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Effect of the atmospheric pressure on surface displacements

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Summary. Atmospheric pressure variations with periods of some days and months can be considered as loading functions on the Earth's surface and can induce quasi-periodic surface deformations. The influence of such surface displacements is calculated by performing a convolution sum between the mass loading Green's functions and the local and regional barometric pressure data (geographically distribution in a $1^\circ \times 1^\circ$ grid system extending to more than 1000 *km*). The results for 5 stations in Europe show that the average values reach about 22.9-30.2 *mm* depending on the ocean response: the inverted or non-inverted barometer ocean model. The corresponding admittances are 0.576-0.758 *mm/mbar* respectively. The horizontal displacements are not negligible but always smaller. The magnitudes are about 2-3 *mm* for East-West component and 0.5-1.0 *mm* for North-South component.

The results of the dependence on the lateral extension of the pressure load show that the admittance for radial displacement varies from 0.250 *mm/mbar* for a column load of 100 *km* radius to 0.539 *mm/mbar* for a column load of more than 1000 *km* extension. It means that the main contribution of the loads comes from the horizontal distribution of the air pressure in a broad region.

The time dependent effects of the atmospheric pressure are also computed with the two-coefficient correction equations provided by Rabbel & Zschau (1985) using ground pressure data in a $1.125^\circ \times 1.125^\circ$ grid system. The computations demonstrate that the results are in good agreement with those obtained with a convolution sum. It shows that this method can provide us with a good approximation for vertical displacement caused by the deformation of the Earth.

1. Introduction

The local and regional atmospheric pressure variations affect the measurements of the surface displacements through the loading deformation of the solid Earth. The total influence induced by such loads is usually in the order of 20-30 *mm* if a regional pressure change as large as 50 *mbar* appears. The space techniques such as the very long baseline interferometry (VLBI) have already the capability of measuring displacements over long distances to within a few millimeters and the satellite laser ranging (SLR) gives a precision of 1-2 *cm*. The data obtained by these new methods should be an important new source of information on the forces which control tectonic plate motion as well as the crustal deformation of the Earth. Absolute gravity observations used to detect the crustal deformation can achieve *μgal* accuracy corresponding to subcentimetric displacements. It is therefore important to estimate the atmospheric pressure effects on surface displacements in order to correct the observations used in the geophysics and geodesy study field.

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The effect of the atmospheric pressure on surface displacement is caused by the horizontal distribution of the atmospheric masses inducing deformations of the Earth's crust. In recent years, many scientists in geophysical and geodetical research fields payed close attention to the study of the atmospheric pressure effect. Some of methods for computing air pressure corrections on surface displacements as well as the gravity measurements are already discussed in other papers (Warburton & Goodkind 1977, Rabbel & Zschau 1985, De Meyer & Ducarme 1986, Van Dam & Wahr 1987, Merriam 1992, Sun, Ducarme & Dehant 1993, 1994, Van Dam & Herring 1994 and MacMillan & Gipson 1994, $\cdots$).

Rabbel & Zschau (1985) presented the results for the two hypothetical weather systems of radii of 160 km and 1000 km in a modelled atmosphere of thickness of 8.4 km considering one layer for this scale height. They investigated the influence on VLBI results of the deformation of the Earth due to atmospheric loading. They emphasized that the precise air pressure corrections of radial displacements and gravity changes cannot be achieved by using a single regression coefficient. The characteristic wavelengths of the atmospheric pressure distribution have to be taken into account. They used the TCCE method (two-coefficient correction equations) which consists in considering the local pressure at the station and the average of the air pressure variation in the surrounding region of 2000 km, and seting to zero the pressure values on the ocean areas.

Van Dam & Wahr (1987) calculated the effects of the global atmospheric pressure, including those associated with short-term synoptic storms, on surface point positioning measurements and surface gravity observations, by performing a convolution sum between daily, global barometric pressure data and mass loading Green's functions. In the analysis of the distance between radio telescopes determined by very long baseline interfermetry (VLBI) between 1984 and 1992, Van Dam & Herring (1994) suggested that in many of the cases studied there is a significant contribution to the baseline length change due to atmospheric pressure loading. The results from all baselines are consistent with $\sim$ 60% of the computed pressure contribution being present in the VLBI length determinations.

For the calculation of the atmospheric effects on surface displacements, we use the data for the year 1987 from the European Center for Medium-Range Weather Forecasts (*ECMWF*) namely the geographical distribution of isobars in a $1° \times 1°$ grid system extending to more than 1000 km around the station and over 6 layers until 12 km above the Earth's surface. The sampling rate is 6 hours, the longitude is ranging from $-10°$ to $25°$ and the latitude, from $40°$ to $60°$. We also use the ground atmospheric pressure data in a $1.125° \times 1.125°$ grid system. The sampling rate is the same as that in the $1° \times 1°$ grid system, the longitude and the latitude range from $-10.125°$ to $25.875°$ and from $39.375°$ to $60.750°$ respectively.

The purpose of this work is to study the magnitude of the surface displacements induced by the local and regional variations in atmospheric pressure and the effect of the lateral extension, in order to provide the air pressure correction values for high precision displacement measurements in the study of the crustal deformation, tectonic plate motion and so on.

2. Methods of computation

The theory of the loading effect calculation for a given Earth model and for a given load distribution is now standard (Longman 1962). Farrell (1972) constructed the Green's functions to describe the response of an elastic Earth to a point load on its surface. We can then conveniently determine the displacements due to atmospheric load by performing a convolution sum between the local and regional barometric pressure data and the mass loading Green's functions (CONV method). The discrete convolution form is given as

$$\left.\begin{array}{l} U(\Omega,t) \\ V(\Omega,t) \end{array}\right\} = \sum_{i,j=1}^{N,M} L_{j,i}(\Omega',t) \left(\begin{array}{c} u(\psi) \\ v(\psi) \end{array} \right) d\Omega' \quad (1)$$

where $\Omega = \Omega(\theta,\lambda)$ and $\Omega' = \Omega'(\theta',\lambda')$ are the spherical coordinates of the point under investigation and those of the grid element center. θ, λ and θ', λ' denote the colatitudes and longtitudes of the station and of the grid element center. t is the universal time, $d\Omega'$ is the area of the grid element of the load. $U(\Omega, t)$ and $V(\Omega, t)$ are time dependent surface displacements in vertical and horizontal components. $L_{j,i}(\Omega', t)$ indicates the amount of air load on the $(j, i)th$ grid volume around and above the station: the index j corresponds to the number of the atmospheric layer and i, to the sequence number of the grid element. ψ is the angular distance of the station. $u(\psi)$ and $v(\psi)$ represent vertical and horizontal displacements Green's functions. These Green's functions can be determined by load Love numbers h'_n, l'_n

$$u(\psi) = \frac{a}{m_e} \sum_{n=0}^{\infty} h'_n P_n(cos\psi) \qquad (2)$$

$$v(\psi) = \frac{a}{m_e} \sum_{n=0}^{\infty} l'_n \frac{\partial P_n(cos\psi)}{\partial \psi} \qquad (3)$$

where a and m_e are the radius and the mass of the Earth and $P_n(cos\psi)$ are the Legendre function. $\partial/\partial\psi$ represents the differential with respect to the angular distance ψ. The Green functions for Gutenberg-Bullen A Earth model are used in our computations according to the determinations published by Farrell (1972). The values of Green's functions which are assigned to each grid element, are functions of the angular distance. Each Green's function is multiplied by atmospheric loads at the points corresponding to the different angular distances and the related results are simply summed together over all the grid elements.

Since the atmospheric pressure changes, which are caused by the passage of low and high pressure fronts, are regional phenomena on the Earth's surface whose scale length ranges from several km to a few thousand of km, it is considered that the responses induced by the loads reflect mainly the corresponding scales of the pressure cells around the observing station. Horizontal changes in atmospheric mass can be inferred from surface atmospheric pressure measurements. Stolz & Larden (1979) suggested that global seasonal fluctuations in barometric pressure would, in general, contribute to less than one centimeter for surface displacement. The largest pressure variations, however, are those associated with synoptic scale storms.

For this reason, the size of each grid unit should depend on its distance to the surface point for which the loading calculations are carried out. At least, in order to obtain more precise results, a subdivision of the volume close to the station must be considered. For example, when the angular distance is less than 5.8° (i.e., about 640 km around the station), the volume is subdivided by a factor of 10 in horizontal directions and by a factor of 5 in the vertical direction.

For the numerical computation of the radial displacement, we used also the TCCE method (two coefficient correction equations) given by Rabbel & Zschau (1985) and the geographically distributed ground pressure data provided by *ECMWF* in a 1.125° × 1.125° grid system. In this method, Rabbel & Zschau performed the loading Green's function convolution with idealized Gaussian pressure distribution $P(r) = P_m exp[-(r/r_0)^2]$, where P_m is the maximum pressure of the distribution and r_0 is the scale length. They emphasized that there is no unique single regression coefficient between the displacement and the local pressure. The estimation of the characteristic wavelengths contained in a pressure distribution is included in this method and the two regression coefficients represent the properties of both the short-wavelength and the long-wavelength loading. The short-wavelength loads are obtained from the measured pressure variation at the surface point under investigation. The long-wavelength contributions are computed by averaging the pressure variation in a surrounding area of 2000 km and setting to zero the pressure changes for the oceanic regions. This is necessary in order to account for the inverted barometer ocean (*IBO*) effect.

3. Results and discussions

The observed air pressure at the station replaces the mean value in the corresponding grid element in order to obtain higher accuracy. From comparison, the maximum difference between the observed local air pressure values, those in the 1° × 1° and those in the 1.125° × 1.125° grid systems reaches 3-5 *mbar* in 1987 when including the synoptic storms. The reason is that the grid center, where the pressure is taken, is not situated exactly at the station (see Sun He-Ping et al 1993). We checked the importance of this effect on displacement and on gravity. We found a maximum peak to peak amplitude difference of 0.44 *mm* for the vertical displacement which, compared with the maximum peak to peak values, provides us with a 1-2% discrepancy before and after replacing the grid average data by the station pressure data in the corresponding grid element.

The surface displacements caused by atmospheric pressure, calculated by executing a convolution sum between mass loading Green's functions and the local and regional barometric pressure data (geographically distribution extending to more than 1000 *km* around the station and over 6 layers until about 12 *km* above the Earth's surface), are listed in table 1. For a grid element column, as only the total changes of the atmospheric mass over this column are required when computing the displacements, only the surface pressure is needed. When using the isobar approach, we must add together the effects caused by the different changes in mass at the different heights in the column considered. The results show that the average maximum peak to peak amplitude for 5 stations in Europe is 22.9 *mm* and the corresponding admittance is about 0.576 *mm/mbar* for an IBO model. The horizontal displacements are not negligible but always smaller: the maximum peak to peak magnitudes are about 2-3 *mm* for the East-West (EW) component and 0.5-1.0 *mm* for the North-South (NS) component.

Surface displacements are calculated by using both the inverted barometer ocean (IBO) hypothesis and the non-inverted barometer ocean (NIBO) hypothesis. In the IBO model, the ocean is often assumed to behave as an 'inverted barometer', i.e., an increase in barometer pressure leads to a depress in sea level in the static ratio of 1.01 *cm/mbar*. This implies that the ocean basins experience none of the forces associated with barometric pressure fluctuations and is equivalent to setting the total incremental mass load over the ocean basin equal to zero. The NIBO model provides larger estimates of atmospheric loading effects. The results show that the average maximum peak to peak amplitudes reach 22.9-30.2 *mm* and the corresponding admittances 0.576-0.758 *mm/mbar* in the IBO and the NIBO models respectively (see table 1). However, for the station situated near the coastal lines, such as at Brussels which is close to the Atlantic ocean, the amplitudes of the radial displacement are 26.7-37.0 *mm*, depending on the IBO and the NIBO models, which is much larger than those for continental stations.

The figures 1(a)-(b) show the comparisons between the IBO results and the NIBO results of the surface radial displacement as temporal variations for Brussels' and for Bad Hombourg's stations. The solid line represents the amplitude obtained with the IBO hypothesis and the dashed line represents the one obtained with the NIBO hypothesis. In the figure, there is no physical meaning for the zero line on the vertical axis. We arbitrarily rescale our graphic so that the results at time $t = 0$ are zero. The discrepancy in the results between the two models reaches 10.3 *mm* at Brussels, a coastal station, and 6.4 *mm* at Bad Hombourg, a more continental station. It proves that the load responses at Brussels are significantly affected by inclusion of an IBO or a NIBO model. Van Dam and Wahr already had a similar conclusion between Onsala (Sweden) a coastal station and Boulder (California) a continental station.

The figure 1(c) shows the surface horizontal displacements for the EW component at Brussels for both the IBO model (solid line) and the NIBO model (dashed line). The results show that the effect of the different ocean hypotheses is much smaller for the horizontal components than that for the vertical component.

The effect of the dependence of the surface displacements and admittances on the lateral scales of a atmospheric pressure load at Brussels are also investigated. The results show that the

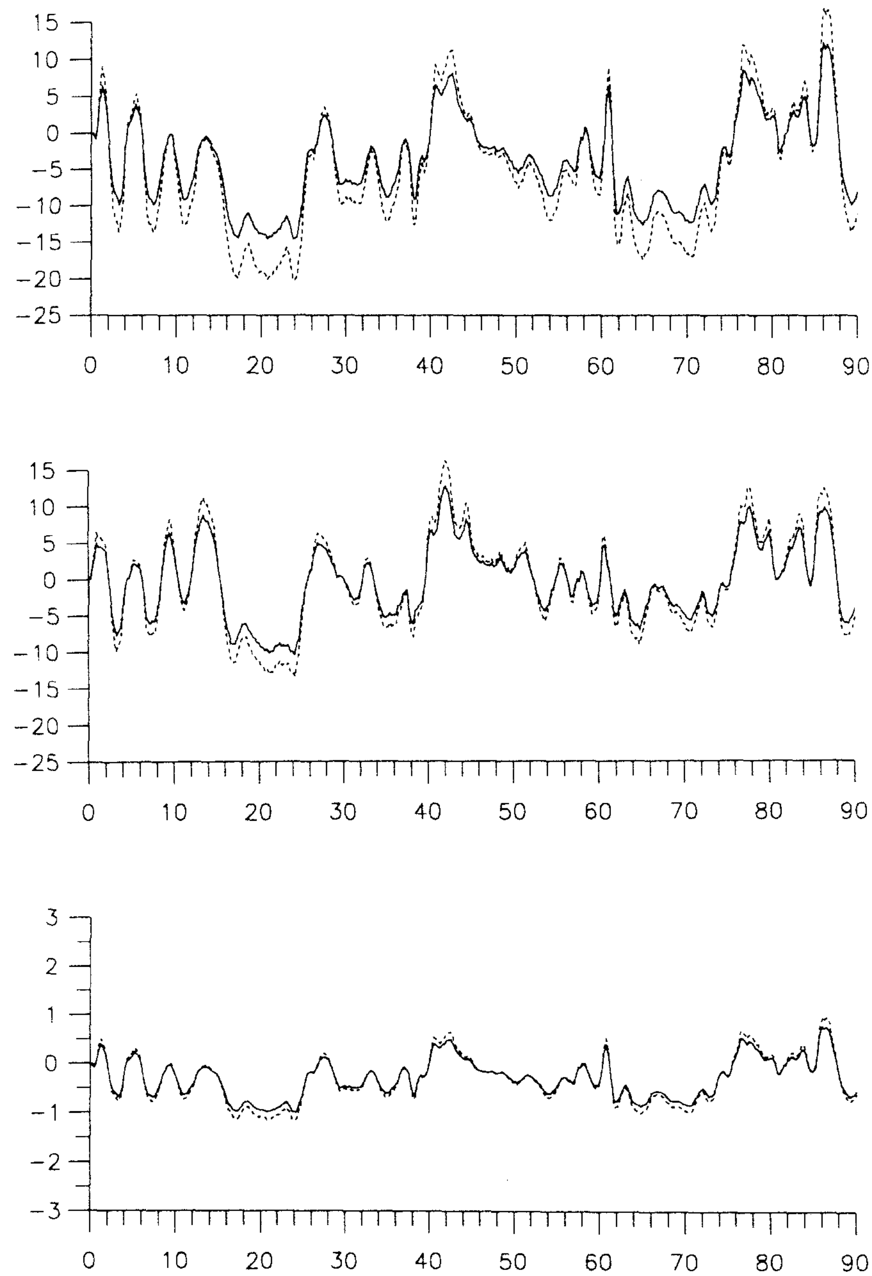

Figure 1: Effect of the oceanic models on surface displacements

Note: The abscissa is the time in *days* and the ordinate are surface displacements in *mm*. The begin time is January 1, 1987. The solid line represents the results obtained in the case of the *IBO* model and the dashed line are those obtained in the case of the *NIBO* model. (a) and (b) are the vertical displacement at station of Brussels and of Bad Hombourg. (c) are the horizontal displacement (*EW* component) at station of Brussels. The results are obtained by using the data from the $1^\circ \times 1^\circ$ grid system and with a *CONV* method.

maximum peak to peak amplitude is increasing from 12.3 *mm* to 26.7 *mm* when considering a column load of 100 *km* radius or an area of more than 1000 *km* extension. The corresponding admittance ranges from 0.250 to 0.539 *mm/mbar* respectively for an IBO model. Table 2 shows the maximum peak to peak amplitudes and the admittances of the vertical and horizontal components in surface displacements as a function of the lateral scales. The pressure values are set to zero at all the grid elements outside the defined radius. From this table, one can see that the surface displacement is mainly caused by the horizontal distribution of the air pressure flutuations in a broad region extending to more than 1000 *km*. Figure 2(a) shows the comparison between the results obtained with a column load of 100 *km* radius and those obtained for a column load of 200 *km* radius, figure 2(b) shows the same kind of comparison between the results obtained with a column load of 100 *km* radius and those obtained for a column load of more than 1000 *km* radius. This is done in order to verify the temporal evolution of the amplitude of the radial displacement.

The radial displacement induced by atmospheric pressure is also calculated with the TCCE method using the ground pressure in a $1.125° \times 1.125°$ grid system. The average maximum peak to peak amplitude for 5 stations is about 23.0 *mm* (table 3). Figure 3 gives a comparison between the results obtained with both the TCCE and those obtained with the CONV methods for Brussels' station. One can see that there exists generally a good agreement between the results obtained with these two different methods. It proves that the TCCE method can provide us with a good approximation in the calculation of the vertical displacement caused by atmospheric pressure fluctuations. This conclusion is also confirmed by the results published by Van Dam & Wahr (1987).

The results obtained by us agree generally quite well with earlier theoretical studies of atmospheric pressure loading and VLBI data analysis found in publications. The observed small discrepancies may have different causes: (1) the model of the atmosphere used for calculation, (2) the time and space intervals of the observations, (3) the extension of the region where the regional and global air pressure are considered, (4) the scale height of the atmosphere, including the division of the atmosphere into different layers, (5) the distance of the station to the oceanic areas, (6) the treatment for the subdivision of the grid elements near the station.

4. Conclusions

The surface displacements induced by the local and regional air pressure changes can be calculated with the accuracy requested in present measurement techniques, such as VLBI or SLR, by performing a convolution sum between mass loading Green's functions and the barometric pressure isobar data (geographically distributed in a $1° \times 1°$ grid system extending to more than 1000 *km* around the station and until about 12 *km* above the Earth's surface) or ground pressure data (in a $1.125° \times 1.125°$ grid system extending to more than 1000 *km* around the station).

The average maximum peak to peak amplitudes of the radial displacements for 5 stations in Europe can reach 22.9-30.2 *mm* depending on the IBO and the NIBO hypotheses for the ocean response. The corresponding admittances are 0.576-0.758 *mm/mbar* respectively. From the magnitude of these effects, it is clear that it is necessary to take into account the correction of the atmospheric pressure in surface point position measurements and baseline measurements.

The calculations of the surface displacements due to the pressure are mainly influenced by the lateral extension of the considered load. For Brussels' station, the admittance varies from 0.250 *mm/mbar* for a load of 100 *km* radius to about 0.539 *mm/mbar* for a column load of 1000 *km* or more. We conclude that in the calculation of the surface displacements, it is necessary to consider a column load of at least 1000 *km* around the station. In the future we want to use the spherical harmonic coefficients of the global

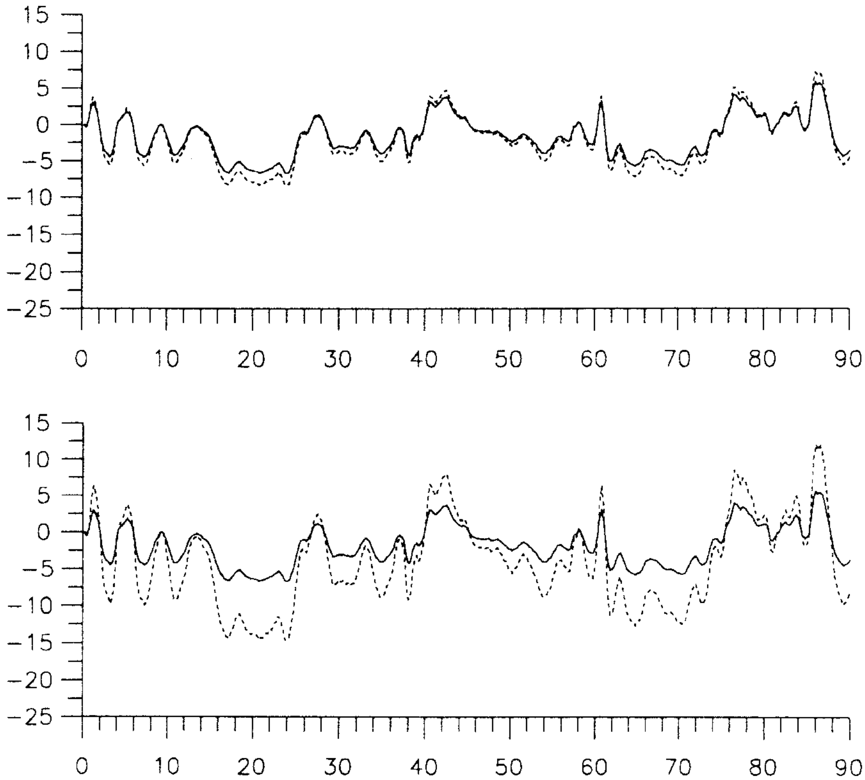

Figure 2: Effect of the lateral scale on displacemnet

Note: The abscissa is the time in *days* and the ordinate is displacement in *mm* at station of Brussels. The begin time is January 1, 1987. (a) shows the comparison between the results obtained with a column load of 100 *km* radius and those obtained for a column load of 200 *km* radius (b) shows the same kind of comparison between the results obtained with a column load of 100 *km* radius and those obtained for a column load of more than 1000 *km* radius. The results are obtained by using the data from the 1° x 1° grid system and with a *CONV* method in the case of the *IBO*.

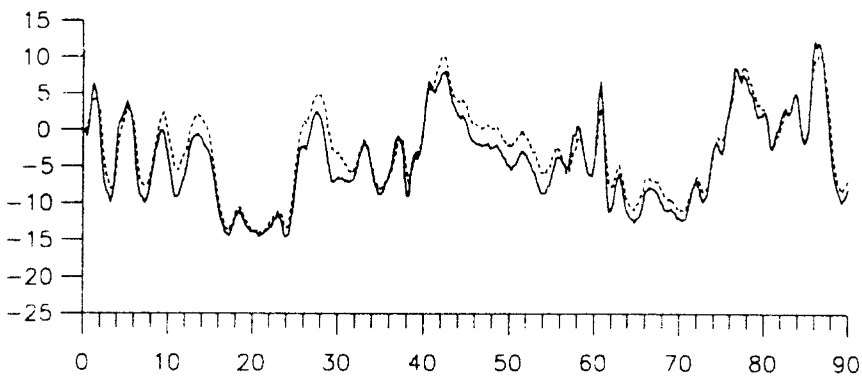

Figure 3: Comparison of the calculation methods

Note: The abscissa is the time in *days* and the ordinate is radial displacement in *mm* at station of Brussels. The begin time is January 1, 1987. The solid line represents the results calculated with *CONV* method in the case of an *IBO* model and the dashed line are those obtained with the *TCCE* method.

Table 1: Results of the CONV method

model	station name	radial		horizontal			
		U	ad.	EW	ad.	NS	ad.
IBO	Brussels	26.654	0.539	1.764	0.036	0.771	0.016
	Luxembourg	24.179	0.629	1.321	0.034	0.474	0.012
	Strasbourg	19.736	0.544	1.214	0.033	0.606	0.017
	Bad Hombourg	22.971	0.536	2.710	0.063	1.005	0.023
	Wettzell	20.954	0.631	0.139	0.004	0.224	0.006
	average	22.899	0.576	1.430	0.034	0.616	0.015
NIBO	Brussels	36.969	0.748	2.127	0.043	0.138	0.003
	Luxembourg	31.921	0.828	1.247	0.032	0.600	0.016
	Strasbourg	26.268	0.725	1.203	0.033	0.133	0.004
	Bad Hombourg	29.415	0.687	2.837	0.066	0.442	0.010
	Wettzell	26.569	0.800	0.178	0.005	0.471	0.014
	average	30.228	0.758	1.518	0.036	0.357	0.009

Note: The *IBO* corresponds to an inverted barameter ocean hypothesis and the *NIBO* to a non-inverted barometer ocean hypothesis. The pressure data in 1987 in $1^{\circ} \times 1^{\circ}$ gird system are used. U, EW and NS represent the radial, east-west and north-south components in *mm*. *ad.* is the admittance between the corresponding component of the surface displacements and the local pressure in *mm/mbar*.

Table 2: Effect of the lateral scale

radius in *km*	radial		horizontal			
	U	ad.	EW	ad.	NS	ad.
100	12.341	0.250	1.872	0.0378	1.658	0.0335
200	15.372	0.311	1.685	0.0341	1.699	0.0344
300	17.998	0.364	1.690	0.0342	1.732	0.0350
400	19.465	0.394	1.600	0.0324	1.555	0.0315
500	20.767	0.420	1.569	0.0317	1.467	0.0296
600	21.693	0.439	1.554	0.0314	1.398	0.0283
700	22.719	0.460	1.563	0.0316	1.324	0.0268
800	23.648	0.478	1.580	0.0320	1.231	0.0249
900	24.519	0.496	1.608	0.0325	1.172	0.0237
1000	25.205	0.510	1.616	0.0327	1.094	0.0221
all grid	26.654	0.539	1.764	0.0357	0.771	0.0156

Note: The results are calculated with the *CONV* method. The pressure values are set to zero at the grid elements outside the defined distance from the station. U, EW and NS represent the radial, east-west and north-south displacement components in *mm*. *ad.* is the admittance between the displacement and the local pressure at the station of Brussels in *mm/mbar*.

Table 3: Results of the TCCE method

No.	station name	ϕ	λ	h	U	ad.
304	Brussels	59.799	4.358	101.0	24.678	0.571
347	Luxembourg	49.665	6.158	295.0	23.652	0.589
390	Strasbourg	48.620	7.870	138.0	22.839	0.649
410	Bad Hombourg	50.229	8.611	190.0	21.713	0.579
495	Wettzell	49.146	12.879	612.0	21.836	0.629
	average				22.944	0.603

Note: The results are calculated with the two-coefficient correction equations (*TCCE*) provided by Rabbel and Zschau (1985). Only the ground pressure data in 1987 are used in the $1.125^{\circ} \times 1.125^{\circ}$ grid system. ϕ, λ, h represent the coordinates (latitude, longtitude and height) of the station. U represents the surface vertical displacement in *mm* and *ad.* is the admittance between the displacement and the local pressure in *mm/mbar*.

surface pressure obtained from SBAAM (Sub-Bureau for Atmospheric Angular Momemtum) in order to calculate the corresponding global atmospheric pressure effect in the evaluation of the influence of the loading further than 1000 *km* from the station. To this aim we will compare the results obtained from a column load of 1000 *km* and those obtained from a load expressed in spherical harmonics and situated in a zone larger than 1000 *km*.

The results obtained with the TCCE method provided by Rabbel & Zschau (1985) agree with those obtained with the CONV method for the radial displacement except for some small differences. This conclusion is also confirmed by the results published by Van Dam & Wahr (1987). According to our analysis as well as the results found in publications, we emphasize that the discrepancies may have different causes, such as the model of the atmosphere, the time and space intervals of the pressure data, the scale height, the lateral scale of the load considered, the distance of the station to the ocean areas and the treatment for the subdivision of the grid elements near the station.

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