Northland: the climate of a world with a hemispheric continent and a hemispheric ocean

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Abstract

Join us in an exploration of the climate of Northland, a world where the entire northern hemisphere is covered by a continent, and the entire southern hemisphere is covered by an ocean! On the continent, we will visit the seasonally moist tropics, the subtropical desert, and the Great Northern Swamp. We explore the interplay between water, energy, land, ocean, and atmosphere in this idealized climate model study. We find that the presence of a continent greatly increases the poleward extend of the ITCZ over both the land and ocean hemispheres compared to an aquaplanet, as a result of hemispheric energy imbalances introduced by (a) the small heat capacity of land and (b) large reductions in atmospheric water vapor (and thus reduced longwave trapping) over the continent. A combination of moisture transport from the tropics and local water recycling results in a polar swamp over the continent. We explore how the climate state responds to changes in the albedo and evaporative resistance of the continent. While making the land surface darker leads to warming, we find that decreasing evaporation from the land surface leads to global-scale cooling. This is in contrast to past studies, where reduced terrestrial evaporation leads to warming as a result of suppressed evaporative cooling of the land surface. In the case of Northland, the lack of an ocean to provide water to the northern hemisphere means that decreasing land evaporation leads to large reductions in water vapor over the northern hemisphere, in turn reducing strength of the greenhouse effect, resulting in cooling of near-surface air temperatures. This cooling signal is strongest over the continent, but cools air temperatures over the ocean hemisphere as well. We hypothesize that a threshold exists in the temperature response to reduced terrestrial evaporation: for small decreases in evaporation, reduced latent cooling dominates and near-surface temperatures warm, while for large decreases in evaporation, reduced longwave trapping from reduced atmospheric water vapor dominate, cooling near-surface temperatures. Through this idealized study of a hypothetical, Earth-like planet, we gain valuable insight into the connections between water, energy, land surface properties, and continental distribution in controlling global-scale climate.

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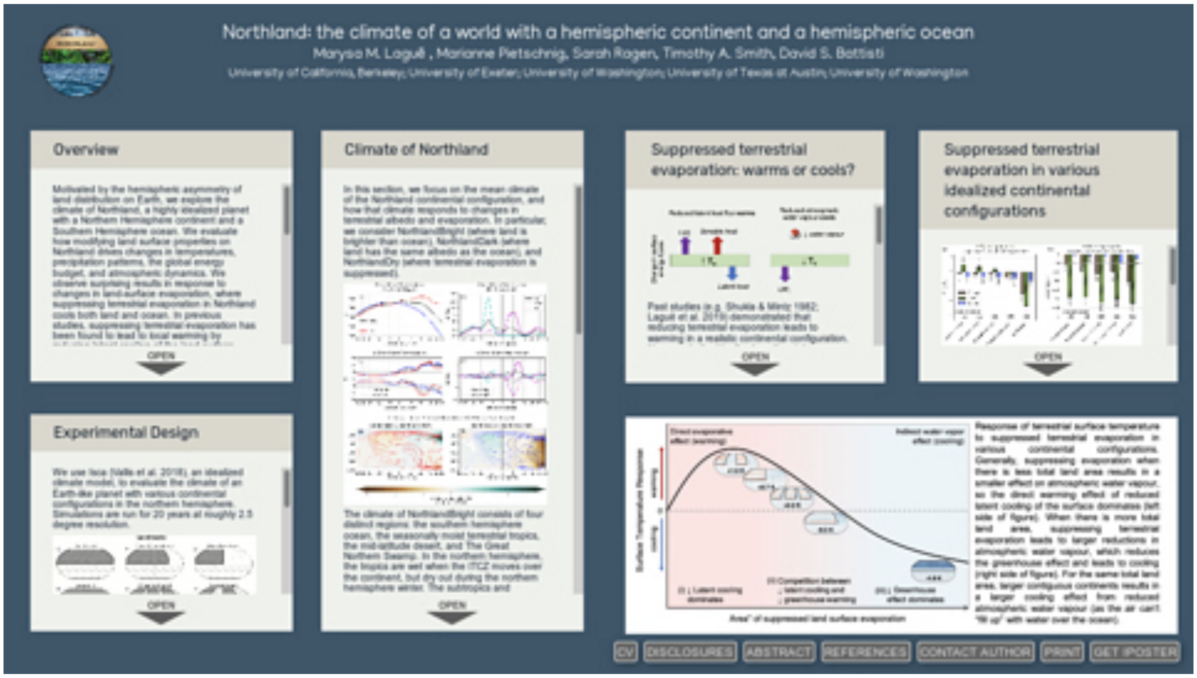

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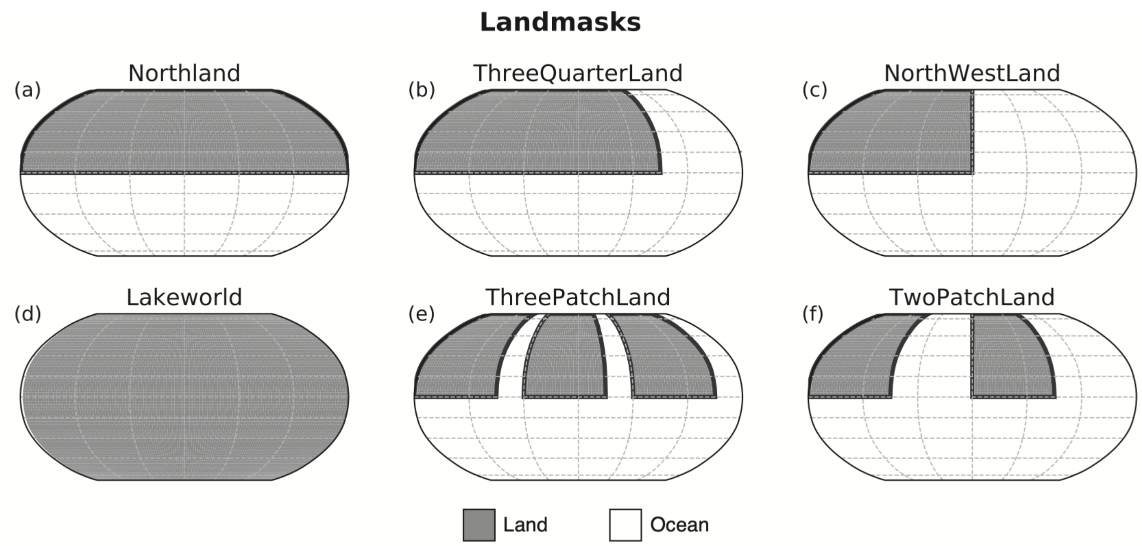
OVERVIEW

Motivated by the hemispheric asymmetry of land distribution on Earth, we explore the climate of Northland, a highly idealized planet with a Northern Hemisphere continent and a Southern Hemisphere ocean. We evaluate how modifying land surface properties on Northland drives changes in temperatures, precipitation patterns, the global energy budget, and atmospheric dynamics. We observe surprising results in response to changes in land-surface evaporation, where suppressing terrestrial evaporation in Northland cools both land and ocean. In previous studies, suppressing terrestrial evaporation has been found to lead to local warming by reducing latent cooling of the land surface. However, reduced evaporation can also decrease atmospheric water vapor, reducing the strength of the greenhouse effect and leading to large-scale cooling. Here, we use a set of idealized climate model simulations to show that suppressing terrestrial evaporation over Northern Hemisphere continents of varying size can lead to either warming or cooling of the land surface, depending on which of these competing effects dominate. We find that a combination of total land area and contiguous continent size control the balance between local warming from reduced latent heat flux and large-scale cooling from reduced atmospheric water vapor. The climate of Northland can be separated into four distinct regions: the Southern Hemisphere ocean, the seasonally wet tropics, the mid-latitude desert, and the Great Northern Swamp. We demonstrate how terrestrial heat capacity, albedo, and evaporation all modulate the location of the ITCZ both over the continent and over the ocean.

EXPERIMENTAL DESIGN

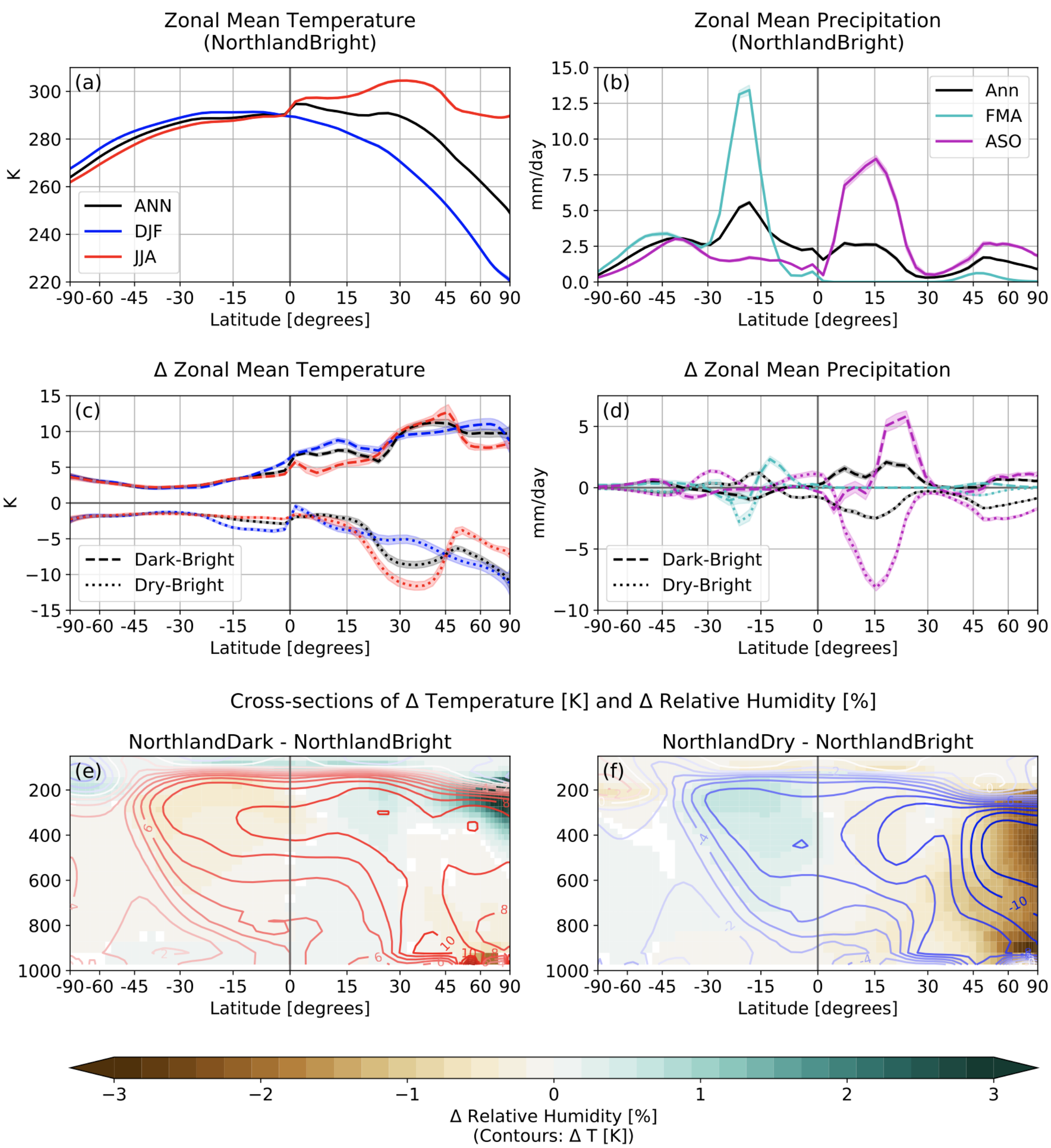
We use Isca (Vallis et al. 2018), an idealized climate model, to evaluate the climate of an Earth-like planet with various continental configurations in the northern hemisphere. Simulations are run for 20 years at roughly 2.5 degree resolution.



Six continental configurations are considered. In Northland, the entire northern hemisphere is covered by land. In TwoPatchLand and NorthWestLand, half of the northern hemisphere is covered by land, while in ThreePatchLand and ThreeQuarterLand, three-quarters of the northern hemisphere are land covered. NorthWestLand and ThreeQuarterLand have large single continents, while TwoPatchLand and ThreePatchLand are broken into separate, equally spaced continents. Lastly, we consider Lakeworld, and all-land planet where the terrestrial bucket hydrology model has been modified to allow the land to form lakes in regions where precipitation exceeds evaporation.

CLIMATE OF NORTHLAND

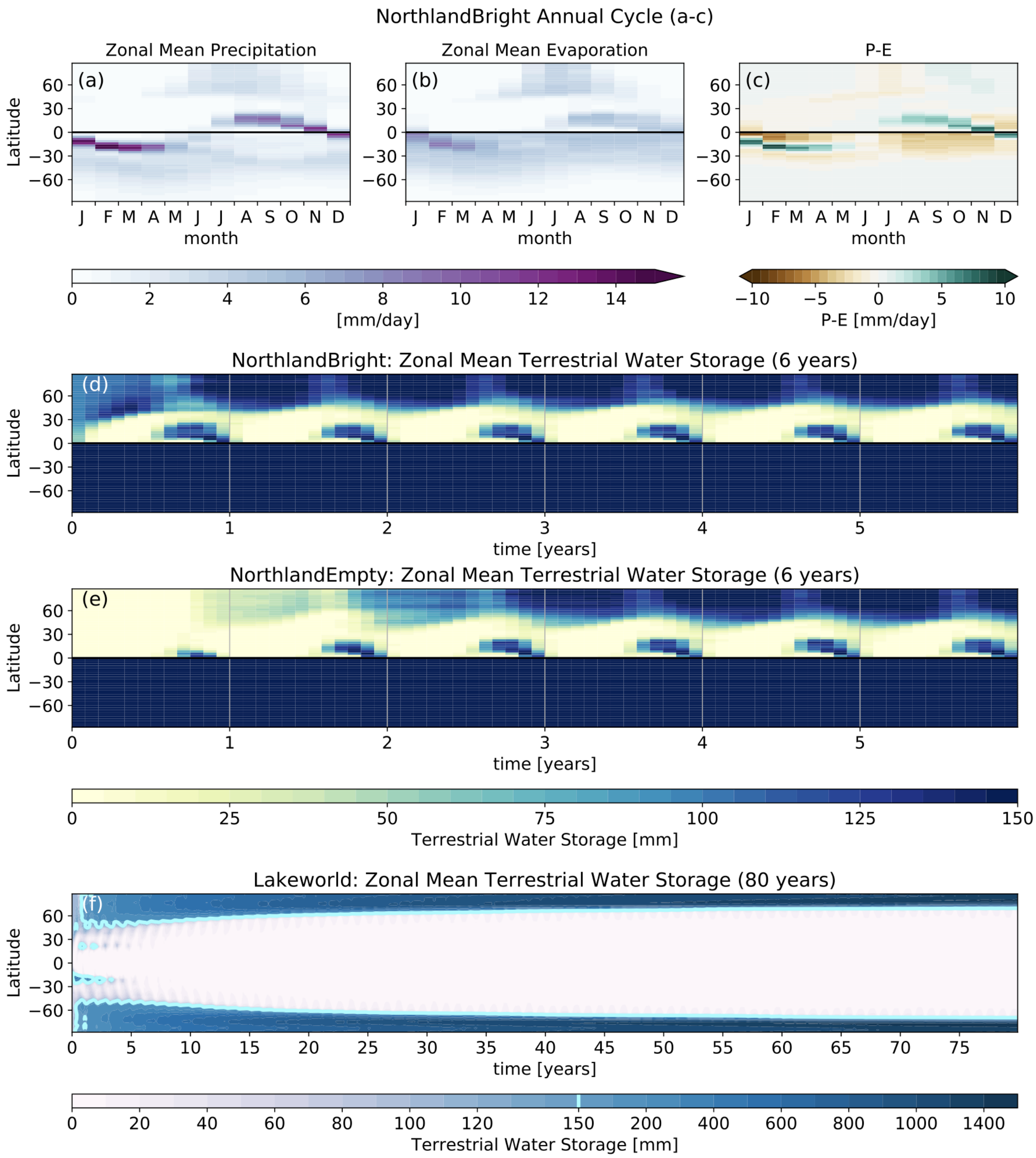
In this section, we focus on the mean climate of the Northland continental configuration, and how that climate responds to changes in terrestrial albedo and evaporation. In particular, we consider NorthlandBright (where land is brighter than ocean), NorthlandDark (where land has the same albedo as the ocean), and NorthlandDry (where terrestrial evaporation is suppressed).



The climate of NorthlandBright consists of four distinct regions: the southern hemisphere ocean, the seasonally moist terrestrial tropics, the mid-latitude desert, and The Great Northern Swamp. In the northern hemisphere, the tropics are wet when the ITCZ moves over the continent, but dry out during the northern hemisphere winter. The subtropics and mid-latitudes are quite dry year-round, while the high latitudes are quite moist year round, forming the Great Northern Swamp. Even when the land is initialized without any water (NorthlandEmpty), the GreatNorthernSwamp "fills up" withing 5-6 years of the start of the simulation, showing that the swamp is supported not only by local water recylcing, but also by moisture transport into the region.

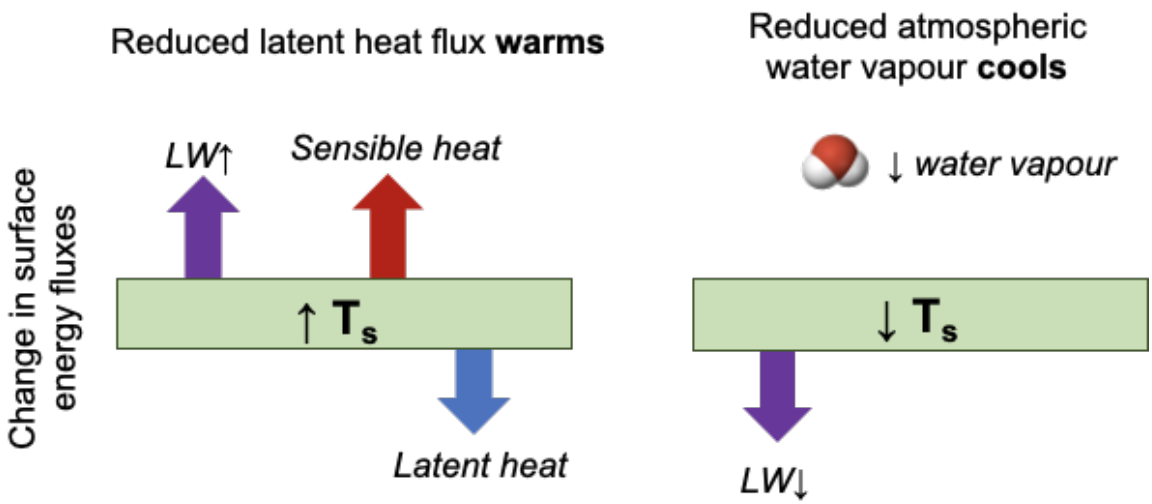
Making the land darker leads to warmer temperatures, as we would expect. It also leads to a northward shift in the ITCZ, consistent with previous literature on albedo-driven hemispheric energy imblances (see, for example, Kang et al. 2008, Swann et al. 2012).

Suppressing terrestrial evaporation leads to cooling, both over the northern hemisphere continent and the southern hemisphere ocean. This is in direct contrast to previous literature (e.g. Shukla and Mintz 1982, Laguë et al. 2019) where reducing terrestrial evaporation warms the land surface, with slight warming or no effect over the oceans. In our simulations, suppressing terrestrial evaporation leads to cooling because it greatly reduces the amount of atmospheric water vapour - a strong greenhouse gas. This is explored further in the rest of this poster.



In Lakeworld, all of the moisture is rapidly transported to the polar regions, where it becomes trapped in two polar lakes. Further discussion of the cliamte of Northland can be found in Laguë et al. 2020.

SUPPRESSED TERRESTRIAL EVAPORATION: WARMS OR COOLS?



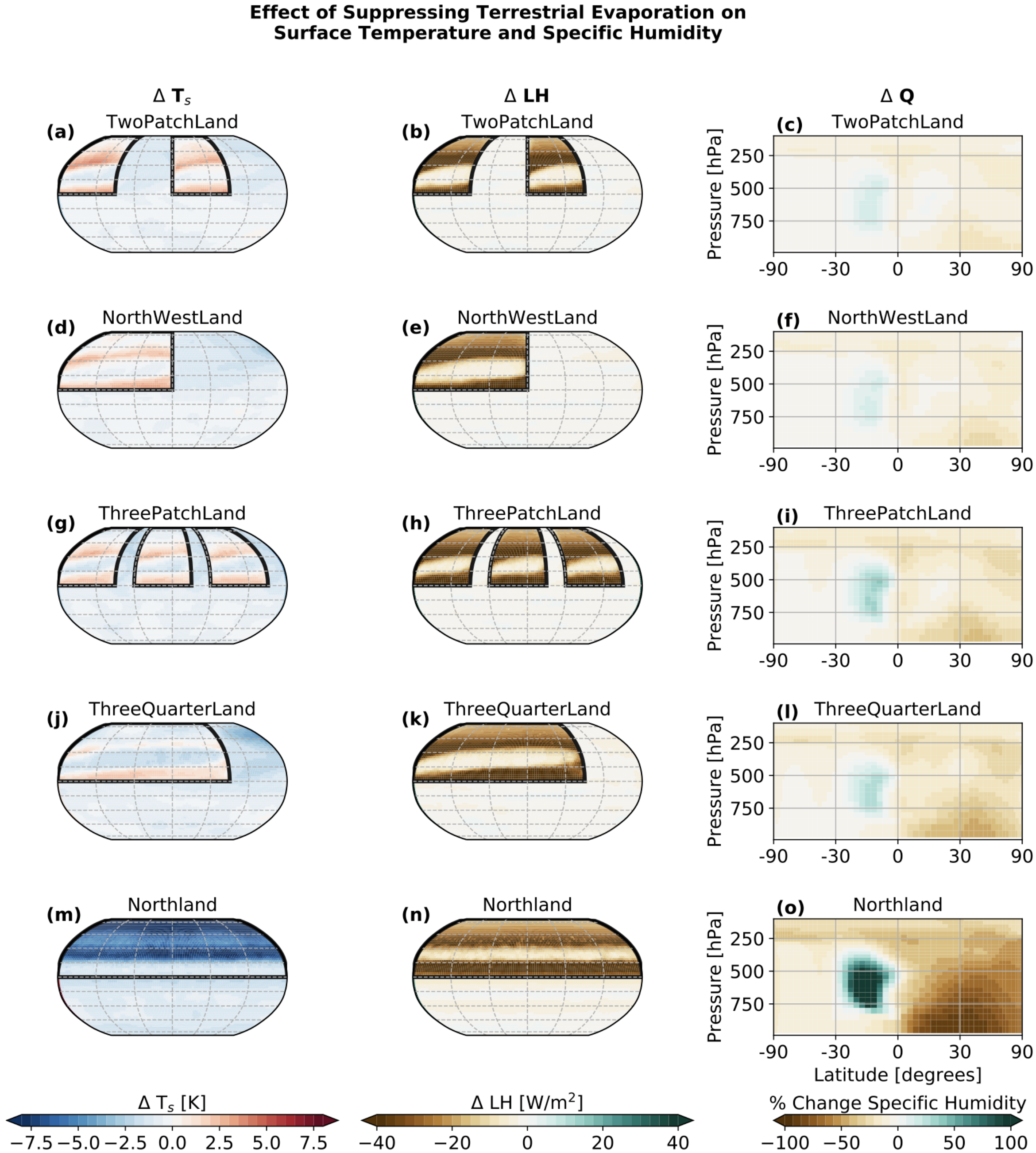
Past studies (e.g. Shukla & Mintz 1982; Laguë et al. 2019) have demonstrated that reducing terrestrial evaporation leads to warming in a realistic continental configuration. However, in the idealized continental configurations considered in this study, competition between **local warming** from suppressed latent cooling and **large-scale cooling** from reduced atmospheric water vapour determine the final terrestrial temperature response to suppressed terrestrial evaporation.

From a surface energy budget point of view, if all else is held equal and terrestrial evaporation is suppressed, we would expect surface temperatures to warm, as energy that was formerly used to evaporate water instead must be shed from the land surface either as sensible heat or emitted longwave radiation. Of course, this only holds true in regions with water available to evaporate in the first place (i.e. not deserts).

However, water vapour is a strong greenhouse gas. If suppressing terrestrial evaporation reduces atmospheric water vapour by a large enough amount to reduce a large amount of the absorption and re-emission of longwave radiation, the reduction in downwelling longwave radiation at the surface could actually lead to cooling.

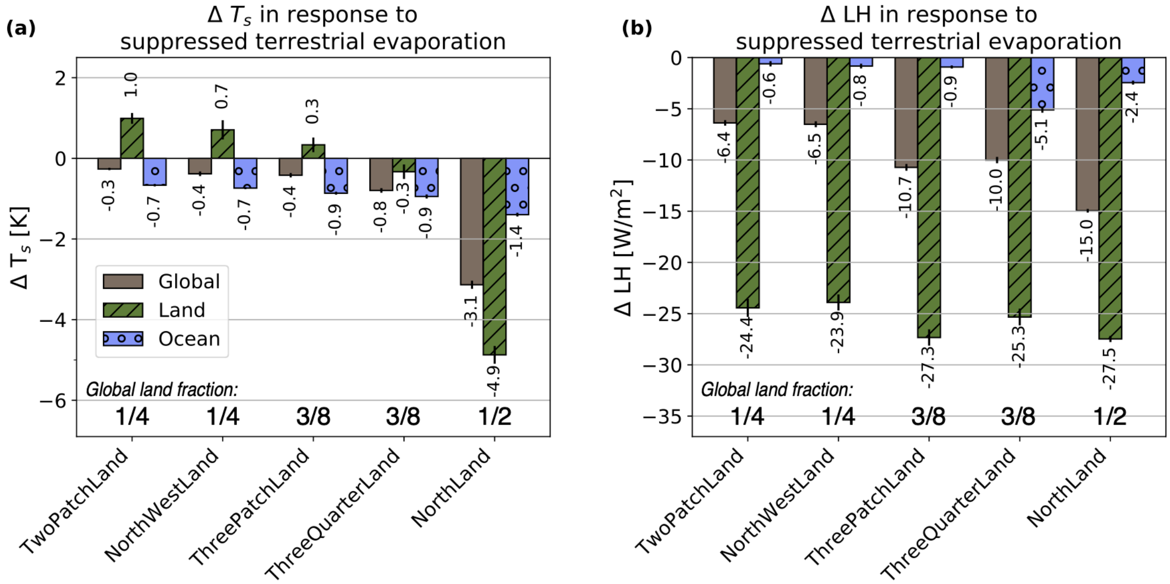
While the direct warming effect of reduced latent cooling of the surface due to suppressed terrestrial evaporation is locally isolated to the region where evaporation is suppressed, the cooling effect of depleted atmospheric water vapour can impact surface temperatures both in the region of supressed terrestrial evaporation, and remotely.

Below, we show the spatial pattern of the change in surface temperature (left), surface latent heat flux (center), and the vertical profile of the percent change in zonal mean specific humidity (right) as a result of suppressing terrestrial evaporation in 5 idealized continental configurations.



In all simulations except Northland, there are some regions of warming and some regions of cooling over the land surface as a result of suppressing terrestrial evaporation. Desert regions only experience the non-local cooling of reduced atmospheric water vapour, while regions with surface moisture (before terrestrial evaporation is suppressed) experience both local warming from reduced latent cooling of the surface as well as cooling from reduced atmospheric water vapour. In the Northland continental configuration, the cooling effect of reduced atmospheric water vapour in the northern hemisphere dominantes any local warming from reduced evaporative cooling.

SUPPRESSED TERRESTRIAL EVAPORATION IN VARIOUS IDEALIZED CONTINENTAL CONFIGURATIONS



Suppressing terrestrial evaporation leads to ~1K of warming over land in TwoPachLand, but 0.7K or warming in NorthWestLand, despite both continental configurations having the same total land area and the same latitudinal distribution of land. Both simulations show warming - that is, the direct local effect of reduced latent cooling of the surface dominates the surface temperature signal. However, the atmosphere in TwoPatchLand can be replenished with water vapour when air travels over the ocean more than it can in NorthWestLand, which has a larger contiguous continent.

A similar temperature response occurs in ThreePatchLand and ThreeQuarterLand, except that because there is more land, and thus a larger depletion of atmospheric water vapour, the warming signal if ThreePatchLand (0.3K) is smaller than in TwoPatchLand or NorthWestLand. In ThreeQuarterLand, the cooling effect of reduced atmospheric water vapour dominates the response of terrestrial temperatures, resulting in an overall cooling signal over land (-0.3K).

In Northland, there is no ocean at any latitude in the northern hemisphere, so dry continental air cannot be replenished with water vapour except in the tropics from the southern hemisphere ocean. This results in the northern hemisphere atmosphere becoming much drier than in any of the other continental configurations when terrestrial evaporation is suppressed, and the resulting terrestrial cooling signal is much stronger (-4.9K).

DISCLOSURES

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