University of Split
Faculty of Science

Atmospheric forcing of the Mediterranean sea level extremes

Master thesis

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Split, November 2022

Temeljna dokumentacijska kartica

Sveučilište u Splitu
Prirodoslovno – matematički fakultet
Odjel za fiziku
Ruđera Boškovića 33, 21000 Split, Hrvatska

Diplomski rad

Atmosfersko forsiranje ekstremno visokih razina Sredozemnog mora

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Sveučilišni diplomski studij Fizika, smjer Fizika okoliša

Sažetak:
U ovom radu opisano je atmosfersko forsiranje koje uzrokuje ekstremne razine mora u Sredozemnom moru. Odabrano je pet postaja za analizu: Valencija, Monako, Napulj, Ravena i Venecija. Analizirane su rezidualne razine mora, koje se definiraju kao razlika između izmjerenih razina mora i plimnih oscilacija. Ekstremni događaji dalje su definirani kao događaji tijekom kojih rezidualne razine mora prelaze 99.9 percentil procijenjen za svaku postaju zasebno. U prvom dijelu istraživanja predstavljeni su rezultati analize razine mora tijekom 31-godišnjeg klimatološkog razdoblja (1984.-2014.), uključujući statistiku učestalosti, trajanja i sezonske distribucije ekstrema. U drugom dijelu istraživanja predstavljeni su rezultati analize sinoptičkih atmosferskih polja povezanih s ekstremno visokim razinama mora. Analizirana sinoptička polja uključuju: prosječni tlak zraka na razini mora, brzinu vjetra na visini od 10 m te geopotencijalnu visinu 500 hPa plohe i pripadne vjetrove. Najviše ekstrema zabilježeno je u razdoblju od listopada do veljače na svim postajama, a njihovo prosječno trajanje ovisi o mjesecu u kojem su zabilježene. Jedan prevladavajući sinoptički uzorak koji prethodi ekstremno visokim razinama mora izdvojen je za Valenciju dok su po dva tipična uzorka uočena za Monako, Ravenu i Veneciju. Tipični sinoptički uzorak nije prepoznat za ekstremne događaje u Napulju.

Ključne riječi: rezidualna razina mora, ekstremno visoke razine mora, statistika ekstrema, karakteristične sinoptičke situacije

Rad sadrži: 33 stranice, 26 slika, 4 tablice, 13 literaturnih navoda. Izvornik je na engleskom jeziku.

Mentor: izv. prof. dr. sc. Jadranka Šepić

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prof. emer. dr. sc. Darko Koračin

Rad prihvaćen: 31. 10. 2022.

Rad je pohranjen u Knjižnici Prirodoslovno – matematičkog fakulteta, Sveučilišta u Splitu.

Basic documentation card

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Master thesis

Atmospheric forcing of the Mediterranean sea level extremes

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Abstract:
Atmospheric forcing of the Mediterranean sea level extremes is studied in this work. The five stations chosen for analysis are: Valencia, Monaco, Naples, Ravenna and Venice. Analysis is done on residual sea levels which are defined as difference between observed sea level and astronomical tide. Extreme sea level events are further defined as events during which residual sea levels are above their 99.9 percentile estimated separately at each station. In the first part of the research, extreme sea level events during a climatological period of 31 years (1984-2014) are analyzed, including statistics on extremes' frequency, duration and seasonal distribution. In the second part of the research, synoptic patterns associated with extreme sea level events are determined. Studied synoptic fields include: mean sea level pressure, 10-m wind, 500 hPa geopotential height and pertinent winds. Most events occur during period from October to February at all stations, and their average duration depends on month in which they are recorded. One dominant synoptic field pattern preceding an extreme sea level event emerged for Valencia, and two dominant fields emerged for Monaco, Ravenna and Venice. There was no recognizable synoptic field pattern for Naples.

Keywords: residual sea level, extreme sea level events, statistics of extremes, characteristic synoptic pattern

Thesis consists of: 33 pages, 26 figures, 4 tables, 13 references. Original language: English.

Supervisor: Assoc. Prof. Dr. Jadranka Šepić

Reviewers: Assoc. Prof. Dr. Jadranka Šepić,
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Thesis accepted: October 31, 2022

Thesis is deposited in the library of the Faculty of Science, University of Split.

Contents

1 Introduction

The Mediterranean Sea is an enclosed basin between Europe and western Asia to the north and Africa to the south. Its brief description is given in [1]. Northern side of the basin is characterized by many islands, peninsulas and mountains, which make geophysical phenomena difficult to study. One of the main phenomena of interest are occasional extreme sea level rises which are frequent in some specific locations like Venice in the northern Adriatic ("acqua alta" - italian for "high water").

Weather situation in the Mediterranean Sea is usually stable during summer, but there are strong pressure gradients and winds during winter and intermediate seasons. Northerly and westerly winds are mostly caused by a low pressure fields moving from west to east, while southerly winds are usually a consequence of localized cyclogenesis [1]. Prevalent wind fields during winter are given in Figure 3 in [2].

Atmospheric phenomena, namely pressure gradients and winds, lead to the rise of the sea level above the predicted astronomical tide. According to [3], extreme sea levels in the most parts of the Mediterranean Sea are mostly caused by atmospheric influences, and tides do not contribute significantly. The exception is the Adriatic Sea. Extreme sea levels in its northwestern part usually occur when the strong atmospheric forcing collides with a high tide. As a result northern Adriatic, in particular Venice, is hit by frequent floods. The northern Adriatic phenomenon is well examined and many case studies are documented, for example in [4] and [5].

The purpose of this work is to examine influences of atmospheric forcing on sea level extremes recorded at five stations across the Mediterranean Sea: Valencia, Monaco, Naples, Ravenna and Venice. In Chapter 2, data sets, software and analyses used for the thesis are presented. Data quality check and visualisation are described in Chapter 3; in Chapter 4 tidal signal is estimated, analysed and removed from data. In Chapter 5, statistical analysis of episodes of extremely high residual levels over the period 1984-2014 is presented. For the most extreme of these episodes, the preceding synoptic situation is examined in Chapter 6. Such analysis aims to find characteristic weather patterns leading to the recorded extremes.

2 Materials and methods

2.1 Sea level data

Hourly sea level data were downloaded from the web-page GESLA-2 (Global Extreme Sea Level Analysis Version 2) [6]. GESLA-2 assembles high frequency, at least hourly, sea level records into a common format with consistent quality control flags. Data were collected through national web sites, authors' personal links and from international data centers, especially the University of Hawaii Sea Level Center. All heights are in meters and time is adjusted to Coordinated Universal Time (UTC) [6].

The first GESLA data set (GESLA-1) was assembled around 2009. It contained 21,197 years of high frequency measurements from 675 records from tide gauges around the world. The second version, GESLA-2, was assembled in 2015 and 2016. It contained 39,151 years of high frequency measurements of sea level from 1,355 records, and is described in detail in [7]. GESLA-3 was compiled in 2020 and 2021, and contains 90,713 years of data from 5,119 records. This version is described in [8].

When choosing stations, my intention was to have them as scattered as possible across the western part of the Mediterranean Sea and the Adriatic Sea, and to include series with longest possible records. As a result, following 5 stations were chosen for analysis: Valencia, Monaco, Naples, Ravenna and Venice (Figure 1). Length of analysed time series was: 31 years for Venice (from 1984 to 2014), 26 years for Ravenna (from 1986 to 2011), 25 years for Naples (from 1986 to 2010), 23 years for Valencia (from 1992 to 2014) and 16 years for Monaco (from 1999 to 2014).

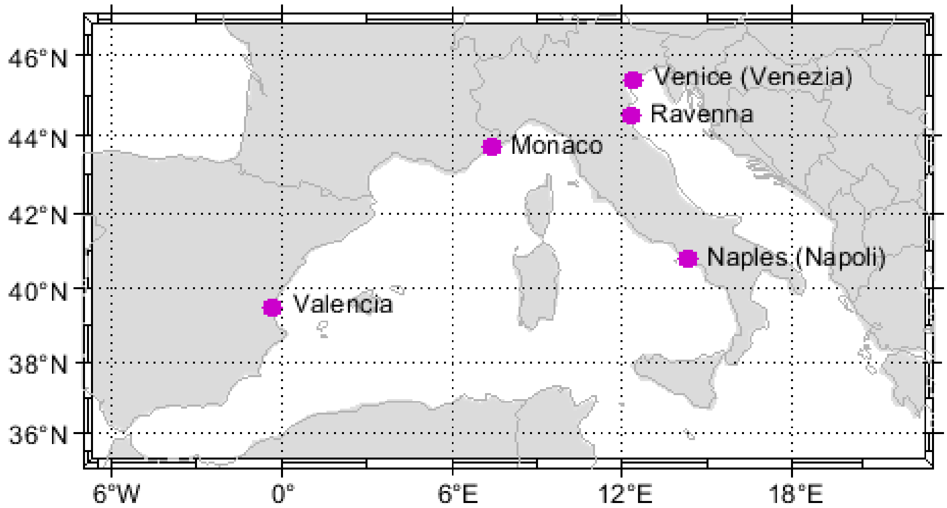


Figure 1: *Depiction of the chosen stations on the map*

2.2 Extraction of tidal signal

For estimating tides, I used the external toolbox *T_TIDE*, described in [9]. The tidal signal is modelled using classical harmonic analysis: tide is a sum of sinusoids at specific frequencies, determined by astronomical parameters. Tidal constituents of periods of up to 1 year are recognized, and some unresolved components are taken into account by means of nodal corrections. Confidence intervals for the analyzed components are also computed in this toolbox.

The output of *T_TIDE* in the Command Window in MATLAB is given in Table 1 in [9]. Names of constituents are given in the first column, and significant constituents are marked with an asterisk. Significant constituents are determined by the squared ratio of amplitude, given in the third column, and error in amplitude, given in the fourth column. This ratio is called SNR (signal to noise ratio) and is given in the last column of output. The cutoff SNR used in *T_TIDE* toolbox is 1, but it is 10^2 in this research because I wanted an error to be negligible.

Components which have SNR bigger than 10^2 on at least one station examined here are: SA (with period of 1 year); O1, P1, S1, K1 (with period of ca. 24 hours); 2N2, MU2, N2, NU2, M2, L2, S2, K2 (with period of ca. 12 hours); M3, SK3 (with period of ca. 8 hours); MN4, M4, MS4 and MK4 (with period of ca. 6 hours).

2.3 Extraction of extreme sea level events

For extraction of extreme sea level events, I wrote a function in MATLAB called *ekstremi*. Its input parameters are column vector *x* containing sea levels, and a chosen percentile *c*. Output parameters are *limit* (the minimum sea level defined by *c*), *indeksi* (indices of data in series *x* where sea level exceeds *limit*), and *epizode* (a matrix where subsequent indices from *indeksi* are grouped). The script and explanation are presented below.

After defining a function, *limit* and *indeksi* are defined using built-in functions in MATLAB:

```
function [limit,indeksi,epizode] = ekstremi(x,c)

    limit = prctile(x,c);
    indeksi = find(x>limit);

    ...

end
```

Epizode is defined as a matrix with three columns. For each extreme event, the beginning index is in the first column, the ending index is in the second, and duration of an event (number of indices) is in the third column. To start with, the code checks whether the first two indices are subsequent or not. If they are, they belong to a same event and its ending index is still unknown. If they are not, they belong to different events, first of them being completely defined.

```
if indeksi(1) == indeksi(2)-1
    epizode(1,1) = indeksi(1);
    epizode(1,2) = 0;
else
    epizode(1,1) = indeksi(1);
    epizode(1,2) = indeksi(1);
end
```

Throughout the matrix, the similar procedure was applied. If an index is not subsequent follower to the previous one, nor the subsequent predecessor to the next one, one extreme event containing only one sea level is completely defined. Furthermore, the end of the previous event can be inferred from this step. If an index is a subsequent predecessor to the next one, but not the subsequent follower to the previous one, it is a starting point to a longer event. The end of the previous event is now defined, but the end of current one remains unknown until the condition is satisfied again. The end of the last extreme event is defined in the next part of the code.

```
br = 1;
for i = 2:length(indeksi)-1
     if indeksi(i) ~= indeksi(i-1)+1 ...
      && indeksi(i) ~= indeksi(i+1)-1
        br = br + 1;
        epizode(br,1) = indeksi(i);
        epizode(br,2) = indeksi(i);
        epizode(br-1,2) = indeksi(i-1);
     elseif indeksi(i) ~= indeksi(i-1)+1 ...
      && indeksi(i) == indeksi(i+1)-1
        br = br + 1;
        epizode(br,1) = indeksi(i);
        epizode(br-1,2) = indeksi(i-1);
    end
end
```

If the last index is not a subsequent follower of the previous one, they belong to two different events, both completely defined now. Otherwise, they belong to the same longer event, the end of which was the only remaining unknown to find.

```
if indeksi(end) ~= indeksi(end-1)+1
    br = br + 1;
    epizode(br,1) = indeksi(end);
    epizode(br,2) = indeksi(end);
    epizode(br-1,2) = indeksi(end-1);
else
    epizode(br,2) = indeksi(end);
end
```

2.4 Atmospheric data

Atmospheric data were downloaded from ERA5 reanalysis data sets: [10], [11]. ERA5 is an ECMWF reanalysis for global climate and weather, containing hourly data from 1959 onward. Since data are collected through observations and modelling, values provided by ERA5 are estimations, and they are available for numerous atmosphere, land and ocean variables. It is the fifth generation reanalysis product, replacing ERA-Interim reanalysis.

Surface data were downloaded from [10], namely mean sea level pressure and horizontal wind components at 10 m height above the surface. Variables pertinent to the 500 hPa pressure surface were downloaded from [11], namely geopotential height and horizontal wind components. Data from both reanalyses used in this research have a regular $0.25^\circ \times 0.25^\circ$ grid resolution.

3 Visualisation and data quality check

For visualisation of downloaded sea level data, equally spaced time-series were created and filled with NaNs at points where values were missing. Original data were mostly hourly, but data sets from Naples and Ravenna contained 10-minute data as well. At both stations 10-minute data started on February 3, 2010 and continued till the end of the time series. Approximately 9 months of data for Naples and 21 months of data for Ravenna contain 10-minute data. Original time series, prior to quality control, are shown in Figure 2.

Obviously spurious values for Naples and Ravenna, indicated as values below dashed lines in Figures 2c and 2d, were omitted from further analysis. Naples and Ravenna sea level series from which extremely negative values were removed are shown in Figures 3a and 4a. Now it becomes visible that missing values were sometimes replaced with zeros. Since too many zeroes would have an impact on mean value calculation and on statistics of extreme events, these values were also removed from analysis. This is shown in Figure 3b for Naples series. Three main segments of different mean values can be noticed for Naples series (Figure 3b). In order to make these segments comparable, mean values were subtracted from each of the three segments. Resulting Naples series are shown in Figure 3c. For Ravenna, gaps between segments were longer (up to 12 months). The shortest three segments, namely the first three, were excluded from further analysis - not only because of their shortness, but also because the third segment contained numerous obviously incorrect values. The resulting Ravenna time series, after complete quality check, are shown in Figure 4b.

Uniform hourly data for Naples and Ravenna were created using the *kaiser* function from MATLAB Signal Processing Toolbox. The window width was set to five data points, where the value measured at full hour had the highest weight, adjacent values (measured at hh:10 and hh-1:50) had lower, and values next to them (measured at hh:20 and hh-1:40) had the lowest weight. I chose this approach after examining several possible options because the hourly series created in this way had the standard deviation closest to that of the original hourly series. In addition, measured data recorded at all stations were oscillating around values other than zero. Since mean value is not relevant for analysis presented in this work, I removed means from all series to make results more intuitive and easier to compare. As mentioned before, mean values were removed separately for the three segments of Naples time series.

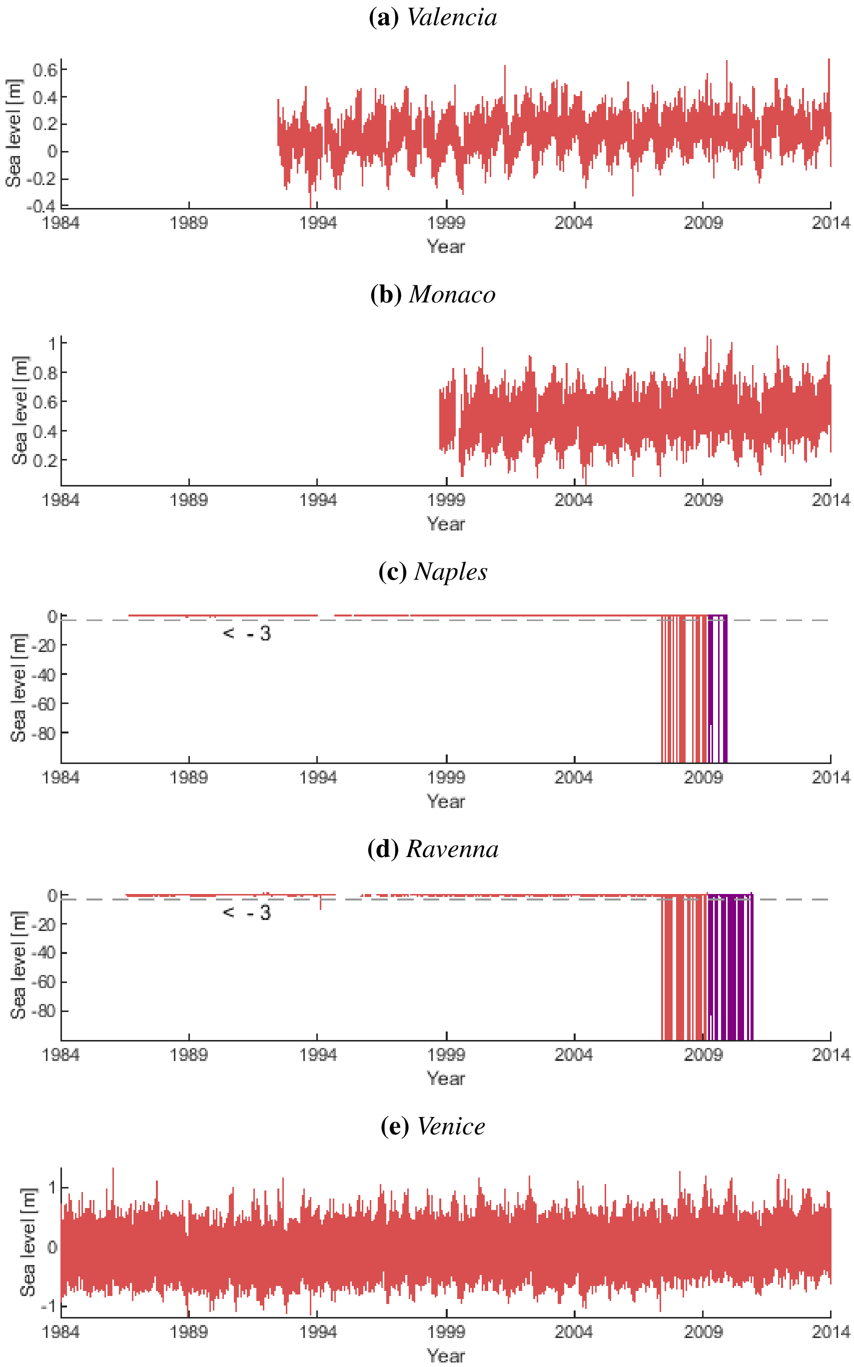
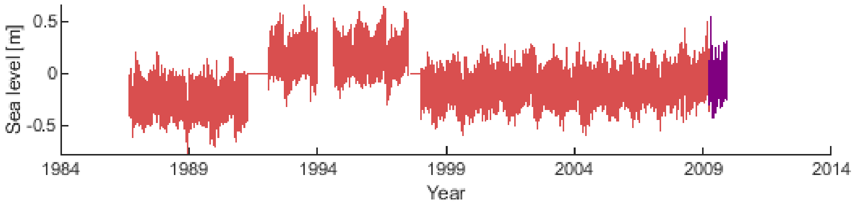
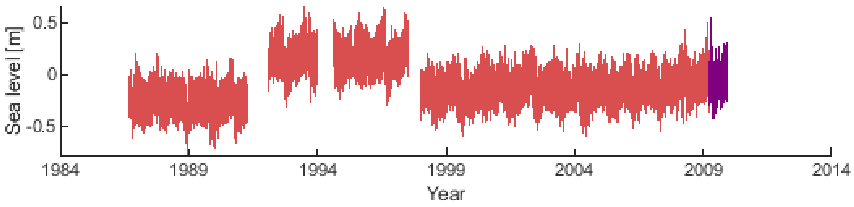


Figure 2: *Available time series within the period of interest, 1984-2014. Pink colour indicates hourly data, and purple colour indicates 10-minute data. Grey lines are limits for obviously false values, which will be removed.*

(a) *After removing extreme negative values*



(b) *After removing spurious values*



(c) *After removing mean for each segment separately*

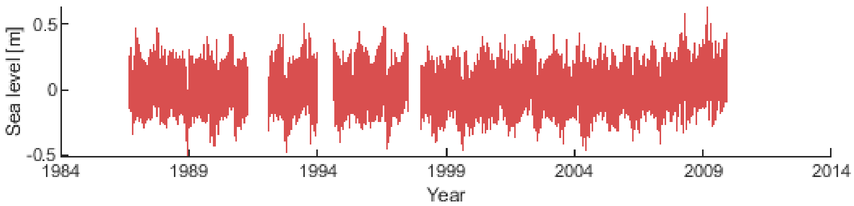
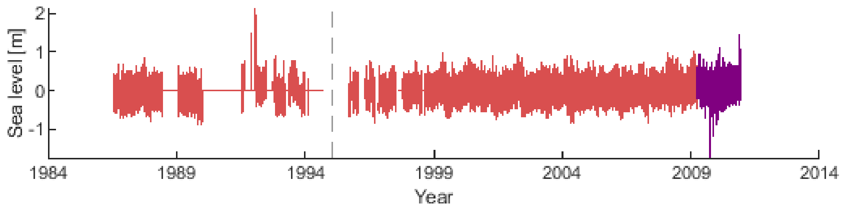


Figure 3: *Naples sea level time series: (a) after removing extremely negative spurious values; (b) after removing zeroes and outliers; (c) after removing means from each segment. Pink color indicates hourly, and purple color indicates 10-minute data.*

(a) *After removing extreme negative values*



(b) *After removing spurious values*

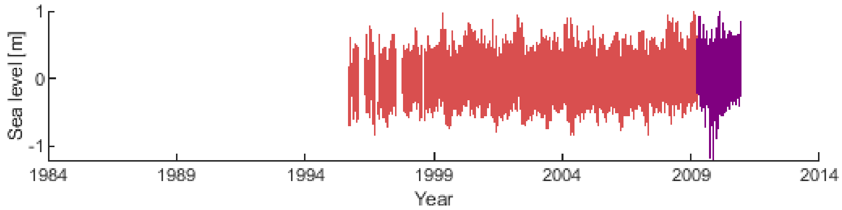


Figure 4: *Ravenna sea level time series: (a) after removing extremely negative spurious values; (b) after removing short segments (left of the grey line in the upper figure), zeroes and outliers. Pink color indicates hourly, and purple color indicates 10-minute data.*

4 Estimation and removal of tidal signal

4.1 Estimation of tidal signal

As mentioned in Chapter 2, tides were estimated using the external toolbox *T_TIDE*, and components were estimated as significant if their signal-to-noise power ratio (SNR) was of order of magnitude 10^2 or larger. In Table 1 all of these components and their periods of oscillation are listed, and significant components for each station are indicated. To obtain residual time series at each station, time series of significant tidal components were subtracted from original time series. The Solar-annual tidal constituent (SA), although significant, was not excluded from Valencia time series, because this signal is more likely due to seasonal steric sea level changes, than to the SA component.

The dominant tidal constituent in the western Mediterranean is M2, reaching heights from 1.75 cm at Valencia to 24.32 cm at Venice station; followed by K1 component, reaching heights from 2.88 cm at Naples to 17.91 cm at Venice station. This can be seen from Table 2, where the strongest tidal constituents at each station are listed. Regarding geographical distribution of tides, tidal signal is strongest over the Adriatic Sea, reaching total values of up to 55.6 cm

Table 1: *Estimated tidal components. Components significant at least at one station are listed in the first column, their periods are given in the second, and at stations for which they are significant a plus sign is given in the appropriate column from the third to the seventh.*
**Component satisfies signal-to-noise ratio, but it is not excluded.*

Component	Period [h]	Valencia	Monaco	Naples	Ravenna	Venice
SA	8764.24	*				
O1	25.82	+	+	+	+	+
P1	24.07	+	+	+	+	+
S1	24	+		+		
K1	23.93	+	+	+	+	+
2N2	12.91		+			
MU2	12.87		+			+
N2	12.66	+	+	+	+	+
NU2	12.63		+			+
M2	12.42	+	+	+	+	+
L2	12.19		+			+
S2	12	+	+	+	+	+
K2	11.97		+		+	+
M3	8.28	+	+	+	+	+
SK3	7.99		+			
MN4	6.27		+			
M4	6.21		+			
MS4	6.1		+			
MK4	6.09		+			

Table 2: *Three strongest tidal constituents at each station.*

Station	Tidal constituent	Height [cm]
Valencia	K1	3.63
	O1	2.46
	M2	1.75
Monaco	M2	8.05
	K1	3.28
	S2	3.07
Naples	M2	11.05
	S2	4.11
	K1	2.88
Ravenna	M2	16.91
	K1	15.43
	S2	9.73
Venice	M2	24.32
	K1	17.91
	S2	14.21

at Venice, and weakest at Valencia station, reaching values of up to 9.3 cm. These values are obtained as maxima from time series of significant tidal components.

4.2 Removal of tidal signal from the time series

By definition, residual is a difference between original time series and tidal signal (Figure 5). It is positive when measured sea level is higher than tidal signal and vice versa. Quality of tidal removal procedure can be checked by spectral analysis of original and residual signal: if spikes at frequencies of tidal constituents are not present in residual spectra, tides were removed successfully. Since series must be continuous for spectral analysis, they were first interpolated linearly. Then spectra from both original and residual time series were estimated (Figure 6). It can be seen that tidal signal has been significantly attenuated. Nonetheless, it obviously still leaks into residual signal at most tidal periods, especially for stations where data were of lower quality - Naples and Ravenna.

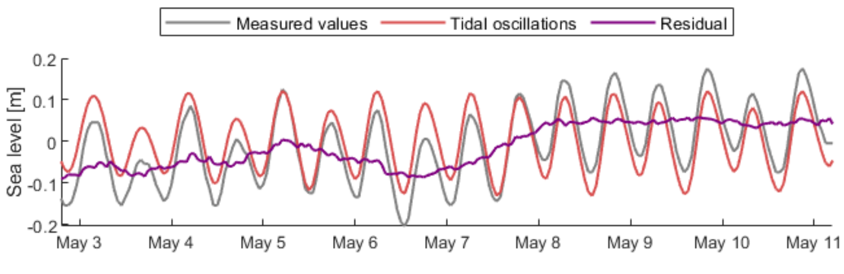


Figure 5: *Time series of measured sea level, tidal and residual signal during 3-11 May 2005 at Monaco.*

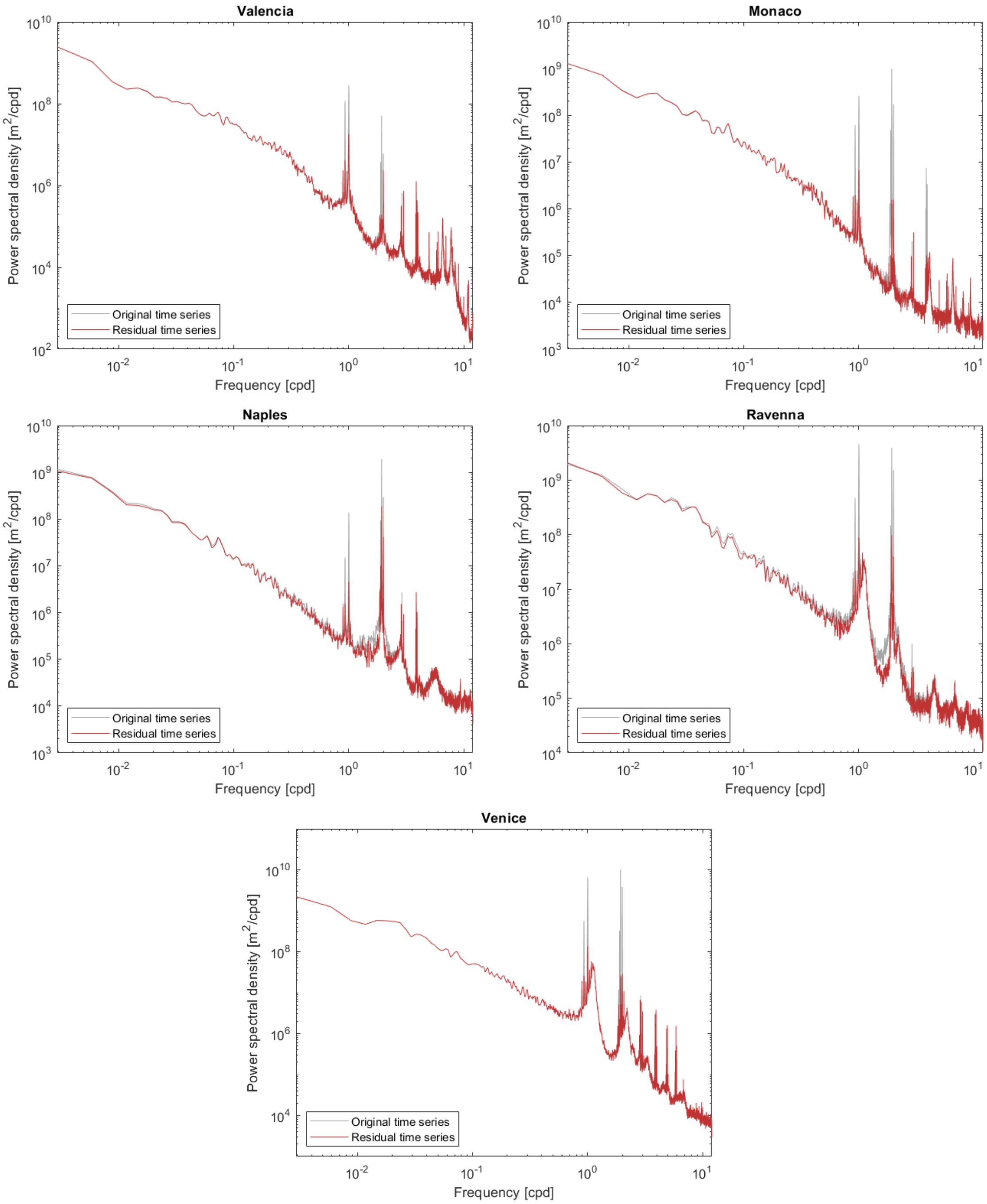


Figure 6: *Spectral analyses of original and residual time series at each station.*

5 Statistical analysis of extreme sea level events

Extreme sea level events were defined as those events during which residual sea level at respective stations surpassed its 99.9 percentile value. As described in Chapter 2, all data points within a continuous time interval were defined as one event. Residual time series and extracted extreme events at each station are depicted in Figure 7. Number of events and number of events per month at each station are given in Table 3. The 99.9 percentile value is highest in Venice (0.7 m) and Ravenna (0.6 m), as expected due to their location in the northern Adriatic. It is approximately the same for other stations and about 40% lower than in Venice. If number of events per month is low, like in Valencia, it means that there are less extreme events, but of longer duration. On the other hand, high number of extreme events per month measured at Naples is due to the fact that Naples has most events, but of the shortest duration.

Table 3: *Number of the extracted extreme events, in absolute values and relative to the length of time series.*

Station	99.9 percentile value [m]	Number of events	Length of time series in months	Number of events per month
Valencia	0.38	10	267	0.04
Monaco	0.36	19	189	0.1
Naples	0.35	65	289	0.22
Ravenna	0.6	34	203	0.17
Venice	0.7	48	372	0.13

For each station and for each extreme sea level event, maximum values of measured sea level and residual series are depicted in Figure 8. This analysis gives us an idea on whether the tidal oscillations further contributed to increased sea level, or not. If total maxima were much higher than residual maxima, it can be concluded that tidal oscillations contribute significantly to total extreme sea levels. Tides seem to be contributing factor when assessing total extreme sea level at all stations except for Valencia.

Temporal distribution of extracted extreme sea level events is depicted in Figure 9. It appears that there are two years with relatively large number of events at every station, namely 2009 and 2010. During these two years, most events (47) were recorded at Naples, followed by 22 events at Ravenna, 11 at Monaco, 10 at Venice, and 5 events at Valencia. On the other hand, there is a period with less events at every station, 1999-2007. The least number of events (only 1) during these nine years was recorded at Valencia. There were 2 events at Naples, 4 at Monaco, 5 at Venice and 8 at Ravenna. Periods 1984-1998 and 2011-2014 cannot be compared for all stations because no data were available for some of them.

Distribution of extreme events over months is depicted in Figure 10. To avoid double counting, events which covered two different months were assigned to a month in which the maximum residual value occurred. Most of the events occurred in fall and winter, and the

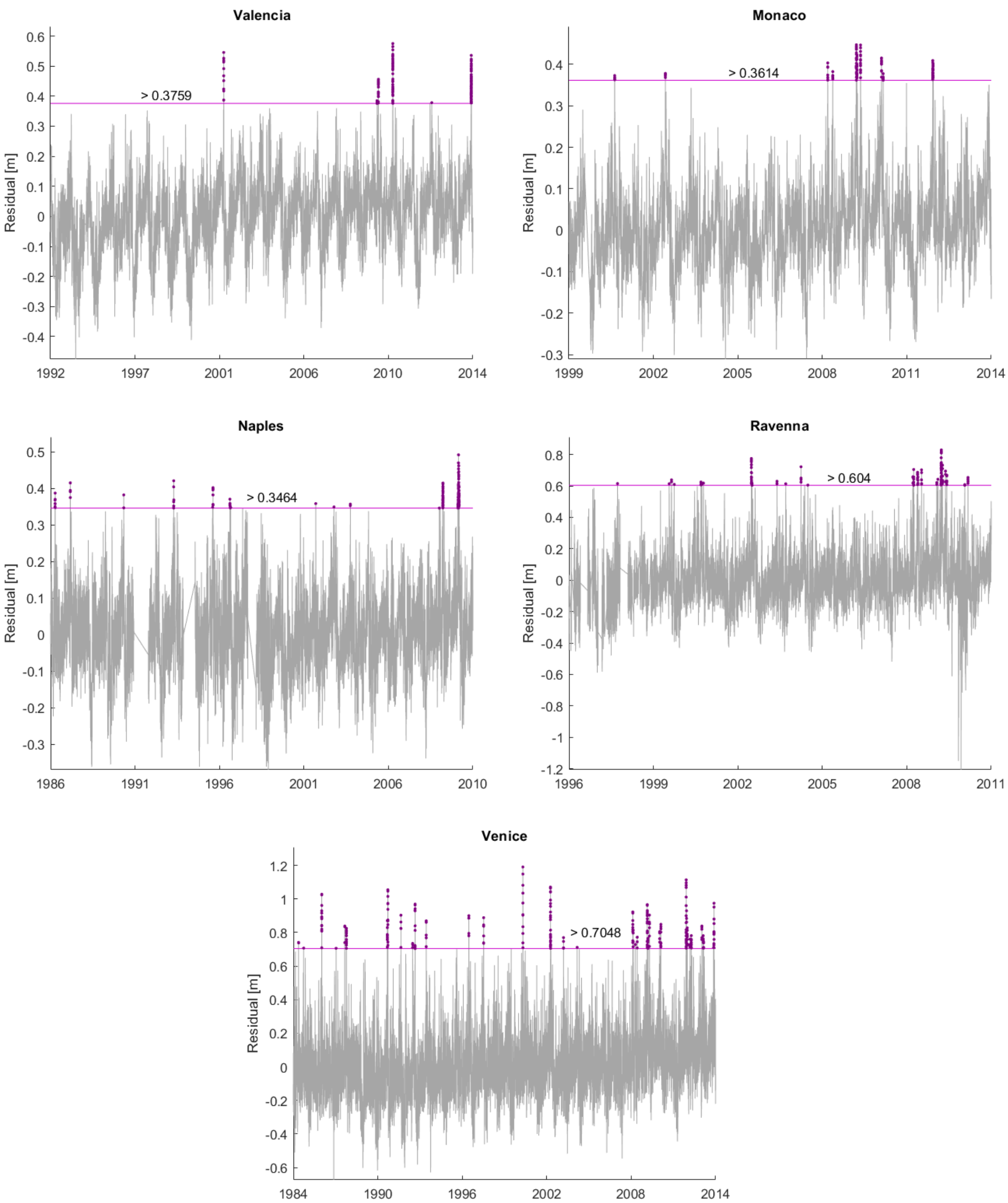


Figure 7: *Residual time series with limit (purple line) and extreme residual sea level events (purple squares).*

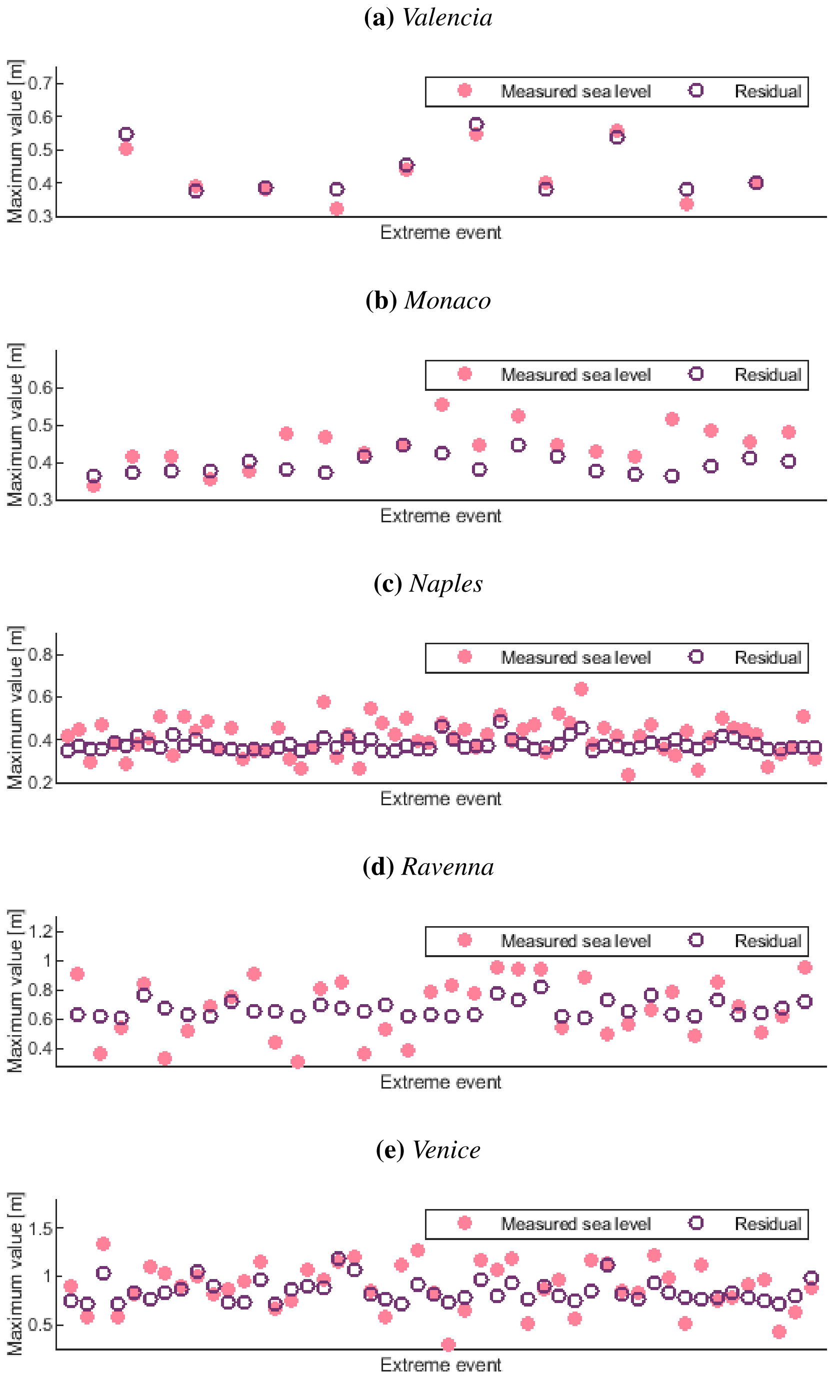


Figure 8: *Comparison between measured and residual maxima for each extreme sea level event and for each station. Residual values are higher than measured values if tidal oscillations were below average, i.e. the low tide was present.*

month at which events most commonly occur is December. This is valid for all stations, aside for Venice where most of extreme events occur in November, and Naples for which number of extreme events is similar in January, February and December.

Figure 11 depicts cumulative and average duration of extreme sea level events in each month. Number of events can be estimated from this picture by comparison of the two bars. If one of them is much lower than the other, i.e. the average duration is much less than the cumulative duration, there were many extreme events in a month of interest. On the other side, if one bar is behind the other, there was only one event in a month of interest (for example, in January in Valencia). Since this figure resembles the previous one, the validity of distribution over months is confirmed.

In Table 4, average duration of extreme sea level events in each month and at each station is shown. There are some differences in duration of extreme events in different months for all stations except Naples, where events last for 2-4 hours regardless of a month. In Valencia, events in October and December last twice as long as events in November. A short event occurred in Valencia in January only once during the analysed period. Events in Monaco are shortest in November, have an intermediate duration in February and December, and are longest in January and October. In Ravenna, extreme events last for 1-4 hours throughout the year, with March being the exception with events lasting approximately 9 hours. Finally, short lasting events occur in Venice in May and October, and longer events in Janurary, February, March, November and December.

Table 4: *Average duration of extreme events (in hours) in each month and at each station.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Valencia	1	0	0	0	0	0	0	0	0	22.5	11	19.5
Monaco	10	7.33	0	0	0	0	0	0	0	9.67	2.5	6.56
Naples	2.74	3.88	2.5	0	0	0	0	0	0	1.67	2	2.41
Ravenna	1.75	3.8	9	0	3	0	0	0	4	1	3.13	3.67
Venice	5	5.33	6	0	2	0	0	0	0	2.71	6.83	6.17

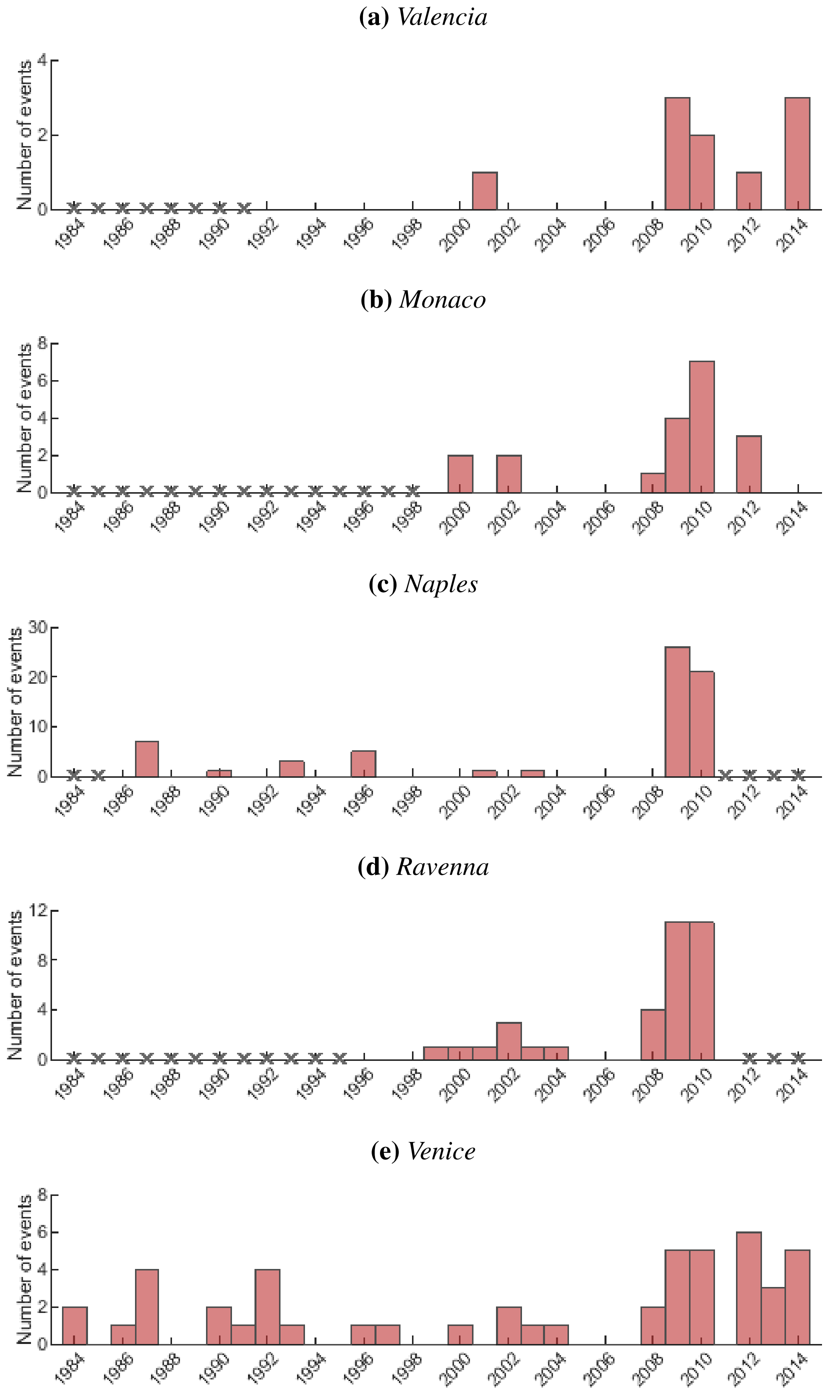


Figure 9: *Distribution of extreme sea level events over years. Grey crosses are used for years for which there were no data available.*

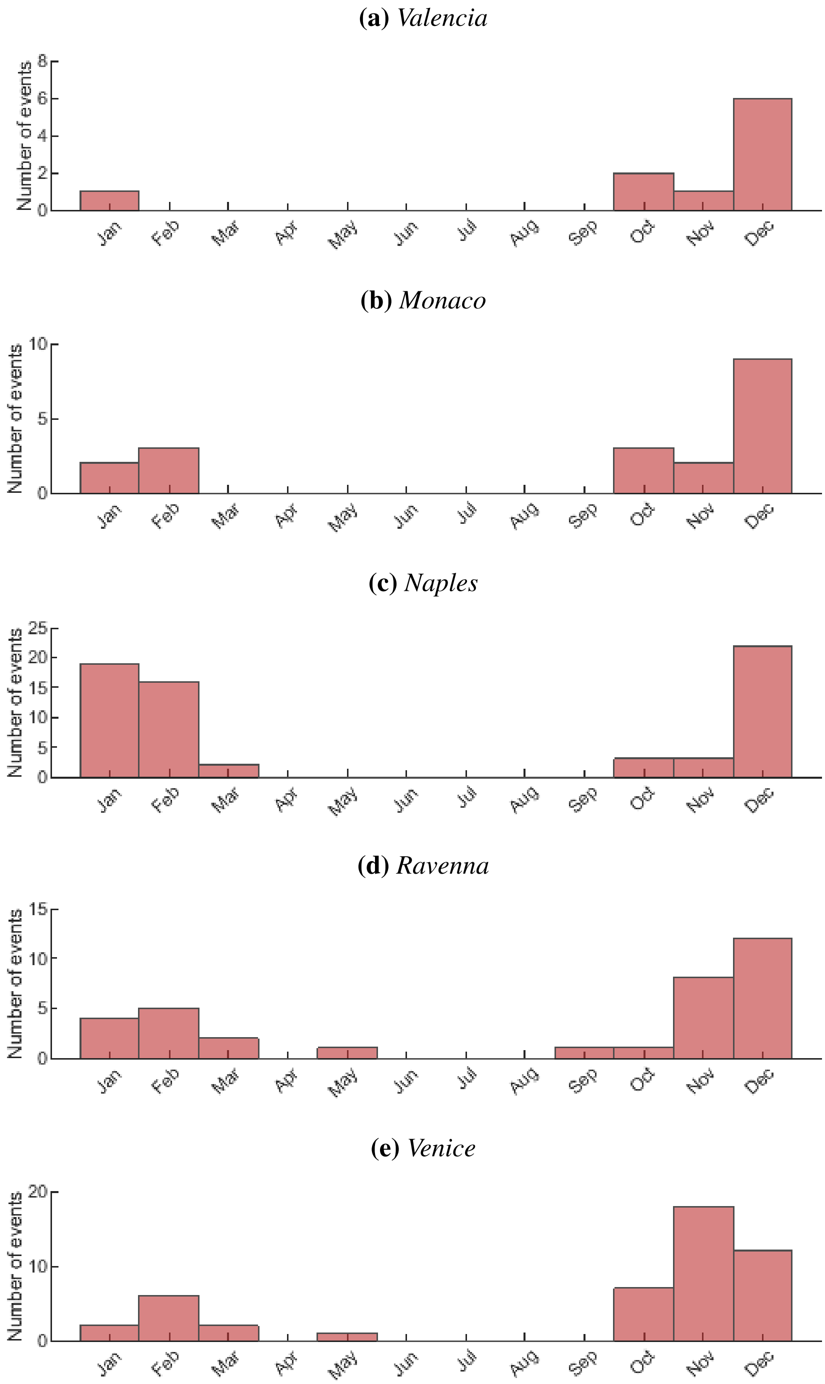


Figure 10: *Monthly distribution of number of extreme sea level events.*

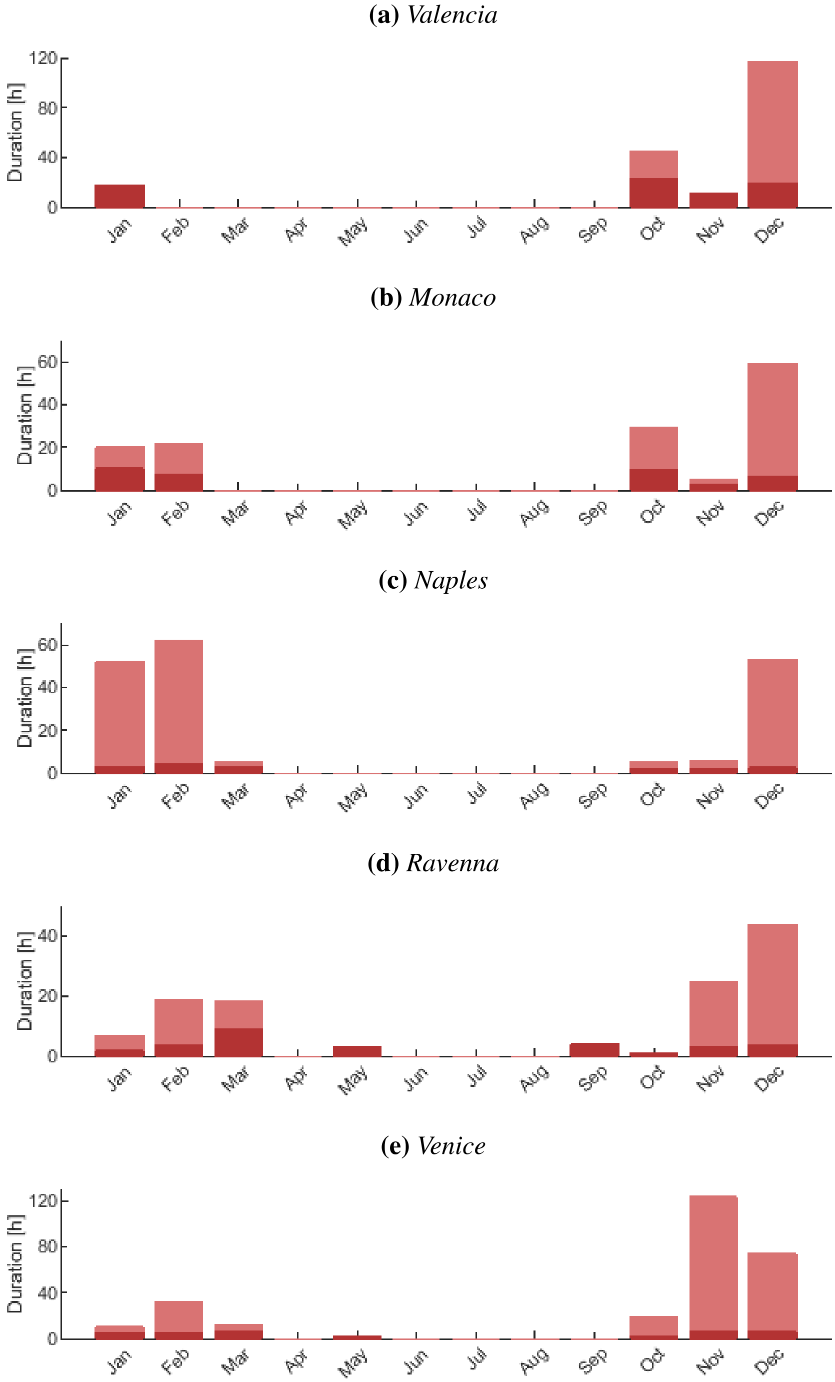


Figure 11: *Monthly distribution of cumulative (light pink) and average (dark pink) duration of extreme sea level events at each station.*

6 Analysis of characteristic atmospheric situations

In order to estimate what kind of atmospheric conditions govern sea level extreme events, I analysed synoptic situations related to the strongest of them. For each station, maxima of residual values (indicated by purple rings in Figure 8) were assessed - and synoptic situations related to 10 strongest events per station were analysed. Synoptic situation was examined across the Mediterranean Sea at an hour preceding the mentioned residual maxima. As mentioned earlier, data from the ERA5 reanalyses [10], [11] were used for the purpose. Results of analyses are presented below for each station separately.

6.1 Valencia

One dominant characteristic atmospheric situation was recognised for Valencia extreme sea levels. At the surface, this situation includes a mid-latitude cyclone over the western Mediterranean Sea, and wind blowing towards the coast from the northern directions (N to NE). To be more precise, in 7 out of 10 events a mid-latitude cyclone was present over the western Mediterranean Sea, in 2 events over the land of Spain and northern Africa, and in one event over the Atlantic Sea. The location of mean sea level pressure minimum was close (distance less than circa 400 km) to the station in 5 events. All locations of mean sea level pressure minima are indicated by rings in Figure 12. As mentioned, wind usually blew from northern directions (8 events), mostly N and NE along the eastern Spanish coast. There were also two events with S and SE winds along the coast.

At the 500 hPa surface, one dominant geopotential height field and one dominant wind pattern were noticed. Closed lows centered to the east or northeast of the Gibraltar Strait were reproduced for 7 events. Other fields include closed lows over the central Europe (2 events) and closed lows over the Atlantic Sea (1 event). All locations of the 500 hPa surface geopotential height minima are indicated by triangles in Figure 12. The 500 hPa surface wind usually blew from the southern directions (5 events). There were 2 events with weak northern winds and 3 events characterised by weak winds.

As an example of characteristic conditions, Figure 13 depicts synoptic situation on November 15, 2001 at 21:00 UTC. At the surface, there was a mid-latitude cyclone centered between the Balearic Islands, northern African coast and the island of Sardinia, and a northern wind was blowing along the eastern Spanish coast, both representative for dominant pattern. At the 500 hPa surface, a closed low to the northeast of Gibraltar is representative for the dominant pattern, with the strongest wind to the west of the station, over Portugal.

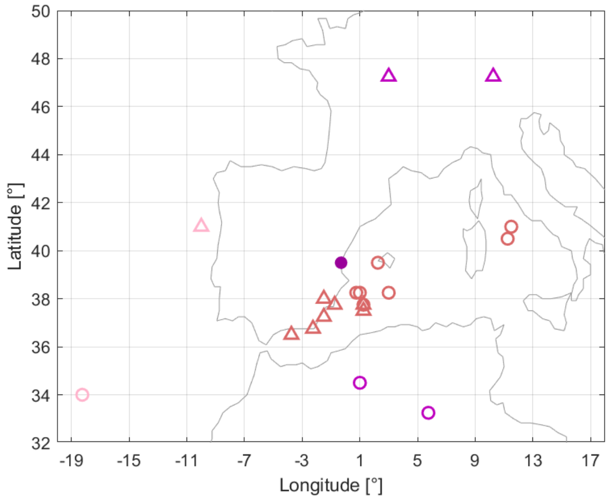


Figure 12: *Positions of mean sea level pressure and the 500 hPa geopotential height minima corresponding to extreme residual sea levels in Valencia. Rings indicate centers of cyclones at the surface: over the western Mediterranean Sea (dark pink), over Spain and northern Africa (purple), and over the Atlantic Sea (light pink). Triangles indicate centers of closed lows at the 500 hPa surface: to the east or northeast of the Gibraltar Strait (dark pink), over the central Europe (purple), and over the Atlantic Sea (light pink). Position of Valencia is indicated by filled purple circle.*

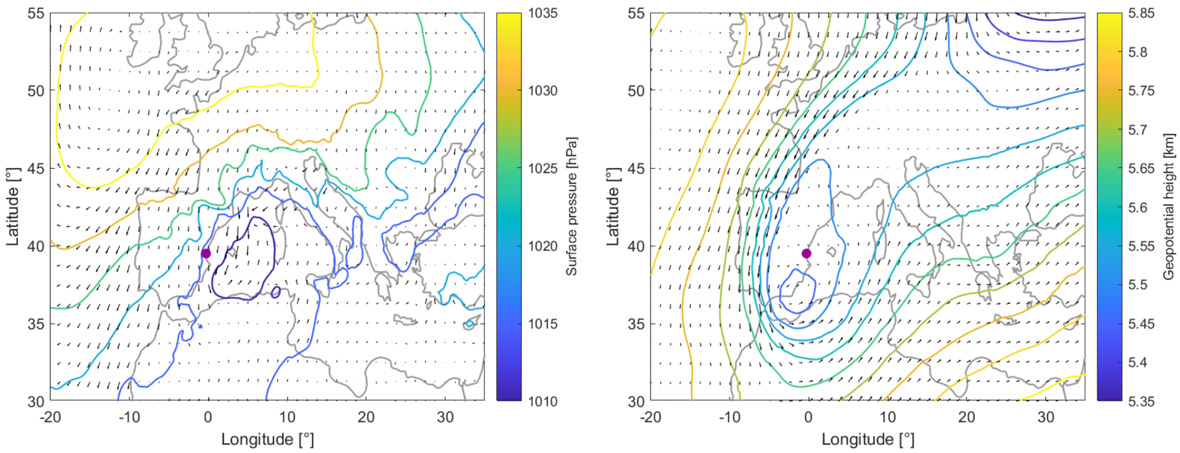


Figure 13: *Synoptic situation on November 15, 2001 at 21:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 21.36 m/s at 10 m and up to 49.61 m/s at the 500 hPa surface.*

6.2 Monaco

Two characteristic synoptic situations were recognised for extreme sea level events in Monaco. Regarding the mean sea level pressure, a mid-latitude cyclone was present over the central Europe in 6 out of 10 events, depression over the central Europe in 2 events, cyclone over the western Europe in 1 event, and very shallow depression over the southern Europe in 1 event. The location of mean sea level pressure minimum was close (distance less than circa 500 km) to the station in 5 events. Figure 14 depicts locations of surface pressure minima for 7 events during which mid-latitude cyclone was present. Winds at a 10 m height were either cyclonic around the station (5 out of 10 events), or southern (3 events). The cyclonic circulation can be described as dominant, not only because it appeared more often, but also because it was more likely to appear together with the dominant mean sea level pressure field.

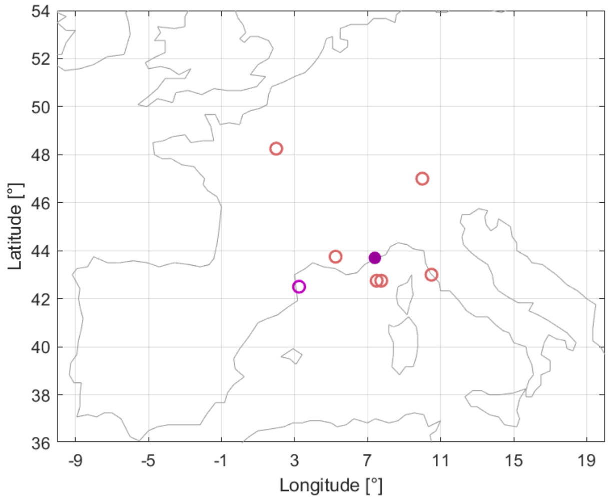


Figure 14: *Mean sea level pressure minima corresponding to extreme residual sea levels in Monaco. Centers of cyclones are indicated by colours: over the central Europe (pink), and over the western Europe (purple). Position of Monaco is indicated by filled purple circle.*

At the 500 hPa surface, there is one dominant geopotential height field and one dominant wind direction over the station. Depression over the northern Europe occurred in 8 out of 10 events. Winds blew from the southern directions in 9 out of 10 events, but they were relatively weak compared to the area maximum in 5 out of these 9 events.

As an example of characteristic conditions, Figure 15 depicts synoptic situation on October 28, 2012 at 03:00 UTC. At the surface, there was a mid-latitude cyclone centered over the western Mediterranean and central Europe, and surface cyclonic winds over the Ligurian Sea. At the 500 hPa surface, there was a depression over the northern Europe, and SW wind which was relatively weak compared to the wind over the UK.

6.3 Naples

I was not able to recognize one characteristic synoptic pattern related to Naples extreme sea level events. A mid-latitude cyclone over the central Europe occurred in 4 events; a depression over the central Europe, a mid-latitude cyclone over the western Mediterranean Sea and a mid-latitude cyclone over the Atlantic Sea all occurred in 2 events. Figure 16 depicts locations of mean sea level pressure minima for 8 events when a mid-latitude cyclone was formed. Wind fields were more consistent with wind blowing from the southern direction toward the Naples coast in 9 out of 10 events: S in 5 events, SW in 3 events and SE in 1 event.

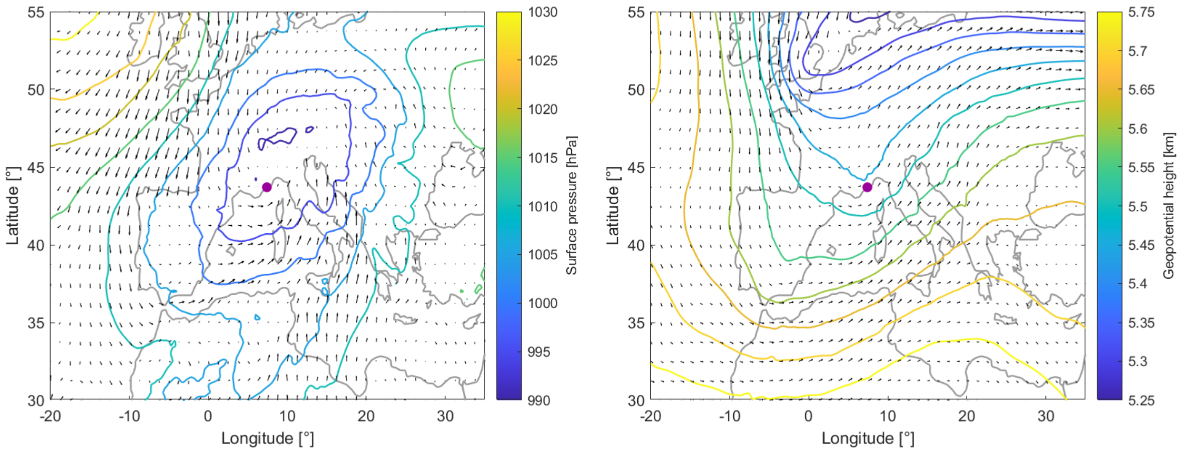


Figure 15: *Synoptic situation on October 28, 2012 at 03:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts 500 hPa geopotential height and wind. Winds speeds are up to 15.95 m/s at 10 m and up to 46.88 m/s at the 500 hPa surface.*

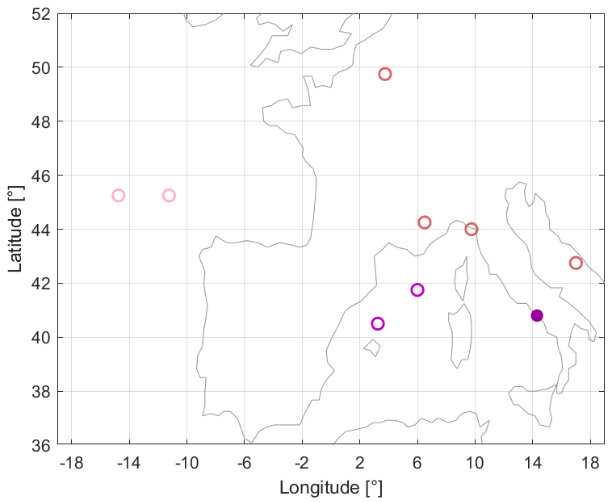


Figure 16: *Positions of mean sea level pressure minima corresponding to extreme residual sea levels in Napoli. Centers of cyclones are indicated by colours: over the central Europe (dark pink), over the western Mediterranean Sea (purple), and over the Atlantic Sea (light pink). Position of Naples is indicated by filled purple circle.*

At the 500 hPa surface, there was one dominant geopotential height field and one dominant wind direction over the Tyrrhenian Sea. Depression over the northern Europe occurred in 7 out of 10 events, and winds blew from the southern directions in all cases, mostly SW (7 events).

Figure 17 depicts a synoptic situtation on February 19, 2010 at 18:00 UTC. At the surface, there was a mid-latitude cyclone over the northern Italy, and SW wind was blowing at a 10 m height over the Tyrrhenian Sea. This represents the most common mean sea level pressure field, but does not represent the most common wind direction. At the 500 hPa surface, there was a depression over the northern Europe and a SW wind was blowing, both representative for the most common field at this level.

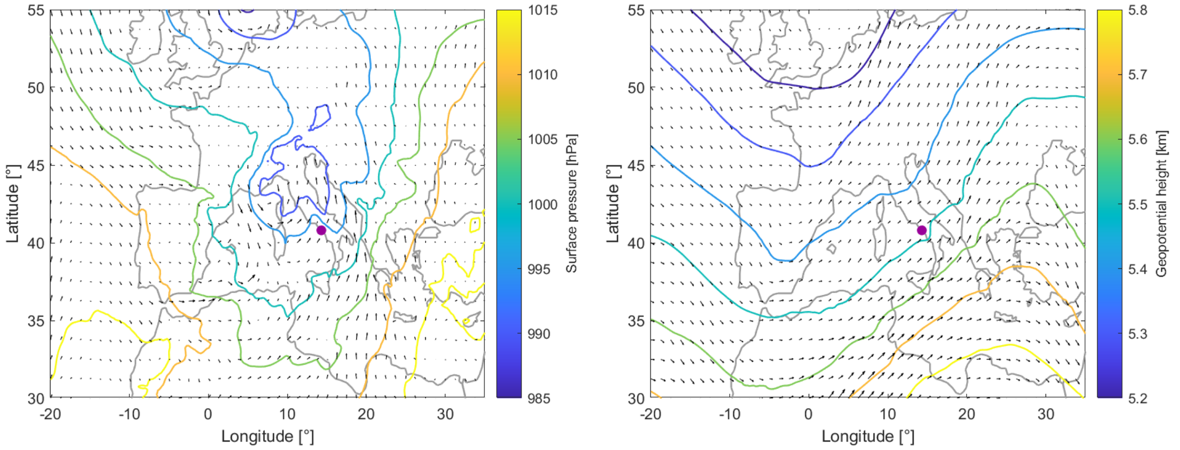


Figure 17: *Synoptic situation on February 19, 2010 at 18:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 19.49 m/s at 10 m and up to 50.65 m/s at the 500 hPa surface.*

Figure 18 depicts synoptic situtation on November 24, 1987 at 16:00 UTC. At the surface, there was a mid-latitude cyclone over the western Mediterranean Sea, and there was a S wind blowing at 10 m over the Tyrrhenian Sea. This field represents the most common wind direction, and one of the least common mean sea level pressure fields. At the 500 hPa surface, there was a closed low over the northern France, which is not representative for the most common field, and there was a representative SW wind.

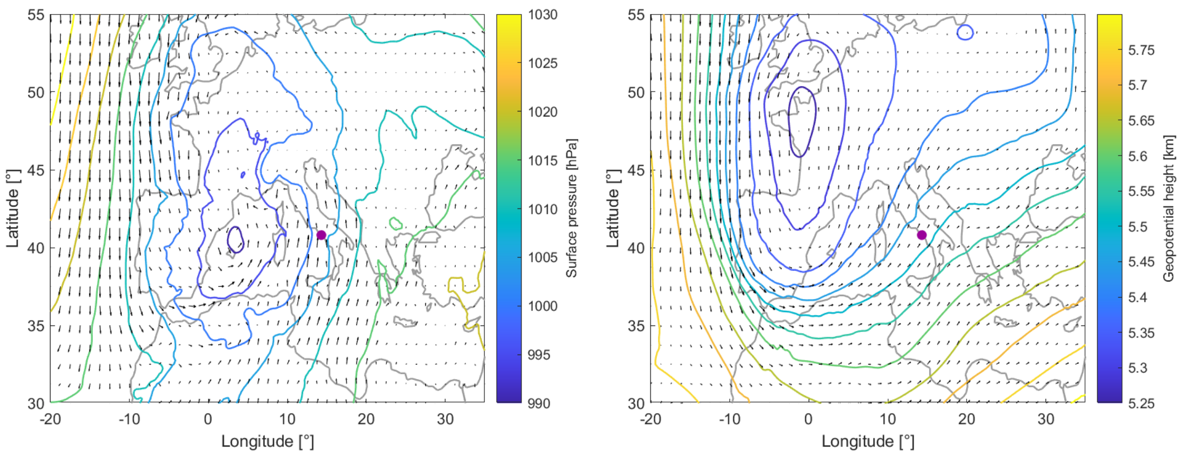


Figure 18: *Synoptic situation on November 24, 1987 at 16:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 17.78 m/s at 10 m and up to 52.53 m/s at the 500 hPa surface.*

6.4 Ravenna

Two characteristic mean sea level pressure fields and one characteristic wind direction at a 10 m height above the Adriatic Sea were recognised. There was a mid-latitude cyclone over Italy in 6 events and a mid-latitude cyclone over the Atlantic Sea in 3 events. A mid-latitude cyclone over the central Europe occurred once. Figure 19 depicts all locations of mean sea level pressure minima. Wind usually blew from the southern directions (8 out of 10 events), most commonly SSE (6 events).

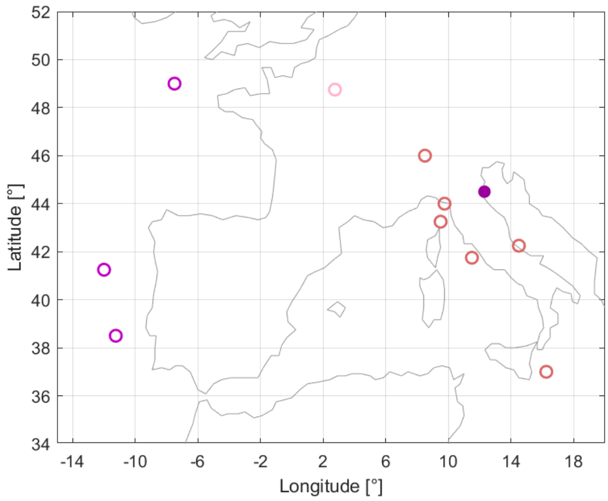


Figure 19: *Positions of mean sea level pressure minima corresponding to extreme residual sea levels in Ravenna. Centers of cyclones are indicated by colours: over Italy (dark pink), over the Atlantic Sea (purple), and over the central Europe (light pink). Position of Ravenna is indicated by filled purple circle.*

At the 500 hPa surface, there was one dominant geopotential height field and one dominant wind direction over the Adriatic Sea. Depression over the northern Europe occurred in 6 out of 10 events, closed low over the western Mediterranean Sea occurred in 3 events, and depression over the northwestern Asia occurred once. Wind blew from the southern directions in all events, SW in 6 events and S in 4 events.

Figure 20 depicts synoptic situation on February 19, 2010 at 15:00 UTC. At the surface, there was a mid-latitude cyclone centered in the Ligurian Sea, and S-SE wind was blowing at a 10 m height over the Adriatic Sea. At the 500 hPa surface, there was a depression over the northern Europe, and SW wind over the Adriatic Sea. All of these characteristics are representative for the dominant synoptic pattern.

6.5 Venice

Two characteristic mean sea level pressure fields and one dominant wind direction at 10 m above the Adriatic Sea were recognised. A mid-latitude cyclone was reproduced in 9 out of 10 events: at latitudes between 48 and 54°N (over the Atlantic Sea or western central Europe) in 4 events, over the western Mediterranean Sea in 4 events, and over the Atlantic Sea, but southern than usual (to the west of Portugal instead around the UK) in 1 event. In 1 event, there was a depression over the northern Europe. Mean sea level pressure minima for 9 events when a

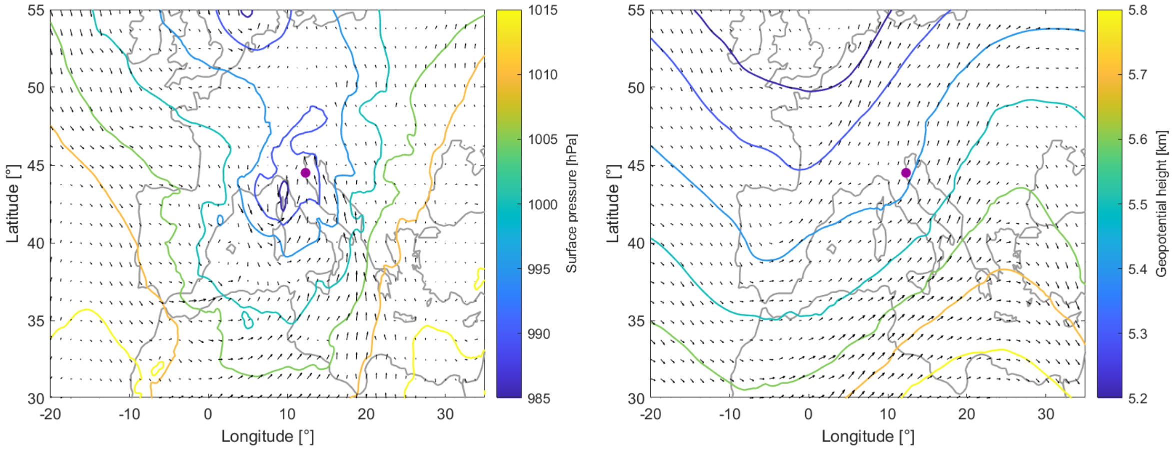


Figure 20: *Synoptic situation on February 19, 2010 at 15:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 17.87 m/s at 10 m and up to 48.76 m/s at the 500 hPa surface.*

mid-latitude cyclone was formed are indicated by rings in Figure 21. Wind in the Adriatic Sea usually blew from the southern directions (9 out of 10 events), most commonly SSE.

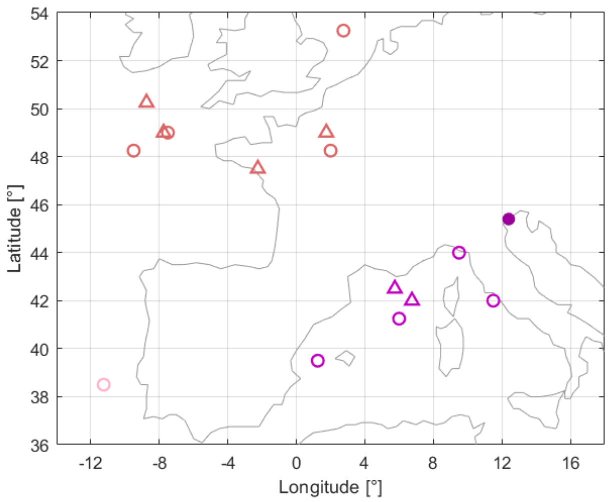


Figure 21: *Positions of mean sea level pressure and 500 hPa geopotential height minima corresponding to extreme residual sea levels in Venice. Rings indicate centers of cyclones at the surface: belt between 48 and 54° (dark pink), over the western Mediterranean Sea (purple) and over the Atlantic Sea, to the west of Portugal (light pink). Triangles indicate centers of closed lows at the 500 hPa surface: belt between 48 and 54° (dark pink), and over the western Mediterranean Sea (purple). Position of Venice is indicated by filled purple circle.*

At the 500 hPa surface, there were two different geopotential height fields and one dominant wind direction over the Adriatic Sea. Depression over the northern Europe occurred in 4 events. In other 6 events, a closed low was formed: at latitudes between 48 and 54°N (over the Atlantic Sea or western central Europe) in 4 events, and over the western Mediterranen Sea in 2 events. Figure 21 depicts locations of 500 hPa geopotential height minima for 6 events when a closed low was formed (indicated by triangles). Wind usually blew from the southern directions (9 events), most commonly from the SW (7 events).

Figure 22 depicts synoptic situation on December 24, 2009 at 21:00 UTC. At the surface, there was a cyclone centered over the northern France, and a 10 m SSE wind blew over the Adriatic Sea. This field represents one of the common pressure fields and the most common wind direction. At the 500 hPa surface, there was a depression over the Atlantic Sea and northern Europe, representative for one of the common fields. There was also a representative SW wind blowing.

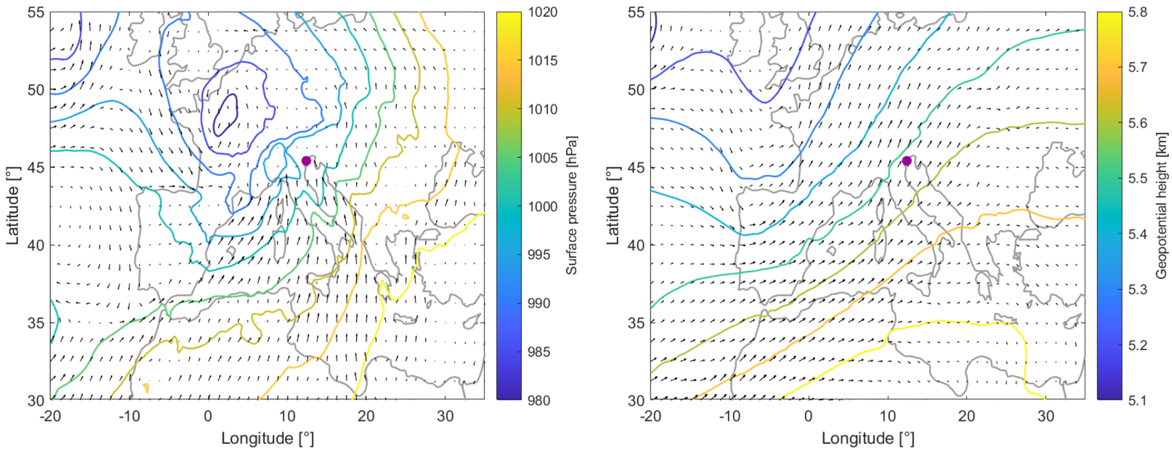


Figure 22: *Synoptic situation on December 24, 2009 at 21:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 16.37 m/s at 10 m and up to 43.54 m/s at the 500 hPa surface.*

Figure 23 depicts synoptic situation on November 16, 2002 at 11:00 UTC. At the surface, there was a mid-latitude cyclone over the Atlantic Sea, and at 10 m height SSE wind was blowing over the Adriatic Sea. This field represents one of the common pressure fields and the most common wind direction. At the 500 hPa surface, there was a closed low over the Atlantic Sea, and SW wind was blowing.

6.6 Case study: Atmospheric fields during December 22-25, 2009

During the period analysed in the thesis, extreme residual sea levels at different stations were several times caused by the same atmospheric conditions and thus occurred within a few hours at different stations. During 22-25 December 2009 two episodes of extreme sea levels were recorded at all stations except Valencia. Extreme residuals occurred first in Monaco on December 22 at 23:00 UTC and five hours later in Ravenna and Venice. After two days, extreme residual sea level occurred again in Monaco and Venice on December 24 at 22:00 UTC, an hour later in Ravenna, and finally on December 25 at 01:00 UTC in Naples.

Figure 24 shows mean sea level pressure and wind field from December 22, 2009 at 12:00

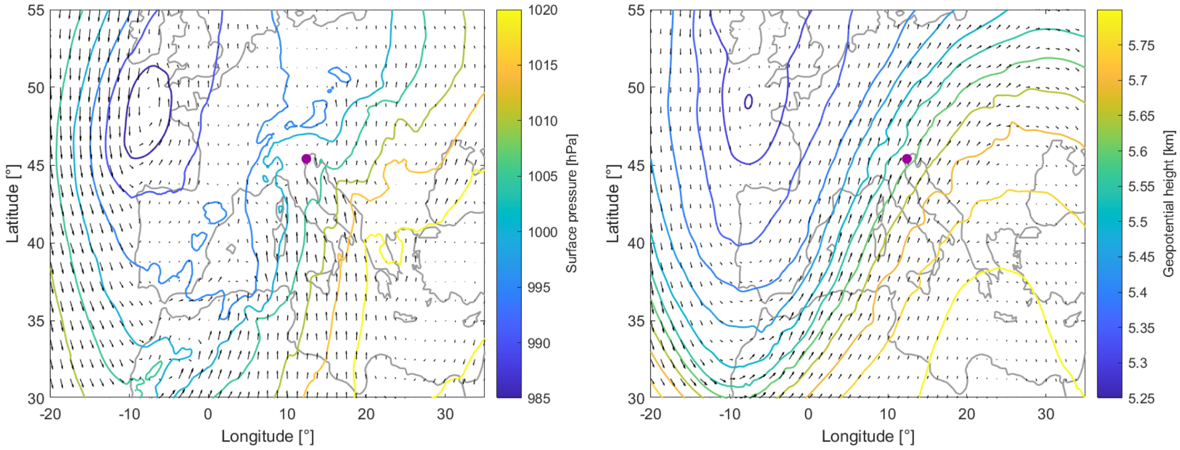


Figure 23: *Synoptic situation on November 16, 2002 at 11:00 UTC. Left figure depicts mean sea level pressure field and wind field at a 10 m height. Right figure depicts the 500 hPa geopotential height and wind. Winds speeds are up to 17.42 m/s at 10 m and up to 50.13 m/s at the 500 hPa surface.*

UTC, every 12 hours, until December 25, 2009 at 00:00 UTC. Initial mean sea level pressure field is characterized by a depression over the northern Europe, average pressure on the western portuguese coast, relatively weak winds over the Atlantic Sea, and strong southern winds over the area of interest in the Mediterranean Sea. Twelve hours later, a newly formed mid-latitude cyclone can be noticed over the Atlantic Sea - west of Portugal, with strong cyclonic winds. Over the area of interest (western Mediterranean and Adriatic), wind speeds remained approximately the same, but gained a more SW direction over the western Mediterranean Sea. At this time, extreme residual already occurred in Monaco, and was about to occur in Ravenna and Venice.

One day after the initial moment, at December 23, 2009 at 12:00 UTC, mean sea level pressure is characterized by a still present mid-latitude cyclone west of Portugal, and two newly formed closed lows, one centered slightly to the south of Ireland, and the other over the central Europe. Winds were a little weaker and had a uniform (S) direction over the entire area of interest. Twelve hours later, at December 24, 2009 at 00:00 UTC the mid-latitude cyclone to the west of Portugal had further strengthened, while the two lows weakened. Strengthening of the mentioned mid-latitude cyclone caused winds in the western Mediterranean and the Adriatic Sea to become stronger again and to turn to same directions as when extremes occurred for the first time: SW to the east of Corsica and Sardinia, S/SW between these islands and Italy mainland, and SE over the Adriatic Sea. Another twelve hours later, at December 24, 2009 at 12:00 UTC, the mid-latitude cyclone is found over the Atlantic, north of Spain, and west of France, with surface winds blowing in similar directions as 12 hours earlier. Finally, the last moment (December 25, 2009 at 00:00 UTC) is captured two hours after extreme residuals in Monaco and Venice, one hour after extreme residual in Ravenna, and one hour before extreme residual in Naples. At this time, the mid-latitude cyclone had propagated further northeast and was centered over France. Wind kept a favorable direction for inducing sea level extremes at

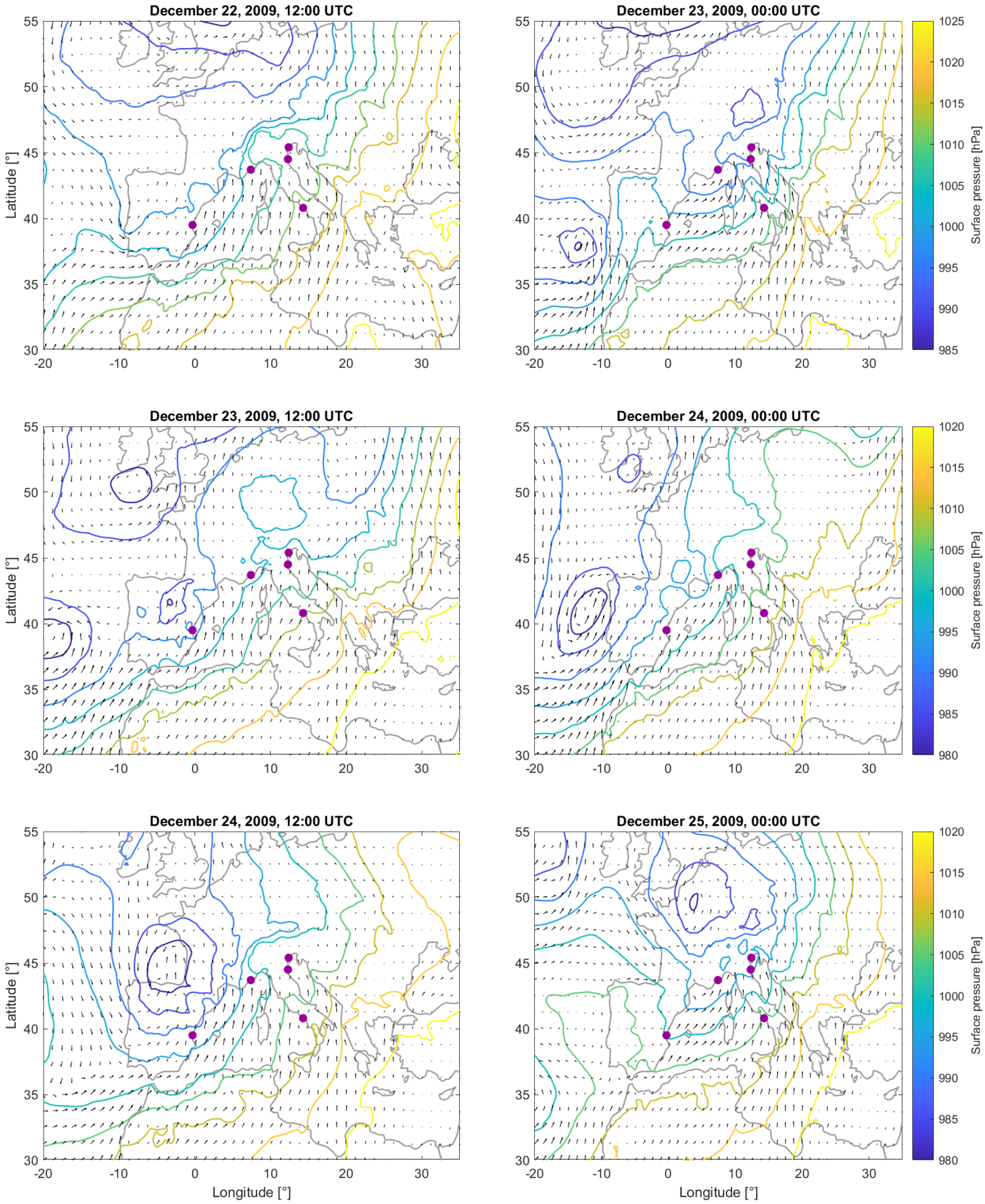


Figure 24: *Mean sea level pressure and 10-m wind fields pertinent to simultaneous extreme events at 4 out of 5 stations. Wind speed is up to 21.72 m/s for December 23 at 00:00 UTC. Positions of stations are marked with filled purple circles, and station names are given in Figure 1.*

studied locations.

Figure 25 shows 500 hPa geopotential height and wind field for the same period and with the same time step, as in Figure 24. During the entire period strong SW winds were blowing over the western Mediterranean and the Adriatic Sea.

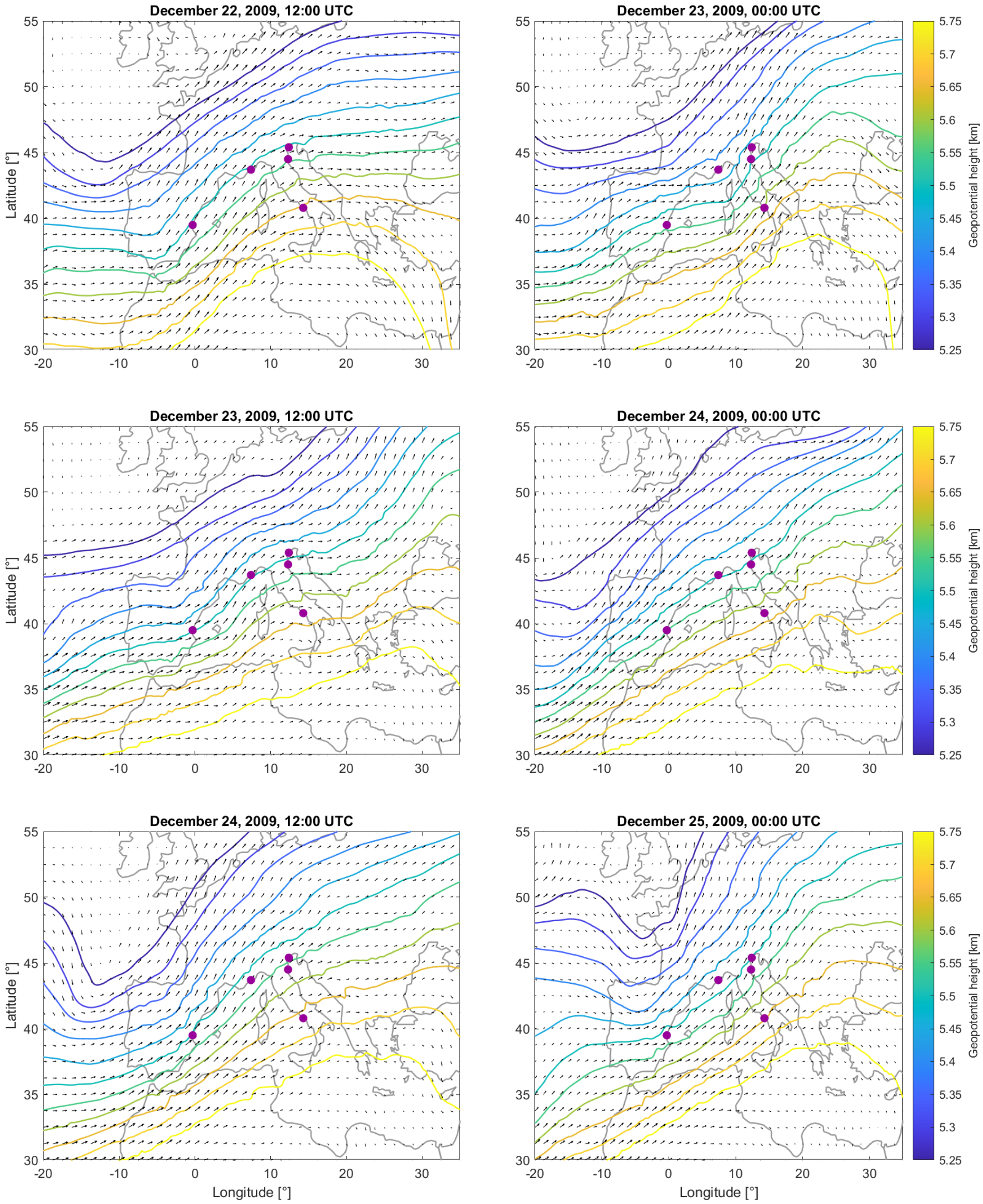


Figure 25: *Geopotential height and wind fields at the 500 hPa pressure surface pertinent to simultaneous extreme events at 4 out of 5 stations. Wind speed is up to 51.66 m/s - reproduced for December 23 at 12:00 UTC. Positions of stations are marked with filled purple circles, and station names are given in Figure 1.*

Residual sea level series for all stations from December 22 at noon until December 25 at 03:00 UTC are shown in Figure 26. There are three peaks for series in Venice and Ravenna, with the first likely representing a storm surge and subsequent ones the Adriatic seiche, again intensified by a surge on December 24-25. Maxima are less obvious for other three stations.

During the first event in these few days (around midnight of December 23), extreme residual occurred in Monaco, Ravenna and Venice. Extreme event occurred in Ravenna again during the period of not so strong atmospheric forcing (around midnight of December, 24), and then again in Monaco, Venice, Ravenna and Naples around midnight of December, 25. The figure also clearly depicts the well known fact that the positive sea level extremes are strongest over the northern Adriatic [3].

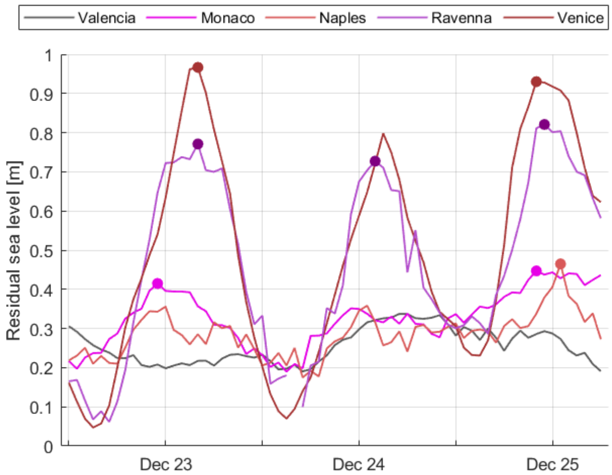


Figure 26: *Residual sea level series from December 22 at 12:00 UTC until December 25 at 03:00 UTC. Grid lines on x axis correspond to time steps in Figures 24 and 25, and dates are denoted at 00:00 UTC. Circles indicate maxima of extreme residuals for which synoptic analysis was performed in this chapter of the thesis.*

7 Discussion and conclusions

The purpose of this thesis was to examine events of extreme residual sea levels across the western Mediterranean and the Adriatic Sea: firstly, to provide temporal distribution and average duration of these events during the period from 1984 to 2014, and, secondly, to analyse the preceding synoptic situations and to extract characteristic synoptic patterns related to these events.

Figures 10 and 11, and Table 4 show that most extreme events occur during period from October to February. The most common wind field during this period includes NW winds over most of the Mediterranean Sea and NE winds in the Adriatic Sea [2]. Wind fields pertinent to extreme events, analysed in Chapter 6 of this thesis, differ from this pattern, which proves an intuitive assumption that extreme residual sea levels are observed during unusual atmospheric conditions.

Extreme sea level events are always related to a low mean sea level pressure field in the area, whether a mid-latitude cyclone or a depression. The result is expected because of the inverse barometer effect - lower atmospheric pressure leads to higher sea levels. [12] In this research, mid-latitude cyclone was more common, usually to the west of a certain station, as found for Naples, Ravenna and Venice. As of Valencia and Monaco, a mid-latitude cyclone was found to be centered over the sea and near the station.

Wind at a 10 m height related to extreme sea level events usually blew towards the coast. This is also expected, because it is known that strong onshore winds coupled with low mean sea level pressure field may cause storm surges. [13] It is important to notice, however, that extreme sea level events examined in this research do not necessarily represent the strongest storm surge events because they were extracted from residual time series, after removing tides, i.e. total sea level during any particular event might have been higher or lower (Figure 8).

At the 500 hPa surface, geopotential height field was characterised by depressions more often than by closed lows. These depressions were most often over the northern Europe, as found for Naples, Ravenna and Venice. Monaco events were also associated to depressions more often than to closed lows, with depressions usually located over the central Europe. Valencia is the only station where closed lows were more common at the 500 hPa geopotential height than depressions, with centeres of the closed lows usually located to the south of the station. Winds at the 500 hPa surface were commonly blowing from the southern directions during extreme sea level events at all stations.

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