University of Reading

The fate of the Caspian Sea under projected climate change and water extraction during the 21st century

Article

Published Version

Creative Commons: Attribution 4.0 (CC-BY)

Open Access

Koriche, S. A. ORCID: https://orcid.org/0000-0003-1285-2035, Singarayer, J. S. and Cloke, H. L. ORCID: https://orcid.org/0000-0002-1472-868X (2021) The fate of the Caspian Sea under projected climate change and water extraction during the 21st century. Environmental Research Letters, 16 (9). 094024. ISSN 1748-9326 doi: 10.1088/1748-9326/ac1af5 Available at https://centaur.reading.ac.uk/99643/

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.

To link to this article DOI: http://dx.doi.org/10.1088/1748-9326/ac1af5

Publisher: Institute of Physics

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the End User Agreement.

www.reading.ac.uk/centaur

University of Reading

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The fate of the Caspian Sea under projected climate change and water extraction during the 21st century

To cite this article: Sifan A Koriche *et al* 2021 *Environ. Res. Lett.* **16** 094024

View the article online for updates and enhancements.

You may also like

- Improving bone marrow stromal cell attachment on chitosan/hydroxyapatite scaffolds by an immobilized RGD peptide
Zhiwei Qu, Jinglong Yan, Baoqiang Li et al.
- Mechanical Properties of Coconut Shell Reinforced Unsaturated Polyester Composites with the Presence of Titanium Dioxide as Additional Filler
Nurzarihah Shahidan, Mohamad Bashree Abu Bakar, Mazlan Mohamed et al.
- Influence of Core and Shell Properties in Core-Shell Positive Electrode Materials for Li Ion Batteries
Rajalakshmi Senthil Arumugam, Ramesh Shunmugasundaram and Jeff R Dahn

This content was downloaded from IP address 134.225.110.27 on 21/10/2021 at 12:03

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
23 February 2021

REVISED
4 August 2021

ACCEPTED FOR PUBLICATION
5 August 2021

PUBLISHED
24 August 2021

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

LETTER

The fate of the Caspian Sea under projected climate change and water extraction during the 21st century

Sifan A Koriche[1,3,4,*], **Joy S Singarayer**[1] **and Hannah L Cloke**[1,2,5,6]

[1] Department of Meteorology, University of Reading, Reading, United Kingdom
[2] Department of Geography and Environmental Science, University of Reading, Reading, United Kingdom
[3] School of Civil and Environmental Engineering, JiT, Jimma University, Jimma, Oromiyaa, Ethiopia
[4] Department of Geoscience, Baylor University, Waco, TX, United States of America
[5] Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[6] Centre of Natural Hazards and Disaster Science, CNDS, Uppsala, Sweden
[*] Author to whom any correspondence should be addressed.

E-mail: s.koriche@reading.ac.uk and numarsanifa@gmail.com

Keywords: Caspian Sea level, CMIP5, CMIP6, water extraction, future climate change, water budget

Supplementary material for this article is available online

Abstract

The Caspian Sea (CS) delivers considerable ecosystem services to millions of people. It experienced water level variations of 3 m during the 20th century alone. Robust scenarios of future CS level are vital to inform environmental risk management and water-use planning. In this study we investigated the water budget variation in the CS drainage basin and its potential impact on CS level during the 21st century using projected climate from selected climate change scenarios of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs), and explored the impact of human extractions. We show that the size of the CS prescribed in climate models determines the modelled water budgets for both historical and future projections. Most future projections show drying over the 21st century. The moisture deficits are more pronounced for extreme radiative forcing scenarios (RCP8.5/SSP585) and for models where a larger CS is prescribed. By 2100, up to 8 (10) m decrease in CS level is found using RCP4.5 (RCP8.5) models, and up to 20 (30) m for SSP245 (SSP585) scenario models. Water extraction rates are as important as climate in controlling future CS level, with potentially up to 7 m further decline, leading to desiccation of the shallow northern CS. This will have wide-ranging implications for the livelihoods of the surrounding communities; increasing vulnerability to freshwater scarcity, transforming ecosystems, as well as impacting the climate system. Caution should be exercised when using individual models to inform policy as projected CS level is so variable between models. We identify that many climate models either ignore, or do not properly prescribe, CS area. No future climate projections include any changes in CS surface area, even when the catchment is projected to be considerably drier. Coupling between atmosphere and lakes within climate models would be a significant advance to capture crucial two-way feedbacks.

1. Introduction

The Caspian Sea (CS) is the largest land-locked lake in the world, with a surface area currently larger than Japan. Over one hundred rivers contribute to its vast catchment (3.6 Mkm^2; figure 1), covering six climatic zones (Chen and Chen 2013). In the past, the CS has experienced large variations in water level, from tens to hundreds of metres on various time scales (Krijgsman *et al* 2019, Koriche *et al* 2020a), and its water level variability through time does not track that of the global ocean. As the water level changes it substantially alters CS surface area. For example, $\pm$>70% change from its current surface area occurred during various time periods in the late Quaternary. Such changes in surface area impact the climate in the regional catchment due to feedbacks with evaporation, precipitation, and wind patterns, as well as the

© 2021 The Author(s). Published by IOP Publishing Ltd

large-scale atmospheric circulation in the northern hemisphere (Arpe et al 2019, Koriche et al 2020b). CS climate impacts extend eastward, modifying summer precipitation over central Asia, and even potentially influencing sea-ice concentrations over the northwestern Pacific (Koriche et al 2020b).

Several previous studies have investigated historical changes in CS level (e.g. Rodionov 1994, Golitsyn 1995, Arpe et al 1999, 2000, Arpe and Leroy 2007, Chen et al 2017a, 2017b). Multiple natural and anthropogenic factors have combined to produce historical sea level variations. There was a dramatic decrease of 3 m in CS level from the 1930s to 1977 (figure 2(a)), which has been attributed partly to precipitation decreases along the Volga catchment and partly to an intense period of reservoir construction (Hollis 1978) that enabled the storage of increasing amounts of catchment water outside the CS (Leroy et al 2020, and references therein). The subsequent two decades saw a rise of 2.5 m in CS, which has been linked to teleconnections between the CS and ENSO (Arpe et al 2000). This was followed by a 1.5 m decrease over the last three decades, even as human extraction has decreased, which has been dominated by enhanced evaporation over the CS itself during that time-period, as regional temperatures increased, according to Chen et al (2017a), who found that precipitation decline over this period also contributed but to a smaller degree.

A few previous studies have addressed the implications of future human-induced climate change for CS level. The results of these studies vary considerably, from predicting increasing CS level over the 21st century (Arpe and Leroy 2007, Roshan et al 2012) to substantial declines in CS level (Elguindi and Giorgi 2006, 2007, Renssen et al 2007) of up to 9–18 m in one study (Nandini-Weiss et al 2020). Elguindi et al (2011) point to model spatial resolution as an important factor in estimating hydrologic balance over the CS, especially in regions with mountainous terrain. Model structural differences also contribute to larger uncertainties in dynamical responses to climate change than in the thermodynamic response (Shepherd 2014), as seen in the coupled model intercomparison projects (CMIP). This produces a broader range of regional outcomes for circulation-controlled climate fields such as precipitation, which results in challenges for assessing climate change impacts on the regional hydrological budget (Woldemeskel et al 2016). The spatial representation of the CS within climate models influences local and remote climate (Koriche et al 2020b), and in many models the rendering of the CS is poor. Equally, as CS area decreases, the area available for evaporation decreases, creating a negative feedback that is not accounted for in these studies (except in Renssen et al 2007).

In addition to climatic factors, artificial water extraction (WE) (in this paper 'extraction' is used in the same sense as 'abstraction', to refer to water taken from a natural source for human purposes) has increased the vulnerability of the CS to desiccation. Discharge along the rivers of the CS catchment is regulated by over 14 000 dams built for agricultural irrigation, domestic, and industrial purposes over the last 90 years, which together have the capacity to store >75% of the total discharge to the CS (Akbari et al 2020). Roughly 25 000 km^2 (6%–7%) of the CS is now vulnerable to desiccation as CS levels fluctuate (Akbari et al 2020). Evaporation from the dams, together with climate change and increased WE driven by population growth and change in lifestyle, could amplify the decline of CS level, leading to accelerated desiccation, especially the northern shallowest part of the lake. Consequently, ecosystems, economies, and livelihoods of many millions in the surrounding nations of the CS could be severely affected in the future. However, modelled projections of future CS level have so far mostly not incorporated human WE (one exception is Kudekov 2006).

The impacts of lake desiccation are serious, as exemplified by the Aral Sea (Micklin 1988, Small et al 2001, Zavialov et al 2003). Hence, robust scenarios of future CS level are vital to inform future planning of industrial, agricultural, and domestic WE, as well as other activities including fisheries, shipping, and oil/gas production. In this study, we investigate the hydrologic budget changes and the water level variation of the CS under 21st century climate change projections and idealized WE scenarios. The research addresses the following questions:

- How does the CS water budget change in the CMIP5 and CMIP6 models in the 21st century?
- How well is the CS represented in the CMIP models and how does this influence their future climate projections?
- What are the implications for CS level given 21st century climate change and future WE scenarios?

We selected a number of climate models from CMIP5 and CMIP6 for analysis of their water budgets, based on their representation of the CS. We collated available WE information and extrapolated 21st century scenarios. Climate-change driven water budgets and human extraction scenarios were then combined to estimate the impacts on CS level using a hydrologic model that accounts for the impacts of changes in CS area on evaporation from the sea.

2. Methods

2.1. Model selection and data preparation

Close to 60 global climate models were included in CMIP5 (Taylor et al 2012) and about 120 models in CMIP6 (Eyring et al 2016). Analysis of their associated land-sea masks indicates that a considerable number of the CMIP5 and CMIP6 climate models either completely ignore, or do not accurately prescribe, CS area. Therefore, we set selection criteria based on (a) how well CS area is represented in the models, and (b) the availability of precipitation and evaporation fields for both representative concentration pathways (RCP) 4.5 and 8.5 (Meinshausen *et al* 2011) for CMIP5 and shared socioeconomic pathways (SSP) 245 and 585 (Riahi *et al* 2017) for CMIP6. RCP4.5 is an intermediate scenario, with 4.5 $\mathrm{Wm^{-2}}$ radiative forcing by 2100, and RCP8.5 is an extreme climate change scenario, with 8.5 $\mathrm{Wm^{-2}}$ radiative forcing by 2100. SSP245 and SSP585 represent similar (although not identical) intermediate and extreme scenarios, respectively, in CMIP6.

At the time this investigation was performed (September 2020), based on the above criteria, we selected in total 18 climate models, of which 11 are from CMIP5 and seven are from CMIP6. We only considered the first ensemble simulation (CMIP5: 'r1i1p1' and CMIP6: 'r1i1p1f1') if a model had multiple ensemble simulations. The list of the models used in this study and their land-sea masks are presented in figure 1. See also supplementary information figures S1 and S2 (available online at stacks.iop.org/ERL/16/094024/mmedia) for land-sea masks of models that were rejected from the main study due to poor CS representation and/or missing climate model fields (for model details see table S1 for CMIP6 models and table S2 for CMIP5 models). For comparison purposes, the model precipitation and evaporation fields were interpolated to the same resolution (6 arcminutes) by a first-order conservative interpolation method (remapcon), which works well for flux conservation (Jones 1999), using the Climate-Data-Operator software (Schulzweida 2019).

2.2. Hydrologic budget assessment and CS level modelling

The hydrologic budget variation was assessed by comparing the mean 'precipitation minus evaporation' (*P*–*E*) field between the start and end of the 21st century from the selected CMIP5 (running between years 2006 and 2098) and CMIP6 (over years 2015–2100) models for the RCP and SSP scenarios. To estimate the CS level variation during the 21st century, we used a hydrologic model constructed for the CS by Koriche *et al* (2020a). The model is based on fluxes of runoff over the CS catchment, *P*–*E* over the CS, and WE for human use (equation (1)). Simulations of lake water level variation in a closed basin like the CS can be substantially affected by the variation of its water level, as this leads to changes in surface area, which would significantly impact the *P*–*E* over the sea at each time step. Therefore, for every time step, the CS surface area is updated based on the volume of the previous time step to be considered for the current time step water balance (*P*–*E*) estimation (equation (1)).

$$\Delta \mathrm{CSV}^t = \left[\left(P^t_{\mathrm{land}} - E^t_{\mathrm{land}}\right) A^{t-1}_{\mathrm{land}} + \left(P^t_{\mathrm{sea}} - E^t_{\mathrm{sea}}\right) A^{t-1}_{\mathrm{sea}} - \Delta \mathrm{WE}^t \right] \Delta t. \quad (1)$$

where: CSV is CS volume, *P* is precipitation, *E* is evaporation/evapotranspiration, and *A* is surface area, all over the land or sea part of the basin as denoted by their subscript, ΔWE is the increment in human extraction of water, Δ*t* is the time step (in this case 1 month). We assume that groundwater contributions are small, based on previous studies (Zekster 1995, Golovanova 2015), and so we have not included a groundwater component.

2.3. Analysis of water extraction

Currently, the CS is fed by rivers from nine different countries whereas WE information is based on national-level data rather than on the CS catchment boundary. This makes it difficult to get appropriate estimations of water withdrawals solely from the rivers flowing to the CS. We have used records covering the period from 1940 up to 1995 (Shiklomanov 1981, Rodionov 1994, Golitsyn 1995), which are derived estimates of what the CS level would be with zero human WE (see figure 2(a), solid colour lines). These are indirect measurements that can then be used to infer the amount of water withdrawn from the rivers contributing to the CS when compared with the measured CS level observational record (figure 2(a), black dotted line). Following calculation of the yearly withdrawal volume, the estimated annual WEs demonstrate a roughly threefold increase between 1940 and 1990 (figure 2(b)). We note that we are referring to net WE (consumptive water use), which is the amount of water leaving the basin after accounting for the return of a proportion of the WE to the CS. Net WE can occur through several mechanisms, including evaporated water that precipitates outside the basin boundary or through export of water in irrigated crops, livestock, and other goods.

An alternative source of information relating to water withdrawal from the Caspian catchment was compiled by Demin (2007) from various economic and government sector reports for the years 1970–2003 (figure 2(b)). These data show a peak in water withdrawals around 1985–1990 before annual consumption decreases again, until it declines to 43 $\mathrm{km^3\ yr^{-1}}$ in 2003. These figures include consumption, as well as evaporation from reservoirs within the catchment. The reasons for the decline in WE include more efficient water consumption in domestic and industrial processes, changes to land-use, and changes to regional population (Demin 2007). However, this decline in WE was not sufficient to balance out the enhanced evaporation over the CS that occurred due to increased regional temperatures (Chen *et al* 2017a), and so CS level declined over the last few decades.

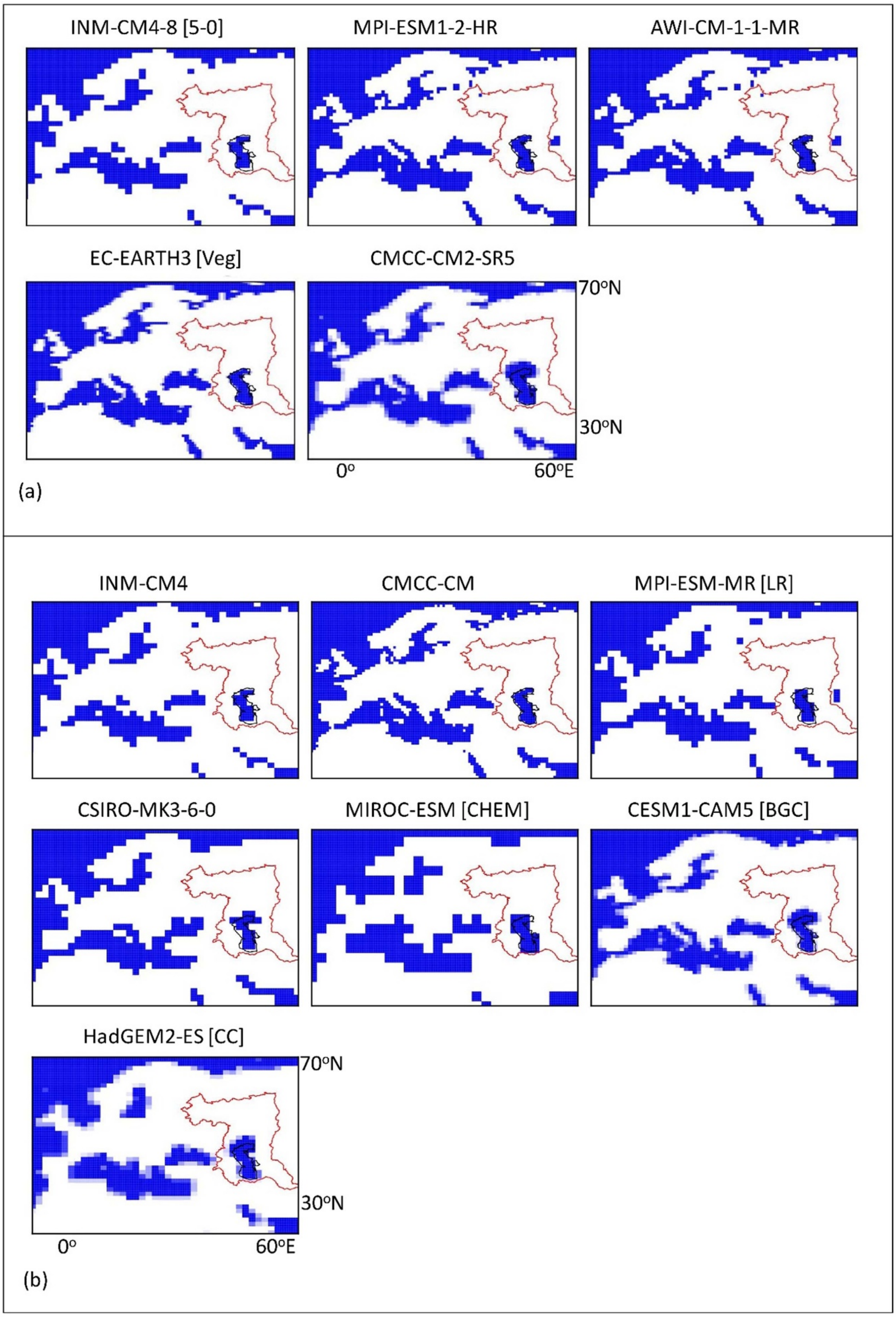

Figure 1. Land-sea mask maps of models used in this study from (a) CMIP6 and (b) CMIP5. The black line represents the current CS extent, and the red line represents the extent of the CS catchment.

For this study, we created future WE values for idealised future projections between 2015 and 2100 in the CS basin based on these estimates (figure 2(b)). The first scenario (FWE1) is a constant extraction rate of 40 $km^3\,yr^{-1}$, based on Demin (2007), and previously used in Kudekov (2006). A second scenario (FWE2) had constant annual withdrawal at 20 $km^3\,yr^{-1}$ (figure 2(b), green dashed line). In a third scenario (FWE3) we used new country level population projections for nations within the

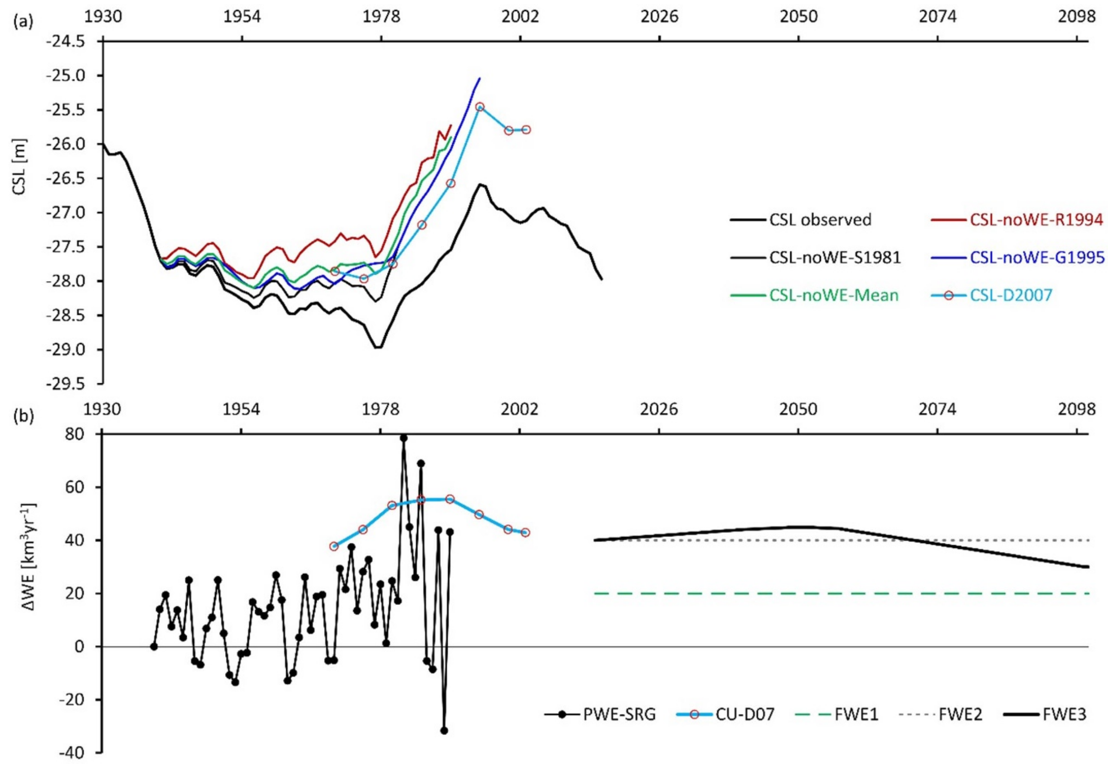

Figure 2. WE information in relation to the CS level: (a) shows the observed (black broken line) and literature-based CS levels (solid lines), (b) volume of water extracted from the CS based on difference between observed and mean estimated (no WE) CS level by Rodionov (1994), Shiklomanov (1981), and Golitsyn (1995) (solid black line with dot marker). This was calculated by converting 'CS level noWE-Mean' and 'CS level observed' to volumes at each time point, and then subtracting to give the accumulated WE. We then subtracted the previous year's volume to give the water withdrawal for each year. The light blue line with circle marker (CU-D07) is the estimated consumptive water use according to Demin (2007). The other three lines (broken grey and green, and solid black) represent the proposed future WE used in this study to evaluate the projected CS level during the 21st century. The broken grey and green line represent 20 and 40 $km^3\,yr^{-1}$ of future WEs (FWE1 and FWE2) respectively, and the solid black line is estimated future WE based on population growth (FWE3). Key: CSL—Caspian Sea level, WE—water extraction, R1994—Rodionov 1994, S1981—Shiklomanov 1981, G1995—Golitsyn 1995, *D2007*—Demin 2007, PWE-SRG—past water extraction based on Shiklomanov (1981), Rodionov (1994), Golitsyn (1995), FWE—future water extraction.

catchment (Vollset *et al* 2020) to scale water withdrawal values. The regional population is projected to increase slightly up to mid-21st century before declining to below present-day levels by 2100 (figure 2(b); see also supplementary information table S3). In our simple translation we assume that the 2015 extraction rate is 40 $km^3\,yr^{-1}$ and that projected changes in population can be linearly transformed to changes in water withdrawals (through domestic water use, agricultural activity, and industrial sector activity). These three WE scenarios bracket the large uncertainties in the compiled historical literature due to the difficulties in sourcing primary catchment level information (described above and shown in figure 2), as the modelled projections will likely be sensitive to the choice of extraction values.

3. Results

3.1. Water budget of the CS basin and its relation to the CS area representation in CMIP models

We find a considerable spread in the annual mean water budget of the CS catchment (*P*–*E*) between climate models in both CMIP5 (figure 3, red symbols) and CMIP6 (figure 3, blue symbols), with some models displaying a positive net water balance and some a negative balance. When *P*–*E* is plotted against the prescribed CS lake area (figure 3) we find that models with larger CS surface areas tend to be drier, whereas models with smaller lake areas tend to be wetter (more positive *P*–*E*). The correlation of the modelled catchment water budget with the size of the prescribed CS is indicative of the importance of the magnitude of evaporation from the sea itself in controlling the overall balance. The larger the prescribed CS the larger the amount of evaporation, which tends to outweigh any resulting increase in precipitation and so produces a smaller overall *P*–*E*. It is also clear here that even though we have selected models that better represent CS surface area, some of the models (particularly in CMIP5) are up to 75% larger than the observed CS over the last century (figure 3, black symbol).

One difficulty faced when attempting to compare and evaluate the modelled *P*–*E* with observational data is that the CS level has been increasingly influenced by human water withdrawals, which are not included in the model boundary conditions. A

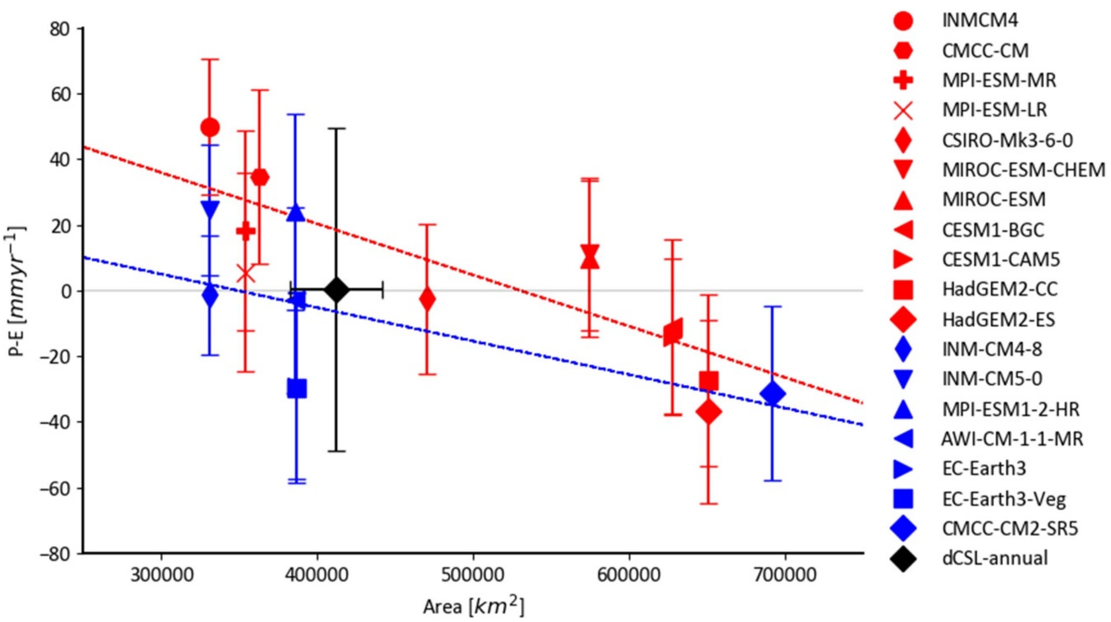

Figure 3. Mean *P–E* over the CS basin for CMIP6 (blue) and CMIP5 (red) models for 1860–1995 plotted against the prescribed CS area in the respective CMIP models. The black symbol represents mean year to another year variation of the CS level, also from 1860 to 1995. The error bars represent one standard deviation (inter-annual) of the mean for the period considered. The linear fits are significant at the 99% level for CMIP5 ($r = 0.82$) and 90% level for CMIP6 ($r = 0.61$).

second potential issue is that there is large interannual to decadal-scale variability in the water budget due to modes of internal climate variability such as ENSO (e.g. Arpe *et al* 2000), and models do not necessarily reproduce the state of those modes at the correct historic time (nor would we expect them to do so). Therefore, comparison of the water balance to a short record or short reanalysis dataset (e.g. ECMWF reanalysis version-5 (ERA5) data, 1979–2005) will not be appropriate. Instead, we compare the model output with the CS level record, corrected to exclude any human water withdrawals (see figure 2(a)), and averaged over a much longer time period 1860–1995 (figure 3, black symbol). The observational data show that the CS has been precariously balanced, fluctuating between positive and negative over the last century. As can be seen in figure 3, models with a prescribed CS surface area closer to historical observations generally also produce a water budget closer to our observationally-derived estimate.

Figures 4(a) and (b) show the mean water budgets (*P–E*) of the CS basin by the end of the 21st century (2070–2100) as projected by CMIP6 and CMIP5 models for medium (SSP245/RCP4.5) and high (SSP585/RCP8.5) radiative forcing scenarios. Models that represent current CS area more accurately in CMIP5 (CMCC, MPI, CSIRO) tend to have a neutral or positive *P–E* by 2100 (figure 4(b)). In CMIP6, models with better prescribed CS area (MPI, AWI, EC-Earth3) tend to have a neutral or negative *P–E* by the end of the century (figure 4(a)). To evaluate the direction of future water budget change in the CS basin, we use the anomalies between the start and end of the 21st century for both modelling groups as presented in figures 4(c) and (d). In both scenarios the model *P–E* anomalies almost all show conditions getting drier (up to 40 mm yr^{-1}) by the end of the 21st century (figures 4(c) and (d)). The drying is generally more pronounced in the high radiative forcing scenario (SSP585/RCP8.5) than the medium scenario (SSP245/RCP4.5). This is the case for all CMIP6 models, and six out eleven CMIP5 models. The CMIP5 multi-model mean (MMM) does not show this trend as it is heavily weighted by the CSIRO-Mk3-6-0 model. This model displays considerable multi-decadal variability and a neutral long-term trend, and so the averaging periods are more affected by 'noise'. It is only the last two decades of the simulation that RCP8.5 anomalies become much wetter than RCP4.5, due to multi-decadal variability.

The CMIP6 models tend to have a more negative (drier) water budget than the CMIP5 models, both historically and in the future projections. These models generally have higher spatial resolutions, better physics parameterizations, and more Earth system components (Eyring *et al* 2016) than CMIP5 models. Recent studies have also found that this generation of models also have higher equilibrium climate sensitivities (ECS) and warmer 21st century projections (Hausfather 2019, Tokarska *et al* 2020, Wyser *et al* 2020), which may play an important role here, given the importance of evaporation over the sea for the overall water budget of the CS. The treatment of the lake in the models (e.g. parameters relating to lake heat absorption and mixing) and coupling of the lake surface to the atmosphere will likewise be

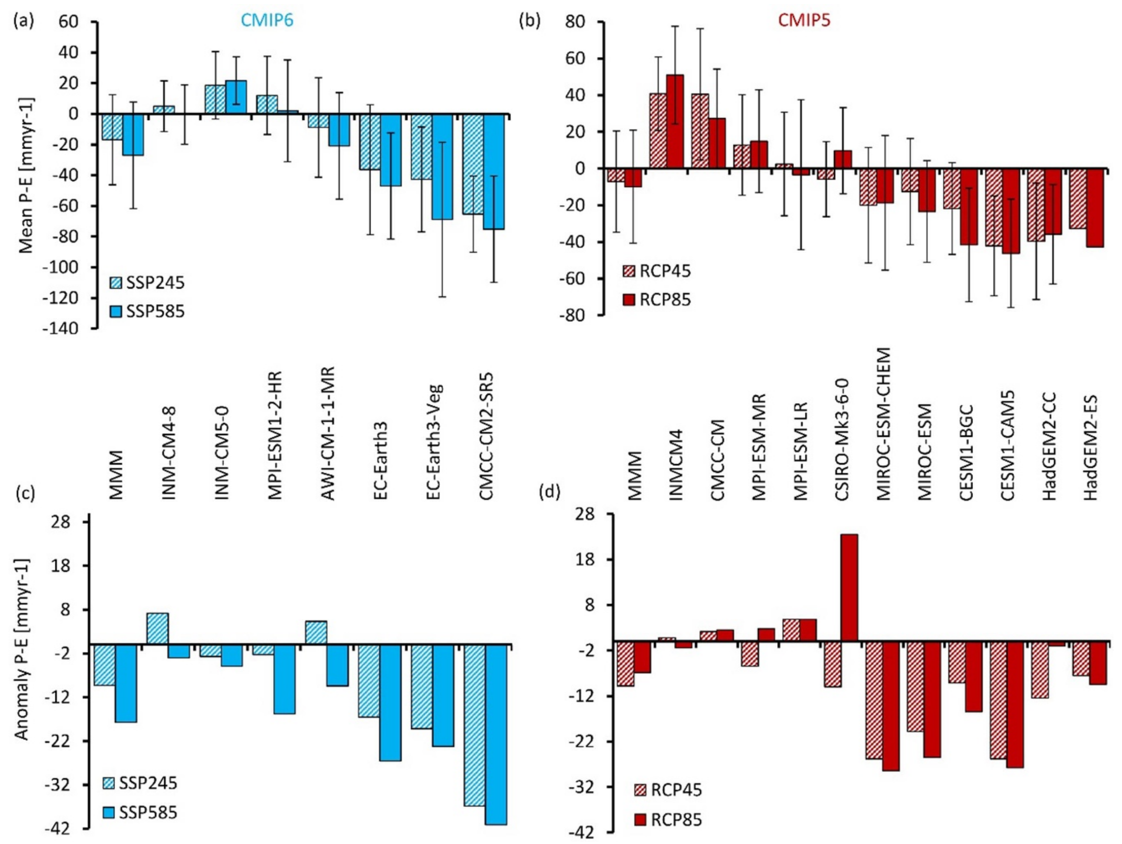

Figure 4. (a) and (b) show mean *P–E* by the end of 21st century (2070–2100) for CMIP6 and CMIP5 respectively, and (c) and (d) show anomalies of *P–E* between the end and start of 21st century for CMIP6 and CMIP5 respectively. For CMIP6, the *P–E* anomalies are based on between the mean *P–E* during 2070–2100 and 2015–2030, and whereas, for CMIP5 between the mean *P–E* during 2070–2098 and 2006–2020. The CS area increases from left to right. MMM refers to the multi-model mean. The error bars represent one standard deviation (inter-annual) of the mean for the period considered.

important in the variation between modelled water budgets. The magnitudes and patterns of the seasonal cycle of precipitation and evaporation over land are relatively consistent (see supplementary information figures S3(a) and (b) for CMIP6 and figures S4(a) and (b) for CMIP5) but highly variable between models over the sea (figures S3(c) and (d) and S4(c) and (d)). The timing of maximum evaporation varies between August and November and the minimum between February and May. Two CMIP6 models (EC-Earth3 and EC-Earth3-veg), which display highly negative water budgets, despite their CS areas being close to observed, have CS evaporation that remains relatively high even in winter compared to other models (figure S3(c)). These models have an ECS that is relatively high (>4 °C; Tokarska *et al* 2020). Conversely, the INM-CM5-0 CMIP6 model, which has a highly positive water budget, has a much lower maximum evaporation than other models and low ECS (<2 °C; Tokarska *et al* 2020). The same model seasonality characteristics are maintained through the future projections (figures S4–S8).

3.2. Simulation of 21st century CS level

In this section, we explore the question of how increasing anthropogenic climate change and human water withdrawals will impact CS level using a water balance model driven by modelled climate projections and idealised extraction scenarios.

The first set of CS level simulations are driven by climate outputs from CMIP6 and CMIP5 models without considering WE (figure 5(a)). By 2100, up to 8 m decrease in the projected CS level is found using CMIP5 models under RCP4.5 and up to 10 m for RCP 8.5. In CMIP6 based simulations, our results show a decrease in CS level of up to 20 and 30 m for SSP245 and SSP585 scenarios respectively (figure 5(b)). The reasons for the larger decreases in CMIP6 CS level than CMIP5 CS level are partly explained in the last paragraph of section 3.1 (in particular, higher ECS). The declines in CS level are larger with models where larger CS is prescribed in the climate model, and those with higher projected evaporation (e.g. EC-Earth3 and EC-Earth3-Veg, which have up to 70% higher evaporation than other models). On the other hand, models where the prescribed CS in the climate model is smaller tend to display increases in the projected CS level (four CMIP5 models but only one CMIP6), since the *P–E* over the CS basin is positive (figures 5(a)–(b)). We observed that the projected CS level increases in models with cold bias and smaller ECS (e.g. INM-CM model families). We also find

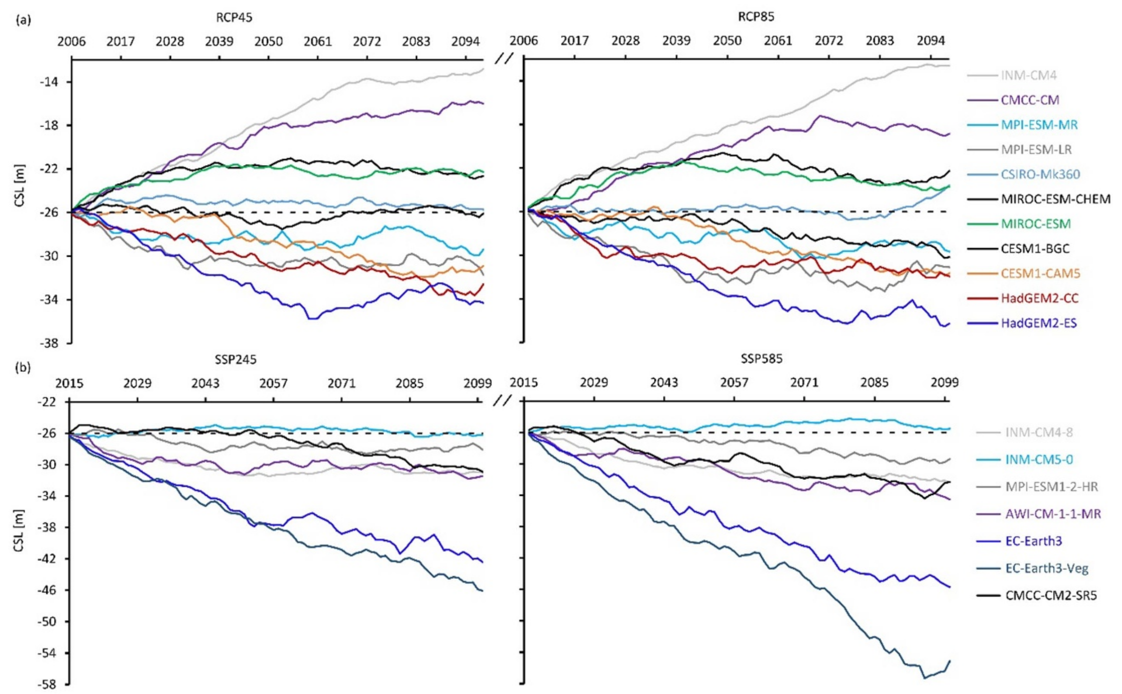

Figure 5. Simulated CS level projections without considering extraction and based on (a) CMIP5 models for RCP4.5 and RCP8.5 scenarios and (b) CMIP6 models for SSP245 and SSP585 scenarios. The models are listed in the order of increasing CS area from top (smallest) to bottom (largest).

that the CS level projections for CESM-CAM5 (5–6 m) from CMIP5 are smaller than found by Nandini-Weiss *et al* (2020) of 9–18 m using the same model. Our water balance modelling results in a negative lake-level-evaporation feedback that is not represented in the other study. Here, as CS level declines the surface area shrinks, which reduces the evaporation component, slowing down the rate of desiccation. As a result, CS level decline is not as pronounced as in Nandini-Weiss *et al* (2020).

Next, we incorporate the three idealised WE scenarios, as described in section 2.3. In our analysis of WE impacts we only consider the results from CMIP6 radiative forcing scenarios (SSP245 and SSP585) as they are based on latest versions of climate models with improved process representations. In all scenarios, all models display a decline in CS level but there is variation in the magnitude of this decline. Up to 7 m decline in CS level is observed due to WE. Under the SSP245 scenario the decline in the CS level ranges from 0.7 to 3.6 m for FWE1, 1.4 to 7.6 m for FWE2, and 1.2 to 7.3 m for FWE3 (figures S9(b)–(d)). Under SSP585 CS level ranges from 0.9 to 4.4 m in FWE1, 2.2–9 m in FW2, and 1.9–7.2 m in FWE3 (figures S9(b)–(d)).

We note that the relationship between CS level and CS surface area is highly non-linear. When CS level varies between −27 and −34 m the CS area changes are proportionately large compared with when CS level is below this. This occurs when the shallow northern part of the CS (average depth ∼ 6 m) comes into play. As a result, even when the long-term trend in CS level is seemingly relatively smooth, there is large interannual variability in the modelled CS surface area of up to 10% (figures 6(a), (b) and S10). This is most evident in those models that have smaller long-term trends in CS level. This interannual variability will result in larger seasonal variation in flooding of surrounding wetlands. The variability in CS area, particularly in the shallow northern CS, has implications for coastal communities and conservation of marginal environments at the edge of the lake.

We considered a key indicator, or threshold, in the future of the CS to be the point when the shallowest northern section becomes completely desiccated (figure 6(d), grey shaded area). We used the CMIP6 MMM projections of the CS level under the two climate change scenarios and four idealised WE cases to calculate at what point in the 21st century this threshold occurs (if at all). In all scenarios, except for SSP245 with no WE (NoWE), this level of desiccation occurs at some point before the end of the century (figure 6(c)). For the extreme SSP585 scenario MMM and the population based FWE3 extractions the northern CS is desiccated by 2050 (and which is a point crossed by five out of the seven individual models). When considering this indicator of CS decline, the rate of WE is effectively as important as the climate change scenario in terms of the timing. The higher the extraction rate the less difference the climate change scenario makes, and vice versa. With FWE3 there is only ∼12 years difference between SWSP245 and SSP585, whereas with FWE1

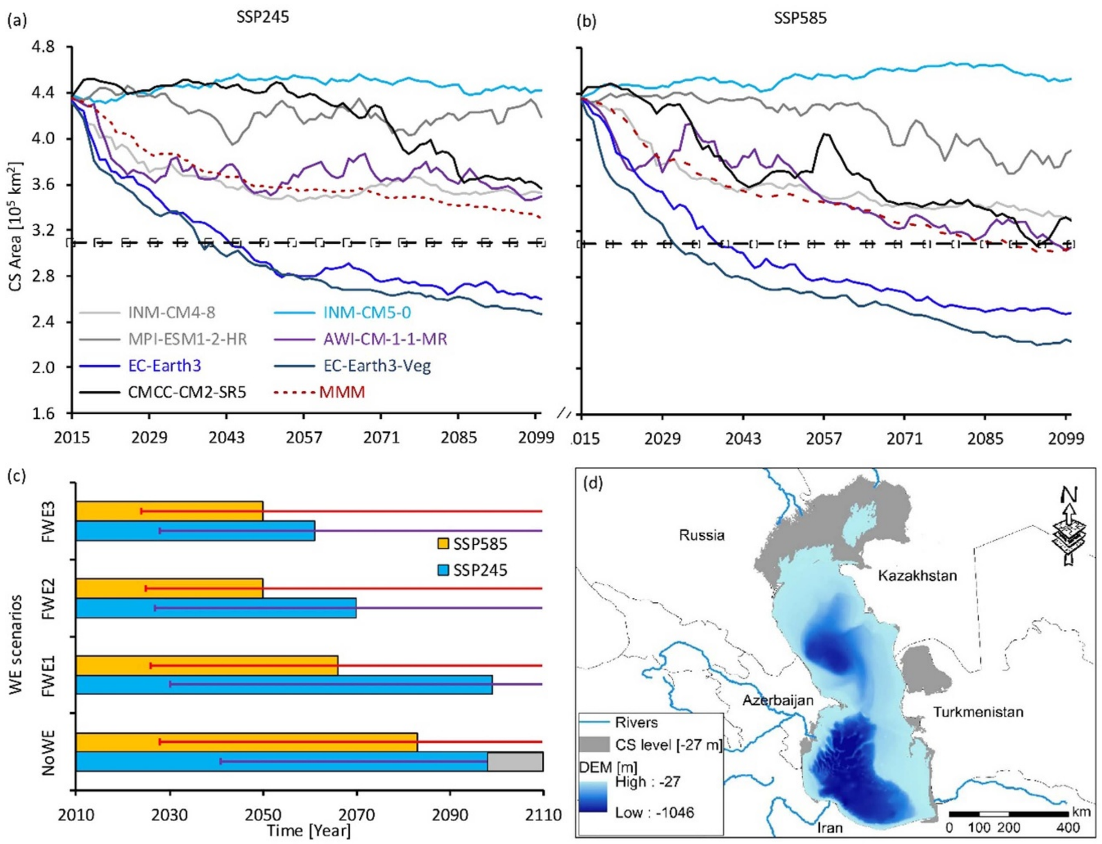

Figure 6. Projected CS area of the 21st century based on CMIP6 (a) medium and (b) extreme emission scenarios and without WE. The broken line with box marker is the magnitude of area vulnerable to desiccation for a 6 m CS level decline. (c) The time at which the northern part of the CS area with average depth of 6 m will be desiccated for four experiments with three WE and a NoWE scenarios using multi-model-mean climate output from CMIP6 extreme and medium emission scenarios. The grey part of the bar-chart of the NoWE scenario indicates that the northern part of CS area will not be affected until the end of 21st century. (d) Map showing area vulnerable to desiccation for a 6 m CS level decline shown in grey. Abbreviations as in figure 2.

there is ~45 years difference (figure 6(c)). The timing of the desiccation among individual models are different (figures 6(a), (b) and S10).

4. Discussion and conclusions

In this study we have investigated water budget variation in the CS basin and its potential impact on the CS level during the 21st century using projected climate change from selected CMIP6 and CMIP5 models (Taylor *et al* 2012, Eyring *et al* 2016). Furthermore, we have explored the impact of idealised human WEs on the future CS level variations. We find that the size of the CS prescribed in the climate models is an important determinant of the modelled water budget (*P*–*E*), which previous studies have not addressed. The *P*–*E* is negative for models with larger prescribed CS and positive for the smaller CS. Models that are closer to the observed size of the CS tend to be closer to the observed water budget.

Most of the future water budget projections by CMIP6 and CMIP5 models show a drying over the 21st century compared to present. CMIP6 models are generally drier than CMIP5 projections in the CS catchment, which could be related the addition of more sophisticated Earth system processes, higher atmospheric resolutions, and higher ECS. The moisture deficits (leading to declining CS levels) are more pronounced for the extreme radiative forcing scenario (RCP8.5/SSP585), and with models where larger CS is prescribed, due to increased over-sea evaporation, as result of increased warming. The projected CS level is variable between models, with some models projecting increased CS level, related to larger prescribed CS area and differences in climate sensitivity. Therefore, caution should be exercised when using a single CMIP model or an ensemble mean to inform policy for mitigation measures.

During the historical period, human extractions from the CS basin had considerable impact on CS level variations, as artificial reservoirs have hindered natural hydrological processes. The ongoing annual withdrawals put added pressure on the CS level, even as water-use efficiency is improved and population stabilises. We find that impacts from WE rates are as important as climate change for projected future declines in CS level. The shallow (6 m average depth) northern part of the CS is at clear risk of desiccation by the end of the 21st century, and occurred in all but one of our modelled future scenarios. This would lead to severe impacts on biodiversity, ecosystems, economies, and geopolitical situations of the surrounding countries. Some of the major impacts that would be anticipated include reduction in major food-source habitats, degradation of river-deltas, increased pollution in the central basin, disruption of ecosystems and unique biotas, and reduction in income generating services (Prange *et al* 2020).

Coupling between modelled atmosphere and lake area within GCMs would be a significant advance to enable incorporation of important two-way feedbacks. As we have found, many climate models either ignore, or poorly prescribe, CS area. No future climate projections include any changes in CS surface area, even when the catchment is projected to be considerably drier. Changes in CS surface area influence the regional atmospheric water budget but also have remote climatic impacts (Arpe *et al* 2019, Koriche *et al* 2020b).

Water mass circulation is one further component that is neglected in these simulations. A recent study by Huang *et al* (2021) simulated the response of CS circulation to doubling of CO_2 in an ultra-high-resolution global model, which included CS circulation. Their model displayed a slowdown of northern and southern CS gyres but an increase in intensity of the central gyre. Resulting impacts on mixing of heat could influence evaporation rates and seasonal cycles. However, the first order CS level decrease found in this model was a similar magnitude to other studies (e.g. Renssen *et al* 2007), although the modelled CS in Huang *et al* (2021) still had a fixed prescribed volume and surface area, and no account was made for changes in surface area in the calculation of CS level.

Considerable uncertainty in the historical drivers of CS variation has arisen due to the lack of coordinated water monitoring systems at catchment level. This has made it difficult to pin down the relative impacts of climate change and human WE, and to fully assess which models are better at reproducing the CS water balance. A coordinated effort among the countries in the CS basin is vital for the implementation of an integrated watershed management approach to better understand hydroclimatic changes in the CS basin, so that improvements could be made to models for better projections of the CS level and area.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.wcrp-climate.org/wgcm-cmip.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No. 642973; and the U.K.'s Natural Environment Research Council (NERC) The Evolution of Global Flood Risk (EVOFLOOD) Project Grant NE/S015590/1. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in tables S1 and S2 of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

ORCID iDs

Sifan A Koriche https://orcid.org/0000-0003-1285-2035
Hannah L Cloke https://orcid.org/0000-0002-1472-868X

References

Akbari M *et al* 2020 Vulnerability of the Caspian Sea shoreline to changes in hydrology and climate *Environ. Res. Lett.* **15** 115002

Arpe K, Bengtsson L, Golitsyn G S, Mokhov I I, Semenov V A and Sporyshev P V 2000 Connection between Caspian Sea level variability and ENSO *Geophys. Res. Lett.* **27** 2693–6

Arpe K, Bengtsson L, Golitsyn G, Mokhov I, Semenov V and Sporyshev P 1999 *Doklady Earth Sciences C/C Of Doklady-Akademiia Nauk* **366** pp 552–6

Arpe K and Leroy S A G 2007 The Caspian Sea level forced by the atmospheric circulation, as observed and modelled *Quat. Int.* **173–174** 144–52

Arpe K, Tsuang B J, Tseng Y H, Liu X Y and Leroy S A G 2019 Quantification of climatic feedbacks on the Caspian Sea level variability and impacts from the Caspian Sea on the large-scale atmospheric circulation *Theor. Appl. Climatol.* **136** 475–88

Chen D and Chen H W 2013 Using the köppen classification to quantify climate variation and change: an example for 1901–2010 *Environ. Dev.* **6** 69–79

Chen J L *et al* 2017a Long-term Caspian Sea level change *Geophys. Res. Lett.* **44** 6993–7001

Chen J L, Wilson C R, Tapley B D, Save H and Cretaux J F 2017b Long-term and seasonal Caspian Sea level change from satellite gravity and altimeter measurements *J. Geophys. Res.* **122** 2274–90

Demin A P 2007 Present-day changes in water consumption in the Caspian Sea basin *Water Resour.* **34** 237–53

Elguindi N and Giorgi F 2006 Simulating multi-decadal variability of Caspian Sea level changes using regional climate model outputs *Clim Dyn* **26** 167–81

Elguindi N and Giorgi F 2007 Simulating future Caspian sea level changes using regional climate model outputs *Clim Dyn* **28** 365–79

Elguindi N, Somot S, Déqué M and Ludwig W 2011 Climate change evolution of the hydrological balance of the mediterranean, black and Caspian Seas: impact of climate model resolution *Clim. Dyn.* **36** 205–28
Eyring V *et al* 2016 Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58
Golitsyn G S 1995 The Caspian Sea-level as a problem of diagnosis and prognosis of the regional climate-change *Izv. Akad. Nauk Fiz. Atmos. Okeana* **31** 385–91
Golovanova O V 2015 Groundwater of the pleistocene aquifer system in the north caspian and near-caspian regions: communication 1. Character of water exchange and factors of sedimentary water integrity *Lithol. Min. Resour.* **50** 231–47
Hausfather Z 2019 Cmip6: The next generation of climate models explained (available at: www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained) (Accessed 02 January 2021)
Hollis G E 1978 The falling levels of the caspian and aral seas *Geogr. J.* **144** 62–80
Huang L, Lee -S-S and Timmermann A 2021 Caspian sea and black sea response to greenhouse warming in a high-resolution global climate model *Geophys. Res. Lett.* **48** e2020GL090270
Jones P W 1999 First-and second-order conservative remapping schemes for grids in spherical coordinates *Mon. Weather Rev.* **127** 2204–10
Koriche S A *et al* 2020a What are the Drivers of Caspian Sea Level Variation during the Late Quaternary? (Under Review at Journal of Quaternary Science Review)
Koriche S A*et al* 2020b Impacts of variations in Caspian Sea surface area on catchment-scale and large-scale climate (Under Review at JGR: Atmospheres)
Krijgsman W *et al* 2019 Quaternary time scales for the pontocaspian domain: interbasinal connectivity and faunal evolution *Earth-Sci. Rev.* **188** 1–40
Kudekov T 2006 Climate change and vulnerability assessment report for the republic of kazakhstan *Caspian Environmental Programme*
Leroy S A, Lahijani H A, Crétaux J-F, Aladin N V and Plotnikov I S 2020 Past and current changes in the largest lake of the world: the Caspian Sea *Large Asian Lakes in a Changing World* (Berlin: Springer) pp 65–107
Meinshausen M *et al* 2011 The rcp greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* **109** 213
Micklin P P 1988 Desiccation of the aral sea: a water management disaster in the Soviet Union *Science* **241** 1170–6
Nandini-Weiss S D, Prange M, Arpe K, Merkel U and Schulz M 2020 Past and future impact of the winter North Atlantic Oscillation in the Caspian Sea catchment area *Int J Climatol* **40** 2717–31
Prange M, Wilke T and Wesselingh F P 2020 The other side of sea level change *Commun. Earth Environ.* **1** 69
Renssen H, Lougheed B C, Aerts J C J H, De Moel H, Ward P J and Kwadijk J C J 2007 Simulating long-term Caspian Sea level changes: the impact of holocene and future climate conditions *Earth Planet. Sci. Lett.* **261** 685–93
Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68
Rodionov S 1994 *Global and Regional Climate Interaction: The Caspian Sea Experience* vol 11 (Dordrecht: Springer Science & Business Media)
Roshan G, Moghbel M and Grab S 2012 Modeling Caspian Sea water level oscillations under different scenarios of increasing atmospheric carbon dioxide concentrations *Iran. J. Environ. Health Sci. Eng.* **9** 24
Schulzweida U 2019 CDO user guide. *Clim Data Oper.*
Shepherd T G 2014 Atmospheric circulation as a source of uncertainty in climate change projections *Nat. Geosci.* **7** 703–8
Shiklomanov I A 1981 The effects of man on basin runoff, and on the water balance and water stage of the Caspian Sea/influence de l'homme sur l'écoulement du basin fluvial, sur le bilan hydrologique et sur les niveaux de la mer caspienne *Hydrol. Sci. Bull.* **26** 321–8
Small E E, Giorgi F, Sloan L C and Hostetler S 2001 The effects of desiccation and climatic change on the hydrology of the Aral Sea *J. Clim.* **14** 300–22
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98
Tokarska K B *et al* 2020 Past warming trend constrains future warming in CMIP6 models *Sci. Adv.* **6** eaaz9549
Vollset S E *et al* 2020 Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the global burden of disease study *Lancet* **396** 1285–306
Woldemeskel F M, Sharma A, Sivakumar B and Mehrotra R 2016 Quantification of precipitation and temperature uncertainties simulated by CMIP3 and CMIP5 models *J. Geophys. Res.: Atmos.* **121** 3–17
Wyser K, Kjellström E, Koenigk T, Martins H and Döscher R 2020 Warmer climate projections in EC-earth3-veg: the role of changes in the greenhouse gas concentrations from CMIP5 to CMIP6 *Environ. Res. Lett.* **15** 054020
Zavialov P O *et al* 2003 Hydrographic survey in the dying Aral Sea *Geophys. Res. Lett.* **30** 1659
Zekster I S 1995 Groundwater discharge into lakes: a review of recent studies with particular regard to large saline lakes in central Asia *Int. J. Salt Lake Res.* **4** 233–49