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1 **Competing local warming and large-scale cooling effects of reducing**
2 **terrestrial evaporation: lessons from Northland, a planet with a hemispheric**
3 **continent**

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ABSTRACT

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

42 **1. Introduction**

43 The physical properties of the land surface and the ocean differ in several fundamental ways. For
44 instance, land has a much lower heat capacity than ocean (Cess and Goldenberg 1981; North et al.
45 1983; Bonan 2008); land has a higher albedo than ocean (Budyko 1961, 1969; Payne 1972; Bonan
46 2008); the ocean has the ability to move heat laterally (Loft 1918; Richardson 1980; Trenberth
47 and Caron 2001; Ferrari and Ferreira 2011; Forget and Ferreira 2019); and there are large climatic
48 impacts of terrestrial orography (Queney 1948; Eliassen and Palm 1960; Manabe and Terpstra
49 1974; Held et al. 1985; McFarlane 1987). Moreover, land stores and evaporates less water than
50 ocean, and soil and vegetation properties provide resistance to evaporation over land (Manabe
51 1969; Bonan 2008, and references therein). The contrast between physical properties of land and
52 ocean are important controls on atmospheric dynamics, profoundly impacting the climate. The
53 hemispheric asymmetry in land-sea distribution has implications for global climate, including the
54 higher sensitivity of the Northern Hemisphere to increases in anthropogenic greenhouse gases
55 (Manabe et al. 1991; Stouffer et al. 1989). In this study, we focus on how the limited capacity of
56 the land to hold water, its small heat capacity, and its higher albedo alter the climate system.

57 The albedo of different land types is much higher than that of ice-free ocean. Land albedo ranges
58 from 0.05-0.25 (vegetated) to 0.5-0.9 (glaciers and snow) (Wiscombe and Warren 1980; Oke 1987;
59 Bonan 2008). In contrast, the surface albedo of the ice-free ocean is generally less than 0.1 (Jin
60 et al. 2004). The difference in top-of-atmosphere (TOA) albedo between land and ocean is less
61 drastic, with TOA albedo ranging from 0.25 to 0.6 over snow-free land, and 0.1 to 0.5 over ice-free
62 ocean for Earth in the present climate. These higher values result from atmospheric controls on
63 the TOA albedo, via the effects of cloud cover, aerosols, and attenuation (Donohoe and Battisti
64 2011).

65 Additionally, land has a much smaller heat capacity than the ocean, and a limited ability to
66 move energy laterally. Oceans can absorb large amounts of energy (Kuhlbrodt and Gregory 2012;
67 Cheng et al. 2017) and transport energy via ocean currents; there are areas of the ocean that can
68 continually take up energy, while other regions act as a source of energy to the atmosphere (e.g.
69 Marshall and Zanna 2014; Forget and Ferreira 2019). In contrast, energy absorbed at one location
70 on land must be released back to the atmosphere at that same location in the form of upwards
71 longwave radiation, sensible heat, or latent heat (evaporation). While the land can store energy
72 on seasonal timescales, the annual mean heat storage of a land surface in equilibrium is near-zero
73 (Milly and Shmakin 2002), and the seasonal storage of heat by the land surface is much smaller
74 than that of the ocean (Marshall and Plumb 2008).

75 The limited capacity of the land surface to hold water and the increased resistance to evapo-
76 ration over land surfaces compared to over open water drastically alters evaporative fluxes over
77 land. Over the ocean, evaporation is determined mainly by the meteorological conditions at the
78 atmosphere-ocean interface (e.g. the surface temperature and atmospheric humidity). In contrast,
79 dry land surfaces have little water available for evaporation, and thus little evaporation occurs re-
80 gardless of the evaporative demand of the overlying atmosphere. Various properties of soil and
81 vegetation further modulate the availability of water to the atmosphere, including total leaf area
82 and roots that can provide access to water deep in the soil column (Canadell et al. 1996; Bonan
83 2008). Moreover, plants directly regulate the movement of water from the land to the atmosphere
84 by opening and closing their stomata (small pores on leaves which modulate gas exchange) (Sellers
85 et al. 1996).

86 These fundamental physical differences between land and ocean result in very different surface-
87 atmosphere interactions. Changes in land surface properties can modify the global climate system
88 (Charney 1975; Shukla and Mintz 1982; Sud et al. 1988; Davin et al. 2010; Laguë et al. 2019).

89 Large hemispheric energy imbalances, such as those generated by sea ice, large-scale vegetation
90 change, or an idealized energy source can drive large-scale changes in the location of the zonal
91 mean ITCZ and the Hadley circulation (Chiang and Bitz 2005; Broccoli et al. 2006; Kang et al.
92 2008; Swann et al. 2012; Laguë and Swann 2016; Kang 2020). In response to a hemispheric energy
93 imbalance, the rising branch of the Hadley circulation moves towards the energy-rich hemisphere,
94 thereby moving energy towards the energy-poor hemisphere and shifting the ITCZ towards the
95 energy-rich hemisphere (Donohoe et al. 2013), provided there are no large changes in gross moist
96 stability (see Geen et al. 2020, and references therein). The distribution of land impacts climate in
97 myriad ways, including by directing storm tracks, shaping ocean circulation, generating planetary
98 waves, and impacting orographic forcing and diabatic heating of the atmosphere (Eliassen and
99 Palm 1960; Hartmann 1994; Donohoe et al. 2020). In this study we investigate the fundamental
100 differences in atmospheric dynamics and climate over land and ocean, as well as the climatic
101 implications of the asymmetry in the distribution of land between the Southern Hemisphere (SH)
102 and the Northern Hemisphere (NH).

103 This study explores the climate of an idealized limit of the distribution of the land-ocean system.
104 At present, 68% of land on Earth is in the NH and 32% is in the SH. The hemispheric asymmetry in
105 this distribution of land has long been thought to drive asymmetries in surface temperature (Croll
106 1870; Stouffer et al. 1989; Manabe et al. 1991), precipitation and ocean heat transport (Nilsson
107 et al. 2013).

108 In this study, we use an idealized atmospheric general circulation model configuration to explore
109 how fundamental differences between the land and ocean affect the climate. To do this, we model
110 the climate of a hypothetical planet that is Earth-like in size and orbital configuration, but has a
111 continent covering the entire Northern Hemisphere, and an ocean covering the entire Southern
112 Hemisphere. We explore the mean state of this planet, which we call Northland, and probe how

113 modifying the albedo and capacity to hold water of the land surface alter the planet’s climate.
114 We also explore the climate of several alternative continental configurations, and consider a land-
115 covered planet.

116 Idealized models are a useful tool in climate modeling as they help to narrow the gap between
117 simulating the climate system and understanding its mechanisms, as highlighted in Sellers (1969),
118 Held (2005), Jeevanjee et al. (2017), and Maher et al. (2019). Idealized models can be traced back
119 to ‘Galilean’ idealizations, in which a problem is simplified to make it easier to solve (McMullin
120 1985). While an idealized model sacrifices realistic representations of physical processes, this
121 approach aides in illuminating fundamental processes of the climate system (Levins 1966) - in this
122 case, differences between land and ocean surface interactions with the atmosphere.

123 **2. Methods**

124 *a. Model*

125 We use Isca (Vallis et al. 2018), a framework for designing idealized atmospheric general circu-
126 lation models (GCMs) to explore the climate of an Earth-like planet with an idealized continental
127 configuration. The atmosphere is coupled to a 20m slab ocean without any ocean heat transport in
128 our simulations. Land gridcells differ from ocean gridcells by having a higher albedo, smaller heat
129 capacity, a finite reservoir of water, and a parameterized representation of soil that reduces the rate
130 of evaporation when the soil is less than saturated. The land parameterization used in this study
131 is similar to that of Manabe (1969), where land hydrology is represented using a bucket model.
132 In this model configuration, there is no snow or sea ice, thus no representation of surface albedo
133 feedbacks; soil moisture does not impact land surface albedo.

134 The atmosphere uses moist dynamics, but does not represent clouds. While cloud responses to
135 land surface properties and their changes can play an important role in determining impacts on
136 surface climate (Cho et al. 2018; Sikma and Vilà-Guerau de Arellano 2019; Laguë et al. 2019;
137 Kim et al. 2020), cloud responses to climate perturbations are also a large source of uncertainty
138 (Stocker et al. 2013; Zelinka et al. 2017). Our idealized modeling framework avoids uncertainties
139 associated with cloud responses to climate perturbations, at the cost of not capturing any cloud
140 interaction effects. The surface albedo α of both water ($\alpha_{ocean} = 0.25$) and land ($\alpha_{land} = 0.325$;
141 table 1) is higher than it would be in a model that included clouds, to allow for a more realistic
142 planetary albedo at the top of the atmosphere (Donohoe and Battisti 2011). Despite the absence
143 of clouds, the model still produces precipitation (see Vallis et al. 2018, for details). Simulations
144 are run using a T42 horizontal resolution (roughly 2.8° latitude by 2.8° longitude) with 40 vertical
145 levels.

146 *b. Experiments*

147 We run a total of 14 simulations, with six continental configurations and various land surface
148 properties modified between simulations (table 1). In all simulations, there is a seasonal cycle in
149 insolation (obliquity = 23.439 degrees, eccentricity = 0) with a 360 day year; atmospheric CO_2
150 concentrations are fixed at 300 ppm.

151 We refer to the six continental configurations as “Northland”, “ThreeQuarter-
152 Land”, “NorthWestLand”, “ThreePatchLand”, “TwoPatchLand”, and “Lakeworld”, (figure 1).
153 All configurations except Lakeworld have ocean in the SH. In the Northland configuration, the
154 whole NH is land. ThreeQuarterLand has land only in the the NH from 90 - 360° longitude (thus
155 spanning $3/4$ of the Northern Hemisphere) and ocean from 0 - 90° longitude. NorthWestLand
156 has land only in the NH from 180 - 360° longitude. ThreePatchLand has the same land area

157 as ThreeQuarterLand, but with three equally-spaced 90° longitude wide continents in the NH,
158 separated by 30° longitude ocean basins. TwoPatchLand has two equally-spaced 90° longitude
159 continents, separated by two 90° longitude ocean basins, and the total land area is the same as in
160 NorthWestLand. In the Lakeworld configuration, the whole world is land, with no ocean. There
161 is also an aquaplanet configuration with no land.

162 For the Northland continental configuration, we consider 4 simulations with varied land surface
163 properties; we refer to these simulations as “NorthlandXX” (where “XX” indicates a specific
164 simulation). Our “control” simulation (to which we generally compare our other experiments) is
165 “NorthlandBright”. In NorthlandBright, the NH continent has an albedo that is 1.3 times that of
166 the ocean ($\alpha_{land} = 0.325$, $\alpha_{ocean} = 0.25$). The heat capacity of the land is 1/10 that of the ocean in
167 our simulations (i.e. equivalent to a 2m mixed layer ocean). This is larger than the heat capacity of
168 land on Earth, but Isca simulations with realistic continents have been shown to compare well with
169 reanalyses when these heat capacities are used (Thomson and Vallis 2019; Geen et al. 2018). The
170 roughness length is 0.2 mm, and is uniform over land and ocean in our simulations. Hydrology
171 is represented by the “bucket model” (Manabe 1969; Vallis et al. 2018), where the capacity of
172 the land to hold water (“bucket capacity”) is set to 150 mm in our simulations, and water on
173 land is initialized everywhere at 100 mm. The bucket receives water when precipitation exceeds
174 evaporation and loses water when the opposite occurs. When the bucket is more than 3/4 full, the
175 resistance to evaporating water from the land surface is the same as over open water. When the
176 bucket is less than 3/4 full, evaporative resistance scales inversely with the amount of water in the
177 bucket.

178 We run three additional Northland experiments to demonstrate various aspects of the land sur-
179 face’s impact on the climate system. In each of these simulations, a single property of the land
180 surface is modified compared to NorthlandBright. In the “NorthlandDark” experiment, the albedo

181 of the land is reduced so that it is the same as the ocean ($\alpha_{land} = \alpha_{ocean} = 0.25$). In the “North-
182 landEmpty” experiment, the land surface is initialized with no water on the land surface; thus, all
183 water that ends up on land must have originated from the SH ocean. NorthlandEmpty differs from
184 NorthlandBright only in the initial conditions. In the “NorthlandDry” experiment, the capacity
185 of the land to hold water is greatly reduced, to near-zero (0.01 mm). This effectively shuts off
186 evaporation from the land surface.

187 For each of the NorthWestLand, ThreeQuarterLand, TwoPatchLand, and ThreePatchLand con-
188 tinental configurations, we run two simulations. In “NorthWestLand”, “ThreeQuarterLand”,
189 “TwoPatchLand”, and “ThreePatchLand”, the land surface has the same properties as Northland-
190 Bright. In “NorthWestLandDry”, “ThreeQuarterLandDry”, “TwoPatchLandDry”, and “ThreeP-
191 atchLandDry”, the land surface has the same properties as NorthlandDry (i.e. terrestrial evapora-
192 tion is suppressed).

193 We run one simulation where the entire planet is covered with land. We refer to this simulation as
194 “Lakeworld”. Lakeworld has the same albedo as NorthlandBright ($\alpha_{land} = 0.325$), but the bucket
195 hydrology is modified to allow the land to form lakes over gridcells that receive precipitation when
196 the soil moisture bucket is already full. When the soil moisture is less than 150 mm, the same
197 rules governing terrestrial evaporation in NorthlandBright apply. However, the soil is allowed to
198 accumulate an infinite amount of water. When the soil moisture exceeds 150 mm, the same rules of
199 evaporation for fully saturated soils (which in these simulations are the same as the rules for open
200 water) apply. The lakes do not impact land albedo or heat capacity. Lastly, we run an aquaplanet
201 simulation (“Aqua”) with no land, where the whole planet is covered with a 20m deep mixed layer
202 slab ocean, with an albedo of $\alpha_{ocean} = 0.25$.

203 Most simulations were run for 20 years, though some Northland simulations were run for 50
204 years to check model drift, and Lakeworld was run for 80 years due to the unique water cycle of

205 the all-land planet. The first four years of each simulation are discarded to allow for model spin-
206 up, after which time there is a global-mean drift in surface temperatures of less than 0.01 K/year
207 in the Northland and Aqua simulations (figure S1). Unless otherwise stated, the results presented
208 here are taken from years 5-20 of the simulations (5-80 for Lakeworld). The Lakeworld simulation
209 does not reach equilibrium in 80 years (figure S1), but this simulation is used to demonstrate the
210 transient migration of water, rather than explored for its equilibrium climate.

211 When statistical significance is shown for a difference between two experiments, a student's
212 t-test is used, with $p < 0.05$ indicating 95% confidence that the simulations differ significantly.
213 When error bars are used, they represent ± 1 standard deviation.

214 **3. Results**

215 Here our goal is to explore the factors that control the surface energy and hydrologic budgets of
216 the idealized Northland planet. We begin with an overview of the climatology in the Northland-
217 Bright experiment (section a), which we view as a control simulation. We then investigate how
218 changes in land albedo (section b) and terrestrial evaporation (section c) impact the temperature
219 and water cycle of the planet. Next, we explore the effect of suppressing terrestrial evaporation
220 with alternate configurations that include some ocean in the NH (section d). Finally, we explore
221 the role of moisture transport (section e), and show that the mere presence of a continent causes
222 the ITCZ to extend farther poleward than in a pure aquaplanet setting (section f).

223 *a. NorthlandBright (control simulation) climatology*

224 NorthlandBright can be divided into four distinct climatic zones: the SH ocean, the seasonally
225 wet tropical land belt, the NH mid-latitude desert, and the NH moist polar region. The mean
226 climate of the NorthlandBright simulation reflects a world where the area-weighted annual mean

227 surface temperature over the continent is slightly cooler (277K) than over the ocean (280K) (ta-
228 ble S1); this is unlike present-day Earth, where – in the extra-tropics – land regions are generally
229 slightly warmer than ocean regions (Wallace et al. 1995; Sutton et al. 2007). However, the con-
230 tinent has a much larger seasonal cycle of temperature than the ocean, reflecting its smaller heat
231 capacity (figures 2, table S1). The hottest part of the continent, with temperatures reaching 304K,
232 occurs around 30°N during NH summer, while temperatures near the North Pole plunge to 220K
233 during NH winter (figure 2a). Temperatures and seasonality over the SH ocean are much more
234 moderate, with a hemispherically averaged temperature difference of only 2K between summer
235 and winter, compared to 34K in the NH (table S1).

236 The globally averaged annual mean rainfall in the NorthlandBright simulation is approximately
237 2 mm/day. Unsurprisingly, more of this rain falls over the ocean (2.9 mm/day) than over the
238 continent (1.5 mm/day), with a strong latitudinal dependence (figure 2b). The ITCZ has a strong
239 seasonal cycle, with heavier rainfall and a peak that extends farther polewards over the ocean than
240 over the continent (figure 2b, 3a). Over the continent, the ITCZ reaches its farthest northwards
241 extent during August and September, with the peak in precipitation reaching approximately 15°N.
242 In contrast, the peak in the ITCZ over the ocean occurs at around 20°S during March, with roughly
243 double the rate of precipitation in the ocean ITCZ-peak than the land ITCZ-peak. The land cannot
244 support as strong an ITCZ because all the moisture for the ITCZ must initially be brought onto
245 the land each season by ITCZ precipitation; in contrast, the ocean provides an unlimited supply of
246 water in the form of nearby evaporation that can subsequently be precipitated in the SH ITCZ.

247 In NorthlandBright, moist air is transported from the ocean onto the continent, where it rains
248 out in the tropics. Terrestrial tropical precipitation is most intense from August to November.
249 The land water evaporates quickly in the tropics due to high insolation (i.e. evaporation has a
250 similar seasonal cycle to precipitation; figure 3a-c). North of 20°N, precipitation is roughly equal

251 to evaporation in the annual mean (not shown). Despite heavy wet-season precipitation in the
252 tropics, the ground between 0-20°N dries out during the dry season (February-June), because of
253 strong seasonal evaporation (figure 3b,d).

254 In the subtropics of the Northern Hemisphere (roughly 20-40°N) there is a desert with dry soil
255 year-round (figures 2b, 3d). Extratropical precipitation in the land hemisphere features a broad
256 maximum in NH summer that extends from 50°N to the pole that is likely due to localized convec-
257 tion (figure 2b). In the ocean hemisphere, the extratropical maximum in precipitation is located
258 at about 40°S, and is storm track precipitation associated with baroclinic cyclones (figure 2b).
259 Precipitation in the ocean hemisphere storm track is nearly seasonally invariant.

260 The high latitude soil is saturated or nearly saturated with water year-round, forming what we
261 call the “Great Northern Swamp” (figure 3d), with slightly less terrestrial water storage during
262 June-July when evaporation (fueled by increased summer insolation) exceeds precipitation (figure
263 3c-d). Interestingly, the soil moisture in the Great Northern Swamp is supplied by water transport
264 from the tropics, and not from local moisture recycling alone. This becomes clear when the land
265 is initialized without any water (NorthlandEmpty). In this simulation, the high latitude soil water
266 is indistinguishable from NorthlandBright within 4-5 years (figures 3d-e). The transport of water
267 to the poles is explored further in section e.

268 *b. Climate impacts of land albedo*

269 As we would expect, reducing the albedo of the land surface (making the land darker) leads to
270 surface warming. In NorthlandDark, the land albedo is the same as that of the ocean. As such,
271 the land hemisphere absorbs more solar energy in NorthlandDark than in NorthlandBright (figure
272 S2b), leading to greater temperatures year-round (figure 2c). The additional shortwave (SW) ra-
273 diation absorbed in NorthlandDark compared to NorthlandBright is released to the atmosphere in

274 the form of longwave (LW) radiation, sensible heat or latent heat (figure S2c-f). Increased temper-
275 atures and increased water vapor (resulting in similar relative humidity over the continent between
276 NorthlandDark and NorthlandBright, figure 2e) lead to more downwelling longwave radiation at
277 the surface (figure S2a). That is, the warming in NorthlandDark is not only due to increased SW
278 absorption, but also due to increased downwelling LW at the surface. NorthlandDark is warmer
279 than NorthlandBright over both land (+7.4K, figure 2c, table S1) and ocean (+2.4K, figure 2c,
280 table S1), due to atmospheric transport of water vapour and heat. The continent in Northland-
281 Dark is not only warmer than NorthlandBright - it is also wetter, particularly during the months of
282 August-October, when the ITCZ shifts north (figure 2d).

283 *c. Climate impacts of reduced terrestrial evaporation*

284 NorthlandDry is the same world as NorthlandBright, except evaporation from the land surface is
285 suppressed. With all else held equal (i.e. the same amount of incoming energy to the land surface,
286 the same water availability, etc.), this reduction in evaporation from the land surface is expected to
287 lead to greater surface temperatures. This is because if evaporative cooling is reduced, the energy
288 absorbed by the surface must be emitted in the form of sensible heat or longwave radiation, both
289 of which require an increase in surface temperatures. Indeed, both Shukla and Mintz (1982) and
290 Laguë et al. (2019) find that reducing evaporation from the land surface leads to surface warming
291 over land.

292 Contrary to previous literature, we find that suppressing evaporation over Northland leads to
293 cooler, not warmer, surface temperatures. Annual mean temperatures in NorthlandDry are 3.2K
294 cooler globally, and 4.9K cooler over land than NorthlandBright (figure 2c, table S1). The cold
295 anomaly is fairly homogeneous over the ocean hemisphere, but is at its greatest during JJA in
296 the northern subtropics (figure 2c). This is surprising as the latent heat flux over land is greatly

297 reduced in NorthlandDry compared to NorthlandBright (figure 5e), which we would expect to
298 lead to warming. However, suppressing terrestrial evaporation also reduces the amount of water
299 vapour released to the atmosphere over terrestrial regions. Water vapour is a strong greenhouse
300 gas, and if atmospheric water vapour is depleted in sufficiently large quantities, the reduction in
301 the amount of longwave radiation absorbed by the atmosphere and re-emitted down towards the
302 surface would lead to net cooling. Moreover, while the direct warming effect of reducing latent
303 cooling is locally isolated to the region where evaporation is reduced, the cooling associated with
304 reduced atmospheric water vapour is much broader in spatial extent, as the atmosphere can mix
305 water vapour (or air with reduced water vapour) beyond the locations where terrestrial evaporation
306 was reduced.

307 The decrease in atmospheric water vapor (figure 2f) due to reduced evaporation from the land
308 surface cools NorthlandDry relative to NorthlandBright by reducing downwelling longwave radi-
309 ation (figure 5a). This reduction in downwelling longwave radiation greatly exceeds the reduction
310 in latent heat flux (which on its own would lead to warming). The reduction in downwelling long-
311 wave radiation reaches 150 W/m^2 in the northern high latitudes, while the reduction in latent heat
312 flux peaks at around 80 W/m^2 , with the largest reductions in the northern tropics and high latitudes
313 (compare figure 5a with 5e). In the dry subtropics, the latent heat flux is already near-zero for most
314 of the year in NorthlandBright, so suppressing evaporation has little impact on temperature in this
315 region (figure 5e). Hence, cooling is strongest in the dry subtropics, particularly during JJA (figure
316 2c), because the cooling due to the reduction in downwelling longwave from reduced atmospheric
317 water vapor has no warming offset from local reductions in latent cooling. There is actually a
318 slight increase in net shortwave radiation absorption at the surface over land during NH summer
319 months due to reduced absorption of shortwave radiation by water vapor (figure 5b). However, the

320 decrease in the downwards emission of longwave radiation from reduced atmospheric water vapor
321 dominates the change in absorbed surface energy (figure 5f).

322 At the TOA, there is a substantial reduction in net energy absorbed over the continent from June-
323 August, and an increase in net energy absorbed at the TOA over the continent from September-
324 December (figure 6c). These changes are dominated by the change in TOA LW. During NH
325 summer, more LW is lost from the TOA as a result of a smaller greenhouse effect, and there is less
326 net SW absorption due to reduced atmospheric water vapor (figure 6). That is, despite the surface
327 being colder during JJA in NorthlandDry than NorthlandBright, there is still more LW lost from
328 the TOA in NorthlandDry because of the reduced greenhouse effect. This contrasts with the driver
329 of changes in TOA LW from September-December, when there is overall more energy absorbed
330 at the TOA in NorthlandDry than NorthlandBright (figure 6c). In this case, NorthlandDry has less
331 LW emission from the TOA, reflecting the overall colder conditions in NorthlandDry compared to
332 NorthlandBright (figure 6b).

333 We can compare the change in land surface temperature over Northland due to suppressed ter-
334 restrial evaporation to an equivalent change in albedo, if we assume land surface temperatures
335 scale linearly with land surface albedo (as suggested holds in Laguë et al. (2019)). The surface
336 temperature change between NorthlandDark and NorthlandBright implies a 9.9K increase in land
337 surface temperatures per 0.1 decrease in land surface albedo for our idealized planet (see table S1).
338 We note that this is much larger than the roughly 2K increase in surface temperatures per 0.1 de-
339 crease in land surface albedo found in Laguë et al. (2019), for a realistic continental configuration
340 in a more complex model. However, intuitively this value should vary with total land area, land
341 distribution, and cloud cover (which is not represented in this model), as modifying land albedo
342 will have a different impact on absorbed SW energy and surface temperatures depending on the
343 presence of clouds, incident solar radiation, and surface moisture in the location of the albedo

344 change. Applying the 9.9K/0.1 decrease in albedo relationship for Northland to the temperature
345 change in NorthlandDry vs. NorthlandBright tells us that suppressing terrestrial evaporation over
346 Northland has the equivalent effect on land surface temperatures as increasing the NH albedo by
347 0.05 (roughly 14%, 0.05/0.35).

348 The response of precipitation to suppressed terrestrial evaporation in the NorthlandDry experi-
349 ment is widespread. In particular, precipitation over the continent decreases almost to zero during
350 August-October, which is the wettest part of the year in NorthlandBright. A very weak ITCZ gen-
351 erates a small amount of precipitation over the southern edge of the continent in August-October
352 (figure 2d), while precipitation is very low over the rest of the continent year round. We note
353 that the structure of the Hadley cell during JJA in NorthlandDry differs from the Hadley cell of
354 the other simulations presented here (figure S3). NorthlandDry does not have a large source of
355 moisture over the land surface in the tropics. The ITCZ is very weak during JJA (figure 4c), and
356 rather than an overturning circulation driven by the release of latent heat, the circulation is driven
357 by direct thermal heating of the surface. The result is two overturning cells stacked on the equator
358 during JJA, with the lower cell circulating anti-clockwise and the upper cell circulating clockwise
359 (figure S3f).

360 *d. Temperature response to suppressed evaporation in various continental configurations*

361 The unexpected cooling of Northland with suppressed terrestrial evaporation is due to the re-
362 duction in downwards LW from reduced atmospheric water vapor (and thus a weaker greenhouse
363 effect) dominating any surface warming from reduced latent heat fluxes. Because the Northland
364 continental configuration has no oceanic water source in the NH, NH atmospheric water vapor be-
365 comes significantly depleted (figure 8o). We further explore the effects of suppressing terrestrial
366 evaporation on surface temperature by considering four additional continental configurations with

367 varying amounts of ocean in the NH: ThreeQuarterLand, NorthWestLand, ThreePatchLand, and
368 TwoPatchLand (figure 1, table 1). We compare simulations where the continents have the same
369 land surface properties as NorthlandBright (i.e. “normal” land surface properties) to simulations
370 where the continents have the same land surface properties as NorthlandDry (i.e. terrestrial evap-
371 oration is suppressed), to explore the trade-off between warming from reduced surface latent heat
372 flux and cooling from reduced atmospheric water vapor.

373 In TwoPatchLand, suppressing terrestrial evaporation leads to 1.0K of warming over land, on
374 average (figure 7a). However, as with the dry regions of NorthlandBright, suppressing evaporation
375 over regions that are climatologically dry in TwoPatchLand (i.e. the subtropics) does not lead to
376 any direct warming through reduced evaporative cooling (figure 8a). Instead, these subtropical
377 land areas experience cooling when terrestrial evaporation is suppressed as a result of decreased
378 downwards LW from reduced atmospheric water vapour. In NorthWestLand, suppressing evap-
379 oration also generally leads to warming over land, with an average warming of 0.7K over land
380 (figures 8b, 7). The warming is not as strong in NorthWestLand as in TwoPatchLand when evap-
381 oration is suppressed, despite both continental configurations having the same total land area and
382 the same latitudinal distribution of land area, with 1/2 of the NH covered by land. The warming is
383 smaller in NorthWestLand despite a comparable (indeed, slightly smaller) reduction in terrestrial
384 latent heat flux (figure 7b).

385 ThreePatchLand and ThreeQuarterLand have the same total land area and in both cases 3/4 of the
386 NH are covered by land. However, suppressing terrestrial evaporation leads to warming of the land
387 for ThreePatchLand, and cooling of the land for ThreeQuarterLand (figure 7a). The warming of
388 0.3K over land in ThreePatchLand is smaller than in TwoPatchLand or NorthWestLand, reflecting
389 the larger reduction in atmospheric water vapor (figure 8f) driven by more land area. In Three-
390 QuarterLand, the reduction in atmospheric water vapour is large enough to dominate warming

391 from reduced latent heat flux, resulting in net land cooling of 0.3K (figures 7a, 8j,l). The reduction
392 in latent heat flux from land is larger in ThreePatchLand than ThreeQuarterLand, but the reduction
393 in latent heat flux from the ocean is much larger in ThreeQuarterLand than in ThreePatchLand
394 (figure 7b). The differences between ThreePatchLand and ThreeQuarterLand (and TwoPatchLand
395 and NorthWestLand) demonstrate that it is not only land area, but also continent size and distribu-
396 tion that modulates the temperature response to suppressed terrestrial evaporation.

397 The change in terrestrial latent heat flux due to suppressed evaporation over land (figure 7b) is
398 approximately equal to the latent heat flux from the simulations with “normal” surface properties
399 (from NorthlandBright), because there is almost no evaporation in the simulations with North-
400 landDry land surface properties. The single large continents have slightly lower latent heat fluxes
401 in the “normal” simulations than their patchy counterparts; that is, TwoPatchLand and ThreePatch-
402 Land have slightly larger terrestrial latent heat fluxes than NorthWestLand and ThreeQuarterLand,
403 respectively, and thus have slightly larger changes in latent heat flux from land when terrestrial
404 evaporation is suppressed.

405 However, we note that the average area-weighted change in latent heat flux from the land surface
406 is of comparable magnitude across all the continental configurations considered here (figure 7b),
407 while total reduction in terrestrial latent heat flux scales with total land area. For simulations with
408 the same total land area (e.g. TwoPatchLand and NorthWestLand), the total reduction in terrestrial
409 latent heat flux is similar, but the surface temperature response differs. The temperature change
410 driven by suppressing terrestrial evaporation is greater when the contiguous continental area is
411 larger. This occurs because the atmosphere becomes more depleted in water vapor over a single
412 large continent than it does over two smaller continents separated by ocean. Thus the water vapor
413 cooling effect is stronger over larger continents than smaller ones, even if the direct warming due
414 to reduced latent cooling of the surface is similar.

415 Over the oceans, surface temperatures cool and evaporation is reduced as a result of suppressing
416 terrestrial evaporation in all the TwoPatchLand, ThreePatchLand, NorthWestLand, ThreeQuarter-
417 Land, and Northland continental configurations (figure 8). The changes in latent heat flux from
418 the ocean (blue bars in figure 7b) must be the result of changes in the local oceanic surface energy
419 budget. For example, cooling over the NH ocean in ThreeQuarterLand is more intense than it is
420 over the NH ocean in ThreePatchLand (figure 8 g vs j), which is consistent with a greater reduction
421 in oceanic latent heat flux in ThreeQuarterLand vs. ThreePatchLand. Despite Northland showing
422 the greatest surface cooling and the greatest global reduction in latent heat flux, the reduction in
423 oceanic latent heat flux in Northland is small compared to the other continental configurations
424 (figure 7b). This reflects the fact that most of the temperature change in Northland occurs over
425 the land hemisphere, and not over the ocean. In the other continental configurations, much of the
426 reduction in oceanic latent heat flux occurs over the NH, where the temperature changes and de-
427 creases in atmospheric water vapour are greatest (figure 8). The cooling over the ocean is due to a
428 reduction in atmospheric water vapor from suppressed terrestrial evaporation leading to reductions
429 in downward LW. In turn, cooling over the ocean reduces evaporation from the ocean due to the
430 Clausius Clapeyron relationship. This generates a weak negative feedback on the ocean temper-
431 ature but also further reduces water vapor flux to the atmosphere. Only in a few ocean regions do
432 we see a slight increase in evaporation (not shown), as might be expected if drier air was being ad-
433 vected off the continent. However, these regions are not all located downstream of the continents;
434 most of the ocean shows a decrease in evaporation due to a reduced greenhouse effect.

435 We can also consider differences between NorthlandDark and Aqua, as the NH in Northland-
436 Dark has the same albedo as Aqua but a limited capacity to hold water. On the one hand, one
437 might expect the NH land surface in NorthlandDark to be warmer than in Aqua because of limited
438 water available for evaporation (thus potentially less latent cooling of the surface). On the other

439 hand, reduced atmospheric water vapor in the NH of NorthlandDark compared to Aqua could re-
440 sult in cooling (due to a weaker greenhouse effect). In the comparison of NorthlandDark to Aqua
441 however, we are not simply considering differences in water availability; the different NH heat
442 capacities in NorthlandDark and Aqua also leads to differences in evaporation and surface temper-
443 atures. The smaller heat capacity over the land surface in NorthlandDark results in a much larger
444 seasonal cycle in surface temperatures, with hotter summers and cooler winters (figure 9d). The
445 difference in heat capacity also generates big differences in NH evaporation between Northland-
446 Dark and Aqua, since the available energy at the surface in NorthlandDark is used not only to heat
447 the surface, but also to evaporate water (figure 9b,e). In NH summer, high surface temperatures
448 cause a high vapor pressure deficit. Combined with the low heat capacity that requires more en-
449 ergy to be lost by the land surface as heat or moisture, this drives larger latent heat fluxes from the
450 high latitude land in NorthlandDark than in Aqua, despite Aqua having effectively unlimited water
451 to evaporate. In the annual mean, the tropics in NorthlandDark are hotter and have lower latent
452 heat fluxes than Aqua, while in the high latitudes, surface temperatures are lower and evaporative
453 fluxes are higher. This results in an atmosphere that is drier over the NH in the low latitudes, but
454 actually less dry over the NH high latitudes in NorthlandDark than Aqua (figure 9c). This is no-
455 tably different from the TwoPatchLand, ThreePatchLand, NorthWestLand, and ThreeQuarterLand
456 simulations, but is driven primarily by differences in the heat capacity of land vs. ocean, rather
457 than differences in water availability/evaporation.

458 In summary, we find that suppressing terrestrial evaporation has a direct local warming effect
459 on the region of evaporative suppression, by reducing latent cooling of the land surface. However,
460 suppressing terrestrial evaporation indirectly cools globally by reducing atmospheric water vapour
461 (a strong greenhouse gas). In the case of TwoPatchLand, NorthWestLand, and ThreePatchLand,
462 the local warming effect dominates the response in most terrestrial regions, while the dominant

463 effect over ocean and desert land regions is cooling associated with decreased atmospheric water
464 vapour (figure 7a). However, when evaporation is suppressed over ThreeQuarterLand and North-
465 land, the atmospheric water vapour effect dominates resulting in cooler surface temperatures ev-
466 erywhere (figure 7a). Because Northland does not have any ocean in the Northern Hemisphere, the
467 atmosphere can become much more depleted in water vapour than occurs in the other continental
468 configurations (figure 8o). In TwoPatchLand, NorthWestLand, and ThreePatchLand, atmospheric
469 water vapor is depleted over the continents, but is replenished over the ocean at all latitudes, such
470 that the zonal-mean reduction in atmospheric water vapor is much less than the water vapor reduc-
471 tion in Northland (figure 8, right column). While the reduction in atmospheric water vapour isn't
472 as large in ThreeQuarterLand as in Northland, it is large enough for the mean response of land
473 temperatures to be an overall cooling (figures 7a, 8j). We deduce that the land surface temperature
474 response to reduced terrestrial evaporation is a function of both total land area (which controls the
475 reduction in terrestrial latent heat flux) and contiguous continent size (which controls how dry the
476 atmosphere becomes).

477 *e. The role of moisture transport*

478 In all the Northland simulations except NorthlandDry (which can't store water on land), a Great
479 Northern Swamp forms in the northern high latitudes. In the absence of a large low-latitude water
480 source, is the Great Northern Swamp sustainable? Here we use an all-land simulation, Lakeworld,
481 to show that the existence of the Great Northern Swamp relies on atmospheric moisture transport
482 from the SH ocean in all other Northland experiments. Lakeworld has no ocean; land surface
483 properties are similar to those in NorthlandBright except that lakes of arbitrary depth are allowed
484 to form on all gridcells, if precipitation exceeds evaporation.

485 Lakeworld rapidly forms two lakes, one over each pole (figure 3f), which deepen as the simu-
486 lation progresses. Within a few years, all of the water on Lakeworld - which is initialized with
487 100mm of water in every gridcell - has been transported to the polar high latitudes, and the land
488 in the tropics is completely dry year-round. The lake edges retreat polewards quickly over the first
489 35 years, then more slowly as the simulation progresses.

490 In effect atmospheric circulation redistributes water to concentrate it in the polar regions. On
491 the present-day Earth, the lower branch of the Hadley circulation transports moisture equatorward,
492 but in Lakeworld the moisture is rapidly mixed poleward by mid-latitude eddies, then trapped too
493 far poleward for this mechanism of equatorward transport. The atmosphere of Lakeworld is very
494 dry, with atmospheric moisture isolated to the lower troposphere near the summer pole (figure
495 S4). Because the atmosphere in Lakeworld is so dry, the greenhouse effect is very weak, causing
496 Lakeworld to be much colder than the simulations that include some ocean (figure S1, S5). Surface
497 temperatures in Lakeworld are above the freezing point year round in the lower latitudes, and at
498 higher latitudes during summer (figure S5).

499 The polar lake in Lakeworld has a much smaller latitudinal extent than the Great Northern
500 Swamp in the Northland simulations. The southern portion of the Great Northern Swamp in
501 Northland receives moisture transport from mid-latitude eddies, which does not occur in Lake-
502 world, where the moisture is trapped at the poles after the first few years of the simulation. The
503 lake continues to drift poleward over the course of the Lakeworld simulation. The Lakeworld
504 simulation would have to be run to equilibrium to determine how far poleward the polar lake will
505 retreat. However, we do not continue the Lakeworld simulation beyond 80 years as (a) the ex-
506 tent of the polar lake in equilibrium is not the focus of this study and (b) the atmosphere in an
507 all-land configuration leaks moisture in the current configuration of Isca (figure S6). We also ex-
508 plore an all-land simulation that cannot form lakes (i.e. it has the same land surface properties as

509 NorthlandBright). Like Lakeworld, that simulation also quickly transports water to the poles, but
510 because runoff is discarded when soil moisture exceeds the bucket capacity, the simulation rapidly
511 loses water from the system (not shown).

512 *f. Land's influence on ITCZ location*

513 Here we discuss the unique behavior of the ITCZ in the Northland continental configurations.
514 We find that the ITCZ in *both* hemispheres of all Northland experiments extends farther poleward
515 than in Aqua (with the exception of NorthlandDry, which has very little precipitation over land),
516 despite the greater water vapour content and absorbed SW radiation in Aqua. There is an extensive
517 literature exploring how hemispherically asymmetric sources of energy to the atmosphere cause
518 the atmosphere to transport energy from the energy-rich hemisphere to the energy-poor hemi-
519 sphere, with a corresponding shift in the zonally averaged ITCZ towards the energy-rich hemi-
520 sphere (Kang et al. 2008; Yoshimori and Broccoli 2008; Fasullo and Trenberth 2008; Donohoe
521 et al. 2013; Geen et al. 2020). The relationship between the magnitude of cross-equatorial energy
522 transport and the location of the ITCZ has been explored for the modern Earth system, where the
523 ITCZ shifts 2.4-2.7°S per PW increase in northward cross-equatorial energy transport (Donohoe
524 et al. 2013). In our idealized simulations, we find a marginally steeper relationship than Donohoe
525 et al. (2013), with a 3.4° southward shift in the annual mean ITCZ latitude per PW increase in
526 northward cross-equatorial energy transport (figure 10, S7).

527 The greater poleward extent of the zonally averaged ITCZ location is best explained by com-
528 paring the NorthlandDark and Aqua experiments, since these two configurations have the same
529 surface albedo and differ only in the heat capacity and capacity to store water in the NH. We argue
530 that the primary reason for the greater poleward extent of the ITCZ in the Northland simulations is

531 the difference in heat capacity between the land and ocean hemispheres, which generates a larger
532 hemispheric energy imbalance than in Aqua (both seasonally and in the annual mean).

533 The lower heat capacity of the NH in NorthlandDark provides less of a buffer to the atmospheric
534 energy imbalance by storing less energy in the surface relative to Aqua during JJA, and releasing
535 less energy during DJF (compare SFC in figure 11f,h and j,l). During JJA, the ITCZ extends
536 farther poleward over the NH in NorthlandDark than Aqua, because the land surface takes up
537 little energy, resulting in a larger atmospheric energy source F_{net} in NorthlandDark than Aqua
538 (Geen et al. 2020). During DJF, the ITCZ extends farther poleward over the SH in NorthlandDark
539 than Aqua because the land surface releases little energy, while in Aqua the ocean releases stored
540 energy to the atmosphere; thus, the NH atmosphere is more energy-poor in NorthlandDark than
541 Aqua during DJF. The net effect is that the NH atmospheric energy source is much larger in
542 NorthlandDark than Aqua during JJA, while the NH atmospheric energy source is more negative
543 during DJF in NorthlandDark than Aqua (compare F_{net} in figure 11f,h and j,l, table S2). In the
544 annual mean, NorthlandDark has a hemispheric imbalance in F_{net} , while F_{net} is symmetric about
545 the equator in Aqua (table S2). This hemispheric energy imbalance results in an annual mean
546 transport of energy across the equator from the SH to the NH, consistent with a zonally averaged
547 ITCZ sitting south of the equator (figure 10). Corresponding to this hemispheric atmospheric
548 energy imbalance, the ITCZ in NorthlandDark extends much farther poleward than the ITCZ in
549 Aqua, both seasonally and in the annual mean. In NorthlandBright and NorthlandDry, the ITCZ
550 extends slightly further south than in NorthlandDark during DJF because the lower surface albedo
551 (NorthlandBright) and lower water vapor (NorthlandDry) reduces the total amount of energy taken
552 up during NH summer and subsequently released in NH winter by the land surface, accentuating
553 the hemispheric imbalance in the atmospheric energy source that already exists as a result of the

554 smaller heat capacity of land vs. ocean (figure 11a,c; table S2). Details of the calculations used
555 for figures 10 and 11 are provided in the supplement.

556 **4. Discussion**

557 *a. Temperature response to suppressed terrestrial evaporation*

558 With all else held equal, reducing evaporation from the land surface should lead to surface warm-
559 ing, as the energy formerly used to evaporate water is instead re-partitioned into sensible heat or
560 emitted longwave radiation. While reducing evaporation from the land surface directly leads to
561 warming (Shukla and Mintz 1982; Laguë et al. 2019), reducing water flux from the land surface
562 also impacts atmospheric concentrations of water vapor, a strong greenhouse gas. Given the com-
563 peting effects of reduced evaporative cooling which would lead to warming, and reduced longwave
564 trapping by atmospheric water vapor which would lead to cooling, we hypothesize that a crossing-
565 point exists in the temperature response to suppressed land evaporation (figure 12). Starting from
566 a state of sufficient atmospheric moisture, reducing evaporation from the land surface should ini-
567 tially lead to surface warming as a result of decreased evaporative cooling of the land surface ((i)
568 in figure 12). However, as atmospheric water vapor concentration decreases, the strength of the
569 atmospheric greenhouse effect also decreases, inducing a cooling effect on the surface; the warm-
570 ing signal from suppressed evaporation competes with the cooling from a reduced greenhouse
571 effect ((ii) in figure 12). Once atmospheric concentrations of water vapor are sufficiently low, the
572 cooling effect from the reduced atmospheric greenhouse effect dominates the surface temperature
573 response ((iii) in figure 12).

574 From our simulations, suppressing evaporation over TwoPatchLand would fit into regime (i),
575 where reduced evaporation warms the land surface. NorthWestLand falls between regimes (i) and

576 (ii), where the direct warming effect of reduced evaporation is weaker than in TwoPatchLand, thus
577 the total warming is more strongly damped by the reduction in atmospheric water vapour. Three-
578 PatchLand and ThreeQuarterLand bracket the crossing-point of the temperature response (regime
579 ii), with ThreePatchLand warming slightly and ThreeQuarterLand cooling slightly. Northland
580 falls firmly into regime (iii), where any direct warming of the surface is more than out-weighted
581 by cooling from reduced atmospheric water vapor. Generally, larger total land areas fall further to
582 the right on this curve; however, for the same total land area (e.g. TwoPatchLand vs. NorthWest-
583 Land), the continental arrangement with the larger contiguous continent size falls further to the
584 right. This occurs because when the continents are broken up, the atmosphere can be replenished
585 with water vapor when it passes over the ocean, while in the case of a larger contiguous continent,
586 the atmosphere becomes more depleted in water vapor. We suggest the present-day continental
587 configuration of Earth falls into regime (i), both because the present-day continental configura-
588 tion of Earth most closely resembles TwoPatchLand (i.e. there is ample ocean at every latitude),
589 and because previous modeling studies (e.g. Shukla and Mintz 1982; Laguë et al. 2019) find that
590 reducing terrestrial evaporation leads to surface warming.

591 In our simulations, suppressing terrestrial evaporation in all of our continental configurations
592 leads to cooling over the ocean. This differs from the results of Shukla and Mintz (1982) and
593 Laguë et al. (2019), who found that reduced evaporation with a realistic present-day continental
594 configuration leads to surface warming not only over the land, but also over parts of the ocean. The
595 continental configuration could be one reason for the difference in our results; in the present-day
596 continental configuration, there is a large area of ocean at every latitude. Thus, even if terrestrial
597 evaporation were completely suppressed, dry continental air could advect over the ocean and gain
598 water vapour. However, this is also the case for TwoPatchLand and ThreePatchLand, where we
599 find the land warms but the ocean cools in response to suppressed terrestrial evaporation. An-

600 other reason to expect differences in the temperature response to reduced terrestrial evaporation
601 in this study vs. previous studies relates to model complexity; both the GLAS (Shukla and Mintz
602 1982) and CESM (Laguë et al. 2019) models which showed oceanic warming include the effects
603 of cloud cover. We suspect the difference in the response of ocean temperatures to suppressed
604 terrestrial evaporation between this study and those of Shukla and Mintz (1982) and Laguë et al.
605 (2019) is driven by model differences. In particular, our idealized Isca simulations do not have any
606 representation of cloud cover, and cloud responses to changes in terrestrial evaporation can have
607 large climate feedbacks (Laguë et al. 2019). Understanding how the presence of clouds, and the
608 response of clouds to reduced terrestrial evaporation, modify the temperature response to reduced
609 terrestrial evaporation both on land and globally requires future study.

610 Based on our results from TwoPatchLand/ThreePatchLand versus NorthWest-
611 Land/ThreeQuarterLand (section d), we postulate that suppressing terrestrial evaporation in
612 continental configurations with large amounts of arid land (e.g. polar continents) would have a
613 much weaker impact on water vapour than continents with moist climates (e.g. in the tropics),
614 and thus would not generate strong large-scale cooling. We note that we have tested an extreme
615 level of reduced terrestrial evaporation here. We do not consider the response of temperature to
616 smaller reductions in terrestrial evaporation such as those driven by the closure of plants' stomata
617 in response to increased atmospheric CO₂, which have been shown to generate terrestrial warming
618 across CMIP 5 and 6 models (Zarakas et al. 2020).

619 We have explored the temperature response to suppressing terrestrial evaporation over ideal-
620 ized NH continents; in doing so, we have demonstrated that continental configuration is of ut-
621 most importance in controlling the temperature response to suppressed terrestrial evaporation. We
622 have identified the competing effects of suppressing terrestrial evaporation on surface temperature
623 without any complicating factors driven by cloud responses. These idealized simulations do not

624 represent cloud cover, thus do not capture either how the presence of clouds may modulate the
625 surface temperature response to reduced terrestrial evaporation, or how cloud changes in response
626 to reduced terrestrial evaporation may further influence surface temperatures, both locally over
627 land and over the ocean. Further study is required to identify the seasonality of this response,
628 which continental configurations lead to warming vs. cooling, what level of reduction in conti-
629 nental evaporation is required for warming vs. cooling, and what role clouds play in modulating
630 the temperature response to reduced terrestrial evaporation. Additional study is also needed to
631 determine where and how much this response may matter on the present-day Earth.

632 *b. Connections to Snowball Earth*

633 Our results raise the question of how past continental configurations and distributions of water
634 and vegetation on those continents may have impacted both terrestrial and global paleoclimate
635 through water vapor feedbacks. What is the distribution of continents that is required such that
636 decreasing evapotranspiration from the land surface leads to a cooling rather than warming? In
637 present-day Earth, the greenhouse effect is due mainly to water vapor, and the source of water
638 vapor is net evaporation in the tropics (equatorward of 35° latitude) which is distributed globally
639 by atmospheric circulation. In our TwoPatchLand and NorthWestLand continental configurations,
640 suppressing terrestrial evaporation results in global-scale cooling through reduced atmospheric
641 water vapour, though the land surface generally warms due to reduced latent cooling. However,
642 in our Northland continental configuration, the continent covers the entire hemisphere, which
643 severely reduces the evapotranspiration of water vapor poleward of the ITCZ in the NH. Further
644 reducing terrestrial evaporation in the NorthlandDry experiment reduces the greenhouse effect
645 and causes cooling. In this regard, it is illuminating to consider the Snowball Earth events: global
646 glaciations during which ice covered the entire surface of the Earth (Kirschvink 1992; Hoffman

647 et al. 2017). There is evidence for two such events during the Neoproterozoic (between 630 and
648 750 million years ago) and one in the early Paleoproterozoic (2.5 billion years ago) (Abbot et al.
649 2013; Hoffman et al. 2017), when most of the continental land masses were located in the tropics
650 (see Kump et al. 2004; Worsley and Kidder 1991, and references therein).

651 The Snowball Earth atmosphere is cold and holds little moisture (Voigt et al. 2011; Hoffman
652 et al. 2017). Past work suggests that paleogeographic continental configurations cause a reduction
653 in atmospheric water vapor compared to an aquaplanet without continents, increasing direct heat-
654 ing by decreasing cloud cover (Fiorella and Poulsen 2013). Future work could test the robustness
655 of this result and probe whether past tropical megacontinents were large enough to cause a suffi-
656 cient reduction in tropical water vapor to cool the tropics and contribute to the onset of Snowball
657 events (though the dry atmosphere of Snowball Earth is attributed to the cold temperatures and not
658 vice versa (Voigt et al. 2012; Hoffman et al. 2017)). This reduction in tropical water vapor would
659 cause even greater cooling in the extratropics as a consequence of reduced atmospheric energy
660 transport (Rose et al. 2014). If this occurred, cooling by reduced terrestrial evapotranspiration
661 would help explain why Snowball Earth happened. However, reductions in continental precipi-
662 tation would reduce the rate of silicate weathering, thus allowing for greater CO₂ buildup in the
663 atmosphere, which would act against the formation of a Snowball Earth event. In addition, past
664 tropical supercontinent configurations would have had some ocean at each latitude band, thus may
665 more closely resemble our NorthWestLand or ThreeQuarterLand simulations than our Northland
666 simulations. Notably, the NorthWestLand and ThreeQuarterLand configurations bracket the tran-
667 sition from warming to cooling when land evaporation is suppressed, suggesting this process could
668 be relevant for Pangea-like continental configurations, though we have not explored the effect of
669 varying the position (e.g. moving the whole continent to the tropics) of the megacontinent here.

670 We note that our NorthlandDry simulation has a similar JJA Hadley cell structure as Snowball
671 Earth. The lack of moisture on the land surface in NorthlandDry means that over the continent
672 during NH summer, as in Snowball Earth, the Hadley circulation is dominated by dry dynamics
673 and produces a much smaller overturning circulation than in the present climate (Voigt et al. 2012;
674 Voigt 2013).

675 *c. Precipitation*

676 In our Northland simulations, we find that the polewards extent of the ITCZ over the ocean
677 hemisphere is influenced by the existence of the NH continent. Specifically, we find the small
678 heat capacity and lower water vapor concentrations of the NH lead to the ocean hemisphere ITCZ
679 extending much farther polewards than it does in an aquaplanet simulation. This is similar to the
680 findings of Bordoni and Schneider (2008) and Wei and Bordoni (2018), that ITCZs in aquaplanets
681 with shallower slab oceans extend farther polewards due to stronger energy gradients between the
682 summer and winter hemispheres. Our Northland simulations also demonstrate the importance of
683 hemispheric asymmetries in surface heat storage.

684 Previous studies have shown how hemispheric energy imbalances drive shifts in the zonal mean
685 location of the ITCZ (e.g. Chiang and Bitz 2005; Broccoli et al. 2006; Kang et al. 2008; Swann
686 et al. 2012; Maroon et al. 2016). In the current continental configuration on Earth, zonal mean
687 changes are not generally representative of regional precipitation change (Byrne and O’Gorman
688 2015; Kooperman et al. 2018; Atwood et al. 2020). However, given our zonally symmetric conti-
689 nental distribution in Northland, the energy balance framework is a useful tool for understanding
690 the seasonal cycle of circulation and the distribution of precipitation.

691 In Earth’s present day continental configuration, roughly 68% of the total land mass is in the
692 NH while the remaining 32% is in the SH. This work raises the question of how much the present

693 day continental configuration impacts the ITCZ location via asymmetries in seasonal heat storage
694 between the hemispheres.

695 The present study ties into previous work exploring the impact of continental land masses on
696 the climate system. The tropical rain belts with an annual cycle and a continent model intercom-
697 parison project (TRACMIP, Voigt et al. 2016) showed that the presence of an idealised tropical
698 continent spanning 45° in longitude generally leads to a decrease in global-mean surface tem-
699 peratures compared to an aquaplanet in several different GCMs. The authors noted that while
700 this cooling might be expected from the increase in planetary albedo, the patterns of change are
701 more complex and probably related to changes in cloud cover. Voigt et al. (2016) used a “jello-
702 continent”, which is essentially a patch of thin (lower heat capacity) ocean with higher albedo and
703 reduced evaporation. In contrast to our study, there is no limit on water availability for evaporation
704 over the jello-continent, which would be equivalent to unlimited soil moisture in our experiments.
705 Simulations with “jello” continents in an Earth-like configuration generally capture the present-
706 day climate well (Geen et al. 2018; Thomson and Vallis 2019), but might be too idealized for
707 studying precipitation change in response to CO_2 forcing in some tropical regions such as the
708 Amazon basin (Pietschnig et al. 2019). While the reduction in evaporation due to the presence of
709 land leads to cooling in TRACMIP, similar to what we see from Aqua to NorthlandDark or from
710 NorthlandBright to NorthlandDry, the mechanisms for the cooling are different. Firstly, clouds are
711 not modelled in Isca but are noted to have an impact of surface temperature patterns in TRACMIP.
712 Secondly, the inability of the jello-continent to dry out makes the “warming due to reduced latent
713 cooling” (figure 12 (i)) less extreme, though at the same time the reduction in atmospheric water
714 vapour – which would lead to cooling (figure 12 (iii)) – would be expected to be less drastic than
715 in our study.

716 *d. Relationship to all-land planets*

717 Our Lakeworld simulation rapidly transports all the surface water to the poles. We expect this is
718 because the climatological equator-to-pole temperature gradient ensures an even greater gradient
719 in moisture (via the Clausius-Clapeyron relationship), and atmospheric storms transport water
720 vapor towards the high latitudes where the vapor condenses and precipitates. The condensate
721 remains at the poles because evaporation is greatly reduced by the cooling resulting from the
722 reduced greenhouse effect. During summer, some of the high-latitude soil moisture evaporates, but
723 is locally recycled. In the absence of an efficient mechanism to transport moisture from the poles
724 towards the equator, all the moisture ends up accumulating in the polar regions. This “leaking” of
725 moisture from the tropics to the poles warrants further study: e.g. how much water does the system
726 require to maintain a moist tropics? What controls the latitudinal extent of the polar lake? This
727 distribution of surface water is similar to that on other planets, such as Mars, which has two polar
728 ice caps (Boynton et al. 2002; Wordsworth 2016; Feldman et al. 2004). While the mechanism by
729 which the water on Mars is concentrated in its polar regions is unclear (Wordsworth 2016), we
730 note that this is an intriguing similarity with our all-land simulation.

731 The presence of large topographical features could potentially modify the distribution of water
732 on a land planet, as it could favour the formation of lakes via runoff into basins rather than at the
733 poles, where the distribution of the lakes would be controlled by surface topography rather than
734 atmospheric moisture transport alone, as is the case in our simulations. Indeed, previous studies
735 of all-land planets that include overland river-like mechanisms to bring water back from the high
736 latitudes to the low latitudes have high soil moisture outside of the polar regions and precipitation
737 maxima in the mid latitude storm tracks (e.g. Kalidindi et al. 2018), unlike our Lakeworld simula-
738 tion which has soil moisture maxima at the poles. In their land-planet simulation, Kalidindi et al.

739 (2018) find two distinct climate states in the absence of a seasonal cycle – one hot and dry, and one
740 cold and wet. Including a seasonal cycle only produces a cold and wet state; while our all-land
741 simulation is cold and wet near the poles, the absence of surface water redistribution means that
742 the tropics in our Lakeworld simulation are cold (compared to Aqua or Northland) and dry. Dif-
743 ferences between our results and those of Kalidindi et al. (2018) arise from the addition of clouds,
744 zero obliquity, and importantly the resupply of water to low latitudes in their study. We suspect
745 that without the water recycling mechanism and with a seasonal cycle, Kalidindi et al. (2018)
746 would also observe low values of soil moisture and precipitation except very close to the poles.

747 *e. Limitations*

748 Certain caveats and limitations are inherent in our idealized framework. In this simplified GCM,
749 there are no feedbacks associated with clouds. While cloud responses to terrestrial forcings have
750 been identified in several studies (Hohenegger et al. 2009; de Arellano et al. 2012; Laguë and
751 Swann 2016; Cho et al. 2018; Laguë et al. 2019; Kim et al. 2020), cloud responses are also a large
752 source of uncertainty (Stocker et al. 2013; Zelinka et al. 2017). Redistribution of water within
753 the land surface (e.g. due to rivers or topography) could significantly modify our soil moisture
754 distribution (Kalidindi et al. 2018). We have also ignored surface albedo feedbacks associated
755 with changes in snow or ice; while our simulations can drop below freezing, that has no effect on
756 the surface albedo. We would expect the addition of an albedo feedback to amplify cooling when
757 temperatures drop below freezing.

758 **5. Conclusions**

759 In this study, we use an idealized climate model to study the climate of Northland, a planet
760 with a continent covering the NH and an ocean covering the SH, and several related continental

761 configurations where the NH contains both land and ocean. The physical properties of the land
762 surface differ from the ocean in several ways, each of which has an effect on the climate system.
763 Land has a limited capacity to hold water, a higher albedo, and a smaller heat capacity than oceans,
764 and evaporation and turbulent energy exchange from the land surface is influenced by properties
765 of vegetation and soils. By conducting a series of simulations where specific properties of the
766 land surface are modified, we test the sensitivity of surface climate and atmospheric circulation to
767 various aspects of the land surface.

768 The climatology of Northland has a seasonal temperature cycle that is greatly amplified over the
769 land hemisphere, due to the limited heat capacity of the land surface. On the continent, the tropics
770 are seasonally wet; moisture is brought onto the continent from the ocean by the land-falling
771 ITCZ, but the soils dry out during NH winter. From 20°N-40°N, there is a desert region. In the
772 high latitudes, soils are moist year round. There is rain over high latitude land during NH summer;
773 in contrast, precipitation declines polewards of 45°S in the ocean hemisphere in all seasons. We
774 show that atmospheric moisture transport forms a swampy region in the high latitudes, both in our
775 Northland simulations and over a land-only planet.

776 Surprisingly, we find that suppressing terrestrial evaporation over the Northland continent leads
777 to global-scale cooling, with particularly large cooling of 4.9K over the NH continent - this is in
778 contrast to previous studies which find reducing terrestrial evaporation warms the land surface.
779 With all else held equal, decreasing evaporation would lead to warming as the land surface would
780 have to shed energy through sensible heat or emitted longwave radiation, both of which are a
781 function of surface temperature. However, in our simulations, we find that suppressing terrestrial
782 evaporation reduces atmospheric water vapor concentrations, and in turn decreases the strength of
783 the greenhouse effect. The decrease in the greenhouse effect due to reduced water vapor leads to
784 surface cooling which outweighs any surface warming resulting directly from reduced evaporative

785 cooling in the Northland continental configuration. Using a series of alternative continental con-
786 figurations where only part of the NH is covered with land, we demonstrate that there is a trade-off
787 between the local warming effect of reduced latent heat flux and the global cooling effect of re-
788 duced atmospheric water vapor. When the NH has two 90° wide continents separated by ocean,
789 suppressing terrestrial evaporation leads to 1K of warming over land, while a single 180° wide
790 NH continent leads to weaker warming of 0.7K over land. Three equally spaced 90° wide NH
791 continents lead to even weaker warming of 0.3K over land, while a single 270° wide continent
792 leads to cooling of 0.3K over land. The land only experiences warming as a result of suppressed
793 terrestrial evaporation in regions with soil moisture. Suppressing terrestrial evaporation leads to
794 reduced atmospheric water vapor and decreased downwelling LW over the oceans, which reduces
795 ocean temperatures and evaporation from the oceans, in turn further reducing atmospheric water
796 vapor. We conclude that both the terrestrial and global temperature response to suppressed terres-
797 trial evaporation is not only a function of total land area or the latitudinal distribution of land, but
798 also of continent size.

799 We find that the ITCZ extends much further polewards, both over the land and ocean hemi-
800 spheres, in our Northland simulations compared to an aquaplanet simulation. This is primarily the
801 result of the difference in surface heat capacity between the land and ocean hemispheres, which
802 leads to a larger hemispheric imbalance in atmospheric energy in the Northland simulations com-
803 pared to an aquaplanet.

804 By exploring the climate of Northland, this study provides insight into the role of hemispheric
805 asymmetries in continental distribution on surface climate and atmospheric circulation, as well as
806 into energetic constraints on the ITCZ location. We have identified a fundamental trade-off in the
807 effect of terrestrial evaporation on surface temperatures which warrants further study. Northland
808 provides an ideal limit for probing fundamental impacts of hemispheric asymmetries and raises

809 new questions about the role of continental distribution, planetary albedo, and terrestrial evapora-
810 tion in modulating the climate system.

811 *Data availability statement.* The Isca climate model is publicly available at <https://github.com/ExeClim/Isca>. The data presented in this paper is archived on Dryad, accessible at <https://datadryad.org/stash/share/k1nIAE1nV4tfbZfbCQ0p49qQp8xv1CyBoF9-c1jCDyU>. We
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1057 **LIST OF TABLES**

1058 **Table 1.** List of the idealized-continent Isca simulations used in this study, along with
1059 the land surface property values for each experiment. 50

TABLE 1. List of the idealized-continent Isca simulations used in this study, along with the land surface

property values for each experiment.

Experiment name	Description	Land albedo	Bucket depth [m H ₂ O]	Initial water in bucket [m H ₂ O]
NorthlandBright	Northern hemisphere continent with an albedo brighter than the ocean.	0.325	0.15	0.1
NorthlandDark	Northern hemisphere continent with the same albedo as the ocean.	0.25	0.15	0.1
NorthlandEmpty	Like NorthlandBright, but initialized with no water on the land surface.	0.325	0.15	0
NorthlandDry	Like NorthlandBright, but with a very small capacity for the land to hold water.	0.325	0.00001	0
Lakeworld	All-land planet with bucket hydrology modified to allow lakes to form.	0.325	0.15	0.1
NorthWestLand	Single 180°-longitude wide continent from 0-90°N, covering 25% of the planet's surface. Land surface properties same as NorthlandBright.	0.325	0.15	0.1
NorthWestLandDry	Same as NorthWestLand, but with the same land surface properties as as NorthlandDry.	0.325	0.00001	0
ThreeQuarterLand	Single 270°-longitude wide continent from 0-90°N, covering 37.5% of the planet's surface. Land surface properties same as NorthlandBright.	0.325	0.15	0.1
ThreeQuarterLandDry	Same as ThreeQuarterLand, but with the same land surface properties as as NorthlandDry.	0.325	0.00001	0
TwoPatchLand	Two equally-spaced 90°-longitude wide continents from 0-90°N, covering a combined total 25% of the planet's surface. Land surface properties same as NorthlandBright.	0.325	0.15	0.1
TwoPatchLandDry	Same as TwoPatchLand, but with the land surface properties the same as NorthlandDry.	0.325	0.00001	0
ThreePatchLand	Three equally-spaced 90°-longitude wide continents from 0-90°N, covering a combined total 37.5% of the planet's surface. Land surface properties same as NorthlandBright.	0.325	0.15	0.1
ThreePatchLandDry	Same as ThreePatchLand, but with the land surface properties the same as NorthlandDry.	0.325	0.00001	0
Aqua	Aquaplanet simulation with 20m mixed layer (no land)	–	–	–

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1064 white areas indicate ocean. 53

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1066 shown in (a) & (b) (solid lines). The anomalies for NorthlandDark - NorthlandBright
1067 (dashed lines) and NorthlandDry - NorthlandBright (dotted lines) are shown in (c) & (d).
1068 In a-d, black lines indicate annual mean values, while blue (red) show values for De-
1069 cember/January/February (June/July/August) in (a,c) and cyan (magenta) show values for
1070 February/March/April (August/September/October) in (b,d). Shading in a-d indicates ± 1
1071 standard deviation. Panels (e,f) show the annual mean change in zonal mean relative hu-
1072 midity (shading) and temperature (contours) for (e) NorthlandDark-NorthlandBright and (f)
1073 NorthlandDry-NorthlandBright. Temperature contours are spaced at 1K. Only humidity val-
1074 ues in (e,f) which differ significantly ($p < 0.05$ using a student's t-test) are shown. 54

1075 **Fig. 3.** Zonal mean seasonal cycle of (a) precipitation, (b) evaporation, and (c) precipitation-
1076 evaporation (P-E) for the spun-up NorthlandBright simulation; the equator/continental
1077 boundary is marked by the solid black line. Zonal mean terrestrial water storage over the
1078 first 6 simulation years for (d) NorthlandBright and (e) NorthlandEmpty. Zonal mean ter-
1079 restrial water storage for (f) the full 80 year simulation of Lakeworld (note the non-linear
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1081 moisture). 55

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1083 NorthlandDark, (c) NorthlandDry, and (d) Aqua. 56

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1086 downwards LW is shown in (b). LW emitted by the surface is shown in (c), while (d) and (e)
1087 show sensible and latent heat, respectively. (f) shows the change in net surface energy uptake
1088 ($E_{in} = SW^{\downarrow} - SW^{\uparrow} + LW^{\downarrow}$), where positive values indicate more energy into the surface; in
1089 the annual mean this would be balanced by $E_{out} = LW^{\uparrow} + LH + SH$ 57

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1091 course of the year. The change in net TOA SW is shown in (a) while the change in outgoing
1092 longwave radiation is shown in (b). The net TOA energy budget (a-b) is shown in (c). The
1093 change in the atmospheric energy source $F_{net} = TOA_{net} - SFC_{net}$ is shown in (d), where
1094 positive indicates more energy into the atmosphere. 58

1095 **Fig. 7.** Bar graph showing the area-weighted annual mean change in (a) surface temperature and
1096 (b) latent heat flux globally (gray), over land only (green), and over the ocean only (blue),
1097 for each continental configuration. Small vertical black lines on each bar indicate 1 standard
1098 deviation. The magnitude of the temperature/latent heat flux change is noted above or below
1099 each bar. The total global land fraction for each simulation is noted along the bottom of each
1100 panel. 59

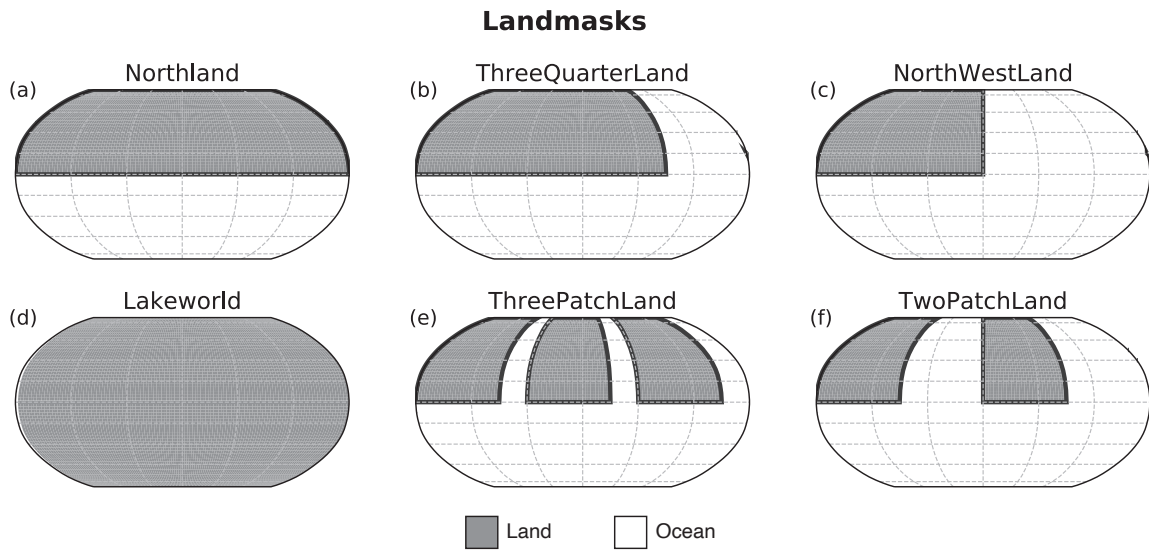
1101 **Fig. 8.** Annual mean change in surface temperature (left), latent heat flux (center), and percent
1102 change in zonal mean specific humidity (right) for suppressing terrestrial evaporation in
1103 various continental configurations. Thick black lines show the continental boundary. 60

1104 **Fig. 9.** Change in surface temperature (left), change in latent heat flux (center), and percent change
1105 in zonal mean specific humidity (right) between NorthlandDark and Aqua. The annual mean
1106 change is shown in a-c, while the zonal-mean seasonal cycle is shown in d-e. 61

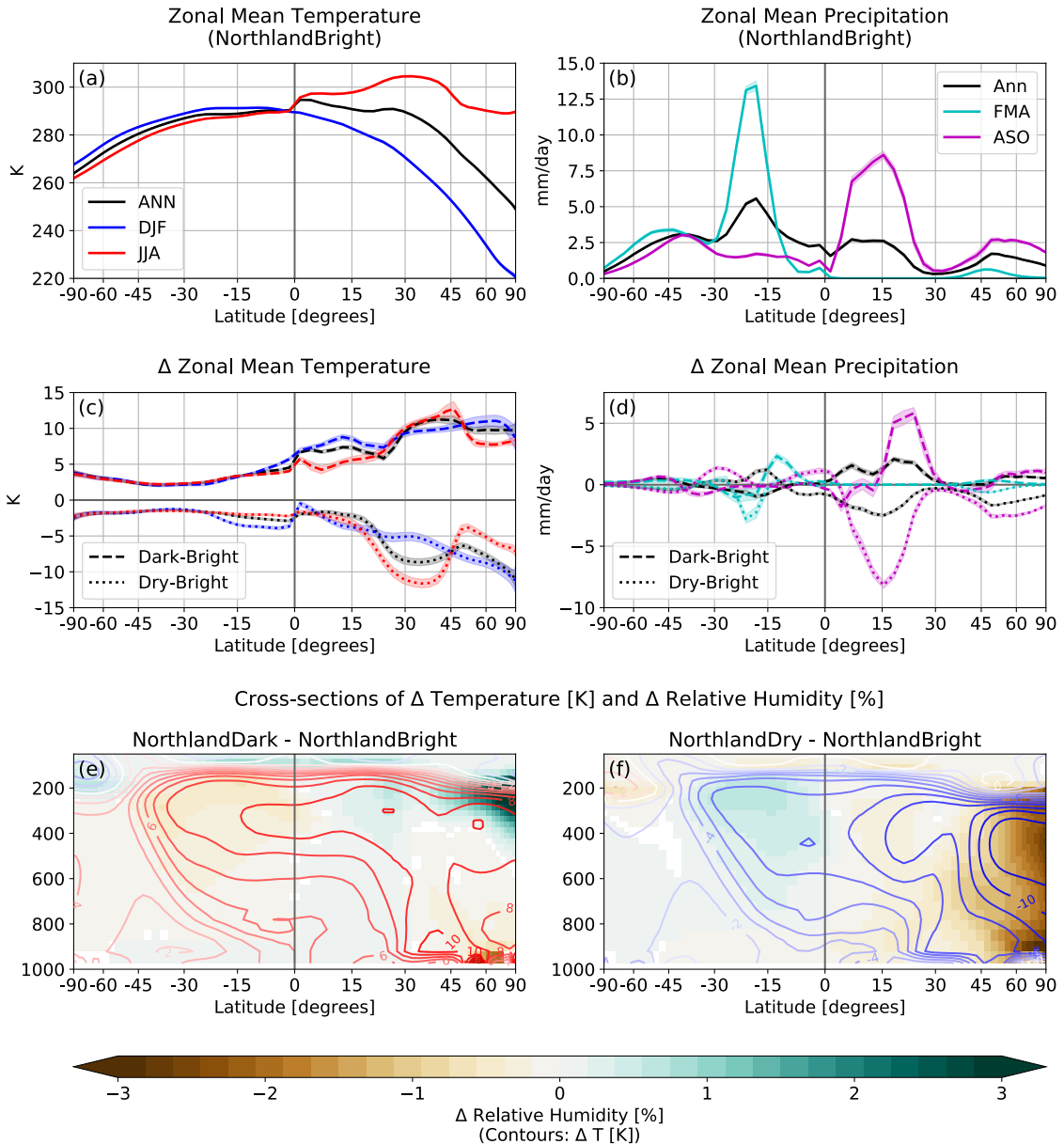
1107 **Fig. 10.** Relationship between the latitude of the ITCZ and the magnitude of cross-equatorial energy
1108 flux. The latitude of the ITCZ is calculated as the center of mass of precipitation between
1109 30°S and 30°N; the magnitude of cross-equatorial energy flux is calculated as the magnitude
1110 of meridional atmospheric energy transport at the equator. Black markers indicate annual
1111 mean values, while blue, purple, green, and red markers indicate DJF, MAM, JJA, and SON
1112 averages, respectively. Circles show values for NorthlandBright, x for NorthlandDark, and
1113 triangles for Aqua. Each individual marker shows the seasonally averaged value for a single
1114 year of the time series. NorthlandDry is not included in the regression calculations here as
1115 the ITCZ effectively collapses over the continent. 62

1116 **Fig. 11.** Zonally averaged net TOA energy flux (TOA , blue dotted line), net surface energy flux
1117 (SFC , green dash-dot line), and the atmospheric column energy source ($F_{net} = TOA - SFC$;
1118 black solid line) for the annual mean (top row), DJF (middle row) and JJA (bottom row).
1119 NorthlandBright is shown in the first column, NorthlandDark in the second, NorthlandDry in
1120 the third, and Aqua in the fourth. The total column integrated cross-equatorial atmospheric
1121 energy transport (positive northwards) for each season is noted in the lower right of each
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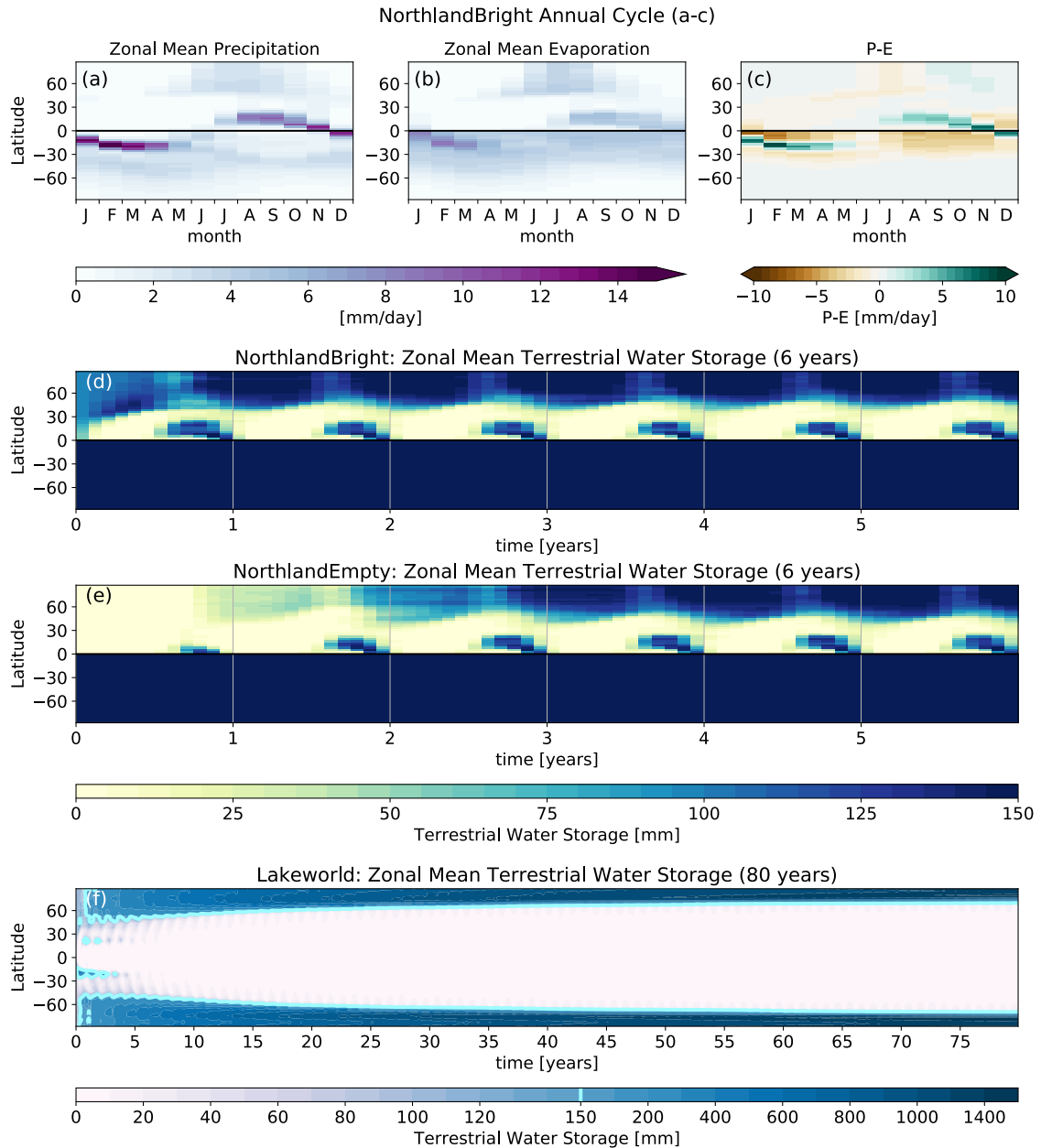
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1126 curve than smaller, more numerous continents. Qualitative locations of suppressing terres-
1127 trial evaporation on TwoPatchLand, NorthWestLand, ThreePatchLand, ThreeQuarterLand,
1128 and Northland are shown by the maps of temperature change for each continental configu-
1129 ration, with the annual mean change in land surface temperature noted on each map. 64



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 1131 indicate ocean.

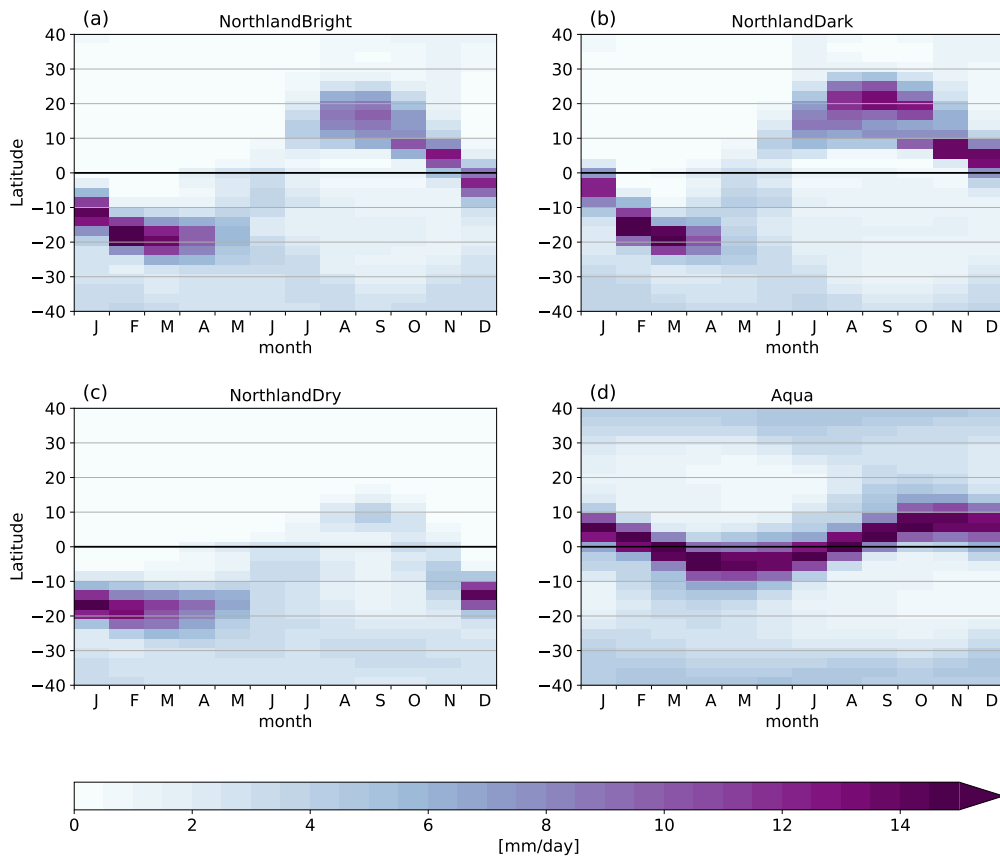


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 1134 - NorthlandBright (dotted lines) are shown in (c) & (d). In a-d, black lines indicate annual mean values, while
 1135 blue (red) show values for December/January/February (June/July/August) in (a,c) and cyan (magenta) show
 1136 values for February/March/April (August/September/October) in (b,d). Shading in a-d indicates ± 1 standard
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 1138 ature (contours) for (e) NorthlandDark-NorthlandBright and (f) NorthlandDry-NorthlandBright. Temperature
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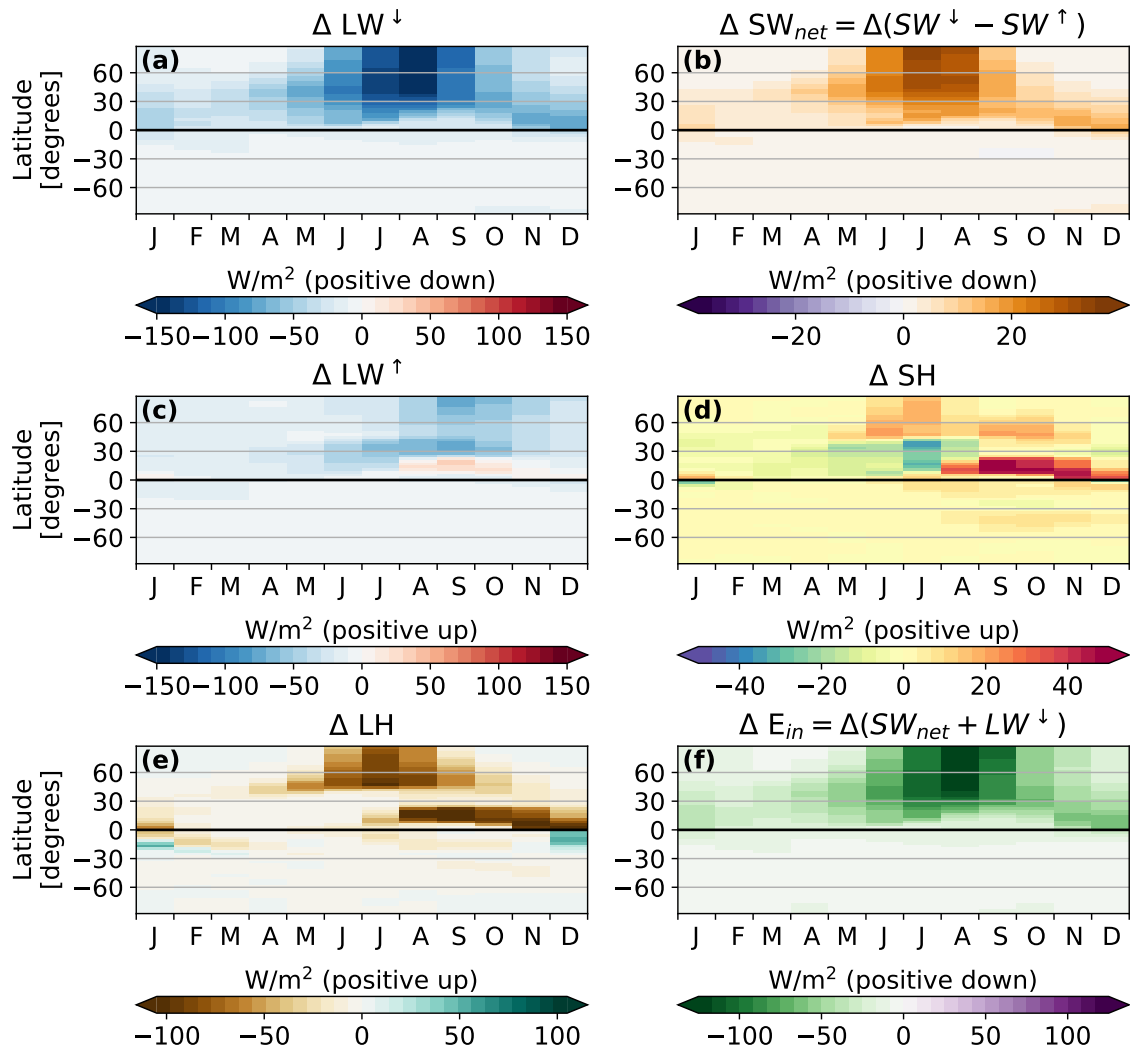
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 1146 moisture).

Seasonal Cycle of Zonal Mean Precipitation [mm/day]

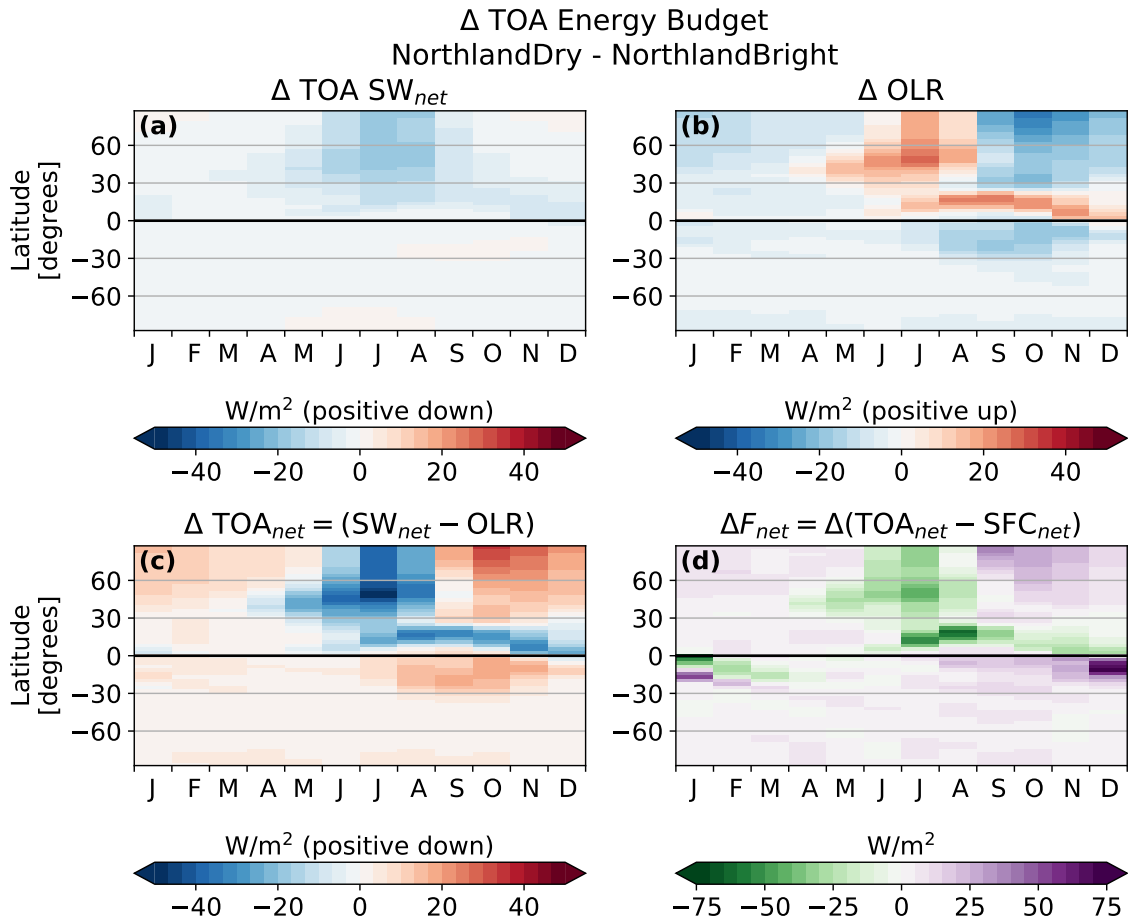


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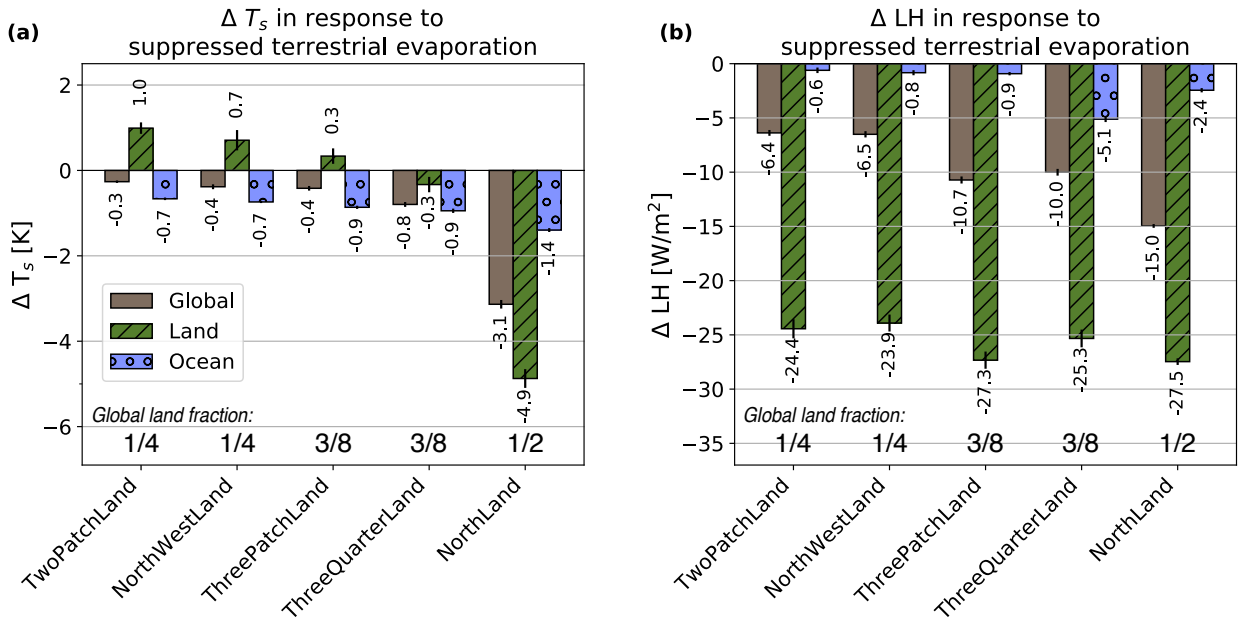
Δ SFC Energy Budget
NorthlandDry - NorthlandBright



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 1152 change in net surface energy uptake ($E_{in} = SW^\downarrow - SW^\uparrow + LW^\downarrow$), where positive values indicate more energy into
 1153 the surface; in the annual mean this would be balanced by $E_{out} = LW^\uparrow + LH + SH$.

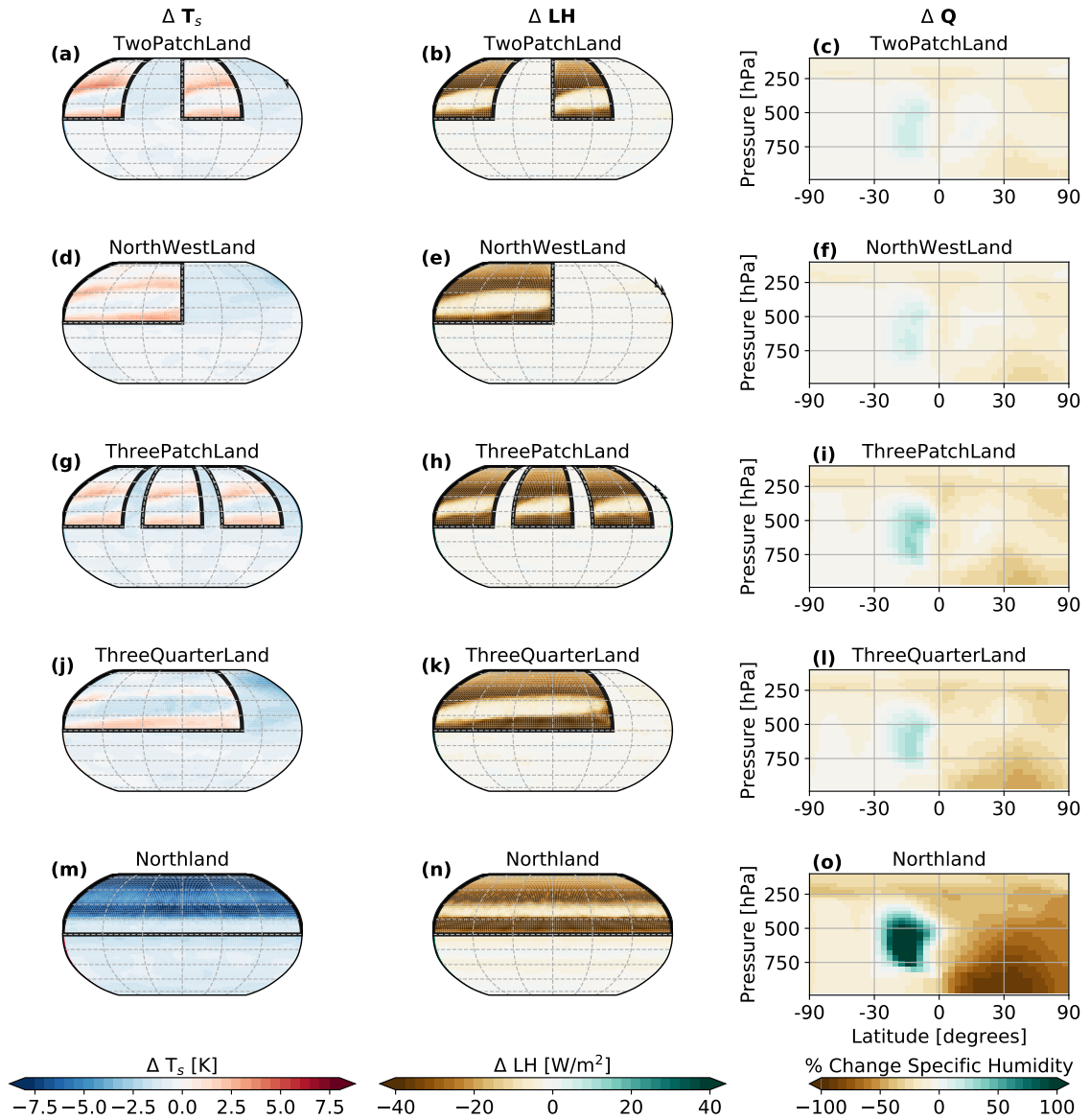


1154 FIG. 6. Change in the zonal mean TOA energy budget for NorthlandDry - NorthlandBright over the course
 1155 of the year. The change in net TOA SW is shown in (a) while the change in outgoing longwave radiation is
 1156 shown in (b). The net TOA energy budget (a-b) is shown in (c). The change in the atmospheric energy source
 1157 $F_{net} = TOA_{net} - SFC_{net}$ is shown in (d), where positive indicates more energy into the atmosphere.



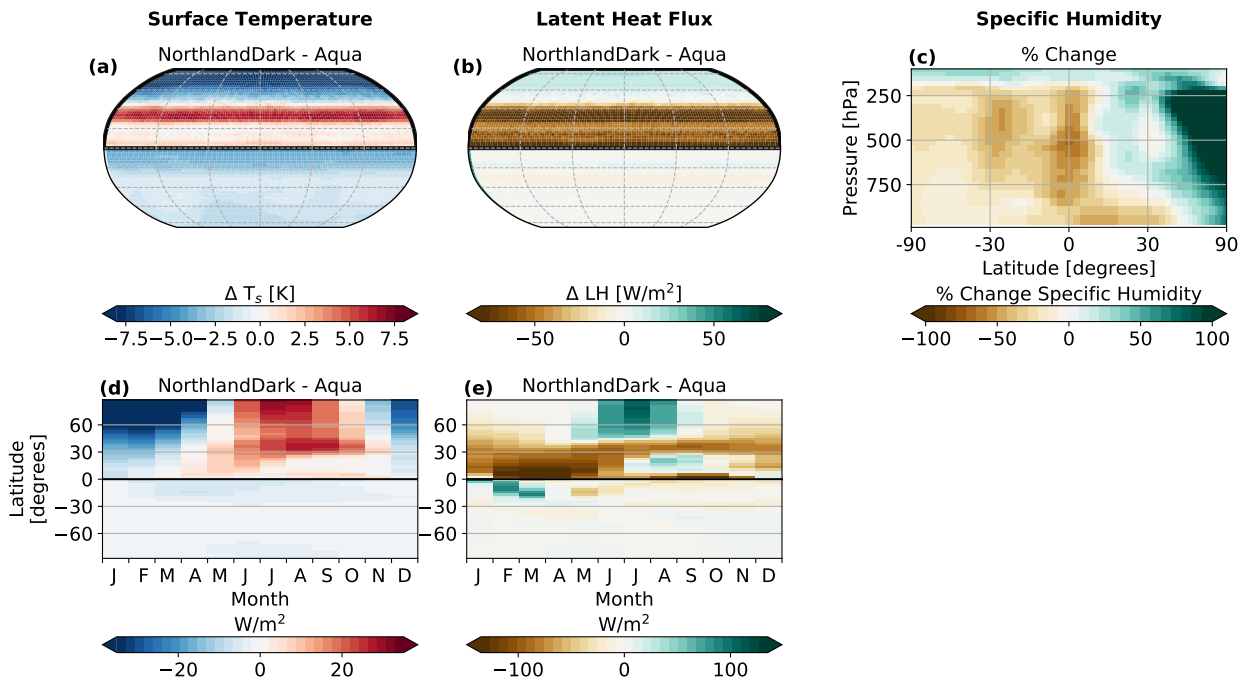
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**Effect of Suppressing Terrestrial Evaporation on
Surface Temperature and Specific Humidity**

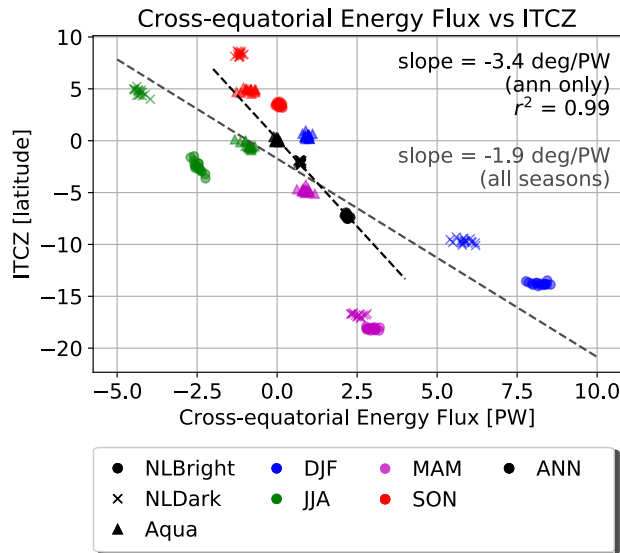


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 1165 Thick black lines show the continental boundary.

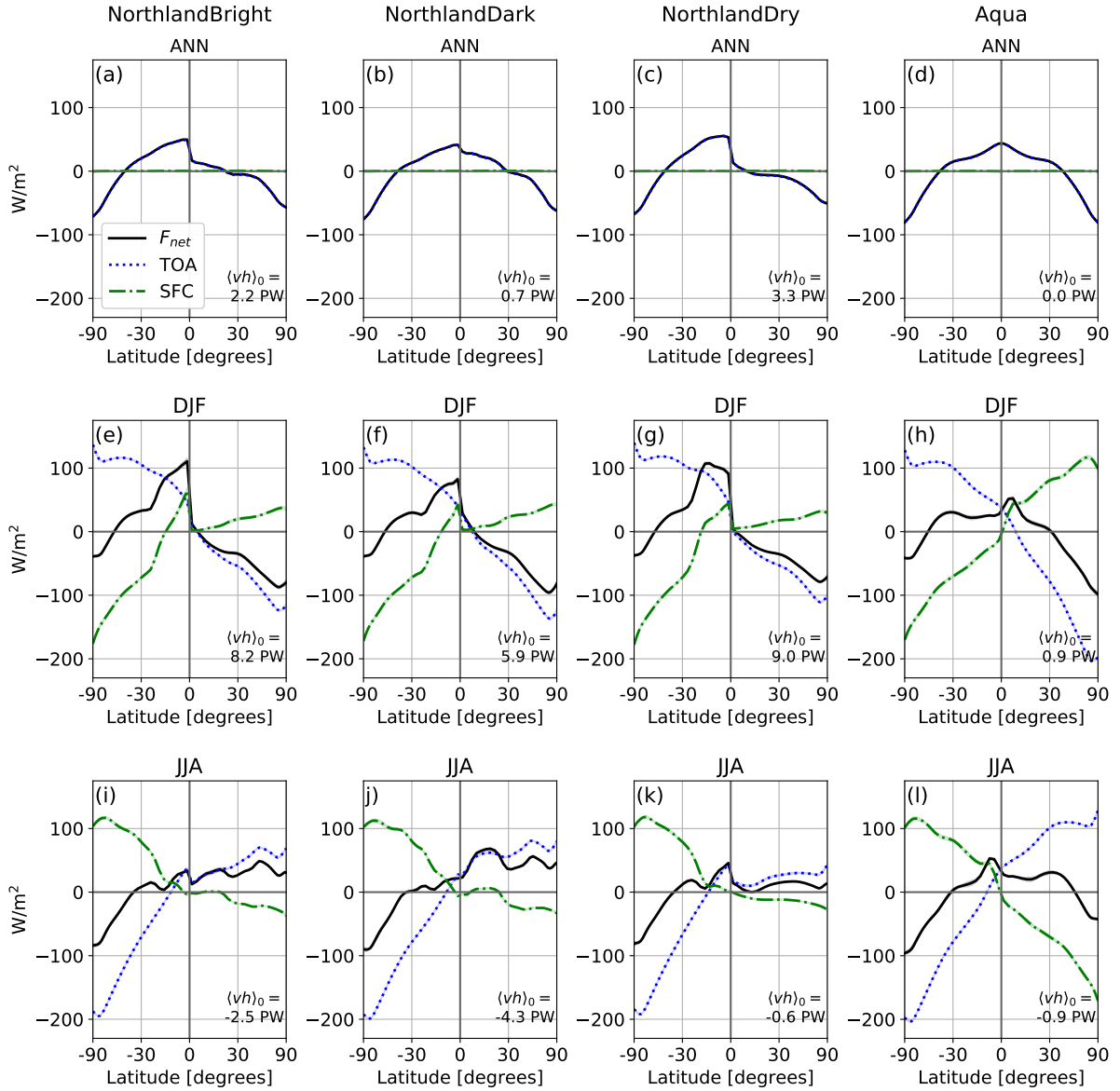
Effect of Suppressing Terrestrial Evaporation on Surface Temperature and Specific Humidity in NorthlandDark vs. Aqua



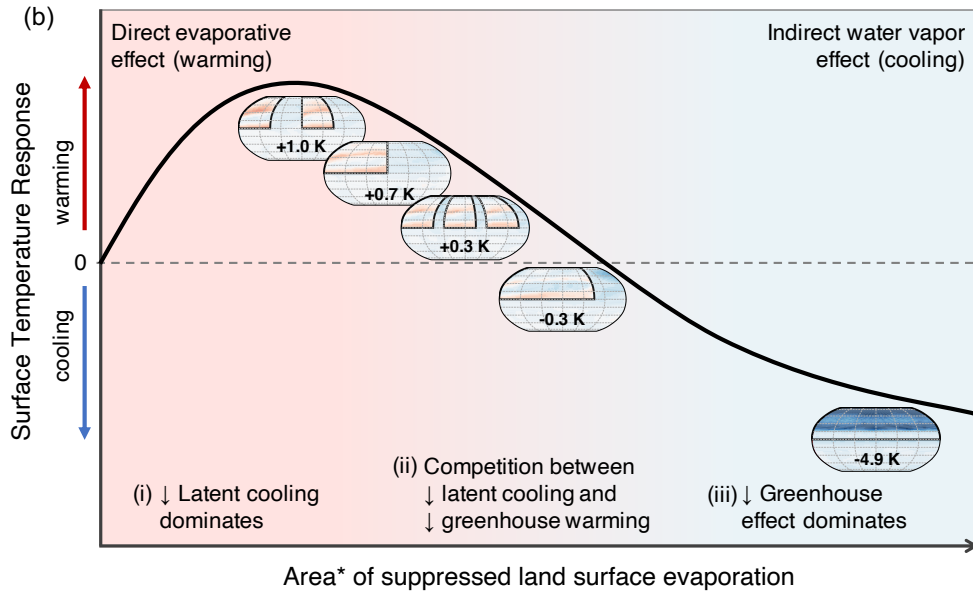
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