Leveraging kilometric resolution ensemble simulations for studying ocean predictability and energy transfers


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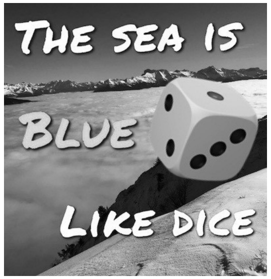

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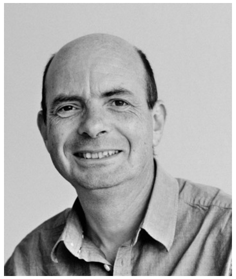
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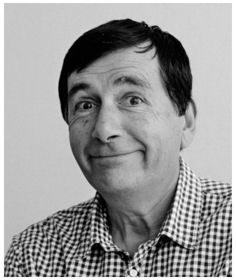
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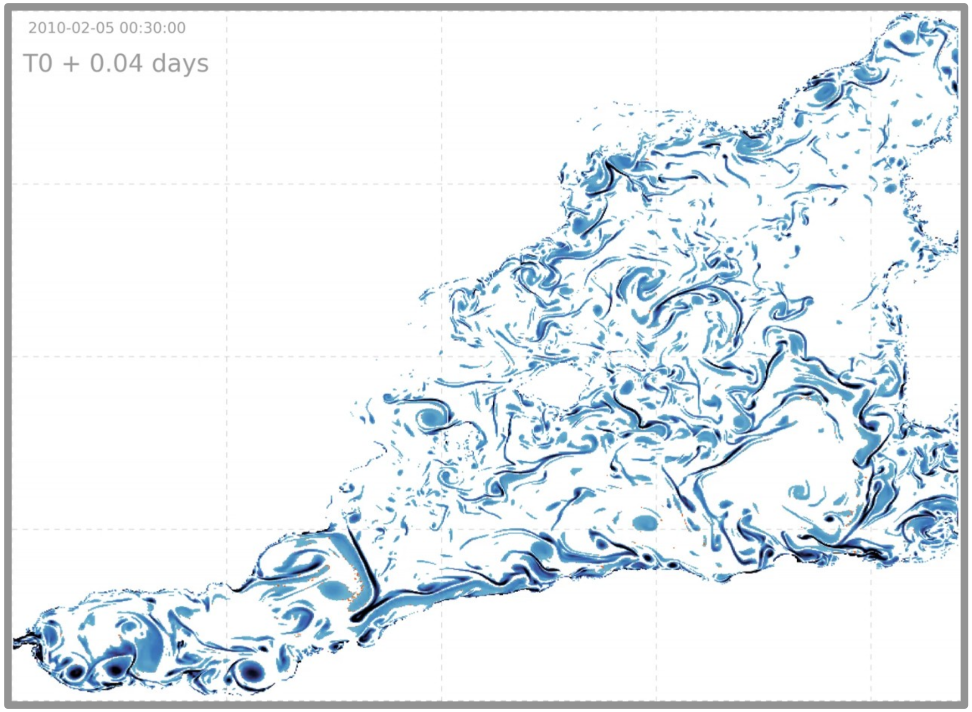
Introduction

- Some background on (ocean) ensemble simulations:
  - A tool to analyse turbulent dynamics in the context of time varying forcing
  - Produce multiples, equi-valide realizations of ocean circulation

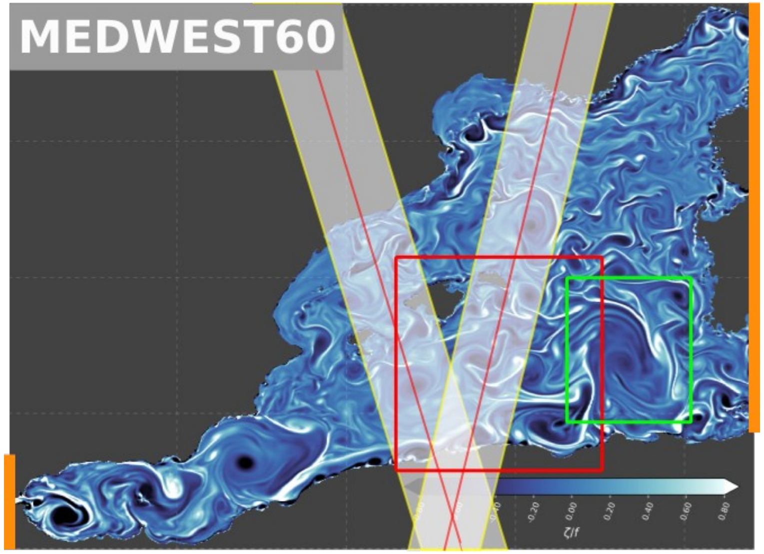


Decorrelation of two ensemble members (surface relative vorticity, [s^{-1}])

- Short-term predictability:
  - How long is a deterministic prediction 'valid'?
  - Sources of forecast errors:
    - Initial Conditions (IC)
    - Model errors
- Energy transfers:
  - An unambiguous definition of '*eddies*'
  - Spatio-temporal structure of eddy-mean flow interactions

Methods

- <u>Model and simulation</u>:
  - MEDWEST60 ; NEMO v3.6, 1/60° (Δx~1.5 km), 212 vert. levels (1-25 m)
  - Forced by:
    - atmospheric forcing (3-hourly ERA-Interim, ECMWF) and tidal potential
    - eNATL60-BLBT02 model state [Brodeau et al., 2020] at the boundaries
  - Initial conditions:
    - spun-up (25 months) eNATL60-BLBT02 model state at February, 5th 2010



ENS-CI	- Initial condition uncertainties - Deterministic model - 120 days long
ENS-1%	- *Small* model errors (1%) uncertainties - Stochastic model - 60 days long
ENS-5%	- *Large* model errors (5%) uncertainties - Stochastic models - 60 days long

- 20-member ensembles
- **ALL exposed to the same forcing !** (surface and boundary conditions)

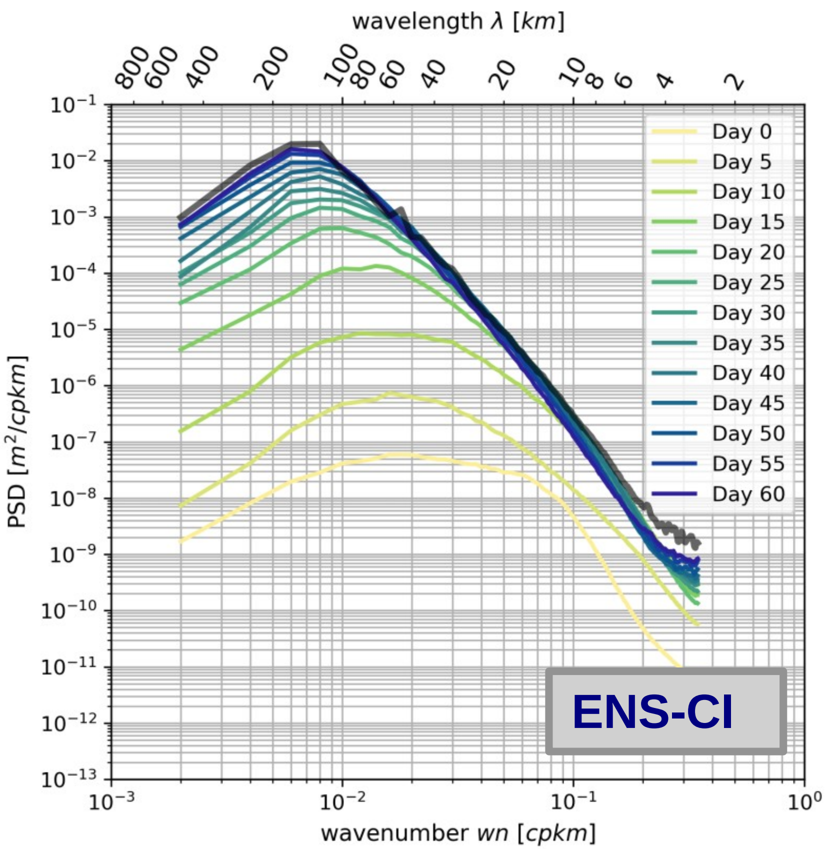
➔ **How regional ensemble simulations could be used to interpret/exploit SWOT observations?**

Short-term predictability

- How long is a deterministic prediction 'valid' (ENS-CI)?

Forecast errors

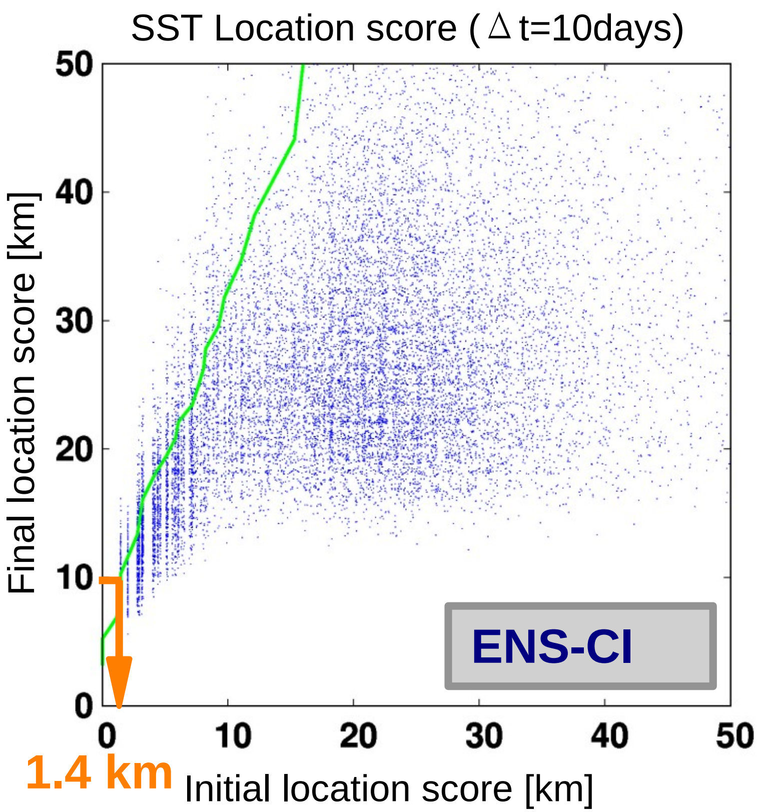
- Compute inter-members 'errors' and estimate their spatial scale



Spectral estimate of SSH forecast errors as a function of time (colour)

Forecast score

- Example for SST:
  10-km accurate 10-day forecast
  → 1.4 km accurate ICs



SST final location score after 10 days as a function of initial location score

Short-term predictability

- How long is a deterministic prediction 'valid' (ENS-CI)?

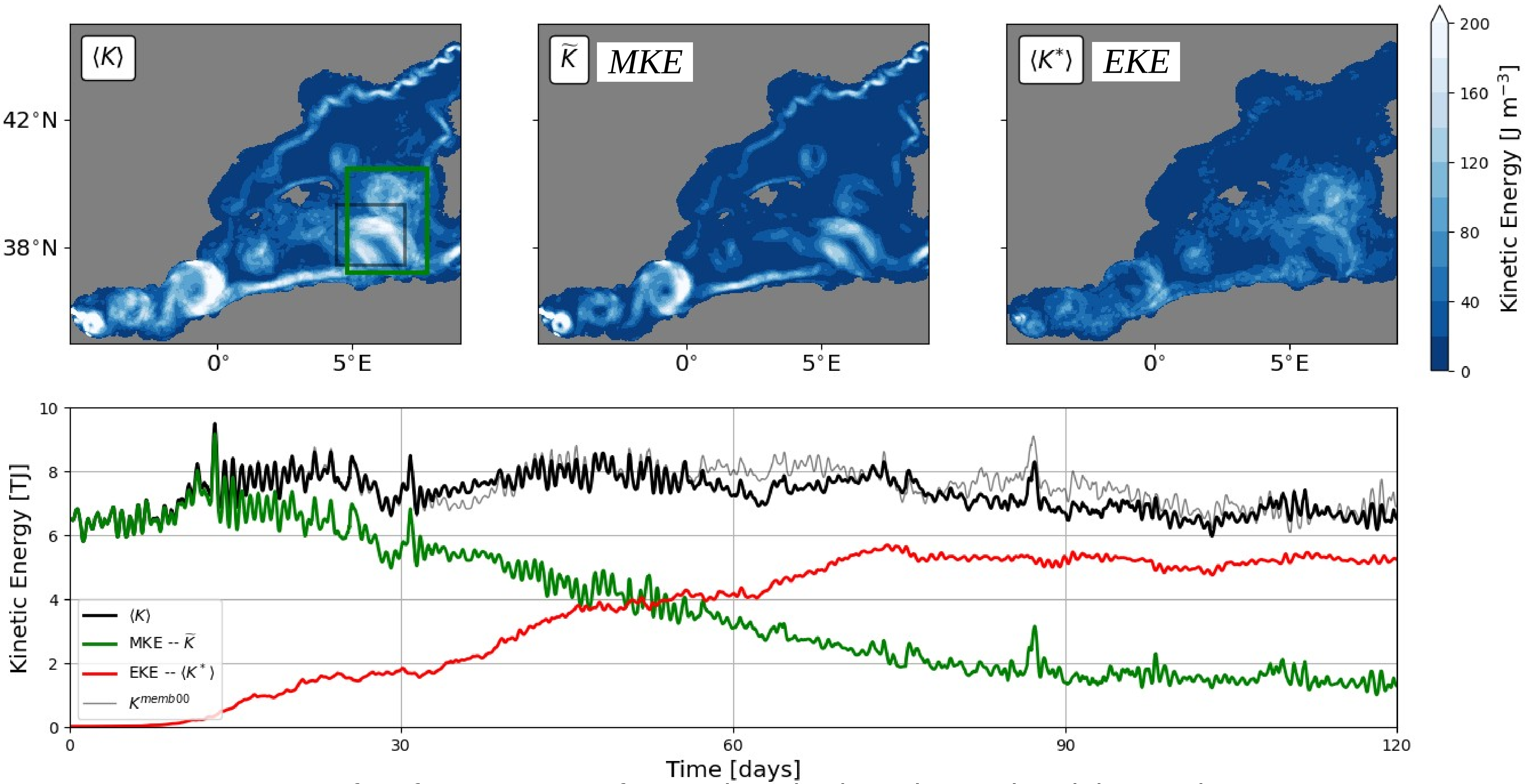
Target forecast score	1 day	2 days	5 days	10 days	15 days	20 days
2 km	1.6 km	1.4 km	—	—	—	—
5 km	3.9 km	3.1 km	1.4 km	—	—	—
10 km	7.9 km	6.2 km	4.4 km	1.4 km	—	—
15 km	11.7 km	10.4 km	6.3 km	3.1 km	1.4 km	—
20 km	16.2 km	14.9 km	10.5 km	5.4 km	2.3 km	1.4 km

Initial location accuracy required (location score, in km) to obtain the target final location accuracy (location score in km, left column) with a 95% confidence for different forecast time lags

➔ Inform on necessary accuracy in observations to achieve specific targeted forecast skills

Energy transfers

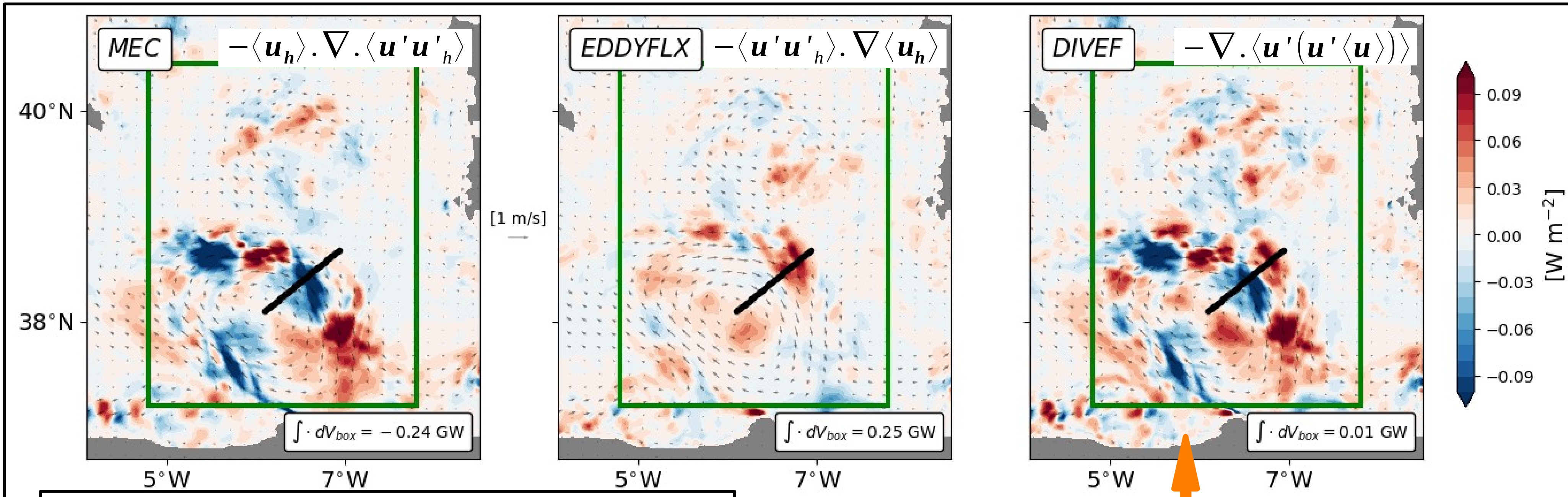
- Decorrelation of the turbulent flow (ENS-CI)
  - Time scale for EKE initial growth: < 1 week
  - Time scale for EKE 'saturation': ~80 days



KE of surface currents after 60 days (top), and associated time series within the Algerian Eddy region (green box ; bottom).

Energy transfers

- Eddy-mean transfers are largely **non-local** at small scales:
  - Involve turbulent fluxes of the **cross-energy** term ➔ $\nabla.\langle \boldsymbol{u}' \boxed{(\boldsymbol{u}'_h.\langle \boldsymbol{u_h}\rangle)} \rangle$
  - **Horizontal constraint** on eddy-mean flow KE transfers ➔ $\boldsymbol{u}'_h.\langle \boldsymbol{u_h}\rangle = 0 \;\; for \;\; \boldsymbol{u}'_h \perp \langle \boldsymbol{u_h}\rangle$



http://ocean.fsu.edu/~qjamet/share/data/nrj_medwest/mec_eflx_box.mp4

Vertically integrated MEC, EDDYFLX and DIVEF after 60 days of simulations

Signature of non-local eddy-mean flow interactions

Conclusions

- Short-term predictability:
  - Introduced a probabilistic approach based on **ensemble simulations**
  - Quantify the **accuracy of observations** and models needed to achieve **targeted forecast skills**
  - The necessary conditions can be translated into **useful guidance** information to **design future ocean observing system**

- Energy transfers:
  - **Spatio-temporal structure** of eddy-mean flow interactions in the context of **time varying forcing**
  - How to treat observations *wrt* ensemble simulations?
    → Need a robust comparison between ensemble *vs*. time/spatial filtering
    → Can we treat **observations as an additional ensemble member** and quantify their statistics?

➔ Exploitation of **ensemble simulations** at medwest cross-over in the context of **BIO-SWOT**

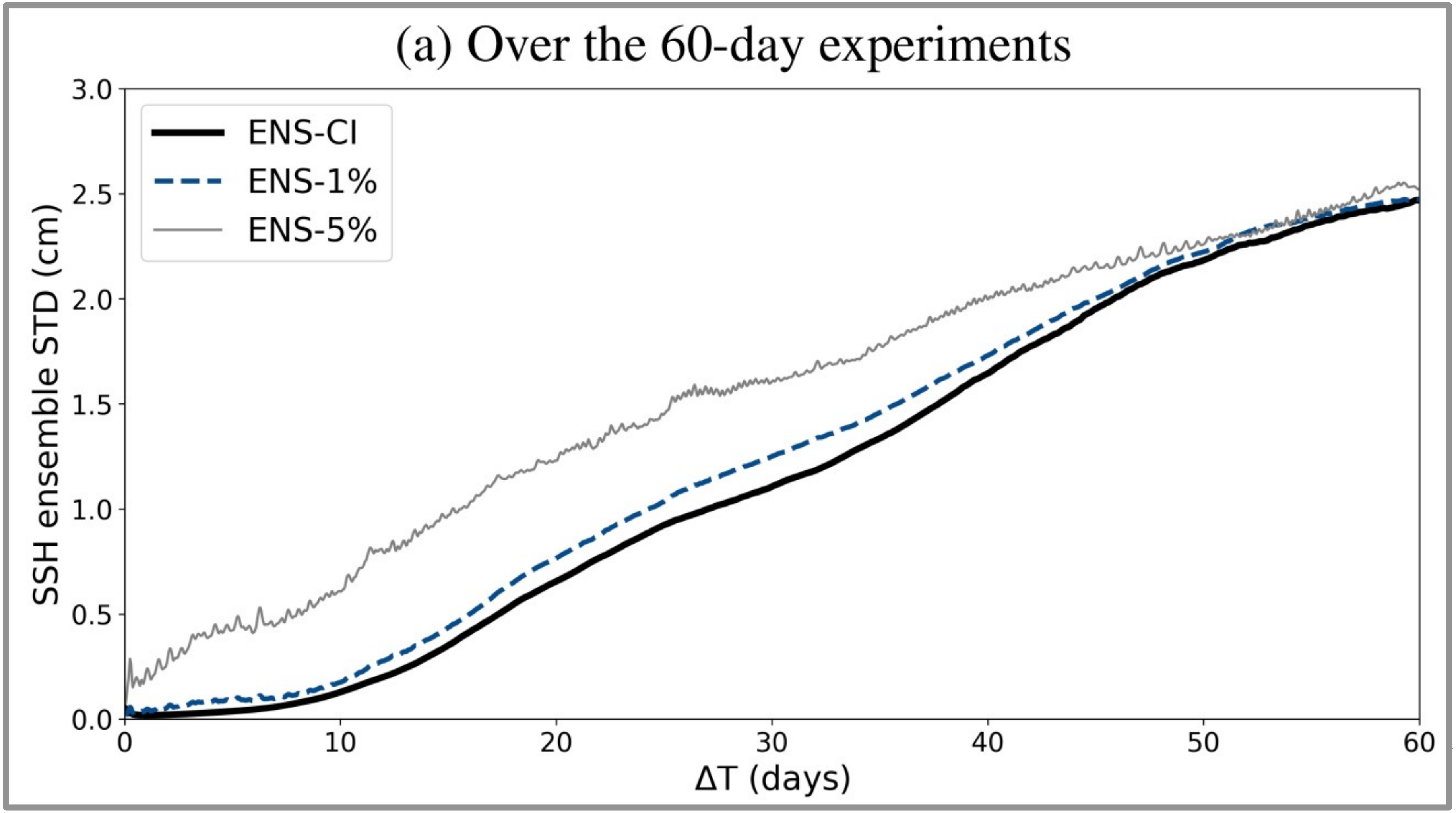
Thank you!

- MEDWEST60 web page:
  - https://github.com/ocean-next/MEDWEST60

- Related papers:
  - Leroux, S., Brankart, J. M., Albert, A., Brodeau, L., Molines, J. M., Jamet, Q., Le Sommer, J., Penduff, T. & Brasseur, P. (2022). Ensemble quantification of short-term predictability of the ocean dynamics at kilometric-scale resolution: A Western Mediter
  - Jamet, Q., Leroux, S., Dewar, W. K., Penduff, T., Le Sommer, J., Molines, J. M., & Gula, J. (In Rev). Non-local eddy-mean kinetic energy transfers in submesoscale-permitting ensemble simulations, ournal of Advances in Modeling Earth Systems

Supplementary

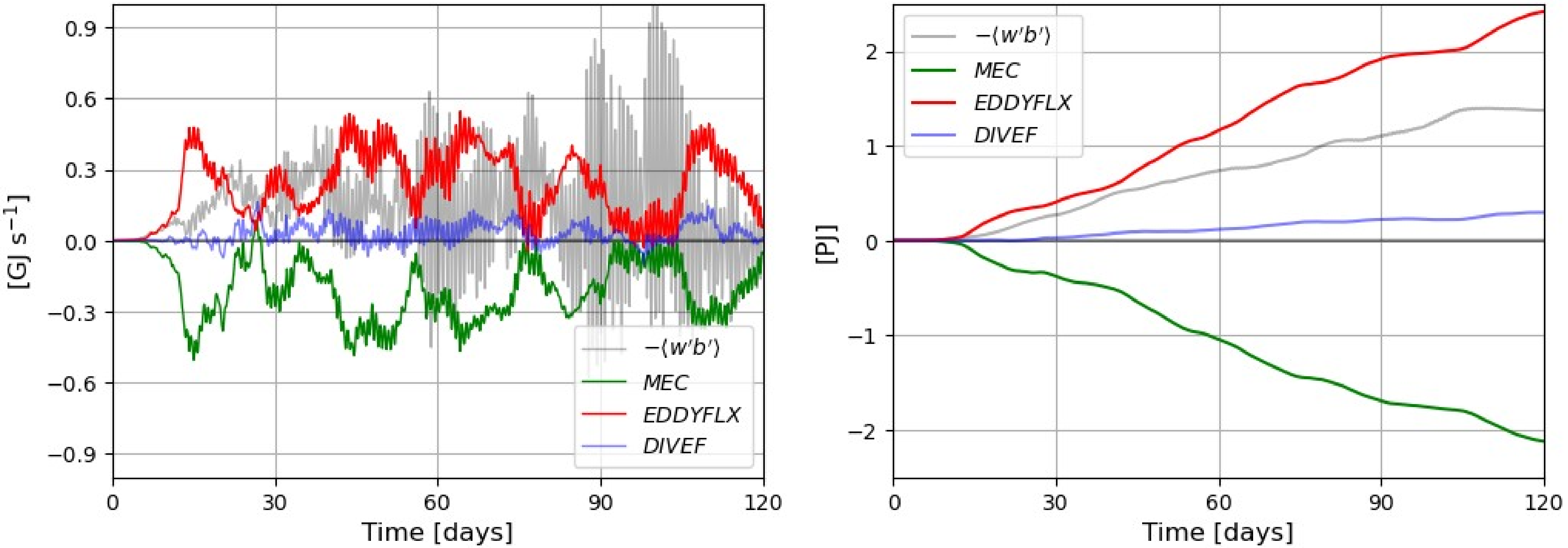
- Sources of forecast errors:
  - Initial conditions *vs*. model uncertainties
  - >1% model uncertainties
    dominates over Initial Conditions



Supplementary

- <u>Eddy-mean flow kinetic energy transfers</u>:
  - Local at large scale (>1º)
  - Strongly non-local at small scale (<1/4º)
  - Quantify the time integrated contribution of eddy-mean KE transfers

$$\partial_t MKE = \ldots - \langle \mathbf{u_h} \rangle . \nabla . \langle \mathbf{u}' \mathbf{u_h}' \rangle$$
$$\partial_t EKE = \ldots - \langle \mathbf{u}' \mathbf{u_h}' \rangle . \nabla \langle \mathbf{u_h} \rangle$$



Time series (left) and time integrated contribution (right) of MEC, EDDYFLX and DIVEF volume integrated within the Algerian Current region

Supplementary

- Non-local interactions have important implications for the development of robust parametrizations [Grooms 2013, 2017]

- We want to find a dynamically consistent solution for the buoyancy equation:

$$\partial_t \overline{b} + \nabla . \overline{\boldsymbol{u}}\,\overline{b} = \overline{Q} \boxed{- \nabla . \overline{\boldsymbol{u}'b'}}$$

where the eddy term needs to be parametrized

- Gent and McWilliams (1990) proposed to model this as (with K a prescribed constant value):

$$\overline{\boldsymbol{u}'b'} \stackrel{\text{def}}{=} K \nabla_h \overline{b}$$

- Subsequent studies [e.g. Cessi, 2008; Eden & Greatbatch, 2008; Mak et al., 2018; Jansen et al., 2019] proposed to refine the definition of K to make it ‘energy-aware’:

$$K \stackrel{\text{def}}{=} L \sqrt{\overline{e}}$$

- Need to solve a prognostic equation for the sub-grid scale kinetic energy:

$$\overline{d_t}\,\overline{e} = - \nabla . \overline{\boldsymbol{u}'e} - \nabla . \overline{\boldsymbol{u}'p'} + \overline{w'b'} - \epsilon \boxed{- \overline{\boldsymbol{u}'\boldsymbol{u}'}_h . \nabla \overline{\boldsymbol{u}}_h}$$

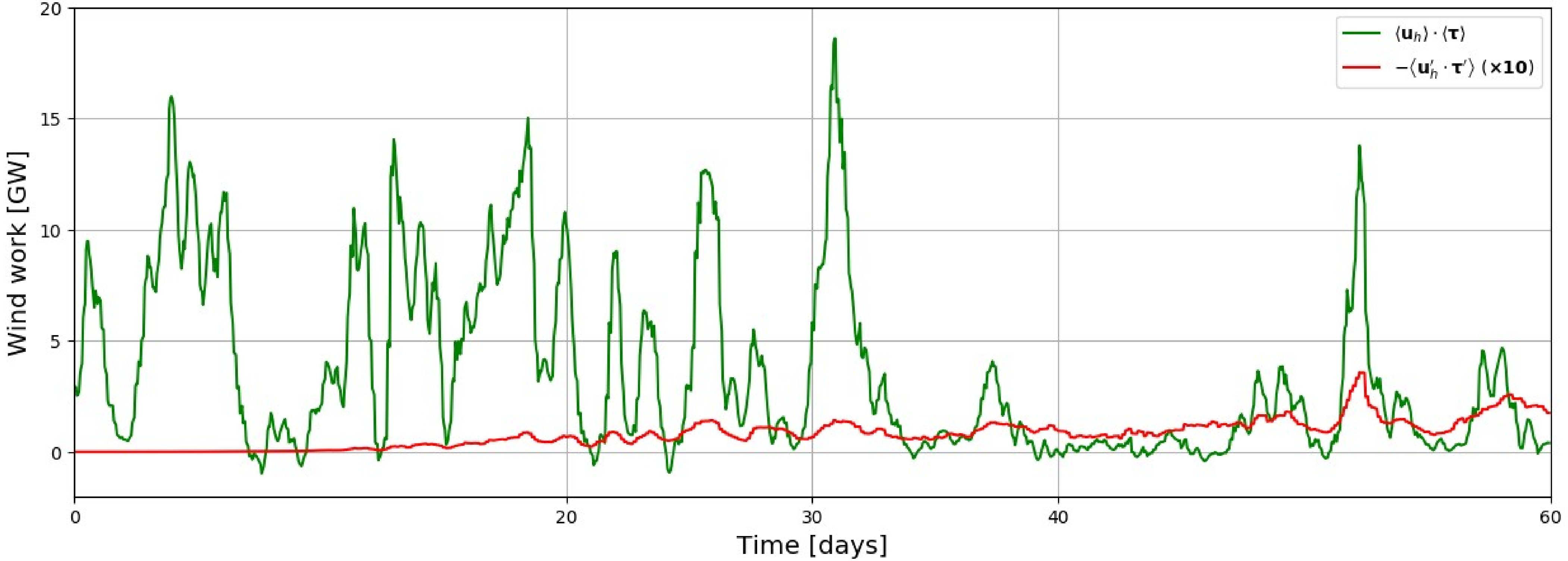
Eddy-mean flow interactions

Supplementary

- Basin integrated EKE budget, a **balance** between:
  - eddy-mean flow interactions
  - exchanges with eddy potential energy
  - dissipation

$$\partial_t \langle X \rangle = \ldots - \nabla . \langle \boldsymbol{u}' X' \rangle$$

$$\partial_t \int_V \langle e \rangle \, dV = \rho_0 \int_V \langle \boldsymbol{u}' \boldsymbol{u}'_h \rangle . \nabla \langle \boldsymbol{u_h} \rangle \, dV + \int_V \langle w' b' \rangle \, dV - \int_V \epsilon \, dV$$



Supplementary

- Eddy-mean flow interactions are ***local*** within the basin:

$$\int_V \left(\nabla.\langle \boldsymbol{u}'(\boldsymbol{u}'_h.\langle \boldsymbol{u_h}\rangle)\rangle = \langle \boldsymbol{u_h}\rangle.\nabla.\langle \boldsymbol{u}'\boldsymbol{u}'_h\rangle + \langle \boldsymbol{u}'\boldsymbol{u_h}\rangle.\nabla\langle \boldsymbol{u_h}\rangle\right) dV = 0$$