Non-local eddy-mean kinetic energy transfers in submesoscale-permitting ensemble simulations


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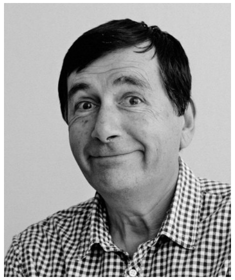
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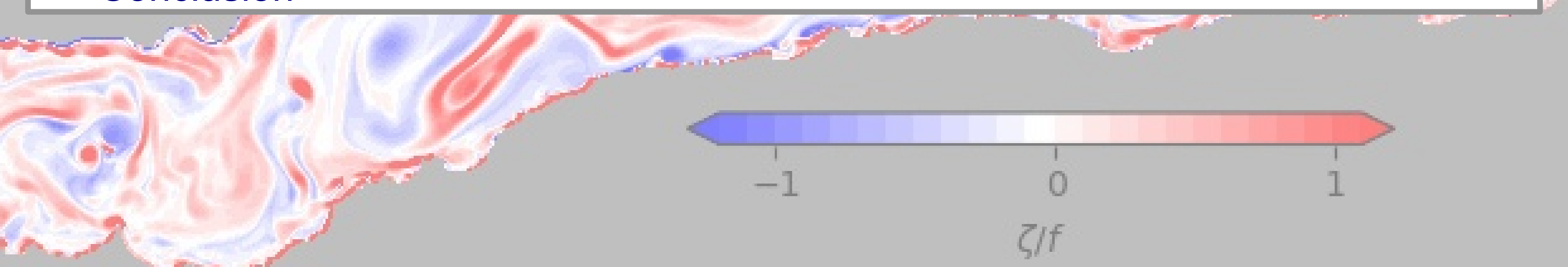
AGENCE NATIONALE DE LA RECHERCHE ANR — INVESTISSEMENTS D'AVENIR — cnrs dépasser les frontières — INSU observer & comprendre — UNIVERSITÉ Grenoble Alpes — IRD Institut de Recherche pour le Développement FRANCE — Grenoble INP ACCÉLÉRATEUR D'AVENIRS SPRINGBOARD TO THE FUTURE

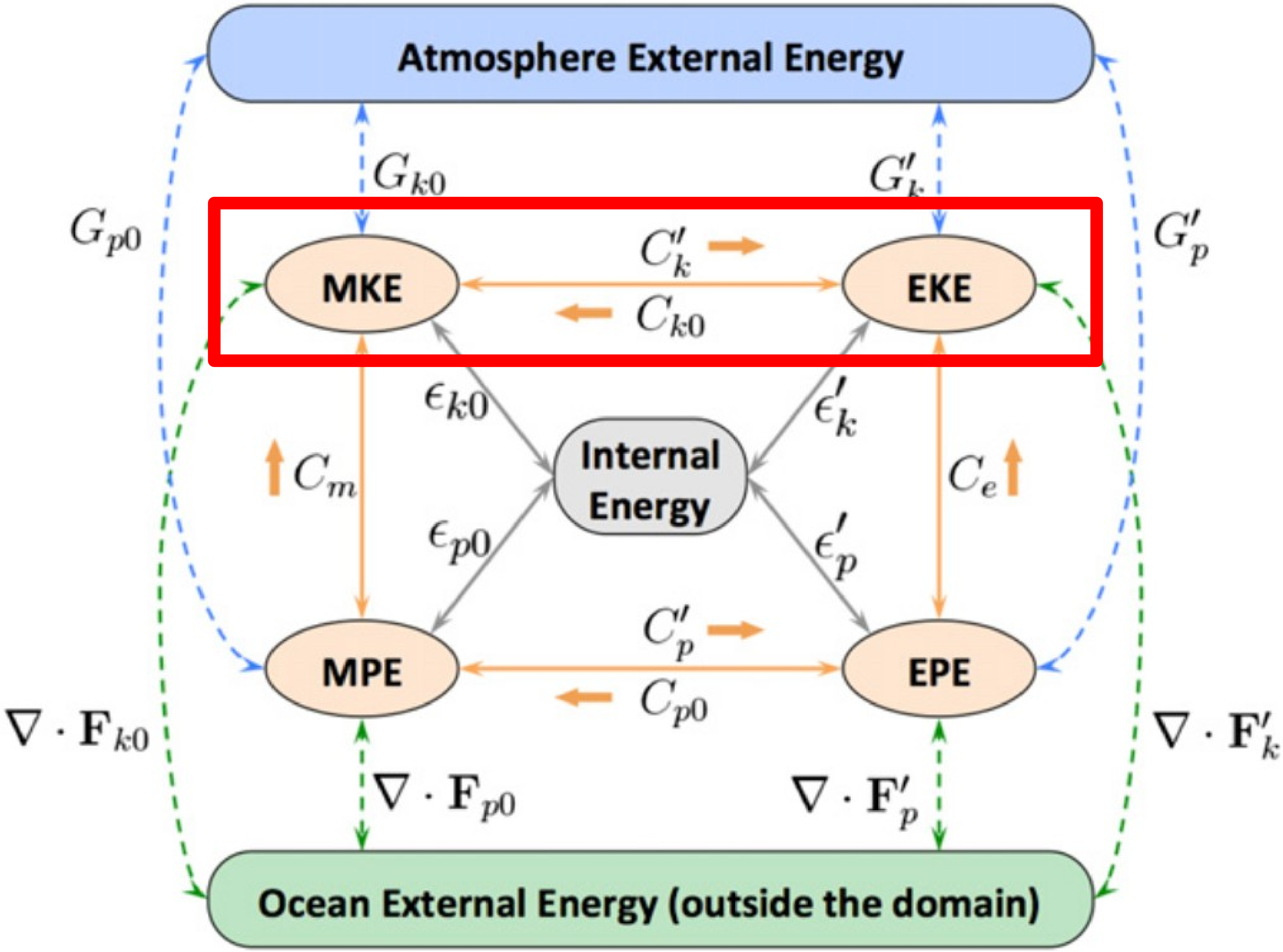
Outline

- Introduction
- Methods
  - Model, simulations and diagnostics
  - Kinetic Energy budget of ensemble simulations
- Results
  - Decorrelation of the turbulent flow
  - Non-locality of MKE-EKE exchanges
  - Horizontal scale dependence
- Conclusion



Introduction

- About energy transfers in the ocean



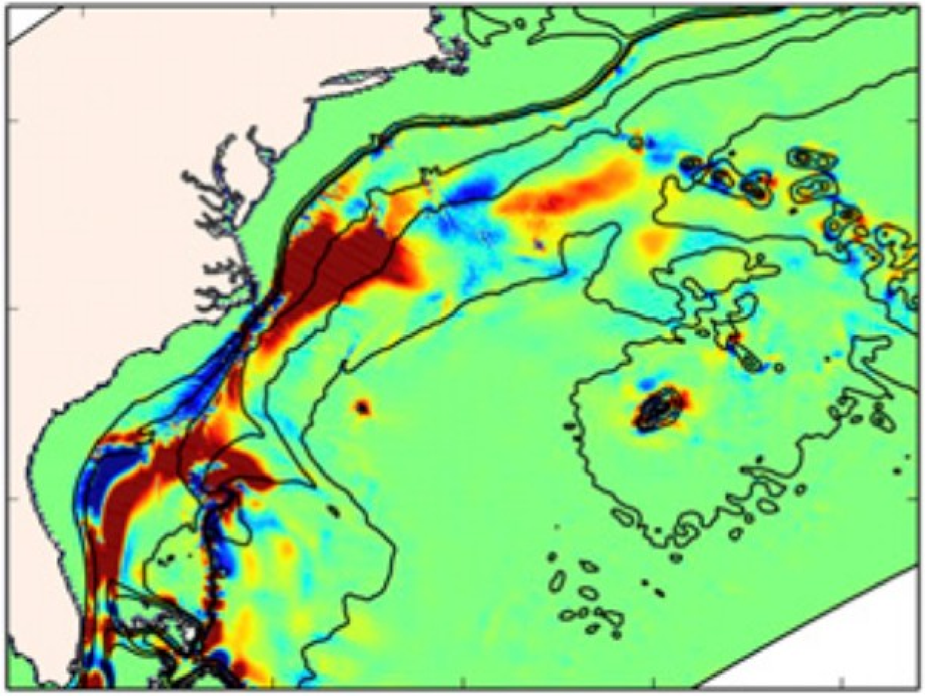
Energy exchange diagram for local ocean domain
[Kang & Curchitser, 2015]

Introduction

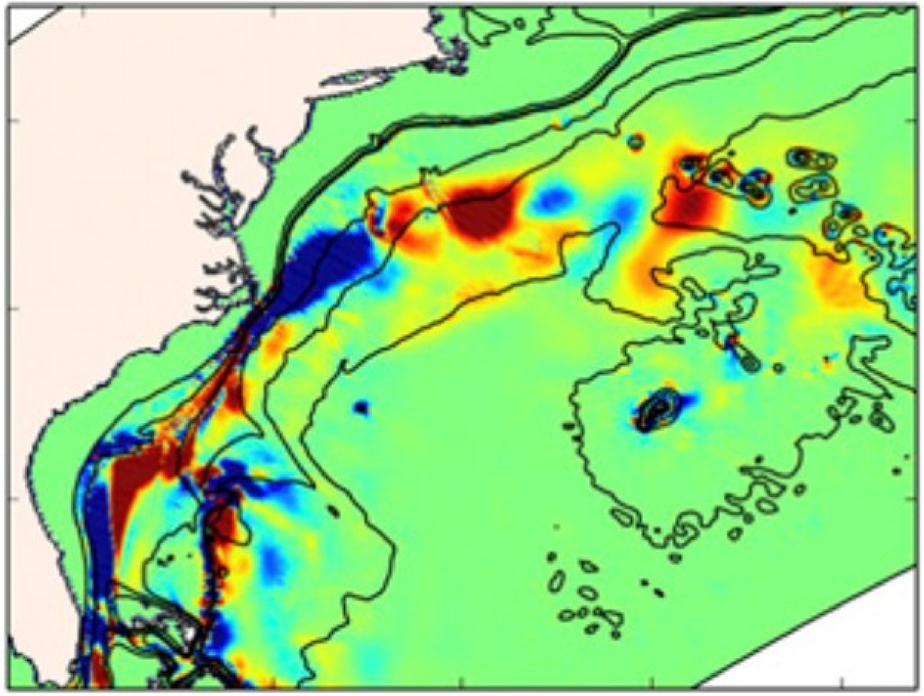
- Focusing on the Kinetic Energy reservoirs (MKE, EKE), and their interactions

- Kang & Curchitser (2015):
  - 50-yr long (1958–2007), regional Gulf Stream ROMS simulation at Δx=7km.
  - Eddies are defined as the residual of the 50-yr time averaging.

$$\partial_t EKE = \ldots - \overline{\boldsymbol{u_h}'\boldsymbol{u}'} . \nabla \overline{\boldsymbol{u_h}}$$



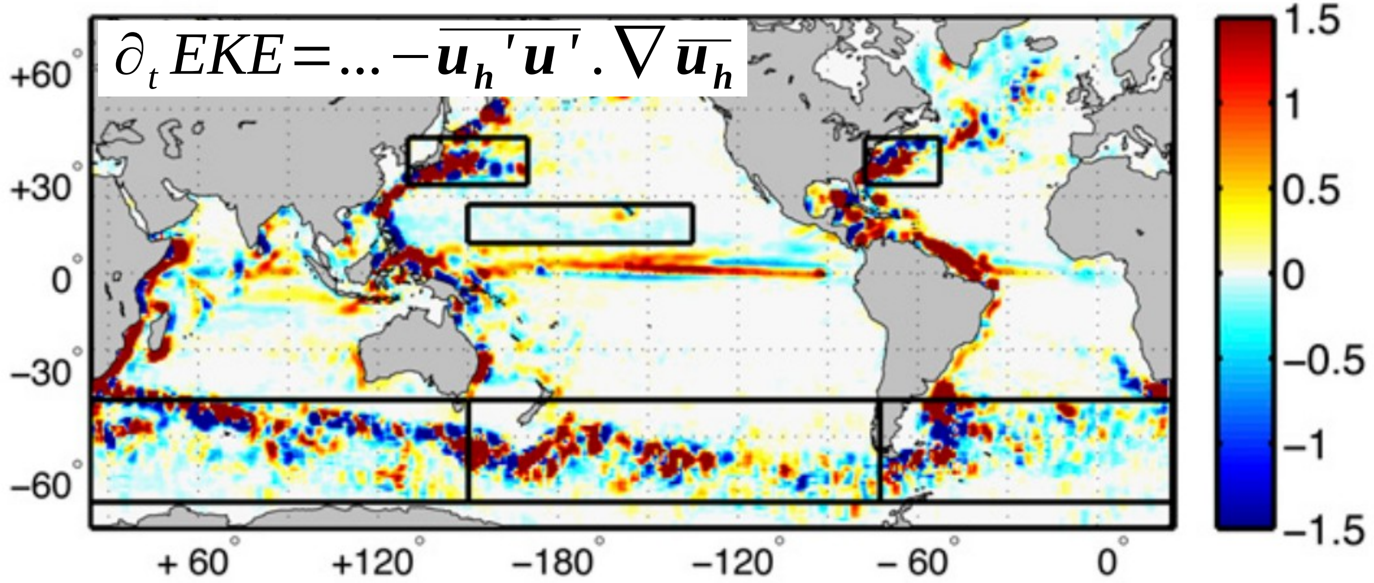
$$\partial_t MKE = \ldots - \overline{\boldsymbol{u}_h} . \nabla . \overline{\boldsymbol{u}'\boldsymbol{u_h}'}$$

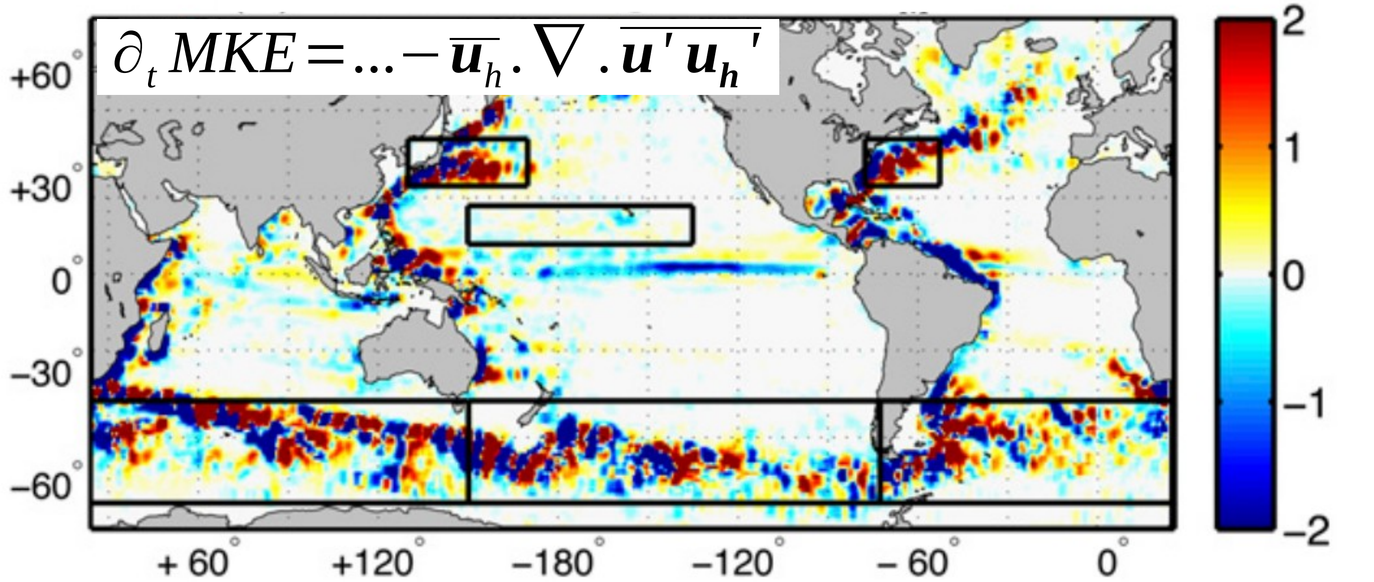


Depth-integrated eddy-mean KE conversion rates
[Kang & Curchitser, 2015]

Introduction

- Eddy-mean KE transfers at global scales [Chen et al, 2014]:





- Non-local dynamics:
  - Southern Ocean
  - Gulf Stream
  - Kuroshio
  - (And likely other western boundary currents ...)

- Local dynamics:
  - “Rest of the world”

Introduction

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

- Find a dynamically consistent solution for the buoyancy equation:

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

where the eddy term needs to be parametrized

- Gent and McWilliams (1990):
with K a prescribed constant value

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

- Energy-aware parametrization [e.g. Cessi, 2008; Eden & Greatbatch, 2008; Mak et al., 2018; Jansen et al., 2019]:

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

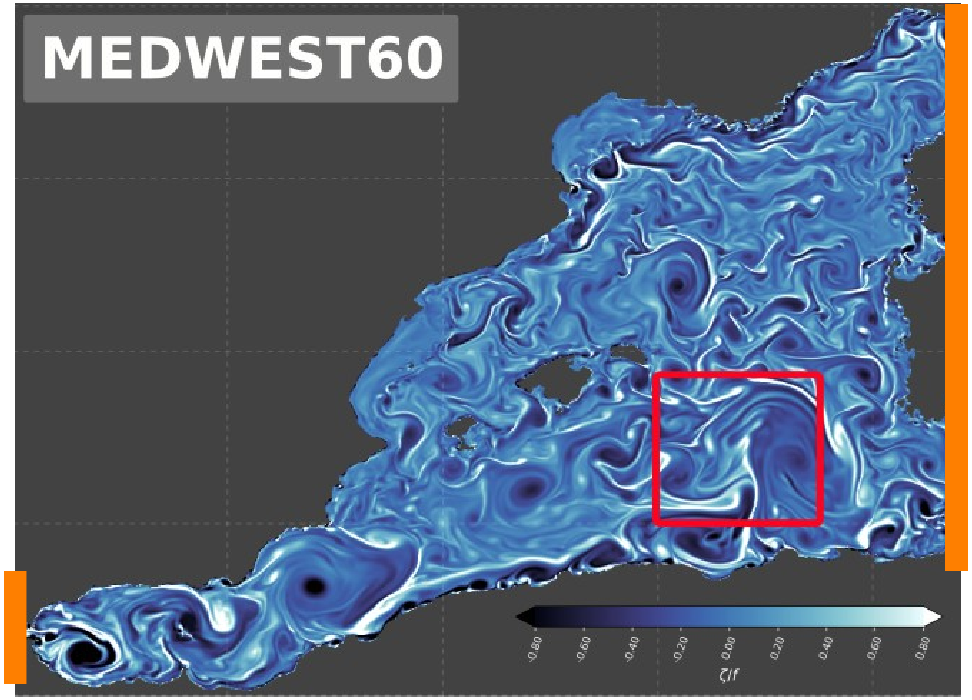
- Need to solve the prognostic equation for the sub-grid scale kinetic energy:

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

Eddy-mean flow interactions

Methods

- Model and simulation:
  - 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)
    - eNATL60-BLBT02 model state [Brodeau et al., 2020], including tidal forcing
  - Initial conditions:
    - spun-up eNATL60-BLBT02 model state at February, 5th 2010
    - + microscopic stochastic perturbations [Mémin 2014; Brankart et al. 2015]
  - 20 members, 120-day long simulations



Snapshot of relative vorticity for one member of the MEDWEST60 ensemble.

Methods

- Kinetic Energy budget of ensemble simulations

  - Basin integrated EKE budget, a balance between:

    → eddy-mean interactions

    → exchanges with eddy potential energy

    → dissipation

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

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

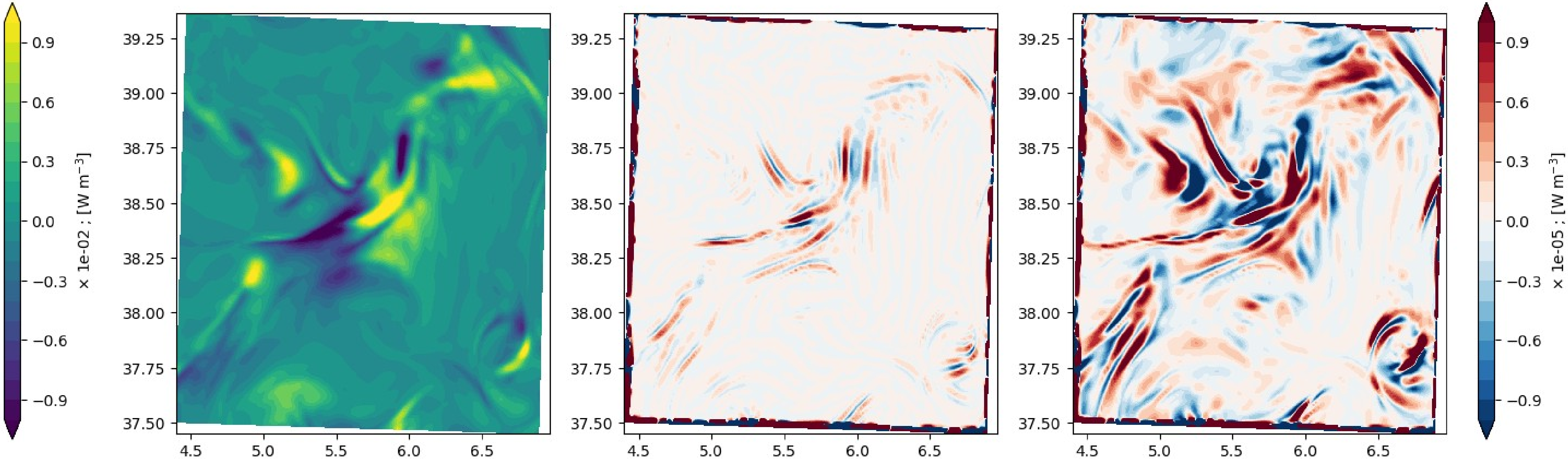
$$\int_V \left(\nabla . \langle \boldsymbol{u}' (\boldsymbol{u}'_h . \langle \boldsymbol{u_h} \rangle) \rangle = \langle \boldsymbol{u_h} \rangle . \nabla . \langle \boldsymbol{u}' \boldsymbol{u}'_h \rangle + \langle \boldsymbol{u}' \boldsymbol{u_h} \rangle . \nabla \langle \boldsymbol{u_h} \rangle \right)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

$\langle \boldsymbol{u_h} \rangle . \nabla . \langle \boldsymbol{u}' \boldsymbol{u}'_h \rangle$ ↓ $\partial_t MKE$

$\langle \boldsymbol{u}' \boldsymbol{u_h} \rangle . \nabla \langle \boldsymbol{u_h} \rangle$ ↓ $\partial_t EKE$

Methods

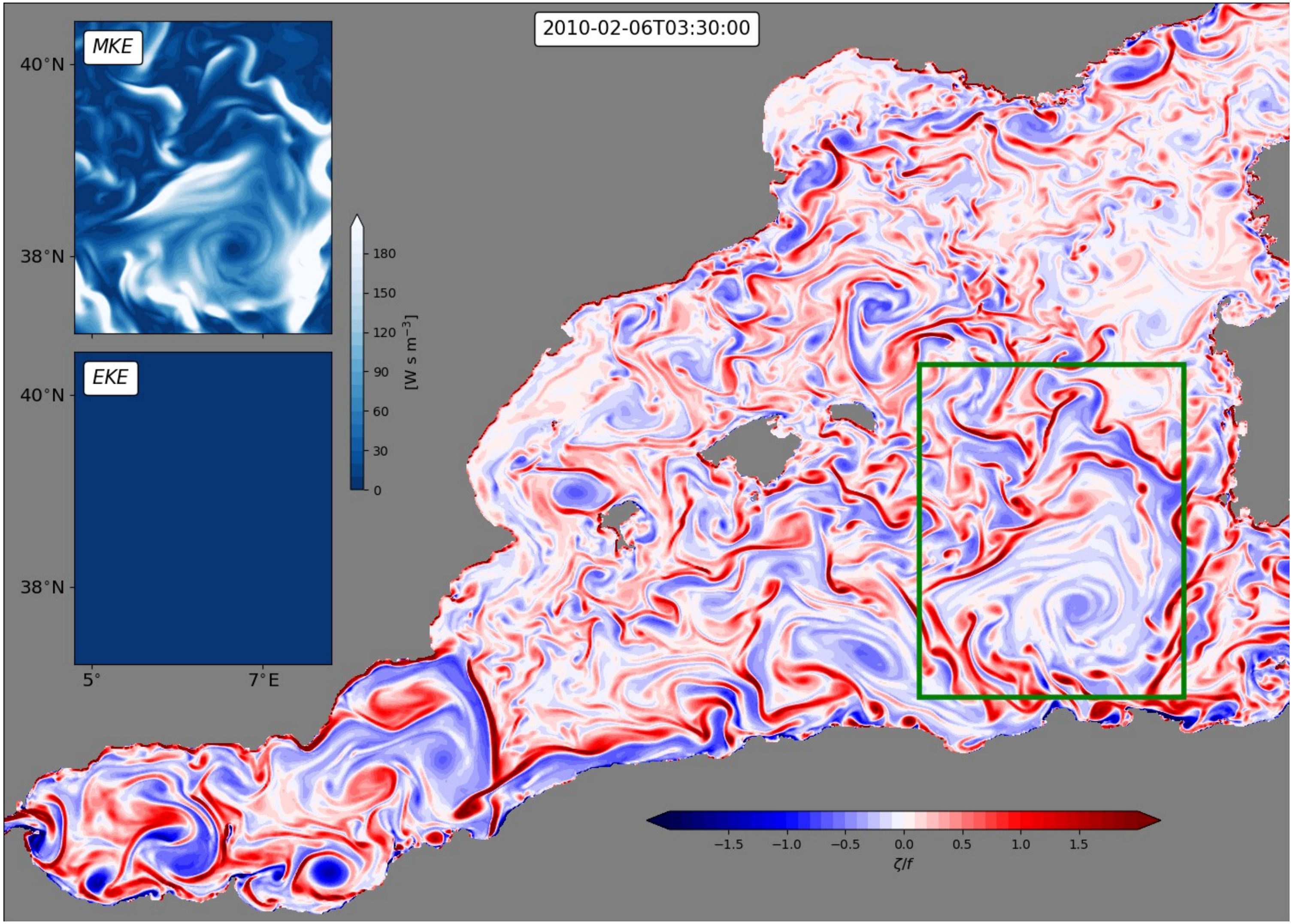
- Offline computation of the simulation:
  - *Offline* estimates of momentum/KE trends
    as part of the CDFTOOLS diagnostic package for NEMO simulations
  - Errors of about ~O(10^{-2}-10^{-3}) as compared to model estimates
    (with hourly averaged model outputs)



*Kinetic Energy trends associated with 3D advection based on model outputs (**left**), its offline estimate based on model time step (**center**) and hourly averaged (**right**) model outputs.*

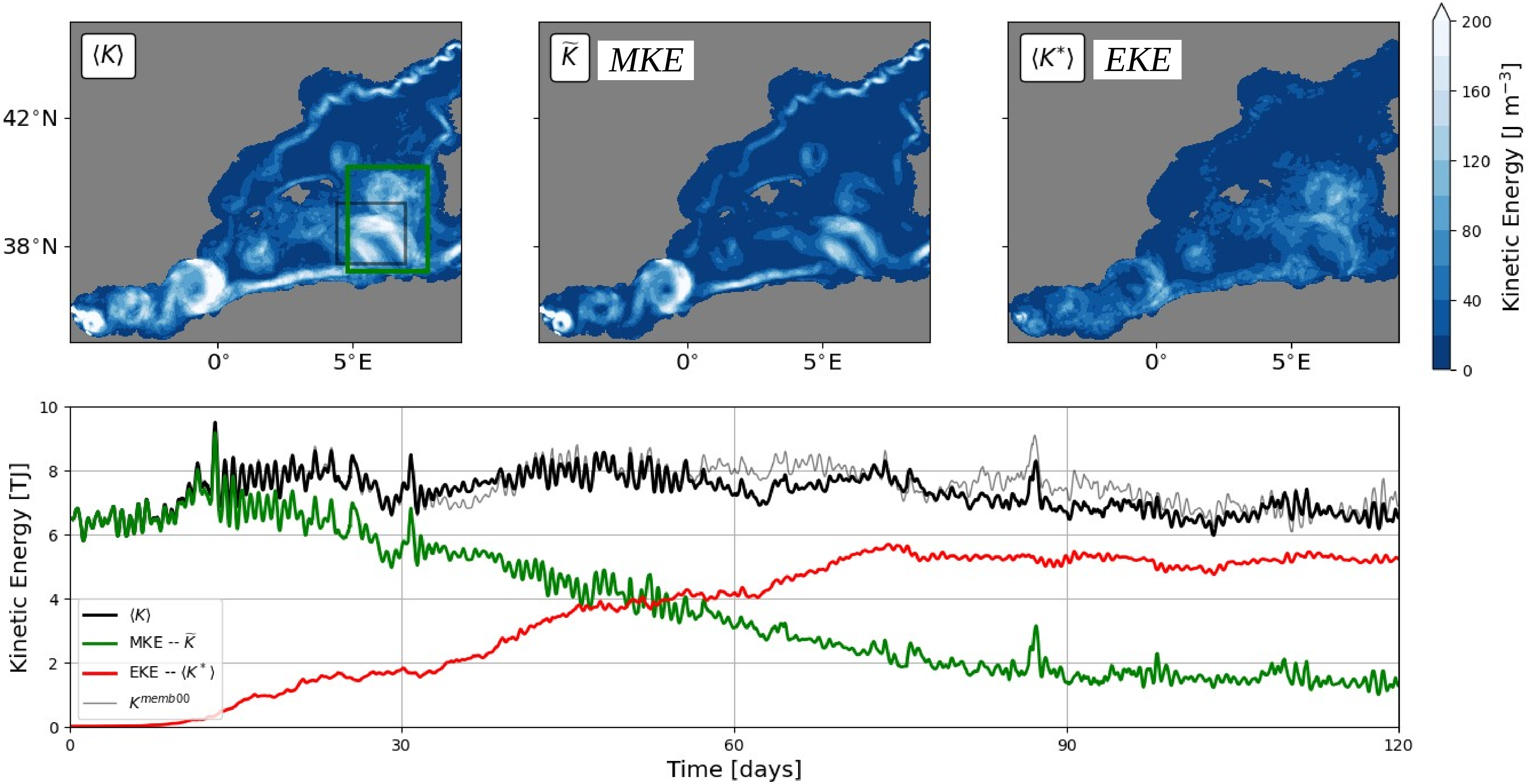
Results

- Decorrelation of the turbulent flow



Results

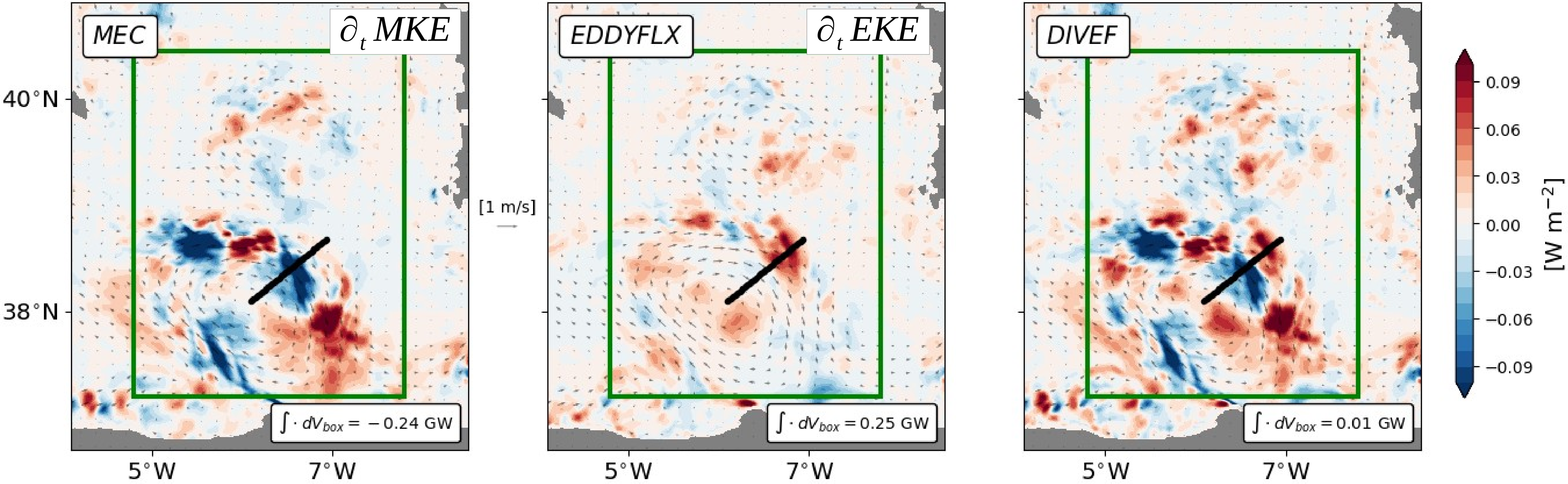
- Decorrelation of the turbulent flow
  - Time scale for EKE initial growth: < 1 week
  - Time scale for EKE 'saturation': ~80 days



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

Results

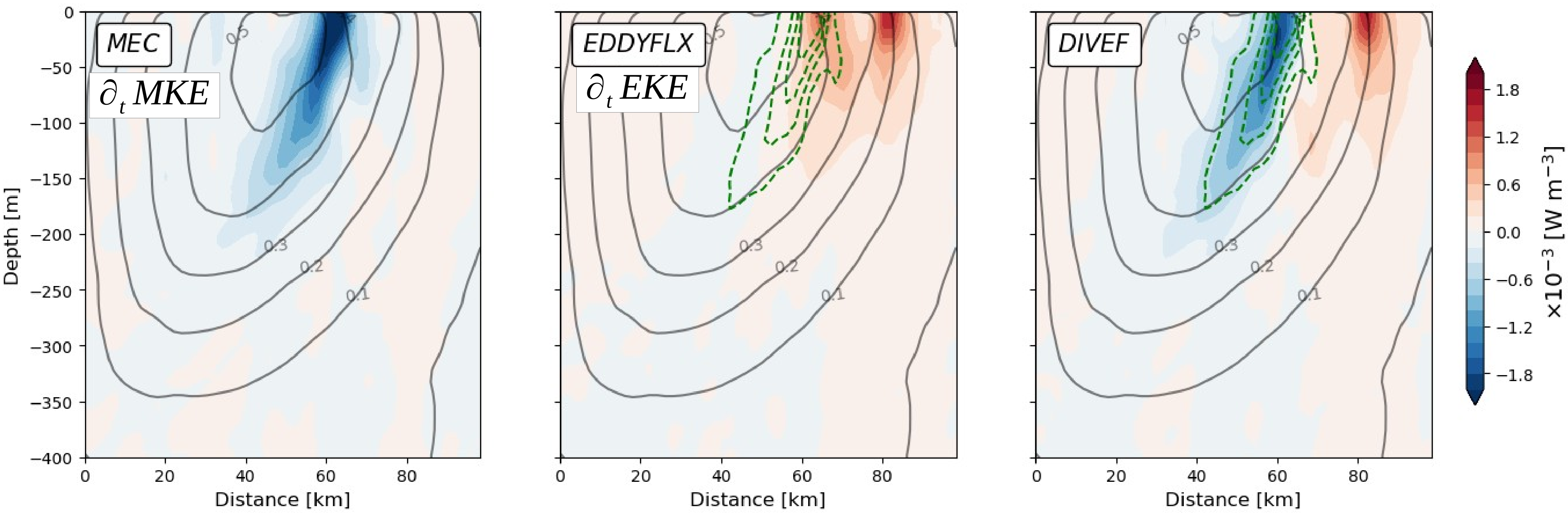
- Non-locality of MKE-EKE transfers
  - Marked differences between MEC and EDDYFLX horizontal structure
  - Leading order contribution of DIVEF: **non-local dynamics**



Vertically integrated MEC, EDDYFLX and DIVEF after 60 days of simulations.
Bottom right inserts: volume integrated estimates ; Arrows: ensemble mean surface currents.

Results

- Non-locality of MKE-EKE transfers
  - MEC is more pronounced near the core of the stream ($\propto \overline{\boldsymbol{u}_h}$)
  - EDDYFLX is more pronounced on the flank of the stream ($\propto \nabla \overline{\boldsymbol{u}_h}$)



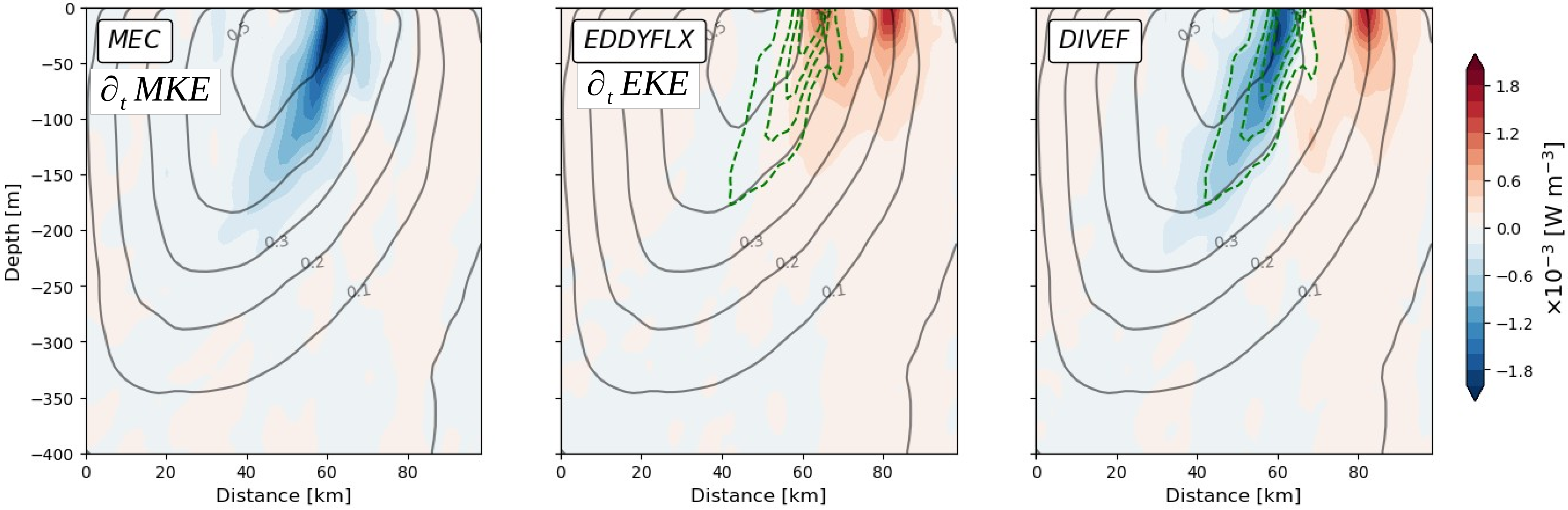
Cross-stream section of MEC, EDDYFLX, and DIVEF.
Gray contours: ensemble mean current across the section.

Results

- <u>Non-locality of MKE-EKE transfers</u>
  - DIVEF: Advection of cross-energy term by the turbulent flow
  - Strong constraint on eddy-mean flow KE exchanges since:

$$\boldsymbol{u}'_h.\langle\boldsymbol{u_h}\rangle=0 \qquad \mathit{for} \qquad \boldsymbol{u}'_h \perp \langle\boldsymbol{u_h}\rangle$$

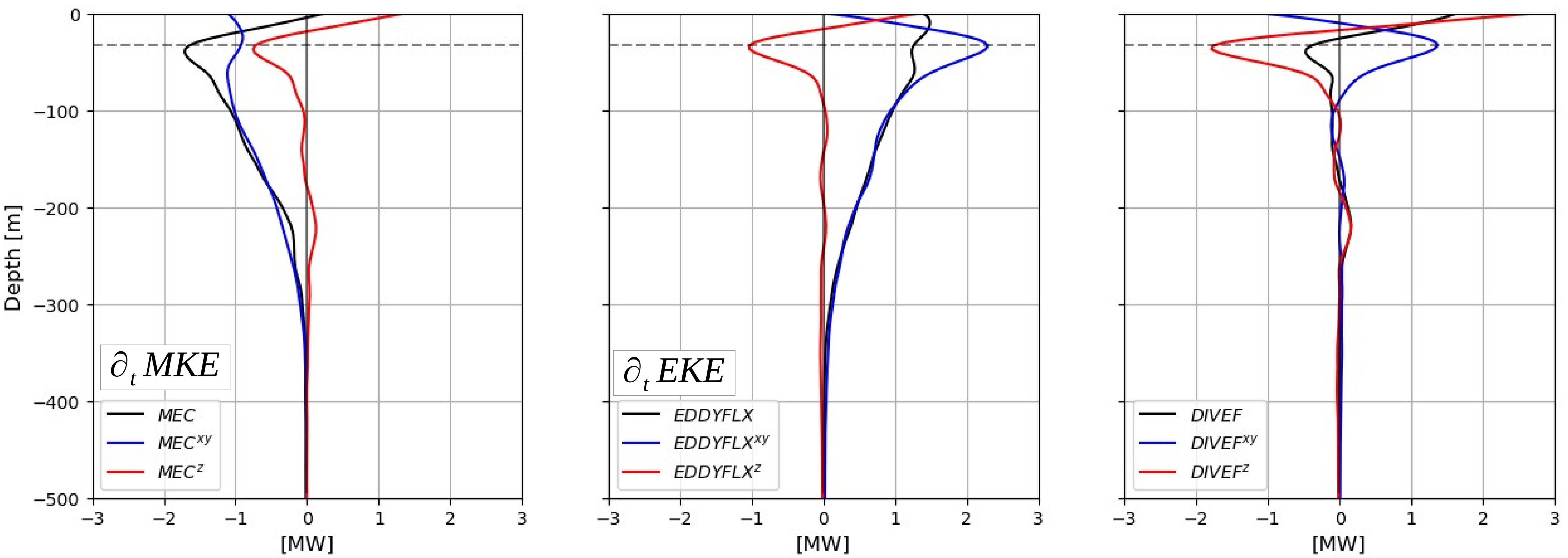
$$\langle\boldsymbol{u_h}\rangle.\nabla.\langle\boldsymbol{u}'\boldsymbol{u}'_h\rangle \quad + \quad \langle\boldsymbol{u}'\boldsymbol{u_h}\rangle.\nabla\langle\boldsymbol{u_h}\rangle \quad = \quad \nabla.\langle\boldsymbol{u}'(\boldsymbol{u}'_h.\langle\boldsymbol{u_h}\rangle)\rangle$$



Cross-stream section of MEC, EDDYFLX, and DIVEF.
Gray contours: ensemble mean current across the section.

Results

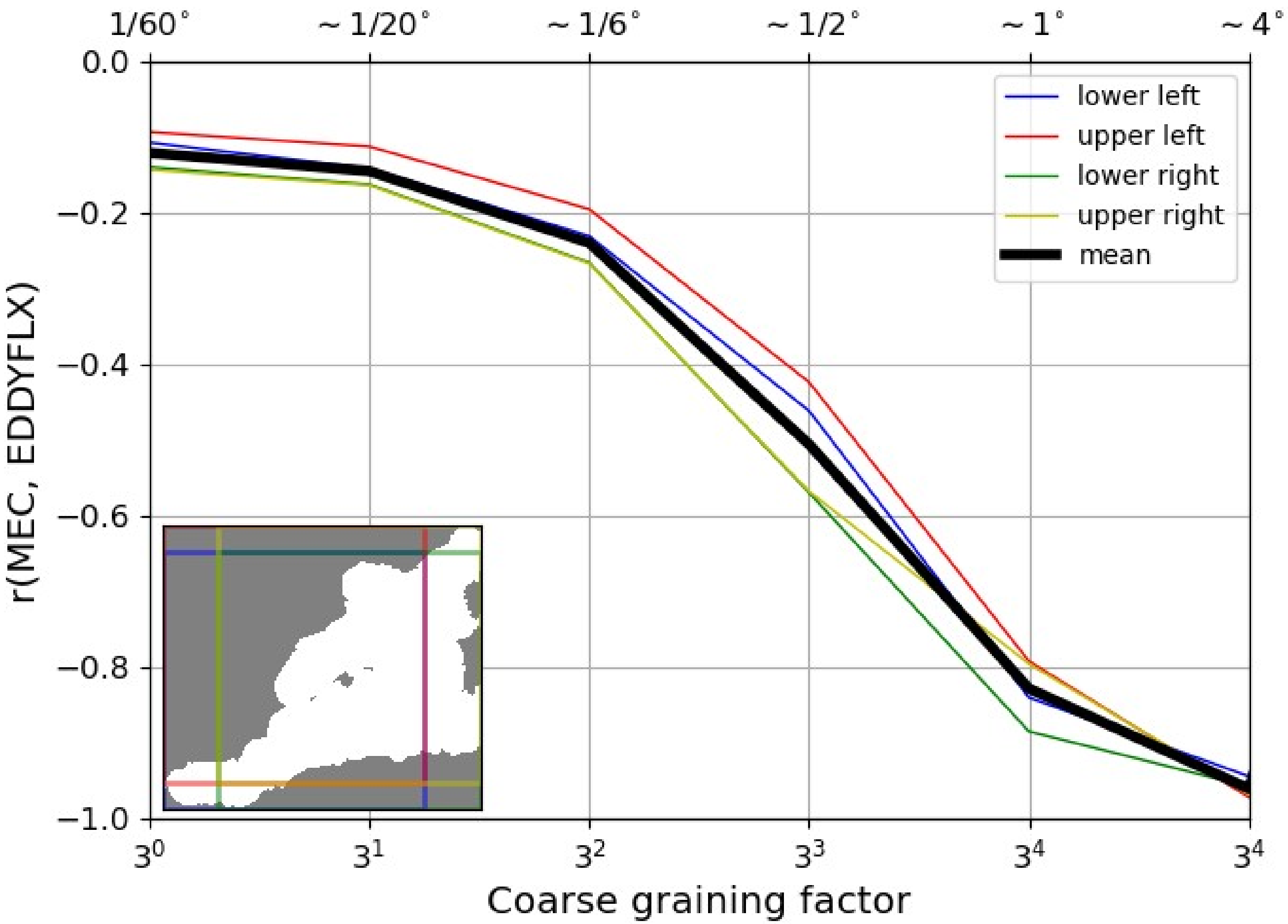
- <u>Non-locality of MKE-EKE transfers</u>
  - Vertical turbulent fluxes: leading order **at large scale** in the upper layers
  - All components (MEC, EDDYFLX, DIVEF) flux energy downward 'in the vicinity of' the MLD



Vertical profile of horizontally integrated MEC (left), EDDYFLX (center) and DIVEF (right). Three-dimensional estimates (black) are decomposed into horizontal (blue) and vertical (red) contributions. Positive = upward ; dashed gray line: spatially averaged mixed layer depth (~30 m).

Results

- Horizontal scale dependence
  - At small scales (1/60º-1/12º): Non-local dynamics
  - At large scales (>1º): Local dynamics
  - Non-locality needs to be accounted for in meso-to-submeso scale range parametrizations



Spatial correlation of MEC and EDDYFLX as a function of the coarse grained grid size. The computation is made on four 3^6x3^6 regions (color lines and insert) and the results averaged (black line).

Conclusion

- Ensemble simulations: a new look at eddy-mean flow Kinetic Energy transfers
- Non-local KE transfers are important,
  in particular in the meso-to-submeso scale range
- Provide a horizontal constraint on eddy-mean flow interaction
  through the cross-energy term.
- Leading order contribution of vertical turbulent fluxes for large scale budgets
  in the upper ocean layers

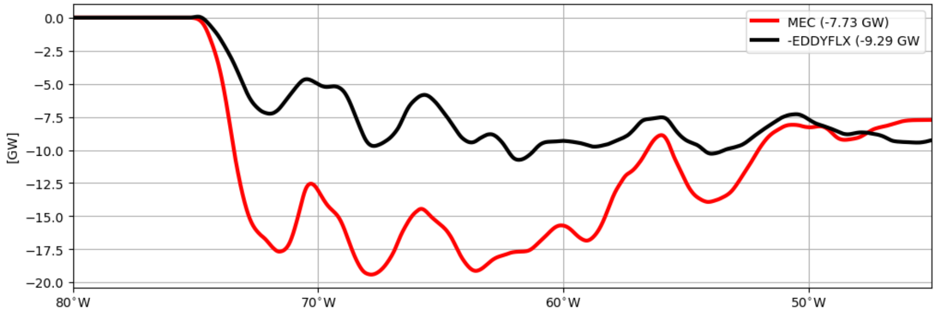
Perspectives

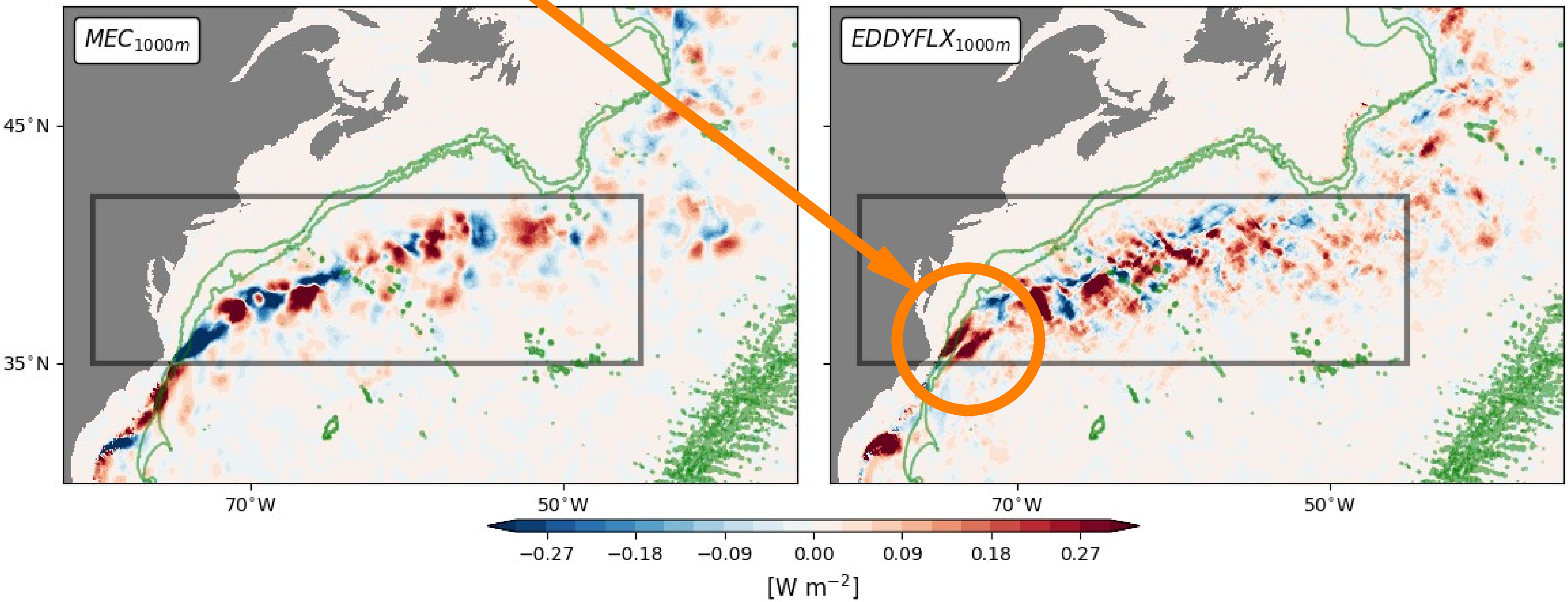
- Implications for Gulf Stream balance (analysing eNATL60)
- Relation with potential vorticity / buoyancy mixing
- Strategies to parametrize these non-local effects

Perspectives

- Implications for Gulf Stream balance (analysing eNATL60)

Double-blade structure
[Ducet & Le Traon, 2001; Greatbatch et al., 2010]

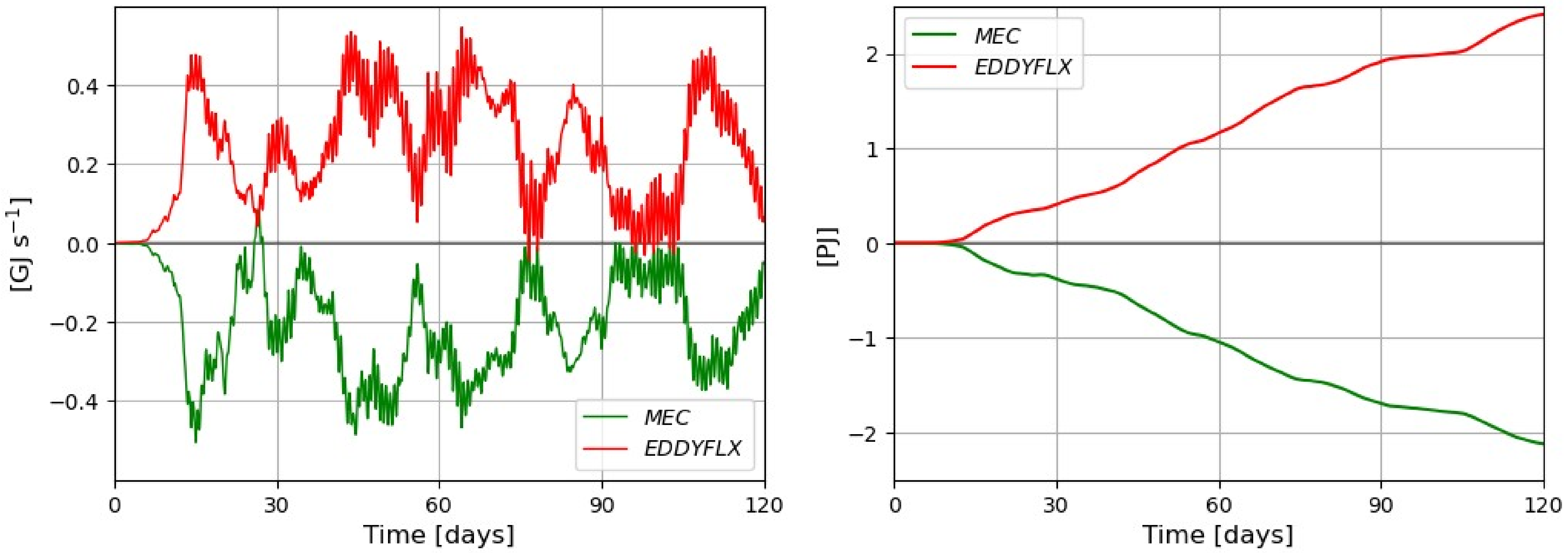




1000m depth integrated MEC and EDDYFLX in eNATL60.
Upper insert: cumulative net transfers within the Gulf Stream.

Results

- <u>Decorrelation of the turbulent flow</u>
  - 120-days integrated MEC: **-2.12** PJ
  - 120-days integrated EDDYFLX: **+2.41** PJ
  - **~240%** of the total MKE and EKE changes ...

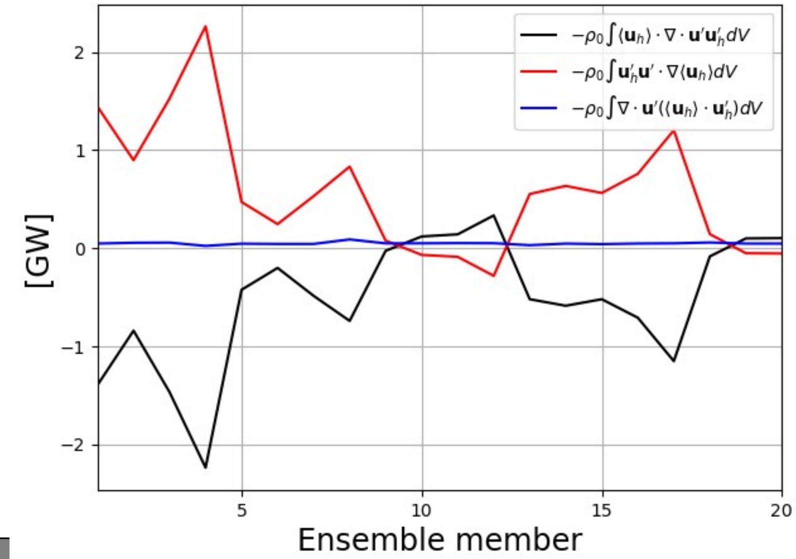


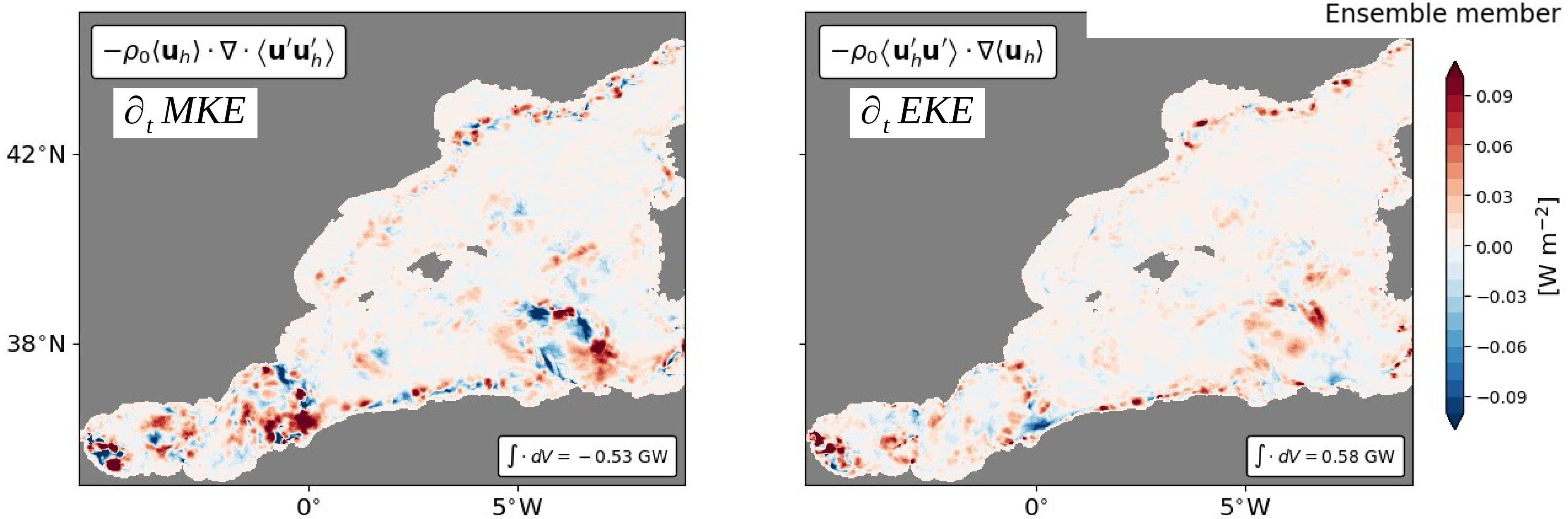
Time series (left) and time integrated contribution (right) of Mean-to-Eddy Conversion (MEC, green) and EDDY momentum FluX (EDDYFLX) associated with MKE and EKE budget, respectively.

Methods

- Kinetic Energy budget of ensemble simulations
  - Eddy-mean flow interactions are *local* within the basin

$$\nabla.\langle \boldsymbol{u}'(\boldsymbol{u}'_h.\langle \boldsymbol{u_h}\rangle)\rangle = \langle \boldsymbol{u_h}\rangle.\nabla.\langle \boldsymbol{u}'\boldsymbol{u}'_h\rangle + \langle \boldsymbol{u}'\boldsymbol{u_h}\rangle.\nabla\langle \boldsymbol{u_h}\rangle$$





Methods

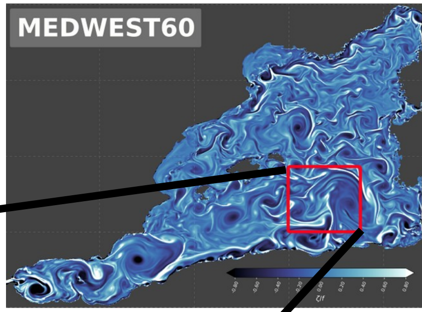
- Offline computation of the simulation:
  - We need estimates of the kinetic energy budget of simulations already produced → develop for this *offline* version of its dynamics.
  - As part of CDFTOOLS, a Fortran-based diagnostic package to analyse NEMO simulations, we have implemented the momentum and 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).

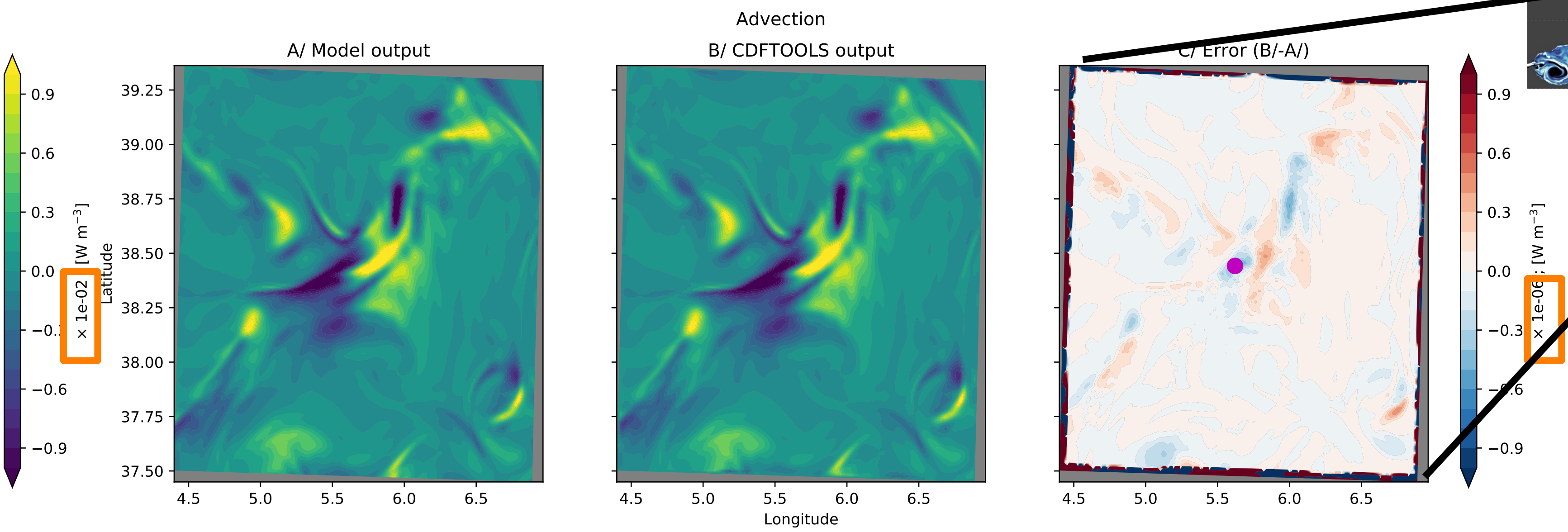
	$\partial_t K = -\nabla \cdot \mathbf{u}K - (u\partial_x p + v\partial_y p) + \rho_0 u \mathbf{D}_u^m + \rho_0 v \mathbf{D}_v^m$			
Model time step	10^{-3}	**10^{-5}**	HPG: 10^{-5} SPG: errors	10^{-1}
Time discretisation		**10^{-4}**		10^{-1}
Hourly model outputs	10^{-2}	**10^{-3}**	HPG: 10^{-3}	10^{-1}

Errors in the Kinetic Energy trends.

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).

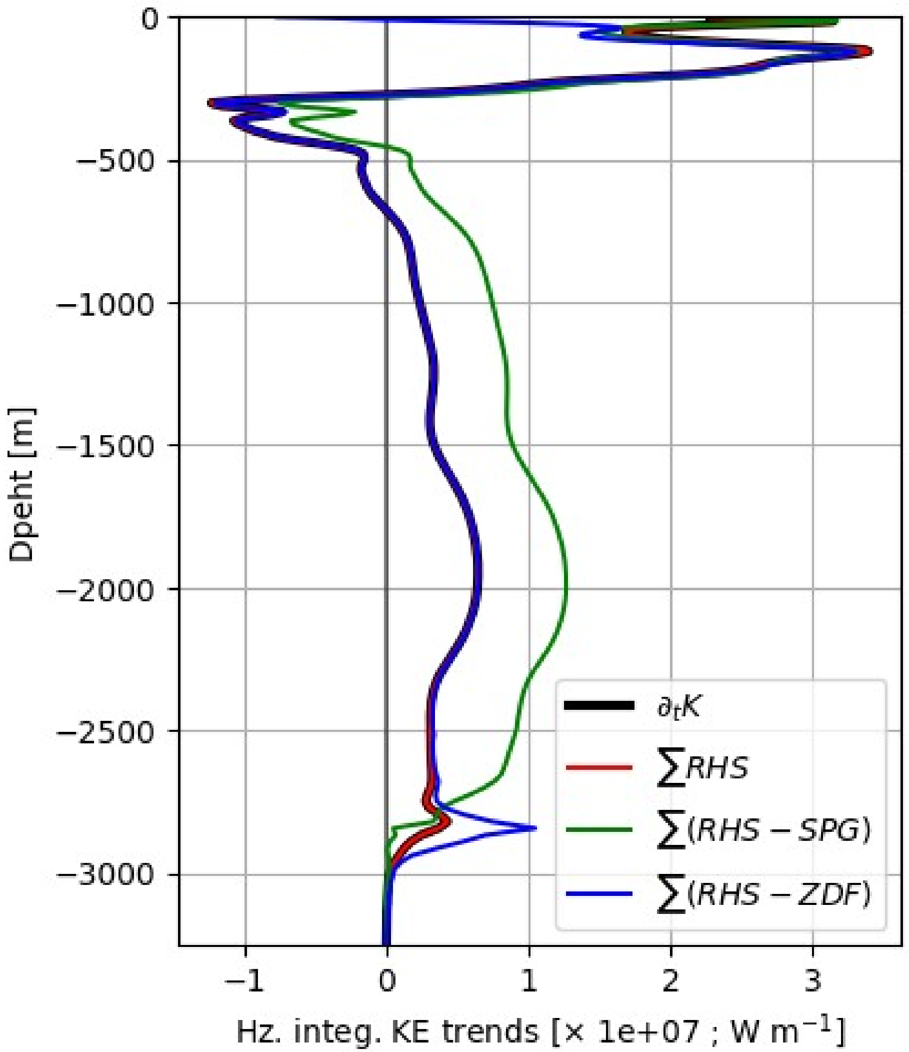




*An example of Kinetic Energy trends associated with 3D advection based on model outputs (**left**), its offline computation (**center**),and the associated errors (**right**). Note the 10^{-4} difference in the colorbar.*

Supplementary

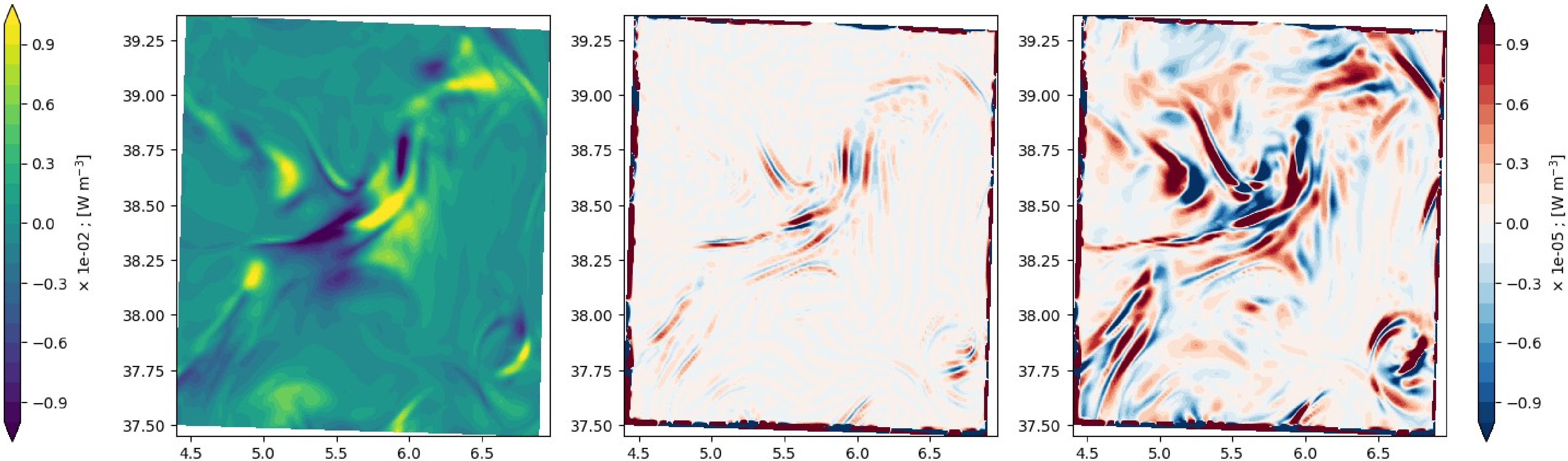
- Vertical viscous processes and pressure work done by surface pressure, computed as residual from NEMO model KE budget, mostly contribute in the (upper and lower) boundary layers and within the interior of the water column, respectively.



*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

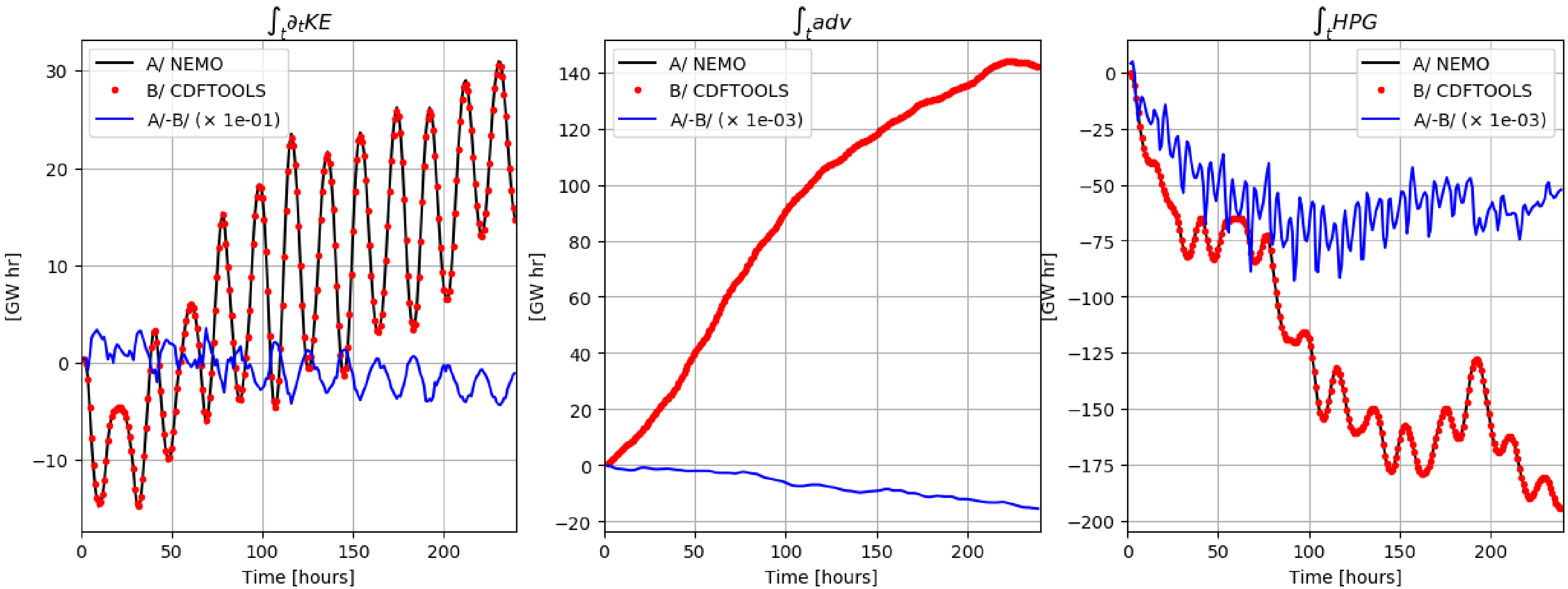
- We then estimate the errors associated with time discretization and time averaged model outputs. For the advection of kinetic energy, this leads to:
  - a decrease of about one order of magnitude of the accuracy of the *offline* computation where local gradients are the largest when the forward time 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.