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Anthropogenic forcings on the climate of the Aral Sea: A regional modeling perspective

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ABSTRACT

The Aral Sea was formerly one of the world's largest lakes and supported critical ecosystem services, fisheries, and major shipping routes. It was also situated in a rapidly industrializing agricultural region and, as such, multiple anthropogenic forcings have modified the Aral's regional environmental conditions over the latter 20th century. In particular, rising atmospheric greenhouse gas (GHG) concentrations coupled with intensive water resource use have had significant regional climate impacts. Sustained abstractions from regional rivers as an irrigation resource for intensified agricultural production has led to the rapid desiccation of the Aral Sea. As of summer 2014, only 10% of its historic extent remained. This paper reports modeling experiments to elucidate the climatic changes resulting from both increased GHG concentrations and an idealized disappearance of the Aral Sea. We utilized the MIT Regional Climate Model to perform 30-year experiments of pre-desiccated and fully desiccated Aral Sea conditions under moderate and enhanced GHG forcings. Complete desiccation combined with the GHG forcings resulted in substantial increases in summertime net longwave radiation, sensible heating, and surface temperature. Additionally, large reductions in evapotranspiration altered the regional soil moisture – surface temperature relationship. Furthermore, a completely desiccated Aral Sea heightened the GHG-induced regional warming. These results demonstrate how a total loss of the Aral Sea might exacerbate regional climate change. At the same time, they suggest that some of the regional warming and moisture regime shifts could be alleviated with the Aral Sea's restoration, requiring the implementation of conservation practices and improved regional water governance.

1. Introduction

While the rise of greenhouse gas (GHGs) concentrations is considered a primary anthropogenic forcing on our global climate system, development activities have also substantially modified regional climates and environments through a host of compounding, non-GHG externalities. For example, the production of industrial pollutants; land degradation from agricultural, urban or extractive use; and the increasing diversion and appropriation of water resources have all had pronounced effects on regional environmental conditions (Bauer et al., 2016; Cook et al., 2014; Foley et al., 2005; Ramankutty et al., 2006; Schneider, 1994). In particular, the Aral Sea region is a prime example of the confluence of multiple regional-scale anthropogenic forcings, including GHG-induced climate change, increased intensity of regional water consumption, and even the profligate introduction of dangerous pollutants in the name of national defense (Micklin, 2016, 2007). In an effort to expand commodity-based agricultural production in the 1970s, the former Soviet Union implemented a series of dams, diversions, and irrigation canals in the Aral Sea Basin that redirected vast quantities of water from its two main influent rivers: the Amu Darya and Syr Darya (Micklin, 2016, 2010, 2007). The widespread uptake and production of cotton, wheat, and maize, among other crops, demanded at least a 60% increase in irrigation water from 1962 to 2002, which served to substantially diminish the inflow to the Aral Sea. In the summer of 2014, the Aral Sea reached near-complete desiccation (Fig. 1, reproduced from Micklin, 2016) when its segregated water bodies totaled a mere ~10% of its historical (1960s) ~65,000 km^2 extent (Lioubimtseva, 2015; Micklin, 2016; Thevs et al., 2015). This effective "disappearance" of the Aral Sea over the late 20th century/early 21st century has substantially impacted the regional climate conditions, also enabling the airborne spread of previously sequestered pollutants

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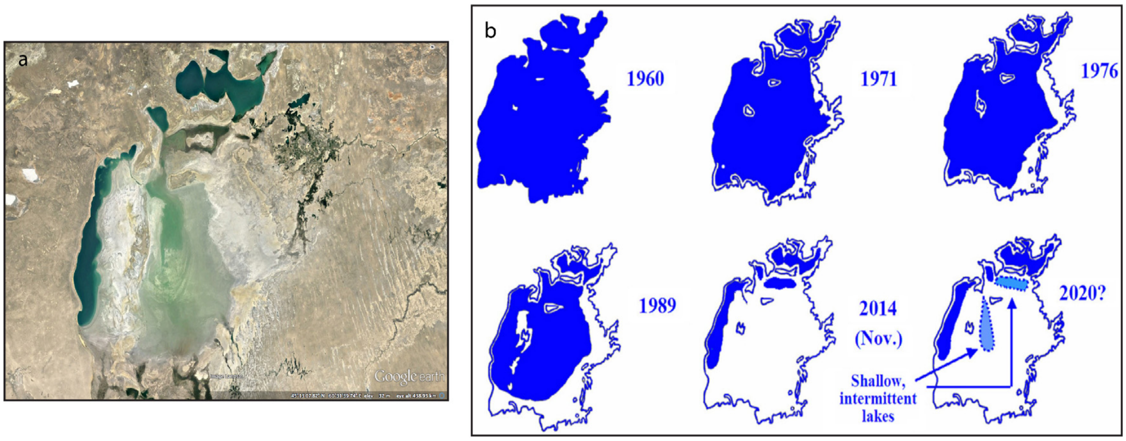

Fig. 1. Aral Sea Extent. a) shows the current state of the Aral Sea as per LandSat imagery, obtained via GoogleEarth. b) is adapted from Micklin, 2016; and indicates the extent per 2014 (down to 10% of the pre-desiccation state during the summer months). The 2020 rendering suggests shallow intermittent lakes, and potential avenues for restoration.

in increasingly severe dust storms (Issanova et al., 2015). Coupled with GHG-driven climate change, which may also drive ongoing regional desertification, the Aral Sea ranks among the worst multi-factor, human-induced environmental disasters in the world (Löw et al., 2013; Micklin, 2016, 2007; Small et al., 2001a).

Large inland seas or lakes can have a pronounced regulation effect on regional climates, particularly by way of modulating synoptic scale weather patterns through altered local atmospheric moisture and energy balances (Miner and Fritsch, 1997). The substantial loss of the Aral Sea's main water bodies has thus significantly impacted climatological surface temperature and wind patterns, and has reduced rainfall over the latter half of the 20th century (Lioubimtseva, 2015). Small et al. (2001a) applied a novel statistical method that removed the long-term trend related to background climate change and variability in observed regional temperature records. This method revealed that the ongoing drying of the Aral Sea has increased the diurnal temperature range and has also contributed to hotter summers and cooler winters in the region (Small et al., 2001a). Through a merged analysis of observed station data and reanalysis products, Khan et al. (2004) showed that the most significant Aral desiccation-related warming trends manifested towards the southern and southwestern portions of the basin. This warming also extended to at least 700 mb, suggesting that the desiccation may have potential impacts on larger-scale regional circulation features. The drying of the Aral Sea, and the exposure of the salt-crusted seabed, has also led to the increased formation and propagation of intense dust and salt storms during the latter half of the 20th century (Indoitu et al., 2015; Issanova et al., 2015; Löw et al., 2013; Micklin, 2007). In fact, an analysis of multiple remote sensing products showed that the dried Aral Sea bed has become dominant source of dust storms regionally, and that these storms – which naturally occur in the pre-desiccation desert areas surrounding the Aral Sea – have now intensified and become more frequent (Indoitu et al., 2015).

Climate modeling approaches can also be useful to understand the mechanisms of climate change in the Aral Sea region, including desiccation. Small et al. (2001b) is among the few studies that used an idealized regional climate modeling approach to simulate the Aral Sea climate. Using the National Center for Atmospheric Research (NCAR) RegCM2, the authors a) quantified the pre-desiccation influence of the Aral Sea and b) compared this to climate conditions with an Aral Sea diminished in its extent and depth. The authors ran ~5-year (1987–1993) simulations to evaluate the Aral Sea at its full extent, half extent (reducing the depth and increasing the salinity), and completely dry and converted to desert. In addition, they performed an experiment that imposed a 1.5 °C cooling by perturbing the model boundary conditions, which served as a basis for evaluating the effects of the "warmer" regional climate provided by the unperturbed experiments. Their results showed that, relative to its full extent, the reduced Aral Sea temperature responses and summertime warming was consistent with statistical analyses conducted by Small et al. (2001a), though the model did underestimate these observed changes. The authors suggested that increased summer atmospheric temperatures and Aral Sea surface temperatures (SSTs) enhanced evaporation and subsequently reduced precipitation minus evaporation.

In general, this modeling exercise demonstrated a strong regional sensitivity to the Aral Sea desiccation that warrants further investigation. The authors' climate change experiments were simplified, neglecting boundary condition responses other than temperature (e.g., zonal and meridional winds, pressure), and the authors were not able to perform longer-term experiments or obtain representative climatologies owing to computational constraints at the time. Understanding the time-varying, multi-factor anthropogenic forcings of increasing GHG concentrations and now near-full desiccation (as of summer 2014) are critical to characterizing future regional climate, and the associated impacts and adaptation strategies.

This study seeks to understand the interactions and relative effects of two major anthropogenic forcings on key climate processes in the Aral Sea region: a near-full desiccation (as of summer 2014) and warming trends associated with global climatic change. Building upon Small et al. (2001b) and references therein, we utilize the most recent version of the Massachusetts Institute of Technology (MIT) Regional Climate Model (MRCM) to conduct idealized sensitivity experiments. These experiments focus on climatological pre-desiccation and complete desiccation conditions, allowing for comparisons with previous modeling efforts for the Aral Sea, and the identification of more robust regional responses and major sources of uncertainty. Specifically, this study includes time-varying boundary conditions (not including the Aral Sea extent) and GHG concentrations for two continuous 30-year time-slices over the Aral Sea domain, thereby filling the previously prohibitive experimental gap of longer, time-varying simulations (Small et al., 2001b).

This paper proceeds as follows. Section 2 provides an overview of MRCM, and describes the boundary conditions and experimental setup. Section 3 presents and compares the experimental results and sensitivity for key climatic variables, particularly those

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