THOR: an open-source climate solver for exoplanetary atmospheres

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SIMULATION
PLATFORM

Exoclime Simulation Platform

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radiative transfer & retrieval

VULCAN
chemistry

THOR
fluid dynamics

NVIDIA

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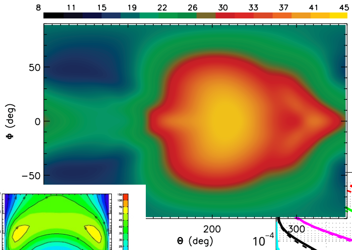
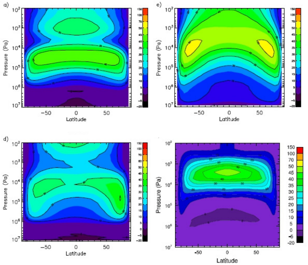
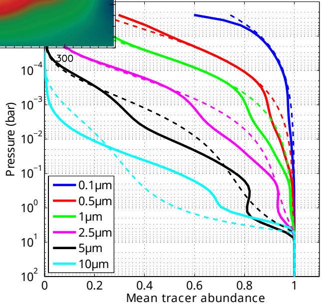
Numerical Study of Exoplanets



2D IR emission map
[Heng (2011)]



Intercomparison of GCMs
[Lebonnois (2011)]



Tracer transport
[Parmentier (2013)]

Numerical Studies

help understand the physics

phase curves (optical and IR)

Why . . . ?

Atmospheric collapse & habitability

Transit spectra probe disequillibrium region

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Earth Atmosphere

- winds of $\sim$ 30 m/s
- moderate temperature, e.g. 280 K
- very shallow atmosphere
- asynchronously rotating

Hot Jupiter Atmospheres

- winds of ~ 5 km/s
- very hot, e.g. 3000 K
- giant gas balls, deep atmospheres
- slowly rotating

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Euler Equations

compressible fluid equations

$$\begin{aligned} \partial_t \rho + \nabla \cdot \rho \boldsymbol{v} &= 0 \\ \partial_t \rho \boldsymbol{v} + \nabla \cdot (\rho \boldsymbol{v} \otimes \boldsymbol{v}) + \nabla p &= \rho \boldsymbol{g} - 2\rho\left(\Omega \times \boldsymbol{v}\right) \\ \partial_t E + \nabla \cdot (E + p)\boldsymbol{v} &= -\rho \boldsymbol{v} \cdot \boldsymbol{g} + \rho Q \end{aligned}$$

$$\partial_t \boldsymbol{U} + \nabla \cdot \boldsymbol{f}\left(\boldsymbol{U}\right) = \boldsymbol{S}(\boldsymbol{U})$$

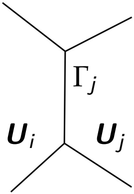
Deep atmospheres, non-hydrostatic.

Finite Volume

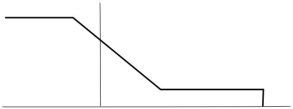
fully conservative
& treats shocks

$$\int_V \boldsymbol{S}(\boldsymbol{U},\boldsymbol{x})\,\mathrm{dV} = \frac{d}{dt}\int_{V_i} \boldsymbol{U}\,\mathrm{dV} + \int_{V_i} \nabla\cdot\boldsymbol{f}\left(\boldsymbol{U}\right)\cdot\mathrm{d}\mathbf{n}$$

$$= \frac{d}{dt}\int_{V_i} \boldsymbol{U}\,\mathrm{dV} + \sum_j \underbrace{\int_{\Gamma_j} \boldsymbol{f}\left(\boldsymbol{U}\right)\cdot\mathrm{d}\mathbf{n}}_{\boldsymbol{F}(\boldsymbol{U}_i,\boldsymbol{U}_j)}$$



$$\boldsymbol{F}(\boldsymbol{U}_i,\boldsymbol{U}_j) = -\boldsymbol{F}(\boldsymbol{U}_j,\boldsymbol{U}_i)$$



1D Riemann Problem

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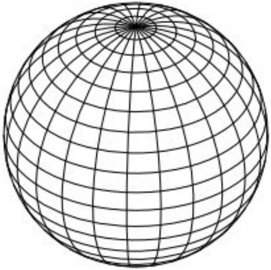
Traditional Polar Grid

too non-uniform

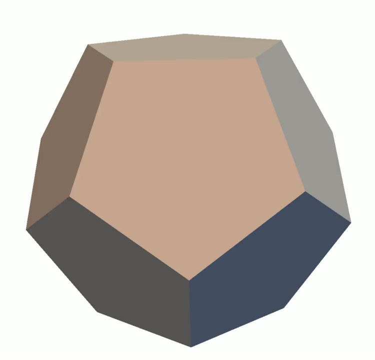


- highly non-uniform
- severe CFL-restriction

$$\Delta t \leq \frac{\Delta x}{v_{max}}$$

Icosahedral Grid (dual)

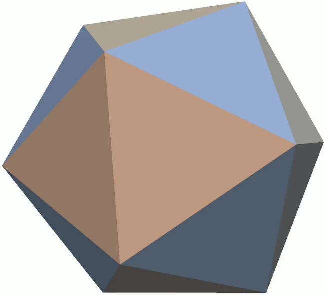
a most uniform mesh



- uniform cells
- 12 pentagons + n hexagons

Icosahedral Grid (primary)

same thing with triangles

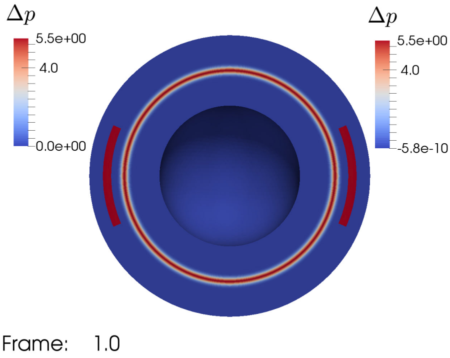


- uniform cells
- triangles

Well-balanced FVM

exactly maintains hydrostatic equillibrium

$$\nabla p = \rho \boldsymbol{g} \qquad \text{(hydrostatic balance)}$$



$$p = p_{eq} + \Delta p$$

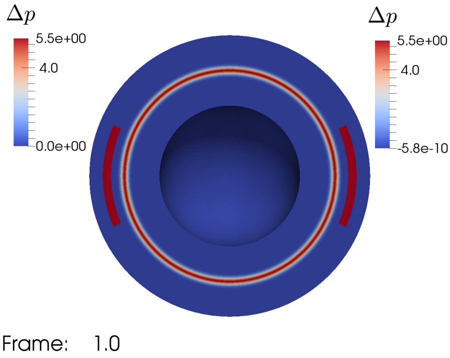
$$\frac{\Delta p}{p} \sim 10^{-5}$$

numerical scheme: [R. Käppeli, S. Mishra (2014)]

Well-balanced FVM

and resolves small perturbations

$$\nabla p = \rho \boldsymbol{g} \qquad \text{(hydrostatic balance)}$$

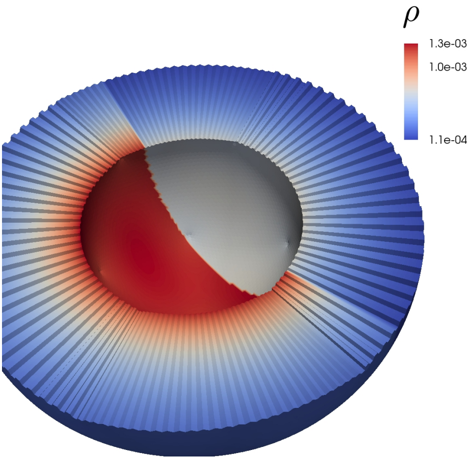


$$\frac{\Delta p}{p} \sim 10^{-5}$$

Naive (left) vs. well-balanced (right).

numerical scheme: [R. Käppeli, S. Mishra (2014)]

Horizontal flow test case



cold, rare, low pressure

hot, dense, high pressure

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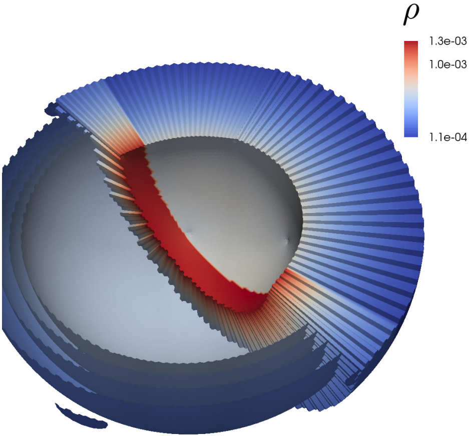
Naive horizontal flow

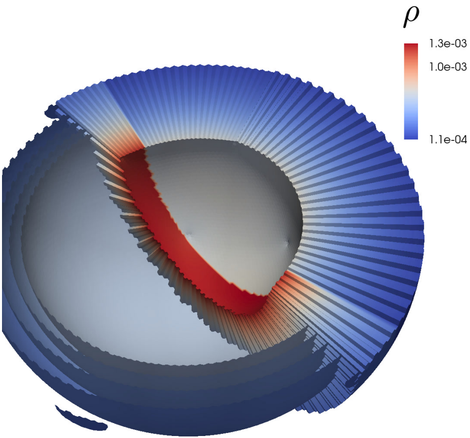
really ugly



- first order
- naive balancing

Proper horizontal flow

much, much better



- second order
- well-balanced

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