Sea response to a sudden strong wind and its predictability

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4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS
Incorporating the 18th International Waves Workshop

CNR ISMAR ISTITUTO DI SCIENZE MARINE

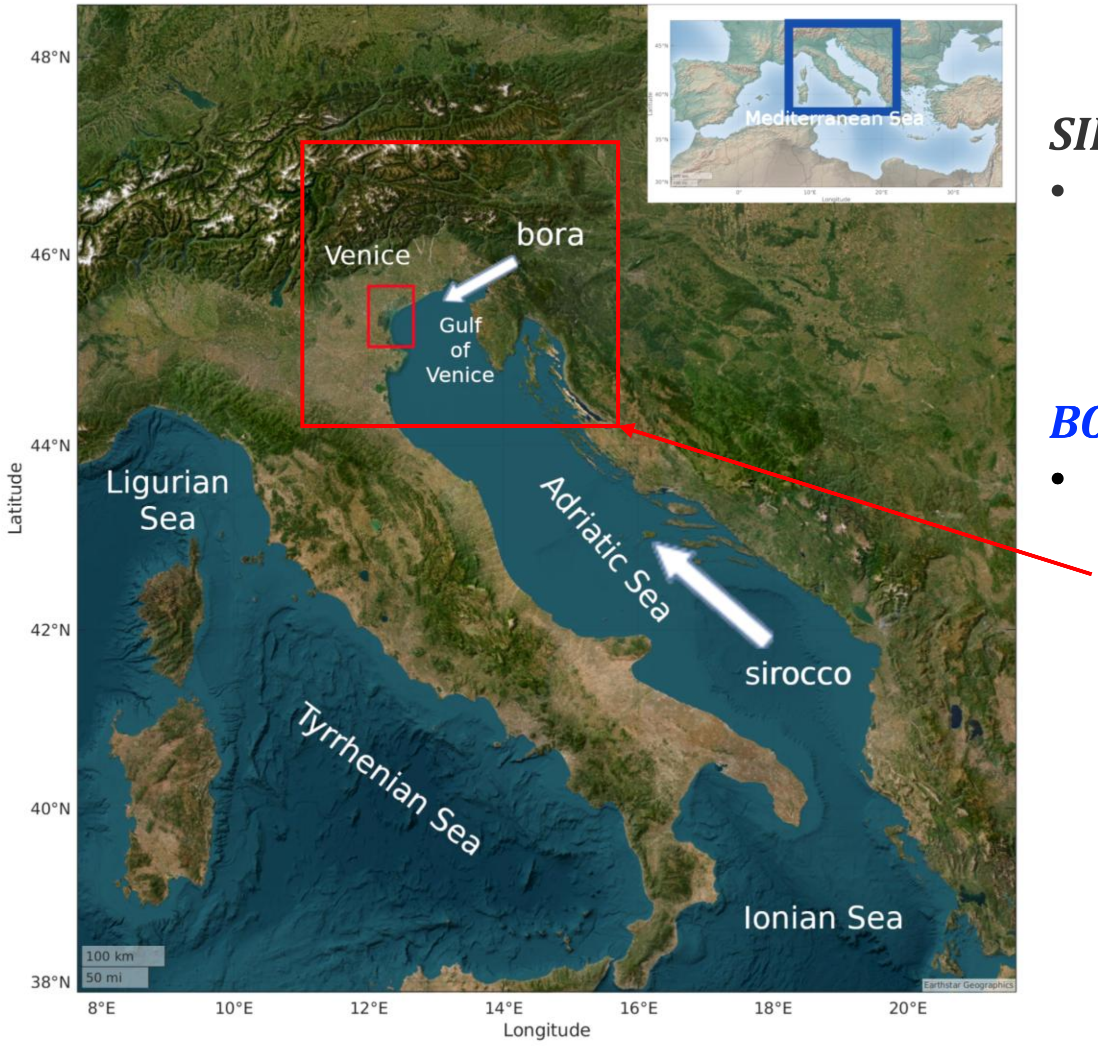
UNIVERSITÀ DEGLI STUDI DELL'AQUILA

Content

1) An intense and sudden wind and its forecasting / modelling

2) What can analysing such an event tell us about air-sea interaction?

The not-so-calm Adriatic Sea



SIROCCO

- It occurs in spring and autumn, rather rarely in gusts, and reaches up to five Beaufort at its peak. Waves up to six meters high. It is responsible of the surge in Venice.

BORA

- Bora winds are strong, cold, and dry northeasterly winds that blow along the Adriatic coast, particularly in winter. They are driven by high-pressure systems over the continent and steep topography, often causing gusts exceeding 200 km/h.

Marine hazards associated with *Bora*

- **Very steep, short-period waves** because of the abrupt onset and strong gusts
- **Strong gust shifts** are particularly dangerous for smaller boats, sailboats, and vessels entering/leaving harbours.
- **Spray and "sea smoke"** (fine droplets whipped up by wind) can reduce visibility.
- In **narrow channels** (e.g., Velebit Channel), the wind can be funnelled and amplified, increasing the risk of capsizing or loss of control.

Sudden onset, often reported, means limited warning time for vessels at sea, making it difficult to adjust sails or course.

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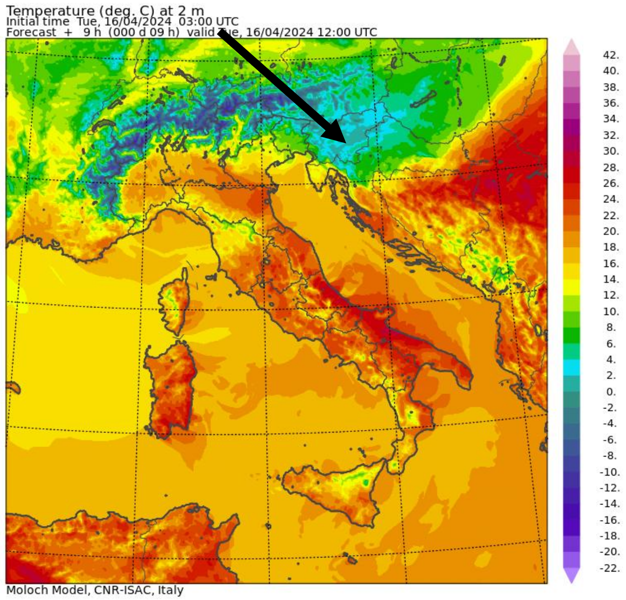
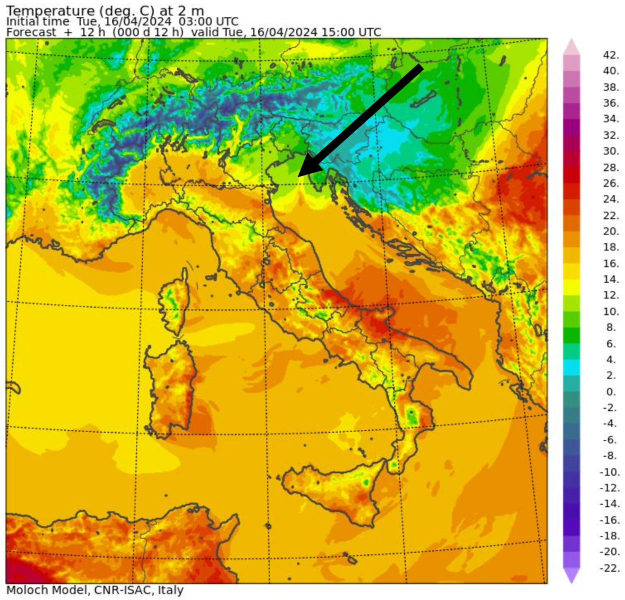
There is no Regulation on ***Wind acceleration***, but we can assume

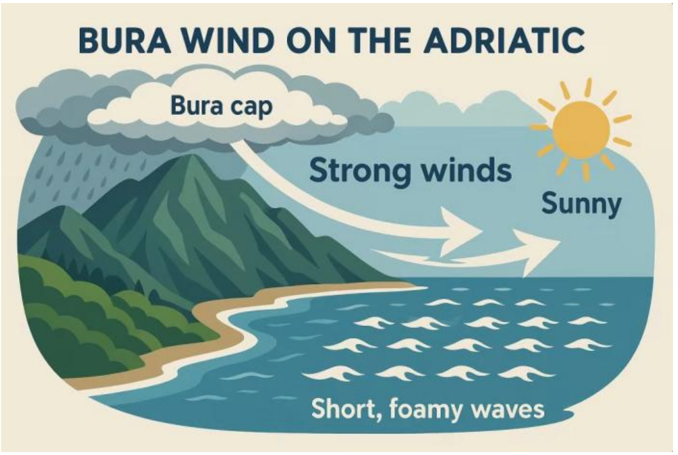
- **Manageable for sailboats**: ≤ +1 m/s per minute (with time to respond)
- **Dangerous/hard to manage**: ≥ +5 m/s in 5 minutes.
- **Unmanageable**: ≥ +10 m/s in < 5 minutes

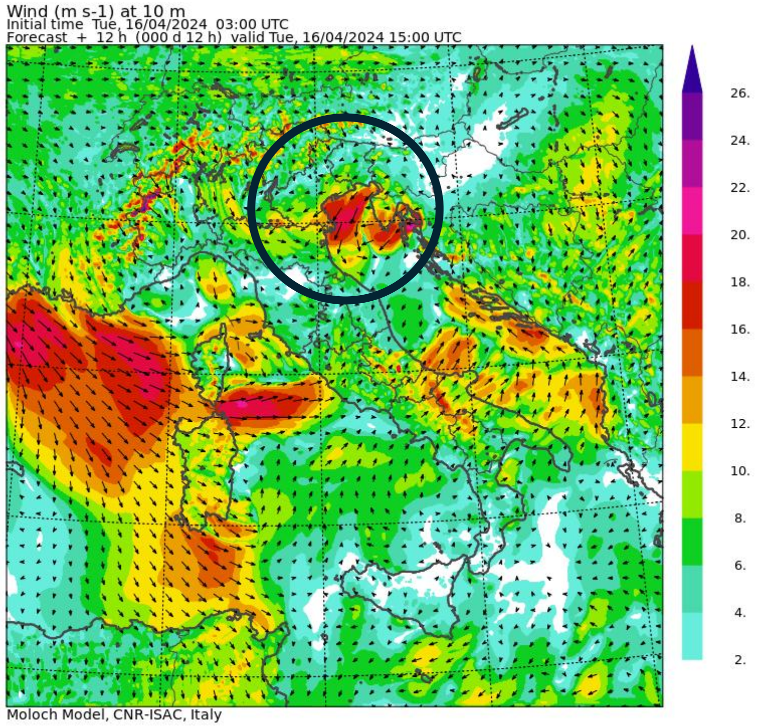
Bora on 16 April 2024



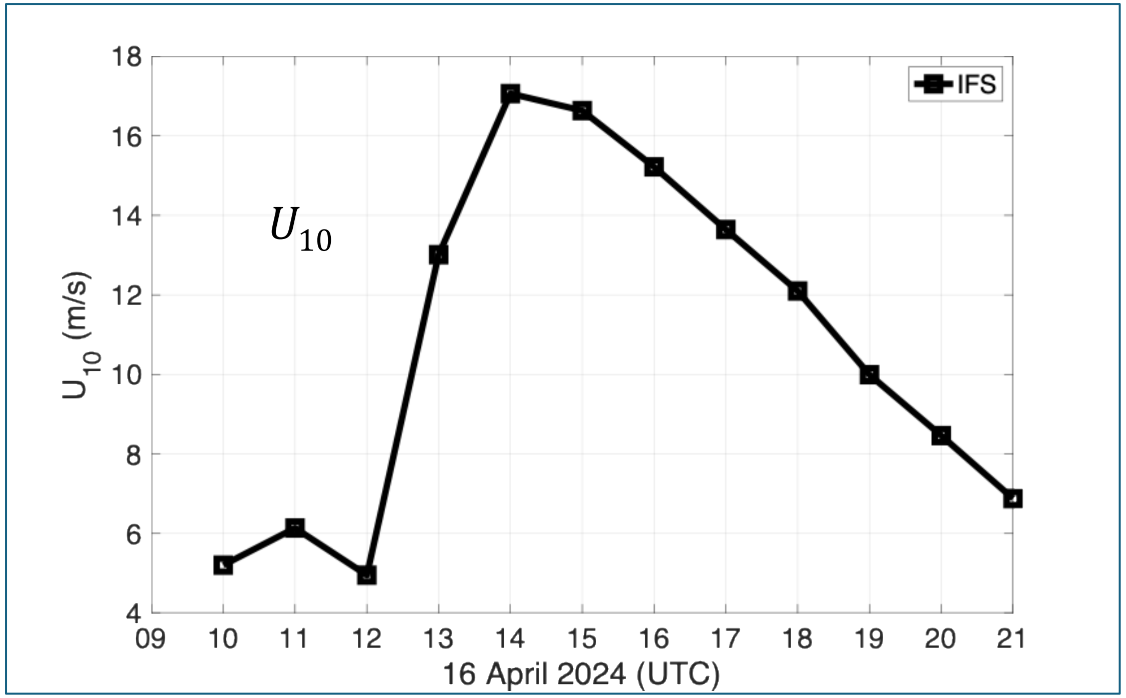


- A **high-pressure** (cold continental) sits inland, and a lower pressure was over the Adriatic Sea.
- The **cold dense air descends** from the elevated inland terrain, flows through mountain gaps and accelerates downhill toward the coast.
- **Strong, gusty, cold, dry downslope wind** that blows from land toward the sea





The local forecast of wind speed

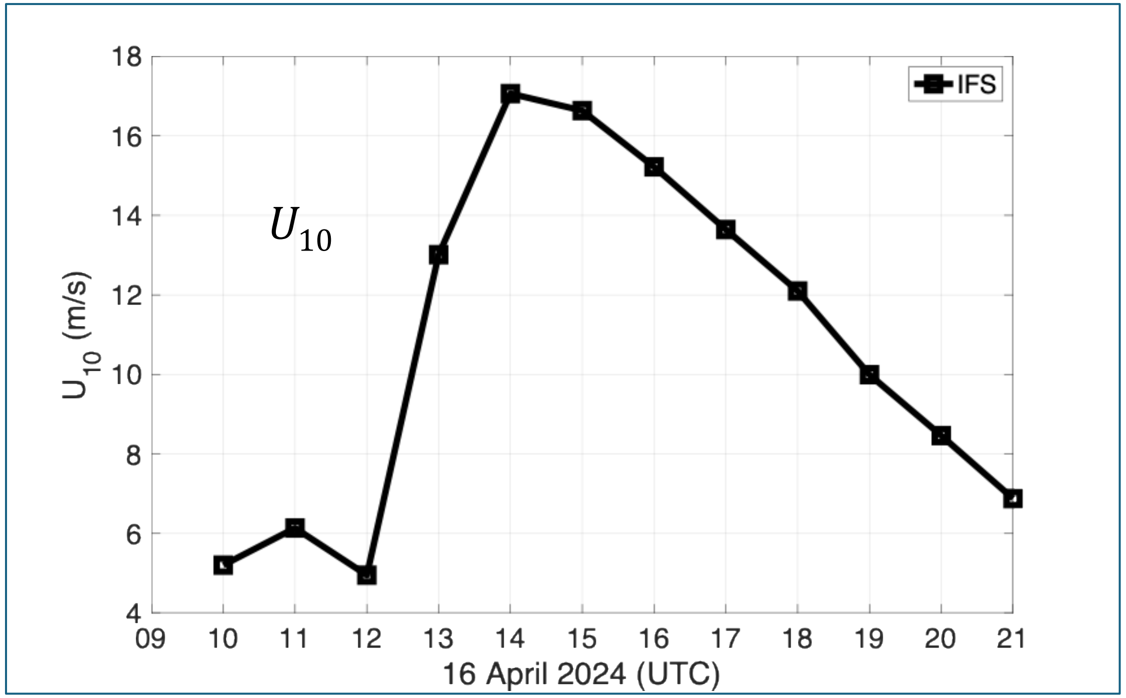


DU / Dt = 8 m/s / 1 hour
12 m/s / 2 hours

Wind acceleration

Manageable

Was it really manageable?



$$DU / Dt = 8 \text{ m/s} \;/\; 1 \text{ hour}$$
$$12 \text{ m/s} \;/\; 2 \text{ hours}$$

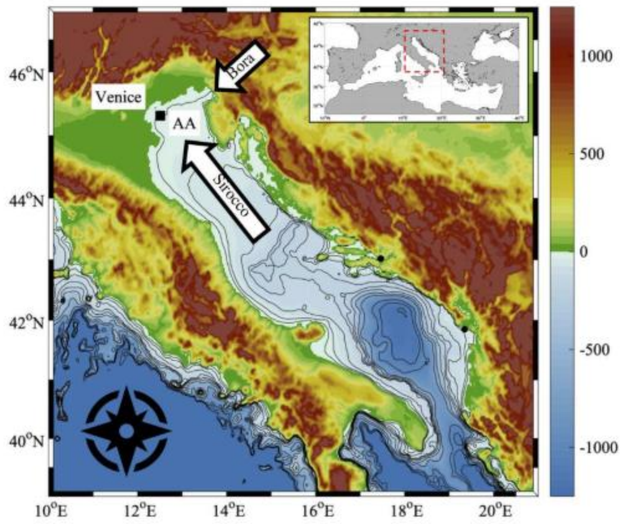
Wind acceleration

A local expert sailor reported that the event on **16 April** caught him and others off guard

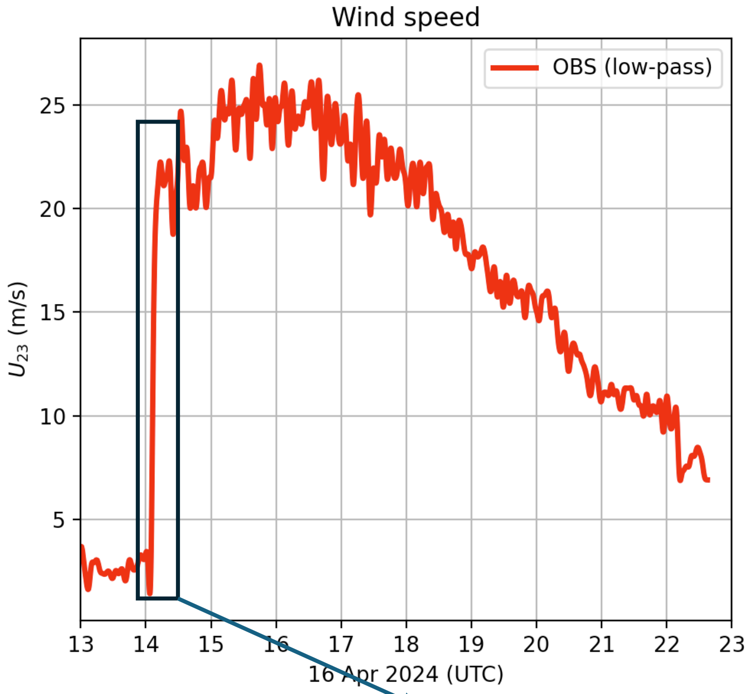
Observations

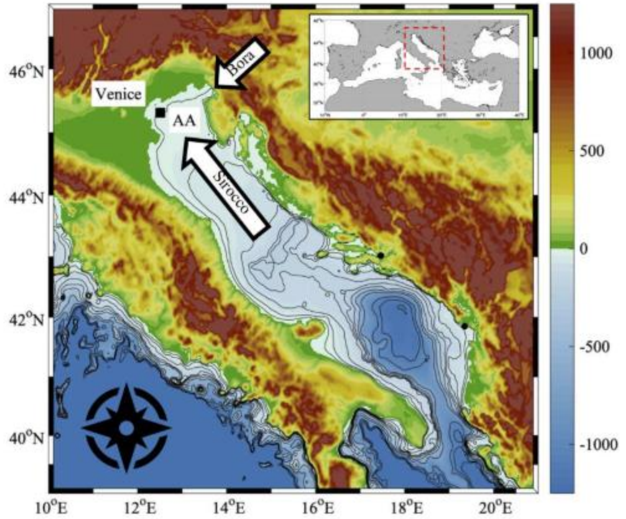
3D wind speed components at 50 Hz

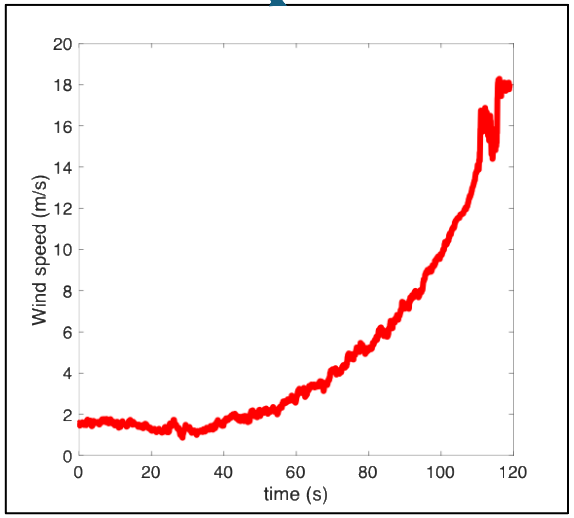
- Mean wind speed
- Friction velocity via eddy covariance



Observations







DU / Dt = 15 m/s / 1’
22 m/s / 8’

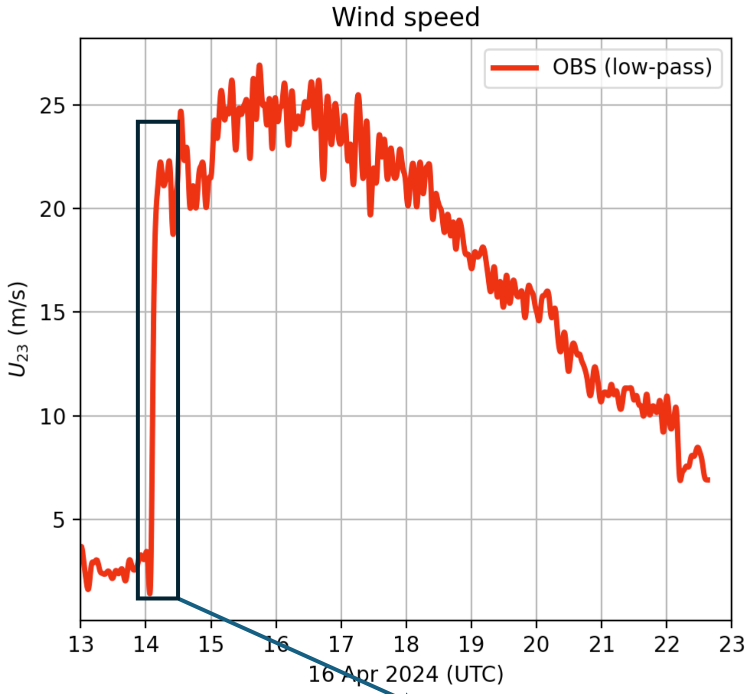
Unmanageable

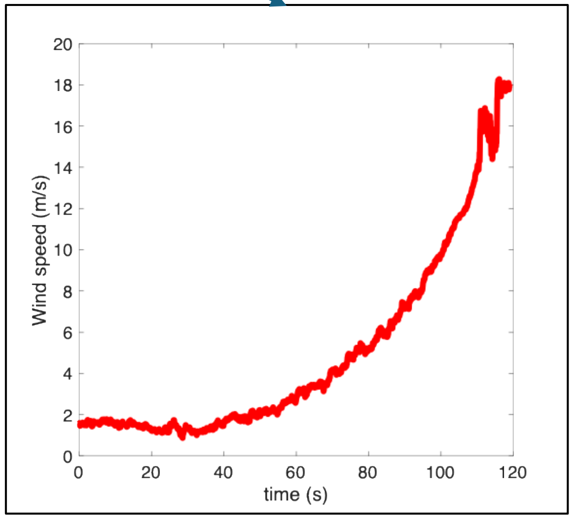
Forecast

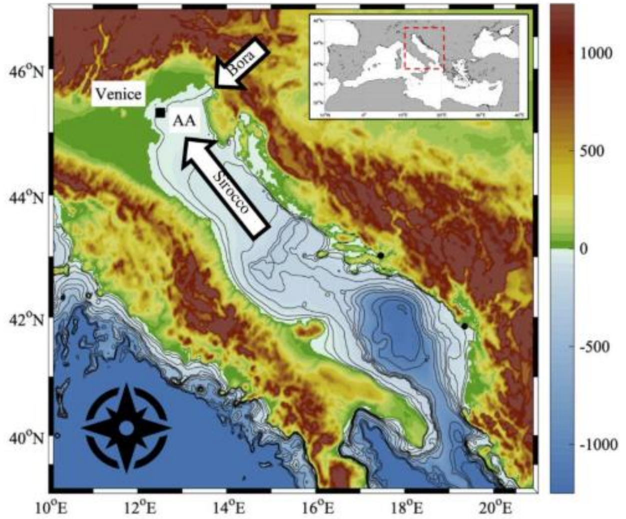
DU / Dt = 8 m/s / 1 hour
12 m/s / 2 hours

Manageable

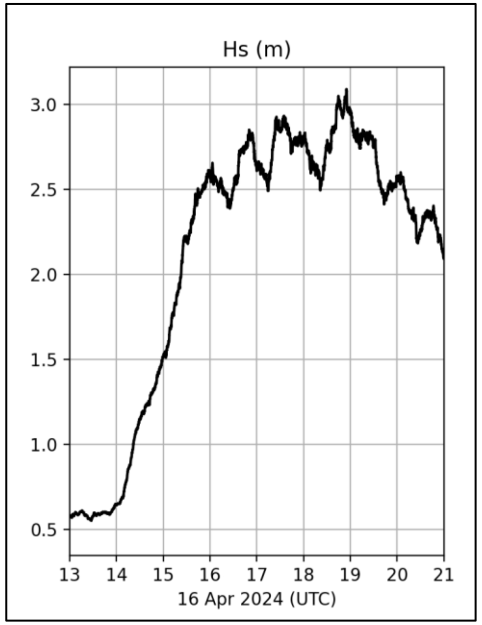
Observations

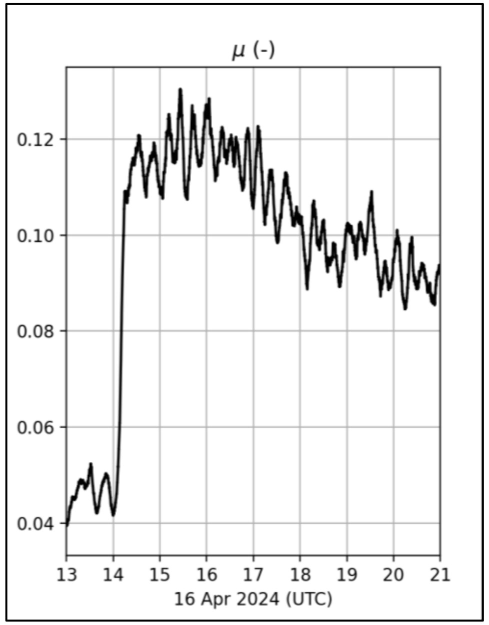






Wave height



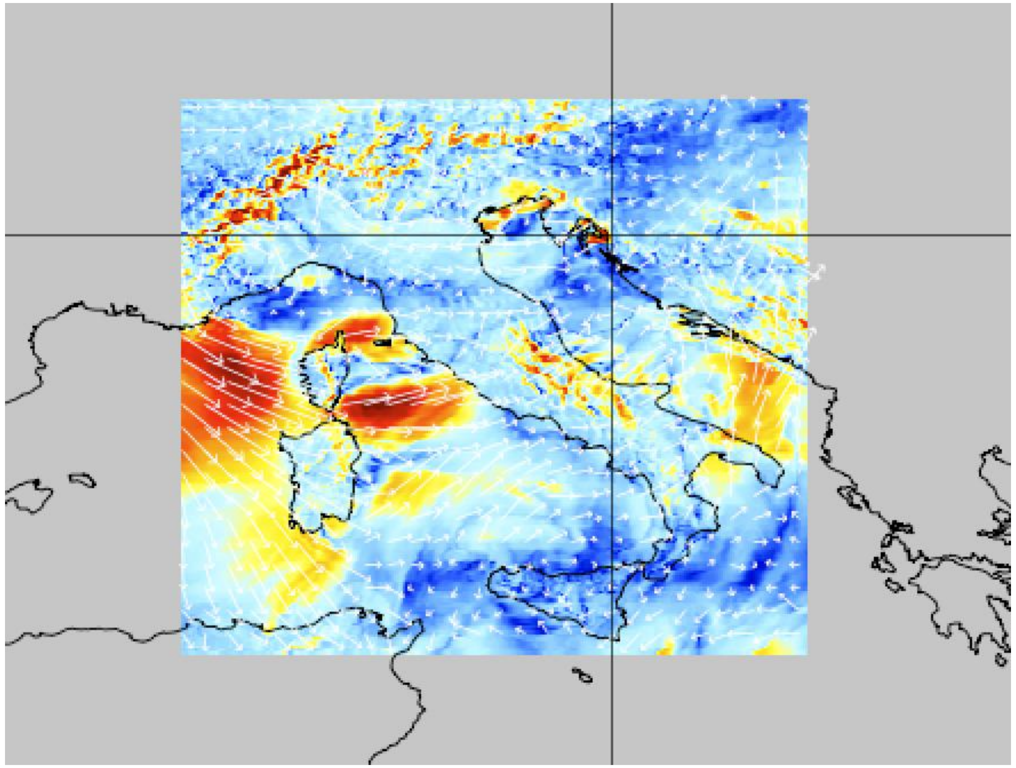


Steepness

Can we model the *Bora* front?

WRF model

- Nested in IFS (ECMWF) boundary conditions
- 3 Km (for topography at the mountain gap + propagation of the front)
- Non-hydrostatic (downslope vertical acceleration)
- Output every 5 min (advancing density currents and gust fronts)
- PBL Mellor-Yamada-Janjic TKE scheme; C_D over sea: Charnock (const. coefficient)



High resolution WRF modelling

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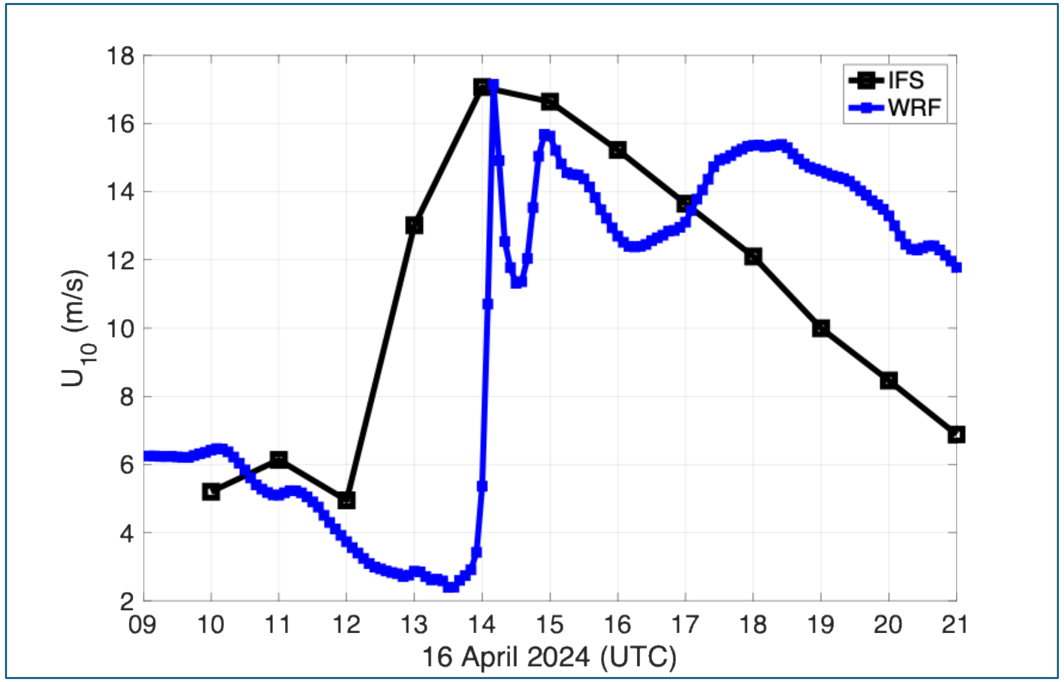

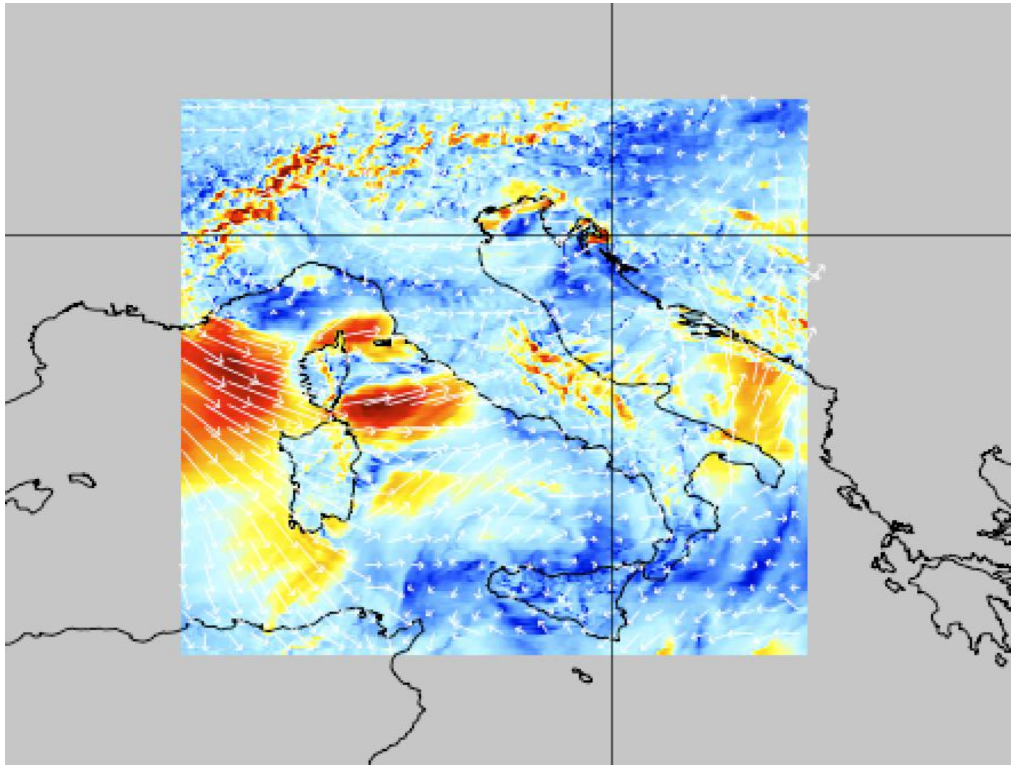

✓ Corrected the time of the onset
✓ Sharper front

The modeled wind acceleration

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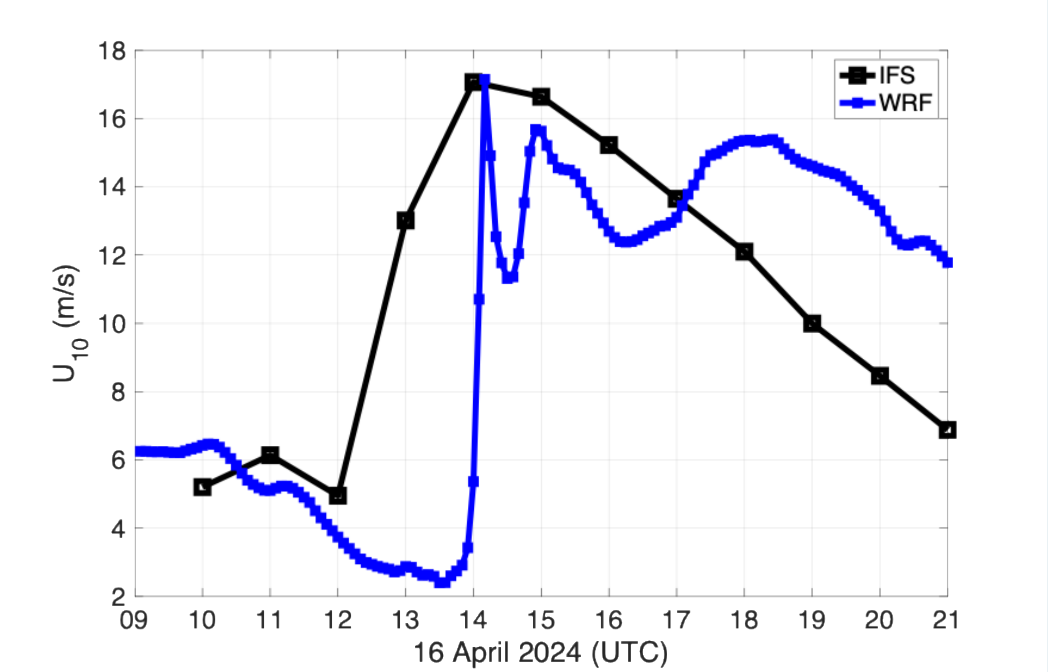

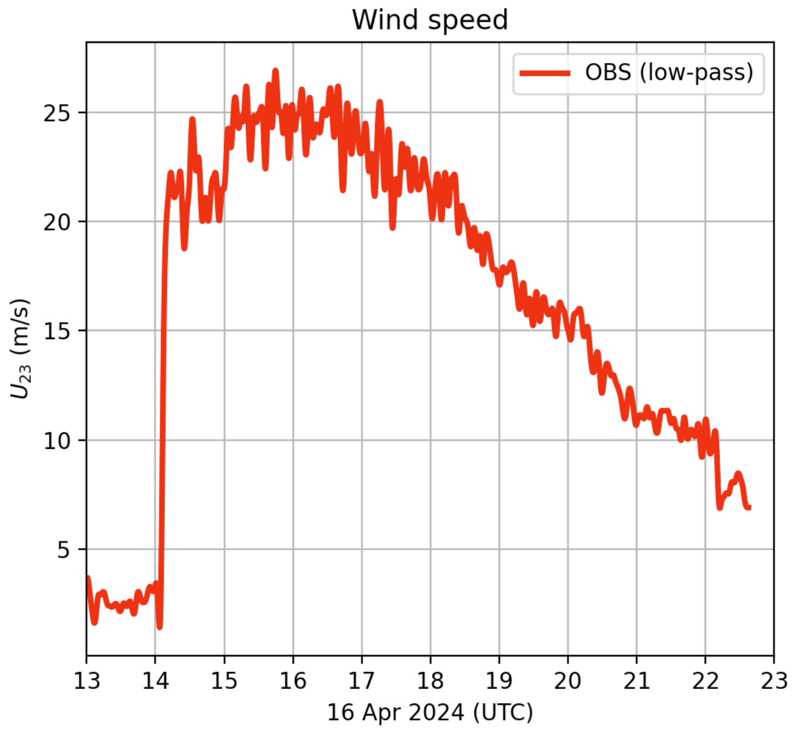

+ 13 m/s in 10’ — WRF → Dangerous

+ 15 m/s in 1’
+ 22 m/s in 8’ — Observations

+ 8 m/s in 1 hour
+ 12 m/s in 2 hours — IFS

Some key points

- *Bora* front can experience **wind acceleration as high as +15 m/s in 1’** (the highest values ever recorded in the North Adriatic)
- *Bora* fronts require mesoscale, **high-frequency modelling with HR** terrain–atmosphere coupling (*Bora* channelling and spilling)

- This is beyond standard forecasting systems (hourly output).
- There are consequences for the **safety of small vessels** (as evidenced by the reports of accidents in the area)

- **Regulations** for marine hazards should be revised
- **Adaptable forecast** for some events

Can we learn about air-sea momentum exchange?

The wind speed $U(z)$ over sea, the way we will use it, is given by

$$U(z) = U_m(z) - U_c \tag{1}$$

with $U_m(z)$ the wind speed measured at some height z above the mean sea level and U_c the surface current component in the wind direction. For $U(z)$ we assume the stability corrected logarithmic wind profile of the Monin–Obukhov similarity theory (Monin and Obukhov, 1954)

$$U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right], \tag{2}$$

where u_* is the friction velocity, defined as the square root of the (kinematic) turbulent stress $\tau = -\langle u'w' \rangle$, with u' and w' the fluctuations in the along-wind and vertical wind components. z_0 is the roughness length (the height at which

A common way to non-dimensionalise z_0 is due to Charnock (1955) who wrote

$$z_0 = \alpha \frac{u_*^2}{g} \tag{3}$$

with g the acceleration of gravity (for which we used 9.81 ms^{-2}). The non-dimensional roughness α is called the Charnock parameter. To remove the (gener-

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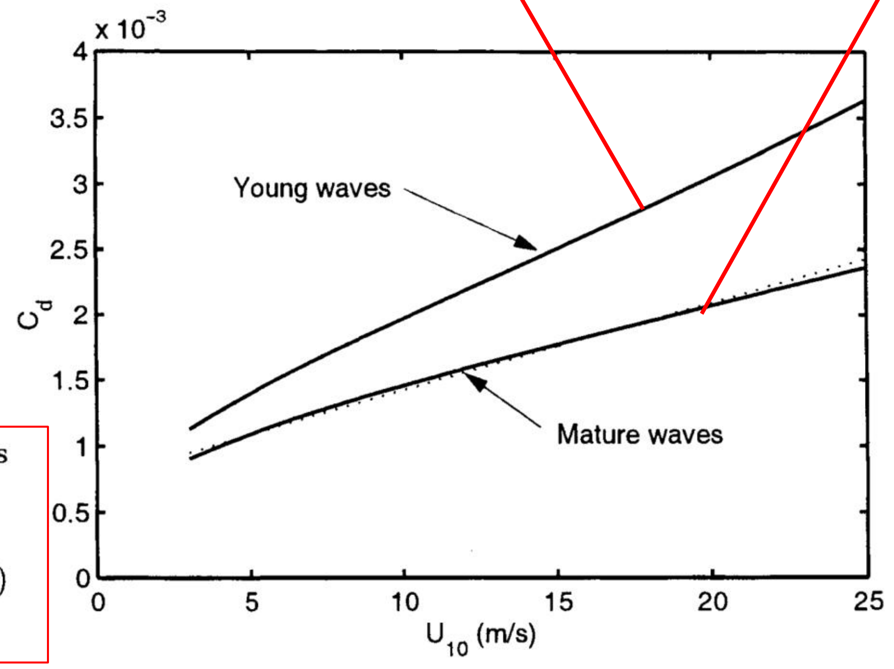
Experimental data suggests that in such cases the Charnock parameter becomes a function of the inverse wave age

$$z_0 \frac{g}{u_*^2} = a_1 \left(\frac{u_*}{C_p}\right)^m \quad (5.15)$$



$$\tau = \rho_a C_d U_{10}^2$$

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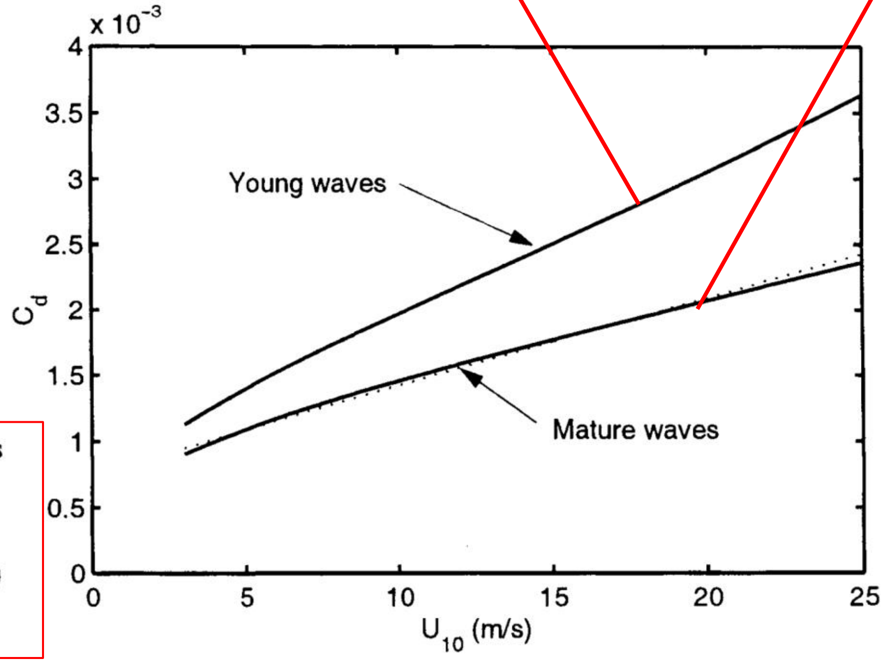

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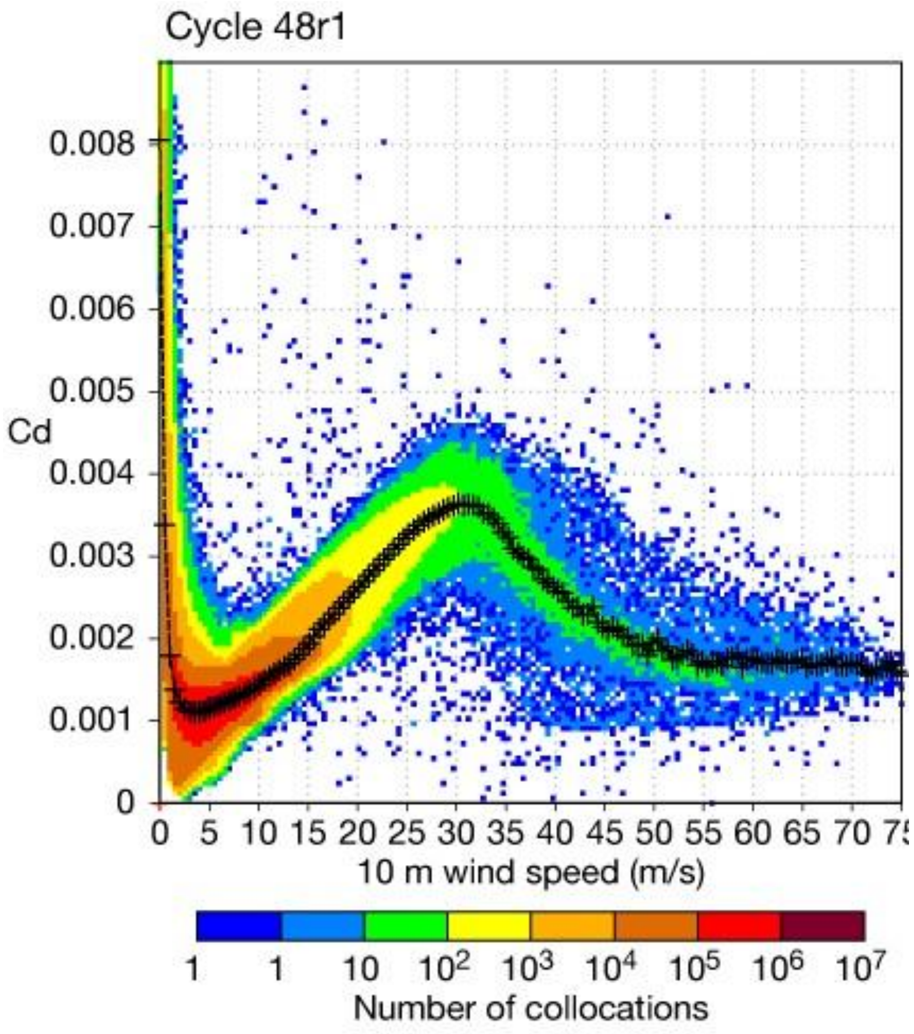
Part, e.g., of the **COARE** model

Drag reduction at high winds



- There is a decoupling between near-surface winds and the ocean surface for strong wind situations, > 30 m/s
- This results in a reduction of the transfer of momentum from the atmosphere into the wave fields.
- Based on this evidence, ECMWF adapted the model to reduce the drag coefficient (Cd), which relates the resistance of the water surface to wind, for high winds.

Effect of surface and sub-surface foam

scientific reports

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Reduction of air-sea momentum flux due to whitecap residual foam observed during a laboratory experiment

Meng Lyu[1]✉, Henry Potter[1], Peisen Tan[2], Brian K. Haus[2], Milan Curcic[2] & Xin Yang[3]✉

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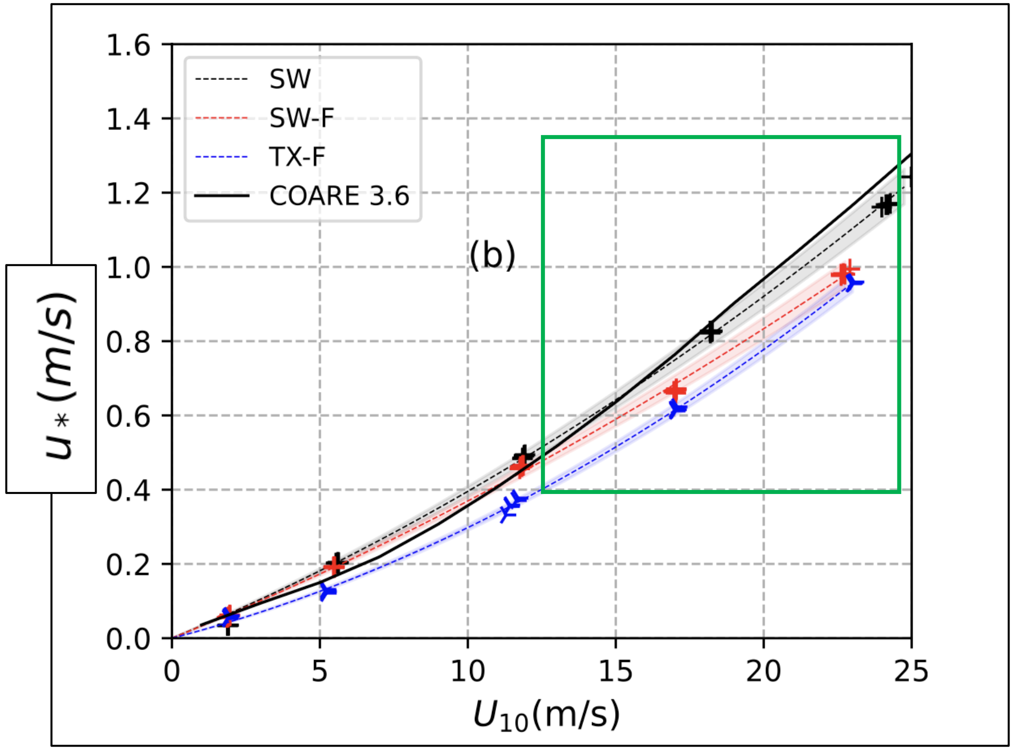

Clean water

Water with bubbles

Water with surfactants

Effect of surface and sub-surface foam

scientific reports

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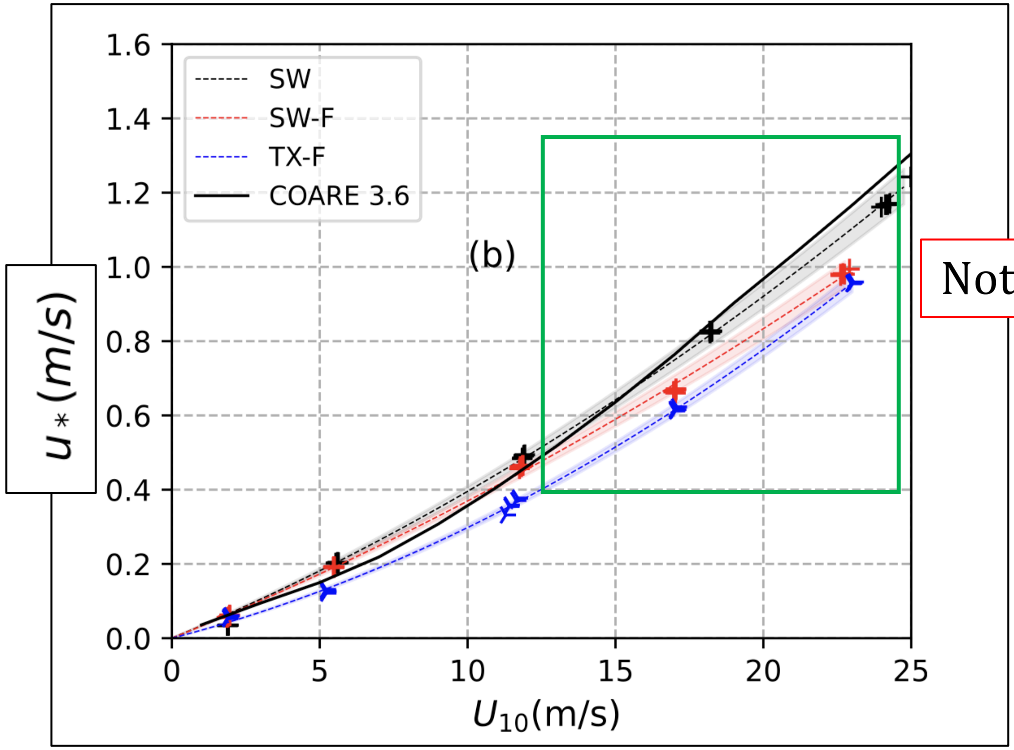
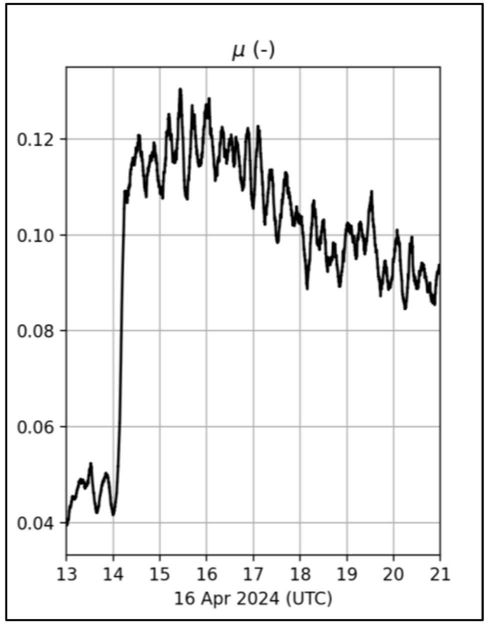


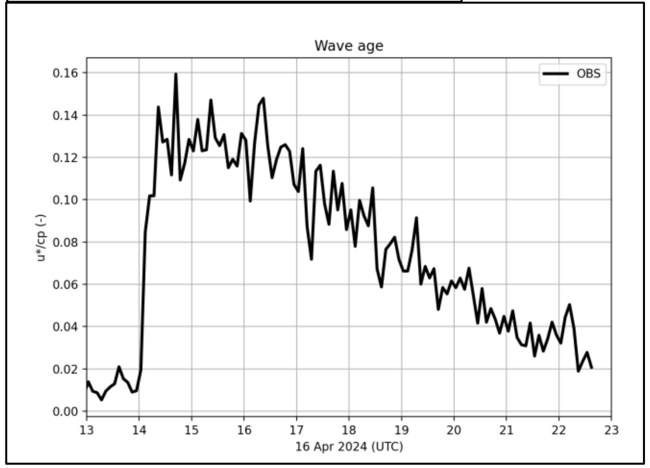
Not parametrized in **COARE**

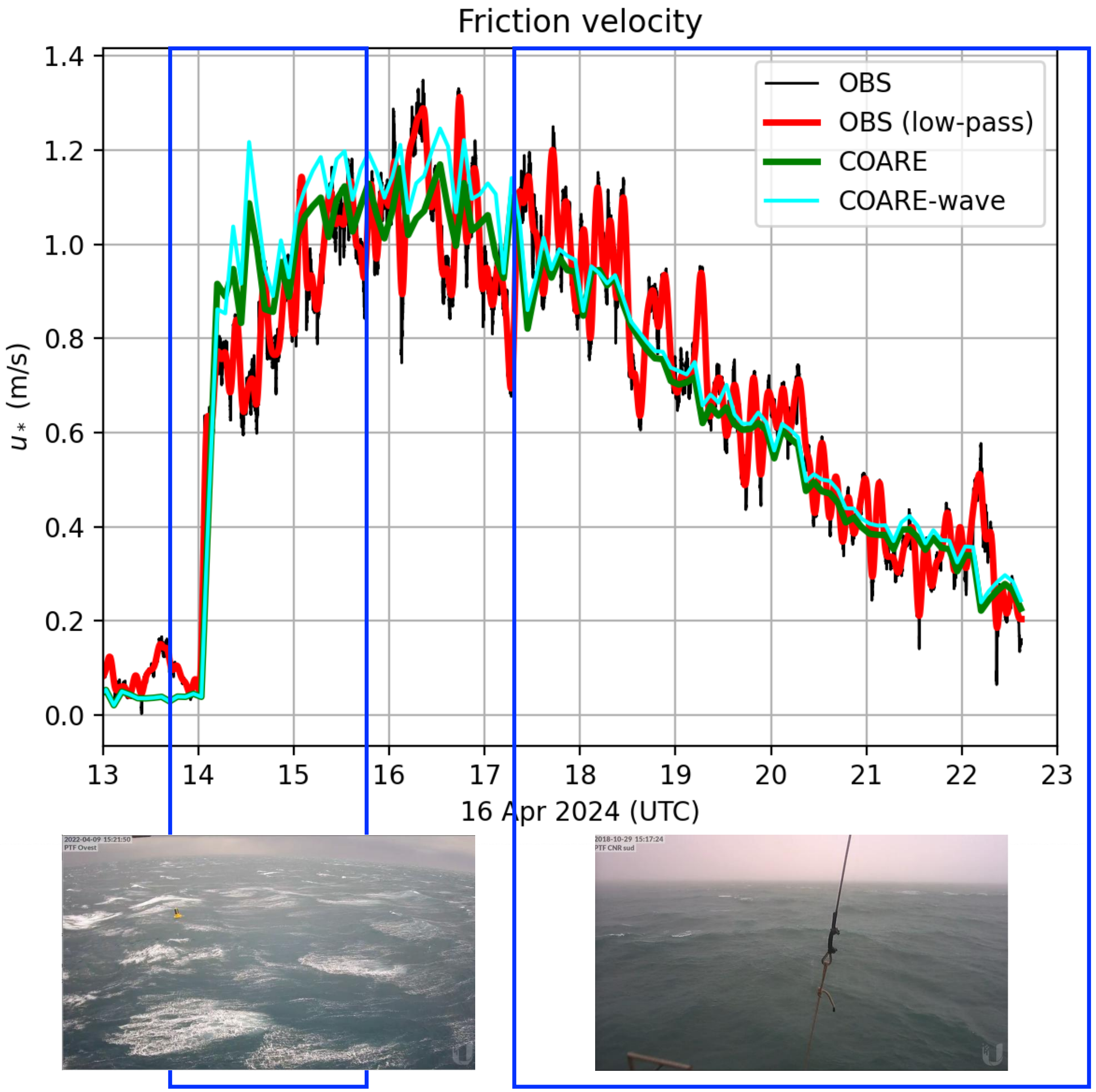
the natural dynamics of wind-driven momentum exchange, as previously demonstrated by[20,41]. When foam is introduced, momentum transfer is reduced at all frequencies. This suggests foam, acting as a viscoelastic medium at the water's surface, influences how the wind interacts with the underlying water by creating a buffer that dampens the momentum exchange across the interface. It has previously been demonstrated that reduction in friction velocity can be linked to decrease in the flux at both isolated and broad frequencies due to gustiness[43], wind-waves angle[44,45], and flow separation[25] but never before has this been linked to surface foam.

Friction velocity: OBS vs. COARE



Wave age

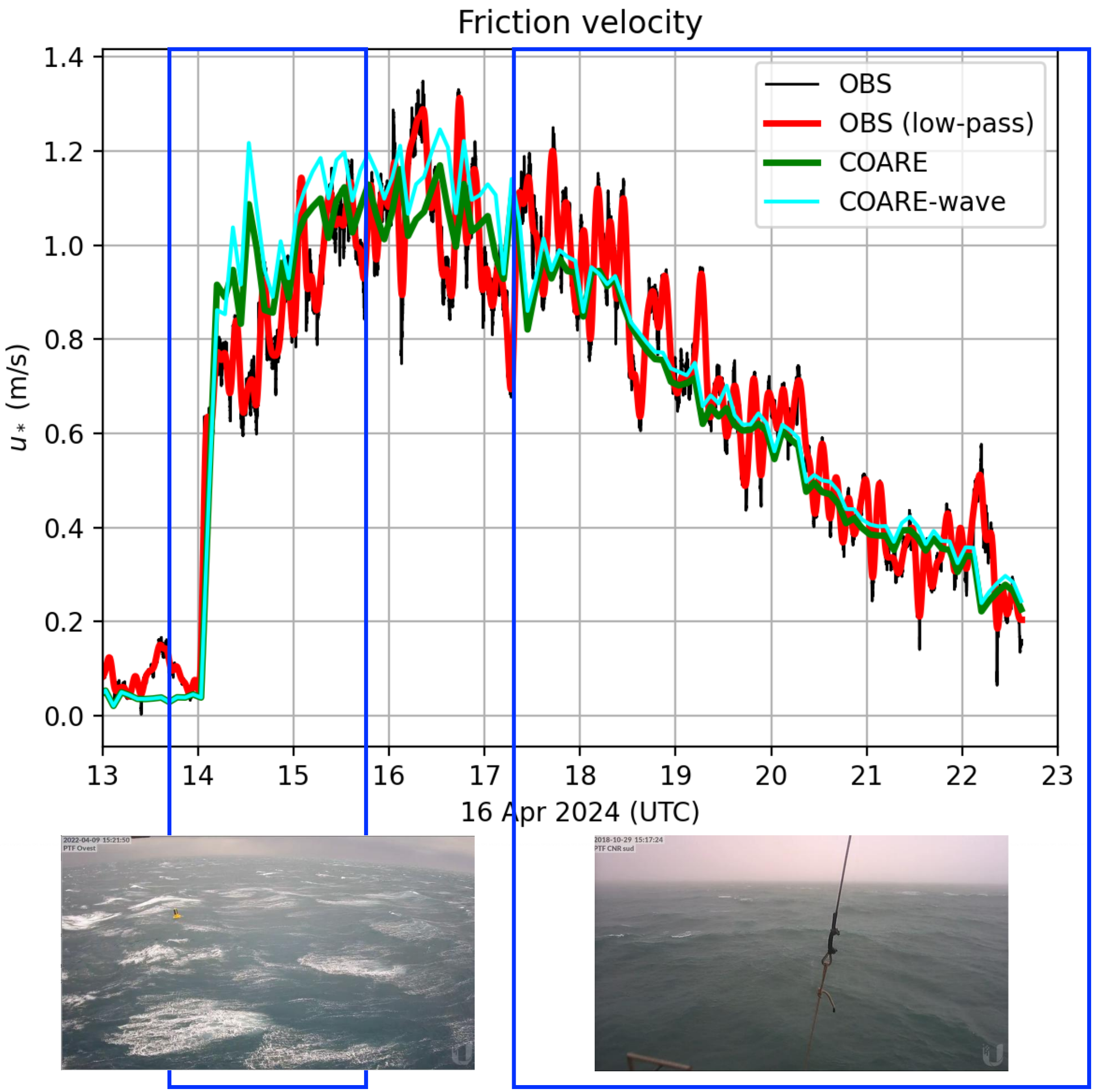




Growth

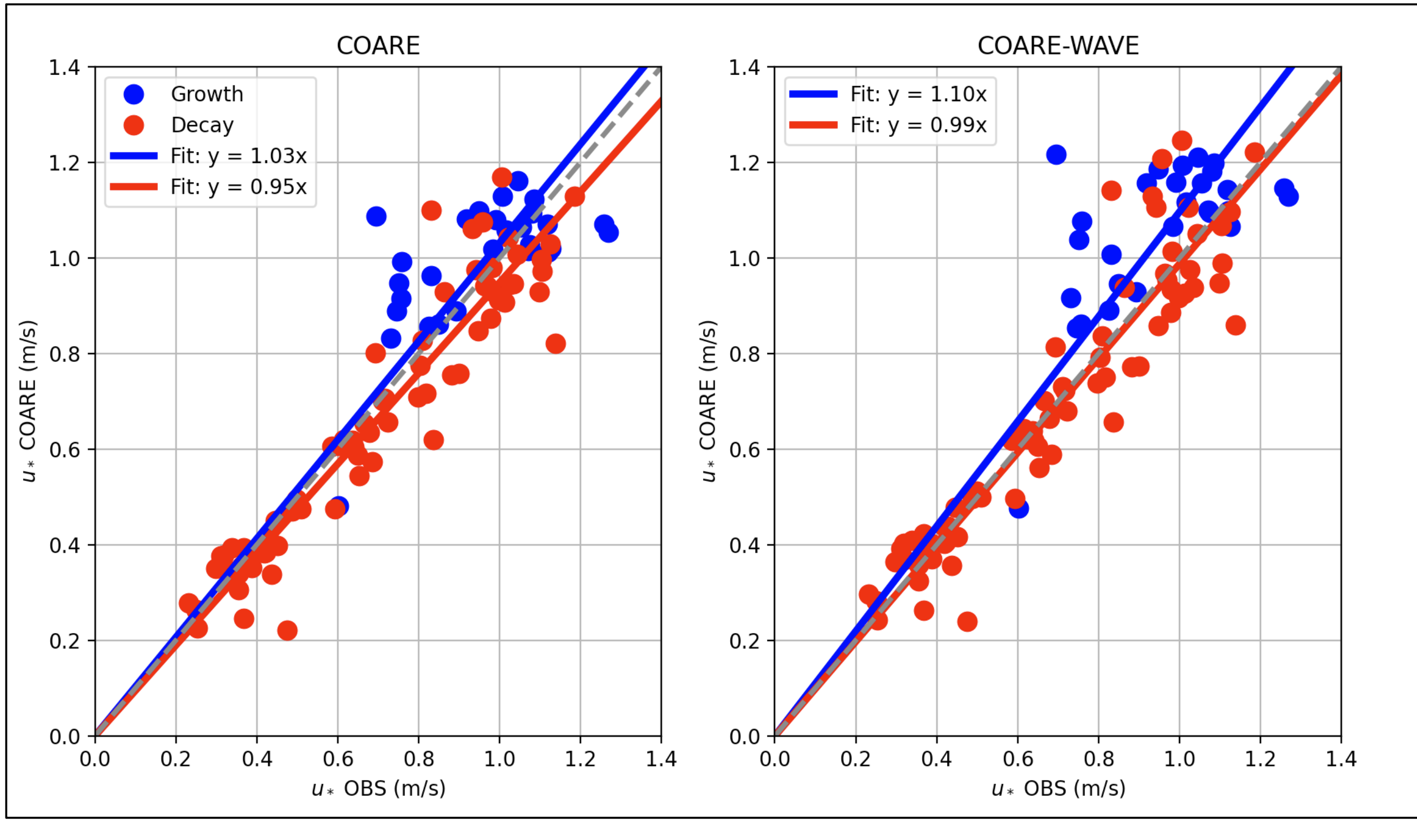
Decay

Friction velocity: OBS vs. COARE



Growth

Decay



Observations: Growth u* < Decay u*
COARE: Growth u* > Decay u*

To conclude

- We have observed that wind **stress,** also at **moderate-to-high winds (15-20 m/s),** may be reduced by the presence of active and residual surface **foam** and sea spray

- This effect is particularly evident in very active and steep sea states that are prone to **breaking,** like *Bora* onset

- These processes affect not only local **wave growth** but also **storm surge** prediction and coupled atmosphere–ocean models.

- More field tests are **required to confirm** this result and the lab evidence

Thank you for the attention

Sudden growth and warning

Marine Structures 23 (2010) 1–21

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/marstruc

Review

Wave forecasts and small-vessel safety: A review of operational warning parameters

Bárður A. Niclasen[a,*], Knud Simonsen[a], Anne Karin Magnusson[b]

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Journal of Operational Oceanography

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjoo20

Development of small vessel advisory and forecast services system for safe navigation and operations at sea

component of the generic wave parameter in 6 h. If the parameter value at the initial time is (‘ξ_i’) and that after 6 h is (‘ξ_f’), then it can be mathematically represented as

$$Z_{6h} = \frac{|\xi_i - \xi_f|}{|\xi_i|} \qquad (3)$$

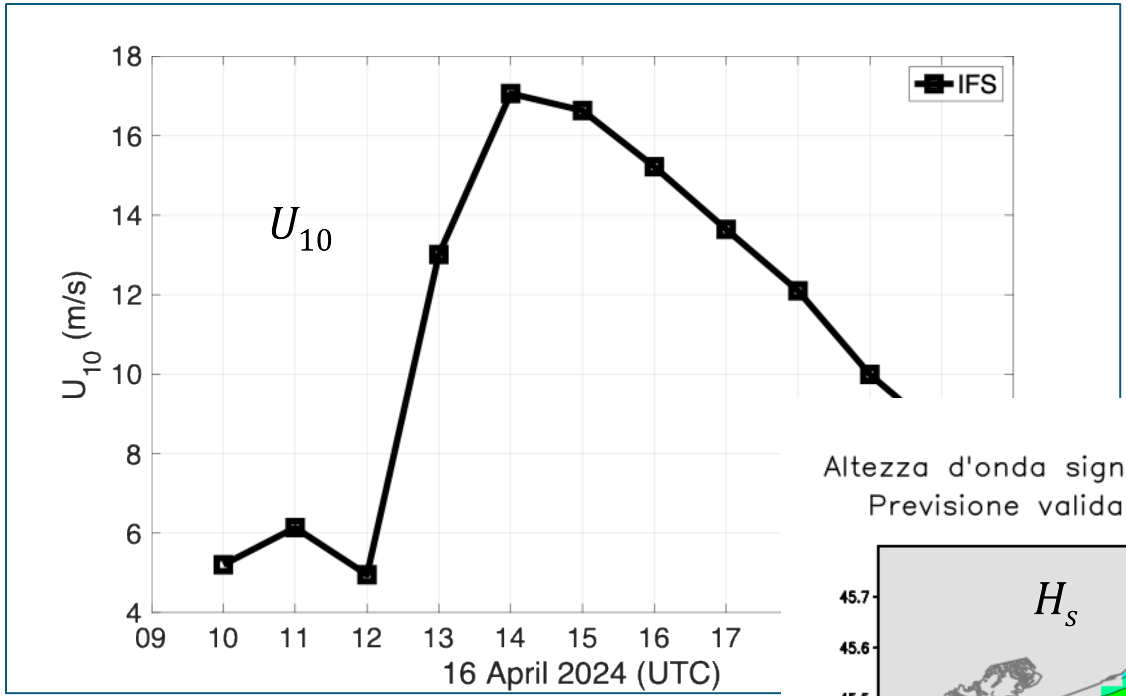
- Ship accident statistics suggest that the H_{m0} value of sea state is not as important as whether this value is unexpected, due to rapid development or compared to local wave climate.

There is not Regulation on wind acceleration, but we can assume

- **Manageable for sailboats**: ≤ +1 m/s per minute (with time to respond)
- **Dangerous/hard to manage**: ≥ +5 m/s in 5 minutes.
- **Unmanageable**: ≥ +10 m/s in < 5 minutes

(NOAA mentions “frequent gusts of 25 knots or greater”)

The local forecast at the time of the event



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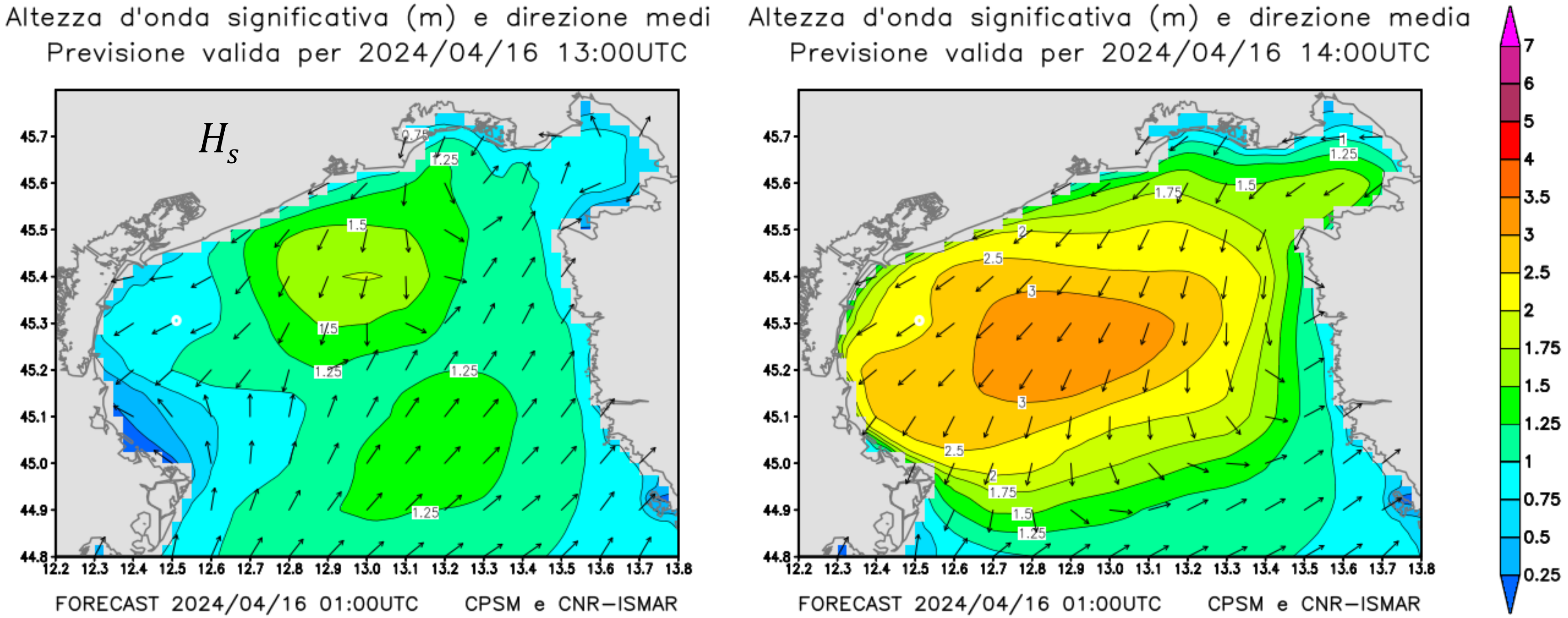
Wind acceleration

Manageable



Bora predictability: Ensemble modelling

📈 **Predictability Before the Event**

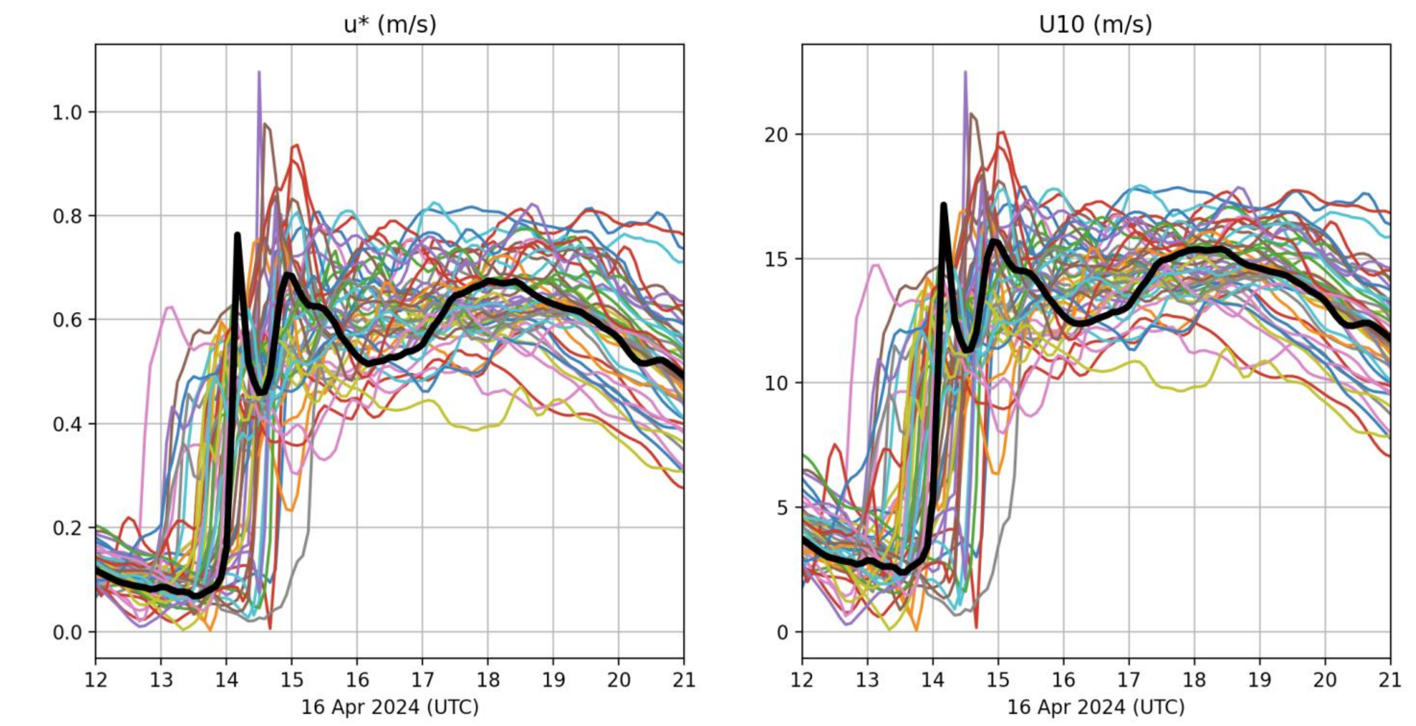
•**Very tight clustering** among ensemble members.
•Low spread in both U10 and u*, indicating **high confidence** in background conditions.
•Good agreement in both timing and magnitude of the initial lull.
✅ **Interpretation**: High predictability prior to the event.

🔺 **During Onset of the Event**

•Sharp, simultaneous increase in all ensemble members.
•Small but noticeable divergence in peak timing and magnitude.
•A few outliers (especially one very low member and one very high spike) suggest some sensitivity to initial conditions or boundary forcing.
🟡 **Interpretation**: Still **moderate-to-high predictability**, but this is the **most sensitive phase**. Spread increases slightly, but the ensemble still agrees on the **timing and presence** of a strong wind burst.

🔻 **After Peak**

•Larger spread in both U10 and u*, especially in magnitude.
•Some ensemble members decrease faster or slower than others.
•The overall structure is still coherent (no major bifurcations), but uncertainty is clearly growing.
🟠 **Interpretation**: **Predictability decreases after the peak**. While all members show sustained elevated wind, there's less agreement on how strong or how persistent it is.



✅ The **event is well captured** by the ensemble: all members show a significant wind increase with consistent timing.
🟡 **Uncertainty increases most after the peak**, not before — suggesting the ensemble system is good at forecasting **onset**, but less confident about **duration and decay**.
🟣 A few outliers exist, but they don't dominate. This suggests **no major bifurcations** in model evolution — a good sign for short-term predictability

Underwater Air-Bubble