

**RESPONSE TO THE REFEREE COMMENTS
DURING THE DISCUSSION STAGE**

Manuscript Ref: acp-2019-126

**Climate benefits of proposed carbon dioxide mitigation strategies for international
shipping and aviation**

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We sincerely appreciate the careful reviews and helpful suggestions provided by the Reviewers, and thank the Reviewers and the Editor for their time. The manuscript has been considerably improved and strengthened based on the changes in response to the comments. Below, we provide information on the major modifications to the paper and respond point-by-point to comments (reviewer comments in blue, responses in black).

Major changes to the paper include:

- The addition of a new figure (Figure 2) providing the emissions profiles associated with the sensitivity analyses for business-as-usual aviation CO₂ emissions.
- The addition of a new figure (Figure 3) showing the radiative forcing estimates for each emitted climate pollutant from the international shipping and aviation industries.
- The inclusion of (27) additional references.
- Improved representation of the current status of emissions regulation in the international shipping and aviation sectors and associated reconfiguring of the modeling scenarios.
- The incorporation of updated CO₂ emissions projections for international aviation from recently published data from the International Civil Aviation Organization.
- The inclusion of an analysis of the potential increase in warming associated with the aviation sector due to the consideration of contrails and contrail-cirrus.
- Explicit comparison of the BAU radiative forcing estimates with those previously published.

Responses to Anonymous Referee #1:

SPECIFIC COMMENTS

Comment 1: Pg1, line 27: “emissions from these” – should this be “emission reductions from these”?

Response: We appreciate this observation, and we have edited the language accordingly to read, “*The Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in the late 1990s urged that emissions reductions from these sectors be pursued through the UN’s International Civil Aviation Organization (ICAO, established 1944) and International Maritime Organization (IMO, established 1948), respectively (UNFCCC, 1997)*” on P1:L28.

Comment 2: Pg1, line 34-35: What is meant by “over a 20- and 100-year timeframe”? Is this because you’re talking about CO₂-equivalent emissions? Please correct/clarify.

Response: Given that we were initially calculating international aviation and shipping’s share of global *greenhouse gas* emissions, we had to employ CO₂-equivalents (which require a time horizon). However, we have since realized that this sentence overcomplicated our message, and we are now comparing these sectors’ emissions to energy-related CO₂ emissions worldwide – eliminating the need for a time horizon. The text now reads: “*While current emissions from international aviation and shipping account for around 4% of global energy-related CO₂ emissions (IMO, 2014; ICAO, 2019a; IEA, 2018), emissions from each sector are forecasted to increase anywhere from 200-400% (Lee 2018) and 50-250% (IMO, 2014) by midcentury, respectively, in the absence of effective policy.*” on P2:L1.

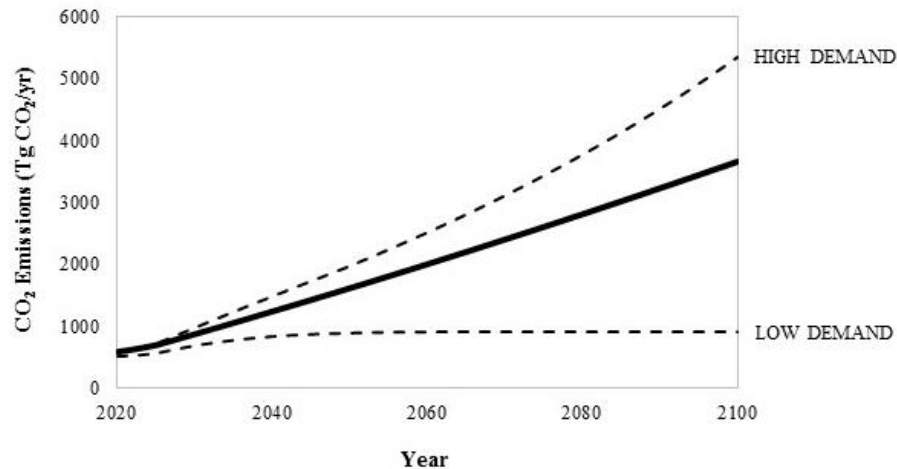
Comment 3: Pg3, line 31-35: does this mean that there are in fact four BAU scenarios for aviation, the three sensitivity ones and the one described above on lines 27-30? Please clarify.

Response: There are three total BAU scenarios analyzed for aviation: the central scenario used for the analysis (described on P4:L5) and two associated with sensitivity tests. We have reorganized the section in which these scenarios are described, and provided additional clarification in order to help make this more apparent. The section now reads as follows on P4:L8: “*Given that there is a range of reasonable growth patterns for aviation emissions in particular (Lee, 2018; Skeie et al., 2009), and our results depend on this baseline, we ran a set of sensitivity tests to evaluate the influence of different CO₂ BAU projection growth patterns on the perceived avoided warming impacts. The two sensitivity tests considered are based on an exponential growth rate pattern through 2100 following the 2005-2050 trend for the high and low demand forecasts as depicted in a previous version of Present and Future Trends in Aircraft Noise and*

Emissions (ICAO, 2013). These emissions estimates are scaled down to calculate the corresponding Low Aircraft Technology and Moderate Operational Improvement Scenarios proportionally to the latest ICAO forecast (2019a), resulting in declining growth rate patterns in which growth rates follow their 2020-2050 declining trend until plateauing at 0% –as is the case for the low demand scenario. These sensitivity tests are analyzed in addition to the Low Aircraft Technology and Moderate Operational Improvement Scenario noted above, for a total of three analyzed BAU scenarios for aviation.” We note that the emissions profiles for the central scenario and the two sensitivity tests have changed slightly based on the release of new CO₂ emissions projections for international aviation provided by a released working paper from the International Civil Aviation Organization (ICAO, 2019a). The emissions projections are highlighted in the new Figure 2.

Comment 4: Pg3, line 31-35: it would be very helpful for the reader if the future emission pathways under the scenarios and alternative BAU were shown.

Response: We thank the referee for this thoughtful suggestion. We have created an additional figure (Figure 2, reproduced below) in order to outline the emissions pathways under the central and alternative BAU scenarios associated with the sensitivity analyses for international aviation.



Comment 5: Pg4, line 4: what’s the rationale for selecting this one?

Response: We thank the reviewer for bringing this question to our attention and highlighting that its answer is not provided in the submitted text. We now provide additional context as to why the central growth scenario was chosen for all figures relating to the future warming associated with aviation. Specifically, because the central growth scenario represents the middle of the road scenario, it allows us to

avoid extreme estimations on either side of the spectrum. This explanation is provided on P4:L20, reading as follows: “*We note that all other figures in the paper reflect the Low Aircraft Technology and Moderate Operational Improvement Scenario, which depicts a limited growth pattern for international aviation as this provides a middle of the road estimation.*”

Comment 6: Pg4, line 29-30: I think this sentence fails to take into account the large amount of previous and ongoing work on contrail-cirrus across many groups. While certainly true that there is a significant uncertainty bar on the contrail-cirrus RF estimate, significant progress has been made over recent years and I encourage the authors to reflect this.

Response: We agree with the reviewer and have refined the text in the Methods section to acknowledge the recent work towards understanding these impacts: “*The latest version of MAGICC is not calibrated for inclusion of linear contrails and induced cirrus cloudiness from aviation, phenomena in which water vapor and impurities released in aircraft exhaust form cirrus-like clouds. This is an active area of research and significant progress has been made in recent years to better understand these uncertain processes (e.g. Lee et al. 2009; Schumann et al. 2015; Brasseur et al. 2016; Bock and Burkhardt 2016).*” (P7:L1).

We have also added text to address this in the Results section, along with discussion of the estimates in the literature and a sensitivity analysis to show the potential impact on our BAU radiative forcing estimates and temperature responses to aviation. The additional text reads: “*Our model does not include radiative effects from linear contrails nor contrail induced cirrus cloudiness. Although studies suggest a low level of scientific understanding for climate impacts of linear contrails and a very low level of scientific understanding of induced cirrus cloudiness (Lee et al. 2009), considerable work has been made recently towards improving our understanding of these effects. Estimates of the present-day radiative impact of linear contrails range from +3 to +12 mW m⁻² (Lee et al. 2009; Brasseur et al. 2016), and of cirrus cloudiness range from +12 to +63 mW m⁻² (Lee et al. 2009; Schumann et al. 2015; Brasseur et al. 2016; Bock and Burkhardt 2016); for context, this is compared to around 30 mW m⁻² from CO₂ emissions – note these values are for both domestic and international aviation. As air traffic rates increase, we expect the radiative forcings from contrails and changes in cirrus cloudiness to increase as well; Bock and Burkhardt (2019) suggest an increase in contrail cirrus radiative forcing by a factor of three from present-day through 2050, due to increases in air traffic and also a slight shift towards higher altitudes.*

Without growth in air traffic, inclusion of these effects would increase our radiative forcing estimates in 2100 by 15 to 75% based on the lower and upper estimates of both linear contrails and cirrus cloudiness. Assuming a fivefold growth in air traffic from 2005 to 2100, our radiative forcing estimate from international aviation could increase by 75 to 350%. The resulting impact on

temperature responses to BAU international aviation could therefore be considerably higher than our projection of 0.05 °C in 2100: 0.06 to 0.09 °C based on current air traffic patterns and 0.09 to 0.23 °C for a fivefold increase in air traffic.” (P12:L23).

Comment 7: Pg. 4, line 26: What about the even more uncertain indirect effect of shipping sulfate aerosols? Is that included and how?

Response: We do include indirect effects from all aerosols. We have added text to acknowledge the uncertainties in both aerosol direct and indirect forcings: *“Whereas radiative impacts of well-mixed greenhouse gases (such as CO₂ and methane) are fairly well understood due to our knowledge of gas absorption, aerosol radiative effects are more complex and uncertain. This is due to spatial and temporal heterogeneity complicating observations; a variety of possible microphysical and optical properties based on varying sizes, shapes, structures, mixtures, and humidity levels; and interactions with clouds that can impact the lifetime and brightness of the clouds. Given that aerosols are quite relevant to both the aviation and shipping sectors (e.g. Unger et al., 2010), we include their direct and indirect effects in our simulations, noting that caution must be applied in interpreting the results. Aerosol direct forcings are approximated by simple linear forcing-abundance relationships. The indirect effects of sulfate, black carbon, organic carbon, nitrate, and sea salt aerosols are also included. The effect on cloud droplet size is determined by scaling optical thickness patterns of each species (as described by Hansen et al. (2005)) by their respective emissions. The effect of aerosols on cloud cover and lifetime is modeled as a prescribed change in efficacy of the cloud albedo (for full parameterization details, see Meinshausen et al. (2011a))” (P6:L17).*

Comment 8: Pg4, line 32: this is not necessarily the case if the offsetting schemes include a switch to biofuels – see e.g., Caiazzo et al. 2017 ERL, Burkhardt et al. 2018 npj Climate and atmospheric science.

Response: We thank the referee for bringing this point to our attention. We have updated this section to include a description of the potential for offsetting schemes including a switch to biofuels to impact the climate benefit of associated policies. We have also highlighted the suggested citations on P14:L19, reading: *“However, offsetting schemes such as CORSIA do implement the use of biofuels and aircraft technology and air traffic management improvements, both of which have the potential to impact future emissions of non-CO₂ climate pollutants and the density of contrail cirrus (Bock and Burkhardt 2019; Caiazzo et al., 2017; Burkhardt et al., 2018).”*

Comment 9: Pg6, line 9: what is the climate sensitivity of MAGICC?

Response: The equilibrium climate sensitivity of MAGICC is 3 °C, and can be found on P6:L7: “MAGICC contains a hemispherically averaged upwelling-diffusion ocean coupled to a four-box atmosphere (one over land and one over ocean for each hemisphere) and a carbon cycle model, with an average equilibrium climate sensitivity (ECS) of 3 °C.”

Comment 10: Pg6, line 24: please be more specific. Are particular parameterizations for the aviation and shipping sectors used? Also, given the large uncertainties in the RF of many climate-relevant components, which in turn are critical for the total temperature impact (see also comment below) and hence the contribution of aviation and shipping, the authors need to provide information about the RF estimates (present day relative to pre-industrial) underlying their simulations. In particular, RF estimates specific to aviation and shipping – e.g., what is the indirect aerosol effect of shipping and aviation? And NO_x-induced O₃ and CH₄ eff discuss the sectors contributions given that not only they, but also the rest of the world makes progress on emissions.

Response: The point about radiative forcings is an excellent one, and we have considerably expanded the text to discuss the radiative forcing estimates of both sectors as well as by species, added a new figure (Figure 3 - below), and compared our estimates to several previous studies. Given that we are modeling future forcing and temperature responses to aviation and shipping, we do not have present-day radiative forcing estimates, which would require historical CO₂ emissions for each sector in order to compute. However, we are still able to compare our future radiative forcing estimates to the literature based on knowledge of emissions inputs, and the fact that most species are short-lived.

The new discussion is as follows (P8:L28):

“The net radiative forcing for international shipping is -47 mW m⁻² in 2020 and +48 mW m⁻² in 2100. The shift from negative to positive is due to the large increase in CO₂ emissions and their accumulation over time in the atmosphere. A considerable amount of the positive radiative forcing from CO₂ emissions in 2100 (+127 mW m⁻²) is offset by a relatively large negative radiative forcing in 2100 from NO_x emissions (-66 mW m⁻²). Net radiative forcing due to NO_x emissions is a combination of negative and positive radiative forcings from indirect effects; negative forcings arise from reductions in methane, production of nitrate, and nitrate’s effect on clouds, and positive forcings arise from production of tropospheric ozone. Indirect aerosol effects from all species yield a radiative forcing of -32 mW m⁻² in 2100.

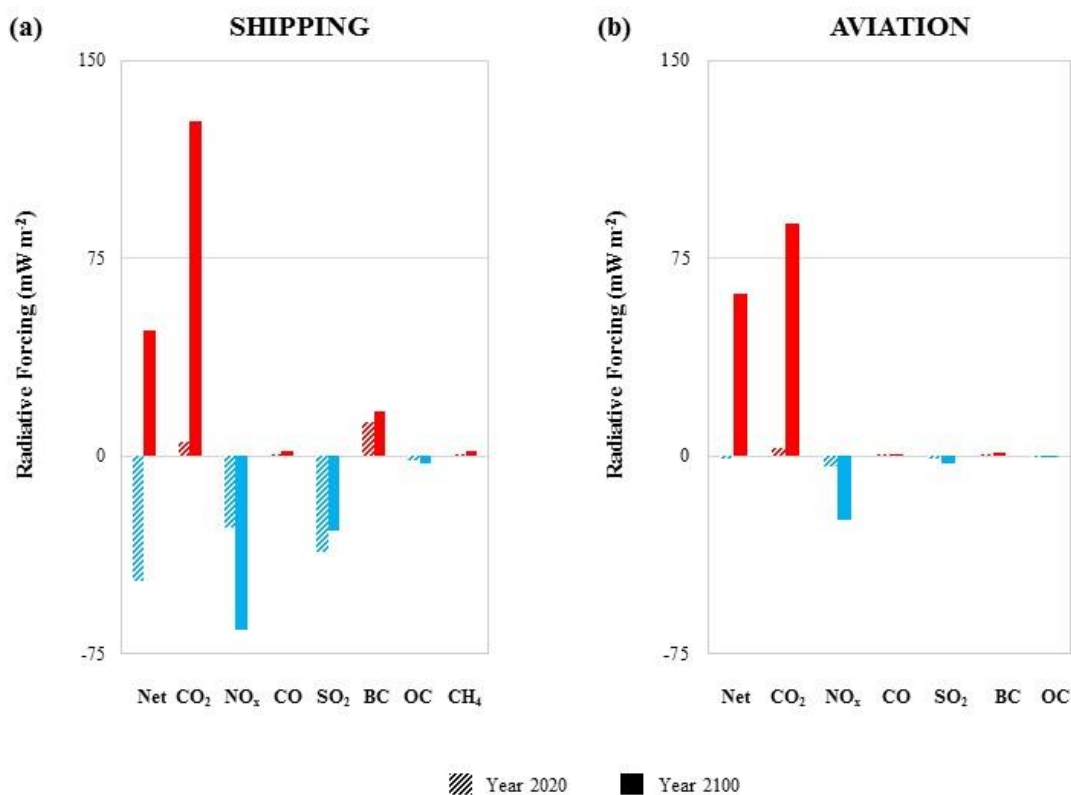
Radiative forcings derived in this study from shipping emissions of CO₂ and NO_x are consistent with the literature. Previous estimates of CO₂’s present-day (early 2000s) impact range from +26 to +43 mW m⁻², corresponding to emissions of 500 and 800 TgCO₂ yr⁻¹ (Eyring et al. 2010). This is consistent with this analysis when accounting for the anticipated growth in CO₂ emissions of more than fivefold by 2100 since the early 2000s (IMO, 2014). Previous studies estimate radiative

forcings from NO_x that range from +8 to +41 mW m^{-2} for indirect effects on tropospheric ozone (compared to our value of +25 mW m^{-2} in 2100) and -56 to -11 mW m^{-2} for indirect effects on methane (compared to our value of -22 mW m^{-2} in 2100) for present-day emissions around 2.9 to 6.5 TgN yr^{-1} (we assume NO_x emissions of 5.6 TgN yr^{-1} in year 2100) (Eyring et al. 2010). For SO_2 emissions from shipping, previous studies estimate direct radiative forcings from -47 to -12 mW m^{-2} due to production of sulfate; our estimate is -14 mW m^{-2} in 2100 from emissions that are lower (2.0 TgS yr^{-1}) than present-day values in the literature (3.4 to 6.0 TgS yr^{-1}) (Eyring et al. 2010). Our estimate of direct radiative forcing from black carbon (+5 mW m^{-2} in 2100 from emissions of 0.2 TgBC yr^{-1}) is slightly higher than estimates in the literature (+1.1 to +2.9 mW m^{-2} in 2000/2005 from emissions of 0.05 to 0.2? TgBC yr^{-1}) (Eyring et al. 2010). Indirect effects of aerosols have enormous ranges in estimates in the literature (Righi et al. 2011), but we note that our estimate appears to be on the lower end.

The net radiative forcing for international aviation emissions (note: not including impacts on contrails and cirrus clouds) is -1.4 mW m^{-2} in 2020 and +62 mW m^{-2} in 2100. Although radiative forcings are smaller for CO_2 for aviation compared to shipping, due to slightly less emissions, there are proportionally less emissions of the negative forcing precursors NO_x and SO_2 , yielding higher net radiative forcing from aviation. As with the shipping forcings, the large CO_2 radiative forcing in 2100 (+87 mW m^{-2}) is partially offset by the strong negative forcing from NO_x emissions (-24 mW m^{-2}). Indirect aerosol effects from all species yield a radiative forcing of -10 mW m^{-2} in 2100.

Estimates of present-day radiative forcing from aviation in the literature include both domestic and international emissions, whereas our estimates of future radiative forcings exclude domestic travel. Our estimates of radiative forcing from CO_2 emissions are in agreement with previous estimates when accounting for different emissions inputs (such as +87 mW m^{-2} in 2100 from emissions of 3670 $\text{TgCO}_2 \text{ yr}^{-1}$ compared to +28 mW m^{-2} in 2005 from emissions of 641 $\text{TgCO}_2 \text{ yr}^{-1}$ in Lee et al. (2009)). Our estimates for radiative forcings from NO_x , SO_2 (direct), and black carbon (direct) are slightly smaller than what is presented in the literature, despite larger emissions projected for year 2100 compared to present-day, but there are large uncertainties associated with these estimates and a low level of scientific understanding (Sausen et al. 2005; Fuglestedt et al. 2008; Lee et al. 2009). For example, Brasseur et al. (2016) estimate +6 to +37 mW m^{-2} for indirect effects of NO_x emissions on tropospheric ozone (compared to our value of +11 mW m^{-2} in 2100) and -8 to -12 mW m^{-2} for indirect effects on methane (compared to our value of -8 mW m^{-2} in 2100). Gettelman and Chen (2013) conduct a more sophisticated assessment of the climate impact of aviation aerosols than what is presented here, and report an estimate of -46 mW m^{-2} from combined sulfate direct and indirect effects; this is considerably larger than our estimate of -3 mW m^{-2} in 2100.”

Further, we note that there are not any particular parameterizations for the shipping and aviation sectors. In particular, we assume that all emissions take place at the surface of the Earth, which is a limitation of our analysis. We have highlighted this shortcoming of the model on P6:L29: “We note that all emissions are treated as surface emissions. Aviation emissions in-flight occur at higher elevations, and this can affect atmospheric chemistry and radiation processes. For example, when sulfate is located above clouds, the radiative efficiency can be halved (less cooling); in contrast, the radiative efficiency of black carbon can be doubled (more warming) when it is located above clouds (Ocko et al. 2012). On the other hand, using more sophisticated climate models that can resolve horizontal and vertical granularities is often complicated by unforced internal variability that makes isolating the climate impact of relatively small radiative perturbations difficult if not impossible (Ocko et al. 2018).”



Comment 11: Pg7, line 30: again, this is an example of where information about underlying RF is critical and should be compared with previous literature.

Response: We thank the referee for this emphasis on the need to discuss the underlying radiative forcings associated with the shipping and aviation sectors. As highlighted in the previous response, we have added a significant discussion of the radiative forcings derived by this study for the shipping and aviation sectors

and compared them to those from the literature. We appreciate how much this suggestion has strengthened our study.

Comment 12: Pg8, line 2: compare with other studies? E.g., Fuglestvedt et al. 2009.

Response: We thank the referee for the suggestion to substantiate our findings with a comparison to additional literature estimating the net climate impact of the shipping industry over the 21st century. We now compare the overall temperature trend associated with BAU emissions from the shipping sector presented by our own analysis and presented by Fuglestvedt et al. 2009, stating on P10:L15: *“This is also consistent with Fuglestvedt et al. (2009), which predicts that the accepted regulations in the shipping sector’s emissions of sulfur dioxide and nitrogen oxides will lead to the sector having a net cooling effect for about 70 years, after which the sector switches to warming. Our analysis predicts a slightly more rapid shift to warming (after about 65 years in 2085), likely due to our inclusion of the warming climate pollutant black carbon which are not featured in the analysis by Fuglestvedt et al. (2009).”*

Comment 13: Pg8, line 19-21: for both sectors, the authors should also note that the calculations assume no change in geographical distribution of emissions. For non-CO2 emissions, location can be critical for the subsequent impact. E.g., Fuglestvedt et al. 2014; ES&T, Köhler et al. 2013 *Atm. Environ*; Frömming et al. 2012 *JGR*; Lund et al. 2017 *ESD*

Response: We appreciate the referee for bringing this detail to our attention. We now note that the geographical distribution of emissions is not included in our calculations for the relative climate impacts of each gas, utilizing the four studies from the literature suggested by the referee. We also highlight this point as a limitation of the MAGICC model overall, as it is not possible to look at vertical or horizontal changes in emissions density in a globally averaged model. We first highlight this challenge on P7:L13, stating *“Further, due to MAGICC’s relative simplicity, parameters are averaged over large spatial scales. This is particularly important to acknowledge as recent literature has demonstrated that radiative forcings associated with the transport sector can differ based on the regional location at which the transport takes place (Berntsen et al. 2006; Fuglestvedt et al. 2014; Kohler et al. 2013; Fromming et al. 2012; Lund et al. 2017; Skowron et al. 2015), particularly for the impact of non-CO₂ emissions”* and again on P11:L3 *“We note that for both sectors, our calculations assume no change in the geographical distribution of emissions. Recent literature has demonstrated that the location of non-CO₂ emissions can have a large influence on their subsequent climate impact (Fuglestvedt et al. 2014; Kohler et al. 2013; Fromming et al. 2012; Lund et al. 2017; Skowron et al. 2015).”*

Comment 14: Pg8, line22 – onwards: As already pointed out in the major comment, I believe this result is misleading given the lack of treatment of contrail-cirrus. While it is possible that the indirect aerosol effects of aviation sulfate and BC could be negative

enough to cause a net cooling, there is nothing in our current best understanding that suggests so. If included I think the authors should make a point of the missing effects at the very start of this paragraph not at the bottom, emphasizing that one should be careful not to read too much into this finding.

Response: We appreciate the suggestion from the referee that we emphasize that contrail-cirrus is not included in these analyses before their results are presented. In both the new section on the radiative forcing estimates associated with the shipping and aviation sectors and the retained section on their related future warming, we have ensured that the exclusion of certain effects have been stated earlier in the text. We have added notes on P9:L17 stating, “*The net radiative forcing for international aviation emissions (note: not including impacts on contrails and cirrus clouds) is -1.4 mW m^{-2} in 2020 and $+62 \text{ mW m}^{-2}$ in 2100*” and on P11:L9 stating, “*However, the inclusion of non-CO₂ climate pollutant emissions does not yield a net cooling effect for several decades as they do with shipping, and reduces warming by end of century to $0.03 \text{ }^{\circ}\text{C}$ (note that we do not include here the impacts on contrails and cirrus clouds).*”

Comment 15: Pg8. line 31: again, the estimates of indirect aerosol RF should be included for comparison with e.g., Gettleman et al. 2013 GRL.

Response: We thank the referee for the suggested reference and we have included a comparison of our indirect aerosol RFs with the results of this study as well as others for shipping (Righi et al. 2011). Additional text includes:

P9:L1: “*Indirect aerosol effects from all species yield a radiative forcing of -32 mW m^{-2} in 2100.*”

P9:L15: “*Indirect effects of aerosols have enormous ranges in estimates in the literature (Righi et al. 2011), but we note that our estimate appears to be on the lower end.*”

P9:L22: “*Indirect aerosol effects from all species yield a radiative forcing of -10 mW m^{-2} in 2100.*”

P9:L33: “*Gettelman and Chen (2013) conduct a more sophisticated assessment of the climate impact of aviation aerosols than what is presented here, and report an estimate of -46 mW m^{-2} from combined sulfate direct and indirect effects; this is considerably larger than our estimate of -3 mW m^{-2} in 2100.*”

Comment 16: Pg9, lines 7-10: Skeie et al. 2009 included both indirect aerosol effects and contrailcirrus forcing – see their figure 2. Please correct or specify which indirect effects beyond there is included in this analysis.

Response: We appreciate the referee for highlighting this detail about Skeie et al. 2009. Upon further inspection of the article, the authors of Skeie et al. 2009 do include the indirect effects of nitrogen oxides via interactions with the lifetime of ozone and methane due to its impact on the lifetime of the hydroxyl radical, as well as the indirect aerosol effect of sulfur dioxide. However, to the best of our knowledge, they do not include the climate impact associated with the production of nitrate aerosols, which yields a significant cooling effect directly and indirectly. We have clarified this on P11:L30 as follows: *“first, our model includes indirect aerosol effects, particularly the climate impact associated with nitrogen oxides’ production of nitrate aerosols, which yield negative forcings that are not considered in the analysis by Skeie et al. (2009).”*

Comment 17: Pg9, line 9: is the net NO_x RF negative in Skeie et al. for shipping?

Response: The net NO_x radiative forcing reported by Skeie et al. (2009) for shipping is positive. On page 6264 of Skeie et al. 2009, the authors write “the emission of NO_x leads to a strong, short-lived positive RF-O₃, but also to a negative, long-lived forcing through changes in CH₄.” While the long-lived, cooling effect of NO_x is larger in the shipping sector than it is in the aviation sector, the net radiative forcing observed for the sector is still positive.

Comment 18: Pg11, line 4: the IPCC report on 1.5 degrees showed that there was a large difference between temperature response and time until reaching temperature thresholds between two simplified climate models. Uncertainties in the background temperature response affects the contribution from aviation and shipping, and should be discussed somewhere in the paper (perhaps the authors should consider a dedicated discussion section).

Response: This is a good point. We have added text to acknowledge this uncertainty: *“It is important to note that the background temperature response to other forcings (anthropogenic and natural) can affect the temperature responses to shipping and aviation. Therefore, even though they are ultimately subtracted out in our calculation, they do impact our results, and uncertainties in BAU emissions from other sectors and the resulting temperature effects need to be acknowledged”* (P8:L5)

We have also significantly expanded the discussion of model uncertainties in Section 2.3 in order to better address how uncertainties may affect our estimates of the contribution to future warming from shipping and aviation.

Comment 19: Figure 4: the authors should show also the CO₂ only cases here, as in Figure 2, allowing the reader to assess the impact of the assumption that non-CO₂ emissions are changed “proportionally”.

Response: We appreciate the suggestion to clarify the impact of the assumption that non-CO₂ emissions are changed proportionally. We initially implemented this change to the graph, but found that the figure was more confusing than its original version. We have thus chosen to show only the all-products scenarios for what is now Figure 6.

Responses to Anonymous Referee #2:

GENERAL COMMENTS

Comment 1: A major criticism is that the results section is quite short and mentions very few previous studies. I would recommend to extend Section 3, adding more details and more citations, in particular concerning the role of the short-lived species. These compounds can be very relevant for the two sectors discussed here, as shown by several previous studies (see suggestions below). Also the uncertainties of the adopted simplified climate model in simulating the effects of short-lived species can be large and should be discussed.

Response: We thank the reviewer for this observation, and have expanded Section 3, discussed more details of radiative forcing estimates and short-lived species, added information about uncertainties, added a sensitivity analysis regarding contrail/cirrus impacts, and added 27 studies to our references.

Expanded discussion of uncertainties includes:

on P6:L17, *“Whereas radiative impacts of well-mixed greenhouse gases (such as CO₂ and methane) are fairly well understood due to our knowledge of gas absorption, aerosol radiative effects are more complex and uncertain. This is due to spatial and temporal heterogeneity complicating observations; a variety of possible microphysical and optical properties based on varying sizes, shapes, structures, mixtures, and humidity levels; and interactions with clouds that can impact the lifetime and brightness of the clouds. Given that aerosols are quite relevant to both the aviation and shipping sectors (e.g. Unger et al., 2010), we include their direct and indirect effects in our simulations, noting that caution must be applied in interpreting the results.”*

on P7:L13, *“Further, due to MAGICC’s relative simplicity, parameters are averaged over large spatial scales. This is particularly important to acknowledge as recent literature has demonstrated that radiative forcings associated with the transport sector can differ based on the regional location at which the transport takes place (Berntsen et al. 2006; Fuglestedt et al. 2014; Kohler et al. 2013; Fromming et al. 2012; Lund et al. 2017; Skowron et al. 2015), particularly for the impact of non-CO₂ emissions.”*

on P6:L29, *“We note that all emissions are treated as surface emissions. Aviation emissions in-flight occur at higher elevations, and this can affect atmospheric chemistry and radiation processes. For example, when sulfate is located above clouds, the radiative efficiency can be halved (less cooling); in contrast, the radiative efficiency of black carbon can be doubled (more warming) when it is located above clouds (Ocko et al. 2012). On the other hand, using more sophisticated climate models that can resolve horizontal and vertical granularities is often complicated by unforced internal variability that makes*

isolating the climate impact of relatively small radiative perturbations difficult if not impossible (Ocko et al. 2018).”

on P8:L5, *“It is important to note that the background temperature response to other forcings (anthropogenic and natural) can affect the temperature responses to shipping and aviation. Therefore, even though they are ultimately subtracted out in our calculation, they do impact our results, and uncertainties in BAU emissions from other sectors and the resulting temperature effects need to be acknowledged.”*

Comment 2: In Sect. 2.1, scaling shipping SO₂ emissions by a factor 7 to account for the IMO regulations in fuel sulfur content (FSC) only makes sense if the RCP8.5 dataset assumes a 3.5% FSC for the global shipping fleet. Is this really the case? The 3.5% cap was enforced in 2012, but it was 4.5% before and the RCPs scenarios start the projection in 2000. Moreover, according to the second IMO Study (Buhaug et al., 2009), the actual FSC in the global shipping fleet was on average 2.7% before the introduction of the IMO regulations. Therefore it could be that the FSC value assumed in RCP8.5 is lower than 3.5% and the scaling factor to get to 0.5% is lower than 7. Please check this.

Response: We thank the referee for pointing out these inconsistencies. We have reviewed the literature associated with the RCP database (Riahi et al. 2011) and recognize that the progressive reductions associated with the amendments to MARPOL Annex VI leading to an eventual 0.5% SO₂ emissions cap are indeed accounted for in the RCP8.5 database. All scenarios have been updated to return to the original sulfur emissions profiles provided by the database and are no longer altered based on the previous ratio.

Comment 3: End of Sect. 2.3: I understand that a full discussion of the model uncertainties is beyond the scope of this study, but I would at least briefly summarize which of them are the most significant for the results presented here.

Response: We thank the referee for this suggestion. We have significantly expanded the discussion of the model uncertainties in Section 2.3, particularly to discuss the potential impact of regional emissions, vertical differences in gas and aerosol concentrations throughout the atmosphere, our inability to accurately project future emissions over large spatial scales, and uncertainties in aerosol direct and indirect forcings. This new section runs from P6:L29 to P7:L23.

Comment 4: P8, L2: you may also want to compare with Lund et al. (Environ. Sci. Technol., 2012).

Response: We thank the referee for this suggestion. We have significantly expanded the comparison of our results to that found within the literature, including a comparison with Lund et al. 2012. The additional paragraph starts on P12:L9 and reads as follows: *“In the RCP scenarios presented by Lund et al.*

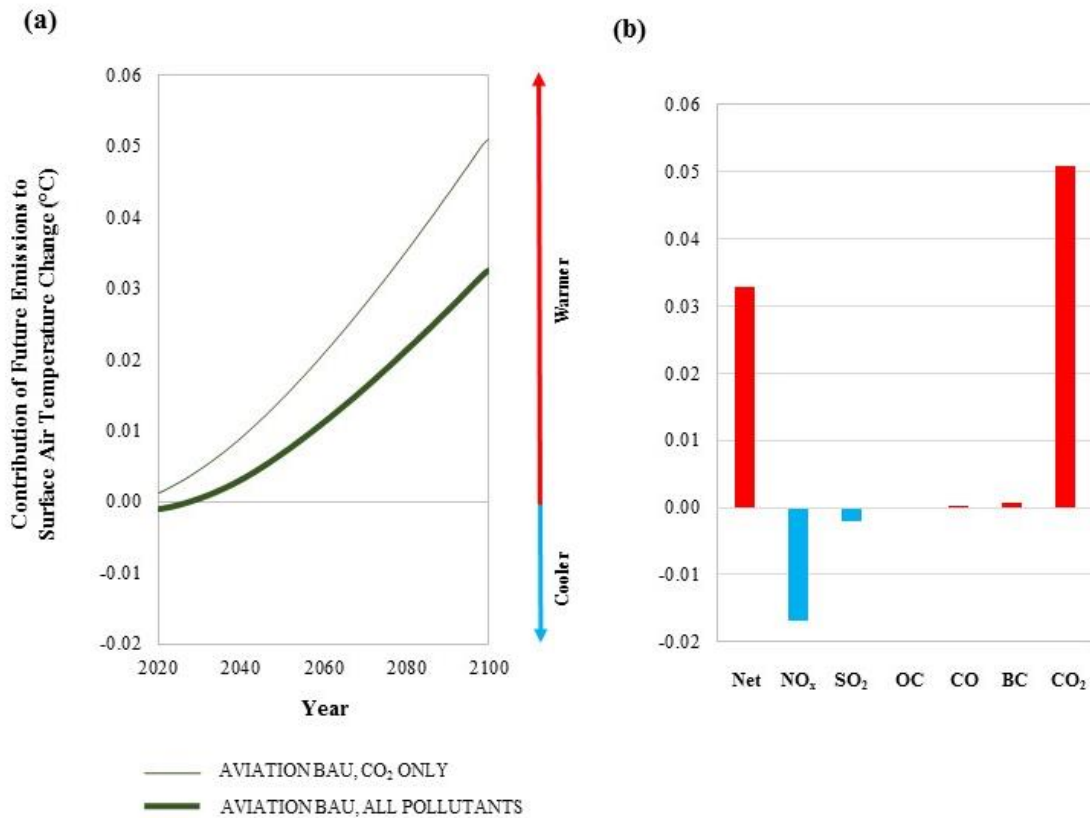
(2012), shipping is projected to cause a cooling of between -0.02 and -0.04 °C by midcentury. Our analysis estimates that shipping is responsible for -0.03 °C in year 2050, which falls within this range. Further, the authors' findings are in agreement with those presented in this analysis through their observation of warming later in the century once the accumulating CO₂ emissions impact overruns the cooling impact of nitrous oxides and sulfur dioxide, particularly due to the reduced sulfur dioxide emissions associated with the implemented fuel regulations." We have also included a comparison to Terrenoire et al. 2019 and Huszar et al. 2013 in order to assess whether our findings are consistent with multiple studies. Further, we have added information on the radiative forcing estimates from our model simulations, and compared the results to several previous studies.

Comment 5: P8, L16: there are a few studies simulating the aerosol indirect effect in low-sulfur shipping scenarios you may want to mention, for example Lauer et al. (Environ. Sci. Technol., 2009) and Righi et al. (Environ. Sci. Technol., 2011).

Response: We thank the referee for bringing these studies to our attention. We have highlighted this additional literature and its demonstration that low-sulfur shipping scenarios have the potential to reduce the indirect aerosol effect from shipping sulfur emissions. This helps strengthen our analysis regarding the net cooling reduction associated with implementation of the sulfur regulation. This section on P10:L29 now reads, "*Given that sulfur dioxide emissions—a precursor to the cooling pollutant sulfate—are projected to decrease significantly due to the sulfur fuel regulation newly adopted by IMO, sulfur dioxide from shipping contributes less significantly to cooling. Recent studies have demonstrated the potential for low-sulfur shipping scenarios to reduce the indirect aerosol effect from shipping sulfur emissions (Lauer et al., 2009; Righi et al. 2011).*"

Comment 6: P8, L26-27: the switch from cooling to warming is not evident in Fig. 2b. Does it occur before 2020? Please clarify.

Response: We thank the referee for bringing this concern to our attention. The switch from cooling to warming takes place around year 2024, but the line is very thick and this is hard to see. We have made the baseline outline a bit thinner in order to help with this, shown in what is now Figure 5a, reproduced below.



Comment 7: P8, L28-33: the issue of aviation effects of short-lived species should be discussed in more detail (see Lee et al., Atmos. Environ., 2010; or Grewe et al., Aerospace, 2018). There are several studies arguing for the effect of aviation soot on natural cirrus clouds (e.g., Penner et al., J. Geophys. Res., 2019) and some groups even argued for an effect on warm clouds (Gettelman and Chen, Geophys. Res. Lett., 2013; Righi et al., Atmos. Chem. Phys., 2013; Kapadia et al., Atmos. Chem. Phys., 2016). Can the simple climate model used here account for these effects?

Response: This is a good point, and we have added discussion of these effects. The MAGICC model is currently not set up to account for effects beyond the standard first and second indirect effects of (all species of) aerosols on clouds. The text on P11:L18 now reads, “We note that some studies have investigated the effect of aviation soot on natural cirrus clouds (Penner et al., 2019) or the effect on warm clouds (Gettleman and Chen, 2013; Righi et al., 2013; Kapadia et al., 2016). MAGICC does take into account indirect effects of soot, such as simplified parameterizations of impacts on cloud brightness and lifetime, but does not include more sophisticated treatments as analyzed in previous studies.”

Comment 8: P8, L29: what is the mechanism behind the cooling effect from nitrogen oxide? This gas can lead to the formation of ozone, which has a warming effect, but it also reduces methane lifetime, resulting in a cooling. Are these mechanisms included in the model?

Response: The net effects from NO_x emissions are due to a combination of formation of ozone (positive forcing), reduction of methane (negative forcing), formation of nitrate aerosols (negative forcing), indirect effects of nitrate aerosols (negative forcing), and a cooler ocean suppressing CO₂ emission into the atmosphere (negative forcing). The overall effect is one of cooling as these mechanisms are all included in the model. We have clarified this in the text (P10:L27): *“The net cooling from nitrogen oxides arises from nitrate formation, indirect aerosol effects from nitrates, formation of tropospheric ozone, reduction of methane, and effects of the net forcings on the carbon cycle (cooling in the ocean suppresses CO₂ diffusion from the ocean into the atmosphere).”*

Comment 9: P8, L31-33: this is confusing, if you include the indirect aerosol effects, then you do address the impacts of aviation on cloudiness. You probably mean contrails and contrail-induced cloudiness here; please clarify and also add a citation to support the last statement in this sentence (warming effect).

Response: We see how this is confusing and we thank the referee for requesting this clarification. We did mean contrails and contrail-induced cloudiness. Considering that we have now included a sensitivity analysis of the climate impacts of contrails and contrail-induced cloudiness, the last part of this sentence has been removed.

Comment 10: End of Sect. 3.1: only one study is cited for comparison. It would be good to add more, possibly more recent, studies.

Response: This suggestion by the referee is greatly appreciated. We have significantly developed the comparison of our temperature results with other results from the literature, including a comparison to Lund et al., 2012; Terrenoire et al., 2019; and Huszar et al., 2013. Each of these studies is more recent than the originally cited Skeie et al. 2009. The comparison of our BAU warming results for international shipping and aviation with those from past literature now runs from P11:L23 to P12:L22. We have also added considerable text regarding radiative forcing estimates and compared our results to several previous studies as well.

Comment 11: Sect. 3.2: the role of short-lived pollutants in the aviation scenarios is not discussed at all. I understand that, unlike the shipping scenarios, the analyzed aviation scenarios do not distinguish between CO₂ and non-CO₂ species, but at least some qualitative considerations could be added here.

Response: We thank the referee for bringing this to our attention. We inserted a discussion at the end of Section 3.2 to underscore the fact that we do not consider the influence of reducing the non-CO₂ impact of the aviation sector like we do for the shipping sector. We have also outlined how the use of biofuels and changes to aircraft technology and air traffic management may impact estimated warming

mitigated through these interventions. This discussion begins on P14:L15 and states, “*Similarly, we do not consider the reduction of non-CO₂ climate pollutants emitted by the aviation sector in the mitigation scenarios. However, offsetting schemes such as CORSIA do implement the use of biofuels and aircraft technology and air traffic management improvements, both of which have the potential to impact future emissions of non-CO₂ climate pollutants and the density of contrail cirrus (Bock and Burkhardt 2019; Caiazzo et al., 2017; Burkhardt et al., 2018). While the influence of these changes on the non-CO₂ impact of international aviation is currently not well-estimated, their impact should be considered in future analyses as understanding develops.*”

SPECIFIC COMMENTS

Comment 1: P1, L14: please specify how much is this allowable warming.

Response: We thank the referee for requesting this clarification. We specified the respective allowable warming for the two temperature thresholds. The clause now reads (on P1:L16): “*which is 12% and 24% of the “allowable warming” we have left to stay below the 2 °C or 1.5 °C thresholds (1.0 °C and 0.5°C) respectively.*”

Comment 2: P1, L33: how does the time-frame affect the share of global CO₂ emissions? Shouldn’t it be rather given for a specific year?

Response: We thank the referee for this clarifying question. We intended this sentence to reflect the sectors’ share of total greenhouse gas emissions in CO₂-equivalents (including non-CO₂ emissions as well – which is why a time horizon was necessary). However, we have realized that this is confusing and overcomplicates our message. Therefore we have changed the sentence to reflect the sectors’ share of CO₂ emissions from energy sources. The sentence on P2:L1 now reads, “*While current emissions from international aviation and shipping account for around 4% of global energy-related CO₂ emissions (IMO, 2014; ICAO, 2019a; IEA, 2018), emissions from each sector are forecasted to increase anywhere from 200-400% (Lee 2018) and 50-250% (IMO, 2014) by midcentury, respectively, in the absence of effective policy.*”

Comment 3: P3, L18: I would change the title of Sect. 2.1, to make more clear that the baseline scenario is discussed here. I would also suggest to make two subsections of 2.1, to better separate aviation from shipping. The same would apply to 2.2. Another option would be to merge 2.1 and 2.2 in a single section on emissions, with two subsections for shipping and aviation, respectively.

Response: We thank the referee for these suggestions in order to better organize our methodology description. We have changed the first section heading (section 2.1) to “Business-as-usual emissions from international bunkers” to reflect that it

is BAU emissions. We also included subsections within Sect. 2.1 to more clearly separate aviation from shipping.

Comment 4: P3, L27: "hold that level constant", I guess you are referring to the growth rate which is held constant, but that could be misunderstood as the actual emissions. I would be more explicit: "hold that growth rate constant".

Response: This scenario has changed in order to reflect the new data released by the International Civil Aviation Organization for future CO₂ emissions projections from the aviation sector. The description of this new scenario begins on P4:L5.

Comment 5: P4, L5: the RCP acronym should be explained.

Response: We appreciate this suggestion from the referee. We now explain on P3:L31 that RCP stands for Representative Concentration Pathways.

Comment 6: P4, L11: what do you mean by "all-forcings" BAU scenario?

Response: We thank the referee for this clarifying question. This first mention of the all-forcings scenario has been removed from the text, but we now provide clarifying language to define the all-forcings BAU scenario as "*the business-as-usual scenario including all natural and anthropogenic climate forcings*" on P4:L32.

Comment 7: P4, L29: there are more recent estimates, for example Burkhardt and Kärcher (Nature Clim. Change, 2011).

Response: We thank the referee for bringing more recent estimates to our attention. In our addition of a sensitivity analysis for the temperature impact of contrails and contrail induced cirrus cloudiness from P12:L23 to P13:L3, we reference five additional studies (namely Lee et al., 2009; Schumann et al., 2015; Brasseur et al., 2016; Bock and Burkhardt, 2016, and Burkhardt et al., 2019), each of which are more recent than Sausen et al., 2005.

Comment 8: P6, L24: please provide a reference for these relationships.

Response: We thank the referee for this suggestion. This relationship is a ratio provided by the EDGAR database as outlined in Crippa et al. 2016. We have provided the reference more explicitly as instructed on P4:L31.

Comment 9: P6, L26: please replace "gas" by "species" or "compound", since also aerosols are considered here.

Response: We appreciate the referee for pointing out this oversight. We replace the word "gas" with "species" as suggested on P6:L25.

Comment 10: P7, L4: $2100 - 1765 + 1 = 336$ years (?)

Response: We thank the referee for bringing this ambiguity to our attention. The number 335 represents the number of integrations we are performing, rather than the number of years. This was unclear in our original language, and we have changed the language to better reflect our intended meaning. The sentence on P7:L25 now reads *“We run 335 year-to-year integrations from year 1765 to 2100 for a set of 14 different simulations.”*

Comment 11: P11, L13: it might be worthwhile to cite Fuglestedt et al. (Environ. Sci. Technol., 2009) in this context.

Response: We thank the referee for this suggestion. We added in this citation to further support the statement on P15:L8.

Comment 12: P11, L14-16: since this is the main motivation behind this work, I would suggest putting this sentence also in the introduction.

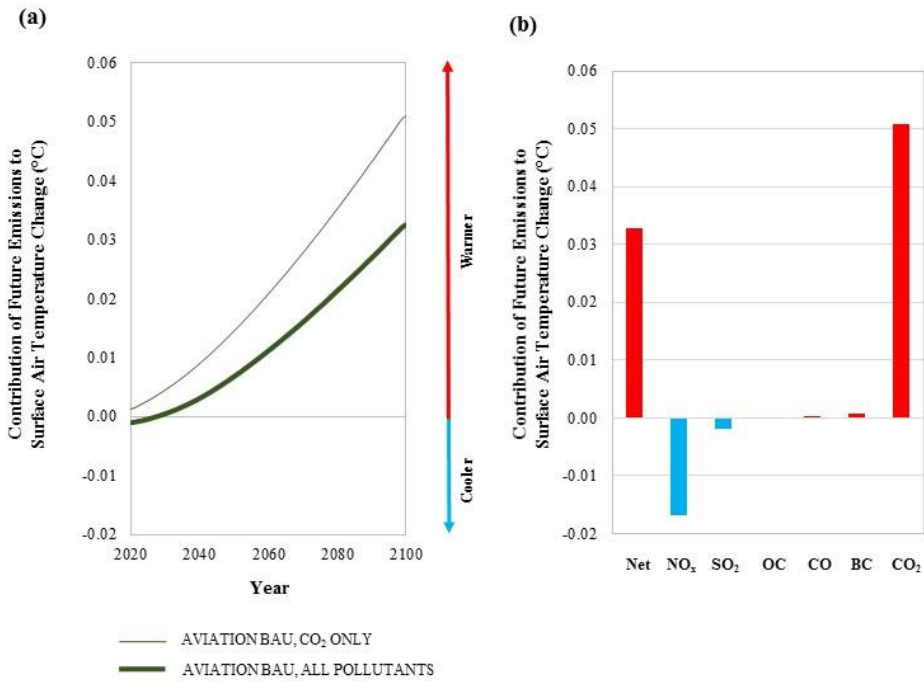
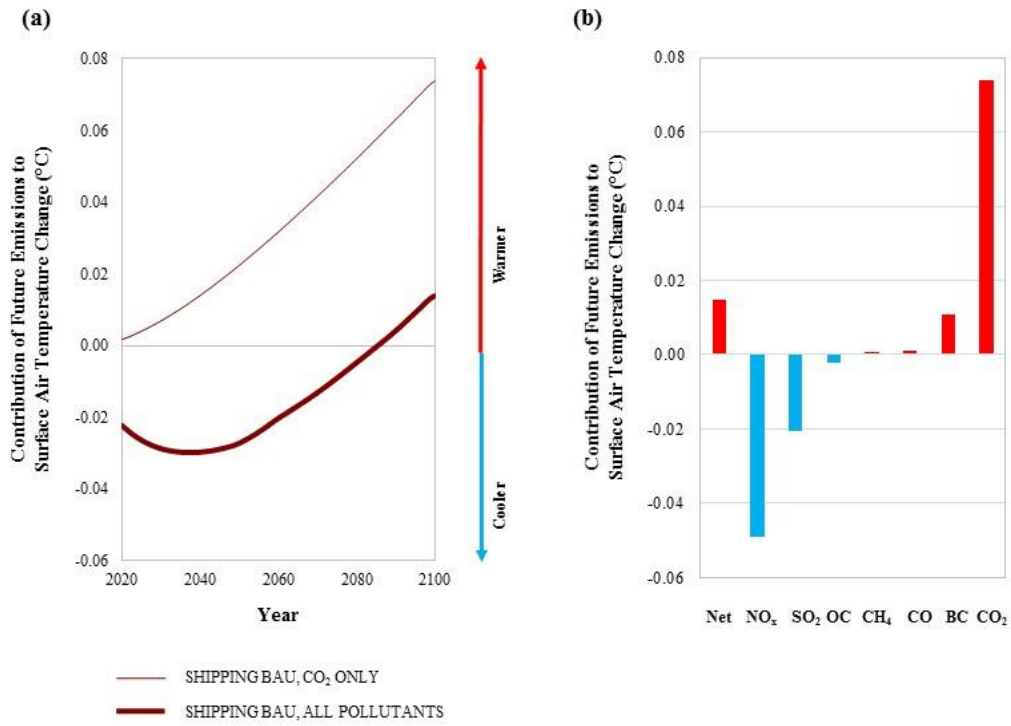
Response: We thank the referee for this suggestion. We have inserted a similar sentence into the introduction in order to provide this compelling context in that section as well on P1:L13 which reads, *“Given that the global average temperature has already risen $1\text{ }^{\circ}\text{C}$ above preindustrial levels, there exists only $1.0\text{ }^{\circ}\text{C}$ or $0.5\text{ }^{\circ}\text{C}$ of additional “allowable warming” left to stabilize below the $2\text{ }^{\circ}\text{C}$ or $1.5\text{ }^{\circ}\text{C}$ thresholds, respectively. We find that if no actions are taken, CO_2 emissions from international shipping and aviation may contribute roughly equally to an additional combined $0.12\text{ }^{\circ}\text{C}$ to global temperature rise by end of century—which is 12% and 24% of the “allowable warming” we have left to stay below the $2\text{ }^{\circ}\text{C}$ or $1.5\text{ }^{\circ}\text{C}$ thresholds ($1.0\text{ }^{\circ}\text{C}$ and $0.5\text{ }^{\circ}\text{C}$) respectively.”*

Comment 13: Figure 1: the acronym MMT should be explained. Also, this is a non-SI unit: I would use Tg or Gg instead.

Response: We appreciate this suggestion from the referee. We have changed these units to the equivalent SI unit, Tg.

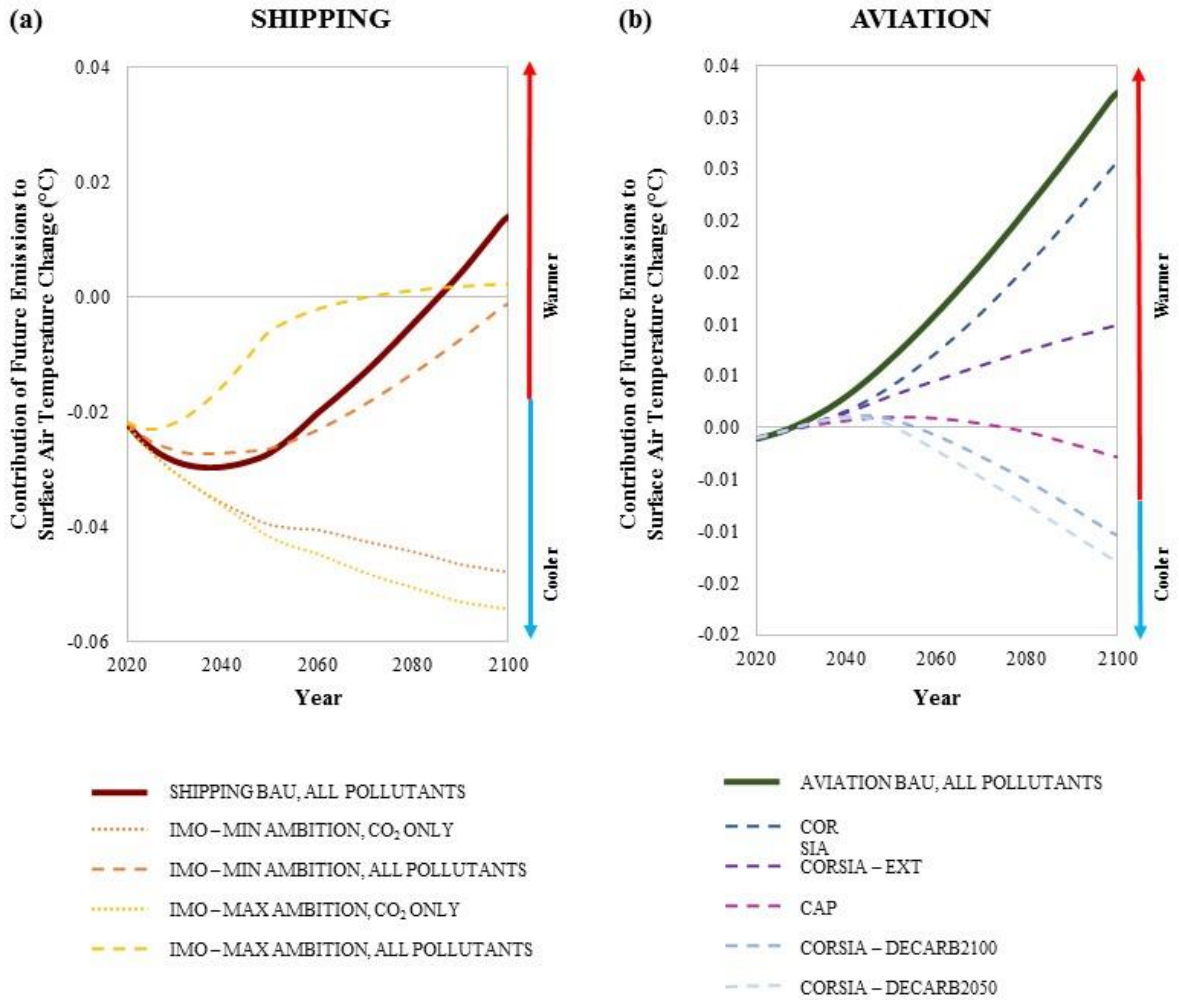
Comment 14: Figure 3a is discussed before Figure 2b. You could think about grouping the plots by sector since this reflects the way they are presented in the text

Response: We thank the referee for this suggestion. We now group the plots by sector, as suggested. The new Figure 4 and Figure 5 are reproduced below, for reference.

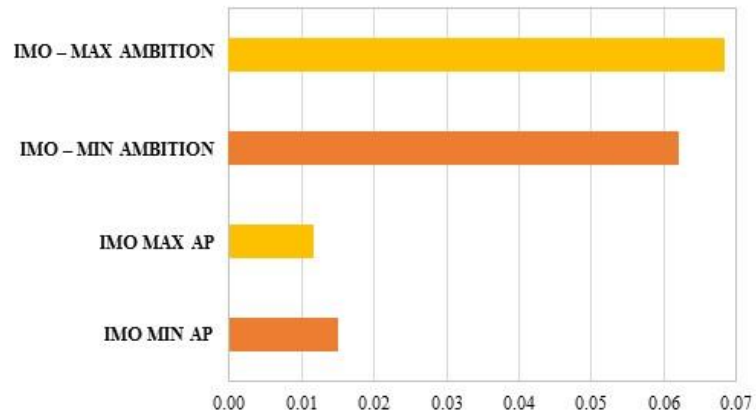


Comment 15: Figure 4: it is hard to distinguish the lines for the different scenarios, since very similar colors are used for them.

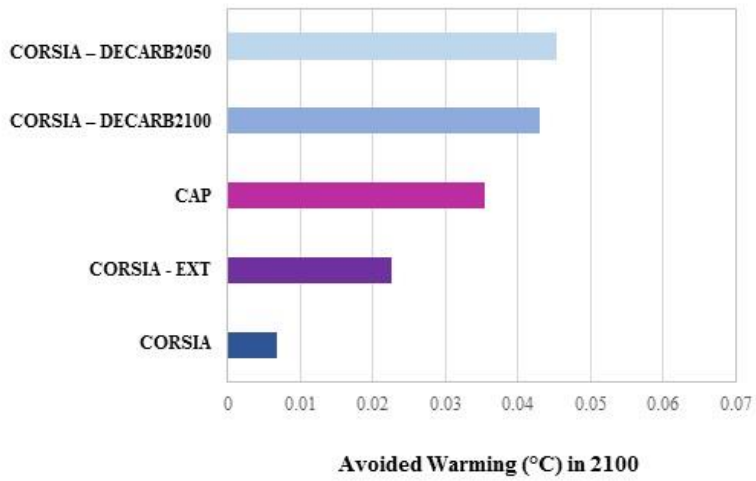
Response: We appreciate this suggestion from the referee. We have changed the colors of the figure in order to better distinguish between the different scenarios. The updated figure (now Figure 6) is reproduced below, for reference. Note that the colors for Figure 7 (also reproduced below) have also been changed in order to keep the color scheme consistent for each policy scenario.



(a) SHIPPING



(b) AVIATION



Avoided Warming (°C) in 2100

Climate benefits of proposed carbon dioxide mitigation strategies for international shipping and aviation

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Abstract. While individual countries work to achieve and strengthen their nationally determined contributions (NDCs) to the Paris Agreement, the growing emissions from two economic sectors remain largely outside most countries' NDCs—~~mostly unregulated outside the bounds of national jurisdictions~~: international shipping and international aviation. Reducing emissions from these sectors is particularly challenging because adoption of any policies and targets requires agreement of a large number of countries. However, the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) have recently announced strategies to reduce carbon dioxide (CO₂) emissions from their respective sectors. Here we provide information on the climate benefits of these proposed measures, along with related potential measures. ~~Given that the global average temperature has already risen 1 °C above preindustrial levels, there exists only 1.0 °C or 0.5°C of additional “allowable warming” left to stabilize below the 2 °C or 1.5 °C thresholds, respectively.~~ We find that if no actions are taken, CO₂ emissions from international shipping and aviation may contribute roughly equally to an additional combined 0.45–12 °C to global temperature rise by end of century—which is 45–12% and 30–24% of the “allowable warming” ~~we have left to stay below the 2 °C or 1.5 °C thresholds, we have left to stay below the 2 °C or 1.5 °C thresholds (1.0 °C and 0.5°C) respectively.~~ ~~respectively.~~ However, stringent mitigation measures may avoid over 85% of this projected future warming from the CO₂ emissions from each sector. Quantifying the climate benefits of proposed mitigation pathways is critical as international organizations work to develop and meet long-term targets.

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1 Introduction

There are clear benefits to limiting global average temperature rise to 1.5 °C above preindustrial levels (IPCC, 2018). However, in order to achieve this, carbon dioxide (CO₂) emissions likely need to reach net zero around midcentury (IPCC, 2018). This would require unprecedented changes to energy systems, land use, transportation, infrastructure, and industry worldwide.

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Two sectors for which establishing carbon dioxide mitigation policy is particularly complex are international aviation and shipping. The Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) decided in the late 1990s urged that emissions reductions from these sectors should be pursued through the UN's International Civil Aviation Organization (ICAO, established 1944) and International Maritime Organization (IMO, established 1948), respectively (UNFCCC, 1997), ~~among other forums~~. While the existence of these UN bodies unites global perspectives for regulation development, this arrangement also requires the agreement of a large number

of countries for the adoption of any new policies and targets, a feat much more difficult than if only one or several countries were involved.

While current emissions from international aviation and shipping account for around ~~2% and 34%~~ of ~~global energy-related global greenhouse gas emissions in CO₂ equivalents over a 20- and 100-year timeframe, respectively~~CO₂ emissions (SOURCE(IMO, 2014; ICAO, 2019a; IEA, 2018), emissions from each sector are forecasted to increase anywhere from 200-400% (Lee ~~et al.~~, 2018) and 50-250% (IMO, 2014) by midcentury, respectively, in the absence of effective policy.

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Therefore, to support the objectives of the Paris Agreement adopted in 2015, ICAO and IMO have recently announced strategies to reduce carbon dioxide emissions from international aviation and shipping, respectively. As part of a “basket of measures” to address aviation emissions, ~~including a CO₂ efficiency standard for aircraft~~, ICAO adopted a resolution in 2016 to establish a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA requires States to ensure airlines limit their net emissions of carbon dioxide to 2020 levels, and allows airlines the flexibility to achieve those reductions directly through improved technologies and operations; by reducing emissions outside the sector; and by using fuels that have lower emissions on a life-cycle basis. Efforts are now underway to implement CORSIA, while ensuring that these emissions reductions are not double-counted (once by Paris Parties where the reductions occur, and again by airlines in CORSIA). A long-term goal for international aviation CO₂ emissions has been in development since 2008, but ICAO has yet to formally adopt such a target.

On the other hand, IMO announced in 2018 a minimum ambition long-term target of cutting international shipping emissions by at least 50% by 2050 compared to 2008 ~~followed by rapid with~~ full decarbonization ~~by the end of the century~~(IMO, 2018). This long-term target was preceded by various policy options facilitating the reduction of carbon dioxide emissions from the shipping sector. These policies include the Energy Efficiency Design Index (EEDI), which requires increasingly stringent minimum energy efficiency levels for new ships, and the Ship Energy Efficiency Management Plan (SEEMP), which provides an approach for monitoring the energy efficiency of current fleets in use. ~~However, these policies will not be legally binding until an IMO convention declares them mandatory.~~

While both of these measures—CORSIA and IMO’s target—will reduce carbon dioxide emissions from international aviation and shipping, respectively, it is important to analyze the impact that these measures will have on global warming. This information is further important as ICAO’s 2019 Assembly considers next steps and IMO revises and reviews its long-term target in 2023 and 2028, respectively.

Several studies have previously quantified the current and future climate impacts of the transport sector, including aviation and shipping. Many studies aggregate the climate impacts of each sector through the use of ~~carbon dioxide equivalences~~CO₂e (Lee et al., 2010; Lee, 2018; Eyring et al., ~~2009~~2010; Azar and Johansson, 2012), but this metric does not account for continuous emissions nor convey warming impacts over time (Ocko et al., 2017). Studies that do investigate climate impacts of these sectors over time often consider the effects of a single emissions pulse or sustained present-day emissions (Fuglestedt et al., 2009; Berntsen and Fuglestedt, 2008; Unger et al., 2010).

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There are a few studies that have modeled the contribution to warming from future aviation and shipping emissions pathways. ~~One of the earliest estimations estimates was produced published in -when-~~ The IPCC ~~released a~~ special report on aviation and its impact on the global atmosphere in 1999; ~~the report, which~~ estimated aviation's expected business-as-usual (BAU) contribution to warming in year 2050 at 0.05 °C to 0.09 °C. ~~Bielvedt-Skeie et al. (2009) also~~ analyzed future warming impacts from shipping and aviation, and included prospective technological improvements in addition to BAU projections. The authors estimated that aviation's contribution to warming in 2100 will range from 0.11 °C to 0.28 °C, while the shipping sector's contribution will range from -0.01 °C to 0.25 °C, depending on future trends in global economic development. ~~The cooling impact of the shipping sector by midcentury was estimated by Lund et al. in 2012 at -0.02 to -0.04 °C, depending on the assumed emissions scenario. Huszar et al. (2013) estimated that the CO₂ emissions from global aviation would produce 0.1 °C warming by the end of the century, and an additional 0.1 °C warming would stem from non-CO₂ impacts. More recent estimates from Terrenoire et al. (2019) project that CO₂ emissions from the global aviation sector will be responsible for up to 0.1 °C by the end of the century in the absence of mitigation action.~~

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Here we build on ~~these~~ previous analyses by providing information on the climate benefits over time of all proposed and prospective mitigation strategies to date in terms of expected avoided warming compared to BAU projections. We focus our analysis on international emissions as opposed to total emissions (international and domestic) ~~in order to investigate the impacts of emissions outside of the bounds of the Paris Agreement.~~ We avoid simple metrics, which do not account for continuous emissions nor convey warming impacts over time, by employing a reduced-complexity climate model. We also account for all climate pollutant emissions from aviation and shipping. We consider the proposed target for international shipping paired with current mitigation policies and more stringent potential revisions, along with various pathways for international aviation which include ~~technology and management improvements;~~ current CORSIA targets; an extension of CORSIA; and similar targets as those agreed upon by the shipping industry.

Action by both sectors simultaneously is essential because the economics of transport are intertwined. Moreover, the climate impacts of international aviation and shipping are inextricably linked; the success of each industry in its efforts to limit greenhouse gas emissions could drive down the costs of climate solutions and open up new clean fuel supply chains.

2 Methods

2.1 Business-as-usual eEmissions from international bunkers

We account for present-day and future emissions of both CO₂ and non-CO₂ pollutants from international shipping and aviation in our BAU baseline scenarios. ~~Future-Projected~~ emissions ~~profiles-over time~~ can be found in Figure 1.

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2.1.1 International shipping

International shipping CO₂ emissions data for years 2007 to 2030 are taken from the Third IMO Greenhouse Gas Study (IMO, 2014) and for the years 2030 to 2050 are taken from the Update of Maritime Greenhouse Gas Emission Projections (Hoen et al., 2017). Following the 2015 to 2050 growth trend for international shipping, CO₂ emissions

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are linearly extrapolated through year 2100. These projections include estimated CO₂ emissions reductions associated with the implementation of EEDI and SEEMP. Because estimations of how these programs will impact the non-CO₂ emissions from international shipping are uncertain, they are not included in the baseline emissions profiles for the sector. International aviation CO₂ emissions data for years 2010 to 2040 are taken from Present and Future Trends in Aircraft Noise and Emissions (ICAO, 2016a). Following a declining year-on-year growth rate between years 2020 and 2040, we extrapolate the aviation CO₂ emissions until it reaches 2.5% growth, and then hold that level constant through year 2100. The long term annual CO₂ emissions growth of 2.5% results from assuming an international aviation output growth of 4.5% consistent with Boeing's Commercial Market Outlook 2018-2037 traffic growth average estimate (Boeing, 2018), and a 2% fuel efficiency gain corresponding to ICAO's fuel efficiency aspirational goal.

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Given that there is a range of reasonable growth patterns for aviation emissions in particular (Lee, 2018; Bielvedt Skeie et al., 2009), and our results depend on this baseline, we also ran sensitivity tests to evaluate the influence of different CO₂ BAU projection growth patterns on the perceived avoided warming impacts. The three BAU scenarios considered are an exponential growth rate pattern through 2100 following the 2035-2050 trend, a limited growth rate pattern in which growth rates follow their 2020-2040 declining trend until plateauing at 2.5%, and a declining growth rate pattern in which growth rates follow their 2020-2040 declining trend until plateauing at 0%. Because of uncertainties associated with how the emissions of non-CO₂ pollutants are linked to these different CO₂ growth rates, we focused our sensitivity tests on emissions of CO₂ in particular. We note that all figures in the paper reflect the limited growth pattern for international aviation.

For non-CO₂ emissions, BAU projections for shipping are taken from the RCP Representative Concentration Pathways Database (RCP Database) using the scenario that most closely represents BAU—RCP8.5 (Riahi et al., 2007). Data are available for the historical and projected shipping emissions of methane (CH₄), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO₂), black carbon, and organic carbon. These projections do include progressive reductions to sulfur dioxide emissions associated with the amendments to MARPOL Annex VI, which lead to a 0.5% sulfur dioxide emissions cap. However, we adjust shipping emissions of sulfur dioxide based on the fuel sulfur regulation adopted by IMO in 2018, enforcing a global 0.5% sulfur limit on fuel content (in comparison to the current 3.5% cap). Emissions after 2020 are assumed to drop to a seventh of their estimated values projected by the RCP Database (using the ratio of 0.5/3.5), and the sulfur emissions of the all forcings BAU scenario is also adjusted to reflect these updates. This simplified approach does not consider current Emission Control Areas (ECAs) around the United States, Canada, and the European Union (mandating a cap of 0.1% sulfur) or the potential for ECAs to be declared in additional regions of the world.

2.1.2 International aviation

International aviation CO₂ emissions data for years 2010 to 2050 are taken from Present and Future Trends in Aircraft Noise and Emissions (ICAO, 2019a). We extrapolate the aviation CO₂ emissions for the Low Aircraft Technology and Moderate Operational Improvement Scenario through year 2100 following the 2020 and 2050 trend.

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Given that there is a range of reasonable growth patterns for aviation emissions in particular (Lee, 2018; Skeie et al., 2009), and our results depend on this baseline, we ran a set of sensitivity tests to evaluate the influence of different CO₂ BAU projection growth patterns on the perceived avoided warming impacts. The two sensitivity tests considered are based on an exponential growth rate pattern through 2100 following the 2005-2050 trend for the high and low demand forecasts as depicted in a previous version of Present and Future Trends in Aircraft Noise and Emissions (ICAO, 2013). These emissions estimates are scaled down to calculate the corresponding Low Aircraft Technology and Moderate Operational Improvement Scenarios proportionally to the latest ICAO forecast (2019a), resulting in declining growth rate patterns in which growth rates follow their 2020-2050 declining trend until plateauing at 0% – as is the case for the low demand scenario. These sensitivity tests are analyzed in addition to the Low Aircraft Technology and Moderate Operational Improvement Scenario noted above, for a total of three analyzed BAU scenarios for aviation. Because of uncertainties associated with how the emissions of non-CO₂ pollutants are linked to these different CO₂ growth rates, we focused our sensitivity tests on emissions of CO₂ in particular. The CO₂ emissions profiles used for this sensitivity analysis are shown in Figure 2. We note that all other figures in the paper reflect the Low Aircraft Technology and Moderate Operational Improvement Scenario, which depicts a limited growth pattern for international aviation as this provides a middle of the road estimation.

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~~Given that there is a range of reasonable growth patterns for aviation emissions in particular (Lee, 2018; Skeie et al., 2009), and our results depend on this baseline, we also ran sensitivity tests to evaluate the influence of different CO₂ BAU projection growth patterns on the perceived avoided warming impacts. The three BAU scenarios considered are an exponential growth rate pattern through 2100 following the 2035-2050 trend, a limited growth rate pattern in which growth rates follow their 2020-2040 declining trend until plateauing at 2.5%, and a declining growth rate pattern in which growth rates follow their 2020-2040 declining trend until plateauing at 0%. Because of uncertainties associated with how the emissions of non-CO₂ pollutants are linked to these different CO₂ growth rates, we focused our sensitivity tests on emissions of CO₂ in particular. We note that all figures in the paper reflect the limited growth pattern for international aviation.~~

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Aviation emissions data for black carbon and nitrogen oxides are also taken from the RCP Database using scenario RCP8.5. Given that the RCP data includes emissions projections for both international and domestic aviation, we use historical data from the Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al., 2016) to estimate the percent of total emissions from global aviation attributed to international flights (using the most recent data from 2012). Historical international aviation emissions data for sulfur dioxide and carbon monoxide are taken from the EDGAR database, and are linearly extrapolated for each gas in order to match the growth patterns for the other non-CO₂ climate pollutant emissions associated with aviation. We estimate international aviation organic carbon emissions based on the RCP black carbon data and using the organic to black carbon ratio (0.49) provided by EDGAR for international aviation emissions (Crippa et al. 2016), again adjusted to reflect only the emissions from international flights. The BAU projections for international aviation sulfur dioxide, carbon monoxide, and organic carbon are added to the business-as-usual scenario including all natural and anthropogenic climate forcings all forcings scenario in order to account for their original absence in the RCP8.5 database.

Our analysis does not include the temperature impact of linear contrails and induced cirrus cloudiness from aviation phenomena in which water vapor and impurities released in aircraft exhaust form cirrus-like clouds. These clouds are optically thin and form at high altitudes, leading to a net warming impact that may more than double the positive radiative forcing from the aviation sector (Sausen et al., 2005). While some studies have evaluated the impact of contrails and cloudiness, there is low confidence in our understanding. Whereas improvements to aircraft technology and management practices may reduce the prevalence and thickness of these clouds, for example due to increased fuel efficiency, offsetting programs analyzed here will not affect the amount of contrail and cirrus cloud formation. The inclusion of cloud effects would thus impact the overall observed magnitude of the contribution to future warming from the aviation sector, but it would not affect the estimations of the climate benefits from policies that involve offsetting. There are some circumstances, however, where offsetting schemes include a switch to biofuels, which renders the climate benefits of associated policies more complex (Caiazza et al., 2017; Burkhardt et al., 2018).

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2.2 Mitigation scenarios

The mitigation emissions pathways are developed based on a series of agreed upon, proposed, or prospective policy scenarios for international shipping and aviation (Table 1). For international shipping, we analyze ~~three~~ two mitigation scenarios: (i) IMO's recently agreed upon minimum ambition mitigation target of reducing carbon intensity by at least 40% below 2008 levels by 2030 and total emissions by 50% below 2008 levels by 2050, followed by full decarbonization of the sector; IMO's recently agreed upon minimum ambition mitigation target of reducing emissions by at least 40% and 50% below 2008 levels by 2030 and 2050, respectively, followed by full decarbonization of the sector by the end of the century; and (ii) the maximum ambition scenario consistent with pathways to achieve the 1.5 °C target (IPCC, 2018) in which a 40% reduction in emissions by 2030 is followed by decarbonization of the sector by year 2050; and (iii) a business as usual projection taking into account the full implementation of EEDI and SEEMP between years 2020 and 2100. The first two These scenarios assume a linear reduction in emissions between target years, specifically 2015, 2030, 2050, and 2100 for the minimum ambition target; and 2015, 2030, and 2050 for the maximum ambition target. The third scenario utilizes the emissions reductions estimated by the Assessment of IMO Mandated Energy Efficiency Measures for International Shipping (Bazari and Longva, 2011), under the most rapid emissions reduction scenario, A1B-4. This scenario assumes the IPCC Special Report Emissions Scenario (SRES) of socioeconomic growth A1B, EEDI uptake as described by the regulation, a high uptake rate (60%) of SEEMP, a high fuel price scenario, and a 5% rate of participants waiving EEDI requirements for up to four years.

While these policies are motivated by the intention to reduce emissions of CO₂, non-CO₂ climate pollutant emissions will likely be impacted as well—although how will depend on the specific methods used to achieve the CO₂ targets (Balacombe et al. 2019; Bouman et al. 2017), (which are currently undecided). Therefore, we analyze scenarios in which the CO₂ mitigation methods do not affect other pollutants, and scenarios in which the CO₂ mitigation methods affect other pollutants proportionally; the desire is to capture a range of plausible climate benefits.

Several policy measures have been suggested to reduce carbon dioxide emissions from international aviation. Here we analyze a scenario with emissions reductions associated with the maximum potential contribution of improved aircraft technology and air traffic management—a scenario with emissions reductions necessary in order to maintain a

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cap on net emissions of international flights to year-2020 levels; and four scenarios based on the adoption of CORSIA. The CORSIA-based scenarios include: (i) emissions reductions due to ~~both offsets, and biofuel use, and improvements in aircraft technology and air traffic management~~ through 2035; (ii) an extension of CORSIA through 2100; (iii) full decarbonization of the international aviation sector by 2100 following CORSIA's completion in 2035; and (iv) full decarbonization of the international aviation sector by 2050 following CORSIA's completion in 2035.

~~Data estimating the capacity for current and future technologies and management practices to reduce emissions from aviation are retrieved from the Present and Future Trends in Aircraft Noise and Emissions report (ICAO, 2016a), whose scenarios ICAO updates periodically. This mitigation potential is measured primarily in improvements to fuel efficiency, and are thus expected to proportionally reduce the emissions of all climate pollutants released by the aviation sector.~~

All CORSIA-based scenarios include their maximum potential contribution of improved technology and management (and this maximum potential encompasses the anticipated effects of ICAO's CO₂ standard); however, the CORSIA component of the scenario only affects CO₂ emissions given that this is an offsetting program. Projections for the CO₂ emissions reductions associated with CORSIA through year 2035 are based on the latest list of participating member countries from ICAO (ICAO, 2016b; ICAO, 2019b; ICAO, 2016b; ICAO, 2016c) and using the Environmental Defense Fund's aviation emissions interactive tool (EDF, 2019). While CORSIA aims to offset international aviation emissions to the point of capping emissions at year-2020 levels, country exemptions to the program allows a small portion of emissions above this cap to remain uncovered. Because no policies currently exist to limit the emissions attributed to these exempt countries, emissions projections for the CORSIA – EXT scenario extend their current growth rate through the end of the century. Projections concerning how both biofuel use and the improvements to aircraft technology and air traffic management will contribute to the future emissions of non-CO₂ climate pollutants in the aviation sector are very limited and contain high levels of uncertainty, so this tradeoff is not considered in the presented analysis.

2.3 Climate model

We employ the reduced-complexity climate model, Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) version 6, because of its widespread and prominent use, and its ability to reliably model climate responses to small forcing changes (Meinshausen et al., 2011a; Ocko et al., 2018). Decades of research have been devoted to improving model parameterizations, and model results demonstrate consistency with sophisticated Coupled Model Intercomparison Project CMIP atmosphere-ocean and C⁴MIP carbon cycle models (Meinshausen et al., 2011a).

MAGICC contains a hemispherically averaged upwelling-diffusion ocean coupled to a four-box atmosphere (one over land and one over ocean for each hemisphere) and a carbon cycle model, with an average equilibrium climate sensitivity (ECS) of 3 °C. Between 1765 and 2005, radiative forcings are determined by historical greenhouse gas concentrations (Meinshausen et al., 2011b); prescribed aerosol forcings and land-use historical forcings (National Aeronautics and Space Administration (NASA) GISS model (<http://data.giss.nasa.gov/>)); solar irradiance (Lean et al., 2010); and historical emissions of ozone precursors (Lamarque et al., 2010). After 2005, radiative forcings are calculated from greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, ozone-depleting substances, and their replacements); tropospheric ozone precursor emissions (carbon monoxide, nitrogen oxides, and non-methane

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volatile organic carbon); aerosol emissions (sulfate, black and organic carbon, sea salt, and mineral dust); and the indirect effects (first and second) of aerosols.

Whereas radiative impacts of well-mixed greenhouse gases (such as CO₂ and methane) are fairly well understood due to our knowledge of gas absorption, aerosol radiative effects are more complex and uncertain. This is due to spatial and temporal heterogeneity complicating observations; a variety of possible microphysical and optical properties based on varying sizes, shapes, structures, mixtures, and humidity levels; and interactions with clouds that can impact the lifetime and brightness of the clouds. Given that aerosols are quite relevant to both the aviation and shipping sectors (e.g. Unger et al., 2010), we include their direct and indirect effects in our simulations, noting that caution must be applied in interpreting the results. Aerosol direct forcings are approximated by simple linear forcing-abundance relationships. The indirect effects of sulfate, black carbon, organic carbon, nitrate, and sea salt aerosols are also included. The effect on cloud droplet size is determined by scaling optical thickness patterns of each gas-species (as described by Hansen et al. (2005)) by their respective emissions. The effect of aerosols on cloud cover and lifetime is modeled as a prescribed change in efficacy of the cloud albedo (for full parameterization details, see Meinshausen et al. (2011a)).

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We note that all emissions are treated as surface emissions. Aviation emissions in-flight occur at higher elevations, and this can affect atmospheric chemistry and radiation processes. For example, when sulfate is located above clouds, the radiative efficiency can be halved (less cooling); in contrast, the radiative efficiency of black carbon can be doubled (more warming) when it is located above clouds (Ocko et al. 2012). On the other hand, using more sophisticated climate models that can resolve horizontal and vertical granularities is often complicated by unforced internal variability that makes isolating the climate impact of relatively small radiative perturbations difficult if not impossible (Ocko et al. 2018).

The latest version of MAGICC is not calibrated for inclusion of linear contrails and induced cirrus cloudiness from aviation, phenomena in which water vapor and impurities released in aircraft exhaust form cirrus-like clouds. This is an active area of research and significant progress has been made in recent years to better understand these uncertain processes (e.g. Lee et al. 2009; Schumann et al. 2015; Brasseur et al. 2016; Bock and Burkhardt 2016). In the absence of these parametrizations in MAGICC, we include a sensitivity analysis to show their potential impact on the BAU radiative forcings and temperature responses to aviation.

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We use default MAGICC properties with the exception of a few updates to reflect the most recent state of the science. Specifically, we modify methane's radiative efficiency (accounting for shortwave in addition to longwave absorption) and atmospheric lifetime, and tropospheric ozone's radiative efficiency (Etminan et al., 2016; Stevenson et al., 2013).

Our analysis does not include the temperature impact of linear contrails and induced cirrus cloudiness from aviation, phenomena in which water vapor and impurities released in aircraft exhaust form cirrus-like clouds. These clouds are optically thin and form at high altitudes, leading to a net warming impact that may more than double the positive radiative forcing from the aviation sector (Sausen et al., 2005). While some studies have evaluated the impact of contrails and cloudiness, there is low confidence in our understanding. Whereas improvements to aircraft technology

and management practices may reduce the prevalence and thickness of these clouds, for example due to increased fuel efficiency, offsetting programs analyzed here will not affect the amount of contrail and cirrus cloud formation. The inclusion of cloud effects would thus impact the overall observed magnitude of the contribution to future warming from the aviation sector, but it would not affect the estimations of the climate benefits from policies that involve offsetting. There are some circumstances, however, where offsetting schemes include a switch to biofuels, which renders the climate benefits of associated policies more complex (Caiazzo et al., 2017; Burkhardt et al., 2018).

As with climate models of any complexity level, there are limitations in our knowledge of climate and carbon cycle processes, radiative forcings, and especially indirect aerosol effects, which introduce uncertainties within the model. While MAGICC uses several calibration methods to determine its parameters from a large collection of sophisticated models, the comprehensive models will pass along their own uncertainties to MAGICC. Further, due to MAGICC's relative simplicity, parameters are averaged over large spatial scales. This is particularly important to acknowledge as recent literature has demonstrated that radiative forcings associated with the transport sector can differ based on the regional location at which the transport takes place (Berntsen et al., 2006; Fuglestedt et al. 2014; Kohler et al. 2013; Fromming et al. 2012; Lund et al. 2017; Skowron et al. 2015), particularly for the impact of non-CO₂ emissions.

MAGICC also does not account for vertical differences in gas and aerosol concentrations throughout the atmosphere, instead treating all emissions as surface emissions. This may not be a major issue for the surface level emissions occurring in the shipping industry, but becomes more complex when considering emissions from aviation at various altitudes. For example, when sulfates are emitted above clouds, the radiative forcing is reduced; in contrast, the emission of black carbon above the cloud level would be enhanced (Oeko 2012). While more sophisticated climate models may be able to include this horizontal and vertical granularity, their internal variation make isolating the climate impact of relatively small sectoral perturbations virtually impossible (Oeko 2018). The ability of MAGICC to identify these climate responses make it a compelling choice for this type of small scale analysis.

Other major sources of uncertainty stem from the innate inability to perfectly accurately project future emissions due to uncertainties in both the human and the climate components of prediction. All mitigation scenarios are compared to an estimated baseline, and the social and economic data utilized in order to inform this estimated baseline cannot be expected to perfectly match the unpredictable nature of human action. Further, the large spatial scales and parameterizations involved in climate modeling contribute to some degree of uncertainty. A full discussion of model uncertainties can be found in Meinshausen et al. (2011a).

2.4 Climate model simulations

We run 335_-year-to-year_ integrations from year 1765 to 2100 for a set of 47-14_ different simulations. These simulations are comprised of five BAU pathways and 42-nine_ mitigation pathways based on current and potential policy scenarios within the international aviation and shipping sectors. For future emissions from sectors other than international aviation and shipping, we use RCP8.5 emissions data, but the climate impacts are subtracted out as described below.

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The five BAU scenarios account for the warming impacts due to: all natural and anthropogenic forcings; isolation of the CO₂ emissions from international shipping; isolation of the CO₂ emissions from international aviation; isolation of the CO₂, black carbon, methane, nitrogen oxides, sulfur dioxides, organic carbon, and carbon monoxide emissions from international shipping; and isolation of the CO₂, black carbon, nitrogen oxides, sulfur dioxide, organic carbon, and carbon monoxide emissions from international aviation. The 42-nine mitigation simulations account for the future emissions pathways for the 42-nine policy scenarios outlined in Table 1.

MAGICC also does not account for vertical differences in gas and aerosol concentrations throughout the atmosphere, instead treating all emissions as surface emissions. This may not be a major issue for the surface level emissions occurring in the shipping industry, but becomes more complex when considering emissions from aviation at various altitudes. For example, when sulfates are emitted above clouds, the radiative forcing is reduced; in contrast, the emission of black carbon above the cloud level would be enhanced (Oeko 2012). While more sophisticated climate models may be able to include this horizontal and vertical granularity, their internal variation make isolating the climate impact of relatively small sectoral perturbations virtually impossible (Oeko 2018). The ability of MAGICC to identify these climate responses make it a compelling choice for this type of small scale analysis.

In order to isolate sector emissions in each BAU and mitigation scenario, we subtract the total emissions of all gases and aerosols associated with each sector from the total RCP8.5 emissions of all gases and aerosols in the all-forcing scenario driven by all natural and anthropogenic forcings (Eq. 1). The annual average mean surface temperature changes from these emissions profiles are subtracted from the temperature changes in the all-forcings scenario in order to determine the contribution to future temperature change from each sector (Eq. 2). It is important to note that the background temperature response to other forcings (anthropogenic and natural) can affect the temperature responses to shipping and aviation. Therefore, even though they are ultimately subtracted out in our calculation, they do impact our results, and uncertainties in BAU emissions from other sectors and the resulting temperature effects need to be acknowledged.

$$Emissions_{all-forcings\ without\ sector} = Emissions_{all-forcings} - Emissions_{sector} \quad (1)$$

$$\Delta T_{sector} = \Delta T_{all-forcings} - \Delta T_{all-forcings\ without\ sector\ emissions} \quad (2)$$

The comparison of each sector's baseline scenario to its respective mitigation scenarios are analyzed independently from other potential mitigation efforts that may occur in the future. Thus, isolating the temperature impacts of a given mitigation scenario does not mandate that all other anthropogenic emissions continue unabated. The same methodology can be used to isolate temperature changes due to individual gases or aerosols for each sector.

$$Emissions_{all-forcings\ without\ sector} = Emissions_{all-forcings} - Emissions_{sector} \quad (1)$$

$$\Delta T_{sector} = \Delta T_{all-forcings} - \Delta T_{all-forcings\ without\ sector\ emissions} \quad (2)$$

MAGICC also does not account for vertical differences in gas and aerosol concentrations throughout the atmosphere, instead treating This may not be a major issue for the surface level emissions occurring in the shipping industry, but becomes more complex when considering emissions from aviation at various altitudes.

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3 Results

3.1 BAU warming climate responses

Both the shipping and aviation sectors emit a combination of warming and cooling climate pollutants and precursors. The net temperature impact depends on the magnitude of emissions, the radiative efficiencies, and the atmospheric lifetimes of the individual species. CO₂ builds up in the atmosphere over time and thus its forcing increases gradually with constant emissions, whereas short-lived species such as all aerosols would yield constant annual forcings with constant emissions. Given that we are analyzing climate impacts of future emissions from international aviation and shipping (year 2020 through 2100), the near-term radiative forcings (defined as the forcing at the tropopause after stratospheric temperature adjustment) are dominated by non-CO₂ pollutants and the long-term radiative forcings are dominated by CO₂ (Figure X3).

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The net radiative forcing for international shipping is -47 mW m⁻² in 2020 and +48 mW m⁻² in 2100. The shift from negative to positive is due to the large increase in CO₂ emissions and their accumulation over time in the atmosphere. A considerable amount of the positive radiative forcing from CO₂ emissions in 2100 (+127 mW m⁻²) is offset by a relatively large negative radiative forcing in 2100 from NO_x emissions (-66 mW m⁻²). Net radiative forcing due to NO_x emissions is a combination of negative and positive radiative forcings from indirect effects; negative forcings arise from reductions in methane, production of nitrate, and nitrate's effect on clouds, and positive forcings arise from production of tropospheric ozone. Indirect aerosol effects from all species yield a radiative forcing of -32 mW m⁻² in 2100.

Radiative forcings derived in this study from shipping emissions of CO₂ and NO_x are consistent with the literature. Previous estimates of CO₂'s present-day (early 2000s) impact range from +26 to +43 mW m⁻², corresponding to emissions of 500 and 800 TgCO₂ yr⁻¹ (Eyring et al. 2010). This is consistent with this analysis when accounting for the anticipated growth in CO₂ emissions of more than fivefold by 2100 since the early 2000s (IMO, 2014). Previous studies estimate radiative forcings from NO_x that range from +8 to +41 mW m⁻² for indirect effects on tropospheric ozone (compared to our value of +25 mW m⁻² in 2100) and -56 to -11 mW m⁻² for indirect effects on methane (compared to our value of -22 mW m⁻² in 2100) for present-day emissions around 2.9 to 6.5 TgN yr⁻¹ (we assume NO_x emissions of 5.6 TgN yr⁻¹ in year 2100) (Eyring et al. 2010). For SO₂ emissions from shipping, previous studies estimate direct radiative forcings from -47 to -12 mW m⁻² due to production of sulfate; our estimate is -14 mW m⁻² in 2100 from emissions that are lower (2.0 TgS yr⁻¹) than present-day values in the literature (3.4 to 6.0 TgS yr⁻¹) (Eyring et al. 2010). Our estimate of direct radiative forcing from black carbon (+5 mW m⁻² in 2100 from emissions of 0.2 TgBC yr⁻¹) is slightly higher than estimates in the literature (+1.1 to +2.9 mW m⁻² in 2000/2005 from emissions of 0.05 to 0.2 TgBC yr⁻¹) (Eyring et al. 2010). Indirect effects of aerosols have enormous ranges in estimates in the literature (Righi et al. 2011), but we note that our estimate appears to be on the lower end.

The net radiative forcing for international aviation emissions (note: not including impacts on contrails and cirrus clouds) is -1.4 mW m^{-2} in 2020 and $+62 \text{ mW m}^{-2}$ in 2100. Although radiative forcings are smaller for CO_2 for aviation compared to shipping, due to slightly less emissions, there are proportionally less emissions of the negative forcing precursors NO_x and SO_2 , yielding higher net radiative forcing from aviation. As with the shipping forcings, the large CO_2 radiative forcing in 2100 ($+87 \text{ mW m}^{-2}$) is partially offset by the strong negative forcing from NO_x emissions (-24 mW m^{-2}). Indirect aerosol effects from all species yield a radiative forcing of -10 mW m^{-2} in 2100.

Estimates of present-day radiative forcing from aviation in the literature include both domestic and international emissions, whereas our estimates of future radiative forcings exclude domestic travel. Our estimates of radiative forcing from CO_2 emissions are in agreement with previous estimates when accounting for different emissions inputs (such as $+87 \text{ mW m}^{-2}$ in 2100 from emissions of $37003670 \text{ TgCO}_2 \text{ yr}^{-1}$ compared to $+28 \text{ mW m}^{-2}$ in 2005 from emissions of $641 \text{ TgCO}_2 \text{ yr}^{-1}$ in Lee et al. (2009)). Our estimates for radiative forcings from NO_x , SO_2 (direct), and black carbon (direct) are slightly smaller than what is presented in the literature, despite larger emissions projected for year 2100 compared to present-day, but there are large uncertainties associated with these estimates and a low level of scientific understanding (Sausen et al., 2005; Fuglestedt et al., 2008; Lee et al., 2009). For example, Brasseur et al. (2016) estimate $+6$ to $+37 \text{ mW m}^{-2}$ for indirect effects of NO_x emissions on tropospheric ozone (compared to our value of $+11 \text{ mW m}^{-2}$ in 2100) and -8 to -12 mW m^{-2} for indirect effects on methane (compared to our value of -8 mW m^{-2} in 2100). Gettelman and Chen (2013) conduct a more sophisticated assessment of the climate impact of aviation aerosols than what is presented here, and report an estimate of -46 mW m^{-2} from combined sulfate direct and indirect effects; this is considerably larger than our estimate of -3 mW m^{-2} in 2100.

~~Ambition for the proposed and agreed upon mitigation policies within the international shipping and aviation sectors is based on the need to cut CO_2 emissions from each sector. We thus isolate the climate impacts from the CO_2 emissions in addition to the net effect from all emitted climate pollutants. Radiative forcings directly impact temperatures – a net positive forcings has a warming tendency, and a net negative forcing has a cooling tendency. Figures 34 and 5 shows the temperature responses over time to projected emissions from both sectors. Given that the~~
Ambition for the proposed and agreed upon mitigation policies within the international shipping and aviation sectors is based on the need to cut CO_2 emissions from each sector, we. We thus isolate the climate temperature impacts from the CO_2 emissions in addition to the net effect from all emitted climate pollutants.

Figure 2a-4a shows the impact of future international shipping emissions (beginning in 2020) on surface air temperature change throughout the 21st Century. In the year 2020, the impact on temperature represents the contribution from that years' worth of emissions only, and then every year forward represents the cumulative effect as some pollutants build up in the atmosphere over time from continuous emissions. While CO_2 's effect is always that of warming, and grows over time from both growing emissions as well as accumulating concentrations due to CO_2 's long atmospheric lifetime, the inclusion of all climate pollutants introduces-yields a net cooling effect in the near-term consistent with the net negative forcings discussed above. It isn't until 2060-the 2080s that shipping's net effect shifts to warming. This is consistent with Unger et al. (2010), who show strong near-term cooling tendencies from the shipping sector that lessen over time as CO_2 builds up in the atmosphere. However, note that their study analyzed

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perpetual year-2000 emissions and not a BAU scenario. This is also consistent with Fuglestedt et al. (2009), which predicts that the accepted regulations in the shipping sector's emissions of sulfur dioxide and nitrogen oxides will lead to the sector having a net cooling effect for about 70 years, after which the sector switches to warming. Our analysis predicts a slightly more rapid shift to warming (after about 65 years in 2085), likely due to our inclusion of the warming climate pollutant black carbon which are not featured in the analysis by Fuglestedt et al. (2009).

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Based on our BAU projections, future CO₂ emissions from international shipping result in an additional warming of 0.07 °C by year 2100. However, when all pollutants are considered, the net warming from shipping in 2100 drops to 0.03-01 °C due to the net warming and cooling effects from non-CO₂ pollutants (Figure 2a4a).

For the year 2100, the temperature impacts attributed individually to emissions of CO₂, black carbon, methane, nitrogen oxides, sulfur dioxide, organic carbon, and carbon monoxide are shown in Figure 3a4b. The indirect effects of aerosols are included in the analysis of the temperature impacts for each isolated pollutant. Specifically, shipping's cooling effect, which offsets CO₂'s warming effect, is dominated by the cooling pollutant precursor nitrogen oxides. The net cooling from nitrogen oxides arises from nitrate production formation, indirect aerosol effects from nitrates, formation of tropospheric ozone, reduction of methane, and the combined direct and indirect effects of nitrate and effects of the net forcings on the carbon cycle (cooling in the ocean suppresses CO₂ diffusion from the ocean into the atmosphere). Given that sulfur dioxide emissions—a precursor to the cooling pollutant sulfate—are projected to decrease significantly due to the sulfur fuel regulation newly adopted by IMO, sulfur dioxide from shipping does not contribute significantly to cooling contributes less significantly to cooling. Recent studies have demonstrated the potential for low-sulfur shipping scenarios to reduce the indirect aerosol effect from shipping sulfur emissions (Lauer et al., 2009; Righi et al. 2011). In fact, implementation of this sulfur regulation from 2020 through the end of the century increases warming from the shipping industry by 0.02 °C by year 2100 when compared to a case without the regulation, at which point nitrogen oxides are responsible for a cooling of 0.05 °C. However, the remaining emissions of sulfur dioxide from the shipping sector throughout the century are still responsible for about 0.02 °C cooling by year 2100.

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While BAU organic carbon, carbon monoxide, and methane, in addition to sulfur dioxide, have nearly negligible contributions to shipping's influence on end of century temperatures, shipping's black carbon emissions are responsible for 0.01 °C warming and add to CO₂'s warming effects (Figure 3a4b). We note that for both sectors, our calculations assume no change in the geographical distribution of emissions. Recent literature has demonstrated that the location of non-CO₂ emissions can have a large influence on their subsequent climate impact (Fuglestedt et al. 2014; Kohler et al. 2013; Fromming et al. 2012; Lund et al. 2017; Skowron et al. 2015).

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Figure 52ab shows the impact of future international aviation emissions (beginning in 2020) on surface air temperature change throughout the 21st Century. The contribution of CO₂ emissions to future warming over time and in the year 2100 is comparable slightly lower than that from the shipping sector (0.08-05 °C by 2100). However, the inclusion of non-CO₂ climate pollutant emissions does not yield a net cooling effect for several decades as they do with shipping, and only reduces warming by end of century to 0.06-03 °C (note that we do not include here the impacts on contrails

and cirrus clouds). For a few years, the net temperature impact from future aviation emissions is cooling, but then quickly switches to warming and increases steadily through the end of the century (consistent with radiative forcing calculations in Unger et al. (2010) for constant year-2000 emissions). Similar to shipping, the cooling effect is dominated by the cooling precursor gas nitrogen oxide (Figure 3b5b). By 2100, nitrogen oxides are responsible for a cooling of 0.02 °C, while the end of century contribution from all other non-CO₂ climate pollutants (sulfur dioxide, organic carbon, carbon monoxide, and black carbon) are negligible. Recall that the indirect effects of aerosols are included in the analysis of the temperature impacts for each isolated pollutant. We note that some studies have investigated the effect of aviation soot on natural cirrus clouds (Penner et al., 2019) or the effect on warm clouds (Gettelman and Chen, 2013; Righi et al., 2013; Kapadia et al., 2016). MAGICC does take into account indirect effects of soot, such as simplified parameterizations of impacts on cloud brightness and lifetime, but does not include more sophisticated treatments as analyzed in previous studies, and that we do not address impacts of aviation on cloudiness, which is considered to significantly add to the warming impacts of aviation.

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Our projections for the contribution to future warming from international shipping and aviation are ~~in agreement~~ slightly lower than with the estimated range for each sector's 2100 share of warming estimated in ~~Bielvedt-Skeie et al. (2009)~~. Our estimate of international aviation's contribution to warming is ~~slightly lower below than~~ the 0.11 °C to 0.28 °C range, but ~~Bielvedt-Skeie et al. (2009)~~ analyzed combined domestic and international transport emissions. Further, the new emissions projections generated by ICAO in 2019 suggest lower projected emissions from aviation over the next century (ICAO 2019). Our shipping warming impact estimates are at the lower end of the -0.01 °C to 0.25 °C range, attributed to differences in methodology discussed below.

First, our model includes indirect aerosol effects, particularly the climate impact associated with nitrogen oxides' creation/production of nitrate aerosols, which yield negative forcings that are not considered in the analysis by ~~Bielvedt-Skeie et al. (2009)~~. This inclusion also explains why nitrogen oxides yield net cooling impacts in our analysis, while they yield net warming impacts by ~~Bielvedt-Skeie et al. (2009)~~, due mainly to warming from the production of tropospheric ozone not canceled out by cooling from indirect effects.

Second, our shipping estimates are also lower because ~~Bielvedt-Skeie et al. (2009)~~ only consider the emissions of CO₂, nitrogen oxides, and sulfur dioxide for each sector, and emissions profiles are based on ~~outdated-older~~ projections. In particular, the projected emissions of CO₂ and nitrogen oxides in ~~Bielvedt-Skeie et al. (2009)~~ are both higher than our projected emissions (which both yield more warming impacts in the absence of indirect aerosol effects), while their emissions of sulfur dioxide are lower than our projections (which means less cooling from sulfate). Acknowledging these differences in methodology, we observe the same general warming trends within our scenarios and the literature, where aviation emissions exhibit an increasing net warming effect, while shipping emissions result in a declining cooling trend until ~~after midcentury~~ the end of the century.

In the RCP scenarios presented by Lund et al. (2012), shipping is projected to cause a cooling of between -0.02 and -0.04 °C by midcentury. Our analysis estimates that shipping is responsible for -0.03 °C in year 2050, which falls within this range. Further, the authors' findings are in agreement with those presented in this analysis through their

observation of warming later in the century once the accumulating CO₂ emissions impact overruns the cooling impact of nitrous oxides and sulfur dioxide, particularly due to the reduced sulfur dioxide emissions associated with the implemented fuel regulations.

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Our estimates for the contribution to global average temperature in year 2100 from the aviation sector's CO₂ emissions of 0.05 °C falls at the lower end of the range presented by Terrenoire et al. (2019), between 0.04 °C and 0.1 °C, based on a set of eight CO₂ emissions projections contrasting in traffic growth and efficiency gains. We note that this analysis includes the impact of both domestic and international aviation. Our estimate of the impact of the aviation sector is also less than that of Huszar et al. (2013), at 0.2 °C or 0.1 °C with and without the impact of the non-CO₂ signal, respectively. This analysis also does not account for aviation-produced aerosols and does include the impact of water vapor emissions (as well as that of contrail-cirrus), leading to an elevated warming associated with the sector in comparison to our analysis.

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Our model does not include radiative effects from linear contrails nor contrail induced cirrus cloudiness. Although studies suggest a low level of scientific understanding for climate impacts of linear contrails and a very low level of scientific understanding of induced cirrus cloudiness (Lee et al. 2009), considerable work has been made recently towards improving our understanding of these effects. Estimates of the present-day radiative impact of linear contrails range from +3 to +12 mW m⁻² (Lee et al. 2009; Brasseur et al. 2016), and of cirrus cloudiness range from +12 to +63 mW m⁻² (Lee et al. 2009; Schumann et al. 2015; Brasseur et al. 2016; Bock and Burkhardt 2016); for context, this is compared to around 30 mW m⁻² from CO₂ emissions – note these values are for both domestic and international aviation. As air traffic rates increase, we expect the radiative forcings from contrails and changes in cirrus cloudiness to increase as well; Bock and Burkhardt (2019) suggest an increase in contrail cirrus radiative forcing by a factor of three from present-day through 2050, due to increases in air traffic and also a slight shift towards higher altitudes.

Without growth in air traffic, inclusion of these effects would increase our radiative forcing estimates in 2100 by 15 to 75% based on the lower and upper estimates of both linear contrails and cirrus cloudiness. Assuming a fivefold growth in air traffic from 2005 to 2100, our radiative forcing estimate from international aviation could increase by 75 to 350%. The resulting impact on temperature responses to BAU international aviation could therefore be considerably higher than our projection of 0.05 °C in 2100: 0.06 to 0.09 °C based on current air traffic patterns and 0.09 to 0.23 °C for a fivefold increase in air traffic.

3.2 Avoided warming from mitigation measures

The policy scenarios analyzed have significant potential to reduce the future temperature impacts associated with emissions from the international shipping and aviation sectors (Figure 46). The IMO greenhouse gas target of a 50% reduction in CO₂ emissions below 2008 levels by 2050 and full decarbonization of the industry by 2100 results in an avoided future warming of 0.06 °C by 2100. This avoided warming reduces the shipping sector's contribution to future warming from CO₂ by more than almost 85% at the end of the century. A more stringent mitigation scenario in which decarbonization is achieved by midcentury (consistent with a 1.5 °C warming cap) increases avoided warming to 0.07

°C by 2100, or almost 100% of the original unabated contribution to warming from the sector's CO₂ emissions. ~~Suggested policies to achieve long-term targets such as the implementation of EEDI and SEEMP have the potential to reduce future warming by 0.04 °C by 2100, about 40% of the BAU end-of-century warming from the shipping sector's CO₂ emissions.~~

5 Because the non-CO₂ climate pollutants emitted by the shipping sector yield a net cooling, the scenarios that reduce their emissions proportional to the reductions in CO₂ outlined in each policy increase each scenario's contribution to future warming and consequently reduce their relative avoided warming. Specifically, ~~both~~ the IMO minimum and maximum ambition greenhouse gas targets reduce the anticipated BAU warming from the shipping sector by about 0.023 °C and 0.01 °C by the end of the century, respectively (in comparison to 0.06 °C and 0.07 °C in the CO₂-only scenarios, respectively). ~~The EEDI/SEEMP, ALL PRODUCTS scenario reduces the anticipated warming by about 0.01 °C by the end of the century, in comparison to 0.04 °C when only considering CO₂ emissions reductions.~~ We expect that the true warming mitigation provided by these policies lies within these bounds.

The various mitigation scenarios outlined in Table 1 for the international aviation sector result in an avoided future warming of 0.01 °C to 0.07-05 °C by 2100, relative to a BAU baseline. ~~Aircraft technology and air traffic management improvements alone account for an avoided warming of 0.01 °C by the end of the century (over 12% reduction of warming from a CO₂ BAU baseline). The most aggressive mitigation policy, completing CORSIA followed by decarbonization of the sector by 2050, results in an avoided warming of 0.07 °C by 2100 (over 87% reduction of warming from a CO₂ BAU baseline).~~ Full implementation of CORSIA under current guidelines (ending in 2035 and then allowing emissions to increase along a business-as-usual pathway) results in an avoided warming of 0.02-01 °C by 2100 (a 25-20% reduction of warming from a CO₂ BAU baseline). However, extending CORSIA's offsetting and reduction program through the end of the century more than doubles the climate benefit (0.05-02 °C avoided warming), avoiding about 60-40% of the CO₂ BAU baseline warming. The scenario that follows CORSIA and then decarbonizes the sector by year 2100 (CORSIA-DECARB2100) reduces future warming by 0.07-04 °C by end of century, avoiding about 8-nearly 90% of the CO₂ BAU warming. ~~The most aggressive mitigation policy, completing CORSIA followed by decarbonization of the sector by 2050, results in an avoided warming of 0.075 °C by 2100 (over about a 87-90% reduction of warming from a CO₂ BAU baseline).~~ The avoided warming in year 2100 associated with each investigated policy scenario for the emissions mitigation of international shipping and aviation are outlined in Figure 57.

30 The warming mitigation potential of the various policy scenarios associated with aviation were evaluated based on three CO₂ BAU growth patterns: ~~an exponential growth pattern, a limited growth rate pattern, and a declining growth rate pattern.~~ While the BAU pathway dictates the magnitude of projected future warming, ~~it does not drastically change the fraction of warming avoided by each policy scenario because the associated~~ avoided warming from each policy scenario is relative to the BAU baseline. For international aviation, in comparison to the 0.08-05 °C contribution to future warming from CO₂-only expected from the ~~limited-central~~ growth rate pattern, 0.102 °C and 0.06-02 °C of

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future warming are expected from the emission of CO₂ in the ~~exponential-upper~~ and ~~declining-lower~~ emissions growth rate patterns, respectively. The mitigation scenario that mimics the structure of the IMO minimum ambition greenhouse gas target (CORSIA – DECARB2100), ~~for example~~, is expected to reduce the warming attributed to the emissions of CO₂ from the sector by 0.07–0.04 °C by end of century in the limited growth rate pattern, and is expected to avoid 0.44–0.09 °C and 0.06–0.01 °C by end of century in the ~~exponential-upper~~ and ~~declining-lower~~ growth rate patterns, respectively. These avoided temperatures from the ~~exponential-upper~~, ~~limited-growth-central~~, and ~~declining-lower~~ growth scenarios represent 9287%, 8884%, and 8666% of the unabated warming levels from CO₂ emissions, respectively. ~~Thus while~~ While the expected BAU warming from the sector’s CO₂ emissions vary significantly between each pattern of growth, the potential to reduce this warming through proposed, stringent mitigation scenarios scales proportionally for the two higher emissions growth rate scenarios. In contrast, the BAU lower growth scenario demonstrates a future in which emissions remain relatively close to 2020 levels throughout the century. Because the most stringent policy scenarios investigated in this analysis focus on emissions reductions taking place in mid-to late-century, a lower percent warming reduction is observed for each policy within the lower growth scenario in comparison to the upper and central scenarios.^y.

~~Although we do not expect that the offsetting programs analyzed here will affect the amount of contrail and cirrus cloud formation, and therefore will not impact the avoided warming potential, improvements to aircraft technology and management practices may reduce the prevalence and thickness of these clouds, for example due to increased fuel efficiency. Similarly, we do not consider the reduction of non-CO₂ climate pollutants emitted by the aviation sector as the primary focus of the analyzed-in the mitigation scenarios. is the implementation of offsetting schemes and decarbonization of the sector.~~ However, offsetting schemes such as CORSIA do implement the use of biofuels and aircraft technology and air traffic management improvements, both of which have the potential to impact future emissions of non-CO₂ climate pollutants and the density of contrail cirrus (Bock and Burkhardt 2019; Caiazzo et al., 2017; Burkhardt et al., 2018). While the influence of these changes on the non-CO₂ impact of international aviation is currently not well-estimated, their impact should be ~~included~~ considered in future analyses as understanding develops.

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4 Conclusions

Quantifying the temperature impacts of future international aviation and shipping emissions—both for business-as-usual pathways and mitigation scenarios—is essential to understanding the benefits of proposed policies and targets. Given that international aviation and shipping are important contributors to the emission of climate pollutants, earlier studies have analyzed their current and BAU future climate impacts using a variety of methods. To build upon these previous analyses, we ~~investigated-analyzed~~ the climate benefits over time associated with accepted, proposed, and prospective mitigation policies for each sector. We use a reduced complexity climate model to determine the BAU temperature contribution due to the future emissions of international aviation and shipping from all emitted climate pollutants, and the potential to avoid future warming based on a series of realistic mitigation scenarios.

Using the reduced complexity climate model MAGICC, we estimate that under BAU conditions, the future CO₂ emissions (2020 through end of century) from the international shipping and aviation sectors would be responsible for 0.07-0.07 °C and 0.08-0.05 °C of future warming by 2100, respectively (0.03-0.01 °C and 0.06-0.03 °C, respectively, when including the sectors' emissions of non-CO₂ climate pollutants; ~~additional note that we do not include impacts of aviation induced contrails and clouds~~ inclusion of aviation induced contrails and clouds could increase ~~this~~ the warming associated with international aviation by up to ~~X~~600%). Planned and proposed mitigation policies in each sector that specifically target CO₂ emissions have the potential to significantly reduce this climate impact. However, policies that target the mitigation of non-CO₂ climate pollutants, often through air quality management, result in emissions reductions that may not always avoid future warming (Kapadia et al., 2016; Sofiev et al., 2018; Yim et al., 2015). For example, if the emissions of all shipping-produced cooling agents (sulfur dioxide, nitrogen oxides, and organic carbon) were immediately halted and the shipping sector successfully decarbonized by midcentury, the sector would increase the world's temperatures through the end of the century (Fuglested et al. 2009).

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Given that we have already reached a global warming level of around 1 °C above preindustrial levels (IPCC, 2018), there is an "allowable warming" of 0.5 to 1.0 °C additional warming should we wish to stabilize at the 1.5 °C or 2 °C thresholds, respectively. Together, future warming from the CO₂ emissions of international shipping and aviation reach about 0.45-1.2 °C by the end of the century, which is ~~45-12~~ 30-24% of this remaining "allowable warming." However, certain policy measures have the potential to significantly avoid the vast majority of this future warming. The IMO minimum ambition greenhouse gas target (decarbonize the sector by 2100) and its mirrored aviation scenario (CORSIA offsetting program extended followed by decarbonizing by 2100) have the potential to reduce future warming associated with the CO₂ emissions from each sector by more than 80%, with even further reductions should both sectors decarbonize by midcentury in comparison to 2100 (a trajectory consistent with achieving 1.5 °C maximum warming).

For context, achieving the Paris Agreement committed pledges and targets are projected to avoid 0.3 °C warming by end of century compared to current policies (CAT, 2019). Adding the avoided warming from the already agreed upon international shipping target of decarbonization by end of century (0.06 °C) and the extension of the CORSIA aviation offsetting program (0.05-0.2 °C) increases this potential by over ~~35~~ 25%. Further, pursuing the most ambitious, yet feasible, mitigation measures for international shipping and aviation could increase the avoided warming from the Paris Agreement by nearly 50%. Overall, the proposed and prospective mitigation measures for both of these sectors have considerable climate benefits in the context of achieving international temperature goals.

30 Code availability

The MAGICC v6 model executable is available for download at: <http://www.magicc.org/download> upon registration, although the model itself is closed source. The user manual can be accessed at: http://wiki.magicc.org/index.php?title=Manual_MAGICC6_Executable. Full model details along with nineteen sets of AOGCM-calibrated parameters used here for ensemble members are found in Meinshausen et al. (2011a). We

update the default values of methane and tropospheric ozone radiative efficiency and methane atmospheric lifetime to values in Myhre et al. (2013) and Etminan et al. (2016).

Data availability

Results from the MAGICC model are available from Catherine Ivanovich (civanovich@edf.org) upon request.

5 Author contributions

Catherine Ivanovich and Ilissa Ocko designed the experiments and Catherine Ivanovich carried them out. Annie Petsonk and Pedro Piris-Cabezas curated data and provided guidance on the policies. Catherine Ivanovich and Ilissa Ocko prepared the manuscript with contributions from all co-authors.

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	Mitigation scenario description	Abbreviation
Aviation	Cap emissions at 2020 levels. Aircraft technology and air traffic management improvements	CAPAT/ATM
	CORSIA (including offsets, biofuel use, and improvements to aircraft technology and air traffic management) ends after 2035, followed by business-as-usual emissions growth. Cap emissions at 2020 levels	CORSIA-CAP
	CORSIA emissions reductions sustained through 2100. CORSIA (including offsets and biofuel use) ends after 2035, followed by business-as-usual emissions growth	CORSIA - EXT
	CORSIA ends in 2035, followed by decarbonization in 2100. CORSIA emissions reductions sustained through 2100	CORSIA - DECARB2100
	CORSIA ends in 2035, followed by decarbonization in 2050. CORSIA ends in 2035, followed by decarbonization in 2100	CORSIA - DECARB2050
Shipping	IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; does not affect non-CO ₂ pollutants. CORSIA ends in 2035, followed by decarbonization in 2050	IMO - MIN AMBITION, CO ₂ ONLY CORSIA - DECARB2050
	Linear decrease in emissions starting in 2020, leading to decarbonization in 2050; does not affect non-CO ₂ pollutants. Implementation of EEDI and SEEMP policies through 2100; does not affect non-CO ₂ pollutants	IMO - MAX AMBITION, CO ₂ ONLY EEDI/SEEMP, CO ₂ -ONLY
	IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; proportional emissions reductions for all non-CO ₂ pollutants. IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; does not affect non-CO ₂ pollutants	IMO - MIN AMBITION, ALL POLLUTANTS IMO - MIN AMBITION, CO ₂ ONLY
	Linear decrease in emissions starting in 2020, leading to decarbonization in 2050; proportional emissions reductions for all non-CO ₂ pollutants. Linear decrease in emissions starting in 2020, leading to decarbonization in 2050; does not affect non-CO ₂ pollutants	IMO - MAX AMBITION, ALL POLLUTANTS IMO - MAX AMBITION, CO ₂ ONLY
	IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; proportional emissions reductions for all non-CO ₂ pollutants	IMO - MIN AMBITION, ALL POLLUTANTS

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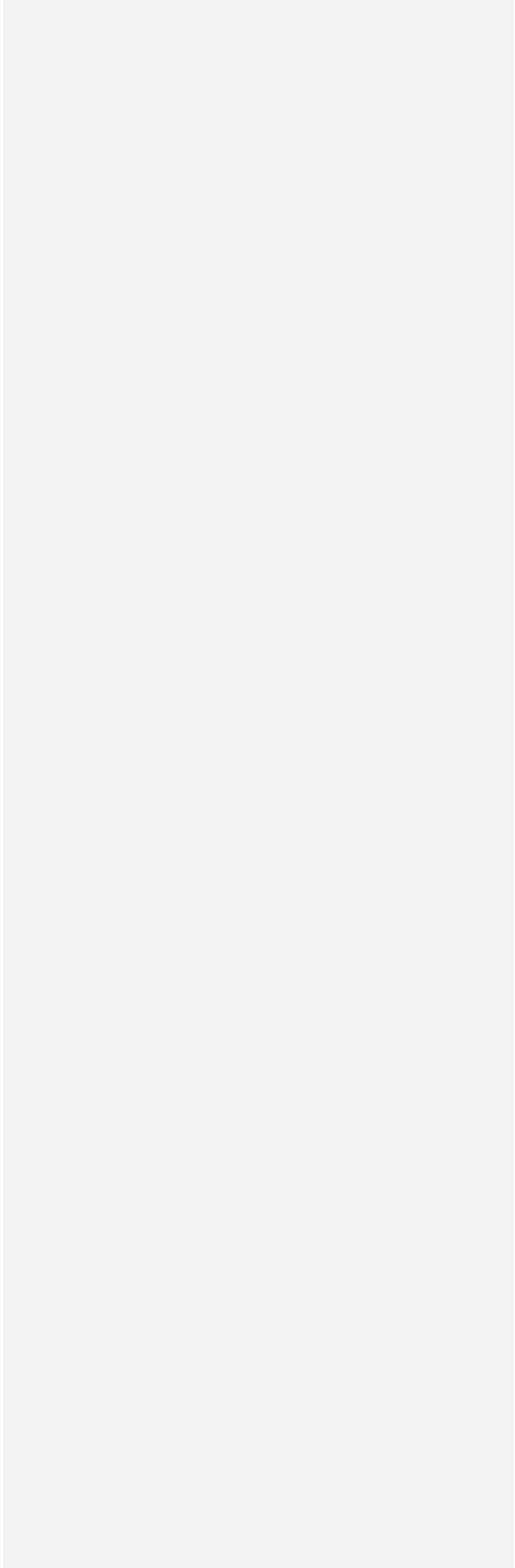
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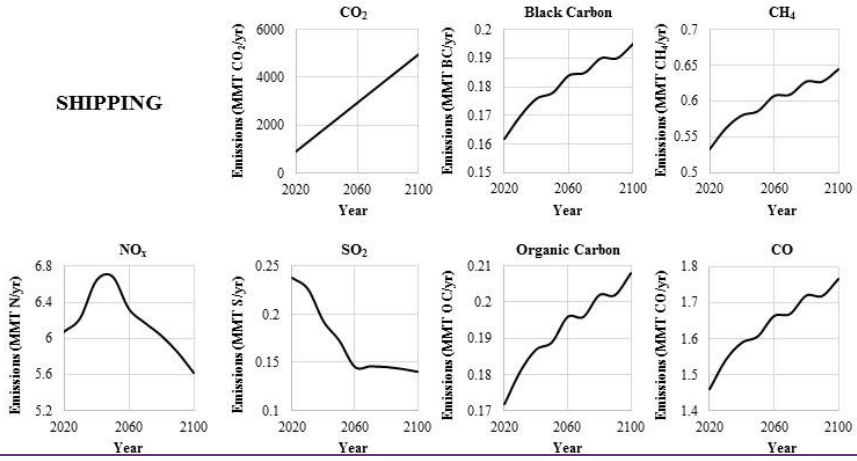
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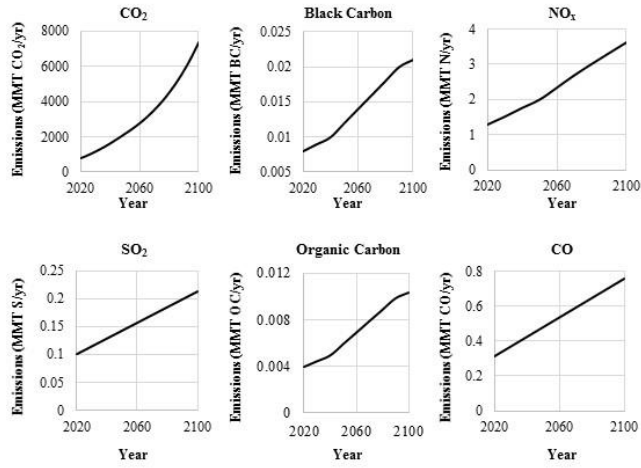
Table 1: Descriptions of mitigation scenarios analyzed in this study for international aviation and shipping.

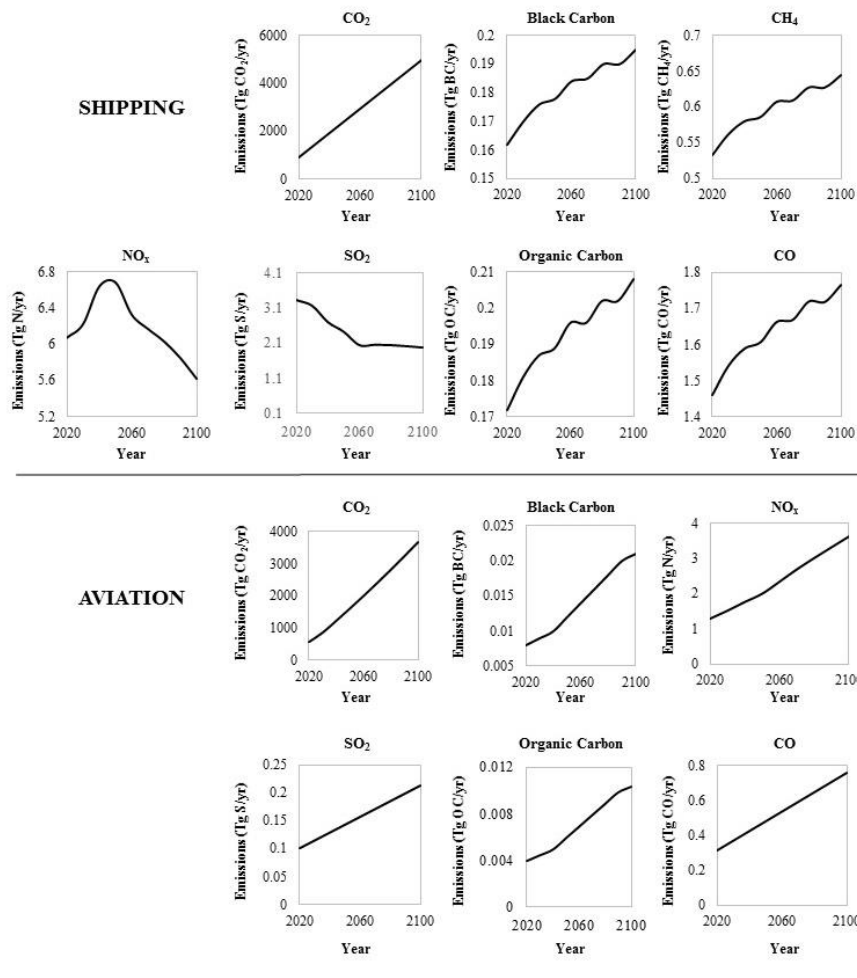


SHIPPING



AVIATION

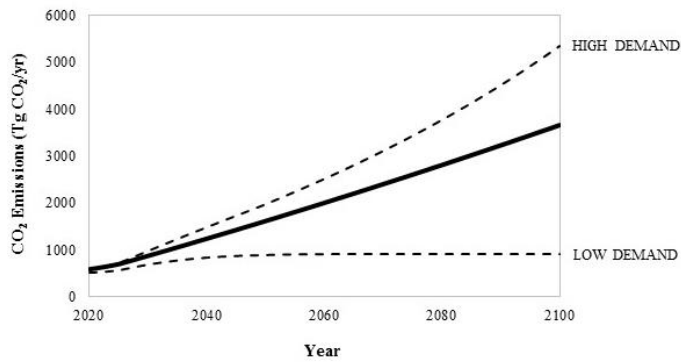




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Figure 1: Projected future emissions from international shipping and aviation. Shipping CO₂ emissions data from Third IMO Greenhouse Gas Study (IMO 2014) and the Update of Maritime Greenhouse Gas Emission Projections (Hoen et al. 2017). Aviation CO₂ emissions data from [Present and Future Trends in Aircraft Noise and Emissions \(ICAO, 2019\)](#) and [Present and Future Trends in Aircraft Noise and Emissions \(ICAO 2016\)](#). Both datasets end in 2050; shipping data is linearly extrapolated through year 2100 and aviation data utilizes the described limited-growth extrapolation after 2040 through year 2100. Aviation black carbon and NO_x emissions and shipping black carbon, CH₄, NO_x, SO₂ (adjusted based on IMO's recently adopted sulfur fuel regulation), organic carbon, and CO extracted from RCP Database for the RCP8.5 scenario. Aviation SO₂ and CO are linearly extrapolated from the EDGAR dataset, and aviation organic carbon emissions are derived from their relationship with black carbon emissions.

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5 Figure 2: Projected future emissions from international aviation used for sensitivity analysis. The sensitivity tests (dashed lines) are based on an exponential growth rate pattern through 2100 following the 2005-2050 trend for the high and low demand forecasts as depicted in a previous version of Present and Future Trends in Aircraft Noise and Emissions (ICAO, 2013).

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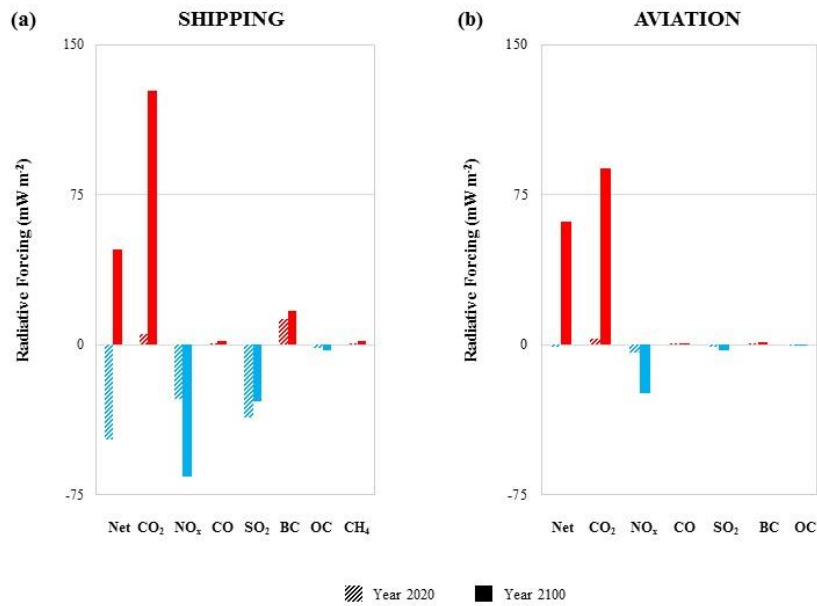


Figure 3: Contribution of future emissionsemitants to radiative forcing in 2100 change- (defined as the forcing at the tropopause after stratospheric temperature adjustment) since preindustrial times associated withfrom business-as-usual emissions starting in 2020 and continuing through the end of the century from a) international shipping and b) international aviation. Radiative forcings are presented for year 2020 (hashed), which represent forcings from emissions that year, and year 2100 (solid), which represent the change in forcings from 2020 to 2100.

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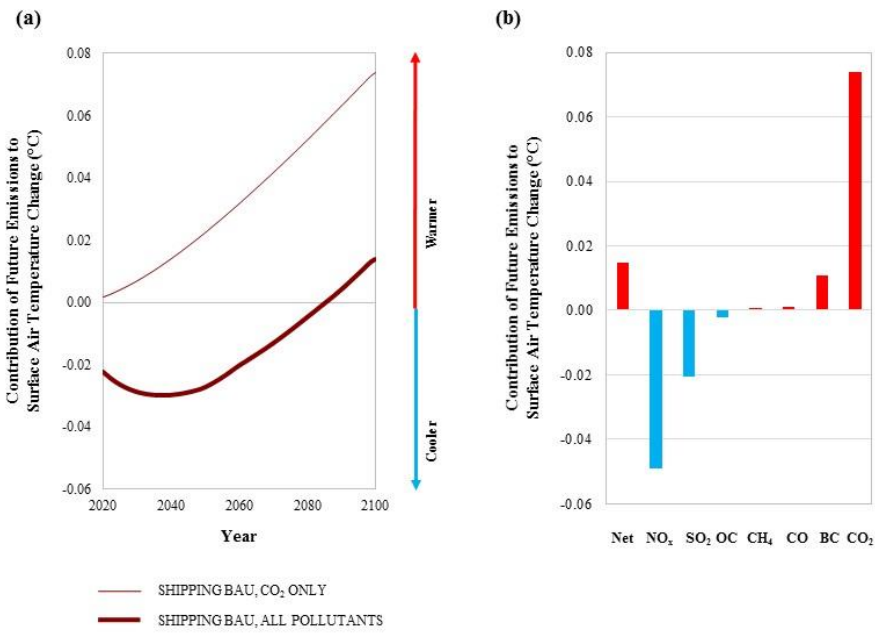
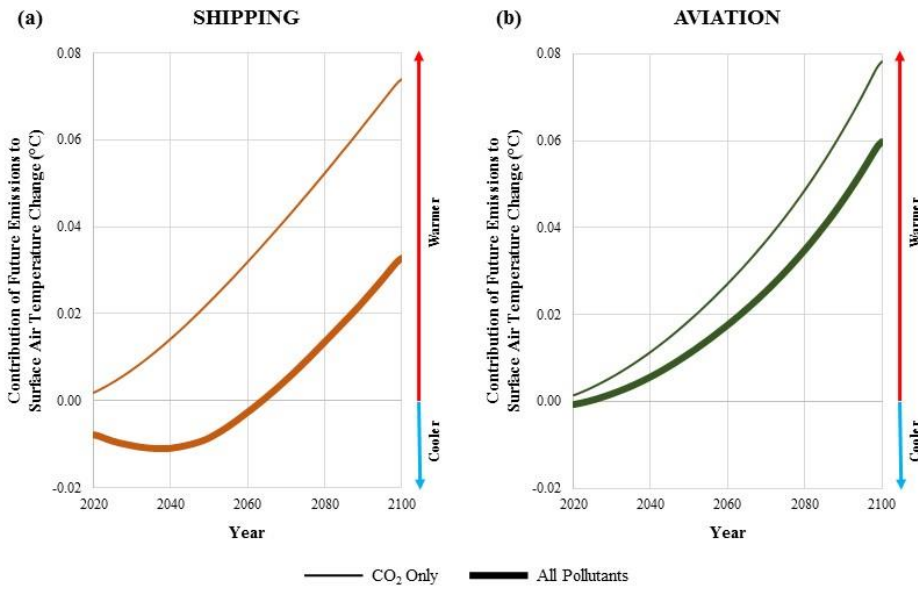
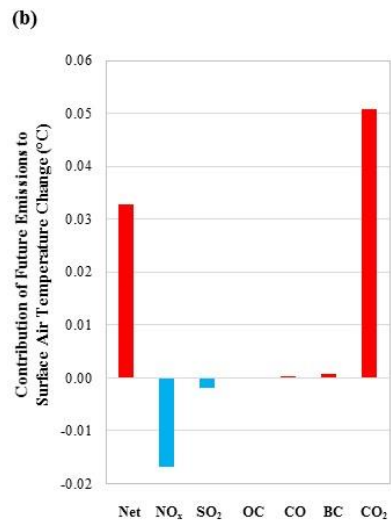
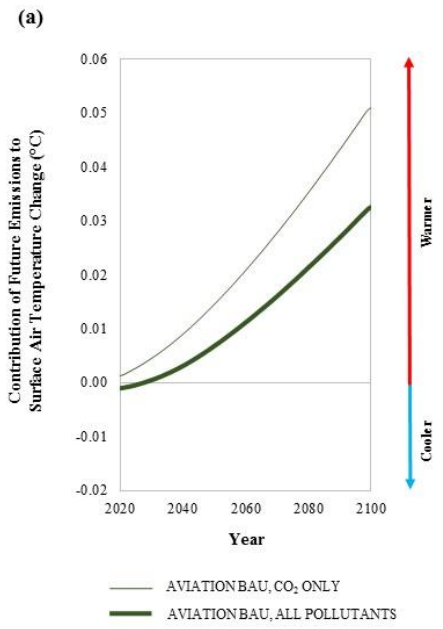


Figure 24: Contribution of future emissions to surface air temperature change in °C associated with business-as-usual emissions starting in 2020 and continuing through the end of the century from international shipping. Future warming temperature impacts are presented a) a) shipping and b) aviation. Future warming is assessed for emissions of CO₂ only (thin line) and all pollutants (thick line), and b) through the contribution of individual pollutants in year 2100.

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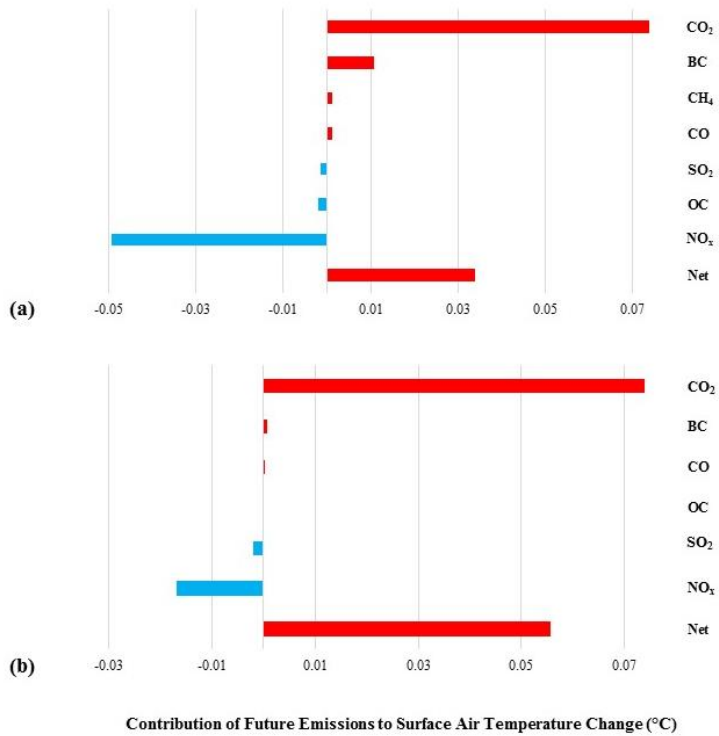
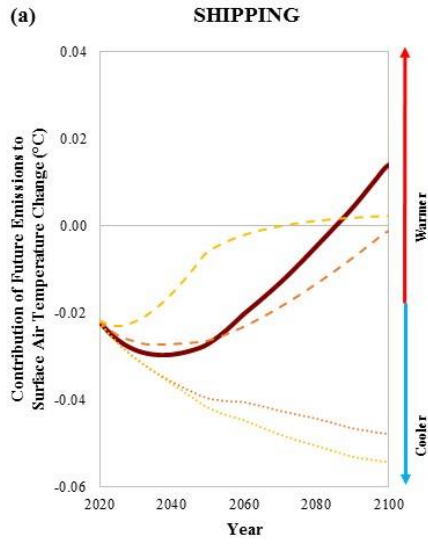


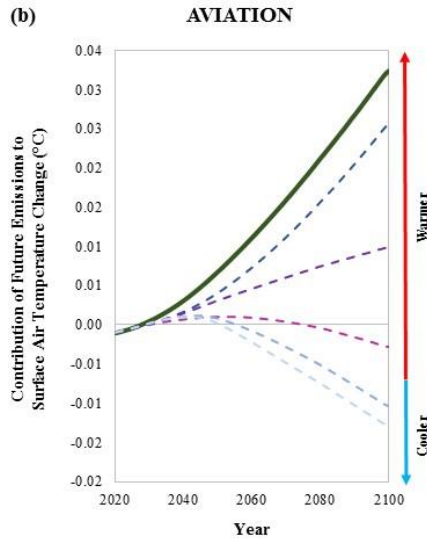
Figure 35: Contribution of future emissions to surface air temperature change in °C associated with business-as-usual emissions starting in 2020 and continuing through the end of the century from international aviation. Future warming temperature impacts are presented a) assessed for emissions of CO₂ only (thin line) and all pollutants (thick line), and b) through the contribution of individual pollutants in 2100. Contribution of individual pollutants' future emissions to surface air temperature change in °C in 2100 associated with business-as-usual emissions starting in 2020 and continuing through the end of the century from international a) shipping and b) aviation.

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- SHIPPING BAU, ALL POLLUTANTS
- IMO - MIN AMBITION, CO₂ ONLY
- - - IMO - MIN AMBITION, ALL POLLUTANTS
- IMO - MAX AMBITION, CO₂ ONLY
- - - IMO - MAX AMBITION, ALL POLLUTANTS



- AVIATIONBAU, ALL POLLUTANTS
- - - CORSIA - EXT
- - - CAP
- - - CORSIA - DECARB2100
- - - CORSIA - DECARB2050

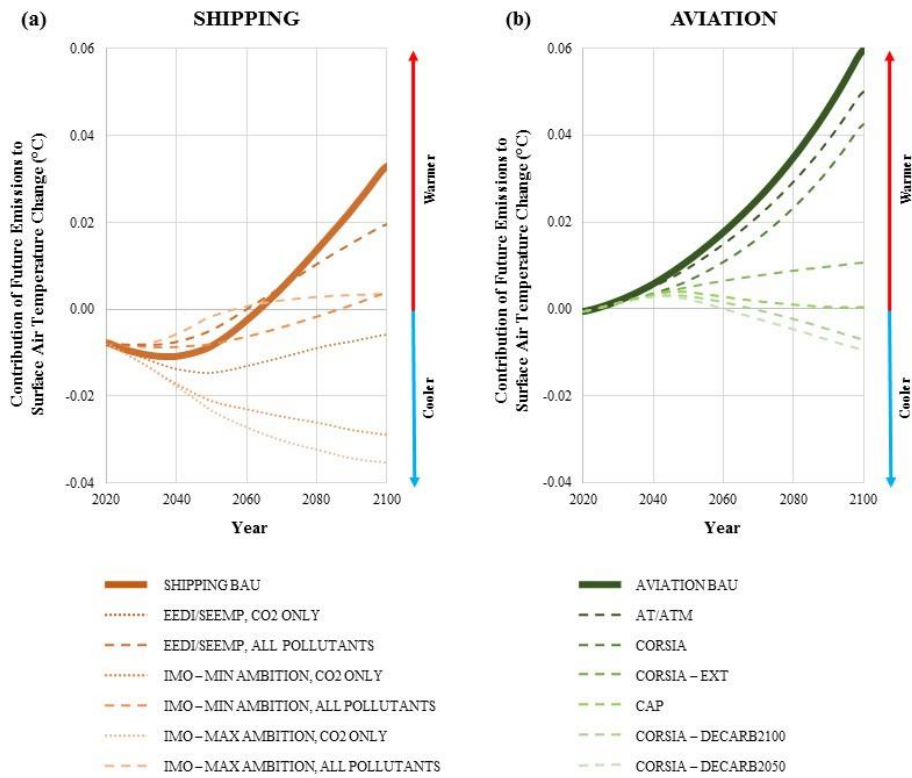
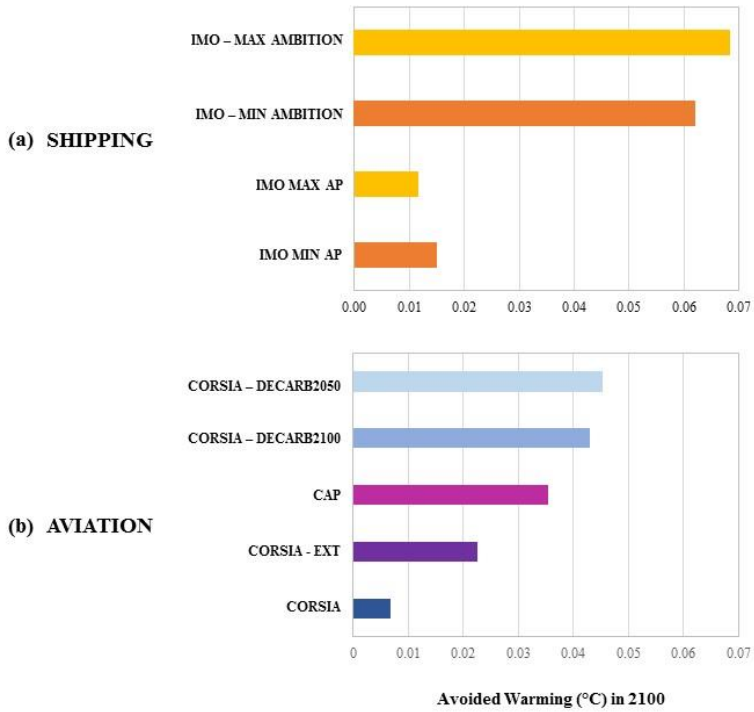


Figure 4 6: Surface air temperature changes associated with various policy scenarios for emissions mitigation in international a) shipping and b) aviation. Each business-as-usual scenario presents the contribution to future surface air temperature from the emissions of all climate pollutants starting in 2020 and continuing through the end of the century.



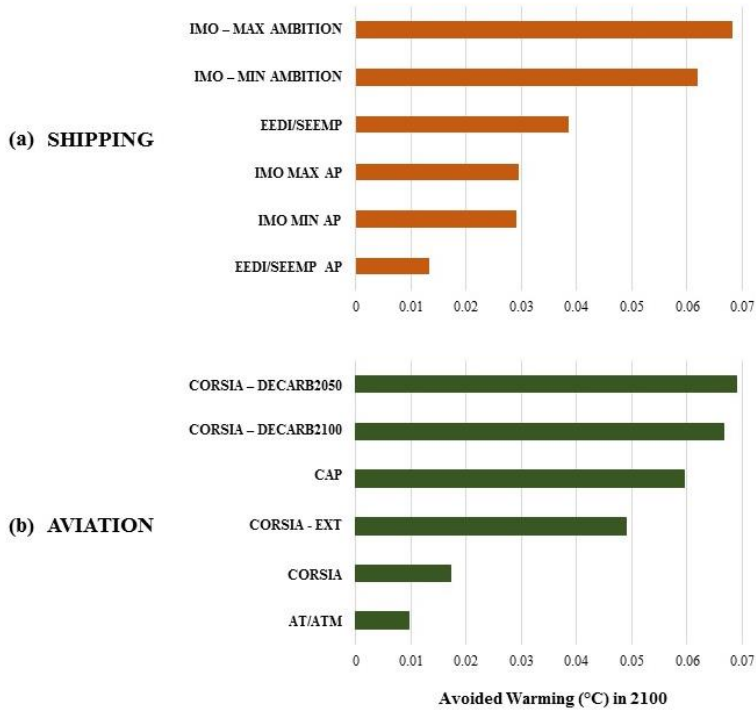


Figure 5.7: Avoided warming in year 2100 associated with various policy scenarios for emissions mitigation in international a) shipping and b) aviation.