

RESEARCH LETTER

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Key Points:

- Caspian Sea is used as a virtual laboratory to investigate thermally direct ocean circulation
- Caspian Sea-averaged overturning and conversion of available to potential energy are quantified for the first time
- Overturning increases with increasing vertical mixing and coincides with stronger horizontal circulation

Supporting Information:

- Supporting Information S1

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Can the Ocean's Heat Engine Control Horizontal Circulation? Insights From the Caspian Sea

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Abstract We investigate the role of the ocean's heat engine in setting horizontal circulation using a numerical model of the Caspian Sea. The Caspian Sea can be seen as a virtual laboratory—a compromise between realistic global models that are hampered by long equilibration times and idealized basin geometry models, which are not constrained by observations. We find that increases in vertical mixing drive stronger thermally direct overturning and consequent conversion of available potential to kinetic energy. Numerical solutions with water mass structures closest to observations overturn $0.02\text{--}0.04 \times 10^6 \text{ m}^3/\text{s}$ (sverdrup) representing the first estimate of Caspian Sea overturning. Our results also suggest that the overturning is thermally forced increasing in intensity with increasing vertical diffusivity. Finally, stronger thermally direct overturning is associated with a stronger horizontal circulation in the Caspian Sea. This suggests that the ocean's heat engine can strongly impact broader horizontal circulations in the ocean.

1. Introduction

Abyssal overturning circulation controls the uptake and distribution of heat and carbon by the deep ocean and therefore significantly influences global climate on centennial time scales (e.g., Kuhlbrodt et al., 2007). The deepest branch of the abyssal overturning is fed by cold dense Antarctic bottom water, which upwells as lighter modified waters. This implies a heat engine where dense water sinks below light water and available potential energy (PE) is converted into kinetic energy (KE) (Nycander et al., 2007; Wunsch & Ferrari, 2004). Although it has received relatively little attention, thermal- and haline-driven overturning can also modify the horizontal circulation of the world ocean (Saenko et al., 2002). The relationship between a potential slow down in North Atlantic Deep Water formation and changes in European climate is a prominent example (e.g., Dixon et al., 1999).

Ocean vertical mixing has long been known to strongly influence the thermally direct overturning. In steady state, stratified vertical mixing can balance a vertical buoyancy flux due to overturning circulation (Munk, 1966; Munk & Wunsch, 1998) (although the degree to which vertical mixing is necessary to drive such a circulation is debated) (see, e.g., Hughes & Griffiths, 2008). Due to the particular dynamics of the Southern Ocean, it is challenging to isolate the roles of wind, buoyancy forcing, and eddy effects in global ocean models (Kuhlbrodt et al., 2007; Marshall & Speer, 2012). Moreover, since abyssal flows have millennial transit times, simulation is computationally prohibitive (England, 1995), especially with even partially resolved eddies. Idealized models are often employed (Nycander et al., 2007; Pedlosky & Spall, 2005) but conversely suffer from a lack of observational constraint and can give varying results depending on topographic details (Hogg & Munday, 2014).

Here we take a complementary approach and investigate the heat engine of the Caspian Sea. Located in midlatitudes (from 37 to 47°N), the Caspian Sea is the largest enclosed body of water in the world, extending to around 1,000 km (north-south) by around 600 km at its widest (west-east) and exhibiting two deep regions (800 and 1,000 m). The Caspian Sea has a strong seasonality, and contrasting behaviors are observed between the three basins. The northern region is shallow, controlled by local winds and freezes during the winter. The formation of dense water originates in the north where warm water transported along the eastern part of the Caspian Sea meets cold fresh water and sea ice. The large-scale horizontal circulation and thermohaline structure of the Caspian Sea has been thoroughly investigated (e.g., Gunduz & Özsoy, 2014; Ibrayev et al., 2010; Kitazawa & Yang, 2012; Knysh et al., 2008; Nicholls et al., 2012; Tuzhilkin & Kosarev, 2005).

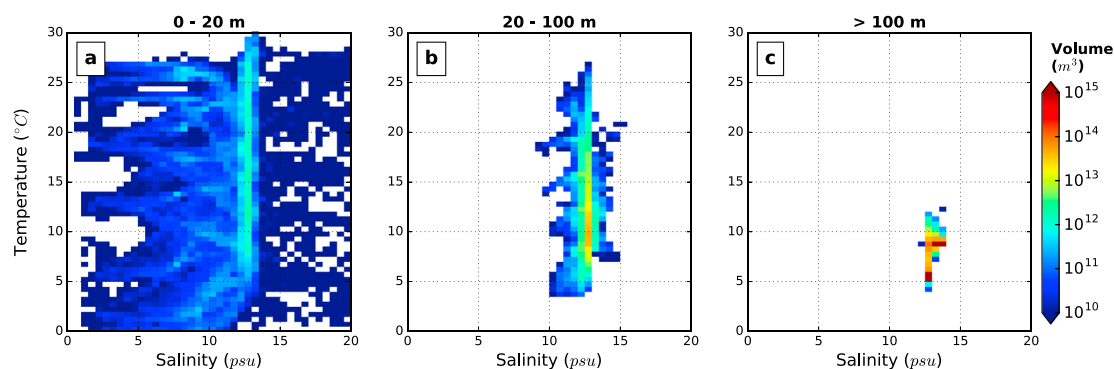


Figure 1. Mean potential temperature versus practical salinity (noted as temperature and salinity) at (a) 0–20 m, (b) 20–100 m, and (c) >100 m water depth for the control run (MEDIUM mixing experiment in Table 1). Baroclinic properties of the Caspian Sea are in agreement with the observed salinity/temperature illustrated in Tuzhilkin and Kosarev (2005).

The aim of this study is to investigate the thermally direct overturning of the Caspian Sea and its sensitivity to thermodynamic drivers such as vertical mixing. Although thermal processes are known to be key drivers of atmospheric and oceanic motions, only recently have diagnostic frameworks emerged to quantify such flows from data (Laliberté et al., 2015; Nycander et al., 2007; Pauluis & Mrowiec, 2013; Zika et al., 2012, 2015). An essential feature of such diagnostics is that the circulation is diagnosed in a coordinate, which follows fluid properties. Nycander et al. (2007) proposed projecting ocean circulation into the density-depth plane quantifying the amount of water, which is exchanged vertically at different densities. This study provides an opportunity to compare the diagnostic approach of Nycander et al. (2007) with more conventional latitude-depth and latitude-longitude perspectives using the Caspian Sea as a virtual laboratory.

2. Modeling Strategy

We employ the three-dimensional, free-surface, sigma-coordinate Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2000; Shchepetkin & McWilliams, 2005) coupled to a one-layer snow and ice thermodynamics model (Mellor & Kantha, 1989) combined with an elastic-viscous-plastic rheology (Hunke & Dukowicz, 1997). We apply the empirical treatments in the Caspian Sea ice model described in Tamura-Wicks et al. (2015). The baroclinic circulations are simulated on a 8 km resolution grid with 32 vertical levels (Bruneau & Toumi, 2016). The momentum viscosity ν_c and tracer heat diffusion K_v are computed with the generic length scale $k-\omega$ model for transport of kinetic energy (Umlauf & Burchard, 2003; Warner et al., 2005), which includes a constant background coefficient. A 40 year spin-up run at 4 km resolution forced by ERA-40 reanalysis data (Uppala et al., 2005), with spatially constant initial temperature and salinity basin-averaged profiles from the World Ocean Circulation Experiment data set and zero velocity fields is interpolated onto the 8 km grid and used as initial ocean conditions (Bruneau & Toumi, 2016; Nicholls & Toumi, 2014; Nicholls et al., 2012). The salinity of the Caspian Sea is around a third of that of the oceans. To reach an equilibrium state, the model is run with a repeated 360 day year with 12 months of 30 days and forced by the NCEP Climate Forecast System Reanalysis (Saha et al., 2010) through a bulk flux formulation (October 2006 to September 2007—averaged surface forcing are presented in supporting information Figure S1). River runoff and evaporation-precipitation are turned off to maintain water volume and salt quantity over long-term simulations. However, to model the dynamics and represent previous turned off processes (supporting information Figure S2), a strong weekly relaxation to the monthly sea surface salinity and temperature climatology is imposed in order to maintain surface water masses (from <https://www7320.nrlssc.navy.mil/caspian/>).

Figure 1 shows the relationship between potential temperature and practical salinity (noted as temperature and salinity hereafter, respectively) for our control run (see Table 1) at different levels in the water column that compares favorably with the observed thermohaline structure presented by Tuzhilkin and Kosarev (2005). The salinity remains mainly between 12 and 13 practical salinity unit (psu). While the surface temperature ranges from a few degrees up to 30°C, the deep water temperature variability is narrower (mainly 5–10°C). Fresh water intrusion (induced by sea surface temperature (SST) and sea surface salinity (SSS) relaxation) are simulated in ROMS and agree with Tuzhilkin and Kosarev (2005). We note that deep water is slightly warmer in our control run than in observations. This may be linked to restoring to an annual climatology, which may not

Table 1
Set of Experiments Based On an Initial Background Heat Diffusion $K_v = 10^{-5} \text{ m}^2/\text{s}^2$

Experiment name	Mixing scheme	Vertical mixing for tracers (m^2/s^2)	Vertical mixing for momentum (m^2/s^2)	SST and SSS relaxation
WEAK	GLS $k-\omega$	$10^{-1} K_v$	K_v	Weekly
MEDIUM (control)	GLS $k-\omega$	K_v	$10 K_v$	Weekly
STRONG	GLS $k-\omega$	$10 K_v$	$10^2 K_v$	Weekly
Extra STRONG	CONSTANT	$10^2 K_v$	$10^3 K_v$	Weekly
TRACER	GLS $k-\omega$	$10 K_v$	K_v	Weekly
WEAK-RELAX	GLS $k-\omega$	$10^{-1} K_v$	K_v	Monthly
STRONG-RELAX	GLS $k-\omega$	$10 K_v$	$10^2 K_v$	Monthly

permit the formation of the coldest dense water anomalies that would subsequently sink into the deep ocean or excessive entrainment of cold anomalies as they sink. Overall, we consider our configuration to be suitable for studying the influence of the vertical mixing on both the overturning and the horizontal circulation.

3. Experiments

To excite a range of overturning circulations in the Caspian Sea model, a set of experiments were carried out (Table 1) with different background vertical mixing rates in addition to the mixing prescribed by the generic length scale (GLS) scheme. Vertical mixing coefficients for tracers such as temperature and salinity (diffusivity) and momentum (viscosity) increase by 1 order of magnitude for each of the experiments WEAK, MEDIUM, and STRONG sequentially. An Extra STRONG experiment was run with no GLS scheme and only strong constant background mixing to assess an extreme case. The median heat diffusion profiles at the steady state are provided in supporting information Figure S3. A TRACER experiment was run to test the sensitivity to tracer vertical mixing only. Both WEAK and STRONG experiments have also been simulated with a monthly SST and SSS relaxation period for sensitivity.

Figure 2 illustrates the temporal evolution of the deep water salinity/temperature relationship until a steady state is reached. As highlighted by the dark box in Figure 2, all experiments except the Extra STRONG are in the range of the observations. Simulations with stronger mixing reach equilibrium faster as would be expected for shorter residence times and more vigorous overturning circulations. The oscillations observed in the STRONG and Extra STRONG experiments are believed to relate to warmer surface temperature in summer and colder surface temperature in winter being mixed down to deeper depths due to stronger mixing. This results in a stronger season cycle in the depth-integrated mean temperature. A similar effect likely influences the depth-integrated mean salinity. For the rest of the study, average diagnostics are computed from the last 5 years when the solution was approximately equilibrated.

4. Diagnostic Framework

Although it is conventional in global climate studies to diagnose circulation in the latitude-depth plane, recently, a number of studies have diagnosed the vertical exchanges of dense and light water directly (Laliberté et al., 2015; Nycander et al., 2007; Pauluis and Mrowiec, 2013; Zika et al., 2012, 2015). Specifically, Nycander et al. (2007) propose projecting ocean circulation into the density-depth plane. The overturning stream function, Ψ , which describes this flow, is defined at a particular depth by

$$\Psi(\sigma^*, z) = \oint_{\sigma < \sigma^*} w(x, y, z) dx dy, \quad (1)$$

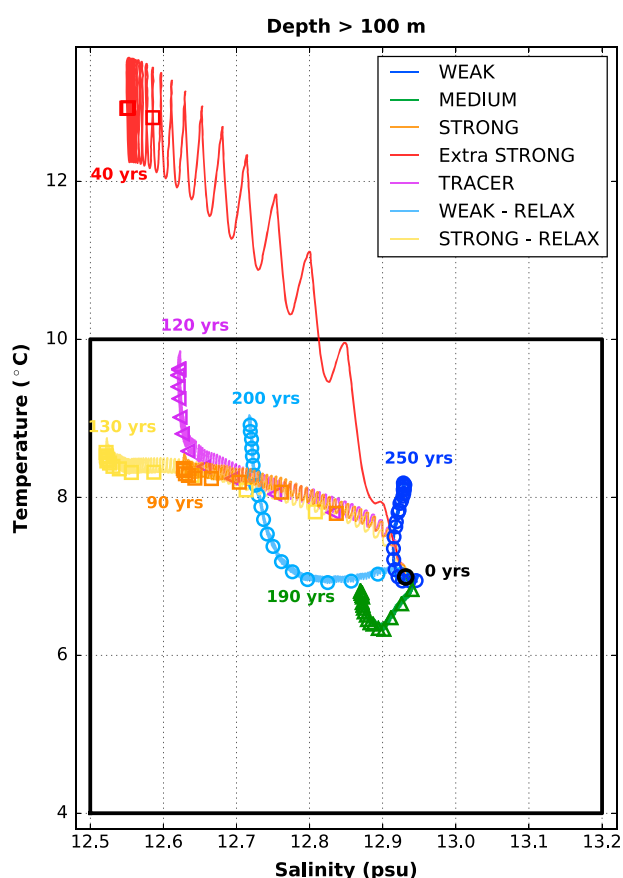


Figure 2. Temporal evolution of the relationship between deep water (>100 m water depth) salinity and temperature for each experiment. The number of years indicates the simulation time to approximately reach a steady state and each marker represents a 10 year interval. The black box represents the range of observations from Tuzhilkin and Kosarev (2005).

where σ is a density variable, w is the vertical velocity, and $\oint_{\sigma < \sigma^*} dx dy$ is the area integral over the constant depth surface where σ is less than σ^* .

In situ density varies substantially with depth so is not an appropriate coordinate to understand the vertical exchange of water parcels (Nycander et al., 2007). In order for Ψ to relate to energetic quantities, the density variable must be equivalent to in situ density at constant pressure to within a constant offset. To satisfy these two criteria, we use a density anomaly variable defined by in situ density, ρ , minus the density that a reference water parcel with a particular potential temperature θ_r and practical salinity S_r would have if taken to the same pressure (i.e., $\sigma(\theta, S, p) = \rho(\theta, S, p) - \rho(\theta_r, S_r, p)$). This density anomaly variable is analogous to and has a 1:1 mapping onto specific volume anomaly (McDougall et al., 2009).

At constant depth there is no sensitivity of the diagnosed overturning strength to the choice of reference θ_r and S_r since it is a constant offset. The main effect of the offset is to produce a diagram that is not skewed diagonally due to the pressure dependence of density (see, e.g., Figure 6a of Nycander et al., 2007). We choose $\theta_r = 7^\circ\text{C}$ and $S_r = 13.1$ psu based on mean properties of the Caspian Sea and found negligible sensitivity to changes between $S_r = 12 - 14$ psu and $\theta_r = 4 - 10^\circ\text{C}$.

Following Nycander et al. (2007), Ψ can be used to infer the conversion of available PE and work W , into KE via

$$W = -g \int \int \Psi d\sigma dz, \quad (2)$$

where g is the gravitational acceleration. Ψ and W have been computed for each experiment as well as the latitude-depth and barotropic stream functions (Ψ_o and Ψ_b , respectively) that characterize a more conventional overturning circulation and the depth-integrated horizontal circulation.

5. Results

Figure 3 shows the density anomaly versus depth stream function Ψ defined in the previous section for the WEAK and STRONG experiments. In the WEAK experiment the thermally direct overturning circulation (blue pattern) has a maximum of 0.12 sverdrup (Sv) and extends from the surface to approximately 250 m depth. Lighter water upwells, gets denser near the surface, and finally sinks around zero density anomaly. This thermally direct cell extracts PE from the stratification and converts it into KE. The STRONG experiment exhibits similar qualitative patterns to the WEAK, while quantitative aspects differ. First, the intensity of the overturning circulation is significantly enhanced in the presence of more intense mixing (reaching a maximum of 0.2 Sv). Second, the cell extends deeper down. Both behaviors are expected where an increase in the vertical mixing coefficient throughout the entire Caspian Sea would lead to increased vertical buoyancy transport to deeper depths requiring a compensating buoyancy transport by a thermally direct circulation.

We note that the intensity of the thermally indirect cell weakens slightly with increasing mixing. An opposing thermally indirect cell is present at depths shallower than 50 m (positive Ψ values). This cell is robust between the WEAK, MEDIUM, and STRONG experiments, as is a minima in the thermally direct cell between 50 m and 150 m. These two features could be linked with a thermally indirect circulation potentially stretching from -3 kg/m^3 density anomaly and 30 m depth to close to 0 kg/m^3 and 200 m depth superimposed on the dominant thermally direct cell. Winds could provide the required mechanical energy input and convective mixing could provide the required subsurface cooling to maintain such a cell. This cell is not present in the Extra STRONG experiment likely because the strong thermally direct cell overwhelms any thermally indirect effects.

The conventional latitude-depth stream function is presented in Figures 3c and 3d for the WEAK and STRONG experiments, respectively. WEAK's depth-latitude circulation has two cells, one to the south and one to the north. As is often the case in the global ocean, Lagrangian pathways, which link two regions, may be masked in Eulerian/zonally averaged coordinates creating apparently distinct overturning cells (for example, dense water flowing downward and southward at the same latitude and depth that light water flows upward and northward). Such Lagrangian pathways are typically captured when a thermodynamic or quasi-Lagrangian coordinate is used (Döös & Webb, 1994; Zika, Le Sommer et al., 2013) as is the case here. The maximum strength of the latitude-depth circulation (0.1 Sv) is substantially smaller than the maximum of the depth-density stream function (0.2 Sv). This further supports the hypothesis that substantial water mass exchanges are masked in Eulerian coordinates. Other thermally forced circulations such as the atmospheric heat engine

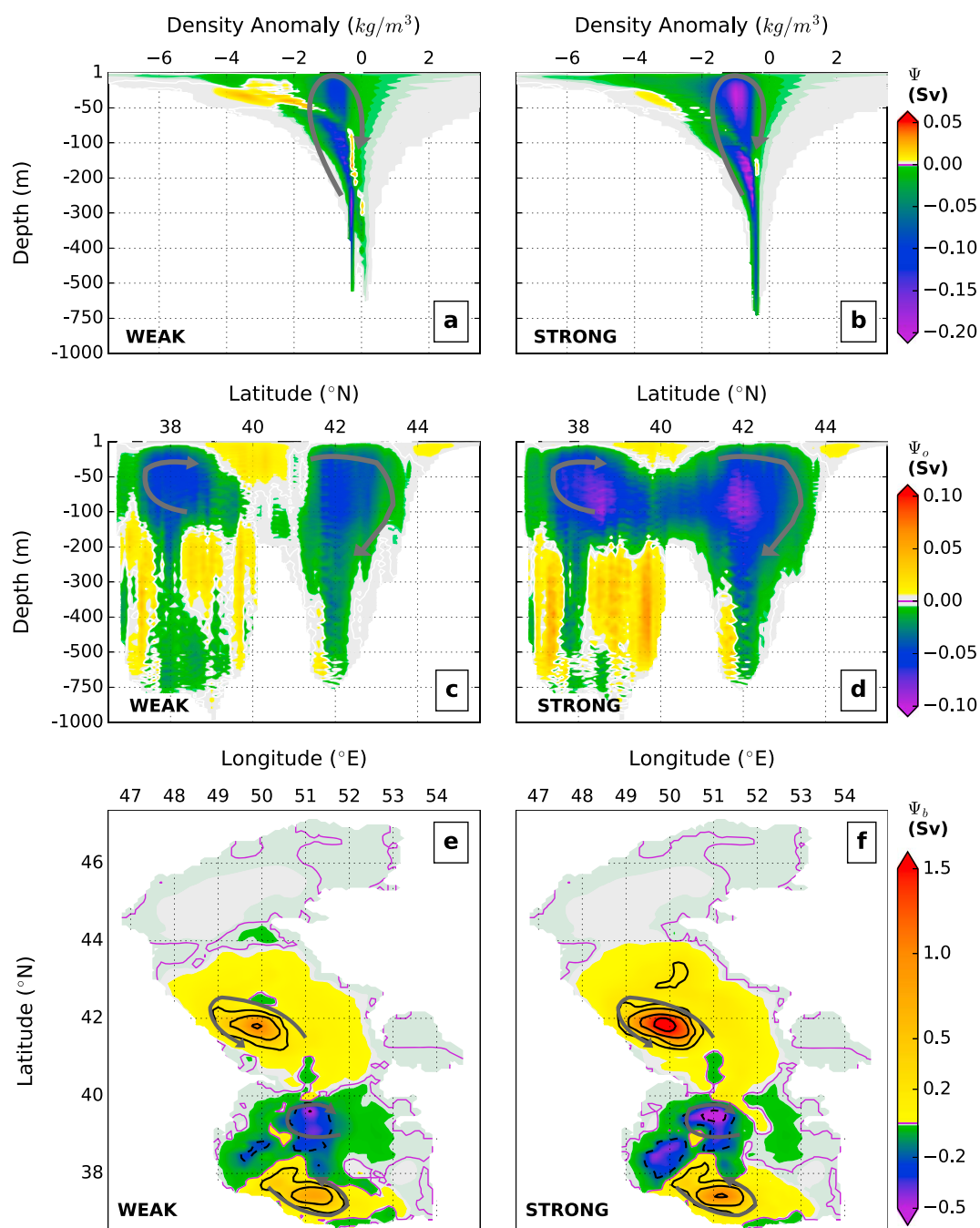


Figure 3. Characteristics of the general overturning circulation from 5 year average. (a and b) Density anomaly versus depth stream function Ψ for the WEAK and STRONG experiments, respectively. (c and d) Same as Figures 3a and 3b but for latitude versus depth stream function Ψ_o . Gray arrows represent the direction of the thermally direct circulation. Note the nonlinear depth axis. (e and f) Barotropic stream function Ψ_b for the same two experiments. Gray arrows indicate the direction of prevailing flow within the cyclonic and anticyclonic gyres.

show increasing maximum overturning when diagnosed in thermodynamic rather than Eulerian coordinates (e.g., Kjellsson et al., 2014).

While the central region exhibits a cyclonic barotropic circulation cell, two opposite circulations appear in the southern regions with an anticyclonic one in the north and a cyclonic circulation further south (Figures 3e and 3f). These circulations correspond to the gyres present in the Caspian Sea and previously reported (e.g., Bruneau and Toumi, 2016; Gunduz and Özsoy, 2014). In the WEAK experiment the barotropic cyclonic

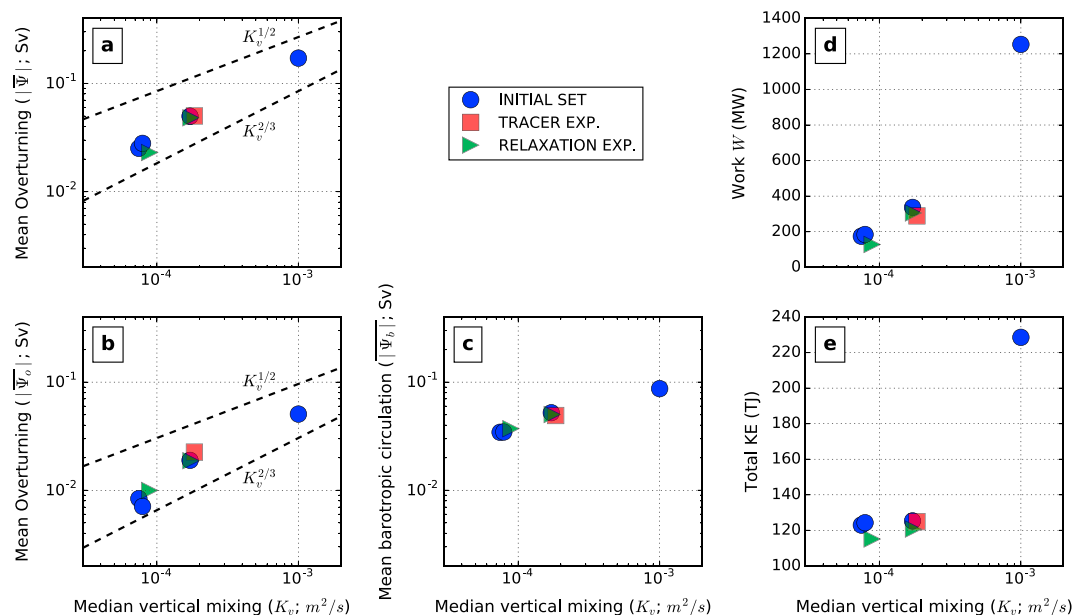


Figure 4. Five key metrics are presented for each experiment: (a) the 5 year averaged Ψ for density anomalies ranging from -2 to 0 kg m^{-3} and depths between 20 and 250 m, (b) the averaged Ψ_o for depths between 20 and 350 m, (c) the average of the absolute Ψ_b by analogy to the kinetic energy, and (d and e) the equivalent work W and the total kinetic energy for all density anomalies and depths. The red (green) squares (triangles) represent the TRACER (RELAX) experiments. The median of the *model* heat diffusion between 20 and 250 m is used here.

gyres have an average intensity of around 0.5 Sv (peak at 1 Sv) and the anticyclonic gyre of around 0.3 Sv. As for the density anomaly versus depth stream function, increasing the vertical mixing in the model (STRONG experiment) leads to an increase of the barotropic circulations with averaged intensities of around 1 and 0.5 Sv for the cyclonic and anticyclonic gyres, respectively (reaching 1.8 Sv for the northern cyclonic gyre). The locations, extensions, and patterns of these gyres are similar between the experiments. More available PE is converted in KE with increasing mixing, and therefore, we would expect the increased work done by the circulation to lead to larger energy in the variability and/or the mean circulation, in the later case leading to stronger mean ocean currents.

To assess the relationship between vertical mixing and the overturning circulation, five key diagnostics are plotted in Figure 4 for all experiments described in Table 1. Figures 4a and 4b show an increase of the density-depth- and the latitude-depth-weighted average stream functions Ψ and Ψ_o with increasing mixing, respectively. By analogy to the KE, the average of the absolute barotropic stream function (Ψ_b) is computed in Figure 4c. Likewise, an increase in the circulation is seen with increasing mixing. Ψ being related to the total conversion of available PE to KE or work (Nycander et al., 2007), increasing the vertical mixing leads to a systematic increase in the work (Figure 4d). Finally, Figure 4e shows the total KE. The extreme experiment shows the largest sensitivity to vertical mixing with only modest sensitivity in other three simulations. In the WEAK, MEDIUM, and STRONG experiments the weak changes in KE with vertical mixing might be due to two compensating effects: (i) an increase in work and (ii) a dissipation of wind-driven near-surface ocean currents due to stronger vertical viscosity reducing kinetic energy. This compensation is corroborated by a decrease in KE in the near-surface layers compensated by an increase in the deeper ocean between the WEAK and STRONG experiments (not shown).

For each diagnostic, the Extra STRONG experiment leads to extreme thermally direct overturning and barotropic circulations. The diagnostics for the TRACER experiment (change of tracer diffusivity only—red square in Figure 4) are similar to the STRONG experiment, suggesting that the key driver for the thermally direct circulations is the heat and salt diffusion and not the eddy viscosity in the momentum equations. Finally, the influence of the SST and SSS relaxation periods (RELAX experiments) is given by the green triangles and shows no significant impact.

6. Discussion and Summary

A first estimate of the Caspian Sea overturning has been established (0.02–0.04 Sv for water mass structures closest to observations), providing a maximum work output of around 150–350 MW (Figures 4a and 4d). We have investigated the relationship between the Caspian Sea's heat engine (characterized by a projection of the circulation into density anomaly versus depth coordinates) and its horizontal circulation. Enhanced vertical mixing increases subgrid vertical heat transport and drives a heat engine, which converts available PE into KE, leading to stronger horizontal circulation. This is consistent from a thermodynamic point of view (Nycander et al., 2007) and in terms of some idealized model studies (e.g., Pedlosky and Spall, 2005); however, it is the first time such an effect has been identified in a realistic modeling context that we are aware of.

Theories for the relationship between vertical mixing and abyssal overturning have been proposed, leading to predictions of the following scaling relationships: (i) a thermally forced circulation in the absence of wind forcing where $\Psi \propto K_v^{2/3}$ and (ii) with wind-driven control of the upper ocean thermocline structure where $\Psi \propto K_v^{1/2}$ (see Vallis, 2006, chap. 16). Such theories assume a constant background mixing rate and stratification. Therefore, comparison with the present simulations is complicated by state-dependent mixing due to the GLS mixing scheme. However, using the median mixing coefficient (effectively excluding extreme values where stratification is close to zero) at depths between 20 and 250 m (where the overturning is strongest), our model results are plausibly within the range of the theoretical scaling relationships (Figures 4a and 4b), closer to the $K_v^{2/3}$ scaling; however, it is sensible to the depth range chosen.

There are a number of differences between the Caspian Sea and the global ocean's abyssal overturning, three of which we highlight here. First, because of its scale difference, the ocean is far more subject to the effects of rotation such that broader aspects of global circulation may not behave analogously to the Caspian Sea. Second, the pattern of ocean surface wind stress permits the formation of currents such as the subtropical and subpolar gyres, which strongly influence the ocean's horizontal circulation and are not present in the Caspian Sea. Lastly, the ocean is zonally unbounded in the Southern Hemisphere near 56°S allowing winds to play a substantial role in driving the deep ocean through thermally indirect circulation (Toggweiler & Samuels, 1995; Zika, Sijp et al., 2013). Despite the above complicating factors, our findings have relevance to closed and marginal seas and the ocean as a whole in, so far, as their overturning circulation has a thermally direct component (e.g., Antarctic bottom water). Indeed, the ocean's heat engine may have a substantial role to play not only in vertical exchanges of heat and chemical properties but also in controlling or at least influencing the horizontal circulation that maintains regional climate.

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