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A projected decrease in lightning under climate change

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Lightning strongly influences atmospheric chemistry[1–3], and impacts the frequency of natural wildfires[4]. Most previous studies project an increase in global lightning with climate change over the coming century[1,5–7], but these typically use parametrisations of lightning that neglect cloud ice fluxes, a component generally considered to be fundamental to thunderstorm charging[8]. As such, the response of lightning to climate change is uncertain. Here, we compare lightning projections for 2100 using two parametrisations: the widely-used cloud-top height (CTH) approach[9], and a new upward cloud ice flux (IFLUX) approach[10] that overcomes previous limitations. In contrast to the previously reported global increase in lightning based on CTH, we find a 15% decrease in total lightning flash rate with IFLUX in 2100 under a strong global warming scenario. Differences are largest in the tropics, where most lightning occurs, with implications for the estimation of future changes in tropospheric ozone and methane, as well as differences in their radiative forcings. These results suggest that lightning schemes more closely related to cloud-ice and microphysical processes are needed to robustly estimate future changes in lightning and atmospheric composition.

Changes in climate over the next century are expected to alter atmospheric temperature, humidity, stability and dynamics[11]. The leading theory for electrical charge generation in thunderstorms[8,12] suggests that the occurrence of lightning depends on all these factors, through their effect on convection and colliding ice and graupel particles. Lightning is an important source of nitric oxide (NO), a precursor of ozone and the hydroxyl radical (OH) which governs the lifetime of greenhouse gases such as methane[1]. Both ozone and methane are important greenhouse gases, and changes in their concentrations can lead to a warming or cooling of the atmosphere. Thus, lightning needs to be represented in chemistry-climate models to fully simulate the interactions and feedbacks between atmospheric composition and climate change. Future changes in lightning are also of importance for aerosol chemistry[2,3], wild-fire ignition[4], and damage to infrastructure and to human health.

Recent studies[4,6,7,13,14] simulating future lightning over the next century with the CTH approach have reported 5-16% increases in lightning flashes per degree increase in global mean surface temperature. Observational studies have shown lightning to be positively correlated with surface temperature on daily to decadal time scales, but such relationships become highly uncertain on longer time scales[15,16]. An alternative[6] to the CTH scheme, using cold cloud depth to parametrise lightning, suggested a smaller increase in lightning under climate change of ~4% K^{-1}. Furthermore, a decrease in future lightning has been found using a convective mass flux-based lightning scheme[17] in two recent studies[6,18]. However, this scheme has been found to perform poorly against observations[6,10,19].

Only one study to date has used a lightning scheme dependent on cloud ice particles to project future lightning. This study found a decrease in lightning associated with an increase in temperature[20]. However, the study had a near-term focus on 2030 and the global surface temperature increase was less than 0.2K. It is not clear whether a similar response occurs for larger changes in temperature at the end of the century[20].

In this study we use both the established CTH scheme[9] and the recently developed and evaluated IFLUX scheme[10] (see Methods) in a chemistry-climate model to simulate future lightning and its influence on atmospheric composition and radiative forcing. Atmospheric dynamics are decoupled from changes in atmospheric composition so that both lightning schemes use the same underlying meteorology. With the same model as used here, the IFLUX scheme has shown a more realistic representation of present-day global lightning and tropospheric ozone than the CTH approach, especially in the tropics[10,21]. For instance, the spatial correlation of the global, annual lightning distribution compared to observations was r=0.78 using the IFLUX scheme and r=0.65 using the CTH scheme. The temporal correlation of the annual cycle of southern/northern tropical upper tropospheric ozone against observations was r=0.93/0.65 with the IFLUX scheme and r=0.79/0.26 with the CTH scheme[21]. Whilst accurately representing present-day lightning does not guarantee that long-term trends can be captured, it does increase our confidence in the lightning scheme. In the IFLUX scheme, the upward ice flux is sampled at a specified pressure level. Shifts in the tropopause and vertical temperature profile (Supplementary Figure 1) suggest a shift in the vertical extent of deep convection and ice particle formation, and therefore a higher sampling level is found to be more appropriate under future climate change (see Methods).

Lightning NO_x emissions (LNO_x) from existing lightning parametrisations scale linearly with changes in global mean surface temperature across chemistry-climate models[18]. Therefore, we use the year 2100 under Representative Concentration Pathway 8.5 (RCP8.5)[22] to obtain a clear lightning response to substantial climate change. We provide the first estimate of the future lightning response to long-term global warming in 2100 using a cloud ice-based lightning parametrisation, and compare with results from the widely-used CTH scheme.

We simulate a decrease in global total lightning of 2.2 (1.9-2.5) $\times 10^8$ fl. yr^{-1} by 2100 with the IFLUX scheme (Table 2 Global lightning and atmospheric composition properties, simulated for present-day and future with different lightning schemes and with no lightning. Percentage changes are relative to year 2000 for each approach.

Figure 1), where the range is the 95% confidence interval based on the simulated interannual variability. A sensitivity test diagnosing the ice flux at the same level as under present-day climate shows a decrease of 5.8 (5.6-6.1) $\times 10^8$ fl. yr^{-1} (Supplementary Figure 2b), suggesting that the choice of level does not influence our conclusions. With the CTH scheme, we simulate an increase in the global flash rate of 6.1 (5.9-6.2) $\times 10^8$ fl. yr^{-1} in year 2100.

Regionally, the IFLUX and CTH approaches result in increases in *total* lightning over the USA of 3.4 and 14.2 $\%K^{-1}$, respectively. Assuming total and cloud-to-ground lightning respond similarly to climate change, our results are consistent with a recent study that used convective available potential energy and precipitation to parametrise lightning[23]. In that study it was estimated that *cloud-to-ground* lightning over the USA would increase by 12 $\%K^{-1}$ under RCP8.5[23] (with a range of 3-18$\%K^{-1}$ across models). However, this increase does not apply to all mid-latitude locations. For instance, we find no significant change over most of Europe with either lightning scheme.

Whilst several studies have considered how climate variability, such as El Niño driven events, affects tropical lightning[15,24], the impact of climate change on tropical lightning has not received much attention. This is despite ~80% of global lightning flashes occurring in the tropics and subtropics[25]. With the IFLUX approach, a decrease in tropical lightning is simulated, in contrast to an increase with the CTH approach. The tropical cloud top height, used to diagnose lightning in the CTH scheme increases by 900m (7%) in the future. This has a large impact on lightning due to the fifth-order dependence on cloud top height in the scheme. Furthermore, basing the change in lightning solely on cloud-top height disregards key changes in updraughts and ice content of the cloud, displayed in Figure 2, that govern lightning generation.

The cloud ice content and convective updraught mass flux decrease over tropical land in the mid-troposphere in the future (Fig. 2), where the thunderstorm charging zone is located. A shift in the distributions to higher altitudes is apparent, justifying the use of a higher sampling level in the future climate. Reductions in the convective and total cloud fraction throughout most of the troposphere in future are consistent with a ~20% reduction in the probability of lightning with the IFLUX scheme (Supplementary Table 1). A 28% reduction in the magnitude of total tropical flashes with the IFLUX approach (Supplementary Table 1) results from a combination of the change in probability of lightning flashes and decreases in cloud ice content and updraught mass flux.

The responses of the convective and cloud ice variables in the model to climate change are physically reasonable. For instance, the increase in cloud top height largely reflects the increase in tropopause height, a robust feature of global warming[26]. A reduction in cloud ice content, even when sampling at a higher altitude in the future climate (Fig. 2a), is consistent with an increase in tropospheric temperatures. The Intergovernmental Panel on Climate Change (IPCC)[11] reports a projected future decrease in mean updraught mass flux associated with weakened tropical ascent in the climate models, and a decrease in cloud fraction over tropical land except around the tropopause.

Despite the consistency between our results and IPCC models, the meteorological drivers of the IFLUX scheme, and their response to climate change, remain highly uncertain. For instance, many models underestimate tropical cloud ice content[27]. The formation of cloud ice depends on ice nuclei and secondary formation processes which are not well-represented in global models, and model resolution is generally insufficient to explicitly simulate storm-scale updraughts, highlighting the challenges in parametrising lightning at the global scale. Nevertheless, it is evident from our results that these key drivers of the lightning response to climate change are not captured by the CTH approach.

Most studies report future increases in LNO_x, as they employ the CTH scheme. One previous study found these future increases in LNO_x more than offset the reduction in tropospheric ozone arising from lower anthropogenic emissions of NO_x and other ozone precursors[7]. In our study, other ozone precursor emissions are kept constant so that changes in ozone burden due to changes in climate and LNO_x can be quantified. In our model, each lightning flash produces 250 mol of NO. Given a present-day lightning emission of ~5 TgN yr^{-1}, the responses to climate change using the IFLUX and CTH schemes are -0.15 TgN K^{-1} and +0.44 TgN K^{-1}, respectively. The CTH response closely matches results from a recent multi-model intercomparison of 10 models using the CTH scheme[18].

Global lightning and atmospheric composition responses for model simulations are given in Table 1. In the absence of lightning (ZERO simulations) there is a decrease in the tropospheric ozone burden and methane lifetime under climate change. This occurs primarily because increased water vapour in the warmer climate leads to greater loss of ozone[28], mainly via the increase in OH radicals through reaction of water with O(^{1}D). The OH also acts as a sink for methane, reducing the methane lifetime.

Table 1 Global lightning and atmospheric composition properties, simulated for present-day and future with different lightning schemes and with no lightning. Percentage changes are relative to year 2000 for each approach.

Simulation	Global lightning ($\times 10^9$ fl. yr^{-1})	Tropospheric ozone burden (DU)	Tropospheric ozone lifetime (days)	Methane lifetime (yrs)
ZERO-2000	0.00	209	18.7	12.5
ZERO-2100	0.00 (0%)	191 (-9%)	15.5 (-17%)	9.9 (-21%)
CTH-2000	1.41	271	20.1	9.9
CTH-2100	2.02 (+43%)	266 (-2%)	16.9 (-16%)	7.5 (-24%)
IFLUX-2000	1.42	266	19.8	9.9
IFLUX-2100	1.20 (-15%)	237 (-11%)	16.3 (-18%)	8.1 (-18%)

In addition to the direct effects of climate change, increases in LNO$_x$ increase ozone and OH production. Therefore, using the CTH scheme, the tropospheric ozone burden decreases (-2%) much less than in the simulations without lightning (-9%), almost offsetting the direct effects of climate change, whilst methane lifetime decreases are proportionally larger (-24%). In contrast using the IFLUX scheme, where LNO$_x$ decreases in future, tropospheric ozone burden decreases are larger (-11%) than in the ZERO simulations but methane lifetime decreases are smaller (-18%). Importantly, many of these changes occur in the tropical upper troposphere (Supplementary Figure 3), where the ozone radiative forcing efficiency is highest.

The link between lightning NO$_x$ and radiative forcing from ozone has been the focus of several studies[29–31]. A positive feedback has been proposed through increased lightning, ozone and radiative forcing (RF) producing further warming, and therefore more lightning.

However, the long-term net cooling effect[32] from reduced methane driven by the increase in LNO_x is often neglected.

We provide the first estimate of the radiative forcing of LNO_x under future climate considering both ozone and methane (Fig. 3). The radiative forcing by year 2100 without lightning, where changes in atmospheric composition are due to direct effects of climate change alone, is negative for both ozone and methane, as expected from the composition changes (Table 1).

Importantly, the two lightning schemes have opposite effects on radiative forcing from ozone and methane, arising from the different effects on composition. The difference in ozone radiative forcing between the two schemes is 83 mW m^{-2} (Fig. 3, Supplementary Table S3), which is approximately a third of the total ozone radiative forcing between 2000 and 2100 under RCP8.5[33]. This total forcing is an average of multi-model projections that use the CTH scheme. Therefore, the new IFLUX scheme suggests future total ozone radiative forcing may be substantially lower than previously estimated. For methane, there is a difference of 54 mW m^{-2} between the two schemes which accounts for ±5% in the total methane radiative forcing between 2000 and 2100 under RCP8.5. We find a net positive radiative forcing with the CTH approach, permitting a positive lightning-climate feedback as previously suggested. However, there is little net radiative forcing with the IFLUX approach, and therefore the results with this scheme do not support the positive feedback argument.

In conclusion, we find very different impacts on atmospheric composition and radiative forcing when simulating future lightning using a cloud-ice relationship and the commonly-used cloud-top height relationship. The latter approach is less closely related to the underlying ice-graupel collisions of cloud electrification, and may underrepresent this critical component in climate change projections. Therefore, quantification of future atmospheric composition and radiative forcing of methane and ozone should account for the uncertainty in the response of lightning NO_x presented here.

Given the disagreement between schemes in future tropical lightning, field campaigns and long-term measurement studies focusing on tropical lightning are needed. Further research is also needed to evaluate simulations of cloud ice and quantify its response to climate change, and to test how global ice-based lightning schemes such as IFLUX perform against fully explicit fine-scale models of cloud microphysics and electrification. Alongside such work, implementation of the ice flux parametrisation in other chemistry-climate models would further enhance our knowledge of the response of lightning to climate change.

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Author contributions

DLF, RMD and OW designed the study and interpreted the results with input from other co-authors. OW and DS advised on the radiative forcing analysis. DLF performed the analysis, developed the code and ran the simulations. DLF prepared the manuscript with contributions from RMD and OW; all co-authors reviewed the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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List of Tables/Figures

Table 2 Global lightning and atmospheric composition properties, simulated for present-day and future with different lightning schemes and with no lightning. Percentage changes are relative to year 2000 for each approach.

Figure 1 Changes in lightning flash rate between the 2000s and 2100s using lightning schemes based on cloud ice flux (top) and cloud-top height (bottom). Hatching shows areas with no significant change at the 5% level, determined using the simulated interannual variability.

Figure 2 Mean vertical distributions of meteorological variables in the 2000s (solid) and 2100s (dotted), over tropical land. Dashed lines show the 440 (black) and 390 (grey) hPa sampling levels used in the present-day and future IFLUX simulations, respectively (see Methods).

Figure 3 Estimated ozone, methane and the net radiative forcing between 2000 and 2100 resulting from climate change and LNOx emissions. Triangular points are estimates using high (upward triangle) and low (downward triangle) methane feedback (see Methods).

Methods

Model. The model used in this study is the UK Chemistry and Aerosols model (UKCA) coupled to the atmosphere-only version of the UK Met Office Unified Model (UM) version 8: UM-UKCA. The atmosphere component is the Global Atmosphere 4.0 (GA4.0)[34]. Both tropospheric and stratospheric chemistry processes are represented. The tropospheric scheme, most relevant to this study, is described and evaluated in another study[35]. There are 75 species with 285 reactions that include the oxidation of methane, ethane, propane, and isoprene. The model is run at horizontal resolution N96 (1.875º longitude by 1.25º latitude). Vertically there are 85 terrain-following hybrid-height levels between the surface and 85 km. The cloud parametrisation of GA4[34] uses the Met Office Unified Model's prognostic cloud fraction and prognostic condensate (PC2) scheme[36,37] along with modifications to the cloud erosion parametrisation[38]. PC2 uses prognostic variables for water vapour, liquid and ice mixing ratios as well as for liquid, ice and total cloud fraction. The cloud ice variable includes snow, pristine ice and riming particles. The model used is identical to that used in an evaluation of the lightning scheme for present-day[21], where further details can be found. However, cloud ice observations by satellite remains highly uncertain from satellite observations and is poorly represented in models[27,39,40]. The global representation of cloud ice, liquid and water have been evaluated in some configurations of the Met Office Unified Model at four pressure levels, including two levels in the mid to upper troposphere (215 and 600 hPa)[27]. At these levels the Unified Model configurations rank in the top 3 out of 19 models. We therefore have confidence that the simulated distribution of cloud ice is a useful one.

Simulation setup. Seven simulations were performed with different lightning schemes and representing either the year 2000 or the year 2100 under Representative Concentration Pathway 8.5 (RCP8.5). Following one year of spin-up from present-day initial conditions, each simulation is performed for a further 10 years using the same driving conditions for each year. The interannual variability of the simulation is used to provide 95% confidence intervals on the decadal-average changes (see main text). In addition, when calculating the significance level for Figure 1 and Supplementary Figure 2, an adjustment has been made to the sample size to account for temporal auto-correlation of lag 1 year, though the effect of this is small. In all simulations, the chemistry scheme uses the same anthropogenic and biomass burning emissions and Greenhouse Gas (GHG) concentrations representative of the year 2000[41]. Well-mixed GHG concentrations in the future scenario are altered in the model radiative scheme in order to represent changes in the radiative properties of the atmosphere, and hence climate under RCP8.5. Fixed present-day climatologies of ozone and aerosol are used in the radiative scheme. Methane mixing ratios in the chemistry model are fixed at present-day levels in all simulations using a prescribed lower boundary condition. A methane radiative forcing is calculated for the simulations, and this is described in the *Radiative Forcing Calculation* section of the methods. Sea surface temperatures (SSTs) and sea ice concentrations for present-day simulations are taken from decadal average climatologies based on 1995-2004 analyses[42]. For SSTs and sea ice in the future scenario, decadal average anomalies from the Coupled Model Intercomparison Project Phase 5 (CMIP5) HadGEM2-ES simulations for 1995-2005 and 2095-2105 were applied to the present-day SST and sea ice analysis fields. In the model, the chemistry scheme does not feed back to the radiative scheme so that all model simulations within the same time period experience the same meteorology, and consequently the same changes in surface temperature between the two time periods.

The IFLUX parametrisation. The cloud ice flux based lightning scheme was developed using meteorological variables in reanalysis data and satellite observations of lightning[10]. The scheme uses cloud ice flux which is related to the collision of cloud ice particles, since this is the principle component of the leading theory for thunderstorm charging, the Non-inductive Charging mechanism[8]. The lightning flash rate (fl. m_{cell}^{-2} s^{-1}) is calculated with:

$$f = A\phi,$$

where ϕ is the upward cloud ice flux at a sampling pressure level, and A is a constant (6.58×10^{-7} fl. kg_{ice}^{-1} m_{cloud}^{2} m_{cell}^{-2} over land, and 9.08×10^{-8} fl. kg_{ice}^{-1} m_{cloud}^{2} m_{cell}^{-2} over ocean). The upward cloud ice flux in the model is calculated as:

$$\phi = \frac{q\Phi}{c},$$

where q is the specific cloud ice water content (kg_{ice} kg_{air}^{-1}), Φ is the updraught mass flux (kg_{air} m_{cell}^{-2} s^{-1}), and c is the fractional total cloud cover (m_{cloud}^{2} m_{cell}^{-2}). All variables are grid cell mean values and are interpolated to the sampling pressure level. The grid cell mean updraught mass flux is the product of the convective updraught mass flux and the convective cloud fraction, and both of these variables are shown in Figure 2. For present-day simulations a sampling level of 440 hPa is used. This pressure level is based on the definition of deep convective clouds by the International Satellite Cloud Climatology Project[43]. It is noted that more detailed lightning schemes are possible in mesoscale and cloud-resolving models that resolve microphysical processes in deep convection[44–48].

Details of the future IFLUX sampling level calculation. For the future climate simulations, the sampling level, p_{sample}, is adjusted for changes in the atmospheric temperature profile. This adjustment is made relative to two reference levels and the sampling level is calibrated to the relative position of the 440 hPa level between these under present-day conditions. The lower reference level is global mean pressure of the 0ºC isotherm, $\overline{p}_{0C}$, chosen because it marks an approximate level at which ice can begin to form (a vital process for cloud electrification). The upper reference level is the global mean tropopause pressure, $\overline{p}_{trop}$ (determined using a combined isentropic-dynamical approach[49]), which was chosen because vertical development of clouds becomes greatly inhibited above this height. The equations used for the calculation, with *t=2100* for the future time period, are:

$$p_{sample}(t) = \overline{p}_{0C}(t) - K_{2000}(\overline{p}_{0C}(t) - \overline{p}_{trop}(t))$$

where

$$K_{2000} = \frac{\overline{p}_{0C}(t = 2000) - 440hPa}{\overline{p}_{0C}(t = 2000) - \overline{p}_{trop}(t = 2000)} \approx \frac{1}{3}$$

Using this approach, a sampling level of 390 hPa is calculated for the future simulation. An alternative upper limit of the -40ºC isotherm, based on the approximate top of the mixed phase cloud region, also suggests a future sampling level of 390 hPa. All the sampling levels discussed above are presented in Supplementary Figure 1. Simulations using the 440 hPa sampling level in the future have been performed in order to test sensitivity to the sampling level, and the results of these simulations are presented in the Supplementary figures and tables. In addition, supplementary text discusses how the sampling pressure could be refined within transient simulations.

Lightning NO_x scheme. The lightning parametrisations provide the lightning flash rate. Each flash corresponds to a NO emission of ~250 mol(NO)[1,21]. There is a total global present-day emission of ~5 TgN using both lightning schemes[1,21]. The LNO_x is distributed vertically based upon prescribed vertical profiles[50] between the surface and the cloud top. Both lightning schemes are normalised to give a global annual average of 46 flashes s^{-1} (or 1.45 x

10^9 fl. yr^{-1})[51] in a one-year present-day simulation, using factors of 1.57 for the CTH scheme and 1.11 for the IFLUX scheme. The same factors are used in the future climate change simulations but the global annual flash rate changes in response to the changing meteorology.

Radiative forcing calculation. With a fixed lower boundary condition for methane, the methane mixing ratio is heavily constrained and there is little adjustment to the oxidation rate as the OH concentration is modified by changes in climate and LNO_x. The equilibrium methane mixing ratio can be calculated using the change in methane lifetime and a feedback factor which is typically around 1.30 in models[33] with a range in the literature of 1.19 to 1.53[7,33,52,53]. This equilibrium methane mixing ratio is then used to determine the methane radiative forcing (RF)[54]. For ozone, the short-term radiative forcing is calculated using the differences in the annual mean spatial distribution of the tropospheric ozone column between each simulation and CTH in year 2000. These differences are multiplied by the horizontal spatial distribution of the radiative forcing efficiency of ozone (mW m^{-2} DU^{-1}), using a multi-model average spatial distribution from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) study[33]. The area-weighted mean over the distribution provides the global short-term ozone radiative forcing. As ozone is also influenced by changes in methane, there is an additional long-term ozone radiative forcing resulting from the equilibrium methane change. The tropospheric ozone response to a 20% reduction in methane from present-day levels across a range of models contributing to the Task Force on Hemispheric Transport of Air Pollution studies is 0.95±0.25 DU. This range is used to estimate the long-term ozone change associated with the inferred methane change, accounting for the non-linear response of ozone to methane changes[55]. The long-term ozone RF is calculated from this change, and the combined long and short term ozone radiative forcings provide the total ozone radiative forcing. The ozone and methane radiative forcings presented therefore correspond to radiative forcings after atmospheric composition has fully equilibrated with the perturbed LNO_x. Parameter uncertainty in the RF estimate is represented using three sets of parameters that represent a typical, low and high sensitivity to methane change, and are shown as bars, downward triangles and upward triangles in Figure 3. To isolate the effects of LNO_x, we subtracted the radiative forcing in the absence of lightning (ZERO simulations) from that with each lightning scheme. The results of this are shown in Figure 3, while the original radiative forcing values for each set of simulations is given in Supplementary table 3.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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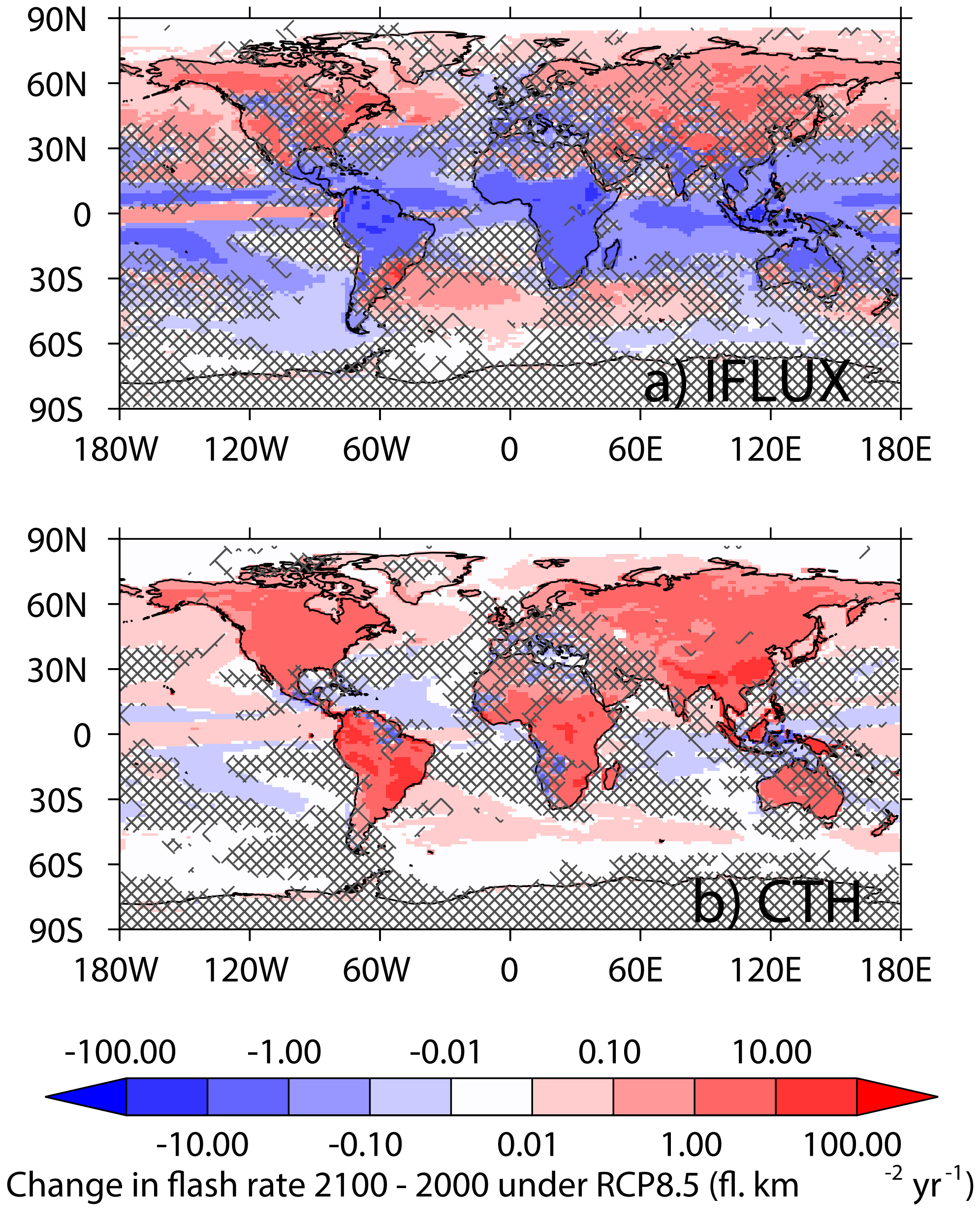
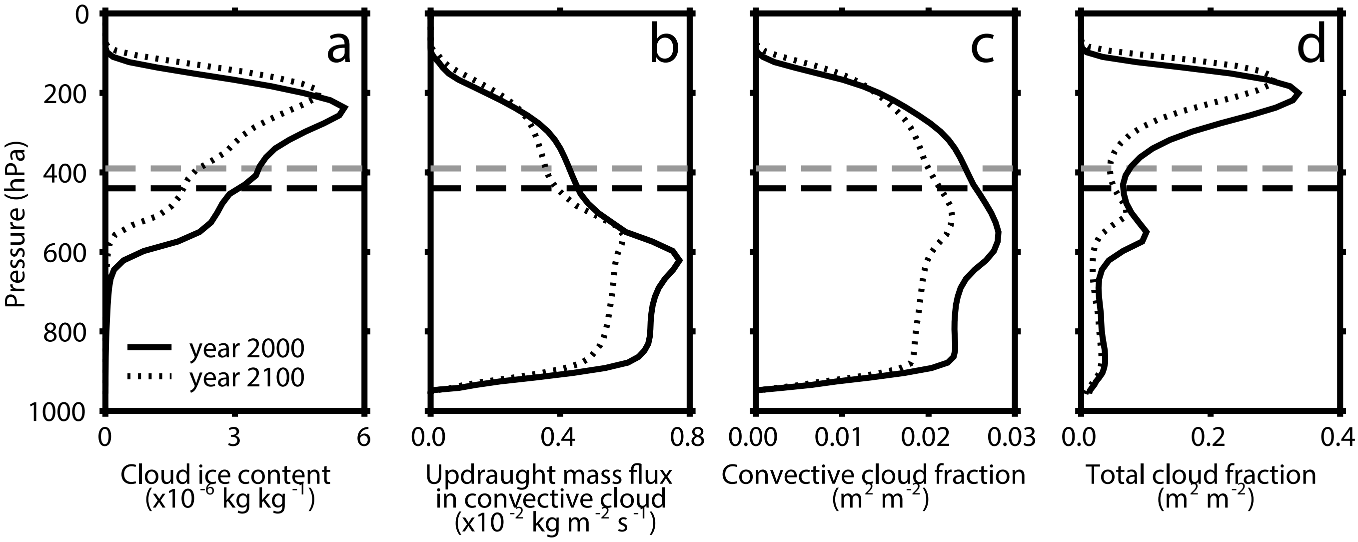
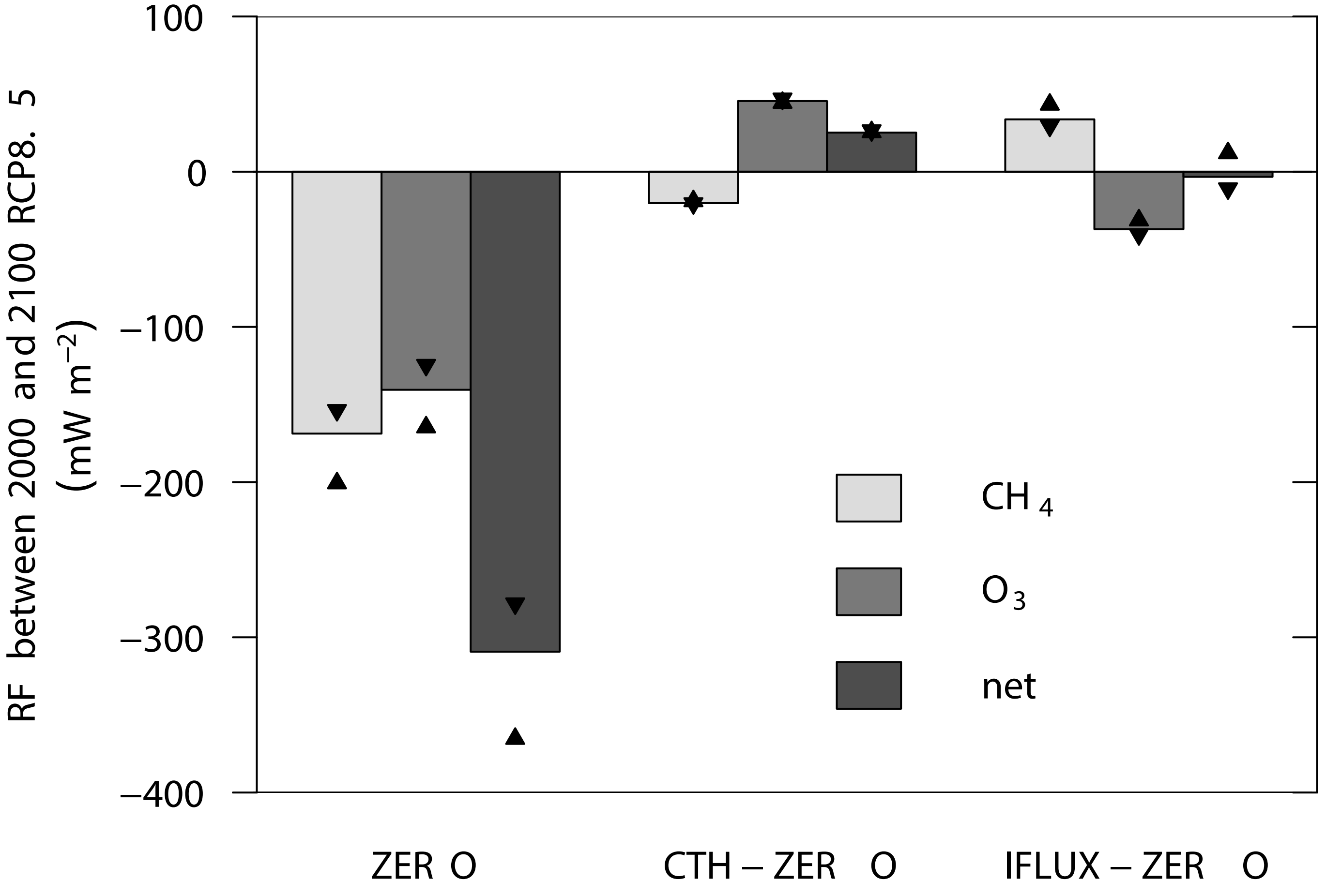

a) IFLUX
b) CTH
90N
60N
30N
0
30S
60S
90S
180W
120W
60W
0
60E
120E
180E
-100.00
-1.00
-0.01
0.10
10.00
-10.00
-0.10
0.01
1.00
100.00
Change in flash rate 2100 - 2000 under RCP8.5 (fl. km^{-2} yr^{-1})


a
b
c
d
Pressure (hPa)
0
200
400
600
800
1000
year 2000
year 2100
0
3
6
Cloud ice content
(x10⁻⁶ kg kg⁻¹)
0.0
0.4
0.8
Updraught mass flux
in convective cloud
(x10⁻² kg m⁻² s⁻¹)
0.00
0.01
0.02
0.03
Convective cloud fraction
(m² m⁻²)
0.0
0.2
0.4
Total cloud fraction
(m² m⁻²)


RF between 2000 and 2100 RCP8. 5
(mW m^{-2})
100
0
−100
−200
−300
−400
CH$_4$
O$_3$
net
ZER O
CTH – ZER O
IFLUX – ZER O