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Milestone M4.2.4

Analysis of the land/sea warming ratio and potential processes in CMIP integrations to guide further development of the coordinated experimentation

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PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	

1. Introduction

Climate model results show that in response to rising levels of greenhouse gases Earth's climate warms, but some regions warm more rapidly than others. Such regional variations in warming have obvious consequences for climate impacts; thus, understanding the causes of these variations is an important challenge.

The response of simulated surface air temperature to greenhouse gas forcing was summarized in the Third Assessment Report (AR3) of the Intergovernmental Panel on Climate Change [Cubasch et al, 2001], which will shortly be updated in the Fourth Assessment Report, AR4. On the largest scales, two features stand out. First, there is greatest warming at high northern latitudes. This "polar amplification" is generally attributed to snow and sea-ice albedo feedback, although recent studies suggest that other processes are also important [e.g., Hansen et al., 1997; Hall, 2004; Holland and Bitz, 2003; Alexeev et al., 2005; Winton, 2006]. Secondly, climate models consistently show that warming is greater over land than over sea [Cubasch et al, 2001; Braganza et al., 2003; 2004]. This land/sea warming contrast is the subject of our study. It is sometimes assumed that this contrast arises as a simple consequence of the contrast in heat capacity between the ocean and the land. However, as we will show, the contrast in heat capacity is not the most important factor. Our report is based on analysis of results from 20 climate models obtained from the IPCC AR4 data base, and includes comparisons with recent observations. The major findings in this analysis have been published in a recent paper [e.g., Sutton et al. 2007].

2. Multi-model ensembles

The observational data used are the Hadley Centre HadCRUT2v data, which is the product of combining the Hadley Centre Sea Surface Temperature data set [HadISST1: Rayner et al., 2003] with the Climate Research Unit (CRU) land-surface air temperature data set [Jones et al., 2001].

We analyze several sets of model integrations. The first, and primary, set ("1pc-stab") are integrations in which CO_2 increases at 1% p.a. from a pre-industrial value, reaching twice the pre-industrial value after 70 years. The integrations are then continued for a further 70 years with the CO_2 forcing maintained (i.e. stabilized) at twice the pre-industrial value. The second set ("1pc-cont") are identical to the "1pc-stab" set for the first 70 years, but after year 70 the CO_2 forcing continues to increase at 1% p.a., reaching 4 times its pre-industrial value at year

140. The third set ("slab") are equilibrium CO_2 doubling experiments performed with atmospheric GCMs coupled to simple "slab" ocean models. In the case of the transient forcing experiments the results for each model were differenced from a corresponding control integration (in which radiative forcing is held constant) to remove possible climate drift. Results from the "slab" experiments are only available for some models.

The models considered are: CCSM3 (NCAR, USA), CGCM3.1 (T47, T63) (CCCMA, Canada), CNRM-CM3 (CNRM, France), CSIRO-Mk3.0 (CSIRO, Australia), ECHAM5/MPI-OM (MPI-M, Germany), FGOALS-g1.0 (LSAG/IAP, China), GFDL-CM2.0 and GFDL-CM2.1 (GFDL, USA), GISS-EH and GISS-ER (NASA/GISS, USA), INM-CM3 (INM, Russia), IPSL-CM4 (IPSL, France), MIROC3.2(hires) and MIROC3.2(medres) (CCSR/NIES/FRCGC, Japan), MRI-CGAM2.3.2 (MRI, Japan), PCM (NCAR,USA), UKMO-HadCM3 and UKMO-HadGEM1 (Hadley Centre, UK), and ECHO-G (MIUB, Germany). Model references, and full details of institutional abbreviations, can be obtained from http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

3. Results

3.1 Global mean model results

Fig 1 shows the multi-model ensemble mean surface air temperature change in response to doubling CO_2, computed from the 1pc-stab integrations. The enhanced warming over land, compared to over sea, is clearly evident, as is the large warming at high northern latitudes. Minima in the Southern Ocean and North Atlantic Ocean are associated with large ocean heat uptake [Cubasch et al, 2001].

Fig 2 shows the land/sea warming ratio plotted against the global mean temperature change. (The land/sea warming ratio is the global mean surface air temperature change over land regions divided by the global mean surface air temperature change over ocean regions. For brevity this quantity is henceforth referred to as simply "the warming ratio"). The 20-year averaged global mean surface air temperature change around the time of CO2 doubling (at year 70) ranges from 1.0 to 2.3^{o}C with a mean of 1.6°C and a standard deviation of 0.4^{o}C. This range of values reflects differences in climate sensitivity and in ocean heat uptake [Raper et al., 2002]. The warming ratio ranges from 1.36 to 1.84 with a mean of 1.55 and standard deviation of 0.13. Importantly, Fig 2 shows clearly that *there is no simple relationship (e.g. linear correlation) between the warming ratio and the global mean temperature change*, thus the warming ratio appears to be an independent dimension of inter-model variation. The coefficient of variation (standard deviation/mean = 0.08) is not as great as for global mean temperature (0.25) indicating that the warming ratio is a more robust feature of the simulated climate change. Nevertheless, uncertainty in the warming ratio could still be an important factor for projected climate impacts.

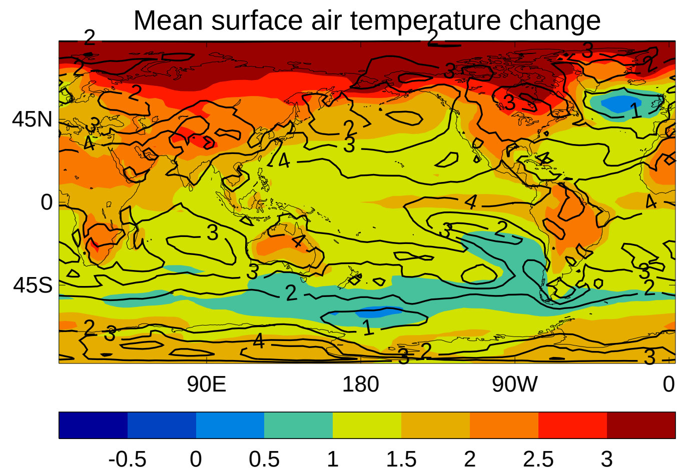

Figure 1: The multi-model (20 models) ensemble annual mean change of surface air temperature (colour shading), (Unit: °C) and the multi-model mean change divided by the multi-model standard deviation (black line) for the "1pc-stab" IPCC AR4 experiments. Shown is the difference between the 20 year mean centred at the time of CO_2 doubling (y61-y80) and the initial 20 year mean. To remove any climate drift, the corresponding means from the control run were subtracted before computing the difference.

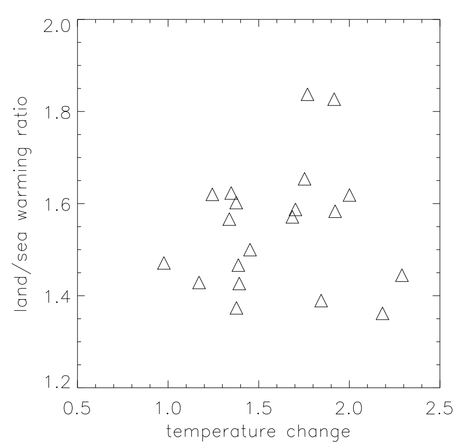

Figure 2: Scatter plot of land/sea warming ratio against global mean air temperature change for 20 models computed from the "1pc-stab" integrations using differences of 20 year means as in Figure. 1.

Fig 3 shows how the warming ratio varies with time in the 1pc-stab and 1pc-cont integrations, and also shows the warming ratio for the equilibrium slab integrations. The figure reveals several interesting features. First, it shows again that the warming ratio varies significantly between models, and the range is consistent with Fig 2. Secondly, in the 1pc-cont experiments, even though the CO_2 forcing is continuing to increase at a significant rate, for most individual models the warming ratio is comparatively constant in time (with a few exceptions, variations are generally at or below the 10% level). This finding, which was noted in an earlier study by Huntingford and Cox [2000], shows that *the processes that determine the degree of enhanced warming over land scale with climate change*. If there were a fixed temperature difference between land and sea then we would expect the ratio to fall towards a value of unity as the climate warmed; the fact that it remains comparatively constant indicates that this temperature difference is *increasing* with planetary warming.

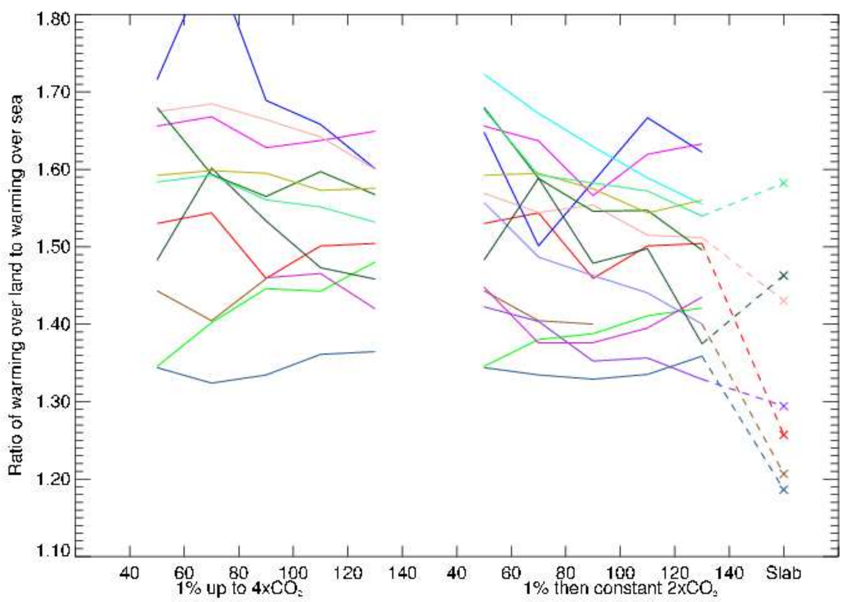

Figure 3: Time series of land/sea warming ratio for “1pc-cont” (left) and “1pc-stab” (right) integrations. Also shown are land/sea warming ratios for equilibrium “slab” integrations (crosses, far right). Different lines/crosses correspond to different models. Dashed lines connect slab model results to results from the coupled model with the same atmosphere component. Note that, for the transient integrations, the first 50 years are omitted because estimates of the warming ratio are noisy until significant warming has occurred. Also, the full 140 years of data were not available for some models.

The 1pc-stab and slab integrations provide information about the importance of thermal inertia (the heat capacity of the ocean) in determining the warming ratio. After the forcing is stabilized in the 1pc-stab integrations (year 70) most models show a small (~10%) decrease in warming ratio. This decrease is likely to be a consequence of the ocean approaching equilibrium. Importantly, however, the warming ratio remains significantly above unity, suggesting that the large heat capacity of the ocean is not the primary reason for the enhanced warming over land. This suspicion is confirmed by the results from the slab model experiments. These experiments are in equilibrium, and yet the warming ratio remains significantly above unity for all the available models (range ~1.18 – 1.58; mean 1.33; standard deviation 0.13.). Manabe et al [1991] reported a similar finding in an early slab model experiment. Comparison with the stabilization integrations shows that in most cases the warming ratio is lower in the slab integration than at the end of the corresponding (i.e. using the same atmospheric model) stabilization integration, but in two cases it is higher. Differences between the slab and stabilization integrations are likely to be related to differences in the simulated sea surface temperature patterns and related differences in simulated climate feedbacks. Lastly, the fact that the inter-model spread in warming ratio is similar in the slab model integrations (standard deviation = 0.13) to that found in the coupled integrations (standard deviation = 0.13) suggests that this spread is unlikely to be dominated by the ocean component of the models.

3.2 Comparison to observations and variation with latitude

Figure 4 shows global land and ocean temperature anomalies relative to the climatology of 1961-90 based on observations [HadCRUT2v, Jones et al., 2001]. Consistent with the models, it suggests faster warming of the land surface temperature than the ocean surface temperature in the last two decades, with an increasing land-sea temperature difference. Global mean temperatures averaged for the last 25 years (1980-2004) over land and ocean were 0.38 +/- 0.14^{o}C and 0.19 +/- 0.06^{o}C respectively, above the 1961-90 climatology. These numbers suggest a warming ratio of ~2.0. Braganza et al [2004] argue that the emerging land/sea warming contrast is a signal of anthropogenic warming. However, the high warming ratio (relative to the model results) may indicate a significant component of natural variability. As discussed in Folland et al [2001], recent warming (1976 to 2004) has been greatest over the mid-latitude Northern Hemisphere continents in winter, and a component of the signal may be explained by the sharp increase in the positive phase of the North Atlantic Oscillation (NAO) /

Northern Annular Mode (NAM) [e.g., Hurrell, 1995; Thompson et al., 2000] since about 1970 (though the change in the NAO/NAM may itself have had an anthropogenic component).

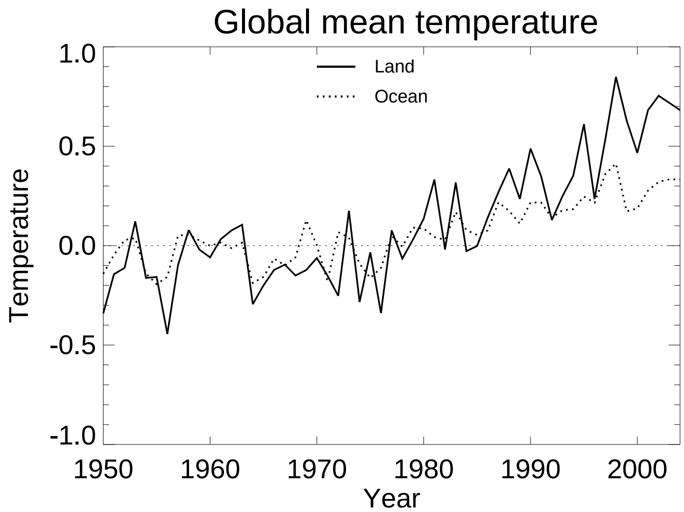

Figure 4: Global and annual mean surface (land and ocean) temperature anomalies relative to 1961-1990 mean based on HadCRUT2v data, calculated from combined land-surface air and sea surface temperatures adapted from Jones et al. (2001).

Figure 5 shows how the warming ratio varies with latitude, both in the model simulations (Fig 5a) and in observations (Fig 5b). The model simulations show a very consistent pattern in the lower latitudes, with a minimum (multimodel mean ratio ~1.2) in equatorial latitudes, and maxima (multimodel mean ratio ~1.5-1.7) in the subtropics. The only outlier is the HadCM3 model; its different behavior is attributable to a large warming that occurs over South America, associated with a strong drying signal in the Amazon region [Williams et al., 2001; Johns et al., 2003]. At middle and higher latitudes the inter-model spread in the warming ratio is larger; for example, in the latitude band 40-60^{o}N ratios range from less than 1 to more than 3. This large spread could reflect differences in the representation of snow and ice albedo feedbacks, or differences in vegetation and soil moisture (see discussion section).

The variation of the warming ratio in observations shows considerable similarity to the model results (Fig 5b). In particular, the equatorial minimum and southern subtropical maximum are seen in the observations and the quantitative comparison is good. For the low-latitude (40^{o}S-40^{o}N) mean, the models suggest a warming ratio of 1.51 +/- 0.13, while the observations suggest a ratio of 1.54 +/- 0.09. In middle and high northern latitudes the observations suggest ratios at the high end of, or above, the range spanned by the models. These high ratios may be related to the change in the NAO/NAM.

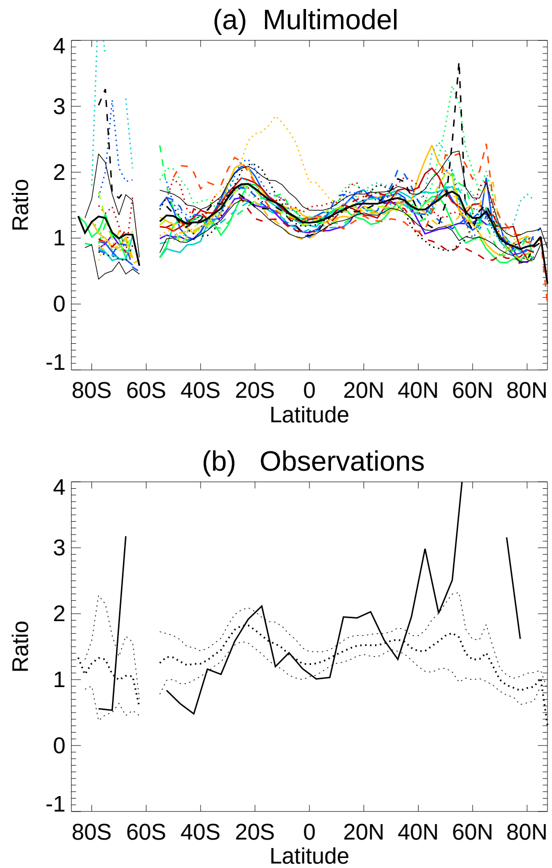

Figure 5: Latitudinal distribution of land/sea warming ratio for (a) models and (b) observations (HadCRUT2v). The land/sea warming ratio for the models was computed as for Fig 1, while for observations it was computed using the difference between the periods (1980-2004) and (1961-1990). The thick dotted line in (a) is the multimodel mean, and thin dotted lines show one standard deviation variation; these lines are also plotted in (b) to aid comparison with the observations. Ratios are shown at every latitude for which there is at least one land grid point.

4. Discussion

The results show that enhanced warming over land is a robust feature of climate model responses to increasing CO_2, and that at least in lower latitudes the warming ratio shows a robust variation with latitude. The robustness of these responses suggests a simple explanation. Here we present a simple argument based on surface energy balance. Consider the anomalous surface energy budget. The increase in CO_2 causes a radiative forcing at the top of the atmosphere (or at the tropopause) and also a forcing at the surface. Following Shine et al [2003], we will define the *surface forcing* as the anomalous downward surface energy flux that would result from increasing CO_2 whilst keeping *surface* land and sea temperatures fixed, but allowing atmospheric temperatures and humidities (stratospheric and tropospheric) to adjust. It is important to note that the surface forcing is not purely radiative. Increased trapping of long wave radiation will cause the troposphere to warm, changing the turbulent as well as the radiative surface fluxes; thus the surface forcing will include contributions from both.

Assume for simplicity that the surface forcing is equal over land and sea. In equilibrium the anomalous downward energy flux must be balanced by an equal anomalous upward energy flux. As pointed out by Manabe et al [1991], over sea or wet surfaces it is likely that much of the additional energy will be used to enhance evaporation (since evaporation is very sensitive to changes in surface temperature, as a consequence of the Clausius-Clapeyron relationship). The energy budget will therefore be substantially balanced by an enhanced upward latent heat flux. By contrast, over a comparatively dry land surface there is much less potential to enhance evaporation, thus a greater portion of the additional energy will be used to raise the temperature. The energy budget will then be balanced by the resultant enhanced upward sensible and longwave heat fluxes (which are less sensitive than is the latent heat flux to changes in surface temperature). This simple argument neglects many possible complexities. For instance, feedbacks related to lapse rate, water vapour, cloud and albedo might well differ over land and sea. The surface forcing may also differ, e.g. as a consequence of the humidity contrast between land and sea. However, the point of the argument is to suggest how the different nature of the land and sea surfaces might explain the greater warming over land than sea. Supporting evidence comes from analysis of the global surface energy budget in the 1pc-stab integrations. This analysis shows that doubling CO_2 leads, over the ocean, to an enhanced latent heat loss of 2.52 Wm^{-2}, and a *decrease* in the sensible heat loss of 1.29 Wm^{-2}. By contrast, over the land the latent heat loss increases by only 0.83 Wm^{-2} (i.e. approximately one third of the increase seen over the ocean), and the sensible heat loss *increases* by 0.86 Wm^{-2}. (All flux values are global and multimodel mean anomalies computed from the 1pc-stab integrations as differences between the mean of the years 61-80 and the mean of the first 20 years.)

Although it neglects many complexities, the simple surface energy budget argument offers a possible explanation for the observation that the warming ratio is comparatively constant as the climate system warms (as shown in Fig 3). Assume that the surface forcing is F, and that a linear approximation to the total anomalous upward surface flux is αT_l over land and βT_s over sea, where T_l is the anomalous land surface temperature, T_s the anomalous sea surface temperature, and α and β are constants. Then equilibrium requires that: $F = \alpha T_l = \beta T_s$. It follows that $T_l/T_s = \beta/\alpha$ (a constant). Furthermore, the fact that the latent heat flux is highly sensitive to temperature change implies that $\beta > \alpha$, thus the constant is greater than 1, as observed. (This argument can be generalized to the case of different surface forcings over land and sea, so long as their ratio remains constant in time.)

A further prediction of the above theory is that one might expect the warming ratio to be higher in regions where land is relatively dry, and lower in regions where land is relatively wet. This idea offers an explanation for the variation in warming ratio that is seen at low latitudes in Fig 5, with a minimum near the equator where there are high rates of precipitation associated with the ITCZ, and maxima in the subtropics where the precipitation rate is much lower and rates of evaporation are typically high. The theory is also supported by analysis of the seasonal variation of the warming ratio (not shown), which indicates that the location of the equatorial minimum in warming ratio moves seasonally, and is always situated in the summer hemisphere where land precipitation is highest as a consequence of the movement of the ITCZ. We have also confirmed that latent heat flux anomalies over land are indeed at a maximum at the equatorial latitude where the warming ratio is minimum.

Lastly, the theory suggests that some of the inter-model variation in warming ratio could be caused by inter-model variations in soil moisture, snow, and vegetation characteristics (which would affect the α coefficient defined above, while leaving β unaltered.). The fact that global mean land surface warming shows a greater inter-model range of values (1.23-2.93^{o}C) than global mean sea surface warming (0.86-2.03^{o}C; both ranges for the 1pc-stab integrations) is in line with this suggestion.

5. Conclusions

Using IPCC AR4 model integrations we have investigated the tendency for greater warming over land than over sea in response to greenhouse gas forcing. In all the 20 models examined warming over land exceeds warming over sea, i.e. the land/sea warming ratio is greater than 1. Global mean warming ratios for the coupled GCMs are in the range 1.36 – 1.84. There is no simple relationship between the global mean warming ratio and global mean temperature change, indicating that the warming ratio is an independent dimension of inter-model variation. For a given model, the warming ratio in the presence of increasing radiative forcing is fairly constant in time, implying that the land/sea temperature difference increases with time. Furthermore, the enhanced warming over land is not simply a transient effect caused by the greater heat capacity of the ocean: it is also present in equilibrium conditions. A simple explanation for these findings based on surface energy balance arguments has been provided. Consistent with the model results, recent observations also suggest that surface temperatures over land have been increasing more rapidly than surface temperatures over the ocean.

The land/sea warming ratio varies with latitude, showing a minimum (multimodel mean ratio ~1.2) in equatorial latitudes, and maxima (multimodel mean ratio ~1.5-1.7) in the subtropics. This pattern of variation is largely consistent between models, and is also seen in observations. Variations in soil moisture may be responsible, though other factors (e.g. changes in clouds) could also be involved. The inter-model spread in the land/sea warming ratio is smallest in the tropics, and largest at high northern latitudes. In the lower latitudes there is good quantitative agreement between the model results and observations. For the low-latitude (40^{o}S-40^{o}N) mean, the models suggest a warming ratio of 1.51 +/- 0.13, while the observations suggest a ratio of 1.54 +/- 0.09.

The fact that warming over land is more rapid than over sea is clearly important for climate impacts, since people live on land. Our study suggests that further work is needed to understand the causes of the land/sea contrast in surface warming, the variation of this quantity between models, and the consequences of the associated uncertainty for climate impacts. Although less important than uncertainty in global mean temperature, the inter-model uncertainty in the global mean warming ratio is still a factor of 1.35. In northern mid-latitudes the degree of uncertainty is much greater. The specific prediction that the land/sea temperature difference should increase as the planet warms could imply specific impacts which merit investigation, e.g. effects on the large scale circulation [e.g., Jain et al., 1999] or local effects such as stronger sea breezes. There is also a potential for important interactions with changes in the hydrological cycle, such as the apparent land/sea contrast in precipitation trends [Bosilovich et al., 2005].

Although the land sea warming contrast is a robust feature of climate models in response to the increase of greenhouse gases there are still differences among models. What are the processes that are responsible for the land-sea warming contrast difference seen in IPCC AR4 models? Understanding these processes is very important for climate impacts. However, due to the complexity of coupled models, it is not an easy task to understand the land-sea warming contrast and its differences from model to model. The research theme 4 (RT4) coordinated experiments repeated with several different models within the ENSEMBLES project will help us to advance understanding of the factors and processes controlling future climate changes and related uncertainty in climate forecasts.

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References

Alexeev, V. A., P. L. Langen and J. R. Bates, 2005: Polar amplification of surface warming on an aquaplanet in "ghost forcing" experiments without sea ice feedbacks. *Clim. Dyn.*, 24, 655-666. doi: 10.1007/s00382-005-0018-3.

Bosilovitch, M.G., S.D. Schubert and G.K. Walker, 2005: Global Changes of the Water Cycle Intensity, *J. Climate*, 18, 1591-1608.

Braganza, K., D.J. Karoly, A.C. Hirst, M.E. Mann, P. Stott, R.J. Stouffer and S.F.B. Tett, 2003: Simple indices of global climate variability and change: Part I – variability and correlation structure, *Clim. Dyn.*, 20, 491-502. DOI: 10.007/s00382-002-0286-0.

Braganza, K., D.J. Karoly, A.C. Hirst, P. Stott, R.J. Stouffer and S.F.B. Tett, 2004; Simple indices of global climate variability and change Part II: attribution of climate change during the twentieth century, *Clim. Dyn.*, 22, 823-838. DOI: 10.007/s00382-004-0413-1.

Cubasch, U., and Coauthors, 2001: Projections of future climate change. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton, et al., Eds., Cambridge University Press, 525–582.

Folland, C., T. R. Karl, and Coauthors, 2001: Observed Climate Variability and Change. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton, et al., Eds., Cambridge University Press, 101–181.

Hall, A . , 2004: The role of surface albedo feedback in climate. *J. Climate*, 17, 1550-1568.

Hansen, J., M. Sato and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res*., 102(D6), 6831–6864.

Holland, M.M. and C.M. Bitz, 2003: Polar amplification of climate change in coupled models, *Clim. Dyn.*, 21,221-232, doi:00382-003-0332-6.

Huntingford, C. and P.M. Cox, 2000: An analogue model to derive additional climate change scenarios from existing GCM simulations, *Clim. Dyn.*, 16, 575-586

Hurrell, J.W. ,1995: Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation. *Science*, 269, 676-679.

Jain, S., U. Lall and M.E. Mann, 1999: Seasonality and interannual variations of Northern Hemisphere temperature: equator to pole temperature gradient and land-ocean contrast. *J. Climate*, 12, 1086-1100.

Jones, P.D., T.J. Osborn, K.R. Briffa, C.K. Folland, E.B. Horton, L.V. Alexander, D.E. Parker and N.A. Rayner, 2001: Adjusting for sampling density in grid box land and ocean surface temperature time series. *J. Geophys. Res*., **106**, 3371-3380.

Johns, T. C. and coauthors, 2003: Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. *Clim. Dyn*., 20, 583-612. doi:10.1007/s00382-002-0296.

Manabe, S., R.J. Stouffer, M.J. Spelman and K. Bryan, 1991: Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO2. Part 1: Annual Mean Response, *J. Climate*, 4, 785-818.

Raper, S.C.B., J.M. Gregory and R.J. Stouffer, 2002: The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response, *J. Climate*, 15, 124-130

Rayner, N. A. , D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice and night marine air temperature since the late nineteenth century. *J. Geophys. Res*., **108**(D14), No 4407 , doi:10.1029/2002JD002670.

Shine, K. P., J. Cook, E. J. Highwood, and M. M. Joshi, 2003: An alternative to radiative forcing for estimating the relative importance of climate change mechanisms, *Geophys. Res. Lett*., 30(20), 2047, doi:10.1029/2003GL018141.

Sutton, R. T., B.-W. Dong, and J. M. Gregory, 2007: Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. *Geophys. Res. Lett*., 34, L02701, doi:10.1029/2006GL028164.

Thompson, D.W.J., J.M. Wallace and G.C. Hegerl, 2000: Annual modes in the extratropical circulation Part II: trends. *J. Climate*, 13, 1018-1036.

Williams, K. D., C. A. Senior and J. F. B. Mitchell, 2001: Transient Climate Change in the Hadley Centre Models: The Role of Physical Processes. *J. Climate*, 14, 2659-2674.

Winton, M., 2006: Amplified Arctic climate change: What does surface albedo feedback have to do with it? *Geophys. Res. Lett.*, 33 (3), L03701.