Comparison of fully-coupled and atmosphere-only simulations of NorESM2

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Abstract

We analyze the atmosphere-only simulations performed with NorESM2. A first set of these simulations has been run in the period Jul–Oct 2019, however using the standard CESM flux description between ocean and atmosphere (flux=0), instead of the COARE flux description (flux=1) which is used in the fully-coupled NorESM2 simulations. Over the period Nov 2019-Mar 2020, new atmosphere-only simulations have been run using flux=1. Here we show a comparison of these simulations.

The main findings are :

- The flux=1 atmosphere-only simulations reproduce better the results from the fully-coupled simulations for most variables (except for TOA imbalance). It is especially the case for ear-surface fields such as near-surface (2 m) air temperature, near-surface (2 m) specific humidity, near-surface (10 m) wind, and atmospheric boundary layer height.
- The flux=1 atmosphere-only simulations seem to underestimate the emission strength of natural marine aerosol (or its precursors) : DMS, primary organic matter from the ocean, and sea-salt. Lower atmospheric loads of these scattering aerosols will then lead to a positive TOA imbalance (more net downward radiation). This underestimation of the emission strenght seems to be related to a slight underestimation of the 10 m wind. (The flux=0 atmosphere-only simulations sometimes seem to better reproduce the natural emissions strength, but that is because the bias in the wind is compensated by a bias in the temperature.)
- We see the same differences between flux=0 and flux=1, and between the atmosphere-only and fully-coupled approach for all experimental setups where both a fully-coupled and an atmosphere-only version exist : piControl versus piClim-control (both on 1x1 and 2x2), historical versus histSST-histall (2x2), and ssp370 versus ssp370SST.
- Impacts of GHG changes, aerosol emission changes, or land-use changes (mainly AerChemMIP and RFMIP experiments) do not differ significantly between the flux=0 and flux=1 setup.

This document shows only global mean values (time series). Additional analysis can be found in four appendices. The content of these appendices is :

- Appendix A : illustrates some spatial differences (maps) between the fully-coupled and atmosphere-only simulations.
- Appendix B : illustrates zonal mean differences between fully-coupled and atmosphere-only simulations.
- Appendix C : maps of difference in TOA imbalance between atmosphere-only and fully-coupled simulations.
- Appendix D : analys of the difference in marine emission strength between fully-coupled and atmosphere-only simulations.

1 Introduction

1.1 Ocean-atmosphere fluxes

In the coupled NorESM2 simulations, the flux parameterization used for the transfer of heat, moisture and momentum between the ocean and atmosphere is the so-called COARE flux parameterization. This choice is activated by FLUX_SCHEME=1 in env_run.xml, and ends up in the driver_in namelist as flux_scheme=1. This parameterisation is different from the standard flux-parameterzation used in CESM, which is activated by FLUX_SCHEME=0.

In atmosphere-only simulations, one wants to use boundary conditions as close as possible to the coupled simulations. In NorESM2 atmosphere-only simulations, one therefor uses prescribed boundary conditions for SST, sea-ice cover and upper-ocean DMS concentrations (all three fields taken from the fully-coupled simulation), combined with in principle the same flux-parameterisation is in the full-coupled simulation. In the atmosphere-only simulations

Table 1: Overview of the reference simulations.

Resolution	Coupled simulation	Atmosphere-only simulation		
		flux=0	flux=1	flux=1 & ΔDMS
2x2	piControl	piClim-control	piClim-control	piClim-control
1x1	piControl	–	piClim-control	–
2x2	historical	histSST	histSST	–
2x2	ssp370	–	ssp370SST	–

done with NorESM2 over the periods Jul-Oct 2019, we used however erroneously FLUX_SCHEME=0. Once the discrepancy had been noticed, we have redone the atmosphere-only simulations (over the period Nov 2019-Mar 2020), using now FLUX_SCHEME=1.

Another feature of the coupled NorESM2 simulations, i.e., taking into account the fact that the solar zenith angle used for the calculation of the surface albedo changes over the atmospheric model time step of 30 minutes (activated by ALB_COSZ_AVG=.true. in env_run.xml), was also not taken into account in the first set of atmosphere-only simulations (Jul-Oct 2019). In the new Nov 2019-Mar 2020 simulations, we have corrected this and have also used ALB_COSZ_AVG=.true.

In the remainder of the text, the atmosphere-only simulations which had FLUX_SCHEME=0 and ALB_COSZ_AVG=.false. will be referred to as **flux=0** simulations, and those with FLUX_SCHEME=1 and ALB_COSZ_AVG=.true. will be referred to as **flux=1** simulations.

Lately we noticed that an additional change in the description of the DMS emissions, brings the DMS emissions in the atmosphere-only simulations closer to the fully-coupled results. That extra modification will be characterized by **ΔDMS**.

Finally, we want to clarify that atmosphere-only simulations still contain an active land model component. Also the sea-ice component is active, but whenever there is sea-ice, the sea-ice is assumed to have a thickness of 1 m.

1.2 Boundary conditions

For the atmosphere-only simulations to be run, boundary conditions have to be generated to describe the apparent state of the imaginary underlying ocean. The model needs boundary conditions for sea-surface temperature (SST), sea-ice cover, and upper ocean DMS concentration.

Up to now, 4 sets of boundary conditions have been made :

- A pre-industrial climatology (containing 12 months) on 2°x2° based on a 30-year period of 2°x2° piControl (years 1751–1780). This climatology is used for piClim-control (and all type of perturbations) simulations (these are mostly 30-year long simulations).
- As above but on 1°x1°, and based on 1°x1° piControl (years 1351-1380).
- A historical climatology (1849-2015, monthly) on 2°x2°, based on the period 1850–2014 of historical. This climatology is used for histSST (and perturbations) simulations (165 year long simulations).
- A scenario ssp3-7.0 climatology (2014–2101, monthly) on 2°x2°, based on years 2015-2100 of ssp3-7.0. This climatology is used for ssp370SST simulations (86 year long simulations).

The climatologies for piClim-control have been based on a 30-year snapshot of piControl (year 1751–1780 and 1351–1380 as mentioned above). For comparison of piClim-control and piControl, one should focus on those 30-year periods, due to inter-decadal variability or drifts in piControl.

1.3 Available reference simulations

There are four groups of simulations where the difference in behaviour between coupled and atmosphere-only, or between the different versions of atmosphere-only can be analyzed. An overview of these simulations is given in Table 1.

1.4 Structure of this document

This analysis is structured in the following way. In Sect. 2.1 we compare the behaviour of the fully coupled and atmosphere-only simulations for the four groups of experiments for which both approaches exist : piControl/piClim-control on 2°x2°, piControl/piClim-control on 1°x1°, historical/histSST-histall on 2°x2°, and ssp370/ssp370SST on 2°x2°. For the atmosphere-only, we show both flux=0 and flux=1 results whenever available. Although it is a little bit out of focus for the discussion here, in Sect. 2.2, we show results from an identical experiment run on two different HPCs (vilje and fram). In Sect. 2.3, we analyze how the 30-year atmosphere-only simulations behave differently in flux=0 and flux=1. In Sect. 2.4, we compare the 30-year atmosphere-only simulatons in 2x2 and 1x1 resolution. In Sect. 2.5, we show results from the perturbation atmosphere-only simulations run with flux=0 and flux=1.

2 Results

2.1 Coupled versus fixed-SST simulations

Here we compare the coupled reference simulations (i.e., piControl, historical, and ssp370) with the atmosphere-only reference simulations (i.e., piClim-control, histSST, and ssp370SST). Results from perturbed simulations (mainly AerChemMIP and RFMIP) are shown later.

Comparison of piControl and piClim-control (2°x2°) Figure 1 shows timeseries of global- and annual-mean averages for various variables. One has to remember that for the 2°x2° piClim-control atmosphere-only experiments, the period on which the climatologies are based consists of the period years 151–181 – this implies that for that period the best correspondence is to be expected between piControl and piClim-control. For near-surface variables (near surface (2 m) air temperature and specific humidity, boundary layer height and 10 m wind), the flux=1 behaves better than flux=0. Only for temperature, there seems to be still some underestimation in flux=1. The flux=1 & ΔDMS behaves similaryly to flux=1.

The TOA imbalance, however, is worse in flux=1 than in flux=0. Both have considerable positive bias, which is strongest for flux=1. An underestimation of the natural aerosol emissions which is more pronounced for in flux=1 might contribute to this (see later), but is probably not the only cause for this warm bias. There is especially a strong bias over sea-ice covered regions.

Precipitation behaves much better in flux=1 than flux=0.

The global-mean sea-ice cover in the period 151–180 seems to agree well between the fully coupled and all the atmosphere-only simulations.

Emissions of natural marine aerosols or their precursors (i.e, DMS, organic matter from the ocean, and seasalt) are consistenly underestimated in flux=1. The emissions of in flux=0 are higher and show a smaller bias – this might however be caused by higher 10 m winds. The underestimation of natural marine aerosol emissions in flux=1 seems to be related to the small underestimation of the 10 m wind. As emission strengths often scale with some power of the 10 m wind (power 2 for DMS emissions, and power 3.74 for seasalt and organic matter emissions), regional small underestimations in wind can lead to considerable underestimations in emission strengths.

Land-based aerosol emissions or their precursors (dust, isprene and monoterpene) correspond well between fully-coupled and atmosphere-only simulations. Concerning isoprene and monoterpene emissions, the flux=1 atmosphere-only simulations behave slightly better than the flux=0 simulations.

Cloud fractions are rather similar bewteen the fully-coupled and atmosphere-only simulations. Although the medium cloud fraction in flux=1 looks a bit too strong, it actually corresponds well if one looks at the 151-180 period.

The only difference between flux=1 and flux=1+ΔDMS becomes apparent in the DMS emission strenghth. The DMS emission strength is closed to the piControl for flux=1+ΔDMS, however a small underestimation is still present.

Comparison of piControl and piClim-control (1°x1°) Figure 2 shows timeseries for the 1°x1° simulations of piControl and piClim-control (flux=1). There exist no flux=0 simulations for 1°x1°, as those simulations have been done only later. Almost all difference observed in the 2°x2° comparison (see above), are also valid in the 1°x1° comparison. However, for 1°x1° the TOA imbalance compares better with the full-coupled simulation than for 2°x2°.

Comparison of historical and histSST (2°x2°) Figure 3 shows the comparison of the fully-coupled historical simulation, and the atmosphere-only histSST (flux=0) and histSST (flux=1) simulations. As here the prescribed SSTs, sea-ice fraction and upper-ocean fields keep the inter-annual variability of the fully coupled historical simulation, the variability in the atmosphere-only simulations is generally more in phase with the coupled simulations (than in the piControl/piClim-control cases shown earlier).

For the near-surface variables (2 m temperature, specific humidity, boundary layer height and 10 m wind) and precipitation, the flux=1 histSST simulation behaves more like the fully-coupled historical simulation than flux=1. Now it becomes clear that flux=0 considerably overestimates the 2 m temperature, and that flux=1 behaves better, although with a slight underestimation. Again, the TOA imbalance is higher in flux=1 than in flux=0. Marine aerosol (or their precursor) emissions are again consistently underestimated in flux=1, whereas for flux=0 the agreement seems better. Land emissions of isoprene and monoterpene behave best in flux=1. From these simulations, it also becomes clear that medium clouds behave better in flux=1.

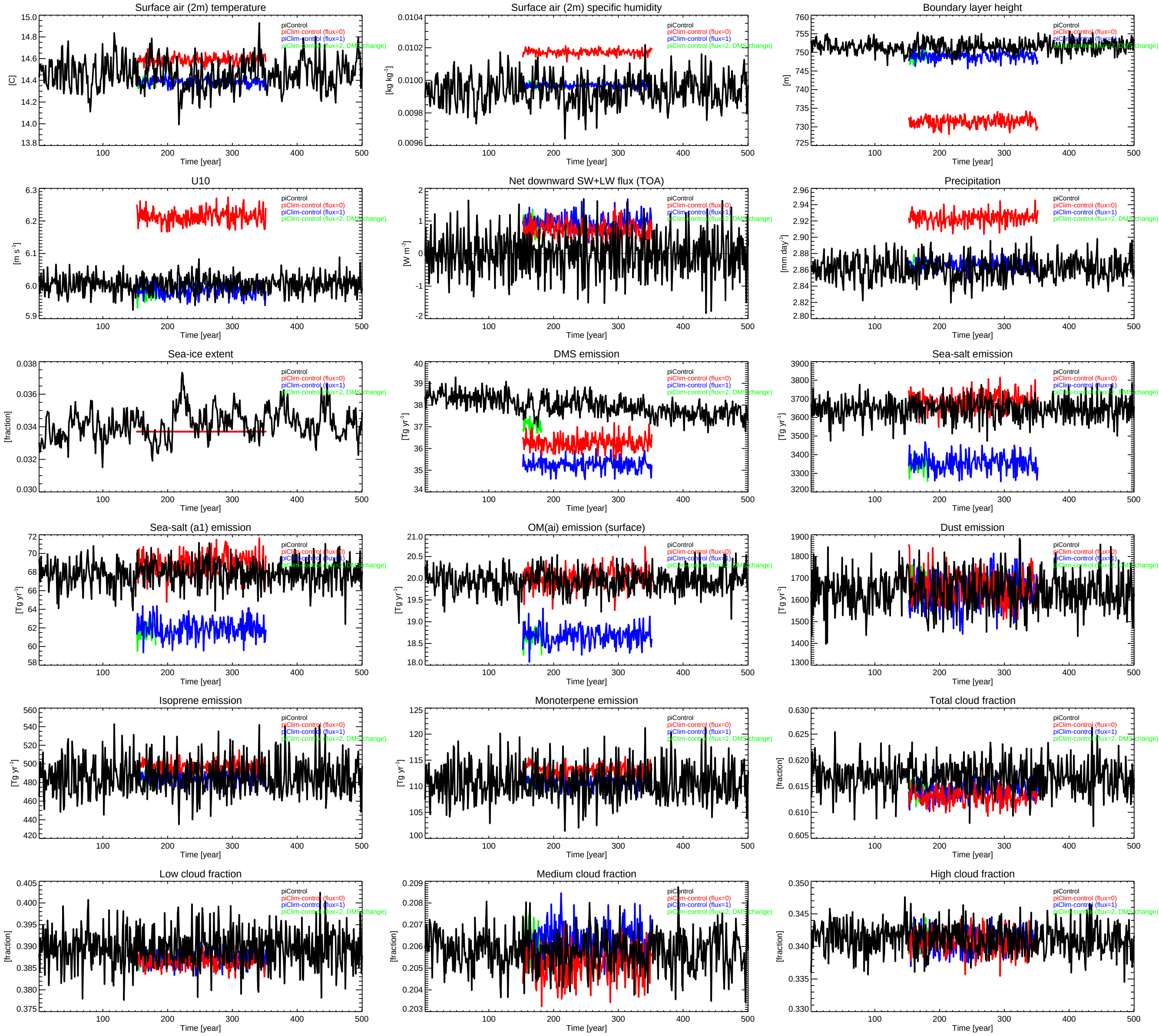

Figure 1: Global and annual mean timeseries in the 2°x2° control simulations : piControl (black), piClim-control (flux=0, red), piClim-control (flux=1, blue) and piClim-control (flux=1, ΔDMS, green).

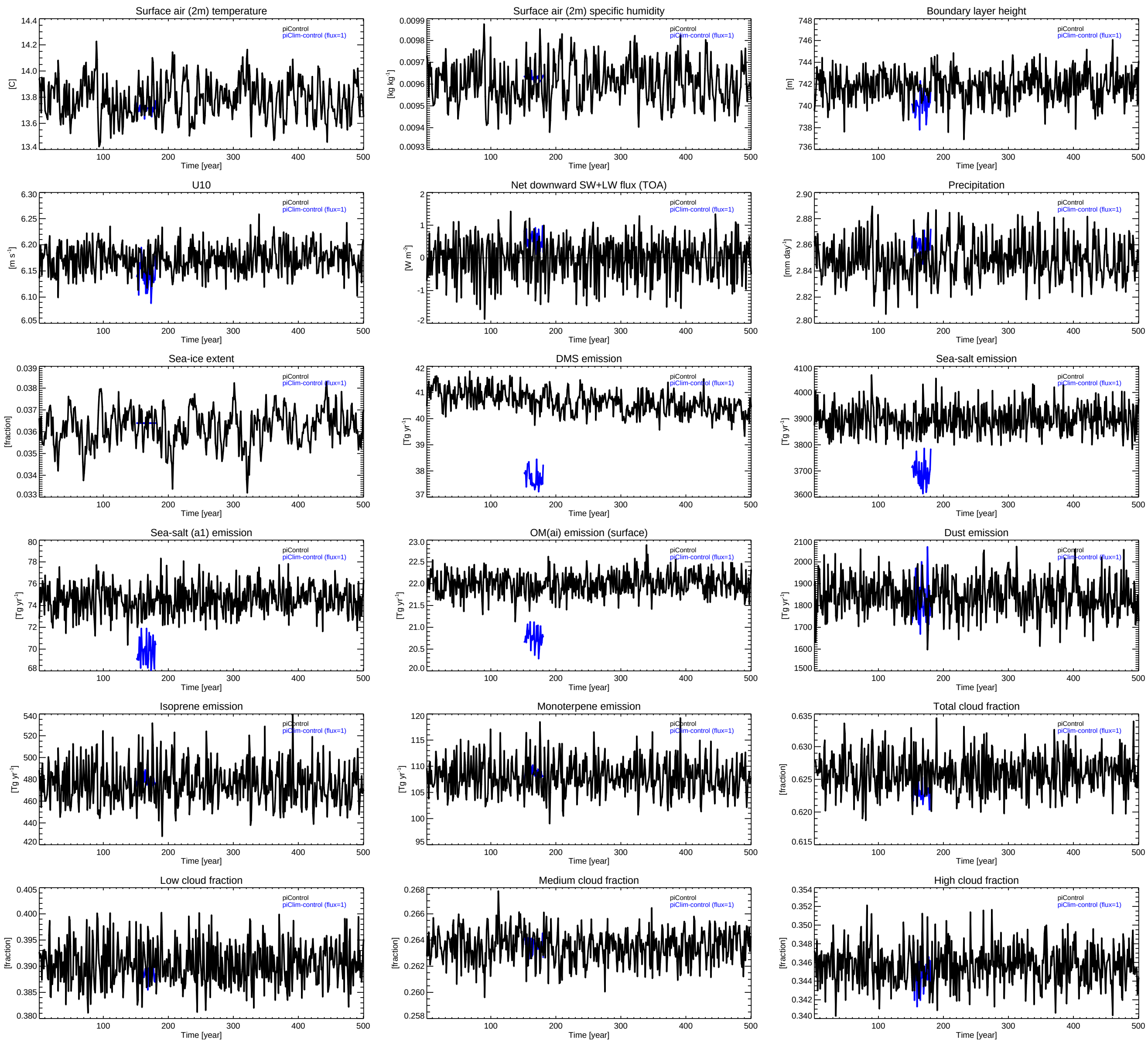

Figure 2: Global and annual mean timeseries in the 1°x1° control simulations : piControl (black) and piClim-control (flux=1, blue).

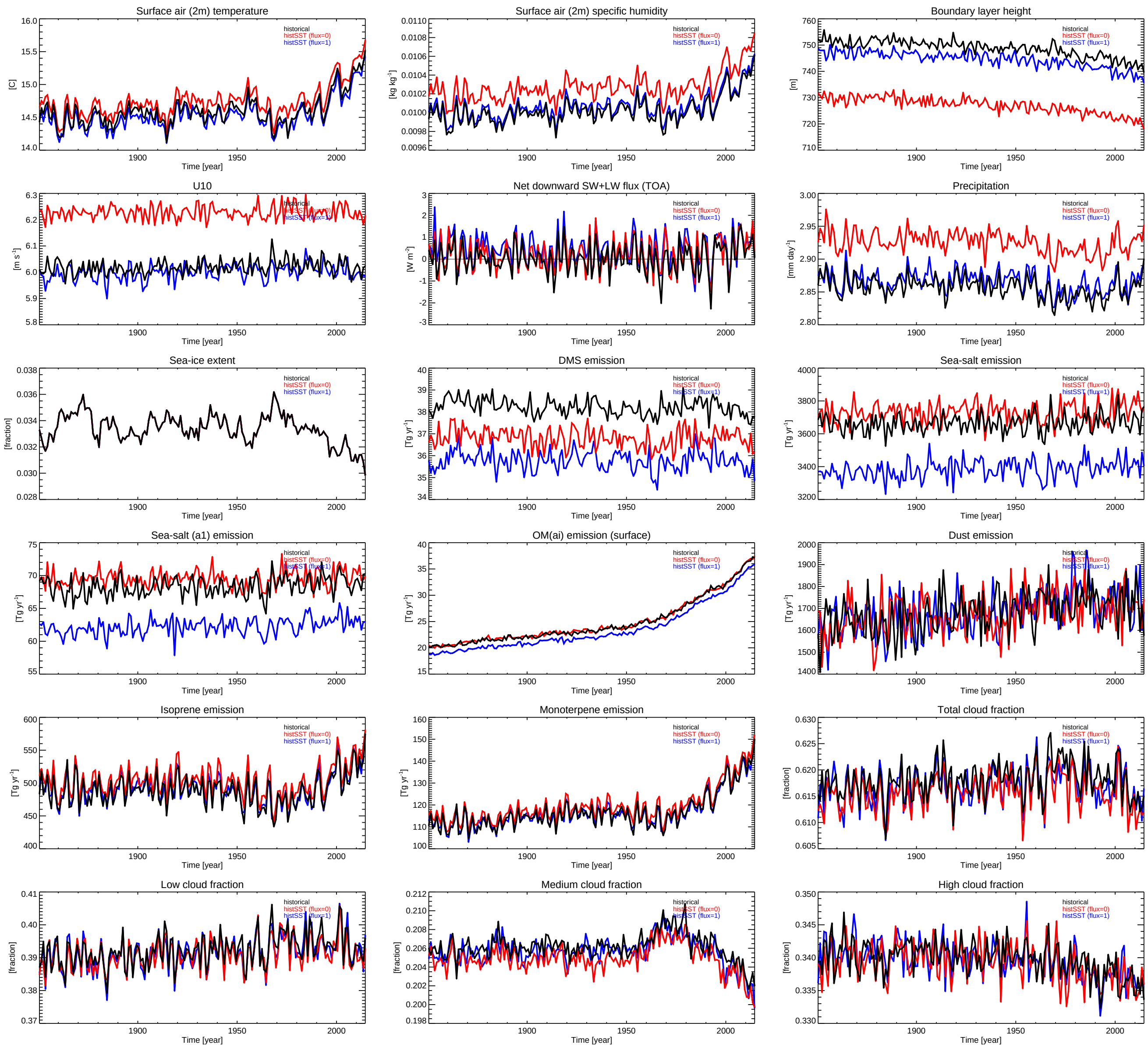

Figure 3: Global and annual mean timeseries in the 2x2 historical simulations : historical (black), histSST (flux=0, red) and histSST (flux=1, blue).

Table 2: Overview of the 30-year long atmosphere-only simulations.

Experiment	2°x2 flux=0	2°x2° flux=1	2°x2° flux=1&ΔDMS	1°x1° flux=1
piClim-control	ok	ok	ok	ok
piClim-4xCO2	ok	ok	–	ok
piClim-ghg	ok	ok	–	–
piClim-ghg-noH2O	ok	ok	–	–
piClim-CH4	ok	ok	–	–
piClim-CH4-noH2O	ok	ok	–	–
piClim-N2O	ok	ok	–	–
piClim-aer	ok	ok	–	ok
piClim-aer-oxid	ok	ok	–	ok
piClim-BC	ok	ok	–	–
piClim-OC	ok	ok	–	–
piClim-SO2	ok	ok	–	–
piClim-SO2-oxid	ok	ok	–	–
piClim-O3	ok	ok	–	–
piClim-NTCF	ok	ok	–	–
piClim-anthro	ok	ok	–	–
piClim-oxid	ok	ok	–	ok
piClim-H2O	ok	ok	–	–
piClim-lu	ok	ok	–	–
piClim-2xDMS	ok	ok	–	–
piClim-2xdust	ok	ok	–	–
piClim-2xss	ok	ok	–	–
piClim-2xVOC	ok	ok	–	–

Comparison of ssp370 and ssp370SST (2°x2°) Figure 4 shows the comparison of the spp370 and the ssp370SST flux=1 simulation (there exists no flux=0 simulation). Similarly to historical/histSST, parts of the inter-annual variability of ssp370 becomes also visible in ssp370SST. Near surface variables (near surface (2 m) temperature and specificd humidity, boundary layer height and 10 m wind) together with precipitation seem to agree well. Again, the TOA imbalance has a positive bias in the atmosphere-only simulations. Again, natural marine aerosol (or their precursor) emissions are underestimated. Notice the change in trend in total organic matter emissions, due to the change in anthropogenic emissions (the POM emissions from ocean probably have almost no trend).

2.2 Running on vilje versus fram

One experiment has been run on two different HPCs, i.e., a historical atmosphere-only simulation where all changes over the 1850–2014 period have been switched off except for the land-use change. The lower boundary conditions are given by the (one seasonal cycle) climatology of the piControl simulation.

Figure 5 shows global- and annual mean timeseries for the same variables as shown earlier. There are no significant systematic differences visible between the simulation on vilje (black) and fram (red).

2.3 Impact of flux=0/1 on 30-year fixed SST simulations

In AerChemMIP and RFMIP, a set of 30-year simulations had been suggested, where some of the forcings were changed w.r.t. piClim-control. These simulations are designed to give an estimate of the effective radiative forcing (ERF). Those simulations have all been done once with flux=0 (in the period Jul-Oct 2019), and once with flux=1 (in the period Nov 2019-Mar 2020). To study impacts of individual forcing, we have performed more simulations then requested for in AerChemMIP and RFMIP. An overview of the simulations is given in Table 2.

Figure 6 shows a comparison of the flux=1 and flux=0 approach, for a selected set of variables. It contains the 30-year averaged of the fixed-SST simulations, principally done for AerChemMIP and RFMIP, but it contains also results from some addtional simulations.

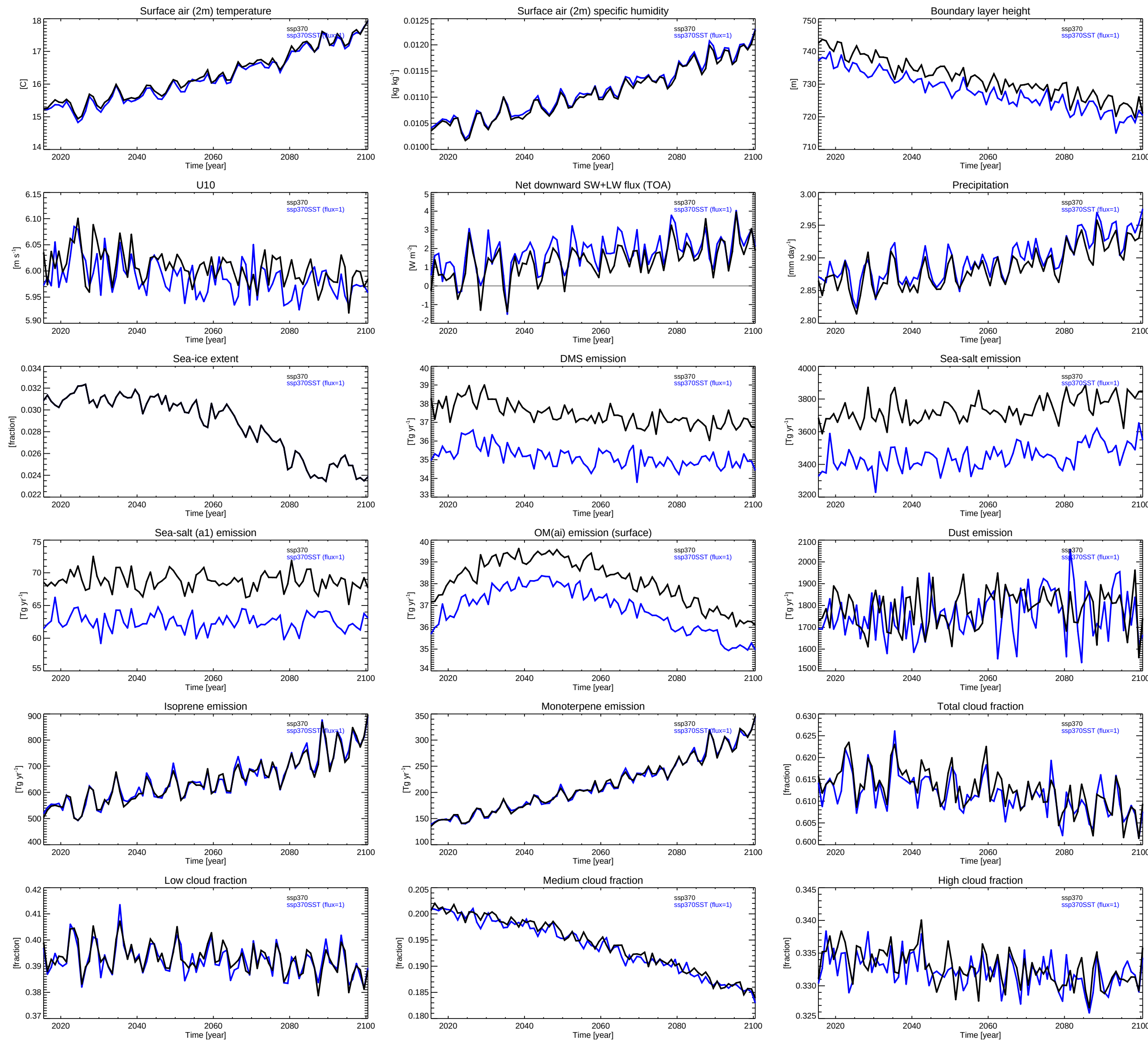

Figure 4: Global and annual mean timeseries in the 2x2 SSP3-7.0 scenario simulations : ssp370 (black) and ssp370SST (flux=1, blue).

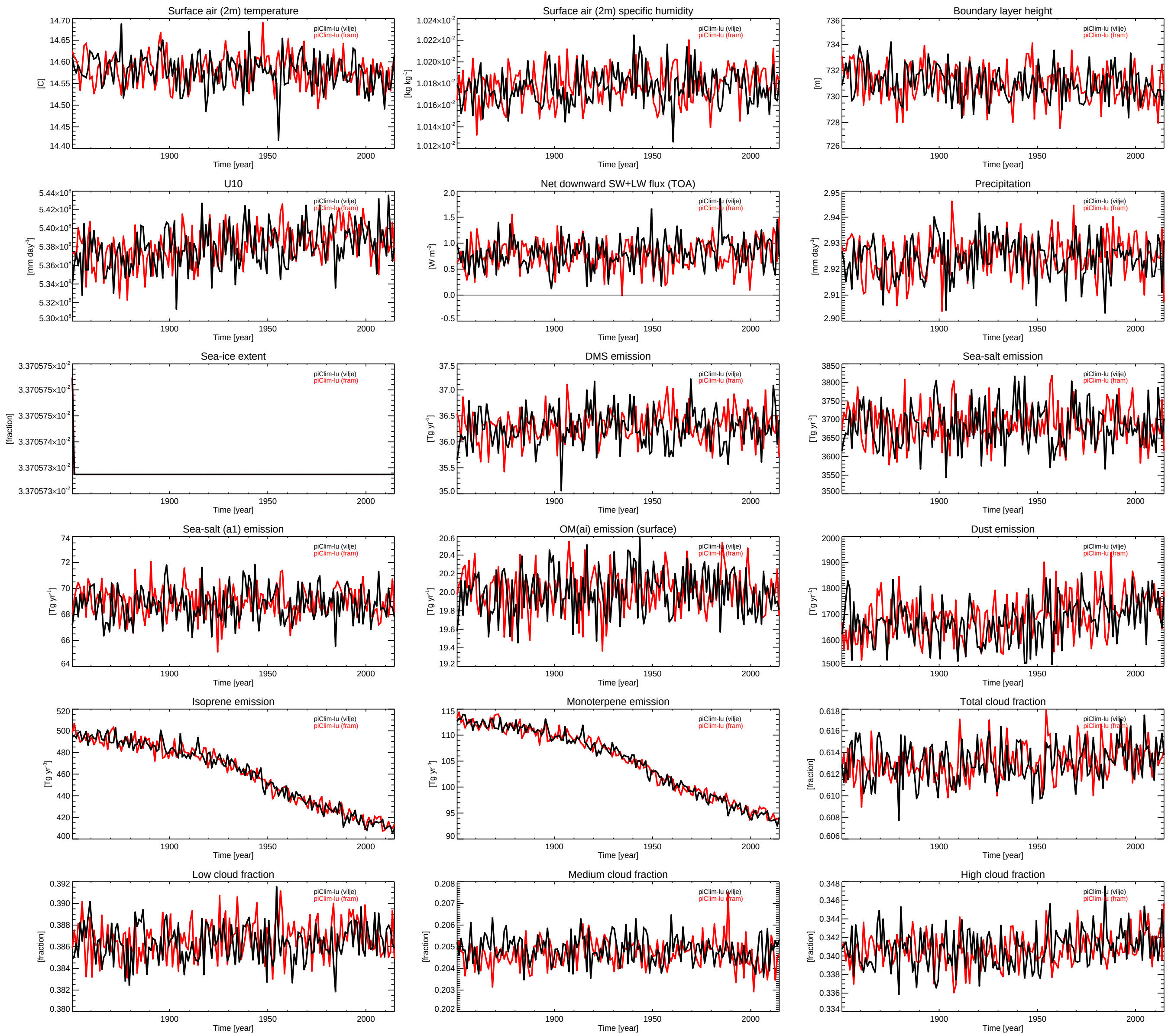

Figure 5: Global and annual mean timeseries in the lu-only historical fixed-SST simulation on vilje (black) and fram (red).

Table 3: Overview of the historical atmosphere-only peturbation experiments.

Experiment	2x2 flux=0	2x2 flux=1
piClim-histall	ok	ok
piClim-histghg	ok	ok
piClim-histnat	ok	ok
piClim-histaer	ok	ok
piClim-histO3	ok	ok
piClim-histlu	ok	ok
piClim-histoxid	–	ok
piClim-histaeroxid	–	ok

The results shown here between the flux=0 and flux=1 approach are very much inline with the results shown above. In the flux=1 approach, temperature is around 0.2 K lower, and also the TOA imbalance is higher by around $0.2\,\mathrm{W\,m^{-2}}$. The flux=1 have less outgoing LW radiation, but also less net incoming SW radiation. Precipitation is lower in flux=1 than in flux=0. Cloud fractions (low, middle and hight) are slightly higher in flux=1 than in flux=0.

Figure 7 shows how the flux=0 and flux=1 approaches affect the impact results (difference between piClim-*perturbation* and piClim-control simulation). It shows that the impact strenghts are very similar between both setups : all results fall onto the 1-1 line when one takes into account the uncertainty.

Figures 8 and 9 contain the same information as the Fig. 7, but presented in a different way. It shows that for all variables, the impact results using flux=0 and flux=1 do not differ significantly : the best estimate of flux=0 falls within the uncertainty range of flux=1, and vice-versa. Figure 8 shows a broad range of different types of forcings (GHGs, aerosols, ozone, land-use), and Figure 9 shows results specifically related to aerosols (both anthropogenic as natural).

2.4 Fixed-SST simulations of 30 year : 1°x1° versus 2°x2°

With the 1°x1° model version, only a limited number of atmosphere-only simulations have been performed. These simulations are piClim-control, piClim-4xCO2, piClim-aer, piClim-aer-oxid and piClim-oxid. Here we compare how the these 1x1 results (flux=1) compare to the 2°x2° (flux=0) and 2°x2° (flux=1) results.

Figure 10 shows the relation between the 2°x2° (flux=1) and 1°x1° (flux=1) results for various variables (near-surface 2 m air temperature, TOA imbalance, net SW TOA imbalanc, net LW TOA imbalance, precipitation, and cloud fractions (low, medium, high). In 1x1 atmosphere-only simulations, the surface temperature is aroun 0.6 K lower than in the 2x2 simulations. As noted aerlier, the TOA imbalance is considerably smaller in the 1x1 than in the 2x2.

All cloud fractions are higher in 1x1 than in 2x2 - the difference is most pronounced for the medium clouds.

Figure 11 shows for various variables the impact of different forcings for the 2x2 (flux=0), 2x2 flux=1, and 1x1 (flux=1).

2.5 Impact on historical perturbation simulations

Here we present the atmosphere-only historical simulations. Table 3 gives an overview of the various simulations. Four of those were suggested by RFMIP (piClim-histall, piClim-histghg, piClim-histnat, and piClim-histaer), but we have done 4 extra (piClim-histO3, piClim-histlu, piClim-histoxid, and piClim-histaeroxid).

Figure 12 shows a comparison of the global- and annual near-surface (2 m) temperature evolution in historical atmosphere-only simulations between flux=0 and flux=1. As a reference, we have also shown the piClim-control simulations for flux=0 and flux=1, which have been extended to 165 yr (instead of their requested 30 yr)

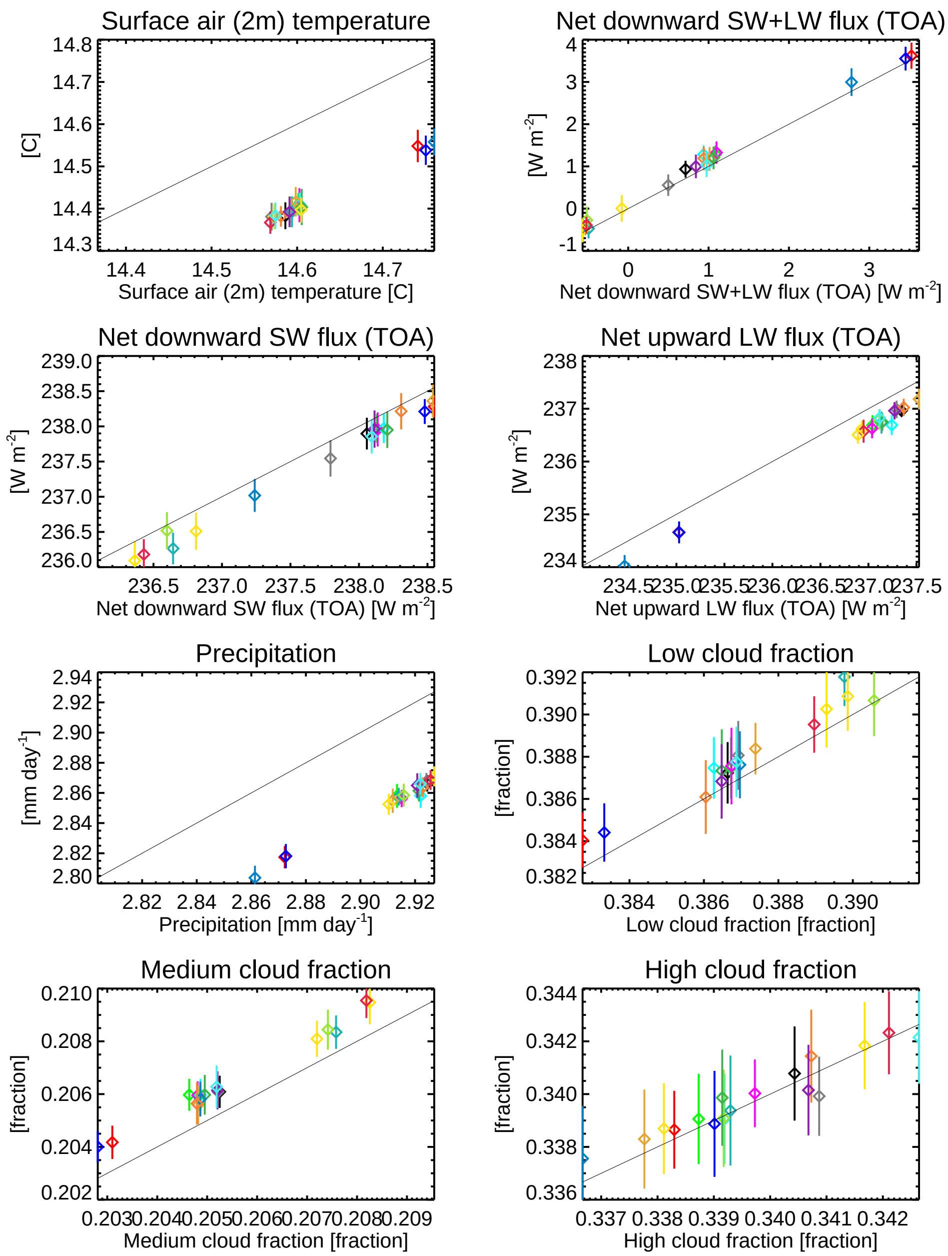

Figure 6: Comparison of fixed-SST simulations with flux=0 (x-axis) and flux=1 (y-axis). Uncertainty ranges in the x-direction are not shown but are very similar to uncertainty ranges in the y-drection.

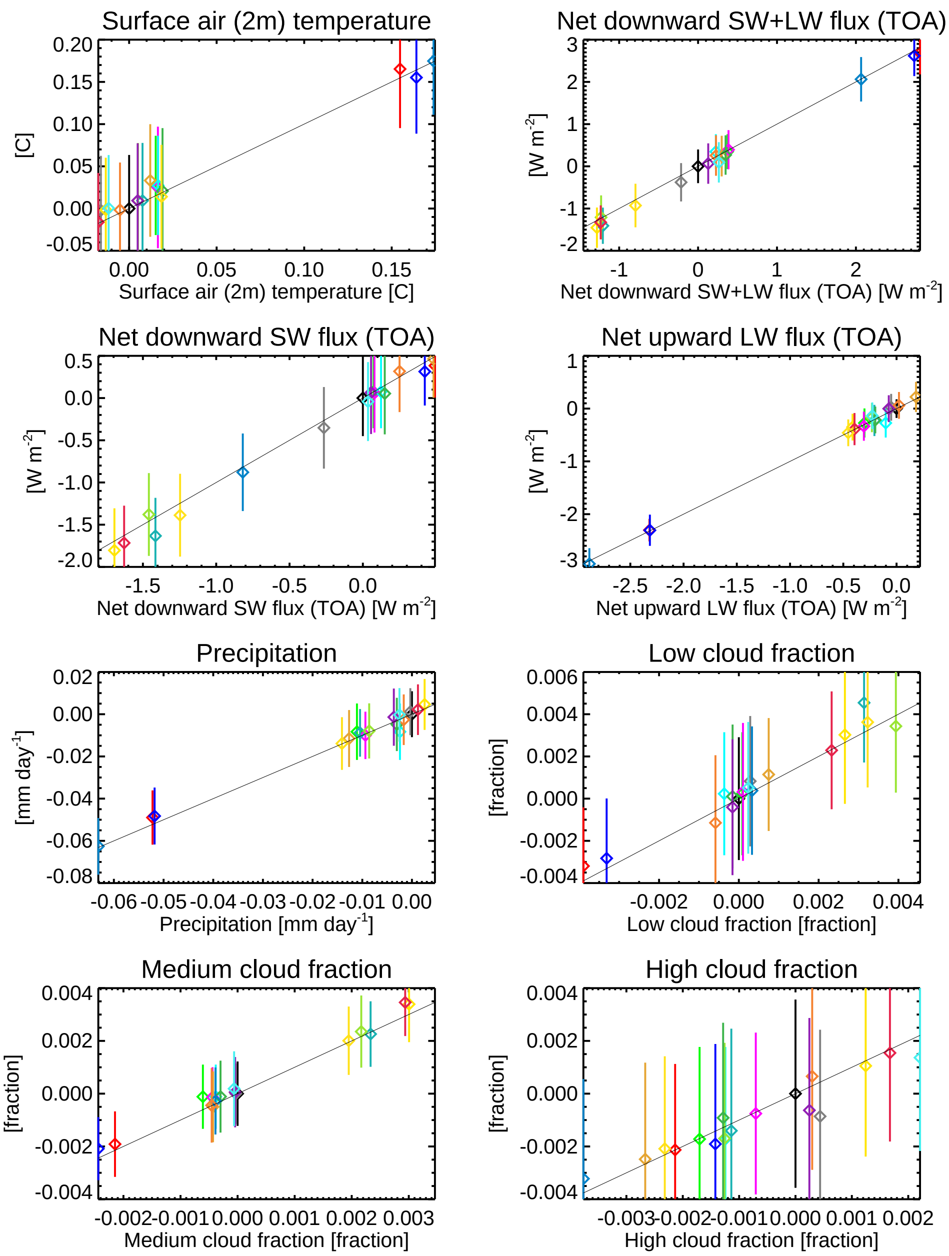

Figure 7: Comparison of fixed-SST simulations with flux=0 (x-axis) and simulations with flux=1 (y-axis). Uncertainty ranges in the x-direction are not shown but are very similar to uncertainty ranges in the y-drection.

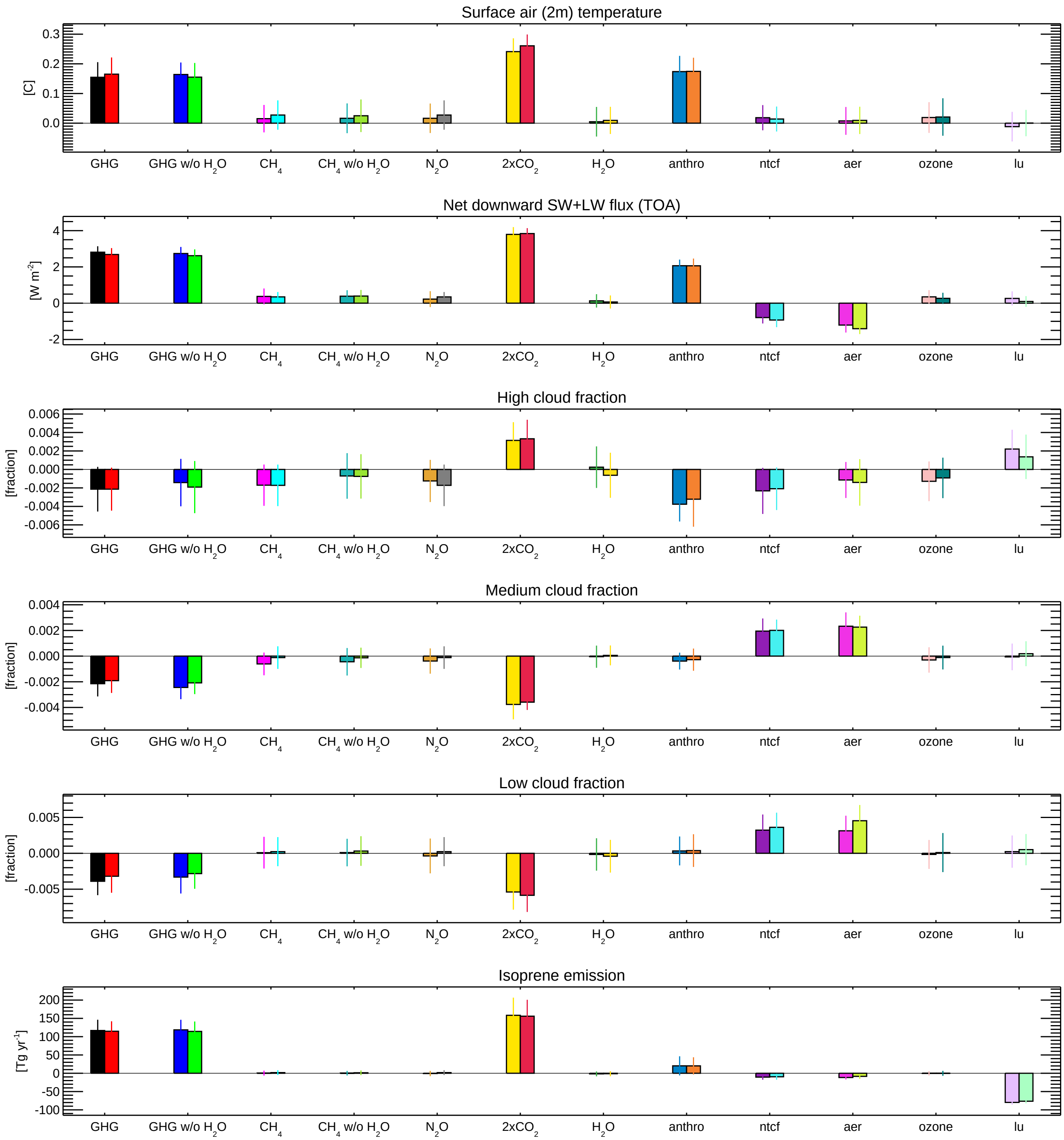

Figure 8: Impact of various forcing experiments in flux=0 (left bar) and flux=1 (right bar). Experiments have been run for 30 years, and uncertainty bar indicates error on the mean.

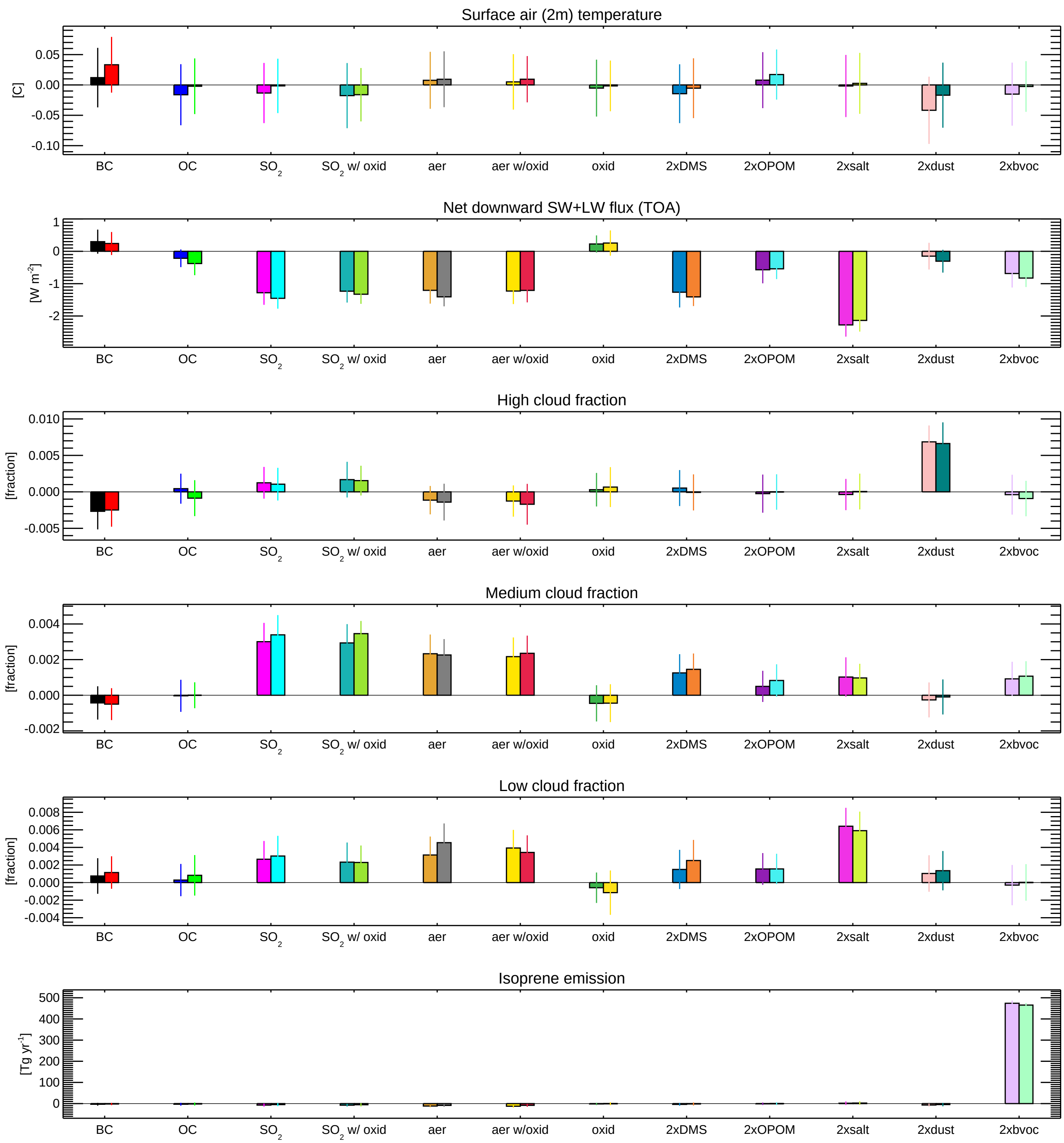

Figure 9: Impact of various forcing experiments (mainly aerosol related) with flux=0 (left) and flux=1. Experiments have been run for 30 years, and uncertainty bar indicates error on the mean.

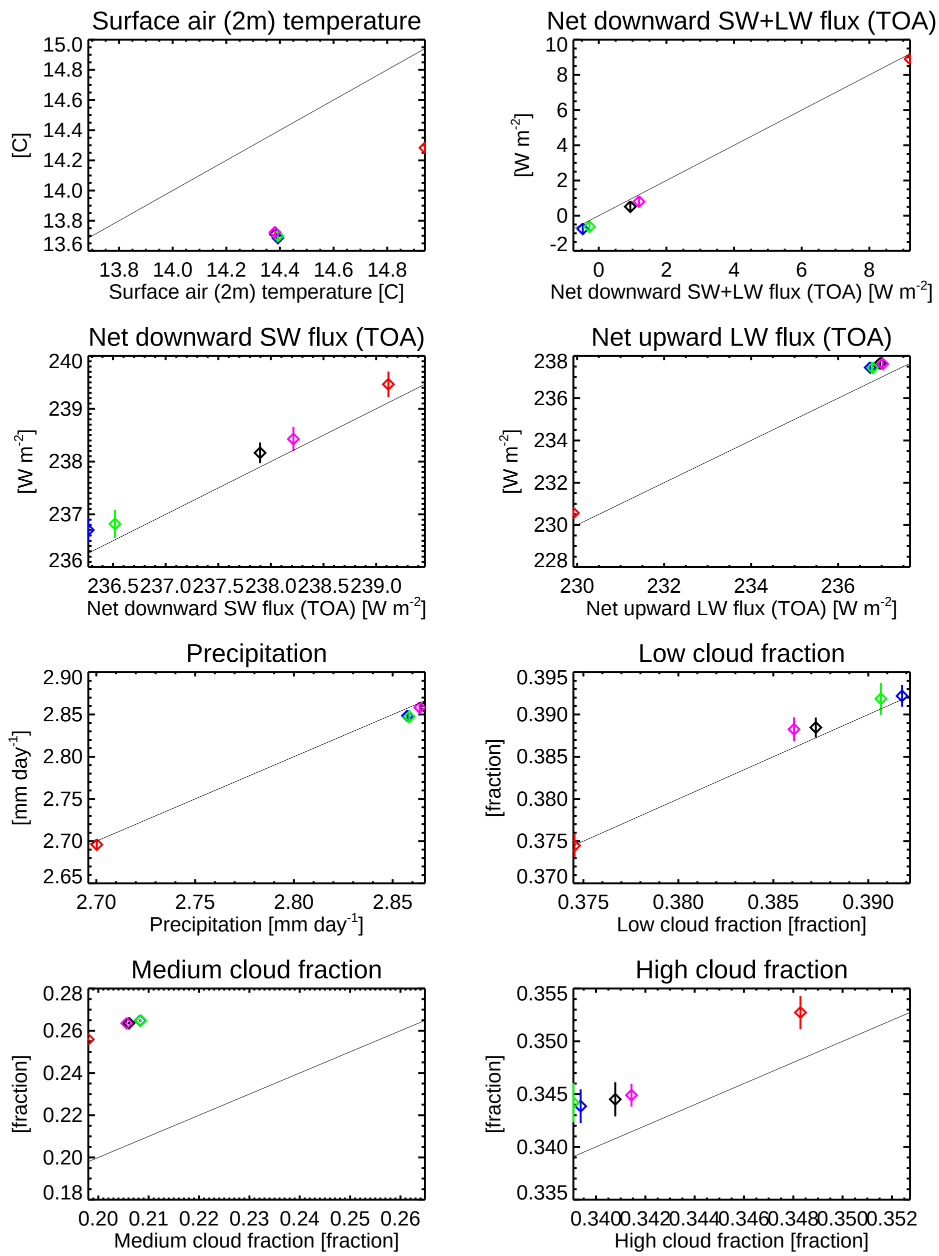

Figure 10: Comparison of fixed-SST simulations with flux=0 (x-axis) and simulations with flux=1 (y-axis). The uncertainty range in the x-direction is not shown but is very similar to the uncertainty range in the y-drection.

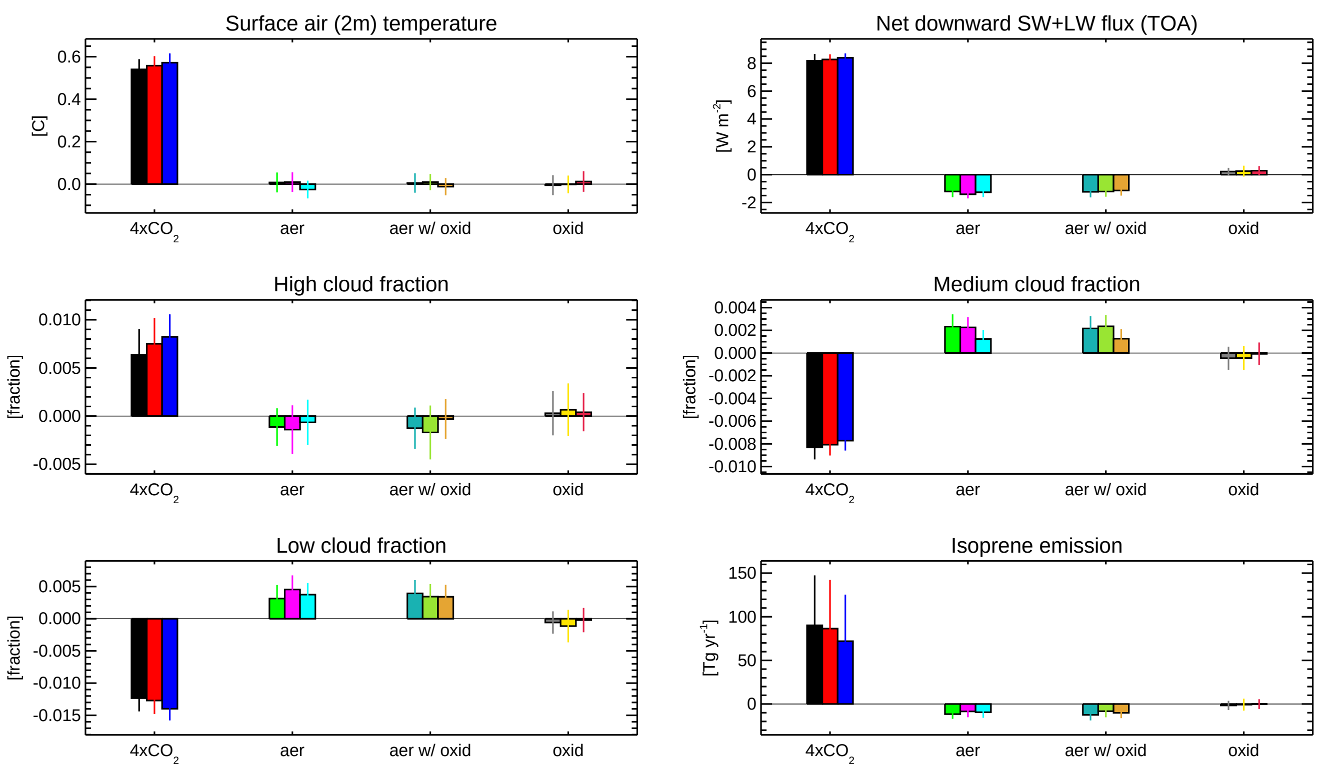

Figure 11: Impact in 30-year fixed-SST simulation from $4xCO_2$, aerosols, aerosols with oxidants, and oxidants only for 2x2 flux=0 (left bar), 2x2 flux=1 (middle bar), and 1x1 flux=1 (right bar).

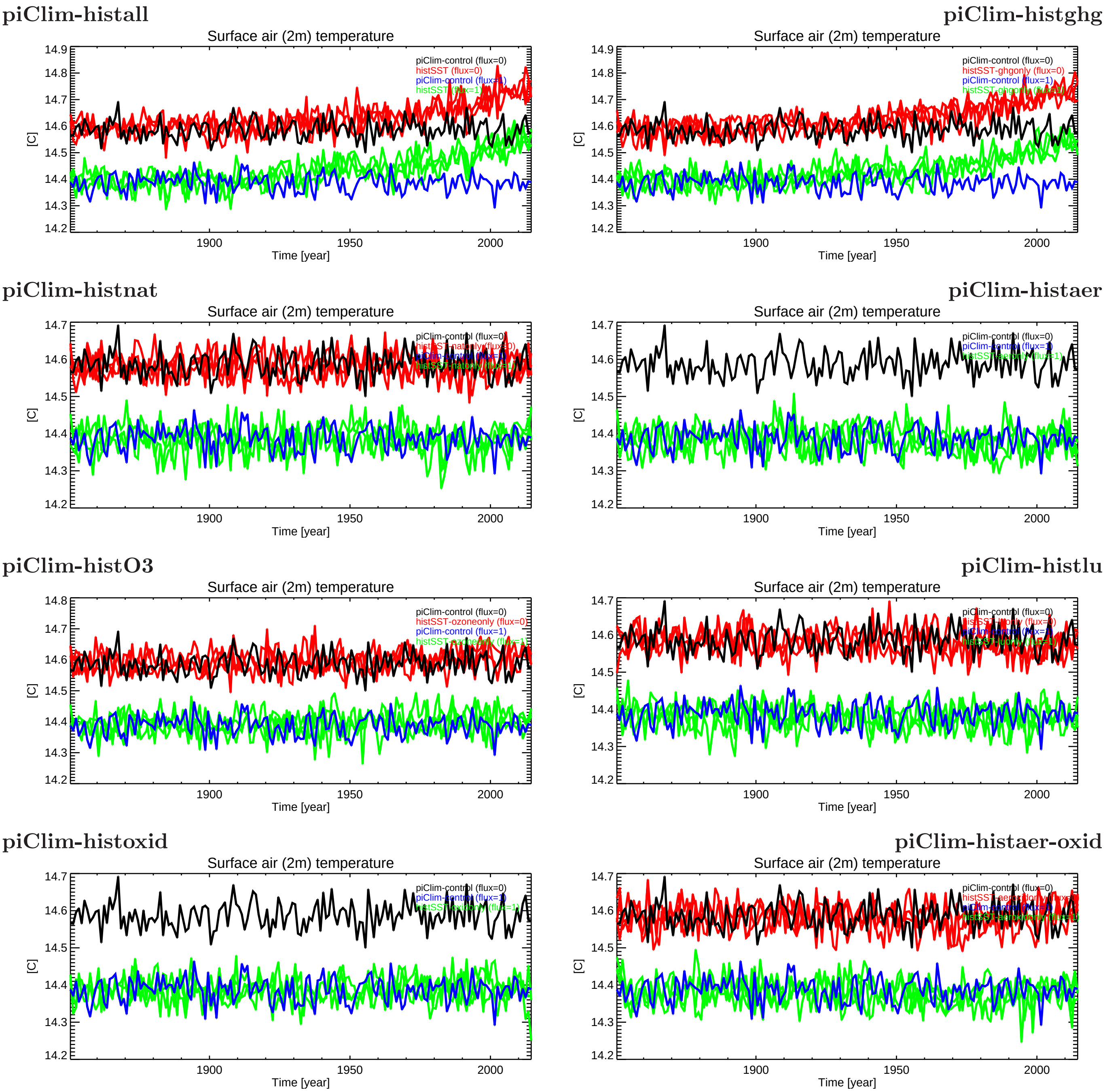

Figure 12: Annual- and global-mean timeseries of near-surface (2 m) air temperature : piClim-control (flux=0, black), histSST-perturbation (flux=0, red), piClim-control (flux=1, blue), and histSST-*perturbation* (flux=1, green). The various perturbations are (from upper-left to lower-right panel) : all forcings, GHGs, natural forcings (i.e., solar + volcanic forcings), anthropogenic aerosols, ozone, land-use, oxidants, and anthropogenic aerosols+oxidants together. For some simulations three members are available.

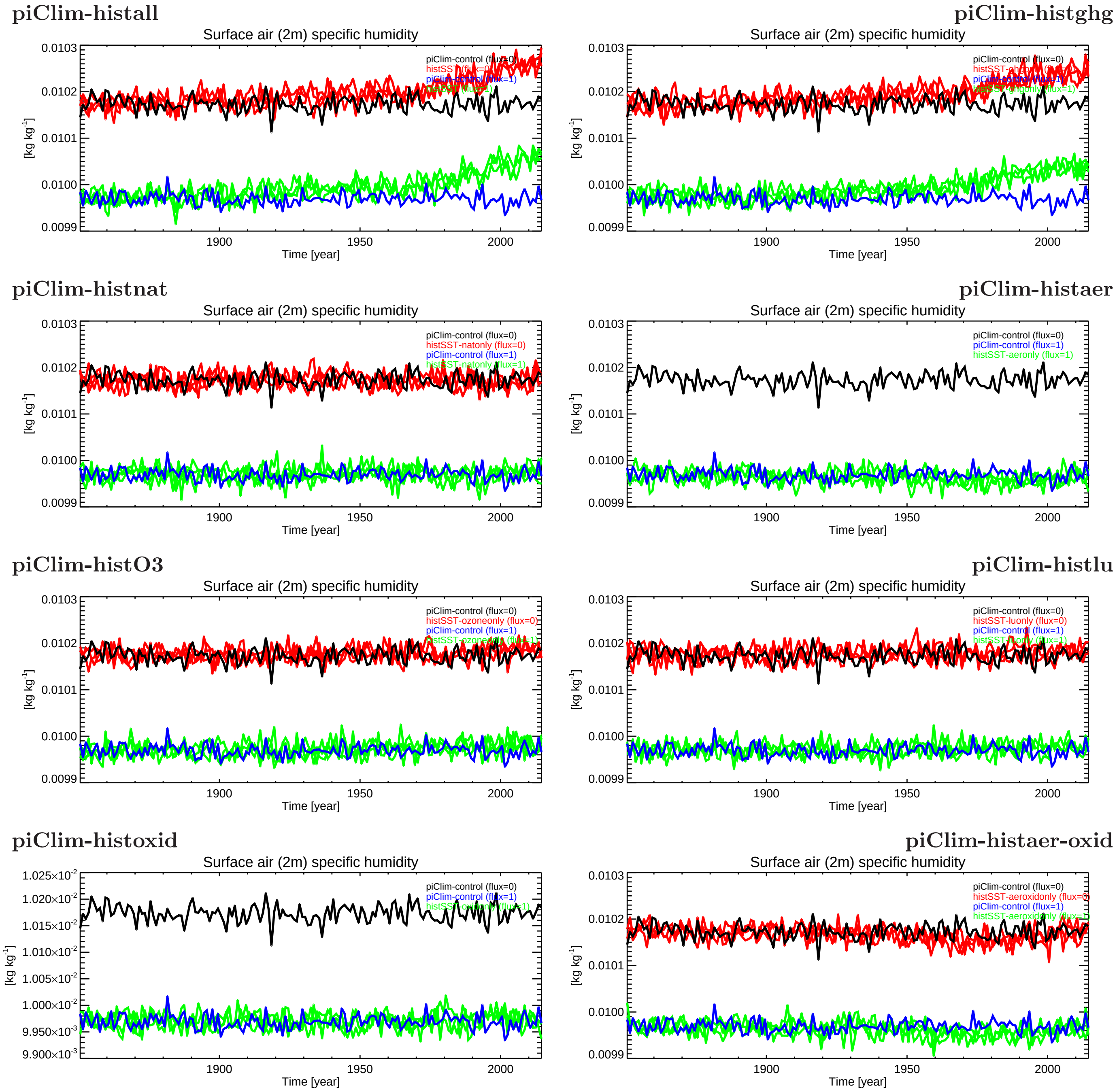

Figure 13: As Fig. 12, but annual- and global-mean timeseries of near-surface (2 m) specific humidity.

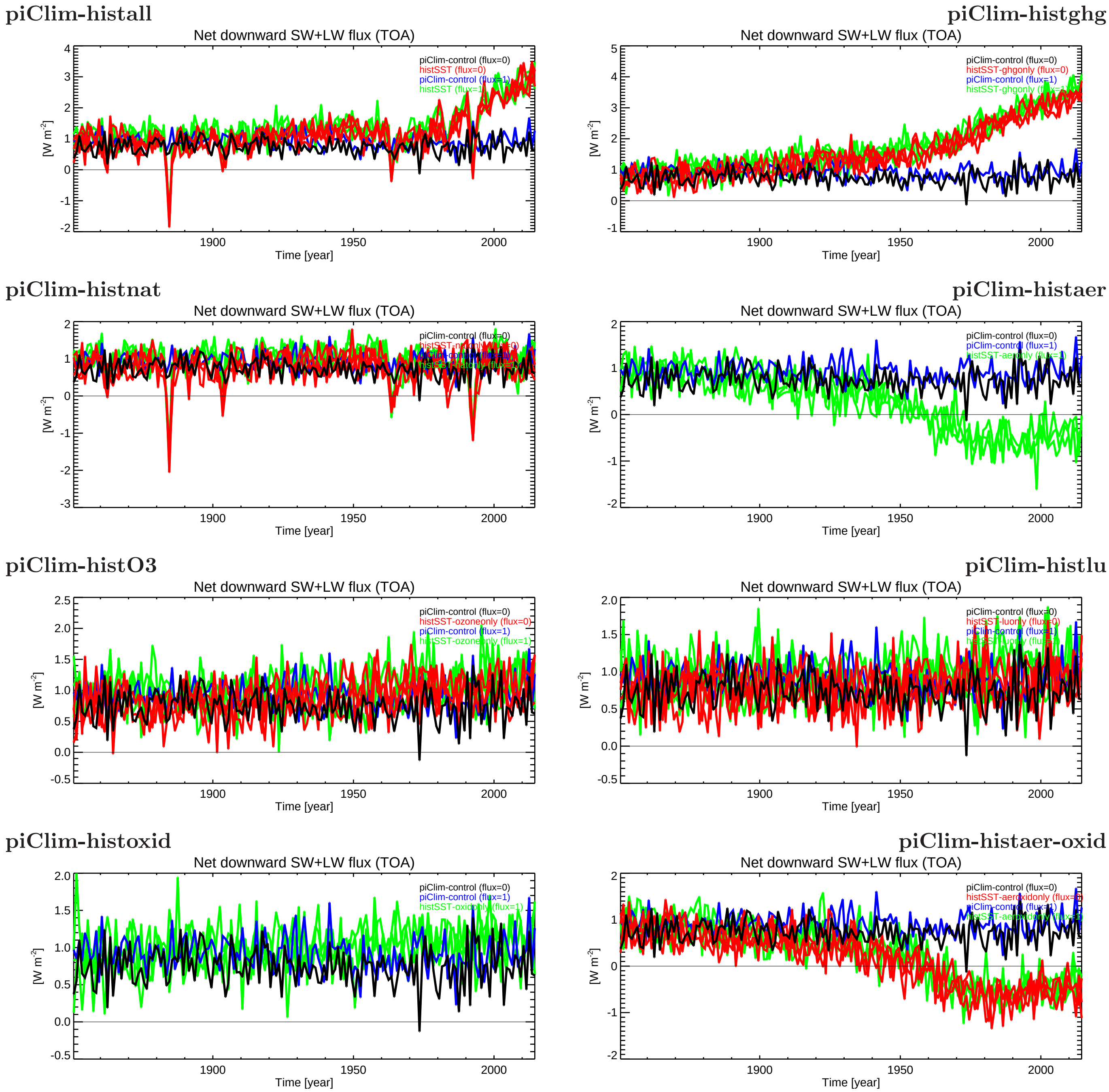

Figure 14: As Fig. 12, annual- and global-mean timeseries of TOA imbalance.

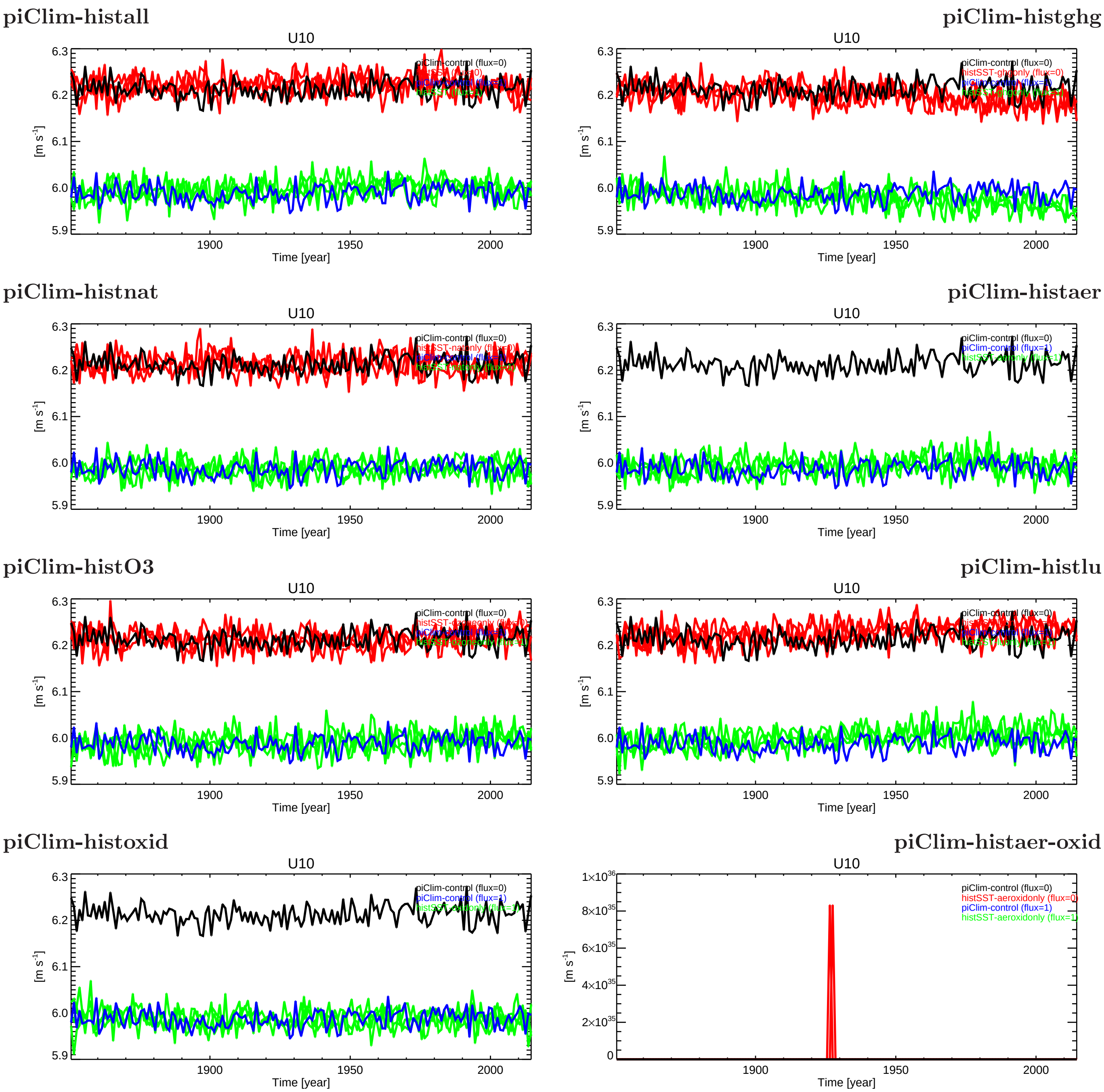

Figure 15: As Fig. 12, but annual- and global-mean timeseries of near-surface (10 m) wind.