ATHAM-Fluidity: A moist multimaterial compressible atmospheric model with cloud microphysics

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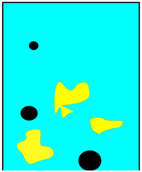
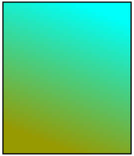
ATHAM Fluidity

- ATHAM: The Active Tracer High-resolution Atmospheric Model. Originally developed at Max-Plank Institute, Hamburg. Used to study convective scale thunderstorm formation, volcanic plumes, wild fires etc.
- Fluidity: Advanced finite element Navier-Stokes solver with unstructured mesh and mesh adaptive capability.
- Synergy combines advanced numerics, modular form, simple GUI and adaptive capability of Fluidity with ATHAM's comprehensive library of microphysical process modules and parameterizations.

ATHAM: key Modelling Assumptions

- Key modelling assumptions:
  - Single temperature
  - single pressure.
- Bulk momentum equation.
- Materials sink/rise relative to bulk velocity parallel to gravitation
- Fall out a function of material only.





ATHAM-Fluidity Solution Algorithm.

- Compressible bulk Navier-Stokes equations solved via iterated pressure correction method.
- Gas phase satisfies ideal gas law.
- Semi-Implicit formulation filters fast acoustic waves

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot \rho u u = \nabla p - \rho g,$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0,$$

$$\frac{\partial \Theta}{\partial t} + \left(u + u'_{\Theta}\right) \cdot \nabla \Theta = S_{\theta},$$

$$p = \rho_g R_g T,$$

ATHAM-Fluidity Solution Algorithm.

- Tracer equation for each material mass fraction
- Tracers advected by bulk flow (plus fallout velocity)
- Bulk potential temperature related to in situ temperature through material heat capacities (sum of linearized entropies)
- Nonlinear equation of state relates bulk density, pressure, material constituents & bulk potential temperature.

$$\frac{\partial q_i}{\partial t} + (u + u_i') \cdot \nabla q_i = 0,$$

$$p = \rho_g R_g T$$

$$T = \frac{\left(c_{p,g} q_g + \sum_{\text{incomp}} c_{p,n} q_n \right) \Theta}{\left(\frac{p}{p_0}\right)^{\frac{R_g}{c_{p,g}}} c_{p,g} q_g + \sum_{\text{incomp}} c_{p,n} q_n}$$

$$\frac{1}{\rho} = \frac{q_g}{\rho_g} + \sum_{\text{incompressible}} \frac{q_n}{\rho_n},$$

Microphysics routines

- Microphysics (or "physics") routines parameterize phase changes on scale of raindrops (mm-cm) in terms of bulk dynamic variables.
  - Total material mass conserved through exchange,

$$\sum_i q_i = 1$$

  - ATHAM process pentagram for mass exchange

Herzog et al. (1998)

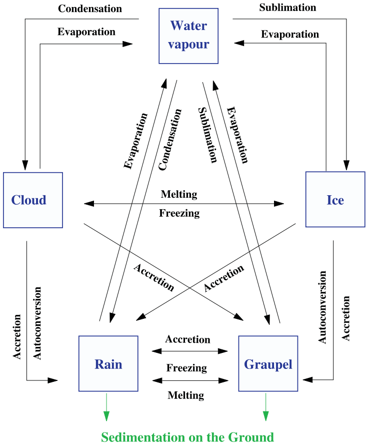


Fig. 1. Scheme of the microphysics for water.

Example: Condensation of Supersaturated Water

- Gvien enough cloud condensation nuclei, water vapour condenses out of air when water vapour partial pressure is higher than saturation pressure over flat liquid surface
- Empirical curve fitting gives (other choices available)

$$p_{\mathrm{sat(vap)}} = 611.2 \exp\left(\frac{17.62\,(T-273)}{T-30}\right)$$

- Obtain saturation mass fraction by considering partial pressure of water vapour only.

$$q_{\mathrm{sat}} = q_g \frac{p_{\mathrm{sat}}}{\rho_g R_v T},$$

Example: Condensation of Supersaturated Water

- Relative humidity, $RH = \frac{q_v}{q_{sat}}$, between a bit above 0 and 1 and a bit.
- Assume superaturated water relaxes to saturation pressure over single timestep
- Mass removed from vapour phase

$$\frac{dq_v}{qt} = -\frac{q_v - q_\text{sat}}{\Delta t}\mathscr{H}\left(q_v - q_{sat}\right) + \dots$$

- Mass inserted into cloud water phase

$$\frac{dq_c}{qt} = \frac{q_v - q_\text{sat}}{\Delta t}\mathscr{H}\left(q_v - q_{sat}\right) + \dots$$

Example: condensation onto cloud droplets

- Condensation a function of number of droplets and their size

$$\mathrm{Con}\,C\left(\rho, p, T, q_g, q_v, q_c\right) = 4\pi \frac{q_g}{\rho_g} N_c r_c \frac{S_w - 1}{F_k + F_d}$$

$$\begin{aligned}
\rho_g =& \frac{\rho\, q_g}{1 - \sum_{n \neq g} \frac{\rho\, q_n}{\rho_n}} \\
N_c =& \frac{q_c}{\rho_w \pi r_c^3} (\text{number of cloud droplets/gas volume}), \\
r_c =& 10\mu m \text{ (droplet radius)}, \\
S_w =& q_v / q_{sat} \\
F_k =& \left(\frac{L_v}{R_v T} - 1\right)\left(\frac{L_v}{K_a T}\right), \quad \text{(heat conduction)} \\
F_d =& \frac{R_v T}{p_{\mathrm{sat}} D_v}, \quad \text{(water vapour flux)}
\end{aligned}$$

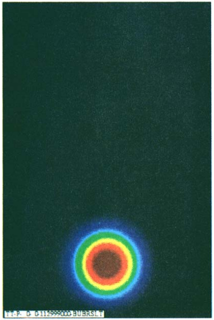
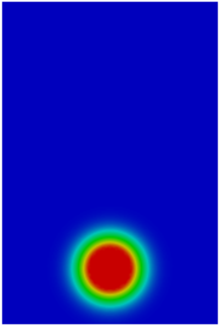
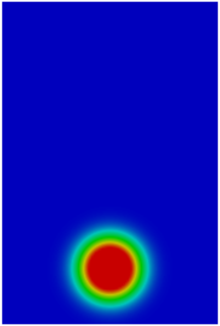
Example: condensation onto rain droplets

- Same idea as with cloud water, but rain drops assumed to be distributed around a mean radius, λ_r

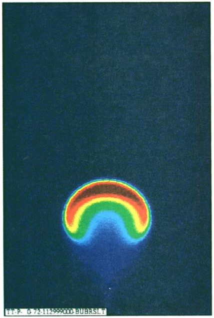
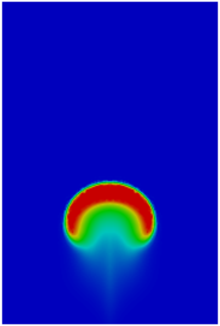
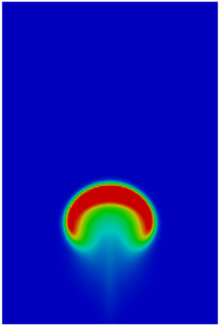
$$\begin{aligned} \mathrm{Con}R &= 2\pi\frac{q_g}{\rho_g}N_{0,r}\frac{S_w-1}{F_k+F_d}, \\ &\quad\times\left(\frac{1}{\lambda_r^2}+0.22\Gamma(2.75)\frac{\sqrt{a_r}}{\nu}\left(\frac{\rho_0}{\rho_g}\right)^{\frac{1}{4}}\frac{1}{\lambda_r^{11/12}}\right) \\ \lambda_r &= \left(\pi\frac{q_g\rho_w}{\rho_g q_r}N_{0,r}\right)^{1/4} \\ \rho_w &= \text{(water density)} \end{aligned}$$

- Rain fall out velocity assumed a function of radius (Newtonian terminal velocity).

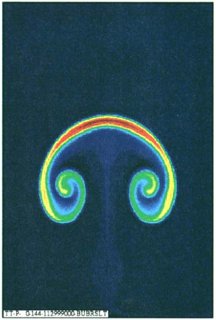
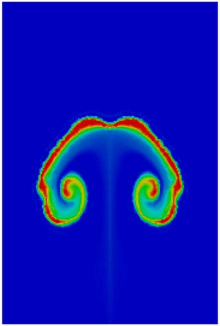
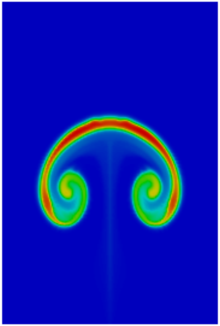
Warm Bubbles

Roberts (1993)	Low Resolution (DG unstructured)	High Resolution (CV quads)
		

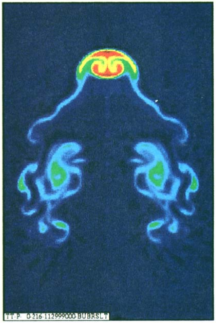
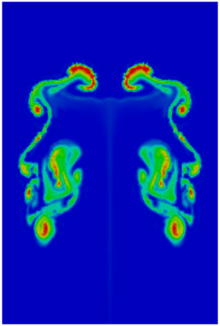
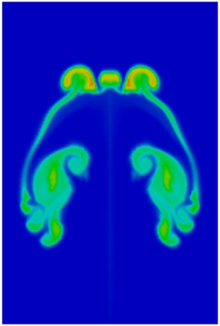
Warm Bubbles

Roberts (1993)	Low Resolution (unstructured DG Tracer)	High Res (CV quads)
		

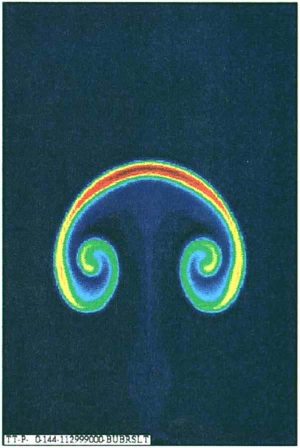
Warm Bubbles

Roberts (1993)	Low Res (unstructured)	High Res (quads)
		

Warm Bubbles

Roberts (1993)	Low Res (unstructured)	High Res (Quads)
		

Constituent driven rising Bubble

Roberts (Dry pot temp.)	Moist (density)
	

Examples: Steam/ash rollers

- 2D problem showing adaptive meshing capability
- Moist (steamy) rising bubble below dense ash bearing cloud in neutrally balanced atmosphere.
- Rising/falling bubbles interact through tangling of trailing rollers
- Adaptive mesh adds resolution to capture vorticity filaments
- To the movie

2D Chimneys

- 2d problem with adaptive mesh (periodic domain)
- Warm, moist, polluted air introduced through chimney into a background flow.
- Buoyancy driven plume forms.
- Significant settling of model pollutant observed downstream of chimney due to lee effects.
- To the movie

3D Chimney/Power Station

- Using the Fluidity toolset example last chimney example can be extended near trivially into 3 dimensions or for complicated domains
- 3d Model based on Battersea power station in London
- Water vapour: movie
- Large particulate: movie

Towards the future

- ATHAMFluidity: a moist, multimaterial model on unstructured and adaptive meshes

- Future: To produce full atmospheric model
  - Coupling to sun following radiative transfer model (RADIANT)
  - Advanced element choices
  - Addition of atmospheric/pollutant chemistry routines
  - Coupling to regional models & other fluidity components

For Further Reading I

H. Byers
Elements of Cloud Physics
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