From wake dynamics to climate impact:
What controls contrail mitigation during formation flight?

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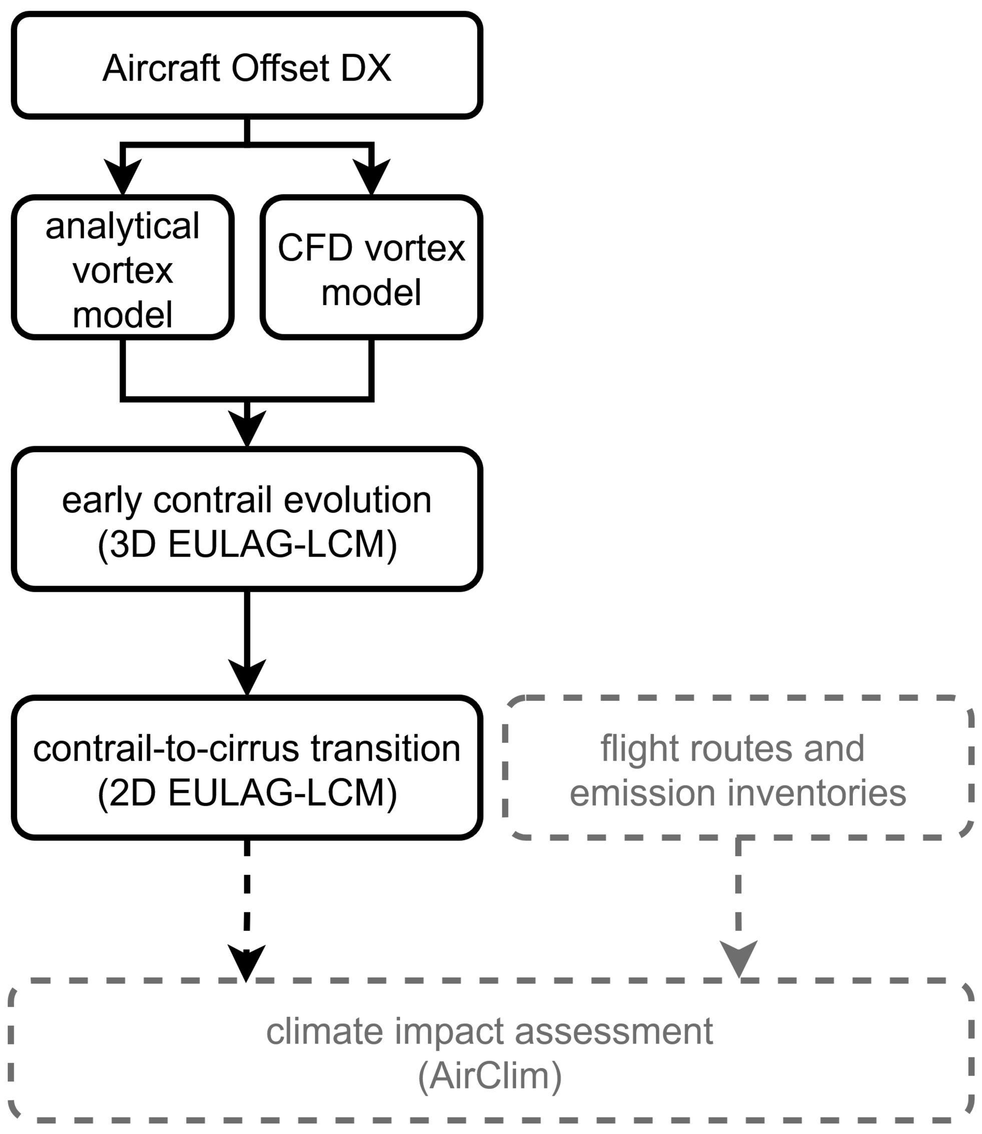

Fig. 1. Model chain for evaluating contrail climate impact.

Overview

An aircraft operating in the upwash region of a wake vortex offers aerodynamic advantages, thereby reducing fuel consumption and decreasing CO_2 and NO_x emissions. During formation flight (**FF**), twice as many ice crystals as those produced by a single aircraft (**SA**) compete for a similar amount of water vapour in the atmosphere. This leads to a saturation effect that reduces the contrail's climate impact. The mitigation potential of contrails in FF depends on wake-vortex dynamics, aircraft offset, and atmospheric conditions. The following aircraft flies about 2.5 – 3 km behind the leading one.

Research question

How sensitive is the mitigation potential of contrails in **FF** to wake-vortex initialization, aircraft offset, and atmospheric conditions?

Model Chain

For given aircraft offsets **DX** (Fig. 2), a novel, more realistic approach is employed to generate the wake vortices. This involves a CFD simulation to model the interaction between the follower's wing and the leader's vortex. The resulting flow field is then employed to initialize the contrail simulations. This new approach (**CFDInit**) is compared to vortices prescribed analytically (**anaInit**). Further steps in the model chain are shown in Fig. 1. In this study, results of a formation of two A350 are shown.

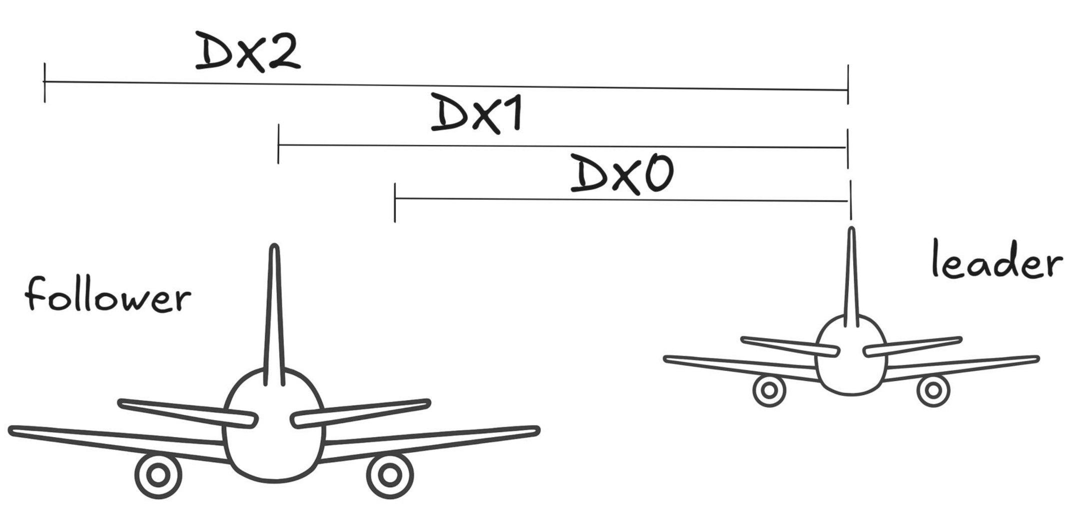

Fig. 2. Three different aircraft offset DX.

Results

1. Wake vortex initialization changes young contrail

The trajectory of the vortex core is strongly influenced by **CFDInit** and **DX**, affecting the thickness of the young contrail (Fig. 3). The surviving ice crystal number is similar for **CFDInit** and **anaInit**.

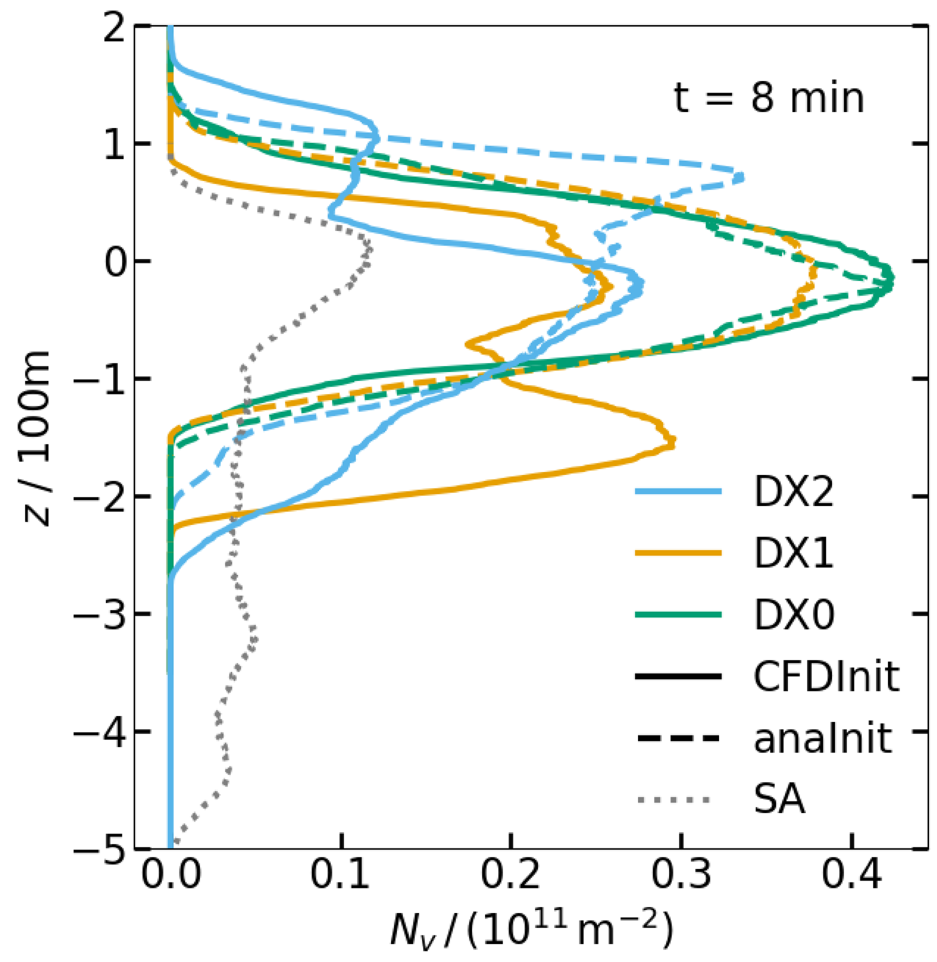

Fig. 3. Thickness of young contrails behind FF and SA after 8 min at RH_i= 140%.

2. Long-lasting effect of initialization method

Wind shear tilts the young contrail, so its thickness determines the width of the aged contrail-cirrus (Fig. 4). E.g., a larger thickness leads to a long-lasting increase in the contrail width exposing the ice crystals to a greater amount of atmospheric water vapour. This increases the contrail's ice mass and total extinction.

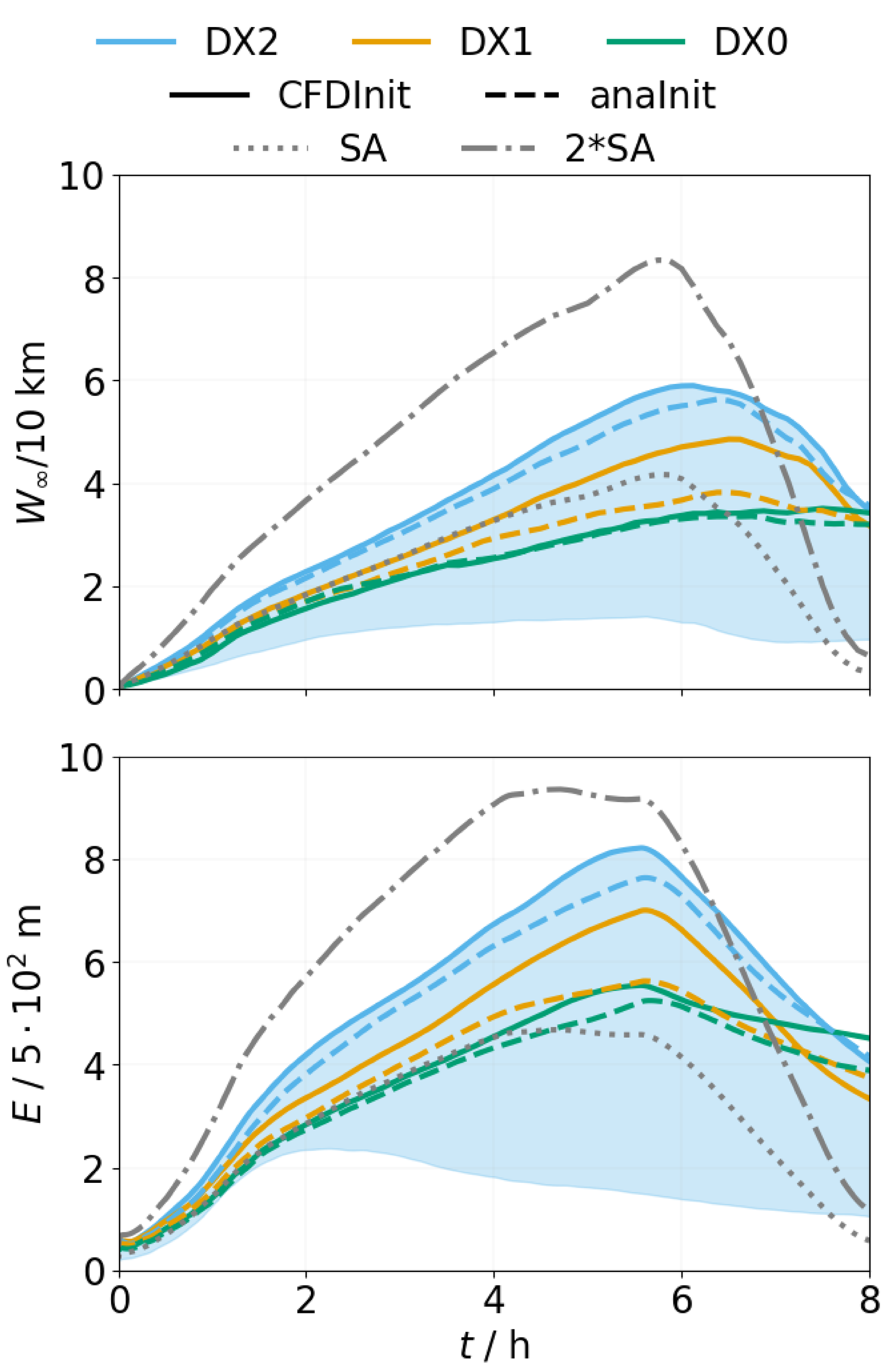

Fig. 4. Evolution of contrail width W_∞ and total extinction E of FF and SA for one atmospheric scenario. The shaded area represents a range of various atmospheric scenarios of the DX2 offset.

3. Atmospheric conditions and aircraft offset dominate the long-term evolution

Atmospheric conditions, including relative humidity, wind shear, and updraught velocity predominantly influence the long-lasting evolution of the contrail (shaded area in Fig. 4). The impact of **DX** is a secondary factor. In comparison to this, the initialization method has a minimal impact.

4. Implications for contrail climate mitigation

The contrail mitigation potential is defined as

$$1-\frac{\int E_{FF}\,dt}{2\cdot\int E_{SA}\,dt}=1-\hat{E}\,,$$

using the ratio of the integrated total extinction between a **FF** scenario compared to a scenario, where the **SA** result is doubled. The total extinction can be seen as proxy of the climate impact of a single contrail. **FF** has the contrail climate mitigation potential of about 30% to 50% compared to two **SA** contrails (Fig. 5). Table 1 shows a summary of the controlling parameters.

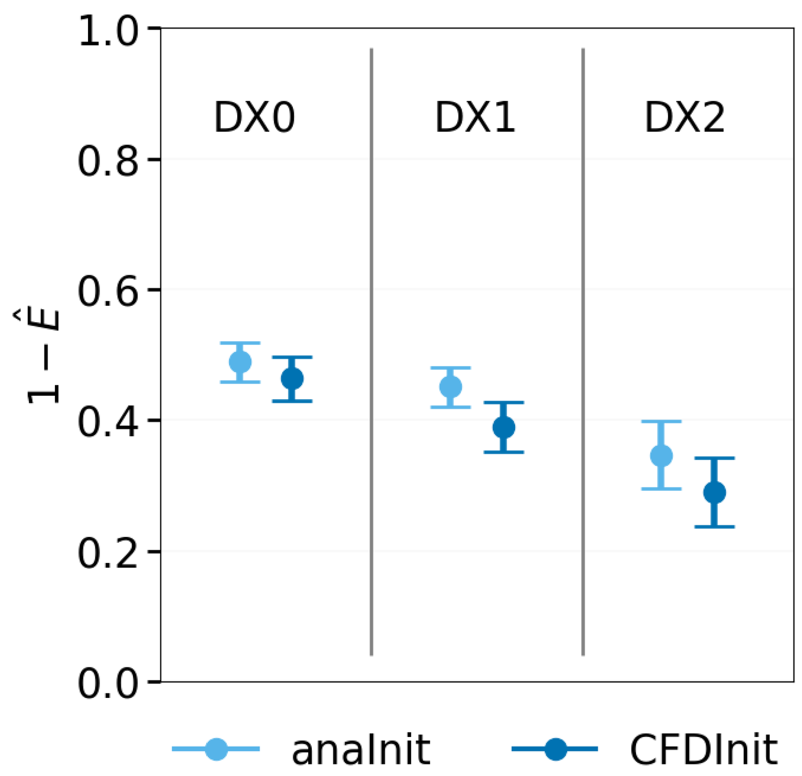

Fig. 5. Contrail climate mitigation potential of FF. The variance represents various atmospheric scenarios.

Parameter	Effect
Wake vortex initialization	Physical fidelity of the young contrail
Aircraft offset	vortex interaction, long-lasting impact on evolution & mitigation
Atmospheric conditions	(strong) long-lasting impact on evolution & mitigation

Table 1. Controlling factors of FF contrail evolution and the climate mitigation potential it offers.

Take-Home Messages

- Formation flight reduces fuel consumption, CO_2 and NO_x emissions.
- The contrail climate mitigation potential is 30 - 50% compared to single aircraft.
- Long-lasting contrail evolution in formation flight is driven more by atmospheric conditions and aircraft offset than by wake-vortex initialization.

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