

Geophysical Research Letters[®]



RESEARCH LETTER

10.1029/2025GL119040

Key Points:

- A salinity variance framework is developed to study the balance governing global and regional ocean salinity distributions
- Large-scale seasonal cycle advection at low latitudes plays an important role in the global budget by mixing long-term mean salinity
- Locally, freshwater forcing and mixing do not occur in the same regions; both are balanced by advection

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Hochet, A., Sévellec, F., & Kolodziejczyk, N. (2026). The role of large-scale seasonal cycle advection in maintaining the mean ocean salinity distribution. *Geophysical Research Letters*, 53, e2025GL119040. <https://doi.org/10.1029/2025GL119040>

Received 25 AUG 2025

Accepted 17 FEB 2026

The Role of Large-Scale Seasonal Cycle Advection in Maintaining the Mean Ocean Salinity Distribution

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Abstract Anthropogenic climate change is projected to intensify the global hydrological cycle, posing substantial risks to human societies. However, monitoring these changes through direct observations remains challenging, particularly over the oceans. Since long-term shifts in the hydrological cycle are expected to alter ocean salinity distribution, understanding the processes governing its evolution is essential. Salinity distribution is known to result from a balance between freshwater fluxes, which broaden the distribution, and mixing processes, which narrow it. Using a novel diagnostic based on the mean salinity variance budget applied to the Estimating the Circulation and Climate of the Ocean (ECCO), we estimate that the large-scale salinity flux—primarily driven by the seasonal cycle—contributes approximately 23% to this mixing. Our framework also enables us to understand the regional balances, and to identify the regions where these balances are most significant. Our results suggest that accurately representing the seasonal salinity cycle in ocean and climate models is important for simulating the ocean salinity distribution.

Plain Language Summary Climate change caused by human activities is expected to intensify the Earth's water cycle, making dry regions even drier and wet regions even wetter. Since the oceans absorb most of the water cycle's changes, these shifts directly affect ocean salinity, turning it into a key indicator of water cycle transformations. Understanding how ocean salinity is distributed and changes over time is therefore essential. While freshwater fluxes (like rain evaporation and river runoff) widen the range of ocean salinity, mixing processes narrow it. By applying a new diagnostic to an ocean state estimate, we find that seasonal changes in ocean currents and salinity contribute significantly (23%) to this mixing process. This underscores the importance of accurately capturing seasonal salinity variations in both climate and ocean models to enhance our predictions of future ocean conditions.

1. Introduction

The warming of the atmosphere due to anthropogenic climate change is expected to increase the water holding capacity of the air at a rate of approximately 7% per degree Celsius of warming (Held & Soden, 2006). This intensification is projected to amplify evaporation minus precipitation patterns and worsen extreme hydrological events—such as heavy rainfall, floods, and droughts—posing significant risks to agriculture and human societies (Dai, 2011). Despite its importance, monitoring these changes remains challenging due to high uncertainties in atmospheric freshwater flux observations (Hegerl et al., 2015), particularly over the oceans—the dominant recipients of global freshwater exchange. Because the atmospheric freshwater fluxes leave a strong imprint on ocean salinity (Yu et al., 2020), numerous authors have proposed to use ocean salinity as a proxy for tracking changes in atmospheric freshwater fluxes over the ocean (Durack & Wijffels, 2010; Kerr et al., 2010; Schmitt, 2008; Yu, 2011). However, salinity is also controlled by ocean dynamics (Vinogradova & Ponte, 2013), making the study of its long-term variations a critical research focus.

Zika et al. (2015) developed a successful framework for studying the relationship between the salinity field and the hydrological cycle, which was later applied by Skliris et al. (2016, 2020). Instead of investigating the direct relationships between sea surface salinity and freshwater fluxes, the authors derived an equation describing the evolution of the ocean volume distribution as a function of salinity. The main advantage of this water mass framework approach is that the effect of ocean circulation in spatially redistributing salinity is filtered out by the volume integral: only the dia-haline terms remain. Using the water mass framework, Zika et al. (2015) have shown that the volume distribution as a function of salinity is controlled by a balance between two effects: (a) the effect of atmospheric freshwater fluxes (precipitation-evaporation) and river runoff, which acts to broaden the

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distribution by adding (removing) freshwater in low (high) salinity regions; and (b) and the effect of mixing water of different salinities, which acts to narrow the distribution by adding (removing) freshwater to high (low) salinity regions. The two effects should exactly balance each other to reach a steady state where the volume distribution as a function of salinity remains constant. In the context of climate change, the intensification of the global hydrological cycle will lead to a broadening of the volume distribution, as shown by several studies based on climate projections (Skliris et al., 2016, 2020). However, the rate of this broadening is also contingent on the amount of mixing, which is expected to be modified by climate change. For instance, an increase in near-surface stratification resulting from ocean warming could have a significant impact on the mixing process (Zika et al., 2018). Although this diagnostic has proved useful for understanding the global balance that controls the distribution of ocean volume across different salinity classes, a significant limitation is the lack of insight into the regional localization of the terms that control the global budget. For example, it does not provide information on the region in which the effect of atmospheric fluxes is most efficient at broadening the volume distribution. In this study, we present a new diagnostic that enables us to link the global balance to the local one and thus gain insight into the localization of each term.

When considering the mechanisms controlling salinity over climatic scales periods of decades or more, advective terms come into play due to the correlation between salinity and velocity anomalies over shorter timescales. The time average of salinity advection can be decomposed as $\overline{\mathbf{v}S} = \overline{\mathbf{v}}\overline{S} + \overline{\mathbf{v}'S'}$, where the overline represents the time average, and $\mathbf{v}'$ and S' represent the velocity and salinity anomalies, respectively. In this framework, $\overline{\mathbf{v}}\overline{S}$ is the advection of mean salinity by mean velocity and $\overline{\mathbf{v}'S'}$ is the transport due to the correlation between anomalies of salinity and velocity. In this second term, no assumption is made on the spatial scales of the variability and it therefore contains mesoscales but also smaller and larger scales. The important role of mesoscale variability in the time-mean meridional salt transport is well-documented, supported by both high-resolution numerical simulations (A.-M. Treguier et al., 2012; A. Treguier et al., 2014) and observational data (Dong et al., 2014; Melnichenko et al., 2021; Mo et al., 2024). However, the effect of large-scale variability (such as the seasonal cycle), which also transports salt due to the correlation between large-scale salinity anomalies and velocities, is less well understood. In A. Treguier et al. (2014), seasonal variability was identified as a significant contributor to meridional salt transport in the tropics. Nevertheless, little is known about its effect on the salinity volume distribution, which is the subject of this study.

This article is organized as follows: Section 2 describes the framework used to analyze the mechanisms controlling ocean salinity at global and local scales. Section 3 introduces the ECCO v4r4 ocean state estimate, on which our analysis is based. Section 4 presents the results, and Section 5 provides a discussion and conclusions.

2. Methods

2.1. Evolution Equation for the Width of the Mean Salinity Distribution

Using the conservation equations for salt and mass, the evolution of salinity is governed by the following equation:

$$\frac{\partial S}{\partial t} = -\nabla \cdot \mathbf{v}S + D + F \quad (1)$$

where S is the salinity, $\mathbf{v}$ is the 3-dimensional velocity, D is the effect of diffusion, which includes diapycnal and isopycnal components, a mixed-layer turbulence closure and simple convective adjustment, $F = S(E - P - R + SI)$ represents the effect of atmospheric ($E - P$), riverine (R) and sea ice freshwater fluxes (SI). For each field X we note $\overline{X}$ its time mean component which may slowly evolve on climatic scales and X' its time-anomaly corresponding to shorter term variability so that:

$$X = \overline{X} + X' \quad (2)$$

where $\overline{X'} = 0$. Using this notation and calculating the time mean of Equation 1 gives:

$$\frac{\partial \bar{S}}{\partial t} = -\nabla \cdot \bar{\mathbf{v}} \bar{S} - \nabla \cdot \overline{\mathbf{v}' S'} + \bar{D} + \bar{F} \quad (3)$$

The second term on the r.h.s. (i.e., $\nabla \cdot \overline{\mathbf{v}' S'}$) is due to the time correlation between velocity and salinity anomalies. In this study, we focus on the physical processes governing the width of the volume distribution as a function of long-term mean salinity. To this end, and similar to Zika et al. (2015), we define the quantity $\mathcal{W}$ and its local counterpart ω as:

$$\omega = \bar{S} - \langle \bar{S} \rangle \quad (4)$$

$$\mathcal{W} = \langle \omega^2 \rangle \quad (5)$$

Where $\langle \cdot \rangle = \frac{1}{V} \int_V \cdot dV$ is the global volume average. ω represents the local deviation of time mean salinity compared to the globally averaged time mean salinity $\langle \bar{S} \rangle$ and $\mathcal{W}$ is the global average of the squared local deviation and represents the spatial variance of $\bar{S}$. An increase in $\mathcal{W}$ indicates an increase in the width of the volume distribution of $\bar{S}$, that is, the spread of the volume distribution of mean salinity values increases. The main difference with the quantity found in Zika et al. (2015), Skliris et al. (2016), or Zika et al. (2018) is that here we consider the square of ω instead of its absolute value. As will be shown below, this equation allows for a rigorous study of the interaction between ω and the salinity time anomalies (S'), an analysis that would be difficult to perform using the absolute value framework. In particular, the framework enables us to decompose the advective terms into conversion terms between different salinity variance reservoirs using methods similar to those employed in kinetic energy budgets (e.g., Storch et al., 2012). An evolution equation for ω is easily obtained as:

$$\frac{\partial \omega}{\partial t} = \frac{\partial \bar{S}}{\partial t} \quad (6)$$

Then, computing the product between this equation and ω gives an evolution equation for ω^2 :

$$\omega \frac{\partial \omega}{\partial t} = \frac{1}{2} \frac{\partial \omega^2}{\partial t} = \omega \frac{\partial \bar{S}}{\partial t} \quad (7)$$

Inserting Equation 3 in Equation 7 gives:

$$\frac{1}{2} \frac{\partial \omega^2}{\partial t} = \underbrace{-\nabla \cdot \bar{\mathbf{v}} \omega^2 - \nabla \cdot \omega \overline{\mathbf{v}' S'} + \overline{\mathbf{v}' S'} \cdot \nabla \bar{S}}_{\omega \text{ADV}} + \omega \bar{D} + \omega \bar{F} \quad (8)$$

where we have used the identity $\omega \nabla \cdot \overline{\mathbf{v}' S'} = \nabla \cdot \omega \overline{\mathbf{v}' S'} - \overline{\mathbf{v}' S'} \cdot \nabla \bar{S}$, and the notation ωADV for the sum of all the advective terms. Then, an equation for $\mathcal{W}$ is obtained by volume averaging Equation 8, that is:

$$\frac{1}{2} \frac{\partial \mathcal{W}}{\partial t} = \left\langle \omega \frac{\partial \bar{S}}{\partial t} \right\rangle = \langle \overline{\mathbf{v}' S'} \cdot \nabla \bar{S} \rangle + \langle \omega \bar{D} \rangle + \langle \omega \bar{F} \rangle \quad (9)$$

where we have used the property that the global volume average of a flux divergence is zero in a closed basin. Thus, the evolution of $\mathcal{W}$ is controlled by the balance between three different terms. The first term on the r.h.s. of Equation 9 is the effect of salinity fluxes ($\overline{\mathbf{v}' S'}$), due to the correlation between S and $\mathbf{v}$ anomalies across mean salinity surfaces. As shown by numerous studies (e.g., Arzel et al., 2018; Colin de Verdière & Huck, 1999; Hochet et al., 2020; Sévellec et al., 2021), this term can be interpreted as a salinity variance transfer between the mean salinity variance reservoir (i.e., $\int_V \bar{S}^2 dV$) and the variable salinity reservoir (i.e., $\int_V S'^2 dV$) and the same term with an opposite sign has been identified in previous work as an important source of salinity variability in the ocean (Hochet et al., 2024, 2025). As this is a transfer term, its sole function is to redistribute salinity variance between reservoirs; essentially, if it acts as a source for the mean salinity variance, it acts as a sink for the variable salinity

reservoir, and conversely. The second term is due to parametrized diffusion and the last term is due to atmospheric fluxes, both of which have already been described in Zika et al. (2015) albeit in a different form. Previous work has shown that the atmospheric freshwater flux term acts to increase $\mathcal{W}$ (i.e., it is positive in Equation 9), while the term associated with diffusion acts in the opposite direction and decreases $\mathcal{W}$. The new term, in the global averaged Equation 9 is the first term in the r.h.s. . The sign of each of the three terms in the r.h.s. of Equation 9 determines if the term act to increase or decrease $\mathcal{W}$. In the following section we further describe how we can improve the interpretation of the advective term in Equation 9 by decomposing it into different dynamical terms.

2.2. Isolating the Effect of the Large-Scale Variability

In this work, we are interested in the impact of the large-scale variability which we define as the variability explicitly resolved by coarse resolution models such as the ocean component of current CMIP6 climate models or the ECCO v4r4 reanalysis that will be analyzed in this study. In these models, the mean horizontal resolution is around 1° and the effect of mesoscale eddies is parametrized using the Gent & McWilliams scheme (Gent & McWilliams, 1990), GM hereafter. To represent the effect of mesoscale eddies, which act to flatten isopycnals and to remove potential energy to the system, this parametrization adds a parametrized velocity ($\mathbf{v}_{\text{GM}}$) to the resolved velocity ($\mathbf{v}_{\text{resolved}}$) (e.g., Vallis, 2017), so that the velocity $\mathbf{v}$ that is used to advect tracers is:

$$\mathbf{v} = \mathbf{v}_{\text{GM}} + \mathbf{v}_{\text{resolved}} \quad (10)$$

Using this decomposition, it is therefore possible to decompose the effect of explicitly resolved large-scale variability and the effect of parametrized mesoscale eddies. We further decompose the resolved velocity into one part associated with interannual ($\mathbf{v}_{\text{int}}$) and another part associated with subannual-to-annual ($\mathbf{v}_{\text{sub}}$) velocities so that the first term in the r.h.s. of Equation 9 becomes:

$$\langle \mathbf{v}' \cdot \nabla \bar{S} \rangle = \underbrace{\langle \mathbf{v}'_{\text{int}} S'_{\text{int}} \cdot \nabla \bar{S} \rangle + \langle \mathbf{v}'_{\text{sub}} S'_{\text{sub}} \cdot \nabla \bar{S} \rangle}_{\langle \mathbf{v}'_{\text{resolved}} S' \cdot \nabla \bar{S} \rangle} + \langle \mathbf{v}'_{\text{GM}} S' \cdot \nabla \bar{S} \rangle \quad (11)$$

2.3. Global Versus Local Salinity Variance Budget

To identify the regional variations of the different terms composing the global budget, we compute the vertical integral of each term X of the local variance budget given by Equation 8. The global variance budget Equation 9 can be obtained from the vertical integral of each term X by computing the horizontal integral and by dividing by the volume:

$$\langle X \rangle = \frac{1}{V} \int_A \left(\int_{-H}^0 X \, dz \right) dS \quad (12)$$

where A , V , H are respectively the ocean Area, total volume and full depth. The first two terms on the right-hand side of Equation 8, which are written as a divergence of a flux, represent the salinity variance redistribution by the ocean circulation. While these terms can be important locally and impact the local balance, they vanish when considering the global, volume-averaged balance (i.e., Equation 9).

3. Model: ECCO

We use the ECCO v4r4 ocean state estimate (Forget et al., 2015) to evaluate the terms controlling mean salinity distribution and close the salinity budget over 1993–2016. This state estimate is computed using the MITgcm and constrained by an ensemble of observations via an adjoint method over the entire integration period (Heimbach et al., 2005). The methodology used by the ECCO consortium implies that there are no un-physical sources or sinks of salinity or heat, making it suitable for calculating physically sound tracer budgets. ECCO v4r4 is forced using 6-hourly ERA-Interim reanalysis fields (Dee et al., 2011) with bulk formulae of Large and Yeager (2004), and incorporates river runoff from the seasonal climatology of Fekete et al. (2002). Surface salinity relaxation is not applied, as freshwater flux corrections are integrated into the state estimation method (Forget et al., 2015). Salinity observations constraining ECCO include in situ data from CTDs, moorings, Argo floats, and gliders, as well as sea surface salinity data from NASA's Aquarius mission. The model configuration has a horizontal

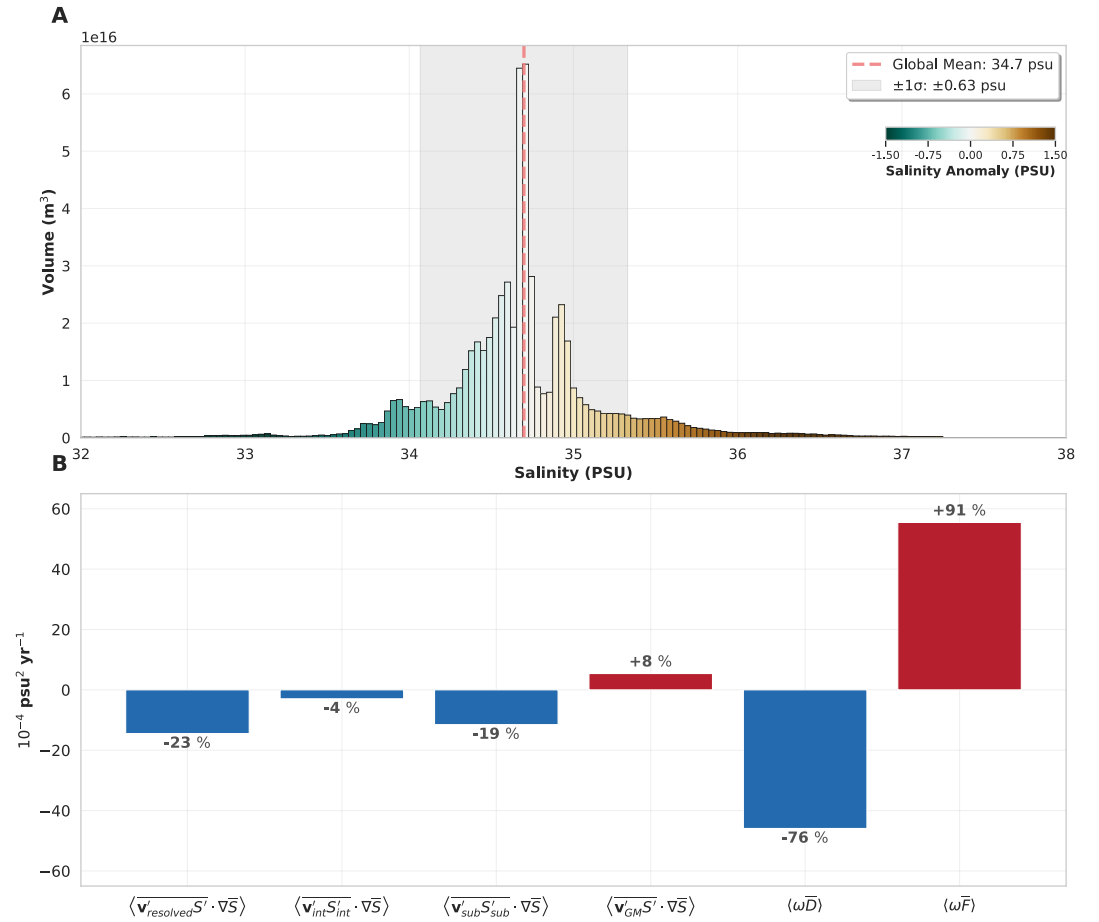


Figure 1. Panel (a) Ocean volume (m^3) distribution as a function of time mean salinity (psu) between 1993 and 2016 in ECCOv4. The dashed red line indicates the global salinity average, the color map shows the intensity of the salinity anomalies and the gray background shows plus/minus one standard deviation. Panel (b) Balance controlling the width of the distribution of mean salinity ($\mathcal{W}$) in Equation 9, units: $10^{-4} \text{ psu}^2 \text{ yr}^{-1}$. $\langle \mathbf{v}'_{resolved} S' \cdot \nabla \bar{S} \rangle$ is the total effect of the resolved variability, $\langle \mathbf{v}'_{int} S'_{int} \cdot \nabla \bar{S} \rangle$ and $\langle \mathbf{v}'_{sub} S'_{sub} \cdot \nabla \bar{S} \rangle$ are the effect of the resolved interannual and subannual-to-annual variabilities, respectively, $\langle \mathbf{v}'_{GM} S' \cdot \nabla \bar{S} \rangle$ is the effect of the GM parametrized eddies, and $\langle \omega \bar{D} \rangle$ and $\langle \omega \bar{F} \rangle$ are the effect of parametrized diffusion and freshwater fluxes forcing, respectively. Sinks and sources are represented by blue and red bars respectively. The percentage indicates the respective contribution to the total source or sink.

resolution ranging from 111 km in the tropics to 40 km at high latitudes and 50 vertical levels. Mesoscale turbulence is parameterized using the GM scheme, as it is not explicitly resolved. All salinity budget terms are computed online and output as monthly averages, except for salinity time tendencies, which are derived from snapshots at the start and end of each month.

4. Results

4.1. Global Balance of the Mean Salinity Distribution

In ECCO v4r4, the global volume mean time-averaged salinity, $\langle \bar{S} \rangle$, is 34.7 psu and the squared width of the salinity distribution, $\mathcal{W}$, is 0.14 psu^2 (Figure 1a) which is comparable to values directly obtained from the World Ocean Atlas 2023. The local maximum in volume at around 35 psu seen in Figure 1a is associated with waters located in the deep, low-to-mid-latitude Atlantic Ocean below 2,000 m. Applying Equation 9 to the ECCO v4r4 outputs allows us to identify which mechanisms control this distribution. The value of the different terms of the r. h.s. of Equation 9 are shown in Figure 1b as well as their contribution in the total source and sink of the budget. Consistent with previous studies, we find that the global effect of freshwater fluxes is to increase $\mathcal{W}$ (at a rate of $55 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$) since $\langle \omega \bar{F} \rangle > 0$. This positive value is explained by the fact that net evaporation

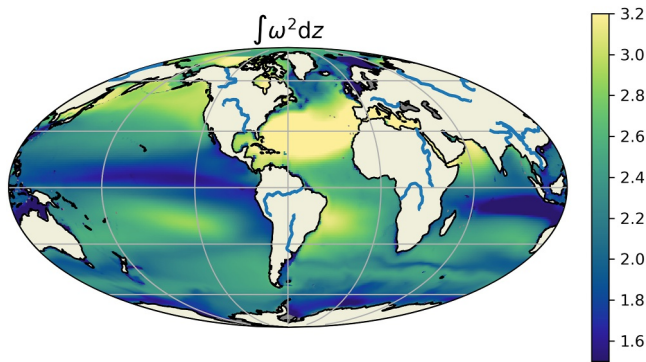


Figure 2. Vertical integral of the squared difference between the time-mean salinity and the global volume averaged time-mean salinity ($\int_{-H}^0 \omega^2 dz$ in $\text{psu}^2 \text{ m log}_{10}$ scale) in ECCO v4r4.

(precipitation) is found in regions where salinity is greater (less) than $\langle \bar{S} \rangle$. The effect of freshwater fluxes account for 91% of all sources, the origin of the remaining 9% is explained below. The freshwater flux term is noticeably larger ($\sim 4.8 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$) in areas where $\omega < 0$ compared to $\omega > 0$ (Table S1 in Supporting Information S1); this effect is compensated by diffusion. The ratio of the freshwater flux intensity ($55 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$) to $\mathcal{W}$ yields a time scale of approximately 25 years. This represents the time it would take to reach $\mathcal{W}$ if no mixing was counteracting the effect of freshwater fluxes. As expected, the diffusion term is negative (i.e., $\langle \omega \bar{D} \rangle < 0$) indicating it reduces the width of the distribution. In ECCO v4r4 the rate found for this term is of $-46 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$, accounting for 76% of all sinks. Using the decomposition of the advective term given by Equation 11, our results show that the effect of the salinity flux in the direction of the mean salinity gradient, due to the co-variance of large-scale variability of salinity and velocity, (i.e., $\langle \mathbf{v}'_{\text{resolved}} S' \cdot \nabla \bar{S} \rangle$) acts to reduce the width of the distribution at a rate of $-14.5 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$ and represents 23% of all sinks. Comparing this term

with the value obtained for the parametrized diffusion reveal that the large-scale variability represents approximately one third of the parametrized diffusion effect and is therefore an important contributor to the balance of $\mathcal{W}$. It is found that most of this term is associated with subannual-to-annual variations ($-11.5 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$, 19% of all sinks) the rest being due to interannual variations ($-3.0 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$, 4% of all sinks). We also show for the first time that the term linked to the parameterization of the eddy-induced velocities (i.e., $\langle \mathbf{v}_{\text{GM}}' S' \cdot \nabla \bar{S} \rangle$) acts to widen the distribution, at a rate of $5.4 \times 10^{-4} \text{ psu}^2 \text{ yr}^{-1}$ and is therefore non-negligible. As explained in more details in the supplementary file, this term is positive because it represents the effect of mesoscale eddies to reduce the potential energy from the system; potential energy is reduced as the center of mass is lowered, implying an upgradient flux of salinity for a stably stratified fluid. Note, that part of the effect of parameterized mesoscale eddies (the diffusive part) is contained in the parameterized diffusion (i.e., in $\langle \omega \bar{D} \rangle$) and that the eddy induced velocities do not represent the full effect of mesoscale eddies.

4.2. Local ω^2 Balance: Contributions of Advection, Diffusion, and Freshwater Fluxes

This section examines the vertical integral of the local budget for ω^2 . The largest squared deviations from the global averaged salinity are found in the North Atlantic subtropical gyre between 15°N and 45°N , in the Mediterranean, in the South Atlantic's subtropical region, in the Arabian Sea and in the Arctic Ocean's Beaufort Gyre (see Figure 2). The smallest deviations occur in the northern equatorial Pacific and southern equatorial Indian Ocean, where salinity is close to the global average (Figure 2). The budget shows that at the regional scale, advection, diffusion, and atmospheric fluxes all significantly contribute to the balance and cannot be neglected (Figure 3). The sum of the three terms—representing the change in local salinity variance over the ECCO v4r4 period—is small globally (Figure 3a). However, weak positive trends in the Mediterranean and Arctic suggest an increase in $\int \omega^2 dz$ (1993–2016), indicating a drift away from the global mean salinity. Investigating the origin of this drift (natural variability or anthropogenic forcing) is beyond the scope of our study. The term linked to the diffusion (Figure 3b) is negative almost everywhere, thus acting to reduce the local deviation from the global averaged salinity. Its largest values are found along the eastern coast of the American continent, notably in the Gulf Stream extension and the Amazon plume. Important values associated with diffusion are also found in the subtropical gyres of the North Atlantic and South Pacific. Intense vertical mixing is known to occur in these regions and is at the origin of density-compensated anomalies of salinity (Kolodziejczyk & Gaillard, 2013; Yeager & Large, 2004, 2007). The freshwater flux term (Figure 3c) is predominantly positive, increasing ω^2 almost everywhere. Its strongest effects occur in the subtropical gyres of the North and South Atlantic, the South Pacific, the Mediterranean Sea, and the Arabian Sea. This term combines contributions from evaporation, precipitation, and river runoff, which vary in sign depending on location (Figure S1 in Supporting Information S1). For example, in the subtropical North Atlantic—where $\int \omega^2 dz$ is high (Figure 2) and local salinity exceeds the global average—evaporation enhances ω^2 , while precipitation reduces it. Conversely, in the Arctic Ocean, where salinity is below the global average, evaporation acts as a sink and precipitation as a source of ω^2 . The advective effect (Figure 3d) varies spatially, being positive or negative depending on location. This term is primarily driven

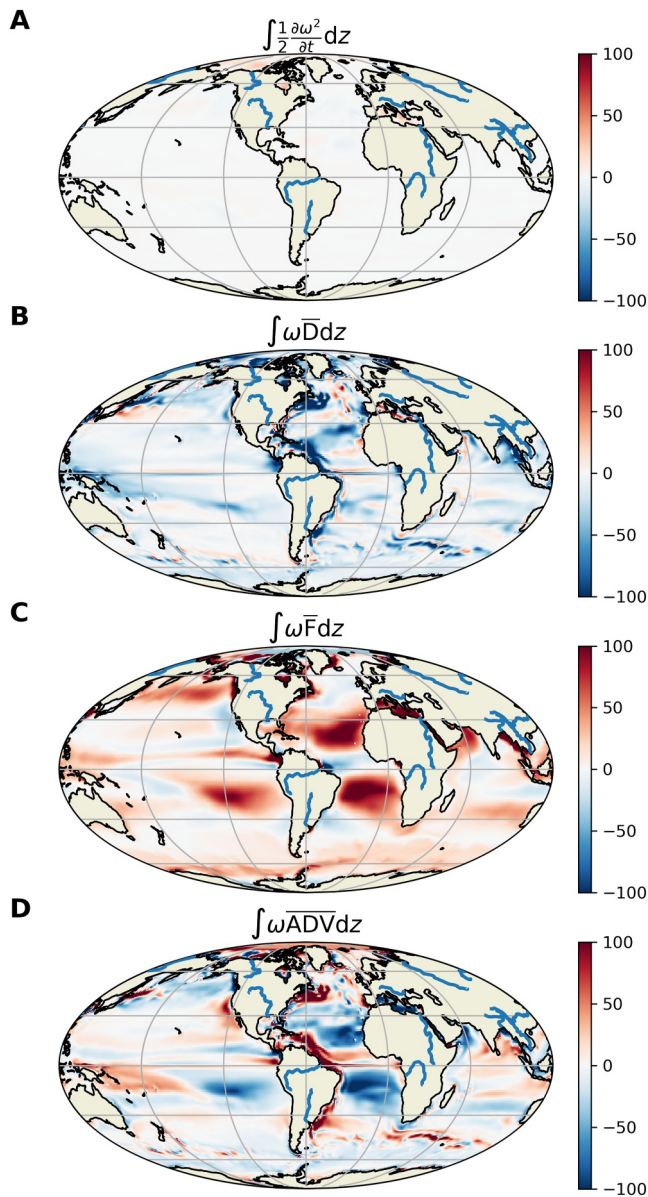


Figure 3. Vertical integral of the local budget for ω^2 (units: $\text{psu}^2 \text{ m yr}^{-1}$). Panel (a) time tendency of the vertically integrated ω^2 over the ECCO v4r4 period, panel (b) effect of the parametrized diffusive terms, panel (c) effect of the atmospheric freshwater fluxes, panel (d) effect of the advective terms.

by the redistribution of salinity variance through ocean circulation (first two terms of Equation 8), balancing regions where freshwater fluxes increase local deviations from the global mean salinity against regions where diffusion counteracts this effect. For example, in the Atlantic, the advective term is negative in the subtropical gyres but positive along the eastern coast of the Americas (Figure 3d). A quantification of the volume-averaged contributions of the terms composing the balance for ω^2 for the IPCC AR6 regions (Iturbide et al., 2020) are presented in Figure S2 of Supporting Information S1.

4.3. Decomposition of the Local Advective Term

The effect of advection on ω^2 shown in Figure 3d is due to the sum of advective terms that act to spatially redistribute ω^2 and of different terms that represent local dia-haline transformations (see also Equation 11). The first category disappears when integrated over the whole ocean volume (as in the global budget shown in Figure 1), while the second category does not and contribute to the global balance of $\mathcal{W}$. The effect of the spatial redistribution of variance due to the circulation on ω^2 is shown in Figure 4a. The comparison with the effect of the total advective terms (Figure 3d) shows that, locally, advection is mostly due to the redistributive effect of the circulation. The effect of the salinity flux in the direction of the mean salinity gradient induced by the large-scale variability (i.e., $\overline{\mathbf{v}'_{\text{resolved}} S'} \cdot \nabla \bar{S}$) is decomposed into components linked to the interannual and subannual-to-annual frequencies in panels b and c of Figure 4, respectively. These two terms are mostly negative, that is, the large-scale salinity flux is down the mean salinity gradient, consistent with the global results obtained in the previous section, and have maximum amplitudes around $20 \text{ psu}^2 \text{ yr}^{-1} \text{ m}$. Most of the subannual-to-annual salinity flux in the direction of the mean salinity gradient ($\overline{\mathbf{v}'_{\text{sub}} S'_{\text{sub}}} \cdot \nabla \bar{S}$) occurs at low latitudes in the Pacific, Atlantic, and Indian Oceans (see Figure 4c). Furthermore, the subannual-to-annual term is largely dominated by the mean seasonal cycle (see Figure S3 in the Supporting Information S1). Given that most coupled climate models tend to overestimate the amplitude of this cycle in tropical regions (Liu et al., 2022), this bias raises important questions about their ability to accurately represent both the salinity distribution and its evolution under climate change. The strongest effect of interannual variability is seen in the western equatorial Pacific and the Beaufort Gyre in the Arctic Ocean (Figure 4d). We also show that the effect of the salinity flux induced by the parameterized eddy velocities is almost everywhere up the mean salinity gradient (Figure 4e), that is $\overline{\mathbf{v}'_{\text{GM}} S'} \cdot \nabla \bar{S}$ is positive. The largest values of this term are found at low latitudes, particularly in regions with large salinity gradients, such as those associated with large tropical river plumes. Significant values are also observed in the Arctic Ocean, particularly within the Beaufort Gyre (consistent with the description of Hochet et al., 2024).

5. Conclusion and Discussion

In this work, we developed a novel diagnostic of mean salinity variance budget to analyze the balance controlling salinity's volume distribution. Applied to ECCO v4r4, we find, in agreement with results obtained in previous studies (e.g., Zika et al., 2015), that the distribution results from a balance between the freshwater fluxes, acting to broaden the distribution, and mixing, acting to tighten the distribution. When considering long-term averages of salinity on periods relevant to climate studies, shorter term variability due to mesoscale and larger-scale variability also contribute to the balance because of the covariability between velocity and salinity anomalies. Defining large-scale by the scales that are explicitly resolved in coarse resolution ocean models such as the ECCO

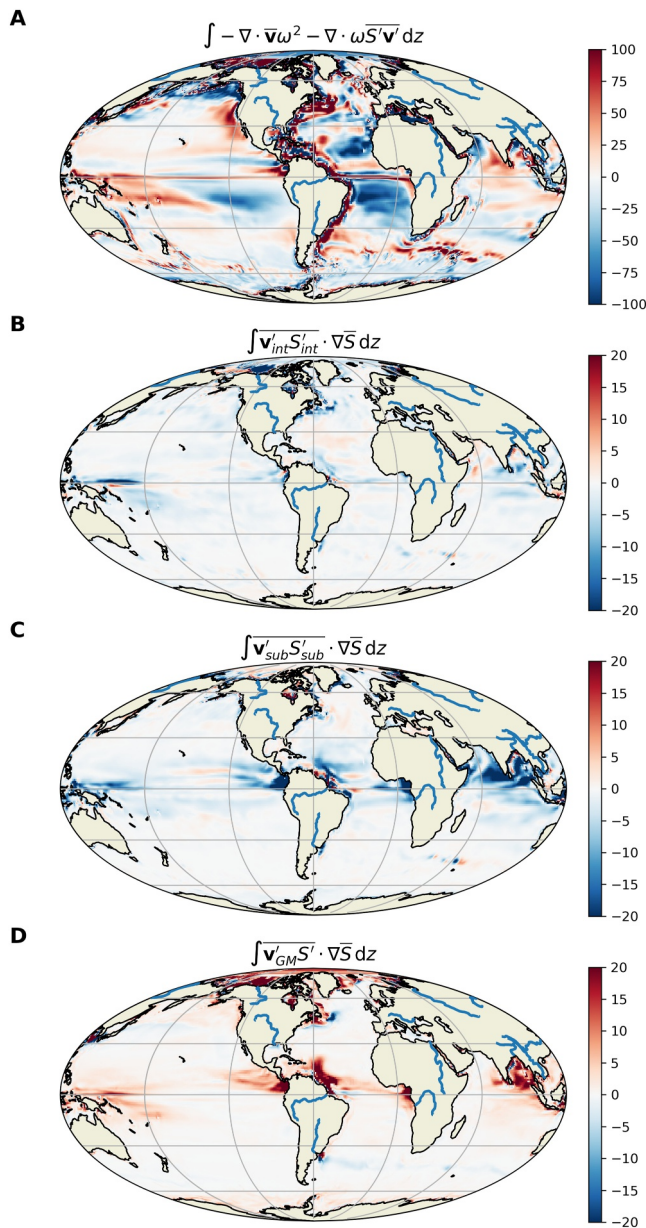


Figure 4. Vertical integral of the decomposed advective term in the local budget for ω^2 ($\text{psu}^2 \text{ m yr}^{-1}$). Panel (a): Redistributive terms that vanish in the global average. Panels (b, c): Effects of interannual and subannual salinity fluxes, respectively, in the direction of the mean salinity gradient. Panel (d): Effect of the parameterized eddy-induced salinity flux in the direction of the mean salinity gradient. Note the differing color map ranges between Panel (a) and Panels (b–d).

v4r4 configuration or current CMIP6 ocean components of climate models (i.e., $\sim 1^\circ$), we estimate that globally, this large-scale variability contributes a non-negligible 23% of the total mixing. Most of this large-scale variability is due to subannual-to-annual variability. The diagnostic also enables the investigation of the local balance controlling the variance of the local salinity deviations from the global salinity average. Using this local budget, it is found that the mixing due to the annual-to-annual large-scale variability that appears in the global balance is mostly associated to the covariability of the mean seasonal cycle of salinity and velocity at low latitudes of all oceans. This result suggests that accurately simulating seasonal salinity variations is important for correctly reproducing ocean volume distribution in salinity space (Liu et al., 2022). Locally the mean salinity deviation variance is mainly the result of a balance between the effect of freshwater fluxes, acting as a source, the diffusion, acting as a sink, and the advection, which can redistribute this variance spatially between the sources and sinks. The largest sources are located in the subtropical gyres of the North and South Atlantic and of the South Pacific, while the largest sinks are located in western margin of the Atlantic ocean, and eastern Indian Ocean, making the variance redistribution by advection key to link these regions and to maintain the balance of salinity distribution. We further demonstrate that the eddy advection associated with the Gent–McWilliams (GM) parameterization—which reduces potential energy through isopycnal flattening—acts to broaden the global salinity volume distribution, similar to the effect of atmospheric freshwater fluxes. Regionally, this term is most pronounced at low latitudes, where tropical river plumes and the Intertropical Convergence Zone (ITCZ) generate strong salinity gradients, and in the Arctic, particularly within the Beaufort Gyre, where mesoscale eddies play a critical role in gyre dynamics (Hochet et al., 2024; Manucharyan et al., 2016). While previous eddy-resolving simulations have shown that eddy-induced salt transport can produce up-gradient meridional fluxes in certain regions (Lee et al., 1997, 2007; A.-M. Treguier et al., 2012), our study is the first to identify this mechanism within the context of the global salinity variance budget. However, as our findings are based on parameterized eddy fluxes, additional research is needed to fully elucidate the role of eddy advection in modulating the seasonal salinity cycle. The primary limitation of our study is the coarse resolution of the ECCO simulation, which precludes explicit representation of mesoscale eddies. Future work should therefore focus on applying this diagnostic to eddy-resolving simulations or directly to observations. However, applying this diagnostic to eddy-resolving models presents challenges, as robust methods to isolate mesoscale eddies must first be developed.

While the ECCO state estimate optimally represents ocean circulation using available observations while maintaining dynamical consistency, uncertainties from model limitations, observational gaps, and atmospheric forcing errors may affect our results. Though quantitative uncertainty estimates in ECCO are not yet available, ongoing work by Wei et al. (2025) addresses this limitation. Future studies using similar approaches should

further quantify these uncertainties to strengthen our analysis. Given that the salinity distribution is projected to widen in response to climate change (Skliris et al., 2016, 2020; Sohail et al., 2022), the diagnostic proposed here could provide valuable insights into the regional mechanisms driving this expansion.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This study uses ECCO v4r4 which can be found here: <https://ecco-group.org/products-ECCO-V4r4.htm>.

Acknowledgments

ECCO v4r4 salinity budget computations were greatly facilitated by the existence of the `ecco_v4_py` Python library, and by several tutorials which can be found at: <https://ecco-v4-python-tutorial.readthedocs.io/>. AH, FS, and NK are supported by the VACARM, ARVOR, and OASIS project funded through the LEFE GMMC and IMAGO French program of the INSU-CNRS. AH and FS are supported by the EERIE project (Grant 101081383) funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

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