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On the spatial and temporal discretization of vertical diffusion in the turbulent planetary boundary layer

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Context: advection-diffusion operator to parameterize unresolved scales in PBLs (and beyond)
The resulting turbulent viscosity/diffusivity $K$...strongly varies spatially, i.e. large values of $\phi/K$ depend nonlinearly on model variables
- $h$ induces stiffness, i.e. large $\phi^2/K^2$

Usual approach: use of (semi-)implicit temporal schemes with 2nd-order FD discretization

What could be wrong with 2nd-order in space?
- With $R(K/dz) = K/dz \neq h/2$, $n \geq 2$
  $$\frac{\partial}{\partial z}(K(dz)^\alpha + h) \frac{\partial}{\partial z} \phi + \frac{\partial}{\partial z} K(dz)^\alpha \phi = \frac{\partial}{\partial z} \phi$$

What could be wrong with (semi-)implicit scheme in time?
- Lack of monotonic damping / inexact damping for large $\Delta t$
- Of $\phi$ errors in coupling with physical parameterizations

Maps of $\phi$ from realistic simulations

Compact Padé Finite Volume methods, e.g. (Kobayashi, 1999)

Unresolved case (for $\Delta t < 0$)

Unresolved case (for $\Delta t > 0$)

3 - Combination with time discretization

Combining Padé type schemes with implicit Euler leads to

- easy to generalize for non-constant grid size
- the tridiagonal solver provides the flux and not $\phi$

Properties for well-behaved numerical solutions

- Unconditional stability
- Monotonic damping (damping increases with increasing wavenumber, i.e. $\partial_\phi < 0$)
- Non-oscillatory (i.e. $A \geq 0$)
- Proper control of grid-scale noise $\phi_{gs}$
- Convergence & stability are often not sufficient

With implicit Euler scheme:

$$A(2\Delta t, \gamma) = \frac{1 + 2\cos \theta + 4\sin^2(\theta/2)}{2\Delta t}$$

2nd-order accurate in space: $\gamma = \frac{1}{2}$

$\gamma \neq 0$, $\partial_\phi < 0$: non-oscillatory if $A(\Delta t, \gamma) \geq 0$

Two possibilities:

- $A(\Delta t, \gamma) = 0 \rightarrow \gamma = 2$
- 4th-order in space

5 - Summary & Perspectives

Summary

- Pade FV approach provides a good combination of simplicity and flexibility to handle diffusive terms with minimal changes in existing codes
- Allows a good combination with surface layer param. and existing time-stepping
- Provides degrees of freedom to modulate numerical errors in time or to impose desired properties
- Simple single column test (Kato & Phillips) indicates a reduced sensitivity to numerical parameters

Perspectives

- Nonlinear stability
- Extension to mass-flux scheme
- Air-sea interface boundary condition
- Neutral case: stratified case
- Single column tests & global ocean simulation
- Add representation of oceanic molecular sublayer + MO layer in the top most oceanic grid box for OA coupling purposes, e.g. (Zeng & Beljaars, 2005)

References