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Two-dimensional stability of a wake vortex dipole in a stratified atmosphere

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Context

- Contrails are the main contributor to aviation-related radiative forcing [Lee et al., 2021]
- But there are numerous uncertainties on the contribution amount
- Improoved physical modeling needed : we focus on the plume spatio temporal distribution

Figure 1: 3 contrails of different shapes at ~ 1 min behind the aircraft

- and the effects of the aircraft wake …

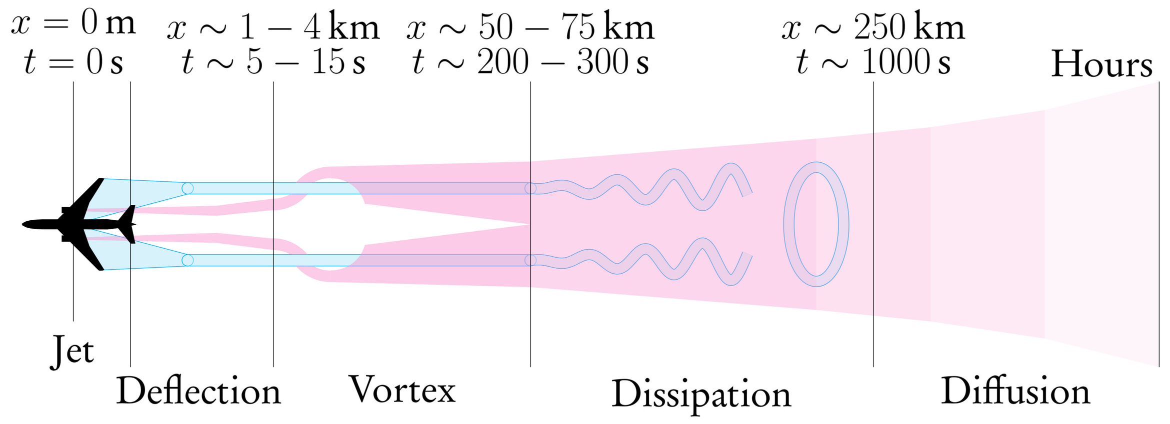

Figure 2: 5 phases of the jet/vortex interaction

… as well as atmospheric stratification [Spalart, 1996]

- The plume is modelled in interaction with the wake vortices and stratified atmosphere in a vertical plane
  - we see the primary and secondary wakes

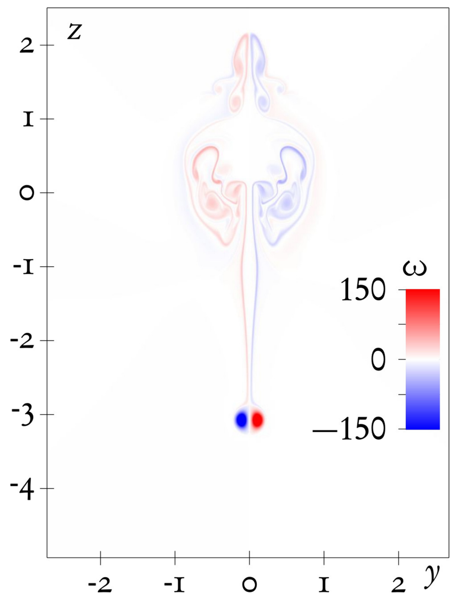

Figure 3: Vorticity field for $t = 4.5$, $\mathrm{Fr}^{-1} = 1$

Approach

- 2D multiparametric study of this interaction with atmospheric stratification (Boussinesq approximation) [Saulgeot et al., 2023]
  - plume dispersion as a function of atmospheric stratification (Froude)

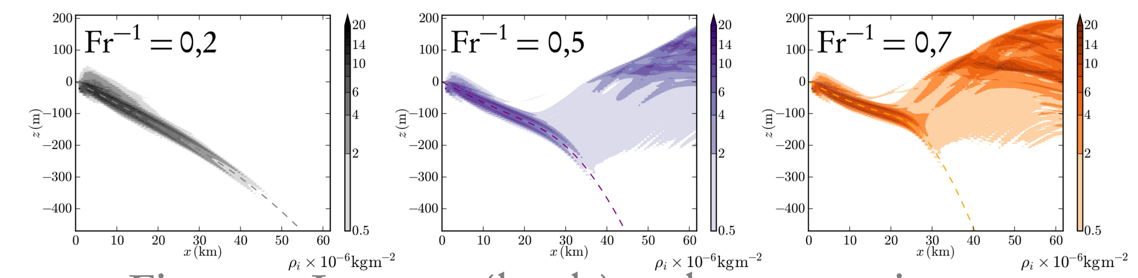

Figure 4: Ice mass (levels) and vortex trajectory (dashed lines), $t = 5\ \tau_0$. Dimensioned for a medium-weight Boeing B777 and $\mathrm{RH}_i = 130\ \%$

- 2D stability is carried out to understand the processes leading to wake and plume disappearance
  - 2D instabilities can be precursors, later masked by 3D effects

Numerical simulations

- Atmospheric stratification ➽ Brunt-Väisälä frequency N
- Natural motion of the vortices: descent at constant speed W_0 caused by mutual induction
  - Characteristic time of the vortex dipole: $\tau_0 = \frac{b_0}{W_0}$
- Effective stratification measured by the inverse of the Froude number $\mathrm{Fr}^{-1} = N\tau_0$
- Boussinesq approximation
- Nek5000 spectral code, validation with published cases
- Stability analysis: linearized equations
  - Local approach: the base flow is a 1D extracted profile (gray line in the y direction if fig. 5, z being the vertical direction)
  - Perturbation: $(\tilde{\boldsymbol{u}}, \tilde{p}, \tilde{\theta})(y)\, e^{ikz+\sigma t}$ $\quad k \in \mathbb{R}^+, \sigma \in \mathbb{C}$

Instabilities from DNS

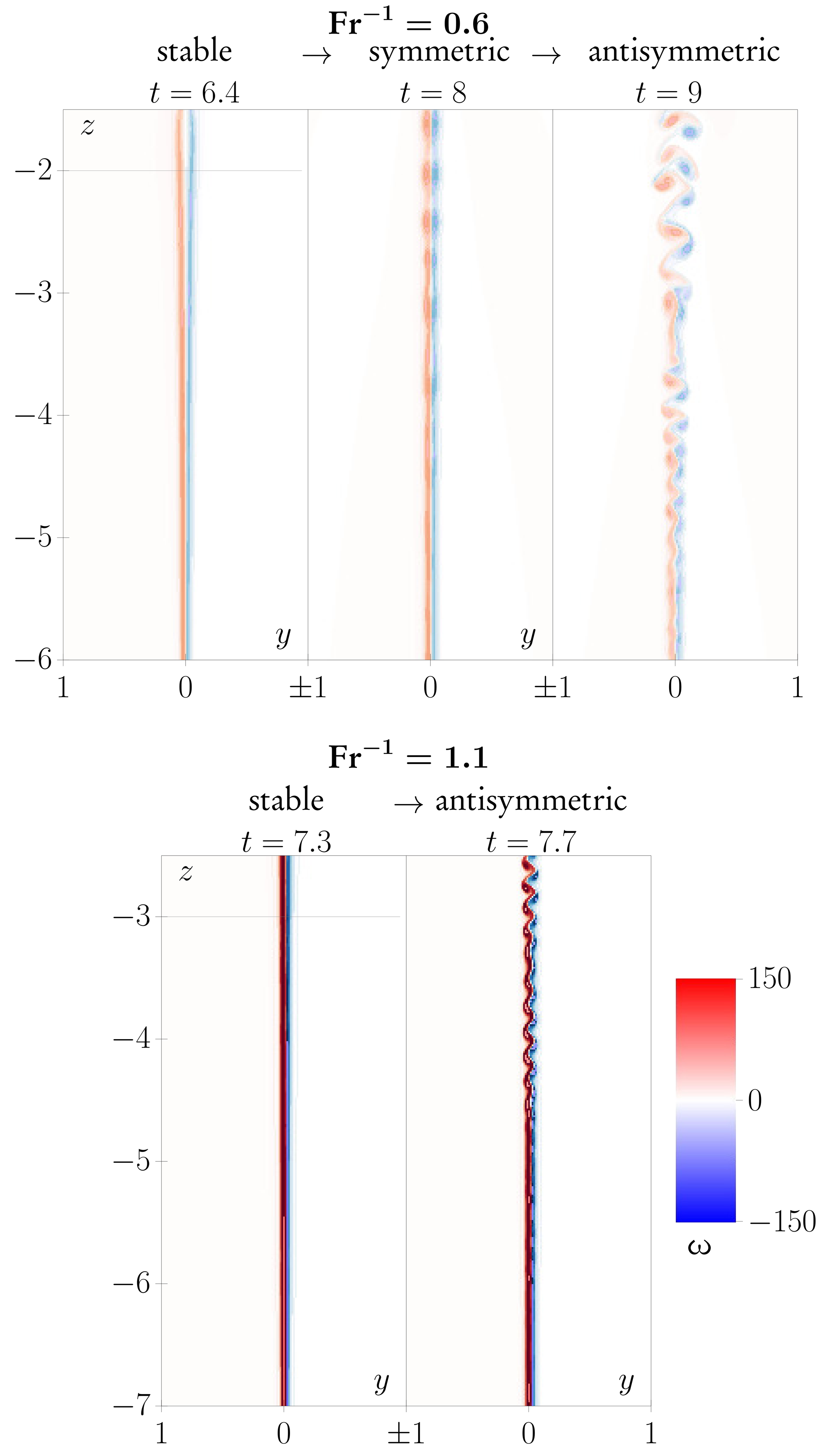

Figure 5: Vorticity fields

Unstable modes

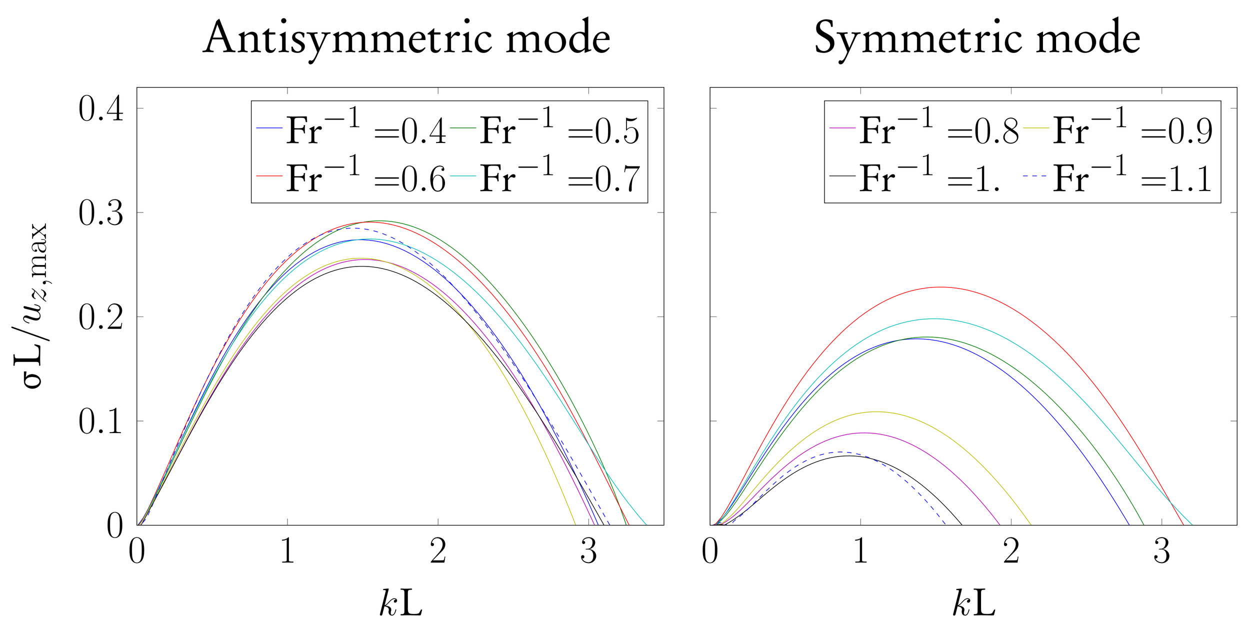

Figure 6: Growth rate as a function of wavelenght. L: jet width; $u_{z,\max}$: maximum vertical velocity in the jet.

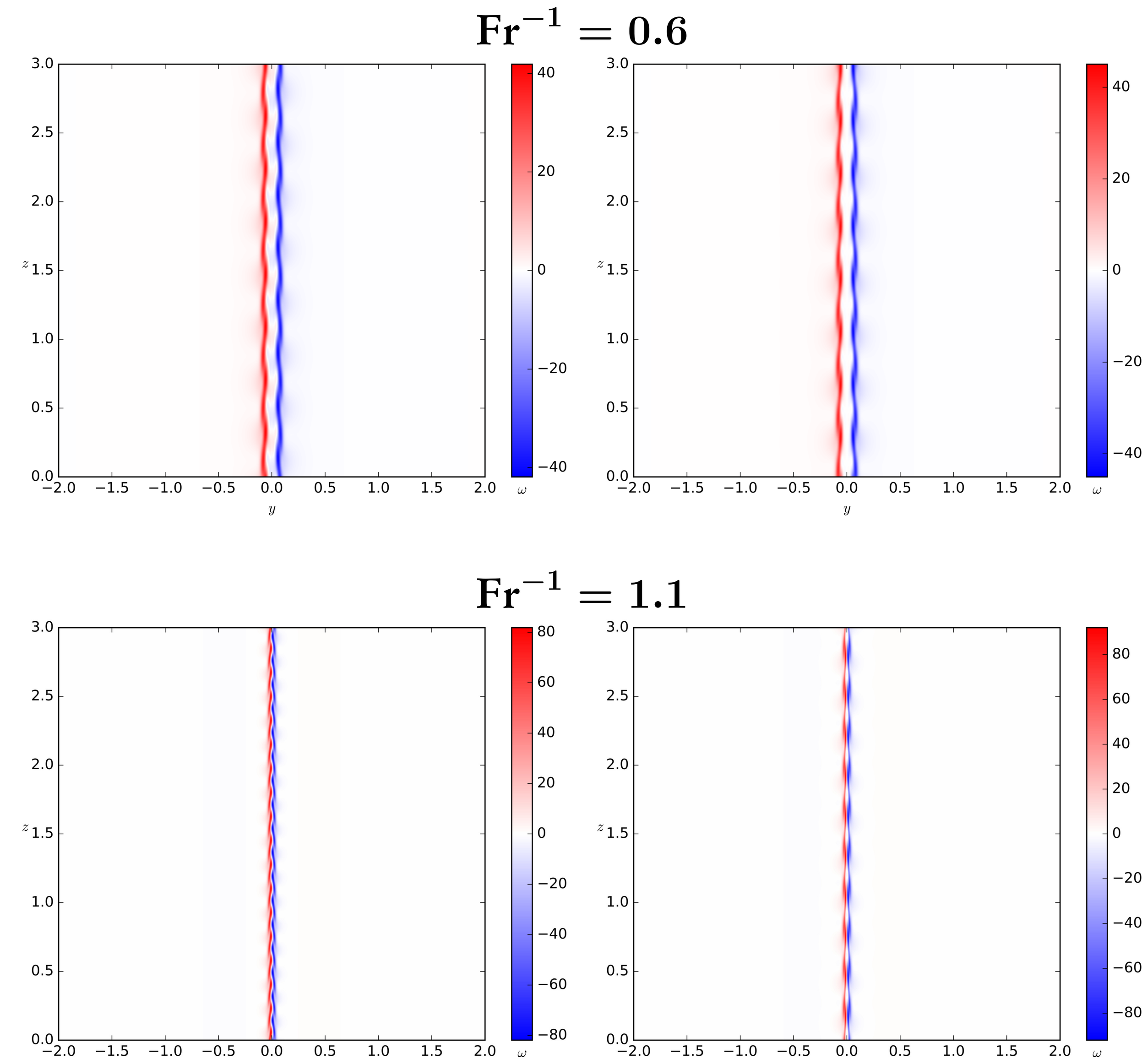

Figure 7: Total vorticity fields

[Lee et al., 2021] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., and Fuglestvedt, J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244.

[Saulgeot et al., 2023] Saulgeot, P., Brion, V., Bonne, N., Dormy, E., and Jacquin, L. (2023). Effects of atmospheric stratification and jet position on the properties of early aircraft contrails. *Phys. Rev. Fluids*, 8:114702.

[Spalart, 1996] Spalart, P. R. (1996). On the motion of laminar wing wakes in a stratified fluid. *Journal of Fluid Mechanics*, 327:139–160.