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Negligible Impact on Precipitation From a Permanent Inland Lake in Central Australia

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Key Points:

- A climate model is used to test the hypothesis that creating a large lake in central Australia would increase rainfall
- Locally, surface cooling effects of the lake suppress the formation of precipitation
- Regionally, moisture from the lake is exported to other areas but the amount is small compared to natural variability in Australian rainfall

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract For over a century, numerous proposals for increasing available water in central Australia have been raised, inspired in part by the natural occurrence of the ephemeral lake, Kati Thanda-Lake Eyre. It has also been proposed that additional rainfall generated by the lake would spread beyond the lake itself, potentially opening up large tracts of uncultivated land to dryland agriculture. Here we use a climate model to examine how adding a permanent lake to Australia's arid center might influence local and regional precipitation. Locally, evaporative cooling from the lake increases low-level divergence, suppressing precipitation. Regionally, additional moisture from the lake is spread thinly over the Australian continent, resulting in little change to total precipitation. Overall, our results do not support the assertion that maintaining a large inland lake like Kati Thanda-Lake Eyre in central Australia would significantly increase precipitation, either locally or regionally.

Plain Language Summary The Bradfield water scheme proposed opening central Australia up to agriculture by diverting water inland. Supporters of the plan have argued that this might also increase rainfall. We use a climate model to simulate how precipitation would be impacted by an idealized permanent lake in central Australia. The model simulations show that the presence of a large lake has negligible impact on rainfall, both locally and regionally.

1. Introduction

Australia is the driest inhabited continent on Earth. Water resources and drought issues have always been critical to Australia, often leading to debate on the possible impact of maintaining a large inland water expanse on Australian rainfall (Hope et al., 2004; Towner, 1955; Warren, 1945). In particular, the Bradfield scheme, which was first outlined in the 1930s but is based on even earlier research conducted in the 1920s (Cathcart, 2010), has returned to the governmental agenda in recent years (Read, 2021; RMIT ABC Fact Check, 2019). The Bradfield scheme and its modern variants proposed turning northern Queensland rivers inland and/or moving water from tropical northern Australia to more arid southern areas, but they have been repeatedly criticized due to the estimated cost relative to the potential benefits (Petheram et al., 2020, 2021).

Such schemes were perhaps inspired by the fact that parts of central Australia do, at times, naturally fill with water. For example, Kati Thanda–Lake Eyre (hereafter referred to as Kati Thanda; the geographical location of the lake is shown in Figure 1) is an ephemeral lake located in central Australia and is the largest lake in Australia when full (~9,500 km^2). Observational records and hydrological model simulations show that Kati Thanda typically holds at least some water (albeit below useable water levels) and fills on average once every 8 years (Hope et al., 2004, 2011; Kotwicki, 1986; Kotwicki & Isdale, 1991).

One of the most contentious claims made by Bradfield was that increased inland water storage and irrigation would ameliorate the climate of inland Australia, through potential increases in precipitation. While this claim has been subject to considerable debate, to our knowledge, only one peer-reviewed study exists that actually tests this claim with climate model simulations: Hope et al. (2004), hereafter referred to as H04. In their groundbreaking study, H04 employed two climate models to investigate the climatic impacts of an idealized, full Kati Thanda. They found that an imposed water expanse in the Kati Thanda region would not cause consistent and significant responses in regional precipitation on the seasonal scale.

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While H04 provided useful insights with the modeling tools available at the time, it suffered major limitations that, in our view, justify revisiting the problem. First, H04 used 10 years of model outputs from two climate models to estimate seasonal averages, and then used Student *t*-tests to determine the statistical significance of differences between precipitation in simulations with and without a lake. However, central Australia has highly variable rainfall: its coefficient of variation is 0.4 (calculated using the Climatic Research Unit gridded data (Harris et al., 2020) over the period 1961–2010). This implies that the ratio of signal (changes to total precipitation caused by the presence of a lake) to noise (natural variability in total precipitation caused by processes unrelated to the lake) will be relatively low, necessitating a larger sample size to identify any possible signal (i.e., to avoid being underpowered). We further investigate the power of H04 in Text S1 in Supporting Information S1. In addition, the reported trivial influence of the permanent lake on local and regional precipitation was not followed by supporting analysis of recycled versus advected precipitation and land-atmosphere processes that led to the net change.

In this study, we revisit the problem with tools that were not available to previous studies, including H04. Specifically, we run a global climate model with water tracers enabled, making it possible to explicitly identify where water originating from the lake falls as precipitation in the model. The key advantage of this approach is that the water tracer is directly attributable to the lake, rather than implied by statistical differences between experiments so that it eliminates some confounding sources of variability in precipitation that are unrelated to the lake (e.g., atmospheric noise). More broadly, our approach allows for the investigation of complex rainfall generation processes triggered by the lake. We examine the mechanisms underlying the potential contribution of lake evaporation to total precipitation changes which was not discussed in H04 and related studies. In terms of previous research on interactions between the land surface and atmosphere in Australia, soil moisture anomalies over the Australian continent have been shown to significantly alter atmospheric conditions in a global climate model (Martius et al., 2021). This study would contribute to a better understanding about how inland lakes, as another important form of water storage on land, influence Australian hydroclimate.

This paper is structured as follows. In Section 2, we introduce the study area and the model setup. In Section 3, we present the results of model simulations and analyze the hydroclimatic impacts of a permanent inland lake at local and regional scales, respectively. In Section 4, we summarize this study and draw conclusions.

2. Methodology

To simulate the global climate, the Community Earth System Model 2 (CESM2) of the National Center for Atmospheric Research (NCAR) is used where the Community Atmosphere Model version 6 (CAM6) is coupled to the Community Land Model version 5 (CLM5) (D. M. Lawrence et al., 2019; Danabasoglu et al., 2020). In prescribed-ocean mode, the model employs transient values of sea surface temperature (SST) and sea ice extent that are the result of merging datasets of sea ice and SST from the Hadley Centre and the Optimum Interpolation (OI) SST analysis from the National Oceanic and Atmospheric Administration (NOAA) (Hurrell et al., 2008). The atmosphere model, CAM6, features a horizontal resolution of $0.9 \times 1.25°$ (latitude by longitude), 32 levels in the vertical direction, and a time step of 30 min. Compared to its predecessors, CAM6 made modifications to most of the atmospheric physics parameterizations including an improved cloud microphysics scheme that carries prognostic precipitation species (i.e., rain and snow) (Gettelman et al., 2015) and a retuned deep convection scheme that is more sensitive to convective inhibition (Zhang & Mcfarlane, 1995). The land model, CLM5, has the same horizontal resolution and time step as CAM6. Compared to previous versions, CLM5 maintains the same biogeophysical and biogeochemical parameterizations while including some updates to, for example, the soil evaporation resistance and canopy interception parameterizations (Swenson & Lawrence, 2014) and the crop model (more crop types and corresponding changes in fertilization and irrigation processes) (Badger & Dirmeyer, 2015; Levis et al., 2018).

Previous generations of CESM have been widely used in studies focusing on atmospheric responses to perturbations of land surface water. For example, based on model simulations, soil moisture anomalies were shown to not only influence local to regional hydroclimate (e.g., surface temperature, precipitation) (Chen & Dirmeyer, 2016; Chou et al., 2018) but also cause changes in large-scale circulation patterns (Teng et al., 2019); the remote effects of soil moisture anomalies in Australia were also found to be sensitive to the phases of ENSO (Martius et al., 2021). Climate models have also been increasingly employed to investigate feedbacks between lakes and the atmosphere (Behravesh et al., 2021; Goyette, 2017; Su et al., 2020; Zhu et al., 2020). For simulating lakes in

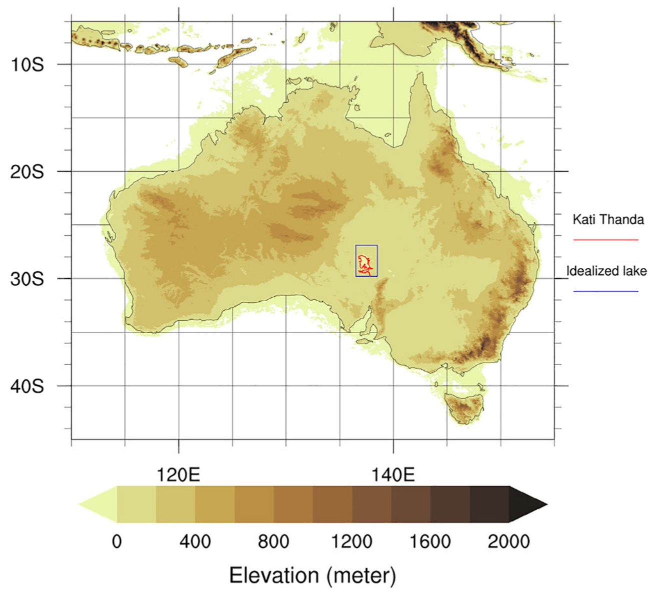

Figure 1. Topographic map showing the location of Kati Thanda and the rectangular region used to represent the idealized lake in model simulations.

CESM, lake parameterizations have been shown to be effective in capturing the atmospheric response to lakes (Subin et al., 2012; Thiery et al., 2015). Climate models suffer from systematic biases at regional and global scales. Nevertheless, CESM2 has been shown to perform reasonably well with major improvements in correcting model biases compared to previous model generations, as well as in a more realistic representation of climatic processes (Danabasoglu et al., 2020).

The intent of this study is to understand the first-order effects of a large inland lake on Australian hydroclimate, meaning our lake does not correspond to the real Kati Thanda in size, depth, and precise location. Instead, our idealized lake is defined to a rectangular domain (30.1°–27.2°S, 136.0°–138.6°E; 76,621.92 km^2) composed of six grid cells (the locations of which are shown by a blue rectangle in Figure 1) covering the lake region of the actual Kati Thanda. Based on the sparse observational records of the depth of Kati Thanda, we used 2.5 m as the depth of the idealized lake. For the control simulation (CTR), percent plant functional types (PFTs) are derived from MODIS satellite data as described in P. J. Lawrence and Chase (2007); the lake region maintains sparsely distributed vegetation (the fraction of grass and temperate shrub ranges from 20% to 40%) rather than being fully covered by bare soil. For the experiment simulation (EXP) with a permanent Kati Thanda, we created the idealized lake by modifying the land surface data set and the land use timeseries data set as inputs to CLM5: specifically, we set the fraction of lake to 100% for the lake cells and correspondingly decreased the fractions of other types of land units such as natural vegetation (represented by PFTs), crops, and urban area to 0% (see D. M. Lawrence et al. (2019) for more details about the nested sub-grid hierarchy in CLM grid cells).

This study compared CTR and EXP to identify resultant changes in energy and water fluxes between the land surface and the overlying atmosphere. More specifically, we used a CESM2 release version that employs an isotope-enabled model with internal numerical water vapor tracers (WVTs) (Nusbaumer et al., 2017; Nusbaumer & Noone, 2018) to "tag" the water originating from the Kati Thanda region from evapotranspiration (ET) (i.e., to enable direct tracking of the water vapor movement from its source region). The CESM WVT scheme has several advantages over some previous approaches to studying precipitation recycling. The traditionally employed bulk recycling approaches (Brubaker et al., 1993) and moisture-tracking models (e.g., the quasi-isentropic back-trajectory algorithm as described in Dirmeyer and Brubaker (1999) and the accounting model as described in van der Ent et al. (2010)) tend to assume a "well-mixed" atmosphere which can lead to underestimation of moisture recycling (Burde & Zangvil, 2001; Goessling & Reick, 2013; Tuinenburg & Staal, 2020). Numerical simulations with WVTs have been increasingly used to get around some of the assumptions made when assessing moisture recycling and to calibrate results obtained by other offline atmospheric moisture recycling models (Dominguez et al., 2022). Previous studies also showed that WVTs were reliable in tracking long-distance moisture transport (Dyer et al., 2017; Wong et al., 2017) which would assist in identifying the impacts of the lake on the hydrologic cycle from local to regional scales in this study. In addition, by activating WVTs along with the model simulations to track water originating from the lake directly, it eliminates many confounding sources of variability in precipitation that are unrelated to the lake. Thus, the signal-to-noise ratio is much higher in our study, even though our sample size is similar to that in H04, which helps avoid problems with the study being underpowered (such as those encountered in H04, described above).

Both CTR and EXP ran for 35 years (1970–2004) but the analyses were only conducted over a 30-year (1975–2004) period with the first five years discarded as spin-up. CAM6 was initialized with a fully moistened atmosphere where WVTs were distributed globally, also with a 5 year spin-up period. In this study, we collected the monthly model outputs and obtained the seasonal results by averaging the monthly results in the corresponding seasons (e.g., averaging the values from December, January, and February to compute the values for austral summer, which is then denoted by DJF). We examined differences between CTR and EXP using the dependent t-test for paired samples with a correction for multiple comparisons to control the false discovery rate (FDR) using the approach proposed by Wilks (2016) ($\alpha_{FDR} = 0.1$) for a domain covering the entire globe.

3. Results and Discussions

3.1. Local-Scale Impacts

This section presents the simulated changes caused by the permanent lake in local precipitation (P) and links those changes to a mechanism responsible for suppressing P. Results are analyzed on both monthly and seasonal scales. Please note that "local" area here refers to the six grid cells parameterized as lake in EXP simulation.

3.1.1. Changes in Precipitation

Figures 2a and 2b show that the permanent lake slightly increases both the monthly P_{tag} (precipitation of water vapor emanating from the lake) and Q_{tag} (water vapor emanating from the lake). The differences between CTR and EXP for both quantities are statistically significant for all months, with the strongest signal in the austral summer. This confirms that our analysis, based on the water vapor tracer, is unlikely to be underpowered. In general, the change in P_{tag} appears correlated with that in Q_{tag}, but of a much smaller magnitude. Specifically, monthly average P_{tag} increases from 0.057 mm/day to 0.159 mm/day, and monthly average Q_{tag} increases from 0.385 to 1.693 mm. These increases may appear large in fractional terms (178% for P_{tag} and 131% for Q_{tag}), however, expressing the increase by fractions may be misleading because, in a desert environment, fractional changes tend to appear large due to the small rainfall amount (denominator). In addition, this study is motivated by the question of whether or not a Bradfield-like scheme would increase precipitation sufficiently to have a meaningful impact on agriculture. For that question, absolute differences better describe the quantity of new water that is made available for agriculture, compared with fractional changes.

The lake causes negligible changes in local P. For reference, Figure 2d shows the monthly difference in total P between EXP and CTR over the lake, similar to the analysis presented in H04. At the monthly time scale, local P in EXP and CTR are statistically indistinguishable from one another (all p-values are greater than 0.05, the specific p-values can be found in Table S1 in Supporting Information S1). The difference is also statistically trivial when the outputs are aggregated to seasonal time scales (not shown here). While the sample size in our study is $n = 30$ years rather than $n = 10$ years, as in H04, it is likely that the tests performed in Figure 2d are still underpowered. This comparison highlights the essential role of the water tracer in our study, for which the analyses are not underpowered. The underlying mechanism of lake-induced precipitation change will be discussed in Section 3.1.3.

While local P does not change very much, the fraction of local ET "recycled" back to the region as local P does increase. Moisture recycling, also known as precipitation or rainfall recycling, is defined as the contribution of local ET to local P (Eltahir & Bras, 1996; Tuinenburg & Staal, 2020). Figure 2c shows that the precipitation recycling ratio, ρ, quantified as the proportion of recycled P (P_{tag}) to total P, increases significantly in all months over the lake. Our estimated values of ρ shown in Figure 2c are within an acceptable range given by previous studies (Holgate et al., 2020; Trenberth, 1999), after accounting for differences in spatial resolutions and differences in the definition of ρ between studies (Holgate et al., 2020). Trivial changes in local P with a statistically significant increase of ρ indicates that recycled precipitation may only be a minor contributor to local precipitation in the region as can be inferred from the comparison of Figures 2a and 2b.

3.1.2. Surface Cooling Effects

In addition to enhanced evaporation, the lake also influences local thermodynamics. Here, we analyze surface cooling caused by the lake. Compared to CTR, the permanent lake EXP shows a decrease in surface albedo (α) over the lake region, resulting in an increase in the net radiation received at the surface (R_{net}). On average, the permanent lake reduces α by 70% and increases R_{net} by 62% (Figures 2e and 2f; changes in both variables are statistically significant at the monthly scale). There is no statistically significant change in cloud fraction (not shown). Due to the increased R_{net} via α changes and more surface water available to evaporate, latent heat flux (LHF) increases at the local scale especially in austral summer. The difference between EXP and CTR can be up to 150 W/m^2 (Figure 2g; the increases are statistically significant in all months). Enhanced LHF causes evaporative cooling, which reduces the near surface air temperature. The increases in LHF are greater for warmer months, for example, in the summer (DJF). As a result, within the lake region, the response of near-surface air temperature to the permanent lake varies seasonally: the 2-m air temperature (TAS) decreases by approximately 2.5 K in summer months (DJF)—a statistically significant decrease—while from March to September, local TAS does not show significant changes when comparing EXP to CTR (Figure 2h).

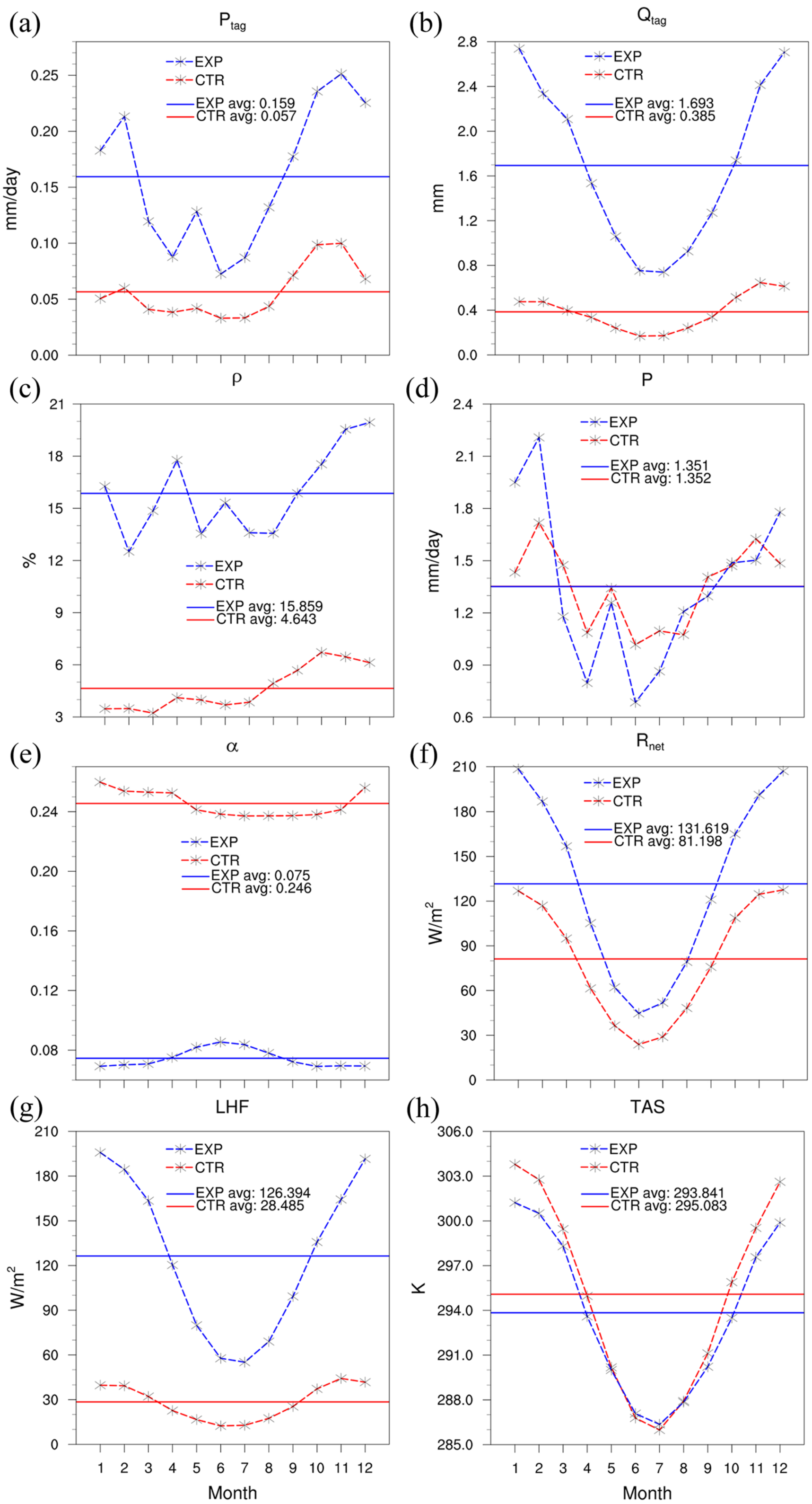

Figure 2. 1975–2004 climatological monthly changes over the lake region in: (a) precipitation of water vapor originating from the lake region (P_{tag}); (b) water vapor originating from the lake region (Q_{tag}); (c) precipitation recycling ratio (ρ); and (d) precipitation (P); (e) surface albedo (α); (f) net radiation at the land surface (R_{net}); (g) latent heat flux (LHF); and (h) 2 m air temperature (TAS). Results from CTR are in red while results from EXP are in blue. Monthly averages are depicted by dashed lines with markers while solid lines show values averaged across the twelve months.

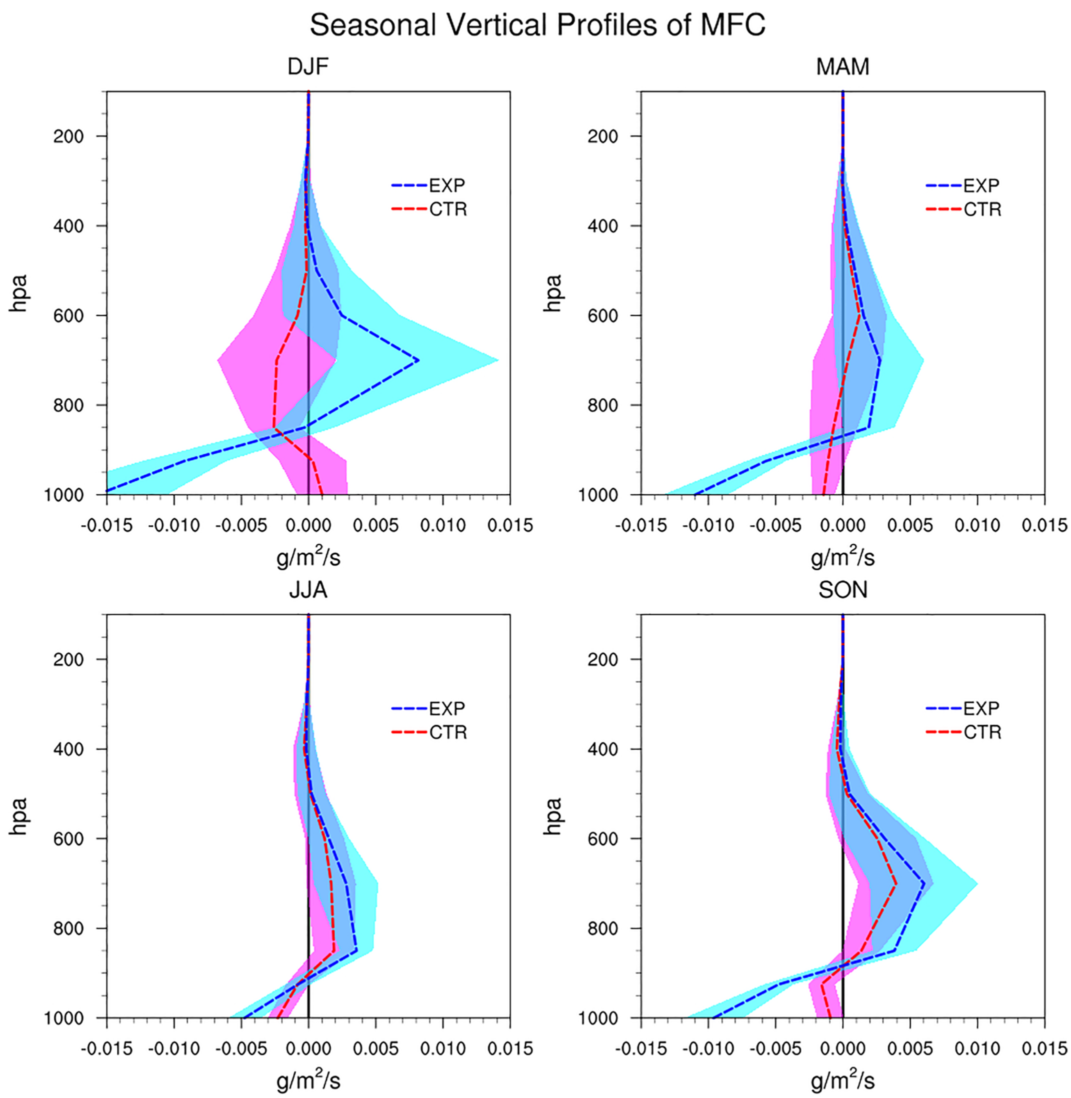

Figure 3. The vertical profile of moisture flux convergence; black reference lines show the zero values on the horizontal axis; shaded areas are for the ±1 standard deviation of moisture flux convergence in CTR (magenta) and EXP (cyan).

The changes in the surface energy budget as shown in Figure S1 in Supporting Information S1 can be attributed to the idealized lake in EXP. In contrast to CTR, all other land cover types were replaced by a water surface over the lake region in EXP. Therefore, EXP ends up with a reduced α, leading to an increase in R_{net}. However, the extra absorbed radiation does not lead to an increase in temperature because R_{net} is mostly partitioned into stronger LHF which contributes to an enhanced evaporative cooling effect (Figure S1 in Supporting Information S1). Consequently, EXP experiences statistically significant decreases in both surface temperature (approx. −2.3 K) and near-surface air temperature (approx. −1.24 K) during spring (SON) and summer (DJF).

3.1.3. Surface Cooling Suppresses Local Precipitation

Why does local precipitation not increase much when the otherwise dry surface is changed to a lake? Some previous studies on the interactions between land surface water and precipitation reported positive feedbacks between soil moisture anomalies and P (Eltahir, 1998; Findell & Eltahir, 2003; Qian et al., 2013; Zheng & Eltahir, 1998) or the contribution of increased surface water (e.g., reservoirs or soil moisture) to the increase of P in the downwind directions (DeAngelis et al., 2010; Degu et al., 2011). Those studies generally attribute the increase of P to an enhanced availability of atmospheric moisture and its subsequent impacts on convection initiation and cloud formation. Clearly, those mechanisms are not dominant here. Figure 3 shows the vertical profiles of moisture

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flux convergence (MFC) over the lake region. MFC of an area quantifies the magnitude of water vapor flux converging into the area (Banacos & Schultz, 2005; van Zomeren & van Delden, 2007). Vertically integrated or near-surface MFC has been used in forecasting the initiation of convection and rainfall (Bothwell, 1988; Hudson, 1971; Kuo, 1974; Walker & Bordoni, 2016). Here we examine the vertical profile of MFC to examine if the atmospheric condition favors precipitation production when there is a lake. Figure 3 shows noticeable decreases in MFC near the surface in the presence of a permanent lake, in all seasons except JJA when MFC in EXP shows only a moderate decrease compared to CTR. After correcting for multiple comparisons, differences in MFC between CTR and EXP are statistically significant below 850 hpa in all seasons. The decrease in near surface MFC in EXP is likely caused by a lower surface (and near-surface) temperature in EXP, which results in a higher surface pressure and reduced convergence. We further partition MFC into the advection term (MFC_{adv}) and the convergence term (MFC_{conv}) using Equations 1 and 2 (Seager & Henderson, 2013):

$$\mathrm{MFC_{adv}} = -\boldsymbol{V}_h \cdot \nabla q = -\left(u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y}\right), \tag{1}$$

$$\mathrm{MFC_{conv}} = -q \cdot \nabla \boldsymbol{V}_h = -q\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \tag{2}$$

where u and v represent the zonal and meridional wind components, respectively, and q is the specific humidity; $\nabla = (\partial/\partial x)\mathbf{i} + (\partial/\partial y)\mathbf{j}$ and $\boldsymbol{V}_h = u\mathbf{i} + v\mathbf{j}$. Results are shown in Figures S2 and S3 in Supporting Information S1: the differences between CTR and EXP are statistically significant for MFC_{conv} in the lower atmosphere with a reduced change in winter, but the near surface MFC_{adv} exhibits much smaller difference between CTR and EXP. This implies that the reduction of near surface MFC (Figure 3) by the permanent lake largely originates from the decreased MFC_{conv}, and MFC_{adv} remains less influenced by the lake.

Our results show that evaporative cooling over the lake strengthens low-level divergence, which suppresses precipitation. A very similar mechanism was reported previously by Cook et al. (2006), where the increase in evaporative cooling was caused by wet soil. Specifically, Cook et al. (2006) showed that increased soil moisture not only decreased the ability to form P by enhancing subsidence (i.e., increasing atmospheric stability) but also decreased the supply of moisture by anomalous surface divergence. Similar research has also been conducted over other dry regions in the world and found that the local cooling effects decreased P via changes in the pressure field and the transportation of water vapor (Lo et al., 2021).

3.2. Regional-Scale Impacts

Unlike the significant surface cooling identified at the local scale, the model simulations in this study do not show changes that are statistically significant in either surface temperature or near-surface air temperature elsewhere within the Australian continent. We also find that specific humidity and total ET in the surrounding area do not show statistically significant change after the idealized lake is added. This section primarily focuses on investigating the impacts of the permanent lake on regional P with the help of WVTs. For the regional-scale assessment of precipitation changes (both magnitude and statistical significance), analysis of outputs is done grid cell by grid cell over Australia outside of the lake grid cells. At the end of this section, we discuss limitations of our analysis.

Precipitation of water vapor originating from the inland lake causes only minor changes in regional precipitation. The third (Figures 4i–4l) and the fourth (Figures 4m–4p) columns of Figure 4 show the difference in 30-year climatology of P_{tag} and Q_{tag} between CTR and EXP by subtracting CTR from EXP (i.e., EXP-CTR), respectively. Those values are clearly small, relative to seasonal mean precipitation (Figures 4a–4d). While small, the differences in both P_{tag} and Q_{tag} are statistically significant, which further confirms that our analysis is unlikely to be underpowered. The spatial distribution of P_{tag} generally exhibits a spatial pattern similar to Q_{tag}. The water vapor plume emanating from the lake is diffused and advected away from the lake by prevailing winds (Figure S4 in Supporting Information S1). For reference, we also show differences in total precipitation between CTR and EXP (Figures 4e–4h), similar to H04. None of the observed differences are statistically significant, which is further consistent with the idea that such an analysis would be underpowered.

In summary, water evaporated from the inland lake causes only minor increases in precipitation elsewhere in Australia, which are very small relative to natural variability in precipitation in the region. Thus, our results ultimately agree with those in H04, which found that widespread and significant changes in P should not be

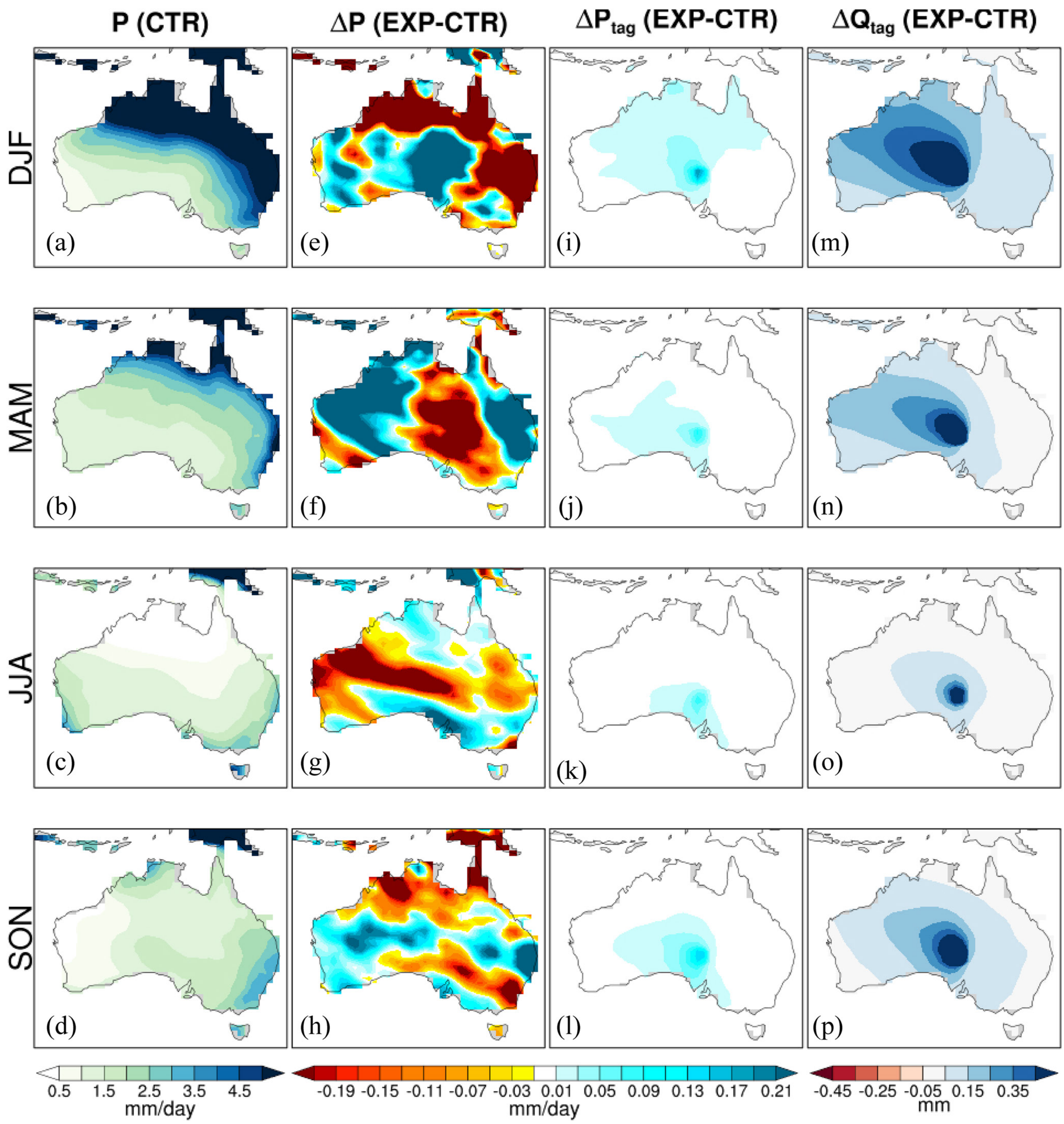

Figure 4. (a–d) Seasonal climatology of P in CTR; (e–h) difference in the seasonal climatology of P between CTR and EXP; (i–l) difference in the seasonal climatology of P_{tag} between CTR and EXP; and (m–p) difference in the seasonal climatology of Q_{tag} between CTR and EXP. The same color scale was used for mapping P and P_{tag} to show that the statistically significant difference in the simulated P_{tag} has a very limited contribution to the changes in the simulated P compared to that by natural variability. For the difference in the seasonal climatology of P between CTR and EXP, the percentage (relative) results and absolute results have been provided as Figure S5 in Supporting Information S1.

expected by introducing a permanent lake to the Kati Thanda region. In contrast to H04, our analysis is not under-powered, due to its use of a water vapor tracer.

Our analysis is subject to various limitations. Like all studies employing climate models, the climate model simulations used here are run at a relatively coarse spatial resolution implying that mesoscale mechanisms will be absent from our simulations (Martius et al., 2021). Higher resolution simulations were not computationally feasible at the global scale, but are worth investigating in future. Besides, the lake we consider is relatively small, and situated in one particular location. In future work, we plan to understand the sensitivity of these results to the size and position of the lake.

4. Conclusions

This study investigated the atmospheric response to a permanent lake in central Australia from local to regional scales. Two simulations were run with the water tracer-enabled CESM: one with default initial conditions and transient boundary and land surface conditions; the other with the identical configurations except for the land mask being used to create a permanent shallow lake in the approximate location of Kati Thanda-Lake Eyre. Using WVTs enables us to estimate the changes in the strength of moisture recycling at the local scale and to assess the regional precipitation effects by tracking the movement of lake-originated moisture, which critically distinguishes our work from the sole previous study on the topic (H04). We propose a potential mechanism that leads to the negligible changes in local precipitation and identify the potential sinks for the additional moisture from the lake, both of which were not resolved in previous studies. Based on analyzing the results of the comparison between CTR and EXP, the following conclusions can be drawn:

1. Either locally or regionally, the presence of a permanent lake does not cause changes in total precipitation significantly. While a plume of moisture recycled from the lake is advected and diffused over much of the Australian continent (the fourth column of Figure 4), the amount of recycled precipitation is very small compared to the natural range of total precipitation in Australia.
2. While the precipitation recycling ratio (the fraction of total local precipitation that originates from the local surface) increases with the presence of a permanent lake, local total precipitation does not change significantly due to the relatively small magnitude of the recycled precipitation.
3. The negligible change in local precipitation can be attributed to evaporative cooling at the surface that increases low-level divergence, suppressing precipitation, similar to the mechanism proposed in Cook et al. (2006).

We conclude that there is no reason to believe that a Bradfield-like scheme would lead to significant increases in local or regional precipitation. This critique of the Bradfield scheme is in addition to existing critiques of such schemes based on cost benefit analyses (Petheram et al., 2020, 2021).

Data Availability Statement

The model release of National Center Atmospheric Research (NCAR) Community Earth System Model 2 (CESM2) with water tracers (WVTs) enabled is available via https://github.com/nusbaume/CAM.git and the monthly results of selected model outputs as discussed in this study are available via https://doi.org/10.26188/22339546.v1.

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Supporting Information for "Negligible impact on precipitation from a permanent inland lake in central Australia"

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Contents of this file

Introduction

This document contains additional supporting information to the manuscript. Figure S1 is mentioned in Section 3.1.2 and shows the energy budgets over the study area; Figure S2 and S3 are mentioned in Section 3.1.3 and show the vertical profiles of the advection term and convergence term of moisture convergence flux, respectively; Figure S4 is mentioned in Section 4 and shows the spatial patterns of tagged precipitation as well as wind field during different periods of the EXP simulation; Figure S5 shows the percentage (relative) and absolute difference in the seasonal climatology of P between CTR and EXP compared to Figure 4.

Text S1. In this section, we quantitatively examine the likelihood that H04 is underpowered. The simulation outputs from H04 are not publicly-available, so we cannot directly examine their results. Instead, we examined the difference between CTR and EXP precipitation in our own simulations using a dependent t-test for paired samples, which addresses the covariance between CTR and EXP caused by the use of identical sea surface temperatures in both simulations. Our simulations are longer than those in H04 (i.e., we increase the sample size), so if this analysis is underpowered for our simulations, it is likely that it is also underpowered in H04. We found that the standard deviation of the difference between CTR and EXP precipitation in our simulations was typically 5-10 times larger than the mean (e.g., for JJA, the mean of the difference between CTR and EXP is 0.19 mm/day while the standard deviation is 1.19 mm/day), and the tests were consistently underpowered. Thus, it seems likely that H04 was underpowered, too. Note that our study avoids this problem by using water tracers.

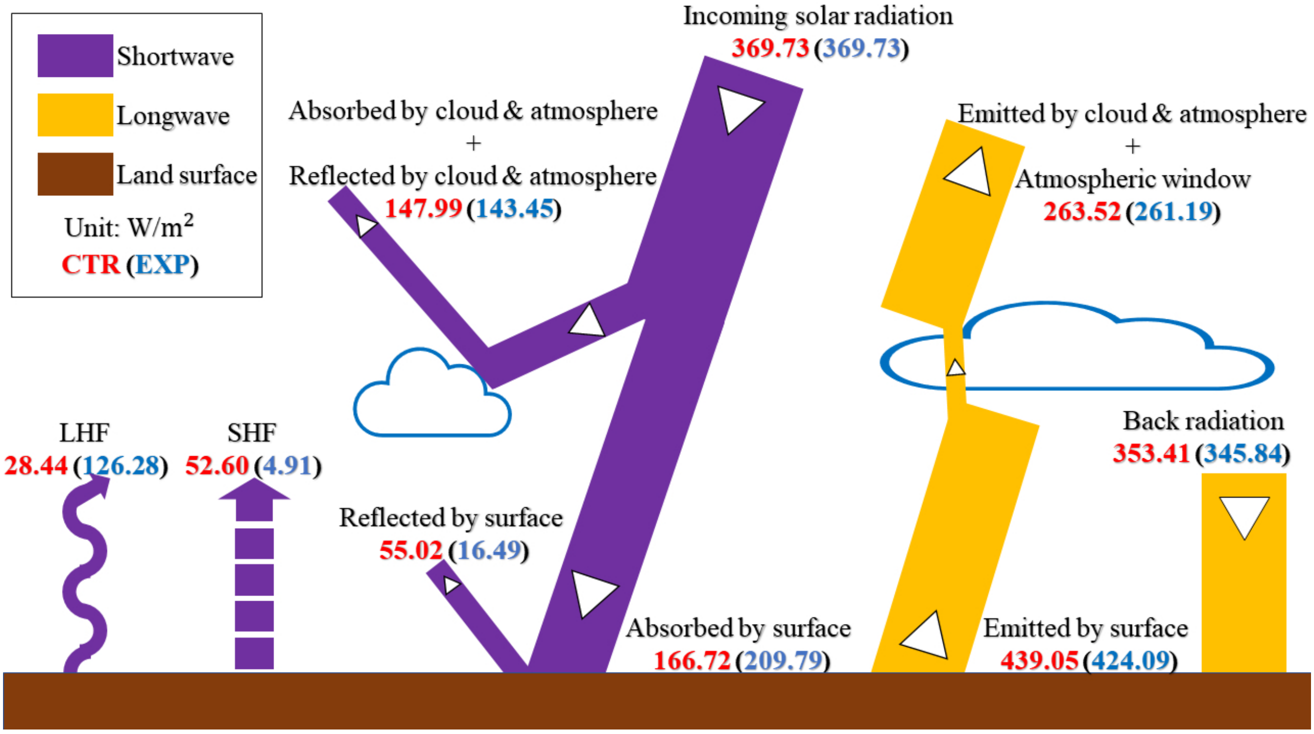

Figure S1: Energy budgets over the lake region for CTR (red) and EXP (blue). Annual averages were calculated for all radiative and non-radiative components.

Table S1: p-values by the dependent t-test for for paired samples of the local precipitation on monthly scale

Grid #	p-values for lake-region grid cells											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.551	0.276	0.551	0.362	0.524	0.219	0.950	0.508	0.589	0.893	0.705	0.444
2	0.681	0.804	0.246	0.261	0.463	0.166	0.713	0.569	0.349	0.836	0.33	0.591
3	0.321	0.102	0.590	0.550	0.705	0.106	0.399	0.465	0.647	0.850	0.931	0.393
4	0.353	0.430	0.336	0.318	0.881	0.104	0.291	0.674	0.592	0.697	0.401	0.641
5	0.196	0.182	0.751	0.422	0.912	0.088	0.228	0.773	0.999	0.946	0.98	0.474
6	0.172	0.413	0.518	0.203	0.836	0.092	0.231	0.990	0.931	0.860	0.167	0.506

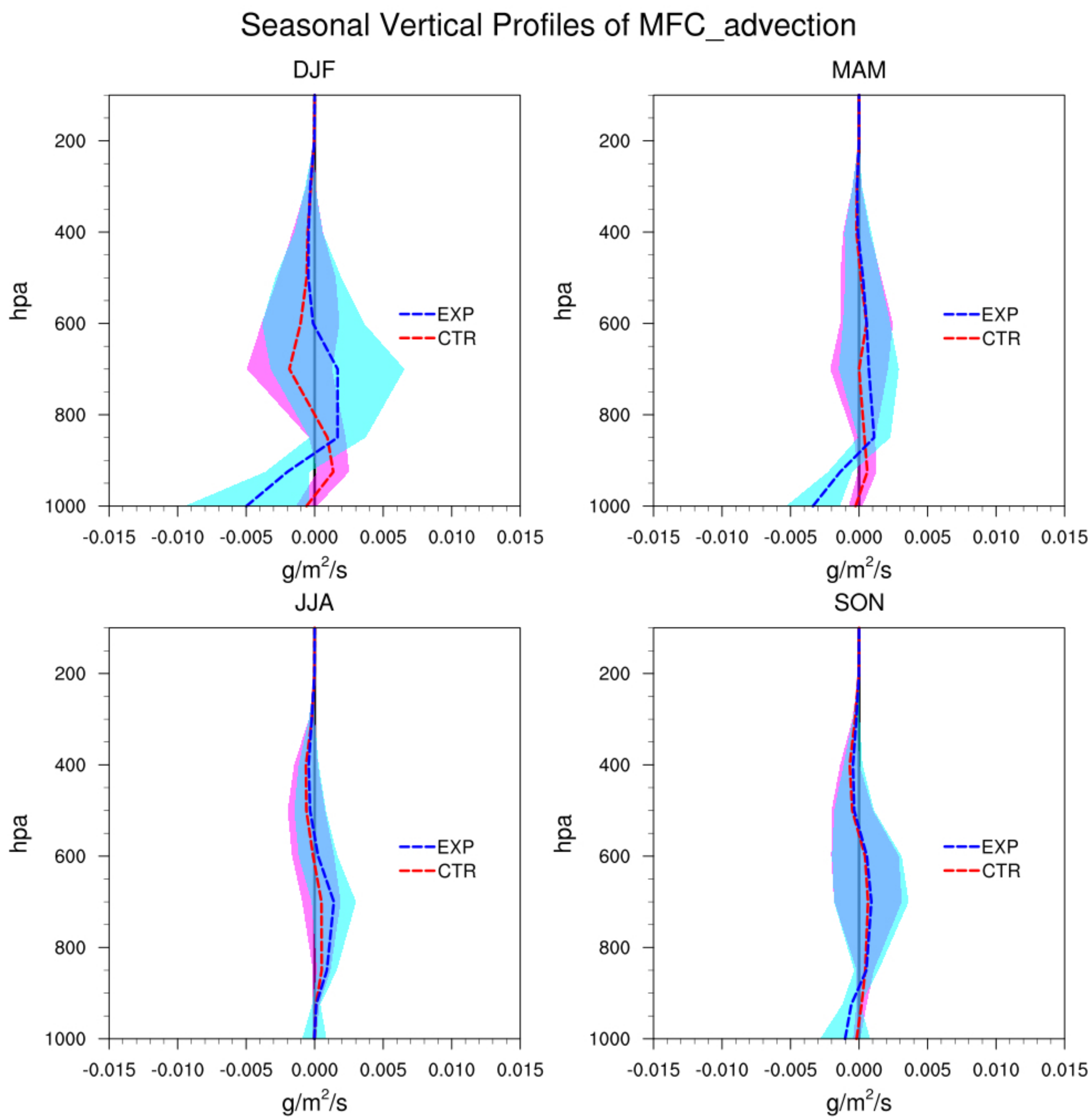

Figure S2: Vertical profiles of specific humidity advection. Black reference lines show zero values on the horizontal axis; shaded areas are for the ± 1 standard deviation of moisture flux convergence in CTR (magenta) and EXP (cyan)

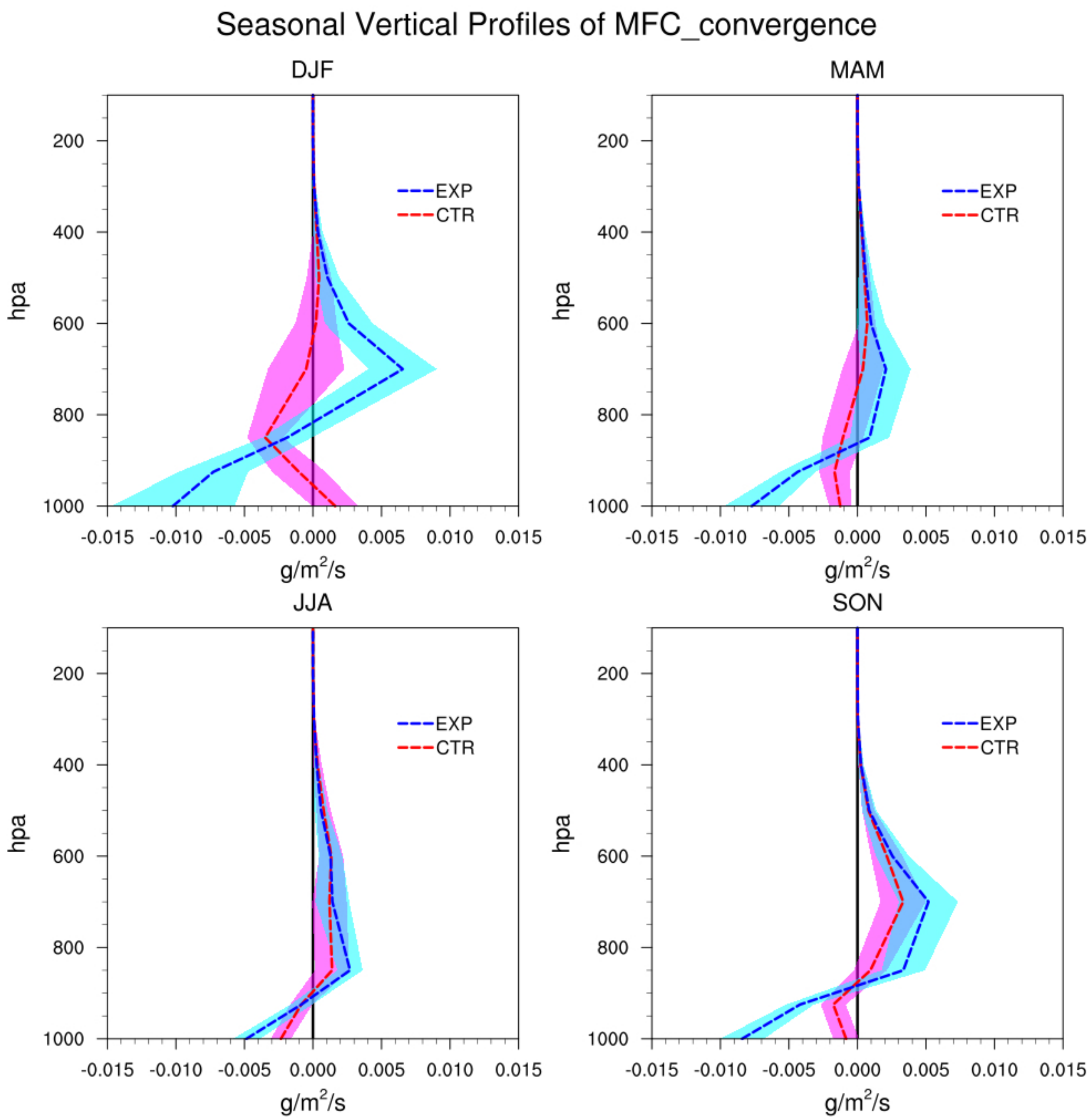

Figure S3: Vertical profiles of wind convergence. Black reference lines show zero values on the horizontal axis; shaded areas are for the ± 1 standard deviation of moisture flux convergence in CTR (magenta) and EXP (cyan)

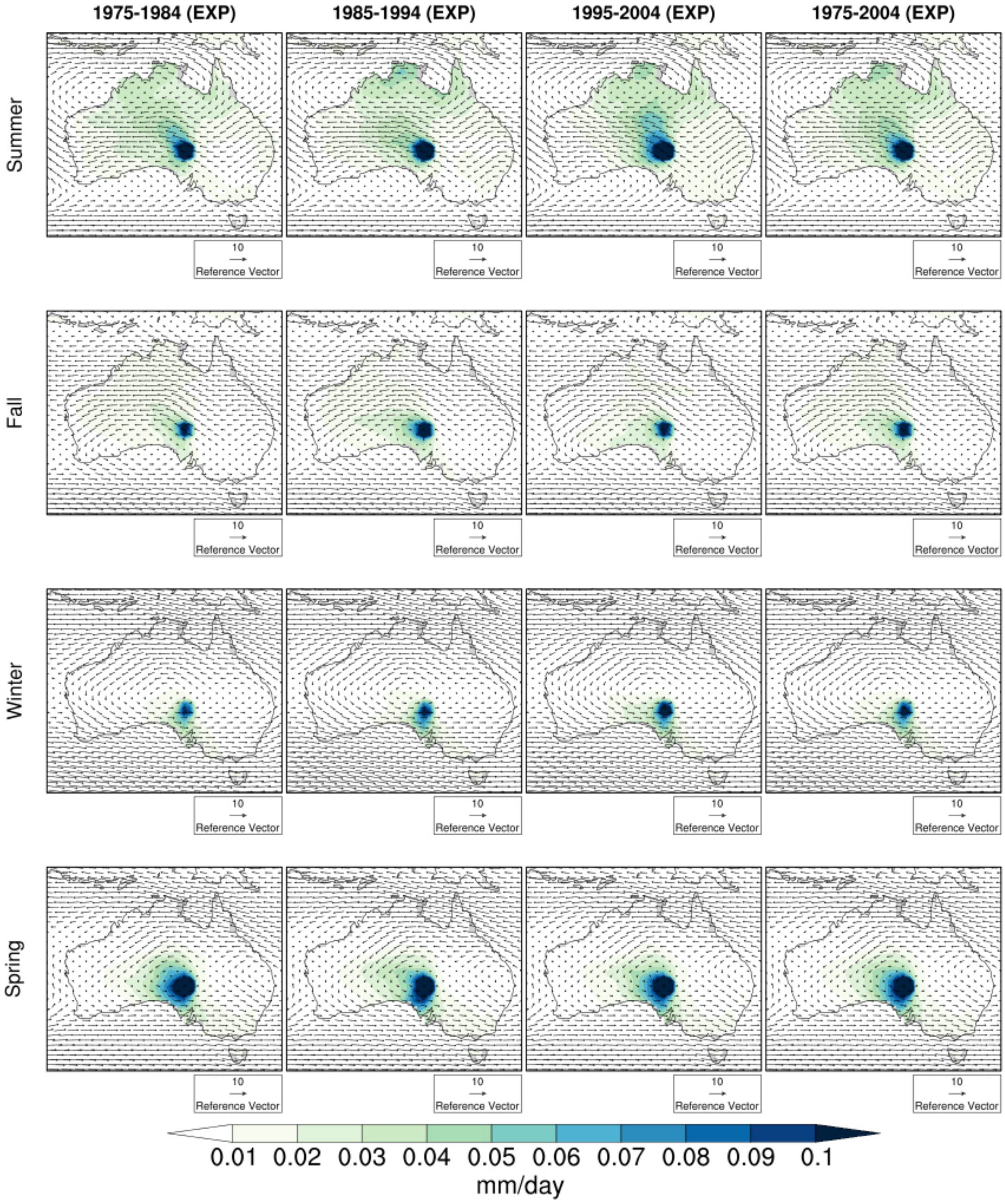

Figure S4: Spatial distribution of P_{tag} in EXP over three 10-year subsets of the simulation period and over the whole simulation period; contour maps are overlaid by the wind field at 850 hpa

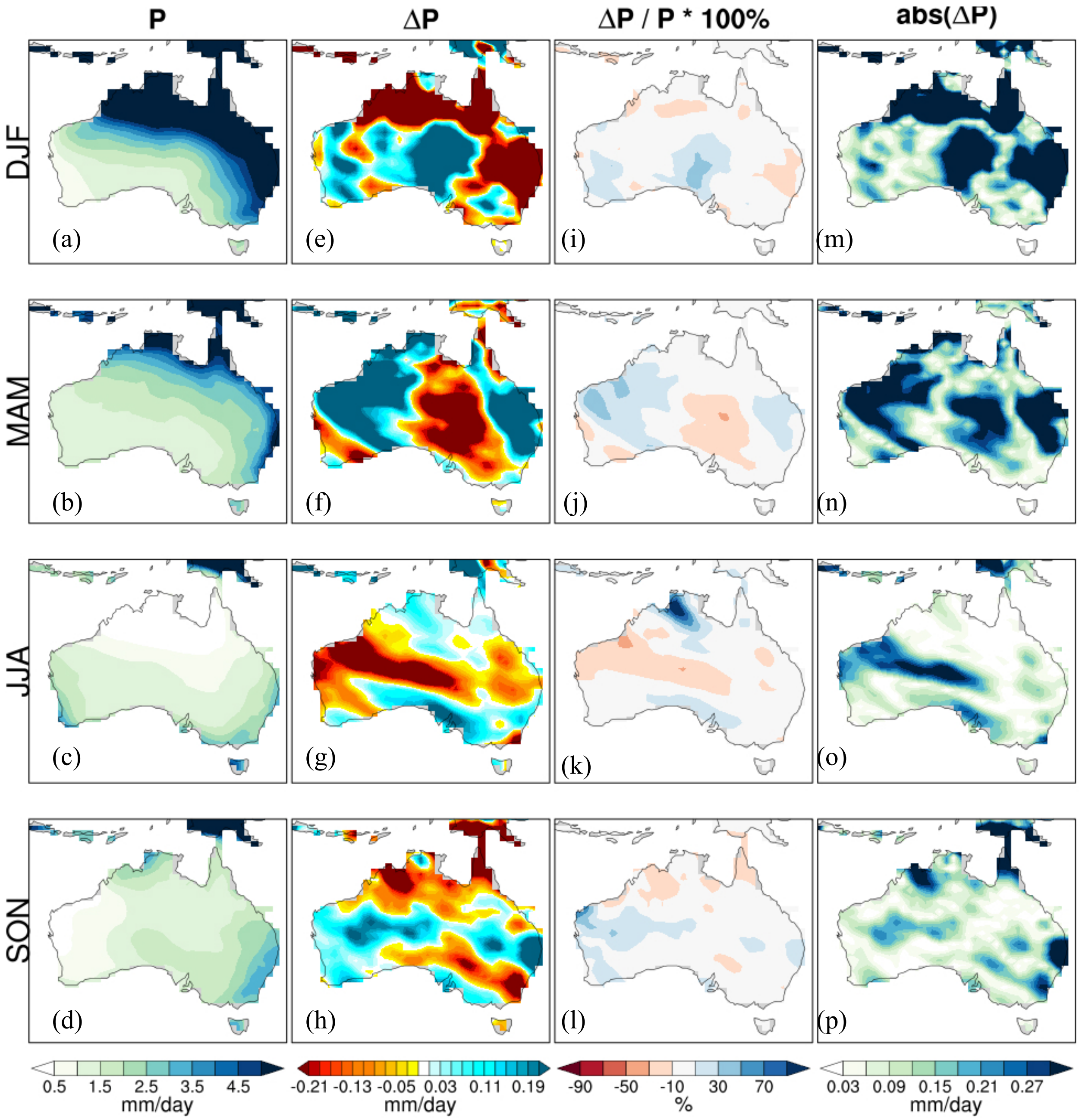

Figure S5: (a–d) Seasonal climatology of P in CTR; (e–h) difference in the seasonal climatology of P between CTR and EXP; (i–l) percentage difference in the seasonal climatology of P between CTR and EXP; and (m–p) absolute difference in the seasonal climatology of P between CTR and EXP.