Harmonic tidal analysis methods on time and frequency domains: similarities and differences for the Gulf of Trieste, Italy, and Paranaguá Bay, Brazil.

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ABSTRACT

Two years of sea level data obtained at Trieste, Italy, and Paranaguá, Brazil, were used to compare the performances of two tidal analysis methodologies, one in the time domain (HMB) and other in the frequency domain (HMF). For each station the first year was analyzed to estimate the tidal constituents while the second year was used to compare observations against forecasted sea levels. Both methodsshowed equivalent performances but HMF is more user-friendly and offered better and more comprehensive results. The main reason seems to be linked to the amount of tidal constituents that HMF can estimate (more that 170) while HMB estimates around 110. Also, HMF showed better results for shallow water and long term components. However, the residuals showed that a significant amount of oscillating energy is left behind by both methods, suggesting that other deterministic signals not presentin the astronomic tidal frequencies have to be considered. We found that the semi-diurnal atmospherictide S2p is disturbing the sea constituent S2, as well as other frequencies, probably, in the diurnal specie, in the subtropical case of Paranaguá. These results are in agreement with the theoretical development of Chapman and Lindzen (1970) and the numerical simulations due to Arbic (2005). [Si mettono riferimenti anche nell'abstract?] It is concluded that a better stochastic model for tidal analysis and forecast needs to be formulated in order to better represent the physics of sea level: while tidal forecast with the usual methods seems to work well in many practical cases, the high dependence of numerical models on initial and contour conditions suggests that sea level harmonic constituents estimation has to be improved.

Keywords: Tides, Analysis, Prediction, Harmonic Analysis, Trieste, Paranaguá

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INTRODUCTION

The astronomical tides has been studied in the last two centuries in different ways but the background of all the analysis and forecasting methodologies is based in the early development by Darwin (1898; 1907), improved by Laplace, Lord Kelvin and other scientists, mostly in the 19th Century. This development is based on the principle that the sea level heights in a given place can be represented by a sum of N harmonic terms (from i= 0 to N-1), each one having an unique pair of amplitude (H_i) and phase (G_i), oscillating at a particular frequency (ω_i) defined by the astronomical tide generating potential and, when present, also by non-linear combination of the astronomical constituents (shallow water tidal components).

From the revolutionary work of Newton, the tides offered a great scientific challenge, but at the beginning of the 20th Century, the great utility of a good acknowledge of the astronomical tides in a given location moved the interest to the applicability of the analysis and prediction techniques, which evolved from the use of complicated analysis tables to determine a restricted number of H,G pairs, passing through the analogue tide prediction machines, to the present digital computer based methodologies with almost no limitations, but the physics, for their determination. However, most if not all the past and present tidal analysis and forecasting methodologies kept the basic Darwin principle unchanged.

Nowadays, a giant number of different digital computer programs are widely used to analyze and predict the astronomical tides, using different algorithms and approaches. In a way, all analyze sea level data (evenly or unevenly time spaced), in the time or frequency domains, determining a set of H and G pairs for the given place, allowing the astronomical tide to be forecasted. All the actual methodologies work properly for prediction purposes but not necessarily when the H, G values are used for other purposes.

However, when we compare the sets of H and G obtained for a same place using the same sea level data but different analysis methodologies (Marone, 1991), we note that the tidal constituents differ in both their parameter values, but mainly in G, notwithstanding their use for forecasting purposes do not show substantial differences, which has not been yet well explained.

The extensive uses of numerical modelling in ocean sciences bring into play the tide as one of the most important dynamical forcing and, in most cases, there is still a need for improvement regarding the tidal constituents used to feed the models, which seems to work better if observed sea level data are used instead (Camargo & Harari, 2003; Harari et al., 2006; Hendershott, 1977; Lyard et al., 2006; Moreira et al., 2010), particularly, coastal and shallow waters numerical model results are still not fully satisfactory, particularly cause the reduced number of used tidal constituents, which covers less that 95% of the tidal energy (Padman et al., 2008).

If the tidal constants are not so constant, not only by physical reasons but also according to the used method of analysis, the efficiency of numerical models is compromised, as well as the interpretation of many ocean phenomena. It has been proved that the ocean micro-structure has high correlation with the turbulent dissipation and the tidal cycles (Polzin 1997; Ledwell et al. 2000). In coastal areas, tides contribute significantly with the vertical mixing, redistributing nutrients and oxygen, which impact marine life (Romero et al., 2006) and, also, with the flow of CO_2 between sea and air (Bianchi et al., 2005).

The basic equations of tidal dynamics (Godin, 1972; Hendershott, 1972, 1977; Pugh, 1987; Munk and Wunsch, 1998; Pugh, 2004; Franco, 2009) are relatively simple and they are well known from Laplace times. However, in numerical modelling for instance, the need of higher precision of tidal constituents, particularly in coastal regions, is being indicated as a relevant scientific challenge (Lefevre et al., 2000; Simionato et al., 2004; Lyard et al., 2006; Moreira et al., 2010).

In recent years, with the great evolution of satellite altimetry, the combination of satellite data assimilation into numerical modelling (Matsumoto et al., 1995) requires, for tidal fields to be well represented in a limited number of location inside the model domain, that constituents in such places have to be well and accurately known (Egbert & Erofeeva, 2002; Kantha, 1995).

It is then clear that the need for a better understanding of the principles and quality of the tidal constituents estimated by different methodologies have to be achieved. Also, when examining many of the actual tidal analysis methodologies, one faces other small but not less important problem: the names given to the tidal constituents are not yet fully standardized, and diverse methodologies identify the same ω_i with different names, making the use of them, the comparisons, and the physical interpretation, more difficult. Also, the names of the different methodologies are so many and were created using such diverse approaches and styles that they help also to create confusion.

In this work we apply two methodologies, both based on the Harmonic Method, one solving the equations in the time domain (HMB) and the other in the frequency domain (HMF), to two sets of one year of 30-minute sampled sea level data obtained in the Gulf of Trieste, Italy (Figure 1, top), and the Paranaguá Bay, Brazil (Figure 1, bottom), the results of the analysis were compared and used for prediction purposes. Having a subsequent year of sea level data for both places (Figure 2), the forecasted sea levels were compared with the observed data and the residuals were studied to clarify the causes of the differences, both physical and methodological, in the search for answers regarding the methodologies quality and, mainly, about the reasons of such differences. Such objective does not intend solely to solve some just formal issues, like the standardization of names or, worst, what methodology is the most accurate.

METHODS

As already mentioned, we used here two analysis and prediction methodologies based in the Harmonic Method (HM) for our purposes, one solving the equations in the time domain (HMB) and other in the frequency domain (HMF). HMB method is based in the developments by Godin (1972) and Foreman (1977) and it is actually a much evolved computer program (Bell et al, 1999), whose fundamentals will be explained below. Also, the HMF is an evolution of the work developed by Doodson (1921) due to Franco & Rock (1971) and its further updates (Franco, 1997, 2009), and it is shortly explained at the following section.

Harmonic analysis in the time domain - HMB

The basic assumption for the application of the HMB method is that the tidal variations can be represented by a finite number N of harmonic terms of the form:

$$\zeta(t) = {}^{N}\sum_{1} H_n \cos(\sigma_n t - G_n);\ n=1,\ldots,N. \qquad \text{Equation 1}$$

H_n is an amplitude, σ_n is an angular speed and G_n is a phase lag on the Equilibrium Tide. Phase lags are conventionally expressed relative to the Greenwich Meridian. Usually, angular speeds are expressed in degrees per solar hour and phase lags in degrees. Each angular speed $\Omega_n = 2\pi\sigma_n / 360$ (in radians per solar hour) is determined as a linear combination of the angular speeds $\omega_1,\ldots,\omega_6$ of the tidal components related to solar and lunar motions, namely mean lunar day (1), sidereal month (2), tropical year (3), Moon's perigee (4), regression of Moon's nodes (5) and perihelion (6). ω_0 is the angular speed related to the mean solar day. The linear combination coefficients are small integers. The most complete work on the subject as well as the determination of the coefficients mentioned above was performed by Doodson (1921). Details on the mathematical procedures can be found, e.g., in Pugh (1987).

In practice, in the harmonic analysis in the time domain we fit a tidal function:

$$T(t) = Z_0 + {}^{N}\sum_{1} \{H_n \; f_n \cos [\sigma_n t - G_n + (V_n + u_n)]\} \qquad \text{Equation 2}$$

where the unknown parameter are Z_0, H_n and G_n ($n = 1,\ldots,N$), to a time series of observed values O(t). The terms f_n are the nodal factors and u_n the nodal angles, while the terms V_n are the equilibrium phase angles for the constituents (for solar constituents $f_n = 1$ and $u_n = 0$). Again, the convention is adopted to take V_n as for the Greenwich Meridian (Pugh, 1987). The fit is performed using the least-square procedure, in such a way that the quantity $S^2 = \Sigma\,[O(t) - T(t)]^2$ is minimum; the sum is made over all the times of the observations.

Harmonic analysis in the frequency domain - HMF

Analysis

The harmonic method used here was originally developed by Franco and Rock (1971) and was permanently updated from their original routines in FORTRAN to modern languages capable to work in personal computers (Franco, 1997; 2009). It is the methodology used by the Brazilian Navy, which is the National tide authority, to analyse and forecast the astronomical tides all along the more than 8000 km of Brazilian coastline.

The HMF is based in the assumption that the observed sea level in a given place can be accurately represented by a stochastic model with a harmonic part (mostly the astronomical tide, as in Eq. 1) and a non deterministic residual (noise).

Departing from a deep acknowledge of the astronomical tidal potential, it uses the harmonic oscillation of the generating forces to identify the tidal frequencies ω_i that may be present in the data record for a given place. The data are then analysed in the frequency domain via, for instance, the Fast Fourier Transform or other algorithm, as the Watts method or the Direct Fourier Transform (Marone, 1991). Once the energy spectrum is obtained, the tricky approach of the HMF is the use, to separate very close but well known astronomic tidal constituents, using the angular frequency differences among neighbour tidal constituents instead of the Rayleigh principle (Pugh, 1987).

In a classical spectral analysis, a set of 2N harmonic equations is solved (in the time or frequency domains) in order to determine N pairs of H and G unknowns. In the HMF, the angular frequencies differences are used also in the array of equations to be solved, generating a redundant (more equations than unknowns) group which enhance the precision and increase the number of frequencies that can be solved for. This is possible because particular spectral peaks of sea level data are not “contaminated” by energy of the other tidal species (diurnal, semi-diurnal, etc.), allowing the method to treat each tidal species in separate sets with a redundant number of equations with respect to the unknowns. The split into sub-systems allows, for instance for the diurnal band ($290<n<380$ cycles per 8192 hours), to have 90 equations to solve just 20 tidal constituents, which can be easily solved using the least square method. The HMF offers another advantage with respect to shallow water non-linear constituents, which are straightforwardly represented as combination of two or more astronomic tidal components in bi-linear or tri-linear arrays (Marone, 1991). Also, the method does not require sea level data series corresponding to exact multiples of half lunation (Franco and Rock, 1972). Finally, the HMF use a simple approach to estimate the quality of the results, calculating the signal-to-noise rate for each tidal species based in the stochasticity of the model and on the energy present in frequencies which do not correspond to astronomical tidal forcing (residual spectrum), and calculated from the variances of the residual energy present on each tidal band (species).

Forecast

As mentioned, the HMF represents the sea level $\zeta_{(t)}$ at any given instant t as a stochastic sum of N harmonic terms (with amplitude H, phase G and a frequency ω) plus a "noise" σ, as follows (Eq. 3):

$$\zeta_{(t)} = \left[{}^{N}\sum_{1} H_i \cos(\omega_i t + G_i) \right] + \sigma_{(t)} \qquad \text{Equation 3}$$

As much as N terms we have, by knowing the pairs H and G obtained with the HMB or HMF (or any other), the better will be the fit. The tidal prediction is then obtained solving the sea level equation (the harmonic development of Eq. 1) of the model for the period T of interest, reconstructing the astronomical tide as the sum of the contribution of each obtained and significant tidal constituent ω_i, characterized by their H and G pairs in Eq. 3, disregarding the noise. It has to be noted that the phases G have to be referred to a common t=0, which in the HMF and HMB is 00:00 hour UT of January the 1st, 1900.

DATA SETS

In order to help the readers with the geographical onset, Figure 3 depicts a couple of maps corresponding to the Gulf of Trieste, Italy, and the Paranaguá Bay, Brazil.

Gulf of Trieste

The Gulf of Trieste lies in the northernmost part of the Adriatic Sea at about 45°40'N latitude and 13°40'E longitude. It is approximately a 20×20 km square, connected with the Adriatic on the SW side and surrounded by land on the three other sides. It is a shallow bay, with maximum depth of about 25 m.

Detailed descriptions of the physical characteristics and of the circulation and water masses of the Gulf of Trieste can be found in Malačič and Petelin (2001). The water body is generally stratified from spring to autumn, with transitory exceptions related to the occurrence of NE (offshore) wind, namely Bora, which causes homogenization by up-welling. Stratification is enhanced by relatively high surface temperature and fresh water run-off, mainly in the north of the bay, where the mean annual river Isonzo discharge is about 200 m^3/s. During winter the water column is generally homogeneous, as a consequence of the surface cooling and frequent up-welling induced by Bora. On average, temperature can range from 8 to 12°C in winter and 20 (in the bottom layer) to 26 (near the surface) in summer. Away from the direct influence of fresh water run-off, salinity ranges are 33-38 PSU in winter and 32-36 PSU(surface), up to 37 PSU (bottom) in spring-summer.

The mean circulation is mostly cyclonic; however it depends very much on the presence of stratification and wind activity, in such a way that different patterns may be observed along the vertical. Particularly in late autumn and winter, cold air spells cause huge surface heat losses and the formation of dense water, which contributes to the Northern Adriatic Deep Water (Artegiani et al., 1997).

The main wind regimes are characterized by Bora and Sirocco. Bora blows from the NE-East sector and causes the decrease of sea level at Trieste. Sirocco blows from SE along the Adriatic basin and it is a major factor responsible for storm surges in the northern Adriatic, whose impact is larger in the area around Venice, but is not negligible in the Gulf of Trieste. However, the most severe storm surges at Trieste are generally connected with SW wind (Libeccio).

The astronomic tide is prevailingly semi-diurnal, the dominant constituents being M2, K1 and S2. In the Gulf of Trieste the amplitude is the largest observed in the Adriatic Sea with a theoretical maximum of about 80 cm, and the second largest in the Mediterranean Sea after the Gulf of Gabes, Tunisia. In the Adriatic Sea the tidal signal propagates counter-clockwise, i.e. from the Croatian coast towards the Gulf of Trieste and then along the Italian Coast, with a period slightly longer than 12 hours.

Systematic sea level observations were started in the autumn of 1859, when a tide gauge was installed on Molo Sartorio (Schaub, 1860), few metres away from the present tide gauge position. Original diagrams and manuscripts are available only from 1905 onwards, whereas sea level data for the 1859-1904 period can be only found in the literature. Since 1905 the sea level time series is characterized by few major gaps (January-December 1916 and January 1925-June 1926) due to missing data or tide gauge operation interruption for maintenance (Raicich et al., 2006; Raicich, 2007).

At present the sea level data are available every minute from two OTT Thalimedes instruments, with near-real-time transmission, as well as a continuous analogue record from a Büsum-OTT instrument. All of them are float tide gauges.

Paranaguá

The Paranaguá Bay estuarine complex is located in a quaternary coastal plain in Southern Brazil (Bigarella et al., 1978; Angulo, 1992; Angulo and Lessa, 1997); it has been classified as a partially mixed estuary (type B), with lateral heterogeneity (Knoppers et al. 1987, Marone et al., 1997), mean depth of 5.4 m, with maximum up to 30 m, total water volume of 14109 m^3 and a residence time of 3.49 days (Marone, 2005). As circulation patterns and stratification vary between seasons, mean salinity and water temperature in summer and in winter are 12-29 psu and 25-30^{o}C and 20-34 psu and 18-25^{o}C, respectively. A salinity-energy gradient from freshwater to marine conditions along the east-west and north-south main axes divides the bay into a high energy, euhaline (average salinity ~30) outer region, a middle polyhaline region, and oligo- and mesohaline (average salinity 0-15) low-energy inner sectors. lateral gradient originates from the freshwater input of rivers and tidal creeks and creates several 'micro-estuaries' in the euhaline and polyhaline sectors of the bay. A temporal gradient, with daily, seasonal and inter-annual components is super-imposed on the above gradients (Lana et al., 2001).

The hydrodynamic is driven by tidal forcing and river runoff (Knoppers et al., 1987; Lessa et al., 1998, Marone et al., 2005; Marone et al., 1997; Marone and Camargo, 1994; Lana et al., 2001). Tides are semidiurnal with diurnal inequalities. Tidal amplitudes increase towards the head of the bay, being amplified less than twice. The tidal phase and amplitudes indicate that the tidal wave propagates in a mixed form, with a progressive form at the outer region and a standing wave form in the upper bay. During neap cycles, strong non-linear interactions allow for the formation of up to 6 high and low tides per day. Also, the double high and low water phenomenon (Godin, 1972) is conspicuous (Marone et al, 2005; Marone & Camargo, 1995). Spring tides range from 1.7 m at the mouth to 2.7 m in the upper bay. The mean tidal range is 2.2 m, with a tidal prism of 1.34 km^3 and a tidal intrusion of 12.6 km. Figure 5 depicts a 15 days period of observed sea level data at Paranaguá harbour area, in the middle of the bay.

Following cold front forcing or extra-tropical cyclones, storm surges elevate water levels up to 80 cm above astronomical tides (Marone and Camargo, 1995). Current velocities increase upstream, with mean maxima of 0.8-0.85 m s^{-1} at flood and 1-1.4 m s^{-1} at ebb.

The average annual freshwater input from the coastal plain catchment area (about 1918 km^2) and from the small and steep drainage basins of the Serra do Mar is higher than 200 m^3 s^{-1} (Marone et al., 2005, Mantovanelli et al., 2004). Groundwater may contribute up to 10% of the total surface freshwater runoff (Suresh Babu et al., 2008; Marone et al., 1997). Seasonal variations of freshwater input correspond to around 30% of mean annual values during the dry period (May/October) and 170% during the rainy period (November/April).

Tidal data are regularly collected at Paranaguá area from the 1970's with continuous analogue record from OTT type instruments and, more recently, with bottom-pressure sensors. Older data, collected irregularly from the end of the 1800's and along the 20th Century exist, but were not used here.

RESULTS

HMB Analysis

In the present work the tidal analysis in the time domain is performed using the TASK-2000 package (Bell et al., 1999). One complete year of observations, namely 1997 for Paranaguá and 2004 for Trieste, is analysed up to 104 tidal constituents, with periods ranging from sixth-diurnal to diurnal and including some long period too. Up to 60 estimated tidal constants are used with the same package to forecast the astronomic tide for 1998 for Paranaguá and 2005 for Trieste.

The resulting tidal constants are shown in Figures 4 and 5 for Trieste and Paranaguá, together with the HMF results. Only components with amplitudes higher than 1 cm are shown, considering that oscillations bellow this limit cannot be estimated by the analysis (Marone and Mesquita, 1997).

HMF Analysis

On the other hand, the tidal analysis in the frequency domain is performed using the PACMARE package (Franco, 2009). The same complete years of observations, namely 1997 for Paranaguá and 2004 for

Trieste, are analyzed for up to 176 constituents, with periods ranging from twelfth-diurnal to diurnal and also including some long period constituents. The accepted estimated tidal constants are used with the same package to forecast the astronomic tide for 1998 for Paranaguá and 2005 for Trieste.

The resulting tidal constants are shown in Figures 4 and 5 for Trieste and Paranaguá, together with the HMB results. Apart of the below 1 cm constituents limit, the signal-to-noise criteria of the HMF was applied to disregard tidal components whenever the constituent was not shown with similar values in both methods.

Forecast

In order to perform comparisons between the forecasting performance of both methods and places, the observed sea level heights for the subsequent years, 1998 for Paranaguá and 2005 for Trieste (Fig. 2) were compared with the hourly predicted sea level using both, the HMB and HMF tidal constituents. These data sets were then analyzed, comparing the residuals between the observed sea level and the forecasted by the HMB and HMF tidal constituents. Figure 6 depicts only the first two weeks of each predicted year for a better look at the results for both, Trieste (top) and Paranaguá (bottom), but the full data and forecasted years were further analyzed.

Residual analysis

In order to compare methodological performances and the quality of the resulting forecasts, a residual analysis was performed following three approaches:

i. The first one was to study the residuals produced by the differences between the forecasted and the corresponding observed sea level series. Figure 7 depicts the same two weeks of Fig. 6, for readiness, of the corresponding residuals between observations and HMB and HMF forecasts, as well as the differences between both forecasts (HMB-HMF), for both Trieste (top) and Paranaguá (bottom).

ii. In the second case, we analyzed the spectrum of the residuals of the full year series, using a FFT routine and a Bartlett window with a 36 data length. These calculations give rise to the results depicted in Figure 8 for Trieste and Figure 9 for Paranaguá, where the spectra correspond to the residuals between the observations and the forecasted hourly data for both HMB and HMF and the spectrum of the differences between the predicted sea levels of both HMB-HMF.

iii. Finally, the HMF method offers a complimentary output, which corresponds to the spectral amplitudes calculated out of the astronomical tidal frequencies, which are used for the signal-to-noise ratio determination, and that are a good measure of how many non tidal but harmonic energy is present in a given data set. Figure 10 shows the spectral residuals for Trieste (top) and Paranaguá (bottom).

DISCUSSION

- **Tidal analysis methods: implementation and reach**

Both methods are fully operational in both countries, are easy to use and can analyze long data series based in desktop computers in a very short time. Data preparation is very simple in both cases but HMB needs more operator intervention provided the analyzed tidal constituents (only up to the 6th diurnal specie) need to be manually introduced, while HMF has all the astronomical components already included and up to the 12th diurnal specie. TASK package can analyze up to 104 tidal constituents (others can be included, but the code assumes that they have no nodal dependence) while HMF arrives to more than 176. Also, HMF has the capability to combine and suggest new shallow water constituents if they appear in a given analysis. Most of the extra constituents present in the PACMARE package are of non linear type, suggesting its use could be more appropriate for places were shallow water tidal components are expected to be significant. The HMF package has many other optional, allowing for the examination of the tidal records for errors, particular high resolution analysis, cross-analysis, long series and extreme analysis, and the so. However, we used the basic analysis, which includes a full output of the spectral results for non astronomical tidal frequencies and criteria to accept or reject tidal constituents. This suggested advantage of HMF is a numerical criteria to accept or disregard tidal components if they do note pass the signal-to-noise ratio test. Even if it is an objective way of testing the quality of the output, the acceptance of very little constituents (below 1 cm), which it is proved cannot be estimated in these cases (Marone and Mesquita, 1997), and the rejection of some significant ones (with around 4 cm amplitudes), which in turn appears with very similar values at the HMB showing a deterministic reiteration, suggest it has to be applied carefully.

- **Tidal analysis methods: results comparison**

HMB and HMF produce very similar results for Trieste (Fig. 4), with closed amplitude values and similar phases, with exception only for M1. All the major tidal components were estimated by both methods up to the 6th diurnal specie, catching also some long period ones.

In the Paranaguá case (Fig. 5), tidal estimated amplitudes are very similar in both methods, but it is possible to note that absolute values differ, always at very low levels, more than in the Trieste case. These result differences are more marked at the phase values but, in both calculated amplitudes and phases, we can say the differences are not significant. On the other hand, the non linear complexity of the co-tidal phenomena at Paranaguá seems to be better fixed by HMF. With the estimation of significant constituents with amplitudes of more than 3 cm (2KN2S2, SP3 and S3) which do not exist in the analyzable constituent set of HMB, HMF seems to be most efficient. Also, HMB does not include outputs for smaller constituents as M(Nu)4, 2MTS4, 3MN4 and SL4 (all with values higher than 1 cm and below 2 cm). On the other hand, HMB has the capability of analyzing the constituent MVS2 (27.4966873 deg/h) which is not present in the HMF set.

Another difficult when comparing the results was the use of different names for the same tidal frequencies: NO3 in HMF is MQ3 in HMB; MA2 and MB2 in HMB are MTS2 and MST2, respectively, in HMF while M(Nu)4 in HMF is named MV4 at HMB.

- **Tidal prediction accuracy**

From Fig. 6, but also for the full forecasted series, it was possible to conclude that the predictions of both methods work better in the Paranaguá case than in the Trieste one, except, for obvious reasons, when meteorological events disturb the sea level. In both cases, Paranaguá and Trieste, the high and low water times are predicted almost equally by HMB and HMF, and with pretty good agreement. Comparing the high and low water times with the observations, it is possible to see that both forecasting methods predict in few cases with some minutes in advance the occurrence of the tidal extremes, but in most of the cases there is a very good fit, more accurate for the HMF prediction than for HMB, but with very low differences.

Some systematic differences can be observed among observations and forecasts, and will be discussed further.

- **Tidal residuals**

  - **Observation vs. Forecast**

Analyzing Fig. 7, it is possible to see that for Trieste (top), the residuals between HMB and HMF against the observed tide are very similar but greater in the HMB forecast. Also, when comparing HMB against HMF, there is a clear positive difference for this period, that could reach maxima of ten centimetres, and it is also noted and oscillation in the residuals mostly with a diurnal period. It is important to note that more long-period constituents are estimated by HMF.

The difference between observations and (both) forecasts in Fig. 7 turns out to be generally negative because of a persistent high-pressure regime over Trieste area, with daily averages between 4 and 18 hPa higher than the climatological January mean. At the very beginning of the month seiche oscillations can be observed, connected with stormy weather conditions in late December 2004.

In the Paranaguá case (bottom of Fig. 7) both residuals between HMB and HMF predictions against observations are extremely similar, even if HMF forecast fits slightly better. Also, the residuals among both forecasts are proportionally lower than in the Trieste case (maxima less than 10 cm for the period), but they oscillate around zero with periodicities near diurnal and semi-diurnal ones.

Statistical parameters of the residuals between the observed sea level (Obs) and the corresponding forecast by the two methods (HMB and HMF) are shown in Table 1 together with the differences between the forecasted sea levels HMB-HMF for both sites. It has to be noted that the standard deviations are lower at the HMF residuals I both ports, being similar for Trieste ($\sigma_{HMB} = 12.794 > \sigma_{HMF} = 12.744$) and around a half for Paranaguá ($\sigma_{HMB} = 44.210 >> \sigma_{HMF} = 23.692$). Residual means are very similar in both cases, Trieste and Paranaguá, for the observed minus forecasted sea level. While for Trieste it is a super-estimation of more than 2 cm (negative values for Obs-HM), for Paranaguá both methods sub-estimate the sea level by around 4 cm. The best results of HMF forecasts can also be observed on the maximum and minimum residuals (Obs-HMB > Obs-HMF): while very similar for Trieste, they show marked differences for Paranaguá.

It has to be noted that while the Paranaguá forecasts shown better agreement with the observations, the Trieste residuals were proportionally greater and both forecasts super-estimate the sea level when compared with the observed one.

- **Spectrum of residuals**

When analyzing the spectra of the residuals (Fig. 8 for Trieste and Fig. 9 for Paranaguá), some interesting features appear. In the Trieste case, both methods left behind great and similar amount of energy for the long period specie. However, at Paranaguá, HMB seems to left behind more long period energy than HMF, even if it is a small amount.

On the diurnal frequencies for Trieste there is a great amount of energy not estimated by both HMF and HMB, being slightly greater at HMF. At these frequencies, HMF does better for Paranaguá while HMB left a little amount of diurnal energy out of the forecast.

The energy in the diurnal band in the residuals is probably due to the effect of the principal uninodal longitudinal seiche of the Adriatic Sea whose estimated period is about 21.2-21.5 hours (Manca, B, F. Mosetti and P.Zennaro, 1974). It is supposed (Cerovecki et al., 1997; Cushman-Roisin et al., 2005) that this periodicity could affect the estimate of tidal analysis in the diurnal band when tidal records are not long enough to increase the frequency resolution.

Examining the semidiurnal band, it is possible to see that the energy left behind by both methods is small for Trieste, while for Paranaguá is the band with greater residual energy after the long period. At Trieste forecasts, HMF shows two semidiurnal peaks of the same magnitude around M2, while HMB also shows both peaks with the first one greater (for frequencies lower than M2).

For higher frequencies (3rd, 4th, 5th and 6th diurnal), Trieste forecasts in both HMB and HMF show non significant residual energy, while Paranaguá forecast still lack spectral energy in the forecasts for the 3rd and 4th diurnal periodicities, in particular the last one.

The spectrum of the residuals shown that, except for the diurnal case of Trieste, HMF forecasts left behind less energy than HMB.

- **Residual of non-tidal spectral energy**

The above results can also be confirmed after examining Fig 10, which shows at top the non astronomic harmonic components extracted by HMF for Trieste, where many components higher than 1 cm (and up to 5 cm) are outside the tidal frequencies in the long period and diurnal bands. This, as explained above, is probably due to the perturbation of the principal seiche on the diurnal tidal group.

At the bottom of Fig. 10, one can see the case of Paranaguá, where non astronomical frequencies show components higher than 1 cm (and up to 7 cm) in the long period, semidiurnal, 3rd diurnal and 4th diurnal species.

- **Atmospheric tidal spectral energy**

In order to try to understand this extra harmonic energy, we analysed the tidal spectrum of meteorological data, as atmospheric pressure, using HMF, which results exposed little energy in the semi-diurnal band for Trieste (only a significant $S2_p$ was found with 0.47 hPa – we use the p subscript to indicate atmospheric/air tidal constituents from now on to differentiate them from the astronomical sea tidal components), while showing some extra energy in the diurnal specie ($RO1_p$, $S1_p$ and $K1_p$ amounting up to 0.5 hPa), while the non astronomical frequencies revealed that atmosphere has no significant energy in those frequencies present in the sea level but at periodicities which do not correspond to well known astronomical forcing. However, when analysing one year of pressure (half hourly) data from Paranaguá, a significant tidal energy in the atmosphere was found in the semi-diurnal band ($2SK2_p$; $S2_p$; $T2_p$ and $R2_p$, adding up to 1.51 hPa; plus another non astronomical semidiurnal frequencies with up to another 0.32 hPa). In Paranaguá, also the diurnal band was populated with significant energy at $PI1_p$, $P1_p$, $S1_p$ and $K1_p$ (up to 0.65 hPa among all). Also, it has to be noted that while in Trieste the pressure analysis did not get any long term atmospheric tidal component, in Paranaguá it was the higher one (at Sa_p periodicity with as much as 4.13 hPa). Another difference in the results was the number of accepted atmospheric tidal constituents, which for Trieste amounted up to 30, while Paranaguá showed only 17.

The surface pressure signal of the semi-diurnal tide in the Tropics is well established both theoretically as in Chapman and Lindzen (1970) and empirically. Haurwitz and Cowley (1973) calculated it from station data, getting amplitude of the surface pressure signal associated with the semi-diurnal tide of 1.05mb. Also, Hsu and Hoskins (1989) in an analysis of ECMWF data detected a semi-diurnal tide of similar magnitude. These observations have been supported by in recent studies (Deser and Smith 1998; Arbic, 2005) and are consistent in both magnitude and structure with the theoretical predictions, even if recent investigations suggest that the theoretical predictions of Chapman and Lindzen over-estimate the contribution to the semi-diurnal tide of the ozone heating and under-estimate that of the water vapour heating.

CONCLUDING REMARKS

Both methods produce similar results while HMF seems to offer some advantages because the greater amount of constituents it can analyze and the corresponding better forecast. In any case, the differences are so small that it is not necessary to discard HMB in favour of HMF.

HMB has the capacity of offering up to 104 and more purely astronomical (including some shallow water) constituents mostly up to the 6th diurnal specie, with some extra effort in the input data preparation, and gives no opportunity to analyse other than tidal frequencies, while HMF analyses up to 176, including many non linear ones, up to the 12th diurnal periodicities, with no extra operator effort. On this sense, HMF seems to be most user friendly than HMB.

We suggest that further investigations have to be performed comparing other tidal analysis methodologies, considering we used just two, very similar, among many today operational all around, as Tide for Matlab (Pawlowicz et al., 2002); etc.

The signal-to-noise test implemented in HMF seems not to be very accurate, because it accept very small components which are not observed (less than 1 cm) and discards others (even greater than 5 cm), which appears with the same values for H and G also in HMB.

The nature of the non astronomic estimated harmonic constituents deserves another discussion. In a first approach, it has to be noted that these constituents contribute to the “noise” in the signal-to-noise ratio analysis at HMF, but being harmonics they should not be treated as random noise, as in the HMF test. This problem might explain why HMF rejects tidal constituents with high amplitudes, particularly at long periods, but also at diurnal and semi diurnal frequencies.

Paranaguá is located at the borderline in the Subtropics and the coupling of atmospheric tide $S2_p$ with sea level could explain the energy left behind particularly at the semi-diurnal specie by both HM. In particular, if we consider that there is a relationship of around 7 cm/hPa (Arbic, 2005) for the semi-diurnal atmospheric tide to the sea level at the same specie, most of the Paranaguá spectral residuals could be explained by this coupling. It is important to note that atmospheric $S2_p$ has a phase lag of around 109^o with respect to the astronomical sea tide constituent S2 (Arbic, 2005). Thus, algorithms as the ones used by HMF and HMB will alias this energy around S2, contaminating other semi-diurnal constituents. It has to be noted that these effects cannot be related with the so called “radiational tide”, which has been proven to be also of non linear origin (Marone and Mesquita, 1995).

Even if not as well studied as the semi-diurnal $S2_p$, diurnal and other atmospheric constituents could also contribute to the spectrum of the sea level (Arbic, 2005). By now, we can only hypothesize that the atmospheric complexity at Trieste, which is in Temperate latitudes, could also contribute to the less accurate sea level forecast we performed with both HMB and HMF, which consider only astronomical tidal forcing on the sea.

The harmonic contribution of the atmosphere to the sea level could also explain, at least partially, the discrepancies obtained when comparing field data analysis with numerical models (D’Onofrio et al., 2009). Also, considering the wide use of tidal induced numerical models, it would be wise if a better representation of the oscillating sea level is used instead of the purely astronomic one.

As we cannot disregard the evidences that non tidal oscillating signals are clearly present in the sea level, we suggest reformulating the analysis and forecasting methodologies considering a better stochastic model for the sea level at a given instant t as:

$$\zeta_{(t)} = \left[{}^{N}\sum_{1} H_i \cos(\omega_i t + G_i) \right] + \left[{}^{N}\sum_{1} h_i \cos(\nu_i t + g_i) \right] + \sigma_{(t)} \qquad \text{Equation 4}$$

Where H, G and ω relate to purely astronomical tidal constituents (including shallow waters ones); h, g and ν correspond to other oscillating signals present in the sea level (as the atmospheric induced) and, finally, with $\sigma_{(t)}$ as a truly random noise.

The nature of the non astronomical estimated harmonic constituents is still a question to be detailed, and will be motive of further investigations.

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REFERENCES

Angulo R.J.; 1992: Geologia da planície costeira do Estado do Paraná. Ph. D. Thesis, Instituto de Geociências, Universidade de São Paulo, Brazil, 332pp.

Angulo R.J., Lessa G.C.; 1997: The Brazilian sea level curves: a critical review with emphasis on the curves from Paranaguá and Cananéia regions. Marine Geology 140:141-166.

Arbic B.K.; 2005: Atmospheric forcing of the oceanic semidiurnal tide; Geophysical Research Letters, Vol 32; L02610.

Bell C., Vassie J.M., Woodworth P.L.; 1999: POL/PSMSL Tidal Software Kit 2000 (TASK-2000). Permanent Service for Mean Sea Level, CCMS Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, UK, 20pp.

Bianchi A. A., Bianucci L., Piola A. R., Pino D. R., Schloss I., Poisson A., Balestrini C. F.; 2005: Vertical stratification and air-sea CO2 fluxes in the Patagonian shelf, Journal of Geophysical Research, 110, C07003, doi:10.1029/2004JC002488.

Bigarella J.J., Becker R.D., Matos D.J., Werner A. (eds); 1978: A Serra do Mar e a porção oriental do Paraná, um problema de segurança ambiental e nacional. Secretaria de Estado do Planejamento do Paraná, 248pp.

Camargo R., Harari J.; 2003: Modeling of the Paranagua Estuarine Complex, Brazil: tidal circulation and cotidal charts. Revista Brasileira de Oceanografia, São Paulo, v. 51, n. único, p. 23-3.

Chapman S., Lindzen R.S.; 1970: Atmospheric Tides. D. Reidel, 200pp.

Cerovecki, I., Orlic, M. and Hendershott, M.C.; 1997: Adriatic seiche decay and energy loss to the Mediterranean. Deep Sea Res., 44, 12, 2007-2029.

Cushman-Roisin B., Wilmott A.J and Biggs N.R.T.; 2005: Influence of stratification on decaying surface seiche modes. Cont. Shelf. Res., 25, 227-242.

Deser, C., Smith C.A.; 1998: Diurnal and semi-diurnal variations of the surface wind field over the tropical Pacific Ocean. Journal of Climate. v11 p. 1730-1748.

Darwin, G.H.; 1898: The Tides and Kindred Phenomena in the Solar System. Phil. Trans. Roy. Soc.

Darwin, G.H.; 1907: The Scientific Papers of Sir George Darwin. 1907. Cambridge University Press (reissued by Cambridge University Press, 2009; ISBN 9781108004497).

Doodson A.T.; 1921: Harmonic development of the tide-generating potential. Proceedings of the Royal Society of London, A100, 305-329.

D'onofrio E., Fiore M., Saraceno M., Grismeyer W., Oreiro F.; 2009: Comparación de constantes armónicas de marea provenientes de modelos globales y de observaciones, en el Rio de la Plata y Tierra del Fuego. Fue presentado en la VII Jornadas Nacionales de Ciencias del Mar realizada entre el 30 de Noviembre y el 4 de Diciembre de 2009 en Bahía Blanca, Provincia de Buenos Aires. Resúmenes pág. 32.

Egbert G.D., Erofeeva S.Y.; 2002: Efficient inverse modeling of barotropic ocean tides, Journal of Atmospheric and Oceanic Technology, 19(2), 183-204.

Foreman M.G.G.; 1977: Manual for tidal heights analysis and predictions. Pacific Marine Science Report, 77-10, 97pp.

Franco A.S., Rock N.; 1972: The Fast Fourier Transform and its application to tidal oscillations. Bol. do Instituto Oceanogr. de S.Paulo.

Franco A.S.; 1997: Tides, Fundamentals, Analysis and Prediction. IPT Press. São Paulo, SP. 286pp.

Franco A.S.; 2009: Marés: Fundamentos, Análise e Previsão. Niterói, RJ: D.H.N. 344pp.

Godin, G.; 1972: The Analysis of Tides, University of Toronto Press, Toronto, 264pp.

Harari J., Camargo R., Picarelli S.S., França C.A.S., Mesquita, A.R.; 2006: Numerical modeling of the hydrodynamics in the coastal area of Sao Paulo State - Brazil. Journal of Coastal Research, USA, v. SI 39, p. 1560-1563.

Hsu H.H., Hoskins B.J.; 1989: Tidal fluctuations as seen in ECMWF data. Quart. J. Roy. Meteor. Soc., 115, 247-264.

Hendershott M. C.; 1972: The effects of solid earth deformation on global ocean tides. Geophysical Journal of the Royal Astronomical Society, 29, p. 389–402.

Hendershott M. C.; 1977: Numerical models of ocean tides. Marine Modeling, E. Goldberg, Ed., The Sea, Vol. 6, John Wiley and Sons, p47–96.

Kantha L.H.; 1995: Barotropic tides in the global oceans from a nonlinear tidal model assimilating altimetric tides. Part I: Model description and results. Journal of Geophysical Research, 100, 25 283–25 308.

Knoppers B.A., Brandini F.P., Thamm C.A.; 1987: Ecological studies in the Bay of Paranaguá. II. Some physical and chemical characteristics. Nerítica 2: p. 1-36.

Lana P.C., Marone E., Lopes R.M., Machado E.C.; 2001: The subtropical estuarine complex of Paranaguá Bay, Brazil. In: Coastal Marine Ecosystems of Latin America ed: Springer Verlag.

Ledwell J.L., Montgomery E.T., Polzin K.L., St. Laurent L.C., Schmitt R.W., Toole J. M.; 2000: Evidence for enhanced mixing over rough topography in the abyssal ocean. Nature, 403, p. 179–182.

Lefevre F., Le Provost C., Lyard F.H.; 2000: How can we improve a global ocean tide model at a regional scale? A test on the Yellow Sea and the East China Sea. Journal of Geophysical Research. 105 (C4), 8707-8725.

Lessa G.C., Meyers S.R., Marone E.; 1998: Holocene stratigraphy in the Paranaguá Bay Estuary, Southern Brazil. J. Sedimentary Research 68:1060-1076.

Liou K.-N.; 1980: An introduction to Atmospheric Radiation. Academic Press, 392pp.

Lyard F., Lefevre F., Letellier T., Francis O.; 2006: Modeling the global ocean tides: Modern insights from FES2004, Ocean Dynamics, 56(5-6), p. 394-415.

Mantovanelli A.; Marone E. ; da Silva E.T., Lautert L.F.C., Klingenfuss M.S., Prata V.P., Noernberg M.A., Knoppers A.M., Angulo R.J. ; 2004: Combined tidal velocity and duration asymmetries as a determinant of water transport and residual flow in Paranaguá Bay estuary. Estuarine, Coastal and Shelf Science, v. 59, n. 4, p. 523-537.

Malačič V., Petelin, B.; 2001: “Regional studies: Gulf of Trieste”. B. Cushman-Roisin, M. Gačić, P.-M. Poulain and A. Artegiani, Eds., “Physical oceanography of the Adriatic Sea: past, present and future”, 167-181, Kluwer Academic Publishers, Dordrecht, 304pp.

Manca B., Mosetti F. and Zennaro P.; 1974: Analisi spettrale delle sesse dell'Adriatico. Boll. Geofis. Teor. Appl., 16, 51-60.

Marone E.; 1991: Processamento e análise de dados de maré. Discurso dos Métodos. PhD Thesis. Instituto Oceanográfico da USP- S.Paulo, SP. 231pp.

Marone E., Mesquita A.R.; 1995: On non-linear analysis of tidal observations. Continental Shelf Research. Vol. 14, No. 6, p. 577-588, 1994/95.

Marone E., Camargo R.; 1995: Marés meteorológicas no litoral do estado do Paraná: o evento de 18 de agosto de 1993. Nerítica 8(1-2):73-85.

Marone, E.; 1996: “Radiational" tides as non linear effects: bispectral interpretation. Continental Shelf Research. Vol. 16, No. 8, p.1117-1126, 1996.

Marone E., Mesquita A.R.; 1997: On tidal analysis with measurement errors. Bolletino de Geofisica Teorica ed Applicata. Vol 38, p. 3-4.

Marone E., Mantovanelli A., Klingenfuss M.S., Lautert L.F.C., Prata Jr. V.P.; 1997: Transporte de material particulado em suspensão, água, sal e calor na Gamboa do Perequê num evento de maré de sizígia. Expanded abstract. VII Congreso Latinoamericano de Ciencias del Mar, Santos, Brazil, p. 134-136.

Marone E., Machado E.C., Lopes R.M., Silva E.T.; 2005: Land-ocean fluxes in the Paranaguá Bay Estuarine System. Brazilian Journal Of Oceanography. v.53, p.169–181.

Matsumoto K., Ooe M., Sato T., Segawa J.; 1995: Ocean tide model obtained from TOPEX/Poseidon altimetry data. Journal of Geophysical Research, 100, 25 319–25 330.

Moreira D., Simionato C.G., Dragani W.C.; 2010: Modeling ocean tides and their energetics in the North Patagonian Gulf of Argentina. Journal of Coastal Research.

Munk W.H., Wunsch C.; 1998: Abyssal recipes II: Energetics of tidal and wind mixing. Deep-Sea Research, 45, 1977–2010.

Padman L., Erofeeva S. Y., Fricker H. A.; 2008: Improving Antarctic tide models by assimilation of ICESat laser altimetry over ice shelves. Geophysical Research Letters, Vol. 35, L22504, doi:10.1029/2008GL035592.

Pawlowicz R., Beardsley B., Lentz S.; 2002: Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. Computers & Geoscience, 28, p. 929-937.

Polzin K. L., Toole J.M., Ledwell J.R., Schmitt R. W.; 1997: Spatial variability of turbulent mixing in the abyssal ocean. Science, 276, p. 93–96.

Pugh D.T.; 1987: Tides, surges and mean sea level. John Wiley and Sons Ltd., Chichester, UK, 472 pp.

Pugh D. T.; 2004: Changing Sea Levels: Effects of Tides, Weather and Climate. Cambridge University Press, 265pp.

Raicich F., Crisciani F., Ceschia M., Pietrobon V.; 2006: La serie temporale del livello marino a Trieste e un’analisi della sua evoluzione dal 1890 al 2003. G.C. Cortemiglia, Ed., La variabilità del clima locale relazionata ai fenomeni di cambiamento globale, 199-220, Pàtron Editore, Bologna, Italy, 326pp.

Raicich F.; 2007: A study of early Trieste sea level data (1875-1914). Journal of Coastal Research, 23, 1067-1073.

Romero S.I., Piola A.R., Charo M., García C.A.E.; 2006: Chlorophyll-a variability off Patagonia based on SeaWiFS data. Journal of Geophysical Research, 111, C05021, doi:10.1029/2005JC003244.

Schaub F.; 1860: Ueber Ebbe und Fluth in der Rhede von Triest, Franz Foetterle, Ed., Mittheilungen der kaiserlich-königlichen Geographischen Gesellschaft, IV, p. 78-82.

Schureman P.; 1988: Manual of Harmonic Analysis and Prediction of Tides, U.S. Department of Commerce, Coast and Geodetic Survey. Special Publication No. 98, 317pp.

Simionato C.G., Meccia V.L., Dragani W.C.; 2009: On the path of plumes of the Río de la Plata estuary main tributaries and their mixing scales. Geoacta, 34, p. 87-116.

Suresh Babu D.S., Sahai A.K., Noernberg M.A., Marone E.; 2008: Hydraulic response of a tidally forced coastal aquifer, Pontal do Paraná, Brazil. Hydrogeology Journal.

LIST OF TABLES AND FIGURES

Table 1

	TRIESTE			PARANAGUÁ		
Residual	Obs-HMB	Obs-HMF	HMB-HMF	Obs-HMB	Obs-HMF	HMB-HMF
Mean	-2.3861	-2.3925	-0.00639	4.2764	4.2866	-0.01027
Median	-2.0000	-2.0000	0.0000	0.0000	3.0000	-4.0000
Minimum	-55.000	-56.000	-8.000	-140.00	-111.00	-61.000
Maximum	66.000	64.000	8.000	187.00	120.00	80.000
Standard Deviation (σ)	12.794	12.744	2.0363	44.210	23.692	27.946

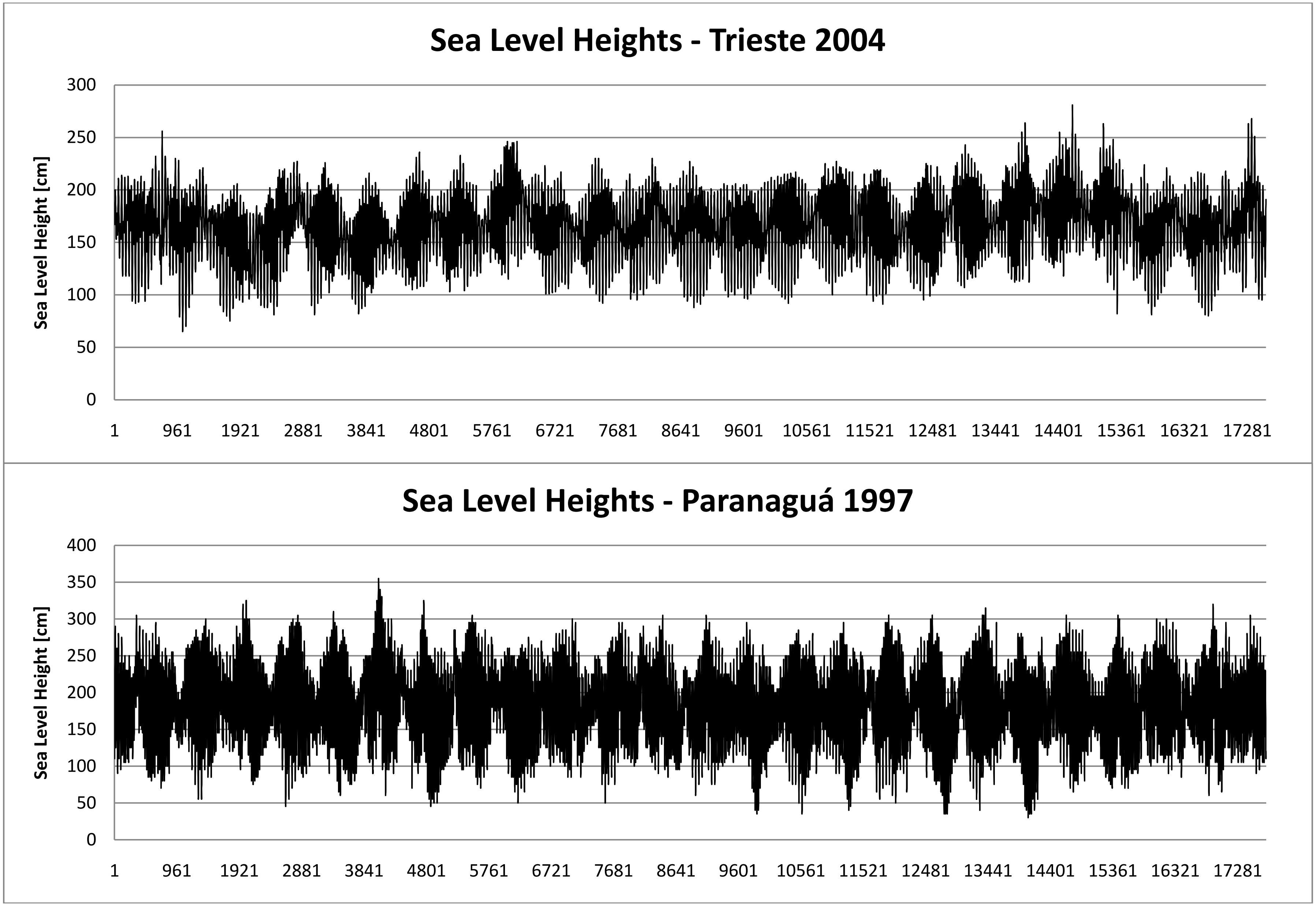

Sea Level Heights - Trieste 2004
Sea Level Height [cm]
300
250
200
150
100
50
0
1
961
1921
2881
3841
4801
5761
6721
7681
8641
9601
10561
11521
12481
13441
14401
15361
16321
17281
Sea Level Heights - Paranaguá 1997
Sea Level Height [cm]
400
350
300
250
200
150
100
50
0
1
961
1921
2881
3841
4801
5761
6721
7681
8641
9601
10561
11521
12481
13441
14401
15361
16321
17281

FIGURE 1

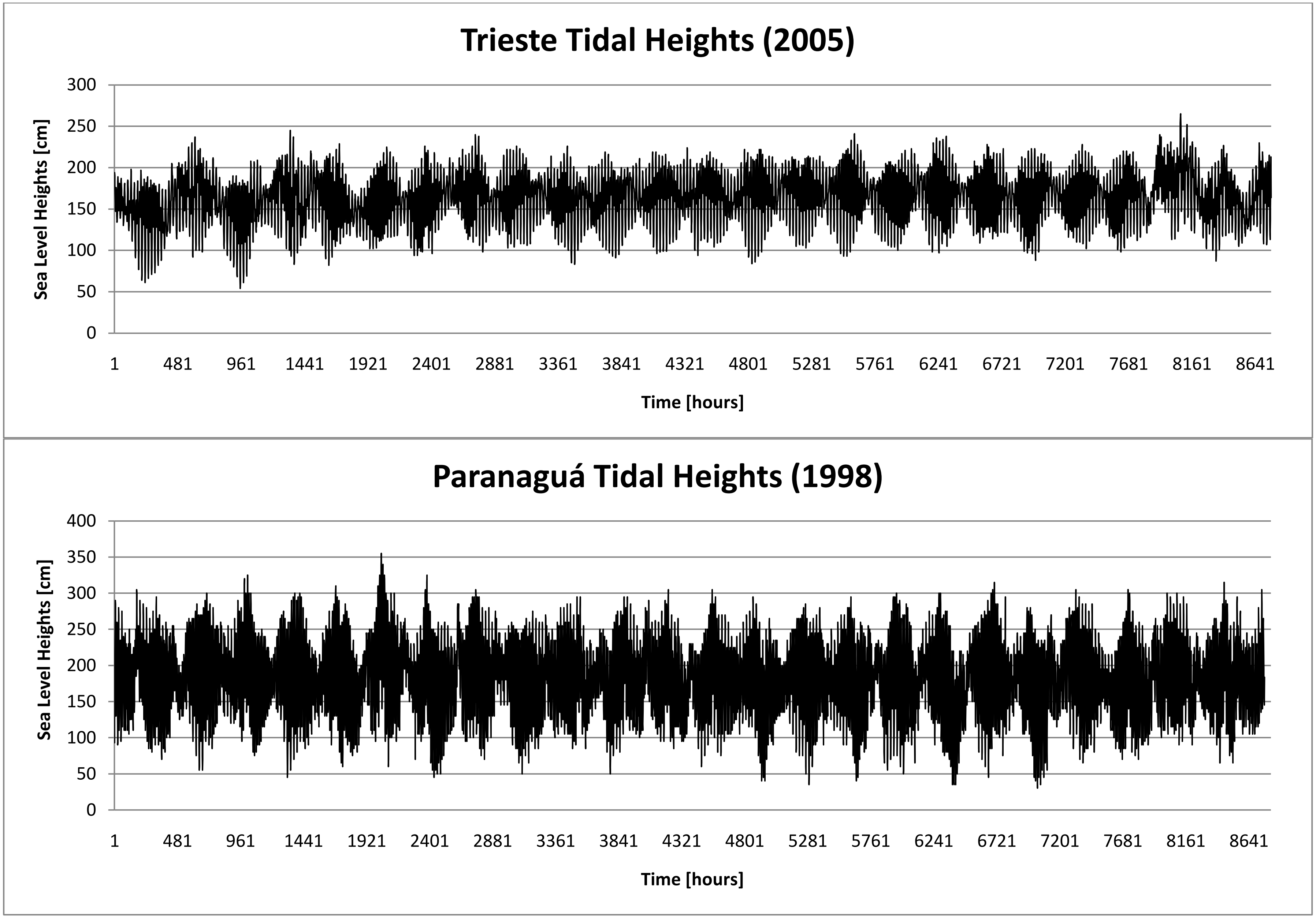
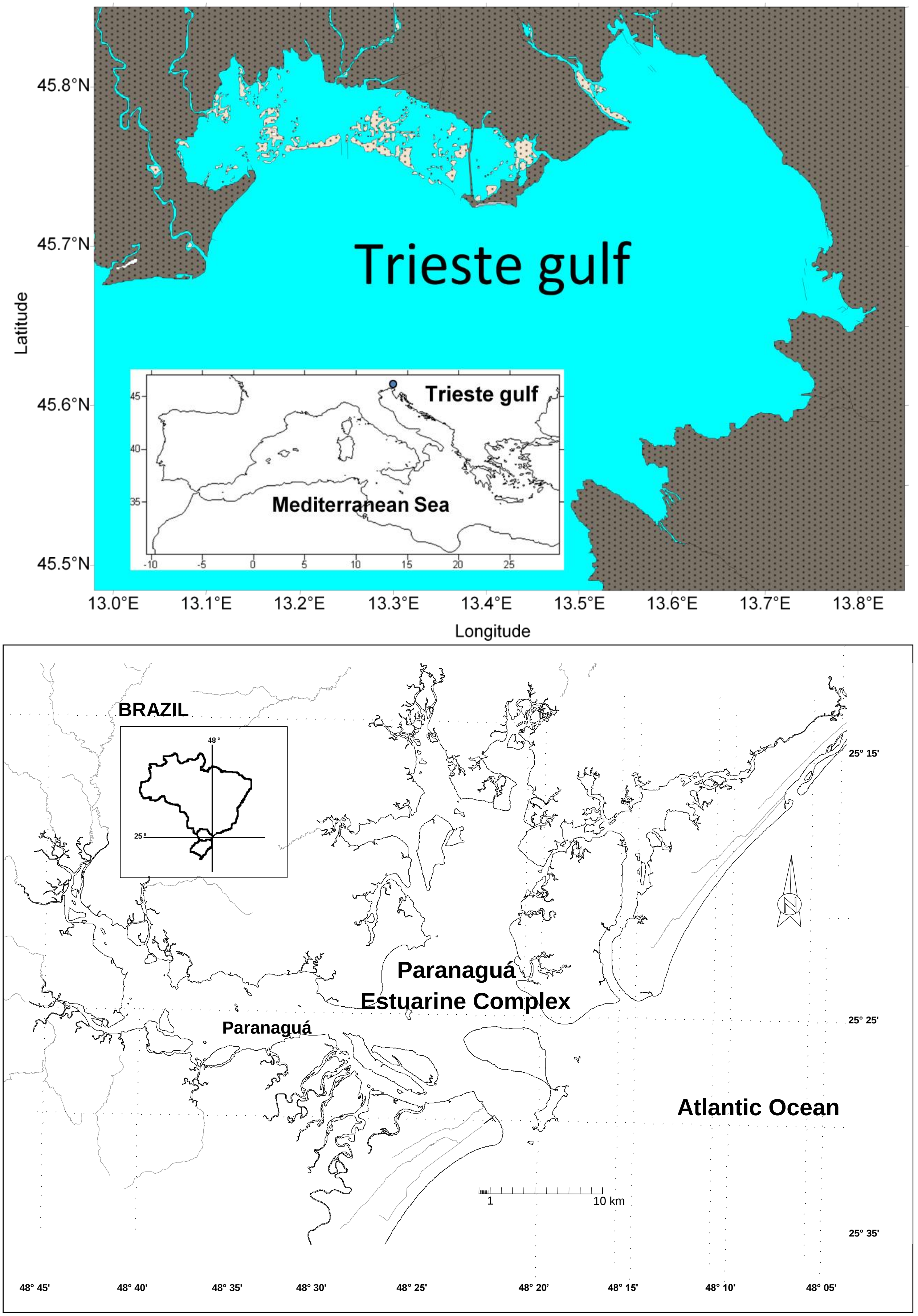
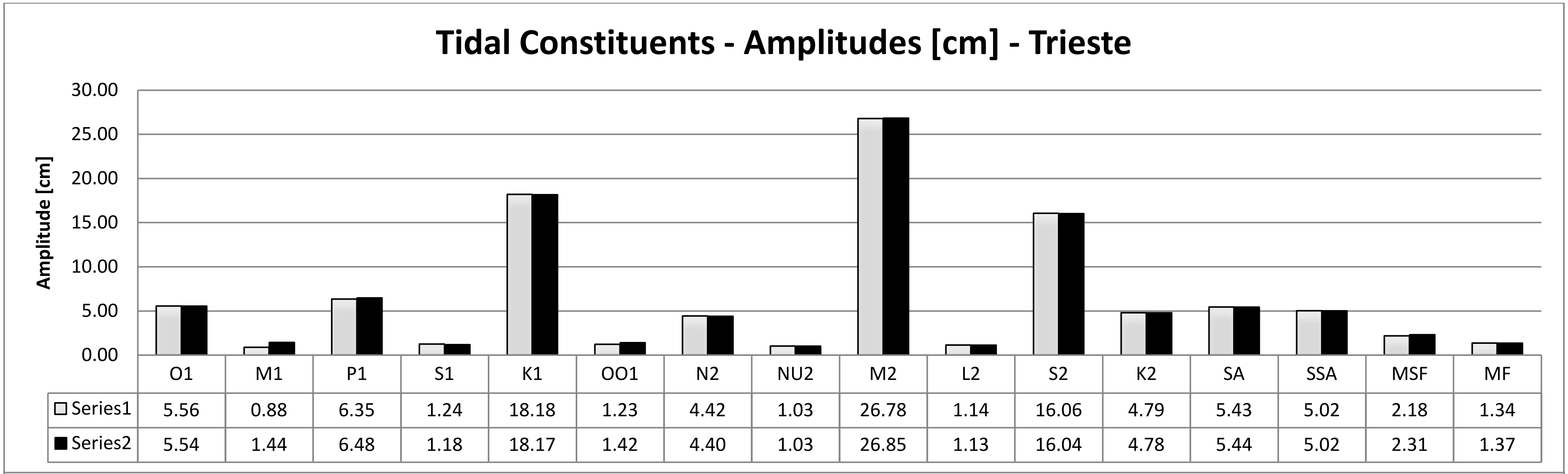

Trieste Tidal Heights (2005)
Sea Level Heights [cm]
300
250
200
150
100
50
0
1
481
961
1441
1921
2401
2881
3361
3841
4321
4801
5281
5761
6241
6721
7201
7681
8161
8641
Time [hours]
Paranaguá Tidal Heights (1998)
Sea Level Heights [cm]
400
350
300
250
200
150
100
50
0
1
481
961
1441
1921
2401
2881
3361
3841
4321
4801
5281
5761
6241
6721
7201
7681
8161
8641
Time [hours]

FIGURE 2

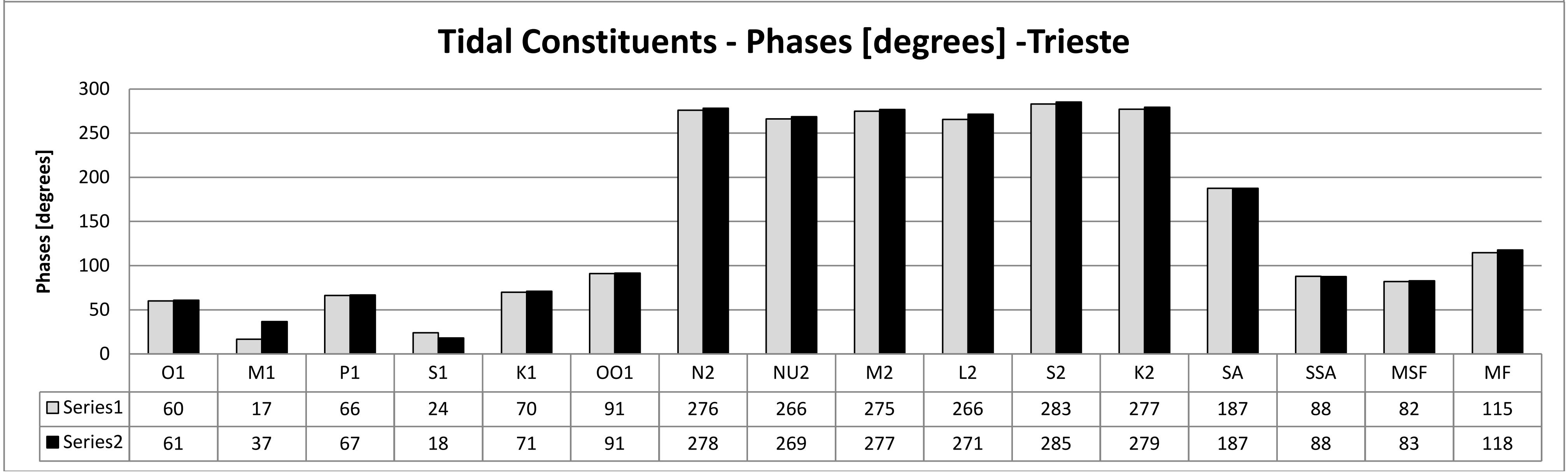


Trieste gulf
Latitude
Longitude
45.8°N
45.7°N
45.6°N
45.5°N
13.0°E
13.1°E
13.2°E
13.3°E
13.4°E
13.5°E
13.6°E
13.7°E
13.8°E
Trieste gulf
Mediterranean Sea
45
40
35
-10
-5
0
5
10
15
20
25
BRAZIL
48°
25°
Paranaguá
Estuarine Complex
Paranaguá
Atlantic Ocean
N
1
10 km
25° 15'
25° 25'
25° 35'
48° 45'
48° 40'
48° 35'
48° 30'
48° 25'
48° 20'
48° 15'
48° 10'
48° 05'

FIGURE 3

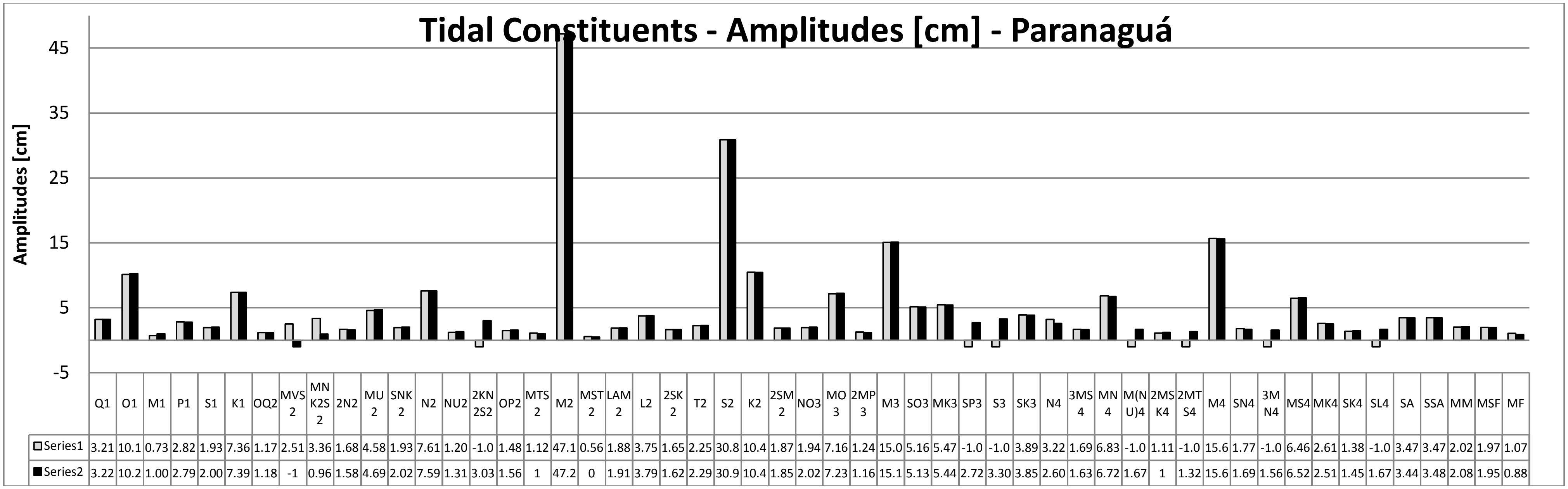


	O1	M1	P1	S1	K1	OO1	N2	NU2	M2	L2	S2	K2	SA	SSA	MSF	MF
☐ Series1	5.56	0.88	6.35	1.24	18.18	1.23	4.42	1.03	26.78	1.14	16.06	4.79	5.43	5.02	2.18	1.34
■ Series2	5.54	1.44	6.48	1.18	18.17	1.42	4.40	1.03	26.85	1.13	16.04	4.78	5.44	5.02	2.31	1.37



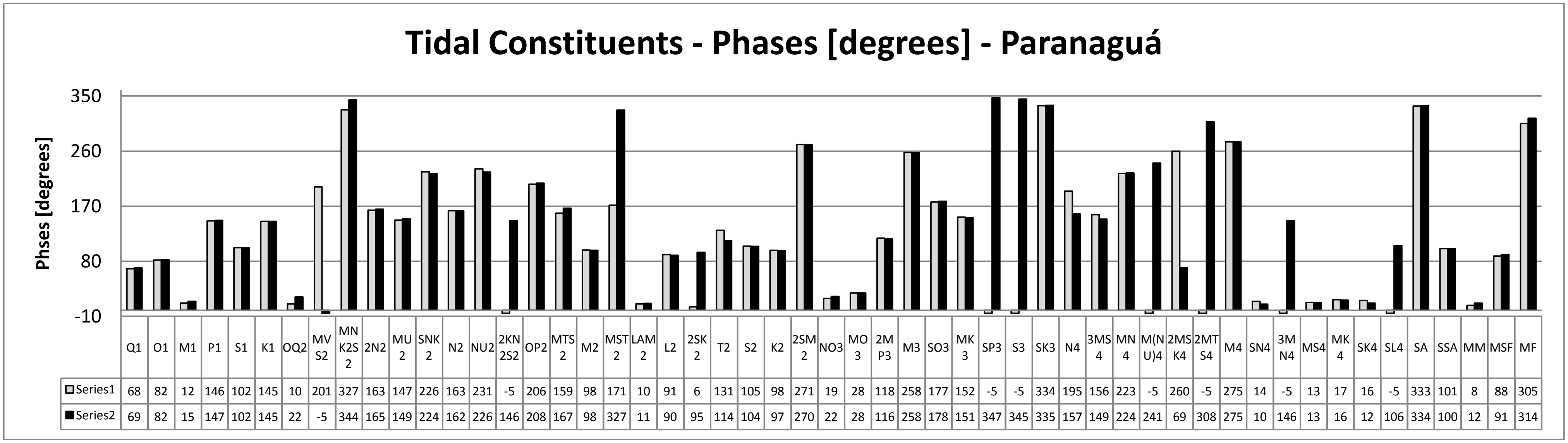
	O1	M1	P1	S1	K1	OO1	N2	NU2	M2	L2	S2	K2	SA	SSA	MSF	MF
☐ Series1	60	17	66	24	70	91	276	266	275	266	283	277	187	88	82	115
■ Series2	61	37	67	18	71	91	278	269	277	271	285	279	187	88	83	118

Figure 4



	Q1	O1	M1	P1	S1	K1	OQ2	MVS2	MNK2S2	2N2	MU2	SNK2	N2	NU2	2KN2S2	OP2	MTS2	M2	MST2	LAM2	L2	2SK2	T2	S2	K2	2SM2
☐Series1	3.21	10.1	0.73	2.82	1.93	7.36	1.17	2.51	3.36	1.68	4.58	1.93	7.61	1.20	-1.0	1.48	1.12	47.1	0.56	1.88	3.75	1.65	2.25	30.8	10.4	1.87
■Series2	3.22	10.2	1.00	2.79	2.00	7.39	1.18	-1	0.96	1.58	4.69	2.02	7.59	1.31	3.03	1.56	1	47.2	0	1.91	3.79	1.62	2.29	30.9	10.4	1.85

	NO3	MO3	2MP3	M3	SO3	MK3	SP3	S3	SK3	N4	3MS4	MN4	M(NU)4	2MSK4	2MTS4	M4	SN4	3MN4	MS4	MK4	SK4	SL4	SA	SSA	MM	MSF	MF
☐Series1	1.94	7.16	1.24	15.0	5.16	5.47	-1.0	-1.0	3.89	3.22	1.69	6.83	-1.0	1.11	-1.0	15.6	1.77	-1.0	6.46	2.61	1.38	-1.0	3.47	3.47	2.02	1.97	1.07
■Series2	2.02	7.23	1.16	15.1	5.13	5.44	2.72	3.30	3.85	2.60	1.63	6.72	1.67	1	1.32	15.6	1.69	1.56	6.52	2.51	1.45	1.67	3.44	3.48	2.08	1.95	0.88



	Q1	O1	M1	P1	S1	K1	OQ2	MVS2	MNK2S2	2N2	MU2	SNK2	N2	NU2	2KN2S2	OP2	MTS2	M2	MST2	LAM2	L2	2SK2	T2	S2	K2	2SM2
☐Series1	68	82	12	146	102	145	10	201	327	163	147	226	163	231	-5	206	159	98	171	10	91	6	131	105	98	271
■Series2	69	82	15	147	102	145	22	-5	344	165	149	224	162	226	146	208	167	98	327	11	90	95	114	104	97	270

	NO3	MO3	2MP3	M3	SO3	MK3	SP3	S3	SK3	N4	3MS4	MN4	M(NU)4	2MSK4	2MTS4	M4	SN4	3MN4	MS4	MK4	SK4	SL4	SA	SSA	MM	MSF	MF
☐Series1	19	28	118	258	177	152	-5	-5	334	195	156	223	-5	260	-5	275	14	-5	13	17	16	-5	333	101	8	88	305
■Series2	22	28	116	258	178	151	347	345	335	157	149	224	241	69	308	275	10	146	13	16	12	106	334	100	12	91	314

Figure 5

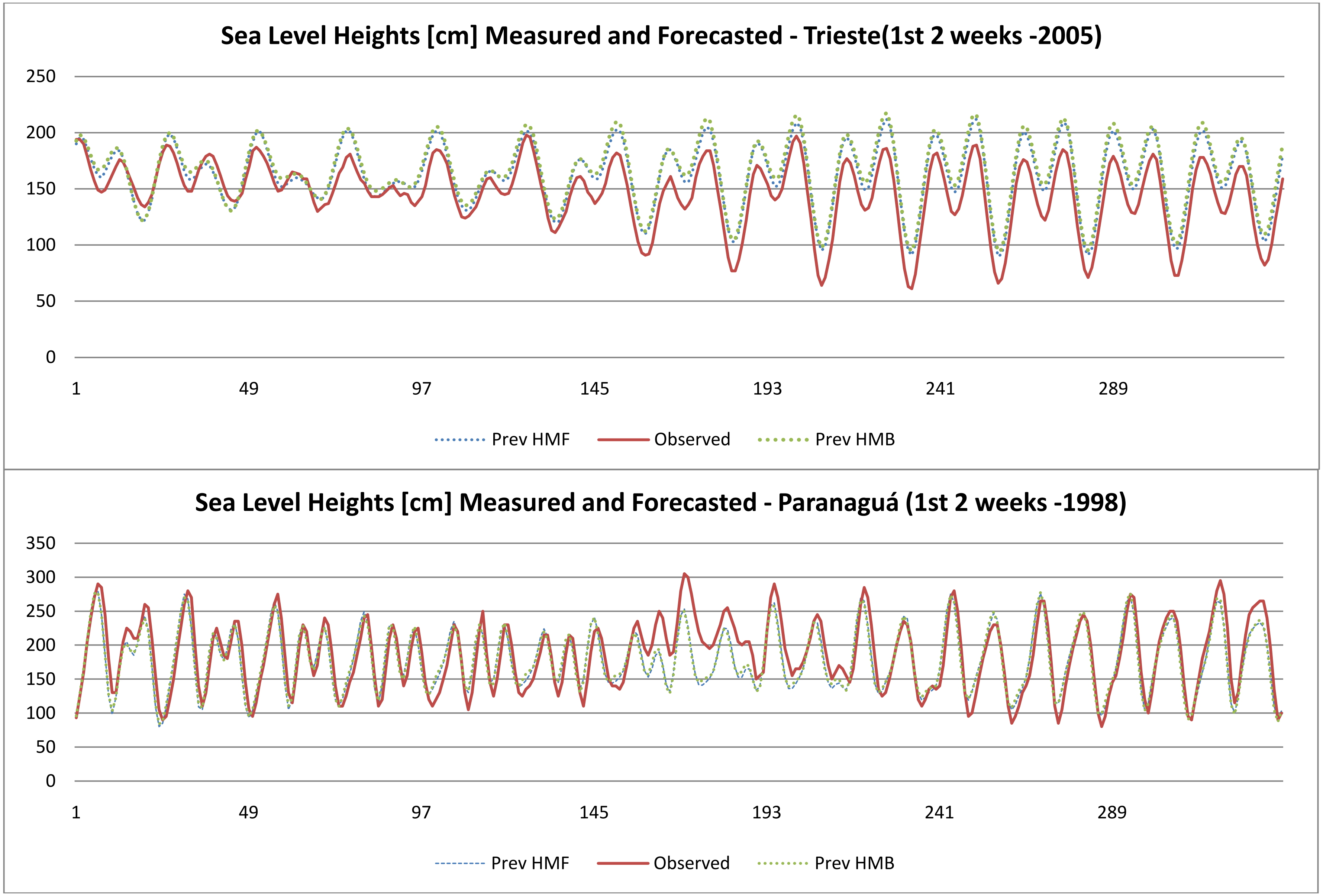

Sea Level Heights [cm] Measured and Forecasted - Trieste(1st 2 weeks -2005)
250
200
150
100
50
0
1
49
97
145
193
241
289
Prev HMF
Observed
Prev HMB
Sea Level Heights [cm] Measured and Forecasted - Paranaguá (1st 2 weeks -1998)
350
300
250
200
150
100
50
0
1
49
97
145
193
241
289
Prev HMF
Observed
Prev HMB

Figure 6

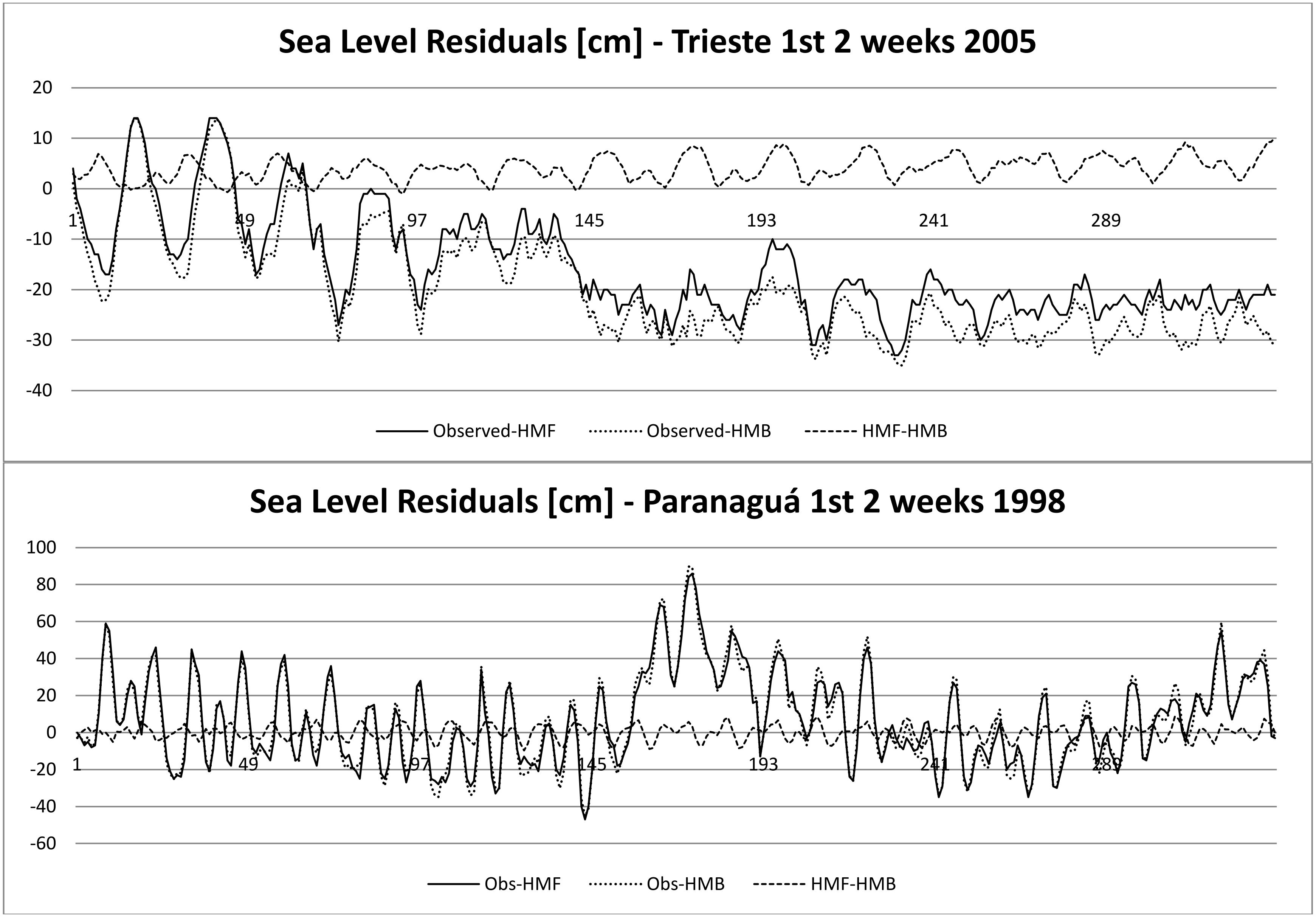

Sea Level Residuals [cm] - Trieste 1st 2 weeks 2005
20
10
0
-10
-20
-30
-40
1
49
97
145
193
241
289
Observed-HMF
Observed-HMB
HMF-HMB
Sea Level Residuals [cm] - Paranaguá 1st 2 weeks 1998
100
80
60
40
20
0
-20
-40
-60
1
49
97
145
193
241
289
Obs-HMF
Obs-HMB
HMF-HMB

Figure 7

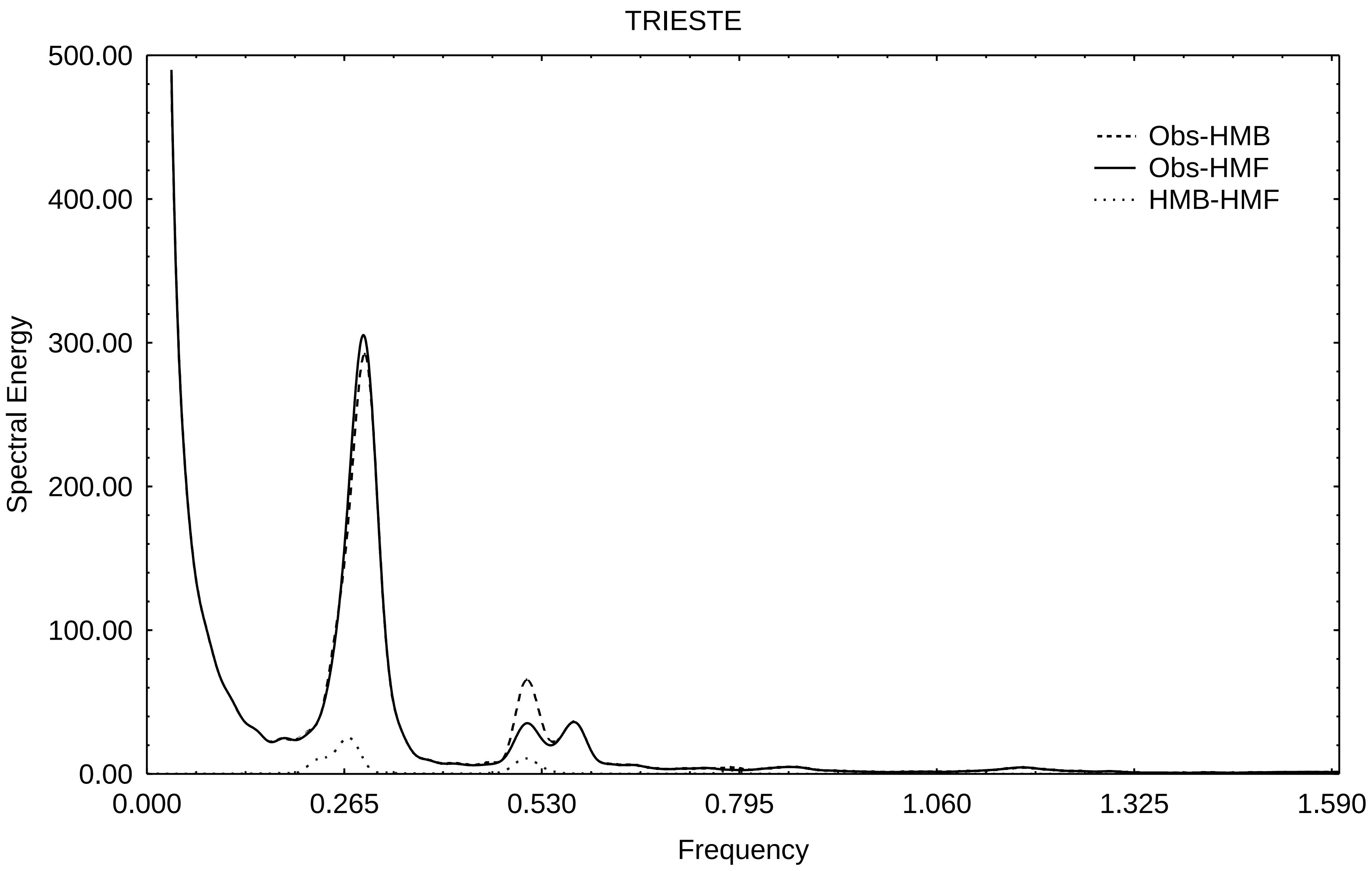

TRIESTE
Spectral Energy
500.00
400.00
300.00
200.00
100.00
0.00
0.000
0.265
0.530
0.795
1.060
1.325
1.590
Frequency
Obs-HMB
Obs-HMF
HMB-HMF

Figure 8

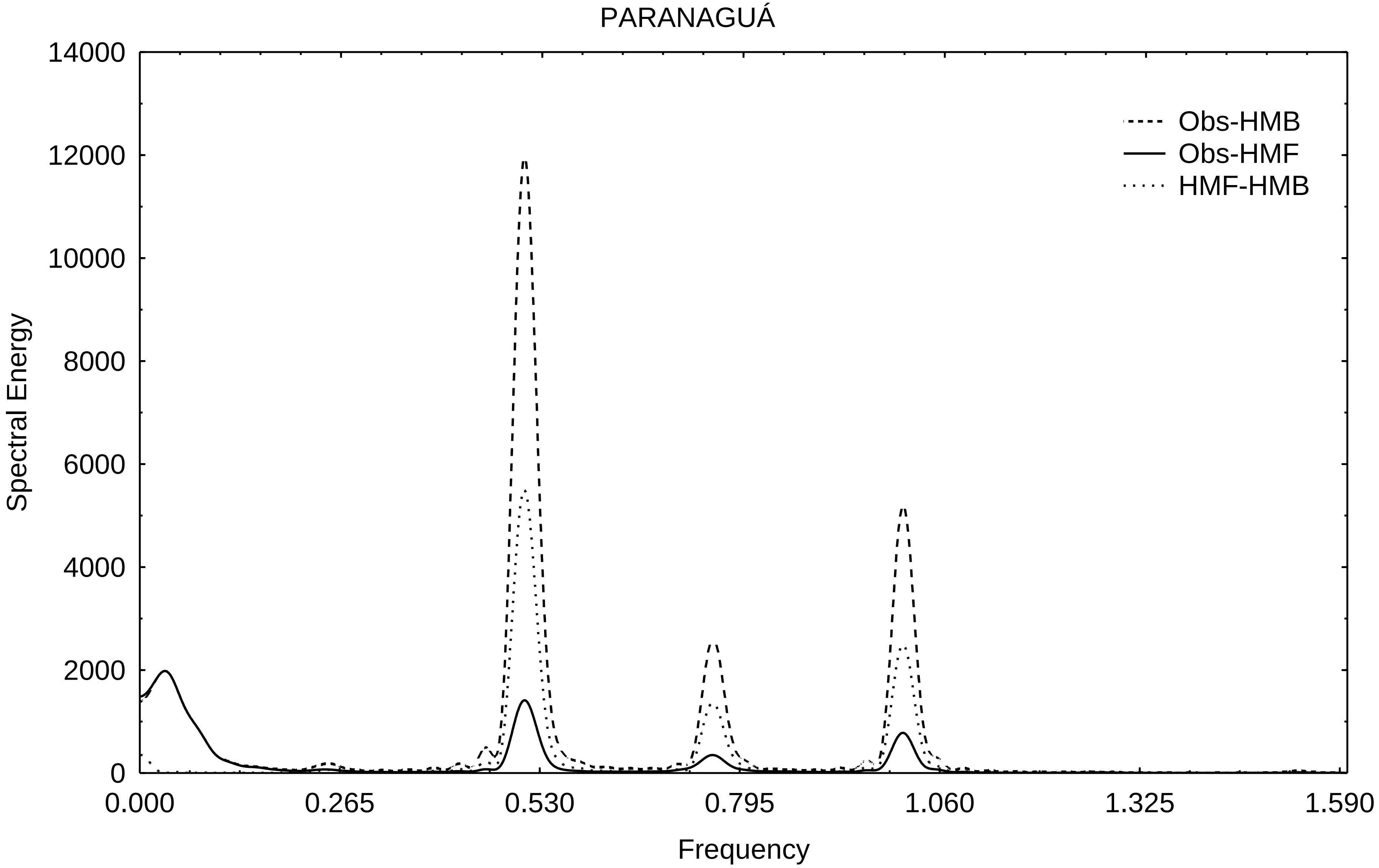

PARANAGUÁ
Spectral Energy
Frequency
14000
12000
10000
8000
6000
4000
2000
0
0.000
0.265
0.530
0.795
1.060
1.325
1.590
Obs-HMB
Obs-HMF
HMF-HMB

Figure 9

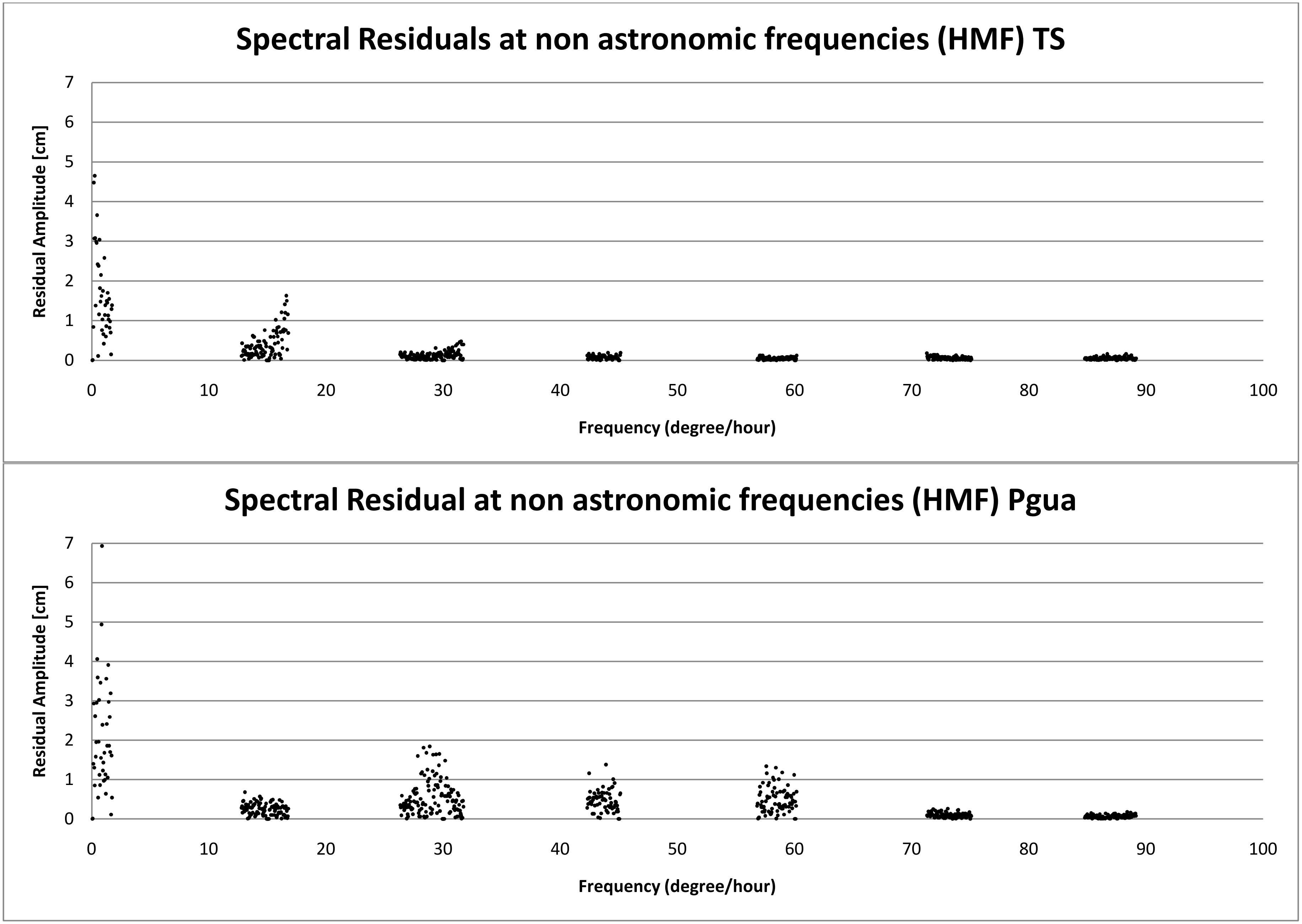

Spectral Residuals at non astronomic frequencies (HMF) TS
Residual Amplitude [cm]
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
Frequency (degree/hour)
Spectral Residual at non astronomic frequencies (HMF) Pgua
Residual Amplitude [cm]
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
Frequency (degree/hour)

Figure 10