North-Atlantic Oscillation and regional-scale sea-surge variability in Gulf of Lions during the 20th century

A. Ullmann[1] (a), V. Moron (b,c,d,e)

(a) Centre de Recherches de Climatologie. UMR-5210. Université de Bourgogne, faculté
des sciences Gabriel, 6 Bd Gabriel, 21000 Dijon

(b) UFR des Sciences Géographiques et de l'Aménagement
Université de Provence, Aix-Marseille I.

(c) CEREGE, UMR 6635 CNRS

(d) International Research Institute for Climate and Society. The Earth Institute at
Columbia University, Palisades, New York

(e) Institut Universitaire de France, Paris

Submitted to *Journal of Climate*

January, 2010

---

[1] Corresponding author: Albin Ullmann, Centre de Recherches de Climatologie. Université de Bourgogne, Dijon.
Mail: albin.ullmann@u-bourgogne.fr

Abstract

Sea-surge variations recorded at three tide-gauge stations (Grau-de-la-Dent, Sète, and Port-Vendres) around the Gulf of Lions (Northwest Mediterranean Sea) are mostly locally forced by onshore winds blowing from 90° to 180° related to an atmospheric depression usually centered between the Bay of Biscay and the British Island, which is more prevalent during the negative phase of the North-Atlantic Oscillation (NAO). During the second half of the 20th century, the long-term increase of sea-surge height at Grau-de-la-Dent finds no counterpart in the positive deviation of the NAO. The relationship between the monthly frequency of sea surges > 20 cm at Grau-de-la-Dent and the monthly mean NAO Index significantly strengthens from 1975. This is synchronous with the eastward shift of the two main centers of the NAO (i.e. Iceland low and Azores high) and an increase of the occurrence of depressions near the Bay of Biscay and of surge-related onshore winds in the Gulf of Lions during negative phases of the NAO.

Key words: sea surge, wind conditions, North-Atlantic Oscillation, Mediterranean Sea, multi-decadal variations.

1. Introduction

In deltaic areas, vulnerability of low coastal areas to short and long-term rises in sea level is particularly high (Nicholls and Hoozemans, 1996). Recent climatic models summarized by the Intergovernmental Panel on Climate Change (IPCC) have predicted a significant warming and global sea-level rise for the 21st century (IPCC, 2007), which is expected to increase the flooding risk along low coasts. In low lying areas, as most of the Gulf of Lions (Northwest Mediterranean Sea, figure 1), strong storm surges can cause flooding and damages. The predominant forcing of flooding risk is related to atmospheric variability (Tsimplis and Josey, 2001; Trigo and Davies, 2002; Wakelin *et al.*, 2003; Tsimplis *et al.*, 2005), including extra-tropical storms (Heyen *et al.*, 1996; Bouligand and Pirazzoli, 1999; Bouligand and Tabeaud, 2000; Pirazzoli, 2000; Pasaric and Orlic, 2001; Svensson and Jones, 2002; Moron and Ullmann, 2005; Ullmann *et al.*, 2007b). The atmospheric forcing leads to a sea surge defined as the difference between the observed sea level and the astronomical tide at the same moment. It is therefore important to better understand the regional and local trends of sea surges and of the associated atmospheric forcing factors.

When each sea surge is considered, the primary forcing is associated with the passage of extra-tropical storms (Pirazzoli, 2000; Pasaric and Orlic, 2001; Trigo and Davies, 2002; Moron and Ullmann, 2005). Travelling mid-latitude low pressure systems act to raise the sea level below them. But the Gulf of Lions (figure 1) is not on the main storm track of the North Atlantic domain (Alpert *et al.*, 1990; Rogers, 1997) and the amplitude of sea level pressure (SLP) variations is reduced relative to the extra-tropical North Atlantic. The most important atmospheric factor is therefore the onshore wind associated with moving mid-latitude low-pressure systems (Ullmann et al., 2007b).

In the context of long-term increase in the frequency and intensity of sea surges in the Northern Mediterranean Sea (Pirazzoli and Tomasin, 2002; Ullmann et al., 2007a), the purpose of our paper is to analyse sea-surge variations around the Gulf of Lions, their local-scale related-winds and their relationships with the North Atlantic Oscillation (NAO). The NAO is one of the major modes of variability in the Northern Hemisphere atmosphere and significantly affects the climate of the North-Atlantic and Europe (Wakelin et al., 2003). Through relationship between the NOA and extra tropical atmospheric circulation, the NAO impacts on many regional/local meteorological parameters, such as wind, pressure and precipitation (Hurell, 1995; Merkel and Latif, 2002). With regards to these considerations, we expected that long-term variability of the NAO leads to changes in regional-scale atmospheric circulation and sea surges in the Gulf of Lions. In the context of climate change and its impact on extreme events, the main goal of our paper is (i) to explore long-term relationship between the NAO's atmospheric variability and sea surges in the Gulf of Lion and (ii) to explain how changes in the NAO's mean conditions affect this relationship over the 20th century.

Atmospheric forcing of sea surges in the Gulf of Lions, from local winds to NAO's atmospheric conditions and their connections are firstly analysed. The relationship between NAO and sea surges in the Gulf of Lions is then analysed over the long-term (1905-2002). Connection between changes in the NAO and long-term sea-surge variability is finally analysed through possible modifications in extratropical stormtracks and winds conditions in the Gulf of Lions.

2. Data and methods

2.1. Sea surges

As the highest sea surges in the Gulf of Lions may be of the order of one metre (Pirazzoli et al., 2007) and occur mainly winter, the October to March period is analysed for all variables and referred to "winter" hereafter (Ullmann, 2008). This work analyses the hourly time series of sea surge height measured at three tide-gauge stations along the Gulf of Lion: Grau-de-la-Dent – GD – (43.36° N – 4.67° E), Sète – SE –(43.40° N – 3.70° E) and Port-Vendres – PV – (42.52° N – 3.11° E) (figure 1) from October 1986 to March 1995 (Ullmann et al., 2005). These time series have been produced through the digitization of the original paper records of sea levels using an integrated and automated tool kit for digitization, transformation and validation of marigrams called NUNIEAU (Ullmann et al., 2005). Sea level measured at 6 a.m is also available from 1905 to 2002 at GD tide-gauge station. Data are missing from 1 October 1915 to 31 March 1916 and from 1 October 1962 to 31 March 1974. Also, monthly mean revised local reference (RLR) sea level data at Marseille (MA; 43.28°N – 5.35°E) have been extracted from the permanent Sea Level database from 1905 to 2002 (Woodworth and Player, 2003; figure 1). The tide-gauge station is located at Endoume on a north-south rocky coast on the eastern side if MA's bay (figure 1). All sea level data are expressed in hours UTC+0 and are relative to the same altimetric reference, i.e. the Nivellement Général de la France (NGF)

The hourly and daily astronomical tide at GD, SE and PV has been computed with the POLIFEMO software (Tomasin, 2005). POLIFEMO performs a least-square fit for the available data with seven constituents, i.e. M2, S2, N2, K2, K1, O1, P1 (referring to "mean lunar period", "mean solar period", "major elliptic lunar period", "luni-solar declinational semi-diurnal period", "luni-solar declinational diurnal period", "major lunar period", "major solar period", respectively). The interannual variability of the tidal components is taken into account. The local astronomical tide is removed from the sea level height to obtain the sea surge component (Ullmann et al., 2007a; Ullmann and Moron, 2008). The problem of the just-mentioned year-to-year variation led to the decision to separate the problem of the mean sea-level (MSL) trend and the problem of isolated spikes (surges). The sea-level change can be estimated using the yearly means, but the surges are better measured and appreciated by referring to such annual averages. The different climatic aspects estimated this way are kept independent as much as possible.

2.2. Sea-level pressure

The mean SLP available from National Centre for Atmospheric Research (NCAR) at 1 p.m UTC from 1 October 1905 to 31 December 1939 and at noon UTC from 1 January 1940 to 31 March 2002 has been extracted from the NCAR web site (http://dss.ucar.edu/). No attempt has been made neither to fill the missing entries in the NCAR data nor to remove the seasonal cycle. The SLP data are standardized to zero mean and unit variance. The SLP data are not available at the exact time of sea surge records, but the weather regimes are persistent large-scale patterns and it is expected that the one observed at noon or 1 p.m is usually the same as 6 a.m. The daily North Atlantic Oscillation Index time series (NAOI) defined as the difference between the SLP anomalies at Gibraltar minus those at Reykjavik (Jones et al., 1997) has been computed from 1905 to 2002.

2.3. Wind

Three-hourly wind direction and speed measurements at PV (1949-2003), SE (1949-2003) and Cap Couronne – CC – (1961-2003) (43.33° N – 5.05° E) were provided by Météo-France. Wind directions are recorded in 20° increments calculated clockwise from the geographical North and correspond to the average direction from which the wind blows during 10 minutes before recording. Wind speed corresponds to the average speed (in m/s) and is measured over the same time interval as the direction.

3. Results

3.1. Sea surge-related wind and atmospheric circulation

For each hourly sea surge > 20 cm at GD, SE and PV, the frequency of local wind direction has been computed at the nearest meteorological station from 3 hours before the sea surge. Results are presented as a wind compass (figure 2b). More than 80% of sea surges > 20 cm are associated with south to southeast onshore winds, blowing from 90° to 180° (figure 2b). More precisely, sea surges at GD and SE (PV) are associated with winds blowing mostly from 100°-120° (120°-180°) (figure 2). For each station, the mean frequency of winds blowing from 90° to 180° during sea surges > 20 cm is significantly higher than the climatology (figure 2a) over 99% level of confidence with a Student's T test. But over 20% of local sea surges > 20 cm at PV are also associated with northerly winds from 320°-340° (figure 2b) due to the local direction of the coast, northwestward opened on the Mediterranean Sea (Ullmann et al., 2007b). To summarize, sea-surges in the Gulf of Lions are mainly regional-scale events (Ullmann and Moron, 2008), associated with southeasterly onshore winds blowing in the whole Gulf of Lions that cause to pill up the water toward the coasts (figure 1).

Figure 3 shows the mean daily frequency of SLP < 1000 hPa for each 5° grid point over 40°W-40°E and 30°N-70°N when daily sea surges synchronously reaches 20 cm at the three tide-gauge station. During sea surges, low pressures are almost never located over Central Europe (figure 3) and are mostly concentrated on the near Atlantic between the Bay of Biscay and British Islands (figure 3). Moreover, less than 5% of sea surges > 20 cm at the three tide-gauge stations are associated with SLP < 1000 hPa over the Gulf of Lions (figure 3). Sea surge at GD, SE and PV don't seem to be favoured by low pressure systems acting in the Gulf of Lions but rather by atmospheric depression centred between the Bay of Biscay and British Islands. These results are fully consistent with those obtained by Moron and Ullmann (2005), with sea surges at GD associated with a strong E-W barometric gradient over the Gulf of Lions between low pressure near the Bay of Biscay and high pressure over Central Europe leading to strong onshore winds blowing in the whole Gulf of Lions.

3.2. Sea surges and NAO

3.2.1. Sea surges and NAO: mean relationship

Figure 4 shows the daily mean NAOI relative to sea-surge heights for different thresholds at the three stations. Lowest sea surges (< 20 cm) are mainly associated with a weak positive NAOI (figure 4), but not significantly different from the mean NAOI of the 1986-1995 period with a Student's T test. Sea surges > 20 cm are mostly associated with negative NAOI (figure 4). Mean daily NAOI for sea surge > 20 cm is significantly more negative than the mean NAOI of the 1986-1995 period with over 99% level of confidence with a Student's T test. Highest daily sea surges (> 40 cm) at the three tide-gauge station are associated with strong negative daily NAO's phase (figure 4), meaning that the probability of strong southerly winds and sea-surges in the Gulf of Lion increase with the negative deviation of the NAO (Ullmann, 2008).

Moreover, the monthly frequency of daily sea surges > 20 cm has been computed for NAOI by class of 5 hPa and compared to the monthly mean frequency of the period 1986-1995 (figure 5a). The same methodology has been used for surge-related onshore winds (90°-180°) at the three meteorological stations (figure 5b) and for low pressure < 1000 hPa between the Bay of Biscay and the British Islands ([15°W-0°W], [40°N-45°N]) (figure 5c). The positive (negative) anomaly of frequency of sea surges > 20 cm, onshore winds in the Gulf of Lions and low pressure < 1000 hPa around the Bay of Biscay clearly increases (decreases) when the negative (positive) anomaly of NAOI strengthened (figure 5a,b,c). From NAOI > 5 hPa and NAOI < -5 hPa, monthly mean frequency of each considered parameter is always significantly different compared to the mean of the 1986-1995 period, with over 99% level of confidence with a Student's T test. In fact, negative phases of the NAO potentially favour a southward shift of the main stormtrack over the Northern Atlantic leading to more prevalent regional-scale onshore winds in the Gulf of Lion (Rogers, 1997; Ullmann et al., 2007b).

Between extreme positive (+15 hPa) and negative (-20 hPa) monthly mean NAOI, the related anomaly of frequency of daily low pressure around the Bay of Biscay ranges from -10% to +20% relatively to the mean (figure 5c). When sea surges > 20 cm and regional-scale onshore winds in the Gulf of Lions are considered, anomaly of the frequency only differs from -5 % to +5 % (figure 5a-b). It means that there is considerable variability in wind conditions and sea surges in the Gulf of Lions for each phase of the NAO Moreover, the daily NAOI (monthly mean NAOI) is significantly correlated with the daily sea-surge height (monthly frequency of sea surges > 20 cm) at each station but the common variance don't exceed 20 % (36 %) on the 1986-1995 period and 15% (18%) on the whole 20th century (table 1). In fact, sea surges in the Gulf of Lions are connected with the NAO through several modes of atmospheric circulation acting at different spatio-temporal scales, such as extratropical storms and regional-scale wind conditions. In other words, negative phase of the NAO favoured sea surges at the three tide-gauge stations but each daily negative NAOI is not always associated with low pressure around the Bay of Biscay and therefore with regional-scale onshore winds in the Gulf of Lions. To summarize, through the relationship between the NAO's atmospheric variability, extratropical storms and regional-scale winds, a monthly mean NAOI indicates the surge-occurrence probability in the Gulf of Lions.

3.2.2. Sea surges and NAO: inter-annual to multi-decadal variability

The wintertime mean NAOI and 90th percentile of sea-surge height (P90) at GD station have been computed from 1905 to 2002 (figure 6). Wintertime P90 of sea-surge height increases during the 20th century with a mean speed of + 0.31 mm/year with a level of confidence > 99% according to a random-phase test (Janicot et al., 1996; Ebisuzaki, 1997). The wintertime frequency of sea surges > 20 cm also increased during the 20th century (Ullmann et al., 2007a). Increase in sea-surge heights and frequency could be partly associated with the increase of the frequency and speed of southerly winds in the Gulf of Lions (Ullmann et al., 2007a; Ullmann et al., 2007b; Ullmann and Pirazzoli, 2007). The wintertime mean NAOI shows a slow negative deviation from 1905 to 1970 when the most negative NAOI is reached (figure 6). From 1970, the wintertime mean NAOI shows a positive deviation until 1990 (figure 6; Rodwell et al., 1999; Cassou et al., 2004). Following the correlation between the monthly frequency of sea surges > 20 cm at the three tide-gauge stations and the monthly mean NAOI (section 3.2.1), the positive deviation of the NAO from 1970 should be associated with a decrease of the frequency of sea surges. But as observed in the second half of the 20th century, the wintertime P90 of sea-surge height at GD slightly increases (figure 6) as well as the frequency of sea surges > 20 cm (Ullmann et al., 2007a; Ullmann, 2008).

Figure 7 shows the running correlation between the monthly mean NAOI and the monthly frequency of sea surges > 20 cm at GD station (figure 7a) and the monthly mean sea level at MA (figure 7b) over periods of 60 months (10 years) from 1905 to 2002. A monthly time scale is chosen here to increase the sample size. The correlation between the monthly mean NAOI and the monthly frequency of sea surges > 20 cm at GD is not stable and shows a considerable fluctuation (figure 7a). The highest correlation coefficients are found around the period 1975-2002 (figure 7). Moreover, synchronous strengthening of the relationship since 1975 is observed between the monthly mean NAOI and the monthly mean sea level at MA, located 40 km eastward from GD (figure 7b). Such strengthening of the relationship have been also observed between winter mean NAO and winter mean sea level at Brest, in the Atlantic coast of France, and in the North Sea and in the Baltic Sea (Anderson, 2002; Wakelin et al., 2003; Jevrejeva et al., 2005). Moreover, the same results have been found using the Arctic Oscillation (Jevrejeva et al., 2005). The highest (lowest) correlation coefficients between the NAO and sea level in the Mediterranean Sea and along the Western European coastal area are always found during the last (first) 30 years of the 20th century (Wakelin et al., 2003; Jevrejeva et al., 2005). The fact that that the relationship is not stable at different stations indicates that other processes, not encompassed by the NAOI, are important and may have change over time (Jevrejeva et al., 2005).

The variation of the relationship between sea surge and NAO could be partly explained by several factors. Firstly, low frequency variability in running correlations, particularly between indices of interannual modes of climatic variability may be affected by pure stochastic processes (Gershunov et al., 2002). A statistical test is performed for measuring the probability to achieve the deviations amongst the correlation computed on two sub-periods: period 1905-1962 and 1974-2002. Time series of monthly mean NAOI and monthly frequency of daily sea surges > 20 cm at GD station are randomly permuted by pairs 1000 times and the correlations are recomputed on the two sub-periods. The standard deviations of the two correlations are sorted in ascending order and the observed standard deviation is compared with this distribution. The standard deviation of the correlation between the monthly mean NAOI and monthly frequency of sea surges > 20 cm at GD station is outperformed by less than 2 % of the permuted pairs. Results are almost similar when the correlation between monthly mean NAOI and monthly mean sea level at MA is considered. Secondly, the reliability of the sea level recorded at GD and MA should be questioned, but excepted from the period 1915-1925, daily sea-surge height time series at GD is considered as a reliable record (Ullmann and Moron, 2008) as well as the monthly mean sea level height time series at MA (Woodworth and Player, 2003). To summarize, the strengthening relationship between NAO and sea surges in the Gulf of Lions is not associated with pure stochastic processes or data reliability.

3.2.3. Changes in the mean NAO's atmospheric conditions and surge-related atmospheric circulation

Changes in the mean atmospheric conditions of the NAO can modify atmospheric circulation at smaller spatial scale than the NAO and increase the frequency of sea surges along the European coastal areas (Omstedt and Chen, 2001; Jevrejeva et al., 2005). The variation of the relationship between NAO and sea surges could be associated with atmospheric variability. Wakelin *et al.* (2003) hypothesized that the intensification of the correlation between winter mean sea level and NAO along the coast of western Europe could be partly explained by an eastward shift of the largest SLPA (SLP anomaly) related to the NAO. In fact, since 1975, the two main poles of barometric anomaly that are used to define NAO indexes (i.e Azores high and Iceland low) tend to displace and enlarge eastwards (Wakelin *et al.*, 2003; Ullmann, 2008). Compare to the first half of the 20th century, sea-level pressure anomalies intensified in the Barents Sea region and over the Iberian Peninsula since 1975, whereas sea-level pressure anomalies decreased further westward (Ullmann, 2008).

Possible impact of long-term SLP changes in the NAO is tested here for surge-related atmospheric circulation in the Gulf of Lions. Figure 8a shows the running correlation between the monthly mean NAOI and the monthly frequency of low pressure < 1000 hPa between the Bay of Biscay and the British Islands ([15°W-0°W], [40°N-45°N]) over periods of 60 months from 1905 to 2002. The same running correlations have been also computed between the monthly mean NAOI and the monthly frequency of E-W SLP gradient > 10 hPa between high pressure over Central Europe ([15°E-30°E], [40°N-50°N]) and low pressure around the Bay of Biscay ([15°W-0°W], [40°N-45°N]) (figure 8b). Relationship is not stable and highest correlation coefficients are observed on the period 1975-2002 (figure 8), synchronous with the highest correlation between the monthly mean NAO and the monthly frequency of sea surges > 20 cm at GD station. On the period 1975-2002, the correlation coefficients are significantly stronger than in the period 1905-1975 with the same statistical test used in section 3.2.2. In other words, eastward shift of the NAO's two main SLPA has increase the occurrence of low pressure around the Bay of Biscay and strong E-W barometric gradient over the Gulf of Lions during negative phase of the NAO (Ullmann, 2008).

The NAO's atmospheric variability exerts its influence on sea level variations mostly by modifying wind directions at regional scale (Wakelin et al., 2003). At regional-scale in the Gulf of Lions, the correlation between the monthly mean NAOI and the monthly frequency of surge-related southerly winds strongly increase since 1975 with a level of confidence over 99% with the same statistical test used in section 3.2.2 (figure 9). This stronger relationship is synchronous with the increase of the correlation between the monthly mean NAOI and (i) the monthly frequency of low pressure around the Bay of Biscay and (ii) the monthly frequency of sea surges > 20 cm at GD station. Moreover these strengthening relationships between NAO and atmospheric circulation at synoptical-scale and regional-scale are synchronous with the eastward shift of the two main NAO's SLPA (Wakelin *et al.*, 2003; Ullmann, 2008).

These changes in the relationship between NAO and atmospheric circulation at smaller spatial scale than the NAO could modify the sensivity of sea surges at GD during negative phase of the NAO. This is illustrated on figure 10. The pair of monthly frequency of daily NAOI < 0 and monthly 75th percentiles of daily sea surge on running 10 years periods is ordered according to the frequency of NAOI < 0. The means, corresponding to the lower (i.e. less daily NAOI than 10 year mean) and upper (i.e. more daily NAOI < 0 than 10 year mean) halves are the computed. The difference of the mean 75th percentiles of daily sea surge between both samples is close to zero around 1915-1925 (figure 10) and could be partly associated with a possible inconsistency of the GD records (Ullmann and Moron, 2008). The mean 75th percentiles of sea surge associated with more NAOI < 0 than decadal mean increases since 1975 (figure 10), synchronous with the eastward shift of the two main NAOS's SLPA, while the mean 75th percentiles of sea surge associated with less NAOI < 0 is almost stationnary from around 1950 (figure 10). Changes in the mean atmospheric conditions of the NAO since 1975 have increased the probability of surge-related atmospheric circulation at smaller spatial scales during negative phase of the NAO. To summarize, the eastward shift of the two main NAO's SLPA since 1975 has increased the surge occurrence probability in the Gulf of Lions during negative phases of the NAO.

Conclusion

Sea surge in the Gulf of Lions are mostly associated with onshore winds blowing from 90°-180° and linked with a strong E-W barometric gradient between low pressure around the Bay of Biscay and high pressure over central Europe. This atmospheric circulation is favoured by the negative phase of the NAO leading to a southerly shift of the main stormtrack over the Northern Atlantic. However, there is a considerable variability of sea surges in the Gulf of Lions relative to the mean for each negative NAOI meaning that all NAO's negative deviations are not always associated low pressure around the Bay of Biscay and onshore winds in the Gulf of Lion. However, monthly mean NAOI is significantly correlated with monthly frequency of sea surges > 20 cm at the three tide-gauge stations in the Gulf of Lions.

Following this relationship, the positive deviation of the wintertime mean NAOI from 1970 to 1990 should be associated with a decrease of the frequency of sea surges in the Gulf of Lions. But the wintertime 90% percentile of sea surge height and the wintertime frequency of sea surges > 20 at GD station slightly increase in the second half of the 20th century. Since 1975, eastward shifts of the two main barometric anomalies that are used to define NAO index (i.e. Azores high and Iceland low) have increased the occurrence probability of low pressure around the Bay of Biscay and of surge-related regional-scale onshore winds in the Gulf of Lions during NAO's negative phase.

Most of climate models predict a positive deviation of the NAO for the next century and for the most part of climate change scenarios (Paeth et al., 1999; Cassou et al., 2004). This NAO's atmospheric variability would have an influence on sea surges in the Gulf of Lions mostly by modifying wind directions and speed at regional scale. However, as shown in the 20th century, future changes in the mean NAO's atmospheric patterns could also modify the relationship between regional-scale meteorological conditions and NAO's atmospheric variability.

Acknowledgments

This study is partly funded by the French Ministry of Ecology and Sustainable development under the IMPLIT (GICC-2) contract. F. Sabatier kindly provided to us the raw sea level time series of GD. We thank A. Tomasin for the extraction of sea surge time series of GD. NCAR are gratefully acknowledged for providing the NCAR sea-level pressure data.

References

Alpert P., Neeman B.U., El-Shay Y., 1990: Climatological analysis of Mediterranean cyclones using ECMWF data. *Tellus*, 42A, 65-77.

Anderson H.C., 2002: Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea-level. *Tellus*, 54A, 76-88.

Bouligand R., Pirazzoli P.A., 1999: Les surcotes et les décotes marines à Brest, étude statistique et évolution. *Oceanologica Acta,* 22, 153-166.

Bouligand R., Tabeaud M., 2000: Les surcotes à Brest depuis un siècle : analyse des paramètres météorologiques influents à l'échelle locale. *Norois,* 47, 201-217.

Cassou C., Terray L., Hurrell J., Deser C., 2004: North-Atlantic winter climate regimes: spatial asymmetry, stationarity with time and Ocean forcing. *Journal of Climate*. 17, 1055-1058.

Ebisuzaki W., 1997: A method to estimate the statistical significance of a correlation when the data are serially correlated. *J. Climate*, 10, 2147-2153.

Guershunov A., Schneider N., Barnett T.P., 2002: Low frequency modulations of the ENSO-Indian rainfall relationship: signal or noise ? *Journal of Climate*. 14, 2486-2492.

Heyen H., Zorita E., von Storch H., 1996: Statistical downscaling of monthly mean North-Atlantic air pressure to sea level anomalies in the Baltic sea. *Tellus*, 48A, 312-323.

Hurrell J.W., 1995: Decadal trends of the North Atlantic Oscillation: Regional temperatures and precipitation. *Science*, 269, 676-679.

IPCC, 2007. Climate change 2001: the scientific basis. Cambridge Univesity Press, Cambridge, 881 p.

Janicot S., Moron V., Fontaine B., 1996: Sahel droughts and ENSO dynamics. *Geophys. Res. Lett.*, 23, 515-518.

Jevrejeva S., Moore J.C., Woodworth P.L., Grinsted A., 2005: Influence of large scale atmospheric circulation on European sea level: results based on the wavelet transform method. *Tellus*, 57A, 183-193.

Jones P.D., Jónsson T., Wheeler D., 1997: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *Int. J. Climatol.* 17, 1433-1450.

Merkel U., Latif M., 2002: A high resolution AGCM study of the El Niño impact on the North American/European sector. *Geophysical Research Letters*, 29, 1029-1032.

Moron V., Ullmann A., 2005: Relationship between sea-level pressure and sea level height in the Camargue (French Mediterranean coast)*, Int. J. Climatol.*, 25, 1531-1540.

Nicholls R.J., Hoozemans F.M.J., 1996: The Mediterranean vulnerability to coastal implications of climate change, *Ocean and Coastal Management*, 31, 105-132.

Omstedt A., Chen D., 2001: Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. *Journal of Geophysical Research*, 106, 4493-4500.

Paeth H., Hense A., Glowienka-Hense R., Voss S., Cubash U., 1999: The North-Atlantic Oscillation as an indicator for greenhouse-gas induced regional climate change. *Climate dynamics*. 15, 953-960.

Pasaric M., Orlic M., 2001: Long-term meteorological pre-conditionning of the North Adriatic coastal floods. *Continental Shelf Research*, 21, 263-278.

Pirazzoli P.A., 2000: Surges, atmospheric pressure and wind change and flooding probability on the Atlantic coast of France. *Oceanologica Acta,* 23, 643-661.

Pirazzoli P.A., Tomasin A., 2002: Recent evolution of surges-relatd events in the northern Adriatic Sea. *Journal of Coastal Research*, 18, 537-554.

Pirazzoli P.A, Tomasin A., Ullmann A., 2007: Extreme sea levels in two northern Mediterranea areas. *Méditerranée*. 108, 59-68.

Rodwell M.J., Rowell J.P., Folland J.P., 1999: Oceanic forcing the wintertime North-Atlantic Oscillation and European Climate. Nature, 58, 322-323.

Rogers J.C., 1997: North Atlantic storm track variability and its association to both North Atlantic oscillation and climate variability of Northern Europe. *J. Climate*, 10, 1635-1647.

Svensson C., Jones D.A., 2002: Dependence between extreme sea surge, river flow and precipitation in eastern Britain. *Int. J. Climatol.,* 22, 1149-1168.

Tomasin A., 2005: The Software “Polifemo” for tidal Analysis, *Tech. Note* 202, ISMAR-CNR, Venice, Italy.

Trigo I.F., Davies T.D., 2002: Meteorological conditions associated with sea surges in Venice: A 40 year climatology. *Int. J. Climatol.,* 22, 787-803.

Tsimplis M.N., Josey S.A., 2001: Forcing of the Mediterranean sea by atmospheric oscillations over the North Atlantic, *Geophys. Res. Letters*, 28, 803-806.

Tsimplis M.N., Alvarez-Fanjul E., Gomis D., Fenoglio-Marc L., Perez B., 2005: Mediterranean sea level trends: atmospheric pressure and wind contribution. *Geophys. Res. Letters*, 32, doi:10.1029/2005GL023867.

Ulbrich U., Christoph M., 1999: A shift of the NAO and increasing strom track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate dynamics*, 15, 551-559.

Ullmann A., Pons F., Moron V., 2005: Tool kit helps digitize tide gauge records, *EOS transactions*. 86, 342.

Ullmann A., Pirazzoli P.A., Tomasin A., 2007a: Sea surges in Camargue (French Mediterranean coast): evolution and statistical analysis on the 20th century. *Continental Shelf Research*. 27, 922-934.

Ullmann A., Pirazzoli P.A, Moron V., 2008b: Sea surges around the Gulf of Lions and atmospheric conditions. *Global and Planetary Change* 63, 203-214.

Ullmann A., Moron V., 2008: Sea surges around the Gulf of Lions and atmospheric conditions. *Int. J. Climatol.*. 28, 159-171.

Ullmann A., Pirazzoli P.A, 2007: Recent evolution of extreme sea surge-related meteorological conditions and assessment of coastal flooding risk on the Gulf of Lions. *Médittérannée*. 108, 69-76.

Ullmann A., 2008: Surcotes dans le Golfe du Lion et conditions atmosphériques: variabilité contemporaine et future (1900-2100). PhD Thesis. Université Aix-Marseille I, Aix-en-Provence.

Wakelin S.L., Woodworth P.L., Flather R.A., Williams J.A., 2003: Sea-level dependence on the NAO over the NW European continental shelf, *Geophys. Res. Letters*, 30, doi:10.1029/2003GLO17041.

Woodworh PL., Player R., 2003. The permanent Service for Mean Sea Level: an update to the 21st century. Journal of Coastal Research, 19: 287:295.

Figure legends

Figure 1. Localisation of the Grau-de-la-Dent, Cap Couronne, Sète and Port-Vendres stations.

Figure 2. (a) Mean frequency (in %) of winds directions at Cap Couronne (full line), Sète (dashed line) and Port-Vendres (dotted line) on the 1986-1995. (b) The same for sea surges > 20 cm.

Figure 3. Mean frequency (in %) of daily SLP (12h TU) < 1000 hPa for each 5° grid point and when daily sea surges (12h TU) reaches synchronously 20 cm at Grau-de-la-Dent, Sète and Port-Vendres.

Figure 4. Daily mean NAOI (in hPa) relative to sea surges by class of 10 cm height at Grau-de-la-Dent (in white bars), Sète (in Grey bars) and Port-Vendres (in black bars) on the period 1986-1995.

Figure 5. Monthly anomalous frequency (in %) of (a) daily sea surges > 20 cm (12h UTC) at Grau-de-la-Dent (in white bars) Sète (in grey bars) and Port-Vendres (in black bars) relative to the mean monthly frequency (1988-1995) and for monthly mean NAOI by class of 5 hPa on the period 1986-1995. (b) the same for winds from 90°-180° at Cap Couronne (in white bars), Sète (in grey bars) and Port-Vendres (in black bars) and (c) for SLP < 1000 hPa over [15°W-0°W], [40°N-45°N].

Figure 6. (a) wintertime (October to March) 90th percentile of daily sea surges at Grau-de-la-Dent and (b) wintertime mean NAOI on the period 1905-2002 with low-pass filtered variation removing periods below 1/30 cycle-per-year superimposed as full line.

Figure 7. (a) Running correlation (on 60 month segments) between monthly (October to March) mean NAOI and monthly frequency of sea surges > 20 cm at Grau-de-la-Dent on the period 1905-2002 and (b) the same for monthly mean sea level at Marseille.

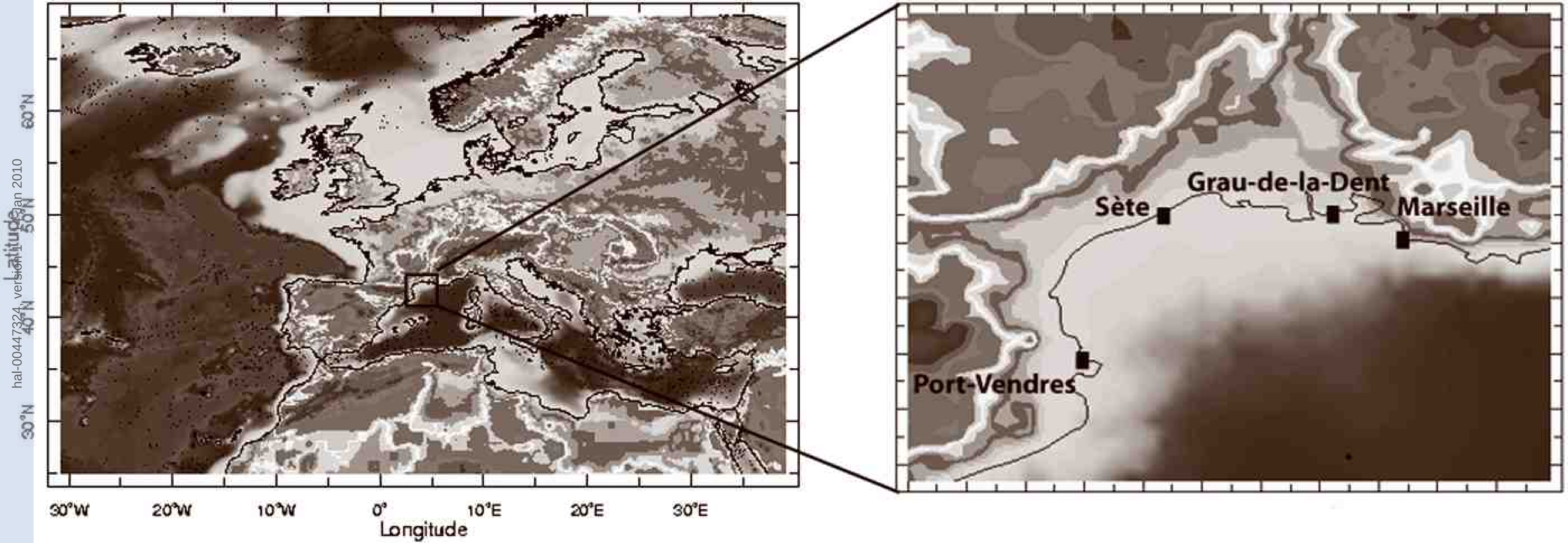
Figure 8. (a) Running correlation (on 60 month segments) between monthly (October to March) mean NAOI and monthly frequency of SLP < 1000 hPa over [15°W-0°W], [40°N-45°N] on the period 1905-2002. (b) The same correlation between the monthly mean NAOI and the monthly frequency of E-W SLP gradient > 10 hPa between high pressure over Central Europe ([15°E-30°E], [40°N-50°N]) and low pressure around the Bay of Biscay ([15°W-0°W], [40°N-45°N]).

Figure 9. Running correlation (on 60 month segments) between monthly (October to March) mean NAOI and monthly frequency of winds from 90°-180 at (a) Cap Couronne (1961-2003) and (b) at Sète and (c) Port-Vendres (1949-2003).

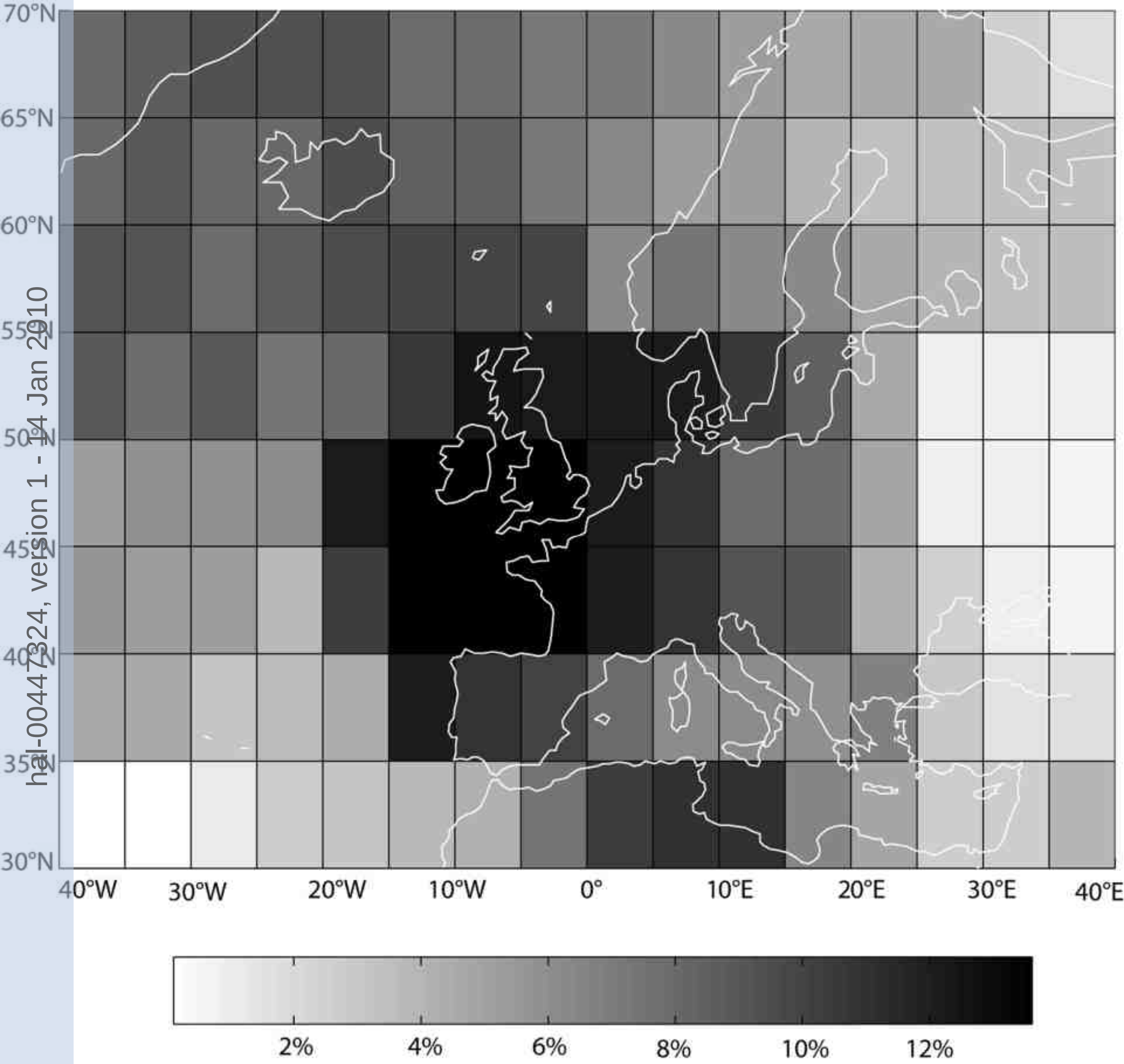
Figure 10. Mean of the upper (bold full line) and lower (full line) halves of the monthly frequency of daily NAOI < 0 on the 60 month segments with the associated mean 75th percentile of daily sea surge at Grau-de-la-Dent when negative NAOI are less (dashed line) and more (dotted line) frequent than the running 10-year mean.

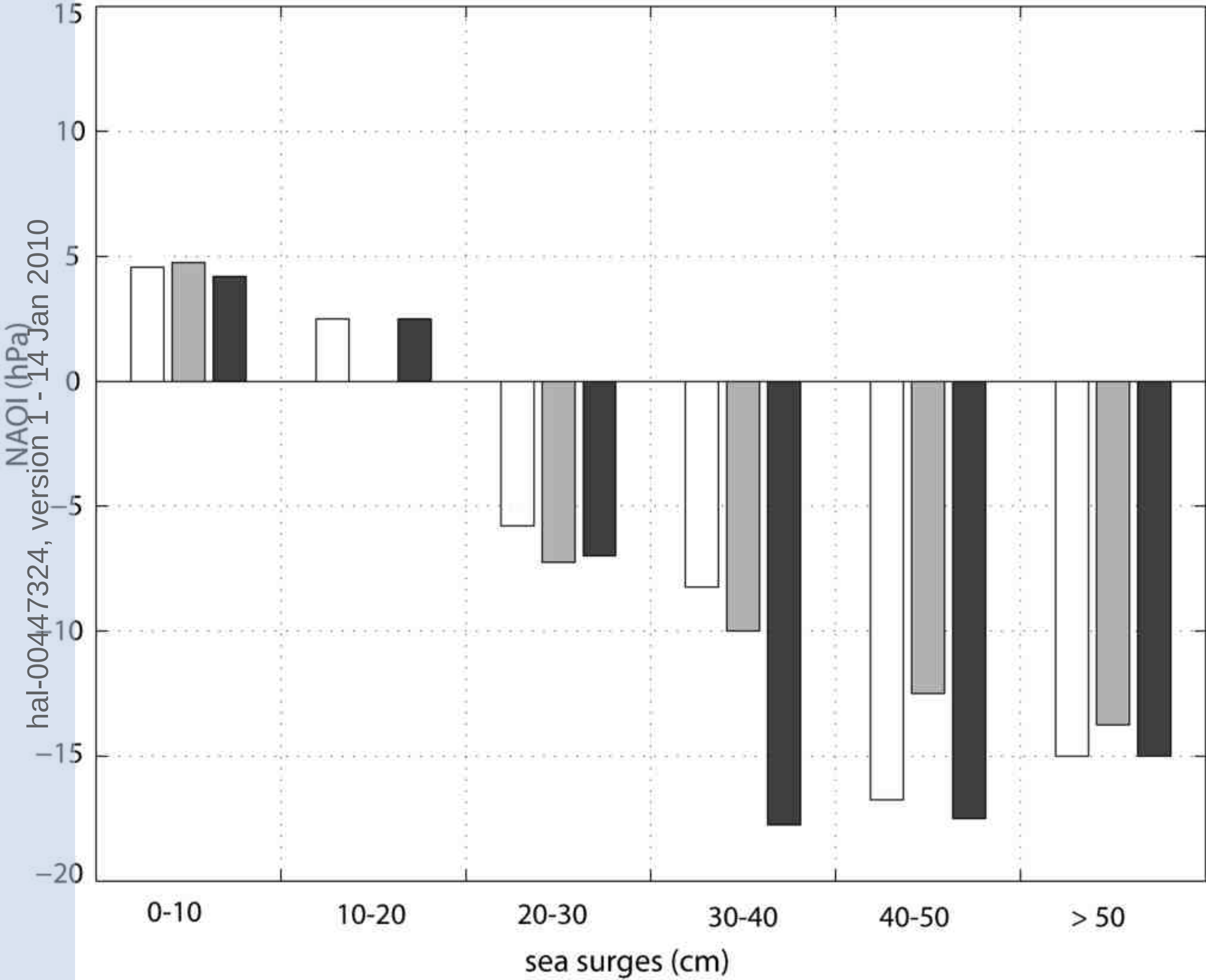
Table lengend

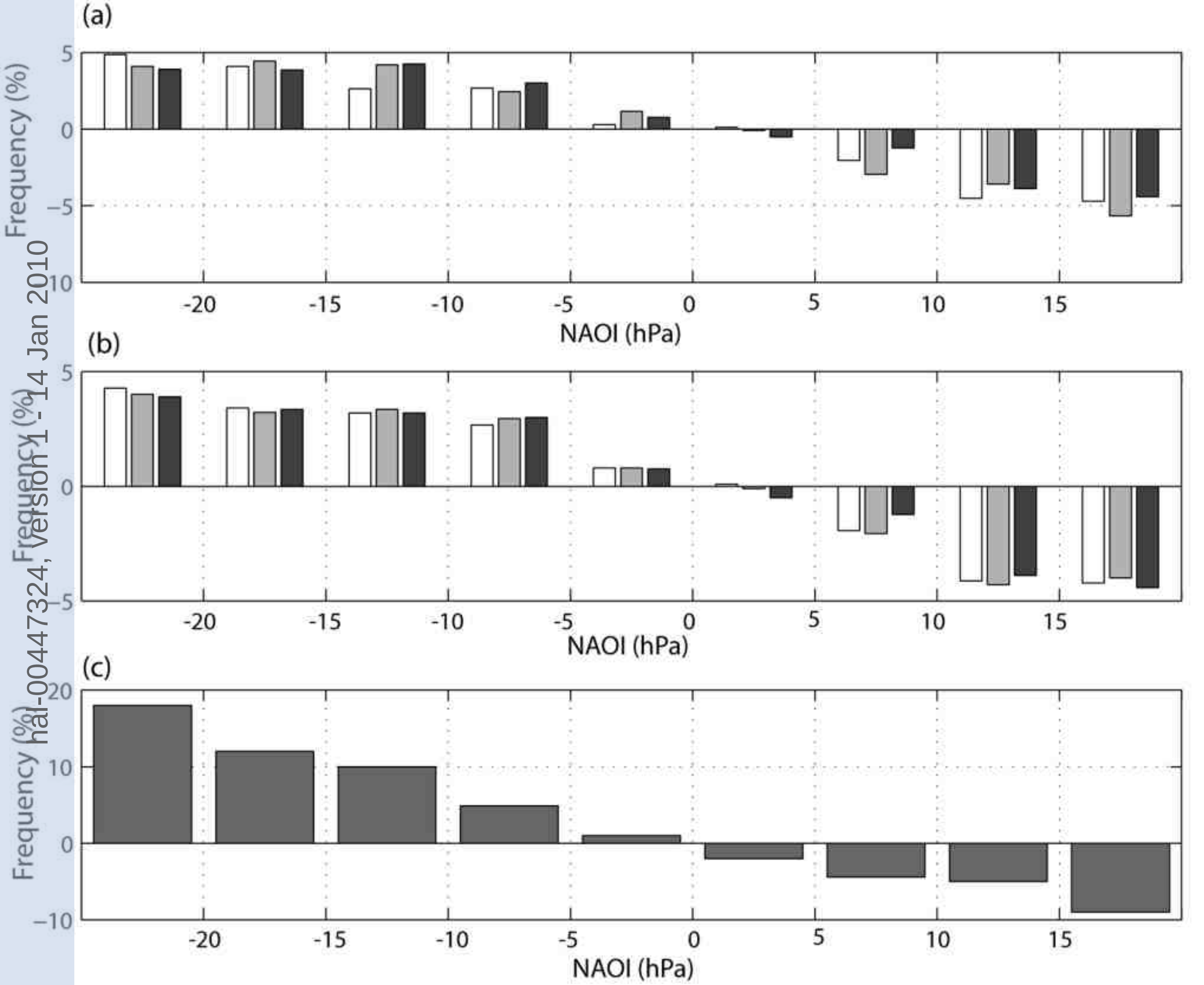
Table 1. Upper part: correlation between daily NAOI (12h TU) and daily sea surges (12h UTC) at Grau-de-la-Dent, Sète and Port-Vendres on the period 1986-1995 and on 1905-2002 at Grau-de-la-Dent only. Lower part: correlation between monthly mean NAOI and monthly frequency of sea surges > 20 cm at Grau-de-la-Dent, Sète and Port-Vendres on the period 1986-1995 and on 1905-2002 at Grau-de-la-Dent only. Two and three stars indicate the two sided 90 and 95% level of significance according to a random-phase test (Ebisuzaki, 1997).

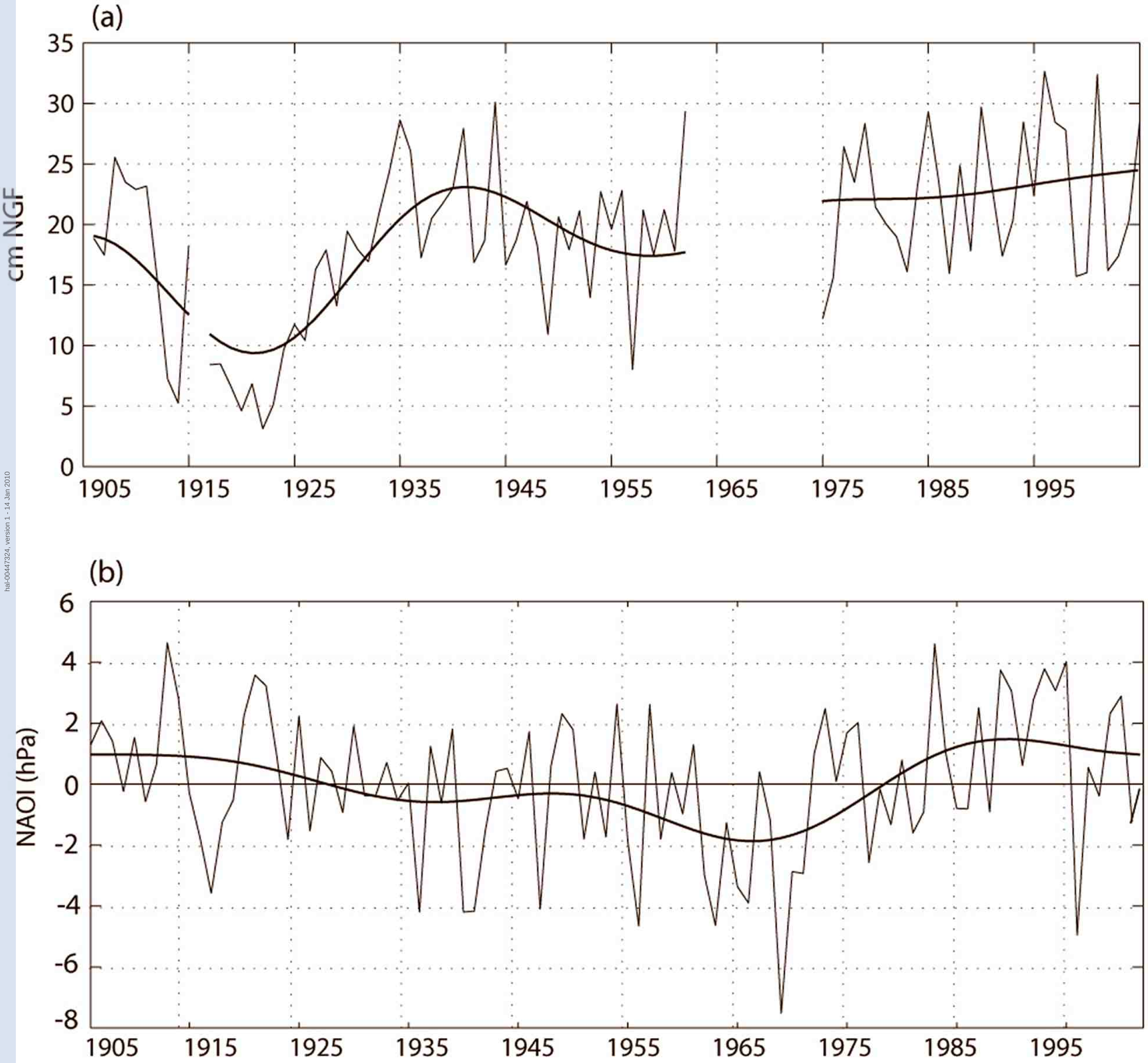

60°N
50°N
40°N
30°N
Latitude
30°W
20°W
10°W
0°
10°E
20°E
30°E
Longitude
Sète
Grau-de-la-Dent
Marseille
Port-Vendres

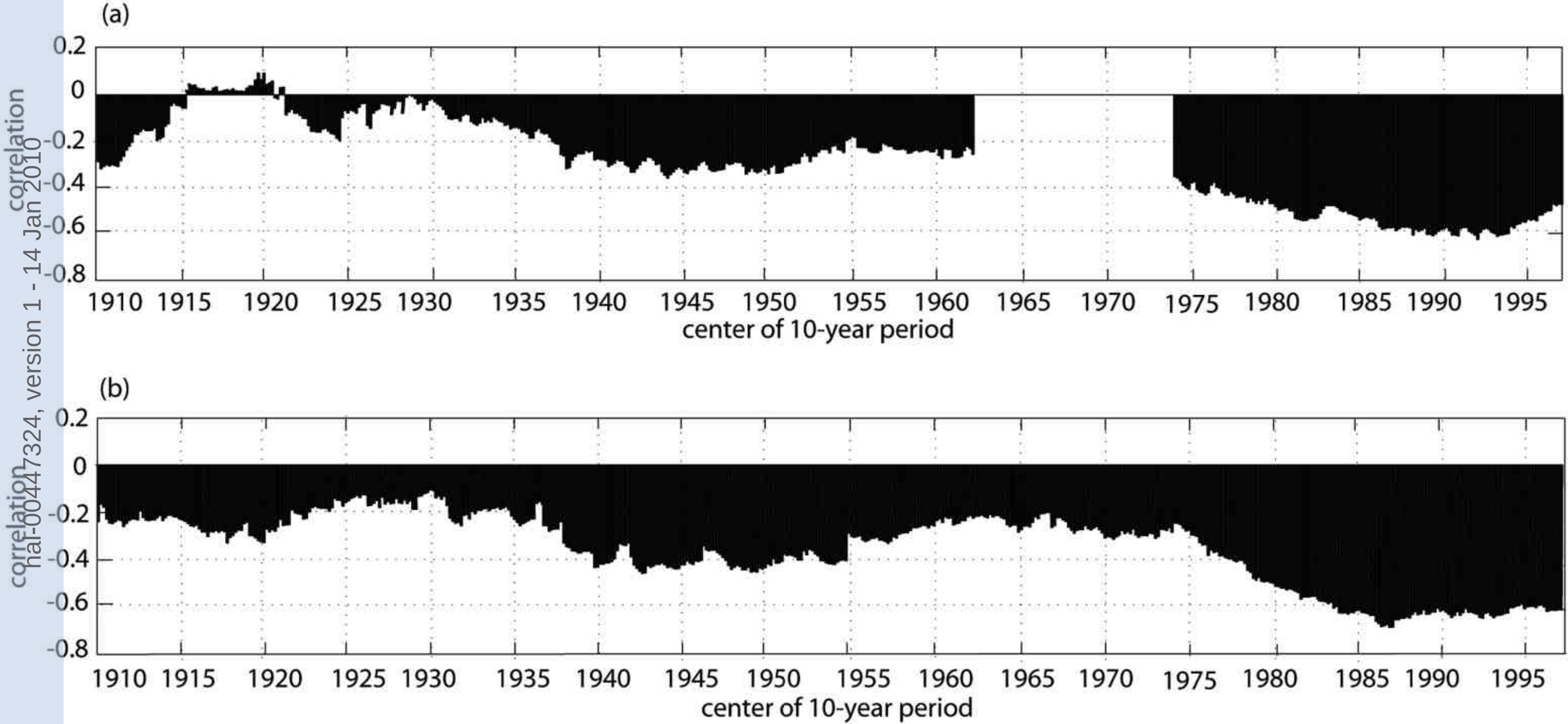

(a)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
25
20
15
10
5
0
(b)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
80
70
60
50
40
30
20
10
0

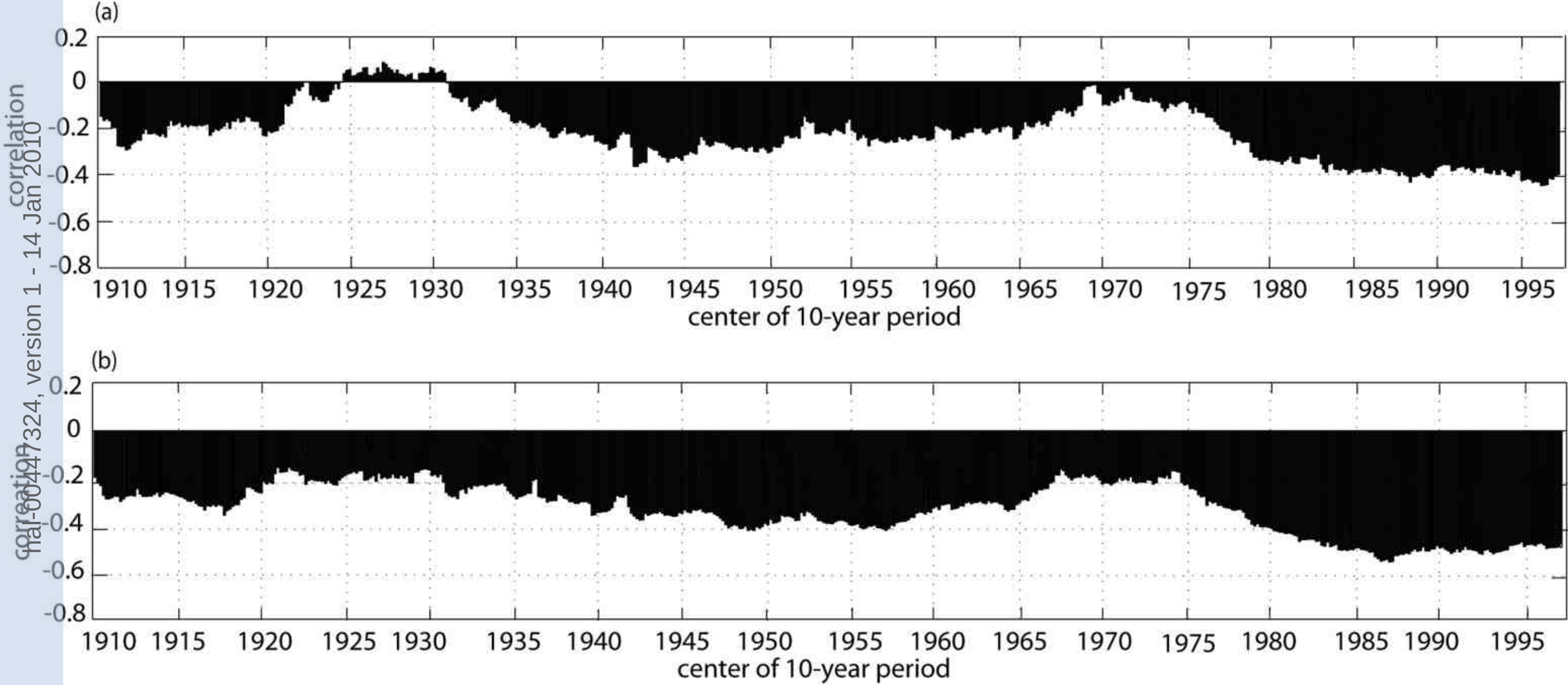

70°N
65°N
60°N
55°N
50°N
45°N
40°N
35°N
30°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
2%
4%
6%
8%
10%
12%


15
10
5
0
−5
−10
−15
−20
NAOI (hPa)
0-10
10-20
20-30
30-40
40-50
> 50
sea surges (cm)

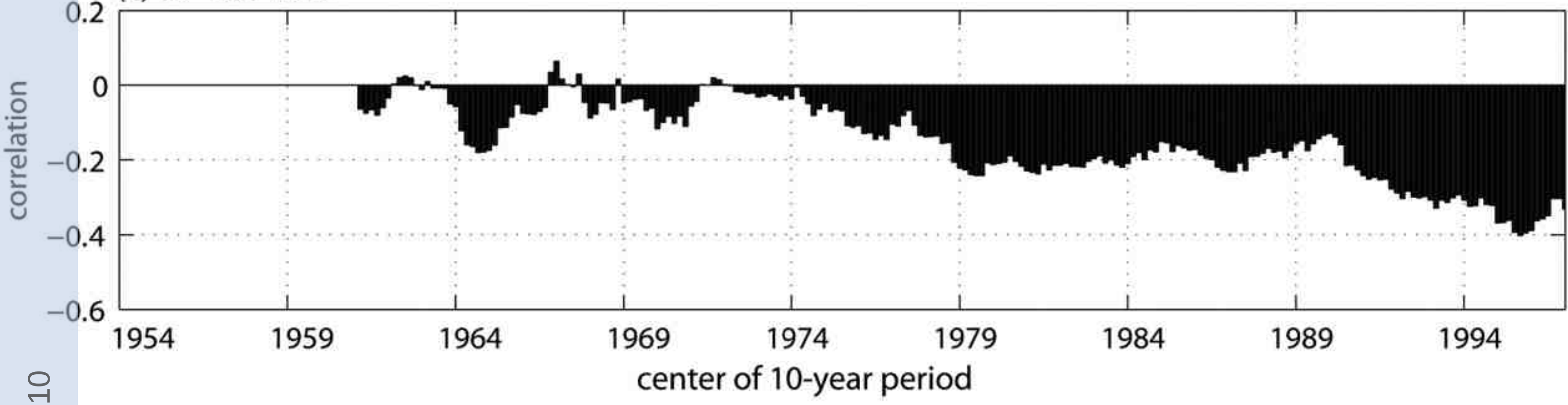

(a)
Frequency (%)
5
0
−5
−10
-20
-15
-10
-5
0
5
10
15
NAOI (hPa)
(b)
Frequency (%)
5
0
−5
-20
-15
-10
-5
0
5
10
15
NAOI (hPa)
(c)
Frequency (%)
20
10
0
−10
-20
-15
-10
-5
0
5
10
15
NAOI (hPa)


(a)
cm NGF
35
30
25
20
15
10
5
0
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995
(b)
NAOI (hPa)
6
4
2
0
-2
-4
-6
-8
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995

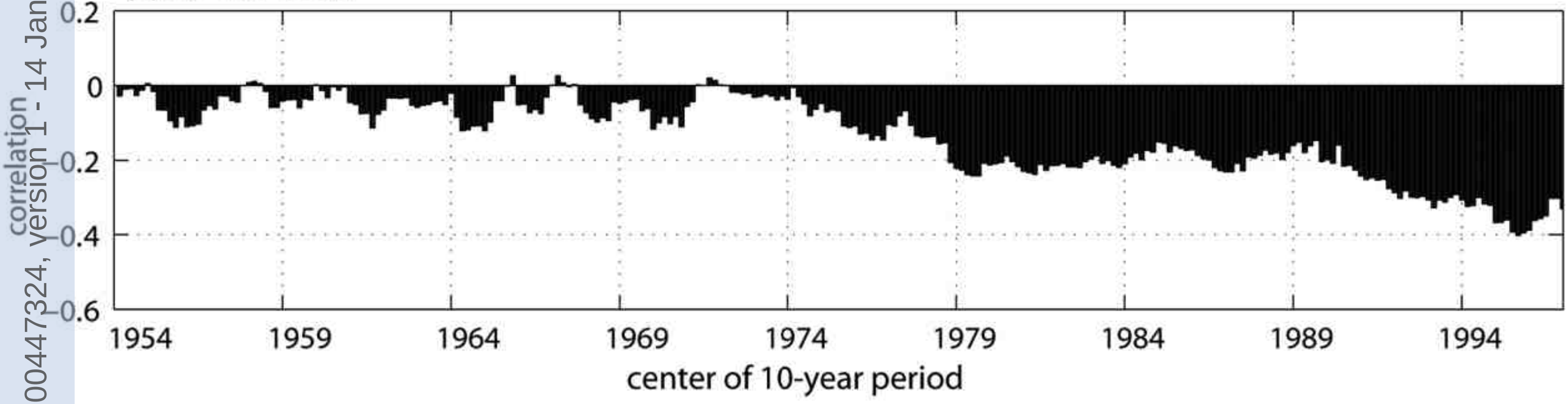

(a)
correlation
0.2
0
-0.2
-0.4
-0.6
-0.8
1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995
center of 10-year period
(b)
correlation
0.2
0
-0.2
-0.4
-0.6
-0.8
1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995
center of 10-year period


(a)
correlation
0.2
0
-0.2
-0.4
-0.6
-0.8
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
center of 10-year period
(b)
correlation
0.2
0
-0.2
-0.4
-0.6
-0.8
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
center of 10-year period

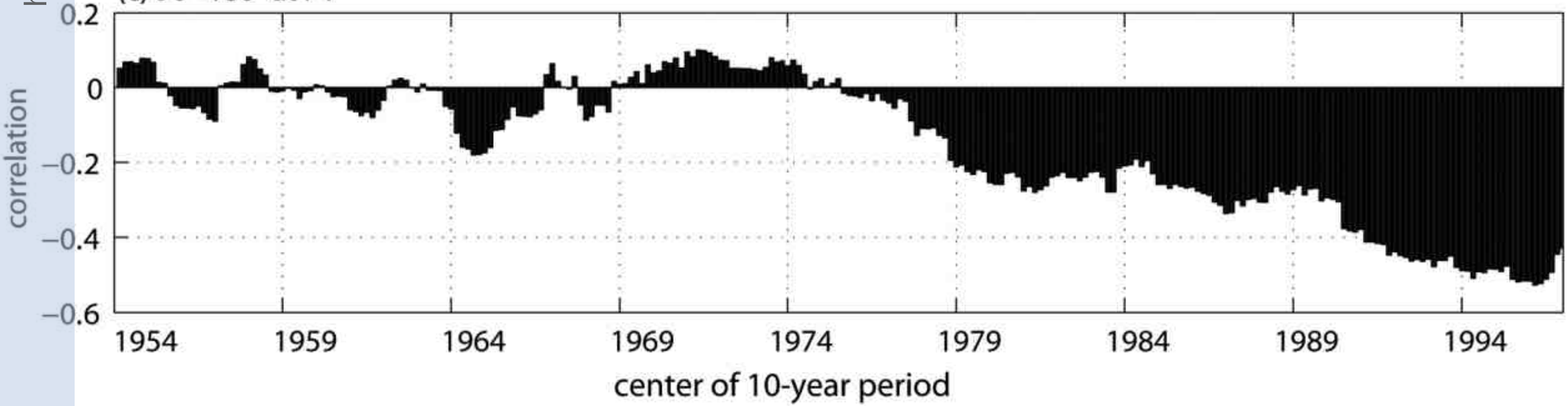
(a) 90°-180° at CC

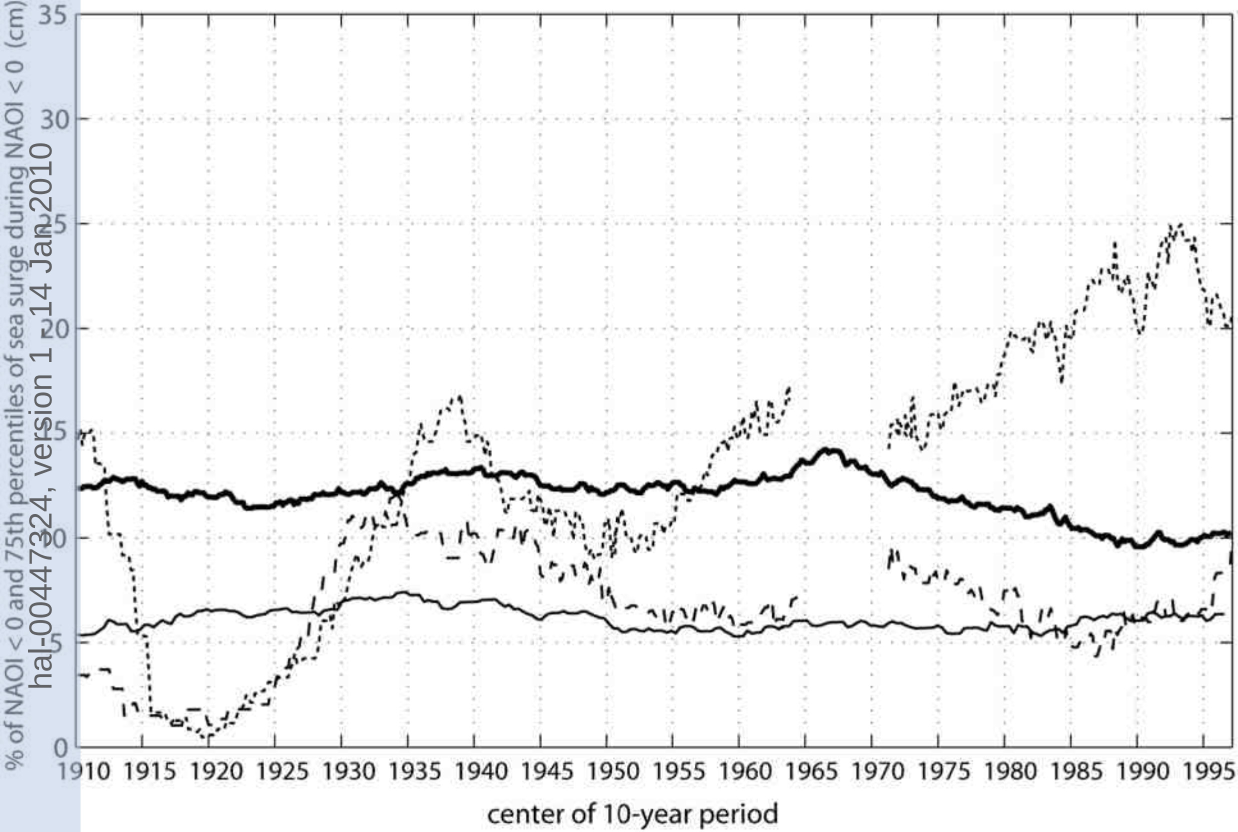


(b) 90°-180° at SET



(c) 90°-180° at PV




% of NAOI < 0 and 75th percentiles of sea surge during NAOI < 0 (cm)
35
30
25
20
15
10
5
0
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
center of 10-year period

	1986-1995	**1905-2002**
Day		
Grau-de-la-Dent	-0.45***	-0.39**
Sète	-0.40***	-
Port-Vendres	-0.40***	-
Montly mean		
Grau-de-la-Dent	-0.61***	-0.43***
Sète	-0.60***	-
Port-Vendres	-0.62***	-