Study of the Variations of the Sea Water Level in the Catalan Coast

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Resumen

**Palabras clave:** marea meteorológica, nivel medio del mar, viento, presión, marea, Costa Catalana.

La Costa Catalana está dotada de una situación privilegiada, resguardada de las grandes mareas astronómicas y meteorológicas, protegida de las grandes corrientes o de los grandes desastres naturales como los huracanes o tsunamis. Sin embargo, aunque se considere que el Mar Mediterráneo es un mar sin mareas existen y pueden llegar a suponer una variación del nivel medio del mar muy grande llegando a provocar inundaciones en las zonas más bajas como el Delta del Ebro o dañando las infraestructuras de la costa. Con este trabajo se pretende demostrar que existe marea meteorológica (creada por el rozamiento del viento y las variaciones de presiones) y evaluarla en la Costa Catalana mediante el análisis de esta misma en siete puntos diferentes. En cada punto se estudia tanto la presión y el viento identificando su evolución en el tiempo y sus valores más significativos. La marea inducida será medida según la ley del barómetro invertido mientras que la inducida por el viento según la ley unidimensional de la marea de tormenta. De esta forma tendremos unos valores y unas leyes de comportamiento de la marea meteorológica que nos permitirá dar una conclusión global de esta a lo largo de la Costa Catalana. Podremos ver como sí existe una marea meteorológica y como sí existe un cierto riesgo de sobreelevación del nivel medio del mar, como ya sucedió por ejemplo en el 2008. Además podremos conseguiremos caracterizar la presión como un fenómeno global y estacionario a diferencia del viento que sufre modificaciones debido a los efectos locales.
Abstract

**Key words**: meteorological surge, mean sea water level, wind, pressure, surge, Catalan Coast.

The Catalan Coast is placed in a really favourable spot. Away from the astronomical and meteorological tides, protected against the big currents and also protected from the big natural disasters as hurricanes and tsunamis. However, even though the Mediterranean is considered a tidal-less sea they do exist and the can lead to floods at the lowest areas as the Ebro Delta or causing damage to the coastline infrastructure. With this project we want to demonstrate that there is meteorological tide (induced by the variations of pressure and wind friction) and study it at the Catalan Coast by the study of this surge in seven different places along the Catalan Coast. In every place we will study pressure and wind evolution in time and their significant values. The pressure surge will be calculated by the inverted barometric effect law and the wind will be calculated by the one dimension storm surge. In this case we will have the significant values and several laws of variation of this surge for each place being able to have a global conclusion of the entire Catalan Coast. We will be able to see how there is a meteorological surge and there is a risk of big increases of the mean sea water level as it happened in 2008. We will also be able to characterize the pressure as a global and stationary phenomenon while the wind is considered a local phenomenon that depends on the local effects.
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1. INTRODUCTION

1.1 Motivation

A raise of the sea water level can cause many damage to the coast. If it raises too much floods of the lowest areas can occur for example the deltas and lagoons (present in the Mediterranean coast). These floods will cause a lot of damage to these areas as the interruption of the biological life in the case of the Ebro delta. This increase of the sea water level will also suppose an erosion of the coast. Being worst if it is varies constantly.

Waves also suppose a problem for the coastline. The dynamics of the water will induce erosion of beaches and transport of sediments along the coast. Even more, overtopping can happen damaging the coast life and the infrastructures next to it.

The Mediterranean is placed in a really favourable spot waves are generated by the wind. The turbulent eddies will periodically touch down on the water causing local disturbances of the water surface (Kamphuis, 2000). The wind makes a tangential force to the water surface transmitting energy to the water. As we can see, wind will lead to waves an then waves will lead to the damages on the previous paragraph.

In the Mediterranean Catalan Coast an extreme wave is considered when it overpasses 2 meters. (ROM 03.91). The mean significant waves in the Mediterranean Catalan Coast are under 1, for example 0,8 in the Ebro delta (XIOM, 2007). Even if we have moderate wave energy conditions during the most part of the year, extreme events can happen causing damages to the coast.

Sea water level variations are not as important in the Mediterranean Sea as in other seas. Nevertheless it is interesting to be studied because of the presence of deltas and alluvial flats. Sea level variations of weeks and hours are associated to the meteorological and astronomical tide (XIOM, 2007). The astronomical tide is very small in the Mediterranean Sea and it has arrived to a maximum of 25 centimetres (Maria Navarro Alonso, 2004).
On the other hand we have the meteorological surge that has the same magnitude of the astronomical tide. The meteorological tide can increase 56 centimetres de sea water level (Montserrat Grobas, 2003).

The combination of these three phenomena at the same time can lead to an extreme sea condition. For example in l’Estartit in December 2008 a storm happened with waves of significant heights of 7 metres and even a maximum of 9 metres (Sergi Corral, 2009).

The mean sea water level in the Mediterranean has not been studied properly as it has been studied in other oceans. This is because the Mediterranean is considered a tidal less sea so without variations. This explains why the gauge net of Puertos del Estado in the Catalan coast is so small. However has we have already said it suffers several variations and it is interesting to study them in a engineer point of view.

1.2 Objectives

The general objective of this work is to characterize the meteorological surge in the entire Catalan coast.

As we will see in the following chapters there are many things that make the sea water level change. The study of the sea water level is an extremely large subject that cannot be studied in the same project properly.

Many projects of study have been done at the Catalan Coast about astronomical tides, climatic change, waves, etc. Nevertheless, none has been done about the meteorological surge. Because of that we will focus our thesis in the meteorological surge.

As we will see the meteorological surge is composed by the wind and the pressure influence on the sea surface.

We will try to analyse how the meteorology influences on the sea water level. We will study both components of the meteorological surge, the wind and the pressure.
We will see the influence both of the components to the surge and we will compare them. We will try to analyse their properties trying to find specially their evolution in time and their main values as average, standard deviation or maximum and minimum.

The point of this thesis is to be able to know when will we have the maximum surges, their values and why they happen. But the Catalan Cost has different meteorology all along it so we have chosen different points to add reliability to our conclusions.

We have seven points of study where we have data measured from private people. From each place we have wind and pressure data. To add more reliability to this data and being able to compare it to another data source we have the SIMAR points data and the data of pressure from two buoys.

So from each point we want to analyse the meteorological surge, searching the significant values, analysing its evolution in time and where it this surge comes from.

1.3 Thesis structure

In the second chapter we will explain the theory concerning to the mean water level oscillations. We will explain the three components that produce variations in the Catalan coast. Firstly we will talk about the waves, secondly about the astronomical tide and finally about the meteorological tide. The idea in this chapter is to give an idea to the reader of why and how can vary the sea water level.

In the following chapter, the number three, we will characterize our area of study. We will show some interesting values that can be used as a reference when discussing the results. Next to this we will talk about our data sources and what we have obtained from them. Finally in this chapter we will explain how we have done our calculations to obtain the results.

In the fourth chapter we have all the data results and discussion of this data. We have structured this chapter in the different places of study.
Finally we have the conclusion of our project. In this chapter we will conclude about our results and we will see if our project has accomplished the objectives shown in the beginning.
2. MEAN WATER LEVEL OSCILATIONS

2.1 Introduction

On earth we have many stationary water bodies which they occupy a certain volume. This volume has boundary layers that make them to be still on these boundaries. However, most of them are non-confined and the have a free surface that can move depending on the forces acting on it.

For example the astronomical tides will induce to an increase or a decrease of the mean water level (the free surface) and will also lead to oscillations in this free surface. Also other factors act on this variations of the mean water level. The wind and the atmospheric pressure will induce a storm surge that might be able to raise the mean water level considerably.

There are also other reasons for the variation of the mean water level; the amount of water on the water body is for example the most important. Furthermore, the climatic change is also acting on this variation because all the ice is being converted to water, which will increase the mean water level of oceans and seas.

These variations have to be predicted as much as it is possible. An extreme raise of the mean water level can be dangerous and risky for humans and other living beings.

We have many examples around the world about how these variations can cause big disasters, not only economical but also social as the death of many people. Because of this, the study of these variations must be done. Event that some places are more exposed to critical variations, this does not exclude the study in other areas more protected as seas and lakes.

On the following pages we will explain what causes these variations.
2.2 Waves

2.2.1 Introduction

Waves are fluctuations of the surface level (in our case sea water) accompanied by local currents, accelerations and pressure fluctuations. The waves can be regular if this fluctuation is repeated constantly or irregular if it’s not.

For defining the different parts of a wave we will use the simplest wave shape; regular waves pictured at the following figure.

![Wave Diagram](image)

Figure 2.1 Basic wave nomenclature. Source: Advanced series on ocean engineering Vol.16

When the level is on his maximum we are in a wave crest, the lowest levels are wave troughs. The difference between those two levels (the maximum and the minimum) is the wave height H. The distance between two crests is the wave length L. The wave propagates with a velocity of C and the time needed for covering the length between two crests is the wave period T. The inverse of the wave period is the wave frequency. The horizontal line SWL is the sea water level. The wave steepness is \( H/L \).

Those parameters are well represented in a regular wave and they are easy to identify because they are constant. However, in irregular waves those parameters varies in time and they are no longer constant and easy to recognise. In any case this parameters will always mean the same.
2.2.2 Regular Waves

As it has already been said recently, regular waves are those were the fluctuation of the water surface is repeated constantly on time.

Many theories have been done for representing this kind of waves. Airy (1845) proposed Small Amplitude Theory Wave. Theories try to represent reality the best way it’s possible however many assumptions are done. These assumptions have to be accord and not disturb the results from reality.

Airy, for his theory of linear waves did the following assumptions:

- Homogeneous and incompressible liquid (density is constant)
- Surface tension is neglected
- Coriolis effect because of earth rotation is neglected
- Pressure on the water level is uniform and constant
- Ideal fluid (no viscosity)
- Not rotational flow
- The bottom of the sea is always flat
- Waves are considered in 2D
- Amplitude of the wave is small compared to the SWL (A/SWL<<1)

Airy started with the equation of the mass conservation:

\[
\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0
\]  

(2.1)

Applying the assumptions, the water surface fluctuations maybe described by a sinusoidal fluctuation defined by:

\[
\eta(x, t) = \frac{H}{2}\cos(2\pi L)
\]  

(2.2)

Where \( \eta \) is the altitude of the water surface respect SWL, \( H \) is the wave height, \( k \) the wave number and \( \omega \) is the angular frequency.

\[
k = \frac{2\pi}{L}
\]
\[ \omega^2 = gk \tanh(kh) \]

And because of \( c = \omega/k \), we can write:

\[ c^2 = \frac{g}{k} \tanh\left( \frac{2\pi}{L} h \right) \]  

(2.3)

Finally, we can obtain:

\[ L = \frac{gT^2}{2\pi} \tanh\left( \frac{2\pi}{L} h \right) \]  

(2.4)

Where \( h \) is the height of the SWL.

So as we can see, the different parameters of the wave will be different depending on the value of \( h \). We will distinguish three cases depending on the value of \( h \): shallow, intermediate and deep water.

2.2.2.1 Shallow water

We will assume that \( h/L < 0.05 \) so:

\[ c = \sqrt{gh} \]

\[ L = T \sqrt{gh} \]

2.2.2.2 Deep water

We will assume \( h/L > 0.5 \) so:

\[ L_0 = \frac{gT^2}{2\pi} \]

\[ c_0 = \frac{gT}{2\pi} \]
2.2.2.3 Intermediate waters

We will assume that \(0.05 < h/L < 0.5\) so:

\[ L = L_0 \tanh \left( \frac{2\pi}{L} h \right) \]
\[ c = c_0 \tanh \left( \frac{2\pi}{L} h \right) \]

Figure 2.2 shows water particle trajectories for short and long waves as function of depth.

Figure 2.2: Particle motion. Source: CEM

2.2.3 Irregular Waves

Besides the facilities of calculations and studies that regular waves may allow us, they are not always a good way of representing reality because in many cases waves are irregular.
In this case there is not a sinusoidal variation of the free surface but neither there is any shape repeated along time. If we want to know about the different parameters (mainly water high and wave period) we will have to use instruments to provide ourselves of this data.

It is requested to differentiate between Short-Term and Long-Term wave analysis. In the first case we will analyse the waves that occur within one wave train or within a storm. On the other hand, Long-Term makes reference to the statistical study of data distribution over many years.

2.2.3.1 Short-Term Wave Analysis

As it has already been said, short-term analyses consist in collecting data from the same train of waves.

![Water Level Record](image)

*Figure 2.3: Water Level Record. Source: Advanced series on ocean engineering Vol.16*

In those water level records we will have to recognise the different waves, with their period and wave height. To identify a wave we will use the zero up-crossing method. So we will obtain in a same train of waves N waves with $T_i$ and $H_i$ for each of the waves.

Another short-term analyse might be done, is called the spectrum analysis. In this one we apply to $\eta$ the Discrete Fourier Transformation (DFT) and we will obtain a spectrum of the energy of the waves depending on their angular frequency.
We can obtain many different types of spectrums, wide spectrums or more narrow spectrums. When the spectrum is narrow we would be able to say that there are no many different frequencies. When this happens, periods tend to be longer. We call this phenomenon *swell*. When the spectrum is wide is because there are many different values for the frequencies. This happens when the frequencies are distributed randomly. It would correspond to a chaotic sea that could be the result of a storm or waves induced by the wind. This phenomenon is called *sea*.

From the spectrum we can obtain:
\[ m_0 = \int_0^{\infty} S(\omega) d\omega \]  

(2.5)

From which we can obtain the Characteristic Wave Height or Zero Moment Wave Height:

\[ H_s \approx H_m = 4\sqrt{m_0} \]

2.2.3.2 Long-Term Wave Analysis

The data provided in this case comes after a year or more of observation and data collection. As more years of data collections more precise will be your analysis and you it will be possible to identify the different cyclic variations.

This data has to main purposes: to organise the wave height data and to extrapolate the data set to extreme values of wave height occurring at certain probability.

2.2.4 Shoaling and Refraction

As we have seen in 2.2.2 Regular Waves there is a wave transformation as soon as the wave changes from deep into shallow waters.

The changes of \( h \) (water depth) will lead changes in the wave celerity. These changes in celerity will lead some changes in the wave steepness (\( H/L \)) as we can see in the formulas.

Applying equilibrium of energy between the deep and the shallow waters we will find that:

\[ H_2 = K_s K_r H_1 \]  

(2.6)

\( K_s \) is the shoaling coefficient and it is defined as:
\[ K_s = \frac{c_{g_1}}{c_{g_2}} = \frac{1}{\sqrt{2 n \tanh(kh)}} \]  

(2.7)

Where:

\[ n = \frac{1}{2} \left( 1 + \frac{2kh}{\sinh(2kh)} \right) \]

2.2.5 Wave breaking

When the waves arrive to the coast the steepness increases as water depth decreases. When the steepness reaches certain limit the wave will break dissipating energy inducing to an increase of the mean water level and nearshore currents.

Many authors have studied the breaking limit and many limits have been founded. For regular waves we have many different limits that can be applied:

- McCowan criterion (1894):
  \[ \frac{H_b}{h_b} = 0.78 \]

- Miche criterion (1944):
  \[ \frac{H_b}{L_b} = \frac{1}{7} \tanh \left( \frac{2\pi h_b}{L_b} \right) \]

In irregular waves we wont have a constant \( H_b \) so in this case a first approximation can be done (if the sea follows a Rayleigh distribution) as:
\[ H_s = \sqrt{2} H_{rms} \]

The breaking can be classified in four different types (Galvin 1968) depending on the shape of breaking. The breaker type is a function of the beach slope \( m \) and the wave steepness. Iribarren defined surf similarity parameter as:

\[ \xi_0 = \frac{m}{\frac{H_0}{L_0}} \]

In a constant slope of a beach profile:
- Spilling: \( \xi_0 < 0.4 \)
- Plunging: \( 0.4 < \xi_0 < 2.2 \)
- Collapsing: \( 2.2 < \xi_0 < 3.2 \)
- Surging: \( \xi_0 > 3.2 \)

This figure shows the different breaker types defined by Galvin:
2.2.6 Wave setup

When the wave approaches the surf zone (region extended from the seaward boundary of wave breaking to the limit of wave uprush) the depth decreases and the wave will break as we have seen just in the chapter before. Is also important to say that before this setup the water level suffers a setdown as we can see on the picture below.

![Figure 2.7 Definition sketch for wave setup. Source: CEM](image)

Due to the wave action when breaking an increase of the mean water level will be produced. So the total water depth is a sum of still-water depth and setup:

\[ h' = h + \bar{\eta} \]

Where \( h \) is the still-water depth and \( \bar{\eta} \) is the setup.

The cross-shore balance of momentum governs the mean water level.

\[ \frac{\partial \bar{\eta}}{\partial x} = -\frac{1}{\rho g h'} \frac{\partial S_{xx}}{\partial x} \]

The integration of this formula will give us the setdown before the breaking of the wave (Longuest-Higgins and Stewart, 1963):

\[ \bar{\eta} = -\frac{1}{8} \frac{H^2 2\pi}{L} \frac{2\pi}{\sinh \left( \frac{4\pi}{L} h' \right)} \]  

(2.8)

We can estimate the setdown at the breaking point where is maximum as:
\[ \bar{\eta}_b = -\frac{1}{16} \gamma^2 h \]  

(2.9)

Where \( \gamma_b = H/h' \)

After defining the set down we are able to calculate the setup with:

\[ \bar{\eta}_s = \bar{\eta}_s + \frac{1}{1 + \frac{8}{3 \gamma_b^2}} \]  

(2.10)

For having a more clear idea of the wave set up effect we have made an example to represent this phenomenon.

We have taken two representative values for significant wave and its period. We have chosen the maximum value for the Ebro delta coast; 6 meters of significant wave and 14.3 seconds of period. (The Xiom, 2007).

With these values we obtain (values in metres):

\[ H_b = 6 \cdot 0.55 = 3.3 \]
\[ \gamma_b = 0.87 \]
\[ h_b = \frac{3.3}{0.87} = 3.97 \]
\[ \bar{\eta}_b = -0.18 \]
\[ \bar{\eta}_s = 0.58 \]
\[ \frac{\partial \bar{\eta}}{\partial x} = 0.0022 \]

And finally we obtain the following results of wave set up at different depths.
As we can observe, we have a set down of 19 centimetres at the 400 from the coast and a setup of 70 centimetres at the coastline.

### 2.3 Astronomical tides

#### 2.3.1 Tide description

##### 2.3.1.1 Definition

On big masses of water on earth is observed a periodic falling and rising of its water surface. We called that phenomenon tide. When the tide is induced by the gravitational attraction of the moon and the sun we call it astronomical tide. Other celestial bodies can have influence on the astronomical tides but we won’t consider them, as they are really small. For that reason the moon is the celestial body with the biggest influence on the astronomical tide.

##### 2.3.1.2 Tide-producing Force

As we have said the gravitational forces are the responsible of tides. Newton defined in 1686 the gravitational force of attraction between two bodies as:

\[
F_g = G \frac{m_1 m_2}{r^2}
\]  

(2.11)
Where G is the gravitational constant with a value of $6.67 \cdot 10^{-8} \text{N} \cdot \text{m}^2/\text{kg}$, $m_1$ and $m_2$ are the masses of the bodies and $r$ is the distance between them.

So we will have to forces, one for the attraction of the moon and the other for the attraction of the sun. As we can deduce from the formula, the attraction of the moon will be bigger as it is closer to earth.

What it is interesting for us is the force potential per mass of sun and moon:

$$V_s = G \frac{m_s}{r_s^2} \quad V_m = G \frac{m_m}{r_m^2}$$

However this formula it is considered from centre to centre and the interesting points are on the surface of the earth (we will call this point X while the centre will be O). Because of this a centrifugal force will appear. Therefore, the final potential for a point X on the surface will be for the moon:

$$V_m = G m_m \left( \frac{1}{r_{mx}} - \frac{1}{r_m} - \frac{a \cos \theta_{mx}}{r_m^2} \right)$$

And the same for the sun:

$$V_s = G m_s \left( \frac{1}{r_{sx}} - \frac{1}{r_s} - \frac{a \cos \theta_{sx}}{r_s^2} \right)$$

These variables drawn for the moon are referenced to the following figure:
2.3.1.3 Types of Tide

As we have seen before, the tides will depend on the position of the sun and moon. But we have to principal bodies inducing tides. The position between them respect to the earth is also important to identify the different types of tides and when that happens.

As we can see on the picture below the water will flow towards the attraction pole inducing high tides on the attraction pole and his opposite and lower ones on the perpendicular points. When sun and moon are not on a line the water will move towards the moon because the attraction is bigger.
So as we can see on the picture \( a \) and \( c \) correspond to spring tides and they happen when the sand and the moon are on the same line with the earth. This will induce to the highest tides.

On the other hand we have \( b \) and \( d \) that are the neap tides. They will occur when sun, earth and moon form a 90° angle. The tide will be the lowest.

### 2.3.1.4 Tide Cycles

Tides are very difficult to calculate in a theoretical way but after many observations we can say they follow a periodic cycle.

As we have seen just before the different positions will be repeated twice a day so we will expect to have the same increase and decrease of tide every twelve hours. In fact it is 25 minutes more than 12 hours due to the earth translation around the sun. This kind of cycle that it is repeated twice a day is called *semidiurnal*. So as a summary we will expect in the same day two high and two low tides.
However, due to the inclination of the orbits of the earth and moon other kind of tides might be expected. We could also have a diurnal tide where only a high and low tide is expected.

Finally we could also have a mix of both.

![Figure 2.10 Different kind of cycles of the tide. Source: www.oceanservice.noaa.gov](image)

### 2.3.2 Characterization of Tides

As it has been said before, the theoretical approach of tide at any point on earth is impossible to calculate due to its complexities. However the tides are harmonic due to the tide-producing forces (they are also harmonic). Therefore we can say that the tidal height at any location can be written as a function of harmonic constituents:

\[ \eta_T = \sum_{i=1}^{N} a_i \cos(\omega_i t + \alpha_i) \]  

(2.15)

### 2.4 Meteorological tide

As we have seen in chapter before, we have a certain tide that changes periodically in time. However there are some other water level fluctuations due to other factors. The most important factors are the pressure and the wind. The level fluctuations due to these two factors is called meteorological tide. The meteorological is less important in open oceans because the astronomical tide is much higher but in seas as the Mediterranean the meteorological tide is bigger so it will be interesting to analyse the influence of this tide on the water level.
2.4.1 Pressure Effects

The atmospheric pressure acts also on the water level fluctuations. As a normal pressure, it will act pressing down the water decreasing its level. However, higher values of pressure will decrease more than the lowest values the water level. So if we fix the mean water level when there is the medium pressure, we will say that higher pressures than the medium value decreases the water level and lower pressures will act the other way around.

The variations of the water level will be induced by a variation of the atmospheric pressure. These variations follow the inverted barometer effect. This effect follows the next formula:

\[ \Delta h = \frac{\Delta p}{\rho g} \]  

Where \( \Delta h \) and \( \Delta p \) are the increments of the water level and atmospheric pressure, \( \rho \) is the density and \( g \) is the gravity.

Therefore we can deduce from the formula that for every variation of 1hPa of the atmospheric pressure that will mean a variation of 1 cm of the mean water level.

2.4.2 The Wind Effect

As it is common in near-shore areas, wind is induced by a change of temperature. The sun heats the air and the water from the sea at the same time however air warms up quicker than the sea producing airflow in the opposite direction of the sea surface. This flow of air will lead to voids, which will be occupied by new fresh air. This explains the presence of wind in the near shore areas.

Wind is also generated by the speed rotation of the earth and the presence of artificial and natural land barriers. As we our study is placed in a coastal area, there won’t be any barrier.
The wind is not constant along the all atmosphere; as soon as the height changes the wind intensity does it too.

There are many different methods of wind measurements. In our case we will obtain data from sources placed next to the coast. This wind can be considered as sea surface wind. However for predicting fluctuations due to the wind we will take into account the wind at a height of 10 meters. As it has already been said, wind intensity varies with the height. We can obtain the wind intensity depending on the height with this relation:

\[
\frac{U_{10}}{U_z} = \left(\frac{10}{z}\right)^{\frac{1}{7}}
\]

(2.17)

Where \(U_{10}\) and \(U_z\) are the wind speed at 10 and \(z\) meters of altitude respectively and \(z\) is the height in meters.

This relation considers a neutrally stable atmosphere with no gradients of temperature and density. As our measuring points are close to 10 meters high we will be able to consider this relation.

The wind will transfer a momentum to the water by friction with the sea level. This momentum transferred to a column of water (unit surface area) can be written as:

\[
\tau = \rho_a C_D z U_z^2
\]

(2.18)

Where \(\tau\) is the wind stress, \(\rho_a\) is the density of the air, \(C_D z\) is the coefficient of drag at level \(z\) and \(U_z\) is the wind speed at level \(z\).

Once we have translated our wind speed at a certain level to the one at 10 meters we will have:

\[
\tau = \rho_a C_D U^2
\]

(2.19)

Where \(C_D\) is the drag coefficient at 10 meters above the sea level.
Once we have applied the high correction to the wind and we have defined the momentum transferred to a water column by the wind we can go further and try calculate the raise of the sea water level induced by the wind.

The hydrodynamic equation is the one that is able to describe the raise of the water level due to the storm surge. This expresses the mass conservation and the motion equation with the Newton’s second law.

The equation that follows assumes:
1. Vertical acceleration is negligible
2. Curvature of the earth and effects of surface wave can be ignores
3. Inviscid liquid
4. The bottom is fixed and impermeable

We will have two equations, one for each direction in a \((x,y)\) coordinate system. The subscript “\(i\)” can be substituted by \(x\) or \(y\) depending on the direction. The \(j\) subscript is the perpendicular direction. The \(x\) direction is the one that is perpendicular to the shoreline and the \(y\) direction is the one that is parallel.

\[
\frac{\partial V_i}{\partial t} + \frac{\partial M_{ii}}{\partial i} + \frac{\partial M_{ij}}{\partial j} = fV_j - gD \frac{\partial S}{\partial i} + gD \frac{\partial \zeta}{\partial i} + \frac{\tau_{si}}{\rho_w} + \frac{\tau_{bi}}{\rho_w} + U_iP \tag{2.20}
\]

In this formula:
- \(\frac{\partial M_{ii}}{\partial i} + \frac{\partial M_{ij}}{\partial j}\) Advection of momentum.
- \(fV_j\) Coriolis effect.
- \(gD \frac{\partial S}{\partial i}\) Surface slope.
- \(gD \frac{\partial \zeta}{\partial i}\) Inverted barometer effect.
- \(\frac{\tau_{si}}{\rho_w}\) Winter stress.
- \(\frac{\tau_{bi}}{\rho_w}\) Bottom stress.
- \(U_iP\) Rainfall rate

And also:
- \(V_i\) Volume transport per unit of width
- \( M \) Momentum transport quantities
- \( f \) Coriolis effect.
- \( S \) Water fluctuation
- \( U \) Wind speed.
- \( P \) Precipitation

This formula is theoretical and it can be reduced depending on the studied problem by neglecting some factors.

In our case, we will consider only the wind influence (the barometric effect is studied in the chapter before).

So, once we have considered only the terms concerning to our problem the equation can be written as:

\[
gD \frac{\partial S}{\partial x} = \frac{\tau_{sx}}{\rho_w} \quad (2.21)
\]

The momentum transferred to the water by the wind has been calculated a few paragraphs before so we could write:

\[
\frac{\partial S}{\partial x} = \frac{\zeta U^2}{gD} \quad (2.22)
\]

The direction of the wind has to be the x direction. In other cases the wind speed applied will be the projection of the wind speed over the x direction (will be multiplied by the cosine of \( \Phi \) that is the angle between the wind speed direction and the x direction).

As we can see on the following picture, \( D \) is the distance between the real water level (included the storm surge \( S \)) and the bottom. \( D \) will vary with the position along the x direction, because of this; bathymetry of the point studied has to be taken into account.
Figure 2.11 Variation of the distance between water level and the bottom
3. METHODOLOGY

3.1 Study Area

As we have said in the introduction of the previous chapter, studies of the mean water level variations must be done for preventing damages. As it also has been said, some areas are more exposed to risk than other ones but that not exclude this area from the study.

In this case, we will study these variations at the Catalan Coast. The Catalan Coast is placed in the Mediterranean Sea, in the north east of Spain. It starts at the coordinate 42°26’6.03”N; 3°10’29.00”E at the location of Portbou and finishes at the coordinate 40°31’23.06”N; 0°30’52.53”E at the location of Alcanar.

![Figure 3.1 Location of the Catalan coast. Source: Google Earth](image)

The Catalan Coast has 699 km of coast which 270 km of those are beaches which is the main attraction point of the coast. The Catalan coast owns many ports like Barcelona, Tarragona, El Masnou, Sitges, Matarò or Palamós.
The weather, the biological variety and the beaches have converted the Catalan coast as one of the areas with more number of habitants in Catalonia. More than the 50% of the population in Catalonia lives in a coastal area. The number of habitants is increased in summer.

These reasons have made of the Catalan coast a place of progress and opportunity for business, industry and tourism. For example Barcelona or Tarragona.

We might think that because the Catalan coast is placed on the Mediterranean Sea it is not exposed to a risk of overtopping, flooding or very low levels of the MWL.

As we have seen in the previous chapter, the mean water level will depend, on a small part, on the astronomical and meteorological tide. The astronomical tide in the Catalan coast will be very small compared to the ones of the big oceans. The meteorological tide tends to not be considered as dangerous in the Mediterranean Sea, however, the combination of both tides can be really dangerous for the Catalan coast affecting the population and the resources of the coast.

The Catalan coast is subjected also too many risks that cannot be neglected and the knowledge about the risks might prevent big damages.

Because of that we will study the variations of the mean water level induced by the pressure and wind fluctuations.
For having a global idea of what happens all along the Catalan coast we have chosen many places in the coast, we have collected data from these places of wind and pressure and we have done several calculations to obtain surges results. As we will see, we have had interesting results that can explain very well the reality of the meteorological surge.

The places of study are the followings:

1. Palamos
2. San Feliu de Guixols
3. Blanes
4. Calella
5. Mataró
6. Castelldefels
7. Vilanova i la Geltru

These places are all the places from where we have data collected by private meteorological stations. We will see that in the following chapter.

In the Catalan coast the wind is exerted by its topography, the Pyrenees and Balearic Islands work as a barrier which moderate the wind climate (The Xiom, 2007). Because of that the Catalan coast will have small and medium wind velocities. The low wind goes until 6 m/s, the we have moderate winds from 6 m/s until 11 m/s, after that we have strong winds from 11 m/s until 19 m/s, then we have really strong winds from 19 m/s until 34 m/s and then we have winds considered hurricanes (Direccion General de Protección Civil y Emergencias). Font (1990) analysed four years of wind data and he founded that in the fall and winter season the most frequent direction is the NW and it corresponds to the strongest velocities which are around 10 m/s. In summer, the highest percentage corresponds to the SW direction however the highest speeds come from the NW.

The highest wind velocities were found at the Ebro delta around 20 m/s during February, March and September but the highest was in December and it was around 28 m/s (The Xiom, 2007)

In the case of the atmospheric pressure it has a mean value of 1013hPa (Alejandro López, 2015). The Mediterranean coast doesn’t usually have depressions which increase the sea water level and the ones that we have we can consider them stationary. The
highest values of pressure use to happen in December or January while in summer it is much more moderated.

The Mediterranean coast experiments a moderate wave climate. We consider an extreme value when the significant wave is over 2 metres (ROM 03.91). However we have storms that over pass this value. As an example, we have that in the Ebro delta coast the mean significant wave is about 0.8 metres. The maximum wave heights recorded was close to 6 metres (XIOM, 2007).

To have a bigger idea of the waves along the Catalan coast, the XIOM has different buoys along the coast. They are placed in Tortosa, Llobregat, Blanes and Rosas and as we can see on the figure bellow the mean significant wave in all this places is under 1 meter (XIOM, 2007), where the grey scale bar represents number of data.

![Wave height and mean period distributions for the 4 XIOM buoys](image)

*Figure 3.3 Significant wave height (Hs) and mean period distributions for the 4 XIOM buoys. Source: XIOM 2007*
3.2 Data Sources

For our calculations we need wind and pressure data next to the coast. Because there aren’t meteorological stations in the sea (or not as many as we would like) we have used the data measured at the places next to the sea. So, the data is not actually what really is happening at the sea but there is no more than that.

So, the data that we will have consists on measures of wind and pressure that private people or universities do for their own studies or as a hobby. Of course everybody measures what they can. This will lead to variety of data, for example in certain places they don’t measure the wind direction and other they do. For each case we will have to apply different transformations (unity transformations, angle correction, height transformation, etc.) to be able to calculate the meteorological surge.

As we know, as many points you study, better idea you get from the meteorological surge in the Catalan coast. The initial idea was collecting data from every single point at the coast where they had quality data. In www.meteoclimatic.com we can see all the meteorological stations where they collect wind and pressure. Meteoclimatic offers several places but only some of them had a quality star that Meteoclimatic gives to the stations as a price for their quality. So we were thinking of collecting all this quality data and we asked for it. As we can see we only had reply from this seven places and that is what we have studied.

Figure 3.4 Location of the studied meteorological stations. Source: Google Earth
We also have other data source that we have used. It consists on several points around the sea. These points are called SIMAR points. Their data do not come from measuring the reality. They come from other data measured in other places. After it is collected in these places several calculations are done so we can have the data at the SIMAR point.

The data that we have been able to obtain from the SIMAR points are only average wind speed and direction. No pressure appeared in this source so the meteorological surge hasn’t been possible to be calculated. However this source is really interesting to complement the other data because sometimes we are missing the wind direction.

In addition to these other two kinds of sources we have also the data of pressure coming from several buoys in the Catalan coast. There are three buoys in the Catalan coast of Puertos del Estado. However the places of study are closer to two of them, the Begur Buoy and the Barcelona Buoy. The Buoy of Begur gives us the data of pressure from 2001 until 2013 while the Buoy of Barcelona gives us data from 1996 until 2003.

As a summary of the data sources we have the following table:

<table>
<thead>
<tr>
<th>Place</th>
<th>Private data</th>
<th>SIMAR point</th>
<th>Buoy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average wind</td>
<td>Maximum wind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>Speed</td>
<td>Pressure</td>
</tr>
<tr>
<td></td>
<td>Direction</td>
<td>Direction</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Data sources for every station analyzed
3.3 Working process

In this chapter we will explain how we have proceed in our calculations. As we have said before, every point has different data. However it might be quite similar the procedure of calculation, in every point we have done several operations to obtain the wind, pressure and meteorological surges.

For calculating the wind and pressure surge (the meteorological is the addition of both) we have needed to do several transformations before applying the calculations in order to obtain the meteorological surge. We will divide this chapter in transformations and calculations to have a more clear idea of what has been done.

3.3.1 Data transformations

Of course, data never comes as you would like. Every station measures what the can and the units is what they establish. So at the beginning unit transformation has been needed. What we need for our calculations is effective wind speed in meters per second and pressure in hPa. So as a departure we have done the unit transformation of wind and pressure to meters per second and hPa.

Once this has been done, the wind needed has to be measured at a height of 10 meters over the sea water level in order to be able to apply our calculations with Matlab. So height transformation (explained some pages before) has also been done.

Once we have the proper wind speed we need to manipulate our wind direction. In some places we obtain azimuthal directions but in other we get the directions as N, SSW or others. In this last case we have traduced to azimuthal directions in numbers. Once we have the direction we have to obtain the effective angle. This angle is the one defined between the coastline and the wind direction.
As we can see on the picture the effective angle is the one defined between them the angle C.

We calculate this angle because not all the wind speed will affect to the wind surge. Only the perpendicular component to the coast of this direction will affect the wind surge.

So as we could imagine the wind speed in meters per second at 10 meters over the sea water level needs a last transformation. It needs to be multiplied by the sinus of the effective angle. Applying this last transformation we will obtain the effective speed, which we can precede to our calculus.

It has to be said that not all the directions lead to a surge. All the sinus under zero do not produce a surge because there is no perpendicular component towards the coast. So only if the effective angle is between 0 and 180 degrees the wind will create a surge. As we will see on the point 4, we have 8 directions that have a perpendicular component towards the coast from the 16 possible directions. From this 8 directions we have painted in yellow the less perpendicular and in red the four more perpendicular towards the coast.

In some cases we don’t have the wind direction. In those cases we have considered the worst scenario that we could imagine. Of course this consists on having the wind blowing perpendicular to the coast, where the effective angle is 90 degrees. This scenario will be compared with the data from the SIMAR point.
So once we have done our transformations to the effective wind and we have the pressure in hPa we can proceed with the calculations.

### 3.3.2 Data calculations

Once we have the data in order to be applied the calculations we proceed to them. The meteorological surge will be the addition of the wind and pressure surge.

The pressure surge is really easy to calculate. We have used Excel to calculate it with the theory of the barometric effect. As it says, a variation of one hPa means one centimetre of surge variation.

What we have done is to every measure of pressure we have subtracted the average pressure surge of the place of study (it has been calculated previously). After that we divide by 100 to get the pressure surge in meters.

The wind surge is a little bit more complicated to be calculated. As we have seen in the second point of our project, the wind surge is calculated after a non-linear ordinary equation.

If we go back to the equation in the part two of the project we will see that surge can be solved by a non-linear ordinary equation as the following:

\[
gD \frac{\partial S}{\partial x} = \frac{\tau_{sx}}{\rho_w}
\]  

(3.1)

This differential equation is non-linear because either D or S is dependant of x. Keeping in mind the equation 2.19 in mind, the non-linear equation would be:

\[
\frac{\partial S}{\partial x} = A \cdot \frac{1}{D(x)}
\]  

(3.2)
Where $A$:

$$A = \frac{n \cdot \rho_a \cdot C_D \cdot U^2 \cdot l}{\rho_w \cdot g \cdot h_0}$$  \hspace{1cm} (3.3)$$

In this last formula we have:

- $n = \text{shear stress coefficient}$
- $C_D = \text{drag coefficient}$
- $\rho_a = \text{air density}$
- $\rho_w = \text{water density}$
- $g = \text{gravity}$
- $h_0 = \text{initial depth}$
- $l = \text{length where the wind blows}$
- $U = \text{wind speed at 10 meters over the sea water level}$

We have defined the $A$ constant, however the problem of non-linearity comes from the $D$ and $S$ dependence of $x$.

For solving this problem what we have done is discretize in finite element methods the distance $l$. Now instead of having a constant slope of $m$ degrees we will have 1000 (we have divide $l$ in 1000 elements) small elements of height $h = h_0(1 - \frac{x}{l})$ (where $x$ is the distance from the starting point to the element). So what will we just need is to solve the wind surge for every element and add it to the one before.

If we apply the finite element method what we will have is the following equation:

$$\frac{\partial S}{\partial x} = A \cdot \frac{1}{S(x) + ho(1 - \frac{x}{l})}$$  \hspace{1cm} (3.3)$$

So this equation turns to be the following:

$$\frac{x}{l} = \left(1 - \frac{h + S}{h_0}\right) - A' \cdot LN \left(\frac{h + S}{h_0} - A'\right)$$  \hspace{1cm} (3.4)$$

Where:
• $A' = A/h_0$
• $S$ is the wind surge

With the help of Matlab we have been able to solve this equation for every wind speed.

In Matlab we have used a function inside a Script where you have as inputs:

1. Slope of the bed floor
2. Initial depth ($h_0$)
3. Vector v. This vector has all the wind speed of the year

This Matlab Script has been created by the teacher Arash Karimpour. So once Matlab has all these three inputs it solves the equation as many times of components v has.

![Matlab Script](image)

**Figure 3.6 Matlab Script used to calculate the wind surge**

But as we can see on the Matlab Script we will need a slope, a vector v and an initial depth.
Of course the vector v components will be all the wind speed transformed as we have said in the previous points. But the slope and the h0 are values that we can obtain from the place bathymetry. This bathymetry has been obtained from the web page www.portal.emodnet-bathymetry.eu. So for every single place we have an approximated bathymetry.

In every point we have approximated the bathymetry with two different slopes. As we don’t have the wind fetch we have taken an initial depth in between 60 and 80 meters. Calculations have been done with bigger fetches. However the fetch is inversely proportional to the surge so if we increased the fetch the difference of the surge was less than 0.01 millimetres.

On the following sub chapters we can see the place bathymetry.

**Palamos**

![Palamos Bathymetry](image1.png)

**San Feliu de Guixols**

![San Feliu de Guixols Bathymetry](image2.png)
Blanes

Graph 3.3 Blanes bathymetry

Calella

Graph 3.4 Calella bathymetry

Mataro

Graph 3.5 Mataro bathymetry
As we can see in all this graphs, we have the bathymetry of the place approximated by two slopes. Every slope has been discretized by the Matlab script in 1000 elements so we will have every place discretized by 2000 elements that give reliability to our calculations.
4. RESULTS AND DISCUSSION

4.1 Palamos

4.1.1 Data sources for Palamos

As it has been said in the point 3.2 we have several data sources at this point. First of all we have the data that comes from the private meteorological station. This data is available thanks to the daily measurements of Joan Bta. Baren I Cebrian. His station is located at the coordinates 41º 51’ 23” N, 3º 8’ 17” and 20 metres over the sea water level. Height transformations have been needed to have the wind speed at 10 metres over the sea water level.

From this source the data available is the following:
1. Average daily wind speed and most frequent direction from 2009 until 2014.

The data here is one of the largest coming from a private station and it will be really useful to analyse the properties of the meteorological surge. Nevertheless it is does not cover much years so it won’t be possible to detect the extreme cases before 2009.

Secondly we have the data coming from the SIMAR point. As we know we only have wind average direction and most frequent direction but not the pressure. The data here goes from 1958 until 2015. It will be really interesting to study the variation in time of the wind and detect its extreme cases and its ways of behaving during time.

Finally we have the data coming from the Begur Buoy. From this point we have the monthly average pressure from 2001 until 2013 and the minimums of each month. We have selected the minimums because it is when we have the largest surge with the barometric effect.

4.1.2 Results and analyses of the results in Palamos

The meteorological surge has only been calculated with the data coming from the private station because from the two other sources we are missing or pressure or wind data.
We can see in the Annexes part the tables one to six the results for the day of the meteorological surge for each day. Down the table we have the most significant data for each month of every year.

To summarize these tables we have the following table

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>STA DEV</td>
<td>0.067</td>
<td>0.070</td>
<td>0.062</td>
<td>0.065</td>
<td>0.077</td>
<td>0.061</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0.259</td>
<td>0.275</td>
<td>0.205</td>
<td>0.218</td>
<td>0.283</td>
<td>0.190</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>-0.131</td>
<td>-0.163</td>
<td>-0.178</td>
<td>-0.180</td>
<td>-0.196</td>
<td>-0.177</td>
</tr>
</tbody>
</table>

Focusing at this table we can see a really close value to zero in the average in every year. This makes us think in a cyclic variation of the meteorological surge every year. We will have several moments where the surge is over zero but others it is under zero. We will see later on in a graph how it varies through time and we will confirm the cyclic variations.

The standard deviation shows us that the meteorological surge is not very large, we have values around 6.5 centimetres. We may think it is a really low value but it is an elevation of the sea water level so it has to be considered. Even more we have the extreme results that show us that the meteorological surge arrives to values close to 30 centimetres. This is a big value that added to the other factors of increase of the sea water level can cause many damages.

Once we have the results we will study now where they come from and we will try to detect the influence of the wind and pressure in the meteorological surge.

We have plotted the graph 1 to see the evolution in time of the surges. As we can observe the meteorological surge is almost exactly as the pressure surge because its values are much larger than the ones of the wind surge. Even more, the lines of the wind surge is most of the time zero.

We have plotted the graph two for having more detail of the wind surge. As we can see, we have many values that are zero and the others are not extremely large, the maximum
doesn’t even arrives to 1 centimetre. It has to be said that we are talking about average
wind speed which is really small. It has also to be said that the zero values appear
because of the direction. Only the ones that have perpendicular component towards the
coast will suppose a wind surge. The amount of zeros can give us an idea of the wind
direction.

Let’s now see what happens with the maximum wind speed. We have plotted the graph
3 for that purpose. In this graph we can observe the surge induced by the maximum
wind speeds in Palamos. We have several values equal to zero because of the direction
however the other values are high enough to be considered not as the ones of the
average wind. We can see two values over 14 centimetres and a lot of them between 4
and 6 centimetres.

These values can be small if we compare them with the values of the wave height or the
storm surge. However they have to be considered because an extreme wind condition
can suppose big surges as we have seen. It is fair to say also that these values are
extreme values and they happen sometimes. We only have two values over 14
centimetres in 6 years while most of our values stay around 3 centimetres which is not a
big increase.

Having a look to these values and the ones of the pressure surge there is the possibility
of a big increase of the sea water level.

Now we know what can happen with the meteorological surge and what can also
happen when the wind is maximal but let’s study when we will have extreme conditions
and see if the extreme wind conditions and pressure happen at the same time.

Let us focus again on the first graph, especially on the pressure surge line. We will see
that every time we have a period of large surges (positive or negative) we will have then
a period of more moderated surges. The large values always corresponds to the months
between November and March, the rest correspond to the moderate pressure variation.
We have given the idea before of having a cyclic variation in time of the pressure and
now we confirm this idea. The pressure surge will be larger in those months. There is an
interesting point in the months of larger pressure surge. We have either over zero or under zero values. This shows us the quick variations of pressure.

Once the pressure has been analysed lets analyse the wind. The wind has two components, the wind speed and the wind direction.

Let us start first with the wind speed. We have plotted the graphs 4 and 5 with all the wind speed in Palamos from 2009 until 2014 (with the data of the private source). As we can see (in both cases, in average speed and maximum speed) we have that the wind speed stays constant along the year but having an increase usually at the beginning or the end of the year. This goes along with what we have said when we were talking about the pressure, it experiments bigger variations from November to March inducing a larger wind. So if the wind is induced by variations of pressure this makes sense.

As we have observed, the worst scenarios use to happen at the same moments during the year so in these months we could have a coincidence between the worst scenario of the wind and the one from the pressure.

We still have to analyse the direction of the wind. We have counted all the directions every month. In the following table we can see the most frequent direction for every month in the case of average wind speed.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>WNW</td>
<td>WNW</td>
<td>E</td>
<td>SSW</td>
<td>S</td>
<td>SSW</td>
<td>SE</td>
<td>SE</td>
<td>NW</td>
<td>NW</td>
<td>NW</td>
</tr>
</tbody>
</table>

4.2 Direction of the wind in Palamos for each month (average wind speed)

As we can see in the table we have a most repeated direction of the wind, the NW. This direction has no influence on the surge because does not have a perpendicular direction towards the coast. However from April to September we do have a perpendicular component especially in June, August and September. Those months have a particular risk; if the wind blows with intensity it will induce a surge. Nevertheless we know that on those months the winds use to be moderate.
But this is in the case of the average speed; we will now count the directions in the case of the maximum wind speed. We obtain the following table.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>NW</td>
<td>SSW</td>
<td>S</td>
<td>SSW</td>
<td>S</td>
<td>SSW</td>
<td>SE</td>
<td>SSW</td>
<td>NW</td>
<td>NW</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Direction of the wind in Palamos for each month (maximum wind speed)

As we can see, the directions are quite similar despite several months. What is really interesting is that the highest winds that happen from November to October have the direction NW which has no influence on the surge. The other months can be dangerous because of the direction but the speed is not that large. We have seen that during those months the wind surge induce a surge of 5 centimetres.

As we can see we may affirm many conclusions, however we still have to remember that this data only covers six years so it our studies might not have all the reliability we would like. Because of that we have the data from the SIMAR point and the buoy.

Let us start first with the data coming from the buoy. In the Palamos case, the closest buoy is the one in Begur. From this buoy we can obtain the monthly average data since March of 2001 until September of 2013. We also have the minimums of these months. It has to be said that several data during this period is not available.

We have plotted the graph 6 where we can see the maximum surge for every month since 2001 until 2013. We can see again that the maximal values happen on the months we were expecting, from November to March. As a resume of the Graph we have the following table:

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0.088</td>
<td>0.192</td>
<td>0.169</td>
<td>0.109</td>
<td>0.120</td>
<td>0.090</td>
<td>0.117</td>
<td>0.120</td>
<td>0.183</td>
<td>0.195</td>
<td>0.097</td>
<td>0.138</td>
<td>0.155</td>
</tr>
<tr>
<td>STA DEV</td>
<td>0.042</td>
<td>0.066</td>
<td>0.090</td>
<td>0.064</td>
<td>0.077</td>
<td>0.056</td>
<td>0.031</td>
<td>0.046</td>
<td>0.089</td>
<td>0.093</td>
<td>0.070</td>
<td>0.070</td>
<td>0.094</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0.145</td>
<td>0.275</td>
<td>0.325</td>
<td>0.225</td>
<td>0.205</td>
<td>0.145</td>
<td>0.185</td>
<td>0.195</td>
<td>0.315</td>
<td>0.345</td>
<td>0.225</td>
<td>0.265</td>
<td>0.335</td>
</tr>
</tbody>
</table>

4.4 Table 4.4: Maximum pressure surge (Buoy of Begur) from 2001 to 2013
The minimal values are 14.5 centimetres and we have several maximums over 20 centimetres. We have even values over 30 centimetres being the 35 the largest. These values are really big and can produce a lot of damage in case of high astronomical tide, wind surge and wave condition.

The maximum value happened in February of the 2010. Other eleven values are over 25 centimetres. Considering we have the data of 115 months we can say that the risk of overpassing 25 centimetres is 1%. We have to remember that these values are maximum values.

We have also plotted the graph 7. In this graph we can observe the average values that we have from 2001 until 2013. As we can observe this values are much smaller than the ones we had at the maximal values. The standard deviation is around 4 centimetres.

All this values make sense with the ones obtained with the private source. The maximums are close to each other and the standard deviation values are also close. It is also interesting to see how the values increase in the months between November and March as we had predicted with the data coming from the private source.

Finally we will complement our results with the SIMAR point data. We have plotted the graph 8. In this graph we have the surge induced by the average speed in Palamos from 1958 until 2015. As we can see the values are really small, the standard deviation is only 1 centimetre. However we have eight points that are equal or more than 10 centimetres which is a significant value. The maximum is 14 centimetres and it corresponds to January 2010. We have to say that we have around 20,000 days of surge and only eight of them have overpassed the 10 centimetres barrier. It is the average wind but it is clear that the wind as a small influence to the meteorological surge.

We have plotted the graph 9 the wind speed in Palamos from 1958 to 2015. As we can see the wind varies more or less between the same values but increasing a little bit in 2005. The maximum value is 19 meters per second and it happened in March of 2009.

Once we have studied the wind speed let us study the wind direction. The most frequent directions are the following:
As we can see the most frequent direction is the SW, even if it has a perpendicular component towards the coast it is really small. In addition to the low values of the wind speed, this will explain the low values of the wind surge.

As we can see in the directions and the speeds, they vary from the private station. This is due to the difference of position. They are not placed in the same coordinates. One is on the coast line with the presence of obstacles that can vary the wind and the other one is in the middle of the sea. Even more, meteorological conditions change from one point to another.

### 4.1.3 Conclusions

As we have seen in the first table, the standard deviation of the meteorological surge shows us that the increase of the sea water level is not really high, around 6.5 centimetres of surge. This is a medium value; we have to understand that the Mediterranean is considered a tide less so this study says the opposite, we do have a meteorological surge even if it’s small.

We can also see the average values close to zero, this, and the graphs of the meteorological surge, shows that the meteorological tide is cyclic. It is larger at the beginning and ending of the year (in between November and March).

Normally we have that the wind contribution to the meteorological surge is really small. Even more, the meteorological surge follows the variations of the pressure surge. However when we are talking about extreme values the contribution of the wind can be also large.

As we can see on the Graph A 3 we can see a value of 16 centimetres that added to the pressure surge can be really dangerous.
In the case of the wind, we can see that the average wind is a low wind and the maximum wind is normally a moderate wind reaching sometimes strong velocities. Even though the wind speed is not strong the wind direction does not help on the raise of the sea water level. The directions of winds, maximum and average do not have a perpendicular component towards the coast in the months of largest winds, November to March. During the other months we do have a perpendicular component however only during three months is painted in red. It is interesting to see how the maximum winds and the average wind have similar direction. So this tells us that depending on the month we will have one direction or other (or a most frequent direction).

The data from the SIMAR point shows us a wind coming from the SW, it is quite similar with the private data in some months but not from November to March for example. This is explained because they are placed at different coordinates so they will have different obstacles around them (or non in the case of the SIMAR point). In the case of the velocity, we have that in the SIMAR point we have higher values than the private station. This is also explained as the direction.

With the data from the Buoy of Begur we can see similar values to the private station. We can observe the maximums normally in between November and March and the same magnitude of values. Even if the buoy and the private station are not together, we can consider a stationary phenomenon the variation of pressure.

4.2 San Feliu de Guixols

4.2.1 Data sources for San Feliu de Guixols

In San Feliu de Guixols we have data from both kind of sources we can have. We have data from the private meteorological station and data from a SIMAR point.

The private data is measured thanks to Andres Garcia Monge. He measures the data of San Feliu day after day. This station is located at the coordinates of 41° 47’ 22” N - 3° 01’ 44” E and at a height of 57 meters over the sea water level. So, as the other places of study, we have applied several transformations of height.
The data measured in this station is the following:
1. Average daily pressure in hPa since 2012 until 2014

As we can imagine, we will have to apply the worst scenario possible because no direction has been given to this maximum speed. Even more we won’t be able to calculate the average scenario due to the absence of the average wind. We will calculate also the meteorological surge in the worst scenario of wind so we will have to keep that in mind while commenting the results. Of course we will discuss the probability of having this worst scenario with the data of the SIMAR point.

The other data comes from a SIMAR point. As the different places we have only data of wind. More precisely we have the following:
1. Average wind speed from 2005 until 2015 in m/s.

In the case of San Feliu we also have the Buoy of Begur. This Buoy will provide us, as we already have seen in Palamos, the data of the pressure from 2001 until 2013.

4.2.2 Results and analyses of the results in San Feliu de Guixols

We have the meteorological surge from 2012 until 2014 on the Table B 1, Table B 2 and Table B 3. As this is a large amount of data we have summarize with the following small tables below, however to even summarize this amount of data we have written the following table:

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AVERAGE</strong></td>
<td>0,005</td>
<td>0,005</td>
<td>0,004</td>
</tr>
<tr>
<td><strong>ST DEV</strong></td>
<td>0,064</td>
<td>0,072</td>
<td>0,051</td>
</tr>
<tr>
<td><strong>MAXIMUM</strong></td>
<td>0,200</td>
<td>0,265</td>
<td>0,164</td>
</tr>
<tr>
<td><strong>MINIMUM</strong></td>
<td>-0,150</td>
<td>-0,190</td>
<td>-0,134</td>
</tr>
</tbody>
</table>

Table 4.6 Meteorological surge in San Feliu de Guixols from 2013 to 2014

As we can see, the average are around zero, this gives us an idea of the cyclic variation of the surge. We can say that the surge is not as big (the standard deviation is around 6 cm) and at first sight we may say that there is no risk of big increases of the sea water level due to the meteorological conditions. However, if we have a look to the
maximums and minimums we can see extreme surges of 26 cm. This, added to the effect of other tides, climatic change and the waves might suppose a risk of floods and coast erosion.

It has to be said that this is the worst scenario we could have of wind conditions so usually the surge would be smaller.

We will analyse the different surges. On the Graph B 1 we have the different surges plotted at the same time. As we can see (and also as we could imagine) the meteorological and pressure surge are almost identical while the wind surge is next to the zero line. Again, we can say that the meteorological surge is induced by the pressure surge (almost all of it) even if the wind is acting in our calculations as the worst scenario.

As we can see on the same graph, the maximum values appear from November to March in the pressure surge. This is the reason why the meteorological surge is the highest during those months

For adding reliability to our calculations we will use the other two sources that we have.

In one hand we have the Buoy of Begur that has already been commented in the previous chapter. As we know, values around 4 centimetres of standard deviation appear and maximums of 25 centimetres, even one of 34 centimetres in February of 2010.

Another reason is that the Buoy and the private station are not located in the same coordinates so we will find some variations of the results. The maximal values are also quite the same. As we can see, 20 and 26 centimetres are values that we can also observe in the same period of time in our graph 6.

The maximum wind is shown in the Graph B 2. We can see that the maximal values appear between November and March. The maximum is 17 m/s and it happened in July of 2012. This value is not really common because usually has moderate winds. However it can happen as we have seen.
But now let’s analyse the worst scenario. Can it happen? Is it a probable scenario? We will discuss that with the data calculated with the SIMAR point.

The most frequent direction is the one that comes from SW, however it corresponds to a painted area, the perpendicular component towards the coast is extremely small. Also the S direction is quite frequent and it corresponds to the red area. We can say that the worst scenario can happen but not very often because the SW direction has a really small perpendicular component towards the coast.

Finally let’s see what happens with the wind speed over the months. As we can see in the Graph B 4 the wind speed is quite similar through all the months being a bit larger in the months of beginning or ending of the year. The standard deviation is around 3 millimetres so it is confirmed again the small influence of the wind in the meteorological surge.

We have analysed the wind surge but let’s see what happens in the wind speed itself. For that reason we have plotted the Graph B 4. In this graph we can see all the wind speeds in San Feliu. We can observe that all the maximums happen between November and March. We can observe high wind but comparing to the surge table the results are really small. This is because the direction, even if it is not zero, a lot of values have a really small influence (values close to zero in the surge table) because of the angle.

4.2.3 Conclusions

As we have can see in the first table, the risk of a big increase of the sea water level in San Feliu due to the meteorological conditions is not very high as the standard deviation says. As we now, this meteorological surge has been calculated with the maximum wind
and the worst situation. Even though we have chosen the worst scenario, the Graph B 1 shows us the short participation of the wind in the meteorological surge. However we can have maximum values of 26 centimetres which have to be taken into account.

As we have seen in the same graph, the meteorological surge follows a cyclic law because the pressure surge does.

We have taken the worst scenario possible but the SIMAR point show us that only in two months we will have a scenario close to the worst one. Even though the SIMAR data and the private data can vary, the SIMAR point can be used as a reference for the wind direction.

In the case of the wind speed we don’t have sources to compare because we have the maximum wind in the private station and the average in the SIMAR point. Even though the SIMAR velocities have close values to the maximum speeds in the private station. This shows us how the wind is stronger in the sea. It is interesting to see how the wind increases at the end and beginning of the year in both sources.

Finally we have the data of the buoy, we can see that the maximums from the buoy data and the ones from the private source happen at the same period of time and they have similar values, most of the maximum values are around 20 centimetres in both cases.

4.3 Blanes

4.3.1 Data sources for Blanes

As it was pretended in the beginning, from Blanes we have two data sources. On comes from a personal data collection station and the other one from simulations done after other data.

The private data comes from a man who collects data day after day. This person is called David Molner and his station is located at the coordinates 41º 40' 42" N 2º 47' 2" E and the station is placed with a difference of height with the sea level of 30 meters.
Because of this difference of height a height transformation of the wind has been made (following the transformations explained at the beginning).

From this source the data has been the following:

1. Maximum wind speed in km/h of every day in 2013
2. Average pressure of the day in 2013

As average wind data and the direction of the maximum wind were not possible to obtain the results might be incomplete however with the following source interesting results have been obtained.

Because of the absence of the wind direction data, the worst situation has been considered due to get the worst scenario we could imagine. As we can deduce from the formulas presented before, the worst scenario corresponds to a wind blowing perpendicularly to the coast. Afterward we will discus if this worst situation is a probable situation or not.

As it has said in the previous chapters, the data obtained from the SIMAR point hasn’t been measured with instruments. It comes from calculations done after other data collected in other points.

We may think that this data is unreal. However, besides it hasn’t been measured, it can be considered as proper data and be used in our calculations.

The data obtained from this source is the following:

1. Wind speed every three hours since the 01/01/1958 in m/s
2. Wind direction every three hours since 01/01/1958

The wind speed is considered at 10 meters of height over the sea level so no transformation has been done.

From the SIMAR point we have an extremely large amount of data. This, as we will see in the following chapters, will be really useful for detecting periodic changes of the wind direction and the wind speed. However, no pressure is given after this source.
We have finally a third data source. It is the Buoy of Barcelona, which gives us pressure data from 1996 until 2003. This data will be helpful to see all the variations of the pressure for more than one year.

4.3.2 Results and analyses of the results in Blanes

After doing several transformations and calculating the wind surge in Matlab, the results from Blanes have been obtained.

In the Table C 1 we can observe the total surge for every day of the year. As a summary let’s us focus on the lower table. We observe the maximum, the minimum, the average and the standard deviation of the wind surge for every month of the year.

To summarize even more this final table we have the following table below (always in meters):

<table>
<thead>
<tr>
<th>Max</th>
<th>0.242</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.157</td>
</tr>
<tr>
<td>Average surge</td>
<td>0.027</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.059</td>
</tr>
</tbody>
</table>

Table 4.8 Meteorological surge in Blanes

As we can see the maximum total surge is 0.242 meters while the minimum is -0.157 meters. On the other hand, the average and standard deviation of the total surge is around 3 and 6 cm.

We can think, judging after seeing the average and standard deviation results, that the storm surge has a really small impact on the sea water level. Nevertheless, the maximum and the minimum mean important variations of the sea water level.
But, when will we have the extreme conditions of the total surge? Of course, as we have said just before, we have considered the worst possible situation and this is not always true (we will return to this question later) but when are we going to have the worst pressure and wind speed conditions?

In the table we can see the different values but is not visual enough to detect interesting properties of the surge. Because of that we have plotted several graphs that might be useful to detect properties of the surge.

On the Graph C 1 we have plotted the total surge but also the surge induced by the wind and the one induced by the pressure. Before all we have to say that only a year is not enough to affirm a postulate of the total surge but it gives you a really nice idea of what is expected and it will be confirmed on the following studies of the other different places.

From this graph we can see the proximity between the red and green curves that correspond to total surge (meteorological surge) and the pressure surge. As it has already been said, only one year is not enough to postulate that the total surge is influenced much more from the pressure than the wind but at least it invites you to think that way. This theory will be confirmed on the following places studied and comparing the surges of pressure and wind of the other two data sources.

So considering this idea as true (most part of the meteorological surge comes from pressure changes) we will now try to determine some characteristics from the pressure surge and the wind surge.

Focusing still on the same graph we can observe that the pressure surge is twice bigger in winter (months November to March). This induces us to think that maybe, pressure surge is bigger (or the lowest) during winter and smaller during the summer. Because of that, we deduce that the meteorological surge is bigger in winter than summer (we have said before that the most part of the meteorological surge comes from the pressure) and we can think that the meteorological surge follows a cyclic law. However is has to be considered that only a year is being considered. We will discuss this idea on the following points at study.
On the other hand we have the wind, which consists on the wind speed and the wind direction.

From the simulation source (the SIMAR point) we have obtain the main directions for each month. The result is shown in this table:

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
</tr>
</tbody>
</table>

Table 4.9 Direction of the wind in Blanes for each month

This table show us the most estimated direction every month. As we can observe the most expected direction is the Southwest direction at every month so we can deduce that the wind is quite uniform in the sense of blowing direction. This direction has a perpendicular component towards the coast; however this component is really small. However other directions are also frequent as SSW or S.

Even though this directions are not that important because their sinus (of the angle between the direction and the coastline) is really small.

Going back to the worst scenario considered. After these tables we can affirm that the worst scenario has not high probabilities to occur. Because of that we can affirm that the calculations with these scenarios do not reflect the reality.

On the other hand of the wind we have the wind speed. For having a visual idea we have plotted the Graph C 2. In this graph we can observe the wind surge from 1958 until 2015. We can see that the surge is quite constant through all the years with a standard deviation of half millimetre. We can observe a maximum of 10 centimetres which happened in December of 2007.

The maximum surges occur from November to March. In these months we have maximums of 9 centimetres while on the others we have maximums of 4 centimetres.
The wind speed in Blanes is shown in the graph 3. As we can see the wind is quite constant through all the years with a standard deviation of 1.9 m/s. The maximum value happened in December of 2009. The values in the months of November and March experiment the highest winds with values of 16 m/s. On the other hand, the maximum values for the other months are close to 9 m/s.

So it makes sense to have the highest wind when we have the highest surges. Here the direction will not suppose a difference because it is constant through the year.

Finally we have the data coming from the Buoy of Barcelona. As we can see in the graph C 4, we have a maximum value of 30 centimetres that happened in January of the 1997. We can also observe that the largest maximums happen in the winter months. On the graph C 5 we have the average surge for the same buoy and the same period of time. We have a standard deviation of 5 centimetres and as usual, the highest surges are between November and March. To summarize the results of the Graph C 4 we have the following table:

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0.188</td>
<td>0.130</td>
<td>0.095</td>
<td>0.142</td>
<td>0.156</td>
<td>0.129</td>
<td>0.148</td>
<td>0.197</td>
</tr>
<tr>
<td>STA DEV</td>
<td>0.065</td>
<td>0.099</td>
<td>0.046</td>
<td>0.054</td>
<td>0.084</td>
<td>0.070</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0.277</td>
<td>0.307</td>
<td>0.167</td>
<td>0.237</td>
<td>0.267</td>
<td>0.257</td>
<td>0.257</td>
<td>0.197</td>
</tr>
</tbody>
</table>

Table 4.10: Maximum surge (Buoy of Barcelona) from 1996 to 2003

4.3.3 Conclusions

First of all we have to say that the data source of the private person is small and we cannot affirm theories based in our calculations when they come only from a year. For having a reliable result we should have different years so we could compare year after year.

We have seen that the direction of the wind uses to be constant during the months after the years (from the SIMAR source). We have a most common direction, the SW. We can say that the most frequent direction hasn’t a big perpendicular component to the coastline so the wind won’t induce big wind surges.
We can see that the wind intensity is bigger from November to March and lower in the other months. This data is confirmed by the SIMAR point. The wind is considered in Blanes as a low wind and the maximum as a moderate wind. Because of that and the directions adopted by the wind we won’t have big surges induced by the wind.

We can also observe that the meteorological surge is induced (almost all of it) by the variation of pressure so we can predict the meteorological surge (we consider the variation of the pressure cyclic).

With the data coming from the buoy of Barcelona we can observe how the pressure surge is higher at the end and beginning of the year because of the variations of pressure. Even if we have only one year, this data makes sense with the values obtained in the Buoy of Barcelona, around 20 centimetres of maximum surges and even 30 centimetres.

We can observe that the meteorological surge does not mean a big variation of the sea water level itself but there is always an increase or decrease of the level. To this variation we should add the astronomic surge and the waves. Even more, we can observe a meteorological surge of 24 cm (even though the scenario is not really use to happen).

4.4 Calella

4.4.1 Data sources for Calella

In Calella we only have the data collected from the private meteorological station. Ferran Vila I Comas is the owner of this station and has given us as a favour this data.

The meteorological station is placed at the point 41° 36’ 51” N 02° 39’ 53” E at a height of 7 meters compared to the sea water level. Because of that the height transformation of the wind has been done so we could have the wind at 10 meters.
From this source we have the following data of Calella:

1. Wind speed in m/s and wind direction of the average and maximum wind from 2009 until 2015.
2. Pressure in hPa measured every fifteen minutes from 2009 until 2015.

Because of this large amount of data (has been measured every fifteen minutes) we have transformed this data into a daily data. Doing the average of every day of the average wind and selecting the most repeated direction and selecting the maximum wind speed and its direction of every day we have a daily data of Calella.

Besides we have no SIMAR point in Calella we have data of wind and pressure of seven years that will help us to identify several properties of the meteorological surge in Calella.

We also have the data of pressure measured by the Buoy of Barcelona. We have data from 1996 until 2003.

4.4.2 Results and analyses of the results in Calella

After several transformations of the data given at the beginning we have been able to calculate the wind surge with Matlab and the total meteorological surge with Excel.

Once the calculations are done, we have obtained the meteorological surge given in the Tables D 1 to D 7.

Following the way of working of the previous place studied (Blanes) this is a big amount of numbers all together and it is difficult to analyse the results. We have summarized with the small tables that each table from the Annexes has below. To even summarize more our results we can present the following table:
We can see on this table interesting values as the almost zero of the average surge or a maximum and minimum large enough to be considered. The maximum surge happened in January of 2013. As we can also see in this table, the average surge is really small. This is explained because of the cyclic variations.

For having a more visual idea of the surge in Calella we have plotted the Graph D 1, which show us the values from the table below, when they happen and how they are distributed.

It is interesting to see how the distribution of the maximal values. In this case we have the sequence of 7 years and we can see that in all of them the surge is higher in winter (from November until March). So now we can affirm that the surge follows a cyclic variation being higher at the beginning and ending of the year. Calella is next to Blanes so we could also say that the hypothesis that we couldn’t because there was not enough data is true.

As in the other places of study, the pressure surge is almost identically to the meteorological surge being the wind surge almost always close to the zero line. This shows how the meteorological surge is induced especially by the pressure variations. However we are talking about average wind, we will see later on how the maximum wind can induce high surges.

Let us now analyse the wind surge. In this case we have two things that require study; the wind direction and the wind speed.

Let us start with the wind direction.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0,002</td>
<td>0,001</td>
<td>0,002</td>
<td>-0,006</td>
<td>0,028</td>
<td>0,024</td>
<td>-0,003</td>
</tr>
<tr>
<td>ST DEV</td>
<td>0,074</td>
<td>0,071</td>
<td>0,064</td>
<td>0,065</td>
<td>0,074</td>
<td>0,059</td>
<td>0,085</td>
</tr>
<tr>
<td>MAX</td>
<td>0,219</td>
<td>0,284</td>
<td>0,212</td>
<td>0,209</td>
<td>0,309</td>
<td>0,216</td>
<td>0,289</td>
</tr>
<tr>
<td>MIN</td>
<td>-0,128</td>
<td>-0,163</td>
<td>-0,149</td>
<td>-0,182</td>
<td>-0,157</td>
<td>-0,143</td>
<td>-0,206</td>
</tr>
</tbody>
</table>

Table 4.11 Meteorological surge in Blanes from 2009 to 2015
As we can observe in this table, the wind direction normally hasn’t a perpendicular component towards the coast. In most of the months the direction doesn’t induce surge but in May, July and September. Even though, the coastline direction is 67° while the SW direction is 247.5°. The angle between them is 180.5° and the sinus of it is really close to zero. Because of this we can say that the most part of the wind speed won’t have an influence (or it will be really small) on the meteorological surge. However is necessary to say that other directions are also frequent and even the no frequent direction can occur so the worst scenario is possible but not probable.

On the other hand we have the wind speed. We have plotted the Graph D 2 where we can observe the wind through all the years of data. As we can see, is quite constant through the years around 2.7 m/s. However there are several peaks that correspond to the month next to December and January.

But all this wind is only the average wind so let us see what happens with the maximum speed wind. As we can see in the Graph D 3, stills being quite constant through the years with several peaks in the same months as the average wind speed.

As we can see on the table below the maximum winds come from SW and the North. As we can see, the most frequent direction has a big perpendicular component towards the coast. In the case of having extreme winds they will induce an important surge.
We have analysed the wind itself but let us now see the surge induced by this maximum wind.

We have plotted the Graph D 4 where we can see the surge induced by this maximum surge. As we can see it is much larger to the one induced by the average wind because of two reasons. The first it is because the windspeed is maximal and secondly the directions in the maximum case are much more perpendicular towards the coast. It is interesting to see a peak of 40 centimetres November of 2011 and a lot of peaks over 15 centimetres (12 peaks).

Finally let us use the data of the Buoy of Barcelona for study the pressure surge through all this years. This data has already been analysed in the place of Blanes. The Graph C 5 and the Graph C 6 show us the maximum values for the pressure surge and the average ones.

So as we can see, the wind won’t be the largest factor of dependence of the meteorological surge because the most frequent direction has a minimal sinus that converts near to zero the effect wind so the wind surge. Also we have seen that the wind speed tends to be the same so the direction will be who determines the wind surge rather than the speed in Calella.

However, when the wind is maximal we can have surges of 40 centimetres. If both phenomenon (pressure and wind) are extreme we can have surges around 70 centimetres high which a really large value that can be really dangerous for the coast line.

4.4.3 Conclusion

Besides the data from the SIMAR point has not been able to obtain interesting results have been observed. We should also add that the seven years of data measured gives us a real idea of what is going on in Calella and we can say that the results show the reality almost as good as it is.

First of all we can say that, as the other places of study, the meteorological surge follows a cyclic law variation induced by the cyclic variations of the pressure.
The pressure induces the larger percentage of the meteorological surge and the wind has a less important signification in the meteorological surge.

The wind won’t normally induce high surges on average because as we can see the it is a low wind and the direction of it has no perpendicular direction towards the coast (or it is minimum).

In the case of the maximum wind, we have from moderate to strong winds which are high for the Mediterranean Sea. Even more, the most frequent directions have an important perpendicular direction towards the coast. If the wind is maximum we could have big surges as we can see on the Graph D 4 with several values over 20 centimetres and even one of 40 centimetres. This values added to the pressure surge and the other tides can suppose a really big increase of the sea level producing a lot of damages to the coastline.

We can finally say about the wind that the speed is a bit larger in from November to March.

We have finally the data of the Buoy of Barcelona. The maximum values are quite similar to the ones of the private data station. The maximum values happen on the same periods in time and they are of the same order.

4.5 Mataro

4.5.1 Data sources for Mataro

In Mataro we have two data sources. We have the data coming from the private meteorological station and the one that comes from the SIMAR point. The private data comes from Josep Delhort.

The private station is located at the point 41° 32’ 30” N 02° 27’ 00” E at a height of 37 meters over the sea water level so height transformations have been done. In this source
we have large amount and complete data so the results will be really interesting to analyse. More precisely we have the following data:

1. Average daily wind speed and direction from 2013 until 2015.
3. Daily average pressure.

As we can see in this case we have the wind direction when the maximum wind speed. So we won’t have to consider the worst scenario and we will be able to discuss if the maximum wind speed always blows the same way.

From the SIMAR source we have the same as always. But in this case we only have data since 2005. For being more precise:

1. Wind average speed every 3 hours since 2005
2. Most frequent wind direction every 3 hours since 2005

Finally we have the data of pressure coming from the Buoy of Barcelona.

**4.5.2 Results and analyses of the results in Calella**

We have taken the private data and we have done several modifications to be able to calculate the meteorological surge. First of all, the height transformation has been done from 37 meters to 10 meters over the sea water level. After that we have calculated the effective direction of the wind towards the coast. Once this is done the meteorological surge has been calculated. We can observe the results at the Table E 1, Table E 2 and Table E 3. Because there is a lot of numbers all together we have summarize this data in the following table:

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0.003</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>STA. DEV</td>
<td>0.061</td>
<td>0.060</td>
<td>0.092</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0.208</td>
<td>0.185</td>
<td>0.291</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>-0.157</td>
<td>-0.165</td>
<td>-0.199</td>
</tr>
</tbody>
</table>

*Table 4.14 Meteorological surge in Blanes from 2013 to 2015*
As we can observe on the table the average is zero. It is induced by the cyclic variations of the meteorological surge (and of course because the pressure surge that we will see later on). We can also see that the standard deviation is around 6 centimetres but 9 in 2015 (probably because the data of the year is incomplete and we are missing the smallest surges in summer. We can observe maximum surges of 29 centimetres that can suppose a big problem to the coastline and the urban zone next to it.

Now let’s analyse why this happens. We have plotted for that purpose the Graph E 1 where we can see the three surges all together.

As we can see there is a line that is almost always close to the zero and then another one that varies. We cannot see the third one because the pressure surge and the meteorological surge are almost the same. So again we can affirm that the largest part of the meteorological surge is induced by the pressure variations.

We can see how the surge is larger at the beginning and the ending of the year as we can suppose. The maximum surge happened January of 2015 and it reached an increase of 29 centimetres. These values are calculated with the average wind, we will see later on how the maximum wind acts in the surge in Mataro.

Let’s now analyse the wind itself. As we know the wind has two components of study, the wind speed and the wind direction. For starting let’s analyse the wind direction. As we can see on the following table the most frequent direction is SW and it has a minimum responsibility of the surge because it is quite parallel to the coast. To summarize the wind direction we have plotted the following table (private data source)

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>NW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SSW</td>
<td>SSW</td>
<td>SW</td>
<td>SW</td>
<td>WNW</td>
<td>WNW</td>
</tr>
</tbody>
</table>

Table 4.15 Direction of the wind in Mataro for each month (average wind speed)

Now we just have to analyse the wind speed. As we can see in the Graph E 2 the wind speed is larger in the February and March. The two highest values of average surge
happened in March of 2014 and 2015. However when the wind speed is higher the
direction is quite parallel to the coast (or even does not affect because it has not
perpendicular direction to the coast) so as we can imagine the wind won’t suppose a big
problem of increase of surges.

But in all this calculations we were using the average wind. Now we will study what
happens with the maximum wind speed.

First of all we have plotted the Graph E 3. In this graph we can observe velocities twice
as bigger than the average surge. We can see that the highest winds happen between
November and March as usual. However the winds are not really high.

The directions of the maximum speed are shown in the following table. As we can see
the most frequent direction is the SW direction as it was the average direction. As we
can see on the colours of the table, even though the SW direction as a certain
perpendicular component towards the coast it is really small. Even more, two of the
months of highest’s winds do not have influence on the surge because of their direction.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
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</thead>
<tbody>
<tr>
<td>NW</td>
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<td>SW</td>
<td>ENE</td>
<td>SW</td>
<td>SSW</td>
<td>SSW</td>
<td>SSW</td>
<td>SW</td>
<td>NW</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.16 Direction of the wind in Mataro for each month (maximum wind speed)

Finally we will analyse the surge induce by this maximum wind speed. We have plotted
the Graph E 4 for having a visual idea of the maximum wind surge. As we can see the
surge is really small due to the wind direction of the maximum wind speed. We can
observe a maximum of 4,5 centimetres. The average of it is 4 millimetres and 3,5 the
standard deviation

Let us now compare both sources as we have done in Castelldefels. It has to be said
that we will compare only the average wind because is the only data we can obtain in
the SIMAR source.
The most frequent directions depending from the data of the SIMAR point are the following.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
<td>SW</td>
</tr>
</tbody>
</table>

Table 4.17 Most frequent direction of the wind

As we can see the most frequent direction is the SW and it is the same as the private data source.

For the average wind speed we have plotted the Graph E 5. In this graph we can observe that the highest winds happen around December and January as it is common. The highest peak is 16.6 m/s and it happened in December of 2009. The wind in the SIMAR point is higher than the one of the private data. This can be explained by the absence of obstacles in the SIMAR point and the presence of those in Mataro. It is surrounded by mountains and the wind normally comes from the land instead of the sea so it will be stopped by the different obstacles.

Let us analyse now the surge induce by the wind from the SIMAR point. The results are in the Graph E 6. As we can see the surges are really low due to the direction of the wind. In this case, the maximum surge happened in March of 2010.

Finally we have the data of the Buoy of Barcelona, as we have seen in the previous chapters the maximum surges happen in between November and March with a total maximum of 30 centimetres in January of 1997. The maximal values of the Buoy of Barcelona make sense with what we have for the private station because, as we can see on the Graph C 4, the values of maximums are quite similar.
4.5.3 Conclusion

As we can see in the Table 4.12, the meteorological surge has a standard deviation of 6 centimetres (the last year hasn’t finished yet). Although it is a low value there is a tide. We can observe a value close to zero (or even zero) on the average surge reminding us the cyclic variations of the surge. It is confirmed in the Graph E 1 where we can see the largest surges from November to March.

We can observe how the pressure and meteorological lines are close to each other. This explains that in the case of the average daily surge, it is induced (almost the entire of it) by the pressure. Because the variation of pressure surge is cyclic, the meteorological surge is.

Even if we have low values for the meteorological surge, maximum values can also happen as in January of 2015 that we had 30 centimetres.

All of this is with the average wind but what could happen if we had the maximum speed? The maximum wind in Mataro is a moderate wind with some strong wind values. Even though the direction of it has a low influence towards the coast so also the maximum wind won’t be a big problem.

It is interesting to observe how in the three data of wind directions we have similar directions and it is one direction with a really small component towards the coast. However we can see how in the SIMAR point, the average direction is higher than the one from the private station. Knowing the emplacement of Mataro, we can say that the presence of obstacles next to the private station is the explanation for that.

4.6 Castelldefels

4.6.1 Data sources of Castelldefels

In the case of Castelldefels we have the data from two sources, the private meteorological station the SIMAR point and the Buoy of Barcelona.
The private data has been measured thanks to a person lover of the meteorology. Thanks to the measurements of MeteoCastelldefels day after day we have data of wind and pressure. His meteorological station is placed at the coordinates 41º 16’ 3’’ N 1º 56’ 6’’ E and it is placed at a height of 62 meters of difference with the sea water level. Of course, several transformations have been required as the height transformation to 10 meters.

The data obtained of this source is the following:

1. Average daily pressure from February 2013 until 2015 in hPa.

Following the way of working in the previous paces, because there is no direction of the maximum wind speed the worst scenario has been represented. We will discuss later on the probability of this scenario.

A SIMAR point close to Castelldefels gives us data from the wind speed and direction since 1958 until 2015. Exactly we have the following data:

1. Average wind speed since 1958 until 2015 measured every three hours (m/s)
2. Average wind direction since 1958 until 2015 measured every three hours.

As you can imagine, we have a large amount of data that will be useful to determine the variations of the wind directions and wind speed as the most frequent directions.

We finally have the data measured by the Buoy of Barcelona. From this Buoy we have the pressure data.

We must also say that we have only data from three years in the case of the private source. For adding reliability to our results we will compare it with results coming from the SIMAR and Buoy source.
4.6.2 Results and analyses of the results in Castelldefels

The results obtained of the surge in Castelldefels from February 2013 until 2015 are shown on the Table F1, Table F2 and Table F3.

To summarize this large amount of numbers and try to obtain the most significant data the following table has been edited:

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0.001</td>
<td>-0.004</td>
<td>-0.039</td>
</tr>
<tr>
<td>STA. DEV</td>
<td>0.060</td>
<td>0.059</td>
<td>0.087</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0.201</td>
<td>0.181</td>
<td>0.255</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>-0.111</td>
<td>-0.177</td>
<td>-0.251</td>
</tr>
</tbody>
</table>

Table 4.18 Meteorological surge in Castelldefels from 2013 until 2015

As we can see in this table, the average of the three years is really close to zero; this explains the cyclic variations along the year. The standard deviation values are next to 6 centimetres (in 2015 we are missing months).

Once we have the results let's look for interesting properties in them. We have an idea of what can happen having a look to the previous places of study. So let’s compare the total meteorological surge, the wind surge and the pressure surge.

As we can see on the Graph F1, the meteorological surge is almost the same as the one of the pressure surge. Even more, the wind surge is represented almost as a straight line near the zero. Once again, we can affirm that the pressure induces the most part of the meteorological surge. We can see how the maximums happen always in between November and March when the variations of pressure are higher. We then think in a cyclic evolution of the storm surge because the pressure surge varies in a cyclic way.

On the other hand we have the wind surge. As we can see, it is similar to a line next to the zero. We will see why this happens in the following paragraphs.
First of all we will analyse the wind direction of the average speed. On the following table we can see clearly that the most frequent direction is the S direction (in the case of the private source)

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
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<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 4.19 Directions by month in Castelldefels from 2013 until 2015

As we can see it is painted in yellow which means that has a minimum influence in the surge because of its small perpendicular component.

Once we have studied the directions let us see the wind speed in Castelldefels. We have plotted the Graph F 2 the wind speed measured from the private station. We can observe that the highest values (we are talking about average values) happen, as always, between November and March. However we can see in this graph several peaks out of these months, for example in July of 2014.

But this is the average situation; let’s study the case of the worst scenario in the maximum wind. Before all, it has to be said again that in the case of the maximum wind speed the perpendicular direction to the coastline has been applied. The reason of it is trying to represent the worst scenario that we could imagine in Castelldefels because of the absence of direction of the maximum wind.

So let’s analyse the maximum wind itself and let’s see when the worst wind situation could happen. Of course we will have the worst situation when the wind blows perpendicular to the coast and when the wind speed is the maximum.

Let’s start with the wind direction. We can see the wind direction distribution along the 2013 until 2015. As we can see in the previous table, the most frequent direction is the S direction. This direction is the most frequent in the average wind and we have seen in
other places that the direction of the maximum wind can vary from the average wind. However it gives us an idea of the direction that the wind could adopt. In this case, the S direction has a minimal influence in the surge.

Going now to the wind speed, we have plotted the Graph F 3. In this graph we can see the wind through 2013 until 2015. It is interesting to recognise again the months of highest winds (November to March). The maximum wind speed was in March of 2015. Even being the maximum wind, it is low or moderate wind so the surges won’t be extreme.

Looking to these results we have that the wind speed won’t lead to large surges, however the direction always blows towards the coast (almost perpendicular to it) so in the case of wind it leads almost always to an increase of the sea water level. If we had extreme wind speed conditions this could be a problem, nevertheless wind speed will not be very big.

We will now take the data coming from the SIMAR point and we will analyse the average wind. We will discuss about the direction and the velocity of it.

On the Graph F 4 we have plotted the wind speed from 1958 until 2015. As we can see the velocity is quite constant through time experiencing peaks in the ending or beginning of the year. The maximum wind is 17 m/s and it happened in March of 2008. As we can see this wind is higher than the one measured in the private station. However the wind in Castelldefels from the SIMAR point stills being moderate and low. This variation in the wind from the SIMAR to the private station is explained by the presence of obstacles on the land.

Let’s now compare the wind direction, as we have seen before, the most frequent direction of the private station is the south direction, however as we can see in the following table the most frequent direction is the SW direction. As we can see, wind changes direction depending on the source, as the wind speed.
On the Graph F 5 we can see the wind surge in Castelldefels since 1958 until 2015. As we can see the surge has not large values. However we have some surges that are really high as in November of 1982 where the surge was 33 centimetres.

Finally we have the data coming from the Buoy of Barcelona. As it has already been commented in the previous points, the maximum of the pressure surge is 30 centimetres and we have a standard deviation of 5 centimetres. The maximal values are always in between November and March and they are around 25 centimetres, which quite similar to what we have in the private station.

### 4.6.3 Conclusions

First of all we can see that there is a tide, with a standard deviation of 6 centimetres. It is a low value but there is a surge and even more it is considered the average situation.

We can say again that the meteorological surge follows a cyclic variation because the pressure does, being higher from November to March.

The wind will not suppose a high increase of the meteorological surge because it is a really low wind (average daily wind), even more, the direction is not really perpendicular to the coast (painted in yellow). Although we are considering the average wind, the maximum wind is also low.

The SIMAR point velocities are a little bit higher but they are still being low wind with some of the being moderate. Only from 2007 until 2014 we have strong winds but only from November to March.
We can say that the data collected from both sources show us different situations (also the direction changes a little bit) but it is only because they are placed in different places.

Finally we have the data from the Buoy of Barcelona, which the values correspond to the same order of magnitude than the private source.

**4.7 Vilanova i la Geltru**

**4.7.1 Data sources of Vilanova i la Geltru**

In the case of Vilanova I la Geltru we have data that comes from the private meteorological station of the university UPC. More precisely, Joaquin del Rio Fernandez has given us the data for our studies.

The station is placed at the coordinates of 41° 13’ 24'' N 01° 44' 10'' E and at a 14 m over the sea water level. So height transformation has been needed in order to get the wind speed at the height of 10 meters over the sea water level.

The data coming from Vilanova is the following:

1. Average wind speed and most frequent direction from 2012 to 2014.
2. Maximum daily wind speed and its direction from 2012 to 2014
3. Daily average pressure.

As we can see we have completed data so we won’t have to imagine a worst scenario and discuss about it. However we don’t have the pressure when the maximum wind happened. Because of that we will discuss about the maximum wind itself, without pressure effects over the pressure.

We also have the data of the Buoy of Barcelona, with this data we will complement our results to the ones obtained from the private station.
4.7.2 Results and analyses of the results in Vilanova i la Geltru

Once the transformations have been done we can calculate the surge. The wind surge on Matlab and the pressure surge with Excel, adding both of them we obtain the meteorological surge.

We can see the meteorological surge results on the Table G 1, Table G 2 and the Table G 3. As we can see no big surges appear in those three years however there are some maximum and minimum surges that should be considered. As on the other points we have the following table to summarize all this data:

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE</td>
<td>0,000</td>
<td>0,003</td>
<td>0,002</td>
</tr>
<tr>
<td>ST DEV</td>
<td>0,067</td>
<td>0,073</td>
<td>0,053</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>0,209</td>
<td>0,289</td>
<td>0,187</td>
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<tr>
<td>MINIMUM</td>
<td>-0,179</td>
<td>-0,193</td>
<td>-0,122</td>
</tr>
</tbody>
</table>

As we can see, the standard deviation it is around 6 cm which does not mean a big increase of the sea water level. It is really interesting the values of the average surge. The number close to the zero gives us an idea of cyclic variations and takes us to the hypothesis where the pressure is the principal responsible of this meteorological surge.

It is remarkable the maximum values, especially the maximum value of 2013. It is around 30 centimetres. This, added to the astronomical tide, waves and other factors can suppose a big increase of the sea water level leading to floods and beach destructions.

As before we suspect that the pressure is the principle agent that increases the sea water level. So, we will plot the meteorological surge and the wind and pressure surge together to have a more global idea and detect new properties of the meteorological surge. Because of that we have plotted the Graph G 1.

As we were expecting, the meteorological and the pressure surge are practically the same while the wind surge is almost a straight line next to the zero. We can say again that the pressure is the principal agent on the meteorological surge. As we can see, the
meteorological surge is larger in winter rather than in summer. As always, because of the pressure we think that the meteorological surge follows a cyclic law because the pressure does.

We can observe how in between November and December we have the highest values, especially at the end of 2012 and the beginning of 2013. As we can see, the maximum value happened in January of 2013 with a value of 30 centimetres.

But now let’s study the wind itself, the speed and the direction. We will study the average wind and after that we will study the maximum wind speed. We will compare their speeds and directions to detect new properties.

Let’s study first the average speed, as we have seen in the previous paragraphs, its influence towards the meteorological surge is really small.

As we can see in the following table, the most frequent direction appear in the painted area and even more, the most frequent is in red. So as we can see the direction it is quite perpendicular to the coast so in the case of high winds we could have a scenario close to the worst. However this is the direction of the average wind, later on we will see the direction of the maximum wind.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
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<tbody>
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<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>NE</td>
<td>NE</td>
</tr>
</tbody>
</table>

By this table we could say that the wind will have the biggest influence from May to October. As we have seen in the previous places of study, these months don’t usually have the highest winds. We have plotted the Graph G 2 where we have all the wind speed from 2012 until 2014. We can see three clear zones of higher peaks. These zones are between December and March. The maximum average wind speed happened in March of 2014 with a value of 4.4 m/s. As we can see the winds use to be low or moderate in Vilanova.
Even more, when we have the maximum average wind speed the directions of it do not have a perpendicular component towards the coast. Only in March but the component it is really small.

What we have analysed is the average wind but, what happens with the maximum wind? Does it behave as the average wind? Let’s analyse, then, the maximum wind and see the results.

As we have done with the average surge, we will study first the wind direction. Collecting all the directions from 2012 until 2014 we obtain the table below. As we can see we have a lot of directions in the painted area and even more, they are in red. So, in case of having high winds they will really affect to the meteorological surge.

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>W</td>
<td>SE</td>
<td>W</td>
<td>SE</td>
<td>SSW</td>
<td>SE</td>
<td>SSW</td>
<td>SE</td>
<td>SE</td>
<td>N</td>
<td>NE</td>
</tr>
</tbody>
</table>

As we can see the wind is quite similar to the average wind however it tends to be more randomly distributed.

Now we will analyse the wind velocity of the maximum wind. We have plotted the Graph G 3. In this graph we can observe the maximum wind distribution from 2012 until 2014. As we can see we normally have moderate winds and several periods of strong winds. These periods corresponds to the months between January and March. It is interesting to see the maximum wind. It happened in August of 2014 and it was a really strong wind, 34 m/s. Fortunately all the strongest winds happen when the direction does not faces the coast but in March. The presence of high winds in March could lead to high surges.

Once we have said that let us see what happens with the surge leaded from the maximum wind speed. We have plotted the Graph G 4. In this graph we have plotted
the surge induced by the maximum wind speed. It is really interesting to see how the highest surges do not happen when the maximum velocities. This is due to the wind direction. When the velocity is maximal the direction of it is not facing the coastline. So, we have the highest surges in between May and October because is when we have the most perpendicular direction. However, the maximum value happened in February of 2012 with a maximum of 17 centimetres which is a significant value.

Finally we have the pressure data coming from the Buoy of Barcelona. This data has been analysed in the previous places. Maximum pressure surge and average pressure surge have been plotted in the Graphs C 4 and 5. As we now, the maximum surge induce by the pressure was in January of 1997 with a value of 30 centimetres. The maximum values are around 20 centimetres which goes along with the private data. The average pressure surge is also close to zero because of the cyclic variations.

4.7.3 Conclusions

Again we have a standard deviation of 6.5 centimetres which demonstrates how the sea is not a tide less sea. Although it is a small surge it can adopt maximums of 29 centimetres as we have seen in 2013.

We can observe the cyclic variations of the meteorological surge because the pressure surge varies that way. We will have the maximum values at the beginning and ending of the year and more moderate in the middle months.

The low contribution to the surge of the wind is due to the low winds in Vilanova, even more the directions when the wind is stronger do not have a perpendicular component towards the coast. However during the year the directions are painted in red.

On the other hand we have that the maximum wind is a moderate wind sometimes being a strong wind. However the worst directions happen when the wind is lower, from May to October. We also have March with a critical direction; here the wind uses to be a moderate-strong wind so there can be high surges. Besides that, we normally have the highest surges induced by this wind from May to October because of the directions. The
surges are around 5 and 6 centimetres high but maximums of 17 centimetres have been
registered so it can be dangerous added to the pressure surge.

The Buoy of Barcelona confirms the values of the private data station; we have the
same order of magnitude and they happen (the maximums) on the same period of
months, November to March.

4.8 Geographic discussion of the results obtained

Until now we have seen every place separately; we have studied their variations of
surge and analysed their characteristics. We have found some similarities between each
place of study. Now we will show this similarities and differences between each place
and search the geographic characteristics of the Catalan Coast.

First of all we have seen in every place that the months with highest meteorological
surges, no matter if we have calculated them with the worst scenario or the average
scenario, are from November to March. In between these months the variation of
pressure are the biggest ones, we have the maximums and the minimums of the pressure
surge in this months.

Because of these variations of pressures wind is created. So we will have the highest
winds also in these months.

Let us compare the principal data from every place with each other.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>St Deviation</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palamos</td>
<td>-0,009</td>
<td>0,069</td>
<td>0,283</td>
</tr>
<tr>
<td>San Feliu de Guixols</td>
<td>0,005</td>
<td>0,064</td>
<td>0,265</td>
</tr>
<tr>
<td>Blanes</td>
<td>0,027</td>
<td>0,059</td>
<td>0,242</td>
</tr>
<tr>
<td>Calella</td>
<td>0,005</td>
<td>0,068</td>
<td>0,309</td>
</tr>
<tr>
<td>Mataro</td>
<td>0,000</td>
<td>0,069</td>
<td>0,291</td>
</tr>
<tr>
<td>Castelldefels</td>
<td>-0,008</td>
<td>0,067</td>
<td>0,255</td>
</tr>
<tr>
<td>Vilanova i la Geltru</td>
<td>0,000</td>
<td>0,066</td>
<td>0,289</td>
</tr>
</tbody>
</table>

Table 4.24: Meteorological surge in the Catalan Coast

Before all it has to be said that the data used in this table has been the private stations
from each place. In Blanes we only had one year of data and we only had the maximum
wind speed without direction. In San Feliu we had the same as Blanes but with three years of data.

First of all let us focus on the average column. We can observe some values equal to zero and the others really close to it. This is because the variations are cyclic and with the same deviation over and under the average surge.

On the other hand we have the standard deviation. As it shows us, there is in every place a variation of the sea water level even if it is not large. So, the theory of tide less sea is wrong. The standard deviation is quite similar for all the Catalan Coast. The reason of it is because the pressure is the main character on the meteorological surge as we have been seeing during the places of study. The pressure is considered a stationary and big scale phenomenon. So we will have similar values for every place of study.

Even more, the maximums are of the same order of magnitude. This is also because the wind has a really low influence on the meteorological surge.

As it has been said all of this is because of the pressure; it is considered a stationary phenomenon so in all the Catalan Coast will we have similar values. But what happens with the wind surge? We have seen that not only the velocity matters, also the direction does.

We have created this table for having a better idea of how the wind works in the Catalan Coast.

<table>
<thead>
<tr>
<th>Private Station</th>
<th>Average Speed</th>
<th>Maximum Speed</th>
<th>SIMAR Point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>St Dev</td>
<td>Max</td>
</tr>
<tr>
<td>Palamos</td>
<td>1,72</td>
<td>0,72</td>
<td>6,62</td>
</tr>
<tr>
<td>San Feliu de Guixols</td>
<td>5,09</td>
<td>1,81</td>
<td>17,11</td>
</tr>
<tr>
<td>Blanes</td>
<td>6,35</td>
<td>2,47</td>
<td>20,25</td>
</tr>
<tr>
<td>Calella</td>
<td>2,47</td>
<td>1,04</td>
<td>8,39</td>
</tr>
<tr>
<td>Mataro</td>
<td>1,07</td>
<td>0,53</td>
<td>4,22</td>
</tr>
<tr>
<td>Castelldefels</td>
<td>0,66</td>
<td>0,44</td>
<td>2,98</td>
</tr>
<tr>
<td>Vilanova i la Geltru</td>
<td>0,58</td>
<td>0,57</td>
<td>4,52</td>
</tr>
</tbody>
</table>

Table 4.25: Wind speed and direction in the Catalan Coast
First of all let us focus on the SIMAR speed, as we can see, the strongest winds appear in the north of the Catalan Coast. As we can see the average is larger in the north. Even more the standard deviations are the largest ones. This is explained by the large increase of the wind in between November and March. As we can see, the most frequent direction is the SW in all the Catalan Coast which goes along with the XIOM, 2009.

We can also see that normally we have low winds. The averages are lower than 6 m/s. However, the standard deviations show us that in many cases we have moderate winds, as R. Bolaños said in the XIOM, 2009.

The wind varies a lot from one place to another as we have seen along the fourth point of the thesis. The position of the private station could modify the characteristics of the wind so that is why the wind from the SIMAR point and the one on the private station could present some differences. This explains why the average wind is smaller than the SIMAR point.

As we can see, the wind is higher in Calella and then in the north, however maximum velocities have been measured in Vilanova I La Geltru, on the south.

But not the highest winds will induce the highest surges. For that reason we have done this table where we show the surges obtained from the SIMAR point.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>St Dev</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palamos</td>
<td>0,008</td>
<td>0,011</td>
<td>0,1359</td>
</tr>
<tr>
<td>San Feliu de Guixols</td>
<td>0,003</td>
<td>0,003</td>
<td>0,0340</td>
</tr>
<tr>
<td>Blanes</td>
<td>0,003</td>
<td>0,005</td>
<td>0,0982</td>
</tr>
<tr>
<td>Calella</td>
<td>0,005</td>
<td>0,005</td>
<td>0,0751</td>
</tr>
<tr>
<td>Mataro</td>
<td>0,005</td>
<td>0,005</td>
<td>0,0751</td>
</tr>
<tr>
<td>Castelldefels</td>
<td>0,018</td>
<td>0,020</td>
<td>0,3353</td>
</tr>
<tr>
<td>Vilanova i la Geltru</td>
<td>0,018</td>
<td>0,020</td>
<td>0,3353</td>
</tr>
</tbody>
</table>

Table 4.26: Surges obtained from the SIMAR point

We can see how the highest wind surge occurs in Castelldefels, even the largest average happens in Castelldefels. On the Table 4.23 we can observe how in Castelldefels we don’t have the highest winds. However, because of the also large amount of frequencies with a certain perpendicular towards the coast (as S and E) we have this high values.
Even more, the low slope of Castelldefels bathymetry also helps the surge to by higher because of its small slope next to the coast.

The data from the SIMAR is the average wind. Let us see finally the wind surge induced by the maximum wind obtained from the private data source.

We have done this table to see more clearly the maximum wind surges along the Catalan Coast obtained from the private data sources.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>St Dev</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palamos</td>
<td>0.013</td>
<td>0.017</td>
<td>0.158</td>
</tr>
<tr>
<td>San Feliu de Guixols</td>
<td>0.005</td>
<td>0.064</td>
<td>0.260</td>
</tr>
<tr>
<td>Blanes</td>
<td>0.026</td>
<td>0.067</td>
<td>0.242</td>
</tr>
<tr>
<td>Calella</td>
<td>0.022</td>
<td>0.037</td>
<td>0.407</td>
</tr>
<tr>
<td>Mataro</td>
<td>0.004</td>
<td>0.005</td>
<td>0.045</td>
</tr>
<tr>
<td>Castelldefels</td>
<td>0.007</td>
<td>0.005</td>
<td>0.037</td>
</tr>
<tr>
<td>Vilanova i la Geltru</td>
<td>0.018</td>
<td>0.021</td>
<td>0.166</td>
</tr>
</tbody>
</table>

Table 4.27: Maximum wind surges obtained from the private stations

It has to be said that in the case of Blanes and San Feliu we have chosen the worst scenario (perpendicular to the coast) and in the case of Blanes we only have one year of data.

This table shows us how the surge is higher in the north but also is high in Vilanova, in the south. The values are small (in the average column) because we have a lot of values equal to zero because of the wind direction.

It is important to see the magnitude of the maximum surges. All this winds are measured next to the coast but not in the coast so that would be approximated results of the reality, even more if we have said that the wind climate is not considered a stationary phenomenon. For example, the Castelldefels station is placed 800 metres away from the coast.

So all this values can be bigger in the reality. The maximum values are already large as the one in Calella. The wind surge is a reality in the Catalan Coast and if the climate conditions are critical (high winds and perpendicular directions) high surges can be induced.
5. Conclusion

The study of the meteorological surge along the Catalan Coast has been analysed. For being able to characterize properly the Catalan Coast we have chosen 7 points in the coast. From each point we have obtained data from a private meteorological station, the closest SIMAR point and Buoys of Begur or Barcelona.

We have calculated separately the surge induced by the wind and the one induced by the wind. The addition of both is the meteorological surge. The pressure surge has been calculated with the inverted barometric effect law with the data coming from the buoys and the private stations. The wind surge has been calculated with the one dimension surge model with the data of the SIMAR point and the one from the private station.

Before concluding it has to be said that all the data collected does not cover the same span of time. Even more, in certain places some data was missing as the direction. This fact has to be taken into account as a first estimation of the results.

With the private data source we have obtained values quite similar for the different points. As we have seen in the table 4.23, values are quite similar for all the places. Maximum of average meteorological surges of 25 centimetres are normal during the years, the maximum value has been in Calella with 31 centimetres. However we were talking about average situations. The maximum wind (see Table 4.26) surge happened in Calella with 41 centimetres.

From the SIMAR point we have obtained similar data from one point to another. However the results show a big variety between them. As it is shown in the Table 4.24, the maximum wind happened in Palamos with a value of 19 m/s (SIMAR point provides average values of three hours range). Nevertheless, as we can see on the Table 4.25 the maximum wind surge happened in Castelldefels with a value of 33 centimetres. It is interesting to see how lower wind speeds generates higher surges. As we have seen in our calculations it is due to the wind direction and bathymetry of the place.

The values of the two different buoys are very similar. Firstly we have the data from Begur, a maximum of 35 centimetre has been observed in 2010. In Barcelona we have
similar values of maximums, average and standard deviations. The maximum measured in Barcelona was in 1997 with 30 centimetres. It has to be said again that the data covers different windows of time.

As we have already commented on the geographic discussion, we have seen that similar values appear on the different data sources (buoys and private stations). Not even that, similar values appear on the different places of study. Because of this we can affirm that the pressure is a stationary and global phenomenon. We can then say that the results show the reality how it is.

On the other hand we have the wind. As we have seen the wind is higher in the SIMAR point rather than the private stations. Even more, the directions of the wind in both sources change is some places. The wind is not a global phenomenon; it is governed by the local effects that make the wind change depending on the circumstances of each place.

For the future studies data collection should be more accurate. Much more places of study should be taken into account. Even more, from each place we should have different station of data measurement for the wind and pressure in land (extremely near to the coast) and several offshore for wind to have a better characterization of the wind. The time span should cover the same window of time of at least 10 years to have a global idea. Finally, the data measured should show the average wind, the maximum wind and its directions.
6. Bibliography


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7. Annexes