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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
- Improved physical modeling needed : we focus on the plume spatio temporal distribution



Figure 1: 3 contrails of different shapes at  $\sim 1$  min behind the aircraft

- and the effects of the aircraft wake ...

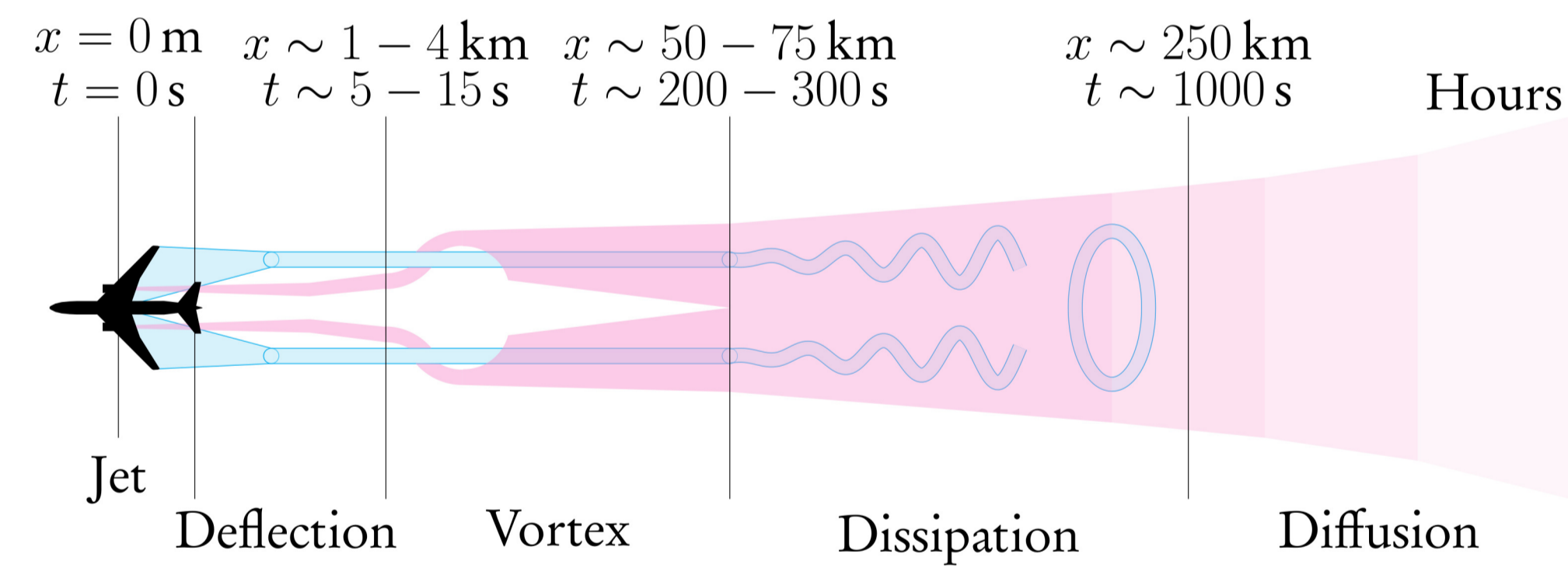


Figure 2: 5 phases of the jet/vortex interaction

... 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

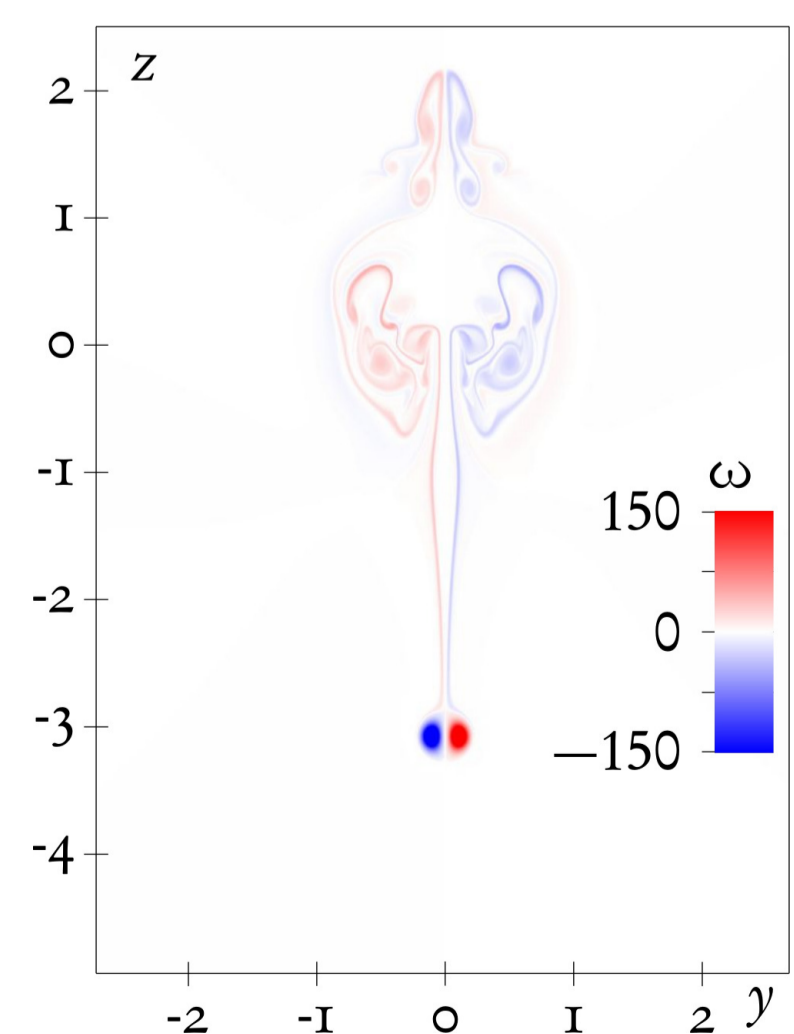


Figure 3: Vorticity field for  $t = 4.5$ ,  $Fr^{-1} = 1$

## 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)

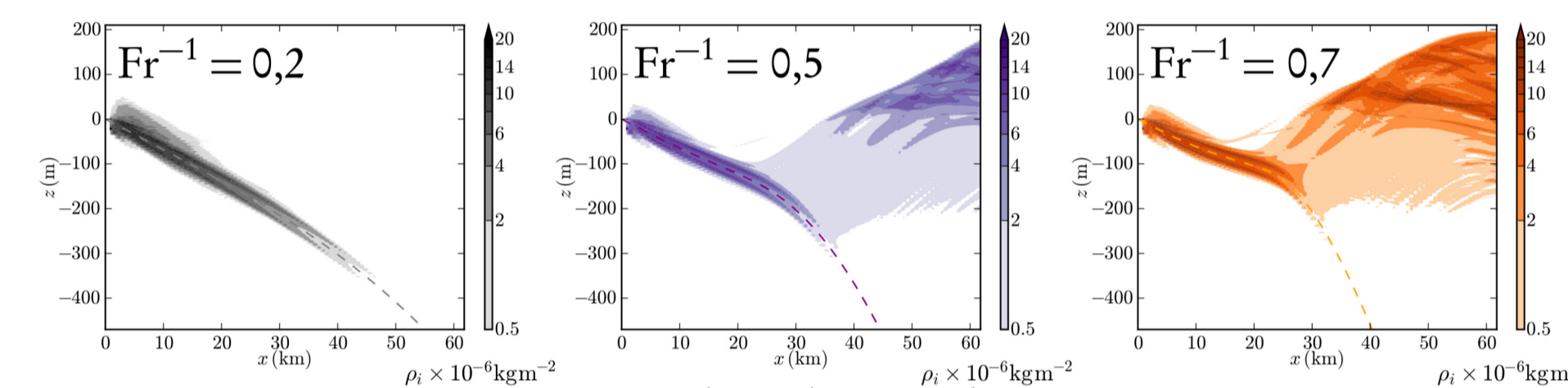


Figure 4: Ice mass (levels) and vortex trajectory (dashed lines),  $t = 5 \tau_0$ . Dimensioned for a medium-weight Boeing B777 and  $RH_i = 130\%$

- 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  $Fr^{-1} = N\tau_0$
- 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:  $(\tilde{u}, \tilde{p}, \tilde{\theta})(y) e^{ikz + \sigma t}$   $k \in \mathbb{R}^+$ ,  $\sigma \in \mathbb{C}$

## Instabilities from DNS

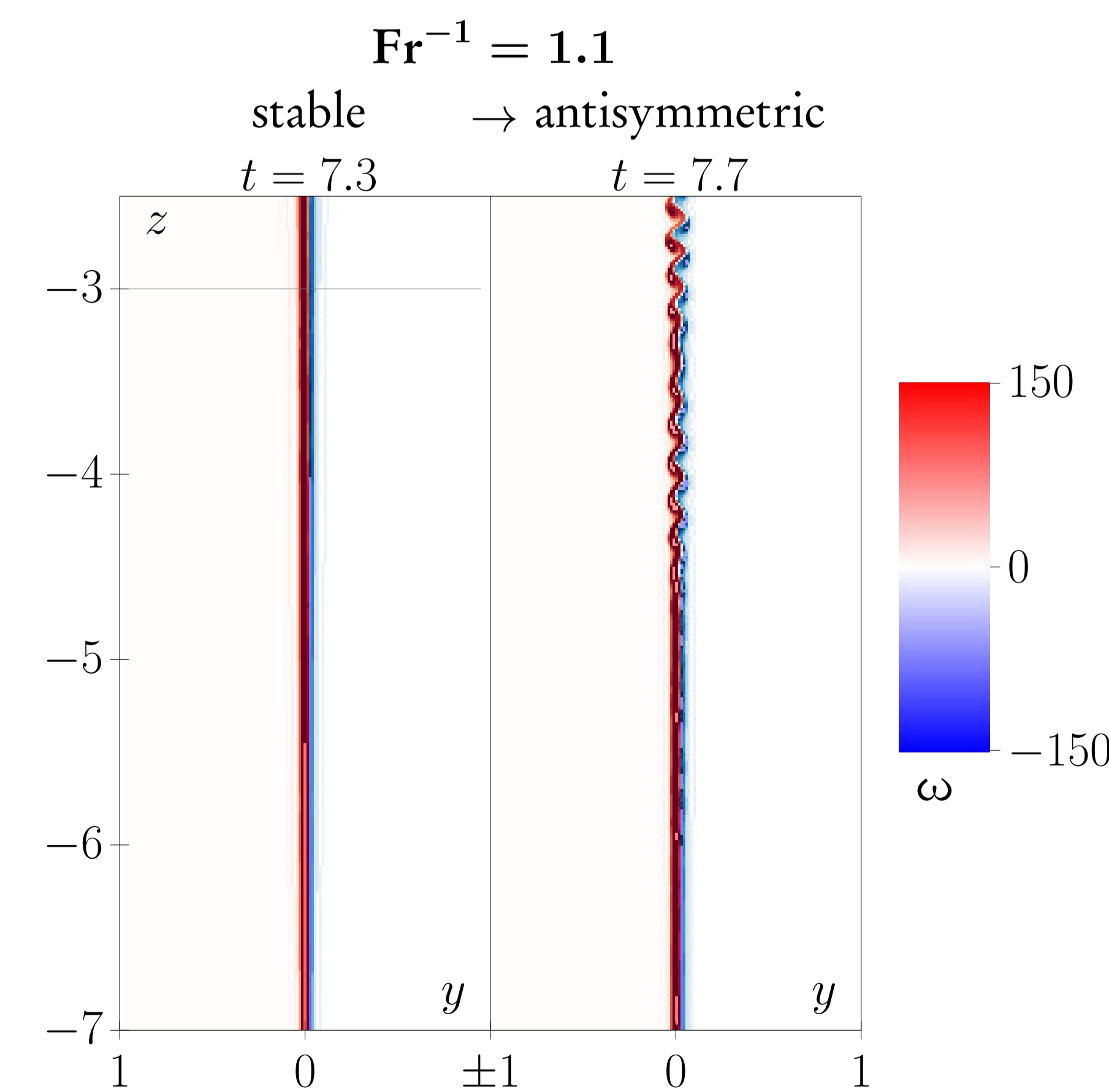
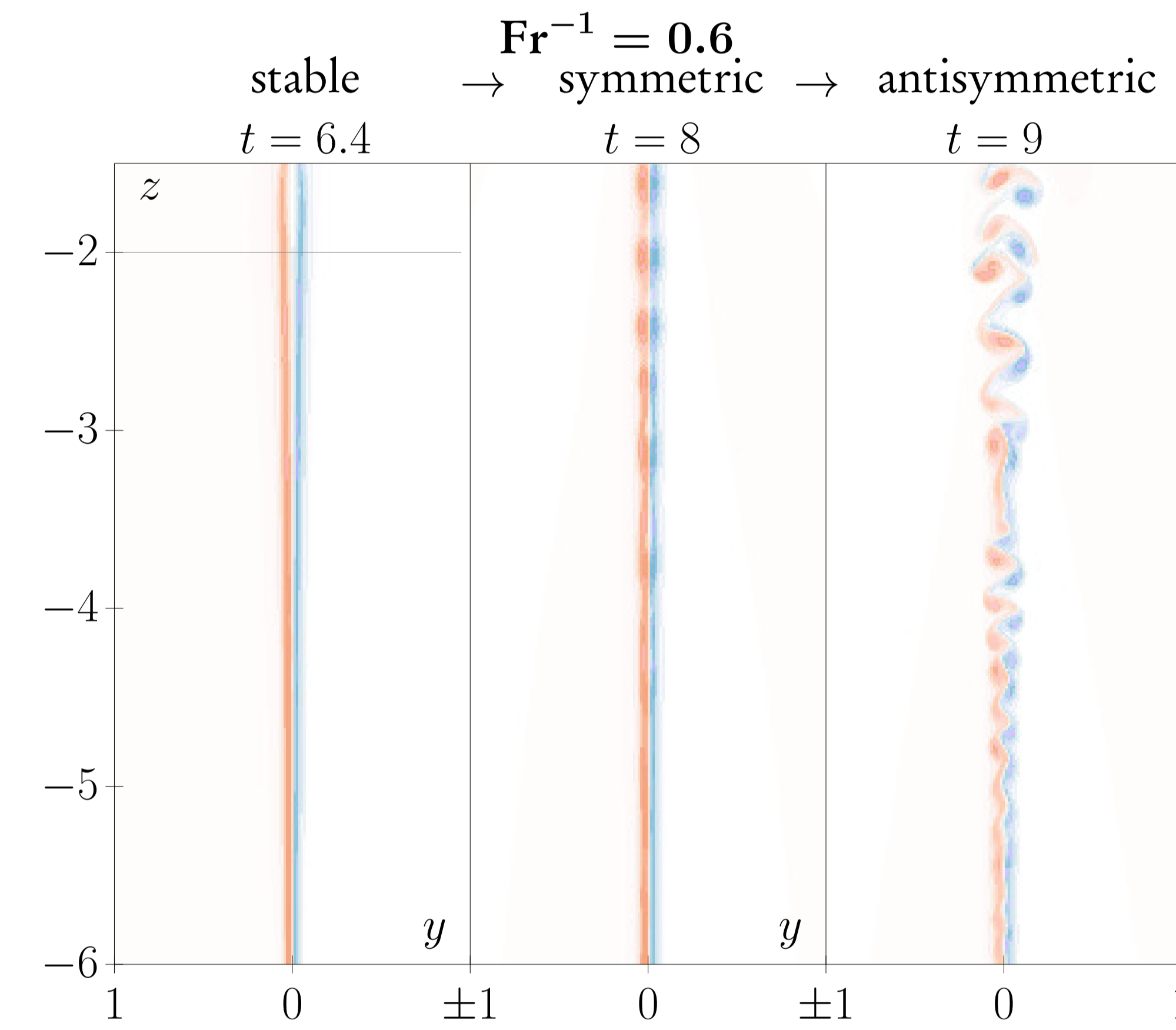


Figure 5: Vorticity fields

## Unstable modes

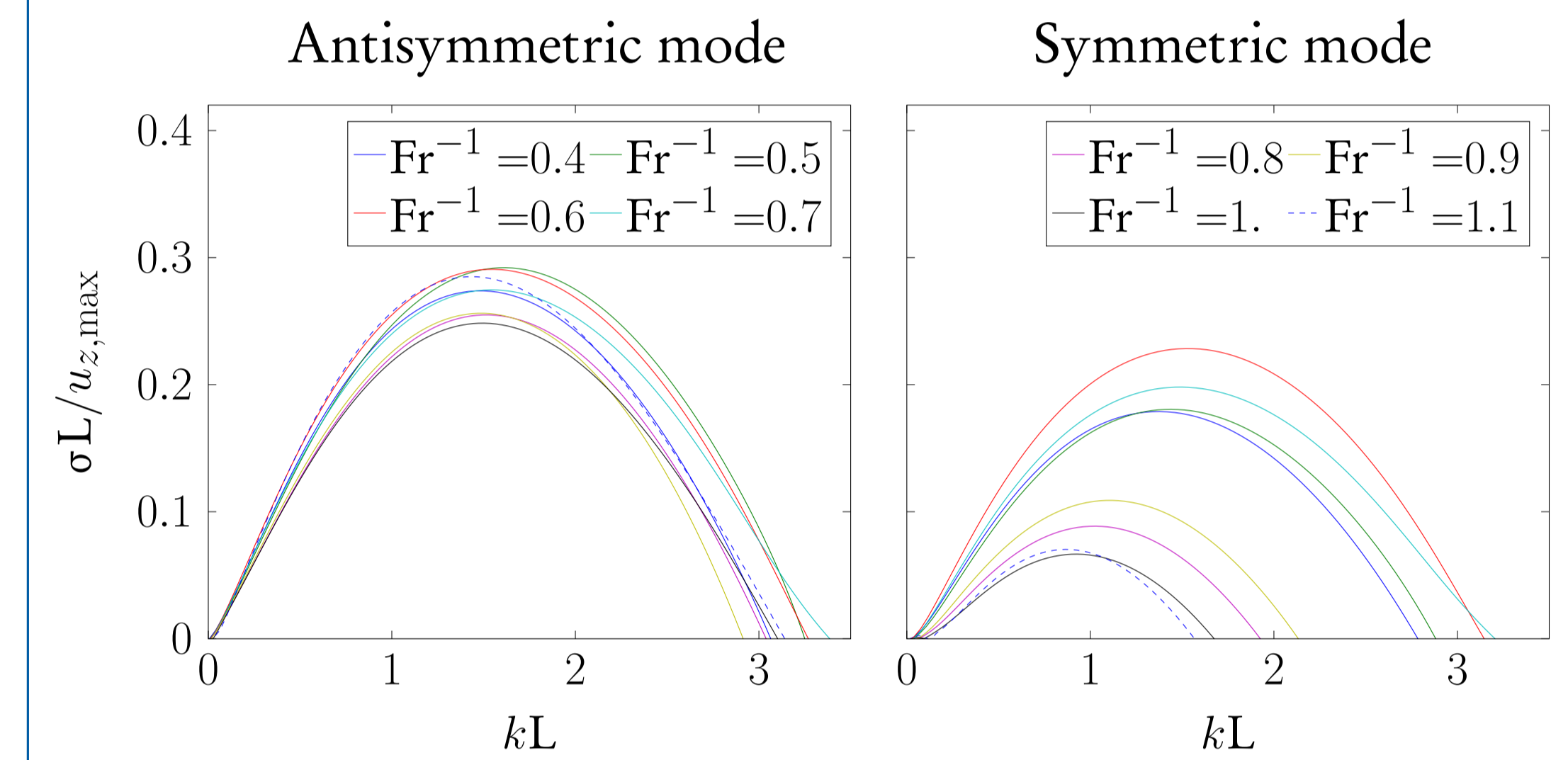


Figure 6: Growth rate as a function of wavenumber.  $L$ : jet width;  $u_{z,max}$ : maximum vertical velocity in the jet.

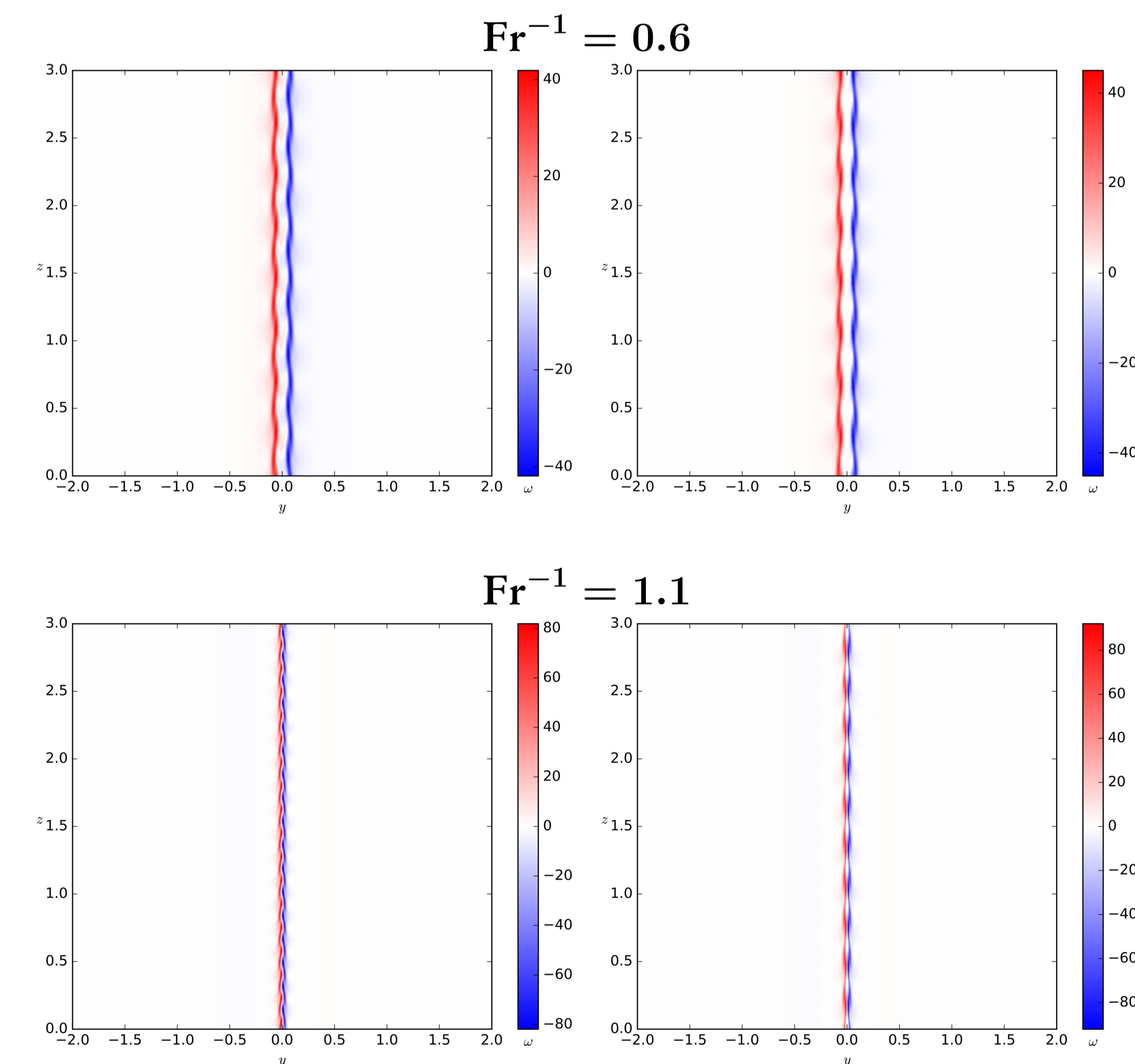


Figure 7: Total vorticity fields

[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 Fuglestedt, 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.