Contribution of GGFC to ITRF2020

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April 9, 2021

Summary

The document describes the contribution of the Global Geophysical Fluid Center (products available at http://loading.u-strasbg.fr/ITRF2020/) to the next terrestrial reference frame realization: ITRF2020 (http://itrf.ensg.ign.fr/).

1 Environmental models

1.1 ERA5 and TUGO-m models

We choose to model environmental loading contributions to surface displacements (North, East, Up), time-variable gravity field (Stokes coefficients) and geocenter motions using latest ECMWF (European Centre for Medium-range Weather Forecasts) reanalysis model ERA5 (atmospheric pressure, soil-moisture and snow) (Hersbach et al., 2020) available from 1979 at hourly and 0.25^o resolutions and TUGO-m (Toulouse Unstructured Grid Ocean model, update of Carrère & Lyard, 2003) barotropic ocean model forced by ERA5 surface pressure and winds, at hourly and 0.125^o resolutions.

At high-frequencies (periods typically below 1 month), TUGO-m is more accurate to describe the oceanic variability compared to the classical inverted barometer (IB) assumption. Mémin et al. (2020) showed that there are no significant differences between TUGO-m barotropic ocean model and classical baroclinic ocean models (such as ECCO or GLORYS) at seasonal timescales when compared to GPS vertical displacements.

1.2 Products available

We provide hourly surface displacements (North, East and Up components), time-variable gravity field (Stokes coefficients) and geocenter motions for 3 different loading models:

- ERA5 atmospheric loading assuming an inverted barometer (IB) ocean response.
- ERA5 atmospheric and TUGO-m induced oceanic response loading.
- ERA5 hydrological loading (soil-moisture and snow).

1.3 Air tides in ERA5

Because of their temporal resolution (hourly), atmospheric tides (S1, S2 and their modulations) are fully represented in ERA5. Figure 1 and 2 show respectively the S1 and S2 tides (amplitude and phase) computed from almost 40 years of ERA5 surface pressure and the Ray & Ponte (2003) (RP2003) model, derived from 6-hourly and 1.125^o ECMWF surface pressure, currently used in the processing of space geodetic data. Because of

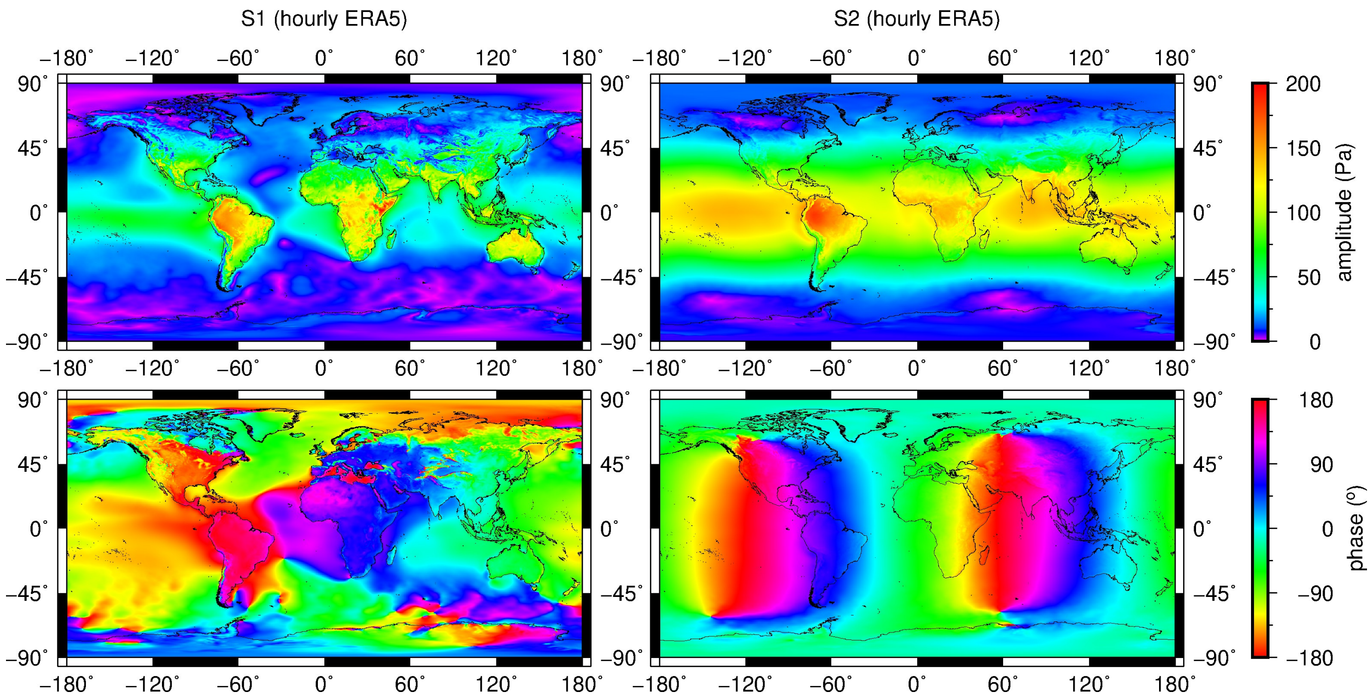

Figure 1: Amplitude (top) and phase (bottom) of S1 (left) and S2 (right) barometric tides computed from hourly ERA5 surface pressure (1980/01 - 2018/12).

its temporal resolution (6 hours), the retrieval of S2 tide is based on the assumption of a westward propagation at 15$^o/hr$ velocity. The analysis of the hourly ERA5 surface pressure data shows that the amplitude of the S2 tide may be underestimated in the RP2003 model, and a slightly more complex spatial structure.

We choose to leave the air tides (S1, S2 and their modulations) in all our products, as they are in better agreement with barometric records (R. Ray, personnal communications).

We removed the S1, S2 and their harmonic modulations in the TUGO-m model to avoid any double-counting with the gravitational ocean tides.

1.4 Corrections of offsets in hydrology products

As mentioned in Hersbach et al. (2020) (Section 3 and Table 3), ERA5 was produced in different streams to speed up the production and availability. We discover that any start of a new production stream may cause apparent offsets in the hydrological fields (soil-moisture and snow); this is particularly the case of a new EDA (Ensemble of Data Assimilation) system (see Table 3 in Hersbach et al., 2020). We then correct for jumps occuring in April 1986, August 1993, January 2000, January 2010 and January 2015.

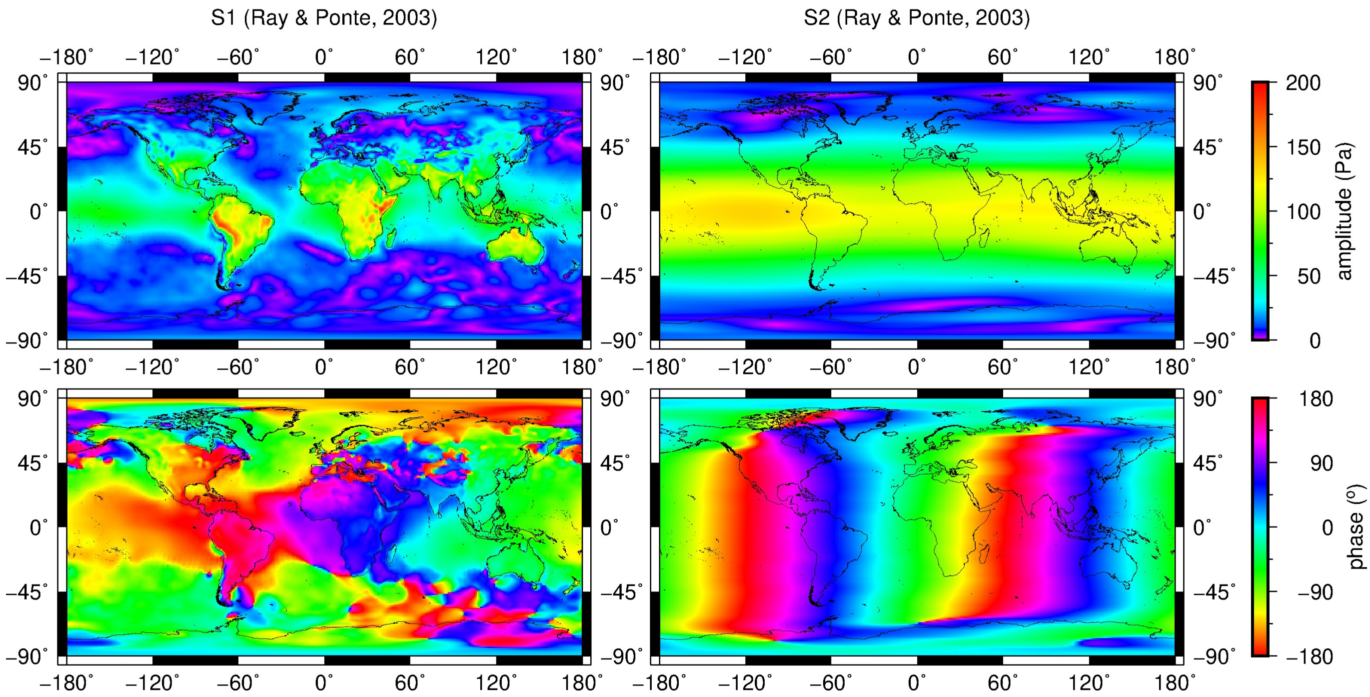

Figure 2: Amplitude (top) and phase (bottom) of S1 (left) and S2 (right) barometric tides according to Ray & Ponte (2003) model.

2 Surface displacements

2.1 Loading computations

Surface displacements due to pressure changes Δp are computed using the Green's function formalism (Farrell, 1972; Petrov & Boy, 2004).

Vertical displacements are:

$$u_R(\theta, \lambda, t) = \iint \Delta p(\theta', \lambda', t) G_R(\psi) ds' \tag{1}$$

with the vertical displacement Green's functions:

$$G_R(\psi) = \frac{G}{a g_0^2} \sum_{n=0}^{+\infty} h_n' P_n(\cos\psi) \tag{2}$$

G, a, and g_0 are respectively the universal constant of gravitation, the mean Earth radius and the surface gravity.

The North and East displacements are are equal to:

$$u_N(\theta, \lambda, t) = \iint \Delta p(\theta', \lambda', t) G_H(\psi) \cos\alpha ds' \tag{3}$$

$$u_E(\theta, \lambda, t) = \iint \Delta p(\theta', \lambda', t) G_H(\psi) \sin\alpha ds' \tag{4}$$

with the horizontal displacement Green's functions:

$$G_H(\psi) = \frac{G}{a g_0^2} \sum_{n=0}^{+\infty} l_n' \frac{\partial P_n(\cos\psi)}{\partial\psi} \tag{5}$$

h'_n and l'_n are the load Love numbers computed from PREM (Dziewonski & Anderson, 1981).

We insure the mass conservation in all loading products:
For the ERA/IB model, we enforce the ocean mass conservation (see Equation 5 in Petrov & Boy, 2003).
We also enforce the total ocean mass using the classical Boussinesq approximation for the ERA5+TUGO-m model.
For the ERA5 hydrological loading, we compensate any lack/excess of water over land by adding/removing a uniform layer in the ocean.

Displacements are computed both in the Earth system Center-of-Mass (CM) and the Center-of-Figure (CF) reference frames. In the CM reference frame, degree 1 load Love numbers are equal to ${}^{CM}h'_1 = +1.2858$ and ${}^{CM}l'_1 = -0.8961$; in the CF frame, ${}^{CF}h'_1 = +0.2858$ and ${}^{CF}l'_1 = +0.1045$.

Figure 3 shows the annual amplitude, the linear trend, and the variability (standard deviation of the modeled displacements after removing seasonal variations) of the modeled vertical displacements (ERA5/IB, ERA5+TUGOm atmospheric and induced oceanic response, ERA5 hydrology).

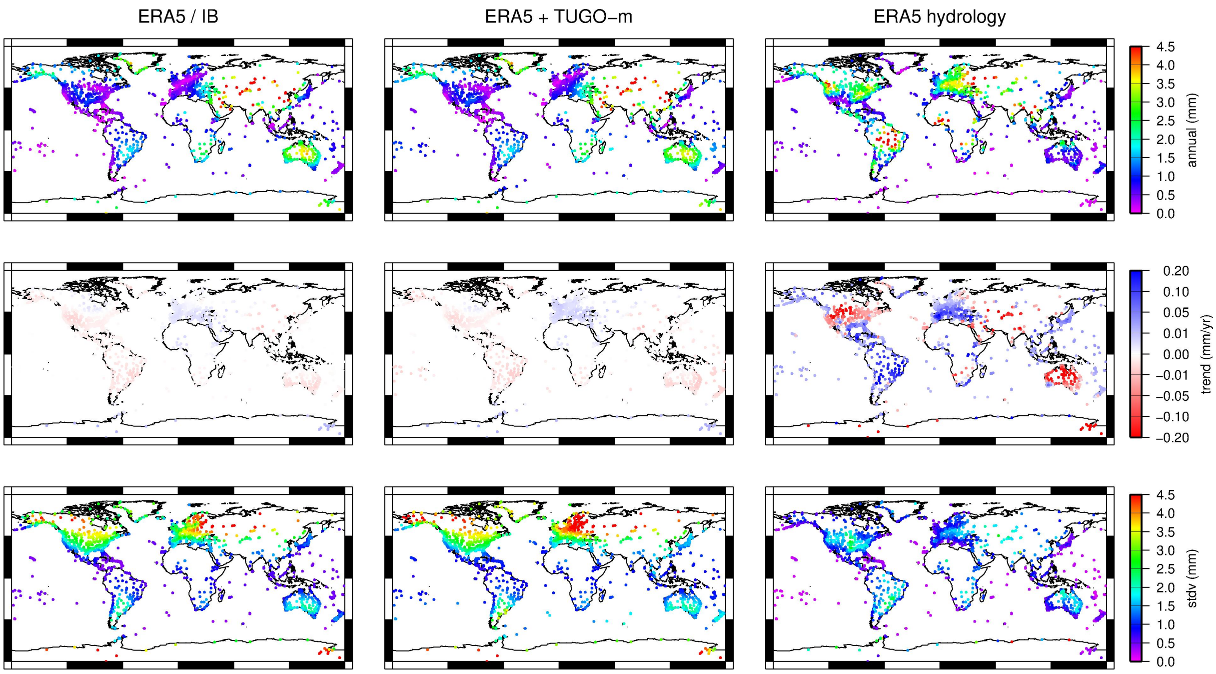

Figure 3: Annual amplitude (top in mm), linear trend (middle in mm/yr) and high-frequency variability (bottom in mm) of modeled vertical displacements at ITRF2020 sites (CF reference frame).

2.2 Format of the products

We provide individual files for each station and model (ERA5/IB, ERA5+TUGOm and ERA5 hydrology) with 4 columns: Modified Julian Day, North displacement (in mm), East displacement (in mm) and Up displacement (in mm) (ENU) (format: `(F15.8,3F10.3)`).

3 Time-variable gravity field

3.1 Loading estimates

$$\left\{ \begin{array}{c} C_n^m(t) \\ S_n^m(t) \end{array} \right\} = \frac{3}{4\pi}\frac{1+k_n^{'}}{2n+1}\frac{1}{\rho_0 g_0 a}\iiint \Delta p(\theta,\lambda,t) P_n^m(\cos\theta) \left\{ \begin{array}{c} \cos m\lambda \\ \sin m\lambda \end{array} \right\} ds \tag{6}$$

with $\rho_0 = 5515$ kg/m^3 the mean Earth density, $g_0 = 9.81$ m/s^2 the mean surface density and $a = 6371$ km the mean Earth radius. P_n^m are the fully normalized (4π) Legendre functions.
$k_n^{'}$ are the load Love numbers for potential, computed from PREM (Dziewonski & Anderson, 1981).

3.2 Format of the products

Time-variable gravity field variations are provided for the 3 models (ERA5/IB, ERA5+TUGO-m and ERA5_hydro) and can be found in `http://loading.u-strasbg.fr/ITRF2020/TVGRA/`.

There is one file per hourly time sample with the following name `yyyymmddhh_v001.agc/hgc`, where `yyyy` is the year, `mm` the month, `dd` the day and `hh` the hour. The extension `agc` is used for atmospheric and induced ocean components (ERA5_IB and ERA5_TUGO) and `hgc` for hydrology (ERA5_hydro).

Each file contains a header (8 lines starting with '!'). Then degree (n), order (m), and C_n^m and S_n^m Stokes coefficients up to degree 120 are provided with this `(2I5,2E16.8)` format.

```
! Version:            1.0
! Source:             Atmospheric loading (IB)
! Model:              ERA5
! Data_types:         Stokes coefficients
! Maximum degree      120
! Epoch:              2017 01 01 00 00 0.0
! Data format         N, M, CNM, SNM
! Comment:            http://loading.u-strasbg.fr
    0    0  0.00000000E+00  0.00000000E+00
    1    0  0.00000000E+00  0.00000000E+00
    1    1  0.00000000E+00  0.00000000E+00
    2    0 -0.27158017E-10  0.00000000E+00
    2    1  0.31219638E-10  0.30145438E-10
    2    2  0.40729552E-10  0.30376441E-10
    3    0 -0.14224392E-09  0.00000000E+00
    3    1 -0.51686147E-11 -0.36860636E-11
    3    2  0.55065782E-10 -0.23419348E-10
    3    3  0.22842313E-10 -0.23431606E-10
    4    0  0.23071789E-10  0.00000000E+00
    4    1 -0.32541199E-10 -0.73806641E-10
    4    2  0.50683742E-10 -0.80914615E-11
    4    3  0.20034091E-10  0.81014004E-12
    4    4  0.19805537E-10  0.89526945E-11
```

Figure 4: Example of a time-variable gravity file (ERA5 with IB assumption) (`2017010100_v001.agc`).

4 Geocenter motions

4.1

$$x(t) = \frac{3\left(1+k_1^{'}\right)}{4\pi\rho_0 g_0}\iint \Delta p(\theta,\lambda,t)\sin\theta\cos\lambda ds \tag{7}$$

$$y(t) = \frac{3\left(1+k_1^{'}\right)}{4\pi\rho_0 g_0} \iint \Delta p(\theta,\lambda,t)\sin\theta\sin\lambda ds \tag{8}$$

$$z(t) = \frac{3\left(1+k_1^{'}\right)}{4\pi\rho_0 g_0} \iint \Delta p(\theta,\lambda,t)\cos\theta ds \tag{9}$$

with $k_1^{'} = 0.0256$ (Wu et al., 2002; Blewitt, 2003; Swenson et al., 2008), $\rho_0 = 5515$ kg/m^3 the mean Earth density and $g_0 = 9.81$ m/s^2 the mean surface density.

Figures 5 and 6 show the geocenter motion due atmospheric and induced oceanic loading (ERA5/IB and ERA5/TUGO) and respectively hydrological loading.

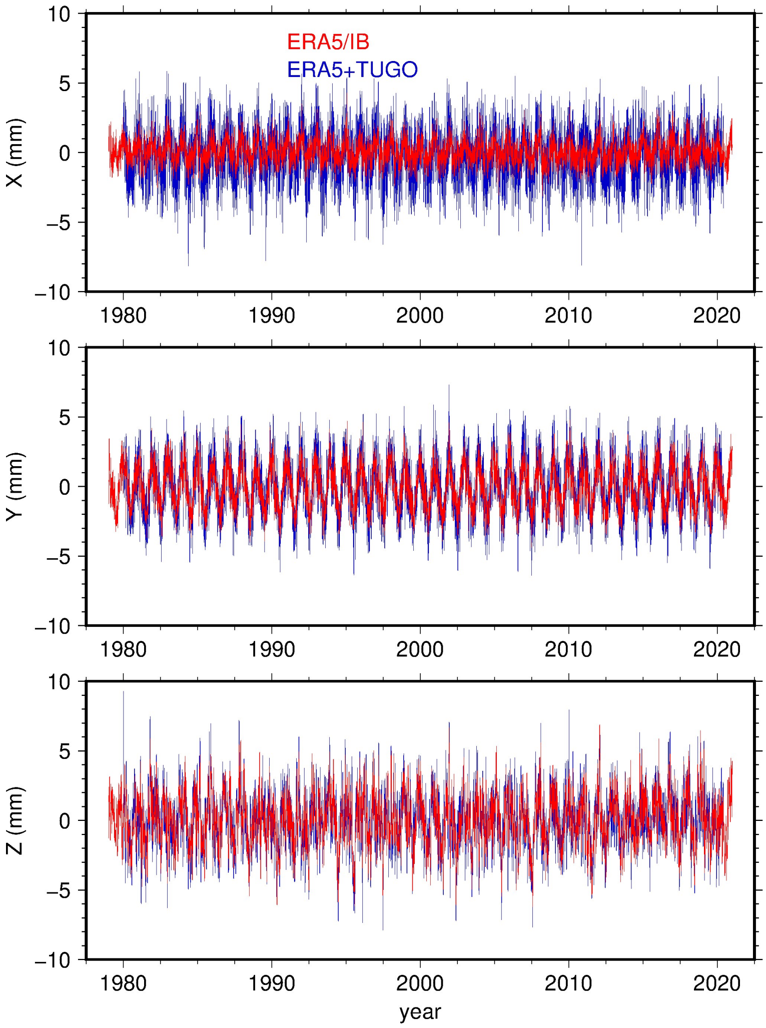

Figure 5: Geocenter motions due to atmospheric and induced ocean loading (ERA5/IB and ERA5/TUGO).

4.2 format of the products

Geocenter products are available at: `http://loading.u-strasbg.fr/ITRF2020/geocenter/`. Files are provided as ascii files with a header (lines starting with '!'), and then time (in modified julian days) and X, Y and Z in mm (format `(F15.7,3F10.4)`).

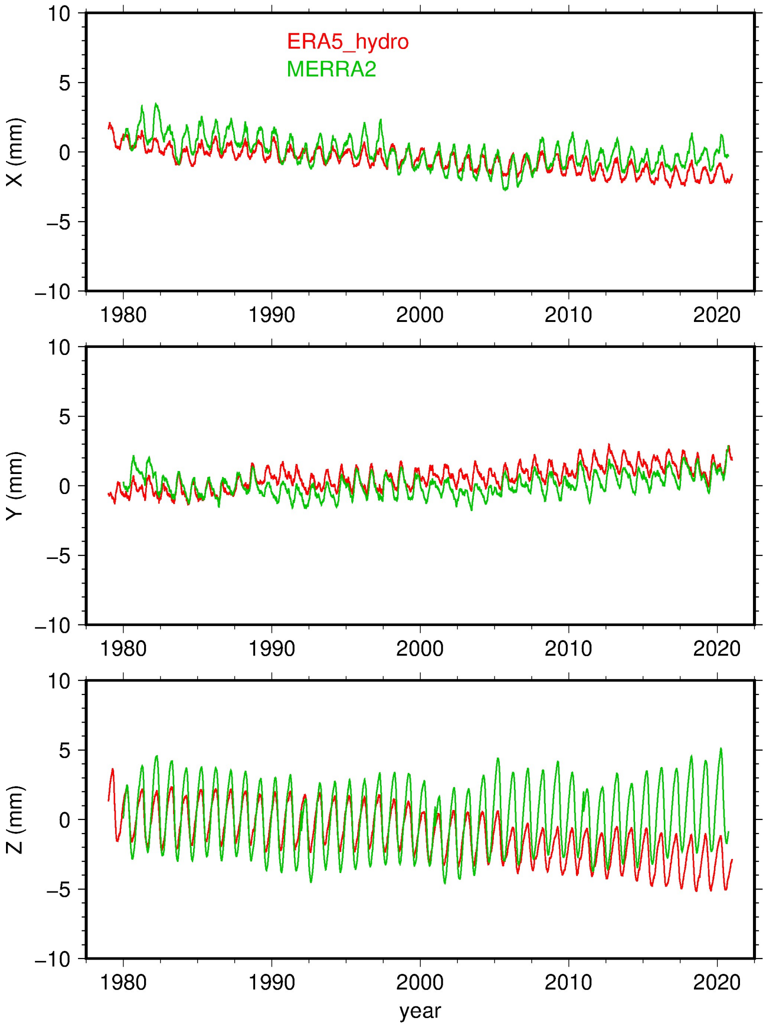

Figure 6: Geocenter motions due to hydrological loading (ERA5) and comparison with MERRA2 hydrology model (Gelaro et al., 2017).

References

[1] Blewitt, G., 2003. Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth, J. Geophys. Res., 108, 2103, doi: 10.1029/2002JB002082.

[2] Carrère, L. & F. Lyard, 2003. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations, Geophys. Res. Lett., 30, 1275, doi: 10.1029/2002GL016473.

[3] Dziewonski, A. M. & D. L. Anderson, 1981. Preliminary Reference Earth Model, Phys. Earth Planet. Inter., 25, 297-356, doi: 10.1016/0031-9201(81)90046-7.

[4] Farrell, W. E., 1972. Deformation of the Earth by surface loads, Rev. Geophys., 10, 751-797, doi: 10.1029/RG010i003p00761.

[5] Gelaro, R., et al., 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), J. Climate, 30, 5419-5454, doi: 10.1175/JCLI-D-16-0758.1.

[6] Hersbach, H. et al., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol Soc., 146, 1999-2049, doi: 10.1002/qj.3803.

[7] Mémin, A., J.-P. Boy & A. Santamaria-Gomez, 2020. Correcting GPS measurements for non-tidal loading, GPS Solut., 24, 45, doi: 10.1007/s10291-020-0959-3.

[8] Petrov, L. & J.-P. Boy, 2004. Study of the atmospheric pressure loading signal in VLBI observations, J. Geophys. Res., 109, B03405, doi: 10.1029/2003JB002500.

[9] Ray, R. D. & R. M. Ponte, 2003. Barometric tides from ECMWF operational analyses, Ann. Geophys., 21, 1897-1910, doi: 10.5194/angeo-21-1897-2003.

[10] Swenson, S., D. Chambers & J. Wahr, 2008. Estimating geocenter variations from a combination of GRACE and ocean model output, J. Geophys. Res., 113, B08410, doi:10.1029/2007JB005338.

[11] Wu, X., D. F. Argus, M. B. Heflin, E. R. Ivins & F. H. Webb, 2002. Site distribution and aliasing effects in the inversion for load coefficients and geocenter motion from GPS data, Geophys. Res. Lett., 29 (24), 2210, doi: 10.1029/2002GL016324.