Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-126
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 9 April 2019

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

Catherine C. Ivanovich[1], Ilissa B. Ocko[1], Pedro Piris-Cabezas[1], and Annie Petsonk[1]

[1]Environmental Defense Fund, 1875 Connecticut Ave NW, Washington, DC 20009

Correspondence to: Ilissa B. Ocko (iocko@edf.org)

Abstract. While individual countries work to achieve and strengthen their nationally determined contributions to the Paris Agreement, the growing emissions from two economic sectors remain outside the bounds of national jurisdictions: international shipping and 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 (CO_2) emissions from their respective sectors. Here we provide information on the climate benefits of these proposed measures, along with related potential measures. We find that if no actions are taken, CO_2 emissions from international shipping and aviation may contribute roughly equally to an additional combined 0.15 °C to global temperature rise by end of century—which is 15% and 30% of the "allowable warming" we have left to stay below the 2 °C or 1.5 °C thresholds, respectively. However, stringent mitigation measures may avoid over 85% of this projected future warming from the CO_2 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.

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 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.

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 that emissions 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). 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 3% of global greenhouse gas emissions over a 20- and 100-year timeframe, respectively, 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.

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, 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 CO_2 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 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 (Lee et al., 2010; Lee, 2018; Eyring et al., 2009; 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 (Fuglestvedt et al., 2009; Berntsen and Fuglestvedt, 2008; Unger et al., 2010).

There are a few studies that have modeled the contribution to warming from future aviation and shipping emissions pathways. The IPCC released a special report on aviation and its impact on the global atmosphere in 1999, 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.

Here we build on 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 Emissions from international bunkers

We account for present-day and future emissions of both CO_2 and non-CO_2 pollutants from international shipping and aviation in our BAU baseline scenarios. Future emissions profiles can be found in Figure 1.

International shipping CO_2 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, CO_2 emissions are linearly extrapolated through year 2100. International aviation CO_2 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 CO_2 emissions until it reaches 2.5% growth, and then hold that level constant through year 2100. The long-term annual CO_2 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.

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 CO_2 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-CO_2 pollutants are linked to these different CO_2 growth rates, we focused our sensitivity tests on emissions of CO_2 in particular. We note that all figures in the paper reflect the limited growth pattern for international aviation.

For non-CO_2 emissions, BAU projections for shipping are taken from the 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 (CH_4), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), black carbon, and organic carbon. 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.

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-CO_2 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, 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 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.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-126
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 9 April 2019

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 mitigation scenarios: (i) 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; (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) full implementation of EEDI and SEEMP between years 2020 and 2100. The first two 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 CO_2, non-CO_2 climate pollutant emissions will likely be impacted as well— although how will depend on the specific methods used to achieve the CO_2 targets (which are currently undecided). Therefore, we analyze scenarios in which the CO_2 mitigation methods do not affect other pollutants, and scenarios in which the CO_2 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 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 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). 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 this maximum potential contribution of improved technology and management, however, the CORSIA component of the scenario only affects CO_2 emissions given that this is an offsetting program. Projections for the CO_2 emissions reductions associated with CORSIA through year 2035 are based on the latest list of participating member countries from ICAO (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 biofuel use will contribute to the emissions of non-CO_2 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 C^{4}MIP 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 volatile organic carbon); aerosol emissions (sulfate, black and organic carbon, sea salt, and mineral dust); and the indirect effects (first and second) of aerosols.

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 (as described by Hansen et al. (2005)) by their respective emissions. The effect 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)).

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). 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. A full discussion of model uncertainties can be found in Meinshausen et al. (2011a).

2.4 Climate model simulations

We run 335-year integrations from year 1765 to 2100 for a set of 17 different simulations. These simulations are comprised of five BAU pathways and 12 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.

The five BAU scenarios account for the warming impacts due to: all natural and anthropogenic forcings; isolation of the CO_2 emissions from international shipping; isolation of the CO_2 emissions from international aviation; isolation of the CO_2, black carbon, methane, nitrogen oxides, sulfur dioxides, organic carbon, and carbon monoxide emissions from international shipping; and isolation of the CO_2, black carbon, nitrogen oxides, sulfur dioxide, organic carbon, and carbon monoxide emissions from international aviation. The 12 mitigation simulations account for the future emissions pathways for the 12 policy scenarios outlined in Table 1.

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). 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.

$$Emissions_{all-forcings\ without\ sector} = Emissions_{all-forcings} - Emissions_{sector} \tag{1}$$

$$\Delta T_{sector} = \Delta T_{all-forcings} - \Delta T_{all-forcings\ without\ sector\ emissions} \tag{2}$$

3 Results

3.1 BAU warming

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. Figure 2a 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 a net cooling effect in the near-term. It isn't until 2060 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 perpetual year-2000 emissions and not a BAU scenario.

Based on our BAU projections, future CO_2 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 °C due to the net warming and cooling effects from non-CO_2 pollutants (Figure 2a).

For the year 2100, the temperature impacts attributed individually to emissions of CO_2, black carbon, methane, nitrogen oxides, sulfur dioxide, organic carbon, and carbon monoxide are shown in Figure 3a. 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 CO_2's warming effect, is dominated by the cooling pollutant precursor nitrogen oxides. The cooling from nitrogen oxides arises from nitrate production, indirect aerosol effects from nitrates, and the combined direct and indirect effects of nitrate on the carbon cycle (cooling in the ocean supresses CO_2 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. 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.

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 CO_2's warming effects (Figure 3a).

Figure 2b shows the impact of future international aviation emissions (beginning in 2020) on surface air temperature change throughout the 21st Century. The contribution of CO_2 emissions to future warming over time and in the year 2100 is comparable to that from the shipping sector (0.08 °C by 2100). However, the inclusion of non-CO_2 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 °C. 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 3b). By 2100, nitrogen oxides are responsible for a cooling of 0.02 °C, while the end of century contribution from all other non-CO_2 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, and that we do not address impacts of aviation on cloudiness, which is considered to significantly add to the warming impacts of aviation.

Our projections for the contribution to future warming from international shipping and aviation are in agreement 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 than the 0.11 °C to 0.28 °C range, but Bielvedt Skeie et al. (2009) analyzed combined domestic and international transport emissions. 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, 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 CO_2, nitrogen oxides, and sulfur dioxide for each sector, and emissions profiles are based on outdated projections. In particular, the projected emissions of CO_2 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.

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 4). The IMO greenhouse gas target of a 50% reduction in CO_2 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 CO_2 by more than 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 CO_2 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 CO_2 emissions.

Because the non-CO_2 climate pollutants emitted by the shipping sector yield a net cooling, the scenarios that reduce their emissions proportional to the reductions in CO_2 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 0.03 °C by the end of the century (in comparison to 0.06 °C and 0.07 °C in the CO_2-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 CO_2 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 °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 CO_2 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 CO_2 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 °C by 2100 (25% reduction of warming from a CO_2 BAU baseline). However, extending CORSIA's offsetting and reduction program through the end of the century more than doubles the climate benefit (0.05 °C avoided warming), avoiding about 60% of the CO_2 BAU baseline warming. The scenario that follows CORSIA and then decarbonizes the sector by year 2100 (CORSIA-DECARB2100) reduces future warming by 0.07 °C by end of century, avoiding nearly 90% of the CO_2 BAU warming. 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 5.

The warming mitigation potential of the various policy scenarios associated with aviation were evaluated based on three CO_2 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 avoided warming is relative to the BAU baseline. For international aviation, in comparison to the 0.08 °C contribution to future warming from CO_2-only expected from the limited growth rate pattern, 0.12 °C and 0.06 °C of future warming are expected from the emission of CO_2 in the exponential and declining emissions growth rate patterns, respectively. The mitigation scenario that mimics the structure of the IMO minimum ambition greenhouse gas target (CORSIA – DECARB2100) is expected to reduce the warming attributed to the emissions of CO_2 from the sector by 0.07 °C by end of century in the limited growth rate pattern, and is expected to avoid 0.11 °C and 0.06 °C by end of century in the exponential and declining growth rate patterns, respectively. These avoided temperatures from the exponential, limited growth, and declining growth scenarios represent 92%, 88%, and 86% of the unabated warming levels from CO_2 emissions, respectively. Thus while the expected BAU warming from the sector's CO_2 emissions vary significantly between each pattern of growth, the potential to reduce this warming through proposed, stringent mitigation scenarios scales proportionally.

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 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 CO_2 emissions (2020 through end of century) from the international shipping and aviation sectors would be responsible for 0.07 °C and 0.08 °C of future warming by 2100, respectively (0.03 °C and 0.06 °C, respectively, when including the sectors' emissions of non-CO_2 climate pollutants; note that we do not include impacts of aviation-induced contrails and clouds). Planned and proposed mitigation policies in each sector that specifically target CO_2 emissions have the potential to significantly reduce this climate impact. However, policies that target the mitigation of non-CO_2 climate pollutants, often through air quality management, result in emissions reductions that may not always avoid future warming. 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.

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 CO_2 emissions of international shipping and aviation reach about 0.15 °C by the end of the century, which is 15-30% 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 CO_2 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 °C) increases this potential by over 35%. 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.

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.

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.

Acknowledgements

Catherine C. Ivanovich was funded by the High Meadows Foundation. Ilissa B. Ocko was funded by the Heising Simons Foundation and the Robertson Foundation. We thank Aoife O'Leary, Bryony Worthington, Nathaniel Keohane, and Steven Hamburg for reviewing our manuscript.

References

Aragon-Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M., and Zickfeld, K.: Global Warming of 1.5 °C, Chapter 1: Framing and Context, Intergovernmental Panel on Climate Change, Incheon, Republic of Korea, 2018.

Azar, C. and Johansson, D. J. A.: Valuing the non-CO_2 climate impacts of aviation, Clim. Change, 111(3-4), 559-579, https://doi.org/10.1007/s10584-011-0168-8, 2012.

Bazari, Z. and Longva, T.: Assessment of IMO Mandated Energy Efficiency Measures for International Shipping, Marine Environment Protection Committee 63rd Session, London, United Kingdom, 2011.

Berntsen, T. and Fuglestvedt, J.: Global temperature responses to current emissions from the transport sector, PNAS, 105(49), 19154-19159, https://doi.org/10.1073/pnas.0804844105, 2008.

Bielvedt Skeie, R., Fuglestvedt, J., Berntsen, T., Tronstad Lund, M., Myhre, G., and Rypdal, K.: Global temperature change from the transport sectors: Historical development and future scenarios, Atmos. Environ., 43, 6260-6270, https://doi.org/10.1016/j.atmosenv.2009.05.025, 2009.

Boeing: Commercial Market Outlook 2018-2037, The Boeing Company, Chicago, Illinois, 2018.

Climate Action Tracker (CAT): https://climateactiontracker.org/publications/warming-projections-global-update-dec-2018/, last access: 4 February 2019.

Crippa, M., Janssens-Maenhout, G., Dentener, F., Guizzardi, D., Sindelarova, K., Muntean, M., Van Dingenen, R., and Granier, C.: Forty years of improvements in European air quality: regional policy-industry interactions with global impacts, Atmos. Chem. Phys., 16, 3825-3841, https://doi.org/10.5194/acp-16-3825-2016, 2016.

Environmental Defense Fund (EDF): https://www.edf.org/climate/icaos-market-based-measure, last access: 29 January 2019.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P.: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophys. Res. Lett., 43(24), 12614-12623, https://doi.org/10.1002/2016GL071930, 2016.

Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S.: Transport impacts on atmosphere and climate: Shipping, Atmos. Environ., 1-37, http://doi.org/10.1016/j.atmosenv.2009.04.059, 2009.

Fuglestvedt, J., Berntsen, T., Eyring, V., Isaksen, I., Lee, D. S., and Sausen, R.: Shipping Emissions: From Cooling to Warming of Climate – and Reducing Impacts on Health, Environ. Sci. Technol., 43(24), 9057-9062, http://doi.org/10.1021/es901944r, 2009.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, J. Geophys. Res., 110(D18104), pp.45, http://doi.org/10.1029/2005JD005776, 2005.

Hoen, M., Faber, J., and Lee, D. S.: Update of Maritime Greenhouse Gas Emissions Projections, CE Delft, Netherlands, pp. 46, 2017.

Intergovernmental Panel on Climate Change: Aviation and the Global Atmosphere, edited by: J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken, and McFarland, M., Cambridge University Press, Cambridge, United Kingdom, pp. 373, 1999.

Intergovernmental Panel on Climate Change: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, edited by: Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, R. Pidcock, C., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., Incheon, South Korea, 2018.

International Civil Aviation Organization: Present and Future Trends in Aircraft Noise and Emissions, Montreal, Canada, 2016a.

International Civil Aviation Organization: CORSIA States for Chapter 3 State Pairs, Montreal, Canada, 2016b.

International Civil Aviation Organization: Resolution A39-3: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme, Montreal, Canada, 2016c.

International Maritime Organization: Third IMO Greenhouse Gas Study 2014, Albert Embankment, London, United Kingdom pp. 327, 2014.

International Maritime Organization: Adoption of the Initial IMO Strategy on Reduction of GHG Emissions from Ships and Existing IMO Activity Related to Reducing GHG Emissions in the Shipping Sector, Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue, 2018.

Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma1, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017-7039, https://doi.org/10.5194/acp-10-7017-2010, 2010.

Lean, J. L., 2010. Cycles and trends in solar irradiance and climate, Wiley Interdiscip. Rev. Clim. Change, 1(1), 111-112, https://doi.org/10.1002/wcc.18, 2010.

Lee, D. S.: International aviation and the Paris Agreement temperature goals, Department for Transport, Manchester Metropolitan University, Manchester, United Kingdom, pp. 15, 2018.

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Bernts

en, T., Iachetti, D., Lim, L. L., and Sausen, R.: Transport impacts on atmosphere and climate: Aviation, Atmos. Environ., 44, 4678-4734, http://doi.org/10.1016/j.atmosenv.2009.06.005, 2010.

Meinshausen, M., Raper, S. C. B., and Wigley, T. M. L.: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration, Atmos. Chem. Phys., 11, 1417-1456, https://doi.org/10.5194/acp-11-1417-2011, 2011a.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Raihi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Clim. Change, 109, 213-241, http://doi.org/10.1007/s10584-011-0156-z, 2011b.

Ocko, I. B., Hamburg, S. P., Jacob, D. J., Keith, D. W., Keohane, N. O., Oppenheimer, M., Roy-Mayhew, J. D., Schrag, D. P., and Pacala, S. W.: Unmask temporal trade-offs in climate policy debates, Science, 356(6337), 492-493, http://doi.org/10.1126/science.aaj2350, 2017.

Ocko, I. B., Naik, V., and Paynter, D.: Rapid and reliable assessment of methane impacts on climate, Atmos. Chem. Phys., 18, 15555-15568, https://doi.org/10.5194/acp-18-15555-2018, 2018.

Riahi, K., Gruebler, A., and Nakicenovic, N.: Scenarios of long-term socio-economic and environmental development under climate stabilization, Technol. Forecast. and Soc. Change 74, 7, 887-935, http://doi.org/10.1016/j.techfore.2006.05.026, 2007.

Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D. S., Myhre, G., Kohler, M. O., Pitari, G., Schumann, U., Stordal, F., and Zerefos, C.: Aviation radiative forcing in 2000: An update on IPCC (1999), Meteorol. Z., 14(4), 555-561, http://doi.org/10.1127/0941-2948/2005/0049, 2005.

Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T., Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Berntsen, T. K., Folberth, G. A., Rumbold, S. T., Collins, W. J., MacKenzie, I. A., Doherty, R. M., Zeng, G., van Noije, T. P. C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D. A., Strode, S. A., Horowitz, L., Lee, Y. H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K. W., Wild, O., and Archibald, A.: Tropospheric ozone changes, radiative forcing, and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos, Chem. Phys., 13, 3063-3085, https://doi.org/10.5194/acp-13-3063-2013, 2013.

Unger, N., Bond, T. C., Wang, J. S., Koch, D. M., Menon, S., Shindell, D. T., and Bauer, S. Attribution of climate forcing to economic sectors, PNAS, 107(8), 3382-3387, http://doi.org/10.1073/pnas.0906548107, 2010.

United Nations Framework Convention on Climate Change: Kyoto Protocol to the United Nations Framework Convention on Climate Change, adopted at: the Conference of the Parties 3, Kyoto, Japan, 1997.

	Mitigation scenario description	**Abbreviation**
Aviation	Aircraft technology and air traffic management improvements	AT/ATM
	Cap emissions at 2020 levels	CAP
	CORSIA (including offsets and biofuel use) ends after 2035, followed by business-as-usual emissions growth	CORSIA
	CORSIA emissions reductions sustained through 2100	CORSIA – EXT
	CORSIA ends in 2035, followed by decarbonization in 2100	CORSIA – DECARB2100
	CORSIA ends in 2035, followed by decarbonization in 2050	CORSIA – DECARB2050
Shipping	Implementation of EEDI and SEEMP policies through 2100; does not affect non-CO2 pollutants	EEDI/SEEMP, CO_2 ONLY
	IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; does not affect non-CO2 pollutants	IMO – MIN AMBITION, CO_2 ONLY
	Linear decrease in emissions starting in 2020, leading to decarbonization in 2050; does not affect non-CO2 pollutants	IMO – MAX AMBITION, CO_2 ONLY
	Implementation of EEDI and SEEMP policies through 2100; proportional emissions reductions for all non-CO2 pollutants	EEDI/SEEMP, ALL PRODUCTS
	IMO Greenhouse Gas Targets: 50% reduction from 2008 levels by 2050, decarbonization by 2100; proportional emissions reductions for all non-CO2 pollutants	IMO – MIN AMBITION, ALL POLLUTANTS
	Linear decrease in emissions starting in 2020, leading to decarbonization in 2050; proportional emissions reductions for all non-CO2 pollutants	IMO – MAX AMBITION, ALL POLLUTANTS

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

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-126
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 9 April 2019

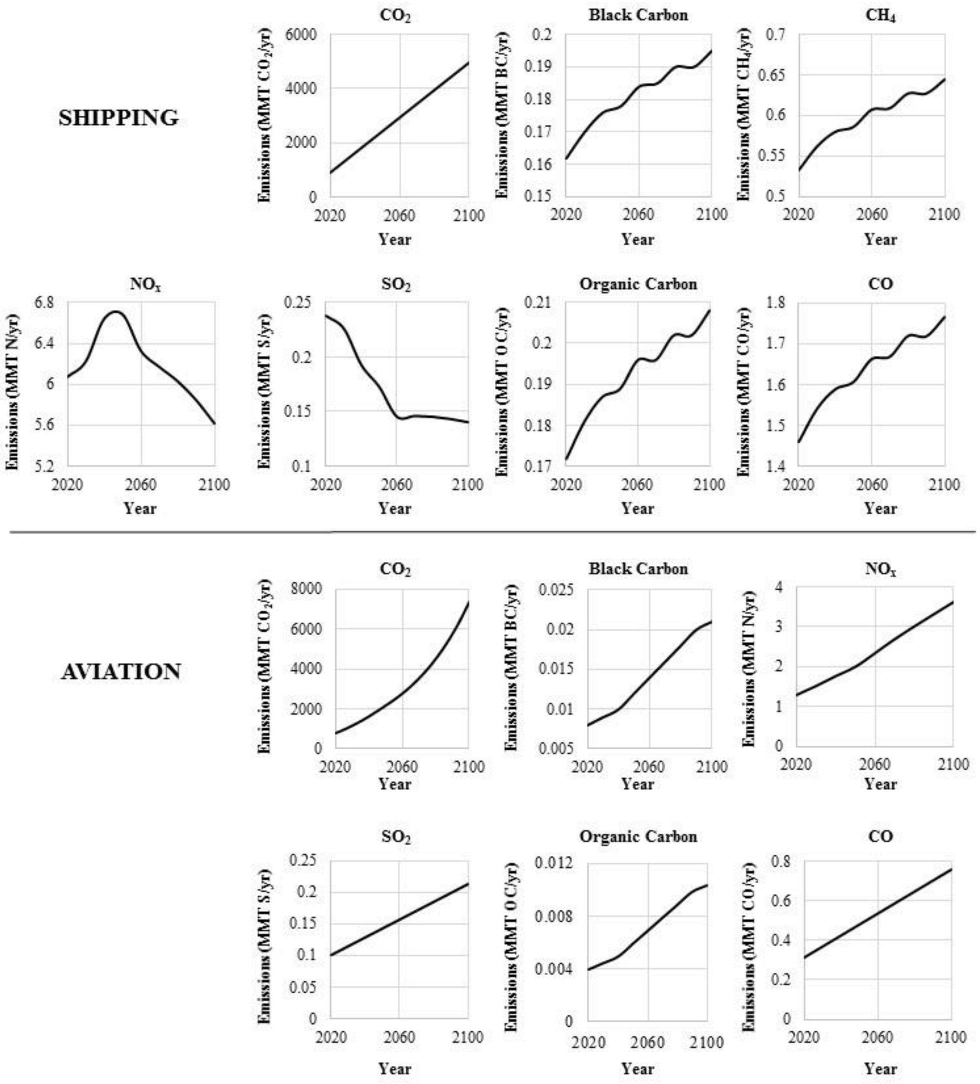

Figure 1: Projected future emissions from international shipping and aviation. Shipping CO$_2$ emissions data from Third IMO Greenhouse Gas Study (IMO 2014) and the Update of Maritime Greenhouse Gas Emission Projections (Hoen et al. 2017). Aviation CO$_2$ emissions data from Present and Future Trends 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, CH$_4$, NO$_x$, SO$_2$ (adjusted based on IMO's recently adopted sulfur fuel regulation), organic carbon, and CO extracted from RCP Database for the RCP8.5 scenario. Aviation SO$_2$ and CO are linearly extrapolated from the EDGAR dataset, and aviation organic carbon emissions are derived from their relationship with black carbon emissions.

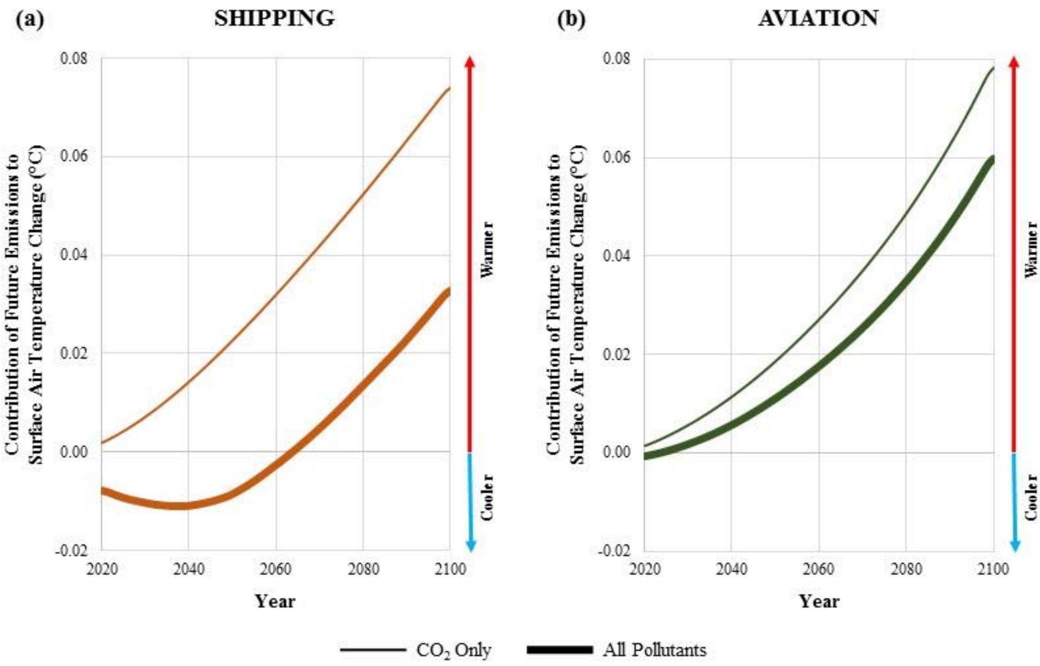

Figure 2: Contribution of future emissions to surface air temperature change in °C associated with business-as-usual emissions starting in 2020 and continuing through the end of the century from international a) shipping and b) aviation. Future warming is assessed for emissions of CO_2 only (thin line) and all pollutants (thick line).

5

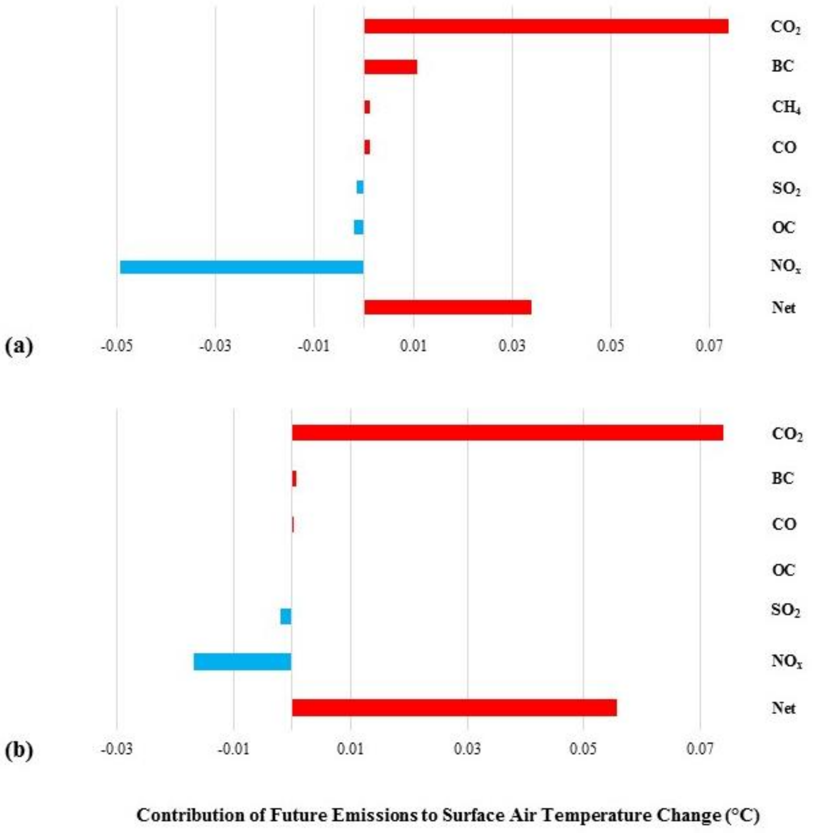

Figure 3: Contribution of individual pollutants' future emissions to surface air temperature change in °C in 2100 associated with business-as-usual emissions starting in 2020 and continuing through the end of the century from international a) shipping and b) aviation.

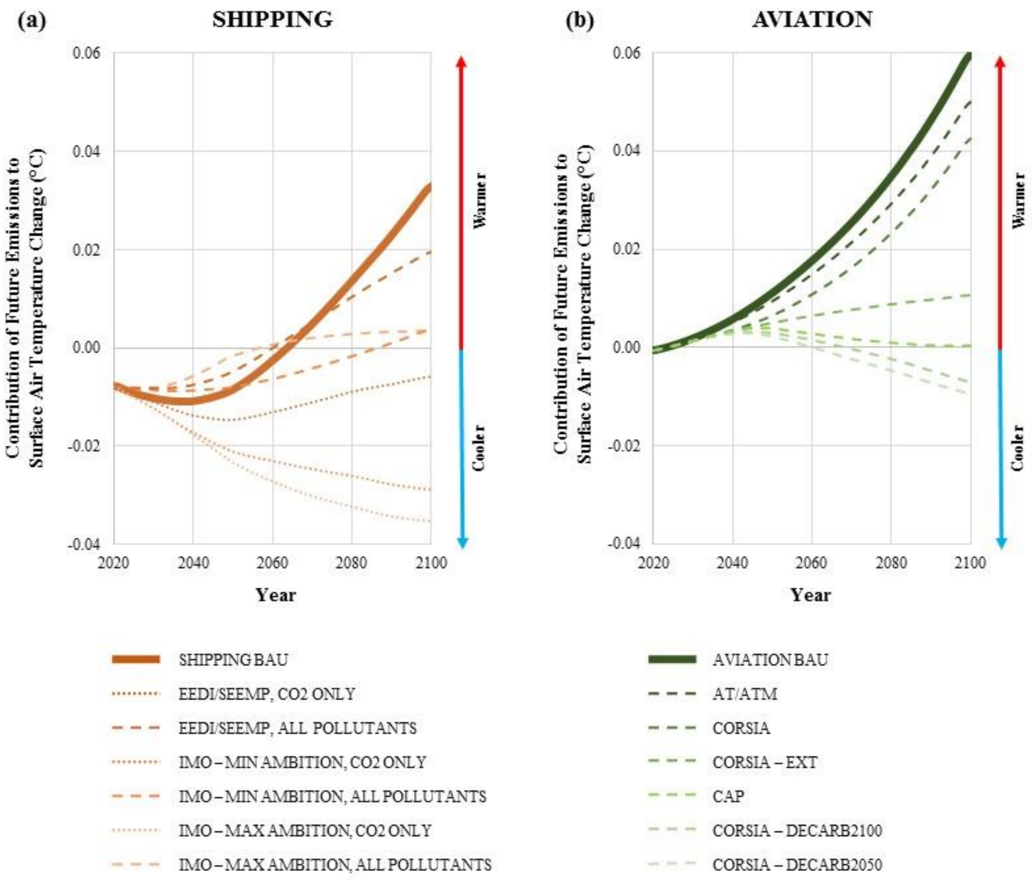

Figure 4: Surface air temperature changes associated with various policy scenarios for emissions mitigation in international a) shipping and b) aviation. Each business-as-usual scenario presents the contribution to future surface air temperature from the emissions of all climate pollutants starting in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

5

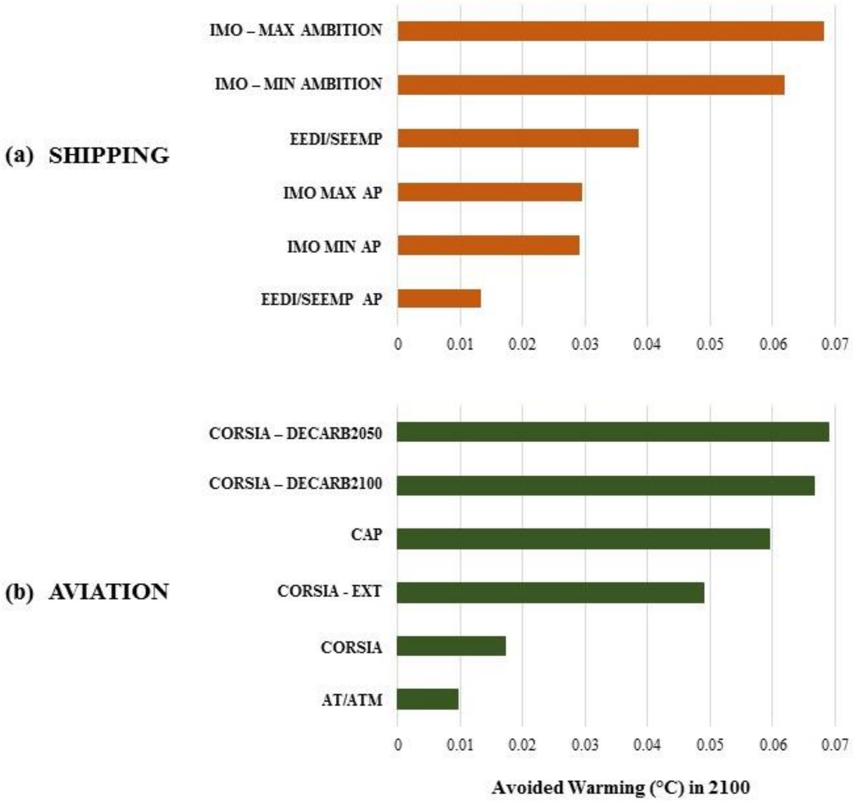

Figure 5: Avoided warming in year 2100 associated with various policy scenarios for emissions mitigation in international a) shipping and b) aviation.