

Eddy-mean flow interactions in the Caribbean Sea and their modulation by current feedback to the atmosphere

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Key Points:

- Current feedback reduces mesoscale eddy kinetic energy by about 35% in the Caribbean Sea, weakening eddy-mean flow interactions
- Weaker eddy-mean flow interactions narrow and intensify the mean Caribbean Current
- Changes in the mean Caribbean Current modify the spatial distribution of mesoscale eddies

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Abstract

The Caribbean Sea exhibits important mesoscale variability and a well-defined mean circulation, yet the role of mechanical air-sea coupling through current feedback in mesoscale variability and eddy-mean flow interactions has not been quantified. Here, we analyze 24 years of Caribbean Sea dynamics using eddy-rich coupled ocean-atmosphere simulations differing only by the inclusion of current feedback. Current feedback directly reduces eddy kinetic energy by about 35% through negative eddy wind work, which transfers kinetic energy from the ocean to the atmosphere through the eddy-killing mechanism. Consistent with this reduction, the kinetic energy of individual mesoscale eddies decreases by about 40%. However, mesoscale eddy diameter, lifetime, and displacement remain largely unchanged. This limited response is consistent with their short mean lifetime (~ 25 days), which limits the cumulative impact of current feedback. In addition to eddy-killing, current feedback indirectly reduces eddy kinetic energy production through barotropic energy conversions by about 35%, while the inverse kinetic energy cascade decreases by more than 50% near 150 km, comparable to the characteristic eddy diameter. These changes indicate weaker eddy-mean flow interactions and reduced upscale energy transfer. Although basin-integrated mean kinetic energy is not significantly modified, weaker eddy-mean flow interactions reorganize the mean Caribbean Current, making it about 8% narrower and at least 20% more intense along the continental slope. This reorganization aligns with a redistribution of mesoscale eddies toward regions previously occupied by the mean current. Finally, coupling coefficients between surface currents and the atmospheric response quantify current-feedback strength and support its representation in forced simulations.

Plain Language Summary

The Caribbean Sea is a tropical ocean region connected to the Atlantic Ocean and the Gulf of Mexico. Its circulation is dominated by large meanders and energetic mesoscale eddies, giving rise to a broad westward flow known as the Caribbean Current. In this study, we investigate how the ocean and the atmosphere interact through a process known as current feedback. This occurs when surface ocean currents are able to modify wind stress by interacting with surface winds. In this way, the ocean not only responds to the atmosphere, as is often assumed, but also influences it. Using numerical simulations, we show that current feedback reduces the energy of mesoscale eddies and reorganizes their spatial distribution. At the same time, it strengthens and narrows the mean Caribbean Current. These ocean changes lead to modifications in wind stress, especially over regions with strong eddy activity. Overall, our results highlight that interactions between ocean currents and winds play an important role in shaping both ocean circulation and the atmospheric response in the Caribbean Sea.

1 Introduction

The Caribbean Sea is a semi-enclosed tropical basin extending approximately from 8° to 25° N and 85° to 55° W (Figure 1). It is bounded to the south and west by the South and Central American continents, and to the north and east by the island arcs of the Greater Antilles (Cuba, Jamaica, Hispaniola, and Puerto Rico) and the Lesser Antilles (Barbados, Saint Lucia, Grenada, and Trinidad and Tobago; Andrade-Amaya, 2000; Johns et al., 2002; Jury, 2011; Richardson, 2005). The basin connects to the Gulf of Mexico through the Yucatan Channel and is characterized by a complex bathymetry composed of multiple sub-basins. The main basins include the Cayman, Colombian, and Venezuelan Basins, separated by bathymetric highs such as the Cayman Ridge, Beata Ridge, and the Central American Ridge in the western Caribbean (Figure 1a; Richardson, 2005).

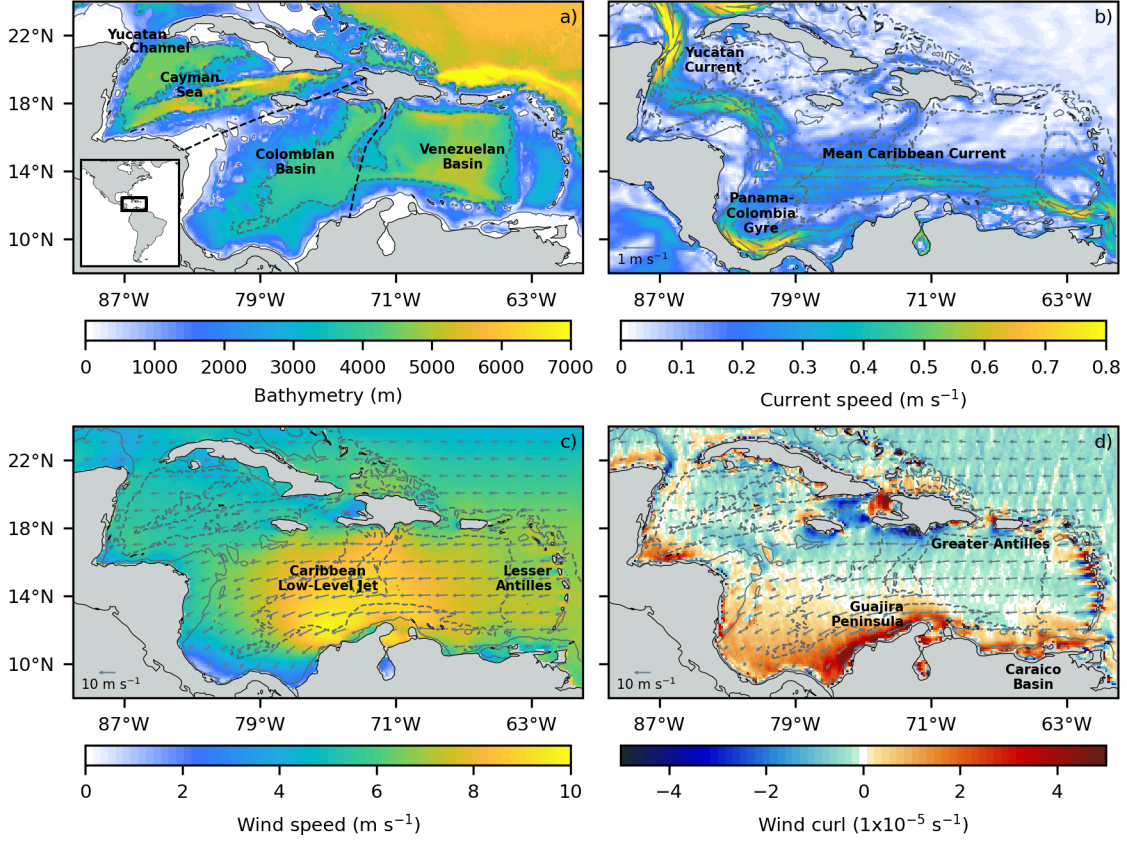


Figure 1. a) Bathymetry and main sub-basins over the Caribbean Sea. Black segmented lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. b) Climatological current speed estimated from altimeter observations (1993-2016). Mean winds (c) and wind curl (d) estimated from the Advanced Scatterometer (ASCAT; EUMETSAT OSI SAF, 2023) along-track winds (2010-2019). The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath.

Large-scale circulation in the Caribbean Sea is driven by Atlantic inflows through multiple passages in the Greater and Lesser Antilles (Johns et al., 2002). Along the southeastern boundary, the North Brazil Current supplies warm, relatively low-salinity waters influenced by the Amazon and Orinoco river plumes, contributing to the upper-layer properties of the Caribbean Sea inflow system (Fournier et al., 2017). Inside the Caribbean Sea, the circulation is dominated by large meanders and energetic mesoscale eddies, giving rise to a broad westward flow known as the Caribbean Current. This current flows northwestward along the southern basin margin before bifurcating near the Isthmus of Panama to form the Panama-Colombia Gyre (Figure 1b; Jouanno et al., 2012). Despite being less intense and spatially coherent than major western boundary currents, it provides a low-latitude pathway through which waters associated with the upper limb of the Atlantic Meridional Overturning Circulation and subtropical gyre transit before supplying the Florida Current (Schmitz & Richardson, 1991; Johns et al., 2002). Surface winds in the Caribbean Sea are dominated by the Trade Winds and their local expression, the Caribbean Low-Level Jet (Wang, 2007), resulting in a predominantly easterly flow across the basin (Figure 1c). The wind regime varies seasonally following the latitudinal displacement of the Intertropical Convergence Zone and fluctuations in the North Atlantic subtropical high (Jouanno et al., 2012; Schneider et al., 2014; Orejarena-Rondón et al., 2022). These wind patterns also drive coastal upwelling along the southern Caribbean

margin, particularly off Colombia and Venezuela, where alongshore wind stress curl induces the rise of colder subsurface waters (Figure 1d; Andrade & Barton, 2005; Jouanno & Sheinbaum, 2013; van der Boog et al., 2019).

Mesoscale eddies play a key role in the redistribution of water-mass properties across ocean basins (Farneti et al., 2010; Dong et al., 2014; Zhang et al., 2014). They actively shape the dynamics of mean currents through nonlinear eddy-mean flow interactions that redistribute momentum, vorticity, and energy across spatial scales (Farneti et al., 2010). Numerical studies have shown that resolving mesoscale eddies is essential to capture realistic boundary current behavior (McWilliams, 2008; Bryan et al., 2007; Chassignet & Marshall, 2008). An accurate representation of the separation and downstream evolution of western boundary currents such as the Gulf Stream and the Agulhas Current depends on the proper balance between mesoscale activity, wind forcing, and available energy sinks (Renault, Marchesiello, et al., 2019). An excess of mesoscale energy near separation points can distort mean paths, producing unrealistic offshore detachment unless effective energy sinks are present (Özgökmen & Chassignet, 2002; Renault, Molemaker, Gula, et al., 2016; Renault, Marchesiello, et al., 2019). Thus, mesoscale eddies can fundamentally reorganize the mean circulation by modifying lateral momentum fluxes and shaping the equilibrium state of boundary currents.

The Caribbean Sea is also characterized by a high occurrence of mesoscale eddies, which not only shape the regional circulation (Richardson, 2005; Kastner et al., 2024), but also influence the Gulf of Mexico through interactions with the Loop Current (Athié et al., 2012; Le Hénaff et al., 2012; Garcia-Jove Navarro et al., 2016; Jouanno et al., 2016; Ntaganou et al., 2023; I. Ma et al., 2026; Larrañaga et al., 2026). These eddies typically range from 80 to 200 km in diameter and have lifetimes from weeks to months (Chelton et al., 2011b; López-Álzate et al., 2022). They propagate westward and tend to intensify along their trajectories (Carton & Chao, 1999; Jouanno et al., 2008; van der Boog et al., 2019; López-Álzate et al., 2022).

Mesoscale variability and the resulting mean circulation are strongly influenced by air-sea interactions through thermal and mechanical feedback mechanisms. The thermal feedback, *i.e.*, the influence of sea surface temperature on the atmosphere, can modulate mesoscale eddies and western boundary currents by inducing turbulent heat flux anomalies that sink potential energy from the ocean to the atmosphere (X. Ma et al., 2016; Seo et al., 2017; Putrasahan et al., 2017; Bishop et al., 2020; Renault et al., 2023). Observational studies have shown that mesoscale sea surface temperature anomalies associated with oceanic fronts and eddies can induce wind and wind stress curl anomalies through modifications of the marine atmospheric boundary layer (Chelton et al., 2001; Chelton, 2004; Chelton et al., 2007). These thermal feedbacks arise primarily from changes in atmospheric stability and turbulent momentum mixing (Chelton et al., 2007; Small et al., 2008; O'Neill et al., 2005; Meroni et al., 2022; Desbiolles et al., 2023), as well as pressure adjustments in the atmospheric boundary layer (Small et al., 2008; Shimada & Minobe, 2011; Rousseau et al., 2021). A review of the processes involved in the thermal feedback can be found in, Small et al. (2008), Seo et al. (2023), and Renault et al. (2026). The current feedback, *i.e.*, the mechanical interaction between sea surface currents and the atmosphere, is a crucial but often missing component in ocean modeling (Bye, 1985; Dewar & Flierl, 1987; Duhaut & Straub, 2006; Seo et al., 2016; Renault, Molemaker, Gula, et al., 2016; Renault, Molemaker, McWilliams, et al., 2016). It induces the so-called eddy-killing effect, *i.e.*, a sink of kinetic energy from oceanic eddies to the atmosphere that reduces the oceanic (sub)mesoscale activity by about 30% (Renault, Molemaker, McWilliams, et al., 2016; Renault, McWilliams, & Penven, 2017; Jullien et al., 2020; Larrañaga et al., 2022; Conejero et al., 2024; Renault et al., 2024). This kinetic energy transfer arises from the interaction between surface currents, wind stress, and wind, where current anomalies generate opposed wind stress anomalies that feed back onto the near-surface wind field. As a result, positive wind stress anomalies tend to induce negative wind anoma-

lies, and vice versa. This asymmetry in wind stress anomalies results in a net transfer of kinetic energy from the ocean to the atmosphere (Renault, Molemaker, McWilliams, et al., 2016; Renault et al., 2026). Several indirect interactions result from the reduction of (sub)mesoscale activity induced by current feedback. As a result, mesoscale eddies exhibit more realistic properties (thermohaline structure, energy levels, dissipation rates, and lifetime) and trajectories, due to changes in their shedding statistics, detachment locations, and preferential trajectories (Renault, Molemaker, McWilliams, et al., 2016; Larrañaga et al., 2022). In addition, weaker (sub)mesoscale activity leads to a reduced inverse cascade of kinetic energy associated with eddy-mean flow interactions. As a result, the representation of western boundary currents such as the Gulf Stream, the Agulhas Current, and the Loop Current is improved (Renault, Molemaker, Gula, et al., 2016; Renault, McWilliams, & Penven, 2017; Renault, Marchesiello, et al., 2019; Larrañaga et al., 2022; Chassignet & Xu, 2026).

In this paper, we highlight the importance of current feedback in modulating the Caribbean Sea mean pathways since they are primarily driven by transient features such as meanders and mesoscale eddies (Fratantoni et al., 1998; Richardson, 2005; Jouanno et al., 2008, 2009). We demonstrate how the inclusion of current feedback reduces mesoscale activity through the eddy-killing mechanism in closer agreement with the observations. It also indirectly weakens eddy-mean flow interactions, narrows the mean Caribbean Current, and redistributes the location of the mesoscale eddies. The study is organized as follows: models, data, and methods are described in Section 2. Section 3 presents an assessment of the spatial and vertical distribution of kinetic energy variability, comparing simulations with and without current feedback against satellite altimetric observations. Section 4 analyzes the eddy kinetic energy budget, quantifying how current feedback modifies eddy kinetic energy directly through eddy wind work and indirectly through changes in barotropic and baroclinic energy conversions. Section 5 explores how mesoscale eddy properties are modified by current feedback, including changes in intensity, lifetime, trajectories, and spatial distribution. Section 6 examines how current feedback impacts the inverse kinetic energy cascade and the transfer of kinetic energy from mesoscale variability to the large-scale circulation in the Caribbean Sea through eddy-mean flow interactions. Section 7 focuses on the estimation of coupling coefficients for representing current feedback in forced numerical simulations of Caribbean ocean dynamics. Finally, the results are discussed in Section 8.

2 Data and methods

2.1 Coupled numerical simulations

Ocean dynamics were performed using the Nucleus for European Modeling of the Ocean (NEMO 4.0; Madec et al., 2022) with a grid spacing of $1/12^\circ$ (about 8 km). The numerical grid covers the Intra-Americas Sea, a region delimited by longitudes 98° to 29° W and latitudes 7° S to 32° N. Atmospheric dynamics were solved using the Weather Research and Forecast (WRF) model (Skamarock et al., 2019) with a spatial resolution of $1/4^\circ$ (approximately 25 km). The regional WRF grid extends slightly outside the NEMO domain to minimize the influence of the WRF sponge layer (4 points; Renault, Marchesiello, et al., 2019). NEMO and WRF are coupled through the Ocean Atmosphere Sea Ice Sol (OASIS-MCT; Craig et al., 2017), enabling hourly average data exchanges between the two numerical models.

Two numerical experiments are carried out over 24 years (from 1993 to 2016): NOCF (without current feedback) and CF (with current feedback). Both experiments consider thermal feedback, as NEMO provides sea surface temperature to WRF, while WRF forces NEMO with momentum, heat, and freshwater fluxes. In NOCF, momentum and turbulent heat fluxes are computed as a function of the absolute winds ($\mathbf{U}_a$) as follows:

$$\boldsymbol{\tau} = \rho_a C_D |\mathbf{U}_a| \mathbf{U}_a, \quad (1)$$

$$Q_s = \rho_a c_p C_h |\mathbf{U}_a| (\Theta_z - T_s), \quad (2)$$

$$Q_l = \rho_a L_e C_e |\mathbf{U}_a| (q_s - q_z), \quad (3)$$

where ρ_a is the air density, C_D , C_h , and C_e are the bulk transfer coefficients for momentum (τ), sensible heat (Q_s), and latent (Q_l) heat fluxes, respectively, c_p is the specific heat capacity of air at constant pressure, L_e is the latent heat of evaporation, Θ_z is the air potential temperature at reference height z , T_s is the sea surface temperature, q_z is the specific humidity at height z , and q_s is the saturation specific humidity at the sea surface. In the CF experiment, in addition to thermal feedback, the current feedback is also considered. To account for this effect, NEMO provides sea surface currents ($\mathbf{u}_{ss}$) to WRF, which then computes wind stress as a function of winds relative to sea surface currents ($\mathbf{U}_r$):

$$\mathbf{U}_r = \mathbf{U}_a - \mathbf{u}_{ss}. \quad (4)$$

It is important to note that, to properly consider current feedback in the coupled numerical simulation, relative winds should also be considered in the tridiagonal problem associated with the discretization of the vertical turbulent viscosity of WRF (Lemarié et al., 2015; Renault, Lemarié, & Arsouze, 2019). Further details on the models' configuration and the initial and boundary conditions can be found in Larrañaga et al. (2022), where this configuration was shown to improve Loop Current variability and eddy detachment statistics in the Gulf of Mexico.

2.2 Altimetric observations

Altimetric observations from the Copernicus Marine Environment Monitoring Service (CMEMS, 2021), provided on a 0.125° grid, are used to compute the surface kinetic energy and mean kinetic energy climatologies. These observations are used to evaluate the numerical simulations and to assess if considering current feedback allows us to better reproduce the mesoscale activity in the Caribbean Sea. The dataset was accessed in September 2025.

2.3 Eddy detection method

Mesoscale eddies are detected using the method described in Chaigneau et al. (2009). The centers of the eddies are identified as the local maximum in sea level anomaly maps. Their periphery is determined from the outermost closed contour of the geostrophic velocity associated with the eddy center. Once the eddy contours are identified, their trajectories are obtained by matching eddies detected on consecutive days (Pegliasco et al., 2015).

3 Spatial distribution of surface kinetic energy associated with geostrophic currents

Kinetic energy provides a quantitative measure of oceanic motion. The kinetic energy per unit mass is defined as:

$$\text{KE} = \frac{1}{2} (\overline{u^2} + \overline{v^2}), \quad (5)$$

where u and v correspond to the horizontal velocity components. Following a temporal Reynolds decomposition, the velocity field is separated into mean (MKE) and eddy (EKE) components:

$$\text{MKE} = \frac{1}{2} (\overline{u^2} + \overline{v^2}), \text{EKE} = \frac{1}{2} (\overline{u'^2} + \overline{v'^2}). \quad (6)$$

The overbar ($\overline{}$) indicates a long-term mean estimated from 1993 to 2016, while the primes ($'$) correspond to the anomalies with respect to the long-term mean. The corresponding kinetic energy quantities computed from geostrophic velocities are denoted by KE_g ,

MKE_g, and EKE_g, respectively. Geostrophic velocity components are computed from the geostrophic balance using the absolute dynamic topography (h):

$$f\hat{\mathbf{z}} \times \mathbf{u}_g = -g\nabla_h h, \quad (7)$$

where f is the Coriolis parameter, $\hat{\mathbf{z}}$ is the upward unit vector, and ∇_h is the horizontal gradient operator.

The following subsections analyze the spatial distribution of surface kinetic energy associated with geostrophic currents in the Caribbean Sea. Satellite observations provide a reference for evaluating the numerical simulations, while differences between NOCF and CF quantify the impact of current feedback. It is important to mention that eddy kinetic energy includes all variability relative to the long-term circulation, capturing seasonal and inter-annual fluctuations, as well as current meander and mesoscale eddies. Smaller-scale features are not adequately represented given the spatial resolution of the altimetric observations (25 km) and numerical simulations (8 km). Because current feedback primarily removes kinetic energy from mesoscale ocean structures through the eddy-killing mechanism, differences in eddy kinetic energy between the CF and NOCF simulations are interpreted mainly as changes in mesoscale eddies and related circulations.

3.1 Satellite observations

Climatological geostrophic kinetic energy fields from satellite observations depicted in Figure 2a provide a reference to quantify the influence of current feedback on Caribbean Sea ocean dynamics. Well-defined kinetic energy patterns around 14°N capture the Caribbean Current in the Venezuelan Basin, which expands and weakens over the Colombian Basin before re-intensifying and narrowing in the Cayman Sea. Alongside the Caribbean Current, the Panama-Colombian Gyre is detected southwest of the Colombian Basin, exhibiting a pronounced coastal signature. Given the strong mesoscale eddy activity in the Caribbean Sea, decomposing the kinetic energy into mean and eddy components allows a more precise characterization of the mean currents and the identification of regions with the strongest eddy signatures. Eddy kinetic energy highlights strong variability across the Caribbean Sea, with local maxima in the southern Venezuelan Basin, the northern and southern Colombian Basin, and the northeastern Cayman Sea (Figure 2b). About 65% of the surface kinetic energy in the Venezuelan and Colombian Basins is associated with eddy kinetic energy, compared with 46% in the Cayman Sea, reflecting the strong mesoscale variability over the Caribbean Sea (Figures 2j-k). The mean kinetic energy exhibits narrower, well-defined currents in the Venezuelan Basin and Cayman Sea, while the Caribbean Current over the Colombian Basin remains weak and broadly expanded (Figure 2c).

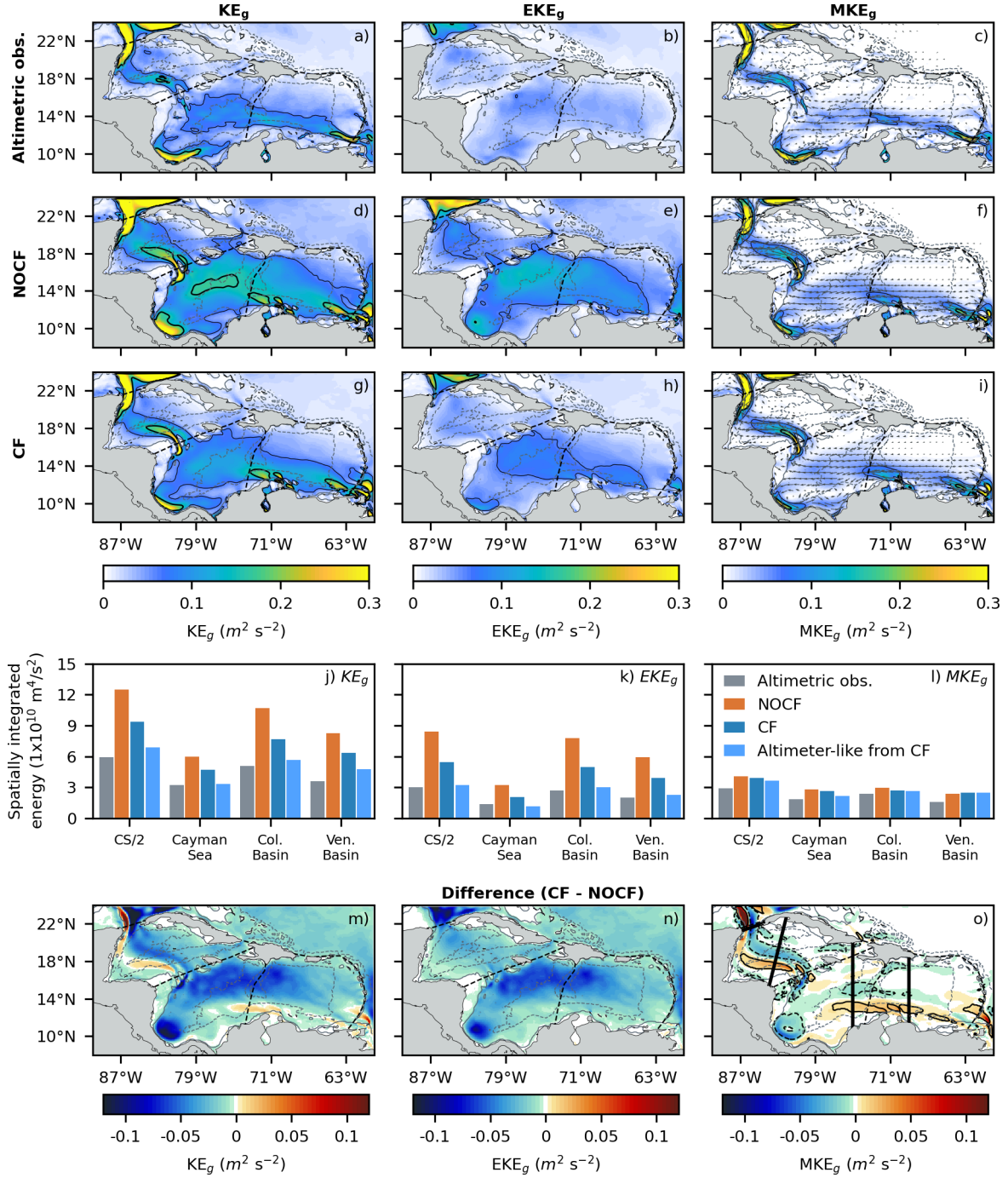


Figure 2. Climatological (1993-2016) estimations of surface kinetic energy (KE_g ; first column), eddy kinetic energy (EKE_g ; second column), and mean kinetic energy (MKE_g ; third column) associated with geostrophic currents from CMEMS (first row), NOCF (second row), and CF (third row). Thin and thick black contours depict associated current speeds of 0.5 and 0.8 $m s^{-1}$. Spatially integrated values for the full Caribbean Sea (CS), Cayman Sea, Colombian Basin, and Venezuelan Basin are shown in the fourth row. Maps of the differences between NOCF and CF are shown in the bottom row. The continuous (segmented) contours in o) exhibit the regions where mean kinetic energy values are 20% higher (lower) in CF than in NOCF. The tick-segmented black lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath.

3.2 Coupled numerical simulations

At first glance, both NOCF and CF numerical experiments reproduce the main spatial patterns of the kinetic energy over the Caribbean Sea. However, NOCF overestimates the kinetic energy by roughly a factor of two in the Venezuelan and Colombian Basins, and 1.8 times over the Cayman Sea (Figures 2a,d,j). This overestimation is mainly related to an overestimation of the eddy kinetic energy (Figures 2j-l). From NOCF to CF, the CF experiment reduces the eddy kinetic energy by approximately 30% in the Venezuelan Basin, 40% in the Colombian Basins, and 27% in the Cayman Sea (Figures 2e,h,k), improving agreement with observations. The reduction in eddy kinetic energy extends below 600 m depth, as shown by the vertical distribution of eddy kinetic energy along transects across the mean Caribbean Current (Figure 3). However, the stronger reduction occurs above 200 m depth, where eddy kinetic energy can decrease by more than 40% in comparison with NOCF. This is consistent with the fact that current feedback directly reduces eddy kinetic energy estimates by inducing a net negative geostrophic eddy wind work through the eddy-killing mechanism (Renault, Molemaker, McWilliams, et al., 2016; Renault, Marchesiello, et al., 2019; Renault, Molemaker, Gula, et al., 2016; Renault et al., 2026). To quantify the impact of current feedback on the production of eddy kinetic energy, we analyze the eddy kinetic energy budget in section 4. It is worth noting that even when current feedback is included, CF still overestimates eddy kinetic energy by 50% relative to satellite observations (Figure 2b,h,k). Without a doubt, some of the discrepancies between altimetric observations and CF can be related to model biases. However, it is also important to consider that altimetric observations have well-known limitations in the construction of gridded datasets, which often underestimate surface current energy due to the interpolation of altimeter track data into gridded fields (Chelton et al., 2011a; Hogg et al., 2015; Athié et al., 2015; Pujol et al., 2016; Amores et al., 2018; Ballarotta et al., 2019; Taburet et al., 2019; Archer et al., 2020; Larrañaga et al., 2022). To assess the impact of these observational limitations, we generate an Altimeter-like dataset by applying a 7-day running window and an 85 km diameter spatial filter to the sea surface height from the CF simulation (Renault, Marchesiello, et al., 2019; Larrañaga et al., 2025). The spatially integrated eddy kinetic energy from the Altimeter-like dataset agrees well with the satellite-derived estimate, suggesting that the smoothing introduced during the construction of gridded altimetric products is a major contributor to the discrepancy between altimetric observations and CF. Overall, including current feedback reduces the excessive eddy kinetic energy in NOCF. The Altimeter-like comparison suggests that the remaining discrepancy with observations largely reflects the smoothing of mesoscale energy in gridded altimetry.

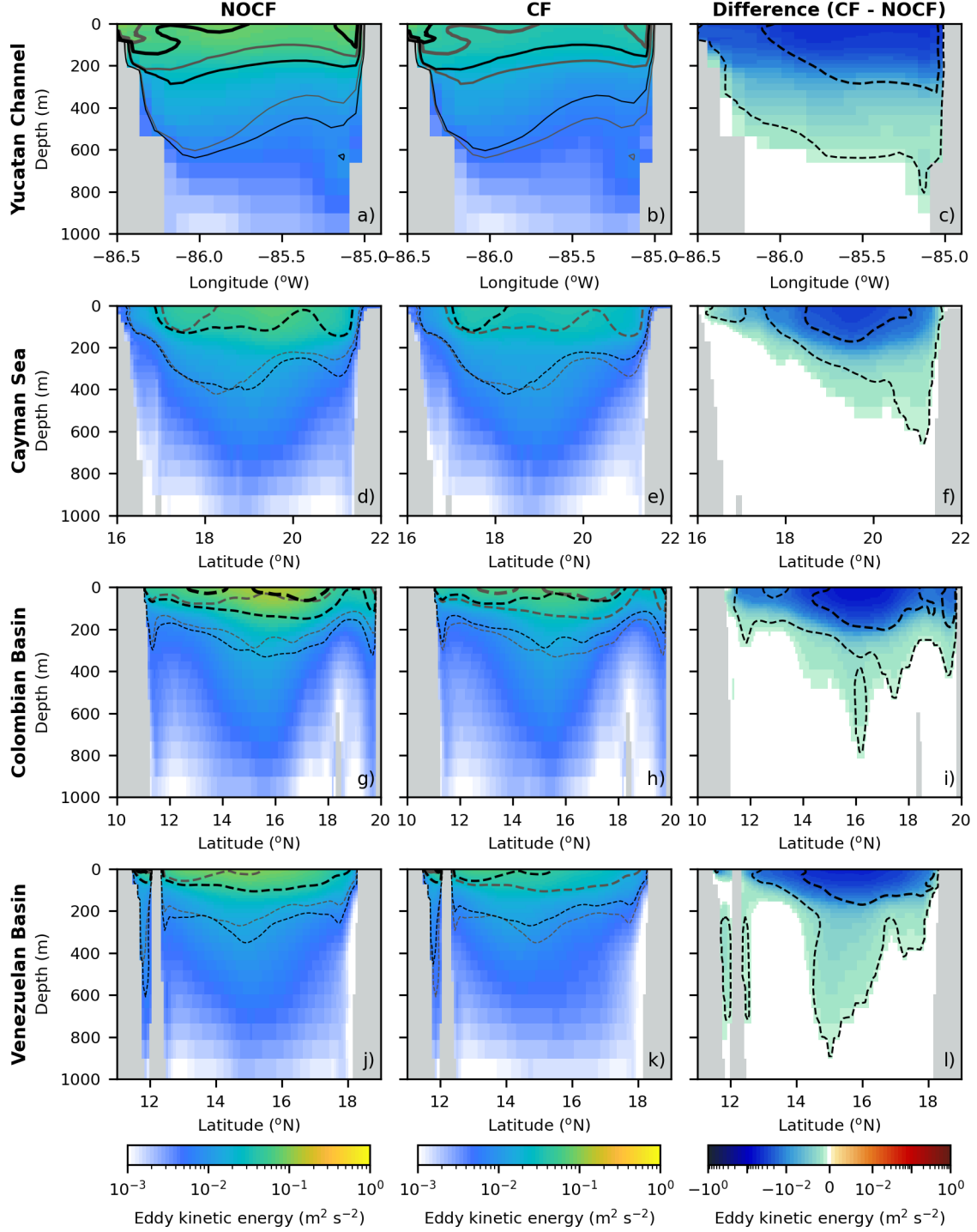


Figure 3. Vertical distribution of eddy kinetic energy along the Yucatan Channel (first row) and across the Cayman Sea (second row), Colombian Basin (third row), and Venezuelan Basin (fourth row) for NOCF (first column), CF (second column), and their difference (CF - NOCF; third column). In the first two columns, black contours show the standard deviation of the current perpendicular to each transect for the corresponding simulation, and gray contours for the other simulation, with thick, medium, and thin contours indicating 0.3, 0.2, and 0.1 $\text{m}^2 \text{s}^{-2}$, respectively. In the third column, solid (dashed) contours indicate higher (lower) eddy kinetic energy in CF, with thin and thick contours indicating differences of 20% and 40%, respectively. Transects are shown in Figure 2o. The third column uses a symmetric logarithmic color scale, linear between -10^{-2} and 10^{-2} $\text{m}^2 \text{s}^{-2}$ and logarithmic outside this range.

Regarding differences in the mean kinetic energy, the overall spatial distribution and integrated values appear similar between NOCF and CF (Figures 2f,i,l). Yet, further examination of the difference maps reveals that current feedback indirectly strengthens the mean Caribbean Current by at least 20%, with a narrower and tighter flow along the coast (Figure 2o). Similar results are obtained from the vertical distribution of mean kinetic energy along transects crossing the mean Caribbean Current (Figure 4). The current speed contours show that current feedback intensifies and narrows the mean Caribbean Current throughout the water column, with the strongest confinement toward the coast occurring above 200 m depth. The effect is more pronounced along the Yucatan Channel, where the mean current is stronger than in the other transects, reaching velocities exceeding 1 m s^{-1} in its core. Consistent with the surface mean kinetic energy differences (Figure 2o), the mean current in CF is about 20% stronger near the coast and weaker offshore compared with NOCF, decreasing the mean Caribbean Current width by around 11 km over the Yucatan Channel, and around 18 km over the Cayman Sea, Colombian Basin, and Venezuelan Basin.

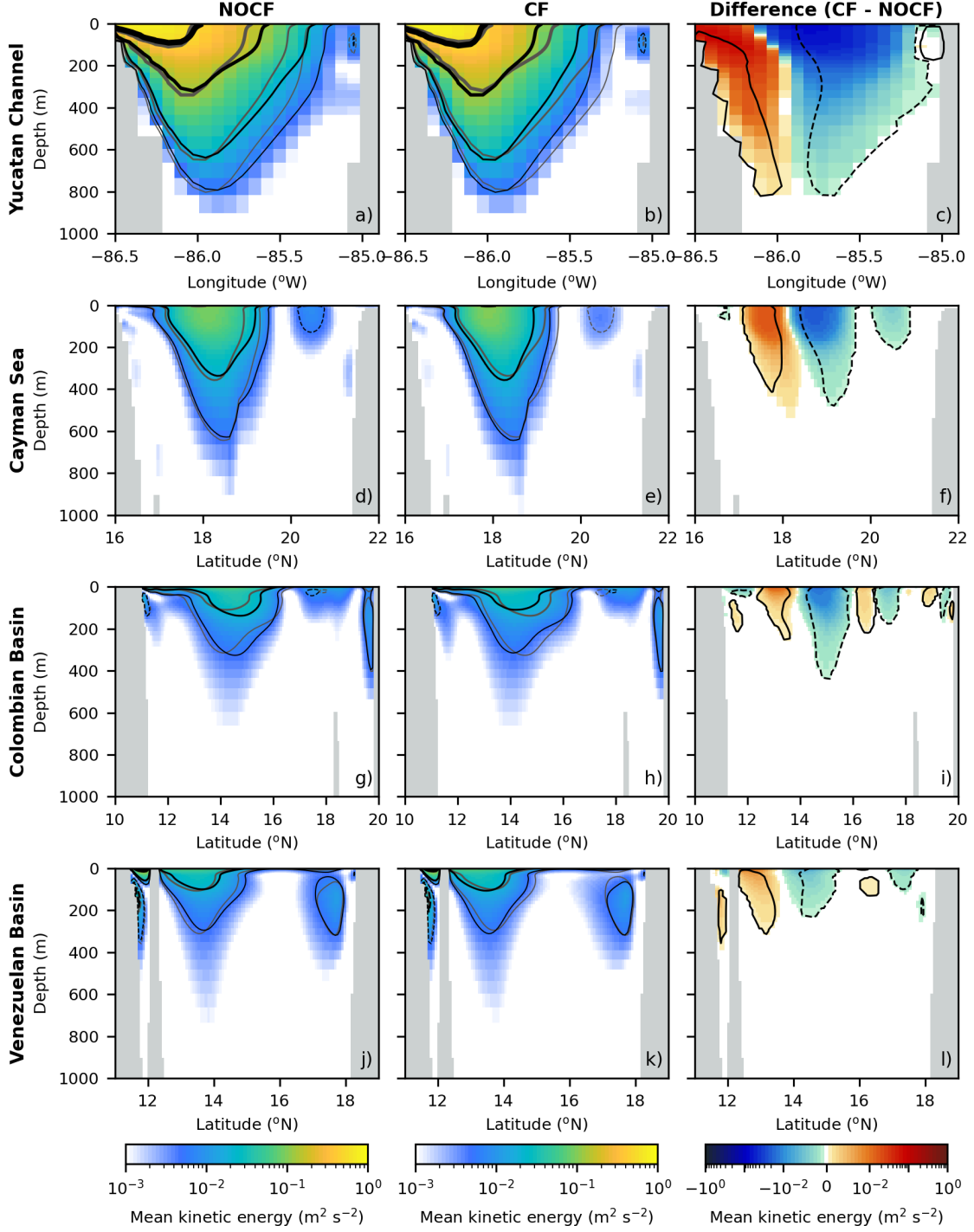


Figure 4. Vertical distribution of mean kinetic energy along the Yucatan Channel (first row) and across the Cayman Sea (second row), Colombian Basin (third row), and Venezuelan Basin (fourth row) for NOCF (first column), CF (second column), and their difference (CF - NOCF; third column). In the first two columns, black contours show the mean current perpendicular to each transect for the corresponding simulation, and gray contours for the other simulation, with very thick, thick, medium, and thin contours indicating 1, 0.5, 0.2, and 0.1 m s^{-1} , respectively. Solid (dashed) contours indicate flow in the direction of (opposite to) the mean circulation. In the third column, solid (dashed) contours indicate mean kinetic energy 20% higher (lower) in CF than in NOCF. Transects are shown in Figure 2o. The third column uses a symmetric logarithmic color scale, linear between -10^{-2} and $10^{-2} \text{ m}^2 \text{ s}^{-2}$ and logarithmic outside this range.

Current feedback can modify mean currents through two main ways: i) directly by modulating the mean kinetic energy transfer between the atmosphere and the ocean, which can be quantified by the mean wind work ($F_m K_{m_g}$; Renault, Molemaker, Gula, et al., 2016; Seo et al., 2023); and ii) indirectly through the eddy killing mechanism, which weakens mesoscale eddies, reduces the inverse kinetic energy cascade, and consequently reduces the transfer of energy from mesoscale variability to the mean circulation through eddy-mean flow interactions (Renault, Marchesiello, et al., 2019; Renault et al., 2026). These mechanisms and their impacts on the mean circulation are analyzed in the following sections.

4 Kinetic energy budget

A simplified kinetic energy budget is used to quantify both the direct and indirect effects of current feedback through the kinetic energy exchange between the atmosphere and the energy conversions between the mean circulation, mesoscale variability, and available potential energy in the Caribbean Sea. The energy budget is computed focusing on the relevant energy sources and eddy-mean conversion terms (Marchesiello et al., 2003):

$$F_m K_{m_g} = \frac{1}{\rho_0} (\overline{u_g \tau_x} + \overline{v_g \tau_y}), \quad (8)$$

$$F_e K_{e_g} = \frac{1}{\rho_0} (\overline{u'_g \tau'_x} + \overline{v'_g \tau'_y}), \quad (9)$$

$$K_m K_e = - \int_z^0 \left(\overline{u' u'} \frac{\partial \bar{u}}{\partial x} + \overline{u' v'} \frac{\partial \bar{u}}{\partial y} + \overline{u' w'} \frac{\partial \bar{u}}{\partial z} + \overline{v' u'} \frac{\partial \bar{v}}{\partial x} + \overline{v' v'} \frac{\partial \bar{v}}{\partial y} + \overline{v' w'} \frac{\partial \bar{v}}{\partial z} \right) dz, \quad (10)$$

$$P_e K_e = \int_z^0 - \frac{g}{\rho_0} \overline{\rho' w'} dz, \quad (11)$$

where g is the gravitational acceleration and ρ and ρ_0 are the potential density and density reference (1026 kg/m^3). u_g and v_g are the zonal and meridional geostrophic velocities at the surface; u , v , and w correspond to the zonal, meridional, and vertical velocities; and τ_x and τ_y are the zonal and meridional wind stress. The terms $F_m K_{m_g}$ and $F_e K_{e_g}$ represent the mechanical energy transfer between the atmosphere and, respectively, the mean geostrophic currents and the mesoscale variability of the geostrophic flow. As shown by Renault, Molemaker, McWilliams, et al. (2016), current feedback-induced modifications of wind work are primarily modulated by geostrophic currents, whereas the contribution of ageostrophic motions associated with Ekman-induced surface currents is secondary. This separation provides the basis for focusing the wind work analysis on the geostrophic component. In addition, $K_m K_e$ represents the barotropic energy conversion from mean kinetic energy to eddy kinetic energy, and $P_e K_e$ corresponds to the baroclinic energy conversion from eddy potential energy to eddy kinetic energy.

In order to characterize the net effect of the different energy sources and conversions over the Caribbean Sea, we analyze the spatially integrated values of the main energy budget terms (Figure 5a). In NOCF, winds largely force mean geostrophic currents through the geostrophic mean wind work ($F_m K_{m_g}$; Figure 5a), mostly because mean currents and winds are aligned in most of the Caribbean Sea (Figures 1b,c). In agreement with Jouanno et al. (2009) and Jouanno et al. (2012), the main source of eddy kinetic energy is related to baroclinic ($P_e K_e$) energy conversions, followed by barotropic ($K_m K_e$) energy conversions and mean geostrophic eddy wind work ($F_e K_{e_g}$; Figure 5a). Barotropic energy conversions, despite exhibiting net values favoring the production of eddy kinetic energy, exhibit mixed positive and negative values over all the Caribbean Sea, with stronger energy fluxes along the mean Caribbean Current (black contour in Figure 5b). Baroclinic energy conversions mainly produce eddy kinetic energy (positive values) across the mean Caribbean Current (black contours in Figure 5e). Both baroclinic and barotropic energy

360 conversions show near-zero values north-east of the Caribbean Sea, over the Venezue-
 361 lan Basin. Geostrophic eddy wind work energy fluxes are one order of magnitude weaker
 362 than baroclinic and barotropic energy conversions, and also exhibit mixed positive and
 363 negative values across the Caribbean Sea, with a predominance of energy transfer from
 364 the atmosphere to the ocean (Figure 6d).

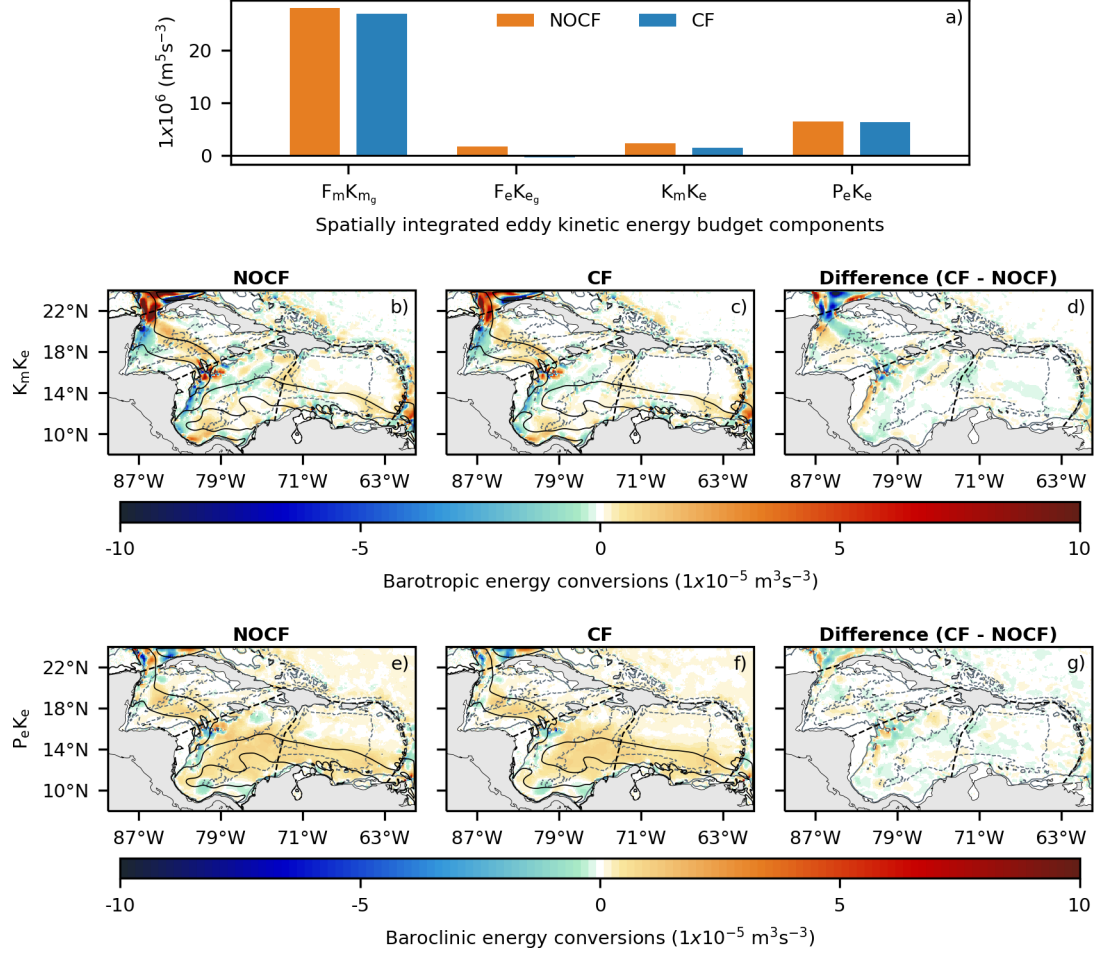


Figure 5. a) Spatially integrated eddy kinetic energy budget. Spatial distribution of barotropic ($K_m P_e$; second row) and baroclinic ($P_e K_e$; third row) energy conversions for the NOCF (first column), CF (second column), and the difference between the numerical simulations (CF - NOCF; third column). The thin black continuous contour, inferred from the $0.03 \text{ m}^2 \text{s}^{-2}$ mean kinetic energy contour, depicts the mean Caribbean Current. The tick-segmented black lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath.

365 From NOCF to CF, the spatially integrated mean geostrophic wind work ($F_m K_{m_g}$)
 366 is reduced by only 4% (Figure 5a). Moreover, the spatial distribution of mean geostrophic
 367 wind remains very similar between the two experiments (Figure 6a,b). However,
 368 the difference map (Figure 6c) exhibits patterns that closely resemble the mean kinetic
 369 energy anomalies described in Section 3.2 (Fig. 2o), with positive anomalies along the
 370 coastal side of the mean Caribbean Current and negative anomalies toward its offshore

flank. This spatial correspondence indicates that mean geostrophic wind work does not drive the mean kinetic energy differences between NOCF and CF. Instead, the mean geostrophic wind work spatial anomalies appear to respond to the changes in the mean circulation induced by current feedback. In contrast, the geostrophic eddy wind work exhibits a markedly different behavior. In NOCF, mean geostrophic eddy wind work is characterized by mixed positive and negative fluxes (Figure 6d), leading to a net positive spatially integrated contribution that reflects a tendency for the atmosphere to energize mesoscale eddies (Figure 5a). When current feedback is taken into account, negative geostrophic eddy wind work becomes dominant outside the coastal regions of the Caribbean Sea (Figure 6e), indicating a net transfer of kinetic energy from mesoscale eddies to the atmosphere. Surprisingly, the spatially integrated geostrophic eddy wind work in CF becomes close to zero (Figure 5a). This near compensation emerges from strong positive fluxes confined to the southern Colombian and Venezuelan Basins (Figure 6e). This positive mean wind work results from the strong and persistent wind stress curl (Fig. 1d), which induces a geostrophic current response that partially flows in the same direction as the wind (Renault, Molemaker, Gula, et al., 2016; Renault, Molemaker, McWilliams, et al., 2016; Larrañaga et al., 2022), largely balancing the widespread negative fluxes elsewhere.

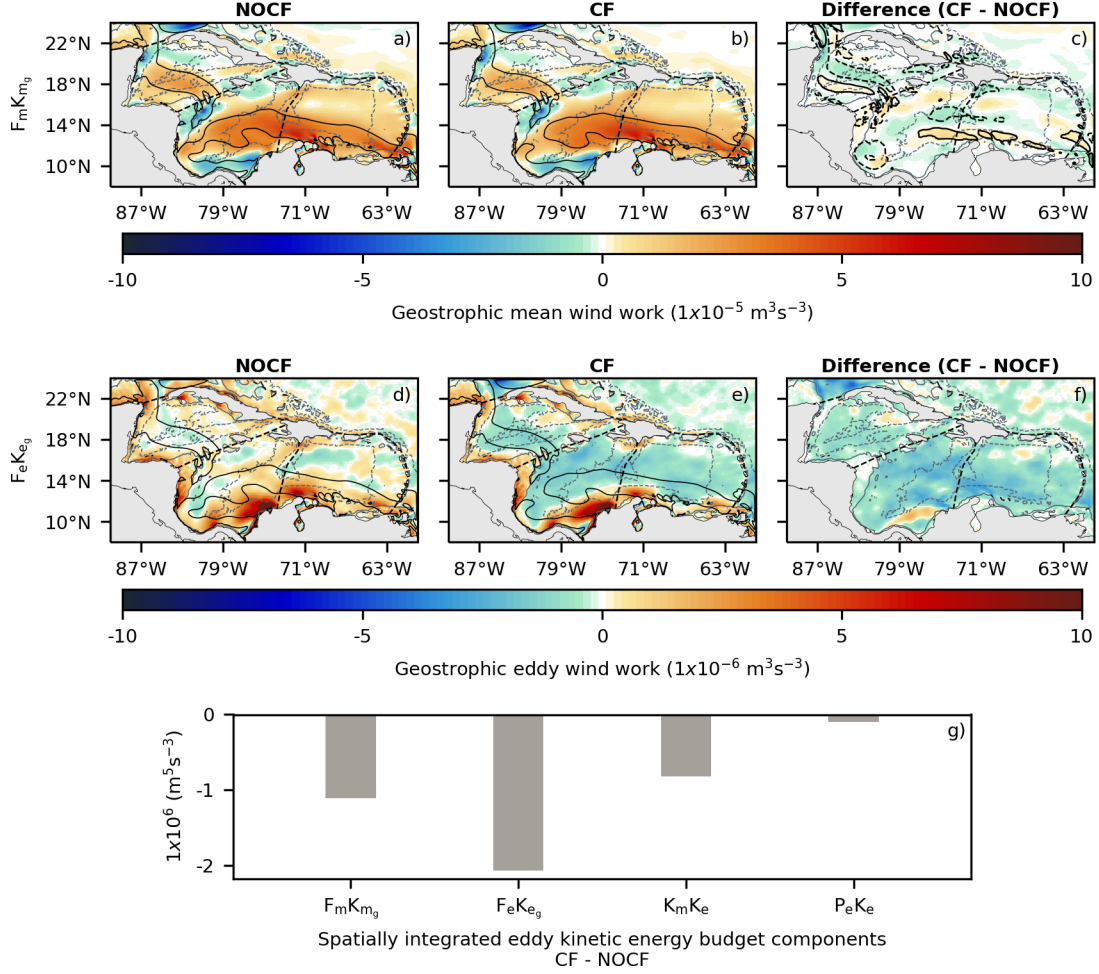


Figure 6. Spatial distribution of geostrophic mean ($F_m K_{m_g}$; first row) and eddy ($F_e K_{e_g}$; second row) wind work for the NOCF (first column), CF (second column), and the difference between the numerical simulations (CF - NOCF; third column). The difference between the spatially integrated eddy kinetic energy budget terms (CF - NOCF) is shown in g). The thin black continuous contour, inferred from the $0.03 \text{ m}^2 \text{ s}^{-2}$ mean kinetic energy contour, depicts the mean Caribbean Current. The continuous (segmented) contours in c) exhibit the regions where mean kinetic energy values are 20% higher (lower) in CF than in NOCF. The tick-segmented black lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath.

As summarized by the differences in the spatially integrated energy budget terms between CF and NOCF (Figure 6g), energy conversions are also affected by current feedback. While the net production of eddy kinetic energy through baroclinic energy conversions decreases by only about 2%, barotropic energy conversions, associated with the horizontal shear of currents, are reduced by 35% (Figure 5a). This stronger reduction in barotropic energy conversions is consistent with the weakening of mesoscale eddies by current feedback, which reduces eddy-mean flow interactions and their contribution to broadening the mean Caribbean Current (Renault, Marchesiello, et al., 2019). The resulting narrower and stronger current exhibits enhanced horizontal shear, which could favor barotropic energy conversions. However, the 35% reduction in spatially integrated

barotropic conversions indicates that this effect is outweighed by the weakening of eddy-mean flow interactions.

To further investigate whether the reduction in barotropic energy conversions is associated with changes in mesoscale eddy activity, the next section examines the sensitivity of eddy properties to current feedback.

5 Mesoscale eddy properties and its modulation by current feedback

We now quantify the impact of current feedback on the properties of mesoscale eddies in the Caribbean Sea by comparing their basic statistics and spatial distribution in the NOCF and CF simulations.

5.1 Basic statistics

Figure 7 summarizes the statistics of the number of detected tracks, kinetic energy, diameter, lifetime, and displacement (*i.e.*, the distance between the first and last detected positions of the eddy center) of anticyclonic and cyclonic mesoscale eddies with lifetimes of at least 10 days. In the NOCF experiment, a total of 1664 anticyclonic eddy tracks were detected in the Caribbean Sea, of which 36% occurred in the Cayman Sea, 26% in the Colombian Basin, and 38% in the Venezuelan Basin. Their averaged kinetic energy of eddies across the Caribbean Sea is approximately $1 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$, with similar values across all subregions and no clear indication of strong asymmetry in the distributions. Eddy diameters show a similar regional consistency, with a median value of about 90 km across the different regions and no clear regional differences in spread or central tendency. Their median lifetime of anticyclonic eddies is approximately 24 days in all subregions. However, the lifetime distribution in the Venezuelan Basin shows a tendency toward longer-lived eddies, with a mean lifetime of 58 days. Eddy displacements exhibit a pattern comparable to that of the lifetime. Mean displacements range from 130 to 219 km among the different regions, and a pronounced tail toward larger displacements in the Venezuelan Basin, where the mean displacement reaches 484 km. This behavior is consistent with the westward propagation of Caribbean eddies, as the Venezuelan Basin represents the easternmost portion of the basin and therefore allows for longer propagation distances.

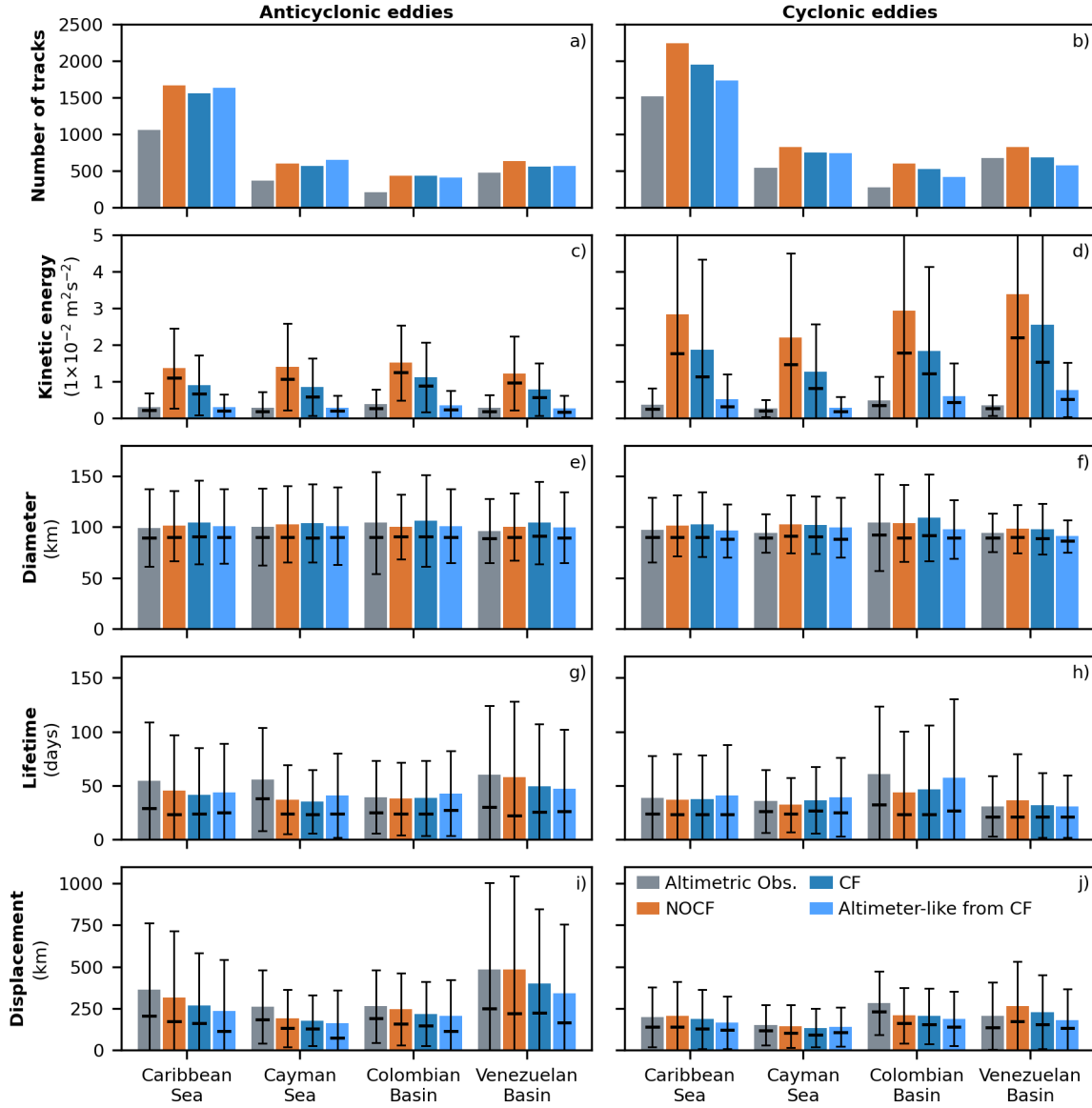


Figure 7. Statistics about the number of tracks, kinetic energy, diameter, lifetime, and displacement of mesoscale eddies in the Caribbean Sea for the altimetric observations (gray), the numerical simulations (NOCF in orange and CF in blue), and the altimeter-like filtered CF output (light blue). The left column shows the statistics for anticyclonic eddies, and the right column shows the statistics for cyclonic eddies. Bars represent the mean values, error bars represent the standard deviation, and the horizontal tick lines represent the median values.

A total of 2245 cyclonic eddy tracks were detected in the NOCF experiment, representing approximately 35% more than the number of anticyclonic eddies. As in the case of anticyclonic eddies, the Cayman Sea and Venezuelan Basin have the largest number of cyclonic eddy tracks (36% and 37% respectively), followed by the Colombian Basin (27%). Cyclonic eddies are approximately twice as energetic than anticyclonic eddies. Their median kinetic energy ranges from 1.4×10^{-2} to $2.2 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$ across the different subregions, with the highest values in the Venezuelan Basin and the lowest in the Cayman Sea. The kinetic energy distribution shows a tendency toward higher values in all regions, with mean values around $2.8 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$. The median diameter and life-

time of cyclonic eddies are approximately 90 km and 24 days, respectively, in all sub-regions. The median displacement of cyclonic eddies is approximately 35% shorter than that of anticyclonic eddies. The displacement distribution is closer to symmetric and does not exhibit the pronounced tail observed for anticyclones in most of the subregions.

From NOCF to CF, the number of anticyclonic and cyclonic eddy tracks decreases by 7 and 13% across the Caribbean Sea, respectively, with a more pronounced reduction in the Venezuelan Basin (11% and 17%, respectively). Consistent with the reduction in eddy kinetic energy, the averaged kinetic energy of mesoscale eddies over the Caribbean Sea decreases by 34% when current feedback is included. The stronger energy reduction occurs in the Cayman Sea (-39% for anticyclones and -43% for cyclones). Despite this substantial reduction in the kinetic energy of mesoscale eddies, the CF experiment does not produce considerable changes in the diameter, lifetime, or displacement. This can be partially attributed to the relatively short lifetime of mesoscale eddies in the Caribbean Sea (around 25 days), which limits the cumulative effect of current feedback on their evolution (Renault, Molemaker, McWilliams, et al., 2016). These statistics are consistent with the eddy kinetic energy budget analysis. Mesoscale eddies primarily dissipate energy through the geostrophic eddy wind work, while the production term associated with baroclinic energy conversions remains largely unchanged, which could be associated with small changes in the potential energy of mesoscale eddies. This suggests that current feedback primarily reduces the kinetic energy of Caribbean mesoscale eddies, while their relatively short lifetime limits its cumulative impact on other eddy properties. A detailed analysis of eddy potential energy is beyond the scope of the present study and will be addressed in future work.

It is worth noting that mesoscale eddy properties such as diameter, lifetime, and displacement are similar between CF and altimetric observations (Figure 7e-j). However, as found for the climatological eddy kinetic energy estimates in Section 3, the kinetic energy of eddies derived from altimetric observations is lower than in CF (Figure 7c,d). This difference is substantially reduced when the altimetric observations are compared with the Altimeter-like dataset, suggesting that the smoothing introduced during the construction of gridded altimetric products is a major contributor to the discrepancy between altimetric observations and CF.

5.2 Spatial distribution of mesoscale eddies

The probability of spatial occurrence of anticyclonic and cyclonic mesoscale eddies in the Caribbean Sea is shown in Figure 8. In the altimetric observations, anticyclonic eddies are more frequently observed along the northern flank of the mean Caribbean Current (black contour in Figure 8a). Their occurrence exceeds 60% of the studied period in the northern Cayman Sea, reaches 40-50% in the northern Colombian Basin, and ranges between 10-20% in the northern Venezuelan Basin. The northern Cayman Sea region is characterized by the presence of long-lived and semi-permanent anticyclonic eddies that subsequently cross into the Gulf of Mexico (Jouanno et al., 2008, 2009; Andrade & Barton, 2000; Ntaganou et al., 2023). In contrast, cyclonic eddies are preferentially concentrated in coastal regions of the Caribbean Sea: i) south of the Greater Antilles (between 10% and 15% of the time), as well as ii) in the southern Cayman Sea (15%), and iii) in the southern Colombian Basin (more than 60% of the time; Figure 8b). Interestingly, regions with a high probability of anticyclonic eddy occurrence generally coincide with regions where cyclonic eddies are less frequent, and vice versa, suggesting that cyclonic and anticyclonic eddies tend to propagate along distinct pathways across the basin. This spatial segregation is therefore highlighted by the difference in the probability of occurrence between anticyclonic and cyclonic eddies (Figure 8c). A reduced probability of occurrence for both cyclonic and anticyclonic eddies is also observed within the region enclosed by the mean Caribbean Current (black contour in Figure 8a-c). The preferential occurrence of anticyclonic and cyclonic eddies north and south of the mean Caribbean

Current, respectively, is consistent with the opposite signs of relative vorticity associated with the horizontal shear of the mean current (not shown). The segregation between cyclonic and anticyclonic eddies is also consistent with nonlinear eddy-eddy interactions, as same-polarity eddies can merge, whereas opposite-polarity eddies can interact as dipoles (*e.g.*, Rodríguez-Marroyo et al., 2011; de Marez et al., 2020).

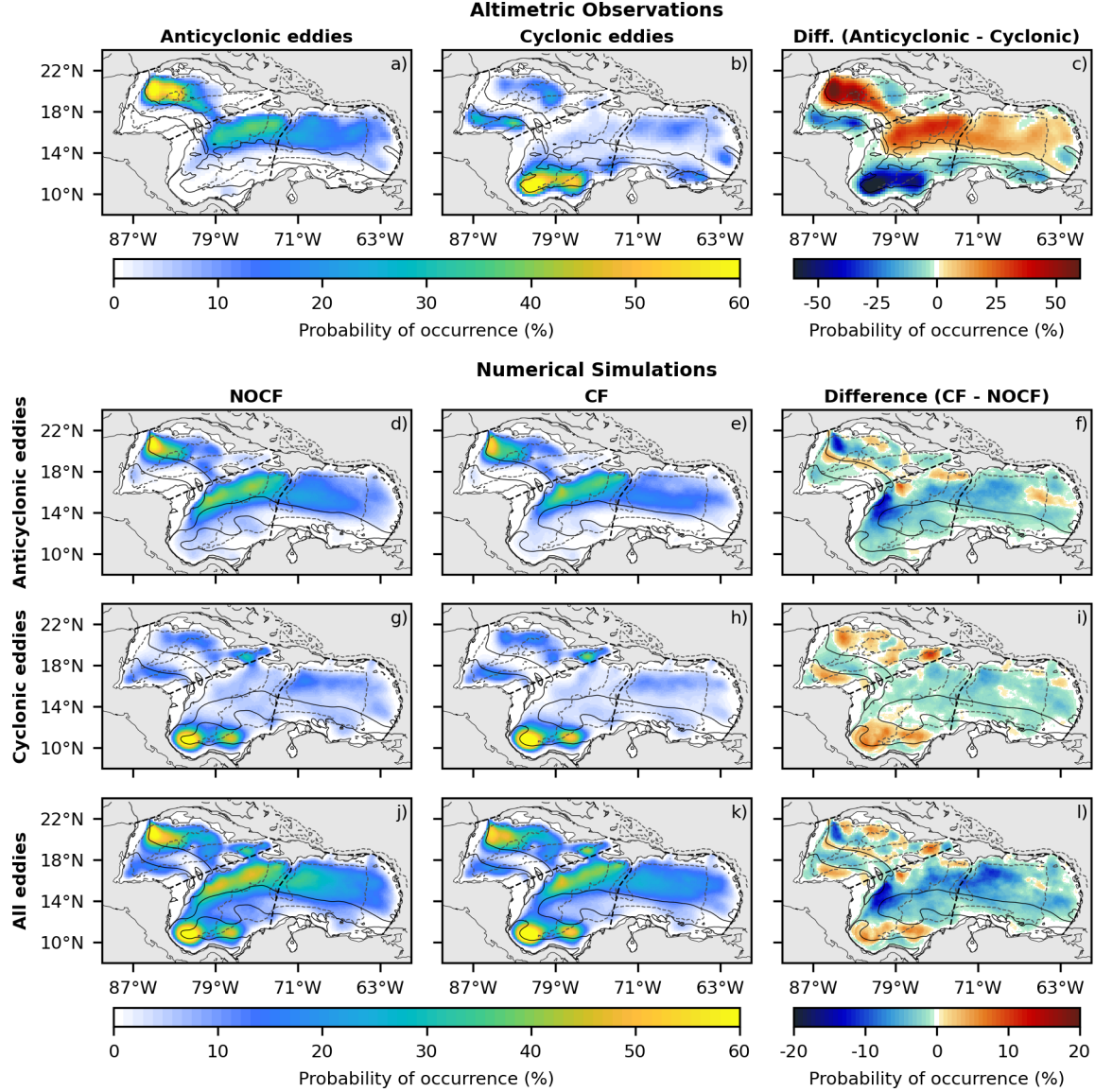


Figure 8. Probability of occurrence of anticyclonic (a) and cyclonic (b) mesoscale eddies derived from altimetric observations, with their difference (anticyclonic - cyclonic) shown in c). The second, third, and fourth rows show the occurrence probabilities for anticyclonic, cyclonic, and all mesoscale eddies, respectively, for NOCF (first column), CF (second column), and their difference (CF minus NOCF; third column). The thin black contour, corresponding to a mean kinetic energy of $0.003 \text{ m}^2 \text{ s}^{-2}$, delineates the mean Caribbean Current.

The probability of occurrence of anticyclonic and cyclonic eddies detected in the numerical simulations, as well as the differences between the simulations, are shown in

the second and third columns of Figure 8d-l. Both numerical simulations exhibit spatial patterns similar to observations. From NOCF to CF, the probability of anticyclonic eddies decreases by about 5% across most of the Caribbean Sea, with a more pronounced reduction of 10-20% in the western Colombian Basin and near the Yucatan Channel, where the long-lived and semi-permanent anticyclonic eddies occur. An increase of approximately 5% in anticyclonic eddy occurrence is observed in only small patches south of the Greater Antilles and north of the mean Caribbean Current in the Colombian Basin. Cyclonic eddies also show a reduced probability of occurrence across most of the Caribbean Sea, although the reduction is generally less than 5% (Figure 8i). In contrast, in a larger portion of the basin, the probability of cyclonic eddy occurrence increases by 5-10%, particularly north and south of the mean Caribbean Current in the Cayman Sea and in the southern Colombian Basin.

The reduction in the energy of mesoscale eddies, along with the reduction in their probability of occurrence, is consistent with the eddy kinetic energy budget analysis presented in Section 4, confirming that current feedback primarily reduces eddy kinetic energy over the Caribbean Sea by sinking mesoscale eddy energy to the atmosphere. The increase in eddy occurrence north and south of the mean Caribbean Current also aligns with the southward displacement of the current, as described in Section 3.2. To investigate the possible role of current feedback in weakening eddy-mean flow interactions, both by reducing the energy of mesoscale eddies and modifying their spatial distribution, we next quantify inverse-cascade eddy-mean flow interactions when current feedback is included.

6 Eddy-mean flow interactions over the Caribbean Sea

Coarse-grained kinetic energy cascades are commonly used to quantify energy transfers between scales in the ocean and are therefore a useful tool for investigating eddy-mean flow interactions (Leonard, 1975; Germano, 1992; Aluie et al., 2018; Rai et al., 2021; Contreras et al., 2023b, 2023a; Srinivasan et al., 2023; Larrañaga et al., 2025). The method separates the flow field into large- and small-scale components defined around a characteristic length, L . This scale separation is obtained by applying a two-dimensional spatial filter, implemented as a running mean of diameter L , to any field $\mathcal{F}(x, y)$. Mathematically, the filtered field is expressed as a convolution $\langle \mathcal{F}(x, y) \rangle = \mathcal{C} \times \mathcal{F}(x, y)$, where $\mathcal{C}$ represents a circular top-hat kernel:

$$\mathcal{C}(\mathbf{r}) = \begin{cases} 1/A, & \text{for } |\mathbf{r}| < L/2, \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

with $A = \pi L^2/4$ defining the normalization area of the circular filter and $\mathbf{r}$ the radial distance vector (Schubert et al., 2020).

As demonstrated by Schubert et al. (2020), filtering the momentum equations produces an additional term that can be interpreted as the horizontal energy flux (Π) at scale L :

$$\Pi = - \left[(\langle u^2 \rangle - \langle u \rangle^2) \frac{\partial \langle u \rangle}{\partial x} + (\langle uv \rangle - \langle u \rangle \langle v \rangle) \left(\frac{\partial \langle u \rangle}{\partial y} + \frac{\partial \langle v \rangle}{\partial x} \right) + (\langle v^2 \rangle - \langle v \rangle^2) \frac{\partial \langle v \rangle}{\partial y} \right], \quad (13)$$

where u and v correspond to the zonal and meridional components of the surface velocity field. As noted by Aluie et al. (2018), Π behaves analogously to the barotropic instability mechanism, which mediates the exchange of energy between mean and eddy kinetic energy. Within this framework, positive values of Π indicate a transfer of energy toward smaller scales (forward cascade), whereas negative values denote a transfer toward larger scales (inverse cascade).

Figure 9a shows the spatially averaged coarse-grained energy fluxes up to the 250 km scale in the Caribbean Sea. In NOCF, nearly zero energy fluxes are observed at scales smaller than 50 km. The absence of a forward energy cascade can be attributed to the model resolution, which does not allow the simulation to resolve the small-scale unbalanced motions responsible for the forward energy cascade at these scales (Contreras et al., 2023b; Larrañaga et al., 2025). In agreement with Contreras et al. (2023b) for the Gulf Stream, a predominant inverse energy cascade is observed at scales larger than 50 km, with a peak of approximately $3 \text{ mW m}^{-2} \text{ km}$ at 150 km, which is primarily driven by balanced (mostly geostrophic) currents. Similar inverse cascade behavior associated with geostrophic currents has been reported for the Gulf Stream and the Agulhas Current (Renault, Marchesiello, et al., 2019). The spatial distribution of horizontal energy fluxes at the 70 km scale is shown in Figure 9b. This scale corresponds to the range where the inverse cascade depicts a stronger slope between scales (Figure 9a). Energy fluxes are predominantly negative, with the strongest values (about $5 \text{ mW m}^{-2} \text{ km}$) occurring along the mean Caribbean Current. Alternating forward and inverse cascade fluxes occur at the Yucatan Channel, between the Cayman Sea and Colombian basins, and in the southwestern region of the Colombian basin. At large scales (150 km; Figure 9e), stronger inverse cascade fluxes (larger than $7 \text{ mW m}^{-2} \text{ km}$) are found in most parts of the Caribbean Sea, consistent with an upscale transfer of kinetic energy toward the large-scale circulation.

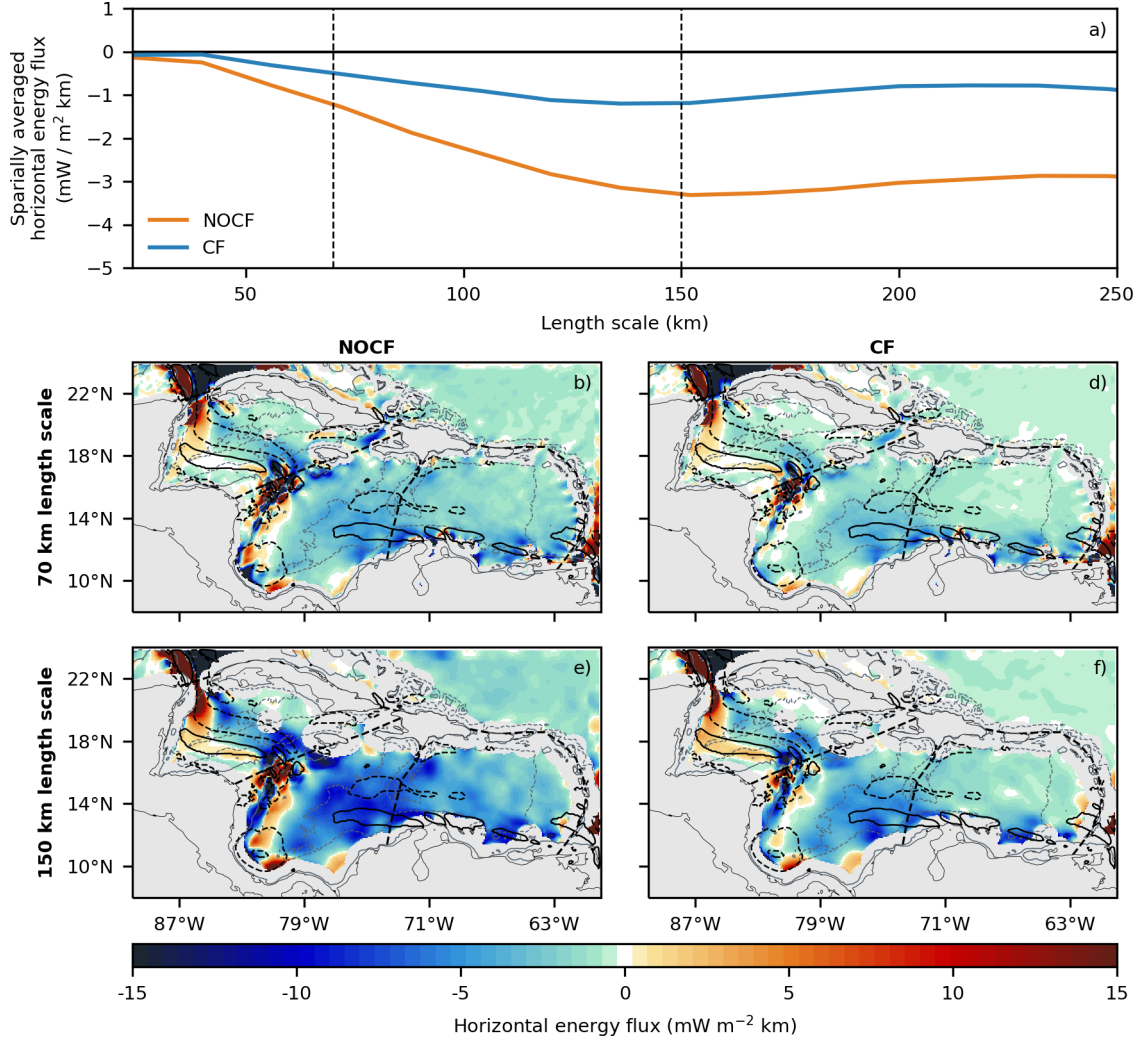


Figure 9. Spatially averaged coarse-grained energy fluxes between different scales in the Caribbean Sea for NOCF (orange) and CF (blue). The x-axis shows the scale in kilometers, and the y-axis shows the energy flux in $\text{mW} / \text{m}^2 \text{ km}$. The 70 km length scale maps of horizontal energy fluxes are shown in the second row for NOCF (first column) and CF (second column), whereas the 150 km length scale maps are shown in the third row. The continuous (segmented) black contours exhibit the regions where mean kinetic energy values are 20% higher (lower) in CF than in NOCF (Figure 2o). The tick-segmented black lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath.

From NOCF to CF, negative but nearly zero energy fluxes are still observed at scales smaller than 50 km, while inverse cascade energy fluxes continue to dominate at larger scales (Figure s9a). However, negative fluxes at scales around 70 km are reduced by more than half. This reduction is even more pronounced at scales around 150 km, where the stronger inverse cascade energy fluxes are found in NOCF. Regarding the spatial distribution of horizontal energy fluxes, the magnitude of negative fluxes is substantially reduced at both 75 (59%) and 150 (64%) km scales. As a consequence of this weakening of the inverse cascade, positive fluxes become more evident along the coastal flank of the

mean Caribbean Current in the southern Cayman Sea, consistent with the intensification of the mean Caribbean Current along the continental coast.

Overall, current feedback indirectly modulates the mean Caribbean Current through its impact on mesoscale eddies. By reducing mesoscale eddy energy, current feedback reduces the inverse kinetic energy cascade, and consequently decreases the transfer of kinetic energy from mesoscale variability to the large-scale circulation through eddy-mean flow interactions, promoting a narrower and more intense Caribbean Current.

7 Coupling coefficients for current-feedback representation in Caribbean Sea forced simulations

This study has shown that accounting for current feedback improves both eddy kinetic energy representation over the Caribbean Sea and the structure of the mean Caribbean Current by reducing the imprint of mesoscale eddies on the large-scale circulation. These results highlight the importance of representing current feedback in realistic ocean simulations. However, although fully coupled ocean-atmosphere simulations at eddy-resolving resolution provide the most complete representation of these interactions, they are computationally demanding, limiting their use for long-term integrations. In this context, Renault et al. (2020) demonstrated that current feedback can be parameterized in forced simulations through coupling coefficients relating surface currents to the atmospheric wind or wind stress response, allowing forced simulations to reproduce the main characteristics of fully coupled simulations. Coupling coefficients can be interpreted as a measure of the efficiency of the eddy killing effect, controlling the amount of kinetic energy that is extracted from oceanic eddies to the atmosphere. As shown by Renault, McWilliams, and Masson (2017) and Renault, Masson, et al. (2019), coupling coefficients are not homogeneous across the ocean, and they vary significantly from one region to another. Therefore, coupling coefficients need to be computed specifically for each region of interest. In this section, we characterize the wind- and wind stress-related coupling coefficients required to represent current feedback in forced simulations of the Caribbean Sea.

In forced numerical simulations, surface wind stress can be computed from prescribed surface winds using bulk formulations or directly imposed as a forcing field. In both cases, the atmospheric response to ocean currents is not explicitly represented. To account for current-feedback effects, an effective wind or an equivalent stress correction must therefore be introduced.

7.1 Wind-correction approach

Following Renault, Molemaker, McWilliams, et al. (2016), the effect of current feedback is represented as an additional wind response to surface currents, expressed as $s_w \mathbf{u}_{ss}$, where s_w is the non-dimensional wind-related coupling coefficient diagnosed from a fully coupled simulation. The modified wind entering the bulk formulation (Eq. 4) can then be written as:

$$\mathbf{U}_{rel} = (\mathbf{U}_a + s_w \mathbf{u}_{ss}) - \mathbf{u}_{ss}, \quad (14)$$

where the first term on the right-hand side represents the atmospheric wind including the parameterized response to current feedback, and the second term accounts for the motion of the ocean surface. This expression can be rewritten as:

$$\mathbf{U}_{rel} = \mathbf{U}_a - (1 - s_w) \mathbf{u}_{ss}, \quad (15)$$

where $(1 - s_w) \mathbf{u}_{ss}$ represents the effective contribution of surface currents to the air-sea relative motion after accounting for the atmospheric response to current feedback.

7.2 Wind stress-correction approach

Renault, McWilliams, and Masson (2017) proposed a wind stress correction to account for current feedback when forcing numerical simulations with prescribed wind stress:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_0 + \boldsymbol{\tau}', \quad (16)$$

where $\boldsymbol{\tau}_0$ represents the prescribed wind stress, and $\boldsymbol{\tau}'$ is the wind stress correction to account for current feedback. The wind stress correction is defined as:

$$\boldsymbol{\tau}' = s_{\tau} \mathbf{u}_{ss}, \quad (17)$$

where s_{τ} is the wind stress-related coupling coefficient.

7.3 Coupling coefficients

The current-feedback coupling coefficients s_w and s_{τ} are diagnosed from the CF simulation following Renault, Molemaker, McWilliams, et al. (2016) and Renault, McWilliams, and Masson (2017). They are defined as the slopes of the linear regressions between surface current vorticity and the corresponding wind curl and wind stress curl, respectively. To isolate the mesoscale current-feedback signal, the large-scale components of surface current vorticity, wind curl, and wind stress curl are removed by applying spatial and temporal high-pass filters based on 250 km and 31-day running means, respectively. Figure 10a-b,e-f show the spatial distribution of coupling coefficients associated with both wind- and wind stress-related atmospheric responses to surface currents in CF, as well as their spatially averaged values over the different basins. In agreement with Renault, Masson, et al. (2019), the wind-related coupling coefficient exhibit predominantly positive values, since surface currents induce wind curl anomalies with the same sign as the surface current vorticity (Renault, Molemaker, McWilliams, et al., 2016). Its spatially averaged value all over the Caribbean Sea is 0.38, with the larger regional differences occurring in the Cayman Sea (13% weaker) and the Venezuelan Basin (11% stronger). Regarding the wind stress-related coupling coefficient, it exhibits predominantly negative values, since surface currents induce wind stress curl anomalies with the opposite sign to the surface current vorticity (Renault, Molemaker, McWilliams, et al., 2016). Its spatially averaged value all over the Caribbean Sea is -0.88×10^{-2} , with the larger regional differences occurring in the Cayman Sea (15% weaker) and the Colombian Basin (9.1% stronger).

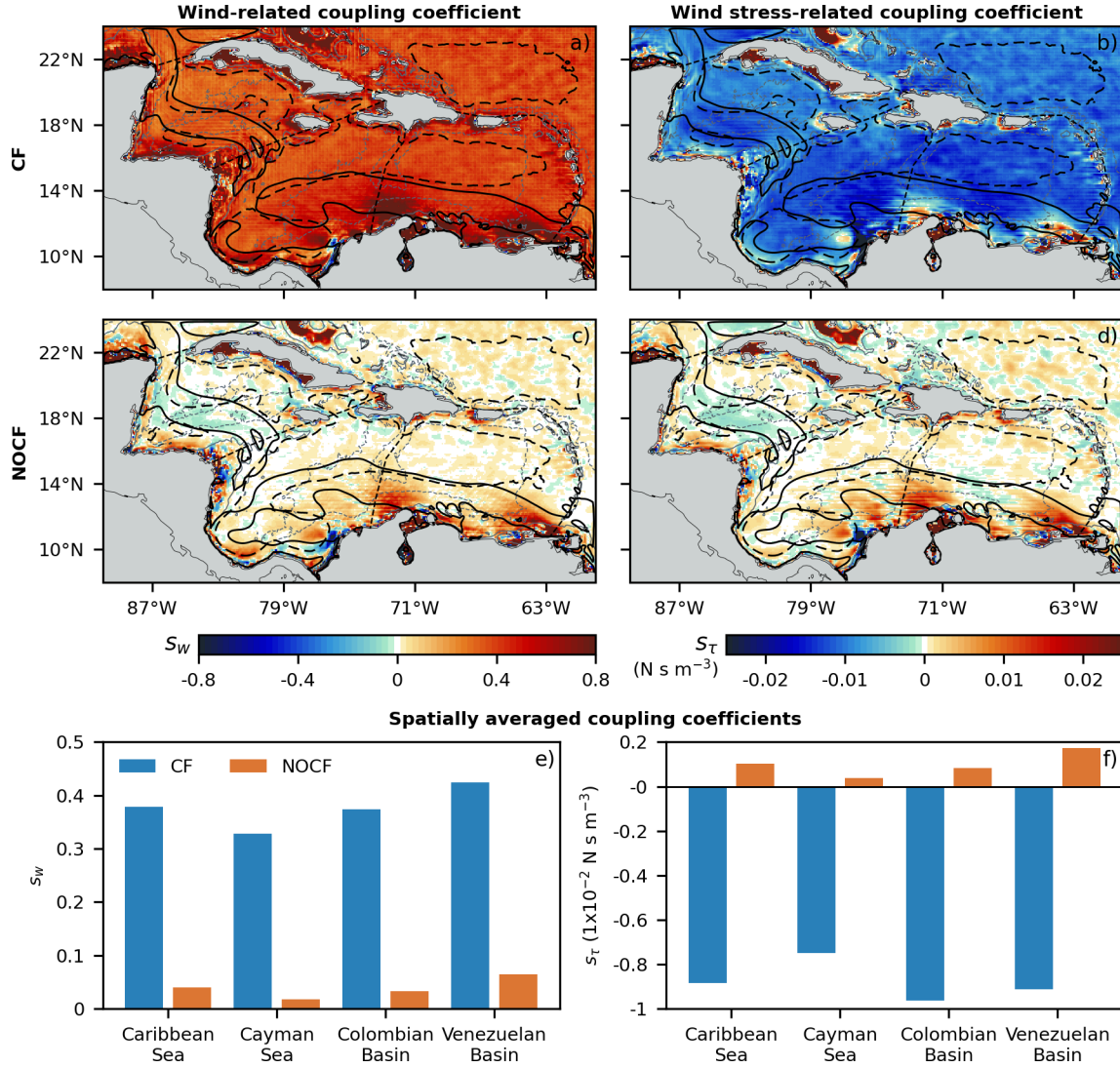


Figure 10. Spatial distribution of wind- (left column) and stress-related (right column) coupling coefficients from the CF (first row) and NOCF (second row) simulations. The thin black continuous contour, inferred from the $0.03 \text{ m}^2 \text{ s}^{-2}$ mean kinetic energy contour, depicts the mean Caribbean Current. The thin black dashed contour depicts the 10% spatial occurrence of mesoscale eddies, including both cyclonic and anticyclonic eddies (Figure 8j,k). The tick-segmented black lines delimit the Cayman Sea, Colombian Basin, and Venezuelan Basin. The continuous gray line corresponds to the 200 m isobath, whereas the dashed gray line corresponds to the 3500 m isobath. Spatially averaged coupling coefficients over the different basins are shown in the third row.

The diagnosed values of both wind- and stress-related coupling coefficients provide an estimate of the strength of current feedback over the Caribbean Sea for the present coupled configuration. However, these values should be considered a first-order estimate, since the diagnosed feedback strength depends on the ocean model configuration, such as resolution and viscosity, which influence the simulated currents and vorticity, as well as on the atmospheric forcing dataset. Therefore, sensitivity experiments using different coupling coefficient values, together with comparisons against observations, are re-

quired to determine the most appropriate values for representing current feedback in forced numerical simulations.

In addition to their application for representing current feedback in forced ocean simulations, coupling coefficients can also be used to characterize the atmospheric response associated with mesoscale ocean circulations. Since coupling coefficients are estimated from wind and wind stress curl anomalies, any air-sea interaction process that modifies these quantities may contribute to their estimation. In particular, thermal feedback associated with mesoscale sea surface temperature anomalies is known to induce wind and wind stress curl anomalies over oceanic fronts and eddies (Chelton et al., 2001; Chelton, 2004; Chelton et al., 2007). To investigate its contribution to the diagnosed coupling coefficients, we compare the wind- and wind stress-related coupling coefficients obtained from the NOCF and CF simulations (Figure 10).

In NOCF, both s_w and s_τ exhibit similar spatial distributions, with predominantly positive coupling coefficients (Figure 10c,d). In the absence of current feedback, wind stress is directly determined by the atmospheric wind through the bulk formulation, and thermal feedback-induced wind anomalies are transferred into stress anomalies with a similar spatial structure. In contrast, in the CF simulation, the stress is computed from the relative wind between the atmosphere and the ocean surface current. The interaction between surface currents, wind stress, and wind generates stress anomalies that oppose the wind response, producing the eddy-killing effect. Therefore, current feedback-induced positive wind anomalies are associated with negative wind stress anomalies, and vice versa. This opposite response between wind and stress reflects the transfer of momentum from mesoscale ocean currents to the atmosphere and explains the opposite signs between s_w and s_τ (Figure 10a,b).

Despite these differences in sign, the magnitude of the coupling coefficients in NOCF is one order of magnitude smaller than in CF. Although thermal feedback can generate strong wind and stress curl anomalies associated with mesoscale sea surface temperature gradients (Chelton et al., 2001; Chelton, 2004; Chelton et al., 2007), this response depends strongly on the orientation of sea surface temperature fronts relative to the background wind, with the strongest response occurring when fronts are perpendicular to the background wind direction. Because current feedback is directly linked to surface current vorticity and does not depend on a preferential background wind direction, thermal feedback is expected to have a weaker projection onto the vorticity-based coupling coefficients. This results in weak coefficients in NOCF and suggests a limited contribution of thermal feedback to the coefficients estimated in CF.

We next examine the differences between the wind- and stress-related coupling coefficients associated with current feedback. The spatial distribution of s_w is relatively homogeneous over the Caribbean Sea, whereas s_τ exhibits stronger spatial variability, particularly over the Colombian and Venezuelan basins, regions characterized by enhanced winds (Figure 1c). This difference can be explained by the nonlinear dependence of wind stress on the relative wind. Surface currents modify the relative wind through $\mathbf{U}_r = \mathbf{U}_a - \mathbf{u}_{ss}$, but the resulting stress response follows the nonlinear bulk formulation $\boldsymbol{\tau} = \rho_a C_D |\mathbf{U}_r| \mathbf{U}_r$. Therefore, the stress response depends not only on the current anomaly but also on the background wind speed and its orientation relative to the surface currents (Renault, McWilliams, & Masson, 2017). This additional dependence introduces stronger regional variability in s_τ compared with s_w .

Finally, relatively large positive values of s_w and s_τ are found in both CF and NOCF between the Guajira Peninsula and the Cariaco Basin (Figure 10a-d), a region characterized by strong positive mean wind curl (Figure 1d). Although large-scale atmospheric variability is removed before estimating the coupling coefficients, this regional enhancement suggests that local background conditions continue to influence the diagnosed coupling coefficients.

Overall, these results support the use of coupling coefficients relating surface current vorticity to wind and wind stress curl as a practical measure of the strength of the mechanical current feedback. However, future work should investigate how current feedback modifies the atmospheric response associated with thermal feedback, as surface currents affect both the relative wind used in momentum flux calculations and the turbulent heat fluxes involved in air-sea thermal interactions.

8 Discussion and conclusions

Long-term coupled numerical simulations were used to assess the impact of current feedback on the Caribbean Sea dynamics. In agreement with other regional studies, *e.g.*, the Gulf Stream, the Agulhas Current, the Western Mediterranean Sea, and the Gulf of Mexico (Renault, Molemaker, Gula, et al., 2016; Renault, Molemaker, McWilliams, et al., 2016; Renault, McWilliams, & Penven, 2017; Renault et al., 2021; Larrañaga et al., 2022), current feedback leads to a reduction of about 35% in eddy kinetic energy over the Caribbean Sea. This reduction is primarily associated with the sink of kinetic energy from mesoscale eddies to the atmosphere, which in turn weakens the generation of eddy kinetic energy through barotropic energy conversions. Baroclinic energy conversions were not significantly affected by current feedback.

As previously documented for the Gulf Stream, the Agulhas Current, and the Yucatan Current (Renault, Marchesiello, et al., 2019; Larrañaga et al., 2022), reduced eddy kinetic energy under current feedback is associated with stronger and narrower mean currents. A similar response occurs in the Caribbean Sea, where the mean Caribbean Current narrows and intensifies by at least 20%. The direct contribution of mean wind work does not explain this narrowing, pointing instead to the indirect effect of current feedback through reduced mesoscale activity and weaker eddy-mean flow interactions. Consistent with the weakening of mesoscale activity, current feedback reduces eddy kinetic energy by about 34% and the number of anticyclonic and cyclonic tracks by 7% and 13%, respectively, while eddy diameter, lifetime, and displacement remain largely unchanged. The limited changes in these properties are consistent with the short eddy lifetime (~ 25 days), which limits the cumulative effect of current feedback on eddy evolution (Renault, Molemaker, McWilliams, et al., 2016). In agreement with results for the Gulf Stream (Contreras et al., 2023b; Larrañaga et al., 2025), the reduction in mesoscale activity weakens eddy-mean flow interactions, reducing inverse energy fluxes by more than 50% near 150 km. As a result, current feedback indirectly narrows the mean Caribbean Current and modifies the spatial distribution of mesoscale eddies, with increased eddy occurrence in regions occupied by the broader mean current in NOCF. Overall, these results demonstrate that current feedback not only reduces oceanic mesoscale kinetic energy through air-sea energy transfer, but indirectly reorganizes the mean Caribbean circulation through weakened eddy-mean flow interactions.

A quantitative characterization of the direct atmospheric response associated with current feedback is provided by the coupling coefficients s_w and s_τ , which can also be used to include current feedback into forced ocean simulations. The present analysis uses spatial maps of coupling coefficients to quantify the regional relationship between surface current vorticity and atmospheric curl anomalies. In agreement with Renault, Masson, et al. (2019), our results suggest that thermal feedback provides only a limited contribution to the vorticity-based s_w and s_τ coupling coefficients. This occurs because the wind and stress curl responses to thermal feedback depend strongly on the orientation of sea surface temperature fronts relative to the background wind, leading to partial compensation of responses with different signs. Therefore, the diagnosed coupling coefficients primarily capture the mechanical response associated with surface current anomalies and provide a suitable framework for quantifying current feedback. As demonstrated by Renault, McWilliams, and Masson (2017), coupling coefficients mostly depend on the wind field, but their spatial distribution also reflects a contribution of local mesoscale activity per-

sistence. Therefore, regional differences in coupling strength reflect both variations in the background wind field and the spatial distribution of mesoscale activity. Regarding their magnitude, the diagnosed coupling coefficients indicate that current feedback over the Caribbean Sea is about 25% stronger than the global mean estimate of Renault et al. (2020). This stronger coupling is consistent with the persistent Trade Winds over the Caribbean Sea, which favor a stronger atmospheric response to surface current anomalies.

As in the Caribbean Sea, current feedback has also been shown to significantly influence the dynamics of the Gulf of Mexico. It directly reduces eddy kinetic energy by about 20%, while indirectly increasing the mean Loop Current penetration into the Gulf of Mexico (Larrañaga et al., 2022). The increased penetration is associated with a 15% reduction in the occurrence of the retracted Loop Current state and an increased occurrence of the canonical and extended states. This shift toward more extended Loop Current configurations results in more realistic Loop Current eddy detachment statistics, trajectories, and properties, such as kinetic energy, energy dissipation, and lifetime. However, the mechanisms by which current feedback enhances the mean Loop Current penetration remain unclear. Recent work has shown that the final separation of Loop Current eddies is associated with the formation of a large cyclonic structure, known as the cyclonic barrier eddy (Larrañaga et al., 2026), which can prevent the Loop Current from extending for several months (Zavala-Hidalgo et al., 2003, 2006). The authors also report that the formation of this structure is linked to the propagation of Caribbean cyclonic eddies into the Gulf of Mexico, in agreement with previous hypotheses associating the arrival of Caribbean cyclonic eddies with the occurrence of separation events (Athié et al., 2012; Jouanno et al., 2016; Sheinbaum et al., 2016). By reducing the energy of Caribbean cyclonic eddies and modifying their spatial distribution, current feedback could modulate their role in the formation of large cyclonic structures in the Gulf of Mexico, thus potentially influencing the variability of Loop Current penetration. Our hypothesis is supported by Le Hénaff et al. (2012), Garcia-Jove Navarro et al. (2016), and I. Ma et al. (2026), who reported that suppressing the mesoscale activity in the Cayman Sea tends to increase the mean Loop Current penetration. The current-feedback-induced shift toward more extended Loop Current states also aligns with changes in transport through the Yucatan Channel. Under current feedback, the reduced occurrence of the retracted state is accompanied by a decrease in mean transport of about 1 Sv, from 27.41 ± 3.8 Sv in NOCF to 26.6 ± 3.27 Sv in CF. This response is consistent with current-meter observations showing that Yucatan Channel transport tends to be stronger during retracted Loop Current states (Durante et al., 2026; Hirschi et al., 2019). Additionally, negative transport anomalies in the Yucatan Channel have been observed after the crossing of large anticyclonic Caribbean eddies into the Gulf of Mexico (Durante et al., 2026; Mildner et al., 2013). These anticyclonic eddies are known to reside near the Yucatan Channel for several months before crossing into the Gulf of Mexico (Jouanno et al., 2008, 2009; Andrade & Barton, 2000; Androulidakis et al., 2021; Ntaganou et al., 2023). Our results show that current feedback can modify these long-lived anticyclonic eddies in two ways: directly, by reducing their kinetic energy through the eddy-killing mechanism, and indirectly, by shifting their predominant location through the narrowing of the mean Caribbean Current. Whether these changes in anticyclonic eddies contribute to the current-feedback-induced reduction in Yucatan Channel transport remains to be determined. Overall, these results highlight the complex connections between Caribbean mesoscale activity, Yucatan Channel transport, Loop Current variability, and LCE shedding, as well as the ability of current feedback to modulate these interactions.

A discrepancy remains between modeled and observed eddy kinetic energy levels. Even after accounting for current feedback, simulated eddy kinetic energy estimates remain about 50% higher than those derived from altimetric observations. This discrepancy is consistent with known limitations of gridded altimetric products such as CMEMS, where objective interpolation smooths sea surface height gradients and leads to an un-

derestimation of mesoscale kinetic energy (Pujol et al., 2016; Ballarotta et al., 2019; Taburet et al., 2019), as we demonstrated by comparing eddy kinetic energy estimation from altimeters with altimeter-like estimations from the CF simulation. The higher spatial resolution of the SWOT mission was expected to reveal sharper gradients and more energetic mesoscale structures (Morrow et al., 2019), further supporting this interpretation. This expected improvement is supported by Larrañaga et al. (2026), who superimposed SWOT sea level anomalies onto CMEMS maps over the Cayman Sea. These findings highlight the need for a systematic quantification of CMEMS underestimation, including its scale dependence and regional variability, to improve the consistency between modeled and observed mesoscale kinetic energy estimates in the Caribbean Sea.

Finally, previous studies have shown that the magnitude of mechanical air-sea energy fluxes and associated coupling coefficients differ between coupled numerical simulations and satellite-based estimates, although their spatial patterns and signs are generally consistent (Renault, Molemaker, Gula, et al., 2016; Renault, McWilliams, & Masson, 2017; Renault, Masson, et al., 2019). These differences can be associated with model uncertainties but also with limitations in the available observations. As discussed above, gridded altimetric products underestimate surface current variability because of the spatial and temporal smoothing introduced during mapping. In addition, surface currents and wind stress are currently inferred from independent satellite observing systems operating at different spatial and temporal resolutions (Chelton et al., 2011a; Arbic et al., 2013; Renault, McWilliams, & Masson, 2017; Archer et al., 2020; Torres et al., 2023; Larrañaga et al., 2025). Consequently, current and stress cannot be simultaneously observed at comparable scales, limiting the accurate quantification of mechanical air-sea energy fluxes. Future satellite missions capable of simultaneously measuring surface currents and surface stress at comparable spatial and temporal scales will be essential to better quantify current feedback and improve the evaluation of coupled numerical simulations. Observing concepts based on simultaneous high-resolution measurements of surface currents and winds, such as ODYSEA (Ocean DYNAMics and Surface Exchange; Rodríguez et al., 2019; Wineteer et al., 2020; Torres et al., 2023; Larrañaga et al., 2025), illustrate the type of observations needed to reduce uncertainties in mechanical air-sea energy fluxes.

Open Research Section

The data used to reproduce the figures in this study are available on Figshare (Larrañaga, 2026), and the scripts used to generate the figures are available on Zenodo (Larrañaga, 2026).

The satellite altimetry observations are available from the Copernicus Marine Service as described in Section 2.

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Conflict of Interest

The authors declare there are no conflicts of interest for this manuscript.

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