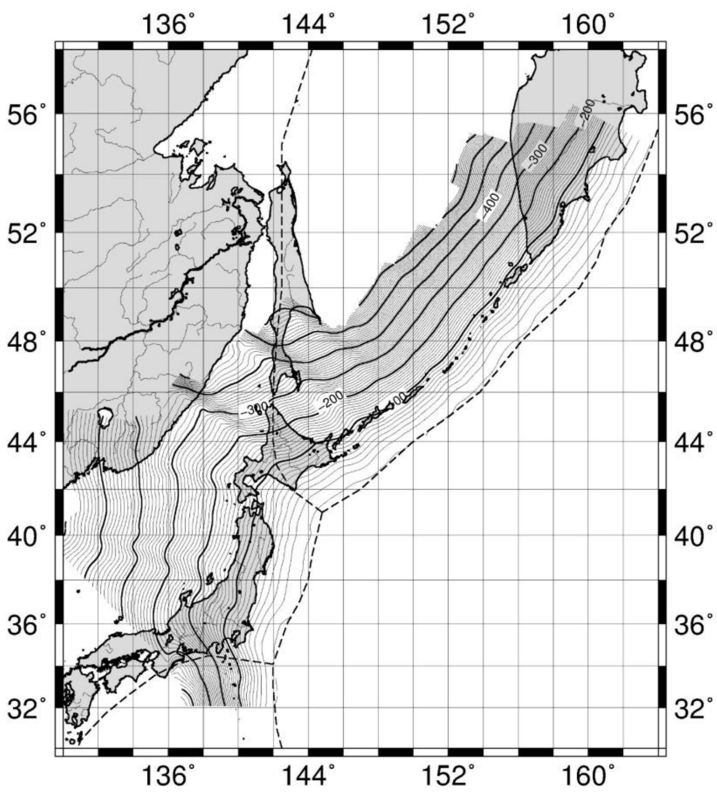
$$\bar{k}: \quad \min_{k}\left\{\sum_i \left|\sum_j M_{ij}k_j - \bar{V}_{(obs)i}\right|^2 + \lambda\sum_j |k_j|^2\right\}$$

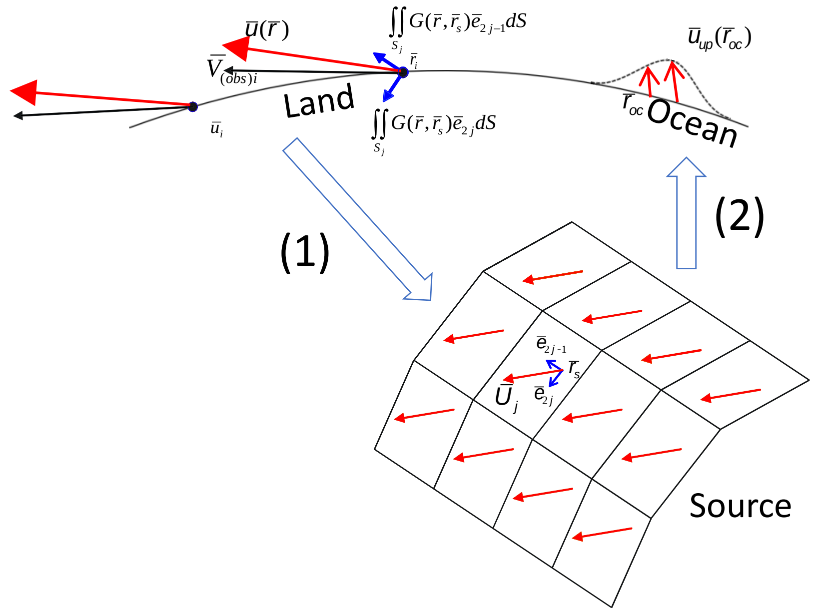
$$\lambda: \quad \frac{1}{n}\sum_i \frac{\left|\sum_j M_{ij}k_j - d_i\right|^2}{\sigma_i^2} \approx 1$$



$$\vec{u}_{up}(\vec{r}_{oc}) = \sum_j \left[k_{2j-1}\iint_{S_j} G(\vec{r}_{oc},\vec{r}_s)\vec{e}_{2j-1}dS + k_{2j}\iint_{S_j} G(\vec{r}_{oc},\vec{r}_s)\vec{e}_{2j}dS\right]$$

Given the subduction zone profile is known, all the time-consuming calculations may be fulfilled beforehand, so the media response functions relating the source slip model with the surface motion are ready for use in timely manner.



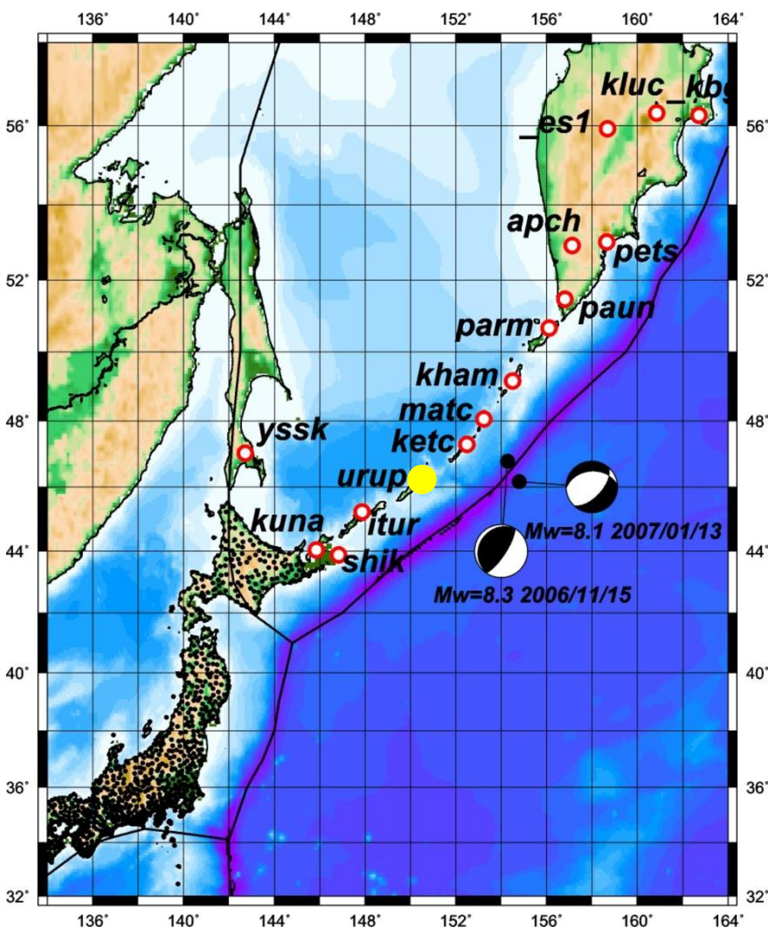


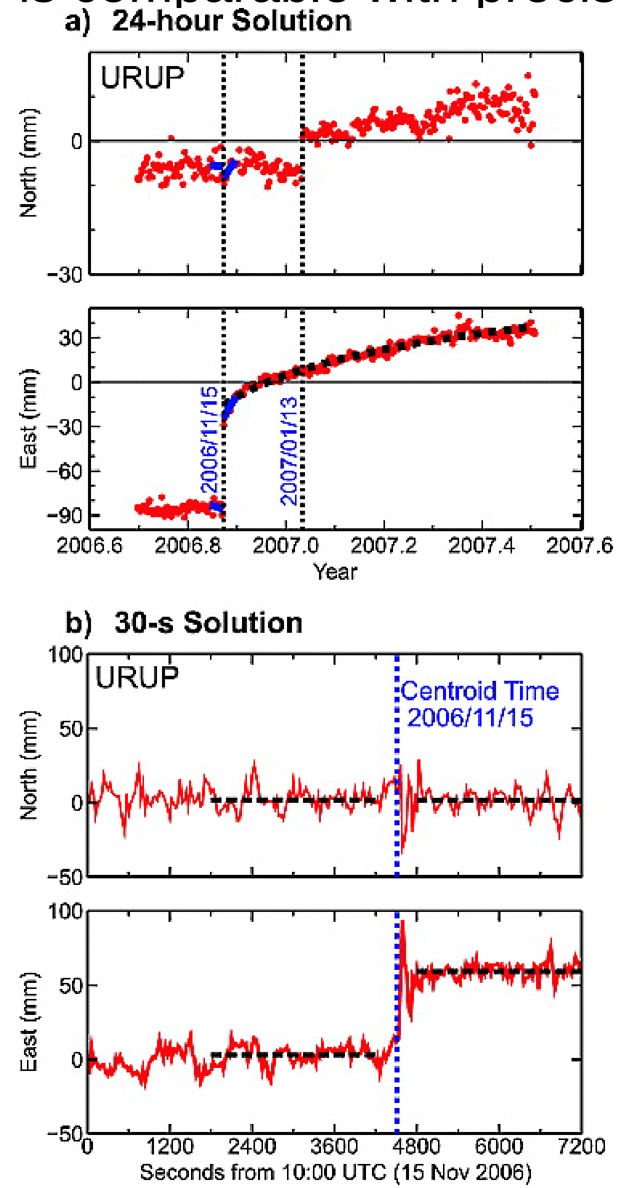
Key issues:

1) accuracy
2) rapidness

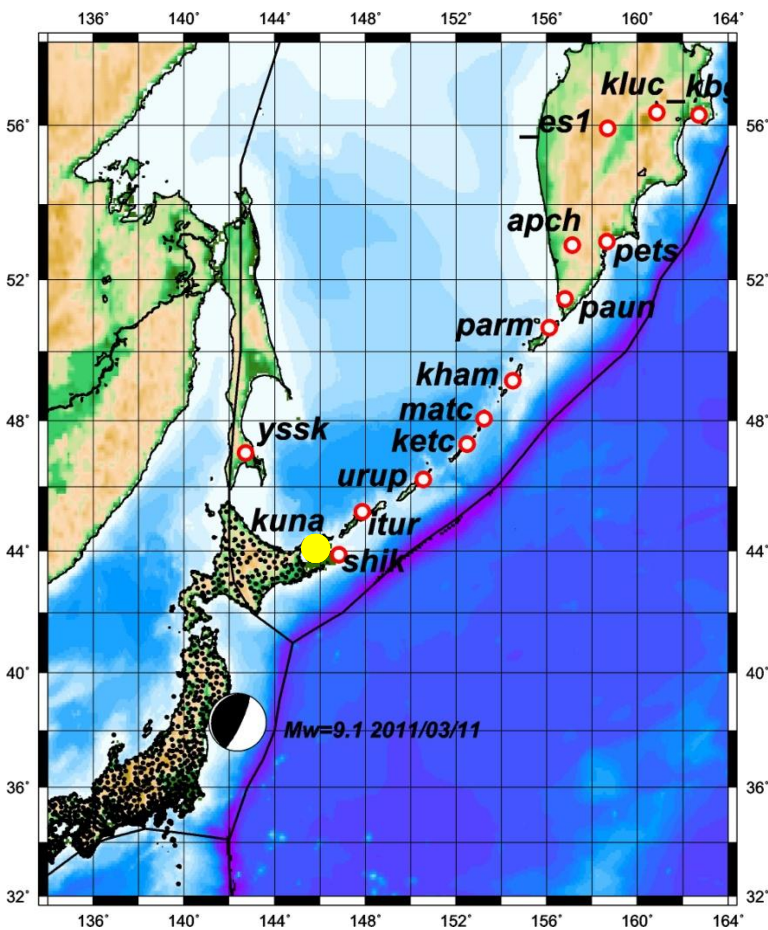
Real-time estimates of coseismic jumps are available in minutes in the vicinity of the seismic rupture (at the distance comparable with the rupture size).

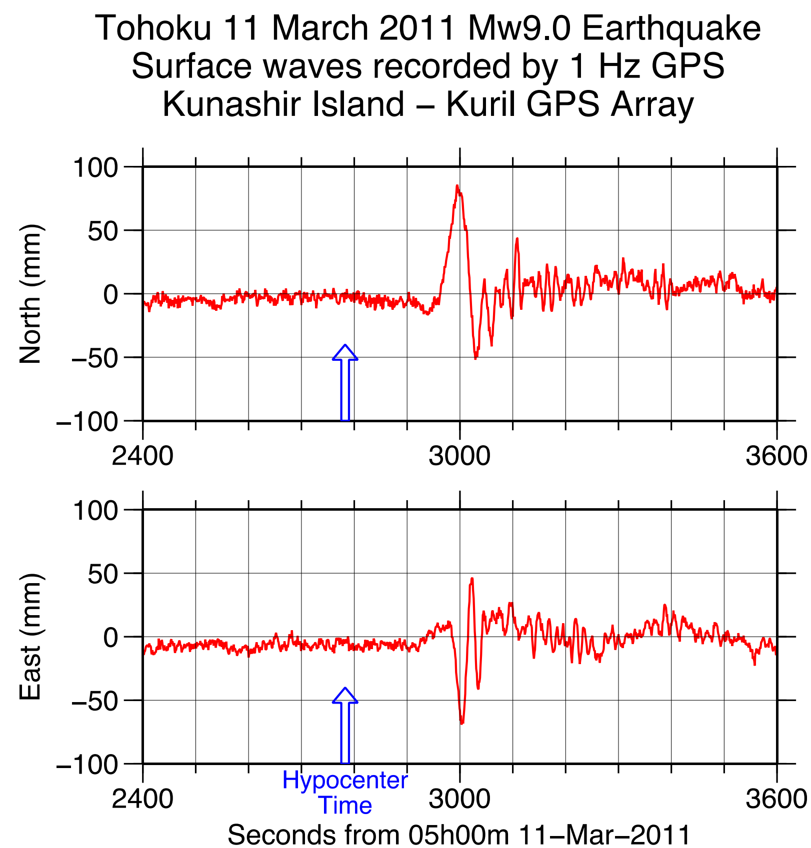
The accuracy of the real-time detected jumps is comparable with precise postprocessing estimates.



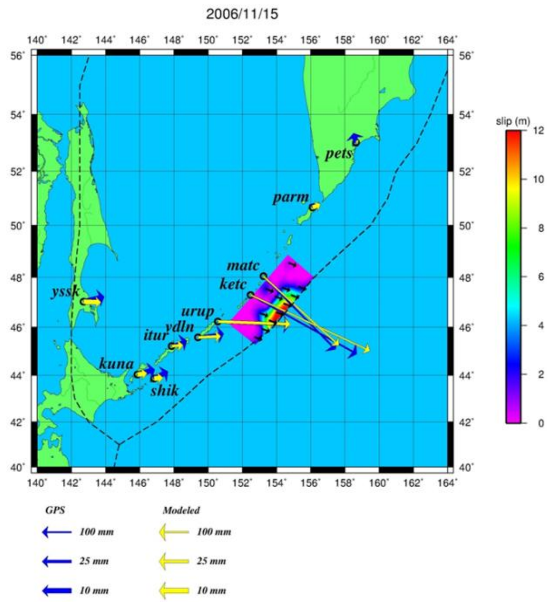


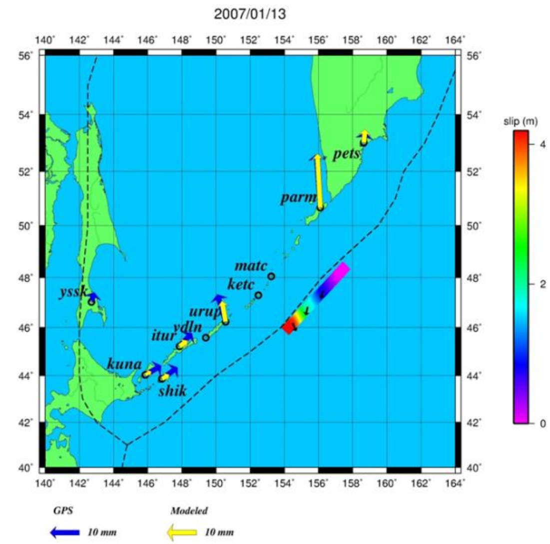
For the strongest events real-time coseismic jumps are also visible in minutes even at larger epicentral distance.



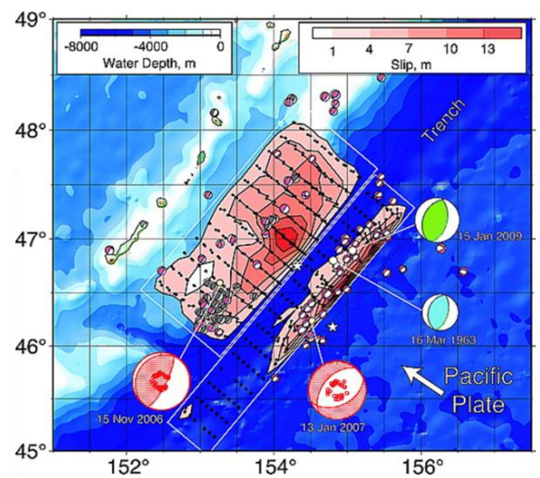


The rupture models calculated from surface displacements using GPS data are usually in good agreement with the refined teleseismic estimates of the distributed slip finite fault model, available in days after the event (for ex. in: Lay et al/ JGR 2009), and can differ significantly from the point source routine model (GCMT) for strong earthquakes.





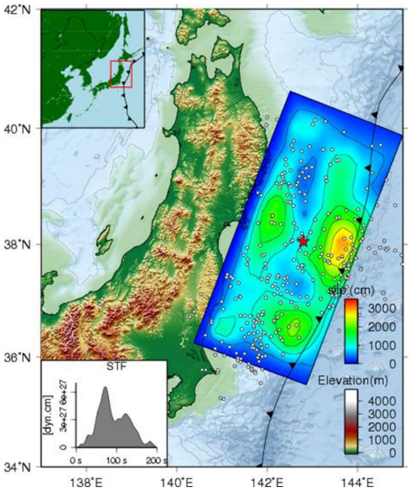
Scalar moment release and magnitude: various estimates.		
Solution	Event	
	2006/11/15	2007/01/13
Distributed slip, this study	M_0=5.93 x 10^{28}, Mw = 8.5	M_0=3.05 x 10^{28}, Mw=8.3
Uniform slip, this study	M_0=1.57 x 10^{28}, Mw = 8.1	M_0=0.85 x 10^{28}, Mw=7.9
CMT	M_0=3.51 x 10^{28}, Mw = 8.3	M_0=1.78 x 10^{28}, Mw = 8.1
P-waves, body-waves [Lay et al, 2009]	M_0=5.0 × 10^{28}	M_0=2.6 × 10^{28}

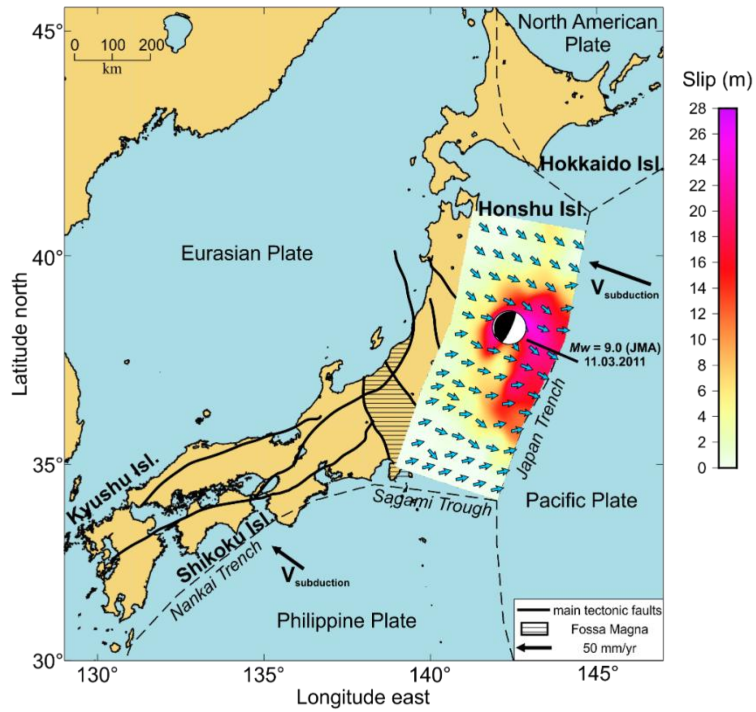


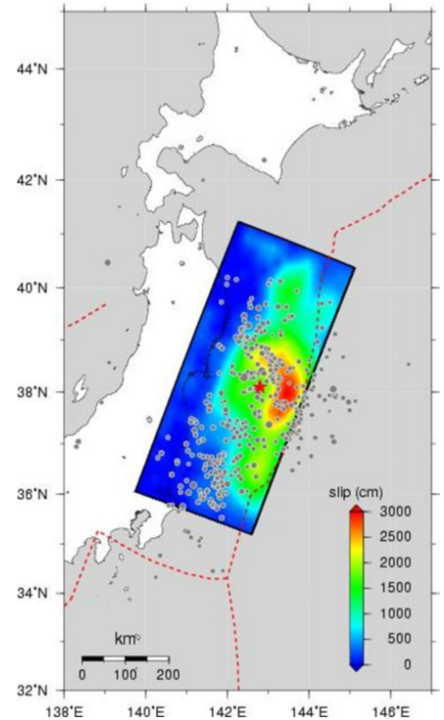
T. Lay, H. Kanamori, C. J. Ammon, A. R. Hutko, K. Furlong, and L. Rivera. The 2006–2007 Kuril Islands great earthquake sequence // J. Geophys. Res., 2009, V. 114, B11308, doi:10.1029/2008JB006280.

Tohoku-oki 2011/03/11: benchmark for validation of geodetic inversion versus seismological

2011/03/11



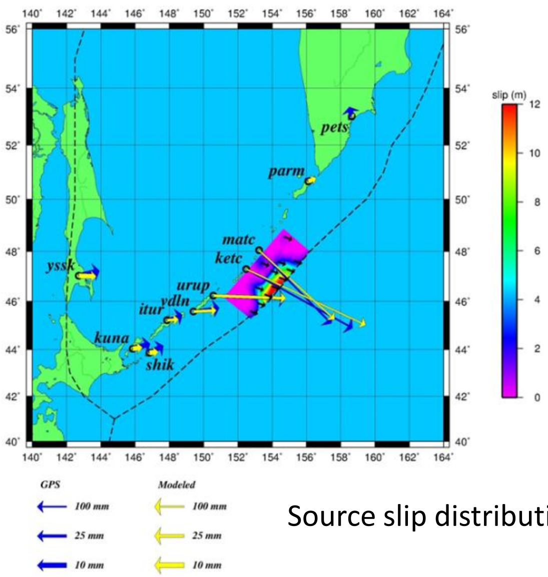




Teleseismic　　　Geodetic　　　Combined

Japan GEONET being one of the best GPS networks can be use as a benchmark

2006/11/15



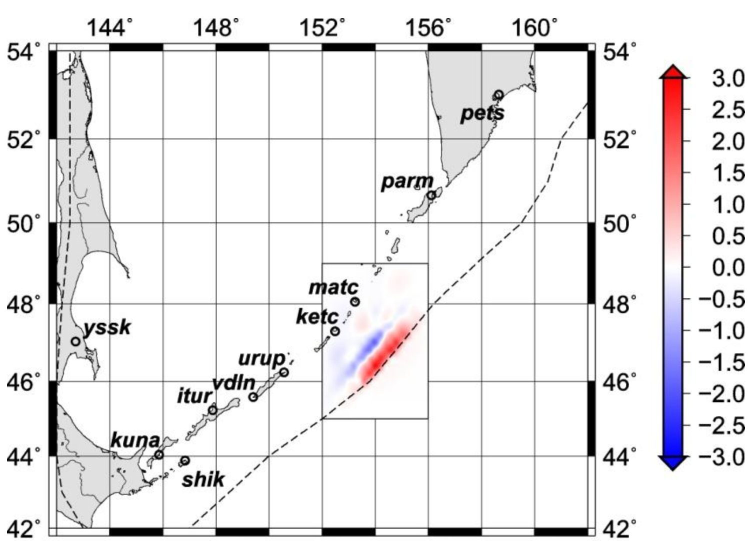
Source slip distribution

Once the source slip distribution is resolved, the sea floor uplift and horizontal slope motion can be estimated.

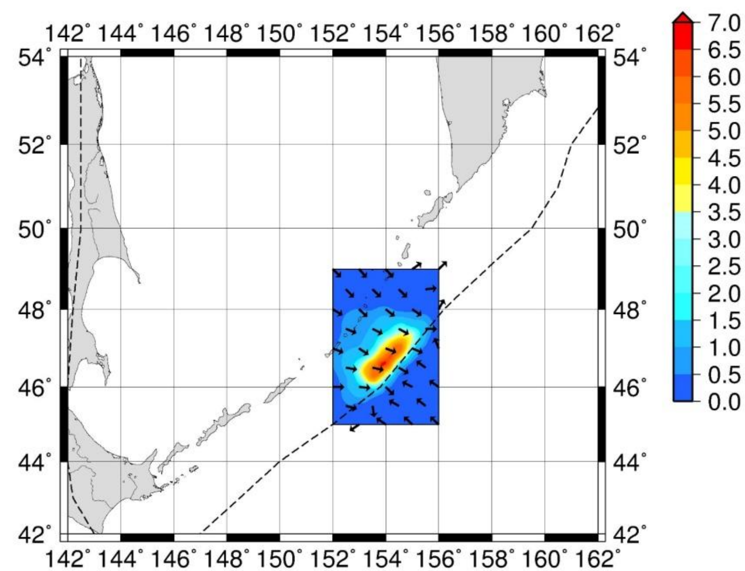
Required information:

- tectonic settings,
- bathymetry data

Results from Steblov" research group

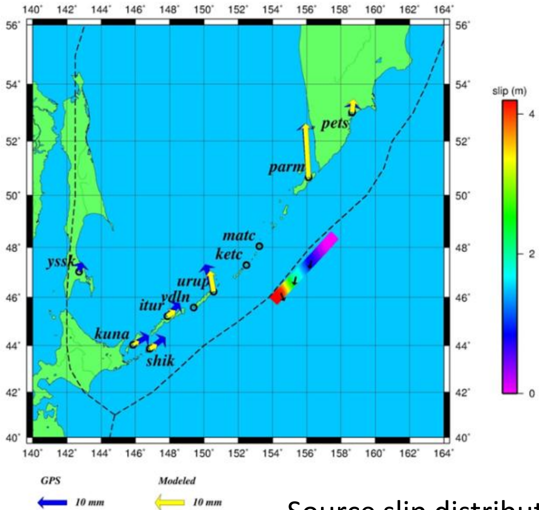


Sea floor uplift



Sea floor horizontal motion

2007/01/13



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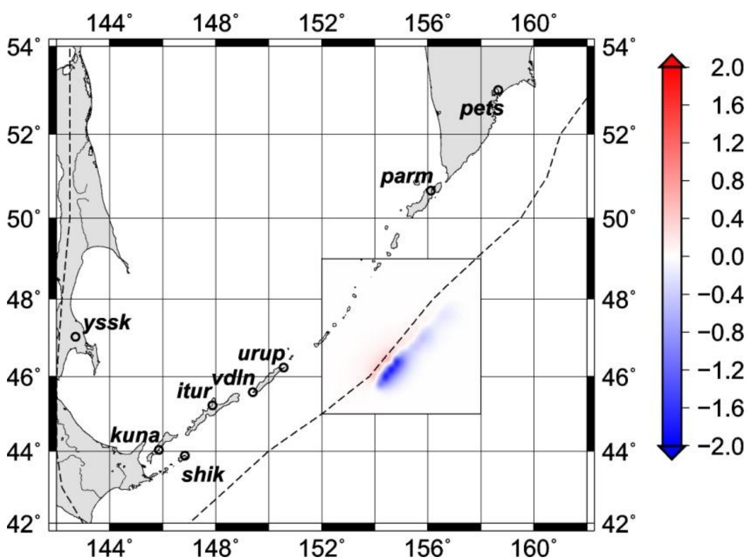
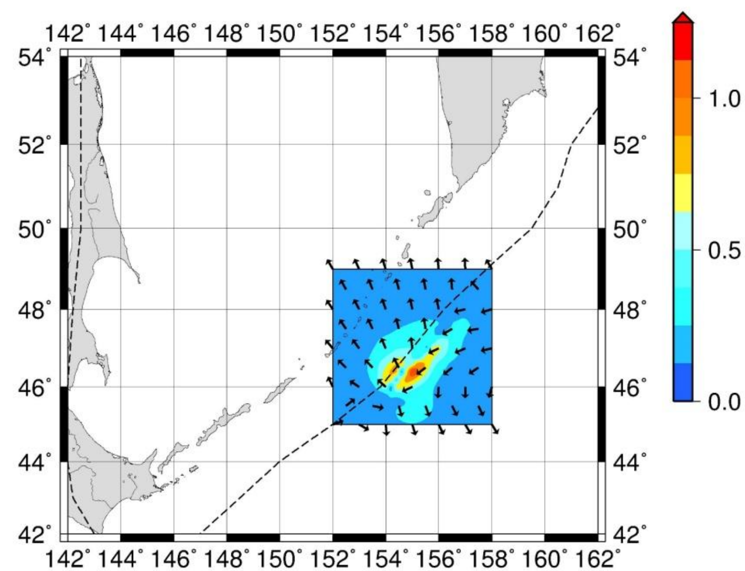
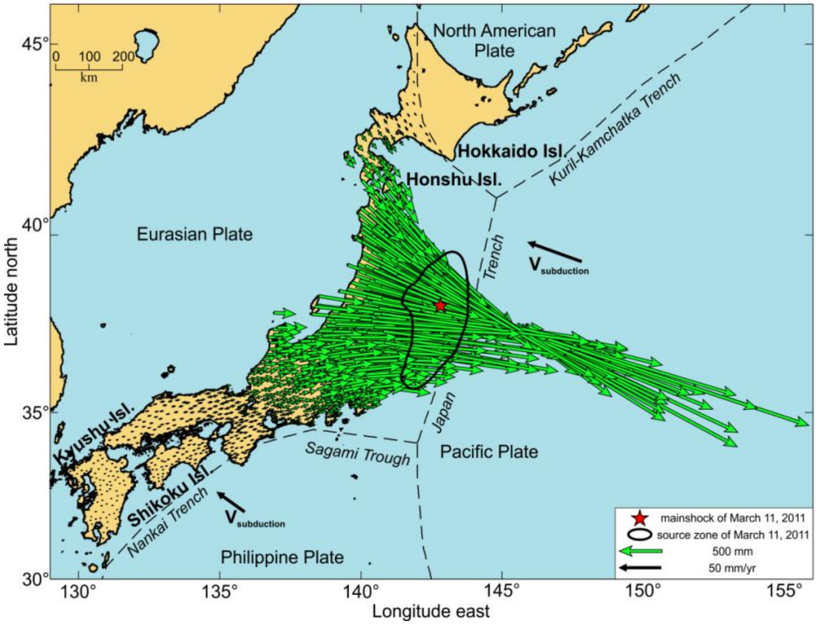


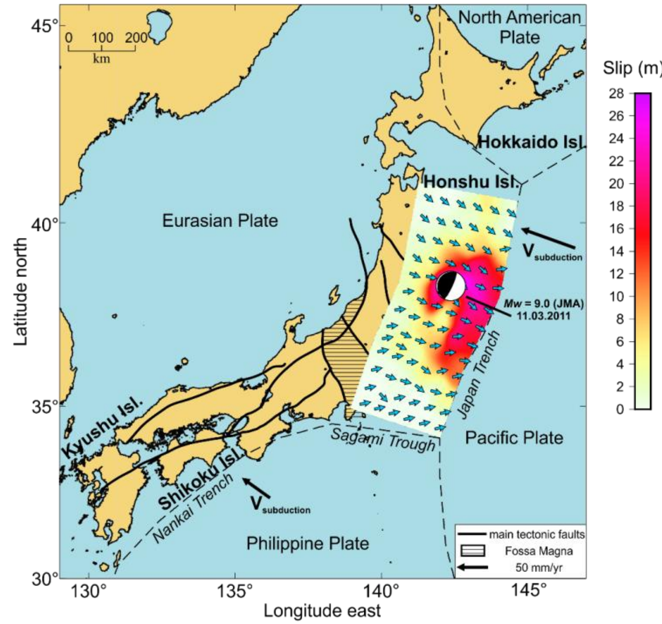
Sea floor uplift



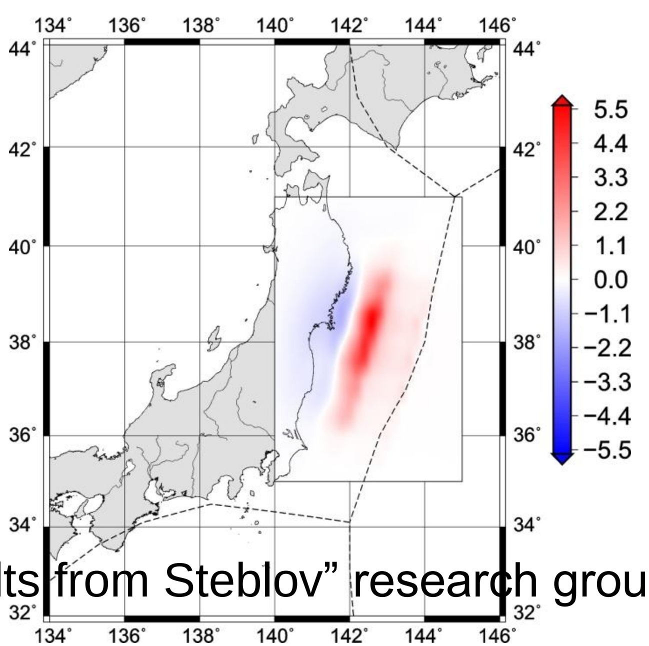
Sea floor horizontal motion

2011/03/11



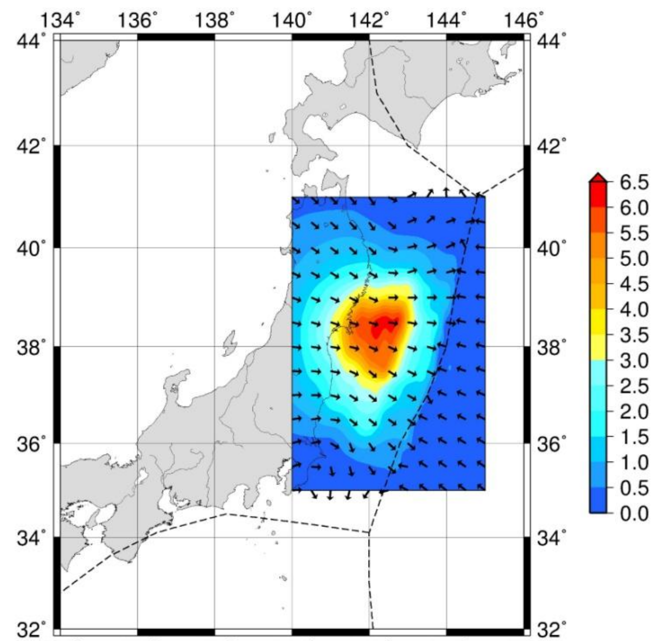


Source slip distribution



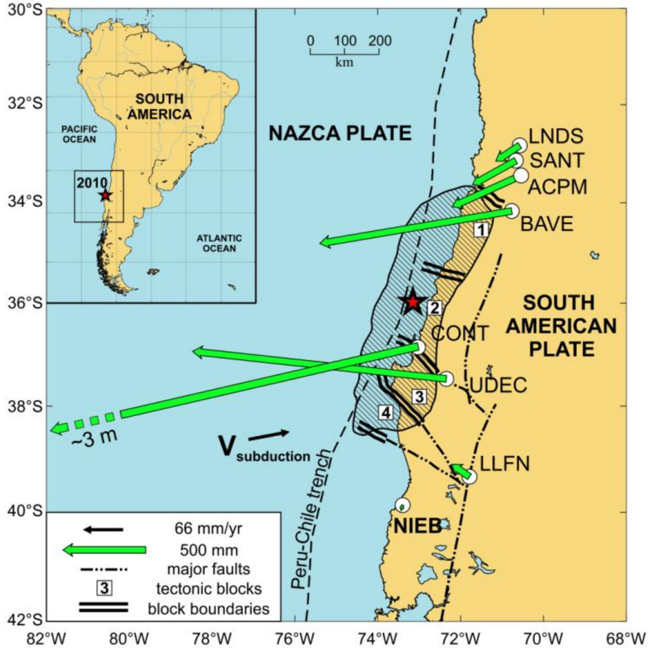
Results from Steblov" research group

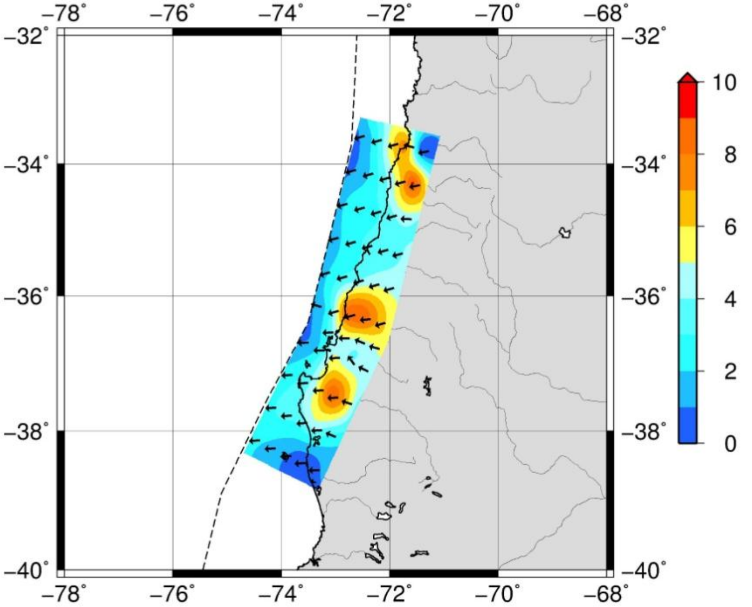
Sea floor uplift



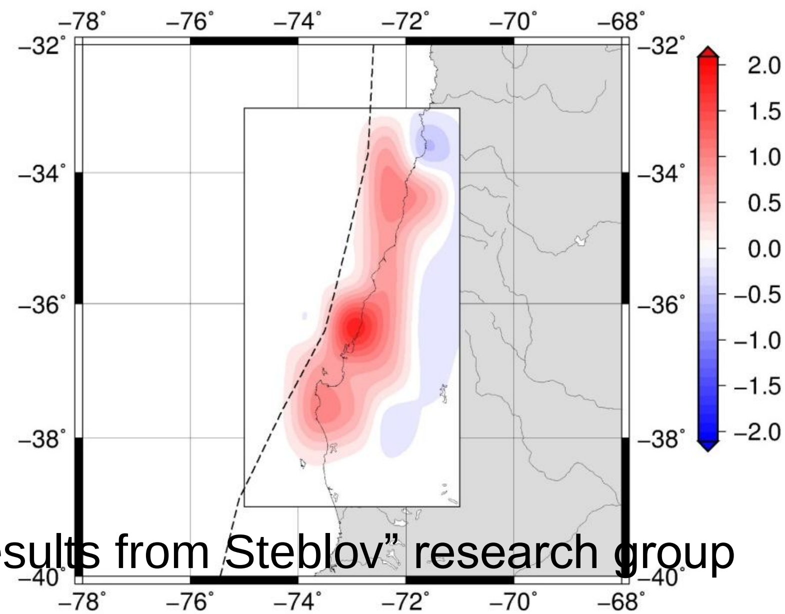
Sea floor horizontal motion

2010/02/27



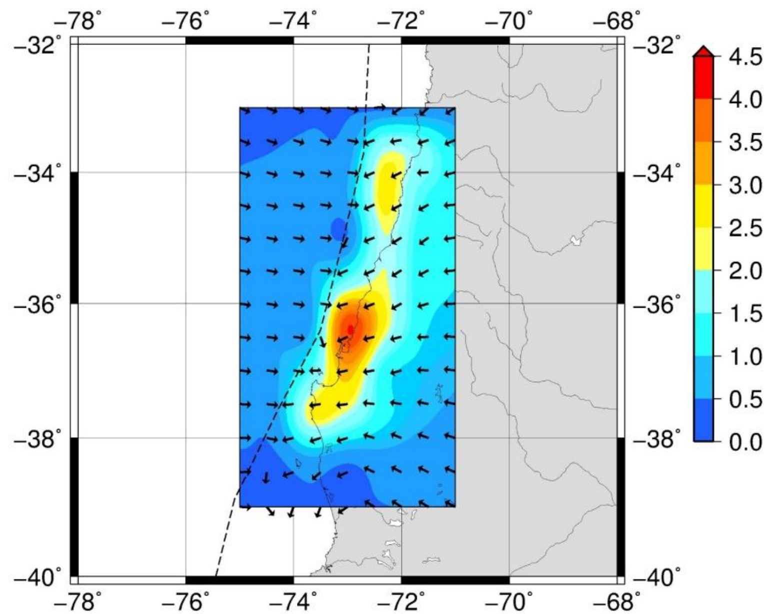


Source slip distribution



Results from Steblov" research group

Sea floor uplift



Sea floor horizontal motion

Summary

- Continuously tracking GNSS network may provide estimates of the sea floor uplift and horizontal slope motion in minutes after the event. Means to reduce the delay time:
  - signal travel time – by nearfield GNSS sites installation;
  - data delivery – by real-time data flow enabled;
  - data processing – by pre-calculated response functions.
- The steps required for integration of a GNSS based augmentation to the global Tsunami Warning System :
  - The regional GNSS networks should be revised to have sufficient near field continuously tracking stations (within 1 rupture length) to capture the permanent displacement signal;
  - The global GNSS network must have sufficient far field stations to provide a reference frame;
  - Regional analysis centers should be arranged, continuously tracking GNSS stations should be upgraded as possible to transmit their data in (near) real time to the regional analysis centers; otherwise global dedicated analysis center may be used.
  - GNSS analysis systems should be developed to handle near real-time data with the precise estimation of GNSS orbits to provide the estimation of GNSS displacements;
  - Precise GNSS displacements inversion algorithms should be implemented and adopted by the observing agencies while the supporting regional geological data should be acquired.
- Integration of a GNSS based augmentation to the global Tsunami Warning System would provide accurate, timely, cost effective and sustainable tsunami warnings for mega-thrust earthquakes around the globe.