Anatomy of energy pathways in the subtropical gyre of the North Atlantic

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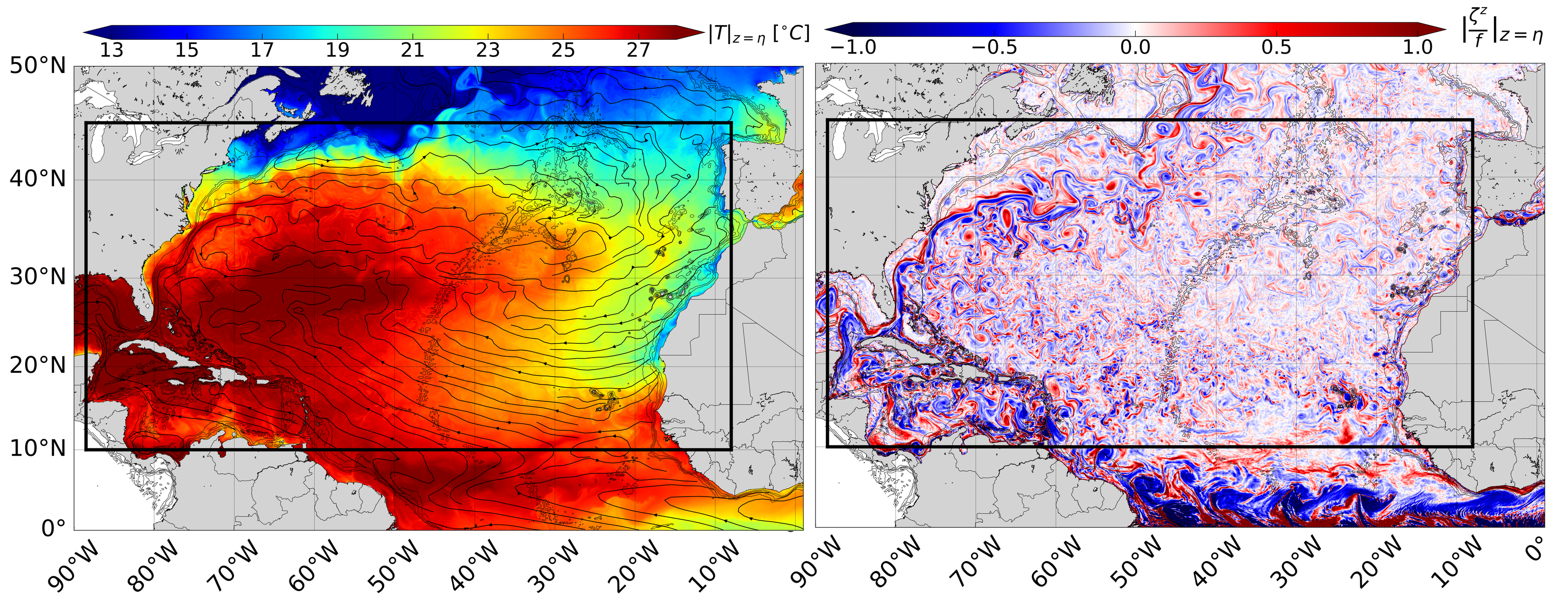
1. Context

What is the leading-order energy balance of the subtropical gyre of the North Atlantic? Which flows does it rely on, and how does it vary in space?



Snapshots of surface (right) temperature and (left) normalised relative vorticity. (Right) Streamlines show 4-year averaged surface currents. Black square denotes the subtropical gyre region.

- **The North Atlantic is a key region in the global ocean circulation and plays a central role in regulating our climate** *(Ganachaud and Wunsch, 2000)*.
- Its **response to climate change is constrained by energy transfers between basin-scale time-averaged currents and smaller-scale** (hundreds to the order of a kilometer) **time-varying currents**, including low-frequency mesoscale and submesoscale currents and high-frequency internal waves.
- **Although understanding the energy pathways of North Atlantic's subtropical gyre is crucial for accurately representing its role in climate models, we lack (1) a description of energy pathways at the basin-scale (2) based on a dataset simultaneously resolving the different time-varying flows.**

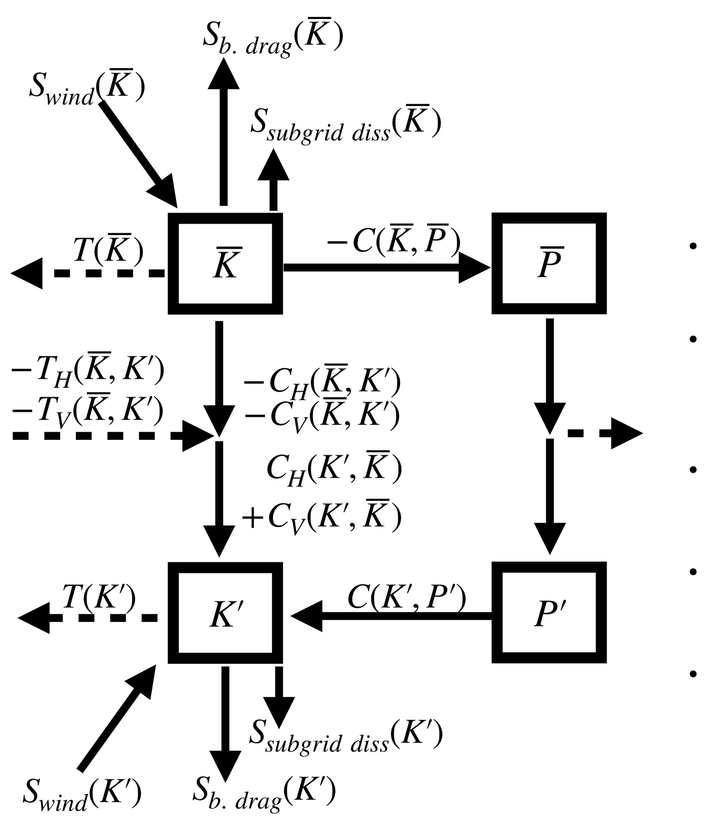
2. Theory

Our energy analysis uses the concept of **energy separation in a time-mean ($\overline{K}$) and time-varying (K') component:**

$$\overline{K} = \frac{1}{2}\rho_0(\overline{u}^2 + \overline{v}^2) \text{ and } K' = \frac{1}{2}\rho_0(\overline{u'^2} + \overline{v'^2})$$

with (u, v) the horizontal velocity components, ρ_0 the reference density, $\overline{(\,.\,)}$ a 4-year average, and $(\,.\,)'$ deviation from this average.

The steady-state balance of $\overline{K}$ and K' reservoirs is analyzed with a regional formulation of the Lorenz Energy Cycle *(Lorenz, 1955)*:



Energy rates of change related to:

- $\mathbf{S}(\,.\,)$: wind stress, bottom drag, subgrid dissipation.
- $\mathbf{T}(\,.\,)$: non-local effects being spatial redistribution due to pressure work and advection.
- $\mathbf{C}(\,.\,,.\,)$: conversion between energy reservoirs.
- $-\mathbf{C}(\overline{\mathbf{K}}, \mathbf{K'})$; $\mathbf{C}(\mathbf{K'}, \overline{\mathbf{K}})$: local and non-local eddy-mean energy conversions.
- $\mathbf{C}(\overline{\mathbf{K}}, \overline{\mathbf{P}})$; $\mathbf{C}(\mathbf{K'}, \mathbf{P'})$: energy conversions related to buoyancy flux.

Scheme of ocean energy pathways as described by the Lorenz Energy Cycle (Lorenz, 1955). Dashed arrows denote non-local effects. Terms are defined positive in the direction of the arrow. Adapted from Capo et al., (2018).

5. Take home messages

$\overline{K}$ and K' budgets:

- $\overline{K}$ and K' budgets have the same order of magnitude.
- $\overline{K}$ and K' budgets spatially vary, from leading-order energy balances to contributions from time-varying flows.
- The leading-order $\overline{K}$ source in the interior is the wind, and it is the spatial redistribution in other regions.
- Regions of net K' sources (western and eastern boundaries) are hotspots of mean-to-eddy energy conversion.

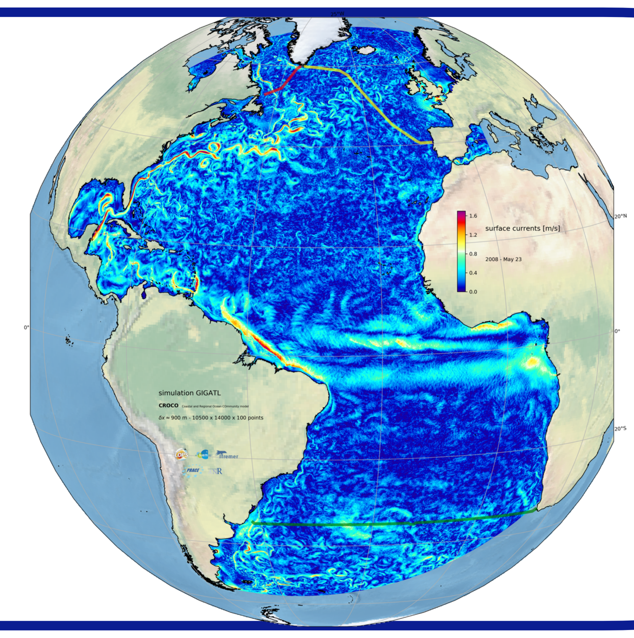
Impact of tidal forcing on $\overline{K}$ and K' budgets:

- Tidal forcing adds a K' source, increases mean-to-eddy energy conversion driven by shear processes and energy spatial redistribution.
- The impact of tidal forcing on energy budgets is the largest east of the basin.
- The impact of internal tides on the time-mean circulation should be represented, together with those of mesoscale and submesoscale currents, in ocean models.

Lorenz, E. N. (1955). Available potential energy and the maintenance of the general circulation. *Tellus*, 7(2), 157-167.
Capó, E., Orfila, A., Mason, E., & Ruiz, S. (2019). Energy conversion routes in the Western Mediterranean Sea estimated from eddy–mean flow interactions. *Journal of Physical Oceanography*, 49(1), 247-267.
Ganachaud, A., & Wunsch, C. (2000). Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, 408(6811), 453-457.

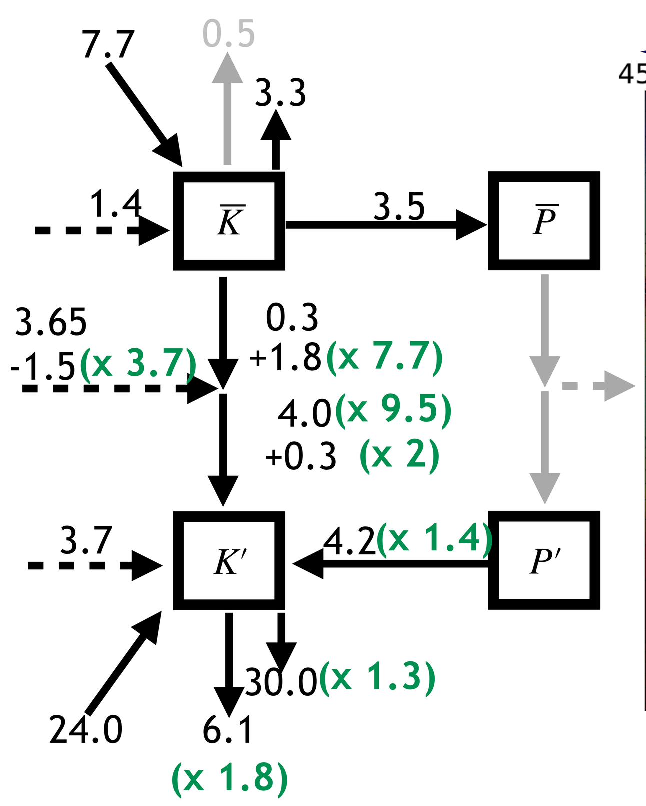
3. Numerical simulation

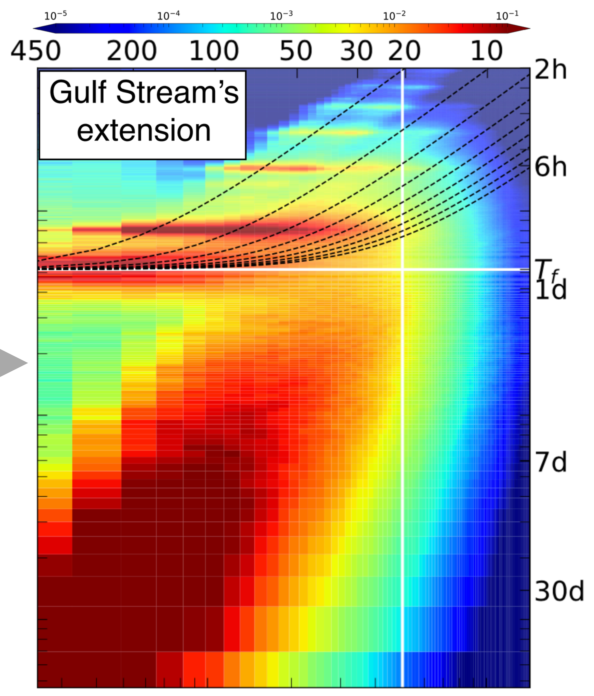
- State-of-the-art numerical simulations of the Atlantic performed using the CROCO model with realistic forcings (https://github.com/Mesharou/GIGATL).
- **Two simulations at 3 km resolution including 1-hour atmospheric forcing, one without and with tidal forcing.**
- Outputs: hourly 3-dimensional variables (u, v, w, b, η) and 5-day averages of online diagnostics of kinetic energy and momentum budgets and quadratic terms $(uu, vv, uv, uw, vw, bb, ub, vb, wb)$.



Snapshot of surface currents performed as modelled by a dx~1km simulation of the Atlantic (https://github.com/Mesharou/GIGATL).

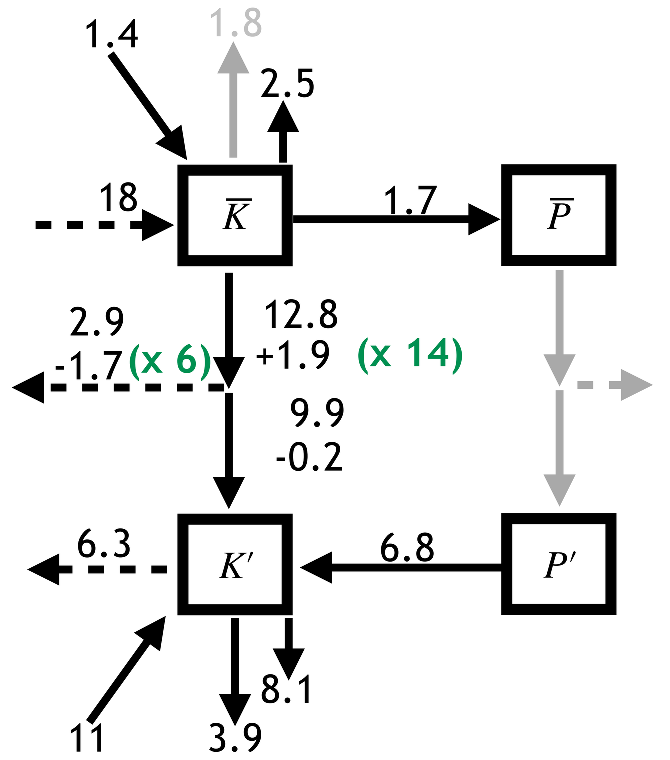
4. $\overline{K}$ (time-mean) and K' (time-varying) budgets for tidal scenario





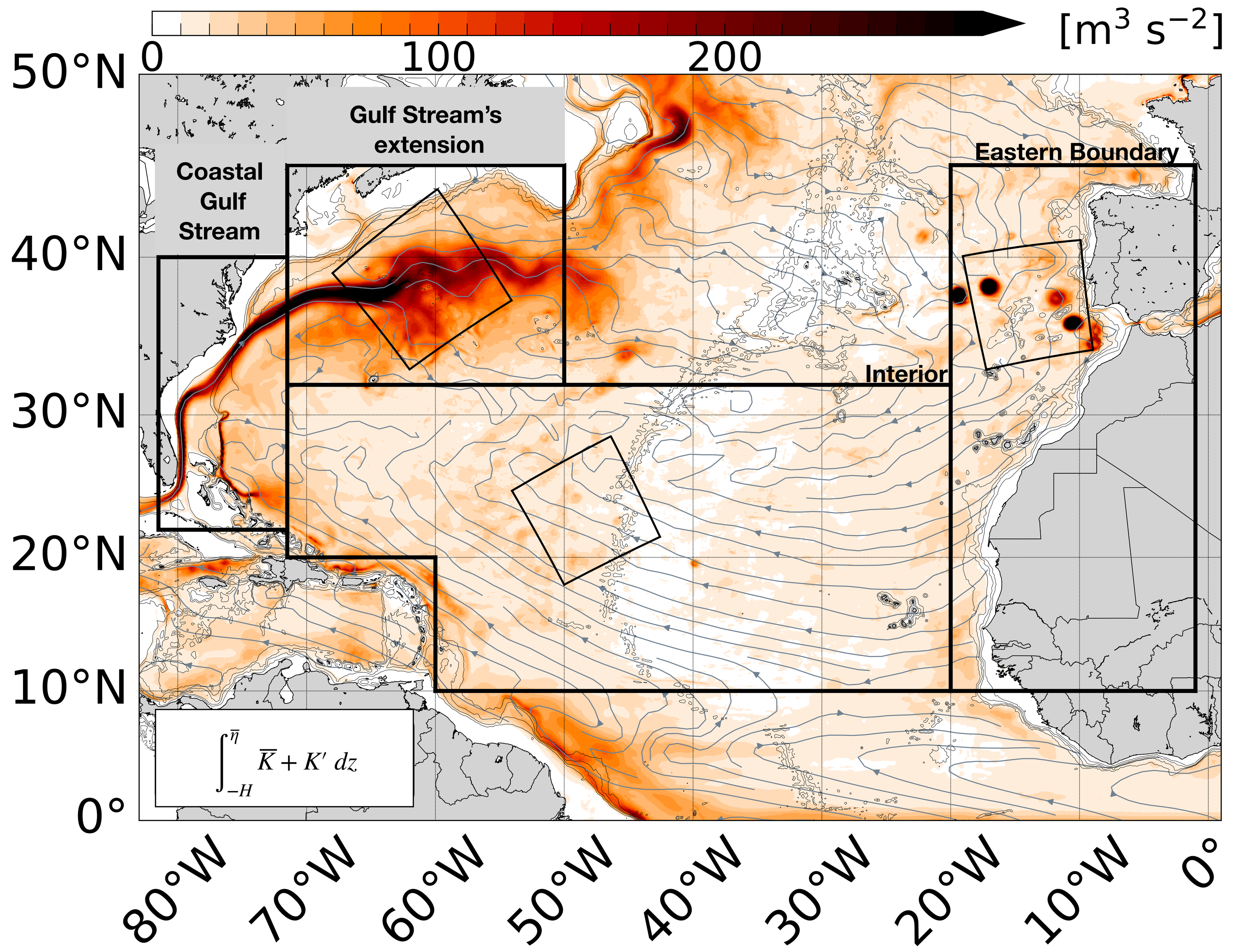
Western Boundary: Gulf Stream's extension

- K' is larger than $\overline{K}$ reservoir by a factor of 3. K' reservoir is dominated by mesoscale, submesoscale currents, and internal waves.
- $\overline{K}$ and K' budgets are sensitive to tidal forcing.
- Net $\overline{K}$ and K' budgets denote local energy sinks.
- $\overline{K}$ is advected within the region, energised by wind, and lost to non-local mean-to-eddy conversion and dissipative processes.
- K' is transported within the region from the coastal Gulf Stream and lost to dissipative processes (although wind and mean-to-eddy conversion are intense K' inputs).



Western Boundary: Coastal Gulf Stream and separation

- $\overline{K}$ and K' reservoirs have comparable magnitudes.
- $\overline{K}$ and K' budgets are insensitive to tidal forcing.
- net $\overline{K}$ budget denotes a local $\overline{K}$ sink, and net K' budget denotes a local K' source.
- $\overline{K}$ is transported within the region (by pressure work) and locally lost to mean-to-eddy conversion and dissipative processes.
- K' is energized by wind, mean-to-eddy conversion, and baroclinic instability and exported to the Gulf Stream's extension.

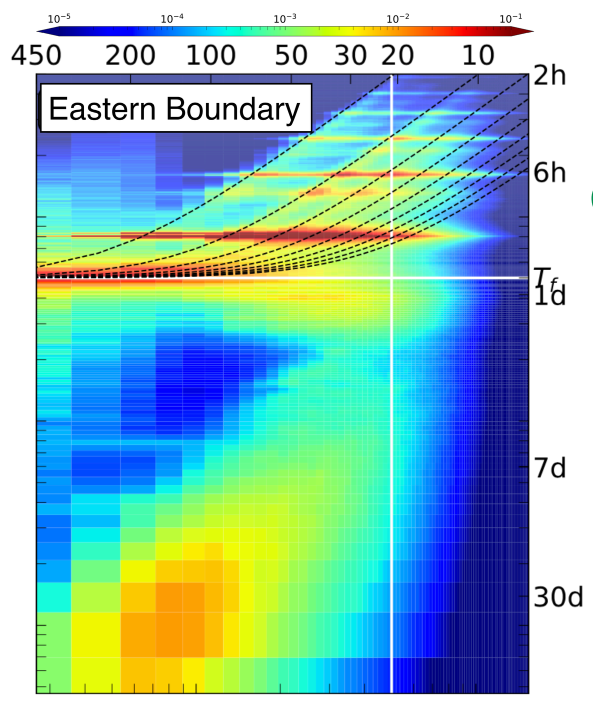


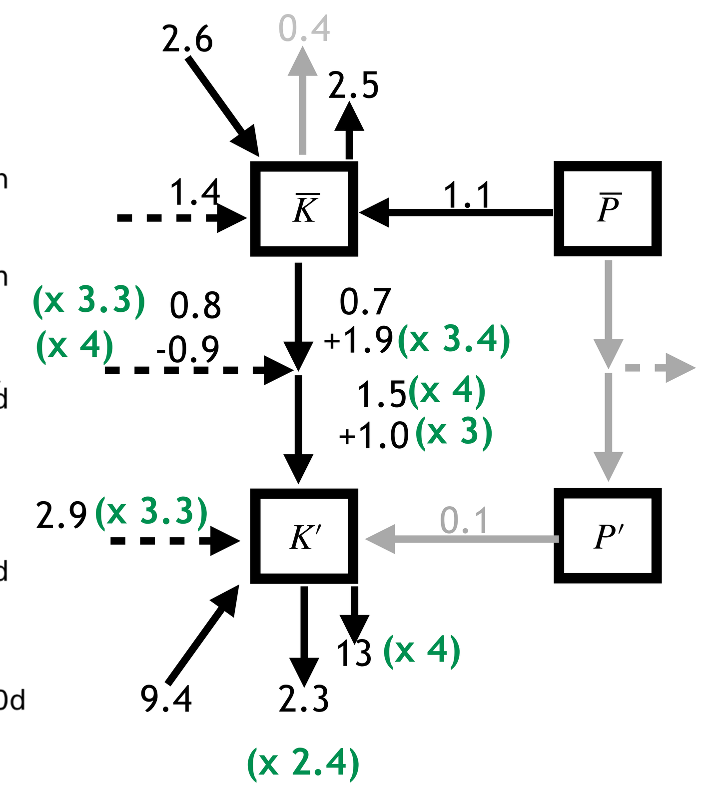
(Top) Vertically-integrated $\overline{K} + K'$ averaged over a 4-year period. The four sub-regions: Coastal Gulf Stream and separation, Gulf stream's extension, Interior and Eastern boundary are shown as squared areas. Streamlines show 4-year averaged surface currents. (Left and right) Frequency-wavenumber K' spectra and scheme of ocean energy pathways for the four sub-regions. In the schemes, amounts have been computed from time-averaged and vertically-integrated terms and then horizontally-averaged [10^{-3} m^3 s^{-3}].

→: main energy balances
→: weak energy pathways
(x <.>): ratio between net contributions in tidal and non-tidal scenarios

Eastern Boundary:

- K' is larger than the $\overline{K}$ reservoir by a factor of 2.5 and is dominated by internal waves.
- $\overline{K}$ and K' budgets are the most sensitive to tidal forcing.
- net $\overline{K}$ and K' budgets denote local energy sinks.
- $\overline{K}$ is transported within the region and lost to non-local mean-to-eddy conversion driven by horizontal and vertical shear processes.
- K' is advected within the region and lost to dissipative processes and bottom drag.





Subtropical gyre's interior

- K' is larger than the $\overline{K}$ reservoir by a factor of 6 and is dominated by submesoscale currents and internal waves.
- $\overline{K}$ and K' budgets are insensitive to tidal forcing.
- $\overline{K}$ budget follows a Sverdrup-like balance: only region with a net $\overline{K}$ export provided by the wind.
- K' reservoir is mainly energised by wind and tides.