REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-08-2011	Conference Proceeding	

4. TITLE AND SUBTITLE
The Effect of High Wind Bora Events on Water pCO2 and CO2 Exchange in the Coastal Northern Adriatic

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)
D. Turk, B. Petelin and J.W. Book

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-6358-A0-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7330--10-0418

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited

20110829004

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Three representative cases studies on the effect of bora wind episodes (1.5-2 days duration with wind speeds over 10 m s^{-1}) on surface water pCO_2 and O_2 in the coastal Northern Adriatic are presented, and in all three studied cases, regardless of pre-bora conditions, pCO_2 suddenly increases by 30-50 μatm a few hours after the onset of bora. We estimate that these winds increased the flux of CO_2 from the atmosphere into the ocean on an annual time scale by more than 30% at this location. Our study contributes to a very limited set of observations currently available on the biogeochemical response to episodic high wind events in costal areas and their role in CO_2 exchange.

15. SUBJECT TERMS
CO2 exchange, high wind, coastal, air-sea interaction

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jeffrey Book
Unclassified	Unclassified	Unclassified	UL	17	19b. TELEPHONE NUMBER *(Include area code)* 228-688-5251

The effect of high wind Bora events on water pCO_2 and CO_2 exchange in the coastal Northern Adriatic

D. Turk[1*,2,3], B. Petelin[1], J.W. Book[4]

[1] *National Institute of Biology, Marine Biology Station Piran, Slovenia*
[2] *Dept. of Oceanography, Dalhousie University, Canada*
[3] *Lamont-Doherty Earth Observatory, Columbia University, USA*
[4] *Naval Research Laboratory, Stennis Space Center, USA*

Abstract. Bora is an episodic ENE high wind in the Northern Adriatic with mean speeds over 15 m s^{-1} and with gusts greater than 30 m s^{-1}. It has a strong effect on the physical environment of the coastal Northern Adriatic, such as its circulation, stratification, and heat and momentum fluxes. However, only limited observations on the biogeochemical response in relation to the bora are currently available.

For the first time, the effect of bora wind episodes on surface water pCO_2 and O_2 in the coastal Northern Adriatic is presented for a variety of water column conditions including: stratified and oversaturated with respect to atmospheric CO_2, stratified (thermal inversion) and undersaturated, and non-stratified and undersaturated. Three representative bora cases of 1.5-2 days duration with wind speeds over 10 m s^{-1} indicate that in all three studied cases, regardless of pre-bora conditions, pCO_2 in the surface water increases suddenly by 30-50 matm a few hours after the onset of bora. In a shallow, semi-enclosed basin, such as the Gulf of Trieste, strong bora wind perturbation can overcome stratification and efficiently mix bottom water pCO_2 with the surface water pCO_2. The winds also play a strong role in moving different water masses, with different pCO_2, through the system and study area. Bora was present 11.6% (around 40 days per year) during 2007 and 2008 and we estimate that these winds increased the flux of CO_2 from the atmosphere into the ocean on an annual time scale by more than 30%. Our study contributes to a very limited set of observations currently available on the biogeochemical response to episodic high wind events in costal areas and their role in CO_2 exchange.

* *D. Turk was at* [1], *presently at* [2,3].

1. Introduction

Bora is a cold katabatic wind prevailing in a northeasterly direction and is the most common wind in the Northern Adriatic. Bora forms narrow sea surface wind jets that are spatially influenced by the local topography and are characterized by a sudden startup and a short duration (order of one to a few days in the summers and six to fourteen days in the winter), with mean speeds over 15 m s^{-1} and with gusts greater than 30 m s^{-1} (Stravisi 2001). Bora winds normally last more than 40 days per year. Bora is most common in autumn and winter, but can also be present during the summer period. The strength, mean positions and extension of bora jets vary considerably between different events (Pullen *et al.* 2007) and therefore the response of the system cannot be determined based on a single bora episode.

It has been well established that bora has a strong effect on the physical environment of the Northern Adriatic, such as its circulation, stratification, and heat and momentum fluxes. It generates a wind-induced "double gyre" circulation, with a cyclonic gyre in the northern part of the basin and an anticyclonic gyre in front of the Southern Istrian coast (Kuzmić and Orlić 1987; Kuzmić *et al.* 2006). A few studies have also addressed the circulation and its response to bora in the Gulf of Trieste (GOT), the most northern semi-enclosed basin in Northern Adriatic (Figure 1). Malačič and Petelin (2009) show a generally cyclonic circulation in the deeper layer in all seasons with an inflow into the GOT which is enhanced during spring time. At the surface, the circulation of the gulf is predominantly anticyclonic during the stratified season due to the inertial plume of the Isonzo River, and there is an outflow from the gulf (Zavatarelli and Pinardi 2003; Malačič and Petelin 2009). During the intense bora episodes in the winter, studies have suggested that bora winds drive flow downwind at the surface, forming an outflow from the gulf in the surface layer (Kuzmić *et al.* 2006; Malačič and Petelin 2009), and compensating intensified inflow at depth.

It has also been suggested that pre-bora ambient stratification plays a role in the response of the Northern Adriatic to bora (Jeffries and Lee 2007). Typically, the water column in the GOT during the winter period is well mixed (Celio *et al.* 2006; Bogunović and Malačič 2009). In April, surface heating and fresh water input lead to stratification and the months between May and September are characterized by strong density stratification (Malačič *et al.* 2006). In October, convective and mechanical mixing of the surface and subsurface layers begin and mixing of the water column continues through November and December.

Modeling studies have also shown significant effects of Bora winds on heat fluxes (Pullen *et al.* 2007; Malačič and Petelin 2006; Dorman *et al.* 2006), and while previous studies in high wind conditions indicated strong increases in CO_2 fluxes (Bates *et al.* 1998), data in the Adriatic are scarce.

Despite the large number of studies on the physical oceanographic response to the bora wind in the Northern Adriatic (Signell *et al.* 2010; Pullen *et al.* 2007; Jeffries and Lee 2007; Kuzmić *et al.* 2006; Malačič and Petelin 2006; Dorman *et al.* 2006; and many other works), only a few observations are available on the biogeochemical responses (Boldrin *et al.* 2009; Turk *et al.* 2010). These studies

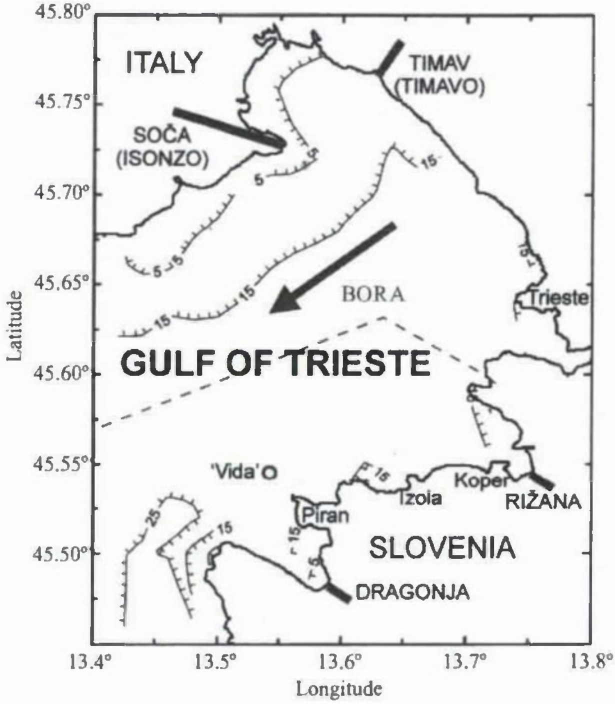

Figure 1 Map of the Gulf of Trieste in the Northern Adriatic. Bold lines indicate rivers, the general direction of bora wind is indicated by the vector, and the location of Vida is marked by a circle. Water depths are marked on contour lines.

mostly focus on a single bora event and do not address differences in pre-bora ambient conditions. Boldrin *et al.* (2009) show the effect of the bora on dissolved nutrients and oxygen, suspended matter, and phytoplankton in the northern Adriatic during September 2002 with stratified conditions. Their observations indicate that the bora caused complete vertical mixing to 20-25 meters in the water column, and an influx of warm salty water from the south along the Croatian coast. During the bora, they also observed an increase in resuspension of bottom sediment which is an important source of nutrients to the water column, and an increase in phytoplankton biomass. Turk *et al.* (2010) discuss a bora wind event in the Gulf of Trieste on October 30^{th}-November 2^{nd}, 2007 with winds reaching approximately 15 m s^{-1}, and sustaining 10-15 m s^{-1} for two days. They observed a sudden decrease of surface water pCO_2 by ~25 matm coinciding strongly with the bora wind event. A possible reason for this could be that the pCO_2 decrease was due to a new water mass being advected to the Vida location, and therefore gas exchange may not have played a significant role.

Table 1 Ambient pre-bora conditions and response during bora episode for three cases.

Case No.	Date in 2008	Pre-bora water column conditions	Bora pCO_{2w} response	Responsible mechanism	Bora F_{CO2} Mean ± SD (mol m^{-2} yr^{-1})	Bora F_{CO2} Max (mol m^{-2} yr^{-1})
1	21st–23rd July	Stratified (SST>T_b) CO_{2a}>CO_{2w}	Increase ~40 μatm	Horizontal advection & vertical mixing	11.4 ± 7.6	29.0
2	13th–16th November	Inversion (T_b>SST) CO_{2a}<CO_{2w}	Increase ~30 μatm	Vertical mixing	−10.0 ± 5.6	-22.6
3	25th–27th November	Non-stratified SST=T_b CO_{2a}<CO_{2w}	Increase ~50 μatm	Horizontal advection	−8.8 ± 6.8	-24.1

Here, we present three representative bora event cases during 2008 (Table 1); 21st - 23rd July, 2008 (Case 1), 13th - 16th November, 2008 (Case 2), and 25th - 27th November, 2008 (Case 3) to address the response of surface water pCO_2 and O_2 concentration during high bora wind events in the coastal Northern Adriatic. We consider different pre-bora ambient conditions; (Case 1) stratified summer conditions with pCO_2 in the surface water above the atmospheric value, (Case 2) an autumn situation with a thermal inversion of bottom water temperature higher than sea-surface temperature (SST) and undersaturated water pCO_2, and (Case 3) a late autumn case when the temperature of the water column is nearly uniform and water pCO_2 is below the atmospheric value. All three bora cases are of 1.5-2 days duration with wind speeds exceeding 10 m s^{-1}.

2. Data and methods

Wind speed (Ws) and direction, SST and sea-surface salinity (SSS), sea bottom temperature (T_b), and currents are measured at the coastal buoy Vida located at 45° 32' 55.68" N, 13° 33' 1.89" E in the entrance of the GOT. Surface water pCO_2 was measured with an autonomous sensor SAMI-CO_2 (Sunburst Sensors LLC) and Aandrea Oxygen optode 3835 was used for O_2 measurements. Wind speed was measured by a Gill 3D sonic anemometer at a height of 5 m. Currents were measured by a Nortek AWAC acoustic Doppler current profiler (ADCP) at one meter depth intervals situated on the sea bed beneath the buoy. Due to the surface echo contamination zone, the upper 4 bins of ADCP data were removed. Data from 3-4 additional bins at mid-depth were also removed as a result of contamination of the ADCP record, although the causes of this contamination could not be determined. For SSS, a Seabird Seacat CT probe was used.

A measure of the thermal forcing on surface ocean pCO_2 (Takahashi *et al.* 2002) is determined as:

$$pCO_{2\text{-}t} = \langle pCO_2 \rangle \exp[0.0423(T_{obs} - T_{mean})] \quad (1)$$

where $\langle pCO_2 \rangle$ and T_{mean} are the mean annual values of pCO_2 and SST at Vida reported by Turk *et al.* (2010). Air-sea CO_2 flux, F_{CO2}, is estimated as:

$$F_{CO2} = k\,S\,(pCO_2 - pCO_{2atm}) \quad (2)$$

where k is the gas transfer velocity and S is the dissolved gas solubility in seawater at in situ temperature and salinity. We use the gas transfer velocity parameterization from Wanninkhof (1992), SAMI-CO_2 measurements of water pCO_2, and atmospheric pCO_2 values from the Lampedusa site in Italy (http://gaw.kishou.go.jp/wdcgg/wdcgg.html) to evaluate this expression.

3. Results and discussion

A Wind rose showing the predominant wind direction at Vida during 2007 and 2008 is presented in Figure 2a. ENE bora wind was present 11.6 % of the time (around 40 days per year). Three representative bora episodes during 2008 (Table 1) of 1.5-2 days duration with ENE wind speeds exceeding 10 m s^{-1} (Figure 2b), acting on different pre-bora ambient conditions are described in more detail below.

Case 1 (21st - 23rd July, 2008): Case 1 represents summer conditions when the water column prior to bora is stratified with SST higher than T_b by about 5°C (Figure 3c). pCO_2 in the surface water (Figure 3b) is above the atmospheric value of 370.4 matm reported at the Lampedusa site on 24th July, 2008. Early in the day of July 21st we observe the onset of ENE bora wind reaching speeds over 10 m s^{-1} (and up to 15 m s^{-1}) which persisted for 1.5 days (Figure 3a). Shortly after the start of bora, pCO_2 and SSS increase by 40 matm and 1 psu, respectively, and the difference between the SST and T_b decreases (Figure 3 b-d). A gradual decrease in O_2 concentration is also observed (Figure 3e). The $pCO_{2\text{-}t}$ decrease (Figure 3b) indicates that factors other than temperature were primarily responsible for the increase in pCO_2

The ocean current response at Vida to this bora event is not simple. Several hours after the onset of strong winds, a strong bottom-layer alongshore (eastwards) inflow is established, followed shortly after by a strong upper-layer offshore (northward) flow directed slightly into the GOT (Figure 4). The latter flow is qualitatively in agreement with what would be expected from Ekman dynamics since the bora are upwelling favorable winds for the Slovenian coast and surface-layer Ekman transport near the coast should be directed to the right of the wind, toward the center of the GOT. However, this surface pulse of current is short-

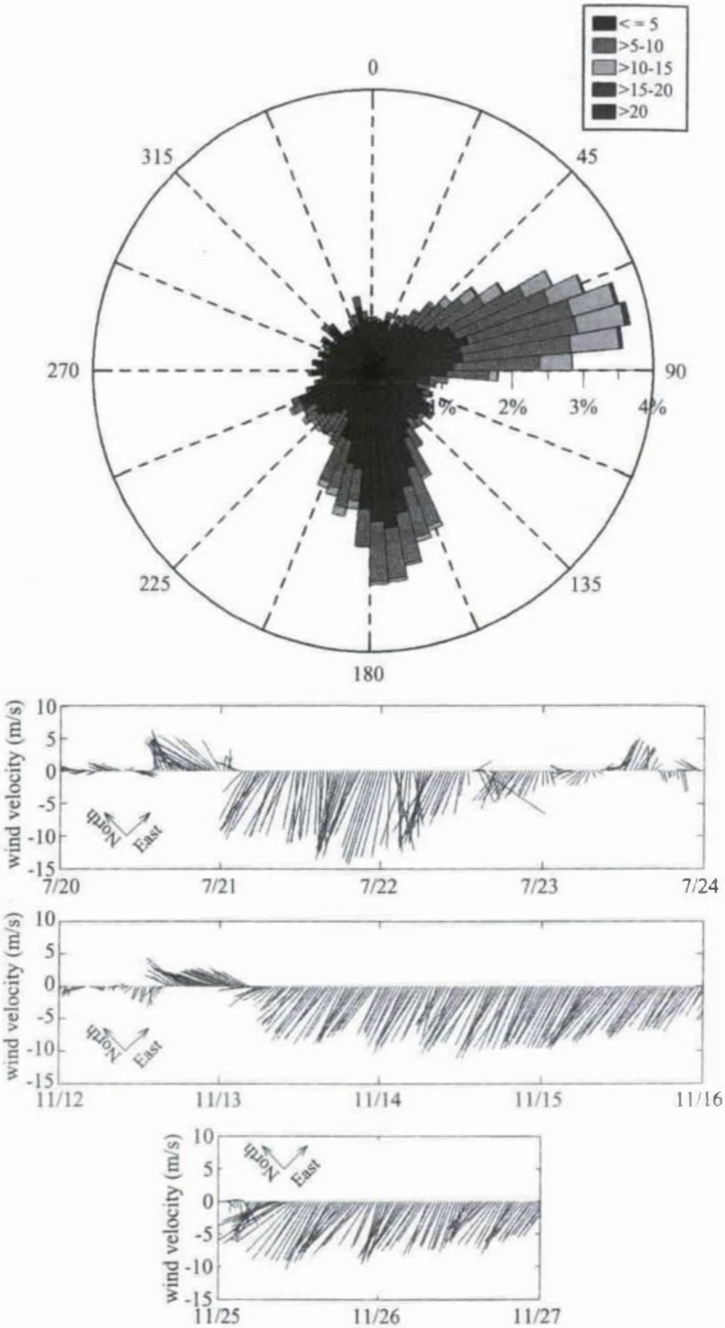

Figure 2 (top panel) Wind distribution at Vida during 2007 and 2008. Bora wind was present 11.6 % of the time (around 40 days per year). (bottom panel) Wind velocity during three bora cases in 2008. Wind sticks indicate the direction that wind is blowing towards.

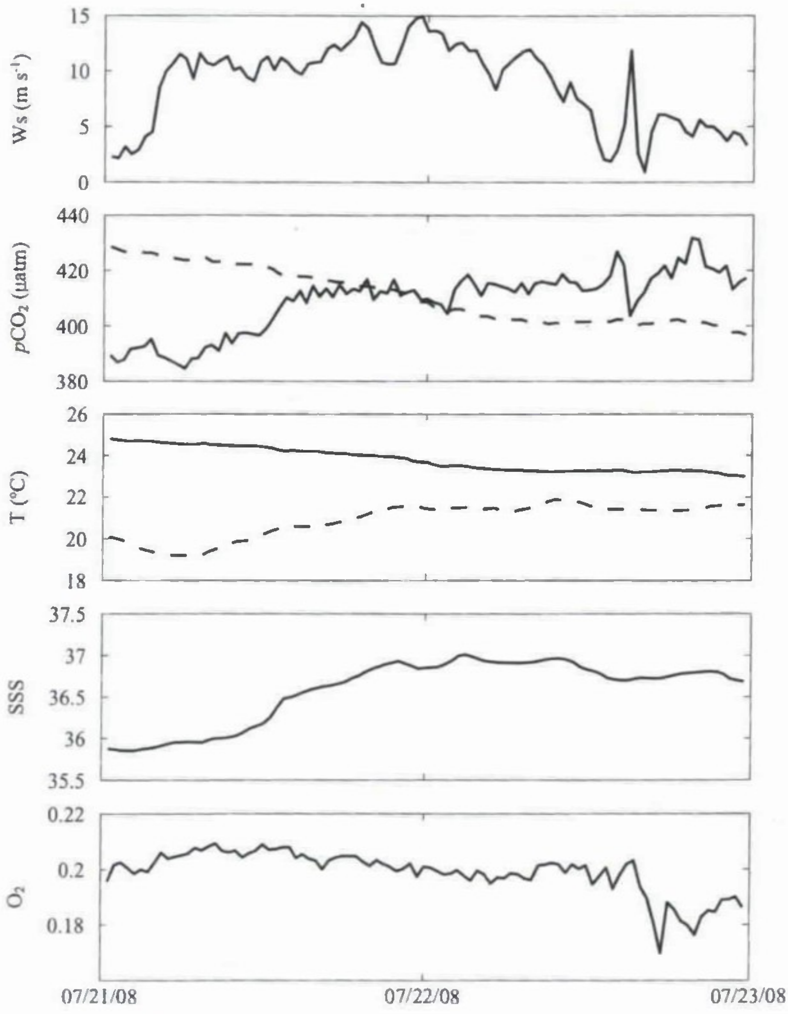

Figure 3 (a) Wind speed, (b) pCO_2 (solid line) and pCO_{2a} (dashed line), (c) SST (solid line) and T_b (dashed line), (d) SSS, and (e) O_2 at buoy Vida during 21st – 23rd July, 2008.

lived and while SSS and surface pCO_2 notably increase during this time, the surface temperature change is much less remarkable. After the upper-layer current pulse has stopped, the bottom-layer alongshore inflow continues with some modulation by the semidiurnal tide and with a steadily decreasing thickness (Figure 4). This latter process is suggestive of vertical mixing as is also the decrease in the temperature stratification observed at Vida (Figure 3).

Without measurements of the vertical and horizontal distribution of pCO_2 there is not enough data to firmly establish the source of the increased pCO_2 for

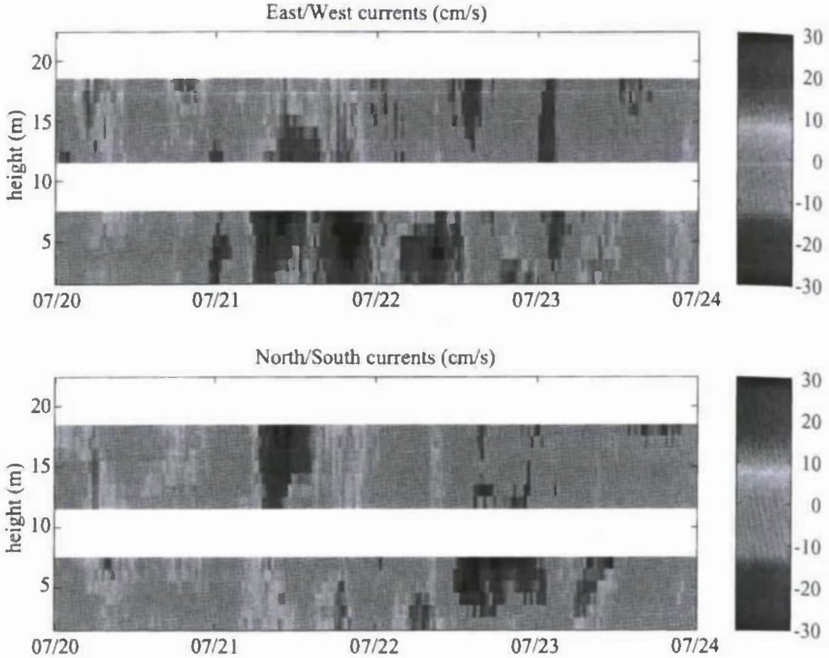

Figure 4 (a) East/West and (b) North/South currents (cm s^{-1}) at buoy Vida during 21st -23rd July, 2008.

this case. Likely, both surface horizontal advection and vertical mixing are playing a role. Horizontal advection could be responsible for the initial change, but waters coming from the Bay of Piran, after the initial upper-layer inflow pulse has stopped, are not expected to carry high SSS and high pCO_2. Upwelling could produce higher pCO_2 values but the temperature change of the surface waters is small and bottom waters are not directed onshore as might be expected from "classic" upwelling. Regardless, the later gradual increases in pCO_2 and SSS and the gradual decreases in stratification and bottom-layer thickness (Figure 3-4) are all consistent with increased vertical mixing due to the continued action of the bora. With increased U_{10} and delta pCO_2, the flux of CO_2 from the ocean into the atmosphere increases (Figure 5) with a maximum of 29.0 mol m^{-2} yr^{-1} and mean value over the event (21st - 23rd July, 2008) of 11.4 ± 7.6 mol m^{-2} yr^{-1}.

Case 2 (13th - 16th November, 2008): Prior to the onset of bora, our data show a thermal inversion with bottom temperatures higher than the SST by about 1.5-2° C (Figure 6c). A similar thermal structure in the fall was reported in the coastal GOT region by previous studies (e.g., Sept.-Oct. 2002 by Boldrin *et al.* (2009)). Surface waters are undersaturated with pCO_2 compared to the atmosphere (379.9 matm at the Lampedusa site on 13th November, 2008). At mid-day of November

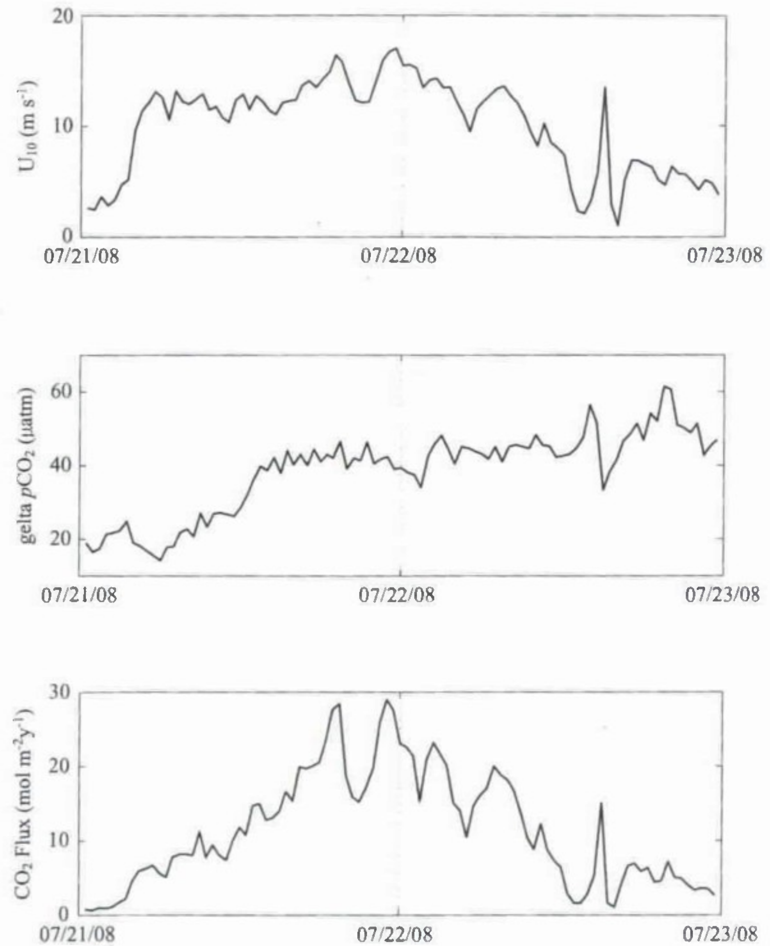

Figure 5 (a) U_{10}, (b) delta pCO_2, and (c) CO_2 flux at buoy Vida during 21st -23rd July, 2008. Positive values indicate flux from the ocean into the atmosphere.

13th, the start of a bora with wind speeds over 10 m s^{-1} is observed and these winds persist for about 2 days (Figure 6a). After about 14 hours, the T_b decreases abruptly and the water column becomes mixed with a nearly homogeneous temperature (Figure 6c). Coincident to this, we observe a sudden increase in pCO_2 (by ~30 matm) (Figure 6b) and decrease in O_2 concentration (Figure 6e), while salinity is only slightly elevated (Figure 6d). $pCO_{2\text{-}t}$ remains almost constant and thus this increase in pCO_2 is not thermally forced.

These changes are strongly indicative of a bora enhanced vertical mixing process where warmer and saltier bottom water with higher pCO_2 and lower O_2 concentrations suddenly mixes with colder and fresher surface water that has

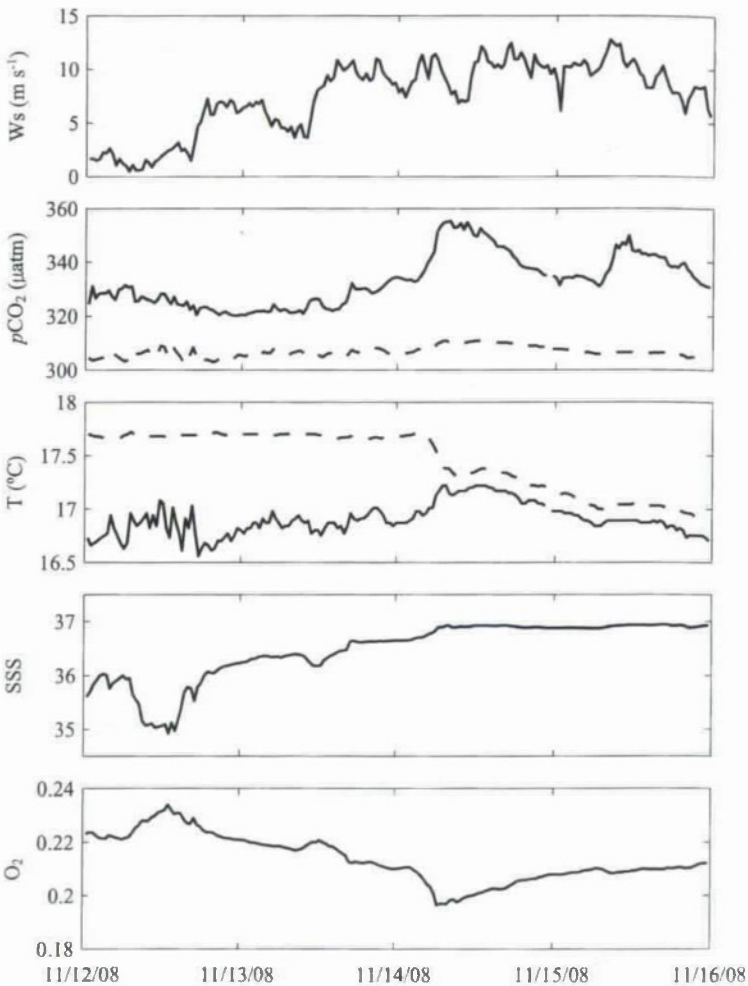

Figure 6 (a) Wind speed, (b) pCO_2 (solid line) and $pCO_{2,a}$ (dashed line), (c) SST (solid line) and T_b (dashed line), (d) SSS, and (e) O_2 at buoy Vida during 12th - 16th November, 2008.

lower pCO_2 and higher O_2 concentrations. ADCP data (Figure 7) are consistent with this explanation as prior to the mixing event the surface flow is characterized by a strong anticyclonic oscillation absent from the bottom flow, but after the mixing event the flow becomes vertically uniform and directed alongshore (eastwards) in an inflowing direction (modulated by tides). The air-to-sea flux of CO_2 increases with the start of high wind (Figure 8) and reaches up to 22.6 mol m^{-2} yr^{-1} in magnitude. However, when the undersaturation of pCO_2 decreases due to increases in surface water pCO_2, the flux magnitude is lowered. Mean flux

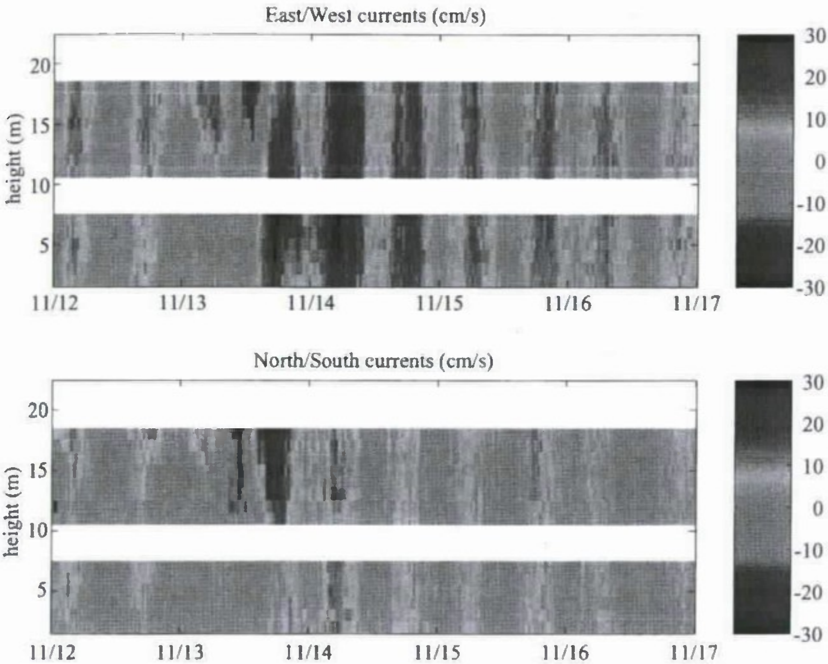

Figure 7 (a) East/West and (b) North/South currents (cm s^{-1}) at buoy Vida during 12th - 16th November, 2008.

over the bora episode, 13th – 16th November, is -10.0 ± 5.6 mol m^{-2} yr^{-1}.

Case 3: (25th – 27th November, 2008). Non-stratified conditions typical for late fall are observed (Figure 9c) prior to the onset of bora and a weak NE to E current is present (Figure 10). Similarly as in Case 2, atmospheric CO_2 value at the Lampendusa site on 27th November, 2008 (379.7 matm) is higher than the surface waters. The onset of bora is observed early in the day on November 25th, reaching wind speeds over 10 m s^{-1} at about mid day (Figure 9a). After about 8 hours of strong wind, sudden increases in pCO_2 (~50 matm), SST and T_b (0.5°C), and SSS are observed, while O_2 concentration decreases. $pCO_{2\text{-}t}$ remains almost constant and therefore the increase of pCO_2 is not temperature related.

ADCP data show vertically uniform currents bursting in an alongshore direction to the NE and E similar to the latter portion of the current response to Case 2 (Figure 10). This barotropic alongshore inflow to the GOT qualitatively agrees with Navy Coastal Ocean Model simulations of strong bora induced flow during 2003 winter (i.e. non-stratified) conditions (see Figure 14 of Martin *et al.* 2006). Thus, water flowing past Vida is expected to have been transported from the south along the edge of a cyclonic gyre occupying most of the northern Adriatic. SST data (not shown) do indicate that waters to the south along the

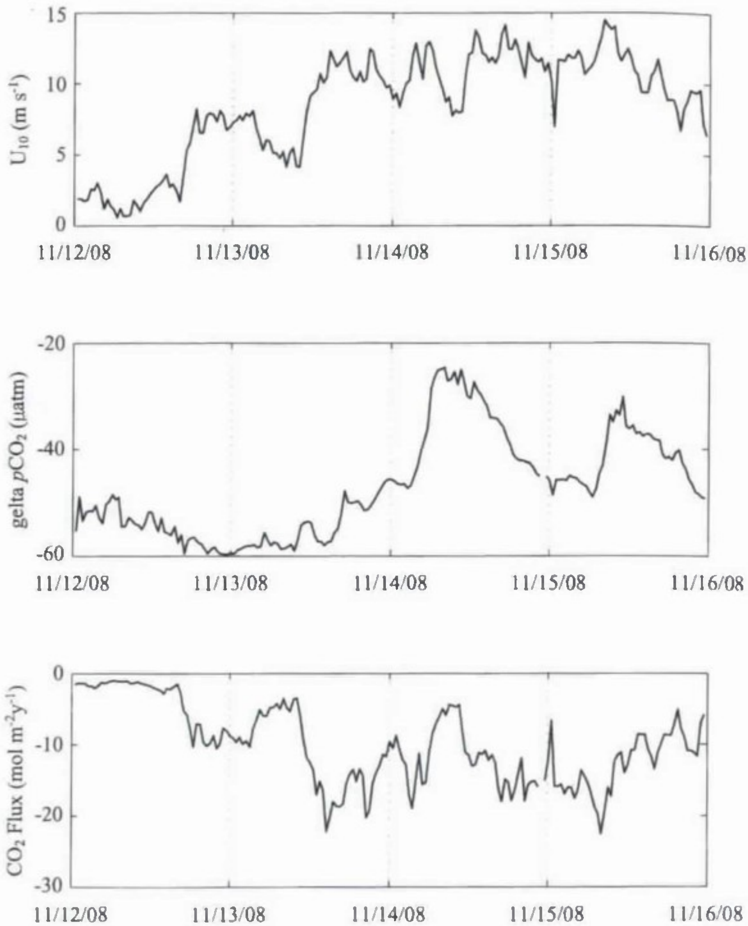

Figure 8 (a) U_{10}, (b) delta pCO_2, and (c) CO_2 flux at buoy Vida during 12th - 16th November, 2008. Negative values indicate flux from the atmosphere into the ocean.

northern Istrian coastline are warmer than waters at Vida and some northward spreading of warmer waters during the bora is observed. The coincident change seen in SSS and pCO_2 suggests that these waters are also saltier and carry higher pCO_2 and therefore the increase in pCO_2 is mainly due to a horizontal advective flux. The change in SSS and pCO_2 is more sustained than the change in temperature because further temperature changes are likely offset by bora cooling of the surface waters.

Similarly as in Case 2, the flux of CO_2 into the ocean initially increases drastically (up to 24.1 mol m^{-2} yr^{-1}) with the start of high wind, but drops to about 5 mol m^{-2} yr^{-1} when the increase of surface water pCO_2 decreases the level of

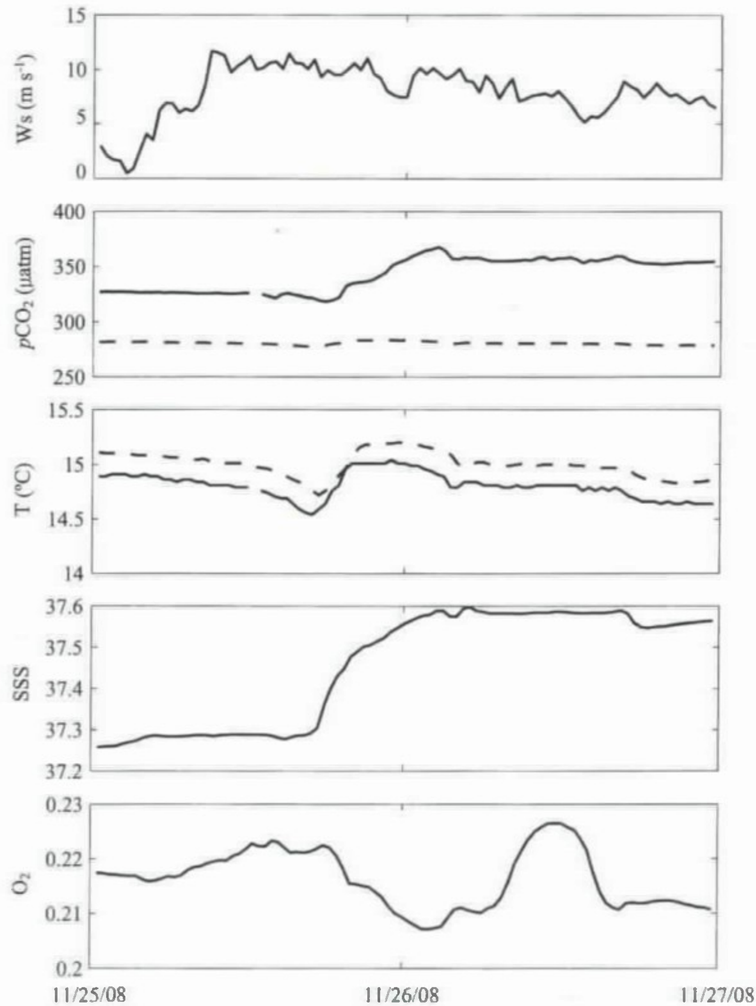

Figure 9 (a) Wind speed, (b) pCO_2 (solid line) and $pCO_{2,s}$ (dashed line), (c) SST (solid line) and T_s (dashed line), (d) SSS, and (e) O_2 at buoy Vida during 25th - 27th November, 2008.

undersaturation (Figure 11). Mean flux over the bora episode, 25th – 27th November, is -8.8 ± 6.8 mol m^{-2} yr^{-1}.

Our results (Table 1) show that CO_2 flux magnitudes during bora episodes peak up to 10 fold (-24.1 mol m^{-2} yr^{-1} to 29 mol m^{-2} yr^{-1}) over the magnitude of the mean annual value of -2 to -3 mol m^{-2} yr^{-1} reported by Turk *et al.* (2010) and have magnitudes about 4 times greater than the annual mean magnitude even when averaged over the duration of the bora events. In the summer time case,

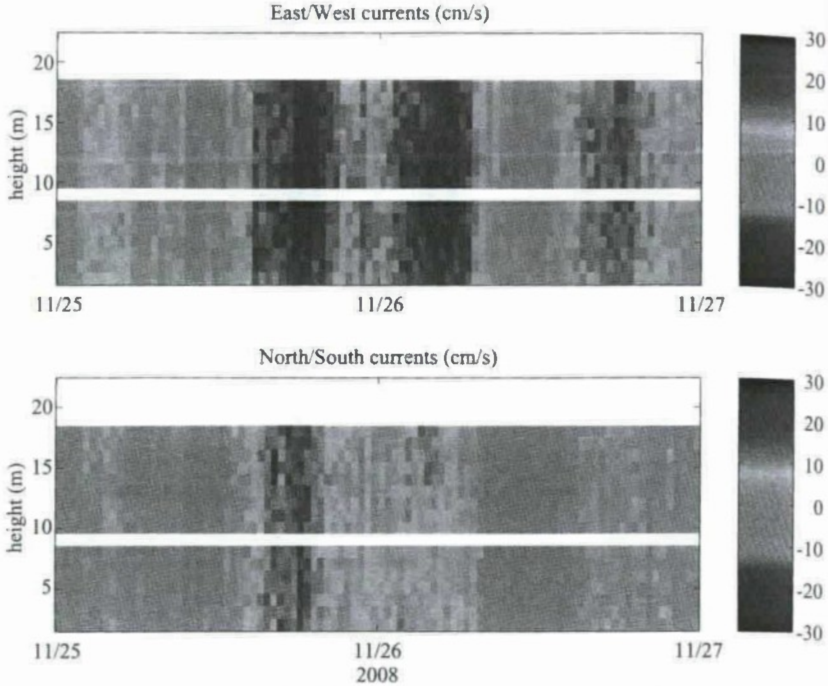

Figure 10 (a) East/West and (b) North/South currents (cm s^{-1}) at buoy Vida during 25th - 27th November, 2008.

when surface waters are saturated with respect to the atmosphere, bora increases the source potential of the GOT by increasing both pCO_2 in the surface waters and transfer velocity. In the other cases, when surface waters are undersaturated, the CO_2 sink to the ocean is enhanced by increases in transfer velocity despite decreasing delta pCO_2 due to increasing surface water pCO_2. Supersaturated conditions in the summer persist only for about two months (Turk *et al.* 2010) and bora events are less frequent during the summer. With 40 days of bora per year and assuming 10% occur over summer, this study implies that bora increases the flux from the atmosphere into the ocean on an annual time scale by 30%. As previous studies show that surface water pCO_2 can decrease during fall conditions (Turk *et al.* 2010) instead of increasing as is found for the cases considered here, the effect of bora wind events on CO_2 flux could possibly be even larger for cases without decreasing delta pCO_2 through the event.

4. Conclusions

In all three studied cases, regardless of pre-bora conditions, bora increased

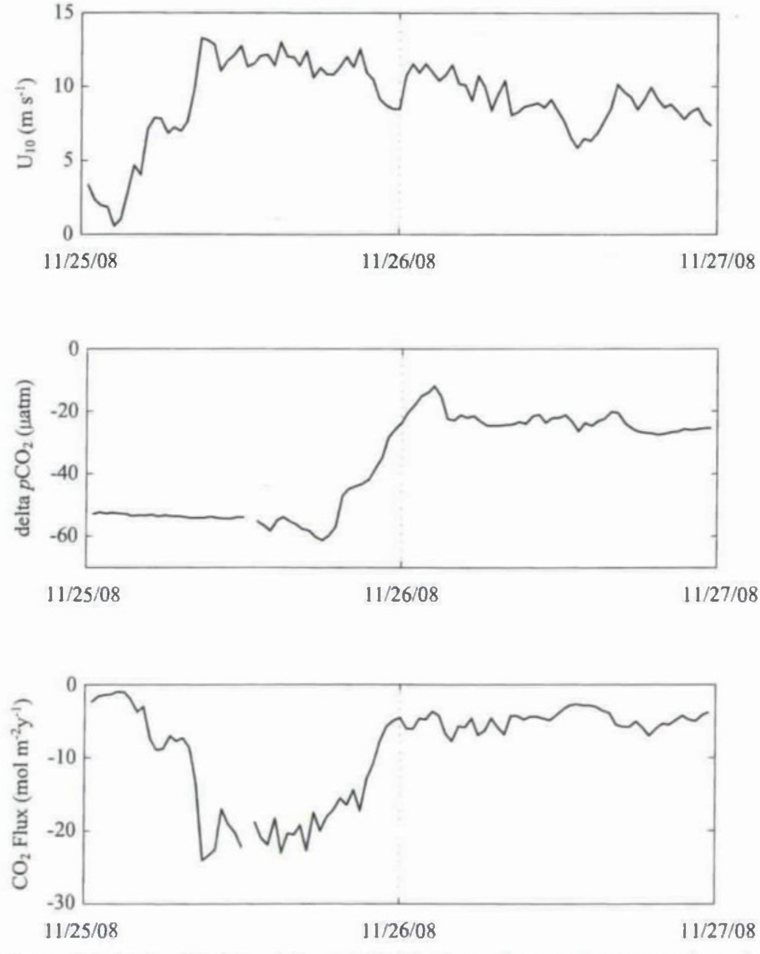

Figure 11 (a) U_{10}, (b) delta pCO_2, and (c) CO_2 flux at buoy Vida during 25[th] - 27[th] November, 2008. Negative values indicate flux from the atmosphere into the ocean.

pCO_2 in the surface water, which is contrary to observations by Turk *et al.* (2010) that show a decrease in surface pCO_2 with the onset of bora. In the three studied cases of this paper, our data show an increase in SSS and a decrease in O_2 concentration coincident with an increase in pCO_2. $pCO_{2\text{-}t}$ values show that the increase in pCO_2 was not mainly temperature controlled. Bora induced circulation was complex during stratified conditions, but bottom-layer flow and flow at all depths during unstratified conditions were always directed alongshore into the GOT.

In a shallow, semi-enclosed basin, such as the GOT, strong wind events can overcome stratification and efficiently mix bottom water pCO_2 with the surface water pCO_2. Winds, especially in shallow coastal environments, also play a strong role in moving different water masses, with different pCO_2 values, around through the local region. Both of these effects highlight the need to better understand and measure horizontal and vertical spatial gradients of oceanic pCO_2 when considering the impact of strong winds on CO_2 flux, as the magnitude (or perhaps even sign) of delta pCO_2 can rapidly change through an event and drastically effect the flux.

Bora was present 11.6% (around 40 days per year) during 2007 and 2008 and we estimate that these winds increased the flux of CO_2 from the atmosphere into the ocean on an annual time scale by more than 30%. Our study contributes to a very limited set of observations currently available on the biogeochemical response to episodic high wind events in coastal areas and their role in CO_2 exchange.

Acknowledgement

We gratefully acknowledge Marine Biology Station Piran (MBS) personnel for help with data, logistics and instrument deployment and W.R. McGillis and R. Wanninkhof for their comments on earlier stages of the work. Support was provided, in part, by Marie Curie FP7-PEOPLE-IRG No. 239465. The work of J. W. Book was supported by the Office of Naval under Program Element Number 0602435N. In memory of our colleague Ziga Dobrajc.

References

Bates, N.R., A.H. Knap, and A. F. Michaels (1998), Contribution of hurricanes to local and global estimates of air-sea exchange of CO_2, *Nature*, *395*, 58-61.

Boldrin, A., S. Carniel, M. Giani, M. Marini, F. Bernardi Aubry, A. Campanelli, F. Grilli, and A. Russo (2009), Effects of bora wind on physical and biogeochemical properties of stratified waters in the northern Adriatic, *J. Geophys. Res.*, *114*, C08S92, doi: 10. 1029/2008JC004837.

Bogunović B., and V. Malačič (2009), Circulation in the Gulf of Trieste: Measurements and model results. *IL NUOVO CIMENTO* Online First, DOI 10.1393/ncc/i2008-10310-9.

Celio, M., V. Malačič, A. Bussani, B. Čermelj, C. Comici, and B. Petelin (2006), The coastal scale observing system component of ADRICOSM: Gulf of Trieste network. *ACTA ADRIAT.*, *47* (Suppl.): 65 - 79. ISSN: 0001-5113 AADRAY.

Dorman, C. E., *et al.* (2006), February 2003 marine atmospheric conditions and the bora over the northern Adriatic, *J. Geophys. Res.*, *111*, C03S03, doi:10.1029/2005JC003134 [printed 112 (C3), 2007].

Jeffries , M. A. and C. M. Lee (2007), A climatology of the northern Adriatic Sea's response to bora and river forcing, *J. Geophys. Res.*, *112*, C03S02, doi:10.1029/2006JC003664.

Kuzmić, M., I. Janekovi= J. W. Book, P. J. Martin, and J. D. Doyle (2006), Modeling the northern Adriatic double-gyre response to intense bora wind: A revisit, J. Geophys. Res., *111*, C03S13, doi:10.1029/2005JC003377 [printed 112(C3), 2007].

Kuzmić, M., and M. Orlić (1987), Wind inducing vertical shearing: Alpex/Metaplex data on modelling exercise, *Ann. Geophys.*, Ser. B, *5*, 103–112.

Malačič, V, M. Celio, B. Čermelj, A. Bussani, C. Comici (2006), Interannual evolution of seasonal thermohaline properties in the Gulf of Trieste (northern Adriatic) 1991-2003. *J. Geophys. Res*, *111*, C08009, 10.1029/2005JC003267.

Malačič, V., and B. Petelin (2006), Numerical modeling of the winter circulation of the Gulf of Trieste (northern Adriatic), *Acta Adriat., 47 (Suppl.), 207-217.*

Malačič, V., and B. Petelin (2009), Climatic circulation in the Gulf of Trieste (northern Adriatic), *J. Geophys. Res*, *114*, C07002, doi:10.1029/2008JC004904.

Martin, P. J., J. W. Book, and J. D. Doyle (2006), Simulation of the northern Adriatic circulation during winter 2003, *J. Geophys. Res.*, *111*, C03S12, doi: 10. 1029/2006JC003511 [printed 112(C3), 2007]

Pullen, J., J. Doyle, T. Haack, C. Dorman, R. Signell, and C. Lee (2007), Bora event variability and the role of air-sea feedback, *J. Geophys. Res*, *112*, C03S18, doi: 10. 1029/2006JC003726.

Signell, R. P., J. Chiggiato, J. Horstmann, J. D. Doyle, J. Pullen, and F. Askari (2010), High-resolution mapping of Bora winds in the northern Adriatic Sea using synthetic aperture radar, *J. Geophys. Res.*, *115*, C04020, doi:10.1029/2009JC005524.

Stravisi, F. (2001), La Bora a Trieste (The bora wind in Trieste), *Unione Meteorologica Friuli-Venezia Giulia, Atti 1 Conv.*, pp. 23-34.

Turk, D., V. Malačič, M. D. DeGrandpre, and W. R. McGillis (2010), Carbon dioxide variability and air-sea fluxes in the northern Adriatic Sea, *J. Geophys. Res.*, *115*, C10043, doi:10.1029/2009JC006034.

Zavatarelli M. and N. Pinardi (2003), "The Adriatic Sea Modeling System: A nested approach" *Annales Geophysicae, 21* (Part 2): 345-364.