A New Global Vertical Land Movement Data Set from the TIGA Combined Solution

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Abstract

Globally averaged sea level has been estimated from the network of tide gauges installed around the world since the 19th century. These mean sea level (MSL) records provide sea level relative to a nearby tide gauge benchmark (TGBM), which allows for the continuation of the instrumental record in time. Any changes in the benchmark levels, induced by vertical land movements (VLM) affect the MSL records and hence sea level estimates. Over the last two decades sea level has also been observed using satellite altimeters. While the satellite observations are globally more homogeneous providing a picture of sea level not confined to coastlines, they require the VLM-corrected MSL records for the bias calibration of instrumental drifts. Without this calibration altimeter instruments from different missions cannot be combined. GPS has made it possible to obtain highly accurate estimates of VLM in a geocentric reference frame for stations at or close to tide gauges. Under the umbrella of the International GNSS Service (IGS), the Tide Gauge Benchmark Monitoring (TIGA) Working Group (WG) has been established to apply the expertise of the GNSS community to solving issues related to the accuracy and reliability of the vertical component to provide estimates of VLM in a well-defined global reference frame. To achieve this objective, five TIGA Analysis Centers (TACs) contributed re-processed global GPS network solutions to TIGA, employing the latest bias models and processing strategies in accordance with the second re-processing campaign (repro2) of the IGS. These solutions include those of the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the German Research Centre for Geosciences (GFZ) Potsdam, the German Geodetic Research Institute (DGF) at the Technical University of Munich, Geoscience Australia (AUT) and the University of La Rochelle (ULR). In this study we present to the sea level community an evaluation of the VLM estimates from the first combined solution from the IGS TIGA WG. The TAC solutions include more than 700 stations and span the common period 1995-2014. The combined solution was computed by the TIGA Combination Centre (TCC) at the University of Luxembourg, which used the Combination and Analysis of Terrestrial Reference Frame (CATREF) software package for this purpose. This first solution forms Release 1.0 and further releases will be made available after further reprocessing campaigns. We evaluate the combined solution internally using the TAC solutions and externally using solution the ITRF2014. The derived VLM estimates have undergone an initial evaluation and should be considered as the primary TIGA product for the sea level community to correct MSL records for land level changes

Introduction

Sea level change as a consequence of climate variations has a direct and significant impact for coastal areas around the world. Over the last one and a half centuries sea level changes have been estimated from the analysis of tide gauge records. However, these instruments measure sea level relative to benchmarks on land. It is now well established that the derived mean sea level (MSL) records need to be de-coupled from any vertical land movements (VLM) recorded at the tide gauge.

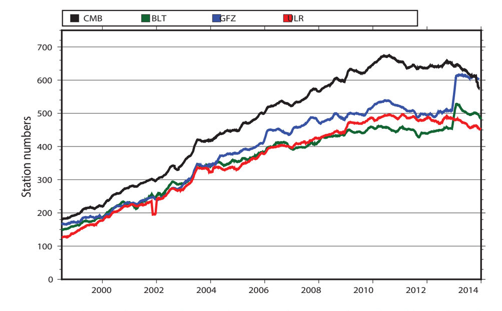
Global Navigation Satellite System (GNSS) technology, in particular the Global Positioning System (GPS), has made it possible to obtain highly accurate estimates of VLM in a geocentric reference frame from stations close to or at tide gauges. Under the umbrella of the International GNSS Service (IGS), the Tide Gauge Benchmark Monitoring (TIGA) Working Group has been established to apply the expertise of the GNSS community to solving issues related to the accuracy and reliability of the vertical component and to provide time series of vertical land movement in a well-defined global reference frame, (Schöne and Thaller, 2009). To achieve this objective, a number of TIGA Analysis Centers (TACs) contribute re-processed global GPS network solutions to TIGA, employing the latest bias models and processing strategies in accordance with the second re-processing campaign (repro2) of the IGS.

One of the objectives of the TIGA Working Group is to produce consistent station coordinates on a daily basis in the form of SINEX files, which are useful for multi-solution combinations, i.e. following largely the example of the routine IGS combinations. In this study we aim to explore the potential in improving the precision and accuracy of the station coordinates and station velocities through network analysis. So far, only three of five TAC solutions have a complete time series and are now available for a preliminary multi-year combination. These include the solutions of the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle (Table 1). The fourth solution from Deutsches Geodätisches Forschungsinstitut (DGFI) is soon to be completed but we have identified an issue in their time series at the start of 2010, coincident with the inclusion of GLONASS observations in their daily SINEX files. Hence, we have not included the DGF solution in this study. The solution from the 5th TAC, Geoscience Australia (AUT) is still to be completed. It is noteworthy that all five contributing TACs have analyzed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations, which is different for earlier TIGA solutions (Schöne and Thaller, 2009).

In this study we present the quality of the final TACs combined solution by the TIGA working group at the TIGA Combination Centre (TCC) at the University of Luxembourg (UL). The combined solution currently incorporate only the three TACs solution using a modified version of the Combination and Analysis of Terrestrial Reference Frame (C-ATREF) (Altamimi et al, 2002). Figure 1 shows the number of stations from the TACs and the distribution of the station that are included in the combination with a total 1093 stations.

TAC	Host Institutions	Software package	Contributors
AUT	GeoScience Australia, Canberra, Australia	BERNESE V.5.2	M. Moore, M. Jia
BLT	British Isles continuous GNSS Facility and University of Luxembourg TAC (BLT), UK and Luxembourg	BERNESE V.5.2	F. N. Teferle A. Huneganw R. M. Bingley D. N. Hansen
DGF	The Deutsches Geodätisches, Forschungsinstitut, Germany	BERNESE V.5.2	
GFZ	GeoForschungsZentrum (GFZ), Potsdam, Germany	EPOS P8	T. Schöne Z. Deng
ULR	Centre Littoral de Geophysique, University of La Rochelle (ULR), France	GAMIT V.10.5	G. Wöppelmann A. Gómez-A. Santamaría M. Gravelle

Table 1. Lists currently available TIGA Analysis Centres. AUT, BLT, DGF, GFZ, and ULR and only three are currently contributing to the TIGA combination (TAC) solution. All the five TACs include core global network list of sites from IGb08 reference stations.

a)


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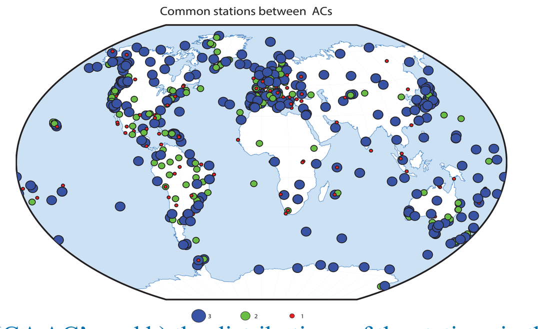

Figure 1: a) Number of stations from the Individual contributing TIGA AC's and b) the distributions of the stations in this study.

Post-seismic deformation modelling

GPS residual position time series show non-linear trajectories during and after earthquakes. This post-seismic displacement (PSD) as experienced by GPS stations are usually located near major plate boundaries. Each of the TAC comprises a significant number of continuous GNSS stations located around these boundaries and their time series show coseismic as well as postseismic deformations. Figure 2 shows the distributions of the GNSS stations affected by earthquakes. Without modifying the trajectories of these affected stations, their velocity estimates are adversely affected. We adopted the model by ITRF2014 (Altamimi et al., 2016). The residual time series fitting is based on four parametric models: logarithmic, exponential, logarithmic + exponential, and exponential + exponential decays.

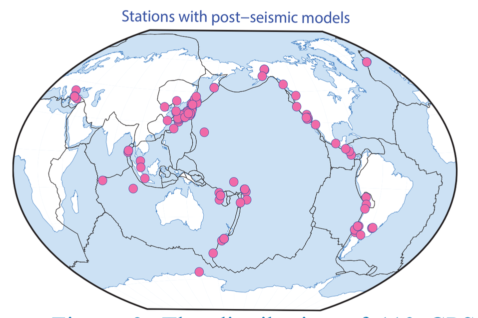

Figure 2. The distribution of 119 GPS stations that are affected by earthquakes with a postseismic parametric models

We have implemented the PSD models in the CATREF software package before we perform stacking of the Individual TAC solution. Figure 3 shows the results of the PSD parametric modelling for selected stations in Japan and Chile. For P104, Oga, Japan, a combination of logarithmic + exponential is fitted for the horizontal components and while only one Exponential parameter is fitted for the Up component. For ANTC, Los Angeles, Chile, the fit is the same for the horizontal components as for P104 but for the up component the PSD uses two exponential decays parameters. After the fit, there is an almost 3 fold improvement in the east component and 60% improvement in the north component while the improvement in the Up component reaches up to 8%.

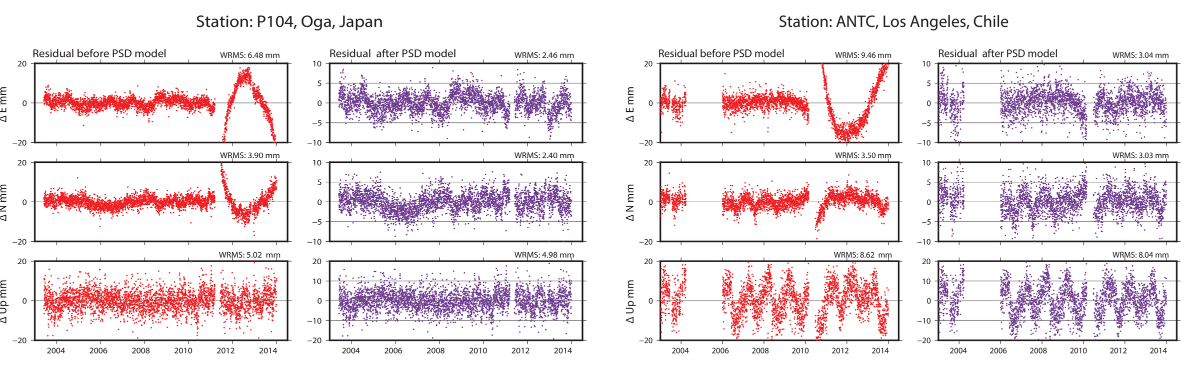

Figure 3. The residual time series for P104, Oga, Japan (left) and ANTC, Los Angeles, Chile (right). Red dots depict the residual times series before fitting a PSD model and dark blue dots depict after fitting the ITRF2014 PSD model. Note, the different scales of the vertical axes. Clearly the PSD parametric modelling has substantially improved the residual time series with a significant decrease in WRMS, especially for the horizontal components – a reduction of the noise level up to 200 % for some stations and a minor, but still discernible improvement for the Up component – a reduction of the noise level up to 8%.

Combination procedures

The main objective of the combination is to determine the best possible estimates for the position coordinates expressed in the realization of the ITRS (IGb08) of the ITRF by combining the solutions derived by different TACs with different analysis strategies. In doing so the combination provides an opportunity to make inter-comparison of TACs and their effect in the combined solution and also their weakness and strength.

Prior to the combination, the TACs solution are pre-processed and checked for inconsistencies. The pre-processing ensures that the contributing solutions are unconstrained and corrected for offsets and station name and domes number inconsistency between TACs solution. CATREF identifies station with their domes number and it is critical that the domes number is the same for the same station between TACs. After the pre-processing step, the best estimates are obtained through the weighted least squares adjustment using the latest CATREF software package. As a final step the long term combined stacked solution is aligned to a chosen core IGb08 stations so that the combined frame inherits its origin and orientation from ITRF2008.

Acknowledgements

The computational resources used in this study were provided by the High Performance Computing Facility at the University of Luxembourg, Luxembourg (ULHPC). The IGS and its ACs are highly appreciated for their data, products. We are especially thankful to the TIGA data providers at www.sonel.org at the University of La Rochelle.

Station position residuals

A global metric of inter-TAC level of agreement on station position can be assessed through weighted RMS (WRMS) of TAC station position residuals. Figure 4 shows the daily WRMS of the individual TAC and the combined solutions. For the early years, higher noise level is visible in general but more so from the BLT solution. There is also a slightly higher noise level in the Up component for the BLT stacked solution. On the other hand, the horizontal components' noise levels are low. The ULR solution shows a slight increase in WRMS in the East and North components as is also reported in Rebischung et al. (2016). In general the WRMS from the three TACs are essentially have a good level of agreement, while the WRMS of the combined solution has the lowest noise. If we only considered the daily WRMS after 2004, the daily WRMS attains an internal precision less than 2 mm in horizontal components and 5 mm for in the Up component for our combined solution. This coincide with the availability of greater number of global tracking GPS stations with a favourable geometric distributions (see Figure 1a).

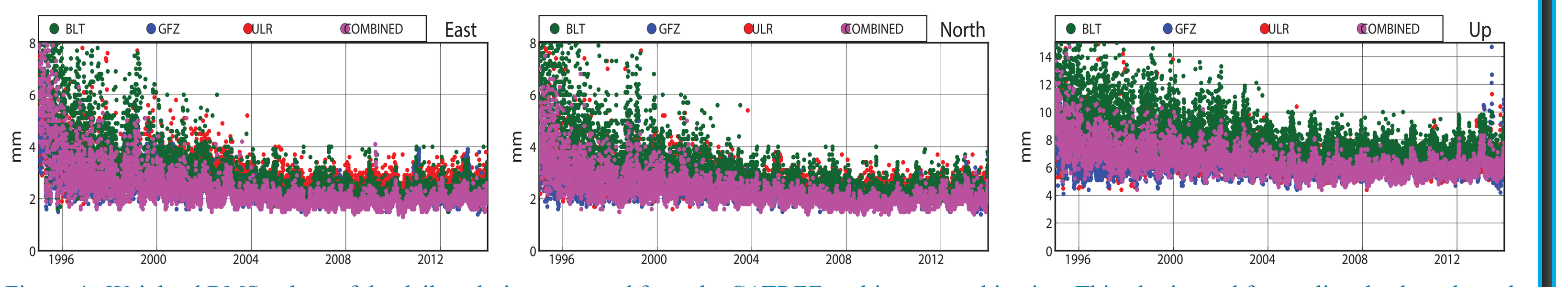

Figure 4. Weighted RMS values of the daily solution extracted from the CATREF multi-year combination. This plot is used for quality checks, where the higher WRMS indicates the presence of outlier(s) in any of the individual station time series. The green dots depicts the BLT, blue dots depicts GFZ, red dots depicts ULR and magenta for the COMBINED solutions for the East, North and Up components.

Stacked power spectra

We have estimated the power spectra of the stacked residual position time series from BLT, GFZ and ULR and the combined solutions. The normalized Lomb-Scargle periodogram is computed for all residual position time series. The power spectra were stacked after we have calculated each individual spectra including now even for those stations that are affected by earthquakes since we have now applied the PSD model. To discriminate dominant features in the power spectra, we have applied a smoothing using a moving average boxcar filter, following Ray et al. (2008). Figure 5 shows the stacked normalized periodograms of the individual (BLT, GFZ, ULR) and the combined solutions. All the spectra show the dominant seasonal peaks as well as peaks at harmonics of the GPS draconitic year. The Up component shows also a prominent peak with fortnightly period even though it is also visible in the horizontal components. A closer look shows three power surges at the fortnightly peak at periods of 13.7, 14.2 and 14.8 days. There is a power at an 8 day period only particular to the BLT solution which is related to the inclusion of GLONASS data during the CODE product generation. This 8 period is no longer appear in the combined solution.

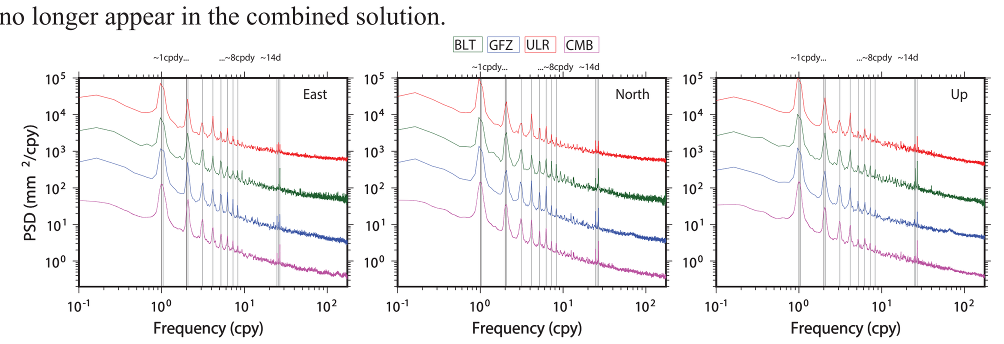

Figure 5. Smoothed stacked power spectra of the residual position time series. Clear seasonal power peaks as well as harmonics of the GPS draconitic frequencies are identified in all components. There is also a sharp power peaks in the fortnightly band in all the three components, but much more pronounced in the Up component. The vertical black lines indicate the annual, semi-annual and fortnightly periods. The gray lines indicate 10 of the harmonics of the GPS draconitic periods including fortnight period. [**cpdy**= *cycle per draconitic year*]

Helmert transformation parameters of the combined solution

Figure 6 depicts the temporal evolution and the corresponding frequency contents of the daily translation and terrestrial scale parameters with respect to a selected set of core sites of the IGb08. There is a clear seasonal variations with no indiscernible drift. The Z translation component shows a higher amplitude variations that is partly inherited from the ULR TAC solution. A spectral analysis of the time series of the translation parameters do contain spectral peaks at various draconitic harmonics of the GPS year, with a pronounced sub annual signal specially of the Z translation component. Table 2 shows TAC combined trend, annual, semin-annual fit to the time series with respect to IGb08.

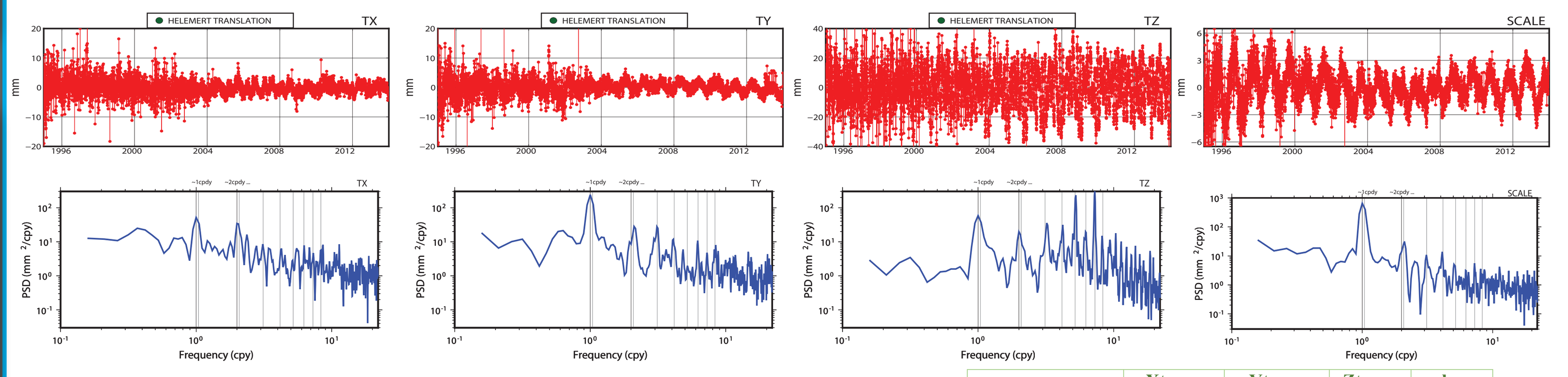

Figure 6. The upper panel is the time series of the Helmert translation parameters in X, Y, Z and terrestrial scale of the combined solution with respect to IGb08. The lower panel is the Lomb-Scargle periodograms of the corresponding translations and scale Helmert parameters.

	Xtrans	Ytrans	Ztrans	scale
bias	-0.10	-2.10	2.30	-1.48
trend	0.07	0.22	0.47	-0.07
amp annual	0.71	1.44	4.86	1.45
amp semi-annual	0.53	0.20	2.79	0.27

Table 2. Seasonal and trend fit to the Helmert transformation parameters: trend, annual, semi-annual. Units

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Vertical rates from TAC combined and ITRF2014 solution (External evaluation)

Figure7 shows the vertical land movement estimates from the TAC combined solution and from the recently released ITRF2014 solution. Clear vertical land movements emerge with similar magnitudes between TAC combined and ITRF2014 solutions with regional footprints. In the regions such as Greenland, North America, and Fennoscandia, the VLM reflect uplift mainly caused by past and present ice load responses. The RMS difference between the two solutions is at 0.97 mm with a bias of 0.2 mm using more than 800 common stations. The rate estimates between the two solutions do not exhibit any longitudinal or latitudinal dependencies.

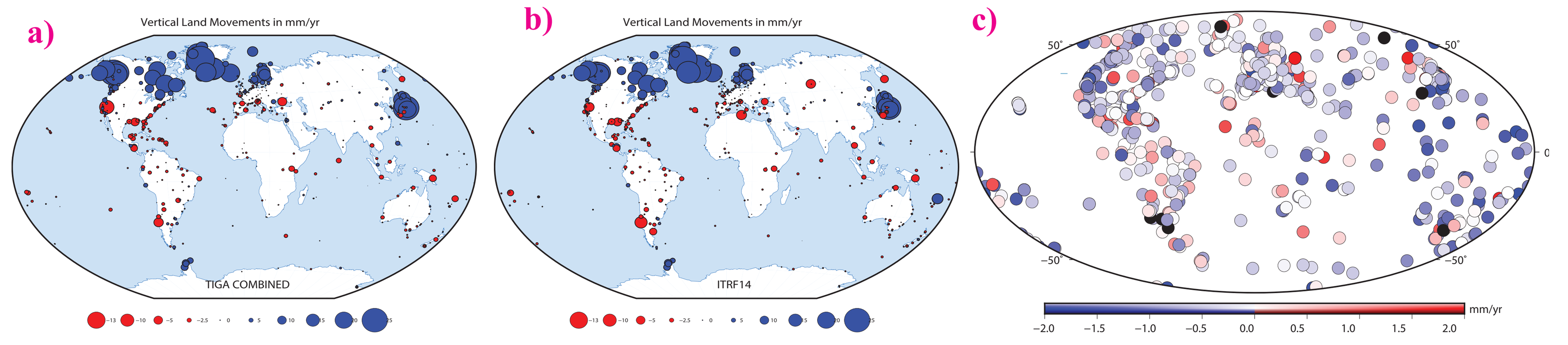

Figure 7. Vertical rate from the stacked TAC combined solution shown in (a), ITRF2014 solution in (b) and their differences in (c). The rate from our TAC combined solution is expressed in the ITRF2008. Units are expressed in [mm]

Regional vertical rate comparison

Global mean sea level significantly vary compared to regional sea level changes and the sea level along coastlines can therefore change with a profound consequence. Here we look how the two solutions agree on regional scale. Figure 8 shows the map of the vertical rates in Japan, Greenland, Europe and North America. The upper panel shows from our TAC combined solution and the lower panel from ITRF2014 for the same set of stations. In the background we have included the ICE-6G (VM5a) model vertical land uplift rate from Peltier, et al. (2015). Table 3 and Table 4 show the RMS and biases between the vertical rate differences between the TAC combined and ITRF2014 solutions. Our combined vertical GPS rates in Fennoscandia, Northern America showed a good general agreement with the predictions of the ICE-6G GIA model rate of Peltier, et al. (2015).

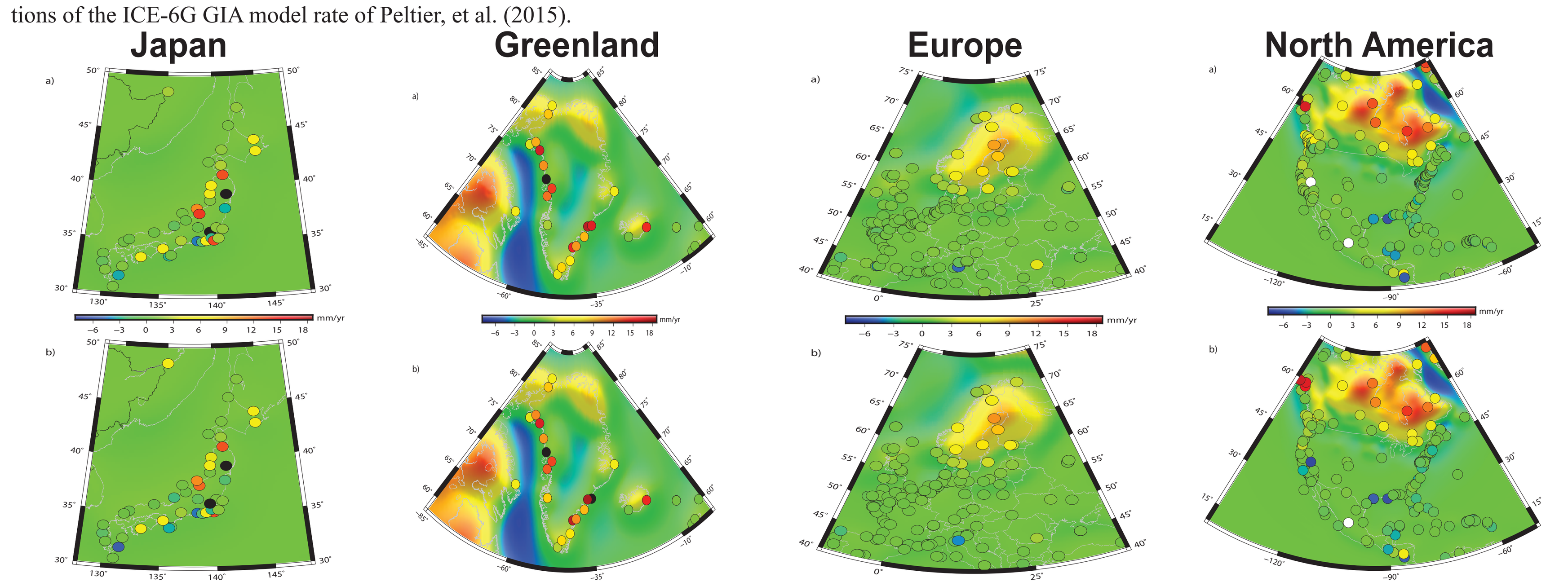

Figure 8. Map of regional vertical land uplift rates from ITRF2014 and TAC combined solutions. An even better agreement emergs with European and Greenland stations perform better. A better agreement with Japan stations are due to the implementation of the PSD model for earthquake affected stations.

	RMS [mm]	Bias [mm]
JAPAN	0.69	0.44
Greenland	0.81	0.05
Europe	0.54	0.16
North America	0.69	0.30

Table 3. Bias and RMS of between the TIGA combined solution vertical land movement estimates with respect to the ITRF2014 estimates. Values are in mm/yr

	BLT	GFZ	ULR	COMBINED
Scatter of Trends w.r.t ITRF2014	1.61	1.60	1.60	0.97
Bias w.r.t ITRF2014	0.2	0.2	0.2	0.2

Table 4. Bias and RMS of the TAC solution vertical land movement estimates with respect to the ITRF2014 estimates. Values are in mm/yr. More than 800 stations are used for the combined-solution comparison

Conclusions

In this study we have presented the first combined long term linear solution from 1995 to 2014. The VLM estimate show a very good agreement between the combined solution and the velocity estimate from the recently released ITRF2014 solution. The combined stacked solution have benefited because of our implementation of the post-seismic deformation model adopted from ITRF2014 using the CATREF software package.

1. All TAC solution and the combined stacked spectra show a prominent and clear seasonal as well spurious spectral peaks at harmonics of GPS draconitic year.
2. The combined solution internal precision after 2004 is at a level of less than 2 mm for the horizontal components and at 5 mm level in the up component.
3. The implementation of the post-seismic deformation model adopted from ITRF2014 has improved the noise level of the residual time series, most notably in the horizontal components but also an apparent improvement in the Up component. Most stations in Japan has benefited most.
4. The VLM estimate show remarkably good agreement in Greenland, Europe and Japanese stations between ITRF2014 and TAC combined solutions. The VLM rates from the combined solution with respect to the ITRF2014 rates show insignificant bias (0.2 mm/yr) using more than 800 common stations.
5. The scales of the TAC stacked solution have no significant trends with minor bias.
6. The first release TIGA combined solution and the stacked individual solution are available at the TIGA website. The VLM estimate should be regarded as a primary source of VLM estimate to correct tide gauge records available at PSMSL and UHSLC for sea level studies