Discussion of the manuscript: https://doi.org/10.5194/egusphere-2025-3359

Title: Quantifying energy barriers associated with density stratification in vertical displacements of water parcels

Dear Professor McDougall. We appreciate the time you take to review our preprint, the detailed mathematical derivation of the buoyant force, and the pertinent comments regarding our approach. As you suggested, the analysis regarding the net force on a displaced fluid parcel was carefully revised and corrected; we provide a better contextualization of our formulation and its limitations. Also, we revised the Introduction, incorporated recent relevant literature, and clarified the objective of our study. We hope you find the corrections satisfactory and that our research contributes to the advancement of oceanographic knowledge.

Reviewer #1 Trevor J McDougall

Comment 1: This manuscript is based on an incorrect expression for the buoyant restoring force on a displaced fluid parcel. I describe what I think is the correct approach, relying heavily on Archimedes (personal communication 213BCE), and then suggest how this energy required to displace a fluid parcel can be calculated using the existing numerical algorithms in the TEOS-10 Gibbs Seawater Toolbox (McDougall and Barker, 2011).

When the manuscript is corrected so that the expression for the net buoyant force is correct at finite amplitude, is it publishable as a new contribution to oceanographic knowledge? Perhaps it is. I, for one, did not know the connection between the Cunningham geostrophic streamfunction and the energy required to move an insulated parcel through the range of pressures. This connection between gravitational potential energy and a geostrophic streamfunction was new to me and only revealed itself when carefully deriving the above results, using the key insightful result of Archimedes of Syracuse.

Answer 1: We appreciate the time you take to review our manuscript, the detailed mathematical derivation of the buoyant force, and the pertinent comments regarding our approach. We agree with you that the expression to calculate the net force is incorrect; it comes from an approximation to the force in terms of the potential density of the environment.

In the revised version of the methodology (see the attached document), we revised our calculations and corrected the expression of the force by describing the physical setting of the problem and the different approaches we took to obtain the final expression of the force (which is an approximated expression). Using real ocean profiles, we examined the accuracy of the approximated expression for the force and found that calculating the force with the potential density of the environment referenced to a fixed pressure, centered at the section of interest, is sufficient for qualitative oceanography. The integrated error (measured in terms of the mean absolute percentage error) is less than 5% for pressure variations not exceeding 2000 dbar.

From the corrected expression for the force, we were able to define the buoyancy potential energy (BPE) to estimate the energy barriers associated with density stratification in vertical displacements of water parcels. We also calculated the energy required to vertically displace an insulated water parcel using the expression for BPE and the algorithms in the TEOS-10 toolbox suggested by you, considering real ocean profiles. As with the force, the integrated error at each depth (measured in terms of the mean absolute percentage error) is less than 5% in vertical sections with pressure variations of up to 2000 dbar.

The connection you revealed between BPE and the Cunningham geostrophic streamfunction is very interesting and worth analyzing in more detail in future work. We greatly appreciate this clever derivation, which will undoubtedly enhance our future research.

1 Introduction

The vertical variation in density in aquatic bodies (i.e., oceans, seas, freshwater bodies, and estuaries), resulting from temperature and salinity differences, constitutes their stratification, which has significant implications for the variability of weather and climate processes as it determines different dynamical, ecological, chemical, and biological processes occurring there. Stratification has a significant role on the flux of particulate organic matter from the surface to sediments (e.g., Kirillin et al., 2012; Omand et al., 2020), the vertical content of chlorophyll (e.g., Cullen, 2015; Carvalho et al., 2017; Briseño-Avena et al., 2020; Cornec et al., 2021; Zampollo et al., 2023), biological productivity (e.g., Franks, 2014; Bouman et al., 2020), the mixed layer (e.g., Sutherland et al., 2014; Gray et al., 2020; Moreles et al., 2025), the ocean-atmosphere coupling and exchanges between them (e.g., Deser et al., 2010; Groeskamp et al., 2019), barrier layers (e.g., Sprintall and Tomczak, 1992; Cronin and McPhaden, 2002), and tropical cyclone dynamics (e.g., Wang et al., 2011; Balaguru et al., 2012; Vincent et al., 2012; Yan et al., 2017).

The vertical structure of aquatic bodies in terms of their stratification and energetics has been intensively studied. Schmidt (1928) derived an equation for the stability of a lake; Idso (1973) subsequently extended that equation to account for the contribution of each lake layer to stability. Simpson et al. (1978) and Herrmann et al. (2008) proposed energy-based indexes to quantify stratification from the surface to a specific depth. Dynamic equations derived from Simpson et al.'s index are used to analyze the evolution of stratification in terms of different processes (Simpson and Bowers, 1981; Burchard and Hofmeister, 2008; de Boer et al., 2008). Using boundary-layer turbulence theory, Reichl et al. (2022) proposed the potential energy anomaly of the water column to estimate the depth to which a given energy could homogenize a layer of seawater; from this, they introduced a framework for diagnosing the ocean mixed layer depth. The potential energy anomaly provides a proxy for the stratification of a layer of seawater by estimating its energetic distance from a well-mixed state. From energetic foundations, Rosenthal and Roquet (2025) developed an index of stratification strength for the global ocean using the height anomaly, defined as the height of the ocean's center of mass relative to the height of a fully-mixed state. The lower the center of mass, the larger the stratification, and vice versa. They also developed a tendency equation for the budget of the height anomaly, which helps identify the overall contribution of different processes to the stratification. Moreles et al. (2025) proposed the buoyancy work required to displace a water parcel vertically as a proxy for the vertical homogeneity of the water column: the lower the work, the greater the vertical homogeneity of the water column, and vice versa. From this, they defined the ocean mixed layer and computed a global monthly climatology of its depth that maintains quasi-homogeneity in energy, density, and temperature along the mixed layer year-round.

Stratification determines mixing, which is commonly associated with the interchange of properties between deep and shallow waters. This vertical interchange of properties is typically linked to the vertical displacement of water parcels, which carry their properties from one isopycnal to another. The vertical movement of a water parcel is, to a certain extent, determined by the density stratification experienced by the water parcel when it displaces upward and downward; the more stratified the water column, the more energy is required to displace the water parcel vertically, and vice versa. What are the characteristics of the energy barriers associated with density stratification in vertical displacements of water parcels? The above is particularly relevant when studying processes (physical, ecological, chemical, or biological) that occur in the subsurface or at a distance from the surface, where the direction of vertical movement of water parcels is relevant. For any intermediate section in the water column, the energy barriers within it depend on the direction (upward or downward) in which they are measured: the barriers experienced by a deep-water parcel when it displaces upward differ from those experienced by a shallow-water parcel when it displaces downward.

The above question has not been addressed in previous studies; thus, our objective is to estimate the energy barriers associated with density stratification in vertical displacements of water parcels. For a water parcel at any depth within the water column, we estimate the energy barriers it would encounter if vertically displaced upward or downward. The magnitude of the energy barriers to vertical displacement of a water parcel can serve as a proxy for the intensity of stratification it experiences along its vertical displacement; the greater the barriers, the more stratified the water column, and vice versa. By focusing on the direction of a water parcel's vertical displacement, we can analyze stratification in terms of the direction of quantification, thus enhancing the analyses of stratification in aquatic bodies. The metric used to estimate energy barriers is presented in Section 2, followed by its application to dynamical and ecological contexts in Section 3, which demonstrates its potential for enriching ocean analyses.

2 Estimating energy barriers

To analyze the energy barriers, we quantified the buoyancy energy required for a water parcel in equilibrium to be displaced upward and downward. Given a vertical density stratification, we first derive an expression to estimate the force F on a water parcel, initially at rest, if it were displaced vertically (upward or downward) from its equilibrium position. If the force is conservative (it is path-independent), we can use classical mechanics arguments to obtain a potential function V from which the force F can be derived (Goldstein, 1980, p. 4),

$$\vec{F} = -\nabla V. \tag{1}$$

The potential function V is the buoyancy energy and is a function of the vertical coordinate. It represents the energy barriers a water parcel would encounter along its vertical movement.

The physical setting of the problem involves a fluid in hydrostatic balance in a constant gravitational field, where rotation effects, horizontal motion, and friction are neglected. This physical setting is typically used when analyzing the oscillation of a fluid perturbed away from its resting state, and the Brunt-Väisälä frequency is derived. For our derivation, we will start from the expression for the net force; for a detailed description of this physical setting and the derivation of the net force, see sections 2.9.1 and 2.9.2 of Vallis (2006) and McDougall (2025). A water parcel at its equilibrium position z_{eq} that is slowly vertically displaced from that level to any depth z, without exchanging either mass or heat with the surroundings, experiences a net force per unit volume given by (Vallis, 2006, p. 92),

$$F(z) = g\left[\hat{\rho}(z) - \rho(z)\right], \tag{2}$$

where g is the acceleration due to gravity, $\hat{\rho}$ is the in-situ density of the environment, and ρ is the in-situ density of the parcel.

Since the parcel is undergoing adiabatic conditions during the displacement, the net force (Eq. 2) can be expressed as a function of pressure P as (McDougall, 2025),

$$g\left\{\hat{\rho}\left[S(P), \Theta(P), P\right] - \hat{\rho}\left[S_{\mathrm{eq}}, \Theta_{\mathrm{eq}}, P\right]\right\} \qquad \text{force per unit volume,} \tag{3a}$$

$$g\left\{\frac{\hat{v}\left[S_{\mathrm{eq}}, \Theta_{\mathrm{eq}}, P\right]}{\hat{v}\left[S(P), \Theta(P), P\right]} - 1\right\} \qquad \text{force per unit mass,} \tag{3b}$$

where $\hat{v}$ is the specific volume of the environment (the reciprocal of $\hat{\rho}$) and the absolute salinity and conservative temperature of the environment have been regarded as a function of P as $S(P)$ and $\Theta(P)$, respectively. The subscript eq refers to the properties of the parcel at the equilibrium position z_{eq} or P_{eq}.

Equations (3), derived from first principles, represent the accurate expressions to calculate the net force on the water parcel when it is vertically displaced from its equilibrium position z_{eq} (or P_{eq}) to any depth z (or P) under adiabatic conditions. However, they are not easily structured to calculate the associated potential function using Eq. (1) because the force is a composite function of pressure in terms of absolute salinity and conservative temperature. To deal with this problem, we explored an approximation for the force, valid for small displacements, calculated in terms of the potential density of the environment referenced to the pressure at the level z (Vallis, 2006, p. 93),

$$F(z) \approx g\left[\rho_\theta(z) - \rho_\theta(z_{\mathrm{eq}})\right], \tag{4}$$

where ρ_θ is the locally-referenced potential density. Eq. (4) is still insufficient to calculate the associated potential function due to the potential density is not referenced to a fixed pressure, which results in that the vertical coordinate is not unique throughout the displacement. In order to calculate the associated potential function using Eq. (1), we must calculate the force with Eq. (4) but using the potential density referenced to a fixed pressure. However, the use of potential density referenced to a fixed pressure ignores the thermobaric effect, which can lead to significant errors for large vertical displacements of the water parcel (McDougall, 1987a,b). Thus, it is necessary to examine whether this approximation of the force is accurate enough to replace the accurate expression (Eqs. 3), at least for qualitative oceanography.

We selected three Argo profiles (first column of Fig. 1), exhibiting different stratification conditions, to analyze the differences between various versions of the force: (*i*) the accurate expression given by Eq. (3b) and the approximate expressions given by Eq. (4), considering (*ii*) the locally-referenced potential density and (*iii*) the potential density referenced to a fixed pressure. For each profile, we calculated the forces at various depths, considering that the equilibrium position P_{eq} of the water parcel is at the isothermal layer depth, defined as the depth at which the conservative temperature has decreased by 0.2°C from the temperature at a depth of 10 m (de Boyer Montégut et al., 2004). Then, we calculated the differences between the approximate forces and the accurate force. Finally, we calculated the mean absolute percentage error (MAPE) between each approximate force and the accurate one at various depths; from P_{eq}, we selected a vertical section that increased in length (both upward and downward) to calculate the MAPE. We used the Thermodynamic Equation of SeaWater 2010 (McDougall and Barker, 2011) to calculate the different variables in the equations of interest.

A visual inspection of the results shows that the calculated force is very similar across all versions (second column of Fig. 1). At each depth, the differences between the approximate forces with respect to the exact force are three orders of magnitude smaller if the locally-referenced potential density is used and one order of magnitude smaller if the potential density is referenced to a fixed pressure (third column of Fig. 1). The differences at P_{eq} are zero and they increase for depths far from P_{eq} and far from the reference pressure used to calculate the potential density. However, since we are interested in integrated measures, the MAPE at various depths is a better measure to quantify the error of the approximate forces (fourth column of Fig. 1). The force calculated with Eq. (4) using the locally-referenced potential density is nearly the same as the accurate one, with MAPE of less than 1% throughout the vertical. The MAPE can be very large when using the potential density referenced to a fixed pressure far from P_{eq}, even if the vertical displacements of the parcel are small; the MAPE can reach up to 30% when the differences between P_{eq} and the reference pressure exceed 1500 dbar. When using Eq. (4) with the potential density referenced to P_{eq}, the MAPE values are less than 5% throughout the vertical (with pressure variations of up to 2000 dbar).

Using inductive reasoning, we assume that the above results are maintained for the world ocean with pressure variations of 2000 dbar, suggesting the following. The approximate force (Eq. 4) calculated with the potential density referenced to a fixed pressure, centered in the section of interest, is sufficient for qualitative oceanography; the integrated error will presumably be less than 5% for pressure variations not exceeding 2000 dbar. This suggestion is in agreement with the findings of Lynn and Reid (1968) and Reid and Lynn (1971), who observed that if the vertical section of interest does not exceed pressure variations of about 1000 dbar, the stability of the water column is adequately described with the potential den-

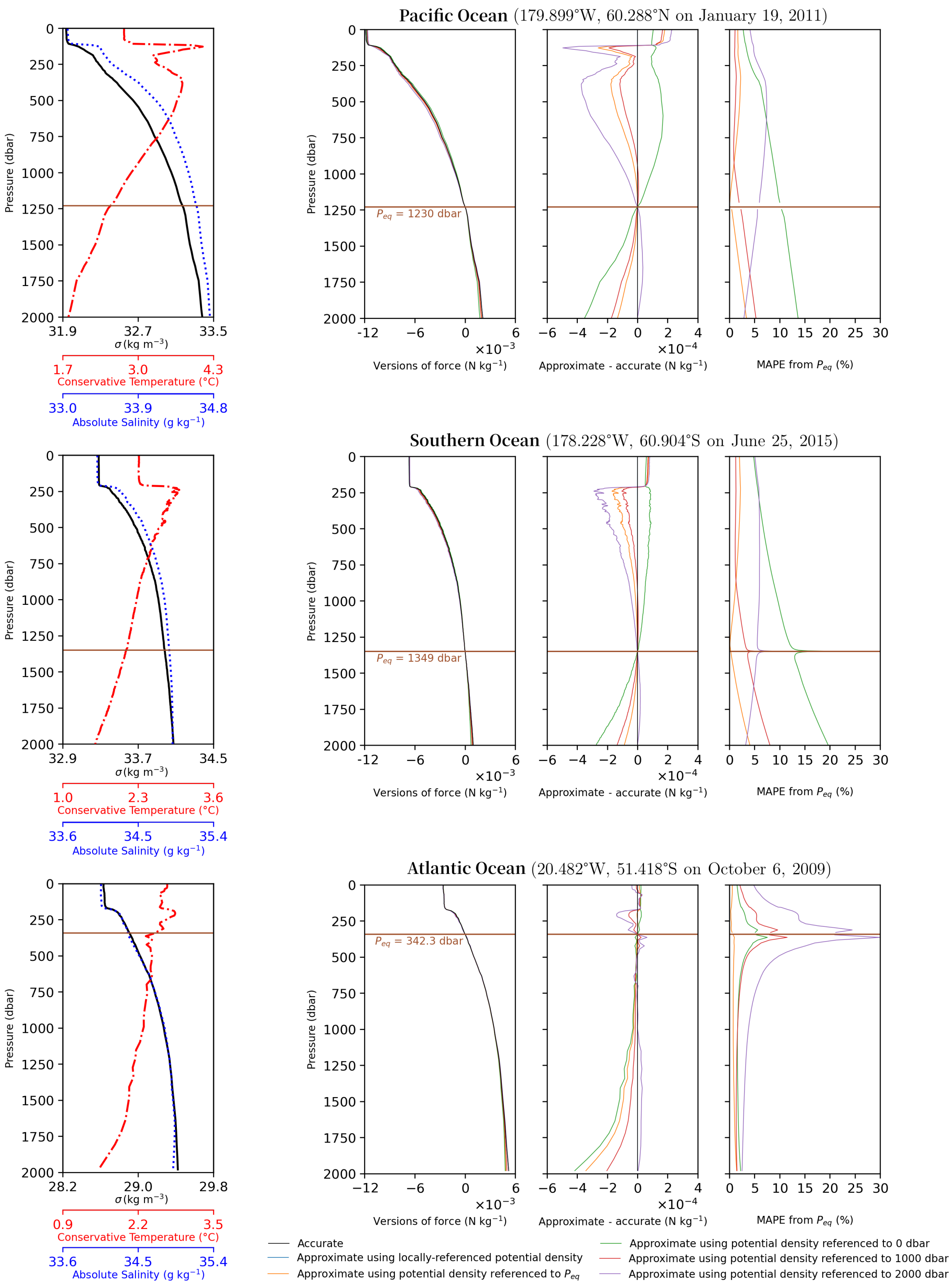

Figure 1: **First column:** ocean profiles in the Pacific, Southern, and Atlantic Oceans; the profiles of potential density anomaly σ are referenced to P_{eq}. **Second column:** accurate net force and approximations to it calculated with different versions of potential density. **Third column:** differences between the approximate forces and the accurate force. **Fourth column:** the MAPE of each approximate force at various depths, calculated from P_{eq}.

sity referenced to a pressure centered in the section of interest. Despite the high accuracy expected when using Eq. (4), we can always calculate the accurate force via Eqs. (3) and quantify the integrated error associated with using the approximate expression.

The above justify using the approximate expression (Eq. 4) to calculate the net force on the water parcel when it is vertically displaced from its equilibrium position z_{eq} to any depth z. Since we are using the potential density referenced to a fixed pressure, the vertical coordinate is unique throughout the displacement and we can calculate the potential energy function associated with the net buoyant force, the buoyancy potential energy (BPE), using Eq. (1),

$$F(z) = -\frac{\mathrm{d}}{\mathrm{d}z}\mathrm{BPE}(z). \tag{5}$$

BPE is obtained by vertically integrating the force in Eq. (4),

$$\mathrm{BPE}(z) = \mathrm{BPE}(z_{eq}) - \int_{z_{eq}}^{z} g\left[\rho_\theta(\gamma) - \rho_\theta(z_{eq})\right]\mathrm{d}\gamma = \mathrm{BPE}(z_{eq}) + g(z - z_{eq})\rho_\theta(z_{eq}) - g\int_{z_{eq}}^{z}\rho_\theta(\gamma)\mathrm{d}\gamma, \tag{6}$$

where ρ_θ is the potential density of the environment referenced to a fixed pressure, centered in the section of interest. When working with potentials, the physically relevant quantity is the potential difference between two depths; thus, we can set $\mathrm{BPE}(z_{eq}) = 0$ without loss of generality. BPE represents the energy barriers a water parcel would encounter if it were displaced from its equilibrium position z_{eq} to any depth z. The work done by the net buoyant force in displacing a water parcel from z_1 to z_2 is $\mathrm{BPE}(z_1) - \mathrm{BPE}(z_2)$. BPE is directly related to the work done by buoyancy proposed by Moreles et al. (2025); thus, all the properties and attributes of the work done by buoyancy are directly applicable to BPE.

The expression given by Eq. (6) is an approximate expression for the total energy required to slowly move an insulated parcel of fluid from its equilibrium location to any final location. The accurate expression is given by vertically integrating the force in Eqs. (3), as shown by McDougall (2025) in his Eqs. (3) and (4). Through a meticulous and detailed review of this preprint, McDougall (2025) identified a connection between BPE and the Cunningham geostrophic streamfunction, a novel result. He then proposed a way to calculate this energy using the TEOS-10 Toolbox (see his Eq. 5). We computed the energy for each profile shown in Fig. 1 using BPE (Eq. 6) and Eq. 5 of McDougall (2025) (plots not shown). Similar to what we found in the force analysis, the differences in the energy values at each depth obtained with these two expressions are minimal (the MAPE between them is less than 5% throughout the vertical), suggesting that BE is accurate enough for calculating the energy in vertical sections not exceeding pressure variations of 2000 dbar. Again, we can always calculate the energy using the accurate expression and quantify the integrated error associated with using the approximate expression.

Our approach provides a physically derived, approximated, and intuitive variable (i.e.,

BPE) to estimate the energy barriers associated with density stratification in vertical displacements of water parcels, which is accurate enough for qualitative oceanography. Depending on the sign of BPE, two physical situations are identified. For BPE > 0, the force and the parcel displacement are in opposite directions, causing the parcel to decelerate when ...
... it continues as it is in the preprint from line 68.

Note: According to the new way for calculating BPE, Fig. 3 regarding the barrier layers will be adjusted to reflect the BPE calculated using the potential density referenced to a fixed pressure, centered between the mixed layer depth and the isothermal layer depth. The prior BPE and the new BPE are nearly identical; therefore, the discussion and results of the new figure are maintained as in the preprint version with this adjustment.

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