CORRESPONDENCE

Reply to "Comments on 'Sea Breeze Geoengineering to Increase Rainfall over the Arabian Red Sea Coastal Plains'"

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We thank authors Branch and Wulfmeyer for pointing us to their publications on the effect of forestation on precipitation in coastal desert areas (Becker et al. 2013; Branch and Wulfmeyer 2019; Wulfmeyer et al. 2014). The idea of our study (Mostamandi et al. 2022) was initially restricted to testing how we can access a vast natural resource of freshwater circulated by breezes from the Red Sea to land. But this "breeze geoengineering" study overlaps with the more general topic of forestation as a method of land surface modification that increases precipitation, and which could remove vast amounts of CO_2 from the atmosphere. We agree that this aspect deserves additional discussion. We are therefore using the response as an opportunity to review a selection of the most recent literature on forestation from a more general standpoint than in the original paper, and we evaluate our results from this perspective.

We are most interested in forestation in the deserts. Desert land could be forested, in addition to an area of 9 000 000 km^2 of land with global tree restoration potential, comprising unforested and unused land in areas with sufficient precipitation to grow trees (Bastin et al. 2019). To maintain forests in deserts, irrigation would be necessary. Recycling evaporated water is important as it decreases the amount of freshwater required for irrigation. The effect of land surface modifications on precipitation and water recycling depends on the type of regional background circulation system where trees were planted. Over the Red Sea coastal plain, it is breeze circulation that dominates the transport of water from sea to land. The Red Sea breezes are among the strongest in the world. These breezes are sensitive to the temperature contrast between land and sea in the coastal area. Any changes to this temperature contrast will feed back into the strength of the breeze circulation. This feedback is at the core of our study.

Afforestation of the coastal plain is just one possible way to affect breezes. We have also considered a change of surface albedo. In fact, our experiments with decreasing albedo are the closest to those considered in Becker et al. (2013), Wulfmeyer et al. (2014), and Branch and Wulfmeyer (2019). They evaluated the effect of *jojoba chinensis* plantations on precipitation in Oman and Southern California. The *jojoba chinensis* trees have a uniquely low water consumption, which differentiates this type of vegetation from almost all known types of broadleaf trees. The *jojoba chinensis* plantations evaporate a negligible amount of water but decrease the surface albedo in comparison with the ambient desert, therefore intensifying radiative heating. The conclusions from our "lower albedo" experiments appear consistent with those of Becker et al. (2013), Wulfmeyer et al. (2014), and Branch and Wulfmeyer (2019). In both of the above cases, precipitation increases, although the physical reasons for the increase in precipitation are different. In our case, we observe the strengthening of breezes due to an increase in the temperature contrast between sea and land, but in Becker et al. (2013), Wulfmeyer et al. (2014), and Branch and Wulfmeyer (2019), convection develops on the background large-scale "Musson-type" circulation pattern, not directly affected by forestation.

We conduct our simulation with a 3-km grid spacing, which allows for resolving deep convection. However, this resolution is insufficient to resolve shallow convection in the atmospheric boundary layer (ABL), which is a drawback of our simulations as well as calculations in Becker et al. (2013), Wulfmeyer et al. (2014), and Branch and Wulfmeyer (2019) conducted with a 4-km grid spacing. The height of the ABL, in our case, reaches 5–6 km, and parameterization of boundary layer turbulent mixing compensates for underresolving

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shallow convection in the ABL. Intensive vertical turbulent mixing in the desert ABL tends to disperse near-surface water vapor, thus preventing condensation and precipitation. Evaporation from the canopy is sensitive to the level of irrigation. Evapotranspiration increases nonlinearly with an increase in irrigation. However, in our study even high evapotranspiration does not force the recycling of water over the Red Sea coastal plain. Accordingly, irrigating the forest requires a tremendous amount of freshwater.

It was recognized that planting and growing forests while also increasing precipitation appears to be an effective way of removing a vast amount of CO_2 from the atmosphere (Griscom et al. 2017; Herrick et al. 2019). Encouraged by these ideas, widespread forestation programs were started in China (Great Green Wall), Germany, and Pakistan (10 billion tree tsunami). The World Economic Forum launched its one trillion trees (by 2030) project (1t.org) in 2020. Recently, Saudi Arabia announced an ambitious Saudi green initiative planning to plant 10 billion trees. Altogether, the Middle East countries pledged to plant 50 billion trees.

To evaluate the overall feasibility of the desert forestation projects, consideration of the freshwater water balance is paramount. Assuming that a tree requires 5 L of water per day, which is half the minimum per-tree water consumption reported in Dawson (1996) and approaches the level of *jojoba chinensis* water consumption (Holl et al. 2007), we find that irrigation for the 10 billion trees assumed to be planted in the course of the Saudi green initiative will need 18 Gt of water per year, which is more than Saudi Arabia's annual freshwater consumption. The increase in precipitation in the forested areas could alleviate the water scarcity problem. Therefore, a better understanding of recycling freshwater evaporated from irrigated areas is paramount. However, we found that little water recycling occurred in our experiments with the forestation of the Red Sea coastal plain.

Along with increased precipitation, forestation has a profound effect on hydrology. Trees consume a significant amount of water and can dry out rivers, lakes, and wetlands. In fact, planting trees reduces freshwater availability since about 30% of water evaporated from land precipitates in the ocean (Hoek van Dijke et al. 2022). The expectation that tree planting effectively removes carbon from the atmosphere underestimates that in the course of climate change, forests could be affected by droughts, insects, diseases, and forest fires that will release carbon back into the atmosphere.

In our study, we suggest that technocratic methods such as strategic distribution of solar panels, along with forestation, could be considered as land modification technologies that affect precipitation in local areas. Implementing such an approach does not carry the additional benefit of carbon sequestration but provides "green" electricity instead. Land modification assessments must be conducted on both regional and local scales in order to account for fine regional circulations and topographic features. It is also important to account for ongoing climate change, since it could affect the efficacy of proposed land-use modifications in the future.

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