Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide

G. WÖPPELMANN[1], B. MARTIN MIGUEZ[2], M-N. BOUIN[3], Z. ALTAMIMI[3]

[1] *University La Rochelle, CLDG, Av. Michel Crépeau, 17042 La Rochelle, France*

[2] *University of Vigo, Spain*

[3] *Institut Géographique National, Saint-Mandé, France*

Corresponding author : Guy Wöppelmann

Tel: +33 5 46 45 86 13
Fax: +33 5 46 45 82 49

Email: gwoppelm@univ-lr.fr.fr

Abstract.

The problem of correcting the tide gauge records for the vertical land motion upon which the gauges are settled has only been partially solved. At best, the analyses so far have included model corrections for one of the many processes that can affect the land stability, namely the Glacial-Isostatic Adjustment (GIA). An alternative approach is to measure (rather than to model) the rates of vertical land motion at the tide gauges by means of space geodesy. A dedicated GPS processing strategy is implemented to correct the tide gauges records, and thus to obtain a GPS-corrected set of 'absolute' or geocentric sea level trends. The results show a reduced dispersion of the estimated sea level trends after application of the GPS corrections. They reveal that the reference frame implementation is now achieved within the millimetre accuracy on a weekly basis. Regardless of the application, whether local or global, we have shown that GPS data analysis have reached the maturity to provide useful information to separate land motion from oceanic processes recorded by the tide gauges or to correct these latter. For comparison purposes, we computed the global average of sea level change according to Douglas (2001) rules, whose estimate is 1.84 ± 0.35 mm/yr after correction for the GIA effect (Peltier 2001). We obtain a value of 1.31 ± 0.30 mm/yr, a value which appears to resolve the 'sea level enigma' (Munk 2002).

Key words: *Sea-level change, Vertical land motion, Tide gauge, GPS, ITRF.*

1. Introduction

Trends in global sea-level over the last century have been estimated based upon tide gauge records with near global coverage (e.g. Gornitz et al. 1982, Barnett 1984, Douglas 1991, 1997, 2001, Church et al. 2004). Satellite altimetry records only inform on the last 15-years or so; a time span obviously too short to derive estimates for the rise in sea level on a century time scale. Several additional decades of measurements with T/P-like radar altimeter missions are required to allow definitive conclusions on the low-frequency global sea-level changes to measure the acceleration of global sea level rise (Nerem and Mitchum 2001, Cazenave and Nerem 2004). However, two important problems arise when using tide gauges to estimate the rate of global sea level rise. The first is the fact that tide gauges measure sea level relative to a point attached to the land which can move vertically at rates comparable to the long term sea-level signal. The second problem is the spatial distribution of the tide gauges, in particular those with long records, which are restricted to the coastlines (see Fig. 1 in Woodworth and Player 2003).

This paper focuses on the first point. The latter problem is only shortly reviewed here, for an extensive discussion and details on both issues, see Pirazzoli (1986), Pugh (1987), Douglas (1991), Emery and Aubrey (1991), for instance. The poor spatial distribution of historical gauges is problematic because of the evidence of regional variability of sea level trends, this being confirmed by satellite altimetry results (e.g. Nerem and Mitchum 2001, Cazenave and Nerem 2004, Holgate and Woodworth 2004). Some authors have attempted to overcome this problem by selecting tide gauge records of a minimum length, e.g. 60 years. Then, even a limited set of poorly distributed tide gauges could filter the decadal and multi-decadal sea level fluctuations that correspond to the redistribution of ocean mass without any change in the total ocean volume. There is, however, some controversy on this major issue, whether global-average sea level change estimates using tide gauges could be really representative of the ‘true’ global mean (e.g. Cabanes et al. 2001, Miller and Douglas 2004, 2006). Though some filtering is expected when the data from the different gauges are averaged, the uncertainty caused by these ocean signals could still be large. To provide definitive conclusions, future research will be useful to know the magnitude of the interannual, decadal, and interdecadal variability of mean sea level at the global scale.

The problem of correcting the tide gauge records for the vertical land motion upon which the gauges are settled has only been partially solved. At best, the analyses so far have included corrections for one of the many processes that can affect the land stability, namely the Glacial-Isostatic Adjustment (GIA) (e.g. Peltier and Tushingham 1989, Trupin and Wahr 1990, Douglas 1991, 1997, 2001, Peltier 2001, Church et al. 2004). However, Woodworth (2003) observes that different GIA models provide very different values in magnitude and sign. Moreover, GIA models do not account for the other sources of vertical land motion that can affect the tide gauges. A few examples of local land motions at individual tide gauge records are given for instance in Pugh (1987) or in Nerem and Mitchum (2001). The situation seems even worse for corrections of tectonic motions by using geological data than for GIA corrections (Gröger and Plag 1993). An alternative approach is to measure (rather than to model) the rates of vertical land motion at the tide gauges by means of space geodesy (Carter et al. 1989, 1994, Neilan et al. 1997, Blewitt et al. 2006). However, this has proven not to be as straightforward as supposed 15-20 years ago.

Our study focuses on the geodetic issue of monitoring the vertical land motions at the tide gauges. It analyses the most recent results that we obtained from the implementation of a dedicated GPS processing strategy at the so-called ULR (Université de La Rochelle, Institut Géographique National) analysis centre consortium (Wöppelmann et al. 2004, 2005) to estimate vertical velocities at each tide gauge with the best possible accuracy to usefully correct relative sea level records. Section 2 briefly describes this GPS processing strategy and its recent updates. The resulting GPS vertical trends are used to correct the tide gauge records, and thus to obtain a GPS-corrected set of ‘absolute’ or geocentric sea level trends (section 3). Since our study focuses on the geodetic tide gauge station stability monitoring issue, we simply adopted the tide gauge analysis approach of one of the most quoted studies, namely Douglas (1991, 1997, 2001) to show up our contribution in this aspect. Section 4 discusses to what extent our approach improves the estimate of the global sea level rise. In particular, we outline the recent performances we have achieved in the implementation of a more stable and accurate reference frame.

2. Data sets and methods

2.1. Tide gauge records

Tide gauge records of annual mean sea level values were selected from the ‘Revised Local Reference (RLR)’ data set of the Permanent Service for Mean Sea Level (PSMSL). These records have been checked and corrected for local datum changes (Woodworth and Player 2003). As stated in the introduction, we adopted the Douglas (1991, 1997, 2001) approach to perform the station selection and to compute the sea level trends. Tide gauge records were rejected if they did not contain more than 85% of valid data and a time span of at least 60 years. The grouping into regions and the method used to compute the averages (regional and global) of relative sea level trends followed that of Douglas (2001) too. The differences with this author’s approach lie in: (a) the length of the records (data up to 2005 was considered) and (b) the requirement of a co-location with a GPS antenna less than about 20 km according to Bevis et al. (2002). The rejection criteria upon the site stability due to land motion were therefore not considered in our study. The subsequent working hypothesis is that we can measure these land motions. Further details on this hypothesis are given in section 3.

2.2. GPS stations and processing

Figure 1 shows the distribution of the 224 GPS stations included in the GPS processing carried out at the ULR analysis centre consortium. Among these stations 160 are less than 15 km from a tide gauge and 92 are stations that are recommended by the International GPS Service (IGS) for the reference frame implementation (Ferland 2005).

Figure 1

Fig.1: Distribution of the GPS stations processed (up to 224, among which 160 are situated less than 15 km from a tide gauge (stars) and 92 (black dots) are included for the reference frame implementation according to Ferland 2005). The labels correspond to the sub-set of stations fulfilling the criteria described in section 2.1 and analysed in section 3.

The GPS data processing is performed using: (i) GAMIT software (King and Bock 2005) for processing on a free network approach the GPS measurements split into several global networks, each with at most 50 stations and (ii) CATREF software (Altamimi et al. 2004) for combining the network solutions into daily and weekly solutions. The GPS data processing employed for the results presented here differs from Wöppelmann et al. (2004, 2005) in the use of:

- absolute antenna phase centre corrections for satellites and receivers (Gendt 2005);
- troposphere VMF or GMF mapping function (Boehm et al. 2006);
- atmospheric pressure loading corrections according to Tregoning and van Dam (2005);

- network extension from 22 (Wöppelmann et al. 2004) to 92 reference frame stations (Ferland 2005).

These changes were implemented in January 2006. The backwards reprocessing of the GPS data set has been performed with the new models from 2005.7 down to 1999.0, which represents a time span of 7.7 years. The processing was accomplished in eight months with the computing facilities available today at the ULR consortium. The weekly solutions that we have obtained are basically sets of station positions with full variance matrices provided in SINEX format (SINEX WG 1996).

2.3. Vertical position time series

To get the time series of vertical positions for a specific station, one can simply extract the corresponding coordinate values from the weekly GPS solutions in the SINEX files. However, it is worth to note that each space geodesy technique, moreover each data analysis within a single technique, defines and realises its own terrestrial reference system. Therefore, a multitude of terrestrial reference frames exist, having systematic differences and bias when one is compared to another. A terrestrial reference frame accurate and stable at the millimetre level is a key issue to ensure a correct geophysical interpretation of our solutions of continuous GPS positions at tide gauges. The use of the International Terrestrial Reference Frame (ITRF) has been recommended for accurate geodetic, geodynamic or oceanographic analysis by an International Association of Geodesy (IAG) resolution adopted in Vienna, in 1991 (Bulletin Géodésique 1991, pp. 192). ITRF2000 is a numerical implementation of the ITRF. It consists of a set of station positions and velocities with the associated covariance matrix, published by the International Earth Rotation and Reference Systems Service

(Altamimi et al. 2002). This specific solution is considered as the “best” datum to be used to express station positions in the ITRF.

There are, however, several ways to express a solution of station positions in a given reference frame like ITRF. Two major methods are: (1) constraining the coordinates of a subset of stations to their ITRF values; (2) applying transformation parameters estimated using a selected subset of ITRF stations, usually these are the seven parameters of the Helmert transformation. Method (1) has the disadvantage of propagating the errors of the constrained values into the network solution. Another disadvantage is that the selected stations will have their coordinates entirely determined (constrained) to their ITRF values, which subsequently prevents carrying out research on high quality stations. The main disadvantage of method (2) is the sensitivity of the estimated transformation parameters to the network configuration, in particular in case of regional networks where systematic errors affect the origin and the scale parameter estimation (Altamimi 2003). We therefore applied an alternative approach in our analysis strategy, the so-called minimum constraints approach. This approach is implemented in the CATREF software and is detailed in Altamimi et al. (2002). It yields to an optimal datum definition that preserves the original characteristics of the solution of station positions.

Considering that significant differences could exist between the reference frame that each analysis realises individually (weekly solution), we chose to construct our time series through the general combination model given in equation (1). The model is derived from the linearized form of an Euclidean similarity of seven parameters : three translations, one scale factor, and three rotations, which is a standard relationship connecting two terrestrial reference frames.

$$\begin{cases} X_s^i = X_{combi}^i + (t_s^i - t_0) \cdot \dot{X}_{combi}^i + T_k + D_k \cdot X_{combi}^i + R_k \cdot X_{combi}^i \\ \quad + (t_s^i - t_k) \cdot \left[\dot{T}_k + \dot{D}_k \cdot X_{combi}^i + \dot{R}_k \cdot X_{combi}^i \right] \\ \dot{X}_s^i = \dot{X}_{combi}^i + \dot{T}_k + \dot{D}_k \cdot X_{combi}^i + \dot{R}_k \cdot X_{combi}^i \end{cases} \tag{1}$$

where for each individual solution s, and each point i, we have position X_s^i at epoch t_s^i and velocity $\dot{X}_s^i$, expressed in a given TRF k. T_k, D_k, R_k are the transformation parameters from the combined solution to each individual frame or solution k and $\dot{T}_k, \dot{D}_k, \dot{R}_k$ their rates.

The results of our global combination process are:

- station positions X_{combi}^i at an epoch t_0 (usually the central epoch of the observation period) and their velocities $\dot{X}_{combi}^i$, both are expressed in ITRF using the minimal constraint approach (Altamimi et al. 2002);
- transformation parameters T_k, D_k, R_k at epoch t_k between the combined solution and each individual frame or solution k.
- post-fit residuals for each station and individual solution included in the combination process.

Note that the station positions and velocities, as well as the transformation parameters are all estimated simultaneously in a single adjustment using the combination model presented in equation (1) and the minimal constraint approach described in Altamimi et al. (2002). The input data are the GPS weekly solutions in SINEX format described in section 2.2.

3. Confronting tide gauge and GPS results

A careful inspection of both the individual tide gauge records and the corresponding co-located GPS time series was conducted prior to any trend computation. The GPS time series editing was based on a graphical tool developed by Xavier Collilieux (IGN) to analyse CATREF outputs from the position time series combination process (section 2.3). It allowed an easy and practical way to identify and to reject outliers, as well as to handle the discontinuities in the time series using the break-wise approach described in Altamimi (2004). Most of the discontinuities are reported in the IGS and could be related to changes in the equipment or earthquakes (Ferland 2006). The data editing was an iterative procedure magnified by the high number of stations taken into account in our global GPS processing (see section 2, figure 1).

Following Blewitt and Lavallée (2002) recommendation, only GPS records greater than 2.5 years were considered so as to minimise the influence of the seasonal signals on the estimated linear vertical velocity. This criteria combined with the tide gauge ones (section 2) resulted in a data set of 28 stations. The average time span of the GPS time series data set is 5.9 years, covering the period 1999.0-2005.7 (table 1).

Two important hypotheses underlie our exercise of combining tide gauge and GPS results to derive 'absolute' trends in sea level: (a) land motions are extremely low-frequency in character so that the current GPS vertical velocities can be applied for the last century, (b) the vertical velocity observed at the GPS station applies to the tide gauge site. The first hypothesis is supported by Douglas (2001) who argues that the very small scatter of the acceleration term estimates for records longer than 50-60 years demonstrates that vertical crustal movement rates are nearly constant at most sites (Douglas 2001, Fig. 3.16, pp. 61). Fig. 2 displays the time series of de-trended GPS weekly vertical positions for five stations, which seemed a priori problematic (they will further be discussed in section 4), but that are representative of the time series variability in the other series. The trends are provided in table 1. The largest residuals about the trend exhibited by some stations, e.g. Nedre Gavle, are cyclic and short enough not to bias the estimation of the trend as was demonstrated by Blewitt and Lavallée (2002). Of course, the danger exists that a change in land motion trend occurred in the past, and longer time series will be welcomed regarding the existence of possible decadal signals. But for the time being there is no evidence in our results to reject the hypothesis. The second working hypothesis obviously weakens with the distance increasing between both observation stations, although Bevis and Merrifield (2002) outline that the critical issue is the relative local stability, not the distance. Vertical motion could indeed be significantly different just at a few metres distance on an unstable peer. On the contrary, GPS and tide gauge stations may be separated by several kilometres as long as the bedrock upon which the instruments are settled undergoes the same vertical motion. In any case, the hypothesis was necessitated here by a lack of levelling data between the GPS antenna and the tide gauge benchmark.

Figure 2

Fig.2: Time series of weekly vertical GPS positions de-trended at Nedre Gavle (Northern Europe), Fernandina and Galveston II (SE North America), Solomon's Is. (NE North America) and Neah Bay (NW North America). The trends are given in table 1. The time series are displayed with arbitrary offsets for presentation purposes (units are in mm).

Table 1 shows the sea level trends obtained from the tide gauge (TG) records and corrected for the vertical land motions with the GPS trends (TG+GPS). The sites are grouped into regions according to Douglas (2001). The sea level trends within a region are expected to be consistent. As a guideline, the table also includes the rates of relative sea level rise due to the GIA, which uses ICE-5Gv1.2 and VM4 models (Peltier 2004), and the corresponding corrected sea level trends (TG-GIA).

Table 1

Table 1: Sea level trends obtained from the tide gauge (TG) records and corrected for the vertical land motions: (i) with the GIA correction (TG-GIA) using the ICE-5Gv1.2 and VM4 models of Peltier (2004) and (ii) with the GPS trends (TG+GPS). The sites are grouped into regions according to Douglas (2001).

4. Discussion

The tide gauge and GPS error estimates are each of comparable size (table 1). These are formal standard deviations derived either from the least squares linear regression adjustment applied to the tide gauge records or from the time series combination process of the weekly GPS position solutions described in section 2.3. The latter error computation is detailed in Altamimi et al. (2002), Appendix 1. These are, however, formal errors which usually appear to be optimistic. The estimation of a realistic error budget is a difficult task because of the many parameters that are involved in the GPS data processing. Inflation factors to multiply the formal standard deviations can be devised upon the serial correlation in the residuals. But this remains more or less a subjective approach to take into account the globally integrated errors caused by the mismodeling of the satellite orbits, the ionosphere or the troposphere propagation, etc., leading to inflation factors ranging from 3 to 8 (e.g. Mitchum 2000, Williams 2003, Nocquet et al. 2005).

The comparison of sea level trends could be taken as a measure to evaluate to what extent our approach improves the estimate of the global sea level rise. The computation of the standard deviation of the GPS-corrected trends from the average value is 1.3 mm/yr, whereas the standard deviation of the individual tide gauge trends without any land motion correction is 2 mm/yr. The dispersion of the estimated sea level trends is thus reduced, and much less variable as a function of location, after the GPS correction. It is also better than those obtained after correcting for the GIA (Peltier 2004): 1.5 mm/yr using ICE-5Gv1.2 and VM4 models for instance. The level of improvement is close to the one expected by the uncertainty introduced by land motion in radar altimeter calibration using tide gauges, currently estimated to be about 0.4 mm/yr (Mitchum 2000). Moreover, a closer look into each region reveals that GPS-corrected trends are generally more homogeneous than GIA-corrected ones (table 1). Figure 3 illustrates this comment in two regions. The GIA correction at Nedre Gavle in the Northern Europe, or at Neah Bay in North West America, leaves a negative sea-level trend which is in disagreement with the other two stations in the region. The GPS correction, on the contrary, provides figures that are much more in agreement within a region. This in turn supports the morphological grouping of tide gauges made by Douglas (2001), which was based on their apparent correlation at low frequencies with their neighbours.

Figure 3

Fig.3: Time series of annual mean sea-level values from: i) tide gauges (left panels); ii) tide gauges corrected for GIA (central panels); and iii) tide gauges corrected with GPS measurements (right panels); in Northern Europe (upper panels) and North West America (lower panels). The time series are displayed with arbitrary offsets for presentation purposes (units are in mm).

In the South-East North America region, the disagreement in the GPS-corrected sea-level trend estimates (table 1) raises the question of the second working hypothesis validity, especially at Fernandina and at Galveston II. It illustrates the danger that exists in attempting to interpret the sea level trend results in the absence of reliable spirit levelling information. In addition, although a short distance separates the GPS antenna from the tide gauge at Solomon's Island (100 m), the structures upon which they are settled could present a differential motion at a rate of around 1 mm/yr. High-precision levelling to monitor the local stability between both the tide gauge and the GPS station is definitely mandatory to validate the hypothesis.

It is worth noting that our results show sea level trends that are somewhat different from one region to another. This, however, does not imply a problem with our analysis. There is indeed no reason to believe that the modern climate change associated with an enhanced greenhouse effect should cause sea level to rise at the same rate everywhere on the planet, in particular if a significant contribution comes from the thermal expansion of the oceans (Church et al. 2001, Levitus et al. 2005).

For comparison purposes, we further computed the global average of sea level change according to Douglas (2001) rules, whose estimate is 1.84 ± 0.35 mm/yr after correction for the GIA effect (Peltier 2001). Despite the slight differences outlined in section 2, we obtained the value of 1.83 ± 0.24 mm/yr after correction for the GIA effect, fortunately close to the above quoted value. When correcting for the GPS vertical velocities, the estimate reduces to 1.35 ± 0.34 mm/yr. Furthermore, our approach allows to include two additional regions, namely 'Northern Europe' and 'NW North America' (see table 1), which were discarded by Douglas (2001) and Peltier (2001) because of land motion uncertainties. In this way we obtained the value of 1.31 ± 0.30 mm/yr. This value agrees well with the sum of the climate contributions obtained by Mitrovica et al. (2006) and Antonov et al. (2005) over the last 50-100 years: 1.4 mm/yr (1 mm/yr from the melting of global land ice reservoirs and 0.4 mm/yr from the thermal expansion of the oceans). Our value is also closer than the previous estimates of about 1.8 mm/yr (Church et al. 2001). Though the differences are within the error bars, further efforts have definitely to be undertaken to understand their origin (thermal expansion, melting ice, terrestrial water storage, etc.).

From a geodetic point of view, to get a better idea of the confidence we attach to our results, we examined the question: how stable and accurate is the reference frame we realised? The accuracy of the vertical component in GPS positioning is indeed very sensitive to the reference frame definition and realisation. We are aiming at a level of performance where serious consideration of the reference frame and its long term stability need to be addressed. A terrestrial reference frame accurate and stable at the millimetre level must be maintained over decades. Figure 4 plots the transformation parameters between each weekly GPS solution and the combined one expressed in the ITRF2000. The attention is focused on the translations and the scale factor. The orientation parameters are of less interest as orientation is purely conventional and has no physical meaning. The left panel plots in Fig. 4 reveal that the reference frame implementation is now achieved within the millimetre accuracy on a weekly basis, and it is probably better for the global solution issued from the combination of the entire weekly SINEX files. As a guideline, the right panels in Fig. 4 show the results that we obtained before updating our GPS processing strategy (see section 2.2), presented in Wöppelmann et al. (2005).

Figure 3

Fig.4: Transformation parameters between each weekly solution and the combined one expressed in ITRF2000 (Altamimi et al. 2002).

5. Conclusions

Munk (2002) stressed that the sum of climate-related contributions to sea level change was low (0.7 mm/yr) compared to the observations over the last 50-100 years (1.8 mm/yr) by referring to this factor 2 difference as the ‘enigma’ of sea level change. Since then, the more recent results now indicate a 1 mm/yr contribution from the melting of global land ice reservoirs (Mitrovica et al. 2006), as well as a 0.4 mm/yr contribution from the thermal expansion of the world ocean (Antonov et al. 2005). We show here an exercise of combining GPS and tide gauge results that reduces the global average sea level rise to 1.3 mm/yr. This appears to resolve the sea level enigma. Moreover, the application of the GPS corrections clearly reduces the standard deviation of the individual tide gauge sea level trends from their mean value, a reduction close to the value anticipated by Mitchum (2000) for the land motion error source in tide gauge calibrations of satellite altimeters. Our corrections assume that the land motions at the tide gauges are linear and uniform over the last 100 years. Nevertheless, this assumption is a step forward than ignoring the land motion source of error or expecting this error to cancel out in the global average. The geodetic monitoring of land motions remains a major scientific issue and an important reason for the development of the TIGA pilot project in relationship with the Global Sea Level Observing (GLOSS) programme (IOC 1997). TIGA stands for “GPS Tide Gauge Benchmark Monitoring”. It is a pilot project of the International GNSS Service (IGS) established in 2001 to analyse GPS data from stations at or near tide gauges on a continuous basis (see Wöppelmann et al. 2004, for a brief review, or the TIGA web pages at http://adsc.gfz-potsdam.de/tiga/index_TIGA.html). A second assumption was necessary in our exercise to apply the vertical velocity observed at the GPS antenna to the tide gauge because of the lack of local high-precision levelling data. This is another key issue that international projects like TIGA and/or GLOSS should address.

As mentioned in section 1, this paper does not enter into the debate of the geographical sampling of historical tide gauge records, a major scientific issue which prevented some authors like Pirazzoli (1986, 1993) or Emery and Aubrey (1991) from providing any estimation of global sea level trend. If the Douglas (1991, 1997, 2001) approach were to be pursued our results argue in favour of installing GPS stations, in particular at the tide gauges previously discarded from the global sea level studies due to land motion considerations. Moreover, whereas the observational information provided by a tide gauge may appear as the most adequate and useful quantity for the coastal management (i.e. a relative sea level height with respect to the underlying land upon which the gauge is settled), to devise any appropriate plan to manage the coastline it is preferable to understand which is the relative magnitude of the mechanisms that potentially underlay the relative sea-level rise (Stewart 1989). Is the relative sea-level rise due to eustatic changes or due to the local land subsidence? To identify the causes of the changes acting at a particular place on the long term time period, monitoring the vertical land motion at the tide gauge becomes mandatory.

An important application or test of the GPS-corrected tide gauge records is the calibration of satellite radar altimeters with tide gauges. Mitchum (2000) reports that vertical land motions remain the dominant error source for determining the altimeter instrument drift using the tide gauges, currently estimated to be about 0.4 mm/yr. He further concludes that the only real long-term solution to this problem is to have geodetic information at each tide gauge used in the analysis. Regardless of the application, whether local or global, we have shown that GPS data analysis have reached the maturity to provide useful information to separate land motion from oceanic processes recorded by the tide gauges or to correct these latter. Future estimates of GPS-corrected tide gauges records will surely improve as the GPS time series get longer.

Although the ULR analysis centre is operational, it is still under development. One of our major technical objectives is to seize its infrastructure to be able to cope with: (1) an increase number of up to 250 stations (reference frame stations and tide gauge co-locations), (2) with the backward processing, to be able to re-process the entire GPS data set as far as possible when new models or strategies are set up. Processing a year of data takes about one month, an unacceptable situation to fulfil objectives like re-processing backwards the entire GPS data set. Solutions are investigated to enhance the GPS computing facilities at ULR in order to reduce the processing time.

Acknowledgements

The work was partly funded by GRGS, which provided a post-doctoral fellowship for B. Martin Miguez. Special thanks are due to Pierre Exertier (GRGS/OCA) and Bernard Simon (GRGS/SHOM). The ULR GPS analysis centre was initially funded by *Conseil Général des Deux Sèvres* and *Région Poitou-Charentes*. We would also like to thank Xavier Collilieux for kindly providing his tools to analyse CATREF outputs. We have to stress that this work was feasible thanks to all the parties involved in the IGS, Stuart McLellan and Pascal Tiphaneau included of course, as well as the tide gauge national authorities for providing sea level data to the PSMSL and the members of POL who contribute to the success of this international service. The significant improvement of the paper occasioned by the remarks of an anonymous reviewer is also gratefully acknowledged.

References

Altamimi, Z., 2003. Discussion on how to express a regional GPS solution in the ITRF. EUREF Publication 12. Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Ponta Delgada, 5-8 June 2002. pp. 162-167.

Altamimi, Z., Boucher, C., Sillard, P., 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. J. Geophys. Res. 107(B10): 2214, doi: 10.1029/2001JB000561.

Altamimi, Z., Sillard, P., Boucher C., 2004. CATREF software: Combination and analysis of terrestrial reference frames. LAREG Technical Note SP08, Institut Géographique National, Paris, France.

Antonov, J.I., Levitus, S., Boyer, T.P., 2005. Thermosteric sea level rise: 1955-2003. Geophys. Res. Lett., 32, L12602, doi: 10.1029/2005GL023112.

Boucher, C., Altamimi, Z., Sillard, P., Feissel, M., 2004. The ITRF2000. *IERS Technical Note n°31*. Online version at http://www.iers.org/iers/publications/tn/tn31/

Barnett, T.P., 1984. The estimation of "global" sea level change: a problem of uniqueness. J. Geophys. Res., 89 (C5), pp. 7980-7988.

Bevis, M., Scherer, W., Merrifield, M., 2002. Technical issues and recommendations related to the installation of continuous GPS stations at tide gauges. Marine Geodesy, Vol. 25, No. 1-2, pp. 87-99.

Boehm, J., Niell, A., Tregoning, P., Schuh, H., 2006. Global mapping function (GMF): a new empirical mapping function based on numerical weather model data. Geophys. Res. Lett., 33, L07304, doi:10.1029/2005GL025546.

Blewitt, G., Lavallée, D., 2002. Effect of annual signals on geodetic velocity. J. Geophys. Res., 107 (B7) doi:1.1029/2001JB000570.

Blewitt, G., Altamimi, Z., Davis, J., Gross, R., Kuo, C., Lemoine, F., Neilan, R., Plag, H-P., Rothacher, M., Shum, C.K., Sideris, M.G., Schöne, T., Tregoning, P., Zerbini, S., 2006. Geodetic Observations and Global Reference Frame Contributions to Understanding Sea Level Rise and Variability, In *Proceedings of the WCRP Workshop* "Understanding Sea-Level Rise and Variability", UNESCO, Paris 6-9 June (2006) 145-170.

Bulletin Géodésique, 1991. IAG Resolutions adopted at the XXth IUGG general assembly in Vienna. Bulletin Géodésique, 65, No. 3, 1991, pp. 192-194.

Cabanes, C., Cazenave, A., Le Provost, C., 2001. Sea level rise during the past 40 years determined from satellite and in situ observations. Science, 294, pp. 840-842.

Carter, W.E., Aubrey, D.G., Baker, T.F., Boucher, C., Le Provost, C., Pugh, D.T., Peltier, W.R, Zumberge, M., Rapp, R.H., Shutz, R.E., Emery, K.O., Enfield, D.B., 1989. Geodetic fixing of tide gauge benchmarks. In *Woods Hole Oceanographic Institution Technical Report*, WHOI-89-31, 44 pp.

Carter, W.E., (Ed.) 1994. Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee. Report of a meeting held 13-15 December 1993 at the Institute of Oceanographic Sciences Deacon Laboratory. *NOAA Technical Report* NOSOES0006. 81 pp.

Cazenave, A., Nerem, R.S., 2004. Present-day sea level change: Observations and causes. Rev. Geophys., 42, RG3001, doi:10.1029/2003RG000139.

Church, J., Gregory, J.A., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., 2001. Changes in sea level. In Climate change 2001: the scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J.T. Houghton et al., pp. 639-693, Cambridge Univ. Press, New York.

Church, J.A., White, N., Coleman, R., Lambeck, K., Mitrovica, J., 2004. Estimates of the regional distribution of sea level rise over the 1950-2000 period. *J. Climate*, 17, pp. 2609-2625.

Douglas, B.C., 1991. Global sea level rise. J. Geophys. Res., 96 (C4), pp. 6981-6992.

Douglas, B.C., 1997. Global sea level rise: a redetermination. Surv. Geophys. Res., 18, pp. 279-292.

Douglas, B.C., 2001. Sea level change in the era of the recording tide gauge. In *Sea Level Rise: History and Conseque*nces, Int. Geophys. Ser., vol.75, edited by B. Douglas, M. Kearney, and S. Leatherman, chap.3, Academic, San Diego, pp. 37-64.

Emery, K.O., Aubrey, D.G., 1991. Sea levels, land levels, and tide gauges. Springer Verlag, 237 pp.

Ferland, R., 2005. IGb00 review - GOUG - YAKT. IGSSTATION-352 of Dec. 31, 2005, available at http://igscb.jpl.nasa.gov/mail/igsstation/2005/msg00035.html

Ferland, R., 2006. Station coordinates time series discontinuities. Last update of the file ALL_ITRF2005.snx, May 2006, available at ftp://macs.geod.nrcan.gc.ca/pub/requests/sinex/discontinuities

Ge, M., Gendt, G. , Dick, G., Zhang, F.P., Reigber, C., 2005. Impact of GPS satellite antenna offsets on scale changes in global network solutions. Geophys Res Lett, 32, L06310, doi: 10.1029/2004GL022224.

Gendt, G., 2005. Switch the absolute antenna model within the IGS. IGSMAIL-5272 of Dec. 19, 2005, available at http://igscb.jpl.nasa.gov/mail/igsmail/2005/msg00193.html

Gornitz, V., Lebedeff, S., Hansen, J., 1982. Global sea level trend in the past century. Science, 215, pp. 1611-1614.

Gröger, M., Plag, H-P., 1993. Estimations of a global sea level trend: limitations from the structure of the PSMSL global sea level data set. Global and Planetary Change, 8, pp. 161-179.

Holgate, S.J., Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990s. Geophys. Res. Lett., 31, L07305, doi:10.1029/2004GL019626.

IOC, 1997. Global Sea Level Observing System (GLOSS) - Implementation plan. Intergovernmental Oceanographic Commission (IOC), Technical Series No. 50.

King, R.W., Bock, Y., 2005. Documentation for the GAMIT GPS Analysis Software. Release 10.2, Mass. Institute of Technology and Scripps Institution of Oceanography.

Levitus, S., Antonov, J., Boyer, T., 2005. Warming of the world ocean, 1955-2003. Geophys. Res. Lett., 32, L02604, doi:10.1029/2004GL021592.

Miller, L., Douglas, B.C., 2004. Mass and volume contributions to twentieth-century global sea level rise. Nature, 428, pp. 406-409.

Miller, L., Douglas, B.C., 2006. On the rate and causes of twentieth century sea-level rise. Phil. Trans. R. Soc. A, 364, pp. 805-820.

Mitchum, G.T., 2000. An improved calibration of satellite altimetric heights using tide gauge sea levels with adjustment for land motion, Mar. Geod., 23, pp. 145-166.

Mitrovica, J.X., Wahr, J., Matsuyama, I., Paulson, A., Tamisea, M.E., 2006. Reanalysis of ancient eclipse, astronomic and geodetic data: a possible route to resolving the enigma of global sea-level rise. Earth an Planetary Science Letters, 243, pp. 390-399.

Munk, W., 2002. Twentieth century sea level: an enigma. Proc. Natl. Acad. Sci. U.S.A., 99(10), pp. 6550-6555.

Neilan, R., Van Scoy, P.A., Woodworth, P.L., (Ed.) 1998. Proceedings of the Workshop on methods for monitoring sea level : GPS and tide gauge benchmark monitoring, GPS altimeter calibration. Workshop organised by the IGS and PSMSL, Jet Propulsion Laboratory, 17-18 March 1997, 202 pp.

Nerem, R.S., Mitchum, G., 2001. Sea level change. In *Satellite altimetry and earth sciences*, Fu and Cazenave, Ed., Academic Press, San Diego, pp. 329-349.

Nocquet, J.M, Calais, E., Parsons, B., 2005. Geodetic constraints on glacial isostatic adjustment in Europe. Geophys. Res. Lett., 32, L06308, doi:10.1029/2004GL022174.

Peltier, W.R., Tushingham, A.M., 1989. Global sea level rise and the greenhouse effect: might they be connected? Science, 244, pp. 806-810.

Peltier, W. R., 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In *Sea Level Rise: History and Consequ*ences, Int. Geophys. Ser., vol.75, edited by B. Douglas, M.Kearney, and S.Leatherman, chap.4, Academic, San Diego, pp. 65-95.

Peltier, W. R., 2004. Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) model and GRACE. Annu. Rev. Earth. Planet. Sci, 32, pp. 111-149, doi:10.1146/annurev.earth.32.08503.144359.

Pirazzoli, P.A., 1986. Secular trends of relative sea-level (RSL) changes indicated by tide gauge records. J. Coastal Res. Spec. Issue 1, pp. 1-26.

Pirazzoli, P.A., 1993. Global sea-level changes and their measurement. Global and Planetary Change, 8, pp. 135-148.

Pugh, D.T., 1987. Tides, surges and mean sea level: a handbook for engineers and scientists. John Wiley & Sons, Chichester, 047191505X.

SINEX Working Group, 1996. SINEX – Solution Independent Exchange format. Appendix 1 in *IGS 1996 Analysis Centre Workshop Proceedings*, Eds. R.E. Neilan, P.A. Van Scoy and J.F. Zumberge, pp. 223-276.

Stewart, R.W., 1989. Sea-level rise or coastal subsidence? Atmos. Ocean, 27 (3), pp. 461-477.

Tregoning, P., van Dam, T., 2005. Atmospheric pressure loading corrections applied to GPS data at the observation level. Geophy. Res. Lett., 32, L22310, doi:10.1029/2005GL024104.

Trupin, A., Wahr, J., 1990. Spectroscopic analysis of global tide gauge sea level data. Geophysical Journal International, 100, pp. 441-453.

Williams, S.D.A., 2003. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. Journal of Geodesy., 76, pp. 483-494.

Woodworth, P.L., 2003. Some comments on the long sea level records from the Northern Mediterranean. Journal of Coastal Research, 19(1), pp. 212-217.

Woodworth, P.L., Player, R., 2003. The Permanent Service for Mean Sea Level: an update to the 21st century. Journal of Coastal Research, 19, pp. 287-295.

Wöppelmann, G., Bouin, M-N., Altamimi, Z., Daniel, L., McLellan, S., 2004. Current GPS data analysis at CLDG for the IGS TIGA Pilot Project. Cahiers du Centre Européen de Géodynamique et de Séismologie, *The state of GPS vertical positioning precision : Separation of earth processes by space geodesy*, ed T. van Dam and O. Francis, v. 23, pp. 149-154.

Wöppelmann, G., Bouin, M-N., Altamimi, Z. 2005. Learning from TIGA global GPS analysis at ULR consortium. Paper presented at the ESEAS Workshop on *Observing and Understanding Sea Level Variations*, Malta, 1-5 November 2004, Rapport interne CLDG No. 06/06, 10 pp.

Figure captions

Fig.1: Distribution of the GPS stations processed (up to 224, among which 160 are situated less than 15 km from a tide gauge (stars) and 92 (black dots) are included for the reference frame implementation according to Ferland 2005). The labels correspond to the sub-set of stations fulfilling the criteria described in section 2.1 and analysed in section 3.

Fig.2: Time series of weekly vertical GPS positions de-trended at Nedre Gavle (Northern Europe), Fernandina and Galveston II (SE North America), Solomon's Is. (NE North America) and Neah Bay (NW North America). The trends are given in table 1. The time series are displayed with arbitrary offsets for presentation purposes (units are in mm).

Fig.3: Time series of annual mean sea-level values from: i) tide gauges (left panels); ii) tide gauges corrected for GIA (central panels); and iii) tide gauges corrected with GPS measurements (right panels); in Northern Europe (upper panels) and North West America (lower panels). The time series are displayed with arbitrary offsets for presentation purposes (units are in mm).

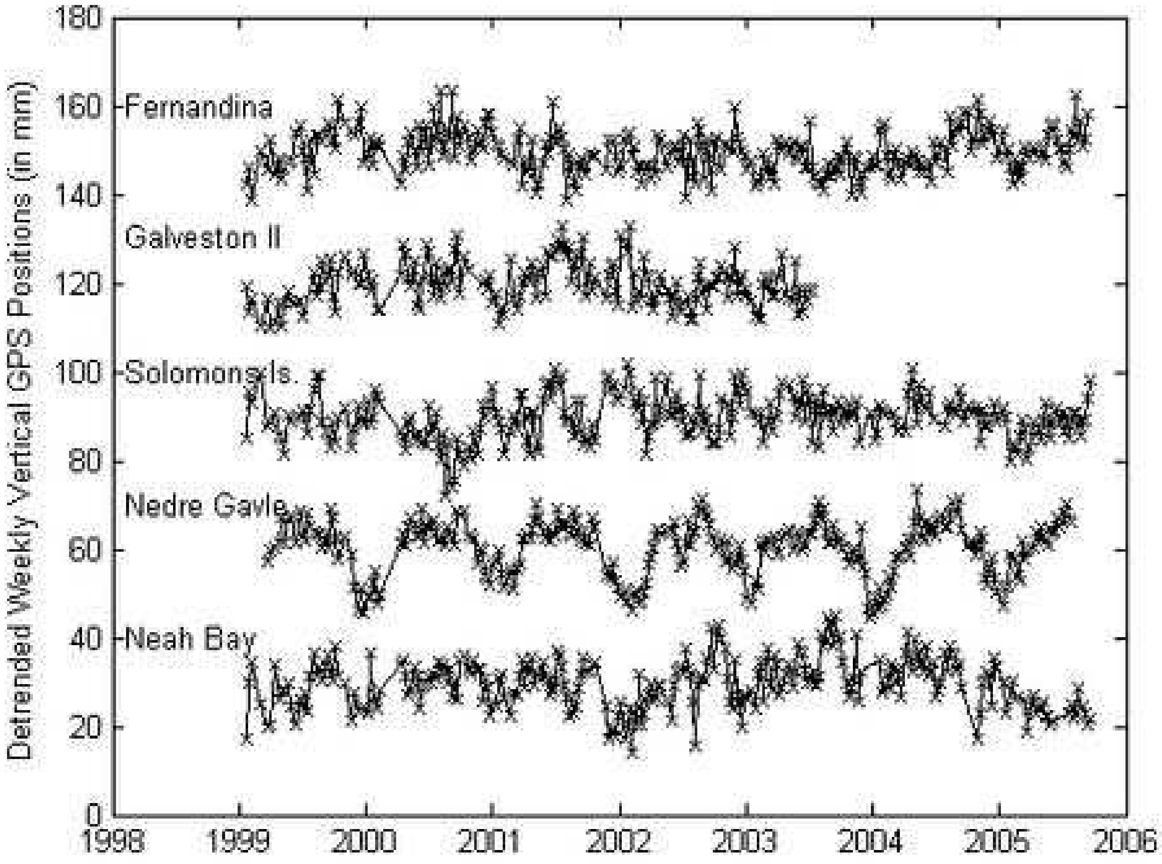
Fig.4: Transformation parameters between each weekly solution and the combined one expressed in ITRF2000 (Altamimi et al. 2002).

Table captions

Table 1: Sea level trends obtained from the tide gauge (TG) records and corrected for the vertical land motions: (i) with the GIA correction (TG-GIA) using the ICE-5Gv1.2 and VM4 models of Peltier (2004) and (ii) with the GPS trends (TG+GPS). The sites are grouped into regions according to Douglas (2001).

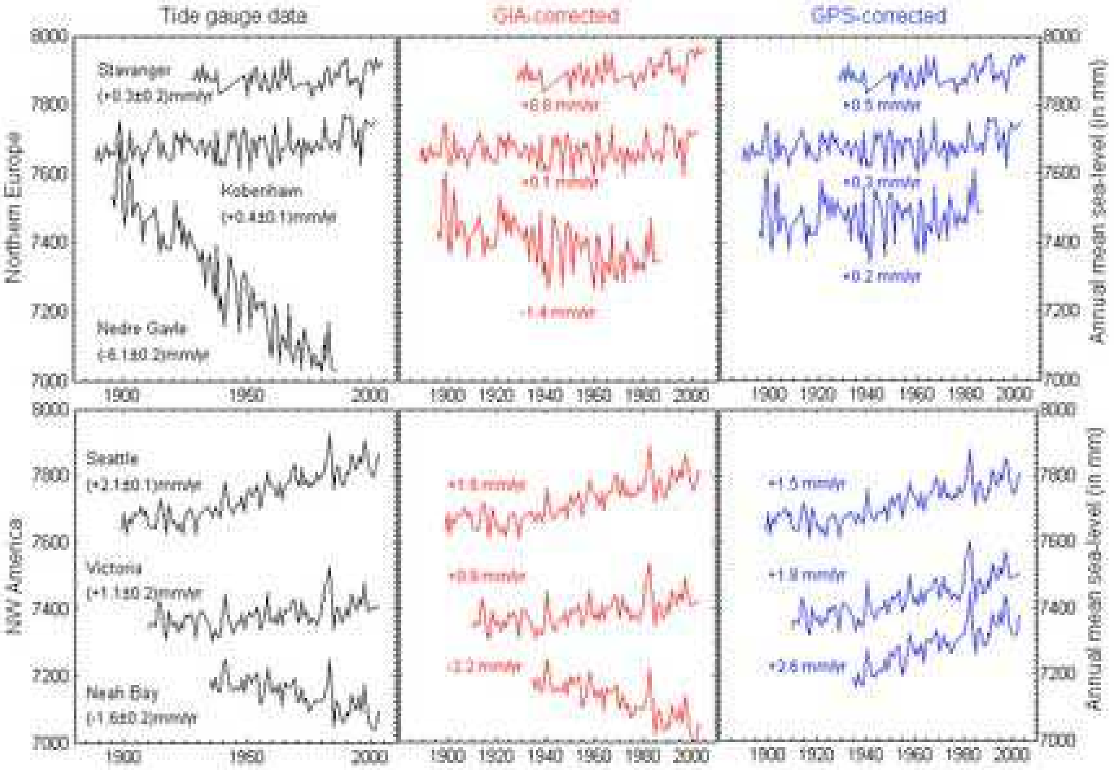
Figure

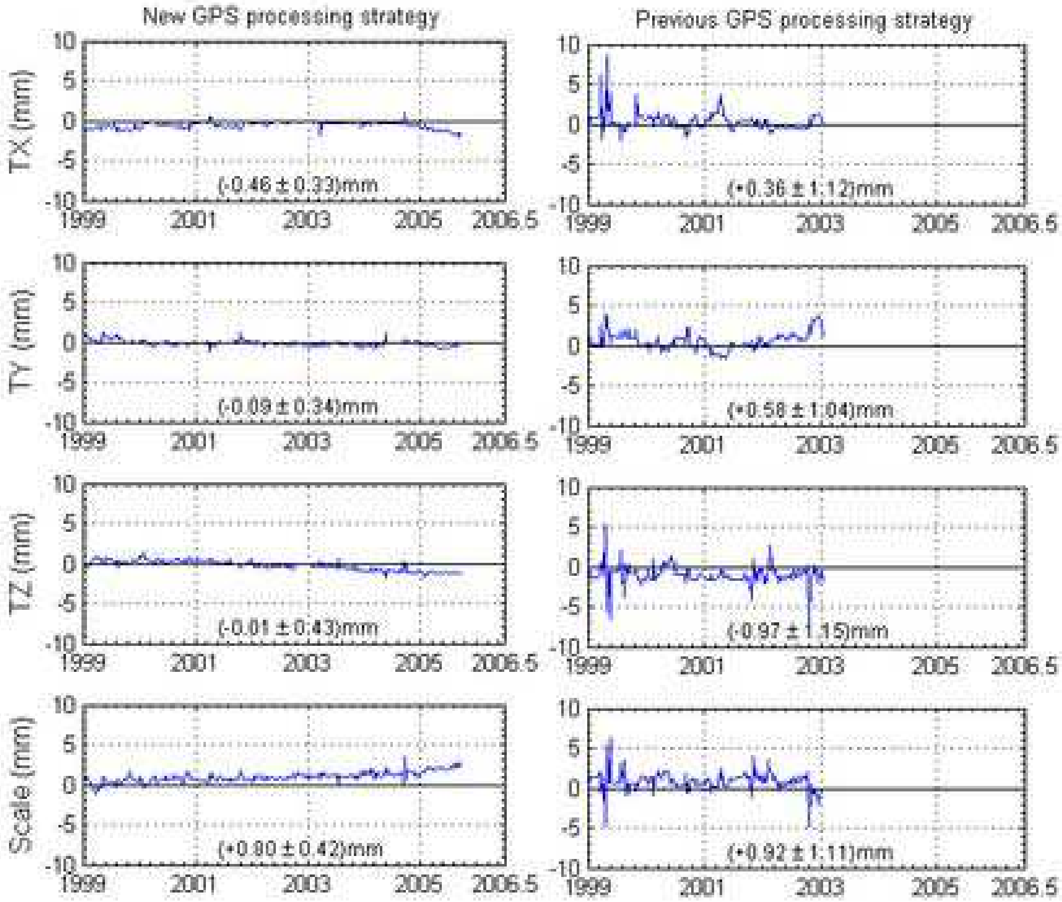
Click here to download high resolution image



Figure

Click here to download high resolution image




New GPS processing strategy
Previous GPS processing strategy
TX (mm)
TY (mm)
TZ (mm)
Scale (mm)
10
5
0
-5
-10
1999
2001
2003
2005
2006.5
(-0.46 ± 0.33)mm
(+0.36 ± 1.12)mm
(-0.09 ± 0.34)mm
(+0.58 ± 1.04)mm
(-0.01 ± 0.43)mm
(-0.97 ± 1.15)mm
(+0.80 ± 0.42)mm
(+0.92 ± 1.11)mm

Table

Table 1.

GROUPS OF STATIONS	**TIDE GAUGES**		**GPS/TG**	**GPS**		**TG+GPS**	**GIA**	**TG-GIA**
NORTH SEA+ENG.CHANNEL	**Span (yr)**	**Trend (mm/yr)**	**Dist. (m)**	**Span (yr)**	**Trend (mm/yr)**	**(mm/yr)**	**(mm/yr)**	**(mm/yr)**
ABERDEEN I+II	103	**0.58** ± 0.10	2	6.7	**0.15** ± 0.11	**0.73**	**-0.77**	**1.35**
NEWLYN	87	**1.69** ± 0.11	10	6.7	**-1.04** ± 0.15	**0.65**	**0.20**	**1.49**
BREST	83	**1.40** ± 0.05	350	6.7	**-1.18** ± 0.12	**0.22**	**0.18**	**1.22**
ATLANTIC								
CASCAIS	97	**1.22** ± 0.10	Unknown	6.7	**-0.58** ± 0.12	**0.64**	**0.03**	**1.19**
LAGOS	61	**1.35** ± 0.18	600	5.3	**-0.32** ± 0.12	**1.03**	**0.09**	**1.26**
MEDITERRANEAN								
MARSEILLE	105	**1.27** ± 0.09	5	6.7	**-0.32** ± 0.22	**0.95**	**-0.07**	**1.34**
GENOVA	78	**1.20** ± 0.07	Unknown	6.6	**-0.26** ± 0.12	**0.94**	**-0.24**	**1.44**
NEW ZEALAND								
AUCKLAND II	85	**1.30** ± 0.13	5	3.9	**1.61** ± 0.28	**2.91**	**-0.29**	**1.59**
LYTTELTON II	48	**2.30** ± 0.21	2	5.8	**1.21** ± 0.14	**3.51**	**-0.34**	**2.64**
PACIFIC								
HONOLULU	99	**1.46** ± 0.13	5	6.5	**0.46** ± 0.17	**1.92**	**-0.16**	**1.62**
SW NORTH AMERICA								
LA JOLLA	72	**2.11** ± 0.16	700	6.7	**-1.36** ± 0.24	**0.75**	**0.09**	**2.02**
LOS ANGELES	78	**0.86** ± 0.15	2200	6.7	**-0.64** ± 0.11	**0.22**	**0.07**	**0.79**
SE NORTH AMERICA								
CHARLESTON I	82	**3.23** ± 0.16	7400	4.8	**-1.80** ± 0.23	**1.43**	**0.16**	**3.06**
FERNANDINA	83	**2.00** ± 0.13	5500	6.7	**-4.28** ± 0.13	**-2.28**	**0.08**	**1.92**
GALVESTON II	94	**6.47** ± 0.17	4200	4.5	**-6.85** ± 0.23	**-0.38**	**0.19**	**6.28**
MIAMI BEACH	45	**2.29** ± 0.26	300	5.2	**0.92** ± 0.22	**3.21**	**0.11**	**2.18**
KEY WEST	90	**2.23** ± 0.10	7800	6.7	**-0.50** ± 0.16	**1.73**	**0.16**	**2.07**
NE NORTH AMERICA								
EASTPORT	63	**2.07** ± 0.16	100	6.2	**1.39** ± 0.20	**3.46**	**0.16**	**1.91**
NEWPORT	70	**2.48** ± 0.14	1100	6.1	**-0.18** ± 0.12	**2.3**	**1.07**	**1.41**
HALIFAX	77	**3.29** ± 0.11	3300	2.8	**-1.57** ± 0.26	**1.72**	**0.70**	**2.59**
ANNAPOLIS	70	**3.46** ± 0.17	Unknown	6.7	**-0.12** ± 0.11	**3.34**	**0.30**	**3.16**
SOLOMON'S ISL.	62	**3.36** ± 0.19	100	6.7	**-3.36** ± 0.35	**0.00**	**0.18**	**3.18**
NORTHERN EUROPE								
STAVANGER	63	**0.27** ± 0.17	16000	4.7	**0.23** ± 0.13	**0.50**	**-0.49**	**0.76**
KOBENHAVN	101	**0.32** ± 0.12	7300	2.6	**-0.08** ± 0.25	**0.24**	**0.31**	**0.01**
NEDRE GAVLE	90	**-6.05** ± 0.23	11000	6.4	**6.22** ± 0.10	**0.17**	**-4.65**	**-1.40**
NW NORTH AMERICA								
VICTORIA	86	**1.10** ± 0.15	2	6.7	**0.68** ± 0.14	**1.78**	**0.23**	**0.87**
NEAH BAY	65	**-1.59** ± 0.22	7900	6.7	**4.21** ± 0.13	**2.62**	**0.56**	**-2.15**
SEATTLE	104	**2.06** ± 0.11	5900	6.7	**-0.57** ± 0.11	**1.49**	**0.46**	**1.60**