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Deliverable D2.2 Report on the evaluation of cloud-aerosols-radiation interactions in ESMs

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SEVENTH FRAMEWORK PROGRAMME

EUCLIPSE Deliverable D2.2:
Assessment of cloud-aerosol-radiation interactions in CMIP5

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Introduction

The radiative forcing by anthropogenic aerosol due to their effect on clouds and radiation is the main uncertainty in climate change forcing. This hampers our ability to quantify climate sensitivity (*Schwartz*, 2008). One reason for the simulated spread in aerosol indirect radiative forcings is the large diversity of Earth System Models (ESMs) in their representation of cloud and aerosol processes. Some ESMs neglect aerosol-cloud interactions entirely (*Stevens*, 2012), while others include complex aerosol cycles and comprehensive cloud microphysics and parameterise aerosol-cloud interactions to various degrees of sophistication (*Boucher*, 2012).
A previous model intercomparison study in the AEROCOM initiative that evaluated the aerosol-cloud interactions in ten different atmospheric general circulation models (GCMs) using satellite data has demonstrated some skill of the models in simulating the effect of aerosols on cloud droplet number, but substantial problems in parameterising the effect on precipitation formation (*Quaas et al.*, 2009). Since this AEROCOM study, some ESMs later used in the 5[th] Coupled Model Intercomparison Project (CMIP5) evolved to include more detailed aerosol and cloud processes (e.g., the GFDL and NCAR GCMs), while others reduced the complexity of aerosol-cloud interactions (MPI-ESM). The study by *Quaas et al.* (2009) thus is not representative for the interpretation of the CMIP5 results.

Consequently, the present report aims at analysing the representation of cloud-aerosol-radiation interactions in the CMIP5 simulations. From the set of simulations carried out within CMIP5 (*Taylor et al.*, 2009), three are selected for this analysis, namely the

- Historical simulation (1850 – 2005, using observed emissions of greenhouse gases and aerosols); experiment 3.2 in the definition of *Taylor et al.* (2009)
- SSTClim simulation (climatological sea surface temperature, SST, and sea ice cover as well as greenhouse gas and aerosol emissions for pre-industrial conditions); experiment 6.2a
- SSTClimAerosol simulation (as SSTClim, but with aerosol emissions for the year 2000); experiment 6.4a.

The Historical simulation is generally used to evaluate and assess the skill of the simulations of each of the ESMs, based on which the reliability of projections of future climate change is often judged. In this report, we aim to understand the aerosol forcing imposed to this simulation by comparing the difference between the last period (2001 – 2005) and the earliest period (1861 – 1865) to the idealised simulations (SSTClimAerosol minus SSTClim). We further compare the simulation results for the recent period in the Historical simulations to satellite observations.

This study relies on the submissions to the CMIP5 archive publicly available, and assesses only those models for which the suite of the three simulations of interest here are available. Among the ESMs contributing to EUCLIPSE, only IPSL-ESM contributed all three relevant simulations to CMIP5. For ECHAM5, EC-EARTH, HadGEM and Arpege, at least one of these simulations was not available.

Idealised simulations to infer aerosol forcing

In this section, the effect of anthropogenic aerosols on individual parameters is analysed by comparing a five-year average of the SSTClimAerosol simulation with the SSTClim simulation. The geographical distributions of aerosol optical depth (AOD), cloud-top droplet number concentrations (CDNC), cloud-top droplet effective radii (CDR), cloud albedo, planetary albedo and finally reflected solar radiation are examined. The change in AOD is a primary metric for the aerosol direct forcing by scattering. The changes in CDNC and CDR, respectively, reflect the aerosol indirect forcing with a particular focus on the first aerosol indirect effect. The change in cloud albedo, defined as the change in all-sky minus clear-sky albedo, is a metric for the total aerosol indirect effect. The change in planetary albedo is a latitude-independent picture of the total solar aerosol effect. The change in reflected solar radiation, finally, is the adjusted forcing of the total aerosol effect.

Fig. 1 shows the change in AOD for the four models for which it is available. As expected, despite some natural variability not averaged out even for five years of data, a general increase is found. Particularly MIROC and CSIRO show large increases over Europe, China and Central Africa, IPSL in the same regions, but a smaller increase. MRI shows smaller changes than the other models.

Analysing CDNC (Fig. 2), IPSL has much smaller changes than the other three models. In MRI, the maritime stratocumulus decks show a large sensitivity to the anthropogenic aerosols advected there, particularly in the Canary island region. In MIROC, substantial increases in CDNC are correlated to the places where AOD strongly increases. CSIRO simulates strong increases in CDNC by up to 150 – 200 cm^{-3} over large areas of the Northern Hemisphere even in the five-year average. These changes are to a large extent mirrored by decreases in simulated CDR (Fig. 3). IPSL, again, shows very little changes. MRI shows decreases in CDR also in large areas where no large effect on CDNC was found. In CSIRO, the changes in CDR are less strong relative to the changes in CDNC compared to the other models, which may hint to a substantial simulated increase in cloud liquid water path. Two more models diagnose CDR, namely HadGEM and NorESM, which both show substantial decreases in CDR over most of the Northern Hemisphere mid-latitudes, more pronounced over ocean than over land in HadGEM, and vice versa in NorESM (not shown).

For cloud albedo, planetary albedo, and adjusted forcing, the results are rather noisy in all simulations (Fig. 4 - 6). MRI, MIROC and HadGEM (the latter not shown) show increases in cloud albedo and subsequently in planetary albedo which reflect the spatial pattern of CDR decreases. For the other models, it is difficult to clearly distinguish consistent patterns. The same conclusions can be drawn for the simulated adjusted forcing (Fig. 6).

Historical simulations

It is interesting to investigate to which extent these findings from the idealised simulations can be extracted also from the historical simulations, because the aerosol forcing, and its historical evolution, in these simulations is important to potentially assess climate sensitivity (*Schwartz*, 2008). Fig. 7 shows the change in AOD between the periods 2001 – 2005 and 1861 – 1865 from the historical simulations. Despite the varying ocean surface condition in these simulations, the main characteristics of the geographical distribution of the AOD increase are very similar between the idealised and historical simulations. The same is found for CDNC (Fig. 8). For CDR (Fig. 9), the patterns are similar, but in general, in all models, either the decrease in CDR is less pronounced, or even an increase is simulated, in the historical simulations compared to the idealised simulations. This hints to an increase in cloud liquid water path in response to the increasing greenhouse gas concentrations in the historical simulations.

Analysing the cloud albedo and planetary albedo (Fig. 10 and 11), for those models that showed distinct patterns of aerosol forcing (MRI and MIROC), the geographical distributions of this forcing can also be found in the historical simulation. A slightly less strong increase, or locally at some places even a decrease, in cloud albedo is simulated in the historical compared to the idealised simulations. Again, the pattern of cloud albedo change and planetary albedo change are mostly consistent. IPSL, which did not show a pronounced aerosol effect in any metric, simulates a widespread decrease in planetary albedo, different from the other models. This decrease may be attributable to a positive cloud feedback to greenhouse-gas warming. MRI and MIROC simulate a strong decrease in planetary albedo, but not in cloud albedo, over the Arctic region in the historical simulation which is not found in the idealised simulation. This is probably a strong snow/ice albedo feedback in these models, which is not equally pronounced in IPSL and CSIRO.

Comparison of historical simulations to satellite observations

For the recent period in the historical simulations (2001 – 2005), a comparison to satellite observations from the MODerate Resolution Imaging Spectroradiometer (MODIS) for AOD, CDNC and CDR, and from the Clouds and the Earth's Radiant Energy System (CERES) for planetary albedo is possible. The results are presented in Fig. 12 – 15. Simulated AOD patterns compare well to MODIS, especially for CSIRO. The other models tend to simulate less AOD than retrieved, especially over the Northern Hemisphere mid-latitudes. CDNC is generally substantially lower in the models compared to the MODIS retrieval, except for CSIRO which shows larger values. Most models show the land-sea contrast with larger concentrations over land than over ocean, which is also found in the retrievals. IPSL, however, simulates even lower CDNC over land than over ocean, where it already is quite low compared to the retrievals. MRI also rather shows larger CDNC over land compared to ocean – perhaps a reason for the large susceptibility of oceanic clouds to anthropogenic aerosols discussed above. Also for CDR, the models do not compare very well to MODIS, and have very large discrepancies compared to one another. HadGEM and MIROC results are rather close to MODIS, but substantially lower over land, perhaps pointing at a too strong aerosol indirect effect. MIROC, CSIRO and especially IPSL simulate much smaller CDR than MODIS retrieves, while MRI diagnoses very large droplets and only a small land-sea contrast. Planetary albedo in general compares comparatively well among models and CERES retrievals. However, the meridional gradient in the models is much lower than in CERES, with substantially larger albedos simulated compared to the retrievals.

Conclusions

From the comparison between model diagnostics and satellite retrievals the conclusion may be drawn that distributions of aerosol optical depth are rather well reproduced. Much worse is the contrast between retrievals and models, and among different models, for cloud droplet number concentrations and cloud-top droplet effective radii. Since not large experience with these diagnostics exists yet in modelling centres, it might be a possibility that the diagnostics are erroneous as well. However, some models do not even reproduce a land-sea contrast in these quantities, hinting at a likely problem in simulating aerosol indirect effects in these models.

All four models for which the relevant diagnostics were available simulate geographical distributions of anthropogenic aerosol optical depths consistent with the emissions. The indirect effect, as seen by increases in cloud droplet number concentrations and decreases in cloud-top droplet effective radii, shows substantial differences among the four models. For two models, the patterns are consistent with the expectations given the AOD changes but of substantially different magnitude. One model simulates very small changes, and in the fourth one, changes are much more pronounced over ocean than over land. The model which simulates the very large sensitivity of cloud microphysics nevertheless has only a small effect on cloud- and subsequently planetary albedo. For the other models, the patterns of cloud albedo reflect what was found for cloud microphysics changes.

In summary, the models compare poorly to satellite retrievals for cloud microphysical properties, and show a large spread. Two models fail to simulate the larger droplet concentrations / smaller droplets over land compared to ocean seen in retrievals. The simulated effects of anthropogenic on cloud microphysics and subsequently planetary albedo show vastly different sensitivities.

The idealised simulations and the difference between present-day and pre-industrial start of the historical simulations for all models show consistent signatures of aerosol effects in AOD, cloud microphysics and albedo. This implies that the idealised simulations are indeed useful to analyse the aerosol forcing in the historical simulations.

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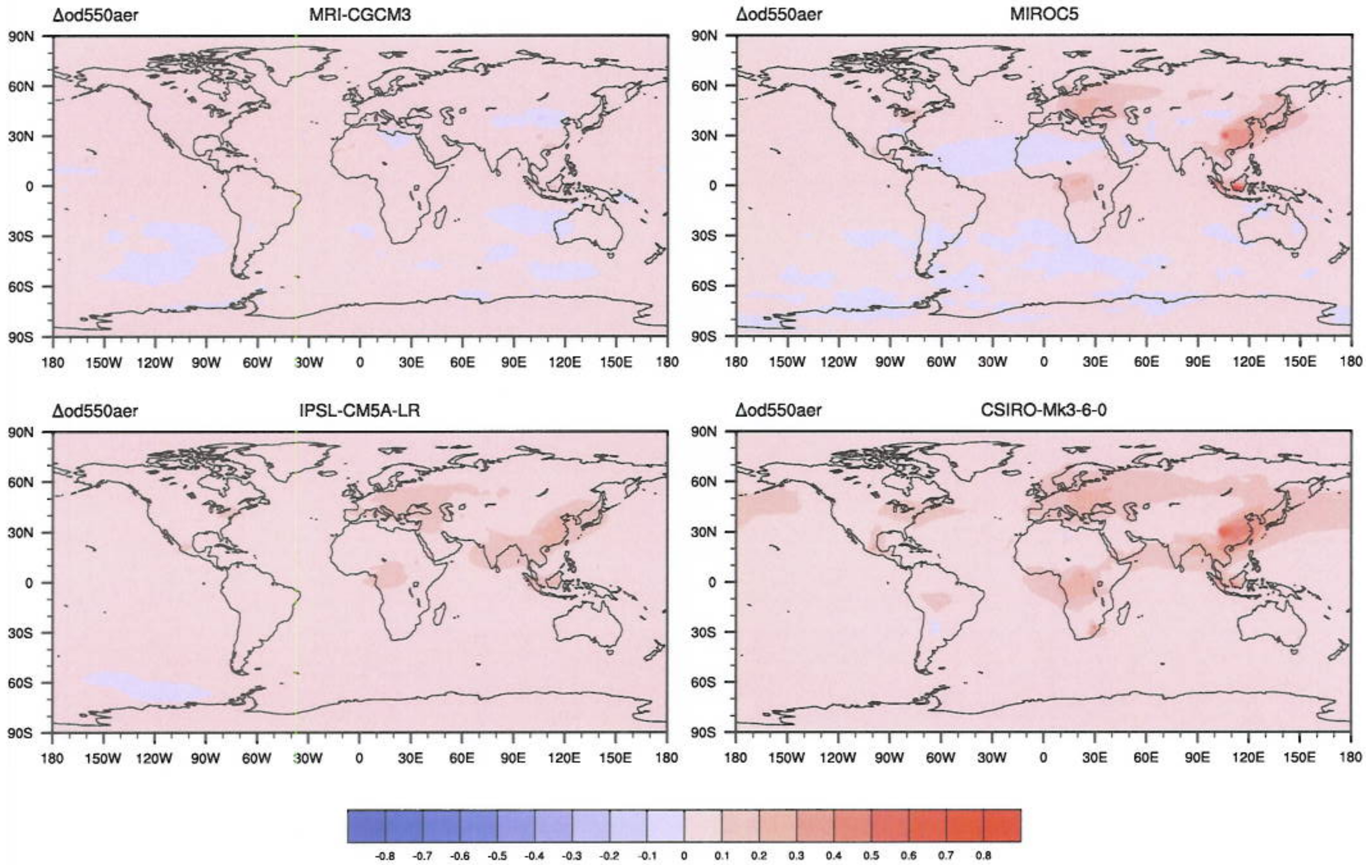
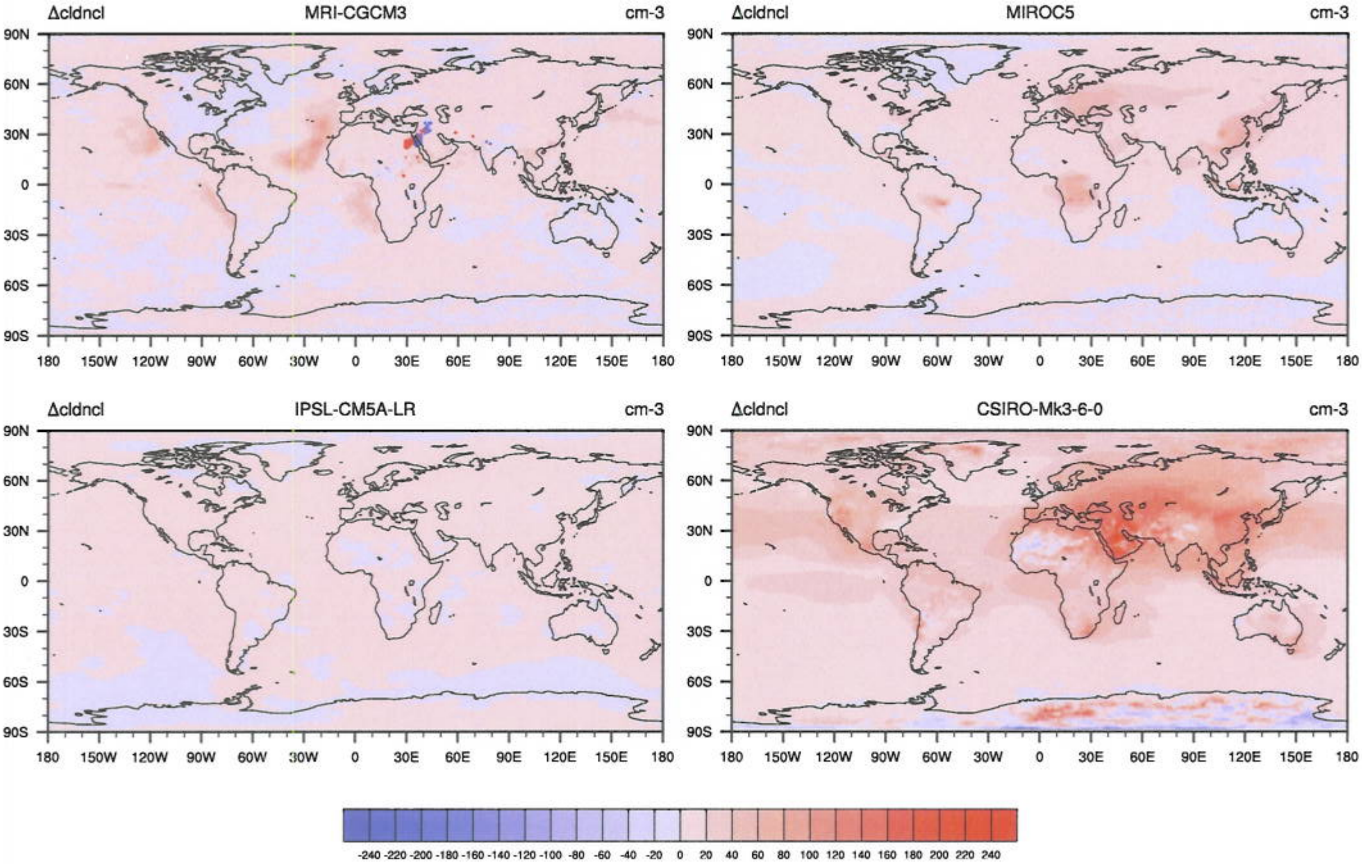
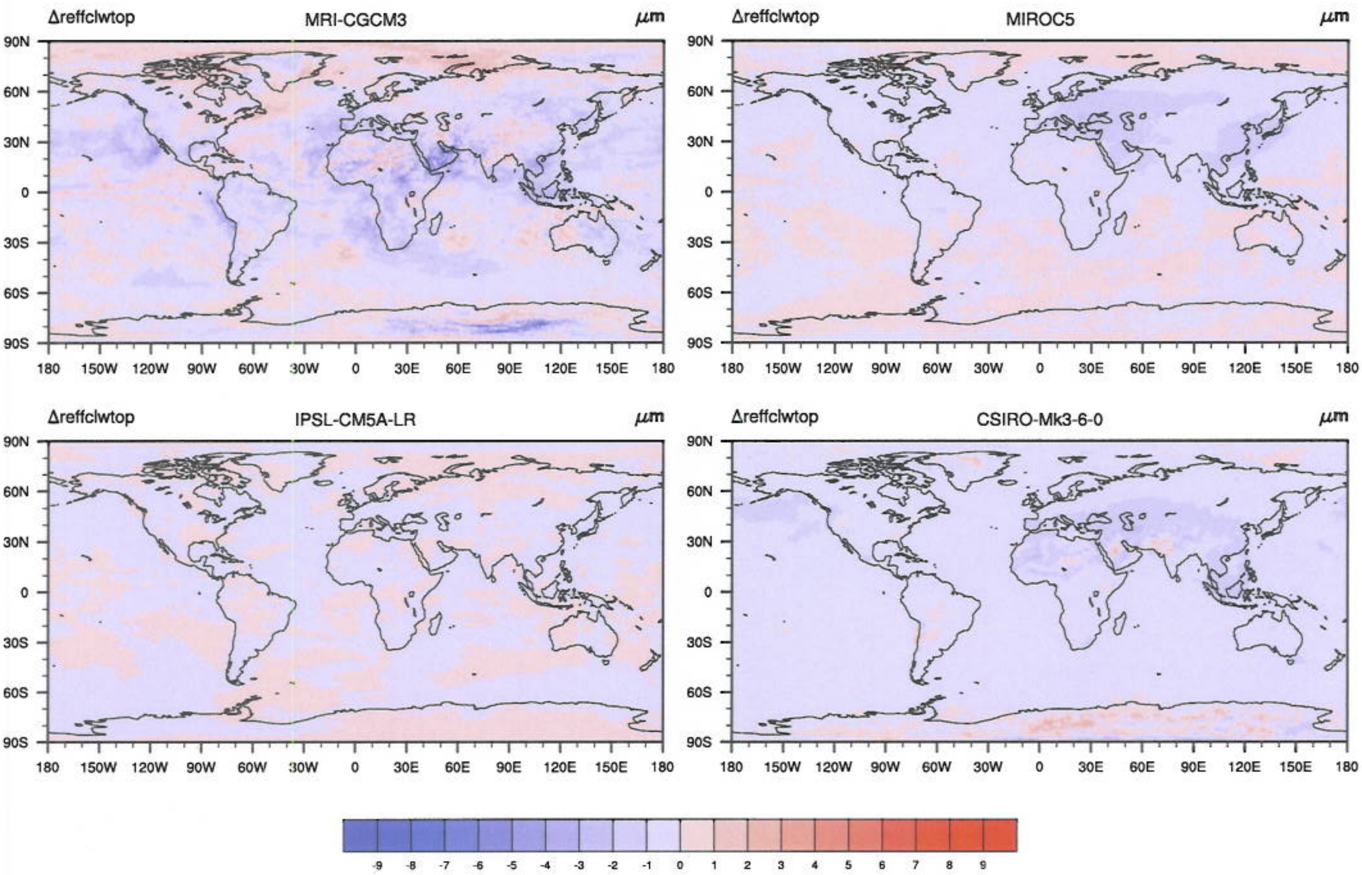
Difference of 5-year means of ambient aerosol optical depth at 550 nm between sstClimAerosol and sstClim



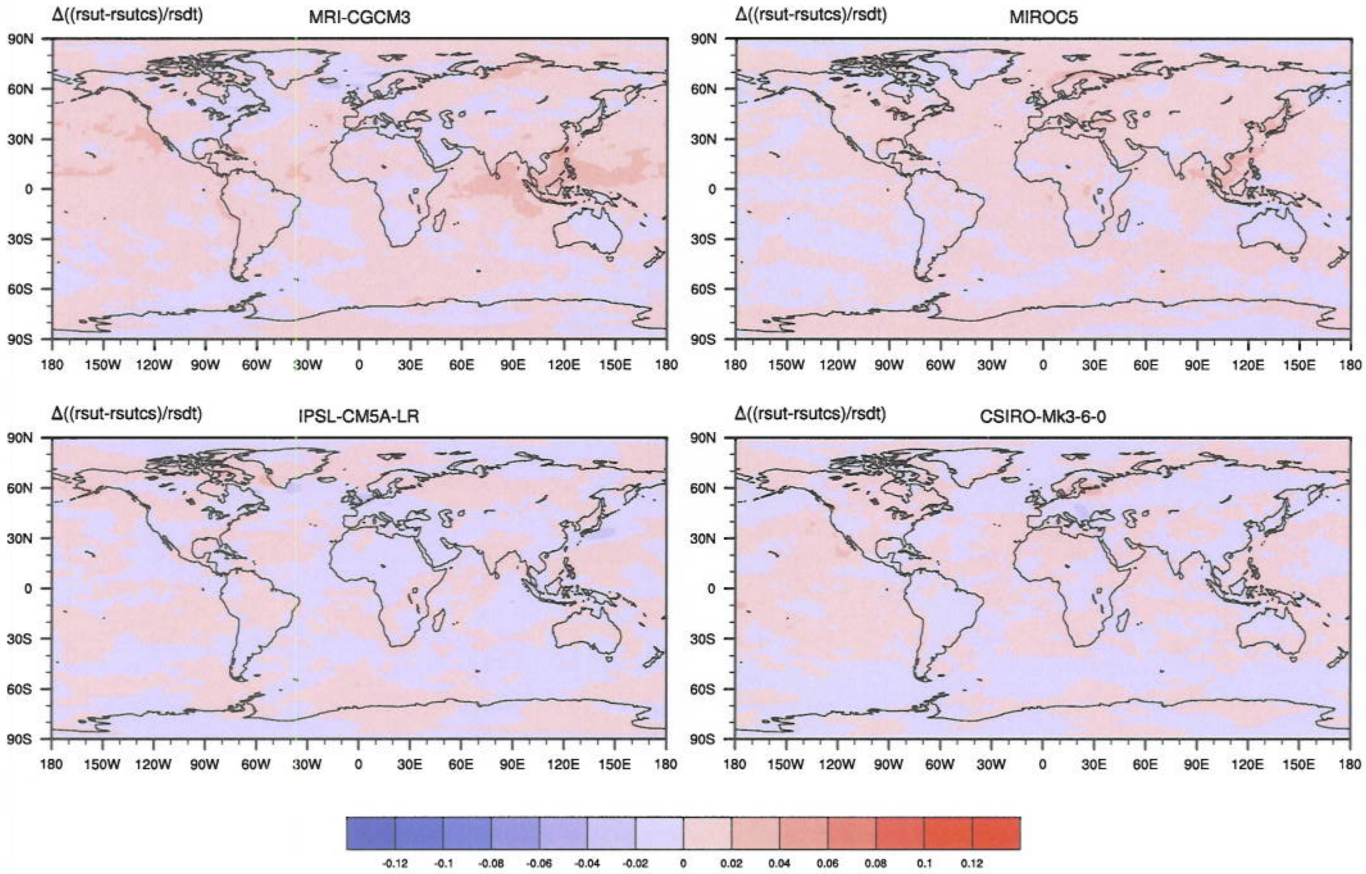
Difference of 5-year means of cloud droplet number concentration of cloud tops between sstClimAerosol and sstClim

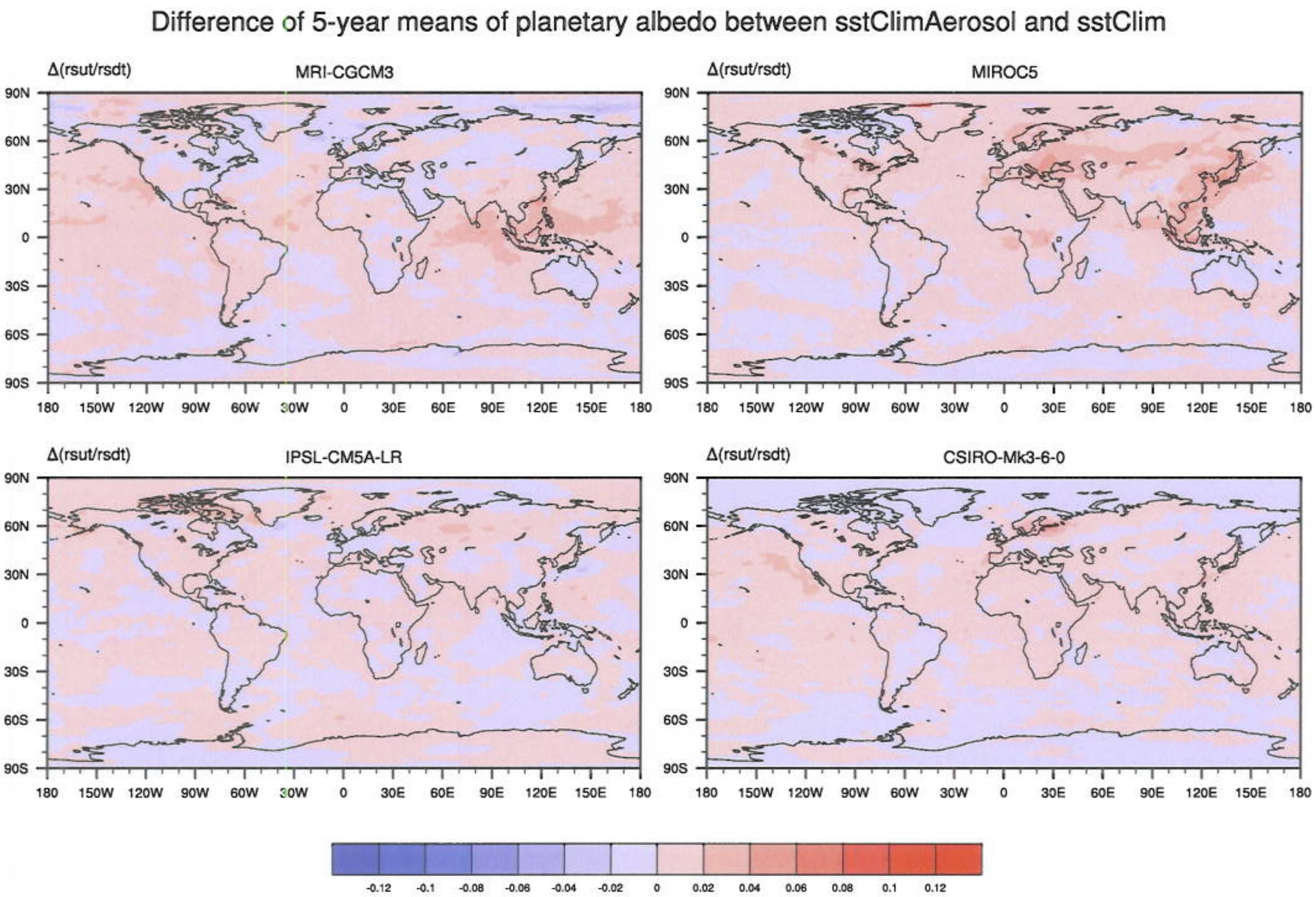


Difference of 5-year means of cloud-top effective droplet radius between sstClimAerosol and sstClim

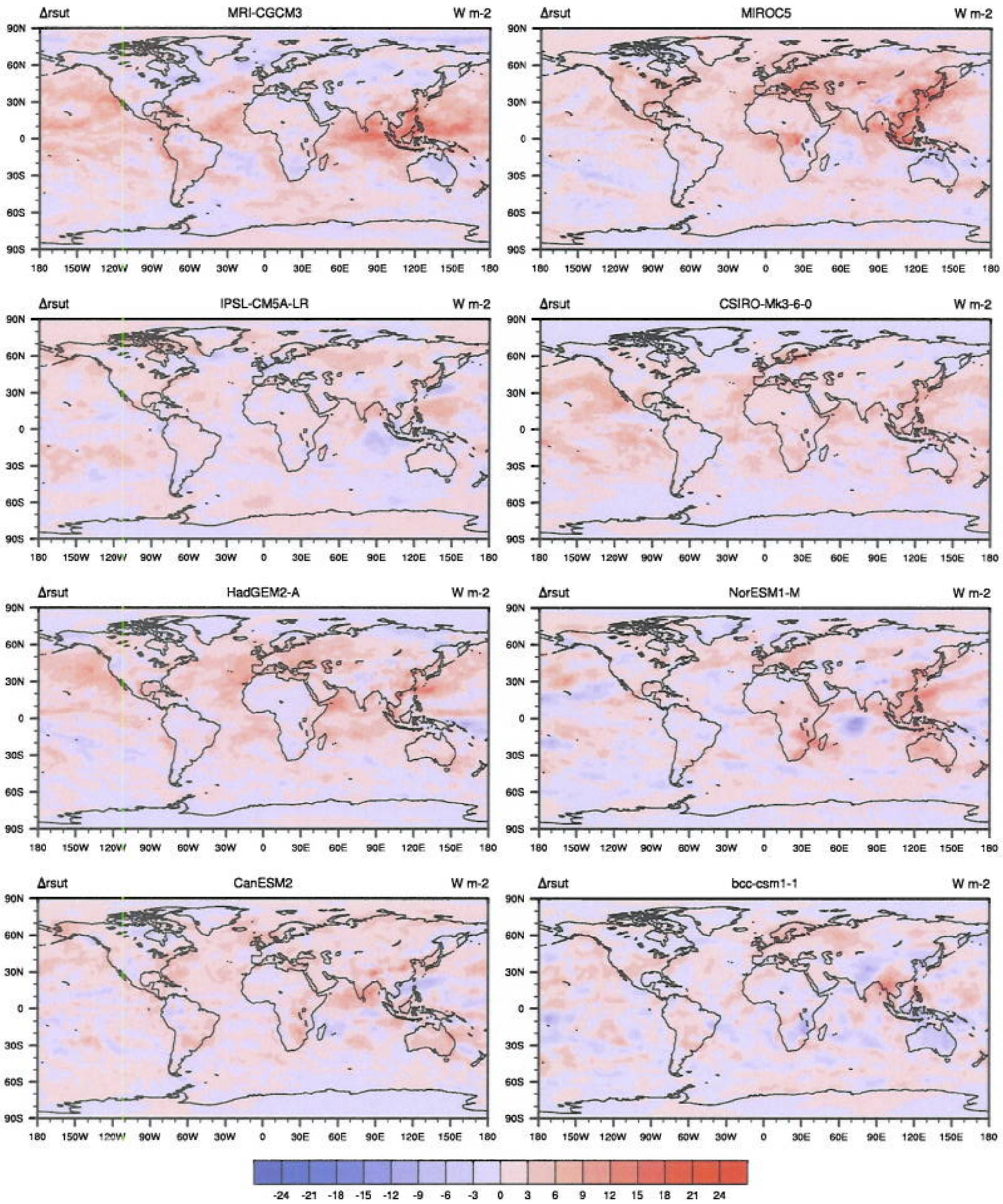


Difference of 5-year means of cloud albedo between sstClimAerosol and sstClim

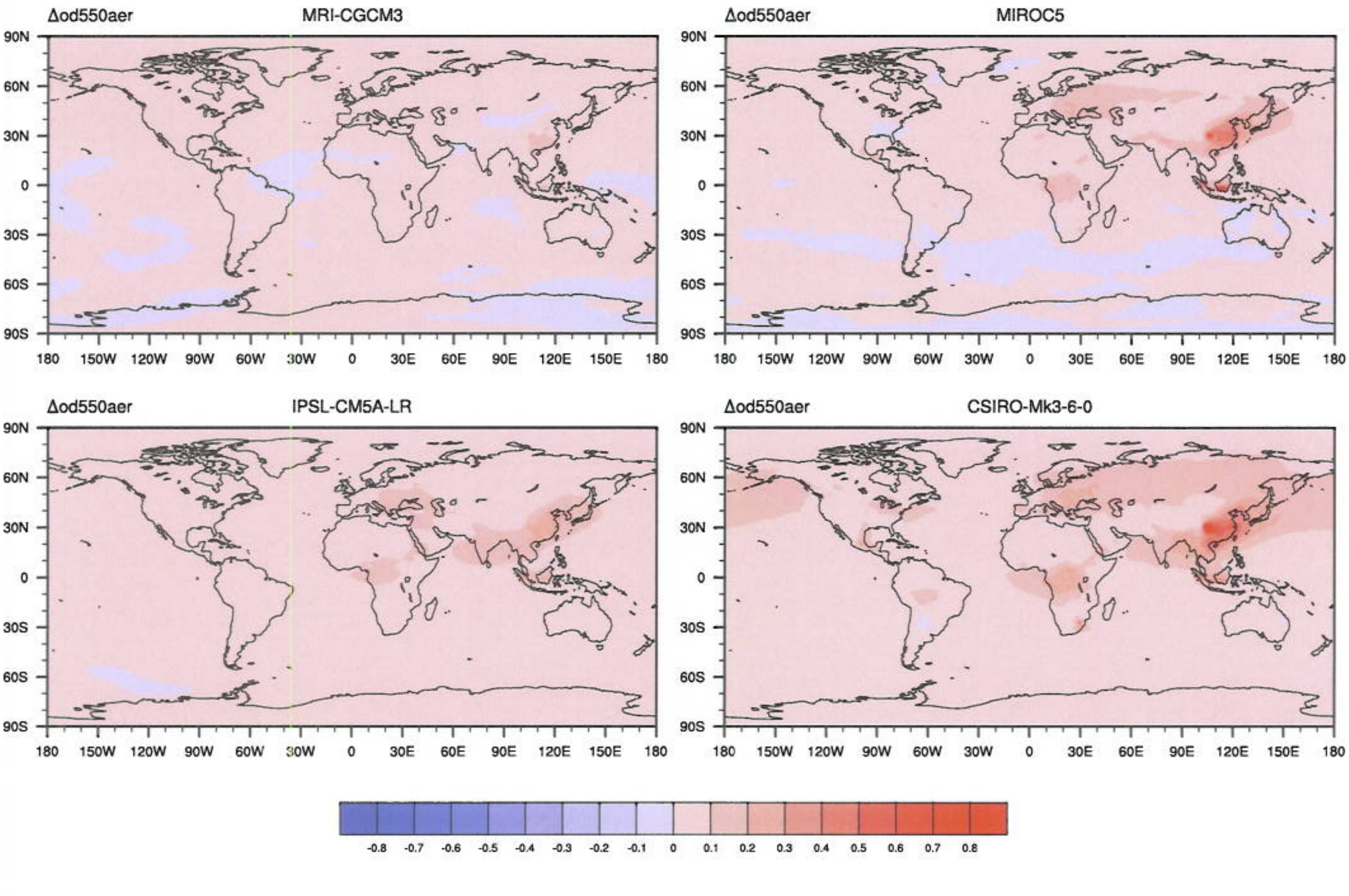



Difference of 5-year means of planetary albedo between sstClimAerosol and sstClim
Δ(rsut/rsdt)
MRI-CGCM3
Δ(rsut/rsdt)
MIROC5
Δ(rsut/rsdt)
IPSL-CM5A-LR
Δ(rsut/rsdt)
CSIRO-Mk3-6-0
90N
60N
30N
0
30S
60S
90S
180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180
-0.12 -0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1 0.12

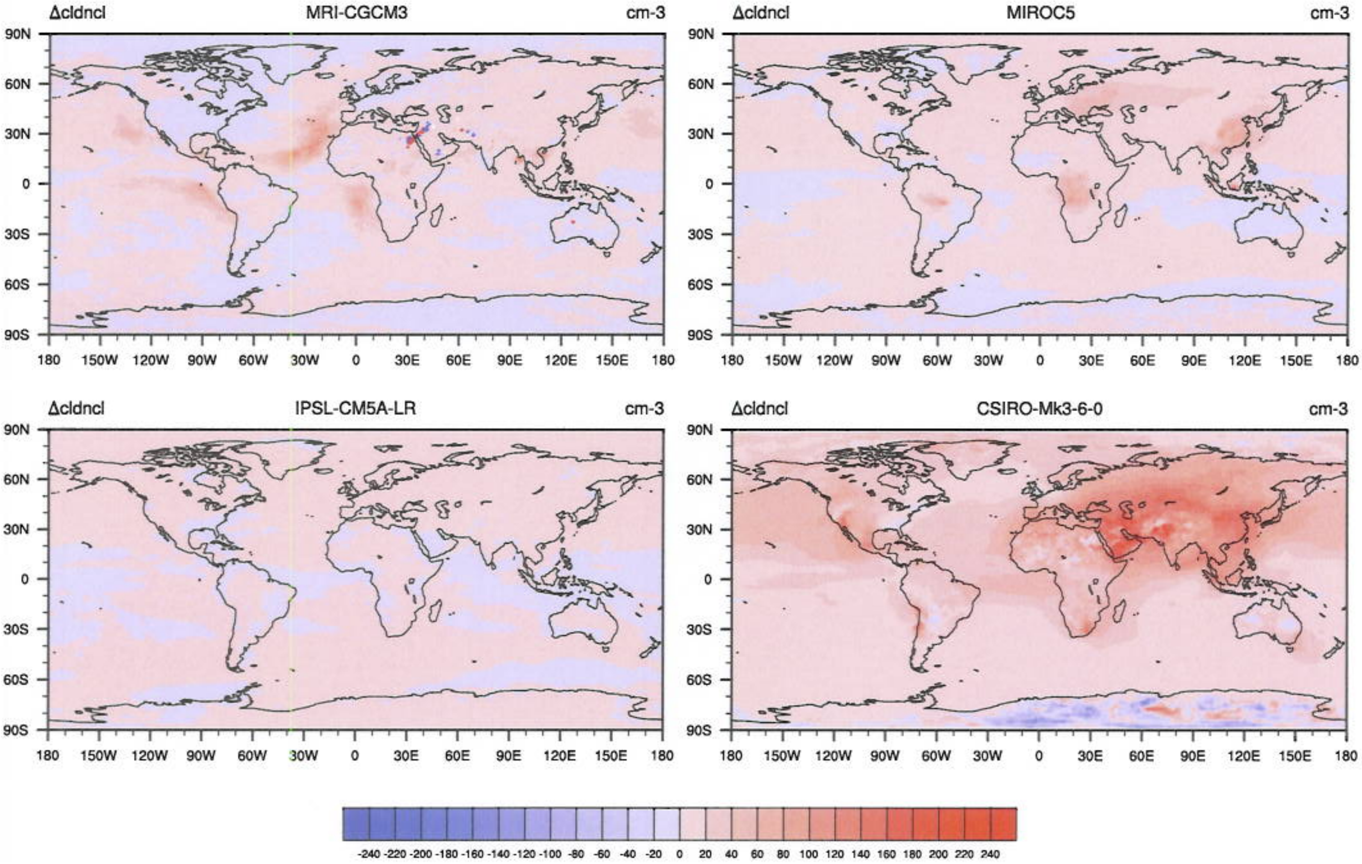
Difference of 5-year means of TOA outgoing shortwave radiation between sstClimAerosol and sstClim



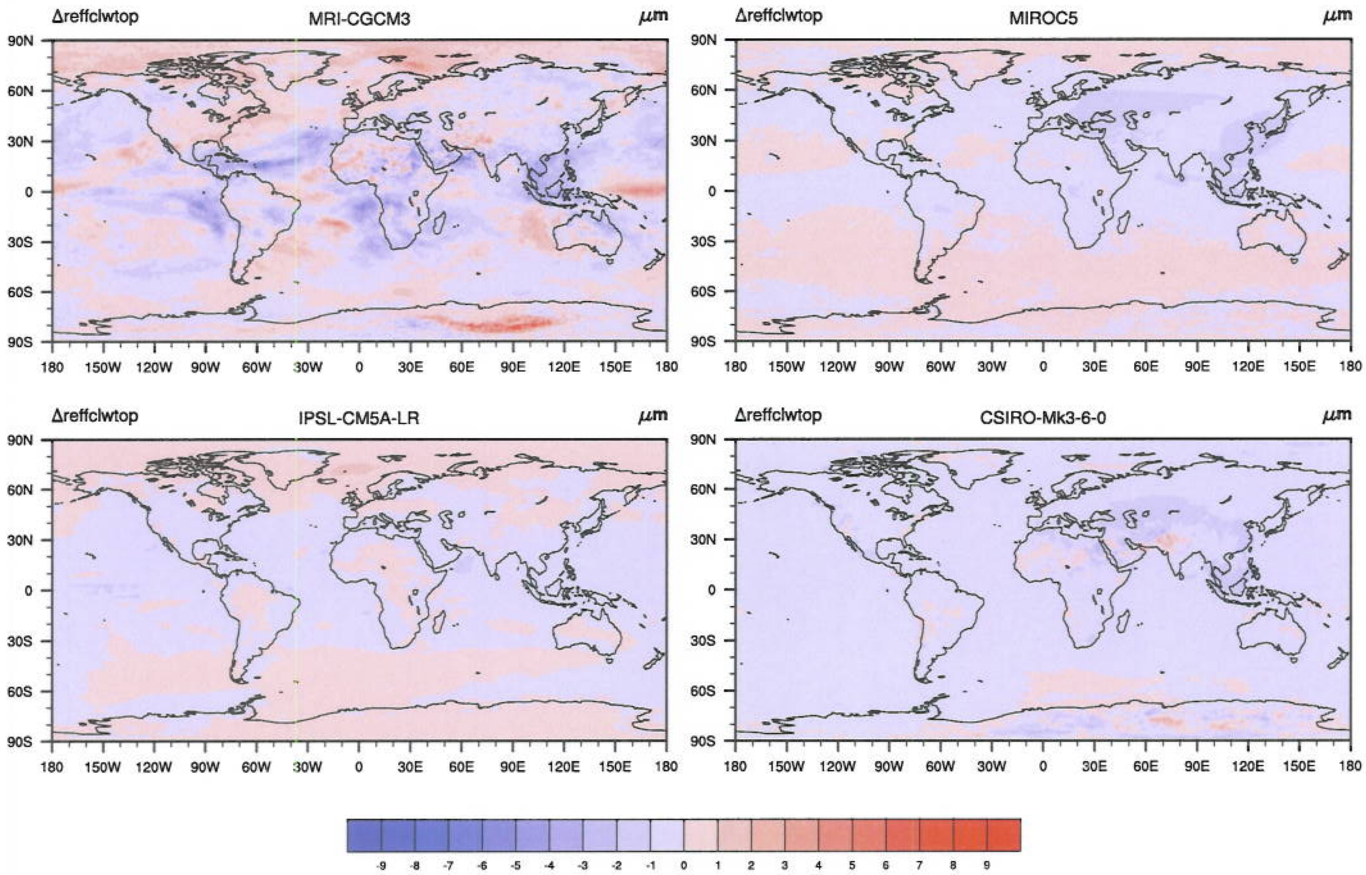
Difference of ambient aerosol optical thickness at 550 nm between time means 2001-2005 and 1861-1865



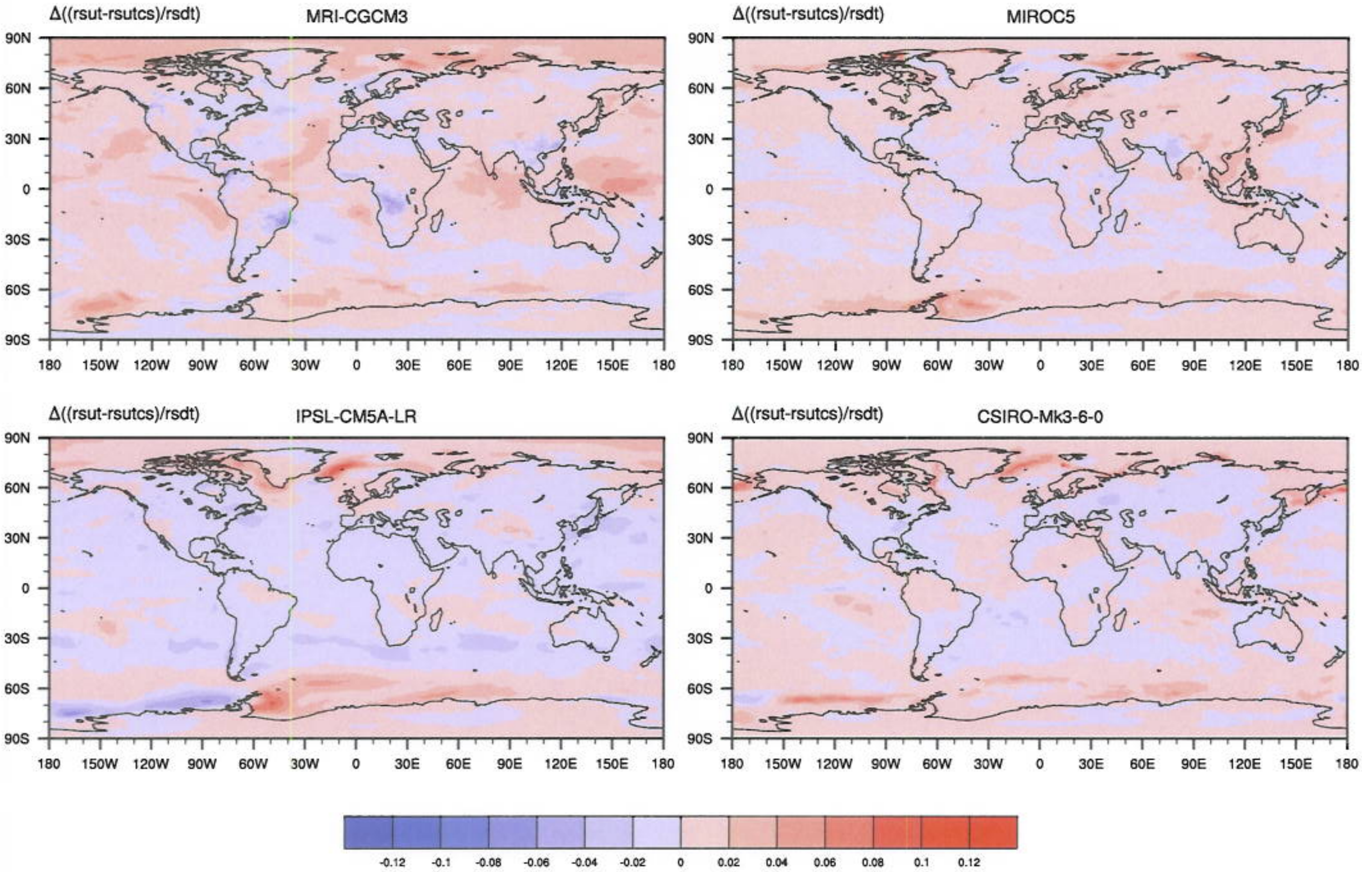
Difference of cloud droplet number concentration of cloud tops between time means 2001-2005 and 1861-1865



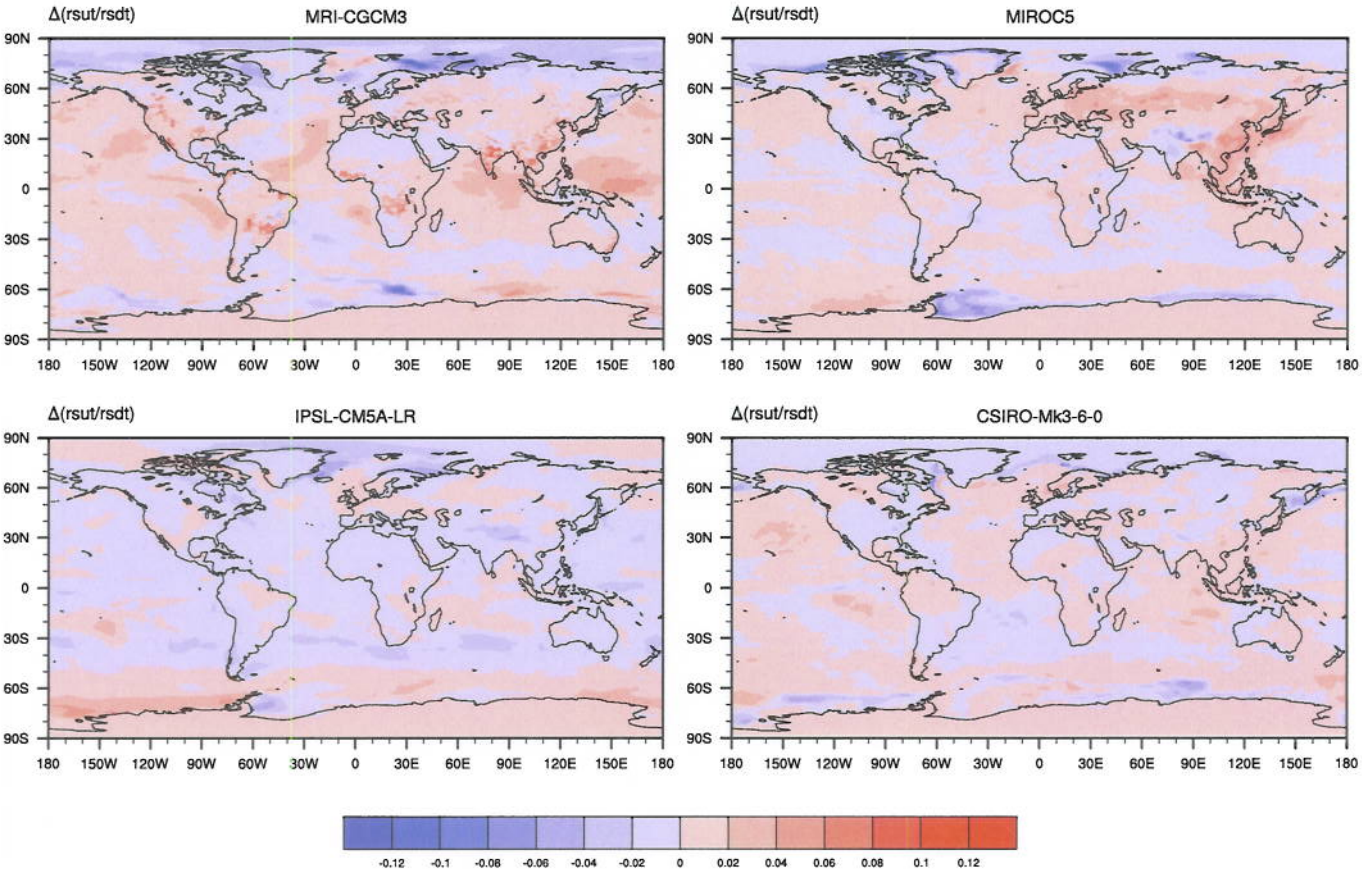
Difference of cloud-top effective droplet radius between time mean 2001-2005 and time mean 1861-1865



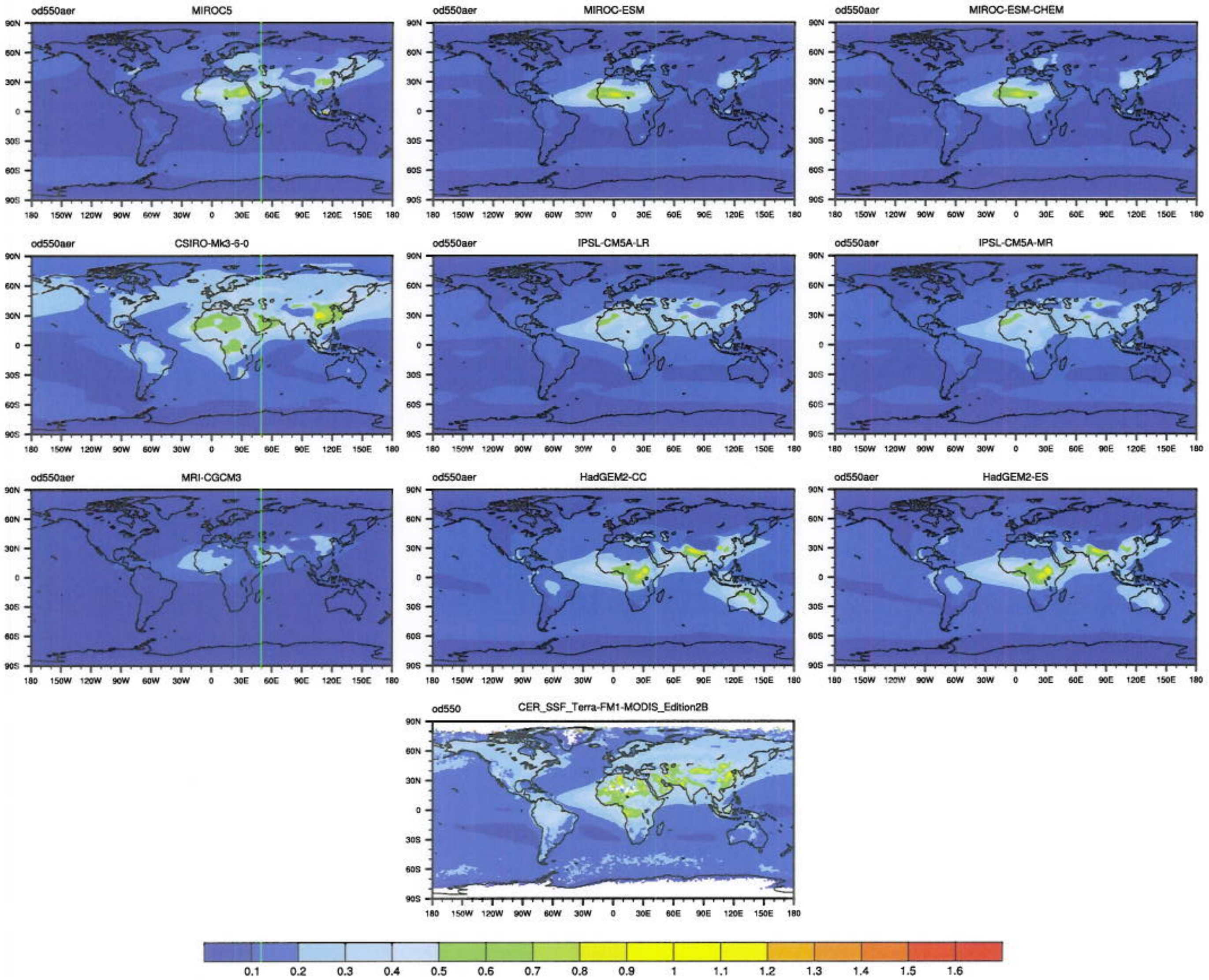
Difference of cloud albedo between time mean 2001-2005 and time mean 1861-1865



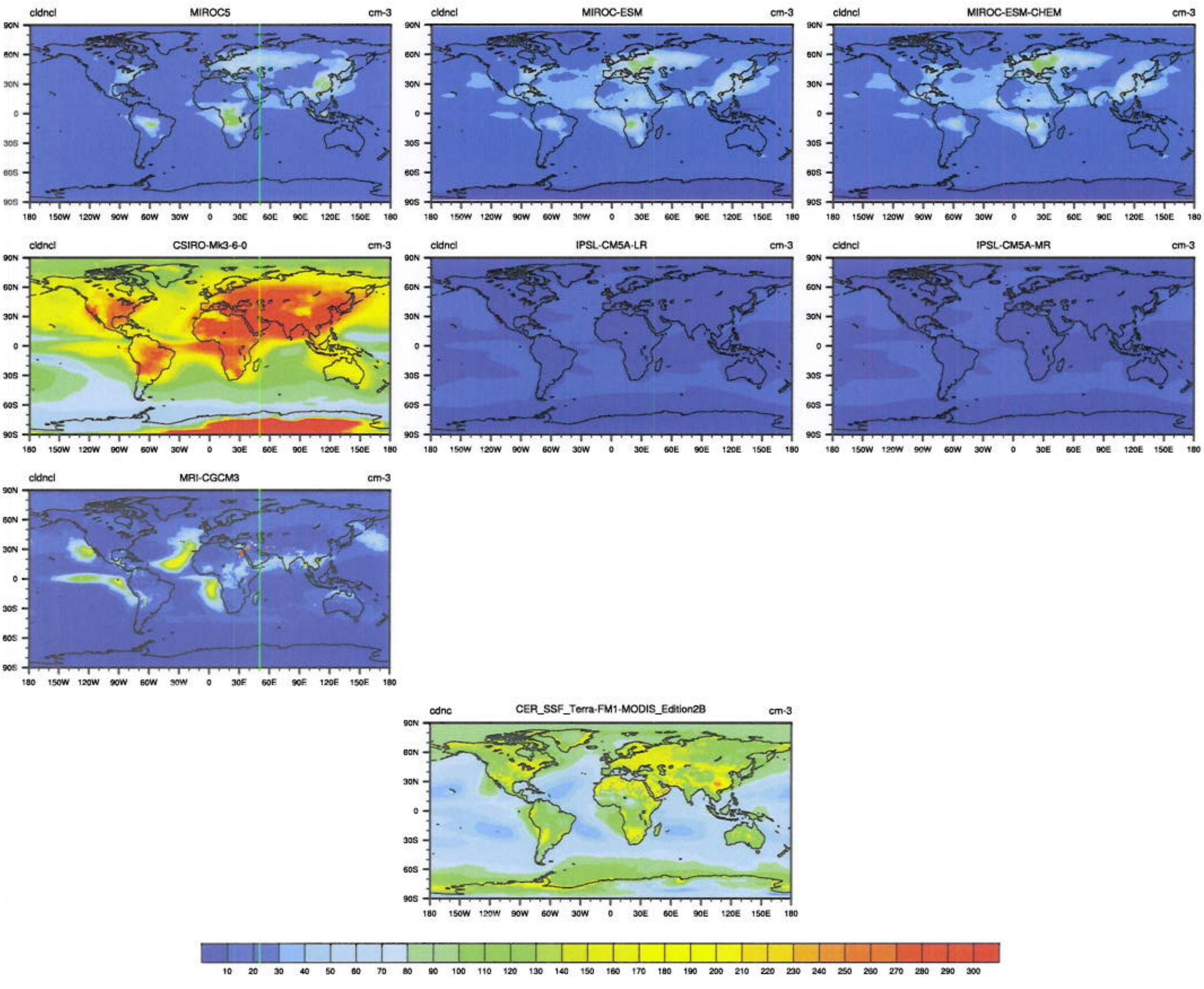
Difference of planetary albedo between time mean 2001-2005 and time mean 1861-1865



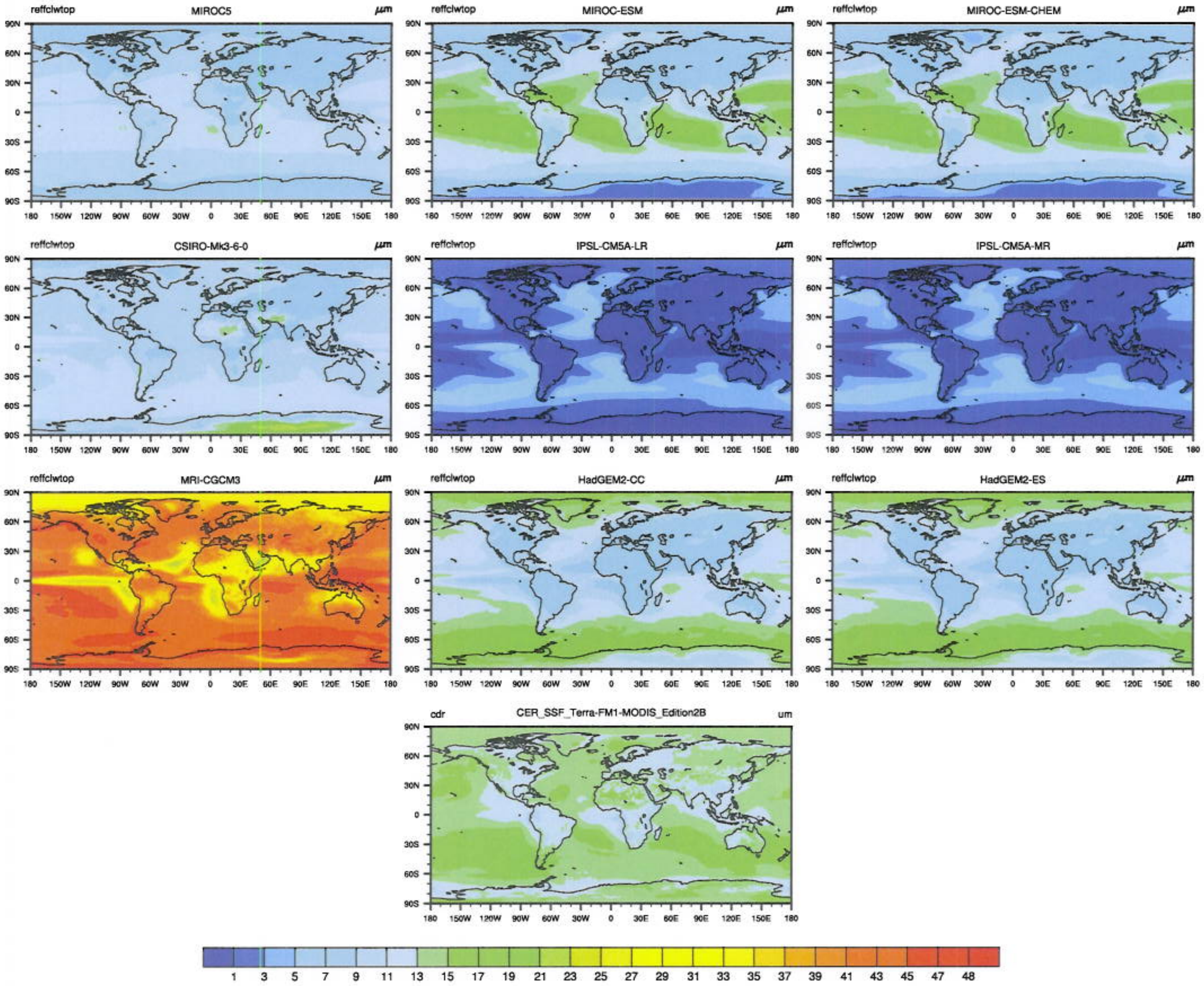
Aerosol optical thickness (Time mean 2001-2005)



Cloud droplet number concentration of cloud tops (Time mean 2001-2005)



Cloud-top effective droplet radius (Time mean 2001-2005)



Planetary albedo (Time mean 2001-2005)