7SM

Clouds and Aerosols
Supplementary Material

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7.SM.1 Supplementary Material to Section 7.2.7.1

Forster et al. (2007) estimated the 2005 radiative forcing (RF) from contrails as +0.01 (–0.007 to +0.02) W m^{-2}, but neglected any increase due to traffic increase for previous estimates and considered 2000 estimates to be representative of 2005. Lee et al. (2009) scaled these estimates upward 18% to account for revised fuel use estimates, propulsive efficiency and flight routes for year 2005.

Estimates of the RF due to contrails published since AR4 are compiled in Table 7.SM.1. These have been scaled by scheduled air traffic distance (in millions of kilometres) as provided by http://www.airlines.org/Pages/Annual-Results-World-Airlines.aspx (see Table 7.SM.2) to produce RF estimates for the year 2011. This simple linear scaling assumes non-scheduled air traffic distance increases at the same rate as scheduled traffic as well as a constant likelihood of persistent contrail formation per kilometre flown despite the changing geographical distributions of flights. The trend in propulsive efficiency (which would increase the trend in contrail formation) and any saturation effect (which would decrease the trend in contrail formation) are neglected. It should be noted that the intervals provided by the individual studies in Table 7.SM.1 generally correspond to minimum–maximum values from sensitivity studies rather than statistical uncertainty ranges. The lower and upper bounds for the Spangenberg et al. (2013) study correspond to the most conservative and most sensitive contrail masks of Duda et al. (2013), respectively.

The average of RF estimates for the year 2011 since AR4 amounts to +0.012 W m^{-2}, which is rounded to +0.01 W m^{-2} to provide a central estimate for this assessment. The 90% uncertainty range is estimated empirically from the published sensitivity studies as 0.005 to 0.03 W m^{-2}. The lower bound is also justified by a sensitivity study to ice particle shape which rules out negative values for observed contrail optical depths (Markowicz and Witek, 2011a). The upper bound also accounts for the potential effect of sub-visible contrails, noting that only one published estimate extends significantly beyond 0.03 W m^{-2}. A *medium confidence* is attached to this estimate. An additional RF of +0.003 W m^{-2} is due to emissions of water vapour in the stratosphere by aviation as estimated by Lee et al. (2009).

Forster et al. (2007) quoted Sausen et al. (2005) to update the 2000 forcing for aviation-induced cirrus (including linear contrails) to +0.03 (+0.01 to +0.08) W m^{-2} but did not consider this to be a best estimate because of large uncertainties. In particular, observationally based estimates of aviation-induced cirrus forcing estimates may unintentionally include cirrus changes not directly caused by aviation.

Only a few estimates of the RF due to aviation-induced cirrus have been published since AR4 (Table 7.SM.3) and all focused on contrail cirrus. Schumann and Graf (2013) constrained their model with observations of the diurnal cycle of contrails and cirrus in a region with high air traffic relative to a region with little air traffic, and estimated a RF of +0.05 (0.04 to +0.08) W m^{-2} for contrails and contrail-induced cirrus in 2006, but their model has a large shortwave contribution, suggesting that larger estimates are possible (Myhre et al., 2009). An alternative approach was taken by Burkhardt and Kärcher (2011), who estimated a global forcing of +0.03 W m^{-2} from contrails and contrail cirrus within a climate model for the year 2002 (Burkhardt and Kärcher, 2009). Their RF for contrails and contrail-cirrus (+0.0375 W m^{-2}) is corrected here for the radiative impact due to the decrease in natural cirrus (–0.007 W m^{-2}). Based on these two studies we assess the combined contrail and contrail-induced cirrus ERF for the year 2011 to be +0.05 W m^{-2} neglecting the possibility that rapid adjustments

Table 7.SM.1 | Estimates of the contrail radiative forcing (RF) and their scaling to year 2011 (W m^{-2}). The uncertainty of the estimate by Markowicz and Witek (2011b) is calculated by combining the uncertainties due to crystal shape and contrail optical depth.

Reference	RF Due to Contrails	Reference Year	RF Due to Contrails Scaled to Year 2011
Forster et al. (2007) - AR4	+0.01 (–0.007 to +0.02)	2000 (2005)	+0.015 (–0.01 to +0.03)
Rädel and Shine (2008)	+0.006	2002	+0.009
Rap et al. (2010b) - offline	+0.012	2002	+0.018
Rap et al. (2010b) - online	+0.008 (+0.004 to 0.012)	2002	+0.012 (+0.006 to +0.018)
Kärcher et al. (2010)	+0.008 to +0.020	2000	+0.012 to +0.030
Burkhardt and Kärcher (2011)	+0.0043 (young contrails)	2002	+0.007
Frömming et al. (2011)	+0.0059 (+0.0049 to +0.0211)	2000	+0.009 (+0.007 to +0.032)
Markowicz and Witek (2011b)	+0.011 (+0.006 to +0.016)	2002	+0.017 (+0.010 to +0.024)
Voigt et al.(2011)	+0.0159 (+0.0111 to +0.0477)	2005	+0.020 (+0.014 to +0.060)
Yi et al. (2012)	+0.0113 (+0.0098 to +0.0165)	2006	+0.014 (+0.012 to +0.020)
Spengenberg et al. (2013)	+0.0057 (+0.0028 to +0.0171)	2006	+0.007 (+0.003 to +0.021)
This Assessment			**+0.01 (+0.005 to +0.03)**

Table 7.SM.2 | Scheduled air traffic distance (in millions of kilometres) as provided by http://www.airlines.org/Pages/Annual-Results-World-Airlines.aspx.

1992	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
15,690	25,517	25,612	25,418	26,264	29,163	30,862	32,099	34,109	35,368	34,039	36,833	38,530

Table 7.SM.3 | Estimates of the radiative forcing (RF)/effective radiative forcing (ERF) due to contrails and contrail cirrus and their scaling to year 2011 (W m^{-2}).

Reference	RF Due to Contrails and Contrail Cirrus	Reference Year	RF/ERF Due to Contrails and Contrail Cirrus Scaled to Year 2011
Stordal et al. (2005) / Sausen et al. (2005) - AR4	+0.03 (+0.01 to +0.08)	2000	+0.045 (+0.015 to +0.12)
Burkhardt and Kärcher (2011)	+0.03	2002	+0.045
Schumann and Graf (2013)	+0.05 (+0.04 to +0.08)[a]	2006	+0.060 (+0.040 to +0.119)[b]
This Assessment			**+0.05 (+0.02 to +0.15)**

Notes:

[a] The range is an expert judgment for a 1-σ interval.

[b] The range corresponds to a 90% uncertainty range.

may reduce this estimate (Ponater et al., 2005; Rap et al., 2010a). We further assess the 90% uncertainty range to be +0.02 to +0.15 W m^{-2} to take into account the large uncertainties associated with spreading rate, optical depth, ice particle shape and radiative transfer. A *low confidence* is attached to this estimate.

7.SM.2 Supplementary Material to Section 7.5.2.1

Figure 7.SM.1 shows the annual zonal mean radiative forcing due to aerosol–radiation interactions (RFari, in W m^{-2}) due to all anthropogenic aerosols from the different AeroCom II models that were combined in Figure 7.17.

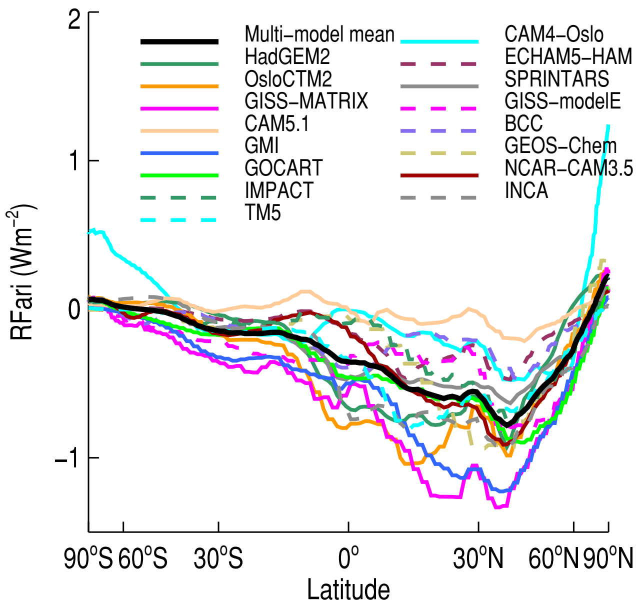

Figure 7.SM.1 | Annual zonal mean radiative forcing due to aerosol–radiation interactions (RFari, in W m^{-2}) due to all anthropogenic aerosols from the different AeroCom II models (Myhre et al., 2013). No adjustment for missing species in certain models has been applied. The forcings are for the 1850–2000 period. See also Figure 7.17.

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