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Dependence of the land-sea contrast in surface climate response on the nature of the forcing

Manoj Joshi[1] and Jonathan Gregory[1,2]

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[1] The land-sea contrast in surface warming is a phenomenon of both transient and equilibrium climate change. Its magnitude, while model-dependent, is invariant with forcing amplitude. Here we demonstrate that the land-sea contrast is dependent on whether the climate forcing is mainly caused by changes to CO_2 or other mechanisms such as solar or volcanic forcing: this is mainly because a CO_2 change affects stomatal conductance in plants, and therefore changes the amount of evaporation from regions with vegetation present. In addition, solar or volcanic radiative forcing has a different latitudinal distribution to CO_2 forcing: when this effect is removed by normalising the land temperature response by the average ocean temperature response at the same latitude, spatial differences between the CO_2 forced run and the solar forced run become more apparent. Our results affect prediction of the land/sea contrast, as well as the interpretation of proxy climate data.

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1. Introduction

[2] The land/sea contrast in surface warming or cooling is a phenomenon whereby a forcing on the climate system causes the land temperature to respond with a larger amplitude than the ocean. It has been diagnosed in several types of climate model simulations, from climate models forced with perturbed sea-surface temperatures (SSTs) [*Joshi et al.*, 2008] and so-called "slab" climate models [*Manabe et al.*, 1991], to full coupled ocean-atmosphere climate model simulations of the 20th century [*Sutton et al.*, 2007] and 21st century [*Joshi et al.*, 2008, Figure 1].

[3] The phenomenon is perhaps surprisingly not primarily due to the differing thermal inertias of land and ocean, but is more due to feedbacks in the hydrological cycle [*Manabe et al.*, 1991; *Joshi et al.*, 2008]. Interestingly, it has been found that while the land/sea response contrast varies significantly amongst climate models [*Sutton et al.*, 2007], and indeed also varies with parameter uncertainty within models [*Joshi et al.*, 2008], in any given climate model it appears to be somewhat invariant in time and with the amplitude of radiative forcing applied [*Huntingford and Cox*, 2000; *Sutton et al.*, 2007].

[4] It is already known that the magnitude of the land/sea contrast depends on whether or not the dependence of stomatal conductance on CO_2 concentration is present [*Joshi et al.*, 2008]. This is because as CO_2 increases, stomata tend to close, thus reducing evaporation and increasing land temperature, and the magnitude of the land/sea contrast. This implies that inclusion of the CO_2 dependence of stomatal conductance increases the land/sea contrast, which is observed in climate models [*Joshi et al.*, 2008]; it also means that the land/sea contrast in surface warming will be greater when the radiative forcing applied is caused by CO_2 increases rather than other forcing agents.

[5] In addition to the above, the land/sea contrast might change depending on whether the imposed climate forcing is in the short wave (henceforth SW) or infra-red (henceforth LW) part of the spectrum, given the different latitudinal responses of climate models to SW and LW forcing [*Forster et al.*, 2000; *Joshi et al.*, 2003], and the importance of SW feedbacks to the land/sea contrast [*Joshi et al.*, 2008].

[6] We have examined these differences in a number of integrations of the UK Met office's climate models: a control integration of the slab ocean model HadSM3 (henceforth C), a run with doubled CO_2 (2C), a run with solar forcing with globally averaged magnitude 3.7 Wm^{-2} (S), and an integration of the coupled ocean-atmosphere model HadCM3 with 1860–2000 volcanic forcing only, with the forcing multiplied by 5 to give an adequate signal to noise ratio. In the last case, we have averaged years from 1920–1960 to form a minimally forced or control state (henceforth VC), and averaged those years with a drop in the average temperature of more than 1K to form the volcanically forced or perturbed state (henceforth V).

[7] Additionally, we isolated the effect of stomatal conductance changes by analysing four members of the Met Office's HadSM3 QUMP ensemble [*Murphy et al.*, 2004]: a run with pre-industrial CO_2 (QA), a run with doubled CO_2 (2CQA), a run with pre-industrial CO_2 and no dependence of stomatal conductance on CO_2 (QB), and a run with doubled CO_2 and no dependence on stomatal conductance on CO_2 (2CQB). The dependence of stomatal conductance on CO_2 is as described by *Cox et al.* [1999, section 2.3]. This causes stomata to constrict in response to increasing CO_2, reducing evaporation from plants, and increasing surface temperature where vegetation is present. The CO_2 concentration felt by the stomata is the atmospheric concentration (290 ppmv in run QA and 580 ppmv in run 2CQA). A summary of all integra-

[1]Walker Institute for Climate System Research, Department of Meteorology, University of Reading, Reading, UK.
[2]Also at Met Office Hadley Centre, Exeter, UK.

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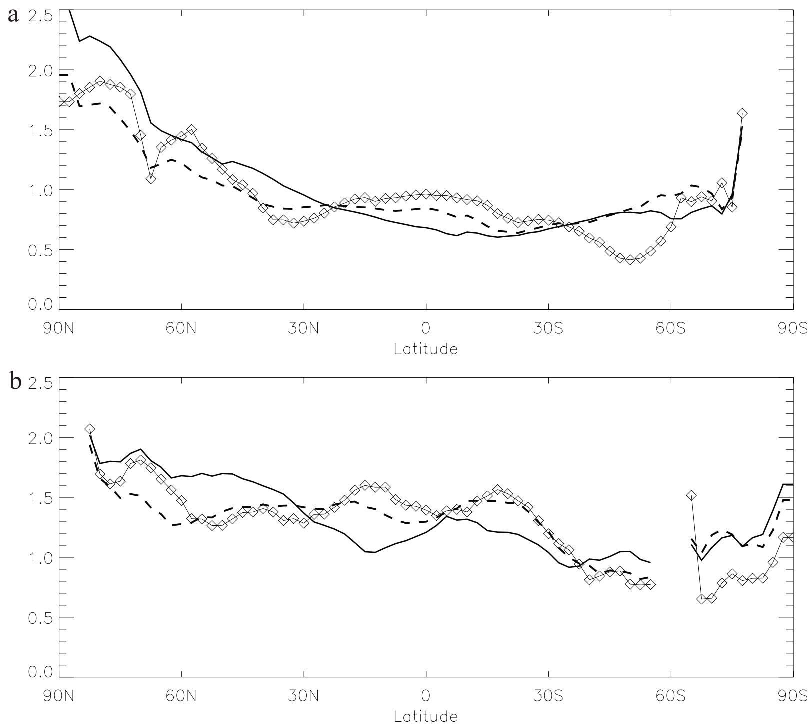

Figure 1. (a) The change in zonally averaged 1.5m temperature over ocean divided by the globally averaged change: 2C minus C (solid); S minus C (dashed); V minus VC (diamonds). Note that "V minus VC" lies above zero because both the zonally and global averaged responses to volcanic forcing are negative. (b) As in Figure 1a but for the land area rather than the ocean area.

tions is shown in Table 1; we note that in all cases, the vegetation fraction is supplied by a monthly varying climatology, so dynamical vegetation feedbacks are not considered here.

2. Results

[8] Figure 1a shows the difference in zonally averaged 1.5m ocean temperature between runs 2C and C, runs S and C, and runs V and VC. In all cases the temperature has been normalised by the globally averaged temperature difference. All three curves show the familiar pattern of polar intensification, especially at northern high latitudes. The curves have slightly difference shapes due to the different meridional structure of the forcing (see above).

[9] The solid curve, (2C-C) has slightly higher values at high northern latitudes compared to the other curves (S-C and V-VC) consistent with the greater radiative forcing at higher latitudes associated with long-wave rather than solar forcing. The solid curve has a correspondingly lower response in the tropics than the other curves. A similar pattern exists in the zonally averaged land response (Figure 1b), i.e., the solid curve is larger at higher latitudes compared to the others. These responses are consistent with previous work [*Forster et al.*, 2000; *Joshi et al.*, 2003].

[10] Figure 2a shows land warming in 2C, but now normalised by the zonally averaged ocean warming at the same latitude, in order to negate the different zonally averaged magnitudes of the climate response in runs 2C, S and V. The pattern is similar to patterns of land/sea contrast observed before, with significant zonally normalised warming in Amazonia, Southern Africa and Australia. Interestingly these regions experience a greater zonally normalised land/sea contrast than arid areas such as the Sahara desert. This is because the subtropical southern ocean itself warms relatively little as shown in Figure 1a.

[11] North of 50–60N, the land experiences a very small zonally normalised land/sea contrast which is consistent with the relatively large SST increase at these latitudes associated with the sea-ice albedo feedback. Another reason

Table 1. Description of Model Runs

Run ID	Slab/Coupled	Stomatal Conductance	Forcing
C	Slab	Y	1xCO2
2C	Slab	Y	2xCO2
S	Slab	Y	Solar
VC	Coupled	Y	Control
V	Coupled	Y	Volcanic
QA	Slab (QUMP)	Y	1xCO2
QB	Slab (QUMP)	N	1xCO2
2CQA	Slab (QUMP)	Y	2xCO2
2CQB	Slab (QUMP)	N	2xCO2

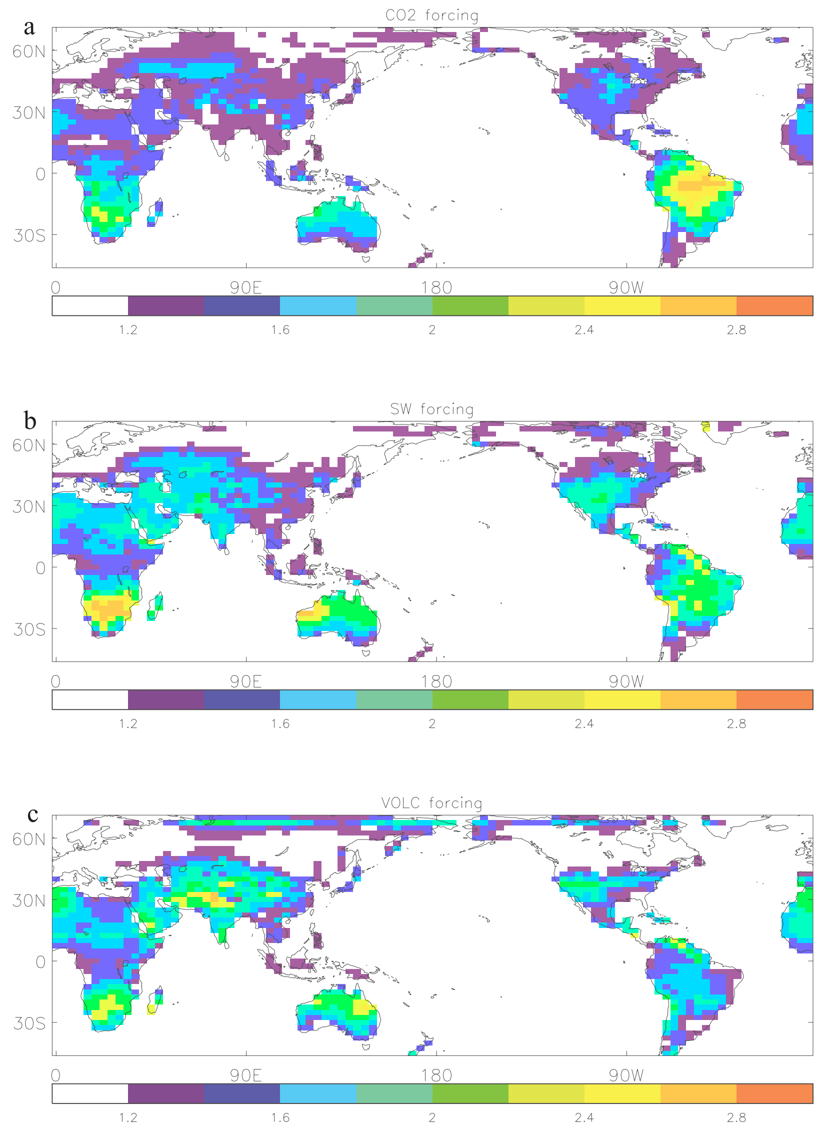

Figure 2. (a) The zonally normalised change in 1.5m temperature between runs 2C and C. The normalisation has been calculated by dividing the temperature change at each land point by the zonally averaged ocean temperature change at the same latitude; (b) as in Figure 2a but for S minus C; (c) as in Figure 2a but for V minus VC.

is the substantial increase in rainfall in these latitudes due to the poleward shift of the storm tracks. This means that increased evaporation associated with a warming climate is effectively counteracted by increases in precipitation, and enhanced warming associated with a drier land surface [*Joshi et al.*, 2008] does not happen.

[12] Figures 2b and 2c show the zonally normalised response for S minus C and V minus VC respectively. To a first approximation, the pattern is broadly similar to that seen in Figure 2a, i.e., that from 2C minus C, with the largest values over the southern tropical regions, decreasing towards the north, with small values in the Arctic. There are differences between Figures 2b and 2c, which we attribute to geographical variations in aerosol optical depth, which cause the meridional structure of the radiative forcing associated with volcanic aerosol to be different to that expected from solar forcing alone [e.g., *Andronova et al.*, 1999].

[13] Figure 3a shows the difference in zonally normalised warming between S − C, and 2C − C. Here two patterns are apparent. Firstly, forested regions such as South American and African rainforests have a smaller zonally normalised warming in S than in 2C, which is consistent with the role of CO_2 in reducing stomatal conductance in 2C but not in S; hence there is more evaporation in S than in 2C for the otherwise similar climatic conditions, resulting in lower surface temperatures. Despite the extra evaporation, the surface moisture is not significantly lowered in these heavily-forested regions with intense rainfall, so evaporation is not restricted.

[14] Secondly, arid areas have a larger zonally normalised warming in S than 2C. This is because arid areas have very small amounts of cloud. Forcing the climate with an increase in solar radiation will cause an enhanced surface forcing where there is little or no cloud.

[15] Figure 3b shows the same pattern as Figure 3a of lower values in forested tropical regions, and higher values

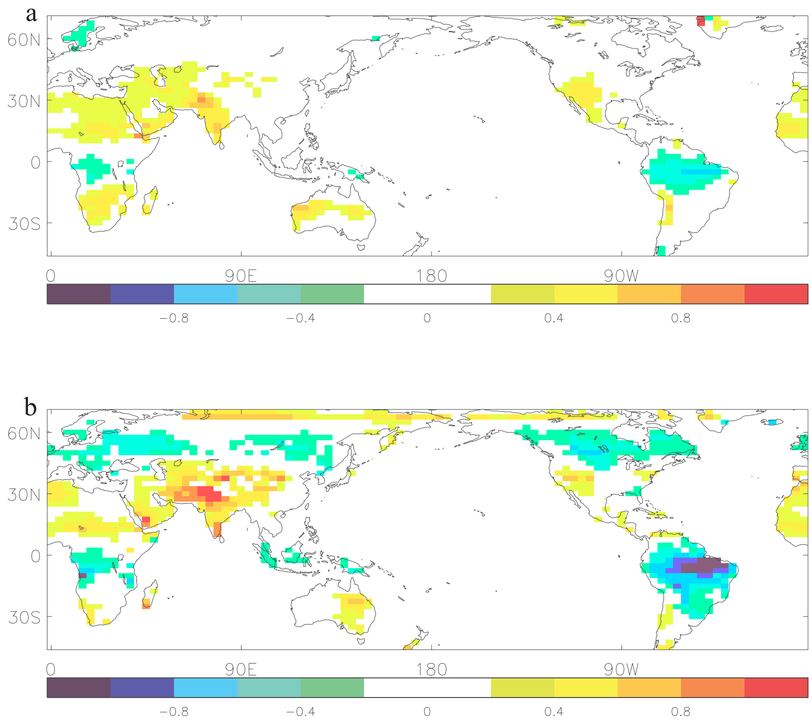

Figure 3. (a) Zonally normalised warming in S minus that in 2C; (b) the same but for V minus 2C. In each case the contours have been masked out where the change is less than two standard errors in zonally normalised warming.

in the arid subtropics, but it is more pronounced, so there is a larger overall difference in zonally normalised warming than Figure 3a This is because V has greater radiative forcing, and hence climate response, than S. Figure 3a shows that apparent differences between S and 2C in Figure 2 in Northern Eurasia are not significant because of the relatively large variability in these regions. However, Figure 3b shows that significant differences do exist between V and 2C in these regions. Since they are forested, the same explanation applies as for the tropical forests.

[16] Finally, in order to isolate the effect of the dependence of stomatal conductance on CO2 from other mechanisms, we have analysed the land/sea contrast in runs 2CQA and 2CQB. Figure 4a shows the normalised warming in run 2CQA; the pattern is quite similar to Figure 2a, the only differences being due to other small differences in physics between runs 2CQA and 2C. Figure 4b shows the zonally normalised warming in run 2CQB, and the difference between the two patterns is shown in Figure 4c, which shows that the effect of neglecting the dependence of stomatal conductance on CO_2 is mainly to reduce zonally normalised warming in heavily forested regions. Figure 4c shows only very small positive anomalies in the arid northern subtropics, because in Figures 3a and 3b these are due to solar forcing.

3. Discussion

[17] Zonally normalised land/sea contrast appears to be a good way of isolating the mechanisms underlying the different land/sea contrast responses of climate models to different forcings. It removes the effect of zonally varying ocean temperature change, which can be very different in model integrations forced by perturbations having different meridional signatures, such as CO_2 and solar radiation in this case.

[18] The differing equilibrium zonally normalised land/sea contrasts in runs 2C and S have implications for how proxies of paleoclimatological temperature data are used to determine climate sensitivity. Generally, proxy data are obtained preferentially over land areas rather than ocean areas, and this can present problems when attempting to assess climate sensitivity from such proxies.

[19] Assume that a proxy for land surface temperature is retrieved at times when the climate forcing had a significant SW component compared to the present day: extrapolating this data to a global average using a value of the land/sea contrast determined mainly from models forced by CO_2 forcing will lead to a bias in the globally averaged temperature difference compared to the present day, depending on the locations where the proxies are measured (see Figures 3a and 3b).

[20] Estimates of ocean temperature variation between 30N and 90N, forced primarily by solar or volcanic forcing during the last millennium, have been obtained using proxies for land temperature at the same latitudes, and the land/sea contrast has been neglected in making these estimates [e.g., *Hegerl et al.*, 2006]. Figure 3 shows that the accuracy of such an assumption will depend on where the land measurements were obtained. South of 40N, the zonally normalised land warming associated with solar or volcanic changes is much larger than unity, so using land data from these locations as proxies for zonally averaged temperature change results in an overestimate of zonally averaged temperature change. Conversely, if the land data is mostly obtained from north of

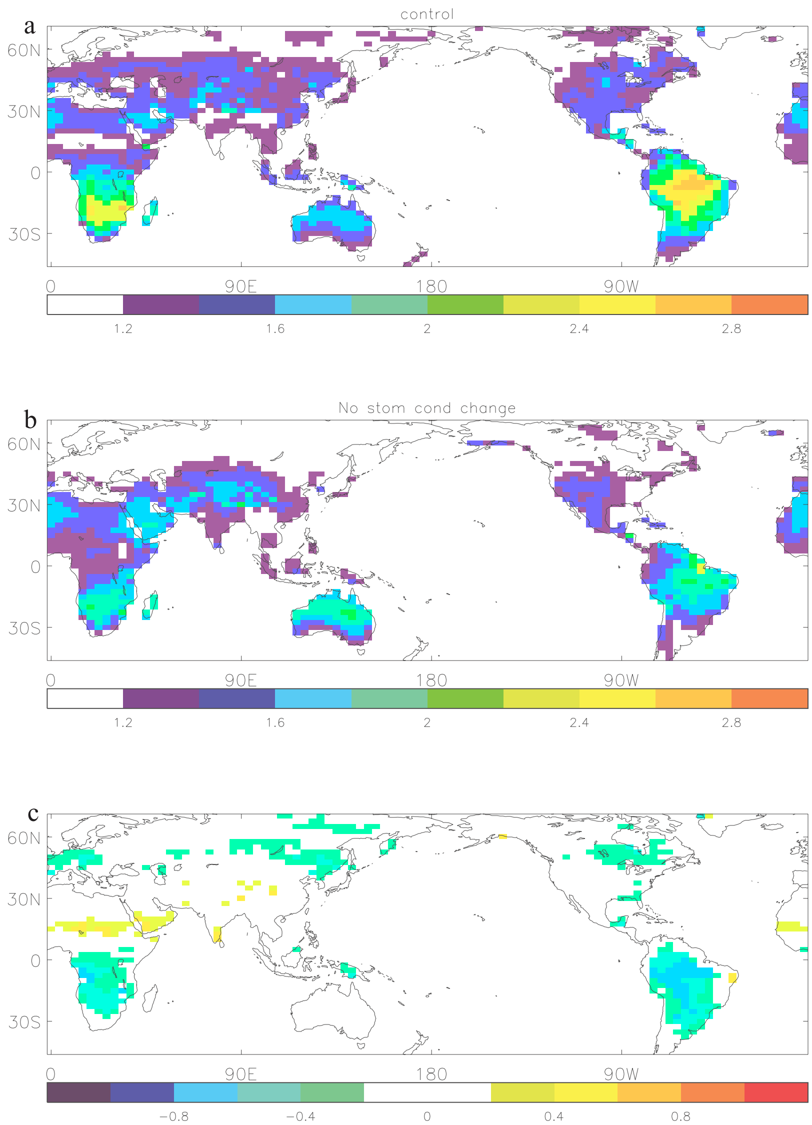

Figure 4. (a) As Figure 2a but for 2CQA minus QA; (b) same as Figure 2a but for 2CQB minus QB; (c) the difference of Figure 4b minus 4a, masked as in Figure 3.

40N, zonally averaged temperate change will be underestimated. The zonally normalised land/sea contrast is therefore important when estimating future global climate change from land data.

4. Conclusions

[21] The land/sea contrast in surface climate change has hitherto been thought of as being independent of the forcing mechanism, whilst being dependent on model structural or parameter differences. We have shown that in fact it varies significantly depending on whether the forcing is based on CO_2 changes, or natural changes to surface forcing brought about by solar or volcanic effects. CO_2 has an effect on stomatal conductance, changing the evaporative fraction of precipitation in vegetated areas, and hence their warming, while differences in the spatial structure of the surface forcing will also affect the land/sea contrast. Normalising the land warming by the zonally averaged ocean temperature change at the same latitude provides a convenient way of identifying mechanisms behind land surface temperature change.

[22] The dependence of stomatal conductance on CO_2 concentration is present in some IPCC AR4 GCMs, but by no means all. In fact the presence or absence of this effect may explain some of the spread in land/sea contrast in these models [*Sutton et al.*, 2007]. Since we find that the dependence of stomatal conductance on CO_2 plays such a significant role in prediction of surface temperature response, this work provides impetus for its inclusion in climate models. This of course should be done with due regard for any increased model uncertainty necessarily introduced by an additional process.

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J. Gregory and M. Joshi, Walker Institute for Climate System Research, Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK. (m.m.joshi@reading.ac.uk)