EGU General Assembly 2021

Analyzing the Kinetic Energy budget of submesoscale-permitting ensemble simulations

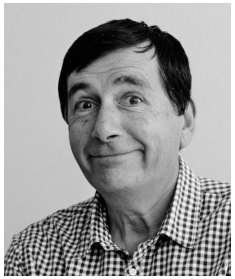
Q. Jamet

S. Leroux

W. K. Dewar

T. Penduff

J. Le Sommer

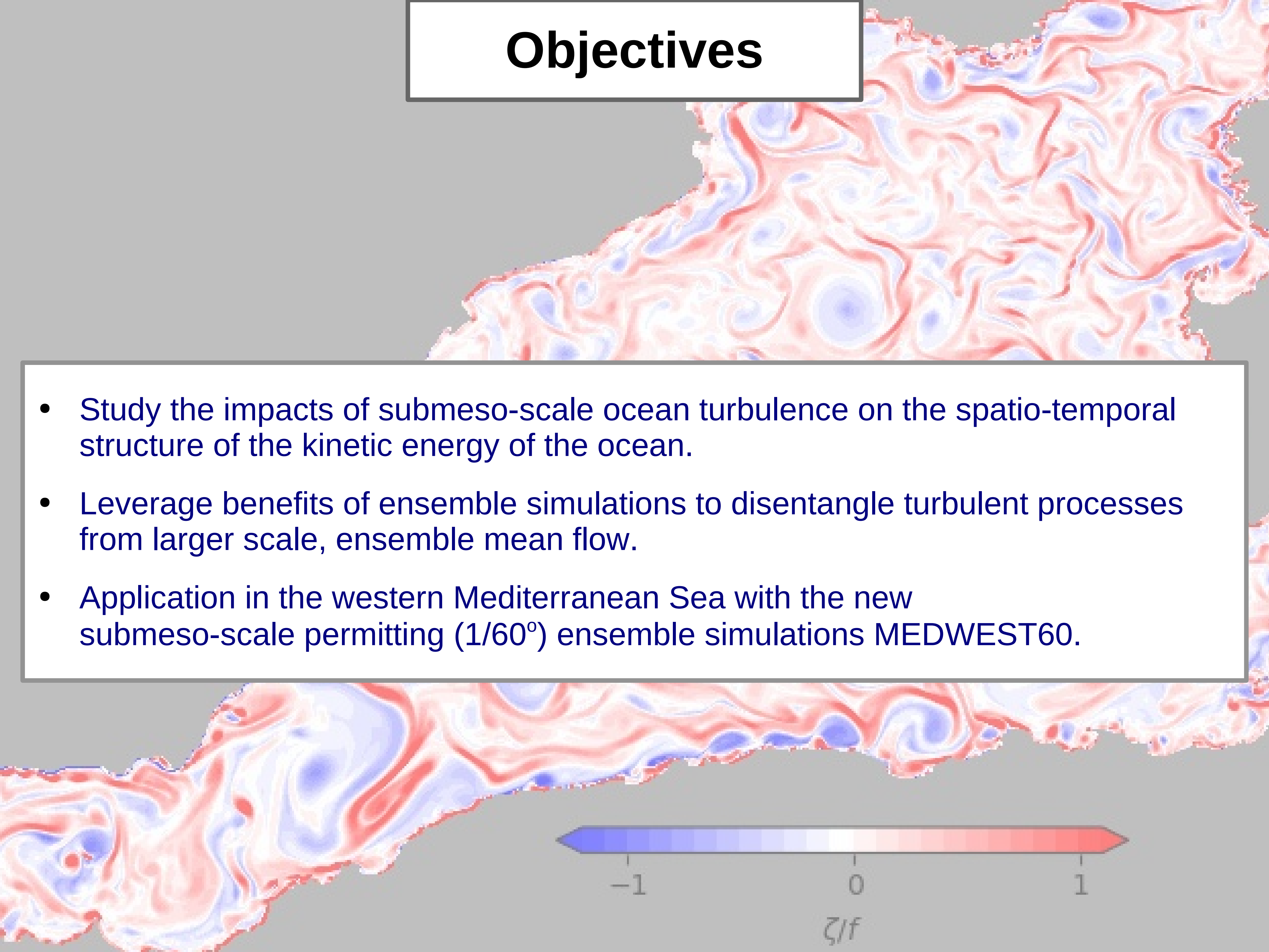


J.-M. Molines

J. Gula

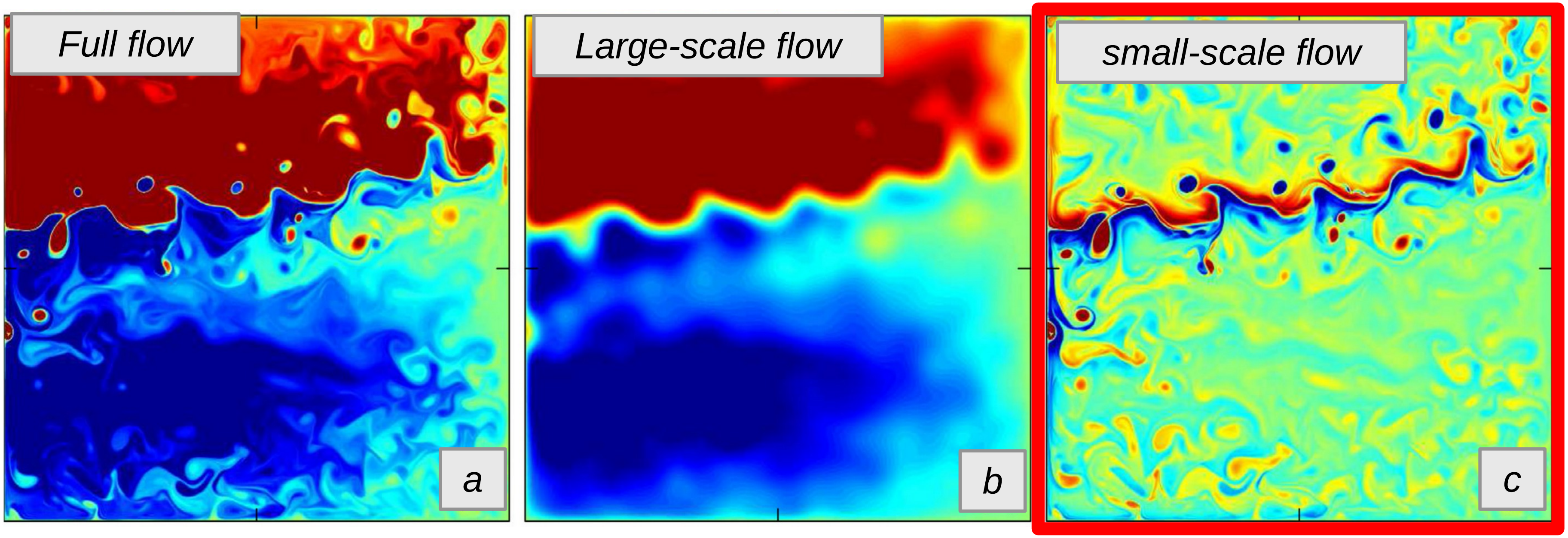
Objectives

- Study the impacts of submeso-scale ocean turbulence on the spatio-temporal structure of the kinetic energy of the ocean.
- Leverage benefits of ensemble simulations to disentangle turbulent processes from larger scale, ensemble mean flow.
- Application in the western Mediterranean Sea with the new submeso-scale permitting (1/60^{o}) ensemble simulations MEDWEST60.



Context

- We need a dynamically consistent representation of submeso-scale ocean turbulence for use in weakly turbulent climate models.
- *Eddy backscattering* is a process of energy transfer between scales that receives increasing attention *[e.g. Berloff, 2015, 2016, 2018 ; Zanna and Bolton, 2020 ; Juricke et al., 2019, 2020]*.



*Surface layer Potential Vorticity (PV) anomalies from an idealized 3 layers, classical double-gyre quasi-geostrophic (QG) model for the instantaneous flow (**a**), decomposed into a large scale (**b**) and a small-scale (**c**) component.*
*The small-scale flow includes processes related to **eddy backscattering** [from Berloff, 2018].*

Problematic

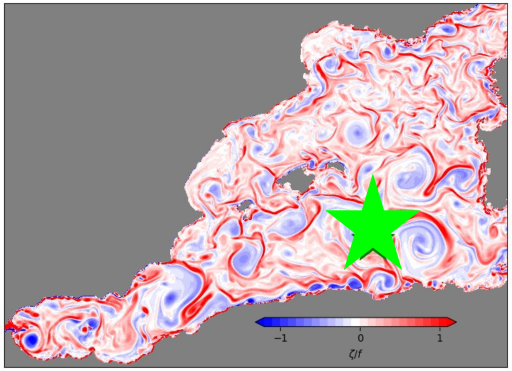
- The separation between large-scale and small-scale flow is traditionally done through spatial filtering *[e.g. Berloff 2018 ; Aluie et al 2018]*.

- This implies:
  - a pre-definition of the scale of separation,
  - complexities near the ocean boundaries,
  - and usually an isotropic assumption.

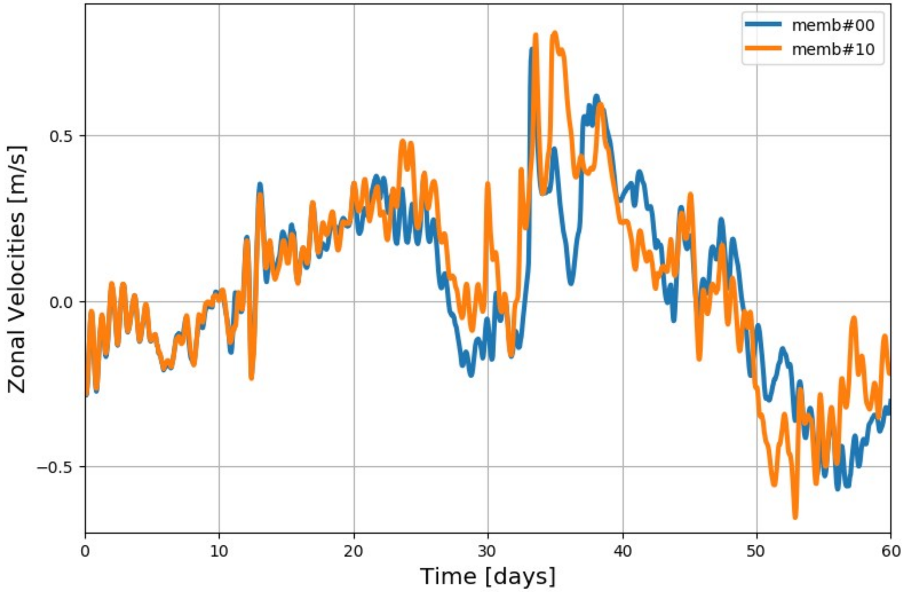
- Here, we leverage the additional dimension provided by ensemble simulations to avoid these limitations.
- In addition, we work with the kinetic energy equation to diagnose energy transfers between the ensemble mean flow and the turbulent flow.

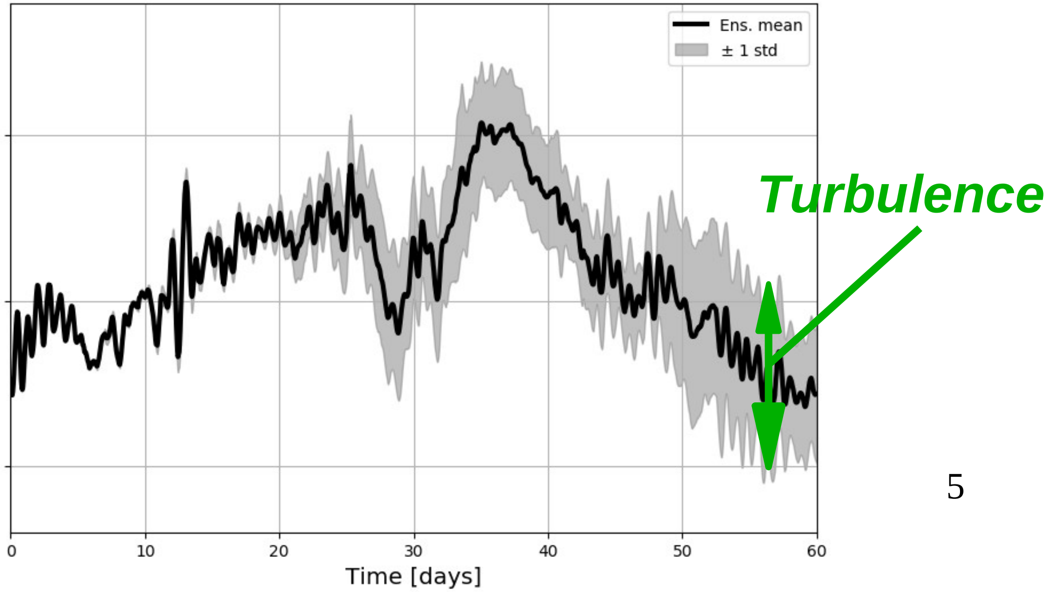
Method

- Ensemble simulations: It provides an unambiguous definition of ocean turbulence.
- Procedure:
  - Produce several simulations subject to identical forcing and numerics, but subject to slightly perturbed *initial conditions*.
  - Non-linearities will produce a divergence in each simulations which we interpret as a signature of *ocean turbulence*.



*(**left**) Time series of zonal velocities in the middle of the basin (green marker on right panel) for 2 members of an ensemble,*
*(**right**) ensemble mean (black) and $\pm$ 1 ensemble standard deviation (grey shading) based on a 20 members ensemble simulation (MEDWEST60).*





Method

- Kinetic Energy equation:
  - Decompose the flow as an ensemble mean and a perturbation:

$$u = \langle u \rangle + u'$$

  - The energy equation for the ensemble mean flow is:

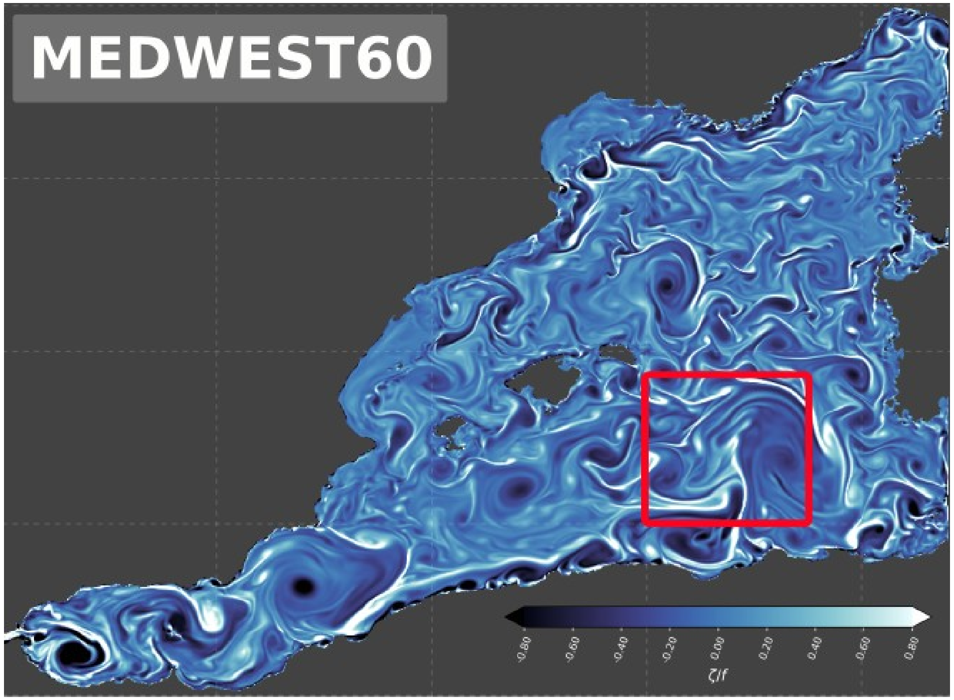
$$\partial_t \tilde{K} = -\nabla . \langle \boldsymbol{u} \rangle \tilde{K} - \rho_0 \langle \boldsymbol{u_h} \rangle \nabla . \langle \boldsymbol{u'u'}_h \rangle - \langle \boldsymbol{u_h} \rangle . \nabla_h \langle p \rangle + \rho_0 \langle \boldsymbol{u_h} \rangle . \langle \boldsymbol{F} \rangle$$

  - with:
    - Kinetic Energy of the mean flow: $\tilde{K} = \rho_0 / 2 \left(\langle u \rangle^2 + \langle v \rangle^2 \right)$
    - time rate of change: $\partial_t \tilde{K}$
    - advection by the mean flow: $-\nabla . \langle \boldsymbol{u} \rangle \tilde{K}$
    - Mean-to-Eddy energy Conversion (MEC): $-\rho_0 \langle \boldsymbol{u_h} \rangle . \nabla . \langle \boldsymbol{u'u'}_h \rangle$
    - pressure work: $-\langle \boldsymbol{u_h} \rangle . \nabla_h \langle p \rangle$
    - forcing and dissipative processes: $\rho_0 \langle \boldsymbol{u_h} \rangle . \langle \boldsymbol{F} \rangle$

➡ Focus on the *Mean-to-Eddy* energy Conversion (MEC) to diagnose the impact of ocean turbulence onto the ensemble mean flow.

Method

- <u>Model and simulation [Leroux et al.]</u>:
  - MEDWEST60 ; NEMO v3.6, 1/60° (1.2 km< Δx <1.5 km) hor. res., 212 vet. levels (1-25 m).
  - Forced by tides, atmospheric forcing (3-hourly ERA-Interim, ECMWF) and lateral boundaries from another 1/60° NEMO simulation run at basin scale (eNATL60, Brodeau et al. (2020)).
  - Initialized with *micro-initial conditions* (i.e. model states after 1 day of integration of another ensemble initialized with stochastic perturbations on the model grid).
  - 60-day long, 20 members ensemble simulation → 80,000 cpu.h.



Snapshot of relative vorticity for one member of the MEDWEST60 ensemble.
The red box indicates the region on which the validation of the offline procedure to recompute the kinetic energy budget of the simulation is performed (see supplementary).

Method

- <u>Offline computation of the simulation</u>:
  - We need estimates of the kinetic energy budget of simulations already produced → develop for this *offline* version of its dynamics.
  - As part of CDFTOOLS, a Fortran-based diagnostic package to analyse NEMO simulations, we have implemented the momentum and kinetic energy budget following MEDWEST60 numerics.
  - Obtained reliable (errors ~O(10^{-2}-10^{-3})) estimates for time rate of change, advection and pressure work.
  - Errors associated with vertical viscous processes are larger (10^{-1}) and issues arose in the computation of the pressure work associated with surface pressure gradients.
  - (see supplementary slides for additional details and validation).

	$\partial_t K =$	$-\nabla \cdot \mathbf{u}K$	$-(u\partial_x p + v\partial_y p)$	$+\rho_0 u \mathbf{D}_u^m + \rho_0 v \mathbf{D}_v^m$
Model time step	10^{-3}	**10^{-5}**	HPG: 10^{-5} SPG: errors	10^{-1}
Time discretisation		**10^{-4}**		10^{-1}
Hourly model outputs	10^{-2}	**10^{-3}**	HPG: 10^{-3}	10^{-1}

Errors in the Kinetic Energy trends computed as $\sigma(b-a)/\sigma(a)$
where b *refers to the offline computation,* a *the model output, and* σ *the 2D spatial standard deviation.*

Results

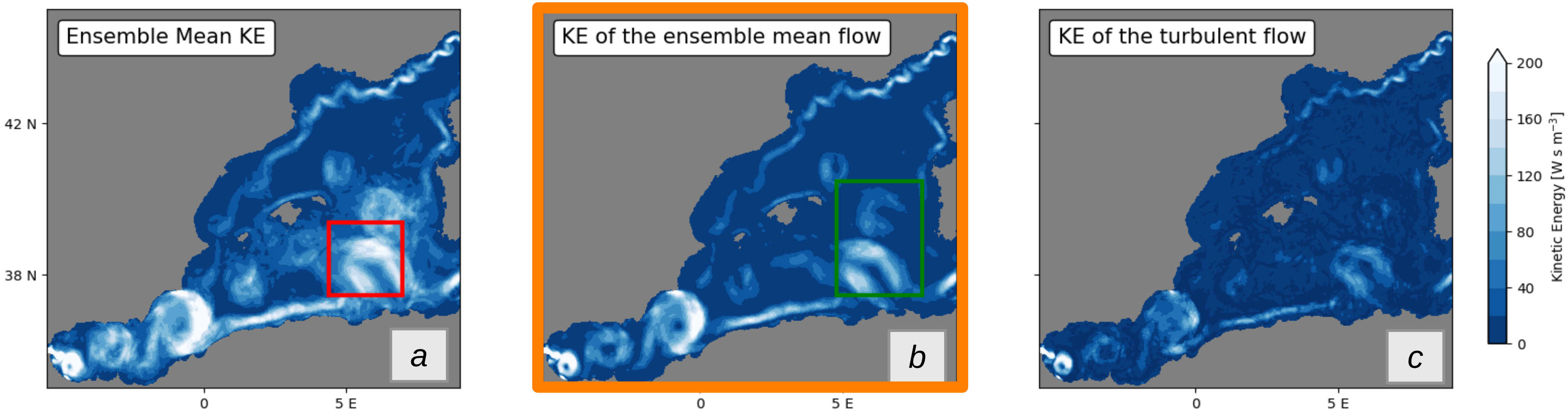
- A first look at the ensemble statistics of the simulation:
  - The ensemble mean KE is the sum of the KE of the ensemble mean flow

$$\widetilde{K}=\rho_0/2\left(\langle u\rangle^2+\langle v\rangle^2\right)$$

  - and the ensemble mean Turbulent Kinetic Energy

$$\langle K^*\rangle=\rho_0/2\left(\langle u'^2\rangle+\langle v'^2\rangle\right)$$

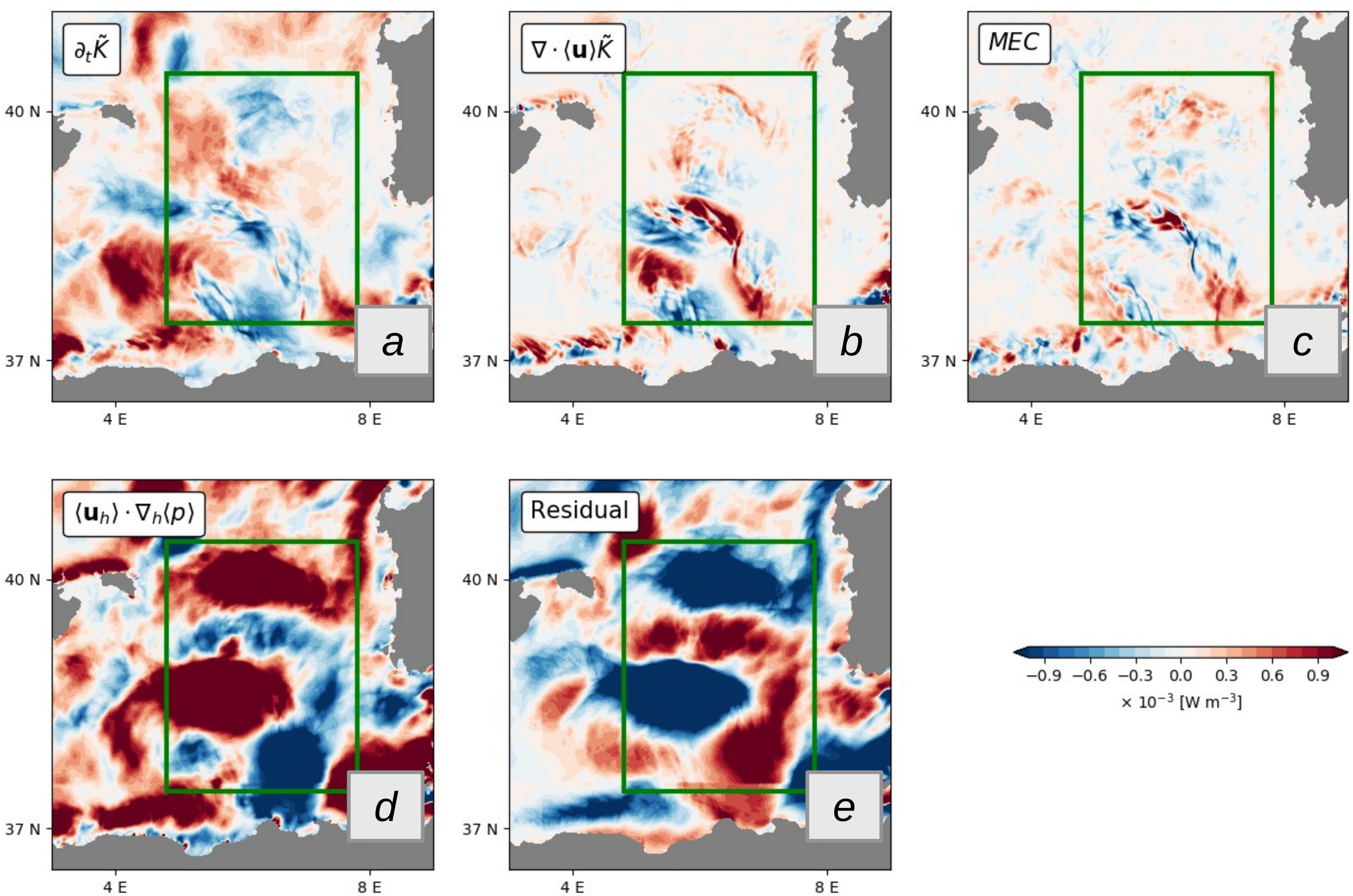
  - We focus on the former in the following in order to first quantify the contribution of ocean turbulence on the mean field.



*Ensemble mean Kinetic Energy (KE) at the end of the 60-day long ensemble simulation MEDWEST60 (**a**), and its decomposition as the KE of the ensemble mean flow (**b**) and the ensemble mean Turbulent Kinetic Energy (**c**).*

Results

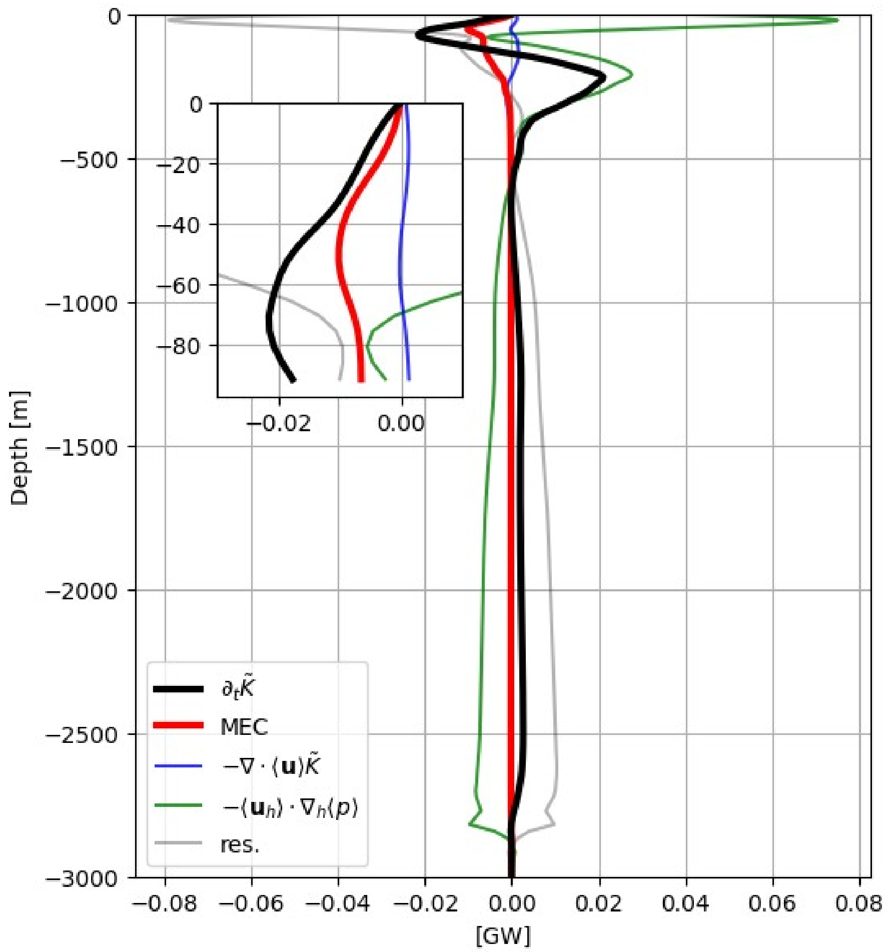
- The surface layer KE budget of the ensemble mean flow reveals that:
  - Vertical viscous processes (computed as a residual, *e*) balance a significant part of pressure work (*d*).
  - Mean-to-Eddy energy Conversion *(c)* shares similarities in shape and amplitude with the advection of KE by the mean flow
    → It is a noticeable contribution of the KE budget.



Surface layer Kinetic Energy budget of the ensemble mean flow.
*(**a**) Time rate of change,*
*(**b**) advection by the mean flow,*
*(**c**) Mean-to-Eddy energy Conversion,*
*(**d**) pressure work*
*(**e**) vertical viscous processes computed as a residual.*

Results

- Horizontally integrated KE trends within the green box (see slide 10):
  - The advection of KE by the mean flow within the box is weak (*blue*).
  - Mean-to-Eddy energy Conversion (*red*) is a significant contribution (>50%) within the upper 40 meters.
  - It acts as a damping term (i.e. MEC < 0).



Horizontally integrated KE trends within the green box (see slide 10).
*(**black**) Time rate of change,*
*(**red**) advection by the mean flow,*
*(**blue**) Mean-to-Eddy energy Conversion,*
*(**green**) pressure work*
*(**gray**) residual.*
The insert is a zoom on the upper 100 meters.

Conclusion

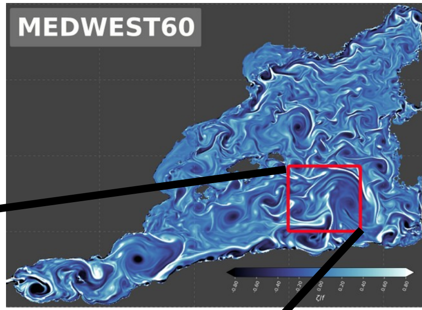
- We have a reliable procedure to compute *offline* most of the kinetic energy trends from pre-produced NEMO simulations (MEDEWEST60).
- Exchanges of energy between ensemble mean and the submeso-scale ocean turbulence is more pronounced in the upper ocean, in agreement with previous studies [e.g. Schubert et al. (2020)].

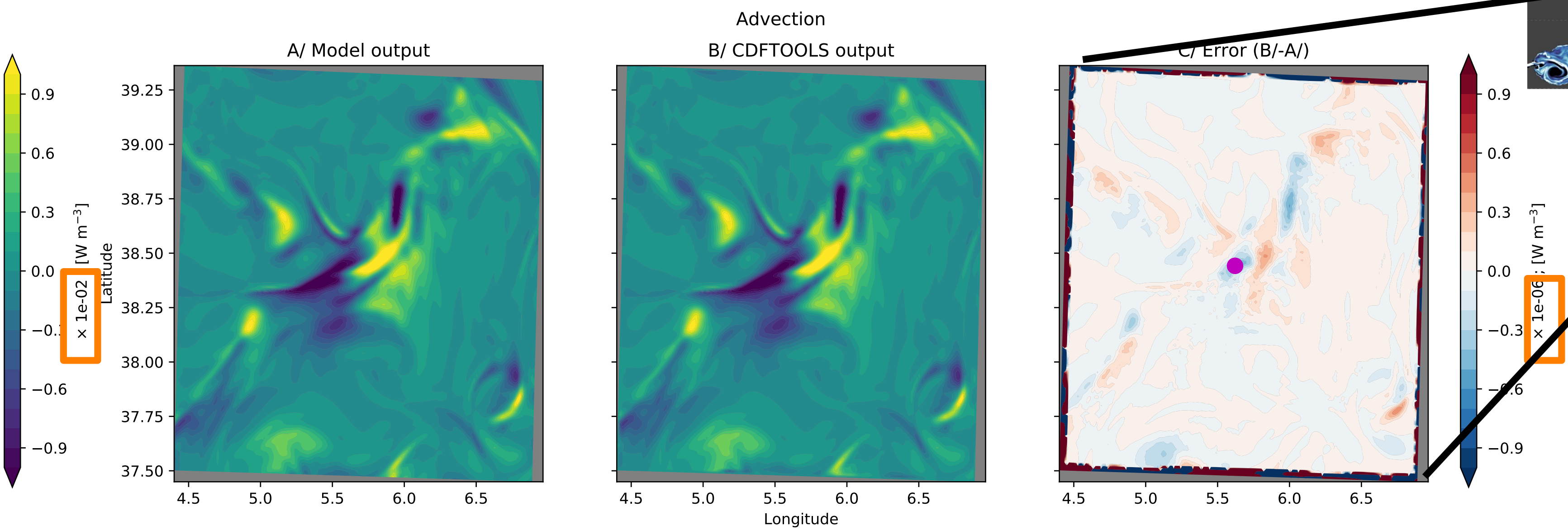
Perspectives

- Leverage the ensemble dimension to further investigate:
  - the contribution of submeso-scale ocean turbulent processes for the kinetic energy of the ensemble mean flow.
  - strategies to parametrize these effects for coarser resolution, non-ensemble simulations such as next generation climate models.

Supplementary

- To estimate the accuracy of our *offline* computation, we first compare its performance with model outputs at model time step:
    - The accuracy is high (10^{-4}-10^{-5}) for time rate of change, advection and pressure work.
    - It is much lower (10^{-1}) for vertical viscous processes
    - we face issues in the computation of pressure work associated with surface pressure gradients due to complexities the implementation of the time-splitting scheme and the interpolation procedure of the forcing terms (atmospheric surface pressure, evaporation, precipitations, runoff).

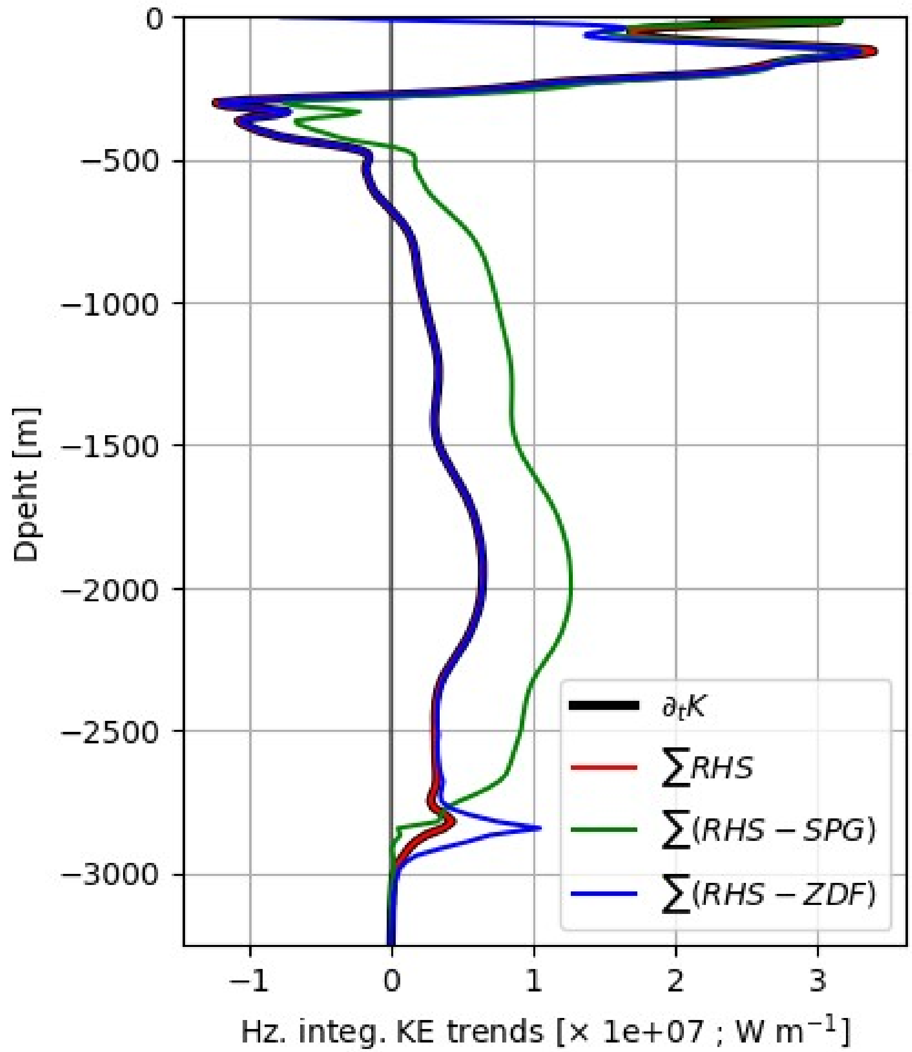




*An example of Kinetic Energy trends associated with 3D advection based on model outputs (**left**), its offline computation (**center**),and the associated errors (**right**). Note the 10^{-4} difference in the colorbar.*

Supplementary

- Vertical viscous processes and pressure work done by surface pressure, computed as residual from NEMO model KE budget, mostly contribute in the (upper and lower) boundary layers and within the interior of the water column, respectively.

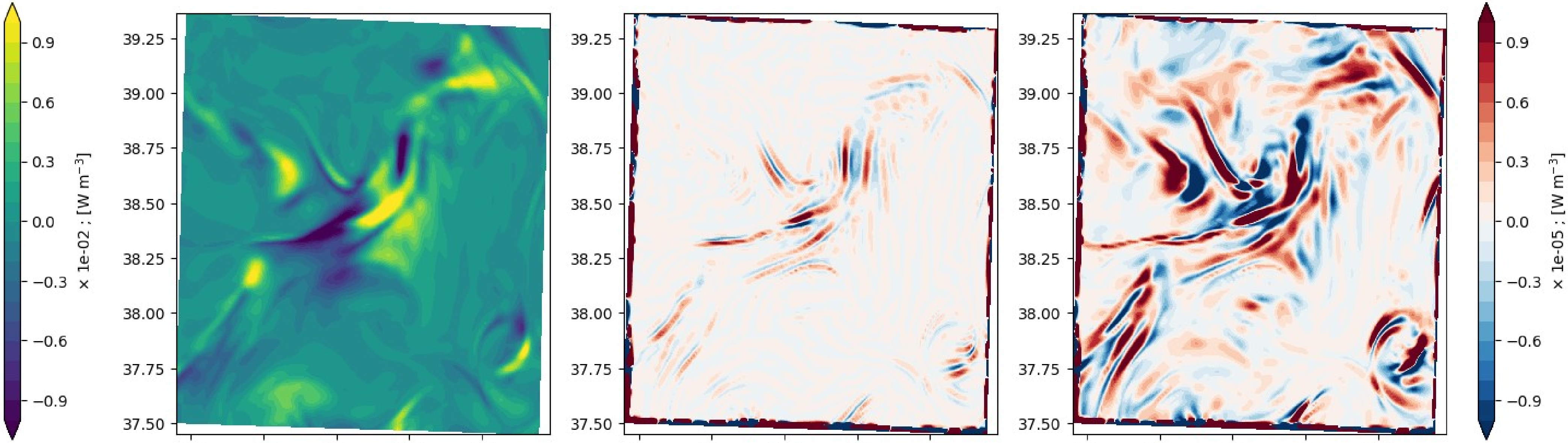


*Horizontally integrated KE trends over the full MEDWEST60 basin, for (**black**) time rate of change, (**red**) sum of the right-hand-side (RHS) of the kinetic energy equation, (**green**) the sum of the RHS minus the contribution of pressure work done by surface pressure, and (**blue**) the sum of the RHS minus the contribution of vertical viscous processes. The computation is made with NEMO model output of the KE budget.*

Supplementary

- We then estimate the errors associated with time discretization and time averaged model outputs. For the advection of kinetic energy, this leads to:
    - a decrease of about one order of magnitude of the accuracy of the *offline* computation where local gradients are the largest when the forward time discretization is not considered, and
    - a decrease of about one order of magnitude distributed more broadly when computing the advection trends based on hourly model outputs.

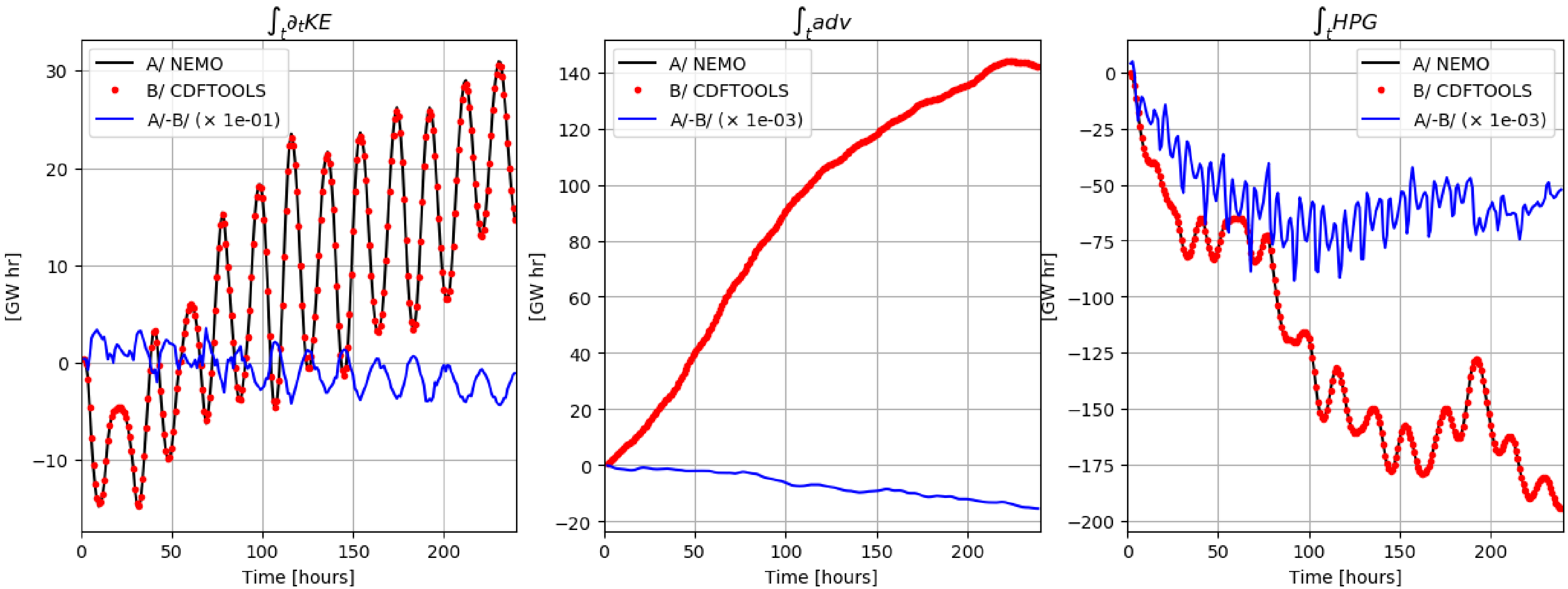
- Similar results are found for other terms.



*An example of Kinetic Energy trends associated with 3D advection based on model outputs (**left**) and its offline computation at model time step without forward time discretization (**center**) and based on hourly model outputs (**right**). Note the 10^{-3} difference in the colorbar.*

Supplementary

- Estimating the error growth with time (cumulative sum over the course of a 10 days simulation) shows that:
  - We systematically underestimate the time rate of change of KE.
  - The errors for advection are weak (10^{-3}) but increase linearly with time.
  - No systematic errors are found for the computation of hydrostatic pressure work.



*Cumulative errors for the volume integrated trends associated with time rate of change (**left**), 3D advection (**centre**), and hydrostatic pressure work (**right**). Model outputs are in black, offline computation (CDFTOOLS) in red and the errors in blue. Note the different scale factors used for errors.*