Large Eddy Simulation of Persistent Contrails

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ABSTRACT: A study of three-dimensional contrail evolution has been conducted using a large eddy simulation (LES) model. The LES solves the incompressible Navier-Stokes equations with a Boussinesq approximation for buoyancy forces. Contrail ice particles are modelled using a Lagrangian tracking approach along with a microphysical model of growth due to ice deposition and sublimation. Initial condition flow fields approximate the wake of a commercial jet one second after the aircraft has passed. We present results of simulations to 1200 seconds after emission. We find that higher levels of turbulence and shear promote mixing of the aircraft exhaust with ambient air, resulting in faster growth of contrail ice particles and wider dispersion of the exhaust plume when the ambient air is supersaturated. These results provide sensitivity information that is used to refine a subgrid model of aircraft exhaust plume dynamics for use within a global climate model.

1 INTRODUCTION

Aircraft are unique among anthropogenic sources of air pollution in that they consume much of their fuel at a cruise altitude near the tropopause, where exhaust has a long residence time and conditions are conducive to the formation of condensation trails (contrails). The effect of contrails and related aviation-induced cloudiness on climate is highly uncertain. The most recent assessment of the effect of aviation on global radiative forcing lists the level of scientific understanding as “low” for linear contrails and as “very low” for induced cloudiness (Lee et al., 2009). The range of estimates for these effects is large, and if the upper end of the range was realized, it would nearly double the overall forcing of aviation.

This paper presents work that is aimed at reducing the uncertainty in these estimates related to understanding the formation and persistence of contrails. We present results from a large eddy simulation (LES) model of contrails that tracks ice particles using a Lagrangian approach. The model has been used to simulate contrail development from 1 to 1200 seconds after emission by a passing commercial jet aircraft under several atmospheric conditions.

2 LES MODEL OVERVIEW

Several researchers have modelled contrail development using an LES approach, including Lewellen and Lewellen (2001), Paoli and Garnier (2005), Huebsch and Lewellen (2006), Shirgaonkar and Lele (2007). Our LES code solves the three-dimensional, incompressible Navier-Stokes equations with a Boussinesq approximation for buoyancy forces on an unstructured grid. The numerical scheme uses a finite volume spatial discretization and an implicit fractional-step method for time advancement, with second order accuracy in both space and time (Mahesh et al., 2004; Ham et al., 2007). Contrail ice particles are modelled using a Lagrangian tracking approach and a microphysical model of growth due to ice deposition and sublimation, similar to Paoli et al., (2004).

The computational domain is stationary with respect to the ground, so the computation represents a temporal simulation in a triply periodic domain. The coordinate axes are positioned such that the y-axis is vertical (opposite gravity), the z-axis points in the flight direction, opposite the cruise velocity, and the x-axis is the cross-stream direction. The coupled fluid equations are listed below, where $\mathbf{u} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$ is the velocity vector, $\rho$ is the fluid density, $p$ is the fluid pressure, $g$

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is the gravitational acceleration vector, $\mu$ is the dynamic viscosity of air, $\theta$ is the potential temperature, $\kappa$ is the thermal diffusivity of air, and $D_v$ is the diffusivity of water vapour in air.

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\rho_0 \frac{D\mathbf{u}}{Dt} = -\nabla p + \rho' \mathbf{g} + \mu \nabla^2 \mathbf{u}
\]

\[
\rho' = \frac{-\rho_0 \theta'}{\theta_0}
\]

\[
\frac{D\theta'}{Dt} = -\frac{d\theta}{dy} v + \kappa \nabla^2 \theta' + \omega_T
\]

\[
\frac{DY'}{Dt} = -\frac{dY}{dy} v + D_v \nabla^2 Y' + \omega_T
\]

\[
\omega_T = -\omega_T L
\]

In addition to the typical set of incompressible Navier-Stokes equations (Equations 1-2) with a Boussinesq approximation (Equation 3), two scalar diffusion equations are solved for potential temperature and water vapour density. We decompose these scalars into a reference part ($\theta_0, Y_0$), an altitude-varying part ($\theta(y), Y(y)$), and a perturbation part ($\theta', Y'$). The altitude-varying part is prescribed to be a constant gradient for both variables. The diffusion equations are solved for the perturbation part of the scalars (Equations 4-5). Equations 4-5 also include source terms ($\omega_T, \omega_Y$) resulting from a coupling to the microphysical equations and related according to Equation 6, where $L$ is the latent heat of sublimation of ice.

Contrail ice particles are modelled using a Lagrangian tracking approach and a microphysical model of growth due to ice deposition and sublimation. Particles are currently tracked as tracers of the background fluid. This approximation is suitable at early phases of contrail development, when particle relaxation time $\tau_p = 4 \rho_p r_p^2 / 18 \mu$ is short compared to flow time scales due to small particle sizes (particle radius $r_p$ 1-10 $\mu$m). For the late stages of simulation, when the largest particles grow to 100 $\mu$m, the effects of sedimentation and particle drag will be added in the future.

The model of microphysical growth is described in detail in Shirgaonkar and Lele (2007). In summary, each ice particle is treated as a spherical nucleus over which ice has deposited. Each computational particle represents a collection of physical particles. Coagulation and coalescence are neglected and re-nucleation is allowed. Particle radius changes due to deposition or sublimation of water to or from the particle surface. The growth rate of a single ice particle is calculated using a simple diffusion model from Kärcher et al. (1996). Growth rates are calculated for each computational particle and integrated over the time step. The source term, $\omega_Y$, is then calculated by integrating the source of water vapour in each Eulerian control volume.

3 SIMULATION DESCRIPTION

Each case described here was simulated as follows. First, a background field of periodic, decaying turbulence was generated. This background field was then scaled such that the energy matched the inertial subrange spectra $E(k) \approx 1.7 \epsilon^{2/3} k^{-5/3}$ at the peak wavenumber, $k_p = 4$, for the given case turbulent dissipation rate, $\epsilon$. The 2-D wake one second downstream of a Boeing 767, calculated by the Boeing Company and provided by Dr. Steven L. Baughcum, was added to the background field. A series of unstructured, periodic grids was used to simulate the development of the contrail, with grid resolution maximized near the contrail structure and decreased out to the domain boundaries. Results on each grid were interpolated to the next. Maximum resolution ranged from 0.37 m during the early stages of the simulation to 2.96 m in the latest stage. Similarly, total domain size ranged from $400 \times 400 \times 400$ m$^3$ to $3200 \times 1600 \times 400$ m$^3$ as the simulation progressed. Grid sensitivity studies showed little variation in results due to these transitions from one grid to the next.
For all of the cases considered here, the potential temperature gradient is stable \( (dθ/dy = 2.5 \text{ K/km}) \) and the water vapour gradient approximates a constant ambient relative humidity with respect to ice (RHi) of 130%. Ambient conditions were consistent with a cruise altitude of 10.5 km in a standard atmosphere. The peak exhaust temperature was 4.4 K, the peak exhaust water vapour density was \( 1.14 \times 10^4 \text{ kg/m}^3 \), and the peak particle number density was 85,000 per cm\(^3\). A total of \( 8 \times 10^6 \) computational particles, each representing \( 2.73 \times 10^8 \) physical particles, were tracked, giving a total of \( 5.8 \times 10^{12} \) per m in the flight direction, and each was initialized with a radius of 0.1 μm. Four cases were simulated, varying the intensity of both ambient turbulence and vertical wind shear. The cases are summarized in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Turbulent Dissipation Rate (m(^2)/s(^3))</th>
<th>Vertical Shear (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Baseline</td>
<td>0.0001</td>
</tr>
<tr>
<td>B</td>
<td>High turbulence</td>
<td>0.001</td>
</tr>
<tr>
<td>C</td>
<td>Moderate shear</td>
<td>0.0001</td>
</tr>
<tr>
<td>D</td>
<td>High shear</td>
<td>0.001</td>
</tr>
</tbody>
</table>

4 LES RESULTS

The following figures show results from the four simulation cases. Figure 1 shows two sets of plots for case A, the baseline case, and for case C, the moderate shear case – the upper plots are flight-direction averaged contours of ice water content, while the lower plots are vertically integrated ice area density. For the lower plots, the domain has been duplicated in the flight direction in order to give an impression of the contrail as it would appear in the sky.

Figure 1. Left plots are for case A, right plots are for case C. Upper plots are flight-direction averaged contours of ice water content. Lower plots are vertically integrated ice area density. Scales and contour levels are identical on all plots.

The overall development of the contrail is as expected. The wake vortices dominate the early flow field and much of the contrail descends with the wake, leaving behind a vertical curtain that detrains due to buoyancy. As the Crow instability develops, the vortices are perturbed from their initial linear shapes and eventually link. The pinching off of vortex loops leads to periodic, puffy shapes in the linear contrail. At late times, the decaying ambient turbulence field continues to spread the contrail plume.
Comparison of cases A and C in Figure 1 shows that moderate shear has little effect on vortex behaviour. The vortex wake descends at approximately the same rate, and develops the Crow instability, again forming periodic puffs. As development continues, the contrail is spread horizontally by the vertical shear. An increase in mixing is evident, shown by the reduced separation between the periodic puffs at later times. This mixing is driven by the vertical shear, which reduces the rate at which the ambient turbulent field decays.

Figure 2 shows a comparison of the flight-direction averaged contours of ice water content at the end of the simulation, \( t = 1200 \) s, for each of the four cases. The intensity of the ambient turbulence and the vertical shear have a large effect on the contrail cross-sectional shape at late times. More intense ambient turbulence increases cross-sectional area as higher mixing rates spread the contrail (cases A and B). When vertical shear is present, however, it dominates horizontal spreading (cases C and D). These effects are important to understanding the climate impact of contrails, since the horizontal and vertical thicknesses of contrails directly affect the cloud fraction and optical depth attributed to these anthropogenic clouds.

![Figure 2](image1.png)

Figure 2. (Left) Flight-direction averaged contours of ice water content for each case after 1200 seconds of simulation time.

![Figure 3](image2.png)

Figure 3. (Right) Particle radius distributions at three times during the simulation. Solid lines are for case A, dashed lines are for case D.

Figure 3 shows the size distribution of ice particles integrated over the domain at three times during the simulation for cases A and D. In both cases, as the contrail ages, the spectrum widens and the peak moves to higher radii as ice particles grow. The distribution peak is higher for case D at late times, reflecting the increased ice growth for this case as explained below.
5 CONCLUSIONS

Our simulations of persistent contrails show the expected results and agree well with previous work. An initial set of four sensitivity cases has shown that ice growth is relatively insensitive to ambient turbulence levels produced by both a decaying isotropic turbulence field and by a linear vertical wind shear. These results have been assimilated into a subgrid contrail model (Naiman et al., 2009) to track contrails within a global climate simulation (Jacobson et al., 2009).

Additional LES cases will vary simulation parameters including aircraft size and engine configuration, and will study the effect of additional microprocesses such as sedimentation. Further study of the sensitivity of contrails to atmospheric and aircraft parameters will allow refinement of the
subgrid contrail model for use in future climate studies. Furthermore, these high fidelity simulations will help establish confidence that the low fidelity subgrid contrail model captures the contrail dynamics that are relevant to climate model simulations.

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REFERENCES


