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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Parameterization of subgrid aircraft emission plumes for use in large-scale atmospheric simulations" *by* A. D. Naiman et al.

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We first want to thank the referee for his/her detailed and helpful comments.

General Comments

POINT 1: The purpose of the paper is not clearly outlined.

It is clear that both referees were confused as to the purpose of the paper. We have changed the title of the paper and reworked the introductory material to make it clear that the purpose of the paper is to introduce a model of plume dynamics - location, shape, and volume - only.

POINT 2: The present contrail-SPM is integrated in the global model GATOR-GCMOM. It should be described in more detail which contrail-related questions are to be addressed on the global scale (contrail coverage only, microphysical properties, radiative forcing, life times, vertical redistribution of water vapour). This is crucial to deciding which contrail processes have to be considered in the contrail-SPM.

We have also included some more details about the model's application in the GCM in Section 4.1. However, we continue to refer readers to the study paper by Jacobson, et al. (2010) for the detailed implementation because relating these details are not the purpose of this paper.

Specific Comments

p.24756, l.3/4: Aircraft emissions do not only form condensation trails. Aircraft emit many chemical species.

p.24756, l.5: Which processes do you mean? Please name them.

p.24757, l.3: "due to them" Unclear to what it refers.

p.24757, l6/7: This sentence could be misunderstood. Please make clear that potential contrail coverage is not a function of air traffic density.

p.24758, l.7: The evolution and dispersion of plumes are subgrid scale processes, only if coarse resolution models for global/regional scale simulations are used. This should be mentioned.

The abstract and introduction have been rewritten to clarify the purpose, and these sentences have been fixed or eliminated.

Abstract as changed in manuscript:

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A new model of plume dynamics has been developed for use as a subgrid model of plume dilution in a large-scale atmospheric simulation. The model uses mean wind, shear, and diffusion parameters derived from the local large-scale variables to advance the plume cross-sectional shape and area in time. Comparisons to a large eddy simulation of aircraft emission plume dynamics, to an analytical solution to the dynamics of a sheared Gaussian plume, and to measurements of aircraft exhaust plume dilution at cruise altitude show good agreement with these previous studies. We argue that the model also provides a reasonable approximation of line-shaped contrail dilution and give an example of how it can be applied in a global climate model.

Introduction as changed in manuscript:

Large-scale atmospheric simulations, such as global climate models, necessarily use coarse spatial grid resolution due to computational cost requirements. Some processes of interest in such models cannot be simulated accurately at the resolved scales because of their nonlinear nature. The chemical reactions and aerosol microphysics that occur in aircraft emission plumes are examples of this problem. Many studies have shown that the chemistry of these plumes proceeds very differently when the emissions are diluted to the grid scale instead of treated as mixing on smaller scales, as happens physically (e.g., Meijer et al., 1997; Petry et al., 1998; Kraabøl et al., 2002). Similarly, the formation of condensation trails (contrails) is a highly visible example of the localized plume processes that would not occur if emitted water vapor and aerosol particles were spread over model grid scales.

Previous studies have treated this problem by means of parameterizations of the nonlinear chemical plume processes (Vohralik et al., 2008; Cariolle et al., 2009). Studies of contrails and the effect of aircraft on cirrus cloud cover have largely neglected subgrid scale processes (e.g., Ponater et al., 2002; Marquart et al., 2003), focusing instead on parameterizing contrail coverage. A recent study developed a parameterization of contrail cirrus based on physical processes including contrail formation, transport, and spreading, tracking coverage, contrail length, and ice mass mixing ratio on the grid

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scale (Burkhardt and Kärcher, 2009). Burkhardt and Kärcher, in the framework of the ECHAM4 climate model (Roeckner et al., 1996), used a parameterization to determine deposition rates to contrail ice particles, as these clouds exist on a scale of 10 km compared to a grid spacing of 270 km. They also parameterized the effect of shear on contrail spreading, specifying both a contrail vertical thickness and a spreading constant. Tests in the study did not examine the sensitivity to the specified thickness, but did show significant sensitivity to the spreading parameter. In order to capture the effect of subgrid scale mixing on nonlinear plume processes, we take a Lagrangian approach in tracking individual aircraft exhaust plumes. We note that a similar approach has recently been taken independently by Schumann (2009). Using a new aircraft emissions inventory that gives individual flight trajectories over a year (Wilkerson et al., 2010) and a global climate model that models aerosol processes on the individual plume level (Jacobson et al., 2010), the parameterizations noted above are exchanged for physical models. In the case of the plume transport and spreading processes, this treatment requires a model that can assess the evolution of the plume location, volume, and shape based on grid scale variables.

This paper presents a model of aircraft plume dilution that is intended to fulfill this role in a large scale atmospheric simulation. It provides prognostic equations for the advancement of the volume and width of a plume based on variables provided by the atmospheric simulation on the grid scale. Although the equations are simple, comparison with a high fidelity model of plume dispersion shows that they are adequate to describe plume dynamics as compared to the level of fidelity of a large scale atmospheric simulation.

Section 2 presents a new model of emission plume dynamics that uses global grid scale variables to advance the plume location, volume, and shape. Section 3 compares the new model to a large eddy simulation of an aircraft exhaust plume, to the analytical solution to the dynamics of a sheared Gaussian plume, and to measurements of aircraft exhaust plume dilution at cruise altitudes. Finally, Sect. 4 argues that the new model also provides a reasonable model of lineshaped contrail dynamics and suggests how it might be used as such in a global climate model.

p.24761, l.7-9: The references (Chlond, Lewellen and Lewellen, Huebsch and Lewellen) study contrails up to 30 minutes age. As the life time of contrails can be of orders of hours, it should not be stated that these studies include contrails at late times. You use a time step of 60 minutes in the global model which implies that initial contrails are 30 minutes old on average, if not introduced at intermediate points of time in the subgrid model. This implies that the latter studies can be used for the validation of your contrail initialisation only. Studies with longer simulation periods are rare, but do exist, e.g. Jensen et al., JGR, 1998. Does this study support your assumption of an ellipsoidal cross-section?

The Chlond (1998) study was of late dispersion stage contrails (10^3 s old), though the simulation itself was for 30 minutes. This paragraph has been changed to make it clearer that some of the studies are of young contrails and some (including Jensen et al. 1998 and Unterstrasser and Gierens 2009) are for later times or longer durations. All of the studies we cite show contrail cross-sections that can be reasonably approximated by ellipses.

Changed in manuscript:

This choice reflects the results of studies of plumes and contrails under turbulent and shear conditions in the early, vortex phase (Lewellen and Lewellen, 2001; Huebsch and Lewellen, 2006), at later times (Dürbeck and Gerz, 1996; Chlond, 1998), and over longer time frames (Jensen et al., 1998; Unterstrasser and Gierens, 2009).

Deficiencies or unclear issues of the contrail model

p.24758, l.9/10: This detail of the GCM implementation has been moved to Section 4.1. The other questions raised here have also been answered in the revised Section

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4.1. We note again, however, that the details of the contrail microphysical model are not the purpose of this paper.

Do I understand correctly that the Lagrangian treatment of individual plumes stops when a single contrail extends over the total gridbox or the contrail crystal ice mass/number concentration have decreased below a certain background concentration? What thresholds do you use for the background concentrations? How is the contrail ice transferred/included in the global model (or is it removed from the system)?

Yes, individual plumes are tracked until they reach the horizontal grid scale or until their water mass concentration is reduced below $10\ \mu g/m^3$. When this occurs, all components tracked within the plume are conservatively added to the discrete, size-resolved grid-scale aerosol distributions.

What prognostic equations for the contrail ice mass/number are used in the SPM?

Within each subgrid plume, particles and their chemical components are tracked over time with a discrete, size-resolved aerosol-contrail size distribution (16 bins). Particles grow within each plume by size-resolved coagulation, condensation/evaporation, and ice deposition/sublimation with mass-conservative and stable numerical methods.

Are there prognostic equations for contrail ice mass/number in the global model?

At the global grid scale, contrail ice is not distinguished from other aerosol particles. Once the plume has been added to the grid scale, water vapor and aerosol particles can immediately affect or induce cirrus clouds. Size- and composition-resolved microphysics is calculated for this material at the grid scale, including sedimentation, coagulation, depositional growth, sublimation, and melting. Horizontal and vertical transport are also calculated at the global grid scale.

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How often does it happen that a contrail covers the whole gridbox?

In practice, plumes always become diluted to the threshold water mass concentration before they reach the grid scale size.

Changed in Section 4.1 in manuscript:

The climate simulation tracks the volume and shape of emission plumes from individual aircraft over time using SPM segments. For each segment, the simulation uses plume volume to calculate the dilution of plume components for a microphysical model and optical property calculation. Within each segment, particles and their chemical components are tracked over time with a discrete, size-resolved aerosol-contrail size distribution. Particles grow within each segment by size-resolved coagulation, condensation/evaporation, and ice deposition/sublimation with mass-conservative and stable numerical methods. The optical properties and shape of each plume segment are used in calculations of radiative transfer through plume-occupied portions of the climate simulation grid cells. Segments are tracked individually until they grow to the grid scale or until their water mass concentration is diluted below $10\ \mu g/m^3$. In practice, plumes always become diluted to the threshold water mass concentration before they reach the grid scale size. When this occurs, all components tracked within the plume are conservatively added to the discrete, size-resolved grid-scale aerosol distributions. Once the plume has been added to the grid scale, water vapor and aerosol particles can immediately affect or induce cirrus clouds. Size- and composition-resolved microphysics is calculated for this material at the grid scale, including sedimentation, coagulation, depositional growth, sublimation, and melting. Horizontal and vertical transport are also calculated at the global grid scale. Details of these calculations are described by Jacobson et al. (2010).

Deposition growth

We note again that the details of the contrail microphysical model are not the purpose of this paper.

How do you include depositional growth in the SPM? What relative humidity with respect to ice do you assume inside the contrail or how fast is it reduced/relaexed to a certain value? Is all excessive water vapour converted to contrail ice? What happens if several contrail partially overlap? How is the water vapour distributed then?

Particles grow within each plume by size-resolved coagulation, condensation/evaporation, and ice deposition/sublimation with mass-conservative and stable numerical methods. No relative humidity is assumed - the ambient and emitted water vapor are added to the plume, and the local relative humidity is calculated. With respect to microphysics, contrails are assumed to not overlap.

Is supersaturation generally allowed in the global model? How is the grid mean value of relative humidity interpreted in the subgrid model? Are subgrid variations assumed?

Supersaturation is calculated separately in each subgrid plume based on the grid-scale water vapor, the water vapor added by the aircraft, and the grid-scale temperature (since the plume is assumed to cool to ambient within a few seconds). The supersaturation is then reduced due to condensation onto subgrid plume particles, which are discretely size and composition resolved. Each size bin sees the relative humidity as the partial pressure of water vapor (emitted plus background) over saturation vapor pressure (from grid-scale temperature), modified by the Kelvin effect and Raoult's law.

Sedimentation:

The vertical extent of a initial contrail is 120 m. On the one hand, your Fig. 6 shows a slow vertical expansion due to turbulence, mainly caused by the fact

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that the vertical diffusivity is much smaller than the horizontal diffusivity. Within 10 hours the vertical plume extent has not yet doubled. On the other hand, you give a crude approximation that 30 μm-diameter contrail particles descend approximately 500 m which is much larger than the initial contrail depth of 120 m. Contrary to your reasoning my conclusion is that the sedimentation process may strongly increase the vertical extent of the contrail and cannot be neglected in the SPM since it has the potential to considerably increase the horizontal spread due to vertical wind shear.

For the above estimate you used the diameter of an average-sized contrail particles. So generally the descent can be even larger for those contrail crystals that are larger.

As the vertical grid size of the global model is 500m, a contrail with an average 500m-descent would completely move to the next gridbox below. The typical thickness of ice-supersaturated air layers (ISSR) ranges roughly from 500m to 1.5km (for an overview see Kärcher et al., 2009, section 2.2.1). If the thickness of the ISSR is small, contrails may fall into a subsaturated layer and finally sublimate. If the thickness of the ISSR is large, a contrail may extend over several grid layers (formation of fall streaks) and can take up much more water vapour than contrails in the SPM restricted to one grid layer. Hence, the contrail evolution may be considerably affected by the inclusion of the sedimentation process.

The vertical extent of an initial contrail is 240 m (twice the initially vertical radius of the ellipse). The following table shows terminal settling velocities for particles of various sizes (based on a slip corrected Stokes' Law estimate, see, e.g., Seinfeld and Pandis, 1998) and their resulting descent distance over five hours.

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Diameter (μm)	Terminal Velocity (m/s)	Descent (m)
10	3.64e-3	65.5
20	1.42e-2	256.
30	3.18e-2	572.

Since settling velocity is approximately quadratic with particle diameter, it is important to characterize the particle diameters expected in contrails to decide whether sedimentation is important. Heymsfield et al., 1998, reported that inside the contrail core, where most contrail particles are found, almost all particles remained small (between 1-10 μm diameter). Schröder et al., 2000, likewise described contrails as containing ice crystals with mean diameters in the 1-10 μm diameter range. They additionally found young cirrus (i.e., recently formed from contrails) with ice crystals in the 10-20 μm diameter range.

The focus of the SPM as used in Jacobson et al., 2010, is to simulate line contrails. While it is true that a small number of particles grow to much larger sizes in line contrails and young cirrus clouds (as reported in the references above), the typical particle is less than 20 μm in diameter and does not descend significantly over the time scale related in our example. Once the plume reaches its dilution threshold, all of its aerosol components are added to the grid scale aerosol bins, where sedimentation is treated as noted above.

p.24767, l.14-18: Reading the explanation of Fig.1 of Unterstrasser and Gierens they state that at t = 17000 s the sedimentation impact is evident in the plot. Although the radiative impact of the sedimenting particles itself is small (as stated there), this does not imply that sedimentation has no impact on the radiative impact of the total contrail. The IWC in the upper part of the contrail is reduced due to sedimentation, as stated. Moreover the study concludes that sedimentation is a second effect besides subsidence that limits the contrail life time (see their conclusions). Thus, neglecting sedimentation may overestimate the lifetime and

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radiative impact of contrails.

These paragraphs have been rewritten to strengthen our justification.

Changed in Section 4.2 in manuscript:

In the case of a plume that is not passive, e.g., a contrail that contains significant numbers of ice particles, the tracer approximation also neglects other effects. Line contrail ice particles have been observed to grow to effective particle diameters of 20 μm within several hours of contrail formation, with induced cirrus particles up to 200 μm observed (e.g., Minnis et al., 1998; Heymsfield et al., 1998; Schröder et al., 2000). This range of particles has terminal settling velocities from 1–10 cm/s (Seinfeld and Pandis, 1998). Sedimentation therefore removes large ice particles from the contrail or contrail-induced cirrus core and increases the vertical extent of the plume directly. In the presence of vertical wind shear, horizontal spread is dominated by the vertical extent of the plume, so sedimentation (to the extent that it occurs) also increases the spread of the plume in the horizontal direction.

Heymsfield et al. (1998) reported that inside the contrail core, where most contrail particles are found, almost all particles remained small (between 1-10 μm diameter). Schröder et al. (2000) likewise described contrails as containing ice crystals with mean diameters in the 1-10 μm diameter range. They additionally found young cirrus (i.e., recently formed from contrails) with ice crystals in the 10-20 μm diameter range. Using a slip corrected Stokes' Law estimate, the terminal settling velocity of a 20 μm diameter particle is approximately 1 cm/s. Over the lifetime of a long-lived line contrail (e.g., five hours), such a particle would therefore descend approximately 200 m - on the same order as the initial vertical depth of an SPM segment in the model. The focus of the SPM as used in Jacobson et al. (2010) is to simulate line contrails. While it is true that a small number of particles grow to much larger sizes in line contrails and young cirrus clouds (as reported in the references above), the typical particle is less than 20 μm in diameter and does not descend significantly over the typical line contrail lifetime. We

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therefore neglect the effect of sedimentation on the line contrails modeled using SPM segments. Particles are still allowed to grow to large sizes while contained in the SPM segment if the line contrail is sufficiently long-lived. Once the plume reaches its dilution threshold, all of its aerosol components are added to the grid scale aerosol bins, where sedimentation is accounted for explicitly as a function of particle size and composition.

Independently of the implementation of sedimentation: If a contrail extends over two grid layers, how are the values passed from the global to subgrid scale determined or averaged? Analogeous question for the horizontal direction.

Line contrail material is confined to the grid cell it was emitted to while contained in the plume sgment. Once the line contrail material (aerosol particles and water) is added to the grid scale (i.e., once the water content of contrails drops below the threshold), horizontal and vertical transport can move the material out of the grid cell to affect clouds and other properties outside the grid cell.

p.24767, l.20-25: Are the contrail ice crystals added to the grid box mean ice water content?

As noted above and now in Section 4.1, at the global grid scale, contrail ice is not distinguished from other aerosol particles. Once the plume has been added to the grid scale, water vapor and aerosol particles can immediately affect or induce cirrus clouds. Size- and composition-resolved microphysics is calculated for this material at the grid scale.

Technical Corrections

p.24766, l.25/26: "contains significant ice particle density"

This awkward wording has been fixed.

Changed:

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In the case of a plume that is not passive, e.g., a contrail that contains significant numbers of ice particles, the tracer approximation also neglects other effects.

Fig. 3 , third row I would prefer to reduce the image size on the left in order to approximately use the same scale for both images.

The original data was not available for replotting these figures, unfortunately. We would prefer to leave the scales as they are rather than reduce the left figure, as it will become illegible, or increase the size of the right figure, as it will become too large. Perhaps the editor can suggest another solution for formatting these figures together.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 24755, 2009.