Transport in global climate models

Desirable properties

Peter Hjort Lauritzen

Atmospheric Modeling and Predictability Section
Climate and Global Dynamics Division
National Center for Atmospheric Research

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Sandia National Laboratories
Albuquerque

It would be a great for us to hear your thoughts on what is necessary for a state-of-the-art transport scheme for climate modeling

1. Mass continuity equations in typical climate models?
2. What are typical spatial distributions?
3. Examples from NCAR's Community Atmosphere Model (CAM)
4. In 1-3 desirable properties will be discussed
5. How is mass represented in a 'real' model
6. Computational speed-up with super-cycling (sub-cycling)

Example mass fields in CAM

Most atmospheric models have at least a handful of continuity equations and, in most cases, many more.

- Air (either dry or moist)

  From a dynamics point of view this is the most fundamental and important continuity equation since it is coupled directly to the other equations of motion (momentum, thermodynamic)

  Assuming a Lagrangian vertical coordinate the hydrostatic equations of motion integrated over a layer can be written as

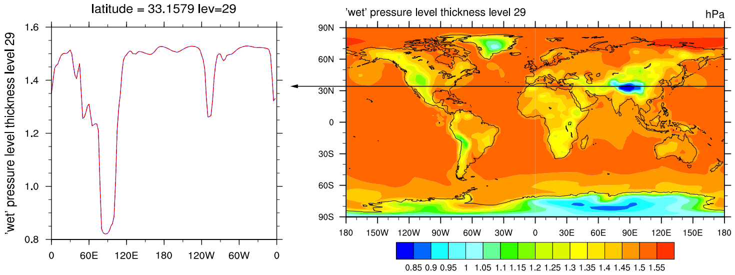
$$
\begin{aligned}
\text{mass air:} \quad & \frac{\partial(\delta p)}{\partial t} = -\nabla_h \cdot (\vec{v}_h \delta p)\,, \\
\text{mass tracers:} \quad & \frac{\partial(\delta p q)}{\partial t} = -\nabla_h \cdot (\vec{v}_h\, q \delta p)\,, \\
\text{horizontal momentum:} \quad & \frac{\partial \vec{v}_h}{\partial t} = -(\zeta + f)\, \vec{k} \times \vec{v}_h - \nabla_h \kappa - \nabla_p \Phi, \\
\text{thermodynamic:} \quad & \frac{\partial(\delta p \Theta)}{\partial t} = -\nabla_h \cdot (\vec{v}_h \delta p \Theta)
\end{aligned}
$$

  where δp is the layer thickness, $\vec{v}_h$ is horizontal wind, q tracer mixing ratio, ζ vorticity, f Coriolis, κ kinetic energy, Θ potential temperature. The momentum equations are written in vector invariant form.

Example mass fields in CAM

Example from CAM5 at 'standard' $1.9^\circ \times 2.5^\circ$ resolution

- Δp in surface layer:



Relatively smooth field that does generally not cause problems for advection operators, however:

- if layers are very thin (.e.g. isentropic vertical coordinate models) the advection operator should not generate negative thicknesses and should be able to deal with mass-less layers.

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- Air (either dry or moist)
- Water species: water vapor, cloud liquid water and cloud ice water. Sometimes also rain, snow and hail.

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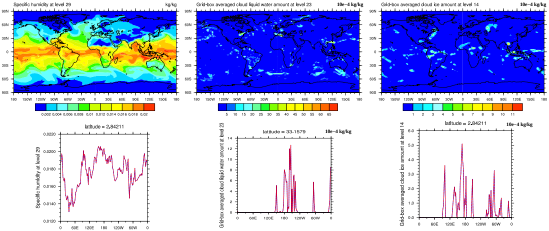
- Specific humidity, cloud liquid water and ice:



Very 'oscillatory' fields:

- Production and loss terms are large, however, clouds (e.g., 'ice clouds' such as Cirrus clouds) can have lifetimes on the other of days.
- Advection operator must not produce negative values!
- Overshooting in water vapor can trigger irreversible physical processes.

Example mass fields in CAM

Most atmospheric models have at least a handful of continuity equations and, in most cases, many more.

- Air (either dry or moist)
- Water species: water vapor, cloud liquid water and cloud ice water. Sometimes also rain, snow and hail.
- Microphysics (e.g. Morrison and Gettelman, 2008): aerosol mass and number concentration.
  - In CAM the microphysics parameterization for aerosols add 22 continuity equations that the dynamics must solve for!
  - Aerosol prognostic variables: Number concentrations for small, medium and large aerosols, particulate organic matter, dust, sea salt, secondary organic aerosols, ...

Example mass fields in CAM

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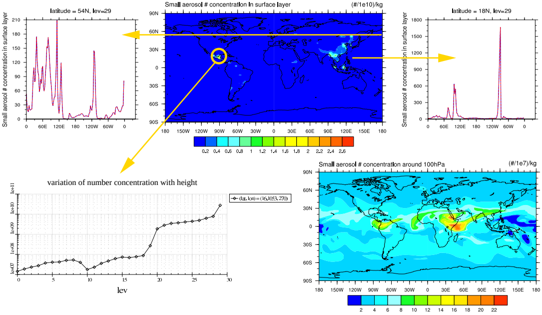

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- Near the surface ‘drastic’ variations in horizontal and vertical!
- Large sources and sinks, however, without scavenging (e.g. with precipitation) aerosols can have long lifetimes (e.g. Saharan dust can be transported 1000s of miles) $\Rightarrow$ advective tendencies can locally be the largest signal !
- Check you scheme for such fields (especially if limiters use ‘magic numbers’!)

Example mass fields in CAM

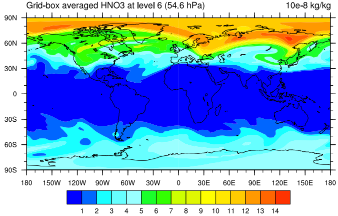
Most atmospheric models have at least a handful of continuity equations and, in most cases, many more.

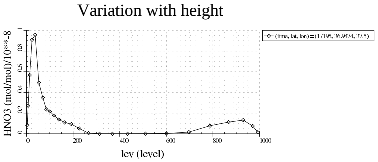
- Air (either dry or moist)
- Water species: water vapor, cloud liquid water and cloud ice water. Sometimes also rain, snow and hail.
- Microphysics (e.g. Morrison and Gettelman, 2008): aerosol mass and number concentration.
- Chemistry: 100+ tracers in chemistry version of CAM. E.g. ozone, chlorine compounds, bromine, ... (some highly reactive; some long lived)

Example mass fields in CAM

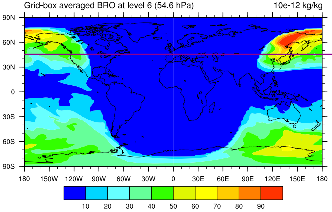
Example from chemistry version of CAM

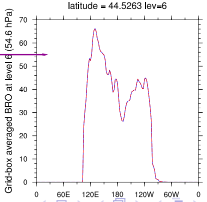
- *HNO_3*: Produced in the stratosphere and wet removed in the troposphere, i.e. strong vertical gradients





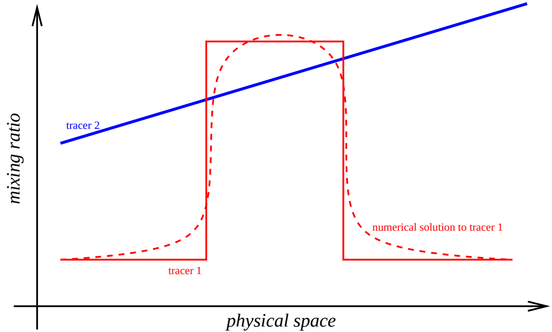
- *Br*: Strong diurnal cycle (produced by photolysis)



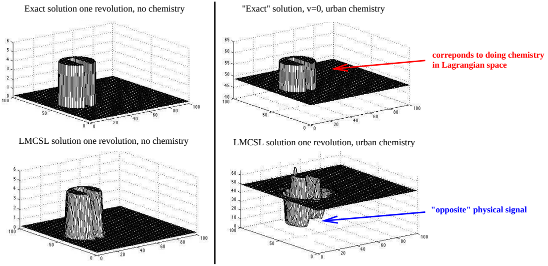


What matters for chemistry

- Relative concentration in Lagrangian space is the important factor for chemistry (reactions between tracers are controlled by relative concentrations!).
- Figure: Relative concentrations are drastically altered by scheme!
- Note: Does not necessarily mean you need to use a Lagrangian scheme
- This is more general than preservation of linear correlations: $q_1 = A + Bq_2$
- Some chemical processes are highly non-linear (e.g., NOx, O_3, example next slide)



Advection of O_3 using 'full' non-linear state-of-the-art O_3 chemistry parameterization suite (all other species are initialized constant)



Chemical parameterization acts on grid point mixing ratio value (no 'communication' in the horizontal i.e. no mixing) $\Rightarrow$ Solution should be independent of translation as a solid body!

Advection scheme flattens the infinite gradient at cylinder edges
$\Rightarrow$ triggers spurious non-linear chemical processes

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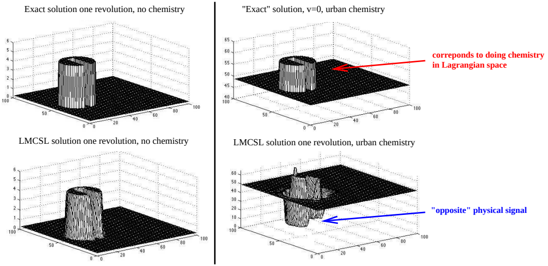

But in the real world there is mixing. Isn't there?

- Depends on meteorological conditions (flow). If strong shear, yes. If linear flow, no!
- Two modeling philosophies: 1. Implicit numerical diffusion in scheme represents physical diffusion. 2. Diffusion is added explicitly. In any case: The resulting diffusion should match the physical diffusion.
- E.g., a fully Lagrangian method needs explicit diffusion operators; traditional finite-volume methods do not.

Representation of air mass in atmospheric models - dry air

Density of well-mixed moist air:

$$\rho_m = \frac{m_d + m_v}{V} = \rho_d + \rho_v = \rho_d + q_v \rho_m, \tag{1}$$

where m_d and m_v is the mass of dry air and water vapor, respectively, and V is small volume. ρ_d and ρ_v density of dry air and water vapor, respectively, and q_v the specific humidity,

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Mass of dry air $\approx$ mass of permanent well-mixed gases:

N_2 (ca. 78.0.8%), O_2 (ca. 20.95%), Ar (ca. 0.93%), CO_2 (ca. 0.038%)

The above correspond to 99.99% of the volume of dry air

$p_s(\text{dry}) = 983.05$ hPa (Trenberth and Smith, 2005)

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Variation in dry air mass is on the order of 0.01% and is due to small amounts of ('non-permanent') trace gases being mixed into the air

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$\Rightarrow$ **for all practical purposes the mass of dry air is constant!**

Representation of air mass in atmospheric models - dry air

The continuity equation for dry air is (flux-form)

$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \vec{v}) = 0, \quad (1)$$

where $\vec{v}$ is the velocity field and '$\nabla \cdot$' is the divergence operator.

- No source/sinks terms on the right-hand side (we'll return to this point in a moment!)
- The mass of dry air accounts for approximately 99% of the total mass of atmosphere and the remaining 1% is approximately the mass of water vapor.

Representation of air mass in atmospheric models - 'moist' air

One may also combine the dry and moist air mass in the prognostic variable for air density:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \vec{v}) = P_{\rho_m} + K_{\rho_m}. \quad (2)$$

where P_{ρ_m} represents condensation/evaporation and K_{ρ_m} diffusion processes.

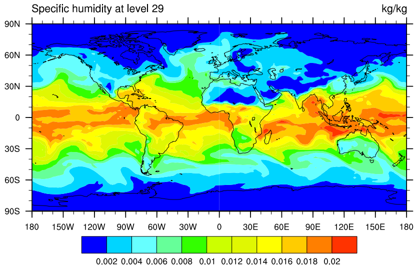
- This equation is similar to the equation for dry air except for the humidity forcing terms.
- This can have consequences for the tracer equations as discussed in a moment ...

Representation of air mass in atmospheric models - humidity

Equation for humidity,

$$\frac{\partial}{\partial t}\left(\rho_m q_v\right) + \nabla \cdot \left(\rho_m q_v \,\vec{v}\right) = P_{q_v \rho_m} + K_{q_v \rho_m}, \qquad (3)$$

- Moisture q_v varies significantly (relatively speaking) with values near zero for cold dry air and a few percent in warm moist air.



Representation of air mass in atmospheric models - tracers

Tracers can be expressed in terms of 'dry' and 'moist' mixing ratios:

$$q_d^{(l)} = \frac{m^{(l)}}{m_d} \quad \text{'dry'} \qquad q_m^{(l)} = \frac{m^{(l)}}{m_d + m_v}, \quad \text{'moist'} \tag{4}$$

The corresponding amount/weight of the tracer is

$$\rho_d \, q_d^{(l)} = \rho_m \, q_m^{(l)}. \tag{5}$$

For a passive tracer the flux-form continuity equation using 'dry' mixing ratios is

$$\frac{\partial}{\partial t}\left(q_d^{(l)} \rho_d\right) + \nabla \cdot \left(q_d^{(l)} \rho_d \, \vec{v}\right) = 0. \tag{6}$$

Note: No source/sinks terms on the right-hand side!

Representation of air mass in atmospheric models - tracers

Tracers can be expressed in terms of 'dry' and 'moist' mixing ratios:

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The corresponding amount/weight of the tracer is

$$\rho_d \, q_d^{(l)} = \rho_m \, q_m^{(l)}. \tag{5}$$

For a passive tracer the flux-form continuity equation using 'moist' mixing ratios is

$$\frac{\partial}{\partial t}\left(q_m^{(l)} \rho_m\right) + \nabla \cdot \left(q_m^{(l)} \rho_m \, \vec{v}\right) = f\left(P_{q_v \rho_m}\right) + f\left(K_{q_v \rho_m}\right). \tag{6}$$

Even if the mass of the tracer is constant the moist mixing ratios may change dues to humidity source/sinks.

Monotonicity and consistency - tracers

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \, \vec{v}) = 0, \tag{7}$$

$$\frac{\partial (\rho \, q)}{\partial t} + \nabla \cdot (\rho \, q \, \vec{v}) = 0, \tag{8}$$

where $\vec{v}$ is the velocity vector. Note that (7) and (8) imply

$$\frac{dq}{dt} = 0, \quad \frac{d}{dt} \equiv \frac{\partial}{\partial t} + \vec{v} \cdot \nabla. \tag{9}$$

q is conserved along trajectories/characteristics of the flow. **Monotonicity!**

Note that the continuity equations (7) and (8) are linked in the sense that ρ appear in both equations. Hence, any numerical error introduced in simulating the evolution of air mass will be reflected in the trace gases.

If $q = 1$ then (8) reduces to (7)! **Mass-wind consistency**

Desirable properties

I already mentioned:

- Conservation of mass
- Mass-wind consistency
- Multi-tracer efficiency (discussed further next!)
- Physical realizability (monotone, positive definite, non-oscillatory, shape-preserving)
- Relative correlation preservation

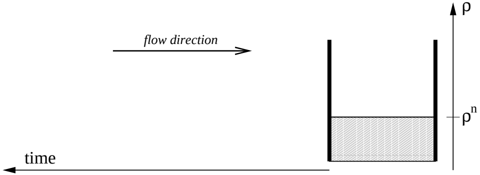
Other:

- Accuracy: Linear and non-linear test cases
- Optimal diffusion and dispersion properties
- Divergence preservation
- Robustness
- Parallel efficiency
- Geometric flexibility

See Lauritzen et al. (2010) for more details and discussion.

Graphical illustration of super-cycling of tracers (in CAM)

Assume no flux through east cell wall.



- Solve continuity equation for air $\rho = \delta p$ together with momentum and thermodynamics equations.

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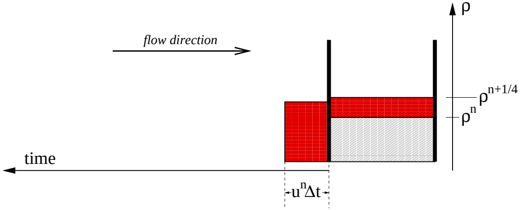

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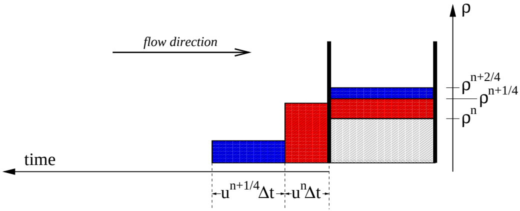

- Solve continuity equation for air $\rho = \delta p$ together with momentum and thermodynamics equations.
- Repeat *ksplit* times

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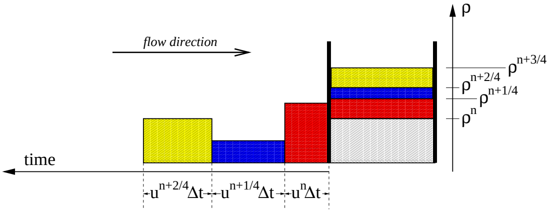

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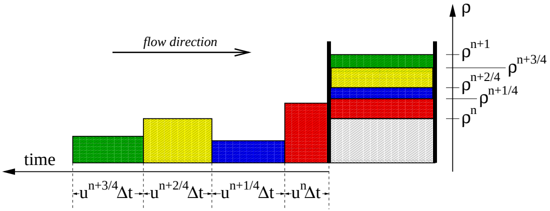

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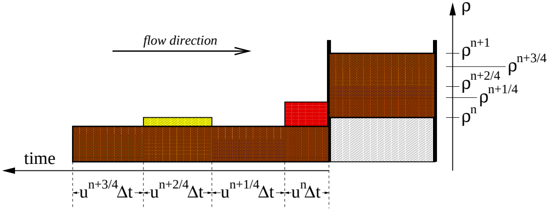
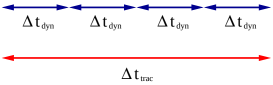


- Solve continuity equation for air $\rho = \delta p$ together with momentum and thermodynamics equations.
- Repeat *ksplit* times
- Brown area = average flow of mass through cell face.
- Compute time-averaged value of q across brown area using Lin and Rood (1996) scheme: $\overline{\overline{< q >}}$.
- Forecast for tracer is: $\overline{\overline{< q >}} \times \sum_{i=1}^{ksplit} \delta p^{n+i/ksplit}$
- Yields 'free stream' preserving solution!

Computational savings using super-cycling of tracers



'standard' CAM5 setup (advanced physical parameterization suite):
Resolution $1.9^\circ \times 2.5^\circ$; number of tracers is 25; $\Delta t_{\text{trac}} = 4\,\Delta t_{\text{dyn}}$ (super-cycling of tracers); Computer = NCAR's Bluefire using 128 or 256 processors:

- Resolved dynamics (including tracer transport) is 18% of total runtime
- If $\Delta t_{\text{trac}} = \Delta t_{\text{dyn}}$ then resolved dynamics cost increases by 56%
- If the number of tracers is 100 the above is 74%

If the number of tracers is large enough and/or super-cycling frequency is decreased (*ksplit* increased), the super-cycling technology may lead to significant run-time savings

Final remarks

From a global climate modelers perspective (resolutions 3° to 0.1°):

More chemistry in models and requirements for scalability is, in my opinion, why we need to redesign global dynamical cores on non-lat-lon grids,

- with consistency between air mass and tracers,
- with optimal preservation of relative concentrations (where flow is linear),
- with strict monotonicity (when needed)
- with multi-tracer efficiency,

rather than better dry dynamics u,v,T,p_s

Other motivations: Regional climate applications with more consistent treatment of 'boundary' regions.

References I

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