Key Points:
- Basin-averaged sea surface temperatures in the Caspian and Black Seas will increase by about 2.5°C/CO2 doubling.
- Reduction of wind stress curl will lead to spin-down of main gyre systems, reaching −20%/CO2 doubling for the main Rim Current in Black Sea.
- Increased evaporation will lead to negative equivalent sea level trends of −0.1 m/year/CO2 doubling for the Caspian Sea.

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

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Plain Language Summary
The Caspian Sea and the Black Sea are the Earth's largest inland seas. How their temperature, circulation, and freshwater balance will respond to greenhouse warming remains unresolved. Previous studies have relied on coarse-resolution coupled or regional uncoupled climate models with limited abilities to resolve regional features. Here, we present results from century-long greenhouse warming simulations conducted with the Community Earth System Model using a global horizontal resolution of 1/10° in the ocean and inland seas and 1/4° in the atmosphere. In response to CO2 doubling surface temperatures in the inland seas increase by about 2.5°C. An overall reduction of wind stress curl causes a spin-down of the main gyre circulations, reaching about −20%/CO2 doubling for the Black Sea Rim Current. Increased future evaporation translates to negative equivalent sea level trends of about −0.1 m/year/CO2 doubling. The robust climate shifts presented here are likely to impact ecosystems, fisheries, and threaten existing coastal infrastructures.

1. Introduction
The Caspian Sea is the largest landlocked water body on the Earth. Five countries border the coastline of the Caspian Sea, which receives most of its freshwater input from the Volga river, which drains an extensive watershed. The Caspian Sea has an average salinity of 12.8 psu and a strong seasonal cycle in temperature and circulation (Gunduz, 2014). Given the large evaporative area of the Caspian Sea and its position in the subtropics, the overall freshwater water balance and the associated sea level can be subject to long-term climate-induced trends (Arpe et al., 2000, 2012; Arpe & Leroy, 2007; Ataei et al., 2019; Chen et al., 2017; Kislov, 2018; Ozyavas & Khan, 2012).

The Black Sea, a large semi-landlocked water body with six adjoining countries, is connected to the Mediterranean Sea through the Turkish straits. The Black Sea is a meromictic basin, which maintains anoxic conditions below 200 m, due to the lack of deep mixing. Wind stress and thermohaline forcing drive a persistent cyclonic shelf-rim current around the Black Sea as well as multi-cell interior cyclonic circulation gyres (Gunduz et al., 2020; Oguz et al., 1993, 1995; Simonov & Altman, 1991; Staney, 1990). Other key features of the Black Sea circulation include an active mesoscale eddy field (Enriquez et al., 2005; Ginzburg et al., 2002; Kubryakov & Stanichny, 2015) and quasi-stationary coastal eddies, which play an important role in the water exchange between coastal regions and the interior (Staneva et al., 2001).
Climate change effects on hydrography and circulation of these inland seas can impact coastal and marine ecosystems and fisheries (Kashkooli et al., 2017). Moreover, future freshwater imbalances over the Caspian Sea may lead to substantial changes in sea level, which in turn can threaten ecosystems, transportation, tourism, and terrestrial and marine infrastructures. Both, the Caspian Sea and the Black Sea play key geopolitical and economic roles for the bordering countries (Aydin, 2009; Celikpala, 2010; Flanagan, 2013; Kubicek, 2013). It is, therefore, paramount to determine whether the recent temperature (Ghasemifar et al., 2020; Miladinova et al., 2017; Shapiro et al., 2010) and sea level trends (Chen et al., 2017) will persist or even accelerate in response to increasing atmospheric greenhouse gas concentrations, or whether they represent phases of multi-decadal natural climate variability. Quantifying future greenhouse warming effects on both inland sea basins will provide a key context for the formulation of new multilateral adaptation strategies.

Until now, most future climate change assessments of the Caspian Sea and the Black Sea are based on coarse-resolution global climate models or regional models, which use low-resolution Coupled Model Intercomparison Project (CMIP) 3 or CMIP5 projections as boundary conditions (Arpe & Leroy, 2007; Efimov et al., 2015; Elguindi et al., 2011; Elguindi & Giorgi, 2006; 2007; Renssen et al., 2007). These modeling studies do not adequately simulate the two-way coupling between atmosphere, surface currents, and temperatures. Here, we set out to resolve this issue with a series of century-long CO2 perturbation simulations conducted with a comprehensive ultrahigh-resolution global Earth system model with an unprecedented horizontal global resolution, capable of resolving air-sea coupling, mesoscale eddies, as well as coastal and topographic features in the inland seas (see the supporting information).

2. Model Experiments

The numerical experiments are conducted with a high-resolution Community Earth System Model (Chu et al., 2020; Small et al., 2014), version 1.2.2 (CESM1.2.2). The 62-level primitive equation ocean model, Parallel Ocean Program version 2 (POP2) (Kerbyson & Jones, 2005), is fully coupled to the atmospheric model (Community Atmospheric Model 5) with a spectral element dynamical core (Dennis et al., 2012), the Community Ice Code version 4, the Community Land Model version 4 (Lawrence et al., 2011), and a river runoff model, which captures the drainage and hydrological characteristics of major river basins. The Black Sea and the Caspian Sea are simulated as part of POP2 with a horizontal resolution of 1/10°. High-resolution bathymetries are used, and there are 47 vertical levels for the maximum depth of 2,247 m in the Black Sea and 40 vertical levels for the maximum depth of 1,000 m in the Caspian Sea. Both inland water bodies are treated as fully enclosed basins. In case of the Black Sea, this assumption may lead to model biases, which need to be considered in our interpretation. The CESM is a fully coupled model, hence the exact observed sea level cannot be reproduced by the coupled model, in contrast to observation-forced atmosphere-only or ocean-only model simulations (see Supporting Information). Due to the Boussinesq approximation, the total volume and surface area of both inland seas remain constant in POP2 and freshwater forcings, that is, river runoff and precipitation are converted into a virtual salt flux. With this setup, the model can simulate realistic circulation features in both the Caspian Sea and the Black Sea, such as large-scale circulation gyres, transient eddies, temperature fronts, and mesoscale variability (Movie S1 and S2, showing the daily temperature and sea surface height distribution of model year 140 in the present-day [PD] simulation).

We conducted a 140 years PD simulation using atmospheric CO2 concentration of 367 ppm. From year 70 of the PD experiment, we branched off a CO2 doubling (734 ppm, 2 × CO2) and a CO2 quadrupling (1,468 ppm, 4 × CO2) experiments. Both simulations were run for 100 years (Chu et al., 2020). We used the last 30 years of each experiment to calculate the long-term mean climatologies. Water budgets of the two basins are calculated from rainfall and evaporation, and run-off discharge (see Supporting Information). Climatological conditions over the Caspian Sea/Black Sea area in the PD experiment are simulated in good qualitative agreement with observational and reanalysis datasets (Supporting Information, Texts S1, S2, S4, Figures. S1, S2, S3, S7, and S8).

To further isolate the primary driving forces of future circulation changes over the Black Sea, we also utilized the simplified barotropic-baroclinic interaction (BARBI) ocean model (Olbers & Eden, 2003) with one baroclinic mode and a smoothed version of the POP2 bathymetry. Climatological mean wind stress of the
last 30 years from the coupled model experiments (i.e., PD, 2 × CO2, and 4 × CO2) was used as stationary forcing to drive the BARBI model. Our analysis of the drivers of Black Sea circulation changes focuses on the barotropic transports, calculated here from the vertical integration of velocities over whole water column.

3. Results

3.1. Temperature Changes

With a climatological average sea surface temperature (SST) of 17.9 ± 1.8°C (range refers to spatial standard deviation) in the Caspian Sea (Figure 1a), the PD simulation exhibits a positive bias of 2 ± 0.8°C (range refers to spatial standard deviation of bias) relative to the satellite observations (Remote Sensing Systems, 2017) (Text S1, Figure S1). In response to CO2 doubling (quadrupling) (Figures 1b and 1c), the basin wide and seasonally near-uniform SST increase amounts to 2.5 ± 0.1°C (5.3 ± 0.2°C) (Figure 1d). Across the Caspian Sea, we see a marked meridional warming gradient. Anomalous heat fluxes and radiation can be integrated more effectively over the shallower mixed layers (∼10 m) in the northern part of the basin (Figure 1a), leading to an enhanced regional warming, relative to the central and southern basin, where mixed layers are considerably deeper (∼30–40 m). Furthermore, the model simulates an anomalous southward surface current along the northwestern coast (Figures 1b and 1c), which transports climatologically colder water toward the central basin.

The long-term average SST of the Black Sea is 17.8 ± 0.6°C in the PD experiment, about 1.9 ± 0.4°C higher than the satellite data (Remote Sensing Systems, 2017) (Text S1, Figure S1). Simulated SST over the northwestern shallow shelf is ∼1.7°C colder than in the central basin (Figure 1e). Warming is spatially and seasonally quite homogenous attaining 2.6 ± 0.1°C for the CO2 doubling experiment and 5.3 ± 0.1°C for the quadrupling, respectively (Figure 1d). Across the Caspian Sea, we see a marked meridional warming gradient.

Figure 1. Temperature changes in the Caspian Sea and the Black Sea: (a) and (e) Climatological mean of sea surface temperature (SST) in the present-day (PD) experiment, contours are the climatological mean of mixed layer depth (unit: meters). (b) and (f) SST changes (color shadings) and surface air temperature changes (white contours) between the 2 × CO2 experiment and the PD experiment. Arrows indicate surface current changes between the two experiments. (c) and (g) are the same as (b) and (f), but for changes between the 4 × CO2 experiment and the PD experiment. (d) and (h) monthly mean of SST for each experiment, that is, PD (green), 2 × CO2 (orange), and 4 × CO2 (purple), over the Caspian Sea and the Black sea, respectively. Note that data of the last 30 years in each experiment were analyzed.
3.2. Circulation Changes

The barotropic gyre circulation in the Caspian Sea has three distinct features: an anti-cyclonic circulation in the northern basin (Figure 2d), which is driven by the prevailing negative wind stress curl (Figure 2a and Figure S3), and two strong cyclonic circulations in the deep central and southern basins, which are driven by a combination of positive wind stress curl and topographic effects (Ghaffari et al., 2013; Figures 2a and 2d, Text S2, and Figure S3). Other factors that contribute to the intensification of the barotropic circulation in the deeper parts of the Caspian Sea include the so-called JEBAR effect (joint effect of baroclinicity and bottom relief) (Sarkisyan, 2006).

In the 2 × CO₂ and 4 × CO₂ experiments, barotropic circulation changes in the northern basin are very weak (Figures 2e and 2f). In contrast, changes in the central and southern basins are more pronounced, namely over the deepest basins of the Caspian Sea, which extend to about 800 m depth. In the central basin, the cyclonic gyre increases in its average magnitude by 33.4% in the 2 × CO₂ experiment and by 6.6% in the 4 × CO₂ experiment. In the southern basin, the corresponding changes amount to 4.4 and 37.4 %, respectively. Concurrently, wind stress curl decreases over most parts of the Caspian Sea (Figures 2a–2c). The nonlinear response over the central and southern gyres is likely related a combination of wind stress curl changes and shifts in stratification and topographic processes (Jamshidi, 2017).

The long-term mean barotropic circulation in the Black Sea (Figure 3d) is characterized by a dominant cyclonic circulation in the main basin. This extended gyre has been documented in both observational
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(Korotaev et al., 2003; Shapiro, 2009) and numerical modeling studies (Oguz et al., 1995). Connected to the steep topographic gradient (Oguz et al., 1995) (Figure 3d), it is often referred to as “Rim Current” (Shapiro, 2009). The cyclonic circulation is mainly driven by the positive wind stress curl in the main basin (Figure 3a). In the 2 × CO₂ experiment, the annual mean wind stress curl decreases by 17.1% and 38.7%, respectively. Correspondingly, we observe an almost linear decrease of the interior gyre circulation by 17.8% and 32.8%, respectively. To further illustrate the underlying mechanism, we apply the diagnosed wind stress curl in the CESM1.2.2 PD, 2 × CO₂ and 4 × CO₂ experiments to the simplified BARBI model for the Black Sea. Using only a single baroclinic mode, mean stationary wind forcing from CESM1.2.2 experiments and the POP2 bathymetry, BARBI successfully reproduces the main gyre circulation in the Black Sea (Figure 3g). In response to the wind stress curl changes simulated by the CESM1.2.2 CO₂ perturbation experiments, BARBI simulates a 25.8% and 50.2% decrease of the barotropic flow (Figures 3h and 3i), which is comparable in terms of magnitude and pattern to the simulated changes in the full CESM1.2.2 experiments (Figures 3e and 3f). This highlights that the projected future weakening of the barotropic flow in the Black Sea can be attributed to the changes of the mean wind patterns.

Previous studies have emphasized the importance of a cold intermediate layer (CIL) for the ventilation and circulation of the Black Sea (Miladinova et al., 2017, 2018). In POP2, this layer is absent due to the weak vertical salinity gradient, which is necessary to maintain the stratification between the CIL and the deep water (Figure S5). The CIL may, at least temporarily, act as a heat buffer to future projected warming. Future research with regional models and better salinity layering may further help to quantify the transient and equilibrium effects of this feature on the projected surface warming. Given that the future simulated changes of the barotropic circulation model are largely wind-driven, as demonstrated by the comparison between CESM1.2.2 and BARBI (Figures 3e, 3f, 3h, 3i), we expect that the CIL will only play a secondary role for future large-scale circulation changes in the Black Sea.

Figure 3. Projected future circulation changes in Black Sea: climatological mean of wind stress curl (a), barotropic streamfunction in POP2 (Sv) (d), and barotropic streamfunction in simplified barotropic-baroclinic interaction (BARBI) simplified ocean model (Sv) (g). Positive values correspond to anticyclonic circulation. Difference between the 2 × CO₂ experiment and the present-day (PD) experiment in wind stress curl (b), streamfunction in POP2 (e), streamfunction in BARBI (h). Difference between the 4 × CO₂ experiment and the PD experiment in wind stress curl (c), streamfunction in the POP2 (f), streamfunction in the BARBI (i). Gray contours in (d) and (g) represent the depth of the basin with intervals of 200 m. Note that data of the last 30 years in each experiment were analyzed.
3.3. Water Balance Changes

The Caspian Sea is a closed basin. The rate of its sea level change is controlled by the imbalance between precipitation and run-off input and evaporation (Text S4). Since precipitation in the watershed and evaporation over the inland sea are not directly coupled, long-term sea level trends are very likely to occur, even without external forcings. Satellite altimeter data reveal a substantial decrease of Caspian Sea level over the last few decades (Chen et al., 2017), which may be due to long-term natural climate variability, anthropogenic factors, or a combination of both. Over the period from 1993 to 2019, the Caspian Sea level dropped by 0.96 m (Figure 4a), which corresponds to a rate of −3.6 cm/year. These values are compatible to the PD experiment (Figure 4a), which exhibits a −5 cm/year drop of equivalent sea level for a 27 years window (Figure 4b) (for a more in depth comparison between PD experiment and ERA5 dataset [Copernicus Climate Change Service {C3S}, 2017] in precipitation, runoff, and evaporation, see Text S4, Figures S7 and S8).

Results of the 2 × CO₂ experiment and the 4 × CO₂ experiment show a more severe decrease in the Caspian Sea level in response to enhanced radiative forcing (Figure 4c). The rate of mean equivalent sea level change decreases by −8 cm/year and −20 cm/year, respectively. Applied, for instance, over a 50-year period such imbalances would translate to a drop in the Caspian Sea level of 4–10 m. Anthropogenic changes in runoff (Figure 4d) and precipitation (Figure 4e) over the Caspian Sea are insignificant. By contrast, evaporation increases substantially in the two experiments (Figure 4f), by an average rate of 15 cm/year and 30 cm/year, respectively. This can be attributed to the temperature dependence of the Bowen ratio (ratio of sensible to latent heat flux) (Wang et al., 2018), which determines how much of the available incoming energy can be used for evaporation. Our results are also qualitatively consistent with previous modeling studies (Renssen et al., 2007), which used coarser resolution climate simulations and an offline hydrological model which projected a 4.5 m sea level drop over the 21st Century.

Figure 4. Projections of equivalent sea level in the Caspian Sea: (a) annual mean sea level anomalies averaged over the Caspian Sea based on satellite altimeter data (Topex & Jason [Macmillan et al., 2004]) (from Global Reservoirs and Lakes Monitor dataset [Birkett et al., 2011]), and equivalent sea level anomalies calculated from a 27 years window of the present-day (PD) experiment using water balance equation. (b) Histogram and kernel density estimation (solid lines) of spatially averaged annual rate of sea-level changes in PD experiment and observations. (c) Histogram and kernel density estimation (solid lines) of mean basin level change rates in the three experiments. (d) Histogram and kernel density estimation (solid lines) of Caspian Sea runoff discharge rates expressed in equivalent sea level change rates over the Caspian Sea. (e) Same as (d), but for spatially averaged precipitation, (f) same as (d), but for spatially averaged evaporation. In (c)–(f), we use data of the last 70 years of PD experiment and 100 years in 2 × CO₂ and 4 × CO₂ experiments.
The Black Sea is a semi-closed basin, which connects to the Sea of Marmara through the Bosporus Strait. Its water balance includes a mass flux through the Bosporus Strait (which can be expressed in terms of an equivalent sea-level rate), the Black Sea river runoff, precipitation, and basin-wide evaporation. The Black Sea is treated as a fully enclosed basin in our POP2 model configuration. Its diagnosed freshwater imbalance can, therefore, be interpreted as an equivalent Bosporus Strait throughflow, even though the narrow topographic straits are not explicitly resolved in CESM1.2.2 (Text S4). The mass transport from the Black Sea to the Sea of Marmara through the Bosporus Strait during period 2008–2010 was estimated to be ∼116.5 ± 90.5 km³/year (Jarosz et al., 2011), which is equivalent to 28 cm/year mean sea-evel change rate. Other estimates suggest higher values of 43 cm/year (Gregg & Ozsoy, 2002) and even up to 80 cm/year (Kara et al., 2008; Nikolay and Alexander, 2020). In our PD experiment, we find a naturally occurring imbalance of 33 cm/year which is close to the two lower observational values.

In response to greenhouse warming, the mean water balance in the 2 × CO₂ experiment and the 4 × CO₂ experiment decreases substantially by 14 cm/year and 27 cm/year relative to the PD experiment (Figure 5a), though it still remains positive in the experiments. We find no clear trend in precipitation, but a decrease in runoff by 6 cm/year and 8 cm/year sea-level-equivalent in 2 × CO₂ and 4 × CO₂, respectively. As for the Caspian Sea, evaporation intensifies considerably attaining values of 43 cm/year (Gregg & Ozsoy, 2002) and even up to 80 cm/year (Kara et al., 2008; Nikolay and Alexander, 2020). In our PD experiment, we find a naturally occurring imbalance of 33 cm/year which is close to the two lower observational values.

The mass balance suggests that the increased trend in evaporation would have to be counterbalanced by an anomalous inflow from the Sea of Marmara to the Black Sea, which would have implications for the salinity exchange between the Black Sea and the Mediterranean.
4. Conclusions

In this study, we present new ultra high-resolution global model projections of temperature, circulation, and sea level changes in the Caspian Sea and the Black Sea. In response to CO₂ doubling and quadrupling, the model simulates a warming of ∼2.5°C and 5.3 ± 0.2°C in both inland seas. Strongest regional warming occurs in the coastal areas, which are characterized by shallower mixed layers. This may have implications for fisheries in these zones and overall ecosystem health and temperature-dependent oxygen levels. According to the model simulations, greenhouse warming will reduce the wind stress curl over both inland sea basins, which leads to a pronounced spin-down of the Rim Current circulation in the Black Sea, which may also influence water quality, the dispersal of larvae, and pollutants. The circulation response over the Caspian Sea is less uniform, showing a slowdown of the northern and southern gyres, but an intensification of the central gyre.

Here, we also quantify the future changes of the water balance in the Caspian Sea and the Black Sea. Consistent with previous studies (Wang et al., 2018), and as a result of a decrease of the Bowen ratio, we find an overall increase of evaporation over both basins, which causes negative trends of equivalent sea level. The projected change clearly exceeds the natural annual variability of sea-level trends and differences are significant beyond the 99% (Student’s t-test under the null hypothesis) confidence level (Figure 4c). For the Caspian Sea, the freshwater imbalance will lead to a negative sea level tendency of about 10 cm/year per CO₂ doubling. Integrated over 50 years, a corresponding 5 m drop in sea level could lead to a massive retreat of the shoreline, thus impacting existing coastal infrastructure as well as ecosystems, such as the unique wetlands of the Volga River estuary. For the Black Sea, these trends are even larger, attaining values of 14 cm/year per CO₂ doubling with some contribution also from run-off changes. The diagnosed freshwater imbalance will be compensated by a ~50% reduction per CO₂ doubling of the mean Black Sea outflow through the Bosporus Strait, using PD estimates of mean mass transport (Jarosz et al., 2011). This process is, however, not explicitly simulated by the CESM1.2.2 experiments conducted here, and its magnitude is therefore prone to uncertainties.

Our global coupled model greenhouse warming simulations, the first ones conducted so far with such a high spatial resolution for the Black Sea and Caspian Sea, document major changes to the hydrology and hydrography of the inland seas, which can impact ecosystems, fisheries, and economies of littoral states, with potential geopolitical implications.

Conflict of Interest

Authors declare no competing financial interests.

Data Availability Statement

The TOPEX/JASON (Figures 4a and 4b) data are available from https://ipad.fas.usda.gov/cropexplorer/global_reservoir. All CESM1.2.2 model simulation data are available to the scientific community and are provided through a customized data distribution service, which can be accessed after contacting the corresponding authors and filling out a specific data request form available on https://ibsclimate.org/research/ultra-high-resolution-climate-simulation-project.

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