Influence of wave driven air-sea interactions on a strong Mediterranean cyclone

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Air-sea interactions at high winds

In situ during the Saint-Jude Storm in 2013

1 hour mean winds of ~ 26 m/s

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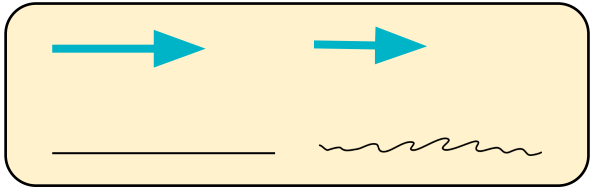
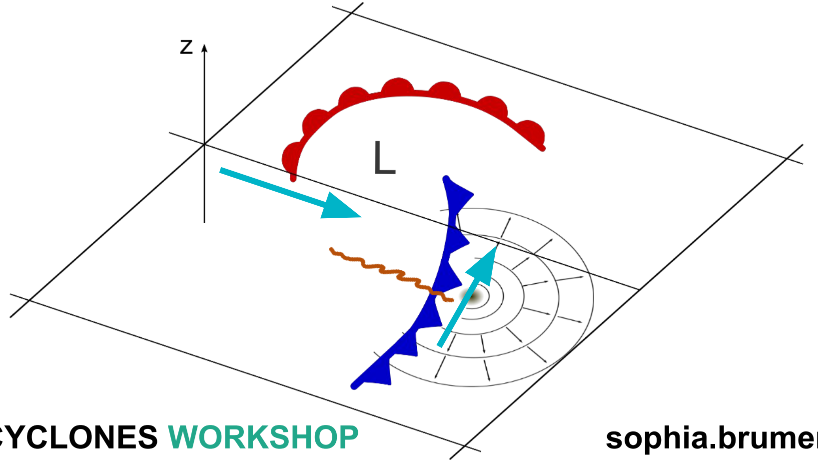
Air-sea interactions at high winds – impacts on the MABL

Waves = roughness →reduction in surface winds



- Complex sea state (wind-sea & swell)
- Misalignment between winds and waves



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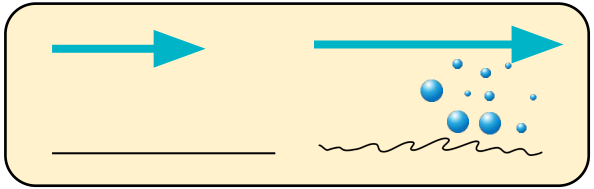
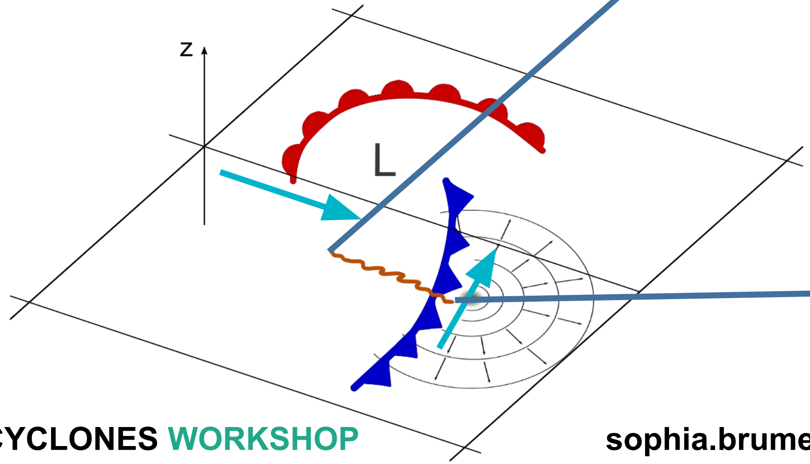
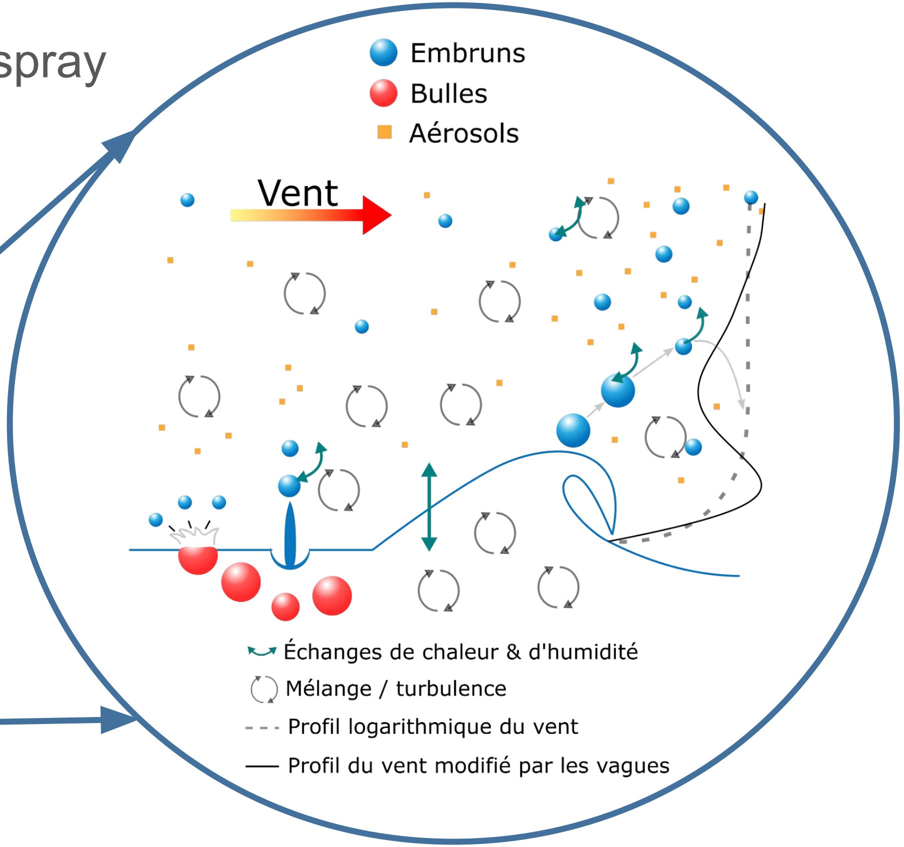
Wave driven air-sea interactions – impacts on the MABL

Waves at high winds →breaking and sea spray
→ reduction of effective roughness
→ acceleration of surface winds







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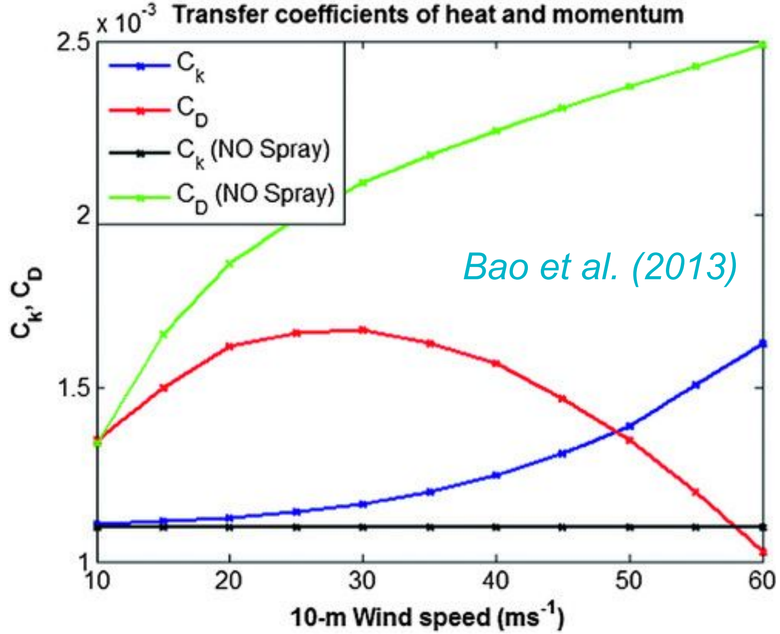
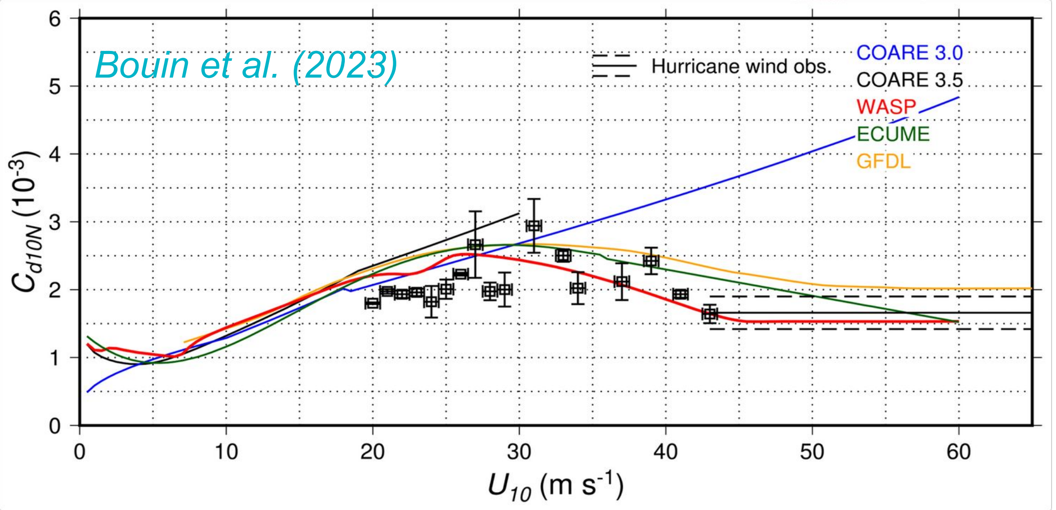
Wave driven air-sea interactions – impacts on the MABL

Evidence of decrease drag in Tropical Cyclones



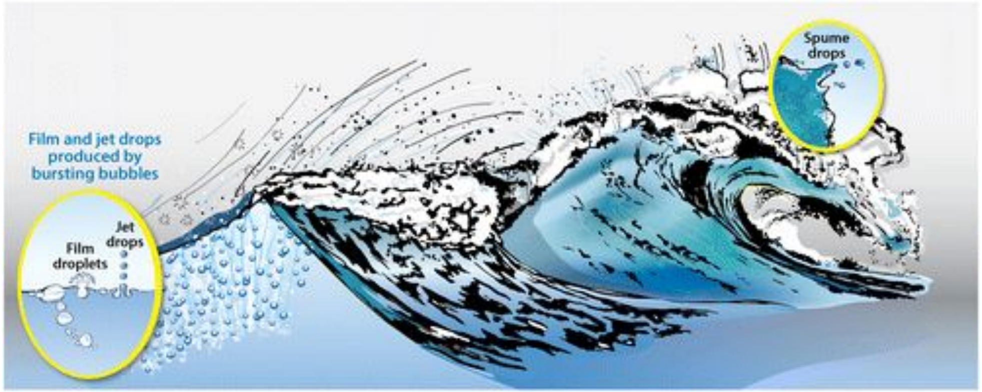


Wave dependent air-sea flux parametrizations with consideration for wave age (WASP, Bouin et al 2023) & sea spray (e.g. Bao et al. 2011)

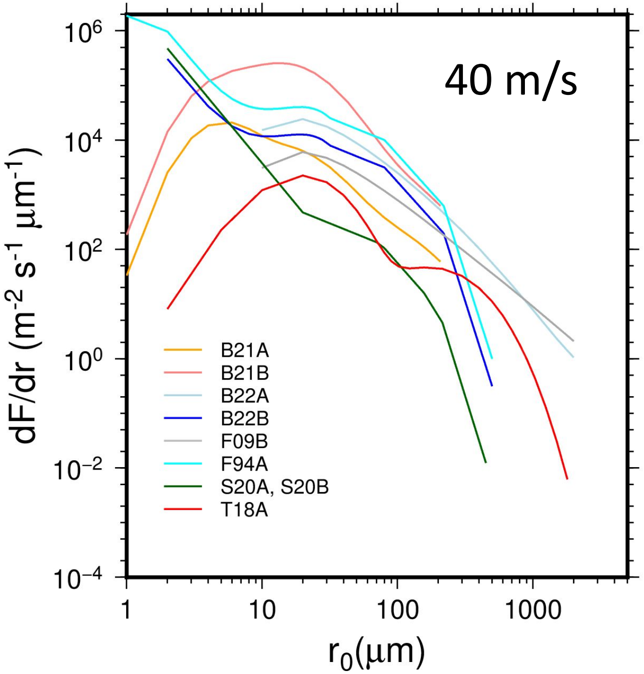
Sea spray impacts

Sea spray generation & transport remain elusive

Orders of magnitude spread in generation function



Veron F. 2015.
Annu. Rev. Fluid Mech. 47:507–38



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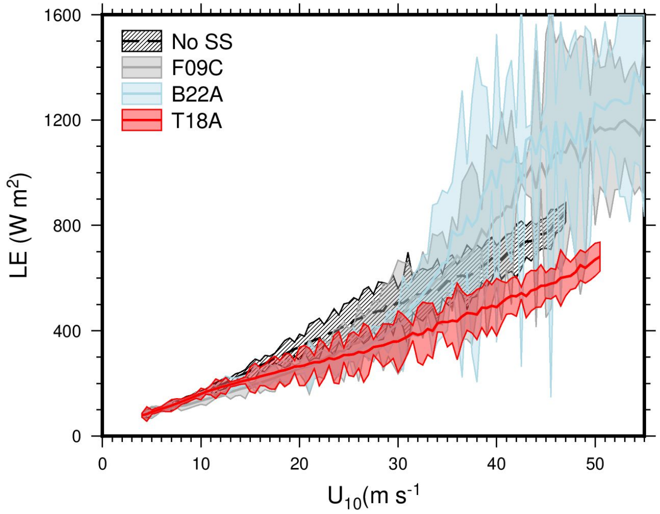
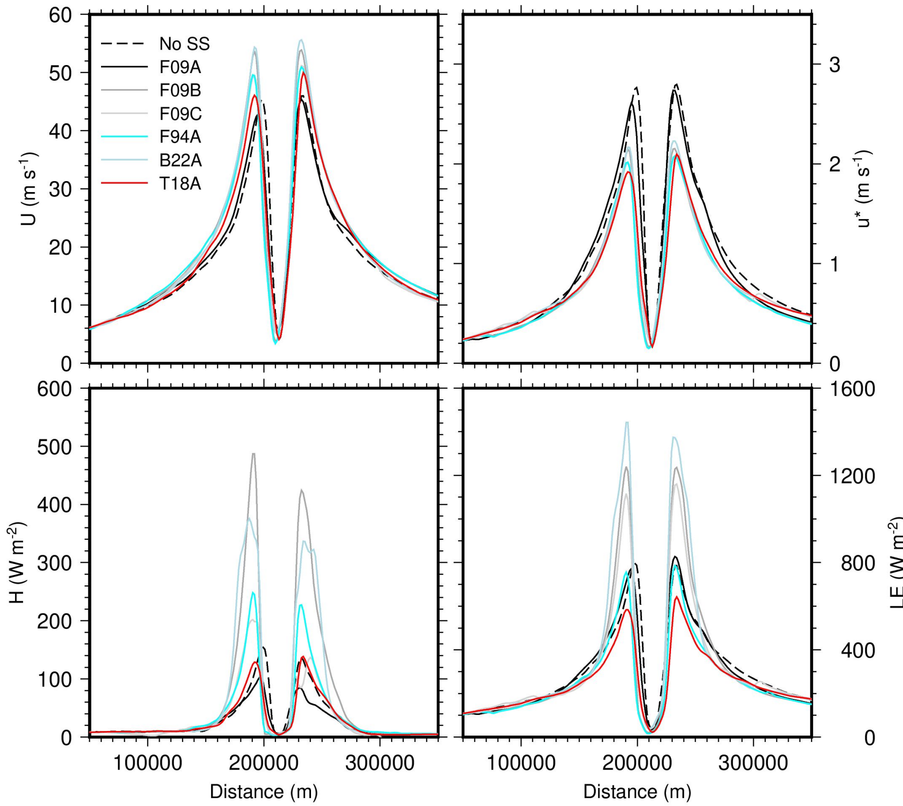
Sea spray impacts on an idealized TC

Sea spray
→increases enthalpy fluxes & reduces drag
→increases intensity
→can contribute to asymmetry



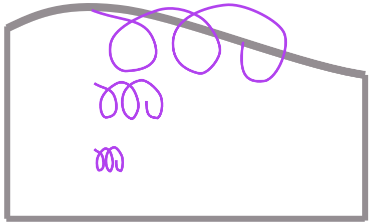


Wave driven air-sea interactions – impacts in the ocean

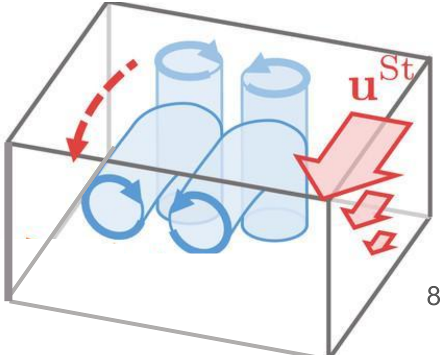
$$\overbrace{\frac{\partial \hat{u}}{\partial t}}^{\text{trend}} = -\overbrace{\left(\hat{u}\frac{\partial \hat{u}}{\partial x} + \hat{v}\frac{\partial \hat{u}}{\partial y} + \hat{w}\frac{\partial \hat{u}}{\partial z}\right)}^{\text{advection}} + \overbrace{\frac{\partial}{\partial z}\left(K_u \frac{\partial \hat{u}}{\partial z}\right)}^{\text{vert. dif.}} + \overbrace{\frac{1}{\rho}\frac{\partial P_i}{\partial x} - g\frac{\partial SSH}{\partial x} - \frac{1}{\rho}\frac{\partial P_a}{\partial x} - \frac{\partial J}{\partial x}}^{\text{Internal + external pressure grad.}}$$
$$+ \underbrace{f\hat{v}}_{\text{Cor.}} + \underbrace{f v_s}_{\text{Stokes Cor.}} + \underbrace{\left(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y}\right) v_s - \frac{\partial \hat{u}}{\partial z} w_s}_{\text{Vortex Force}} \quad (1)$$

Notations:
$\hat{u}$ - quasi-Eulerien velocity
u_s - Stokes drift
u_L - Lagrangian velocity $(\hat{u} + u_s)$

Stokes drift
→ **wave induced particle motion**



Stokes vortex force
→ **advection & tilting**



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Wave driven air-sea interactions – impacts in the ocean

$$\underbrace{\frac{\partial \hat{u}}{\partial t}}_{\text{trend}} = -\underbrace{\left(\hat{u}\frac{\partial \hat{u}}{\partial x} + \hat{v}\frac{\partial \hat{u}}{\partial y} + \hat{w}\frac{\partial \hat{u}}{\partial z}\right)}_{\text{advection}} + \underbrace{\frac{\partial}{\partial z}\left(K_u \frac{\partial \hat{u}}{\partial z}\right)}_{\text{vert. dif.}} + \underbrace{\frac{1}{\rho}\frac{\partial P_i}{\partial x} - g\frac{\partial SSH}{\partial x} - \frac{1}{\rho}\frac{\partial P_a}{\partial x} - \frac{\partial J}{\partial x}}_{\text{Internal + external pressure grad.}}$$
$$+ \underbrace{f\hat{v}}_{\text{Cor.}} + \underbrace{fv_s}_{\text{Stokes Cor.}} + \underbrace{\left(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y}\right)v_s - \frac{\partial \hat{u}}{\partial z}w_s}_{\text{Vortex Force}} \tag{1}$$

Surface Boundary conditions:

$$\tau_{surf} = \tau_a - \underbrace{\tau_{aw}}_{\text{exhausted by waves}} + \overbrace{\tau_{wo}}^{\text{wave to ocean}} \tag{2}$$

Notations:
$\hat{u}$ - quasi-Eulerien velocity
u_s - Stokes drift
u_L - Lagrangian velocity $(\hat{u} + u_s)$

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Wave driven air-sea interactions – impacts in the ocean

$$\underbrace{\frac{\partial \hat{u}}{\partial t}}_{\text{trend}} = -\underbrace{\left(\hat{u}\frac{\partial \hat{u}}{\partial x} + \hat{v}\frac{\partial \hat{u}}{\partial y} + \hat{w}\frac{\partial \hat{u}}{\partial z}\right)}_{\text{advection}} + \underbrace{\frac{\partial}{\partial z}\left(K_u \frac{\partial \hat{u}}{\partial z}\right)}_{\text{vert. dif.}} + \underbrace{\frac{1}{\rho}\frac{\partial P_i}{\partial x} - g\frac{\partial SSH}{\partial x} - \frac{1}{\rho}\frac{\partial P_a}{\partial x} - \frac{\partial J}{\partial x}}_{\text{Internal + external pressure grad.}}$$
$$+ \underbrace{f\hat{v}}_{\text{Cor.}} + \underbrace{fv_s}_{\text{Stokes Cor.}} + \underbrace{\left(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y}\right)v_s - \frac{\partial \hat{u}}{\partial z}w_s}_{\text{Vortex Force}} \quad (1)$$

Surface Boundary conditions:

$$\tau_{surf} = \tau_a - \underbrace{\tau_{aw}}_{\text{exhausted by waves}} + \overbrace{\tau_{wo}}^{\text{wave to ocean}} \quad (2)$$

Tracer (with wave dependent terms):

$$\frac{\partial C}{\partial t} = -\left(\frac{\partial}{\partial x}[(\hat{u} + u_s)C] + \frac{\partial}{\partial y}[(\hat{v} + v_s)C] + \frac{\partial}{\partial z}[(\hat{w} + w_s)C]\right) + \frac{\partial}{\partial z}\left(K_T \frac{\partial C}{\partial z}\right) \quad (3)$$

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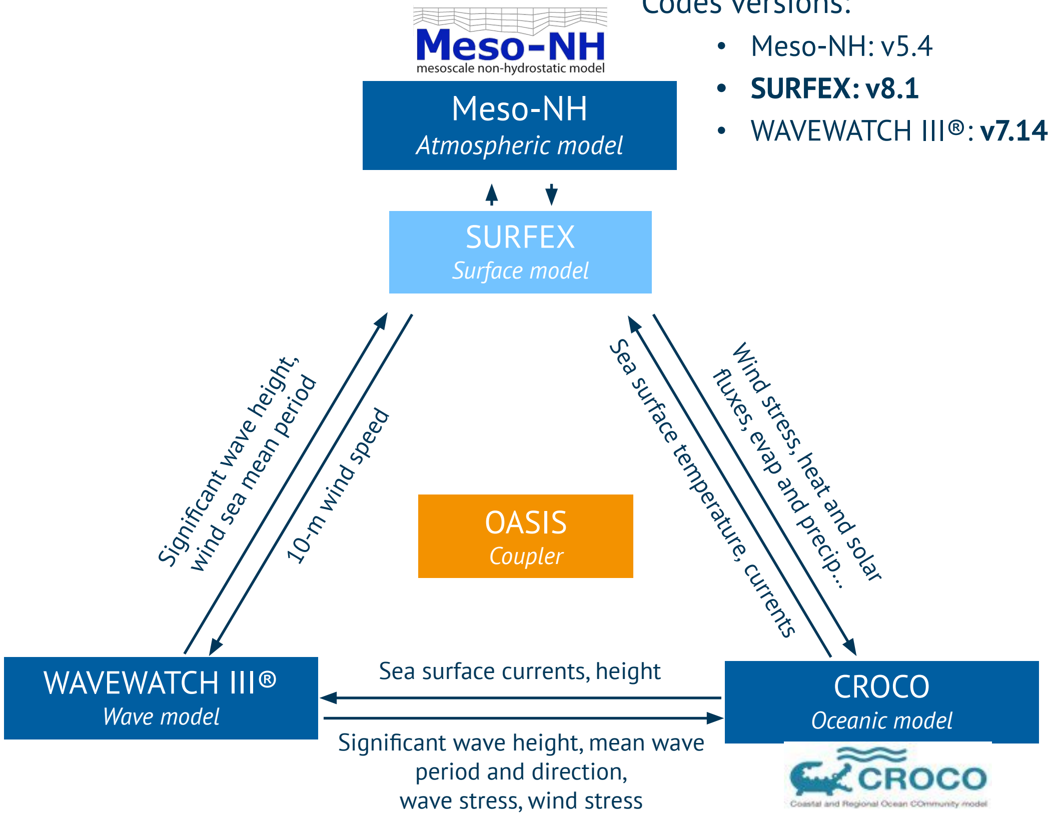
The French coupled model framework

Codes versions:

- Meso-NH: v5.4
- **SURFEX: v8.1**
- WAVEWATCH III®: **v7.14**



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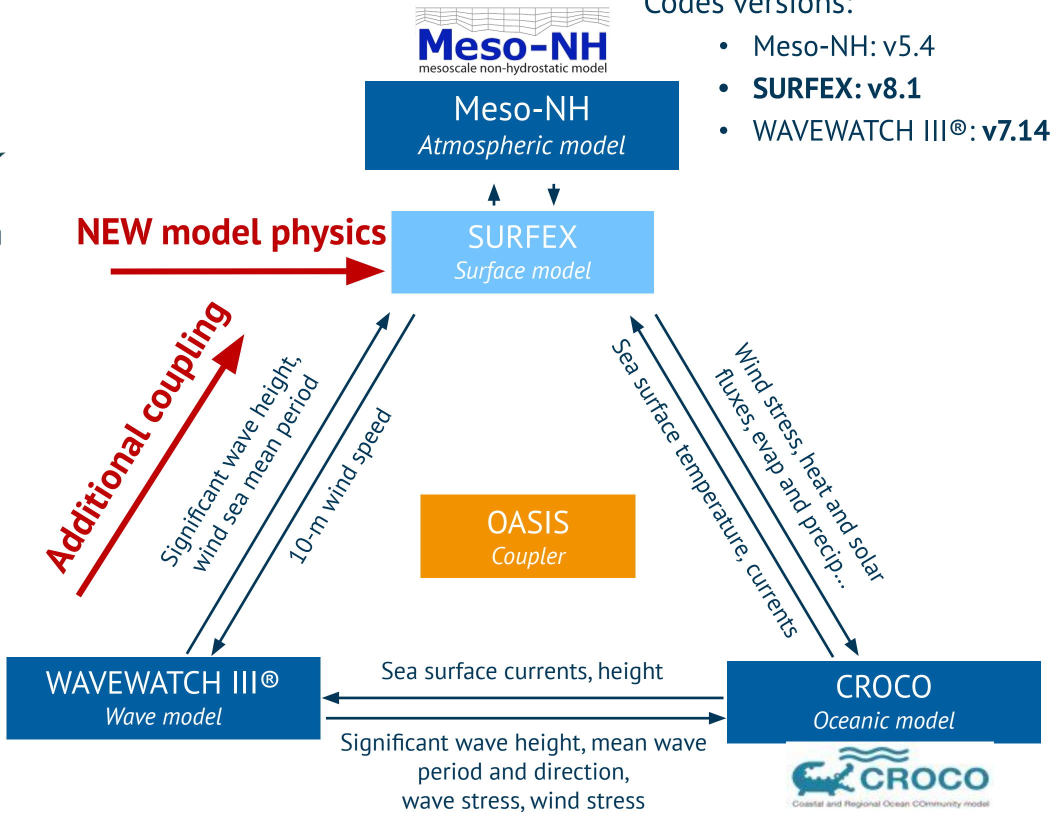
The French coupled model framework

Latest developments:

1. wave-age-dependent stress parameterisation (WASP, Bouin et al. 2023)
2. sea spray fluxes (Brumer et al. in prep)



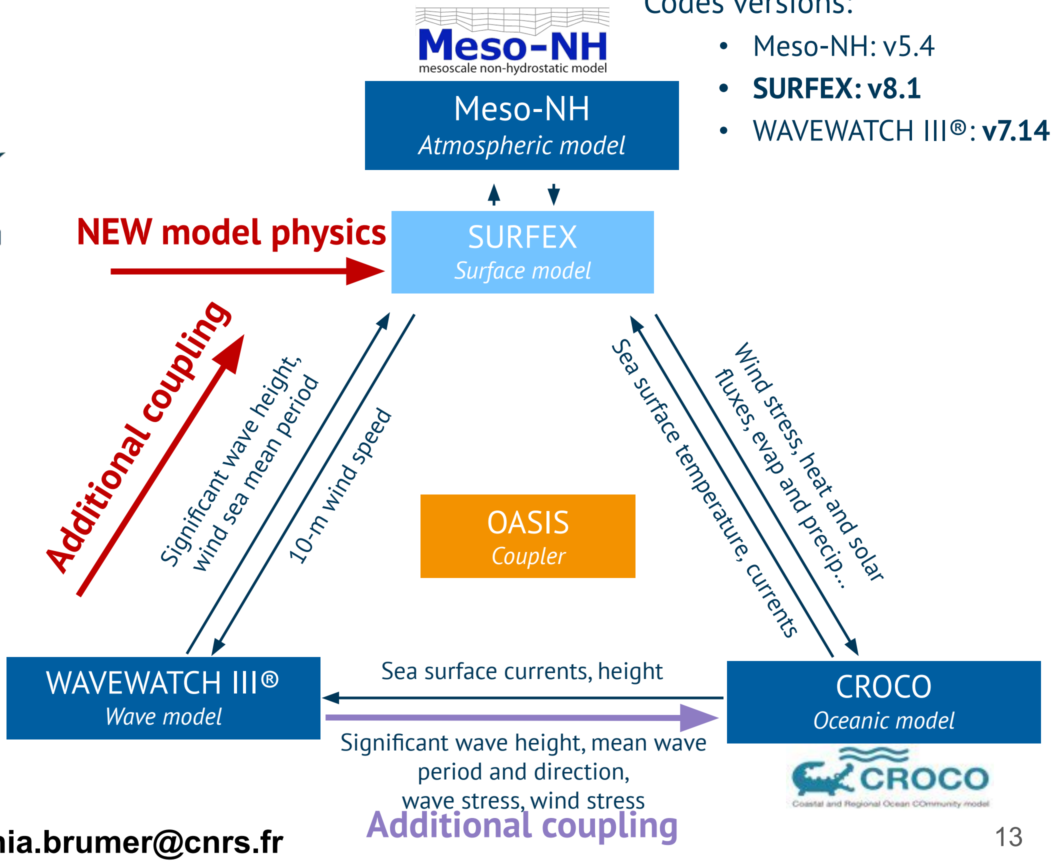
The French coupled model framework

Latest developments:

1. wave-age-dependent stress parameterisation (WASP, Bouin et al. 2023)
2. sea spray fluxes (Brumer et al. in prep)
3. extended Wave-Ocean Coupling (Porcile et al. 2023)
4. GPU porting of Meso-NH & CROCO

Codes versions:

- Meso-NH: v5.4
- **SURFEX: v8.1**
- WAVEWATCH III®: **v7.14**



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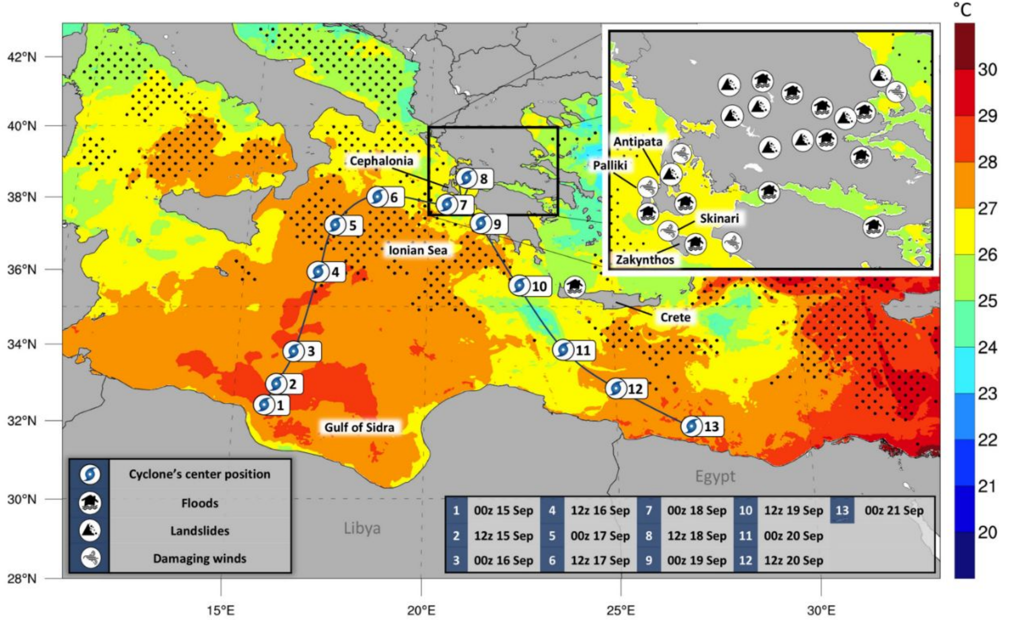
Case study: medicane Ianos of September 2020

AQUA/MODIS 17 Sep 2020 1145 UTC

Lagouvardos et al. (2022) BAMS
https://doi.org/10.1175/BAMS-D-20-0274.1



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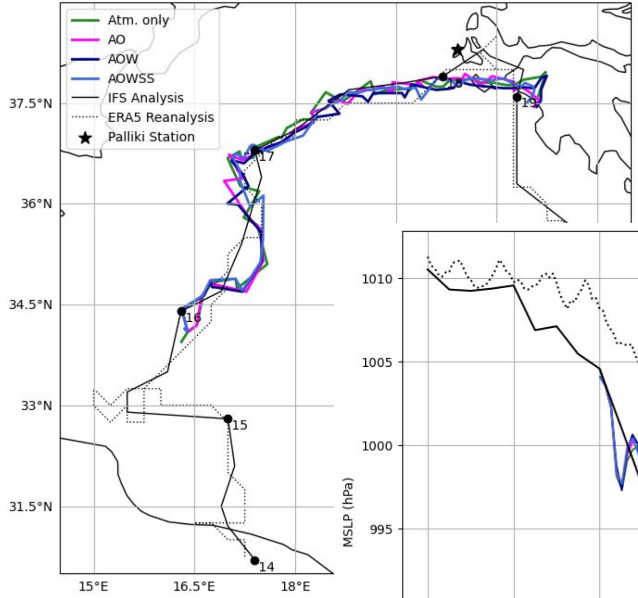
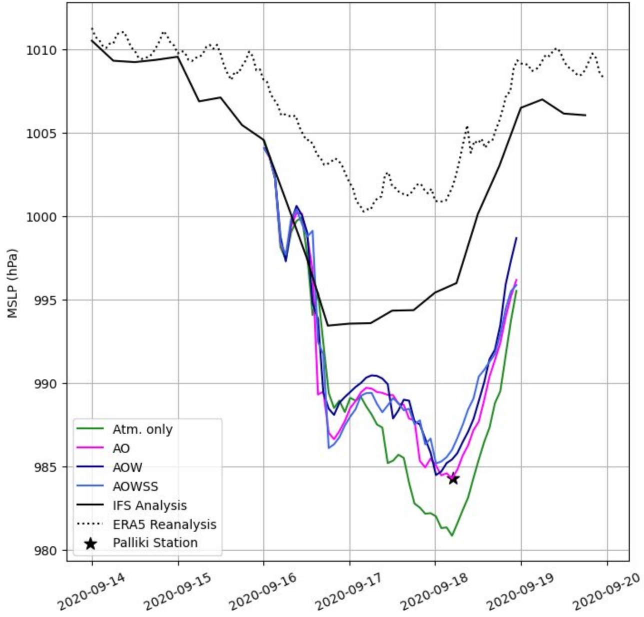
Simulations – Track and Intensity

4 simulations @ 1.8 km resolution:

1. Atmosphere only
2. AO - atmosphere-ocean
3. AOW -atmosphere-ocean-waves
4. AOWSS - AOW with sea spray

→High resolution leads to deep low
→Coupling decreases intensity closer to in situ observation
→Track minimally impacted by coupling and well represented in all simulations





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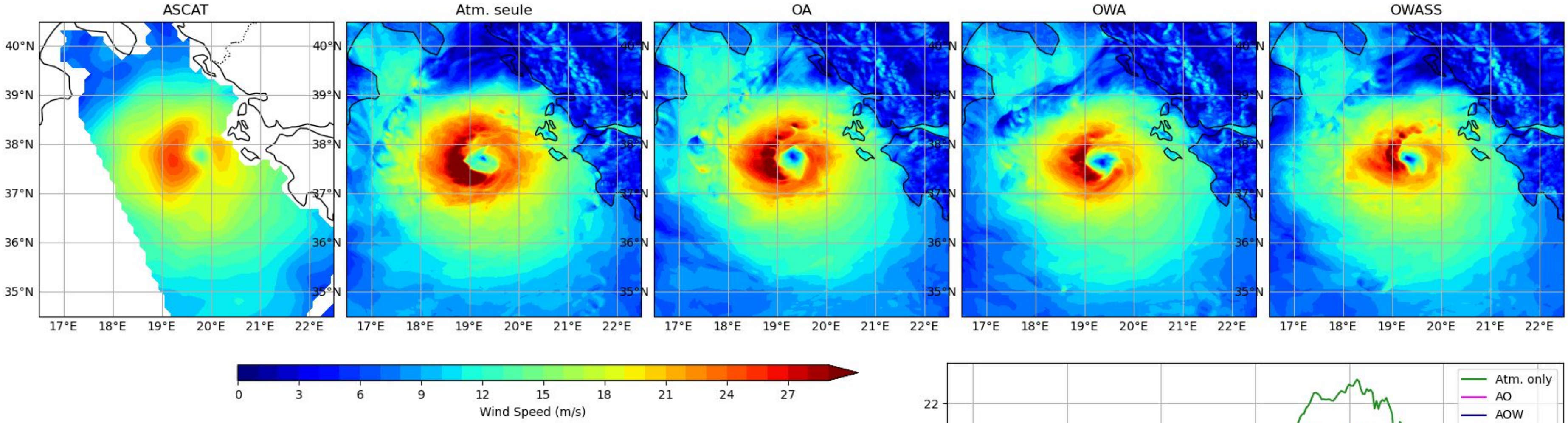
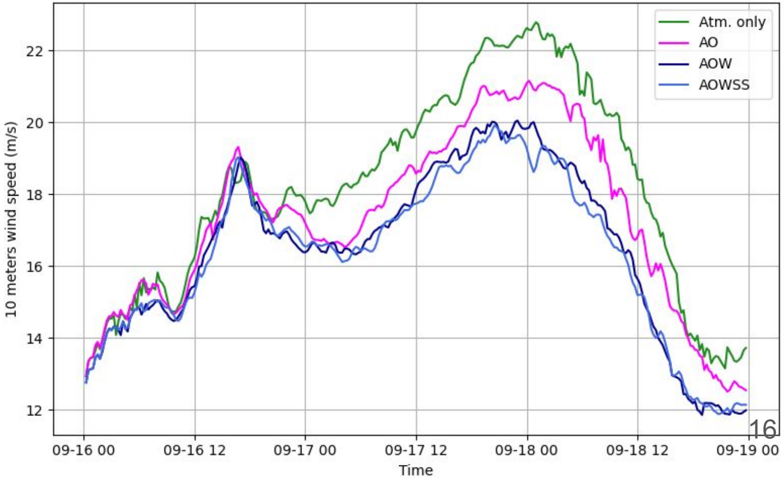
Results – 10 m winds





→Coupling decreases intensity closer to ASCAT observation

→Waves have a clear impact on wind intensity & asymmetry

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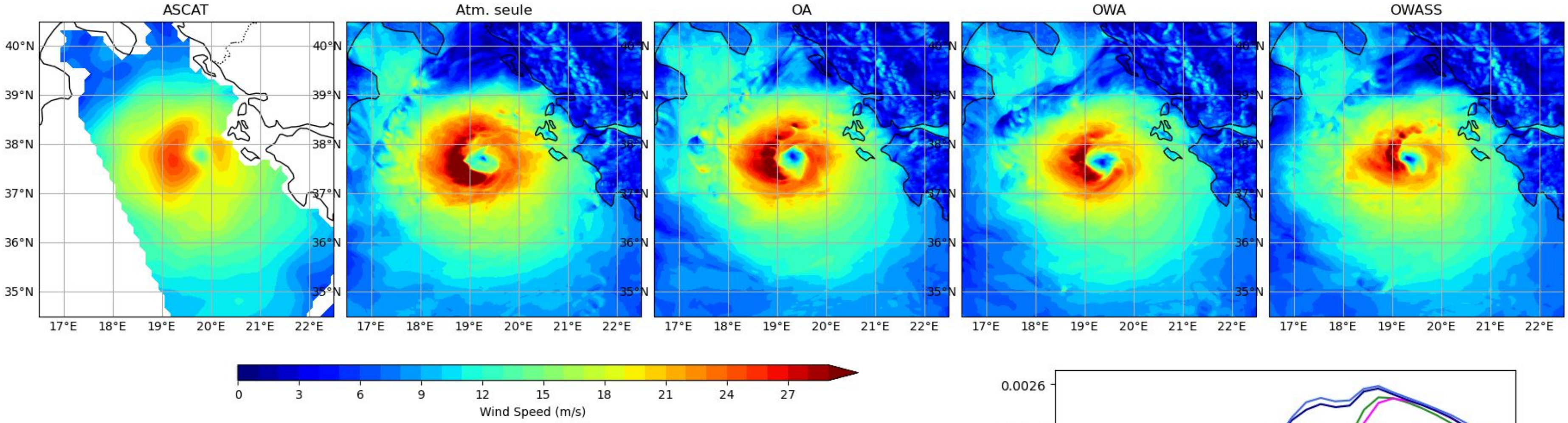
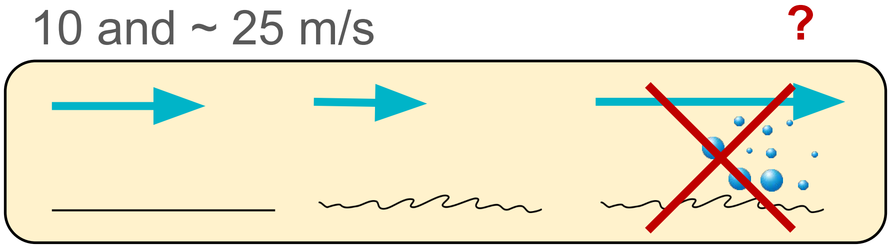
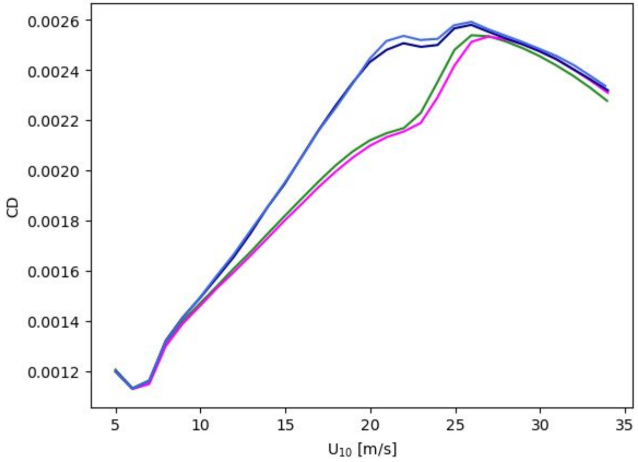
Results – 10 m winds

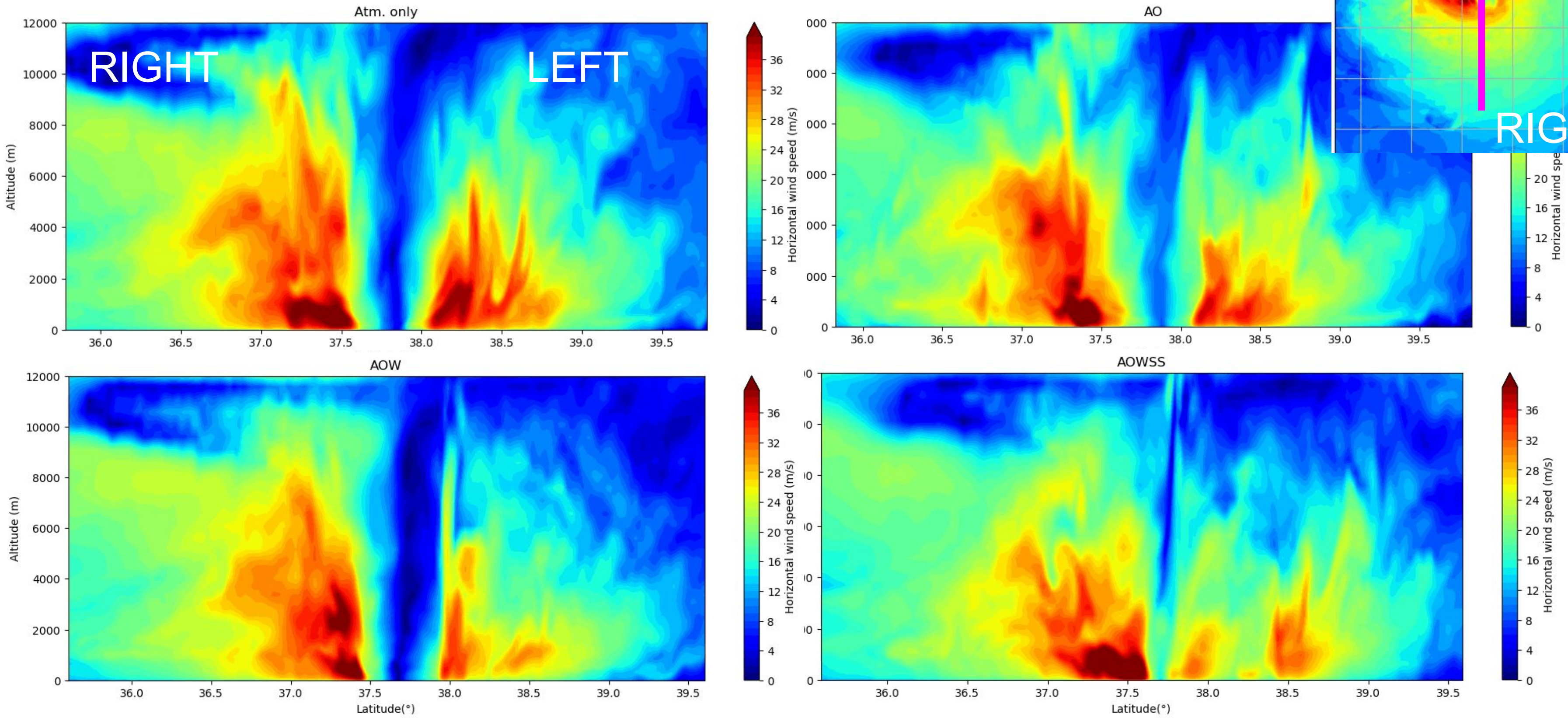


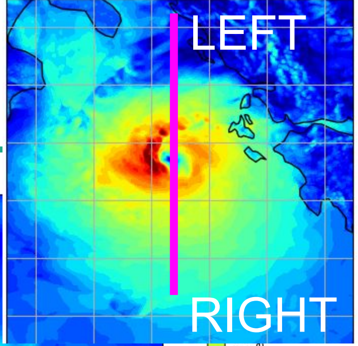
→Waves increase the drag coefficient between 10 and ~ 25 m/s



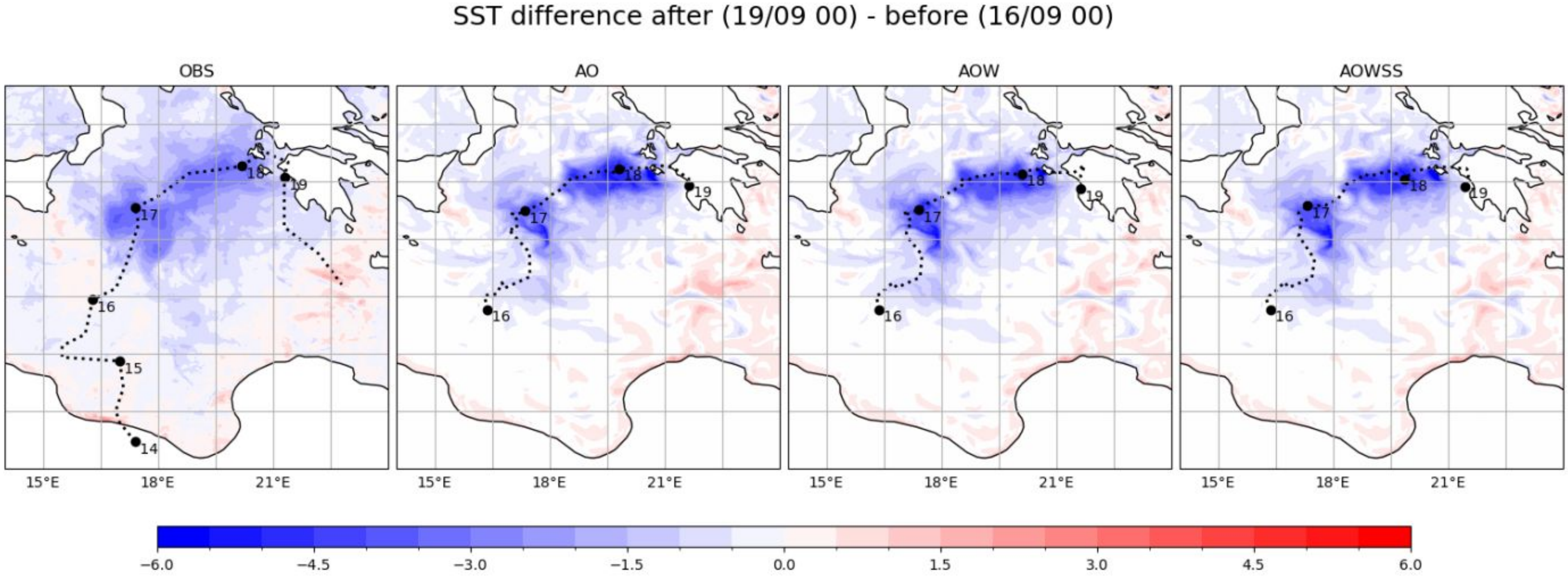


Results – Impact on the 3D wind structure





Results – Cold wakes



Strong cooling (ΔSST > 4°C) along the path in 2 separate patches

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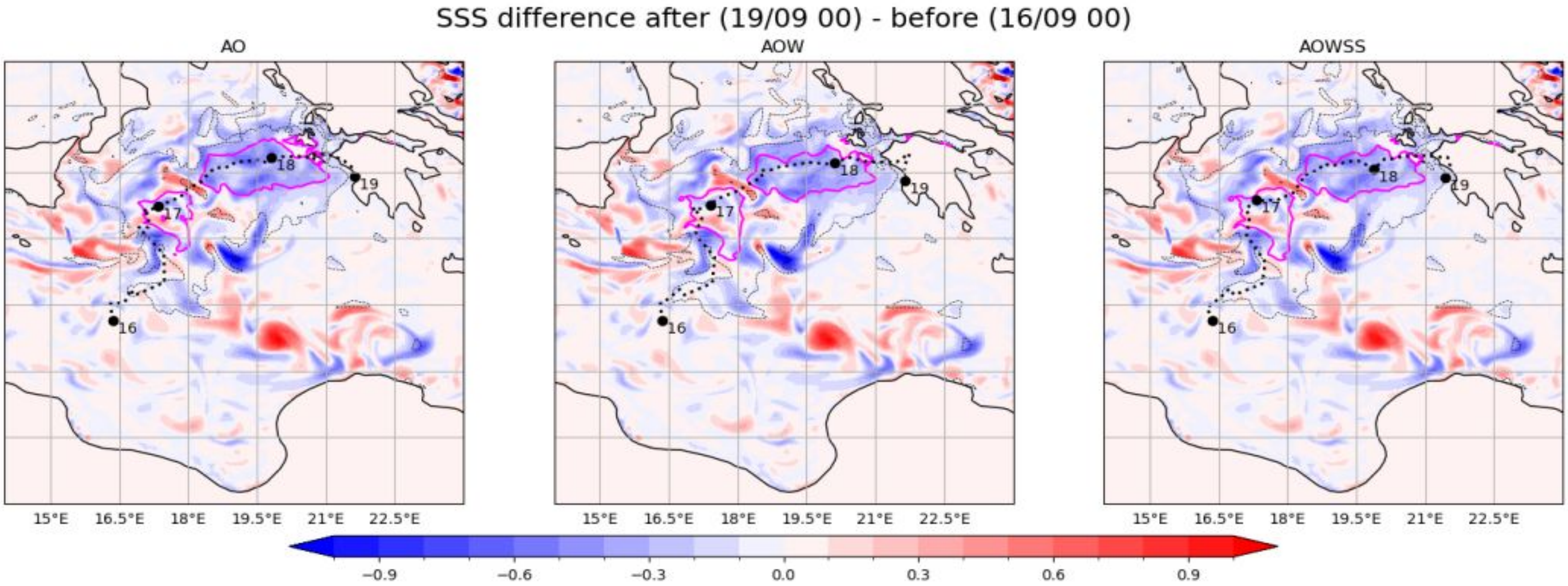
Results – Surface salinity and rain



Freshening in the second cold wake, mixed signal in the first cold wake

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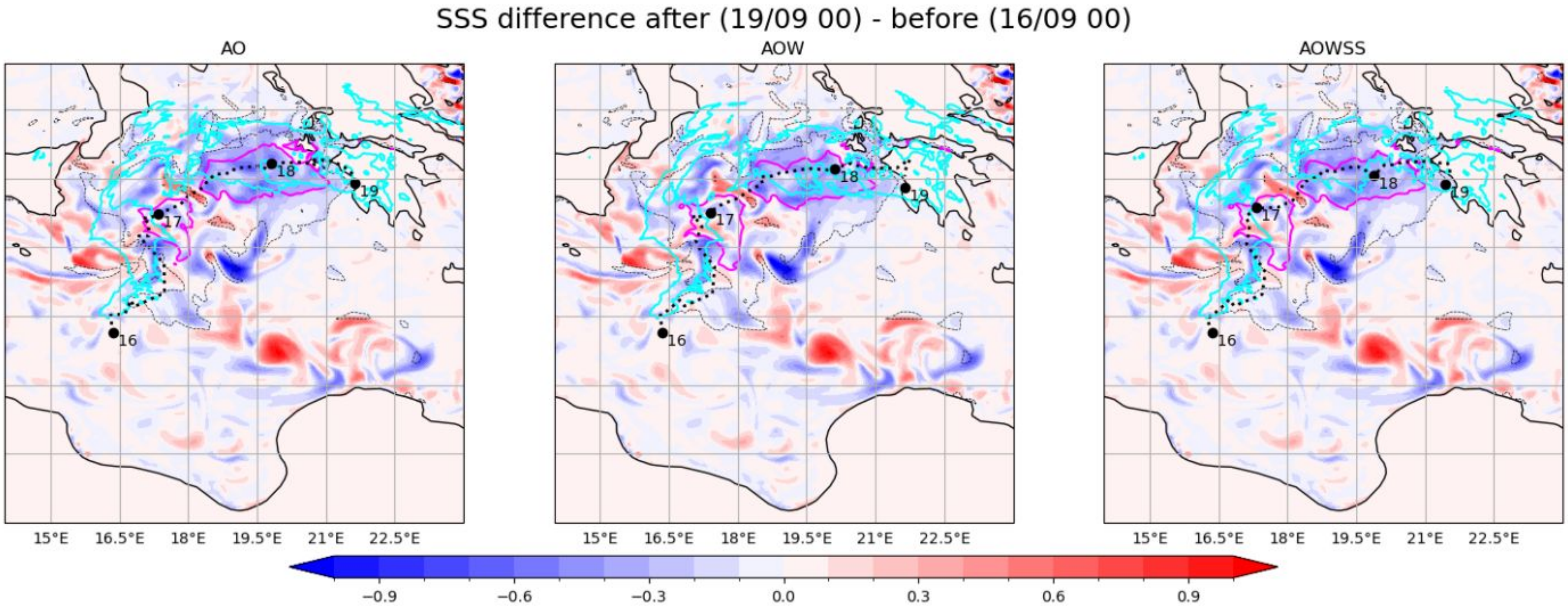
Results – Surface salinity and rain



Freshening in the second cold wake, mixed signal in the first cold wake

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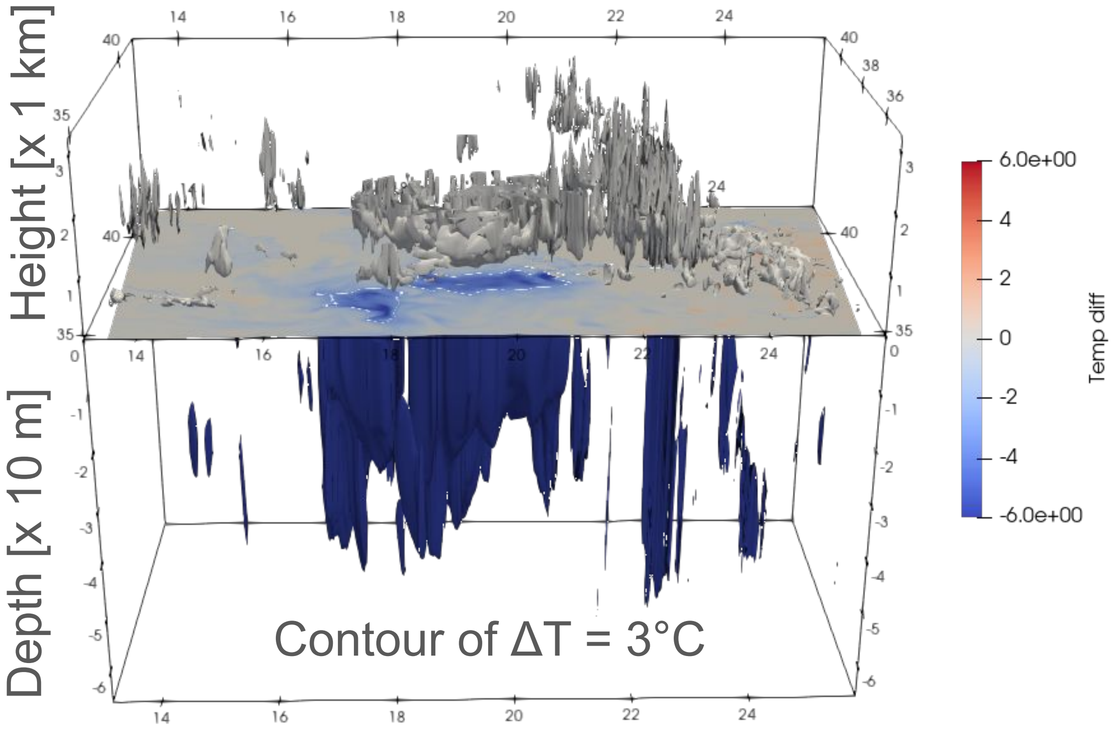
Results – Ocean mixed layer

Temperature anomalies reach 20 to 60 m depth

Similar for salinity anomalies (not shown)

Detailed process study ongoing →budget analysis

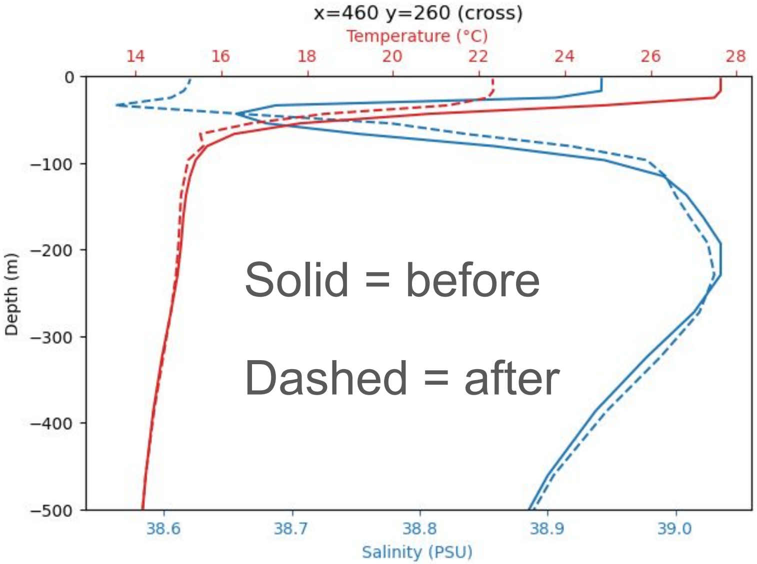


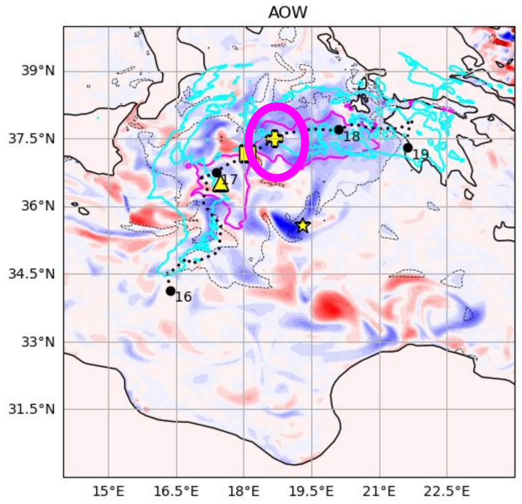
Results – Ocean mixed layer processes

Profiles in 2nd cold wake

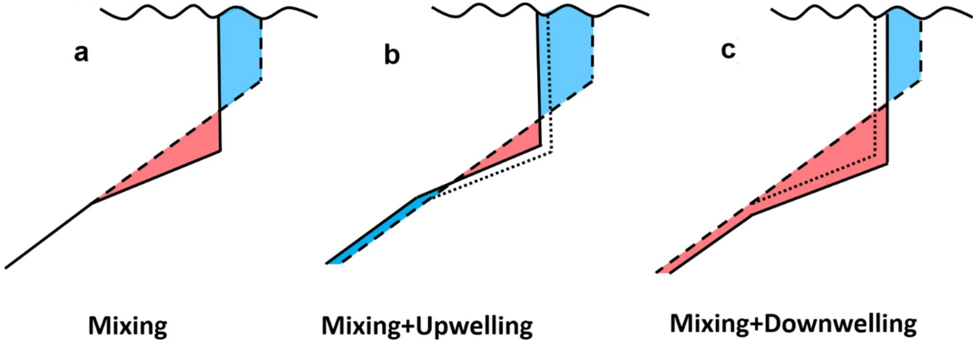
- Cooling and freshening at surface & depth
- 10m deepening of MLD

→ mixing + rain + upwelling

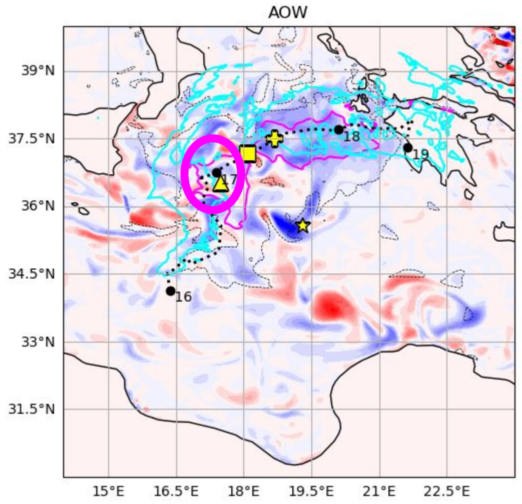




Temperature anomalies
before (dashed lines) and after (solid lines)
mixing only (dotted lines)
Zhang et al. (2021)



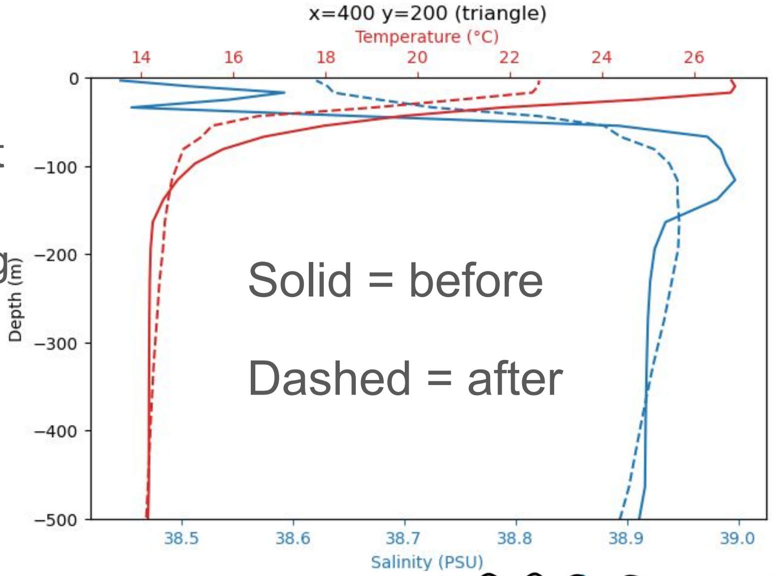
Results – Ocean mixed layer processes



Profiles in 1st cold wake

- Cooling and saltening at surface & depth
- Warming and freshening at intermediate depth
- Little impact on MLD

→upwelling & mixing



Temperature anomalies
before (dashed lines) and after (solid lines)
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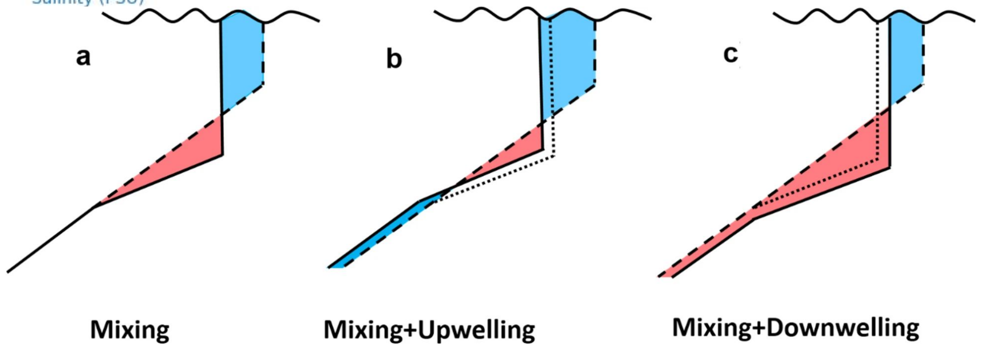
Zhang et al. (2021)

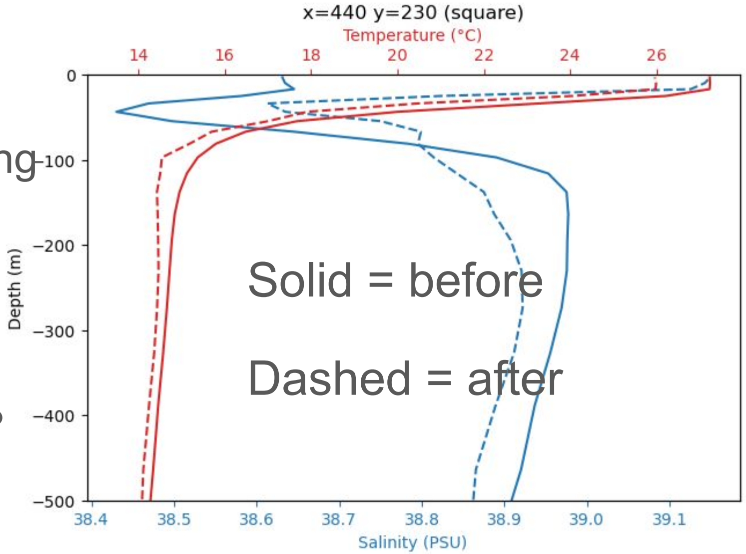


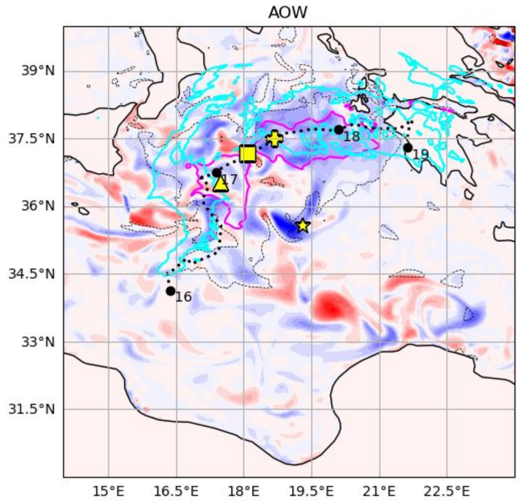
Results – Ocean mixed layer processes

Profiles between wakes

- Little cooling and strong saltening throughout
- Strong vertical advection

→ mixing + internal wave ?





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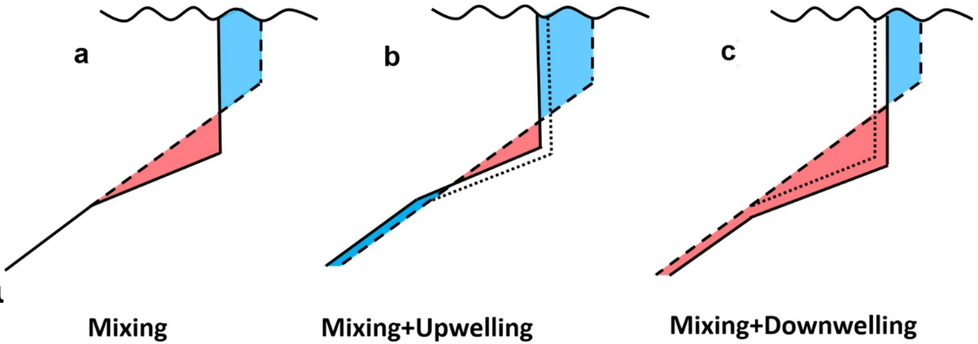


Conclusions & Perspectives

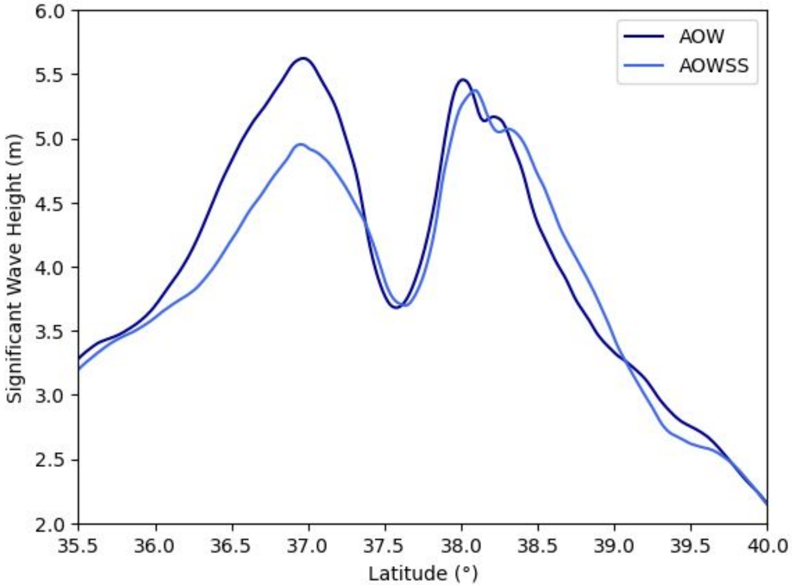
Meso-NH mesoscale non-hydrostatic model · WAVEWATCH III® Wave model · CROCO Coastal and Regional Ocean COmmunity model

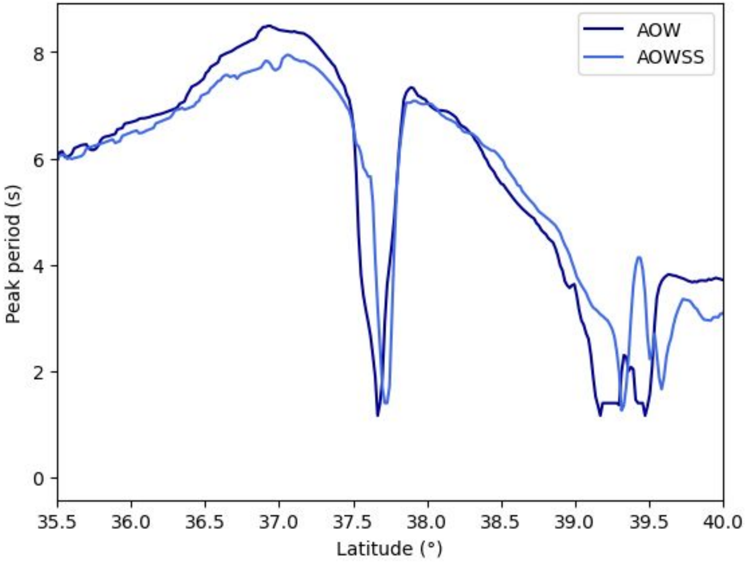
High resolution coupled atmosphere-wave-ocean simulations of medicane Ianos

1. Allowed good representation of the storm track & more realistic intensity
2. Showed intensive cold wakes (ΔSST > 4°C) with negative feedback on intensity
3. Showed how waves & sea spray accentuate MABL asymmetry

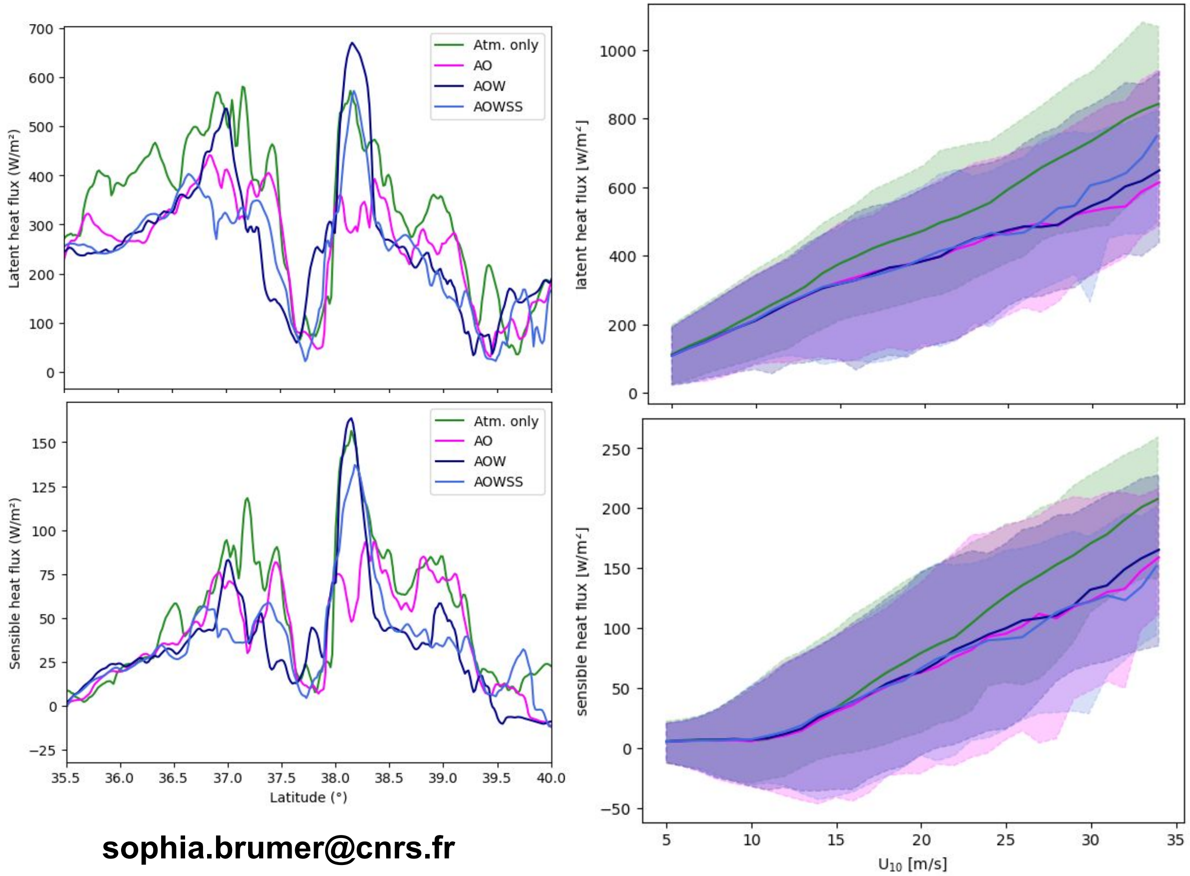
NEXT STEPS:

1. Test stronger sea spray generation functions & look at impact on microphysics
2. Process study contrasting the two cold wakes
3. Comparison to COAWST modelling framework (collab. A. Ricchi, STSM)
4. Coupled AOW large-eddy simulations using the French modelling framework


Significant Wave Height (m)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
35.5
36.0
36.5
37.0
37.5
38.0
38.5
39.0
39.5
40.0
Latitude (°)
AOW
AOWSS


Peak period (s)
8
6
4
2
0
35.5
36.0
36.5
37.0
37.5
38.0
38.5
39.0
39.5
40.0
Latitude (°)
AOW
AOWSS

Results – heat fluxes



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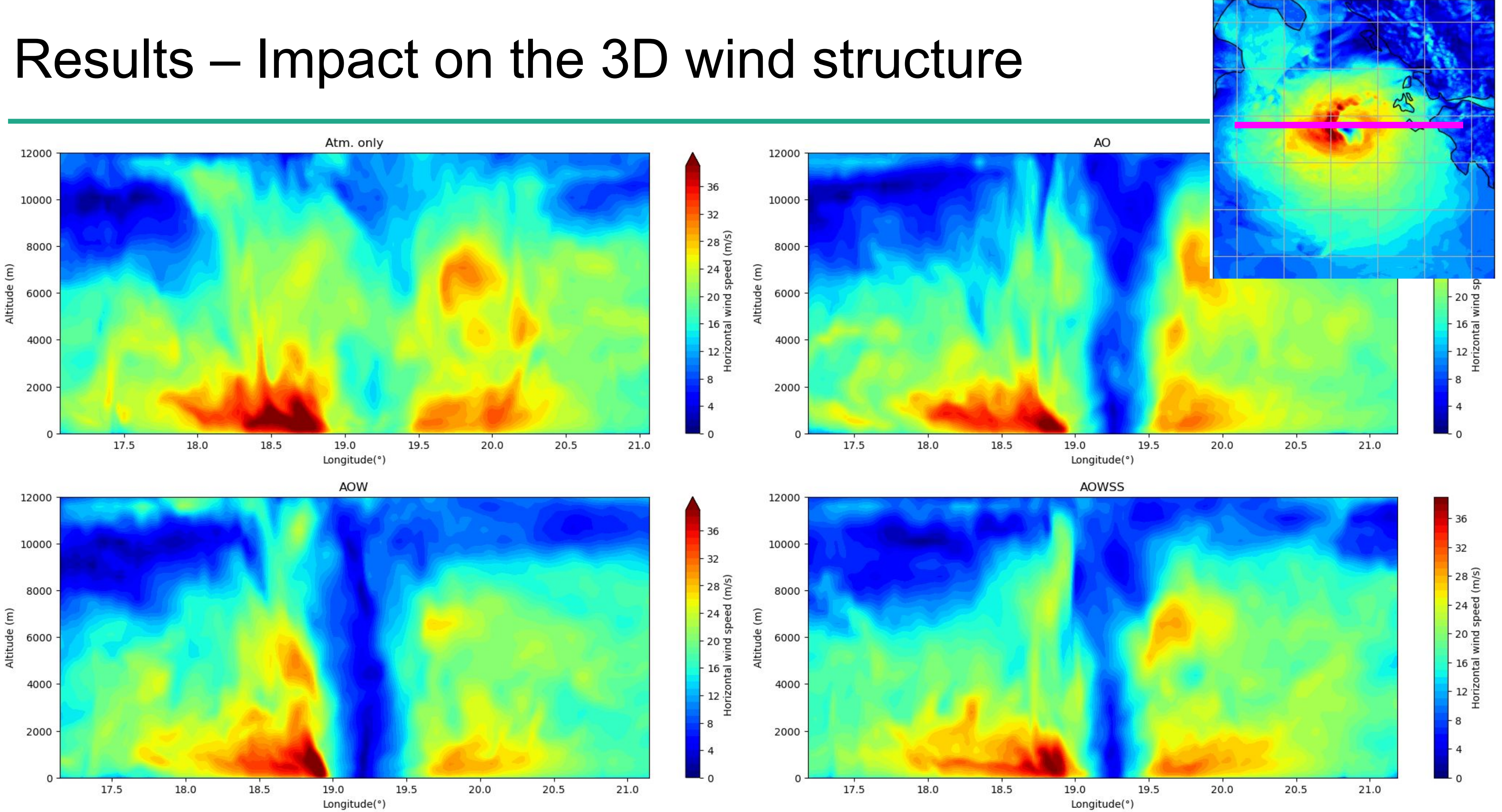
Results – Impact on the 3D wind structure



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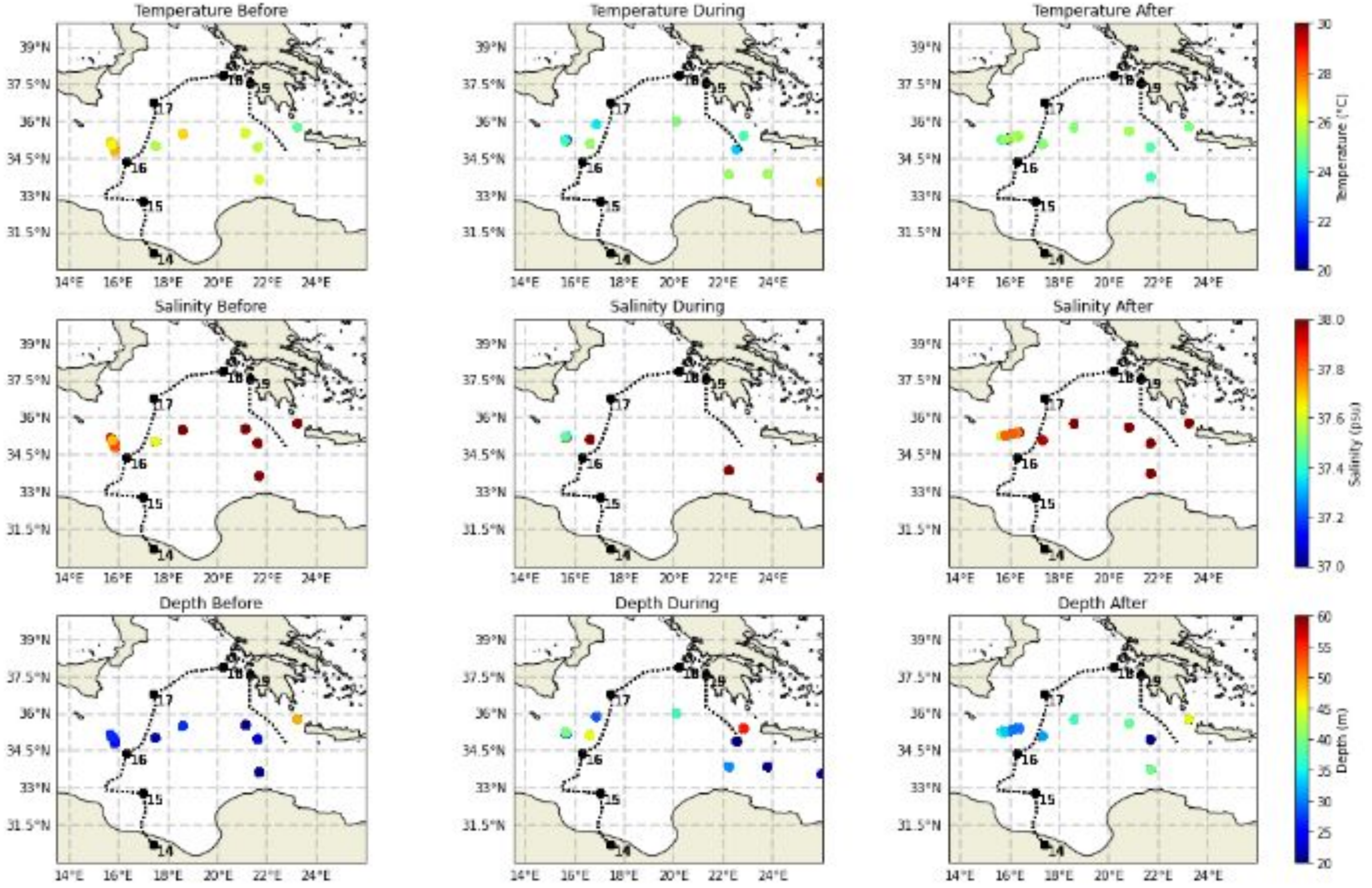

Figure 7: map of the temperature, the salinity and the MLD before, during and after Ianos