Understanding Energy Pathways of the Gulf Stream

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Introduction

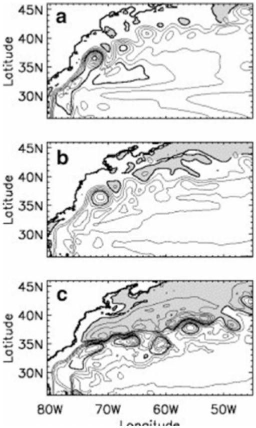

Figure: 3-year mean vertically integrated mass transport streamfunction. (a) 0.4°, (b) 0.2°, and (c) 0.1°. The contour interval is 5 Sv in (a) and 10 Sv in (b) and (c). Fig. 4 from Bryan et al.,, 2007

- The Gulf Stream (GS) is a major and emblematic Western Boundary current, considered as a climate thermostat.
- Satellite observations show a stable mode of the GS separation at Cape Hatteras and a straight eastward penetration into the interior of the Atlantic Basin (Renault et al., 2019).
- However, low-resolution models reproduce an excessive number of eddies, which are detach from the current path, causing excessive GS meandering.
- Increasing the spatial resolution (submesoscale permitting) leads to a better representation of the GS (Chassignet & Xu, 2017).

What is the role of submesoscale processes in energy dissipation?

What are the most relevant energy sinks in the Gulf Stream?

The energy pathway

Geostrophic turbulence theory

- At large scale ($> O(100km)$), atmospheric forcing injects energy into the oceanic circulation.
- At mesoscale, large amounts of eddy kinetic energy is injected though baroclinic/barotropic instabilities of the large-scale currents.
- This eddy energy is transferred back to larger scales (inverse cascade) due to eddy-mean interactions (Charney 1971).
- For energy conservation, some dissipation is needed.

Route dissipation

The energy can be dissipated in

- Interior ocean: Unbalanced motions allow the transfer from large to small scales (forward cascade), where energy is dissipated.
- Surface and bottom boundaries
  - Bottom Drag
    produced by the interaction of oceanic bottom currents and bottom stress
  - Top Drag
    produced by the interaction of oceanic surface currents and wind stress

Methodology

Model Configuration

- CROCO (Debreu et al., 2012), Period 2005-2009 (+ a spin up of 5 years)
- $dx = 1/42^\circ$ (~ 2.2 km) and 50 vertical levels
- Boundary conditions from Mercator Glorys12V1 product ($1/12\ ^\circ$)
- Atmospheric forcing from the hourly CFSR (online interpolation)
- Parameterization of mechanical coupling (Current Feedback, Renault et al., 2020).
- Outputs are 3-hour averaged.
- The GS main path is in very good agreement with the observations.

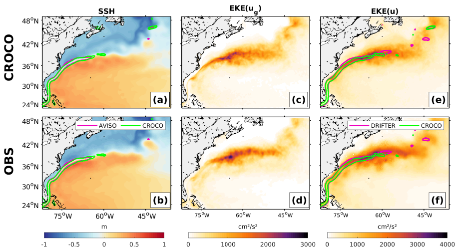

Figure: Time-mean SSH (cm) from the CROCO and AVISO climatology. ontour lines represent the GS path (contour 0.5 m/s) from CROCO (AVISO).

Methodology

Coarse-grained method

- An alternative approach to spectral analysis is the coarse-grained method (Aluie et al., 2018, Schubert et al., (2020);).
- Several advantages: it **does not assume** an homogeneous and isotropic field, and it **avoids the use of windowing**
- From the kinetic energy equation, we derived the term that represents the kinetic energy scale transfer (Π)

$$\Pi = -\rho_0[(\overline{u^2} - \overline{u}^2)\overline{u}_x + (\overline{uv} - \overline{u}\ \overline{v})(\overline{u}_y + \overline{v}_x) + (\overline{v^2} - \overline{v}^2)\overline{v}_y], \tag{1}$$

where $^-$ is a low-pass filter, for example, if $F(x,y)$ is a horizontal field, then $\overline{F(x,y)} = C \times F(x,y)$, where

$$C(r) = \begin{cases} 1/(\pi L^2/4), & \text{if } |r| < L/2, \\ 0, & \text{otherwise} \end{cases}$$

- Π represents the energy transferred from scales $> L$ to smaller scale due to nonlinear interactions.
- Π is estimated at $L = 9, 22, 61, 105$ -km.

Kinetic energy flux

- At the 9-km scale , Π is mainly positive, revealing the presence of a forward cascade.
- At the 22-km scale, Π is characterized by a dipole situated right over the Gulf Stream path.
- At larger scale (61 and 105 km), the inverse cascade becomes dominant.

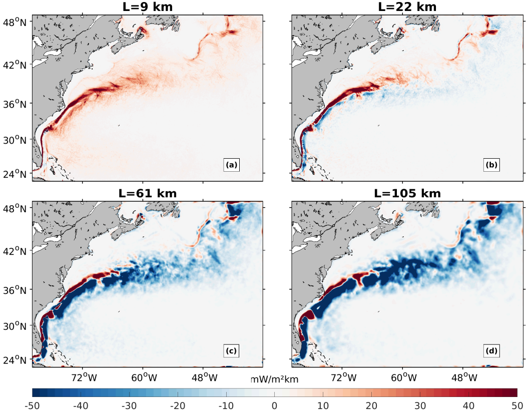

Figure: Time-mean (2005-2009) surface scale kinetic energy flux (Π) estimated using total currents .

Positive (negative) values indicate a forward cascade (inverse cascade).

Kinetic energy flux

However, at submesoscale ($< O(10km)$), the geostrophic balance can be broken more easily, allowing the development of unbalanced motions and the transfer energy to smaller scales.

QG vs non-QG models

- QG models reproduce a much weaker forward cascade than non-QG models (e.g., Capet et al., 2008).
- These results suggests that the ageostrophic flow component plays a major role in the forward cascade.

In order to to disentangle the contributions of balanced and unbalance motions to the energy cascade, we decomposed $\mathbf{u}$ in

$$u = u_r + u_d = \psi_y + \phi_x$$
$$v = v_r + v_d = -\psi_x + \phi_y$$

where ψ and ϕ are the streamfunction and the velocity potential, respectively, and $\mathbf{u_r}$ and $\mathbf{u_d}$ are the rotational and divergent currents(which can be associated with the balanced and unbalanced motions)

Kinetic energy flux

- $\Pi(\mathbf{u_r})$ reveals that the inverse cascade dominates in the GS region
- $\Pi(\mathbf{u_d})$ does not show an important contribution to the total kinetic energy flux.
- The interaction between the rotational and divergent contribution to the kinetic energy flux, especially, for the forward cascade.

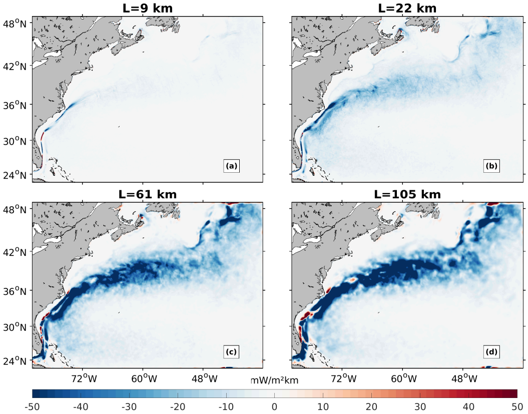

Figure: Time-mean (2005-2009) surface kinetic energy flux estimated using rotational component ($\Pi(\mathbf{u_r})$).

Kinetic energy flux

- We estimated the contribution of the cross-term to the kinetic energy flux from (1) as:

$$\Pi_{CT} = \Pi - \Pi(\mathbf{u_r}) - \Pi(\mathbf{u_d})$$

- It reveals a strong forward cascade
- Previous studies have shown that frontogenesis plays an important role in the forward cascade (e.g. Capet et al., 2008; Klein et al., 2008, Srinivasan et al.,2022).

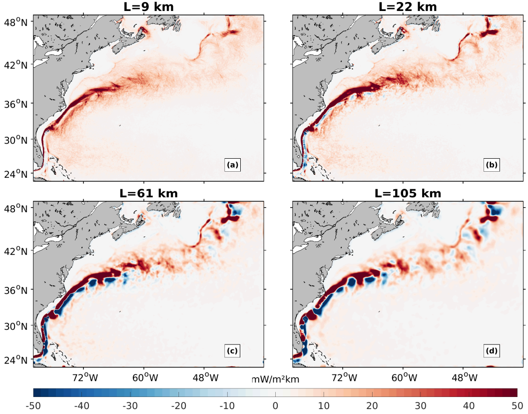

Figure: Time-mean (2005-2009) of the contribution of cross-terms ($\Pi_{CT} = \Pi - \Pi_r - \Pi_d$).

Quantification of energy pathways

- Top Drag $F_e K_e = \langle \mathbf{u_g}'' \tau'' \rangle - \Pi_{\tau_{22km}}$
  where $\langle \rangle$ and $'$ indicate the average over 3-month and its fluctuation, and
  $\Pi_{\tau_{22km}} = \overline{\tau \cdot \mathbf{u_g}} - \overline{\tau} \cdot \overline{\mathbf{u_g}}$ (at 22-km scale)
- Bottom Drag $F_b K_b = \langle \mathbf{u_b}'' \tau_\mathbf{b}'' \rangle$
- Interior dissipation $I_{Diss} = -\int_{-100m}^{0} \Pi_{9km} dz$,
- Numerical dissipation $H_{Diff} = \int_{bottom}^{0} \mathbf{u} \cdot \mathbf{D} dz$

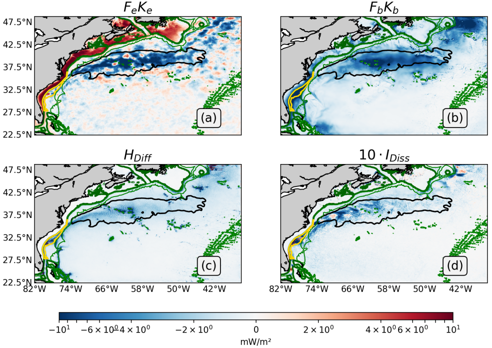

Figure: Time-mean (2005-2009) of the energy sinks (mW/m^2).

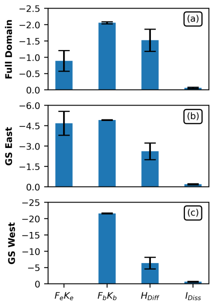

Figure: The energy sinks (mW/m^2) spatially averaged overt he entire domain , the east region (black contour), an the west region (yellow contour).

Conclusion

- We show that:
  - A forward cascade dominates at scales shorter than 9 km
  - At a 22-km scale, the forward (inverse) cascade dominates north (south) of the Gulf Stream.
  - The inverse cascade dominates at scales larger than 61 km.
- Rotational motions drive the inverse cascade
- The forward cascade is produced by the interaction between rotational and divergent components.
- The main energy dissipation processes in the real ocean are at the boundaries, top and bottom drags .