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

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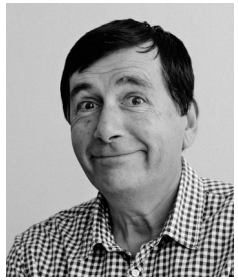

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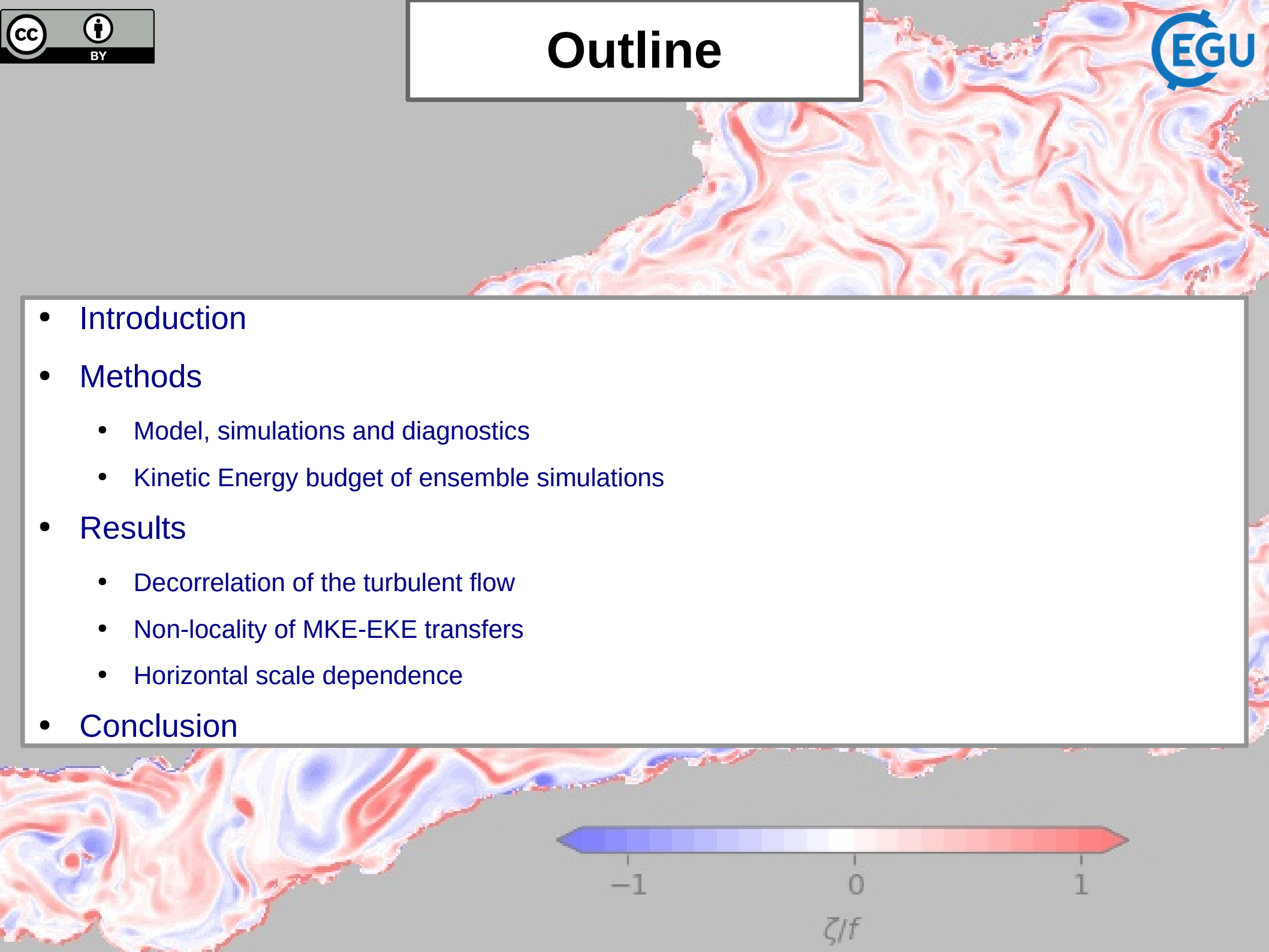
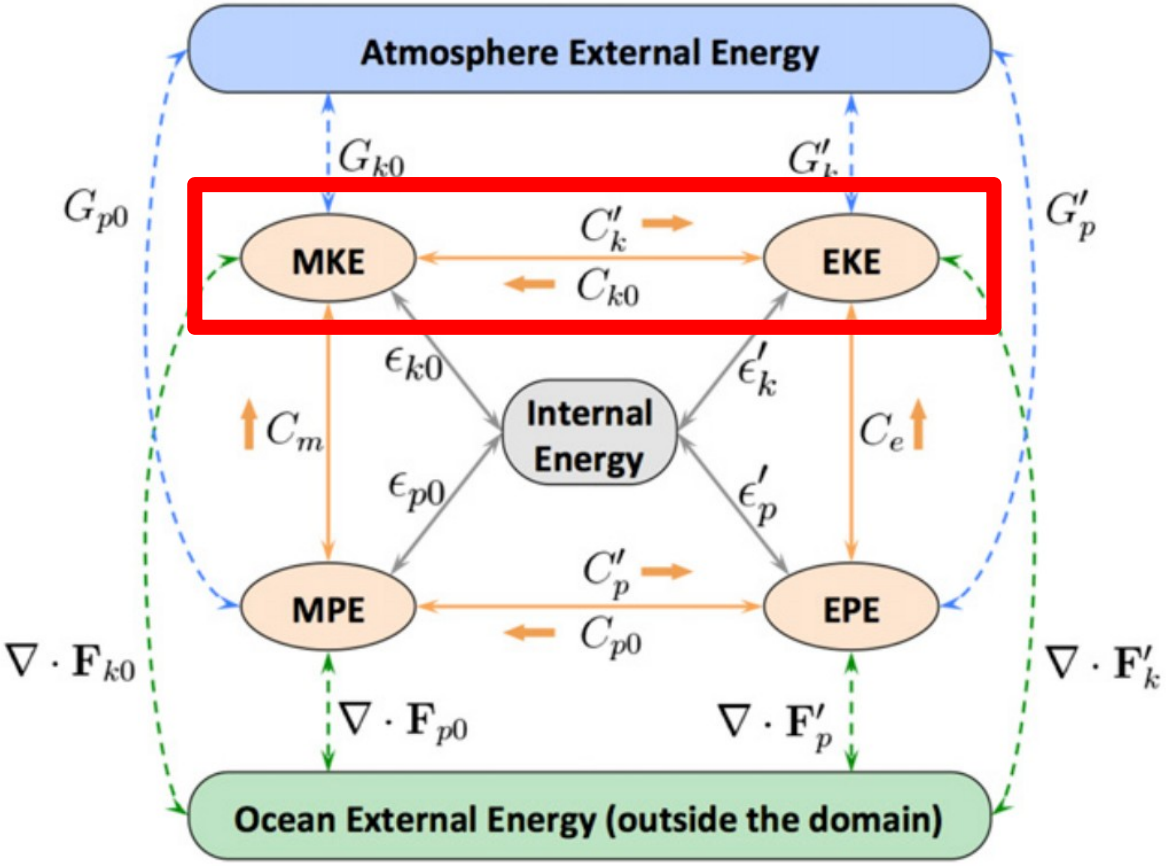
Outline

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



Introduction

- About energy transfers in the ocean ...



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

➔ **Focus on the Kinetic Energy reservoirs (MKE, EKE), and their interactions**

Introduction

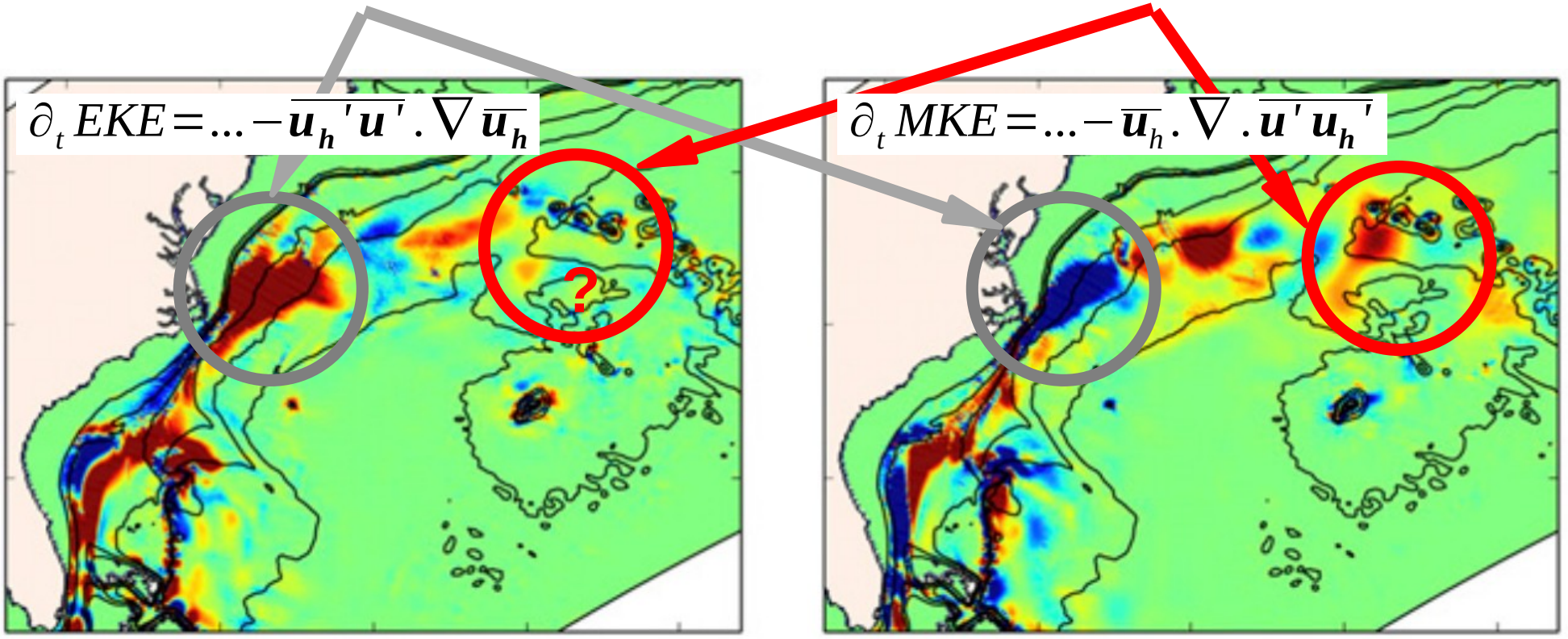
- Kang & Curchitser (2015):
  - 50-yr long (1958–2007), regional Gulf Stream ROMS simulation at Δx=7km.
  - '*Eddies*' are defined as the residual of the 50-yr time averaging.

Local interactions

Gain of EKE ~ loss of MKE

Non-local interactions

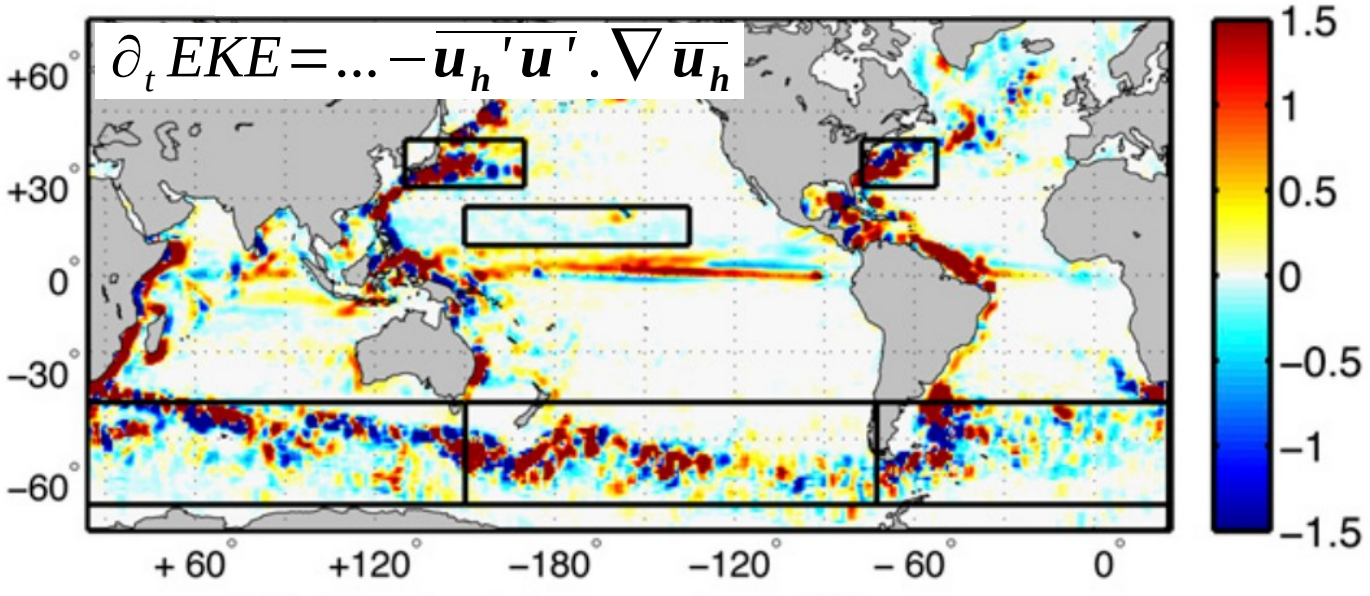
Gain of MKE ≠ loss of EKE

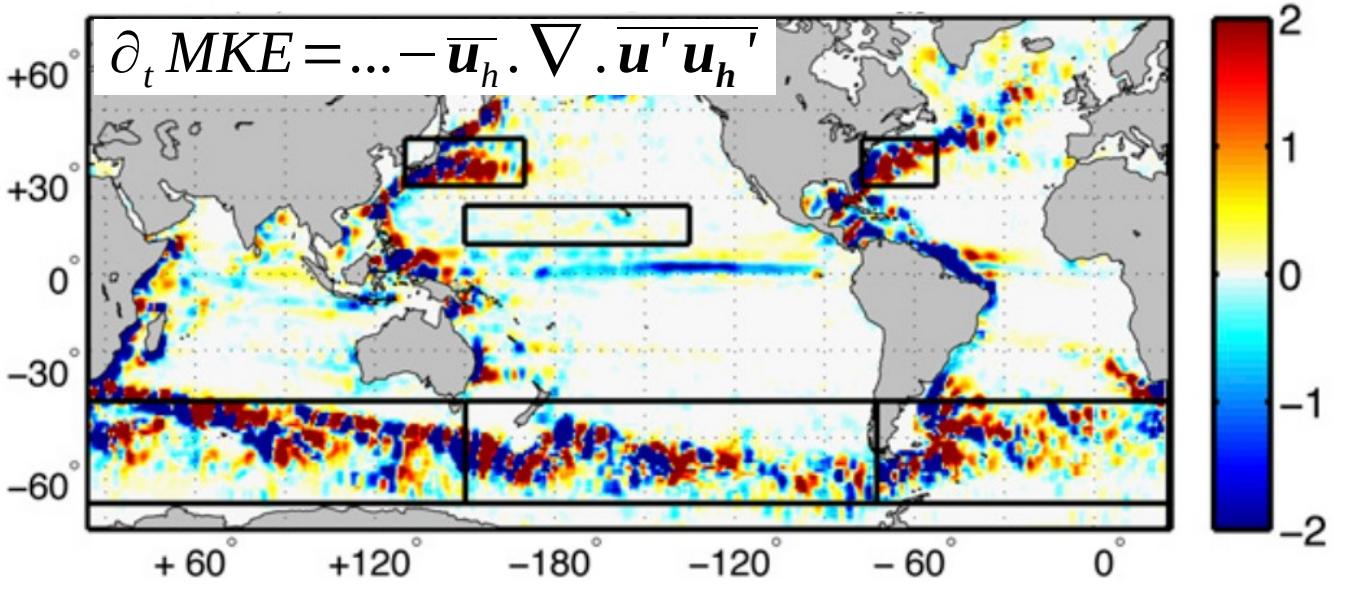


Depth-integrated eddy-mean conversion rates for the EKE (left) and the MKE (right) reservoir [Kang & Curchitser, 2015].

Introduction

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





- Non-local interactions:
  - Southern Ocean
  - Gulf Stream
  - Kuroshio
  - (And likely other western boundary currents ...)
- Local interactions:
  - “Rest of the world”

Introduction

- 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:

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

where the eddy term needs to be parametrized

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

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

- 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':

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

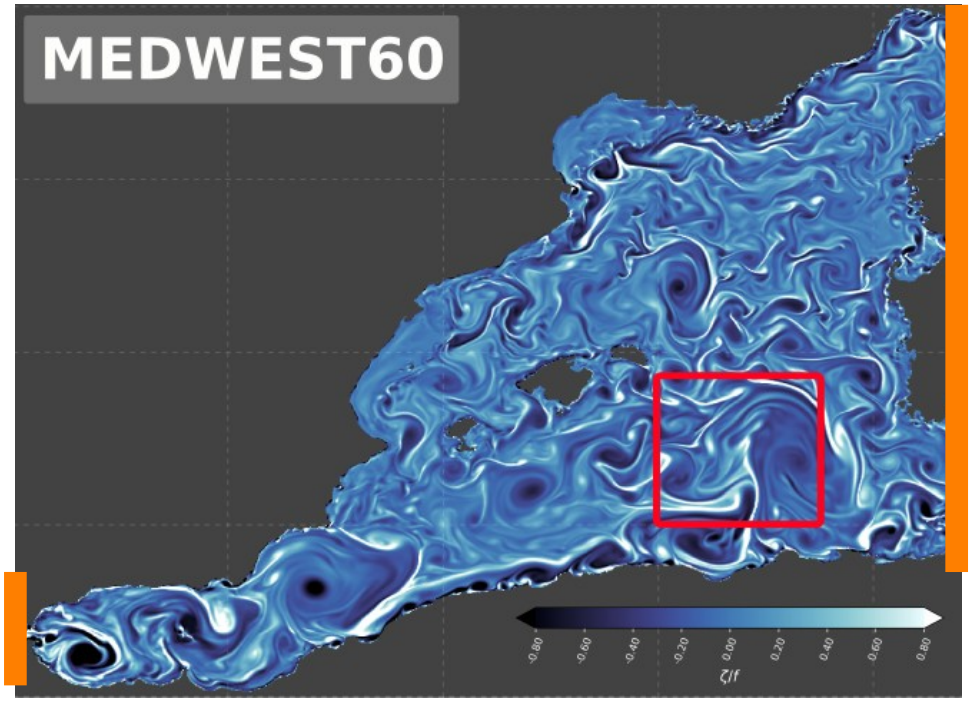
- Need to solve a prognostic equation for the sub-grid scale kinetic energy:

$$\bar{d}_t \bar{e} = -\nabla . \overline{\boldsymbol{u}' e} - \nabla . \overline{\boldsymbol{u}' p'} + \overline{w' b'} - \epsilon - \overline{\boldsymbol{u}' \boldsymbol{u}'}_h . \nabla \bar{\boldsymbol{u}}_h$$

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) 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
    - + *small* stochastic perturbations [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 flow interactions

    ➔ exchanges with eddy potential energy

    ➔ dissipation

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

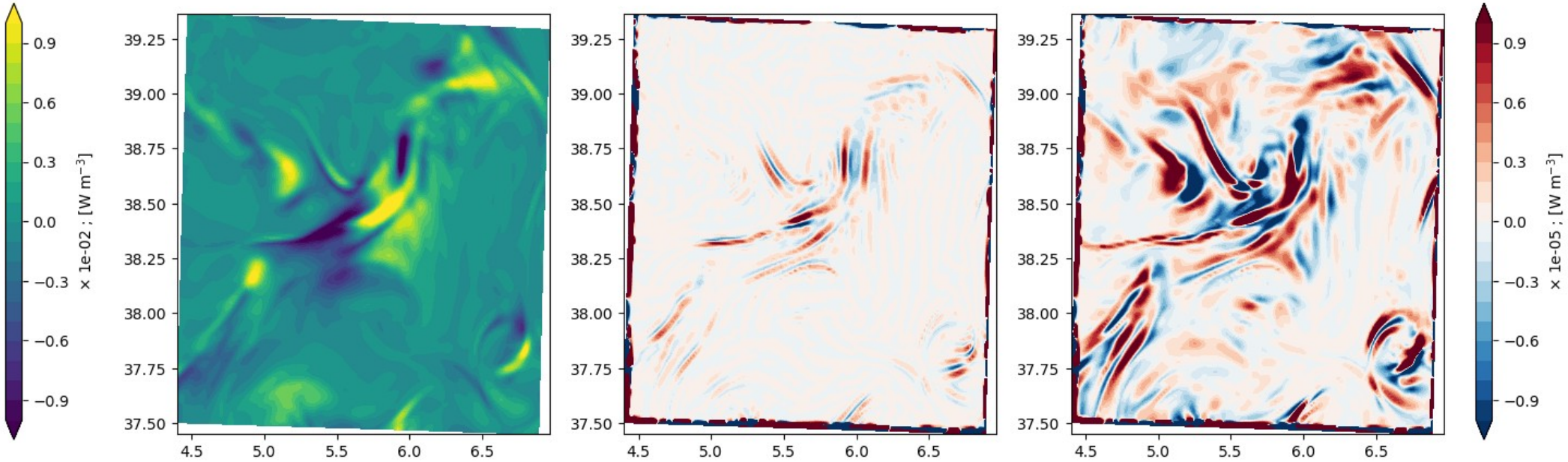
  - Eddy-mean flow interactions are *local* within the basin:

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

$\partial_t MKE$ $\qquad$ $\partial_t EKE$

Methods

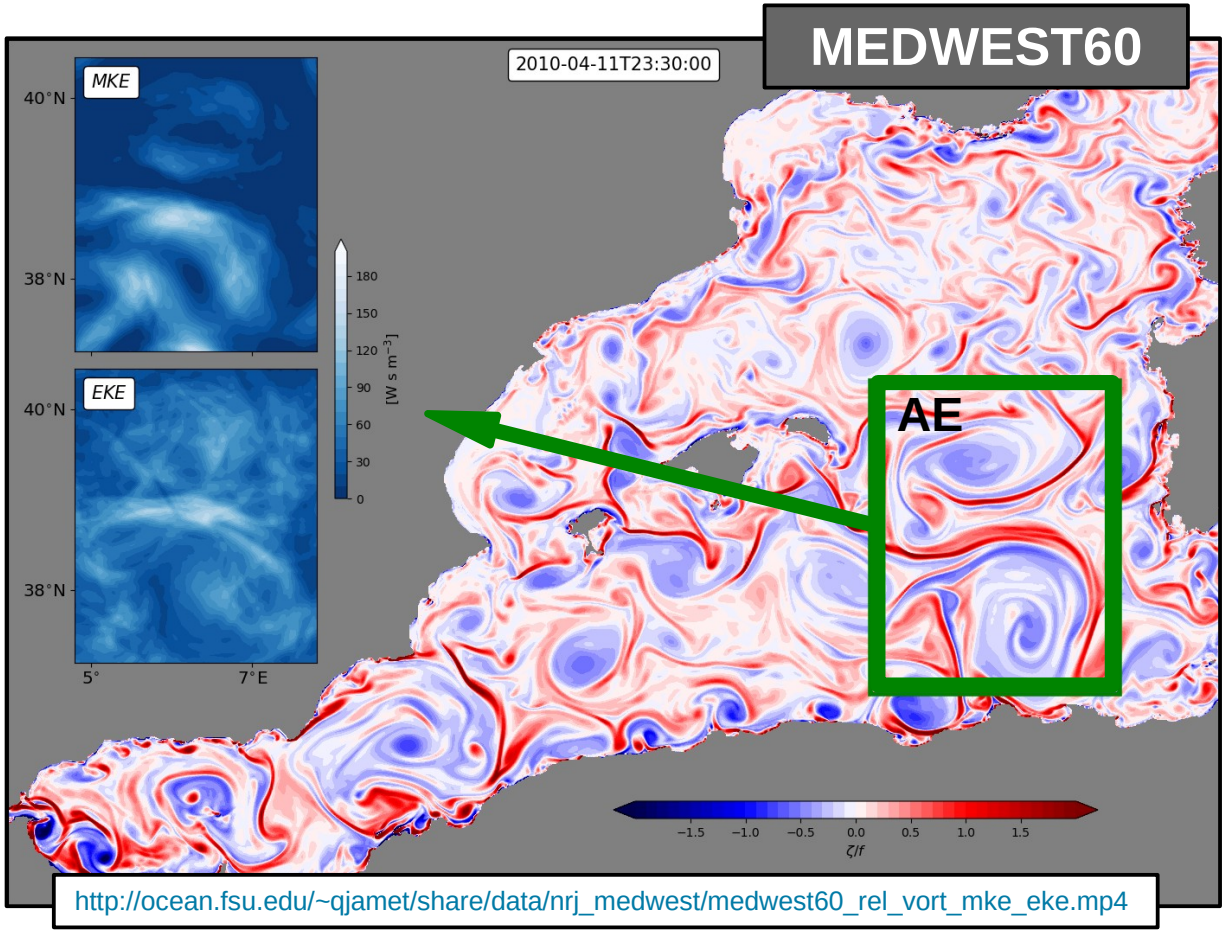
- Offline diagnostic tools:
  - *Offline* estimates of momentum/KE trends
    as part of the CDFTOOLS diagnostic package for NEMO simulations
  - Errors of about ~O(10^{-2}-10^{-3}) as compared to model estimates
    (with hourly averaged model outputs)



*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.*
Note the different scale factors in colorbars.

Results

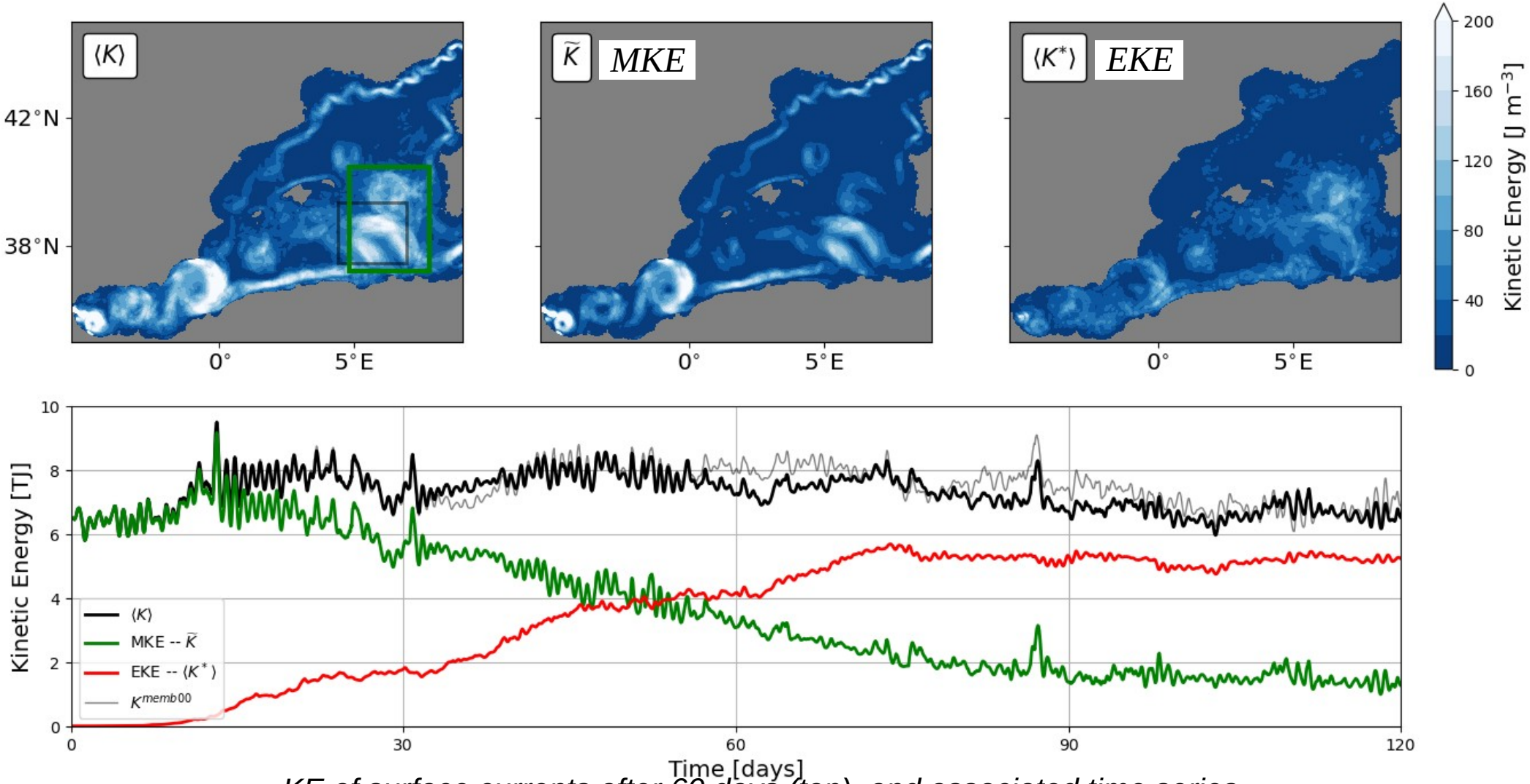
- Decorrelation of the turbulent flow



Surface relative vorticity (main panel),
and associated MKE and EKE within the Algerian Eddy (AE) region (upper left inserts).

Results

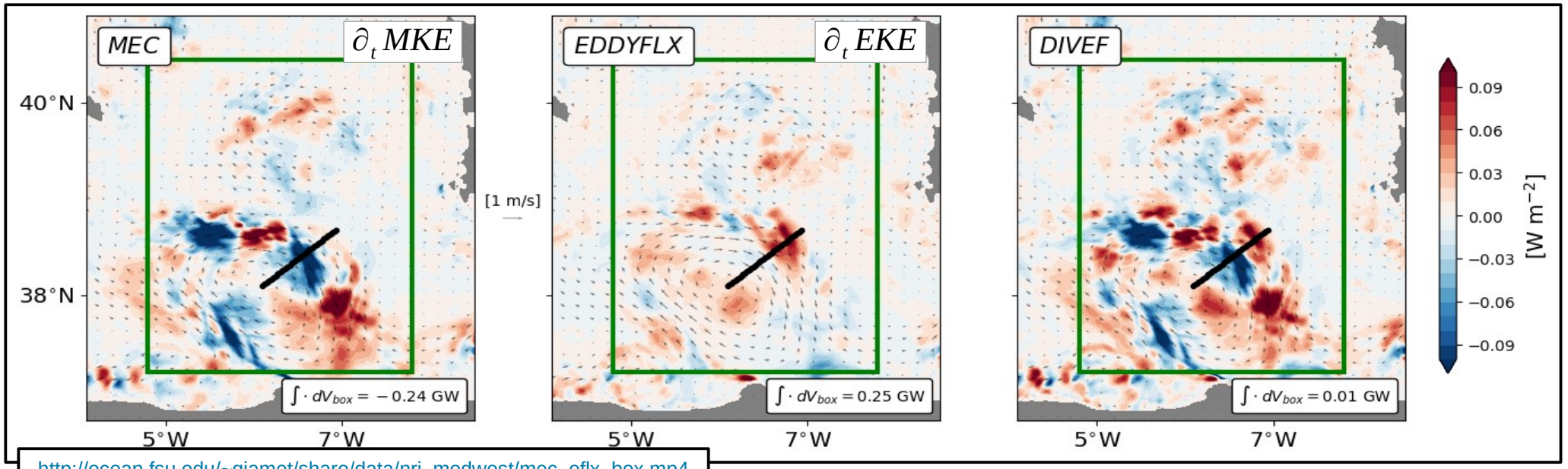
- Decorrelation of the turbulent flow
  - Time scale for EKE initial growth: < 1 week
  - Time scale for EKE ‘saturation’: ~80 days



KE of surface currents after 60 days (top), and associated time series within the Algerian Eddy region (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 interactions**

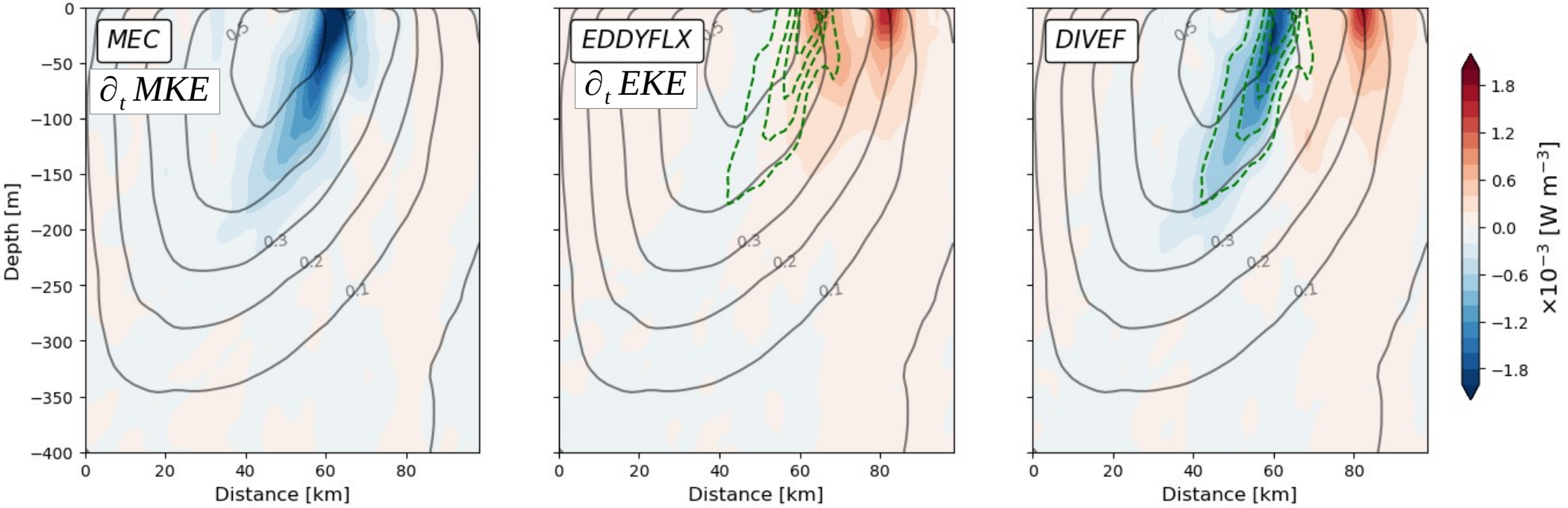


http://ocean.fsu.edu/~qjamet/share/data/nrj_medwest/mec_eflx_box.mp4

Vertically integrated MEC, EDDYFLX and DIVEF after 60 days of simulations.
Bottom right inserts: volume integrated estimates.
Arrows: ensemble mean surface currents.
The black line represents the cross-stream section shown on the next slides.

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.

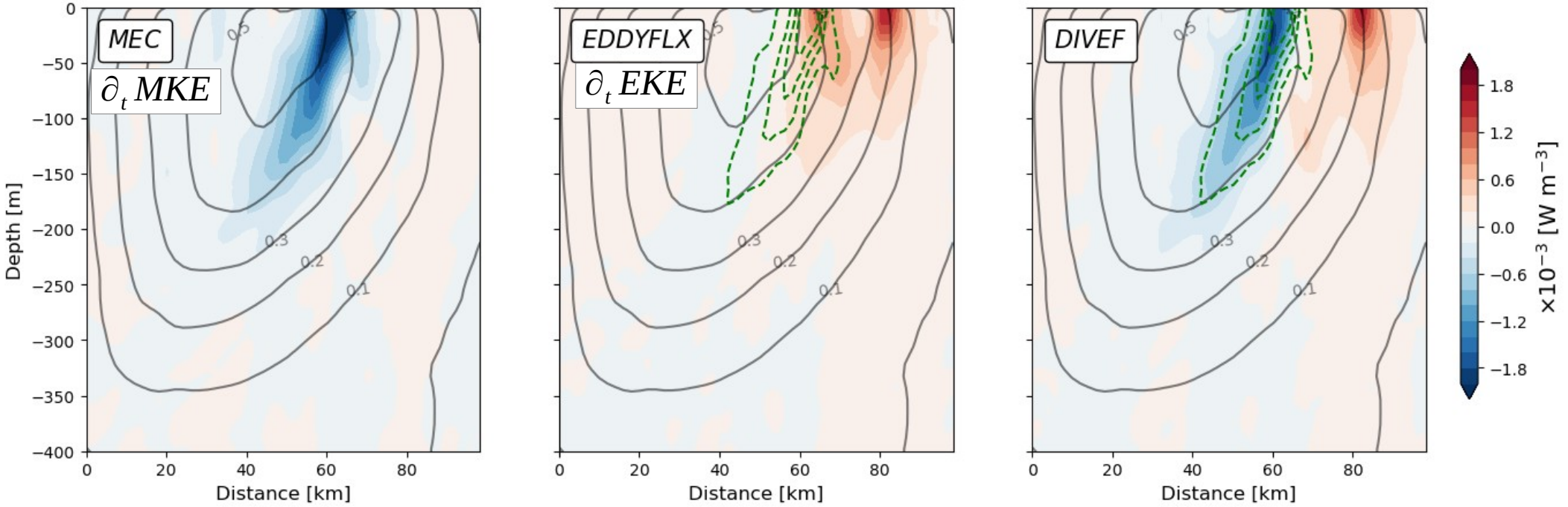
Results

- Non-locality of MKE-EKE transfers
  - DIVEF: Advection of **cross-energy** term by the turbulent flow
  - Strong **horizontal constraint** on eddy-mean flow KE transfers since:

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

Cross-energy term

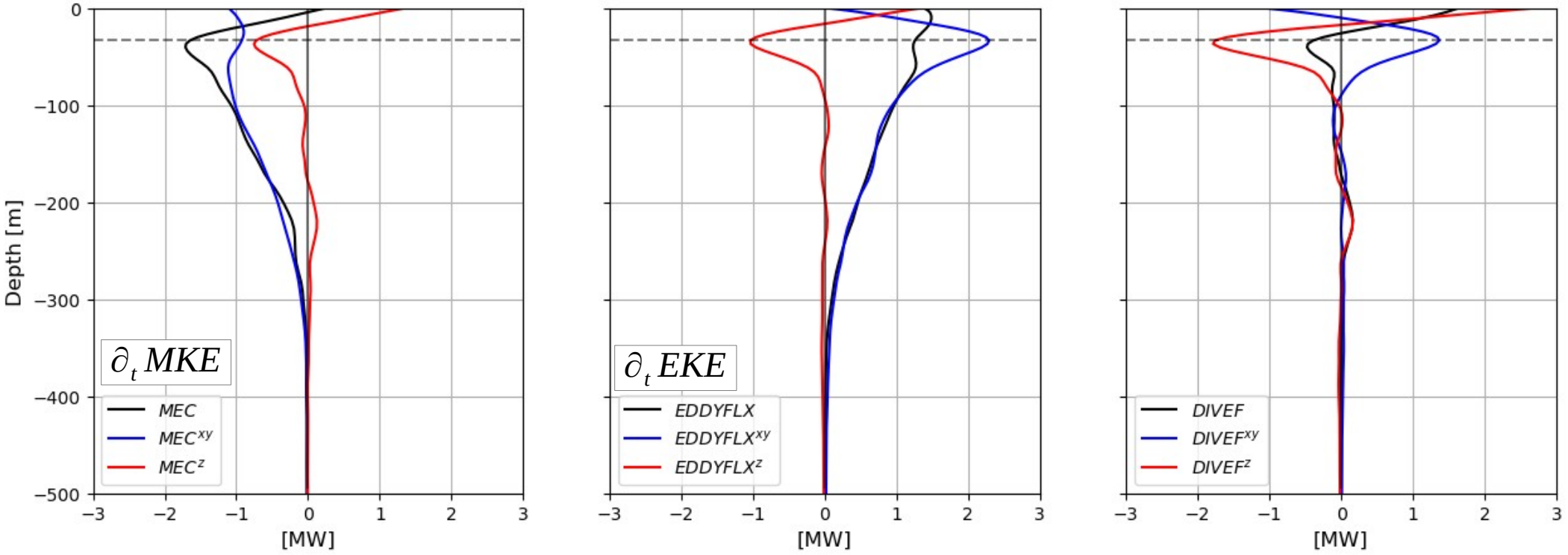
$$\langle \boldsymbol{u_h} \rangle . \nabla . \langle \boldsymbol{u}' \boldsymbol{u}'_h \rangle + \langle \boldsymbol{u}' \boldsymbol{u_h} \rangle . \nabla \langle \boldsymbol{u_h} \rangle = \nabla . \langle \boldsymbol{u}' (\boldsymbol{u}'_h . \langle \boldsymbol{u_h} \rangle) \rangle$$



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

Results

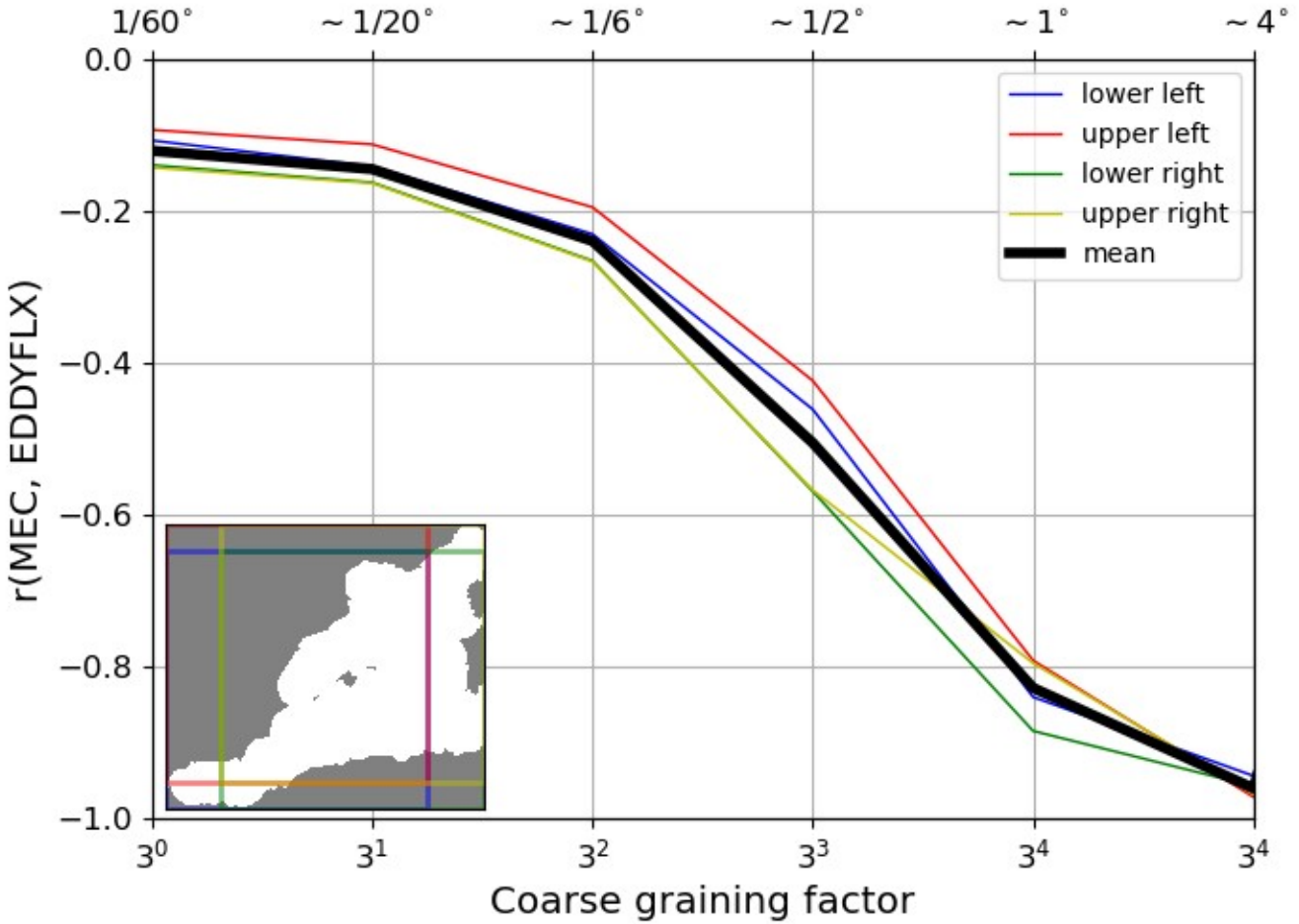
- Non-locality of MKE-EKE transfers
  - Vertical turbulent fluxes: leading order **at large scale** in the upper layers
  - All components (MEC, EDDYFLX, DIVEF) flux energy downward ‘in the vicinity of’ the MLD



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 (1/60°-1/12°): Non-local interactions
  - At large scales (>1°): Local interactions
  - 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 are averaged (black line).

Conclusion

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

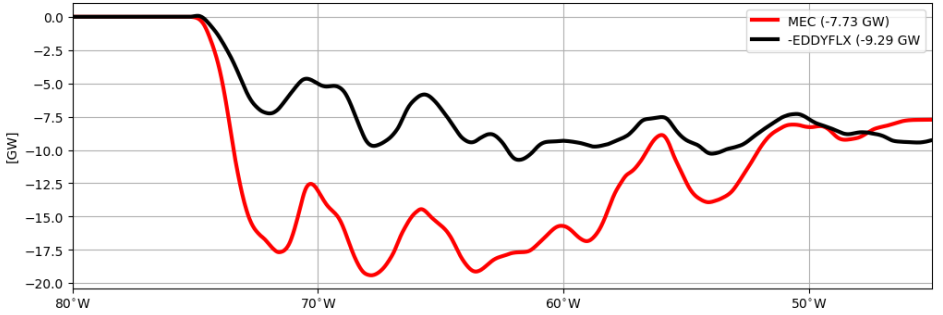
Perspectives

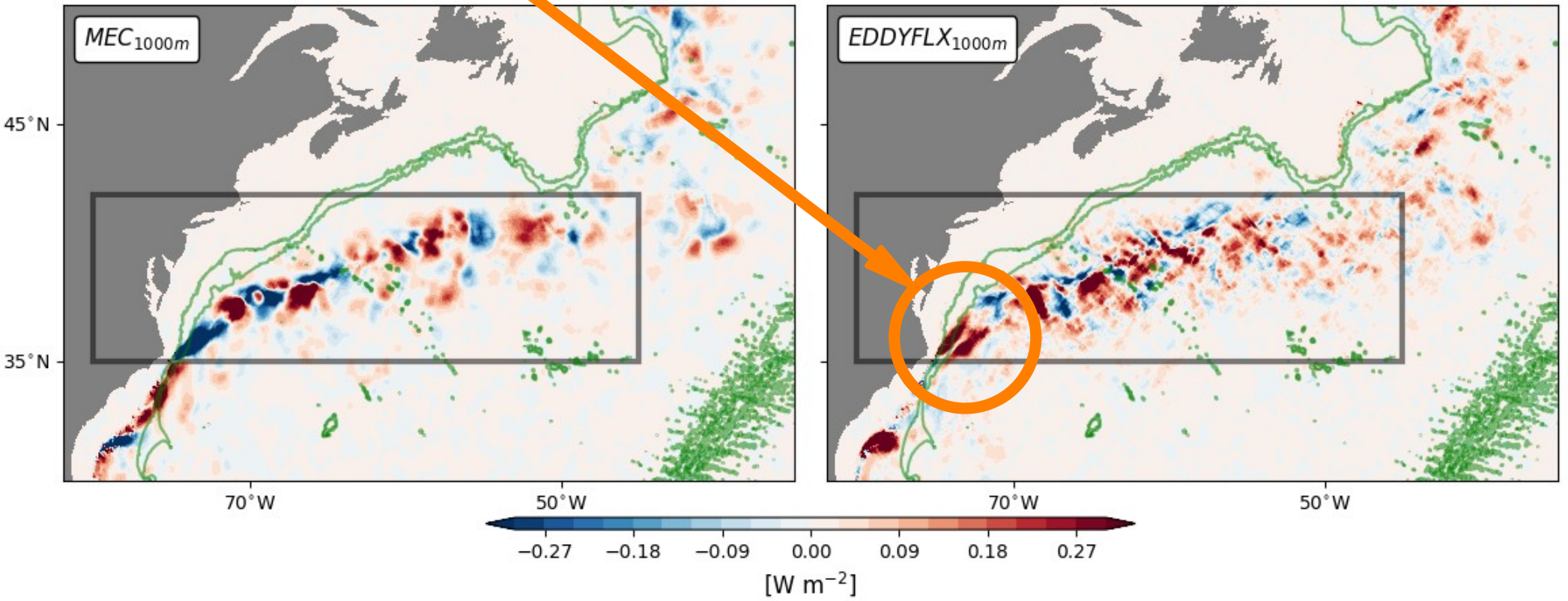
- Implications for Gulf Stream balance (analysing eNATL60)
- Relation with potential vorticity / buoyancy mixing
- Strategies to parametrize these non-local interactions

Supplementary

- Implications for Gulf Stream balance (analysing eNATL60)

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

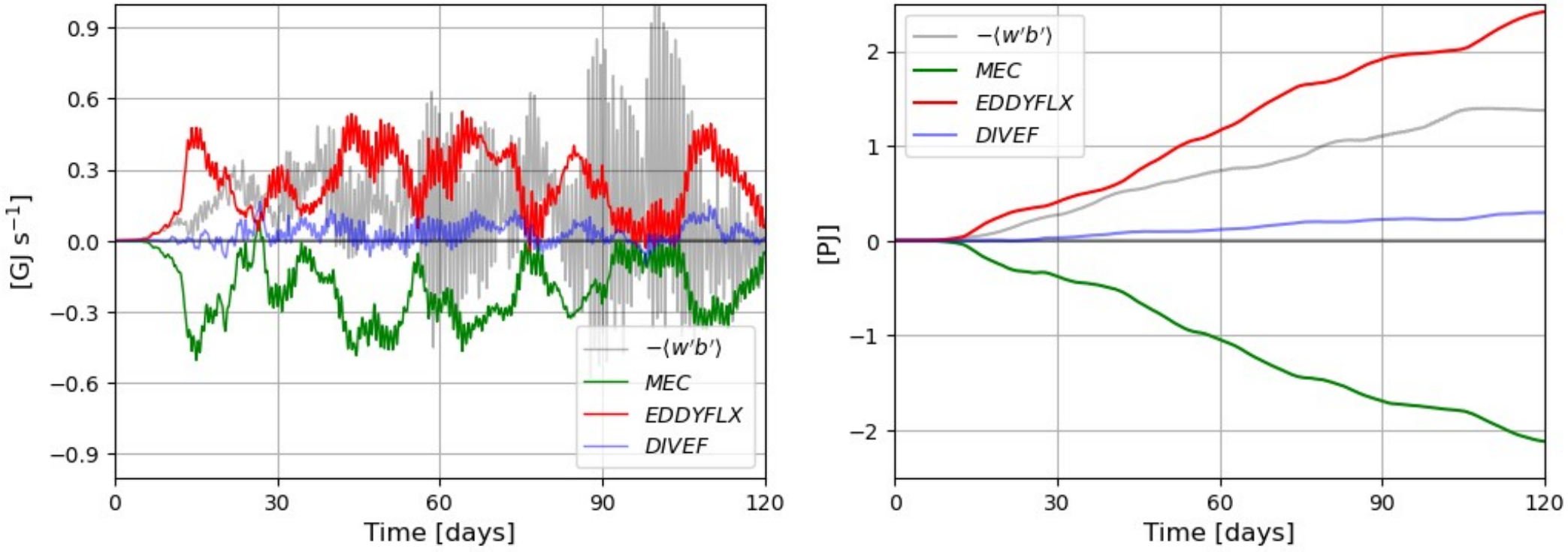




1000m depth integrated MEC and EDDYFLX in eNATL60.
Upper insert: cumulative net transfers within the Gulf Stream.

Supplementary

- Decorrelation of the turbulent flow
  - 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), EDDY momentum FluX (EDDYFLX) associated with MKE and EKE budget, respectively, their divergence (DIVEF, blue) and the potential-to-kinetic energy conversion rate (gray).

Supplementary

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

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