Large-eddy simulation of rotating and stratified turbulence

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Mathematical regularization of the nonlinear terms in the Navier-Stokes equations is found to provide a systematic approach to deriving subgrid closures for numerical simulations of turbulent flow. By construction, these subgrid closures imply existence and uniqueness of strong solutions to the corresponding modeled system of equations. We will consider the large-eddy interpretation of two such mathematical regularization principles, i.e., Leray and NS$-\alpha$ regularization. The Leray principle introduces a smoothed transport velocity as part of the regularized convective nonlinearity. The NS$-\alpha$ principle extends the Leray formulation in a natural way in which a filtered Kelvin circulation theorem, incorporating the smoothed transport velocity, is explicitly satisfied. These regularization principles give rise to implied subgrid closures which are implemented in large-eddy simulation.

The focus is on turbulent flow in a mixing layer. Comparison with filtered direct numerical simulation data and with predictions obtained from popular dynamic eddy-viscosity modeling shows that these mathematical regularization models provide considerably more accuracy at a lower computational cost than the dynamic approaches. In particular, the regularization models perform especially well in capturing the flow features characteristic of the smaller resolved scales. Variations in spatial resolution and Reynolds number establish that the Leray model is more robust but also slightly less accurate than the NS$-\alpha$ model. The NS$-\alpha$ model retains more of the small-scale variability in the resolved solution. However, this requires a corresponding increase in the required spatial resolution. When using second order finite volume discretization, the potential accuracy of the implied NS$-\alpha$ model is found to be realized by using a grid spacing that is not larger than the length scale α that appears in the definition of this model.

The inclusion of rotation and buoyancy allows to study the competition between two- and three-dimensional tendencies in a flow. This poses additional opportunities for assessing the general applicability of regularization models. We will analyze the dispersion of embedded scalars subject to rotation and buoyancy. At low Rossby numbers the dynamic eddy-viscosity models are found to become inaccurate, while regularization models such as Leray and NS-α capture the oscillatory nature of the flow. The transformation properties of these subgrid models will be investigated. To compete with the two-dimensionalization of the turbulence due to strong rotation, unstable stratification is incorporated. This may be characterized by a Froude number. The accuracy with which the turbulent dispersion is predicted as function of the Rossby and Froude numbers will be quantified using level-set analysis.