Transport and effective diffusion of aircraft emissions

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Abstract. The transport and effective diffusion of exhaust are analyzed in the wake flow of a large-bodied aircraft which flies through a stably stratified, sheared, and turbulent atmosphere. The analysis is based on data sets from large-eddy simulations of the wake in the atmosphere. Diffusion and dilution measures are obtained from a chemically inert species concentration. Most of the exhaust is concentrated and isolated in the two wing tip vortices (the "primary wake"). However, as the vortices sink through a stably stratified atmosphere, a baroclinic torque develops between the vortices and the surrounding flow and detrains about 10 to 30% of the exhaust mass from the vortices into the ambient air (the well mixed "secondary wake"). Consequently, the entrainment rates computed for the primary and secondary wakes differ by orders of magnitude. In the period between 1.5 and 3 min the vortices collapse into aircraft turbulence. The trapped emissions of the primary wake are now released and diffused by ambient turbulence and shear. After about 5 min the exhaust concentration has been diluted by $2 \times 10^{-5}$ and $4 \times 10^{-6}$ compared to the value at the nozzle exit for the primary and secondary wakes, respectively, and covers areas of about $5 \times 10^4$ m$^2$ and $2 \times 10^4$ m$^2$. Under flow conditions typically found at cruising heights the emissions are diluted to background concentrations within 2 and 12 hours for wind shear between 0.002 and 0.01 s$^{-1}$. The spatial plume extension does not exceed the lower mesoscale range (20 km horizontally and 0.3 km vertically). Good to excellent agreement is achieved between the numerical results and in situ measured data.

1. Introduction

An exhaust plume disperses because of the combined effects of advection, turbulent diffusion and molecular diffusion resulting in an effective diffusion. The diffusing flow is a superposition of aircraft-induced and atmospheric flow. The former is controlled by the airplane and its flight condition: the circulation around the wings, and thus the strength of the vortices, is proportional to the weight and span and inversely proportional to the speed of the aircraft. Atmospheric turbulence increases mixing and stable stratification reduces/increases the effective diffusion in the vertical/horizontal directions [see, e.g., Dürbeck and Gerz 1995]. A significant wind shear triggers turbulence and distorts the plume, leading to even stronger horizontal dispersion compared to situations without shear.

The wake flow is conveniently divided into three stages which can clearly be observed in the exhaust distribution: In the "jet" regime the vortex sheet around the wings rolls up into two counterrotating vortices positioned roughly at the wing tips. Simultaneously, the hot exhaust jets first expand freely but the evolving wing tip vortices soon draw them in and trap them in the vortex cores [Gerz and Ehret, 1997]. Figure 1 sketches the situation. In the following "vortex" regime, the vortex pair propagates downward by mutual velocity induction. Most of the exhaust also sinks below flight level as it is stored in that primary wake. However, some fraction of exhaust is detrained into the secondary wake, which is the wake produced by the vortices themselves. The secondary wake connects the vortices (primary wake) with the flight level [Lewellen and Lewellen, 1996; Gerz and Ehret, 1996]. The vortex regime is followed by the "dissipation" regime, where the organized vortical motion breaks up in turbulence and where its energy dissipates to the background level. Finally, the aircraft-induced motion ceases and atmospheric processes transport and diffuse the emissions farther on; this flow stage is referred to as the "diffusion" regime.

However, this qualitative picture of the processes in the wake of an aircraft is insufficient to assess the impact of aircraft emissions upon the atmosphere.
mixing properties also have to be known quantitatively because chemical and microphysical processes in the atmosphere often evolve nonlinearly and obey similar timescales as the mixing motions [Daniilin et al., 1992; Mische-Lye et al., 1993; Karol and Ozolin, 1994]. The spatial and temporal scales in the aircraft wake flow are too small to be captured by large-scale or mesoscale climate models. In addition to the direct emissions, however, the dynamics, microphysics, and chemistry in the wake control the amount and composition of exhaust which is finally emitted into the atmosphere at a global scale. Therefore the study aims to elaborate a detailed and quantitative description of the effective diffusion of aircraft exhaust from the jet regime to the diffusion regime. The evaluations are based on simulations of the wake flow controlled by the aircraft [Gerz and Ehret, 1996, 1997; Gerz and Holzpfel, 1998] and of the further transport and diffusion of the exhaust by the atmospheric flow [Dürbeck and Gerz, 1995, 1996].

We choose the input data for the calculations such that they correspond to typical cases with respect to aircraft type, flight condition, and atmospheric state as measured in the North Atlantic flight corridor [Schumann et al., 1995]. For a data comparison we consider in particular a flight on November 13, 1994, when the DLR research aircraft Falcon crossed the path of an eastbound travelling B747 west of Ireland and collected flow and exhaust data in its 82-s-old wake [Schulte et al., 1997, case 1]. The B747 is a typical aircraft type since it alone accounts for about 50% of the NOx emissions in the North Atlantic flight corridor [from Hoinka et al., 1993] which is one of the most frequently used flight routes of the world. The results, however, are applicable to other large-bodied aircraft and other flight routes [Gerz and Holzpfel, 1998]. The B747 aircraft has a span of 60 m and a weight of $2.5 \times 10^6$ N which is about 75% of its maximum take-off weight. It cruises at a speed of 247 m/s, resulting in a maximum circulation of $\Gamma_0 = 600$ m$^2$/s. We assume an elliptical wing load under cruising conditions and model a turbulent boundary layer around the aircraft. The exhaust of the four turbines is considered as a chemically inert species, e.g., CO$_2$.

The mean state of our model atmosphere in the tropopause region, where the chased B747 cruised, is defined by a pressure of 215.9 hPa at 11.3 km height, a density of 0.35 kg/m$^3$, and an absolute temperature of 214.3 K (potential temperature of 332.1 K). For the LES of the wake controlled by the aircraft, we set the mean atmospheric flow to zero and superimpose the measured background temperature gradient in terms of a constant Brunt-Väisälä frequency $N = 0.014$ s$^{-1}$. For the LES of the wake diffused by the atmospheric flow, we vary $N$ between 0.006 and 0.03 s$^{-1}$ and the vertical crosswind shear $S$ between 0 and 0.01 s$^{-1}$. This covers typical values of the upper troposphere and lower stratosphere and includes also more extreme conditions [Dürbeck and Gerz, 1996]. The small-scale ambient flow is simulated as decaying, weak, anisotropic turbulence under the background regime of stable stratification as it is typically measured at flight levels over oceans or flat terrain [Nastrom and Gage, 1985; Nastrom et al., 1987; Schumann et al., 1995; Dürbeck and Gerz, 1996].

Here we distinguish between two cases: one without any atmospheric motion (but including the boundary layer turbulence from the aircraft) and one with atmospheric turbulence typically found at cruise levels. The maximum mean turbulence fluctuations from the boundary layer are 2 m/s and amount to 16% of the maximum tangential velocity of a wing tip vortex ($V_{\text{vortex}} = 12.3$ m/s). This turbulence is found around the vortex cores and therefore has a small length scale. The atmospheric turbulence eddies, on the other hand, are anisotropic with a mean strength (based on the root-mean-square value) of 3% and 1.7% of $V_{\text{vortex}}$ for horizontal and vertical fluctuations, respectively. The most energetic atmospheric eddies have horizontal length scales of about the aircraft wing span.

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Figure 1. Early wake dynamics behind an airplane. The figure sketches the formation of the wing tip vortices (grey) and the trapping of the exhaust jets (black) around the vortex cores.

We collect the species concentration data from all wake regimes to compute the cross-section areas of the exhaust plume, and the horizontal, vertical, and skewed standard deviations of the spatial species distribution, \( \sigma_h \), \( \sigma_v \), and \( \sigma_s \), respectively. From that, Gaussian cross sections can be obtained, assuming that the real plume shapes can be well approximated by Gaussian areas. Using the Gaussian plume model developed by Konopka [1995], the coefficients \( D_h \), \( D_v \), and \( D_s \) of horizontal, vertical, and skewed diffusion result finally.

3. Exhaust Transport by Wake Flow

The simulations by Gerz and Ehret [1997] demonstrate that the four exhaust jets of the B747 are trapped completely by the vortices after 20 s (which defines the end of the jet regime) whereby two jets on each side are mixed homogeneously around the vortex core. During the vortex regime the vortices and the trapped exhaust of the primary wake typically trail 150 to 250 m downward; occasionally they may reach larger depths [Schlager et al., 1996] when the atmosphere is very calm. The descending primary wake warms adiabatically in a stably stratified atmosphere. Therefore the baroclinic force at the border between each vortex and ambient air detains momentum, heat, and exhaust from the primary wake into the secondary wake [Spalart, 1996; Holzäpfel and Gerz, 1998]. This warm mixture of exhaust and air forms a thin "curtain" between the vortices and the flight level, see Figure 3 below. During the vortex stage the primary wake does not grow significantly because most of the exhaust is still trapped around the vortex cores such that the horizontal plume size is determined by the vortex spacing (about 50 m for a B747).

The typical atmospheric conditions at cruising altitudes do not significantly alter the evolution of the wake in the jet regime. Later on however, an influence is noticeable which depends mainly on the degree of turbulence in the environment. Weak to moderate atmospheric turbulence triggers a large-scale instability where the two line vortices begin to oscillate after about 1 min and form rings, which quickly decay further [Gerz and Holzäpfel, 1998]. The vortex structure is mirrored in the structure of the exhaust plume. The vortex regime ends when the exhaust plume tears up at the level of the primary wake, forming mammatus-like cloud structures which reflect the action of the vortex rings (Figure 2, left). Above the primary wake the plume is still connected as a thin curtain. With proper temperature and humidity conditions in the environment, these structures are visible through condensation trail clouds in the sky (Figure 2, right).

Figure 3 displays the evolution of the primary and the secondary wake during the vortex and dispersion regimes in terms of exhaust concentration fields in a stratified but calm atmosphere. The descent of the primary wake ends after 170 s and 280 m below flight level. The detrained exhaust (secondary wake) rises as it is warmer than the ambient air, exceeding the flight level and forming a mushroom-shaped top. Note that the overall plume shape is very smooth for 130 s. Afterwards however, the primary wake bursts suddenly, see \( t = 157 \) s. This burst of exhaust, which labels the end of the vortex regime in this case, is driven by turbulent friction of the two sinking vortices which approach and then "touch" each other [Gerz and Holzäpfel, 1998].

During the dispersion regime the aircraft-induced flow ceases and approaches ambient conditions. Hence the further transport and diffusion of the exhaust becomes more and more a matter of the atmosphere. Figure 4 depicts exhaust plumes of ages between 5 and 8.5 min. The LES has been initialized with 308-s-old wake data from the precursor simulation (see Figure 3 and Dirbeck and Gerz [1995, 1996]). One observes the horizontal growth of the total wake and the vertical shrinking of the secondary wake. The former reflects the action of atmospheric (predominantly horizontal) motions; the latter indicates a gravitational collapse due to the restratification of the exhaust.

4. Effective Diffusion

After these qualitative considerations we turn now to a quantitative analysis of mixing and effective diffusion
Figure 2. Exhaust of a B747 in side view. (left) Cross section of the simulated exhaust plume after 146 s. The flight level is marked by a horizontal line. (right) Video picture of a contrail taken on board of DLR research aircraft Falcon.

Figure 3. Exhaust concentration distribution (averaged in flight direction) at the border of the primary wake and in the secondary wake during vortex and dispersion regimes in calm atmosphere. Lengths are related to the axis of symmetry of the airplane. The horizontal lines mark the flight level. Concentration levels are plotted for $10^{-7}c_0$, in increments of $10^{-8}c_0$. Concentrations inside the vortices are not shown. All figures are in scale.
of the exhaust. Figure 5 gives a synopsis over the entire wake evolution of our B747 from 1 ms to 5 min in terms of absolute maximum exhaust temperature $T_{\text{max}}$ and entrainment rate $\omega = -d/dt (\ln c_{\text{max}})$, based on the maximum value of the species concentration averaged in flight direction. Figure 6 focuses on the jet and vortex regimes in terms of absolute and mean maximum temperature and concentration. The displayed quantities are crucial for the kinetics in chemical box models. The exhaust temperature surpasses the ambient value by 330 K at the nozzle exit, decays to almost that ambient value of 214.3 K within 20 s, rises again in the vortex regime by 1–3 K, and finally decays slowly after 130 s. The entrainment rate increases rapidly during the first 10 ms until the mixing process, starting at the border of the circular jet, has reached the jet axis [Kürcher and Fabian, 1994]. Then $\omega$ decays for a time period of 10 s with $1/t$. We further note that the mixing of the exhaust with ambient air is suppressed almost entirely between 10 s and 2 min, since $\omega$ drops by almost 2 orders of magnitude.

The time series of $\omega$, $T_{\text{max}}$, and $c_{\text{max}}/c_0$ allow to determine the wake regimes precisely: The jet regime terminates when $T_{\text{max}}$ passes through its minimum value and increases afterward or when the strong decay of $c_{\text{max}}$ stops: hence after 20 s [Gerz and Ehret, 1997]. The vortex regime lasts for almost 2 min which is clearly indicated by the temperature increase (due to adiabatic heating of the exhaust in the sinking vortices) and the quite constant concentration of the isolated species. Finally, the wake enters its dispersion regime when the organized vortical motion breaks up after 130 s, which is noticeable by the increase of $\omega$ by the factor of 10 and the continuous decay of $T_{\text{max}}$ and $c_{\text{max}}$. The broken lines in Figures 5 and 6 also demonstrate that atmospheric turbulence does not alter the quality and character of the wake stages.

So far, we have discussed diffusion processes in the primary wake in terms of the temporal change of absolute maxima. Figures 2 and 4 suggest that the diffusion of the exhaust in the secondary wake differs drastically from that in the primary wake. Now we analyze...
the two regions separately by using mean values of the primary and the secondary wake obtained from averaging the data in flight direction. The results in terms of mean dilutions (based on the mean maximum concentrations) and mean maximum temperatures are also presented in Figure 6. As expected, the mean maxima of the primary wake (pluses) resemble the respective absolute maxima (solid curves, discussed before) during the jet and vortex regimes. After 280 s, the temperature in the dissolving vortices has dropped to ambient values. The secondary wake (crosses) emerges during the vortex regime (approximately after 50 s) as confirmed by the strong increase of \( C_{\text{max}} \) and the beginning deviation of \( T_{\text{max}} \) from \( T_{\text{amb}} \). Concentration and temperature in the secondary wake become maximum after 2 min when the adiabatically heated exhaust in the border region of the sinking vortices has been detrained by the baroclinic torque. The warm exhaust rises in the curtain and mixes with ambient air, thereby reducing its temperature and concentration even stronger than the primary wake at that time (150–200 s). We note that even after 5 min the primary concentration maximum is 5 times larger than the secondary maximum (\( = 0.4 \times 10^{-5} c_0 \)) when the background is calm (Figure 6), whereas both maxima approach the same value of about \( 1.8 \times 10^{-5} c_0 \) after 150 s in a turbulent atmosphere (not shown).

The evolution of the plume cross sections \( A \) in a stratified atmosphere without turbulence is depicted in Figure 7 for the total, primary, and secondary wakes. The development of the total plume area again mirrors the stages of the wake life cycle: we observe a strong (very weak) increase during the jet (vortex) regime and again
a strong growth in the dispersion regime when the vortices collapse and suddenly release the exhaust. As an interesting feature we see that A of the primary wake decreases by about 20% during the vortex regime because (1) the separation of the two vortices diminishes during their descent [Holzapfel and Gerz, 1998], (2) the still intact vortices strongly lock up the exhaust in their cores, and (3) the exhaust in the border region of the vortices is detrained by baroclinicity from the primary into the secondary wake. That area indeed grows rapidly, as is visible after 60 s. Note that the secondary plume covers the same area as the primary plume (based on the mean concentration value of $10^{-7} c_0$) at $t = 130$ s, although the secondary wake contains only 11% of the exhaust mass at that time and never exceeds 17% as revealed by Figure 8. The mass fraction stored in the secondary wake, however, increases with atmospheric turbulence to probably more than 30%. This may be considered as a nonnegligible fraction which strongly mixes with ambient air and thus goes through different microphysical and chemical processes (e.g., related to ozone kinetics) than the larger fraction of exhaust, which remains isolated until the vortices collapse.

On November 13, 1994, the DLR research aircraft Falcon encountered the primary wake of a cruising B747 airplane (clearly noticeable by the accelerations experienced by the Falcon) at the plume age of 82 s and 145 m below flight level [Schulte et al., 1997, case 1]. This is in excellent agreement with our simulations, which yield 140 m at that time. In addition, a temperature excess of 0.8 K and a CO$_2$ concentration of $4.6 \times 10^{-4} c_0$ was observed in the primary wake. From the simulations we find values of 0.7 K and $2.2 \times 10^{-4} c_0$ (Figure 6). Hence the agreement is again excellent for the temperature and reasonably good for the exhaust concentration. We further remark that similar temperature excesses have been measured in 1- to 3-min-old primary wakes of aircraft during other campaigns [Busen et al., 1994; Schulte et al., 1997; Baumgardner et al., 1998]. In many of these flights the wakes were measured at various altitudes; the highest concentrations were always found in the vortices, and the lower values were sampled in the secondary plume.

5. Mixing Times

To study and assess the spatially and temporally different impact of the airtraffic emissions upon the atmosphere it is necessary to know at which temporal scale $t_m$ the exhaust is distributed and mixed over an air volume before its concentration becomes undistinguishable from the background value. The maximum value of a concentration within a plume at time $t$ is $c_{\text{max}}(t) = c_{\text{max}}(t_0) A(t_0)/A(t)$, where $t_0$ defines the beginning of the diffusion regime. The measurements in the North Atlantic flight corridor show that the ratio $c_{\text{max}}(t_m)/c_{\text{max}}(t_0)$ is typically 1% [Schlager et al., 1997].

Figure 9 depicts the mixing time $t_m$ as a function of crosswind shear $S$ for seven values of the Brunt–Väisälä frequency $N$ ranging between 0.006 and 0.08 s$^{-1}$ and three different ratios $c_{\text{max}}(t_m)/c_{\text{max}}(t_0)$.

![Figure 8](image1.png)  
**Figure 8.** Time series of the fraction of exhaust mass in the secondary plume compared to the total exhaust mass without (solid line) and with (dashed line) atmospheric turbulence.

![Figure 9](image2.png)  
**Figure 9.** Mixing time $t_m$ as a function of the mean crosswind shear $S$ for seven values of the Brunt–Väisälä frequency $N$ ranging between 0.006 and 0.08 s$^{-1}$ and three different ratios $c_{\text{max}}(t_m)/c_{\text{max}}(t_0)$. 

Table 1 lists typical ranges of $t_m$ and the respective e-folding widths of the Gaussian plume. From the simulation data one has to conclude that the size of an aircraft exhaust plume does not exceed the lower mesoscale range at timescales of $t_m$. This finding has been confirmed by measurements [Schlager et al., 1997]. Since the peak emissions along main flight
Table 1. Typical Ranges of the Mixing Time $t_m$ and the Respective $e$-Folding Widths of the Gaussian Exhaust Plume for Three Different Thresholds $c_{\text{max}}(t_m)/c_{\text{max}}(t_0)$

<table>
<thead>
<tr>
<th>$c_{\text{max}}(t_m)/c_{\text{max}}(t_0)$</th>
<th>5%</th>
<th>2%</th>
<th>1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_m$, hours</td>
<td>5–2</td>
<td>10–3.5</td>
<td>13–5</td>
</tr>
<tr>
<td>$\sigma_{h}(t_m)$, km</td>
<td>2–4</td>
<td>4–8</td>
<td>6–13</td>
</tr>
<tr>
<td>$\sigma_{v}(t_m)$, m</td>
<td>100–70</td>
<td>130–80</td>
<td>160–90</td>
</tr>
</tbody>
</table>

routes have a period of about half a day ($\approx t_m$), it follows that the air traffic exhaust in the North Atlantic flight corridor is not mixed homogeneously but shows a patchy structure at scales which are not yet resolved by global or even regional climate models and thus have to be modelled.

6. Conclusions

The goal of our study was to investigate the complex mixing and diffusion processes of the exhaust during all stages of an aircraft wake and to link the wake flow controlled by the aircraft during the "jet," "vortex," and "dispersion" regimes with the atmospheric motions in the "diffusion" regime.

We showed that the temperature and species concentration values, as measured and simulated in the primary wake, cannot be explained by a freely expanding exhaust jet but demand the description of the trapping and isolation of the exhaust by the wing tip vortices. The isolation of the exhaust delays the mixing compared to free jet dynamics by several minutes. The often used approximation $\omega \sim 1/t$ yields a fair description of the dilution only during the jet regime (Figure 5). Box models which describe the mixing throughout all phases by a $t^{-1}$ dependence (and then also use too low exhaust temperatures) will miss the measured concentration in the primary wake after 82 s in the B747 case by more than 1 order of magnitude (Figure 6).

Our LES data further suggest that one has to distinguish between mixing processes in the primary and secondary wakes in order to explain concentrations as measured during other campaigns. For example, at similar wake ages a ratio NO$_2$/NO$_x$ of 20% was observed in the secondary plume (H. Schlager, personal communication 1997) but only 6% were found in the primary plume [Schulte et al., 1997]. This difference is probably due to the much stronger entrainment of ambient O$_3$ into the exhaust curtain than into the primary wake. All these facts illustrate the importance of an accurate description of the dynamical processes during all stages of an aircraft wake life cycle.

Finally, Table 2 summarizes our attempts to provide modellers with effective diffusions, dilutions, and entrainment rates throughout all stages of the aircraft wake evolution. These data are deduced from our large-eddy simulations and may be utilized in models for larger-scale transport studies and in chemical and microphysical box models. The data which describe the aircraft-controlled wake regimes are based on LES by Gerz and Ehret [1996, 1997] and Gerz and Holzapfel [1998]. The computed horizontal and vertical diffusion coefficients, $D_h$ and $D_v$, illuminate that (1) the plume grows horizontally and vertically at similar rates during the jet regime, (2) the primary wake stagnates horizontally whereas the secondary wake increases vertically during the vortex regime, and (3) the plume collapses vertically by restratification but grows horizontally when the vortices dissolve during the dispersion regime.

The data in Table 2 which describe the diffusion regime were obtained from LES performed by Dürbeck and Gerz [1995, 1996]. Data measured in situ in the North Atlantic flight corridor [Schumann et al., 1995; Schulte et al., 1997].

Table 2. Typical Data for Diffusion, Dilution, and Mixing of Emissions From a Subsonic Large-Bodied Aircraft in a Stably Stratified Atmosphere at Cruising Heights

<table>
<thead>
<tr>
<th></th>
<th>1 s</th>
<th>20 s</th>
<th>80 s</th>
<th>130 s</th>
<th>5 min</th>
<th>1 hour</th>
<th>10 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_h$, m$^2$/s</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
<td>0.1</td>
<td>2–20</td>
<td>14–23</td>
<td>14–23</td>
</tr>
<tr>
<td>$D_v$, m$^2$/s</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>$&lt;0$</td>
<td>0.15–0.18</td>
<td>0.15–0.18</td>
</tr>
<tr>
<td>$c_{\text{pri}}/c_0$, $\times 10^{-4}$</td>
<td>300</td>
<td>2–3</td>
<td>1–2</td>
<td>0.3–1</td>
<td>0.2</td>
<td>0.01</td>
<td>$\leq 0.001$</td>
</tr>
<tr>
<td>$c_{\text{sec}}/c_0$, $\times 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>0.06–0.2</td>
<td>0.1–0.3</td>
<td>0.04</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$A_{\text{pri}}$, 10$^4$m$^2$</td>
<td>0.05</td>
<td>0.3–0.4</td>
<td>0.5–0.9</td>
<td>0.5–2</td>
<td>5</td>
<td>20–50</td>
<td>100 to $\geq$1000</td>
</tr>
<tr>
<td>$A_{\text{sec}}$, 10$^4$m$^2$</td>
<td>—</td>
<td>0.08–0.8</td>
<td>0.5–2</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\omega$, $10^{-3}$s$^{-1}$</td>
<td>800</td>
<td>3–5</td>
<td>3–30</td>
<td>30–40</td>
<td>2</td>
<td>0.1–0.3</td>
<td>0.1–0.3</td>
</tr>
</tbody>
</table>

Wake phases are as follows: jet, 1–20 s; vortex, 20–130 s; dispersion, 130 s to 5 min; diffusion, 5 min to 10 hours. $D_h$ and $D_v$ are horizontal and vertical diffusion coefficients, $c_{\text{ex}}/c_0$ is dilution measure of the exhaust concentration (averaged in flight direction) for primary (pri) and secondary (sec) wake, $c_0$ is concentration at nozzle exit, $A$ is cross-sectional area of exhaust (referring to a mean concentration of $10^{-7}c_0$), and $\omega$ is entrainment rate (referring to the maximum of $\bar{e}$). In the diffusion regime, the thermal stratification $N$ varies between 0.011 and 0.023 s$^{-1}$, the wind shear $S$ varies between 0 and 0.007 s$^{-1}$, and the turbulence is weak; in all other flow regimes the atmosphere is calm or weakly turbulent with $N = 0.014$ s$^{-1}$ and $S = 0$. 
Schlager et al., 1997) were used as input for the LES. We found that the variability of $D_h$ ($D_v$) increases (decreases) with $N$ owing to the anisotropic turbulent eddies in the stably stratified atmosphere which have diameters in the order of the plume size. Shear values typically found at cruising heights do not significantly alter $D_h$ and $D_v$ although — in combination with diffusion — they result in larger plume cross sections and entrainment rates (Table 2). Civil transport airplanes at cruising heights only occasionally meet large shear rates and strong turbulence. In such situations, however, $D_h$ ($D_v$) grows by a factor of 3 (20) compared to the calm conditions. With increasing shear and time, only $D_v$ determines the plume size $A$ [Dürbeck and Gerz, 1996]. The diffusion values listed in Table 2 are very well confirmed by the values obtained from the measurements.

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References


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