Tidal and wave analysis for Ancona (Adriatic Sea) on hourly water level and significant wave height observations

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By

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Abstract

This report analyzes the time series of water level recorded at Ancona by a tide gauge during the period 2000-2005. Ancona is an interesting site because the amphidromic point for the M2 constituent lies just off Ancona. This report analyzes also the relationship between sea level and significant wave height, with particular attention to seasonality of sea level variability. Meteorological factors can affect sea levels. The definition of a coastline cannot leave variability of sea level out of consideration. Such variability is minimum during the summer months with fair weather condition.

1. INTRODUCTION

It is customary nowadays, in tidal heights analysis, to use hourly values of surface elevation obtained from a digital tide gauge. The tide gauges record water level that is the sum of astronomical tides and fluctuations due to sea currents and meteorological events.

Many studies have had as a subject the analysis and prediction of tides in the Adriatic Sea (e.g. Polli, 1959; Defant, 1961). In the last years such studies have been limited to northern Adriatic Sea, where the sea elevation reaches the maximum amplitude (e.g. Malacic et al., 2000; Lionello et al., 2005). The Adriatic Sea is a marginal sea and the astronomical tide theory does not work. Tidal effects happen as a side-effect of the sea level variability of the Mediterranean trough shallower water as combinations of incident and reflected Kelvin and Poincaré waves (Taylor, 1921). Hendershott and Speranza (1971) revisited the Taylor theory and showed that in the analyzed semi-closed basins all Poincaré modes are evanescent and the partial reflection of the Kelvin wave causes a displacement of the M2 amphidromic point from the cannel axis toward the western coast. Moreover, other constituents may have their amphidromic point outgoing the sea making it virtual. The M2 amphidromic point for the Adriatic Sea lies off Ancona and this makes interesting the behaviour of the tide at Ancona.

Simulating the tide in an Adriatic location is not simple for reasons said above and additional non-astronomical factors such as configuration of the coastline, local depth of the water, ocean-floor topography, and other hydrographic and meteorological influences that may play an important role in altering the range of tide, the times of arrival of the tides, and the time interval between high and low water.

The knowledge of water level is important for different reasons, among these the evolution of beaches. The dissipation energy per volume unit caused by sea action on a beach is given by $D = \sqrt{h}\,\frac{dh}{dy}$, where h is the water level and y is the coordinate going from the sea to land (across the shoreline). If we suppose *D* as a constant, increasing of *h*, *dh/dy* must decrease and the shoreline retreats.

On the other hand, the knowledge of fluctuations of high and low water is necessary to define tidal datum, although for a correct definition of such datums observations taken over 19 years are needed.

For marine applications, a vertical datum is defined as a base elevation used as a reference from which to determine relative heights or depths. It is called a tidal datum when defined by a certain phase of the tide. Tidal datums are local datums and should not be extended into areas, which have differing hydrographic characteristics without substantiating measurements.

The application areas of tidal datums are manifold, from coastal management to emergency management; for defining the legal boundaries of a country or to help defining the nautical charts.

In this report, we study the hourly water level recorded by the Ancona tide gauge in order to identify when a reference coastline should be defined, considering the high variability of coastline. Moreover waves and sea levels are compared in order to detect relationship between them.

2. DATA

For this report, hourly data used are those gathered from the Ancona station (Fig. 1) for the period 2000-2005. The data for this station are provided by the “Agenzia Nazionale per la Protezione dell’Ambiente e per i Servizi Tecnici (APAT), which manages a network of buoys and tide gauges whose observations are made available through Internet (http://www.idromare.com) and other media.

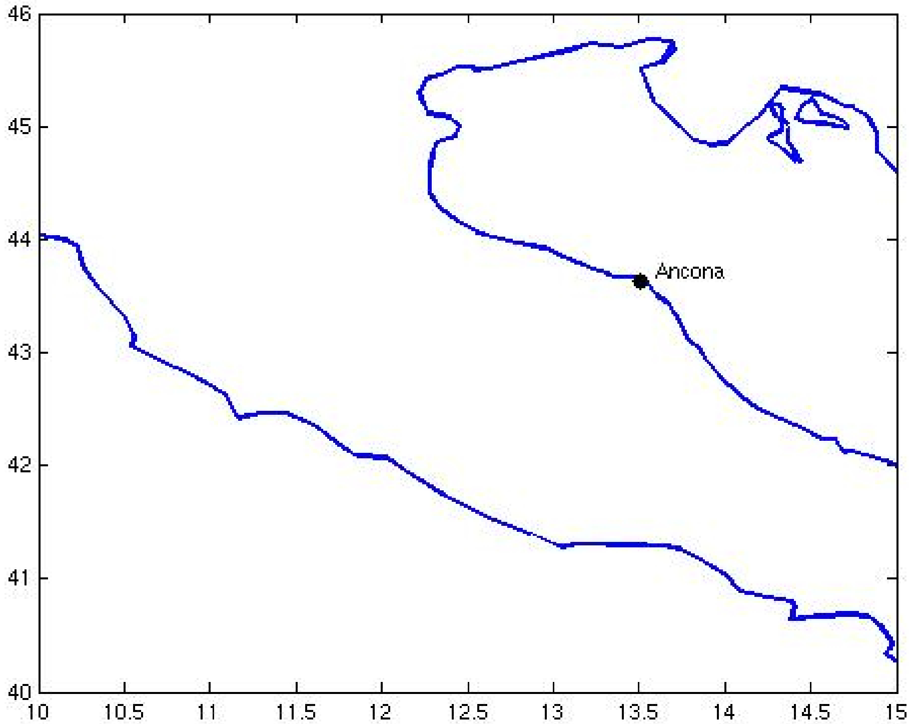

Fig. 1 The Adriatic basin and the location of Ancona tide gauge.

Tide gauges record water level. Although the water level series are available on the web site from 1986, there are several periods having some data missing. Also the time series from 2000 to 2005 have very few missing observations. A quality check was performed and the missing data were replaced by a linear interpolation between the previous and the next values. If a spike was found, again it was replaced by a linear interpolation between two contiguous sea levels.

The statistics characterizing these observations as a function of year are listed in Table 1.

The mean value is always negative indicating a possible bias for the gauge; moreover it changes during the years. This means that we can define only a yearly mean sea level. In order to define the Mean Sea Level as a tidal datum, a period of 18.6 years should be considered, since it is the period of nutation. The annual mean has shown no appreciably change during the 6 last years (fig. 3, Tab.1).

Table 1. Statistics of observations as a function of year at Ancona

Year	**Number**	**Mean**	**Std Dev**
2000	8784	-0.05317	0.179646
2001	8760	-0.01191	0.162019
2002	8760	-0.02375	0.183347
2003	8760	-0.05606	0.180090
2004	8784	-0.03226	0.178699
2005	8760	-0.05476	0.174413

The time series, from the 1st January 2000 to 31st December 2005, of observed water level is shown in Fig. 2.

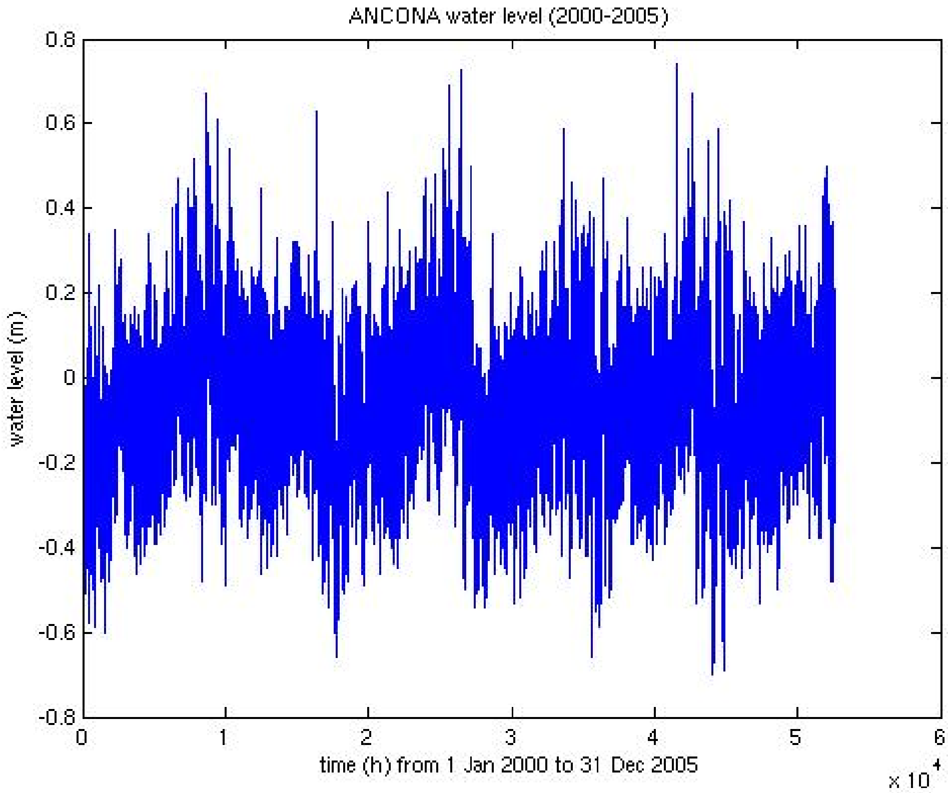

Fig. 2. Time series of water level observations from 1st Jan 2000 to 31st Dec 2005.

Figure 4 shows oneway analysis of observed water level by month. It is worth noting the annual cycle that could be associated with the position of the Earth with respect to the Sun, with the water level reaches the lower and higher levels in years. Instead, such variability is caused mainly by meteorological variability that is maximum during the autumn and winter season (see fig. 4 and fig. 5). Many water levels higher and lower than 99th percentile, indicated by the upper and lower limits of bars, occurred from September to March.

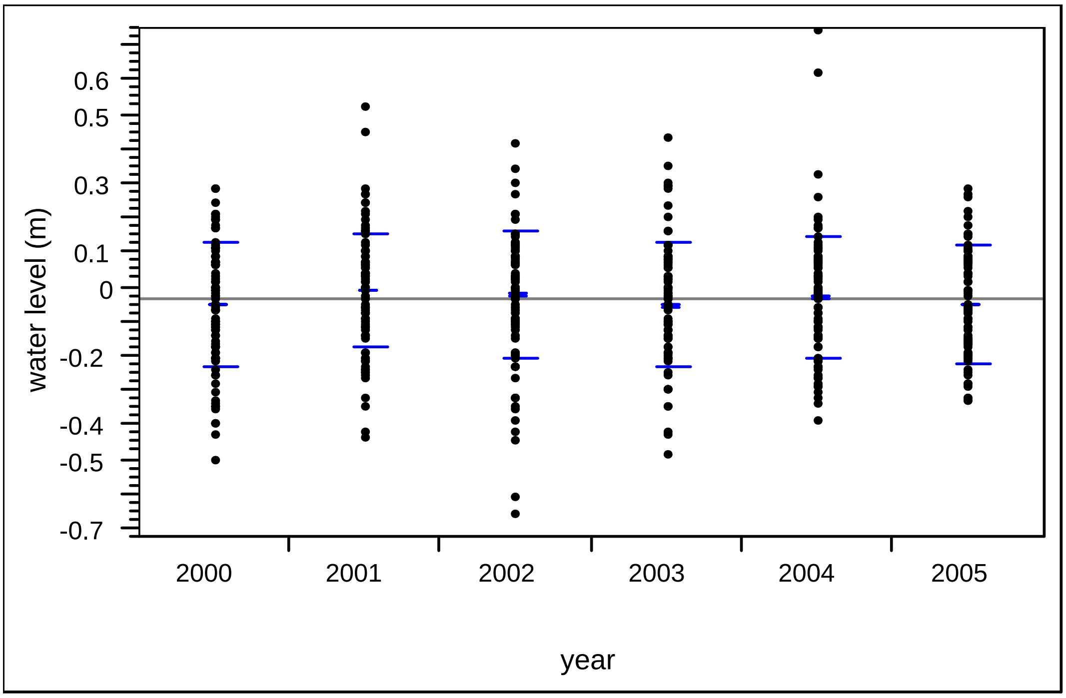

Figure 3 Oneway Analysis of Observed water level (m) by year. Only the median, 25th and 75th quantile are shown.

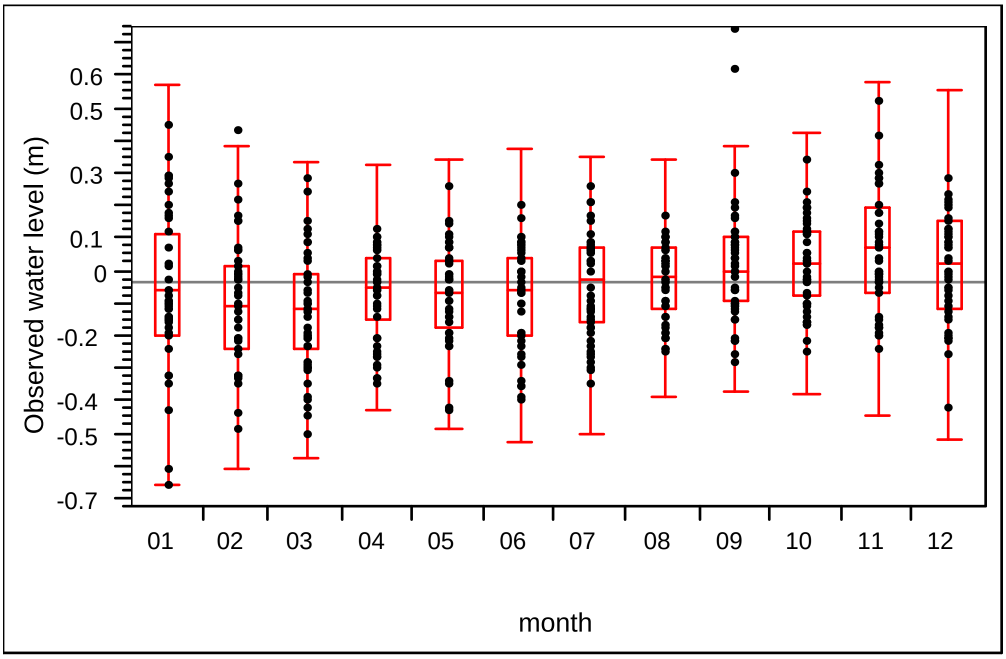

Fig. 4 Oneway Analysis of Observed water level (m) by month. In this figure is shown also the median, the 10th, 25th, 75th and 90th quantile.

Table 2 provides statistics for each month, with quantilies.

Thus, the annual frequency is very important not only for the astronomical factors. There is a huge literature about the prediction of tides on short time, whereas aspects concerning the long-term prediction are lacking. These are many reasons for that. The study of past records enables tide tables to be projected into the future. Experience permits prediction of tidal height to an accuracy of within about 3 centimeters for years in advance. Even so, extraneous factors can affect the tidal estimates. For example, arrival of a storm surge will greatly affect the height or timing of a tide—as will gentle, atmospherically induced seiching of the basin.

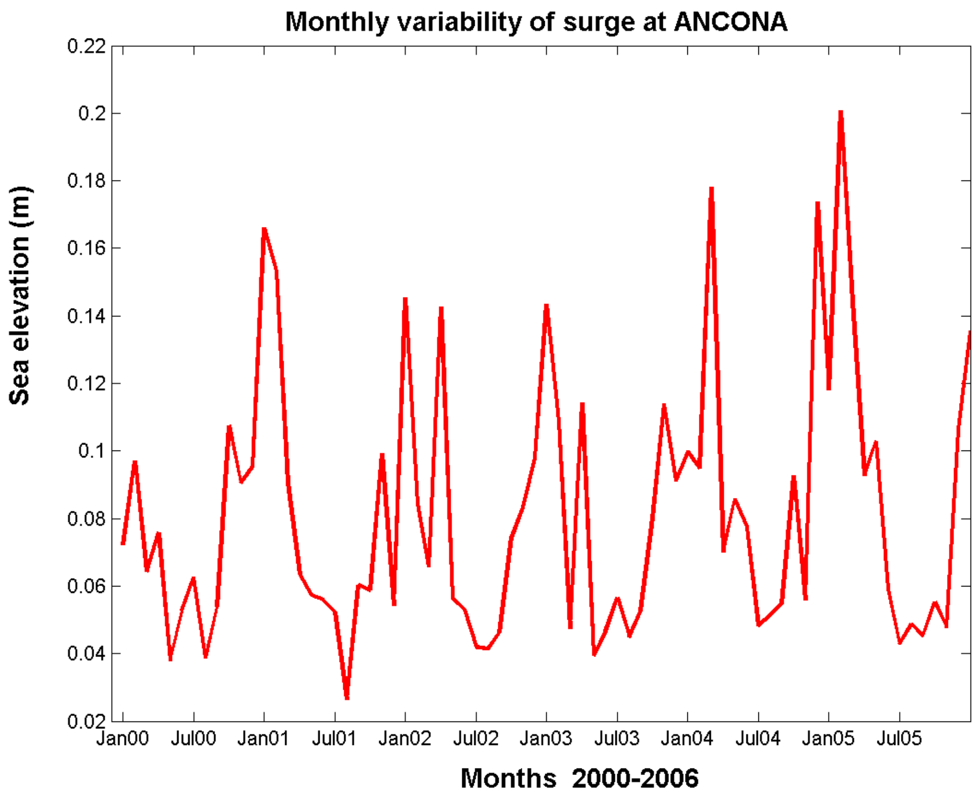

Figure 5. Monthly standard deviation of residuals at Ancona.

Even a strong, steady wind onshore or offshore will affect tidal height and the arrival time of the crest inducing meteorological tides after their origin.

Table 2. Main statistical indicators as a function of month

Month	Minimum	10%	25%	Median	75%	90%	Maximum
01	-0.7	-0.36	-0.2	-0.06	0.11	0.28	0.73
02	-0.69	-0.36	-0.24	-0.11	0.01	0.13	0.5
03	-0.6	-0.34	-0.24	-0.12	-0.01	0.11	0.54

Month	Minimum	10%	25%	Median	75%	90%	Maximum
04	-0.47	-0.24	-0.15	-0.05	0.04	0.12	0.37
05	-0.53	-0.27	-0.18	-0.07	0.03	0.11	0.38
06	-0.53	-0.3	-0.1975	-0.06	0.04	0.11	0.45
07	-0.5	-0.27	-0.16	-0.03	0.07	0.14	0.35
08	-0.41	-0.21	-0.12	-0.02	0.07	0.13	0.34
09	-0.37	-0.18	-0.09	0	0.1	0.18	0.74
10	-0.42	-0.16	-0.08	0.02	0.12	0.2	0.54
11	-0.53	-0.199	-0.07	0.07	0.19	0.31	0.67
12	-0.54	-0.24	-0.12	0.02	0.15	0.28	0.69

In classical harmonic analysis, the tidal forcing is modeled as a set of spectral lines, i.e., the sum of an infinite set of sinusoids at specific frequencies. These frequencies are specified by various combinations of sums and differences of integer multiples of some fundamental frequencies arising from planetary motions (Godin, 1972). A least-squares fit can be used to determine the relative phase and amplitude of each frequency in the response. This phase/amplitude data thus provides a compression of the data in the complete time series, which can then be compared with similar data at other locations to understand the characteristics of tidal dynamics, or can be used to synthesize time series of tidal effects at other times for predictive purposes.

There are several drawbacks to classical harmonic analysis. The first is that, ignoring the modulation of perihelion, which is effectively constant over historical time, about 18,6 year time series is required to resolve all of the listed frequencies (that is, the number of wavelengths of each constituent in the record is at least 1 different from all other constituents). In practice, record lengths are often 1 year or shorter. In order to handle this issue an assumption is made that the phase/ amplitudes of response sinusoids with similar frequencies are in the same proportion as those of the equilibrium response under the reasonable premise that the ocean response should be similar at similar frequencies. In such a cluster, large equilibrium peaks are surrounded by small subsidiary peaks in frequency space which provides ‘‘nodal modulations’’ (or more correctly, ‘‘satellite modulations’’) to the main peak.

The appearance of the total signal will be a sinusoid whose phase and amplitude varies slowly with time.These changes are slow enough to be considered effectively constant for record lengths of up to 1 year.

At much shorter record lengths another problem arises. The frequency resolution further degrades until even dissimilar constituents are unresolvable. The best solution is to apply inference. This technique for finding the absolute phase/amplitude requires that the relative differences in phase/amplitude between the two unresolved unresolved constituents is known from other nearby data. If this is not the case, it is thought best to either discard the smaller constituents or fit only to the largest in a given frequency interval, or to use the equilibrium response to establish the desired differences.

Another drawback of classical analysis is that it provides no easy way to determine whether the resulting phase/amplitude of a given sinusoid is meaningful in a deterministic way (i.e., it is truly a tidal line), or whether it results from fitting to a component of the non-tidal broad-spectrum variability. In general a fit is likely to include elements of both and some kind of confidence interval for the deterministic part is useful. To address this issue, the ‘‘response’’ method was invented (Munk and

Cartwright, 1966). Although this provides better results than classical harmonic analysis, it has not found widespread use.

Further problems with classical harmonic analysis arise in coastal regions where the tidal response is in the form of a wave propagating onshore. In large estuaries, the seasonal change in salinity and flow may change the dynamic response but as these changes can vary from year to year the tidal process is not really stationary.

Instead spectral peaks are broadened so that they are no longer pure lines, but, depending on the situation, such variations may be treated as lines in the analysis. Within smaller estuaries, tidal height variations may be significant compared to water column depth and a variety of non-linear effects can occur. For example, flood periods shorten and intensify and ebbs lengthen. As long as these effects are reasonably deterministic they may be handled by adding extra ‘‘shallow water’’ constituents which occur at sum/difference frequencies of the major constituents. More problematic in these regions are the effects of internal variability. Tidal interactions with varying topography can produce large internal waves and bores whose characteristics are highly sensitive to ambient stratification. In such cases the assumption of ‘‘line’’ frequencies becomes questionable and other techniques such as wavelet analysis have been suggested (Jay and Flinchem, 1999). More comprehensive descriptions of analysis techniques, their uses and limitations are given in, e.g., Foreman et al. (1995) and Godin (1991).

3. SPECTRAL ANALYSIS

The data recorded by tide gauges $D(t)=T(t)+M(t)$ are a sum of a tidal signal $T(t)$ (with m tidal constituents) plus a non-tidal signal $M(t)$.

The response of water to non-tidal forcing may have periodic constituents that are not strictly associated with tides. For example, current driven by breezes, normal modes associated with the oscillations of basin (seiches), impact of different kinds of wind that occur with seasonal frequency and radiative effects on sea water, can give a sort of periodicity to water level that is not dependent on tide causes. Thus the signal *M(t)* could also have periodic constituents.

We are interested in analysis both tidal and extra-tidal constituents. The analysis has been performed by means of tidal analysis software (Pawlowicz et al., 2002) derived from an algorithm developed by Godin (1972) and Foreman (1978). Moreover, we have analyzed the periodic behaviour trough the classical spectral analysis and by means of spectral analysis. Results are shown in fig. 6, the diurnal constituent is the highest one. The annual constituent shows a higher value than other constituents but the K1 and M2.

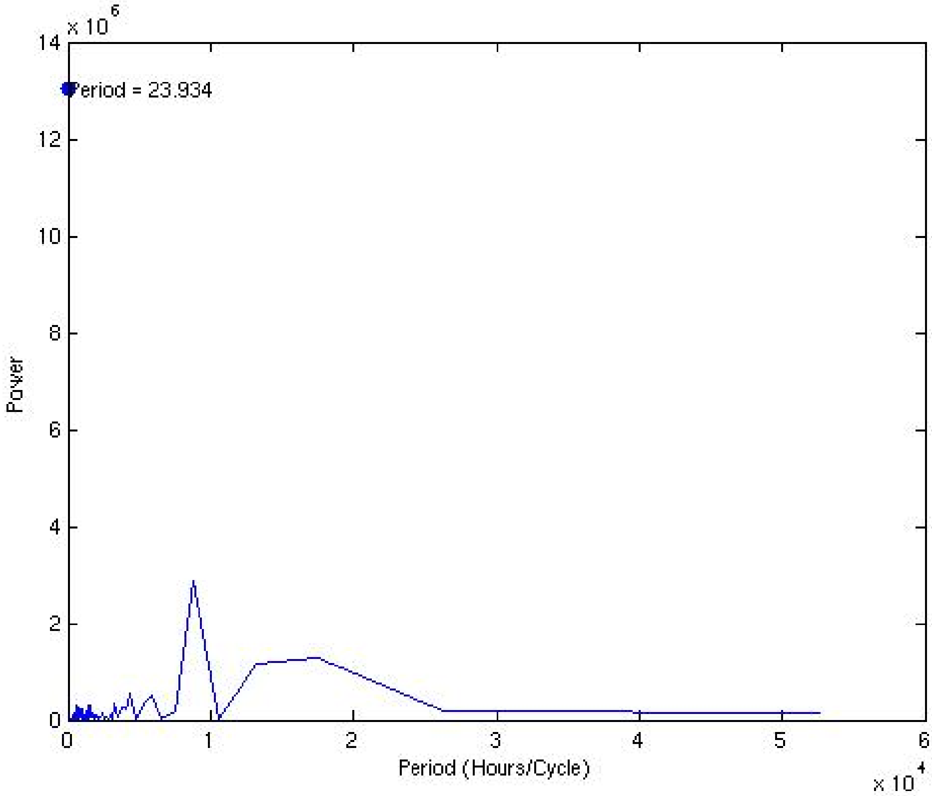

Figure 6. Fourier components at low frequencies of sea level observations at Ancona.

Zooming on higher frequencies and lower period (fig. 7), we can note that together to the 24 hour component, there are near components with an appreciable power density. These components are not associated with seiches, as it will be seen later.

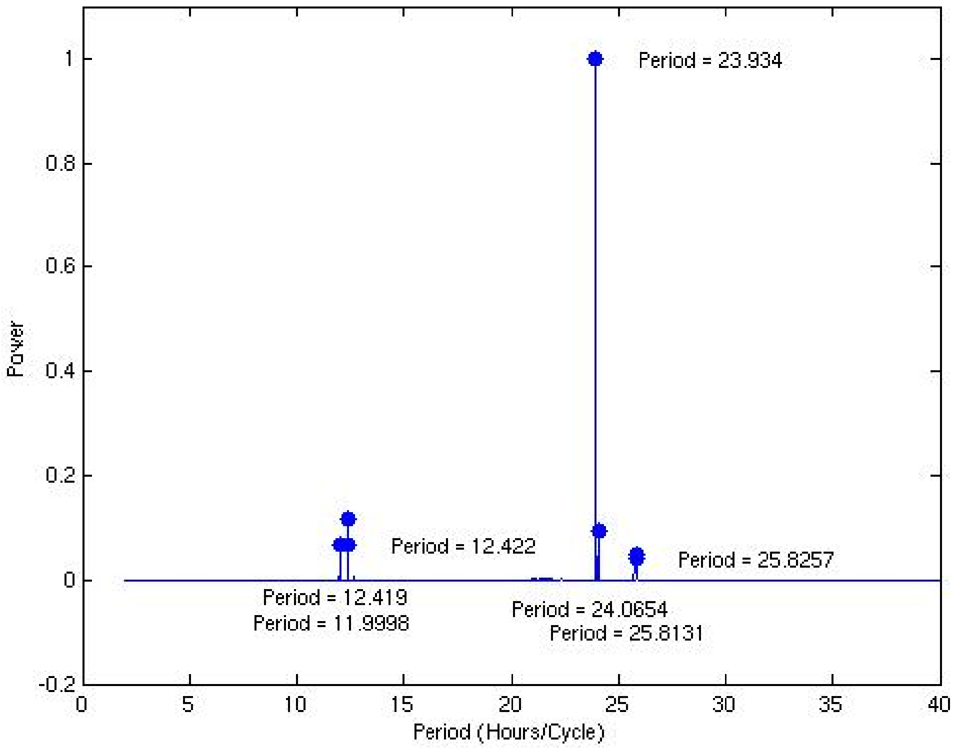

Figure 7. Tidal high frequency components at Ancona. It is worth noting the strong diurnal component, differently from the observed ones at other tide station, where the predominant component is the semidiurnal one.

After eliminating the contribution of tidal constituents found by the t_tide software we have looked through the residual frequencies to see if an important signal is present in the spectrum.

4. SEICHES

At higher frequencies it is possible to see the presence of seiches. The contribution to total spectrum is not very high. Differently to tidal constituents, seiches occur only several times in a year as a response of sea to meteorological forcing from south boundary of the Adriatic. The oscillation of seiches is important above all on the northern Adriatic that represents the head of the basin. Numerical simulations of tide for the Adriatic (Lionello et al., 2004), showed that at Ancona the amplification factor of the seiches is close to 1 whereas at Venice it is higher (1.4).

5. WAVES AND TIDES

Strong winds on the surface of a body of water will cause sea waves that can affect the water level. A buoy is moored off Ancona. It records the significant wave height. We show the scatterplot the wave heights with tide measurements and the wave heights with surge (fig. 8).

It can be noted that at distribution of point corresponding at high value wave height is elongated towards high values of sea level, even though a linear relationship is hard to be found. Strangely, when only residuals are plotted versus significant height of wave, the relationship high wave height equal high values of sea level, due to residuals, is not so clear, at glance.

On the other hand, there is a clear relationship between variability of residuals and seasons (fig. 5), that determines seasonal variability of sea level.

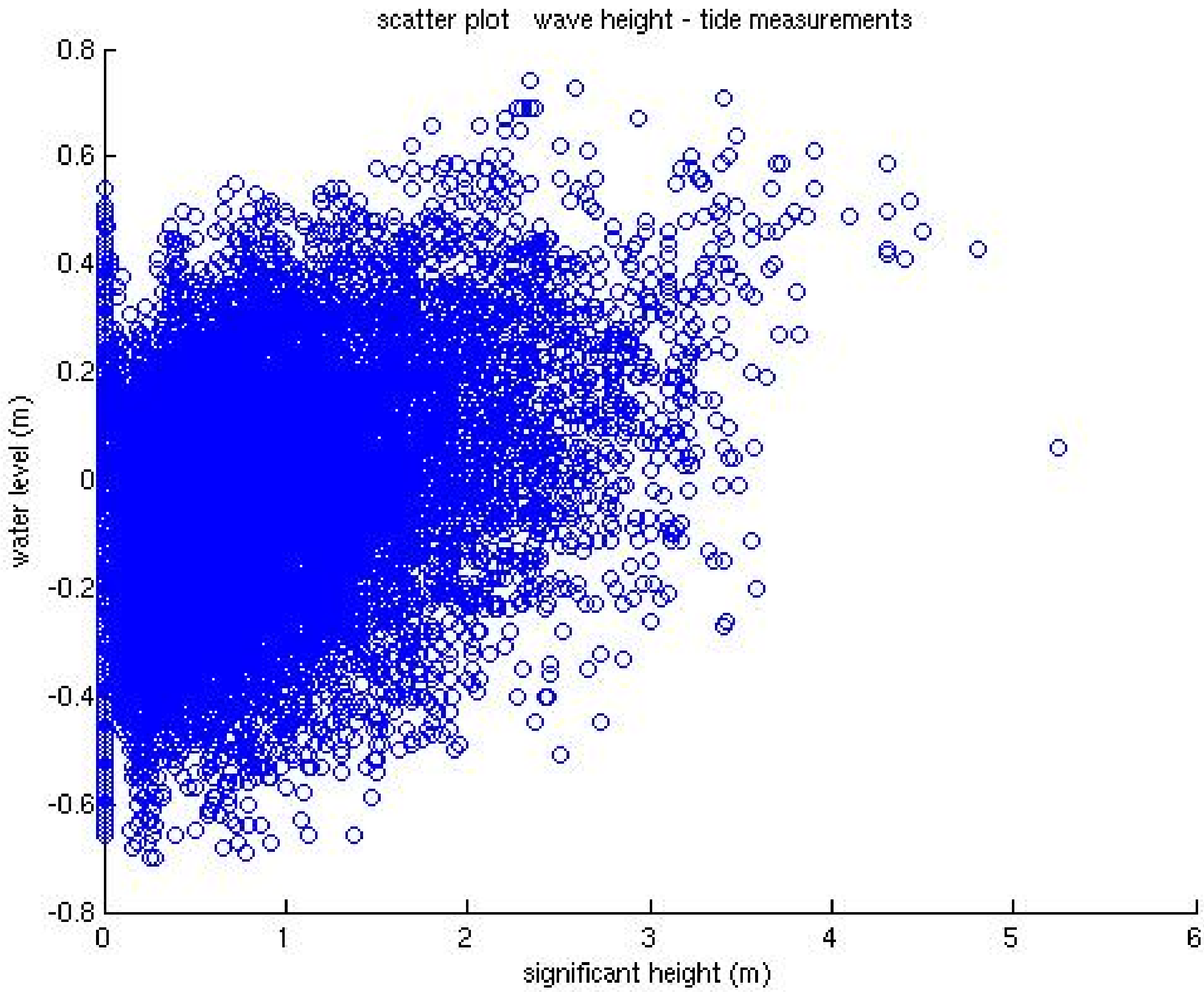

Figure 8 Scatterplot of significant wave heights and sea levels at Ancona

6. Conclusions

In this report we have shown that the tide at Ancona is essentially a mixed tide with a strong diurnal constituent. The annual constituent is very important even because tidal maxima occurring during the winter season when the meteorological conditions force strong winds that affect the water level.

Other than frequencies associated with astronomical forces, there are other effects both at lower and higher frequencies. Seiches are well visible after filtering the astronomical frequencies; it is worth noting that the spectral density of seiches is a hundredth of diurnal K1 frequency. Even seiches are due to meteorological conditions, normally Scirocco winds that excite the normal modes of the Adriatic basin. The relationship between meteorological systems affecting sea level is visible in the variability of sea level and in particular of the residual. In fact, seasonality of surge variability is well evident. Such variability has to be accounted for when defining the coastline. Thus, a coastline should be defined during summer months (July or August) in fair weather conditions.

Appendix A

In this appendix the amplitudes with the associated error and the signal noise ratio (snr) of the tidal constituents are shown.

tide	freq	amp	amp_err	snr
*SA	0.0001141	0.0645	0.018	12
*SSA	0.0002282	0.0285	0.019	2.3
*MSM	0.0013098	0.0033	0.012	0.078
*MM	0.0015122	0.0147	0.015	0.98
*MSF	0.0028219	0.0082	0.012	0.44
*MF	0.0030501	0.0112	0.017	0.44
*ALP1	0.0343966	0.0004	0.002	0.04
*2Q1	0.0357064	0.0005	0.002	0.065
*SIG1	0.0359087	0.0017	0.003	0.46
*Q1	0.0372185	0.0065	0.003	4.5
*RHO1	0.0374209	0.0018	0.002	0.57
*O1	0.0387307	0.0409	0.003	1.80E+02
*TAU1	0.0389588	0.0011	0.002	0.21
*BET1	0.0400404	0.0011	0.002	0.22
*NO1	0.0402686	0.0036	0.002	3.2
*CHI1	0.040471	0.001	0.002	0.21
*PI1	0.0414385	0.0049	0.003	3
*P1	0.0415526	0.0422	0.003	1.70E+02
*S1	0.0416667	0.0061	0.005	1.8
*K1	0.0417807	0.1299	0.003	2.00E+03
*PSI1	0.0418948	0.0018	0.003	0.52
*PHI1	0.0420089	0.0034	0.003	1.4
*THE1	0.0430905	0.0008	0.002	0.15
*J1	0.0432929	0.0092	0.003	9.4
*SO1	0.0446027	0.004	0.003	1.7
*OO1	0.0448308	0.0063	0.002	7.8
*UPS1	0.046343	0.0043	0.002	3.5
*OQ2	0.0759749	0.0005	0.001	0.7
*EPS2	0.0761773	0.0004	0.001	0.68
*2N2	0.0774871	0.0013	0.001	6.3
*MU2	0.0776895	0.0017	0.001	11
*N2	0.0789992	0.0121	0.001	4.40E+02
*NU2	0.0792016	0.0023	0	22
*GAM2	0.080309	0.0001	0	0.13
*H1	0.0803973	0.0006	0.001	1
*M2	0.0805114	0.0663	0.001	1.50E+04
*H2	0.0806255	0.0006	0.001	1.4
*MKS2	0.0807396	0.0004	0	0.98

*LDA2	0.0818212	0.0006	0	1.5
*L2	0.0820236	0.0027	0.001	15
*T2	0.0832193	0.0015	0.001	8.3
*S2	0.0833333	0.0355	0.001	3.90E+03
*R2	0.0834474	0.0004	0	0.77
*K2	0.0835615	0.0104	0	6.50E+02
*MSN2	0.0848455	0.0003	0	0.49
*ETA2	0.0850736	0.0009	0	3.2
*MO3	0.1192421	0.0002	0	0.56
*M3	0.1207671	0.0024	0	37
*SO3	0.122064	0.0007	0	3.6
*MK3	0.1222921	0.0003	0	0.72
*SK3	0.1251141	0.0012	0	10
*MN4	0.1595106	0.0002	0	0.39
*M4	0.1610228	0.0001	0	0.29
*SN4	0.1623326	0.0002	0	0.27
*MS4	0.1638447	0.0002	0	0.41
*MK4	0.1640729	0.0004	0	1.7
*S4	0.1666667	0.0004	0	1.5
*SK4	0.1668948	0.0002	0	0.46
*2MK5	0.2028035	0.0002	0	0.75
*2SK5	0.2084474	0.0002	0	0.75
*2MN6	0.2400221	0.0002	0	0.3
*M6	0.2415342	0.0005	0	1.8
*2MS6	0.2443561	0.0006	0	2
*2MK6	0.2445843	0.0002	0	0.56
*2SM6	0.2471781	0.0004	0	1.2
*MSK6	0.2474062	0.0003	0	1.2
*3MK7	0.2833149	0.0002	0	0.59
*M8	0.3220456	0.0001	0	0.058
*2PO1	0.0443745	0.0031	0.003	0.99

Acknowledgments

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