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Link between land-ocean warming contrast and surface relative humidities in simulations with coupled climate models

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[1] Simulations of warming climates with coupled climate models exhibit strong land-ocean contrasts in changes in surface temperature and relative humidity, but little land-ocean contrast in changes in equivalent potential temperature. A theory that assumes equal changes in equivalent potential temperature over land and ocean captures the simulated land-ocean warming contrast in the tropics if changes in relative humidity and ocean temperature are taken as given. According to the theory, land relative humidity changes and the land-ocean contrast in the control climate contribute equally to the tropical warming contrast, while ocean relative humidity changes make a smaller (but also positive) contribution. Intermodel scatter in the tropical warming contrast is primarily linked to land relative humidity changes. These results emphasize the need to better constrain land relative humidity changes in model simulations, and they are also relevant for changes in heat stress over land. **Citation:** Byrne, M. P., and P. A. O'Gorman (2013), Link between land-ocean warming contrast and surface relative humidities in simulations with coupled climate models, *Geophys. Res. Lett.*, *40*, 5223–5227, doi:10.1002/grl.50971.

1. Introduction

[2] The land-ocean warming contrast is a fundamental feature of the climate system which is evident in observed surface warming over the last century [e.g., *Lambert and Chiang*, 2007] and in simulations of climate change [e.g., *Sutton et al.*, 2007]. It is often quantified using an amplification factor, $A = \Delta T_L/\Delta T_O$, where ΔT_L and ΔT_O denote changes in surface temperatures over land and ocean, respectively. Observations and a variety of general circulation model (GCM) simulations show global amplification factors of approximately 1.5, with significant variations in latitude [e.g., *Sutton et al.*, 2007; *Drost et al.*, 2012; *Joshi et al.*, 2013]. This enhanced land warming relative to the ocean occurs in both transient and equilibrium simulations, showing that the land-ocean warming contrast does not simply result from the different effective heat capacities of land and ocean regions [*Sutton et al.*, 2007].

[3] The land-ocean warming contrast may influence the response of the atmospheric general circulation to climate change [*Bayr and Dommenget*, 2013], and it is also important for regional impacts of climate change. However, the magnitude of the land-ocean warming contrast varies substantially between climate models [e.g., *Joshi et al.*, 2013]. Furthermore, although heat stress depends on both temperature and humidity, it is not clear to what extent the land-ocean warming contrast is linked to the land-ocean contrast in changes in surface relative humidity that is also found in simulations of climate change [*O'Gorman and Muller*, 2010].

[4] Building on work by *Joshi et al.* [2008], *Byrne and O'Gorman* [2013] proposed a convective quasi-equilibrium theory for the magnitude of the warming contrast. This theory relates surface air temperatures and relative humidities over land to those over ocean based on assumptions of moist adiabatic lapse rates and equal temperatures sufficiently far aloft over land and ocean. (*Joshi et al.* [2008] made slightly different assumptions of no warming contrast aloft and lapse rates equal to humidity-weighted averages of dry and saturated moist adiabatic lapse rates.) When applied to simulations with an idealized GCM, the theory captured the warming contrast over a wide range of climates and for a range of continental configurations, although its accuracy is diminished by land-ocean contrasts in surface albedo and its theoretical basis is only valid in the tropics.

[5] Here we apply a generalized version of the theory to simulations from the Coupled Model Intercomparison Project 5 (CMIP5) and assess the extent to which it links the simulated temperature and humidity changes over land and ocean. We begin by discussing the land-ocean contrasts in changes in temperature and relative humidity in the simulations (section 2). We then apply the theory and use it to characterize the contributions to the land-ocean warming contrast in the tropics, and we discuss possible implications for changes in heat stress over land (section 3). Lastly, we briefly summarize our results and their implications (section 4).

2. Land-Ocean contrasts in CMIP5 Simulations

[6] We consider simulations with 27 models from CMIP5 (these models are listed in section S1 of the supporting information). Climate change is defined here as the difference between 30 year time averages in the historical simulations (1975–2004; referred to as the control climate) and the RCP8.5 simulations (2070–2099) using the r1i1p1 ensemble member in each case [*Taylor et al.*, 2012]. We use monthly mean surface air temperatures and monthly mean surface air relative humidities. Relative humidities in the CMIP5 archive are reported with respect to liquid water for temperatures above 0°C and with respect to ice for temperatures below 0°C. To be consistent with the formulation of

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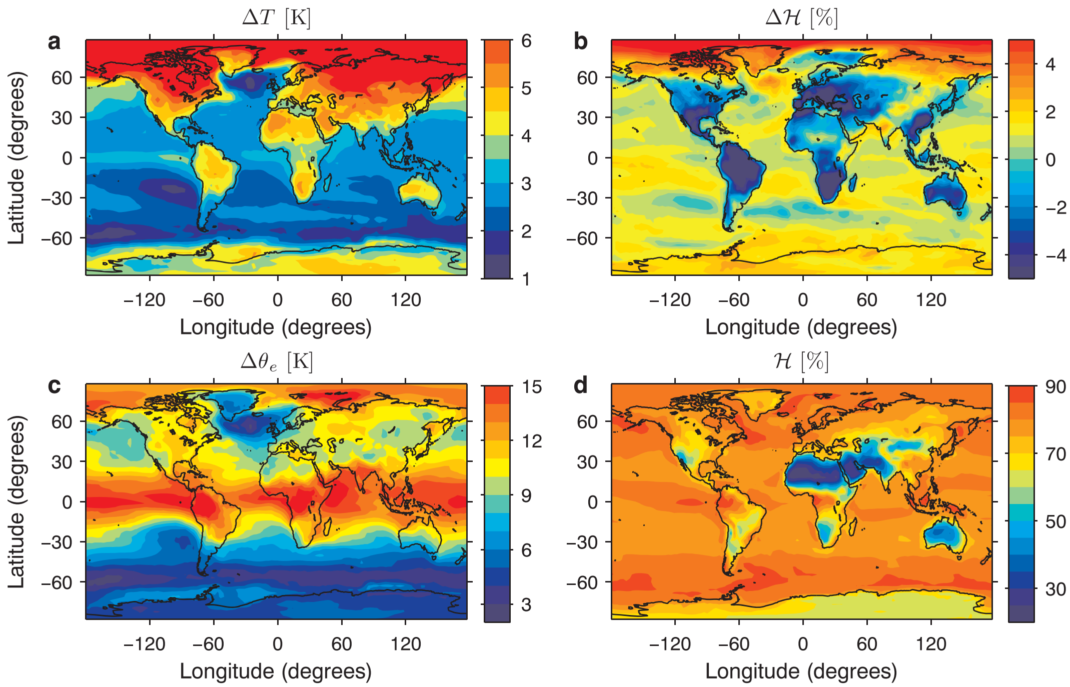

Figure 1. Multimodel-median changes in surface air (a) temperature, (b) relative humidity, and (c) equivalent potential temperature between the historical (1975–2004) and RCP8.5 (2070–2099) simulations. (d) The multimodel-median surface air relative humidity in the historical simulation (1975–2004). Each field is linearly interpolated to a common grid prior to calculation of the multimodel median. Absolute rather than fractional changes in relative humidity are shown in Figure 1b.

equivalent potential temperature we will later use (which does not consider the ice phase of water), we approximately adjust the relative humidities to be always with respect to liquid water using the monthly mean temperatures.

[7] The CMIP5 simulations show substantially greater warming over land than ocean (Figure 1a). To quantify the dependence of the warming contrast on latitude, we calculate the multimodel-median amplification factor based on zonal- and time-mean temperatures (Figure 2). The amplification factor is above unity at almost all latitudes, but it has a local minimum near the equator, maxima in the subtropics, and a general decrease moving from the subtropics to the poles. This variation of the warming contrast with latitude is qualitatively similar to results from the earlier CMIP3 simulations [*Sutton et al.*, 2007; *Boer*, 2011] and from idealized GCM simulations with a meridional land band [*Byrne and O'Gorman*, 2013].

[8] Intermodel scatter in the amplification factor is substantial at many latitudes (Figure 2 and supplementary information Figure S1a). Averaging over the tropics, defined here as 20°S to 20°N, the model amplification factors range from 1.31 to 1.64 (Figure 3a). This represents a large discrepancy between models, especially in the context of the regional and societal impacts of future climate change. By repeating the analysis using different 10 year averaging periods, the effect of internal variability is estimated to be small compared to the intermodel scatter, as shown for the multimodel median in Figure S1b.

[9] There is also a strong land-ocean contrast in the changes in surface relative humidity (Figure 1b) and a land-ocean contrast in climatological mean surface relative humidity at low latitudes (Figure 1d). Surface relative humidity shows increases over ocean and stronger decreases over land, as was also found in earlier simulations [*O'Gorman and Muller*, 2010; *Fasullo*, 2010; *Dommenget and Flöter*, 2011]. Weak increases in surface relative humidity over ocean are consistent with what is expected from surface energy balance considerations and the dependence of evaporation on surface relative humidity [*Held and Soden*, 2000; *Schneider et al.*, 2010]. However, such arguments do not hold over land where there is limited surface water availability. The decrease in land surface relative humidity is partly coupled to the land-ocean warming contrast through the role of the ocean as a source of water vapor transported over land [*Rowell and Jones*, 2006; *O'Gorman and Muller*, 2010; *Simmons et al.*, 2010], but it is also related to changes in factors that affect evapotranspiration such as changes in

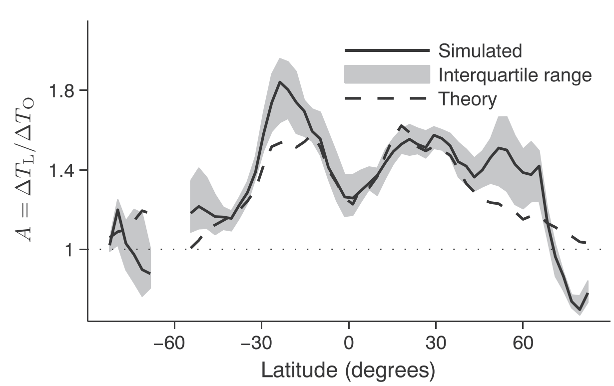

Figure 2. The land-ocean amplification factor, $A = \Delta T_L / \Delta T_O$, versus latitude in the multimodel median (solid line), its interquartile range (gray shading), and the corresponding estimate from theory (dashed line).

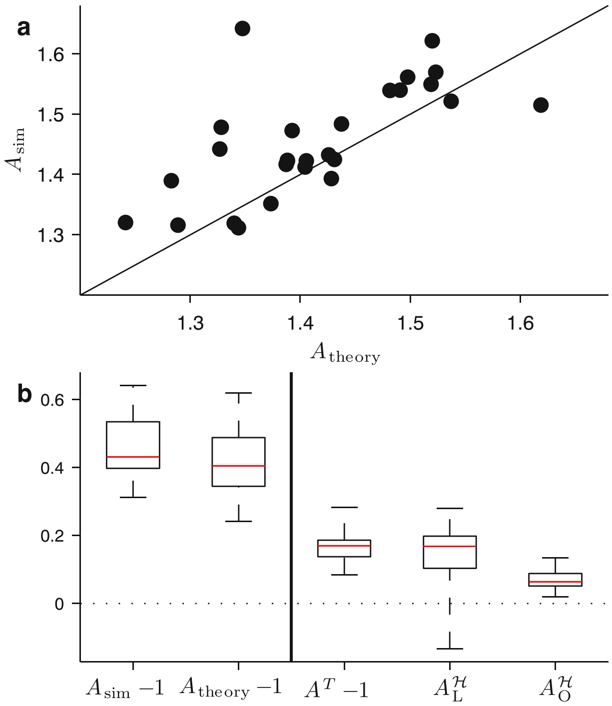

Figure 3. (a) Simulated tropical amplification factors (A_{sim}) versus their theoretical estimates (A_{theory}) for different climate models. The solid line is the one-to-one line. (b) Boxplots showing the tropical amplification factors, their estimates from theory, and the contributions to these estimates as defined by (2). The whiskers show the full model range, the boxes show the first and third quartiles, and the central line shows the median. All amplification factors and contributions in this figure have been averaged between 20°S and 20°N.

stomatal conductance due to increases in atmospheric CO_2 concentrations [e.g., *Dong et al.*, 2009].

[10] In the next section, we show how atmospheric dynamical constraints link the tropical land-ocean warming contrast to the surface relative humidities and their changes, both for the multimodel median and for intermodel differences.

3. Application of Theory

[11] Building on the results of *Joshi et al.* [2008], the theory developed and applied to idealized GCM simulations by *Byrne and O'Gorman* [2013] assumes that (a) temperatures in the tropical free troposphere are equal over land and ocean (consistent with the weak temperature gradient approximation [*Sobel and Bretherton*, 2000]) and (b) that tropical lapse rates are moist adiabatic in the mean over land and ocean, with the result that surface air equivalent potential temperatures are equal over land and ocean. *Byrne and O'Gorman* [2013] briefly discussed a generalized theory, also consistent with convective quasi-equilibrium [e.g., *Arakawa and Schubert*, 1974; *Emanuel*, 2007] that relaxes the assumption of moist adiabatic lapse rates and instead assumes that the degrees of departure of the land and ocean lapse rates from moist adiabats remain constant as climate changes. This generalized theory is formulated by assuming that changes in equivalent potential temperature ($\Delta\theta_e$), rather than the equivalent potential temperatures themselves, are equal over land and ocean:

$$\Delta\theta_{e,\mathrm{L}} = \Delta\theta_{e,\mathrm{O}}. \tag{1}$$

We use the generalized theory here because it is found to be more accurate when applied to climate change in the CMIP5 simulations; the equivalent potential temperature in the control climate is as much as 12 K higher over ocean than land in the zonal and time mean (Figure S2).

[12] We evaluate the equivalent potential temperature based on surface air temperatures and relative humidities (with respect to liquid water) using equation (43) from *Bolton* [1980]. As shown in Figure 1c, the changes in equivalent potential temperature are quite zonally uniform and vary on relatively large spatial scales. Consistent with (1), there is little land-ocean contrast in the changes in equivalent potential temperature, unlike the changes in temperature (Figure 1a) and relative humidity (Figure 1b), both of which vary sharply near coastlines. Because equivalent potential temperature is a nonlinear function of temperature and humidity, equation (1) provides a link between the changes in temperature and humidity and their values in the control climate.

3.1. Estimate of Amplification Factor

[13] Equation (1) is solved numerically at each latitude to estimate the land warming and amplification factor under the RCP8.5 scenario. The primary inputs to the calculation are the control climate temperatures and relative humidities and the changes in relative humidities and ocean temperature. Zonal- and time-mean temperatures and relative humidities are used, but, to allow for seasonal effects, we estimate the land temperature in each of the 12 calendar months individually, prior to taking an annual average. Zonal- and time-mean surface pressures are also used in the calculation of the equivalent potential temperatures.

[14] The theory captures the magnitude and meridional structure of the multimodel-median amplification factor from the equator to approximately 40° latitude north and south, although there is some underestimation in the southern subtropics (Figure 2). According to the theory, the local minimum near the equator is associated with high land surface relative humidity near the ascending branches of the Hadley cells, and the subtropical maxima are associated with low land relative humidity over the arid subtropical land masses. The theory accurately estimates the magnitude of the amplification factor averaged with area weighting over the tropics (20°S to 20°N); the multimodel-median value for the simulations is 1.43 compared with the corresponding estimate from theory of 1.40. The theory also captures the tropical amplification factors in individual models (Figure 3a), with a correlation coefficient across models between the simulated and theoretical values of 0.67. The ability of the theory to capture a considerable amount of the intermodel scatter provides further support for its validity in the tropics.

[15] The theory implies that there should be a general decrease in amplification factor moving from the subtropics to the poles associated with both decreasing temperature and increasing surface relative humidity over land [*Byrne and O'Gorman*, 2013]. However, the theory is not directly applicable to the extratropics because mean extratropical lapse rates are not moist adiabatic and extratropical horizontal

temperature gradients aloft need not be weak. Furthermore, changes in surface albedo may be more important than moisture effects for the extratropical land-ocean warming contrast. Consistent with these expectations, greater deviations from the theory are found in the middle and high latitudes compared with the tropics (Figures 2 and S3). Possible extensions of the theory to the extratropics are discussed in *Byrne and O'Gorman* [2013] (e.g., using the effective static stability of *O'Gorman* [2011]), but here we focus on the tropics where the simplest form of the theory is expected to hold.

3.2. Contributions to the Tropical Amplification Factor

[16] We next assess the contributions to the tropical land-ocean warming contrast when changes in relative humidity and ocean temperature are taken as given. Following *Byrne and O'Gorman* [2013], the amplification factor from theory is decomposed into different components as

$$A_{\text{theory}} = A^T + A_{\text{L}}^{\mathcal{H}} + A_{\text{O}}^{\mathcal{H}}, \tag{2}$$

where A^T is the contribution to the amplification factor that arises from changes in ocean temperature alone (holding land and ocean relative humidities fixed), $A_{\text{L}}^{\mathcal{H}}$ is the contribution that arises from changes in land relative humidity alone, and $A_{\text{O}}^{\mathcal{H}}$ is the contribution that arises from changes in ocean relative humidity alone. The contribution A^T varies nonmonotonically with temperature and has a maximum at an ocean surface air temperature of roughly 290 K when the land-ocean contrast in equivalent potential temperature is zero [*Byrne and O'Gorman*, 2013]. We interpret $A^T - 1$ as the contribution of the land-ocean contrast in the control climate (since it would be zero if temperatures and humidities were equal over land and ocean in the control climate). The magnitudes of the contributions from changes in relative humidity, $A_{\text{L}}^{\mathcal{H}}$ and $A_{\text{O}}^{\mathcal{H}}$, are typically larger for higher temperatures and lower land relative humidities for given changes in relative humidity.

[17] All contributions are evaluated by calculating the land temperature change assuming equal changes in equivalent potential temperature over land and ocean according to (1). Nonlinear interactions between the different contributions are neglected assuming a small change in climate. Changes in surface pressure are not included when calculating the contributions (these changes do not substantially affect the results). The land-ocean contrast in the control climate and the changes in land relative humidity are the largest contributions to the tropical amplification factor (Figure 3b) with equal magnitudes in the multimodel median ($A^T - 1 = A_{\text{L}}^{\mathcal{H}} = 0.17$). Changes in ocean relative humidity make a smaller contribution ($A_{\text{O}}^{\mathcal{H}} = 0.06$). Although the changes in land and ocean relative humidity are typically of different signs, both $A_{\text{L}}^{\mathcal{H}}$ and $A_{\text{O}}^{\mathcal{H}}$ contribute positively to the total amplification factor. The contribution from changes in land relative humidity, $A_{\text{L}}^{\mathcal{H}}$, is strongly correlated across models with the simulated amplification factor ($r = 0.77$). It also has a large intermodel range of 0.4, and changes in land relative humidity are the primary contributor to intermodel scatter in the tropical warming contrast. The other contributions, $A^T - 1$ and $A_{\text{O}}^{\mathcal{H}}$, have smaller intermodel ranges (0.2 and 0.1, respectively), and they are more weakly correlated with the simulated amplification factor ($r = -0.35$ and 0.28, respectively), with a negative correlation coefficient in the case of $A^T - 1$.

[18] In summary, both the land-ocean contrast in the control climate and the land relative humidity change contribute strongly to the warming contrast in the tropics, with a smaller contribution from the ocean relative humidity change that is also positive. Only the land relative humidity change is strongly linked to intermodel differences in the tropical warming contrast.

3.3. Trends in the Historical Simulations

[19] We find qualitatively similar results for temperature and relative humidity trends over the period 1950–2004 in the historical simulations (Figures S4 and S5). In applying the theory to estimate the historical trends in land temperature, we first calculate the seasonally varying climatology of the difference in equivalent potential temperature between land and ocean at each latitude. This climatology is used together with the monthly ocean temperatures and land and ocean relative humidities to estimate a time series of land temperature at a given latitude, which is then used to calculate the theoretical amplification factor based on trends. The multimodel-median tropical amplification factor is 1.37 for the trends compared with an estimate of 1.34 from the theory, both of which are slightly smaller than the corresponding values for the RCP8.5 scenario.

3.4. Sensitivity to the Diurnal Cycle

[20] Because of the strong diurnal cycle of convection over land, it could be argued that the theory should be more applicable to daily maximum temperatures rather than daily mean temperatures. To test the sensitivity of our results to the diurnal cycle, we repeated the analysis (under the RCP8.5 scenario) using monthly means of the daily maximum temperatures and daily minimum relative humidities (mean surface pressures are still used when calculating equivalent potential temperatures as in the standard calculation). Only 11 models (listed in section S1 of the supporting information) in the CMIP5 archive included sufficient data for this analysis. The results for this subset of models show that both the amplification factors and the performance of the theory are similar regardless of whether mean temperatures and relative humidities are used or daily maximum temperatures and daily minimum relative humidities are used (Figure S6), which suggests that the land-ocean warming contrast is not strongly sensitive to the diurnal cycle.

3.5. Implications for Changes in Heat Stress

[21] Equivalent potential temperature is closely related to wet bulb temperature, and changes in wet bulb temperature are a useful measure of changes in heat stress under climate change [*Sherwood and Huber*, 2010]. As a result, changes in heat stress over tropical land are strongly constrained for a given change in ocean temperature and humidity by the equal changes in equivalent potential temperature over tropical land and ocean (equation (1) and shown for individual models in Figure S7). For example, a greater decrease in relative humidity over land due to a change in surface conditions must be compensated for by a greater increase in land temperature, such that the change in equivalent potential temperature matches that over ocean. The link between increases in land heat stress and changes over the ocean is considerably weakened if the changes in land relative humidity are neglected (Figure S7). Because of this compensation

between land temperature and relative humidity changes, our results imply that changes in tropical heat stress over land may not depend greatly on the details of a particular land surface model but are instead constrained by the better understood and simulated changes in ocean temperature and humidity. Further work would be needed to assess whether this constraint on mean quantities is relevant for extremes such as annual maxima in measures of heat stress.

4. Conclusions

[22] We have investigated the land-ocean warming contrast and its links to surface relative humidities in CMIP5 simulations under the RCP8.5 scenario. While simulated changes in surface temperature and relative humidity show a land-ocean contrast and vary sharply near coastlines, changes in equivalent potential temperature are similar over land and ocean and vary on relatively large scales. A theory based on convective quasi-equilibrium that assumes equal changes in equivalent potential temperature over land and ocean is shown to capture the magnitude and intermodel scatter of the warming contrast in the tropics and much of its meridional variation at low latitudes. According to the theory, the land-ocean contrast in the control climate and the changes in land relative humidity are of equal importance for the tropical warming contrast, with a smaller contribution from changes in ocean relative humidity. Similar results are found for trends in the historical simulations, and the amplification factors and the performance of the theory are found to be insensitive to whether daily mean or daily maximum temperatures are considered.

[23] The theory implies a land-ocean warming contrast even in the absence of changes in relative humidity (A^T in equation (2)). As discussed in section 2, this warming contrast leads to a reduction in the land relative humidity (because of the ocean's role as a source for water vapor over land) which then feeds back on the land-ocean warming contrast according to the theory. A more complete theory would take the water vapor budget into account, in addition to the atmospheric dynamical constraints considered here. The extended theory would involve influences on land relative humidity such as changes in water vapor transport and stomatal closure. Such an approach is not attempted here, but the additional constraint from the water vapor budget should be kept in mind when interpreting the results in this paper.

[24] The importance of changes in land surface relative humidity for the intermodel scatter of the tropical land-ocean warming contrast emphasizes the need to better constrain changes in land relative humidity in model simulations. It also provides motivation to better understand the recent drop in land relative humidity in observations and reanalysis [*Simmons et al.*, 2010]. On the other hand, the constraint of equal changes in equivalent potential temperature over tropical land and ocean implies that changes in heat stress over tropical land are strongly constrained by changes in equivalent potential temperature over ocean.

[25] We have focused on the tropics because the assumptions underlying the theory are most applicable there. Further work is needed to better understand the relationship between changes in temperatures and relative humidities at higher latitudes, particularly in the northern midlatitudes.

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