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Earth System Dynamics Discussions

Interactive comment on "An explanation for the different climate sensitivities of land and ocean surfaces based on the diurnal cycle" *by* Axel Kleidon and Maik Renner

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Reply to Review #1

Reviewer comment 1: *"An explanation for the different climate sensitivities of land and ocean surfaces based on the diurnal cycle" by Kleidon and Renner introduces a simple conceptual model to understand why surface temperatures over land respond more strongly than those over ocean to climate change. The mechanism is based on differences in the diurnal energy budgets over land and ocean and is found to agree well with predicted land-ocean warming contrasts from CMIP5 models. I find this paper to be a novel and interesting addition to the literature on the land-ocean warming con-*

trast. My main comments (outlined below) relate to the formulation of the simple model and the validity of these assumptions. If the authors can address these concerns, I will be delighted to recommend publications

Reply: We thank the reviewer for his constructive comments that we reply to below. Most of the comments are minor, and we will incorporate these when we revise the manuscript. As we explain below, much of what the reviewer perceived as assumptions are well-known features of the surface energy balance found in observations and that is essentially knowledge that can be found in textbooks of micrometeorology and general climatology. In the revision we will make it more explicit which parts of the argument are based on textbook knowledge and which parts are novel.

Reviewer comment 2: *Page 1, Line 2: "...with the cause for this difference being still unclear." I do not agree with this statement: Much research on the land-ocean contrast has been conducted over the last 10 years and in particular, the convective quasi-equilibrium theory by Byrne O'Gorman (2013) [cited in this text] can quantitatively capture the warming contrast in CMIP5 models. So I, and many others in the field, strongly believe that we now do have a good understanding of the processes driving the warming contrast and I suggest that the authors might refine this statement in the abstract to reflect this developing consensus.*

Reply: We will adjust the formulation in the revision.

Reviewer comment 3: *Page 1, Line 20: Spelling: "be found" -> "been found"*

Reply: Will be corrected.

Reviewer comment 4: *Page 1, Line 23: Byrne O'Gorman (2013) identified that the land- ocean warming contrast depends not only on changes in relative humidity, but also on the climatological relative humidity over land.*

Reply: We will adjust the formulation in the revision.

Reviewer comment 5: *Figure 1: "loosing heat" -> "losing heat"*

Reply: Will be corrected.

Reviewer comment 6: *Pages 2,3: The following passage of text contains many statements that are key assumptions for the simple model derived in this study, yet are not supported by references. I strongly recommend that the authors better justify these statements by citing observational (preferably) or modeling studies*

Reply: Much of our reasoning is based on textbook knowledge of the surface energy balance (e.g. Oke (1987) "Boundary layer climates", Routledge, and Hartmann (1994) "Global Physical Climatology", Academic Press). In the revision, we will revise this paragraph to make clearer which parts are textbook knowledge and which parts are our interpretation:

"For ocean surfaces, these heat storage changes take place in the surface ocean. Solar radiation penetrates the surface ocean to quite some depth before it is absorbed. Combined with the large heat capacity of water, this results in diurnal heat storage changes that take place below the ocean surface (sketched by the red line on the left of Fig. 1). The build-up of heat storage during the day then maintains radiative cooling and turbulent heat fluxes during the night, resulting in little diurnal variations in surface temperature and turbulent fluxes. **These characteristics of the ocean surface energy balance are very well observed and understood (see, e.g., textbooks by Oke and Hartmann).** Over land this situation is quite different. Solar radiation is absorbed at the surface (or above in a canopy), but not below the surface. This is because land surfaces are not transparent as water, and because the heat conductivity of soils is generally so low that **diurnal variations of surface heating do not penetrate more than 5-10 cm into the ground, resulting in a ground heat flux that is generally small. Even in desert regions or for bare ground with strong surface heating and no evaporative cooling, the ground heat flux does typically not exceed more than 100 W m^{-2}, which is comparatively small to the absorption of 800 W m^{-2} or more of solar radiation (e.g., Oke and Hartmann). Here, we argue that** the strong diurnal variation in solar radiation is thus not buffered below, but rather above the sur-

face in the lower atmosphere. These changes in heat storage manifest themselves in the diurnal growth of the convective boundary layer. This buffering above the surface has an important consequence for the fluxes of the surface energy balance. Turbulent fluxes only take place when the surface is heated by solar radiation during the day that causes the near-surface air to become unstable, while the nighttime is characterised by stable conditions near the surface as little heat can be drawn from the heat storage below the surface. This prevents turbulent fluxes to take place at night. **These consequences for turbulent fluxes over land surfaces are well observed (e.g., Oke and Hartmann). We suggest that because of this absence of turbulent fluxes at night** the cooling at night is determined only by radiative exchange. Turbulent cooling of the surface thus takes place during half of the whole day, while the other half it is cooled by radiative exchange. ..."

Reviewer comment 7: *Page 5, line 7: "which is typically small on a diurnal time scale" -> reference needed to support this statement*

Reply: We will refer to the introduction where this is being discussed (see reply 6).

Reviewer comment 8: *Page 7, line 14: "For the land surface, we assume that the heat storage changes take place in the lower atmosphere" -> is this a reasonable assumption? Reference needed again. Land surfaces can get very hot during the daytime so it is not obvious to me that the surface storage term should be negligible.*

Reply: Even in deserts, the ground heat flux typically does not exceed 100 W m^{-2}, which is much smaller than the heating by absorption of solar radiation of up to 800 W m^{-2} during the day. This is well established, found repeatedly in observations, and is described in textbooks. Rather than addressing this point here, we added this clarification to the introduction (see reply 6).

Reviewer comment 9: *Page 7, line 20: Is it reasonable to assume a net LW radiative flux of zero overnight over land? Are there observations to support this key assumption?*

Reply: Yes, this is a reasonable assumption. Observations of the land surface energy balance generally show a net longwave cooling at night with values typically well below 100 W m^{-2}. This value is small compared to the magnitude of the diurnal cycle in solar radiation. In the revision, we will change the text to emphasize that this is well established in observations, and that we make the simplifying assumption to set this flux to zero.

Reviewer comment 10: *Page 8, section 3.1 Table 2: Various numbers are assigned to parameters in the simple model here but it is not clear which are based on observations and which are tuned so as for the simple model to give a reasonable climatology. A but more detail behind these choices is requested.*

Reply: We apologize for not being clearer. We use observations of total absorbed solar radiation as well as the absorption of solar radiation at the surface from Stephens et al 2012. To obtain a mean surface temperature of about 288 K, we then chose a value of $\tau = 1.74$ for the longwave optical depth. The value of τ is the only parameter we adjusted in the model. We will clarify this description in the revision.

Reviewer comment 11: *Page 8, line 26: The change in LW optical depth is chosen to be 0.11 - how does this compare to observed/modeled radiative forcings? It is important that this number is reasonable as this would validate the simplified radiation parametrisation used.*

Reply: The increase in optical depth by 0.11 was inferred from a surface temperature increase of +5K. It implies an increase in downwelling longwave radiation of about +20 W m^{-2} (when using the grey atmosphere approximation, $3/4\Delta\tau R_{s,toa}$). This increase compares fairly well to the range found in CMIP5 simulations, which range from +22 to +51 W m^{-2} (averaged over land) and are associated with a warming of +4 to +8.5 K of the near-surface air temperature over land (4xCO2 scenario - PI control). In the revision, we will add this information to the manuscript. Unfortunately, we are not aware of a reference for these changes in downwelling longwave radiation in the literature, and

the values used here are from our own analysis (see Figure 1 in this reply), so we will not add a reference. Note also that the particular value used for $\Delta\tau$ does not affect the results (in form of eqn. 20), as the ratio of land to ocean warming is independent of $\Delta\tau$.

Reviewer comment 12: *Page 13, lines 10+11: "First, our results show that the diurnal dynamics of the surface energy balance of ocean and land surfaces are distinctively different." -> I would argue that you assume the diurnal dynamics are different when constructing the simple model. More justification for these assumptions is greatly needed in order to make the results more compelling.*

Reply: As we already described in the replies above (esp. reply 6), many of these are not assumptions, but well-known observations. In the revision, we will make clearer which parts are well-established based on observations, and which is our interpretation.

Interactive comment on Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-44, 2017.

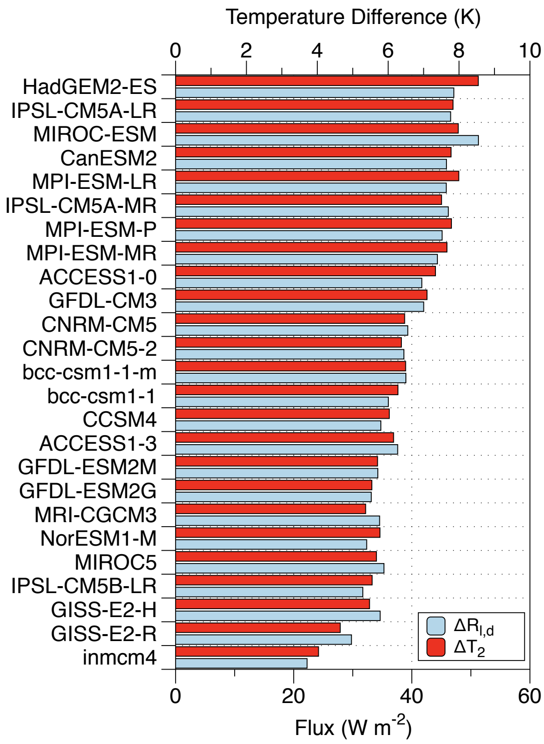

Fig. 1. Difference in downwelling longwave radiation (Delta Rl,d, blue) and near surface air temperature (Delta T2, red) between the 4xCO2 scenario and the PreIndustrial (PI) control simulations of CMIP5.