Effects of Global Mean Atmospheric Pressure Variations on Mean Sea Level Changes from TOPEX/Poseidon

J. DORANDEU AND P. Y. LE TRAON

CLS Space Oceanography Division, Ramonville St. Agne, France

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ABSTRACT

The authors used meteorological pressure fields from the European Centre for Medium-Range Weather Forecasts to calculate a mean global pressure to serve as a reference for an improved inverse barometer correction of altimeter data. These global pressure fields, available every 6 h on a ½ degree grid, enabled the extraction of the dominant mean pressure signals. Then, the effect of an improved inverse barometer correction on TOPEX/Poseidon mean sea level variation was estimated. Different low-pass smoothings of global mean pressure were used with cutoff frequencies ranging from (40 to 2 days)$^{-1}$. Best results were obtained with the (2 days)$^{-1}$ cutoff frequency, which was then used for an improved inverse barometer correction. The improved correction reduces the standard deviation of mean sea level variations (relative to an annual cycle and slope) by more than 20% when compared with standard inverse barometer correction and no correction at all. It also slightly reduces the variance of sea surface height differences at crossover points. The impact of the improved correction on the mean sea level annual cycle and slope is also not negligible.

1. Introduction

Variations in atmospheric pressure affect altimetry-derived sea surface heights via the inverse barometer effect, that is, the static response of the ocean to atmospheric pressure (e.g., Fu and Pihos 1994; Gaspar and Ponte 1997). A detailed review of the theoretical background on atmospheric loading and the oceanic inverted barometer effect is given in Wunsch and Stammer (1997). The inverse barometer effect is normally removed by altimetry users for the study of ocean dynamics because it involves no dynamic processes. For the study of mean sea level (MSL) variations, it is also desirable to remove it for reducing the noise in estimating the part of MSL variation that is not related to atmospheric pressure.

The inverse barometer correction (IBC) that must be subtracted from the sea surface height is simply given by

$$\mathrm{IBC} = -1/\rho g(P - P_{\mathrm{ref}}), \tag{1}$$

where P_{ref} is the global ‘‘mean’’ pressure (reference pressure) over the ocean (ρ is sea water density and g gravity). For most applications, P_{ref} is assumed to be a constant (e.g., 1013.3 mbar). For the study of MSL variations, using a constant P_{ref} creates unrealistic signals: the mean correction is no longer zero, which is not consistent with ocean mass conservation. This is the reason why most users do not apply any inverse barometer correction for MSL studies. MSL estimates are actually obtained from the irregular space/time sampling of the altimetric satellite [e.g., TOPEX/Poseidon (T/P)] and the mean IBC $\langle P\rangle_{\mathrm{TP}} - P_{\mathrm{ref}}$ ‘‘seen’’ by the satellite is not necessarily zero (which is the assumption made if no inverse barometer correction is applied). To correct for inverse barometer, we must therefore use a nonconstant reference pressure that is different from the mean pressure estimated along the satellite tracks.

The goal of this study is to estimate the gain achieved by using a nonconstant reference pressure for the inverse barometer correction, in terms of reduction of MSL estimation noise. The European Centre for Medium-Range Forecasts (ECMWF) meteorological pressure fields are analyzed, and different types of smoothing of mean pressure are tested to determine how they affect MSL variations (calculated from four years of TOPEX/Poseidon data).

2. Analysis of mean atmospheric pressure signal

ECMWF atmospheric pressure fields, available every 6 h on a ½ degree grid, were area weighted to obtain 6-hourly values of the mean global atmospheric pressure. Figure 1 shows how mean pressure varies with time between January 1993 and the end of December

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Corresponding author address: Dr. J. Dorandeu, CLS, 8-10, rue Hermes, Parc Technologique du Canal, 31526 Ramonville St. Agne, France.
E-mail: dorandeu@cls.fr

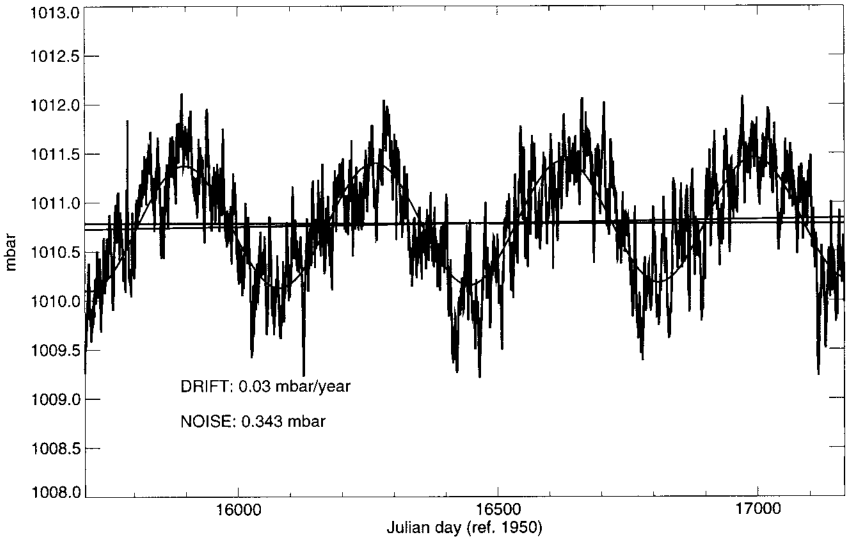

FIG. 1. Global mean pressure (every 6 h) from Jan 1993 to Dec 1996.

1996 (four years). The mean pressure signal is dominated by an annual cycle of around 0.63 mb, with maximum values during the Northern Hemisphere summer. This is because variations in atmospheric pressure are larger in the Northern Hemisphere. The mean pressure slope is around 0.027 mb yr^{-1}. From relation (1), we can see this could affect the MSL slope by 0.2–0.3 mm yr^{-1}, if reference pressure variations are not taken into account.

A mean pressure signal spectrum is given in Wunsch and Stammer (1997). A similar spectrum, but in a variance preserving form, is shown on Fig. 2. The largest amplitudes are obtained for a period of one year (dominant annual signal), and for diurnal and semidiurnal periods (even if the latter cannot be properly determined since it corresponds to the Nyquist frequency). There is a very significant energy for periods between 5 and 30 days. A number of tests were performed by filtering out high frequency signals in order to estimate variance as a function of signal periods. The results of these tests (see Table 1) show that mean pressure signals over periods of a few days represent a significant fraction of the total energy. For example, signals with periods shorter than 10 days account for more than 30% of the total variance (estimated after removing the dominant annual cycle). We therefore need to know to what extent these mean pressure signals affect the mean sea level signal, on a global scale, via an inverse barometer-type response.

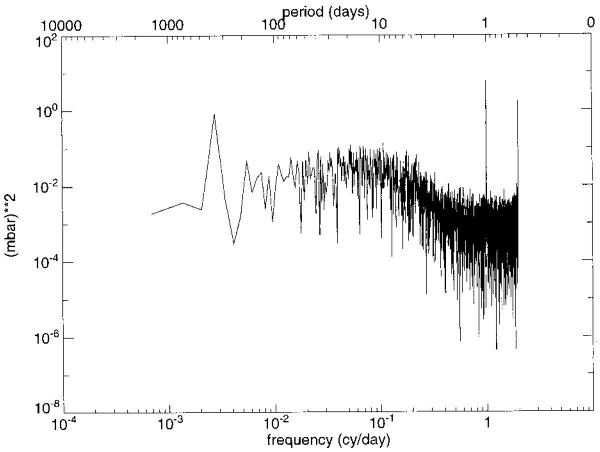

FIG. 2. Variance preserving spectrum of global mean pressure (4 yr).

3. Effects of a nonconstant reference pressure on mean sea level

a. Effect on the standard deviation of mean sea level variations

MSL variations were calculated using four years of TOPEX/Poseidon data. The latest data distributed by AVISO (1996) were used for the period covering cycle 11 to cycle 158 (January 1993 to end of December 1996). Usual editing criteria (Le Traon et al. 1994) and altimetric corrections (see Le Traon and Ogor 1998) were applied. Different inverse barometer corrections

TABLE 1. Variance of mean pressure signals as a function of signal periods relative to total variance (after removing slope and annual signal).

Period	Variance
$0 < T < 2$ days	6.3%
$0 < T < 5$ days	15.1%
$0 < T < 10$ days	31.4%
$0 < T < 20$ days	53.1%
$0 < T < 40$ days	80.4%

TABLE 2. Standard deviation of MSL variations, after fitting a slope and an annual signal, for different types of inverse barometer correction:correction using a constant reference pressure ($P_{\rm ref}$), no correction, and correction using a variable $P_{\rm ref}$ with different low-pass filtering [cutoff frequency from (40 to 2 days)$^{-1}$].

Type of IBC	MSL std dev (cm)
Correction from GDRs ($P_{\rm ref}$ = 1013 mb)	0.537
No correction	0.529
Correction with $P_{\rm ref}$ filtered at (40 days)$^{-1}$	0.468
Correction with $P_{\rm ref}$ filtered at (20 days)$^{-1}$	0.436
Correction with $P_{\rm ref}$ filtered at (5 days)$^{-1}$	0.392
Correction with $P_{\rm ref}$ filtered at (2 days)$^{-1}$	0.391

were tested: 1) the Geophysical Data Record (GDR) inverse barometer correction (i.e., with a constant reference pressure of 1013.3 mb), 2) no inverse barometer correction, and 3) our improved inverse barometer correction using different smoothing of global mean pressure.

We then calculated the sea level anomaly (SLA) relative to the 4-yr mean using a conventional repeat-track analysis. MSL estimates were finally obtained every three days by averaging along-track SLA data using an equiarea weighting. A 3-day mean allows an analysis of short timescales while retaining sufficient global coverage to estimate the mean sea level (the 3-day subcycle samples the whole ocean, but with larger ground-track spacing). A slope and an annual signal were then fitted to these estimates, and the standard deviation was computed relative to this fit. Results obtained for each type of inverse barometer correction are given in Table 2. When applying an inverse barometer correction with a nonconstant reference pressure, the standard deviation is lower than with no inverse barometer correction or with the GDR correction. This shows that using a nonconstant reference pressure corrects for atmospheric pressure effects better. Further, the less we filter the mean global pressure, the more the standard deviation decreases. With a (2 days)$^{-1}$ cutoff, the standard deviation is thus reduced by more than 20%. Estimating the mean sea level over periods of less than three days proves difficult, given the T/P sampling. So the impact of cutoff frequencies higher than (5 days)$^{-1}$ cannot be properly caught using T/P SLA.

b. Effect on variance of crossover differences

Using the same four years of TOPEX/Poseidon data, we selected all crossover points with time lags between 5 and 10 days. This allows us to gauge the impact of mean atmospheric pressure variations over a few days, while limiting the effects of ocean variability. The gain in variance achieved for the full dataset by applying a nonconstant reference pressure [frequencies higher than (2 days)$^{-1}$ were filtered out from global mean pressure series] instead of 1013.3 mb is around 0.2 cm^2. This low but nonnegligible value shows that applying inverse barometer correction using a nonconstant reference pressure improves precision, even for applications other than MSL monitoring.

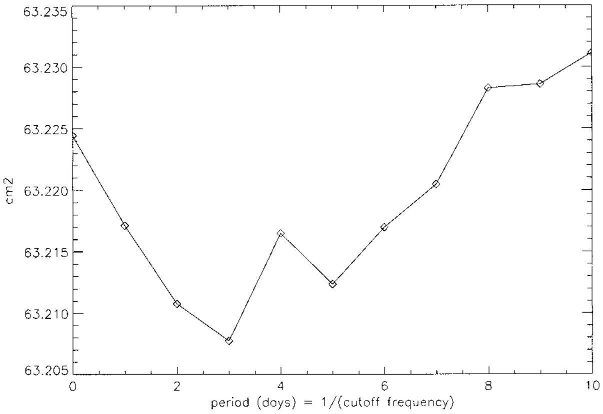

FIG. 3. Impact of mean pressure filtering on variance of 1-day (*ERS-1–ERS-2*) along-track differences.

c. Impact of mean pressure filtering on sea surface height (SSH) variability

We used (*ERS-1–ERS-2*) along-track differences with a 1-day time lag, corresponding to the *ERS-1* and *ERS-2* (CERSAT 1995) tandem phase (more than one year of data from March 1995 to April 1996). Altimetric corrections used for *ERS-1/2* are detailed in Le Traon and Ogor (1998). The explained variance when applying an IBC relative to the case with no IBC, is as large as 30 cm^2. This is less than the variance of the IBC itself, which is about 63 cm^2. The gain in variance shows, however, that an IBC must be applied, even with 1-day differences.

The global mean pressure time series were filtered with different cutoff frequencies varying from (10 days)$^{-1}$ to no filtering at all (i.e., 6-hourly fields). The resulting inverted barometer corrections were then compared. The variance of (*ERS-1–ERS-2*) SSH differences

TABLE 3. Slope, amplitude, and phase of mean sea level variations in three cases (annual signal): 1) GDR inverse barometer correction, 2) no inverse barometer correction, and 3) inverse barometer correction using a nonconstant reference pressure ($P_{\rm ref}$). Phases are in days relative to 1 Jan (i.e., +70 days means maximum occurs on 22 Oct).

		Slope (mm y^{-1})	Ampl. (cm)	Phase (days, ref. 1 Jan)
Standard IBC (case 1)	Global	0.71 ± 0.33	0.81	139
	South	1.15 ± 0.39	1.11	−102
	North	0.07 ± 0.44	3.20	113
No IBC (case 2)	Global	0.95 ± 0.33	0.19	64
	South	0.52 ± 0.53	1.68	−74
	North	1.64 ± 0.66	2.96	99
IBC with variable $P_{\rm ref}$ (case 3)	Global	0.50 ± 0.24	0.43	84
	South	0.94 ± 0.31	1.24	−70
	North	−0.15 ± 0.39	2.92	102

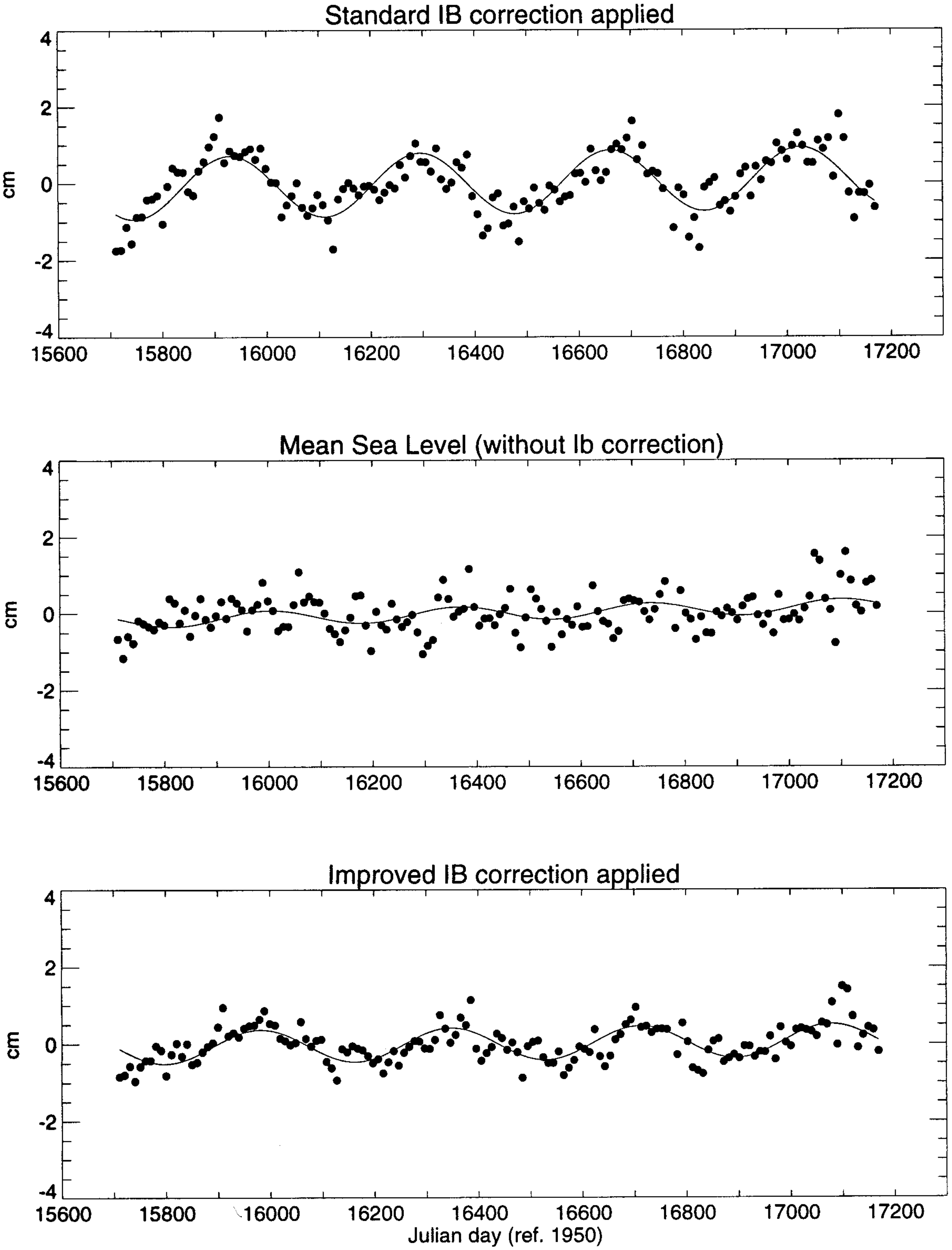

FIG. 4. Mean sea level variations (over 4 yr) using three different inverse barometer corrections.

is plotted on Fig. 3 as a function of cutoff frequencies. Even if only very slight differences are observed (the variances range from 63.208 to 63.231 cm^2), the best results are obtained for (2 and 3 days)$^{-1}$ cutoff frequencies. In the following, we will thus use an improved correction with a mean pressure filtered using a (2 days)$^{-1}$ cutoff frequency, although the above analysis shows that results would be almost the same with a nonfiltered mean pressure.

d. Effects on long period signals of mean sea level variations

To analyze the MSL signals, we built up three time series corresponding to the cycle-by-cycle mean sea level variations obtained from four years of TOPEX/Poseidon data, for the same three cases as in section 3a: standard inverse barometer correction (case 1), no inverse barometer correction (case 2), and inverse barometer correction using a nonconstant reference pressure (case 3) (Fig. 4). As already shown in section 3a, note that dispersion is significantly lower (relative to the slope and annual signal) when applying our improved inverse barometer correction. The impact of the three corrections on the slope and annual signal is summarized in Table 3.

There are first significant variations in the estimated mean sea level slope: values vary by a factor of 2 for cases 2 and 3, which confirms that the influence of a nonconstant reference pressure is important. Furthermore, if we compare cases 1 and 3, we see that the difference is about 0.2 mm yr^{-1}, which is not surprising given the global mean pressure slope. Last, the MSL slope is steeper in the Northern Hemisphere than in the Southern Hemisphere when no inverse barometer correction is applied.

The impact on the MSL annual signal is also nonnegligible. It results from the combination of Northern and Southern Hemisphere annual signals that have large amplitudes, especially in the Northern Hemisphere. When the standard inverse barometer correction is applied, the global MSL annual signal has a large amplitude (around 0.8 cm). In this case, the annual signal from the Northern Hemisphere is less attenuated, as the two hemispheres are not 180° phase-shifted (phase difference is 215 days). The global annual signal for the mean sea level with no inverse barometer correction is not very significant (less than 0.2 cm), and an intermediate value is obtained when a nonconstant reference pressure is applied. The main result of the improved inverse barometer correction is to decrease the annual signal in the Southern Hemisphere, yielding a larger global annual signal. This annual signal comes from the difference between mean pressures as seen by the satellite (due to its space/time sampling) and real mean pressure fields. It is interesting to note that the phases of the annual signals in each hemisphere are very close in the last two cases, but the difference in amplitude in the Southern Hemisphere produces a global phase difference of around 20 days.

4. Conclusions

This study demonstrates the importance of taking the mean pressure effects into account when applying inverse barometer correction. The impact on estimated MSL variations is nonnegligible. The estimated slope calculated from four years of TOPEX/Poseidon data varies by as much as 0.5 mm yr^{-1}, depending on the type of inverse barometer correction used. The improved inverse barometer correction also impacts on the estimation of the annual signal amplitude (0.4 cm instead of 0.2 cm without inverse barometer correction) and phase (shift of 20 days). This improved correction reduces the standard deviation of the mean sea level variations (relative to an annual cycle and a slope) by more than 20% and reduces the crossover difference variance of around 0.2 cm^2. We thus recommend use of such an improved inverse barometer correction in the future.

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