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A Diagnostic Study of the Global Distribution of Contrails Part II: Future Air Traffic Scenarios

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With 4 Figures

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Summary

The global distribution of the contrail coverage is computed for several scenarios of aviation in the years 2015 and 2050 and compared to 1992 using meteorological analysis data representative of present temperature and humidity conditions and assuming 0.5% cover in a reference region 30° W–30° E, 35° N–75° N covering parts of western Europe and the North Atlantic. The mean contrail coverage of the Earth is computed to increase by a factor of about three compared to 1992 and to reach 0.25% in 2015. For three different scenarios of aviation and for constant climatic conditions, the global mean contrail coverage reaches values between 0.26% and 0.75% for 2050. Contrail coverage increases more strongly than total fuel burn mainly because of more traffic in the upper troposphere and because of more efficient engines with cooler exhaust. The overall efficiency of propulsion is expected to grow from about 0.3 in the fleet average of 1992, to 0.4 in 2015, and to 0.5 in 2050. The expansion of air traffic makes Canada, Alaska, the North Pacific route from North America to Japan and most of the Asian continent new regions where contrails are expected to cover more than 0.5% on average.

1. Introduction

The world-wide air traffic increased between 1970 and 1993 by 5–6% p.a. on average, and by about 7% p.a. in the years 1994 to 1997 (ICAO, 1998). Data from IEA (1996) indicate that the aviation fuel burn annually grew by about 3% over the last two decades, reaching values of up to 180 Tg fuel per year. Aviation fuel consumption grows less rapidly than air traffic partly because of more efficient aircraft. About 65% of the fuel is burnt in the altitude range from 10 to 13 km (Gardner et al., 1997) where air traffic often manifests itself through the formation of condensation trails (contrails). Visual inspection of satellite images (Bakan et al., 1994) and an automated objective routine for contrail detection from NOAA/AVHRR data (Mannstein et al., 1999) reveal a mean coverage by line-shaped contrails of at least 0.5% over Central Europe. The global mean coverage by contrails due to present day air traffic was estimated to be about 0.1% by Sausen et al. (1998; hereafter cited as "Paper I").

It is expected that air traffic demand will further increase by about 5% p.a. (Schmitt and Brunner, 1997). The total fuel burn is estimated to increase by an average factor of 2.4 between 1992 and 2015, with large regional differences. While aviation fuel burn within North America is estimated to increase by a factor of 1.8, the corresponding number for domestic air traffic in China is 5.8. The increased fuel usage will result in increased contrail cloudiness, possibly with new regions coming up where contrails become a frequent phenomenon, unless a changing climate will strongly reduce the frequency of atmospheric conditions favouring the formation of contrails.

Whereas estimates of aviation emissions for 2015 (Schmitt and Brunner, 1997) can be considered projections, estimates for 2050 can only be addressed in terms of scenarios. Air traffic scenarios for 2050 in form of 3-D inventories have been designed by FESG (1998) for the forthcoming IPCC Special Report on "Aviation and the Global Atmosphere". These scenarios assume an increase in fuel use by 2050 relative to 1992 by factors of 1.7 to 4.8. Other scenarios assume a much stronger increase in fuel burn (factors up to 10), but provide only global mean values (Vedantham and Oppenheimer, 1998).

Regional enhancements of high cloud cover due to contrails are suspected to significantly change local climate parameters (Changnon, 1981) and even climate on regional and global scale (Ponater et al., 1996). The 1992 global mean radiative forcing due to contrails is approximately $+0.02\,\mathrm{W/m^2}$ (Meerkötter et al., 1999). If this number is simply scaled with the fuel burn, then the radiative forcing would rise to $+0.06\,\mathrm{W/m^2}$ by the year 2050 for the central FESG50a scenario (FESG, 1998), i.e. the radiative forcing would increase by a factor of about 3. However, the shift in flight routing to lower latitudes and the expected improvement of the overall propulsion efficiencies makes the world average contrail cloudiness a non-linear function of fuel use, i.e. radiative forcing is not simply proportional to fuel burn. In order to obtain more reliable estimates of the radiative forcing due to increased contrail cloudiness over various regions of the world, it is essential to know the fractional contrail coverage occurring for future scenarios of increased air traffic.

Aviation generated aerosols may trigger cirrus formation or influence cloud properties also without formation of visible contrails. (This is the so-called indirect effect of aviation exhaust aerosol.) The importance of this indirect effect for cirrus coverage and cloud properties and its possible climatic significance is not known at present, much the less for future scenarios. It is therefore not considered in this paper.

In the present paper we will use air traffic inventories for the years 2015 and 2050 to determine possible future world's contrail coverages. We employ the same method of determination as in Paper I (see also Section 2.1).

2. Method and Data

2.1 Method

Here, only a short outline of the method of calculating the contrail coverage is provided for the sake of completeness. Details can be found in Paper I.

First, we need to characterise the atmosphere in terms of temperature and relative humidity on certain pressure levels. These quantities are from an 11-year period (1983–1993) of the ECMWF re-analysis (ERA) data (Gibson et al., 1997), truncated to a T42 resolution, i.e. a spatially isotropic resolution of approximately 2.8°. These data are provided on the corresponding Gaussian grid with 128×64 longitude–latitude grid cells. Based on temperature and relative humidity on a pressure level, and assuming a certain fleet average of the overall efficiency of propulsion η (Section 2.3), we compute a "potential contrail coverage". The potential contrail coverage is a measure of the cover by air masses that are cold and humid enough so that an aircraft passing that air would trigger a long-lasting contrail. It is an upper bound for the actual contrail coverage, which cannot be exceeded even if the air traffic would grow to infinity.

The potential contrail coverage is then multiplied with a measure of spatial air traffic density. Since most inventories do not provide the number of flights (or distance) per grid volume and time unit, we use the fuel burn as a substitute. The actual contrail coverage is finally obtained by multiplying the product of fuel use and potential contrail cover with a gauge factor. In Paper I the gauge factor was determined such, that the resulting contrail cover in the region 30° W–30° E, 35° N–75° N takes the value 0.5%, as estimated by Bakan et al. (1994) from an analysis of satellite images. The same gauge factor was used for the present study. This gauge factor implies a mean contrail cover of 1.8% in the central European region considered by Mannstein et al. (1999) when the cover scales with the fuel consumption.

If traffic is measured in terms of flight distance (as available for 1992 from Schmitt and Brunner, 1997) instead of fuel consumption, then the 1992 results presented in paper I would be changed slightly because different types of aircraft (having different fuel consumption per distance ratio) dominate over different regions of the world. Over Europe and USA there is a lot of short-haul air traffic that is performed by small aircraft with lower than average fuel consumption per flight distance (less than 5 kg/km). This means that contrail cover, determined via fuel use, is possibly underestimated in these regions. Using instead flown distances as a measure of air traffic yields up to 15% larger fractional contrail cover over Europe and USA. On the other hand, intercontinental flights which dominate the world air traffic, are performed with big aircraft that have larger than average fuel use per flight distance (up to 15 kg/km). Thus, the contrail cover may be overestimated over most regions of the world when fuel use is employed as a measure for air traffic. Using flown distances instead, reduces the mean global contrail cover by 10%, and the contrail cover over South-East Asia even is reduced by a factor of 2 since there a few big aircraft with large fuel consumption per flight distance carry most air traffic. Similar uncertainties are to be expected for the determination of future contrail distribution but cannot be assessed since the scenarios do not provide the data on flight distance.

2.2 *Inventories of Future Air Traffic*

For the current investigation we have used two aircraft emission inventories for 2015 and three for 2050 (Table 1). In the following we give short descriptions of these data sets. For more details the reader is referred to the cited references.

The DLR-2 aircraft emission inventory for the year 2015 (Schmitt and Brunner, 1997) is derived from the corresponding inventory for the 1992 base-year, after application of a matrix of growth factors for fuel burn on routes within and between predefined regions of the world. The growth matrix was determined by air traffic experts in a common European effort (Gardner et al., 1998). Assumptions on aircraft/engine combinations and flight routes (great circles), and spatial resolution (corresponding to a T42 spectral grid) are the same as in the 1992 inventory used for Paper I.

An alternative aircraft emission inventory for 2015, NASA15 (Baughcum et al., 1998) was set up by combining data on aircraft performance, engine fuel consumption, and projected flight frequencies between city-pairs. Great circle routes were assumed. The fuel burn rate was projected onto a $1^\circ \times 1^\circ \times 1$ km latitude–longitude–

Table 1. *Overall Efficiency of Propulsion η, Fuel burn and Contrail Coverage for Various Regions of the World. Numbers are given for Several Aviation Scenarios for the Years 1992, 2015 and 2050. Climate Data Correspond to the Period 1983–1993. Linear Weighting and Actual Cruise Altitude are Used*

Year (Scenario)	η	Fuel burn [Tg/a]		Contrail coverage [%]					
		total	above 500 hPa	reference region[a]	Europe[b]	NAFC[c]	USA[d]	SE-Asia[e]	World
1992 (DLR-2)	0.3	148.6	87.0	0.50[f]	1.07	0.43	1.44	0.12	0.087
2015 (DLR-2)	0.4	270.5	210.8	1.23	2.62	1.04	3.24	0.53	0.23
2015 (NASA15)	0.4	308.8	243.0	1.39	2.62	1.01	2.54	0.56	0.27
2050 (FESG50a)	0.5	470.8	378.3	2.42	4.62	1.69	3.72	1.21	0.47
2050 (FESG50e)	0.5	744.2	604.0	3.56	6.45	2.30	5.32	2.26	0.75
2050 (FESG50c)	0.5	268.1	212.8	1.34	2.62	1.00	2.40	0.55	0.26
2050 (FESG50a)	0.3	470.8	378.3	1.11	1.72	0.88	1.60	0.72	0.38
2050 Jan (FESG50a)	0.5			2.74	5.45	1.73	3.39	1.16	0.46
2050 Apr (FESG50a)	0.5			2.33	4.62	1.67	4.16	1.30	0.51
2050 Jul (FESG50a)	0.5			1.86	3.10	1.52	3.33	1.20	0.42
2050 Oct (FESG50a)	0.5			2.75	5.31	1.82	4.03	1.17	0.49

[a] 30° W–30° E, 35° N–75° N as in Bakan et al. (1994)
[b] mainly Western Europe and Turkey
[c] North-Atlantic Flight Corridor, 82° W–14° E, 28° N–72° N
[d] continental USA, incl. Alaska
[e] 90° E–130° E, 10° S–25° N
[f] *per definitionem* (gauge value)

altitude grid. For our purposes we have interpolated these data to the Gaussian grid corresponding to a T42 spectral model.

The FESG (1998) scenarios of the long-term development of aircraft emissions until 2050 are based on the gross domestic product (GDP) as the most important driving factor for air traffic demand. The future evolution of air traffic is modelled using a logistic function, whose parameters have been chosen such that the historical development until 1995 could be well fitted. The future GDP development corresponds to the IPCC scenarios IS92a, IS92c, and IS92e (IPCC, 1992, 1995). The resulting fuel burn scenarios (FESG50a, FESG50c and FESG50a) for the central, low and high cases, respectively, were obtained from the air traffic scenarios by combining them with a technology scenario that assumes a technological improvement (fuel consumption per seat and kilometre) of 40–50% from 1997 to 2050.

2.3 Overall Efficiency of Propulsion

As aircraft engines become more fuel-efficient (fuel consumption per thrust), contrails will form more frequently at lower (i.e., warmer) flight levels because exhaust plumes are cooler for the same water content (Schumann, 1996; Paper I).

Figure 1 shows the trend in overall efficiency of propulsion η for the years 1960 to 2010, computed from aircraft specific fuel consumption (SFC) data (adapted from Aylesworth, 1997; see also Paper I, App. B), according to $\eta = V(Q \cdot \mathrm{SFC})^{-1}$, with V as the aircraft speed (about 240 m s^{-1}) and Q as the specific heat of combustion of aviation fuels (43 MJ kg^{-1}). The figure illustrates that the overall efficiency of propulsion η increased in the past and will grow until the year 2010 when more modern engines presently under development get installed. The trend suggests fleet averages of $\eta = 0.4$ for 2015 and possibly $\eta =$ 0.5 for 2050.

The critical altitude above which contrails form decreases with increasing η if the relative humidity of ambient air remains constant. In Fig. 1 the critical altitude is indicated at the right axis for 100% relative humidity and the temperature profile of the mid-latitude standard atmosphere. An increase of η from 0.3 to 0.5 in a standard atmosphere increases the threshold formation temperature of contrails by about 2.8 K (equivalent to 770 m lower altitude) (Schumann, 1996).

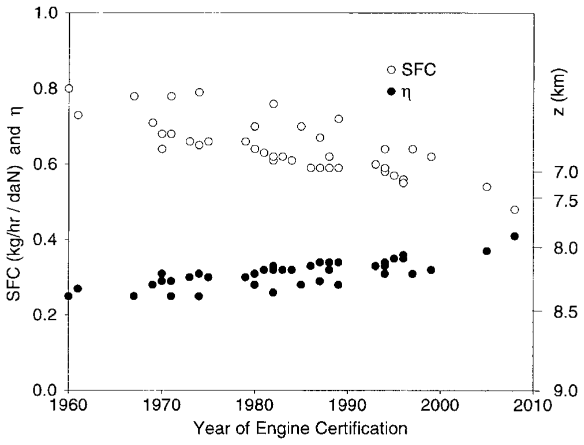

Fig. 1. Trend in the overall efficiency of propulsion η (solid circles), computed from aircraft specific fuel consumption data (SFC, open circles), over the years 1960 to 2010. The solid circles also denote the critical altitude z (right axis) above which contrails form (for 100% relative humidity and the temperature profile of the mid-latitude standard atmosphere)

3. Results and Discussion

3.1 The Year 2015

We used two alternative aviation fuel burn inventories for the year 2015 (see also Table 1): DLR-2 (Schmitt and Brunner, 1997) and NASA15 (Baughcum, 1998). Both inventories only cover subsonic aviation, because it seems rather unlikely that a large fleet of supersonic aircraft, e.g., 500 HSCTs, will be in operation by 2015. DLR and NASA use different methods for the prognosis of future air traffic demand and they differ in translating the traffic demand into fuel burn and emissions. Although their results for 2015 are in reasonable qualitative agreement, there are certain differences which should be discussed before the corresponding contrail coverages are shown. Differences can be found both, in the totals, and in the regional and vertical distributions of fuel burn.

NASA forecasts a total aircraft fuel burn of 310 Tg/a for the year 2015, which is about 10% larger than the corresponding DLR total of 270 Tg/a. NASA also forecasts larger fuel burn (namely 240 Tg/a) than DLR (210 Tg/a) for the atmosphere between 100 to 500 hPa. However, in the most frequently used flight levels around 250 and 200 hPa the DLR and NASA fuel burn values are rather similar, at least on global average. The larger NASA totals result from larger fuel burn in the levels 400, 300, and 150 hPa.

The most notable differences between the NASA15 and DLR-2 datasets occur in the regional distribution of fuel consumption: The mean annual fuel consumption between 100 and 500 hPa is 4.63 g/(m^{2}a) in Europe and 4.10 g/(m^{2}a) in USA according to the NASA15 inventory. In contrast to this, the maxima are exchanged for the DLR-2 inventory: 4.12 g/(m^{2}a) in Europe and 4.64 g/(m^{2}a) in USA. These differences in the fuel burn inventories cause differences in the derived contrail distribution (see below). The sensitivity of the contrail coverage to variations in the underlying traffic data is not constant since it also depends on the atmosphere's capability for contrail formation, i.e. the potential contrail coverage (see paper I).

The 2015 contrail distribution was computed with the underlying climate of the 1983–1993 period and with an assumed overall efficiency of propulsion $\eta = 0.4$ (instead of $\eta = 0.3$ for the 1992 fleet). The total fuel burn in the layer from 100 to 500 hPa is 87 Tg/a in the DLR-2 emission inventory for 1992, which yielded a global mean contrail fractional coverage of 0.087%. The corresponding numbers for the two 2015 traffic are 210.8 Tg/a and 0.235% (DLR-2), and 243.0 Tg/a and 0.272% (NASA15), for fuel use and global mean contrail cover, respectively (Table 1 and Fig. 2). These numbers indicate that the global contrail coverage increases stronger (factor 2.7 for the DLR-2 inventory) than the total fuel burn (factor 2.4). Most of this stronger increase of contrail cover relative to fuel use can be attributed to the enhanced overall efficiency of propulsion of an assumed 2015 aircraft fleet (see also below).

The global distribution of fractional contrail coverage for the two 2015 aviation scenarios are shown in Fig. 3. Corresponding regional mean

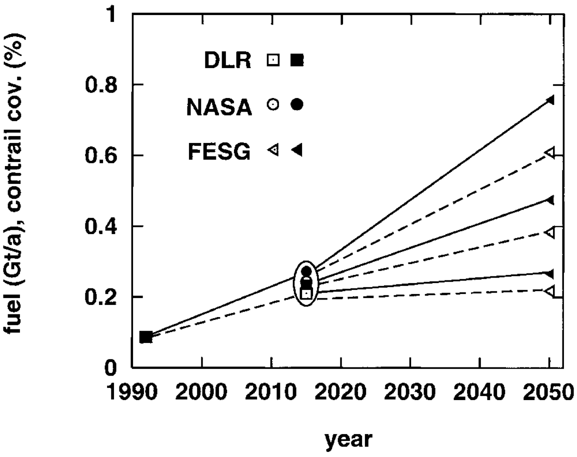

Fig. 2. Overview of the investigated traffic scenarios: Total fuel burn [Gt/a] between 500 and 100 hPa (open symbols), and global mean fractional contrail coverages [%] (filled symbols) for several fixed-year aviation scenarios (see also Table 1): DLR-2 for 1992 and 2015 (Schmitt and Brunner, 1997, squares), NASA15 for 2015 (Baughcum et al., 1998, circles) and FESG50e, FESG50a and FESG50c (from top to bottom) for 2050 (FESG, 1998, triangles). Note that for 1992 the numerical values for fuel burn and contrail cover are accidentally equal (0.087)

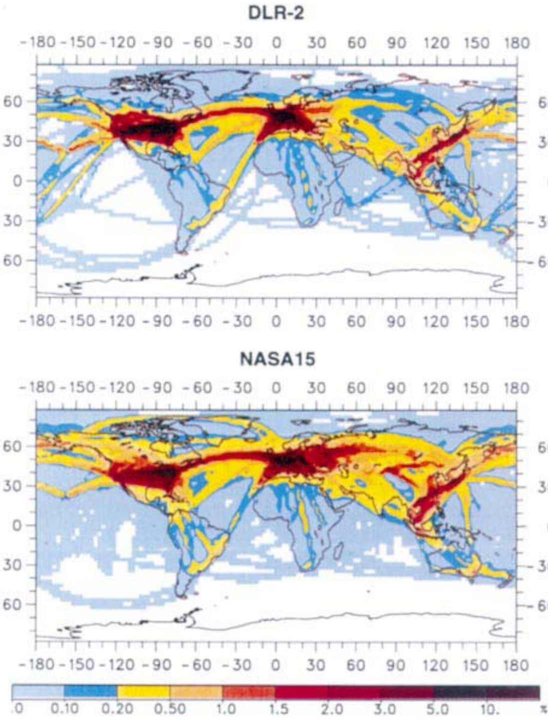

Fig. 3. Annual mean contrail coverage [%] versus longitude and latitude as obtained from the DLR-2 (upper panel) and the NASA15 (lower panel) aviation inventories for the year 2015. The underlying climate refers to the mean of the years 1983–1993. Linear weighting of fuel consumption and an overall efficiency of propulsion of $\eta = 0.4$ was assumed. The colour code is the same as used for Figs. 3 and 4 of Paper I

values are listed in Table 1. All values are computed assuming a linear relation between contrail cover and fuel consumption (see paper I). The higher total fuel use in the NASA15 inventory generally leads to a somewhat broader distribution of contrail cloudiness and to a higher global mean coverage than the corresponding DLR-2 scenario. Compared to 1992 (paper I), more regions appear on the world map where contrails are expected to be a frequent phenomenon in the sky, i.e., where the average contrail coverage exceeds 0.5%. These regions are Canada, Alaska and the route along the Aleutes and Kuriles to Japan, and much of the Asian continent. Also the North Atlantic flight corridor will be considerably broader in 2015 than in 1992. These regions coincide with those where the mean fuel consumption is expected to rise by an amount of 0.1–1 g/(m^2a) between 1992 and 2015, as judged from the respective DLR-2 inventories. The fuel consumption will rise by much larger amounts (1–10 g/(m^2a)) over USA and Europe with corresponding increases in the mean contrail coverages by factors between 2 and 3. Also over South-East Asia the fuel consumption is expected to increase by more than 1 g/(m^2a), leading to an increase in contrail cloudiness by almost a factor of 5 between 1992 and 2015 (see also Table 1). Overall, the computed contrail distribution for 2015 is much more extended than for 1992. From these calculations, the global contrail coverage is expected to nearly triple between 1992 and 2015, assuming the same climate.

3.2 The Year 2050

We considered three aviation scenarios for the year 2050 (FESG, 1998) that were constructed for the IPCC Special Report on “Aviation and the Global Atmosphere” (see also Table 1). One scenario (FESG50a) corresponds to the IPCC IS92a (IPCC, 1992) scenario of the future evolution of world population and gross national products. The other two are high (FESG50e) and low demand (FESG50c) scenarios (corresponding to IS92e and IS92c). The world total aviation fuel consumption between 500 and 100 hPa amounts to 378.3, 604.0, and 212.8 Tg/a for FESG50a, FESG50e, and FESG50c, respectively. Whereas the world total aviation fuel burn does hardly change between 2015 and 2050 in the low demand scenario, it increases by factors of about 1.5 and 2.5 in the central and high demand scenarios, respectively.

The total fuel burn in the central scenario FESG50a for 2050 is a factor 3.2 larger than the total fuel burn in the DLR inventory for 1992. The fuel burn at cruise altitudes between 500 and 100 hPa differs by a factor of 4.3 in these data sets. The world contrail coverage in scenario FESG50a is 5.4 times larger than that for DLR-2 in 1992 and 1.7 times larger than in the NASA15 scenario for 2015, see Fig. 2. The contrail cover increases 70% more strongly than the total fuel consumption and 25% more strongly than the fuel consumption at cruise altitudes. This is mainly a result of the assumed increase in overall efficiency of propulsion from $\eta = 0.3$ in 1992 to a value of $\eta = 0.5$ in 2050. For constant $\eta = 0.3$, the contrail cover would increase by a factor of 4.4 in the FESG50a scenario relative to 1992, i.e., only 2% more than fuel consumption at cruise altitudes. Hence, the contrail cover increases more strongly than total fuel consumption mainly because of the assumed increase in overall propulsion efficiency and larger increase in fuel consumption at cruise altitudes, and to only minor degree because of somewhat more traffic in regions with higher potential contrail cover at tropical and subtropical latitudes. At these latitudes the layers with high potential contrail coverage are at very high altitudes (100–150 hPa, see Paper I). The scenarios do not expect the air traffic to ascend to these altitudes, so the effect of more tropical flights on overall contrail cover is small.

Relative to the NASA15 inventory, the FESG50a air traffic scenario for 2050 assumes increases in mean fuel consumption of generally more than 1 g/(m^2a) over Europe, USA, and South-East Asia, whereas the additional fuel use over the rest of Asia, Canada, Alaska, and some air routes in South-America and Africa amounts to between 0.1 and 1 g/(m^2a). The FESG50a scenario assumes that in 2050 the fuel consumption is largest in Europe (7.33 g/(m^2a)). Accordingly, the largest mean fractional contrail coverage is expected over Europe with a value of 4.62%(see Table 1), which is more than 4 times the present value. Over the USA with fuel burn of up to 5.42 g/(m^2a) the corresponding contrail coverage will grow to 3.72%, which is 2.6 times the present value.

Since we found for both regions potential contrail coverages of more than 10% in the 200 and 250 hPa levels (see Fig. 2 of Paper I), there is still a potential for the further enhancement of contrail cloudiness in 2050, at least when temperature and humidity in the upper troposphere do not change relative to the present climate. However, a mean contrail cover of nearly 5% over a continent will probably lead to significant regional changes in the tropospheric temperature distribution (Ponater et al., 1996).

The computed global contrail distributions for 2050 are displayed in Fig. 4. The structures are similar to those of the 2015 scenarios (Fig. 3), with additional regions of frequent contrail cloudiness over Africa.

A comparison of the results for $\eta = 0.5$ and $\eta = 0.3$ (Table 1) shows that the effect of improved overall efficiencies of propulsion on contrail cloudiness is different for different regions of the world. Whereas the ratio of the global means for both choices of η is about 1.4, the corresponding ratios for the other regions in the table are all larger, often even larger than 2. As has already been discussed in Paper I, the regions where contrail coverage is more sensitive to variations of η are those where a lot of short-range air traffic occurs. These short-haul flights prefer lower flight levels which are nearer to the critical level of contrail formation than usual intercontinental flight levels. (The critical level of contrail formation is that altitude above which the temperature is low enough to allow contrail formation.) A larger overall efficiency of propulsion implies a lower critical flight level (cf. Fig. 1). Hence, improving the fleet mean overall efficiency of propulsion allows more short-haul flights to produce a contrail than without such an improvement.

Finally, let us consider the seasonal variation of the computed contrail coverage for the 2050 scenario FESG50a (see Table 1). We find a strong seasonal variability over Europe and the USA, with maxima in autumn and winter for Europe and with a maximum in spring for the USA. Minima are found for the summer season both in the USA and Europe. The global mean contrail coverage behaves similar with a minimum in boreal summer. This kind of seasonal variation has also been found for the 1992 air traffic (paper I). Since we have assumed an unchanged climate for the present study, the similarity of the annual variations for 1992 and 2050 is not surprising. However, if the traffic over the USA had shifted to higher altitudes then a reversed annual contrail coverage variation would have been expected as explained at the end of Section 4.4 in Paper I. The annual variation of contrail cloudiness over South-East Asia is weak. The seasonal variations derived here are solely due to the seasonally varying meteorological background. The FESG air traffic scenarios do not have a seasonal variation.

4. Summary and Conclusions

In the present paper we gave a first estimate of the growing global and regional contrail coverage response to be expected for air traffic and fuel burn scenarios for the years 2015 and 2050.

The mean contrail coverage of the Earth is computed to reach about 0.25% in the year 2015, i.e., about 3 times the present values. The global mean contrail coverages for the three air traffic scenarios for 2050 considered here range from 0.26% to 0.75%. The upper end of this range means an increase in contrail cloudiness by a factor of nearly 9 relative to the present value. The expansion of air traffic (spatially and by number of flights) has the effect that, relative to the present situation (see Paper I), additional regions appear on the world map where contrails are a frequent phenomenon in the sky.

Contrail cloudiness increases more strongly than the corresponding fuel burn at cruise altitudes. The main reason for this is the expected improvement of aircraft jet engines leading to enhanced overall efficiencies of propulsion with cooler exhaust. The radiative forcing due to contrails must therefore be expected also to increase stronger than the fuel consumption.

The accuracy of the results depends on several parameters as discussed in Paper I. In addition, we note that the method uses fuel consumption as a measure of air traffic density. We admit that this might not be an optimal choice; other measures like flown distances, number of flights, or number of soot particles emitted may be preferable generally or in certain climatic situations. So

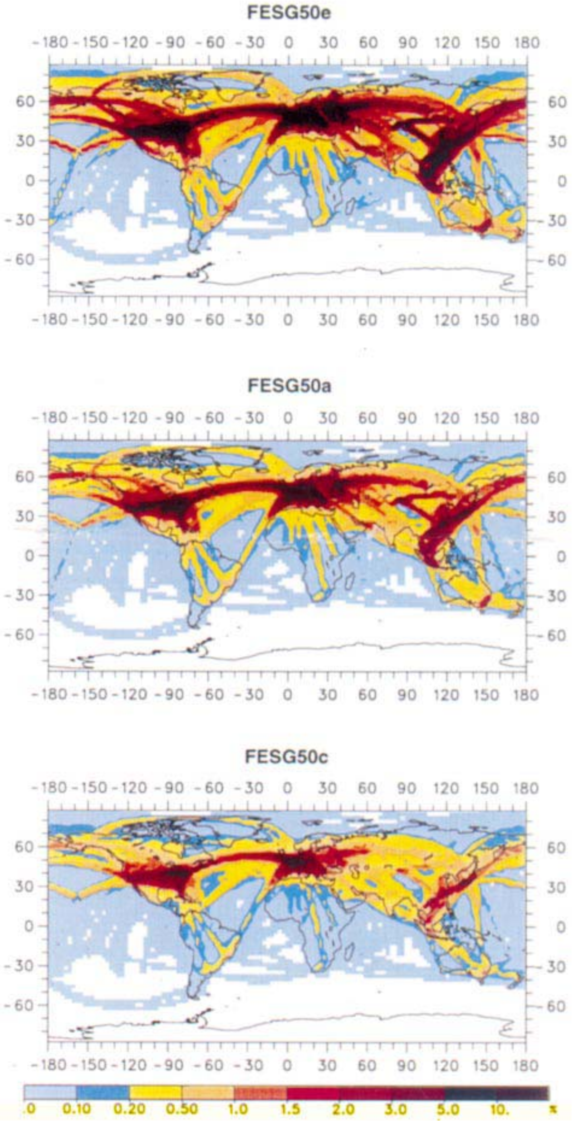

Fig. 4. Annual mean contrail coverage [%] versus longitude and latitude as obtained for the FESG50 air traffic inventories. The inventories refer to the year 2050 and can be interpreted a high demand scenario (FESG50e, upper panel), a central scenario (FESG50a, middle panel), and a low demand scenario (FESG50c, bottom panel). The underlying climate refers to the mean of the years 1983–1993. Linear weighting of fuel consumption and a fleet overall efficiency of propulsion of $\eta = 0.5$ was assumed

far it is not known which is the optimal measure of air traffic for the present purpose. We use fuel consumption since only this quantity is available in all inventories. Flown distances are solely available in the DLR-1992 data set. A test calculation (performed with these data) revealed an about 10% smaller contrail cover globally when computed in terms of flight distance instead of fuel consumption and larger differences (15% more cover over USA and up to factor of 2 less cover over South-East Asia) regionally.

The absolute accuracy of the computed contrail cover depends linearly on the normalisation, for which this study adopted the mean value 0.5% deduced by Bakan et al. (1994) from satellite pictures for the region near the westcoast of Europe. The accuracy of this reference value is basically unknown. It implies 1.8% mean contrail cover over Central Europe, where Mannstein et al. (1999) deduced 0.5% cover at noon and 1/3 this value at night (i.e., a 5 times smaller mean value) using satellite data and an automated pattern recognition algorithm. However, the algorithm detects only part of the line-shaped contrails (Mannstein et al., 1999). Moreover, these methods cannot identify aviation-induced cloud cover deviating from line-shaped contrails.

Finally, it should be noted that the results of the present study were derived under the assumption that the climate stays reasonably constant until 2050. This allowed to determine the immediate effect of the expanding aviation on the future contrail cloudiness. However, the climate is predicted by models to change during the next century, with increasing mean tropospheric temperature and moisture. Both parameters have a direct effect on the contrail cover: whereas a warmer climate will diminish the atmospheres susceptibility for contrail formation (Schmidt–Appleman criterion), an enhanced tropospheric moisture could imply larger ice-supersaturated volumes or higher humidities, leading to larger (longer and wider) contrails, larger contrail groups, and/or contrails with larger ice content, which in turn could mean a larger radiative forcing and a larger fraction of precipitating contrails than observed today. These questions will be addressed in the third part of this paper series.

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