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Climatic oscillations influence the flooding of Venice

Sergio Fagherazzi,[1] Giorgia Fosser,[1,2] Luigi D'Alpaos,[3] and Paolo D'Odorico[4]

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[1] A detailed analysis of the tidal regime in Venice, Italy, during the last century shows that the frequency and magnitude of high tides are correlated to interdecadal climatic oscillations. The monthly high tide maxima and the average elevation of all high tides are negatively correlated to the North Atlantic Oscillation (NAO), to the Arctic Oscillation (AO), to the East Atlantic – West Russian oscillation (EA-WR), and to the Polar Eurasia teleconnection (POL). The correlation is high during winter months for all four indices, whereas in the fall, when most of the city floods occur, the AO and the EA-WR exert a stronger influence on the tidal regime. During negative phases of the climate indices both the average elevation of high tides and the frequency of flooding increase consistently, with negative effects on the city and its monuments. **Citation:** Fagherazzi, S., G. Fosser, L. D'Alpaos, and P. D'Odorico (2005), Climatic oscillations influence the flooding of Venice, *Geophys. Res. Lett.*, *32*, L19710, doi:10.1029/2005GL023758.

1. Introduction

[2] The city of Venice, Italy, is known for being prone to frequent flooding events, which threaten its artistic treasures and disrupt the life in the city [*Camuffo et al.*, 2000; *Bras et al.*, 2001]. Exceptionally high tides have reached in the recent past (November 1966) the level of 174 cm above m.s.l. (mean sea level), causing incalculable damage to the city and its neighboring islands. Because the highest astronomic tide is 74 cm above m.s.l. [*Comune di Venezia and Istituto per lo Studio per la Dinamica delle Grandi Masse*, 1998], more than 60% of that extreme event was due to meteorological forcing, i.e. storm surges caused by strong sirocco winds blowing from South East. The frequency of flooding has been exacerbated by the combined effect of sea-level rise and natural and anthropogenic subsidence, with a loss of about 23 cm in elevation with respect to m.s.l. over the last century. However, the astronomic tide alone is still unable to endanger Venice, in that an 87-cm-tide is needed to flood the lowest 12% of the city area. Thus, sea-level rise and subsidence need to be studied in conjunction with the effects of climate variability to understand and predict changes in the magnitude and frequency of high tides.

[3] Here we relate the high-tide events in the Venice lagoon to major large-scale patterns of climate variability, namely, the principal mode of climate variability in the Northern Hemisphere, known as Arctic Oscillation (AO) [*Thompson et al.*, 2000; *Thompson and Wallace*, 2001], its regional manifestation, i.e., the North Atlantic Oscillation (NAO) [*Hurrell*, 1995; *Hurrell et al.*, 2001], and other teleconnection patterns statistically related to AO and NAO, including the East Atlantic-West Russian (EA-WR) and the Polar-Eurasia (POL) [*Barnston and Livezey*, 1987].

[4] These patterns are known for their impact on winter precipitation, atmospheric pressure and surface temperature across Europe [*Hurrell*, 1995; *Hurrell et al.*, 2001; *Thompson and Wallace*, 2001; *Krichak and Alpert*, 2005].

[5] The interannual climatic oscillations considered in this paper are modes of large-scale climate variability that have impacts on the weather and climate of large areas of the globe. These fluctuations are often caused by anomalies in atmospheric and oceanic circulations as well as in their mutual interactions. The strength of these teleconnections is expressed by indices measuring the variability of a meteorological quantity. For example, the monthly NAO index is based on the difference of normalized sea level pressures (SLP) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland [*Hurrell*, 1995].

[6] Large-scale atmospheric circulation has also been proven to influence the variability of sea level. *Wakelin et al.* [2003] used a two-dimensional model of tides and storm surges to investigate the connection between the NAO and sea level over the northwest European continental Shelf. They found a spatial pattern in the correlation between sea level and the NAO on a winter-mean timescale. *Tsimplis and Josey* [2001] found a link between NAO and sea-level variability in the Mediterranean Sea over the last century, due to the combined effects of atmospheric pressure anomalies and changes in evaporation and precipitation. Moreover, they found that a strengthening of the NAO from 1960 to1990 partly explains the reduction in Mediterranean Sea level in this period. In the context of the Venice lagoon, *Camuffo et al.* [2000] explored the teleconnection between the flooding of Venice and the NAO based on data from 1950 to 1990 without finding a significant correlation. However, in their study they only compared years when extreme sea surges occurred to the correspondent NAO annual index, whereas daily and seasonal tidal data corrected from the influence of sea-level rise and subsidence are necessary for a detailed description of the tidal regime.

2. Methods

[7] We use daily sea level records (1887–2000) taken at Punta della Salute, on the southern side of the city (Figure 1). These data are first referred to mean-sea level by subtracting trends associated with subsidence and sea-

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[1] Department of Geological Sciences and School of Computational Science, Florida State University, Tallahassee, Florida, USA.

[2] Also at Department IMAGE, University of Padova, Padova, Italy.

[3] Department IMAGE, University of Padova, Padova, Italy.

[4] Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA.

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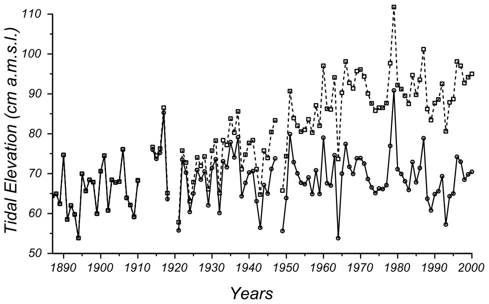

Figure 1. Annual mean of monthly tidal maxima from 1887 to 2000: elevation with respect to tidal gage (dotted line) and after subtracting subsidence and sea-level rise (solid line).

level rise [*Carbognin et al.*, 2005]. The tidal regime is studied through the average elevation of all high tides in a month, the average of the five highest tides measured in each month, the number of high tides exceeding 70 cm above m.s.l., and the number of high tides exceeding 50 cm above m.s.l., which is the elevation of San Marco's square, the lowest point in the city. These four monthly indicators of the tidal regime are then correlated to monthly climate indices measuring the strength of the climatic patterns considered in this study (Table 1). The same analysis is repeated on the seasonal averages of these climate and tidal variables (Table 2). For the seasonal indices, the Spearman's rho and Kendall's tau coefficients are also calculated.

[8] The AO, POL, and EA-WR indices were obtained from the NOAA Climate Prediction Center http://www.cpc.ncep.noaa.gov/data/; the NAO index from the National Center of Atmospheric Research www.cgd.ucar.edu/cas/jhurrell/, seasonal indices were obtained by averaging monthly values.

[9] The analysis is completed by measuring the frequency of flooding events (tidal elevation greater than 87 cm above m.s.l.) and the difference between the average elevation of high tides during negative and positive phases of the climatic indices (Table 2). The statistical significance of the correlation index is determined by testing the null hypothesis $\rho = 0$ with a Student's t-statistic $t = r/\sqrt{(1-r^2)/(n-2)}$ with r the correlation coefficient and n the number of samples [*Zar*, 1999], whereas the statistical significance of the difference in average tidal elevation and flood frequency is calculated with a Student's t-Test on the difference of the means.

3. Results and Discussion

[10] It is found that winter tides are negatively correlated to all these climate signals (Table 2 and Figure 2; r = 0.48–0.59 with NAO in December–March DJFM, r = 0.53–0.80 with AO in DJFM, r = 0.46–0.55 with EA-WR in DJF, r = 0.39–0.70 with POL in JF).

[11] The higher correlations for the seasonal indices indicate that climatic oscillations have a stronger influence on the seasonal tidal regime, rather than on its monthly variability.

[12] Because more than 70% of flooding events occur in the fall (October–December, OND) we investigated in particular the climatology of the tidal regime in this season. A relatively strong dependence was found mainly between high tides, and the AO and EA-WR (r = 0.33–0.57 for AO in OND, and r = 0.53–0.57 for EA-WR in OND); while NAO has only a limited impact on the tides during the fall season (see Table 1) and POL is either inactive (in October–November) or not correlated with the tidal regime in Venice (in December, see Table 1). The dependence on the EA-WR is equally strong in the fall and winter, while the relation with AO is stronger in winter than in fall.

[13] The highest correlation is found for the average of all high tides, whereas the cross correlation coefficient decreases for the five highest tides in each month. We attribute this difference to the strong variability in extreme

Table 1. Cross Correlation Between Climatic Indices and Monthly Average High Tide (ρ_1); Average Five Highest Tides in Each Month (ρ_2); Number of High Tides > 70 cm a.m.s.l. (ρ_3); Number of High Tides > 50 cm a.m.s.l. (ρ_4); Difference of Monthly Average High Tide (Δ_1) in Years With Negative and Positive Climatic Index; Difference of Average of the Five Highest Tides in Each Month (Δ_2) in Years With Negative and Positive Climatic Index[a]

	North Atlantic Oscillation (1887–2000)						Arctic Oscillation (1950–2000)					
	Oct	Nov	Dec	Jan	Feb	Mar	Oct	Nov	Dec	Jan	Feb	Mar
ρ_1	−0.00	−0.18	**−0.39**	**−0.46**	**−0.42**	**−0.51**	**−0.60**	**−0.43**	**−0.56**	**−0.64**	**−0.59**	**−0.68**
ρ_2	0.05	0.03	**−0.28**	**−0.43**	**−0.34**	**−0.31**	**−0.51**	−0.12	**−0.33**	**−0.66**	**−0.43**	**−0.41**
ρ_3	0.05	0.04	**−0.28**	**−0.41**	**−0.24**	**−0.22**	**−0.46**	−0.16	**−0.34**	**−0.52**	**−0.31**	**−0.39**
ρ_4	−0.02	−0.14	**−0.37**	**−0.45**	**−0.38**	**−0.39**	**−0.56**	**−0.30**	**−0.42**	**−0.55**	**−0.39**	**−0.44**
Δ_1 (cm)	-	-	**8.5**	**9.3**	**9.8**	**7.8**	**8.0**	4.6	**10.9**	**14.0**	**13.5**	**8.8**
Δ_2 (cm)	-	-	**8.4**	**10.2**	**9.1**	**6.9**	**12.4**	−1.3	**8.8**	**20.2**	**13.5**	**7.6**
	East Atlantic-West Russian (1950–2000)						Polar-Eurasia (1950–2000)					
	Oct	Nov	Dec	Jan	Feb	Mar	Oct	Nov	Dec	Jan	Feb	Mar
ρ_1	**−0.31**	**−0.47**	**−0.65**	**−0.49**	−0.26	**−0.30**	-	-	−0.17	**−0.55**	**−0.56**	-
ρ_2	−0.23	**−0.56**	**−0.58**	**−0.36**	**−0.35**	**−0.40**	-	-	−0.15	**−0.62**	**−0.42**	-
ρ_3	−0.21	**−0.45**	**−0.64**	−0.21	−0.14	−0.17	-	-	−0.07	**−0.44**	**−0.37**	-
ρ_4	**−0.28**	**−0.46**	**−0.63**	**−0.38**	−0.23	−0.24	-	-	−0.12	**−0.44**	**−0.43**	-
Δ_1 (cm)	-	**6.6**	**9.5**	**9.1**	-	-	-	-	-	**10.4**	**10.8**	-
Δ_2 (cm)	-	**11.5**	**11.2**	**10.3**	-	-	-	-	-	**14.7**	**9.2**	-

[a] Boldface values are statistically significant with $p < 0.05$. The climate indices were provided by the NOAA Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html) and by the National Center for Atmospheric Research (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

Table 2. Cross Correlations Between Climatic Indices and Seasonal Average High Tide (ρ_1); Seasonal Average of the Five Highest Tides in Each Month (ρ_2); Number of High Tides > 70 cm a.m.s.l. (ρ_3); Number of High Tides > 50 cm a.m.s.l. (ρ_4); Difference of Seasonal Average High Tide (Δ_1) in Years With Negative and Positive Climatic Index; Difference of Seasonal Average of the Five Highest Tides in Each Month (Δ_2) in Years With Negative and Positive Climatic Index; Seasonal Average Number of Extreme Events (i.e., >87 cm a.m.s.l.) in Years With Positive (f_1) and Negative (f_2) Climatic Index[a]

	NAO (1887–2000)	AO (1950–2000)	AO (1950–2000)	EA-WR (1950–2000)	EA-WR (1950–2000)	POL (1950–2000)
	DJFM	DJFM	OND	DJF	OND	JF
Correlation Coefficient						
ρ_1	**−0.59**	**−0.80**	**−0.57**	**−0.55**	**−0.57**	**−0.70**
ρ_2	**−0.52**	**−0.71**	**−0.33**	**−0.55**	**−0.57**	**−0.69**
ρ_3	**−0.48**	**−0.53**	**−0.45**	**−0.51**	**−0.57**	**−0.39**
ρ_4	**−0.52**	**−0.59**	**−0.48**	**−0.51**	**−0.53**	**−0.56**
Spearman Rho						
ρ_1	**−0.56**	**−0.78**	**−0.56**	**−0.46**	**−0.61**	**−0.69**
ρ_2	**−0.50**	**−0.74**	**−0.31**	**−0.52**	**−0.61**	**−0.64**
ρ_3	**−0.46**	**−0.63**	**−0.40**	**−0.50**	**−0.53**	**−0.37**
ρ_4	**−0.51**	**−0.67**	**−0.48**	**−0.44**	**−0.58**	**−0.62**
Kendall Tau						
ρ_1	**−0.40**	**−0.60**	**−0.40**	**−0.33**	**−0.43**	**−0.51**
ρ_2	**−0.34**	**−0.60**	**−0.23**	**−0.38**	**−0.43**	**−0.47**
ρ_3	**−0.31**	**−0.44**	**−0.29**	**−0.34**	**−0.38**	**−0.25**
ρ_4	**−0.35**	**−0.47**	**−0.34**	**−0.32**	**−0.40**	**−0.44**
Δ_1, cm	**6.5**	**8.7**	**7.1**	**6.9**	**6.1**	**12.2**
Δ_2, cm	**7.0**	**9.9**	**5.2**	**8.6**	**8.8**	**15.0**
f_1	1.17	1.17	2.31	**0.83**	**1.76**	0.33
f_2	1.86	1.54	3.08	**1.79**	**3.58**	0.73

[a] Boldface values are statistically significant with $p < 0.05$

events, which are less representative of the tidal regime since they are determined by the superimposition of several adverse conditions. This finding is in agreement with previous studies [e.g., *Krichak and Alpert*, 2005, *Jevrejeva et al.*, 2005] indicating that interannual teleconnections are more correlated to mean meteorological conditions than their extremes. This is also reflected in the correlation with the number of tides higher than 50 cm, which is higher than the correlation with tides higher than 70 cm.

[14] The Spearman's rho coefficient and the Kendall's tau coefficient (see Table 2) support our findings, proving that the tidal regime and the selected teleconnections are monotonically related even without considering a linear association. Furthermore these rank correlations show that the results are not sensitive to outliers. The lower values of the Kendall's Tau coefficient can be ascribed to the characteristics of the method, rather than to a lower correlation [*Zar*, 1999]. Both of these nonparametric analyses show that the tidal regime and the EA-WR oscillation are more correlated in fall than in the winter season, and indicate that the tidal regime in the fall has a stronger dependence on the EA-WR teleconnection.

[15] We have also explored the influence of other teleconnections (namely the East Atlantic Pattern, the East Atlantic Jet Pattern, the Scandinavia Pattern, and the Asia Summer Pattern) on Venice's tidal regime, without finding any significant correlation.

[16] Negative phases of the NAO and AO are associated with the persistence of low-pressure conditions over Southern Europe, and to consequently high precipitation, storminess and frequency of storm-surge occurrences in the Mediterranean basin [*Hurrell*, 1995, *Thompson and Wallace*, 2001]. Opposite conditions occur in northern Europe, where negative phases of the NAO correspond to anomalous high pressure and below-average sea level over the NW European continental shelf. Similarly, low pressure conditions are observed over the Mediterranean basin during negative EA-WR phases [*Barnston and Livezey*, 1987], enhancing the occurrence of extremely high tides in the Venice lagoon.

[17] In fact, high tide events are always related to the passage of storms that induce persistent low Sea Level Pressure (SLP) over the Venice lagoon and south-southeasterly winds over the Adriatic sea. The low SLP causes a rise in sea level driven by hydrostatic balance, whereas persistent winds produce storm surges that pile up water in the northern part of the Adriatic sea, where Venice is located [*Camuffo*, 1993; *Trigo and Davies*, 2002].

[18] Negative phases of the AO and EA-WR increase the average high-tide elevation by 7.1 and 6.1 cm with respect to positive phases, and the monthly five highest maxima by 5.2 and 8.8 cm, respectively. These values are significant for Venice, since 80% of the city lies within 30cm in elevation [*Pirazzoli*, 1991]. The influence of these climate patterns is even more evident if we compare the number of tides higher than 87 cm occurring during positive and negative phases of the AO and EA-WR. On average, in the fall season (OND) 3.08 of these extremely high tides occur during negative AO phases, versus 2.31 during the positive phases. For the EA-WR the influence is even stronger, with 3.58 high tides occurring on average in negative EA-WR phases and 1.76 during positive phases. Caution is advised in using the flood frequency data, since only for the EA-WR they are statistically significant, given the high variability of flooding events in each year.

[19] During the late 70's and 80's both the AO [*Hurrell*, 1995] and the EA-WR [*Krichak et al.*, 2002] persisted in a positive phase, whereas during the late 90's a decline of

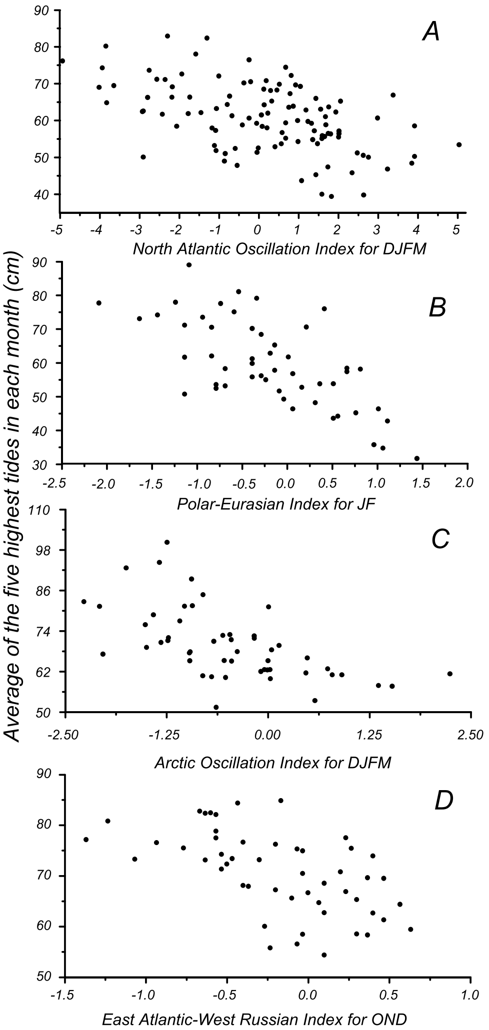

Figure 2. Average of the five highest tides in each month as a function of climate index: (a) NAO during winter, (b) POL during winter, (c) AO during winter, (d) EA-WR during fall.

subpolar North Atlantic circulation has been observed [*Häkkinen and Rhines*, 2004]. The positive trend of these indices during the last decades of the twentieth century has been associated with winter warming over the Northern Hemisphere [*Shindell et al.*, 1999; *Serreze et al.*, 2000], whereas other studies argue that the positive trend is due to the natural climate variability [*Corti et al.*, 1999]. In correspondence to changes in large-scale atmospheric circulation, the long term meteorological conditions of the Northern Adriatic have also experienced variations in the last decades. The persistence and intensity of adverse conditions (south-southeasterly winds and low sea-level pressure) for the occurrence of sea surges in Venice have been generally decreasing [*Trigo and Davies*, 2002], together with an abatement of easterly winds in the Northern Adriatic [*Pirazzoli and Tomasin*, 1999]. Such changes in wind patterns, probably linked to interdecadal climatic oscillations, might have decreased the frequency of the flooding of the city.

[20] Our results suggest that global warming has two distinct, sometimes conflicting, effects on the flooding of Venice: i) a generalized increase in sea level and related tides ii) a modulation of high tides by changes in large-scale atmospheric circulation. In fact changes in large-scale circulation can modify the climatology of the western Mediterranean, with also an effect on the frequency of sea surges.

[21] The positive trends of AO and EA-WR might have mitigated the frequency of floods from the seventies to the early nineties, leading to the underestimation of Venice's exposure to high tides. In fact, a scenario with prolonged negative phases of AO and EA-WR could double the frequency of flooding events and increase the monthly peaks of up to 9 cm, with respect to positive phases (see Table 2), thereby increasing the vulnerability of the city.

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L. D'Alpaos, Department IMAGE, University of Padova, Via Loredan 20, I-35131 Padova, Italy.

P. D'Odorico, Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904, USA.

S. Fagherazzi and G. Fosser, Department of Geological Sciences, Florida State University, Tallahassee, FL 32306, USA. (sergio@csit.fsu.edu)