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Aerosol contribution to the rapid warming of near-term climate under RCP 2.6

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The importance of aerosol emissions for near term climate projections is investigated by analysing simulations with the HadGEM2-ES model under two different emissions scenarios: RCP2.6 and RCP4.5. It is shown that the near term warming projected under RCP2.6 is greater than under RCP4.5, even though the greenhouse gas forcing is lower. Rapid and substantial reductions in sulphate aerosol emissions due to a reduction of coal burning in RCP2.6 lead to a reduction in the negative shortwave forcing due to aerosol direct and indirect effects. Indirect effects play an important role over the northern hemisphere oceans, especially the subtropical northeastern Pacific where an anomaly of 5-10 $\mathrm{W m^{-2}}$ develops. The pattern of surface temperature change is consistent with the expected response to this surface radiation anomaly, whilst also exhibiting features that reflect redistribution of energy, and feedbacks, within the climate system. These results demonstrate the importance of aerosol emissions as a key source of uncertainty in near term projections of global and regional climate.

1. Introduction

The forthcoming Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) will, for the first time, include a separate chapter on climate projections for the near term (i.e. the next few decades). This development reflects the growing importance of adaptation alongside mitigation in the portfolio of policy responses to climate change. Trustworthy projections for the near term are required to inform adaptation policy. It follows that understanding and quantifying the sources of uncertainty in such projections is an important challenge.

Previous research has established that near term projections are not very sensitive to alternative scenarios for greenhouse gas emissions (e.g. Hawkins and Sutton [2009]). The major reasons are the long lifetime of carbon dioxide in the atmosphere and the long response time of the climate system. However, the situation for emissions of aerosols and their precursors is quite different. Aerosols have a much shorter lifetime in the atmosphere and changes in emissions have the potential to affect climate rapidly. Consequently, uncertainty in future aerosol emissions and atmospheric loading and in the subsequent climate response to such emissions, is a potential source of uncertainty in near term climate projections [Johns *et al.* , 2011].

Aerosols affect the climate through their direct and indirect interaction with the radiation budget. They scatter and absorb shortwave (SW) and longwave (LW) radiation, and interact with clouds, affecting their optical depth and thus their interaction with radiation, as well as affecting precipitation processes [Haywood and Boucher, 2000]. The consensus is that aerosols currently impose a negative forcing on the climate [Forster *et al.*, 2007], although there is significant uncertainty surrounding the magnitude of this forcing.

Results from the international CMIP5 project provide a new opportunity to investigate the sensitivity of climate projections to alternative scenarios for anthropogenic emissions - specifically the RCP scenarios. In these scenarios the emission of primary aerosols, and the pre-cursors of secondary aerosols, were explicitly specified each model then being free to produce its own self-consistent atmospheric aerosol distributions.

This study is based on analysis of CMIP5 projections with the HadGEM2-ES model [Jones *et al.*, 2011]. Whilst all the RCP scenarios show future reductions in aerosol emissions, differences in the timing and location of implementing pollution controls lead to differences in atmospheric aerosol burden, which have the potential to affect climate. We focus on a comparison between the RCP2.6 and RCP4.5 scenarios, because of relatively large differences in near term aerosol emissions between these two scenarios. Our aims are to understand whether the different emissions lead to significant differences in the projected evolution of climate in the near term, to quantify the extent of any differences, and to gain insights into the mechanisms involved.

2. Comparison of near term climate in RCP 2.6 and RCP 4.5

Figure 1 shows global annual mean temperature, sulphate, and GHG forcing time series for the mean of four ensemble members under the RCP 2.6 and RCP 4.5 scenarios simulated by the HadGEM2-ES climate model. It can be seen that between 2018 and 2037 (marked by the black dashed lines), RCP 2.6 has a warmer global mean surface air temperature than RCP 4.5 despite a lower GHG forcing (shown in Figure 1c).

During this time, the global annual mean sulphate load in RCP 2.6 shows a rapid decrease, and is significantly lower than in RCP 4.5. This is due primarily to the reduction in coal use without CCS (Carbon capture and storage), which is a significant source of both CO_2 and sulphate aerosol emissions [van Vuuren *et al.*, 2011a]. The decrease in sulphate emission is therefore a necessary consequence of the methods of CO_2 reduction assumed in this scenario in order to achieve such a low radiative forcing target. The rapid decrease in sulphate load under RCP 2.6 reduces its negative forcing (due to both the direct effect and indirect effect on cloud reflectivity), resulting in a positive forcing perturbation which is consistent with a warming of surface temperature.

The difference in global and annual mean components of the energy balance (RCP2.6-RCP4.5) are shown in Figure 1d. There is more net downward shortwave (SW) flux at the top of the atmosphere and at the surface in RCP2.6 consistent with reduced sulphate aerosol (and also with reduced cloud reflectivity or low altitude cloud fraction). The similarity of the surface and top of the atmosphere changes suggests that there is little change in the proportion of SW radiation which is retained/absorbed in the atmosphere (which would be the case if absorbing aerosol were playing a major role). The difference is most apparent over ocean areas. The net downward longwave (LW) flux at the top of the atmosphere is reduced in RCP2.6 due to increased LW emission from the warmer surface. The majority of the additional SW flux reaching the surface is balanced by an increased latent heat flux over ocean regions.

Sulphate is one of four anthropogenically emitted species simulated by HadGEM2-ES: sulphate, fossil-fuel black carbon (FFBC), fossil-fuel organic carbon (FFOC), and biomass-burning aerosol (BB) which is a composite aerosol. The relative importance of the aerosol types is best compared using the optical depth due to each type (i.e. by multiplying the aerosol load by the extinction coefficient for each species, given by Bellouin *et al.* [2011]). Although the extinction co-efficient is dependent on humidity (except for FFBC), for this comparison we have assumed a humidity of 100%, giving an upper limit on the AODs. Figure 2a shows that sulphate aerosol is by far the most optically thick anthropogenically emitted aerosol in both scenarios; it therefore remains the focus of this study.

Figure 2b shows the spatial distribution of sulphate AOD in RCP 2.6 averaged between 2018 and 2037. Sulphate aerosol is concentrated over south-east Asia, the Indian subcontinent, the Arabian peninsula and Africa. Sulphate AOD over the ocean increases towards the equator. Also shown are the differences in the 2018 to 2037 mean between RCP 2.6 and RCP 4.5 of sulphate AOD, surface air temperature, column integrated liquid cloud droplet number concentration (CDNC) and surface down-welling SW radiation.

RCP 2.6 has a lower AOD (indicated by negative values in Figure 2c) over most regions with the exception of South America and the maritime continent. The largest differences between the scenarios (expressed as a percentage of the mean value in RCP2.6) are found over the continents, but there are significantly lower values in RCP 2.6 over all of the northern hemisphere oceans, as well as over the Indian and tropical Atlantic Oceans. The differences over the northern hemisphere oceans are of particular note as these regions are relatively pristine (low levels of background aerosol - see Figure 2b), and cloud properties may therefore show greater sensitivity to changes in aerosol.

Differences in cloud droplet number concentration (CDNC) between the two scenarios (Figure 2e) show a similar spatial pattern to AOD, consistent with the expectation that sulphate aerosols are an important source of cloud condensation nuclei (CCN). The difference in CDNC is mainly negative, implying fewer cloud droplets; if liquid water content remains unchanged these droplets will be larger and lead to less optically thick (and reflective) clouds - contributing to a reduced aerosol indirect effect in RCP2.6. An exception to the general pattern is the large positive anomaly in CDNC seen over Borneo, but not seen in the sulphate AOD. This is due to large difference in BB aerosol in this region (not shown). RCP 4.5 alone shows an abrupt reduction in BB aerosol load until 2020 after which emission remains consistently low. This results from a value being placed on carbon emissions from land use changes. Forested areas then become valuable, leading to reforestation and a dramatic decrease in biomass burning [Thomson *et al.*, 2010].

Differences in surface shortwave radiation between the two scenarios (Figure 2f) reflect aerosol direct effects and changes in clouds. The largest anomaly is an increase in downwelling radiation of 5-10Wm^{-2} over the subtropical northeastern Pacific Ocean in RCP2.6. A smaller increase is also found over the North Atlantic Ocean. Both the Pacific and Atlantic anomalies show a spatial correspondence to regions of decreased CDNC in RCP2.6, suggesting that aerosol indirect effects contribute to the increase in surface shortwave radiation. These effects may be more important over the northern oceans than elsewhere because, as previously noted, these are relatively pristine evironments.

The difference in surface temperature (Figure 2d) shows an overall warming in RCP2.6, as expected. A local maximum (0.5-1K) is located in the northeastern Pacific coincident with the increase in surface shortwave radiation, strongly suggesting that the temperature increase here is a response to the increase in radiation. Other aspects of the pattern of temperature change are likely to reflect redistribution of energy, and feedback processes, in the climate system - for example high latitude amplification is a common signal found in response to many different forcings.

3. Rapid Warming in RCP 2.6

The period during which global mean surface temperature in RCP2.6 is higher than in RCP4.5, discussed in the previous section, is directly related to a rapid increase in global mean surface temperature in RCP2.6, between around 2010 and around 2025 (Figure 1a). In this section we investigate the causes of this rapid warming, and relate this event to the comparison with RCP4.5. Figure 3 shows maps of the differences between the 10 year means before and after the rapid warming. In this case a positive value indicates a larger value after the sudden warming identified in Figure 1.

As expected, there is a large reduction in sulphate load, and corresponding decrease in CDNC over most of the northern hemisphere, consistent with a change in the indirect aerosol effect. An increase in the effective radius is also seen (not shown). This reduces the optical depth of the clouds when they are present, meaning more downward shortwave flux is transmitted to the surface. There is also a prominent decrease in cloud fraction over the subtropical northeastern Pacific Ocean which could be a consequence of the impact of reduced sulphate aerosol on cloud lifetime. Lu *et al.* [2009] show that drizzle rate from clouds in this region is indeed inversely related to aerosol concentration. Kloster *et al.* [2010] also suggested that a change in cloud water path in their simulations with aggressive aerosol reductions resulted from enhanced drizzle formation. We hypothesise that the localised nature of this feature by comparison with the sulphate and CDNC change is due to the cloud in this region being particularly sensitive to a change in aerosol. Climatologically, this region is a transition zone between open and closed mesoscale cellular convection [Rosenfeld *et al.*, 2011], aerosol concentrations being lower in the open celled regions [Woods *et al.*, 2011]. Although the details of these processes are unlikely to be represented explicitly in global models, the localised strong decrease in cloud fraction in the northeastern Pacific ocean would be consistent with a change in cloud regime driven by decreased aerosol. Other regions show increases in cloud fraction, which cannot readily be explained as a direct response to the decrease in sulphate load. It is likely that instead these reflect non-local adjustments of the coupled ocean-atmosphere system in response to the change in forcing.

Figure 3 also shows the difference in surface shortwave flux (panel d), surface air temperature (panel e), and global energy balance (panel f). The predicted increase in surface downward shortwave radiation is seen in the global mean and particularly in the regions of decreased cloud fraction and sulphate load. A negative anomaly in surface SW is co-located with the positive cloud fraction changes. The pattern of surface air temperature change shows large warming over the northern continents and the Arctic, and also a local maximum over the subtropical northeastern Pacific coincident with the region of reduced cloud fraction. The same localised pattern appears in all the simulations of Kloster *et al.* [2010] that include aerosol reductions, but is absent from their simulations considering only future changes in greenhouse gases.

The surface energy budget shows the expected increases in downward shortwave radiation. In addition there is an increase in downward longwave radiation in response to the increase in GHG concentrations between the two periods, and also reflecting changes in clouds. The warming due to increases in net surface downward radiation is balanced by increases in latent and (over land) sensible heat fluxes.

4. Discussion and Conclusions

In this study we have compared projections of near term climate in the HadGEM2-ES model under RCP4.5 and RCP2.6. GHG forcing under these scenarios is almost identical until 2020, and then declines in RCP2.6 relative to RCP4.5. However, between 2018 and 2037 global annual mean surface air temperature is warmer under RCP2.6. The start of this period is characterised by a period of particularly rapid warming.

Our results provide compelling evidence that the warming in RCP2.6 is a result of a rapid decrease in sulphate aerosol load. This decrease is caused by a decrease in sulphur emissions in RCP2.6, as a result of the rapid decrease in coal use needed to reduce GHG emissions. Thus our results highlight the difficulty of reducing the rate of global warming in the near term in this model, even under extreme scenarios for reducing GHG emissions, and is consistent with previous simulations by Wigley [1991] and Johns *et al.* [2011].

HadGEM2-ES includes a representation of both the direct and first and second indirect effects of aerosol. Our analyses indicate that indirect effects play an important role in the rapid warming projected under RCP2.6; in particular, changes in sulphate aerosols over the North Pacific and North Atlantic lead to changes cloud properties which contribute to a large anomaly in downwelling surface shortwave radiation over the subtropical northeastern Pacific Ocean. The pattern of surface temperature change is consistent with the expected response to this surface radiation anomaly, whilst also exhibiting features - such as amplification at high northern latitudes - that reflect redistribution of energy, and feedbacks, within the climate system. The substantial but inhomogeneous temperature response demonstrates the importance of aerosol emissions as a key source of uncertainty in near term projections of regional, as well as global, climate.

A natural question is whether the response we have found in HadGEM2-ES is also found in other climate models. In fact there diversity amongst CMIP5 models (See Figure S1), which is not surprising given the diversity of approaches to representing aerosols effects. Several models -GFDL-CM3, CSIRO-Mk3-6-0, CanESM2 and MIROC-ESM-CHEM - appear to give a similar response to HadGEM2-ES whilst many other models show little difference between the scenarios in the near term. Villarini and Vecchi [2012] found little significant difference in tropical mean sea surface temperature between the two scenarios for most CMIP5 models. Ongoing analysis of the response of CMIP5 models to changes in aerosol optical depth suggest that HadGEM2-ES is one of the most sensitive models, however, further detailed analysis of each model is required. As a final caveat, the aerosol reductions proposed in all the scenarios may also be too optimistic, a simulation with aerosol emissions held fixed at 2005 levels would be useful in confirming the role of aerosol changes discussed here.

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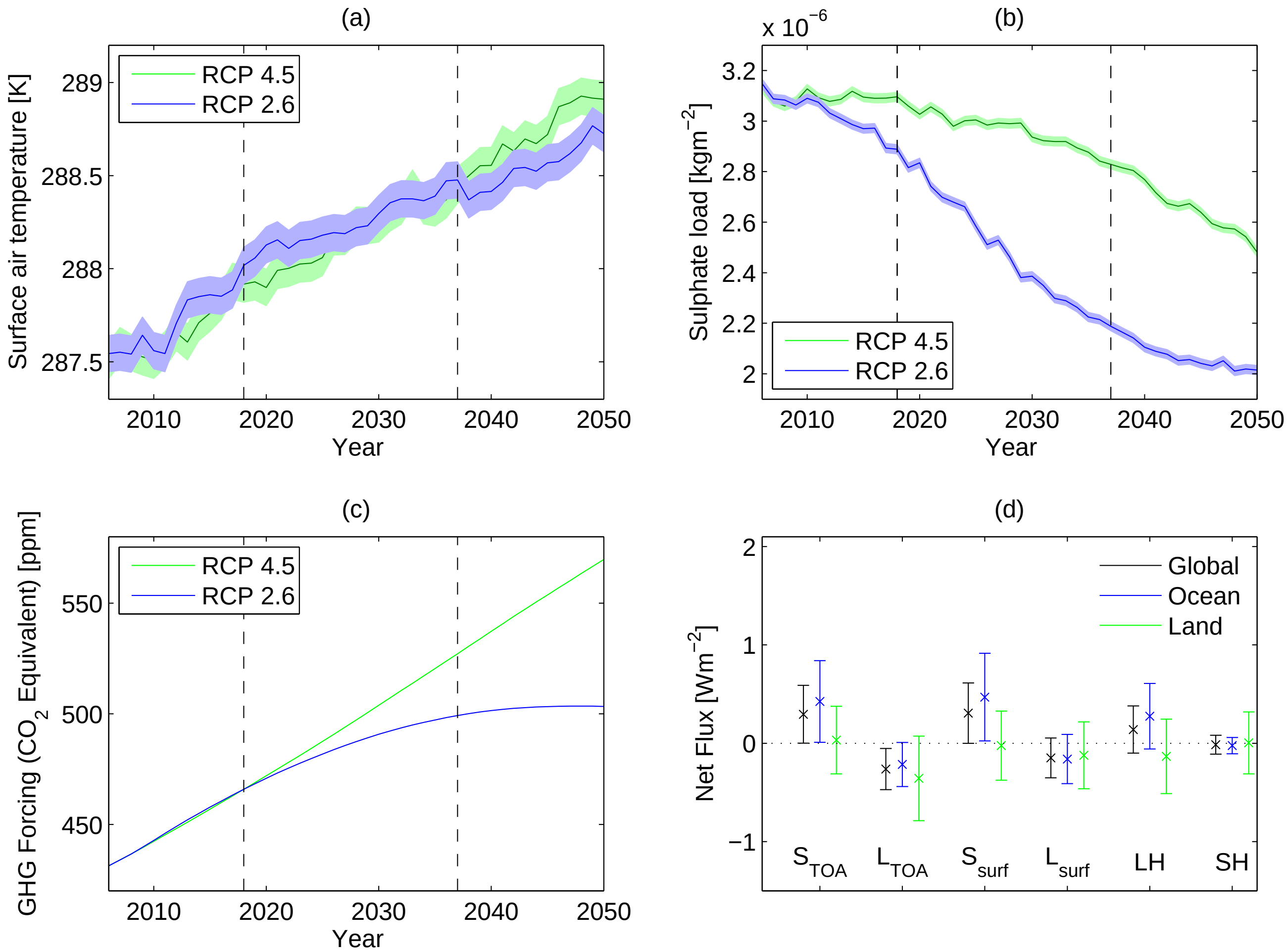

Figure 1. Global and annual mean time series of surface air temperature, sulphate aerosol load, and the GHG forcing expressed in terms of CO_2 equivalent in the ensemble mean of four HadGEM2-ES simulations of two scenarios until 2050. RCP 2.6 is in blue and RCP 4.5 is in green. The shading around the lines represents one standard deviation of the global, annual mean of the pre-industrial control run, giving an estimate of the inter-annual variability. The bottom right panel shows the difference in fluxes (net SW and LW TOA and surface radiative fluxes and surface latent heat (LH) and sensible heat (SH) fluxes) between RCP 2.6 and RCP 4.5 averaged over the globe (black), ocean (blue) and land (green) for the period between 2018 and 2037 (marked by black dashed lines on timeseries.)

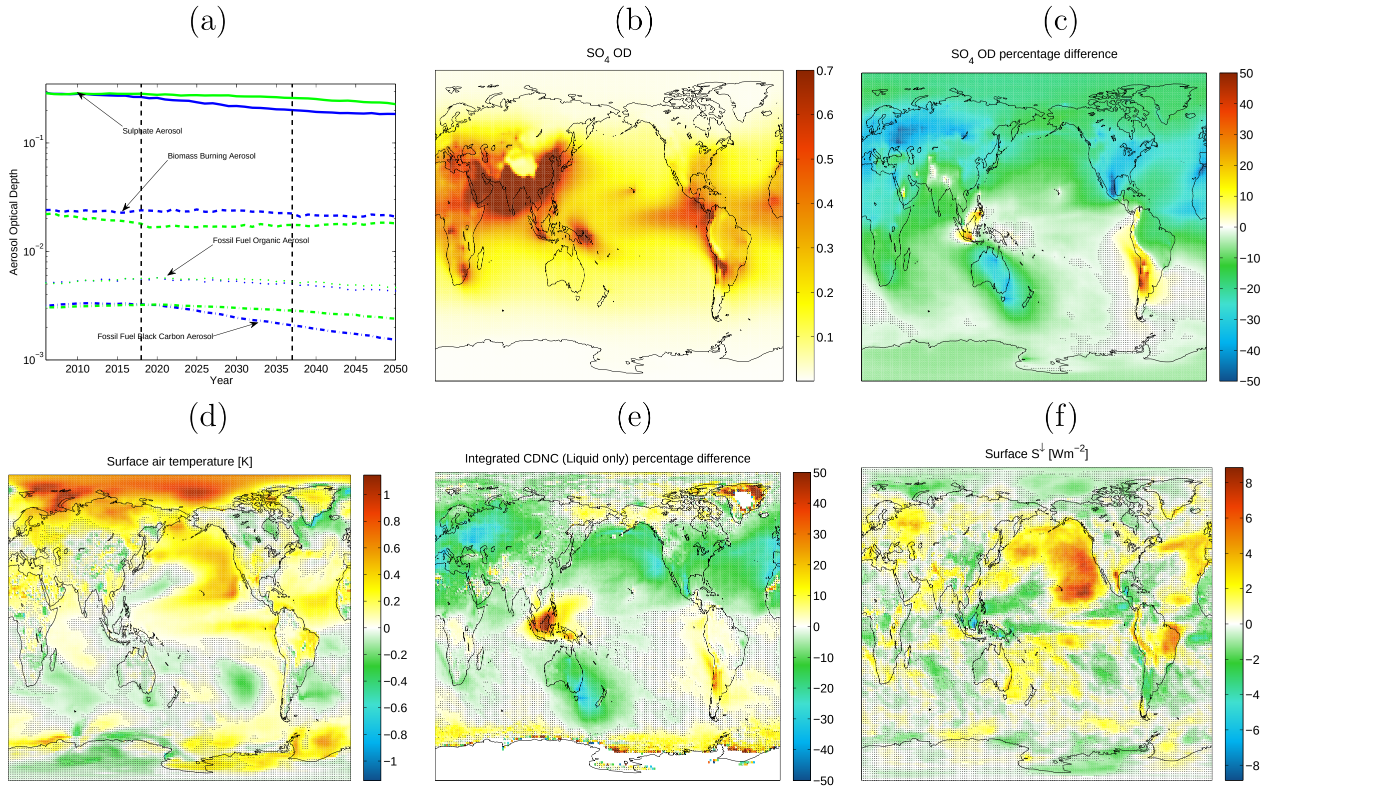

Figure 2. HadGEM2-ES ensemble means of (a) annual global mean timeseries of aerosol optical depth for four anthropogenically emitted species: sulphate aerosol – solid line, biomass burning aerosol – dashed line, fossil-fuel organic aerosol – dotted line, and fossil-fuel black carbon aerosol – dot-dashed line. (b) Map of the sulphate optical depth averaged between 2018 and 2037 in RCP 2.6. (c) Map of the difference of 2018 to 2037 average sulphate aerosol load between RCP 2.6 and RCP 4.5. A negative value indicates RCP 2.6 has a lower value than RCP 4.5. The hatching shows where the difference is not significantly different from zero at the 5% level. (d),(e) and (f) are as (c), but for surface air temperature, CDNC, and surface downwelling SW radiation respectively.

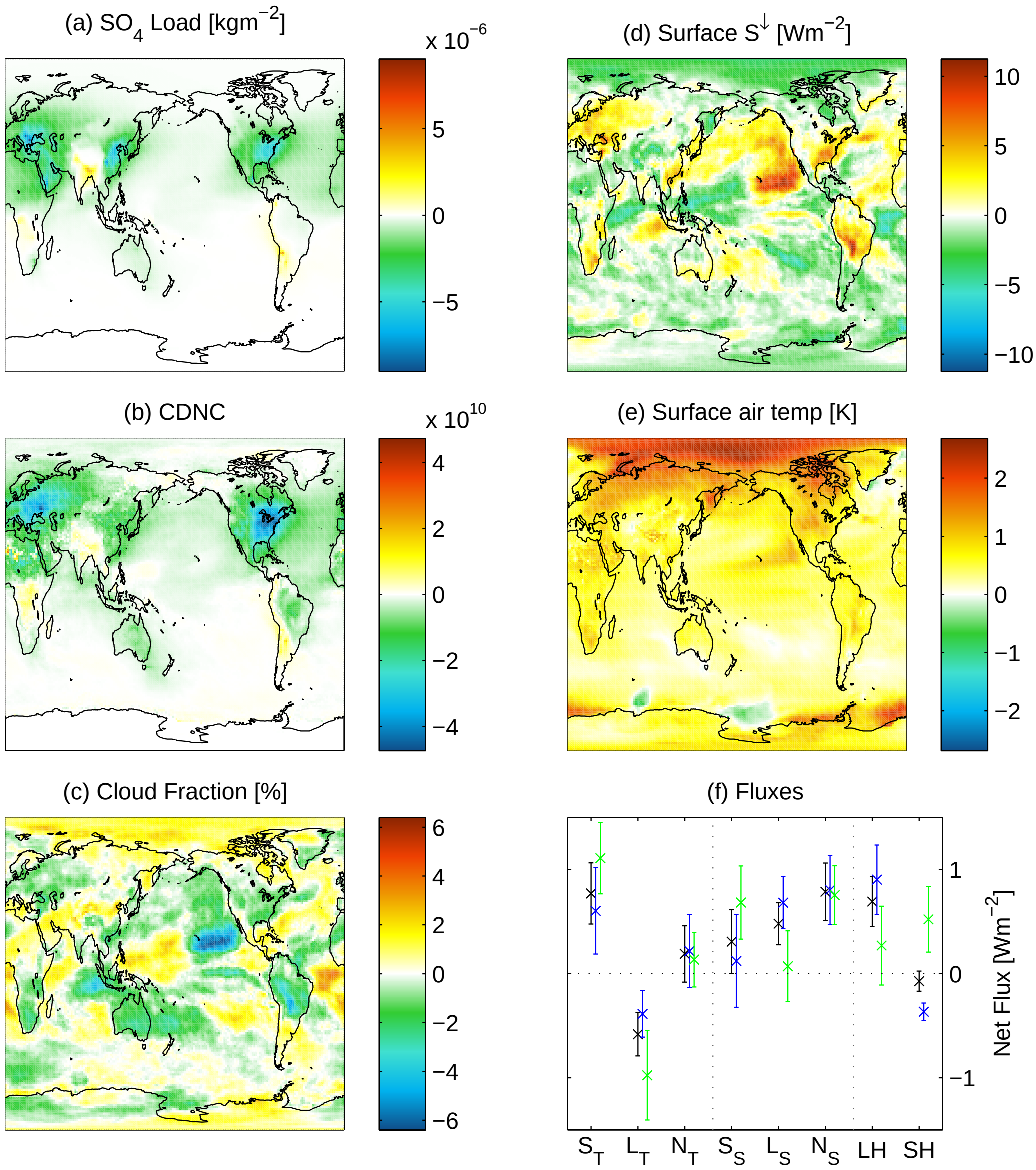

Figure 3. Maps of the difference in the 10 year means (2020 to 2029 mean minus 2006 to 2015 mean) before and after the rapid annual global mean temperature change in HadGEM2-ES simulations under the RCP 2.6 scenario. Variables shown are percentage change in sulphate aerosol load, percentage change in column integrated CDNC (liquid droplets only), change in column cloud fraction, surface $S^{\downarrow}$, surface air temperature, and surface and TOA energy fluxes. A positive change indicates an increase in the later 10 year mean. Panel (f) shows the change in the net SW (S) and LW (L) and Net (N) (SW+LW) TOA (subscript T) and surface fluxes (subscript S), and surface latent heat (LH) and sensible heat (SH) fluxes.

Auxiliary material for Paper 2012GL052848

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Introduction

This auxiliary material comprises additional information demonstrating the diversity in inter-scenario differences across the CMIP5 multi-model ensemble.

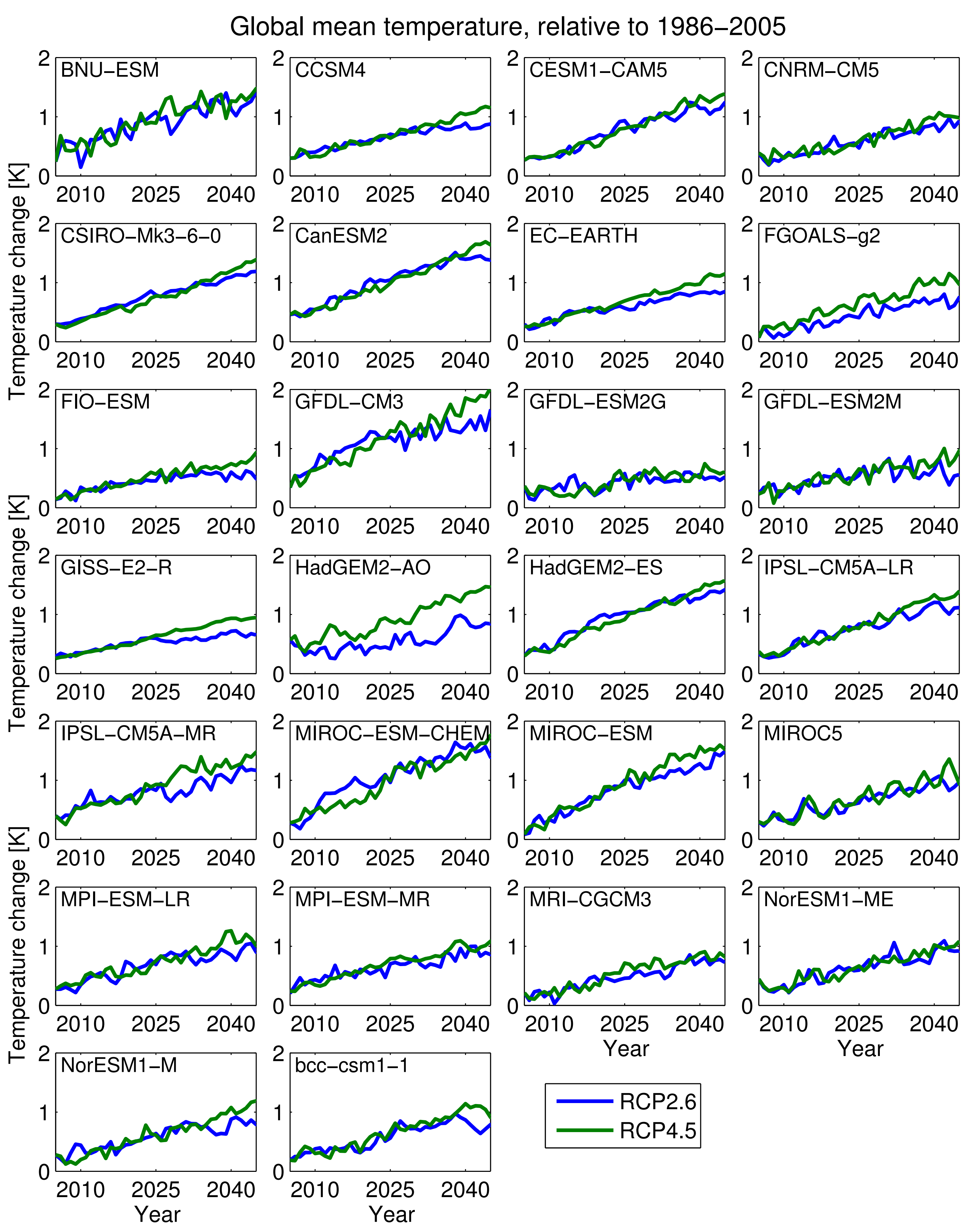
Auxiliary.txt

Paragraph describing the multi-model ensemble results of near term temperature trends in RCP2.6 and RCP4.5 simulations.

auxiliary_figure1.eps

Figure S1: Global and annual mean temperature relative to 1986-2005 mean for each of 26 models in the CMIP5 database. RCP2.6 is shown in blue, RCP4.5 in green.

Figure S1 shows global and annual mean temperature relative to 1986-2005 mean for each of 26 models in the CMIP5 database. HadGEM2-ES shows warmer temperatures in RCP2.6 from 2011 to 2025. This behaviour is also noted in other complex models, GFDL-CM3, MIROC-ESM-CHEM, and to a lesser extent in CSIRO-Mk3-6-0 and CanESM2. 2 models - HadGEm2-AO and FGOALS-g2 - show strikingly cooler temperatures in RCP2.6 compared to RCP2.5, the remaining models show little difference between the scenarios. Such diversity is perhaps not surprising given the diversity in model set-up and indeed in the treatment of aerosol and their effects. This clearly needs to be investigated in future studies.



Global mean temperature, relative to 1986−2005
Temperature change [K]
Year
BNU−ESM
CCSM4
CESM1−CAM5
CNRM−CM5
CSIRO−Mk3−6−0
CanESM2
EC−EARTH
FGOALS−g2
FIO−ESM
GFDL−CM3
GFDL−ESM2G
GFDL−ESM2M
GISS−E2−R
HadGEM2−AO
HadGEM2−ES
IPSL−CM5A−LR
IPSL−CM5A−MR
MIROC−ESM−CHEM
MIROC−ESM
MIROC5
MPI−ESM−LR
MPI−ESM−MR
MRI−CGCM3
NorESM1−ME
NorESM1−M
bcc−csm1−1
RCP2.6
RCP4.5
0
1
2
2010
2025
2040