MITgcm capabilities and development

Lecture 3

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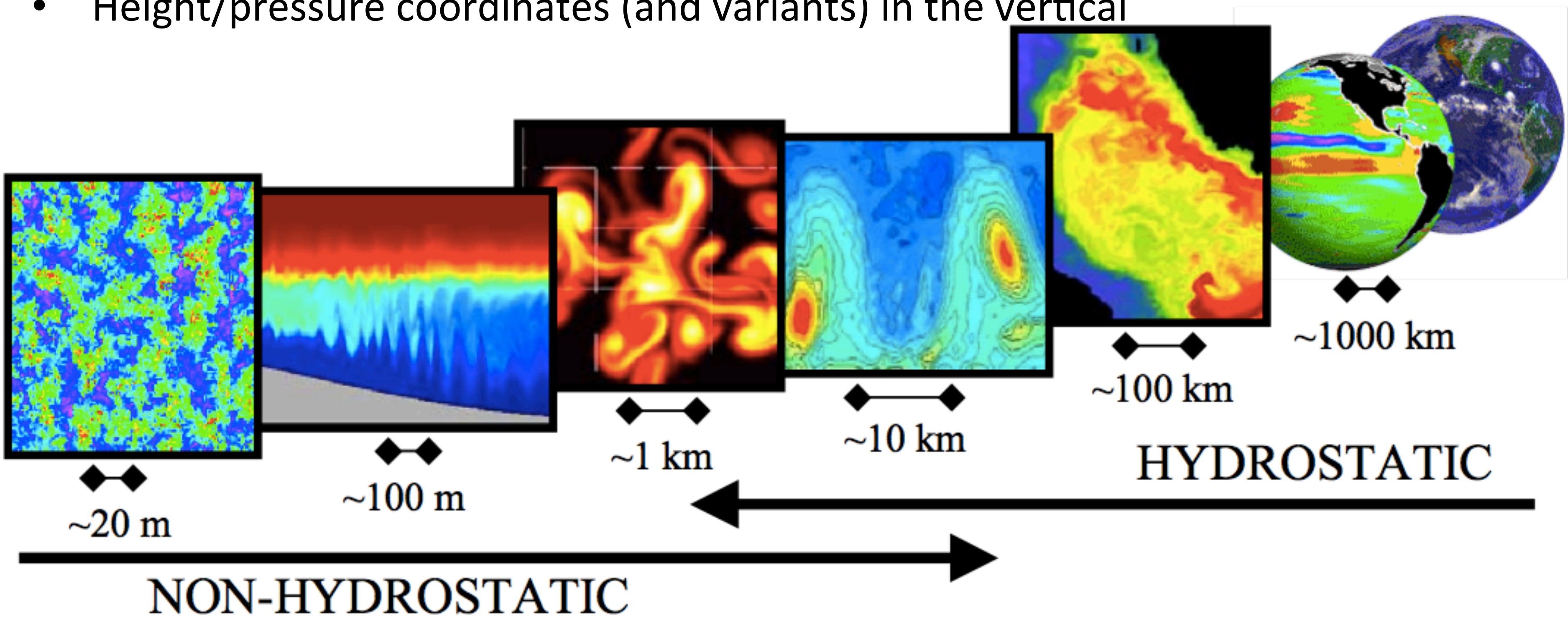
1. MITgcm, structure, capabilities
2. Two exoplanet applications

- Modular/versatile code, from global scale down to small scale processes
- Navier-Stokes equation including non-hydrostatic capability
- Finite volume method
- Horizontal orthogonal curvilinear
- Height/pressure coordinates (and variants) in the vertical



<u>Reference papers:</u>

Marshall et al. 1997a: A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers. JGR, 102, 5753-5766.

Marshall et al. 1997a: Hydrostatic, quasi-hydrostatic, and non-hydrostatic ocean modeling. JGR, 102, 5733-5752.

Adcroft et al. 2004: Overview of the Formulation and Numerics of the MIT GCM (ECMWF Newsletter)

Incompressible Boussinesq height coordinate equations

$$D_t\rho << \rho\nabla\cdot\vec{v} \qquad \rho' = (\rho - \rho_o) << \rho_o$$

$$\rho_o D_t\vec{v} + 2\Omega\times\rho_o\vec{v} + g\rho\hat{k} + \nabla p = \vec{F}$$

$$\rho_o\nabla\cdot\vec{v} = 0$$

$$\partial_t\eta + \nabla\cdot(H+\eta)\vec{v}_h = P\text{-}E$$

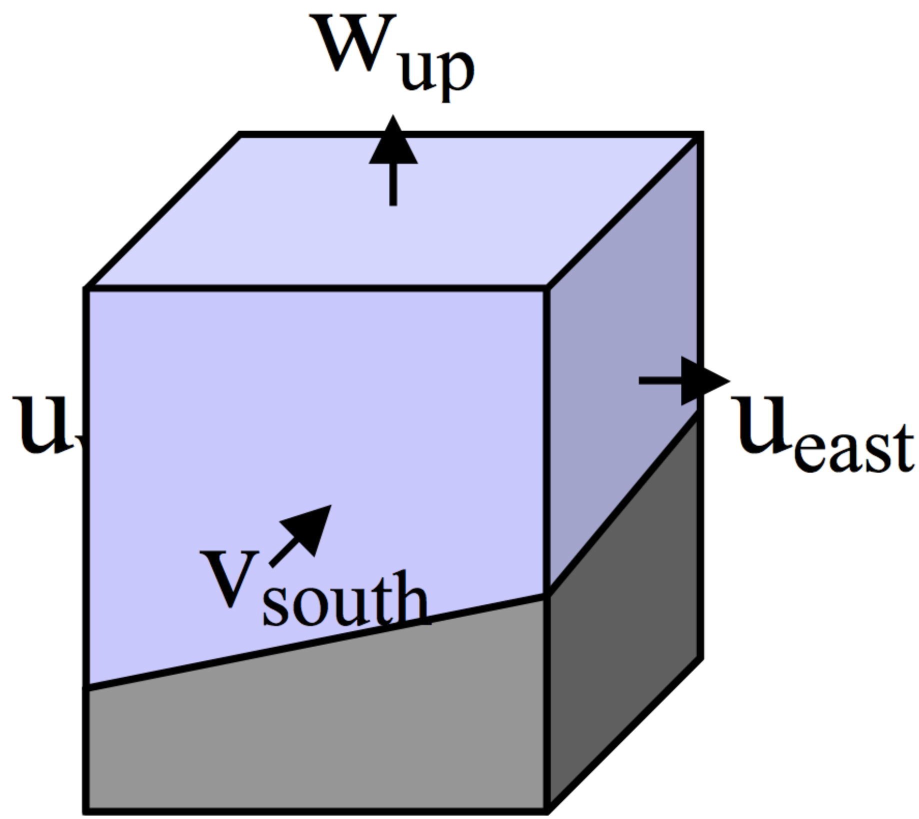
$$D_t\theta = Q_\theta$$

$$D_t s = Q_s$$

$$\rho = \rho\left(s,\theta,p\right)$$

Finite volume discretization

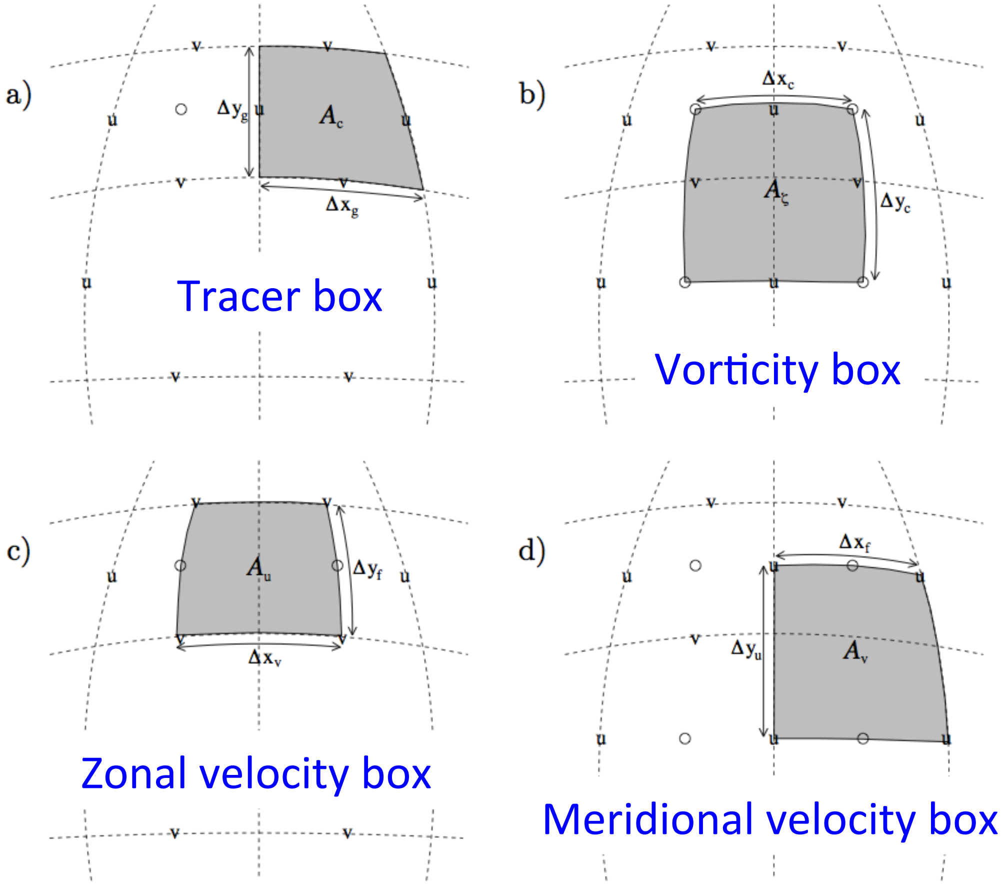
- Budgets integrated over volumes
- Boundary conditions (no flux) naturally accounted for
- Staggered velocities:
  → Arakawa C grid



Ex: volume budget

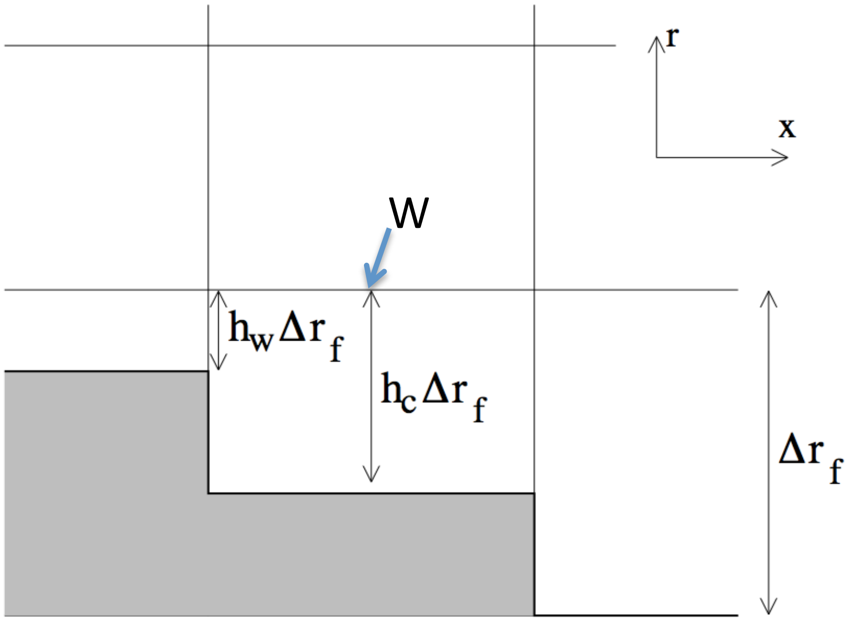
$$A^{u}_{east}\, u_{east} - A^{u}_{west}\, u_{west} + A^{v}_{north}\, v_{north} - A^{v}_{south}\, v_{south} + A^{w}_{up}\, w_{up} - A^{w}_{down}\, w_{down} = 0$$

Horizontal C-grid



Vertical grid

Can include partial/shaved cells →



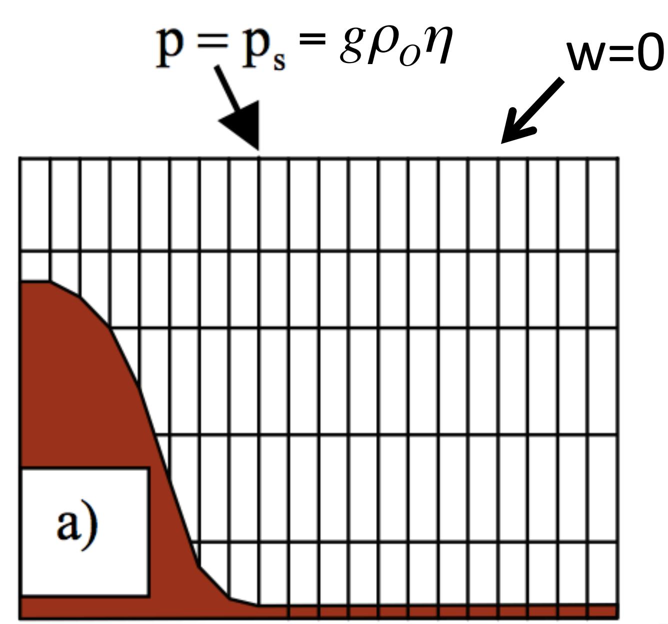
Solving method (illustration for the rigid-lid approximation)

Key step: solve for surface pressure diagnostically: $P = P_s + P_H$

Surface pressure term

includes hydrostatic pressure with $P_H(z=0)=0$
+ advection term
+ friction
+ wind stress
+ …

$$\begin{aligned} \partial_t u + g\partial_x \eta &= G_u \\ \partial_t v + g\partial_y \eta &= G_v \\ \partial_x u + \partial_y v + \partial_z w &= 0 \end{aligned}$$



Vertical integral of non-divergence:

$$\partial_x H\widehat{u} + \partial_y H\widehat{v} = 0$$

$$H\widehat{u} = \int_H u dz$$

Solve for pressure and step forward

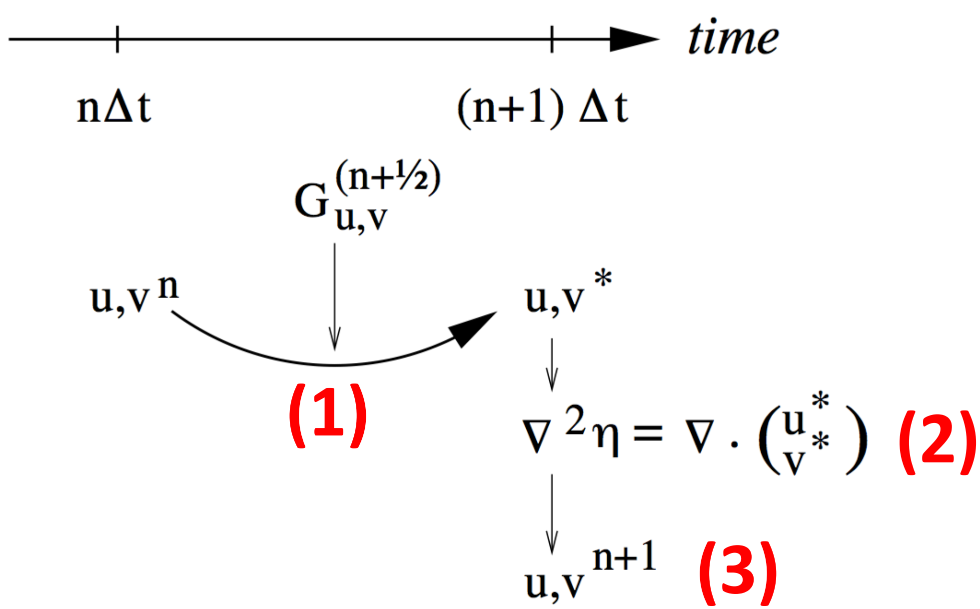
(1)

$$
\begin{aligned}
u^* &= u^n + \Delta t G_u^{(n+1/2)} /2) \\
v^* &= v^n + \Delta t G_v^{(n+1/2)} /2)
\end{aligned}
$$

$$
\partial_x \Delta t g H \partial_x \eta^{n+1} + \partial_y \Delta t g H \partial_y \eta^{n+1} = \partial_x H \widehat{u^*} + \partial_y H \widehat{v^*} \quad \textbf{(2)}
$$

(2)

$$
\begin{aligned}
u^{n+1} &= u^* - \Delta t g \partial_x \eta^{n+1} \\
v^{n+1} &= v^* - \Delta t g \partial_y \eta^{n+1}
\end{aligned}
$$



More than one option of the governing equations

Hydrostatic ←→ Non-hydrostatic

Deep anelastic

$$\phi(x,y,r) = \phi_s(x,y) + \phi_{hyd}(x,y,r) + \phi_{nh}(x,y,r)$$

$$\frac{\partial \vec{\mathbf{v}}_h}{\partial t} + \nabla_h \phi_s + \nabla_h \phi_{hyd} + \epsilon_{nh} \nabla_h \phi_{nh} = \vec{\mathbf{G}}_{\vec{v}_h}$$

$$\frac{\partial \phi_{hyd}}{\partial r} = -b$$

$$\epsilon_{nh} \frac{\partial \dot{r}}{\partial t} + \frac{\partial \phi_{nh}}{\partial r} = G_{\dot{r}}$$

$$G_u = -\vec{\mathbf{v}}.\nabla u - \left\{ \frac{u\dot{r}}{r} - \frac{uv\tan\varphi}{r} \right\} - \{ -2\Omega v \sin\varphi + 2\Omega \dot{r} \cos\varphi \} + \mathcal{F}_u$$

advection, *metric*, *Coriolis*, *Forcing/Dissipation*

$$G_v = -\vec{\mathbf{v}}.\nabla v - \left\{ \frac{v\dot{r}}{r} - \frac{u^2\tan\varphi}{r} \right\} - \{ -2\Omega u \sin\varphi \} + \mathcal{F}_v$$

advection, *metric*, *Coriolis*, *Forcing/Dissipation*

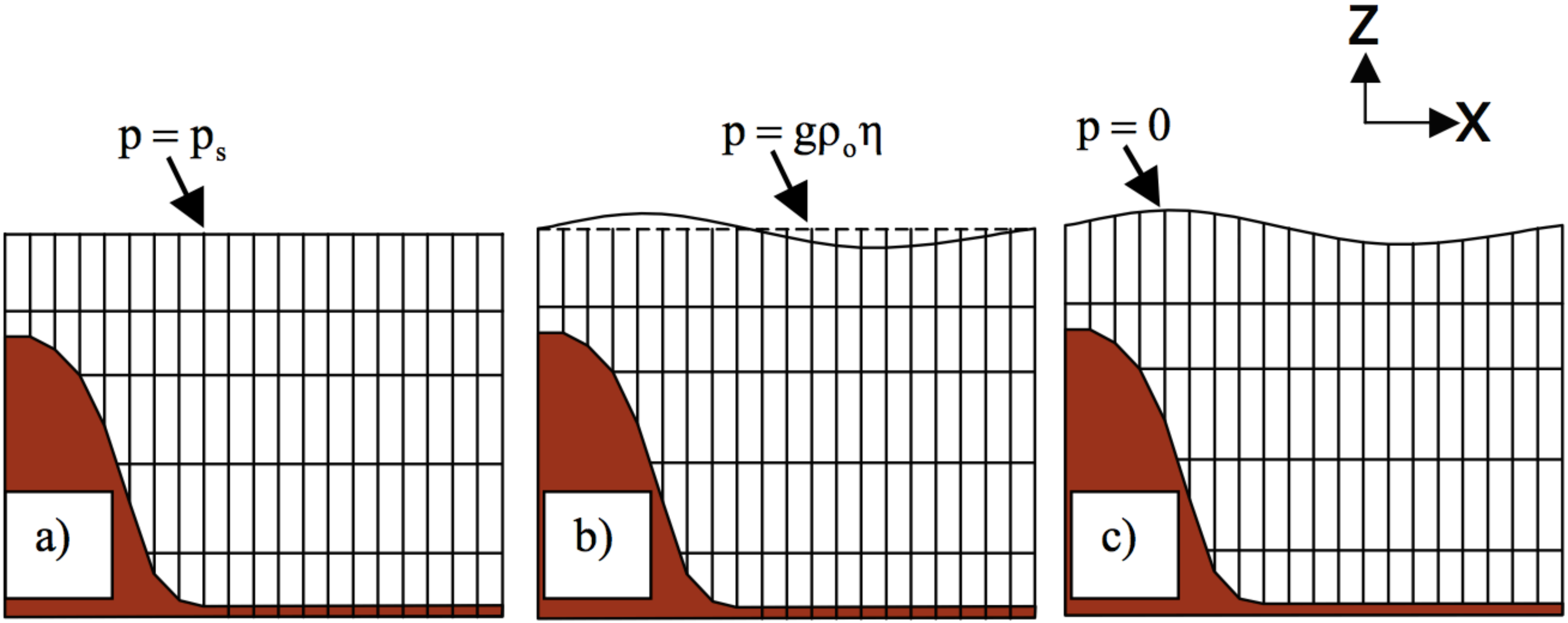
$$G_{\dot{r}} = -\vec{\mathbf{v}}.\nabla \dot{r} + \left\{ \frac{u^2 + v^2}{r} \right\} + 2\Omega u \cos\varphi + \mathcal{F}_{\dot{r}}$$

advection, *metric*, *Coriolis*, *Forcing/Dissipation*

Hydrostatic primitive equation
r → a (radius of Earth)

Quasi-hydrostatic

Non-hydrostatic



P_s (or pseudo η) solved such that

$$\nabla \cdot \int_{-H}^{0} \vec{v}\, dz = 0$$

No surface wave

Neglect small terms in continuity equation

$$\partial_t \eta + \nabla \cdot \int_{-H}^{0} \vec{v} dz = P - E$$

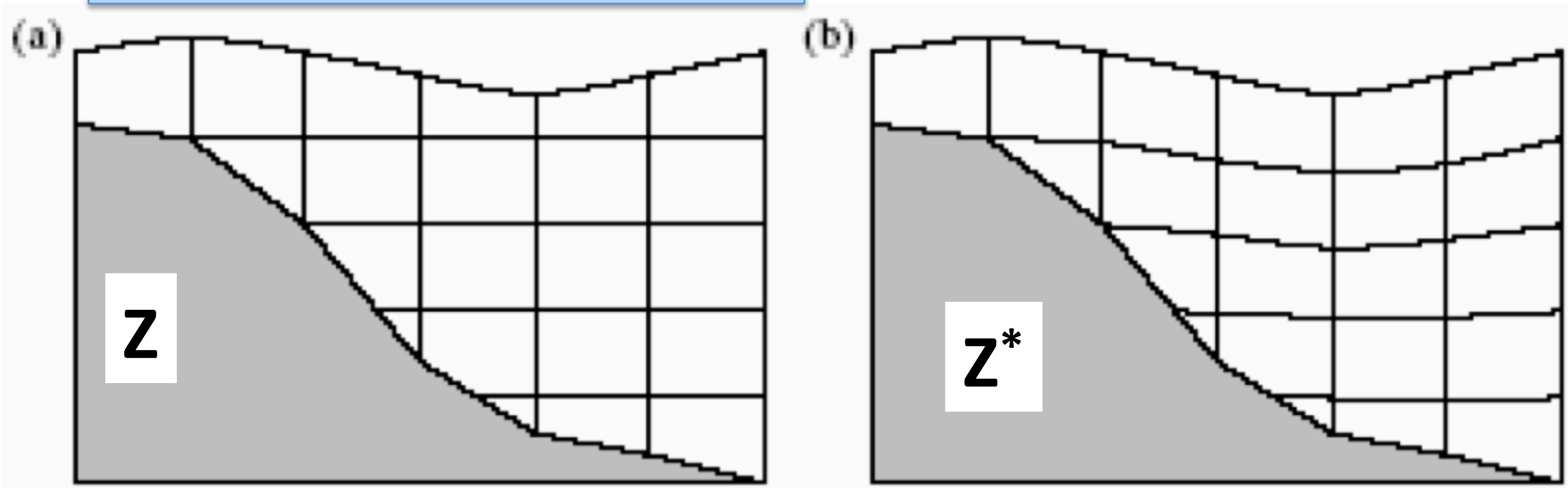
- Surface wave with finite speed
- Good for $\eta \ll H$
- Non-conservation issues

No approximation

$$\partial_t \eta + \nabla \cdot \int_{-H}^{\eta} \vec{v} dz = P - E$$

- Better conservation
- More costly computationally
- Problem for $|\eta| \approx \Delta Z_1$

Stretched vertical coordinate



$$z^* = \frac{z - \eta}{H + \eta} H$$

- Z* close to Z
- Pressure gradient error
- Similarity to terrain following coordinate
- but small slope

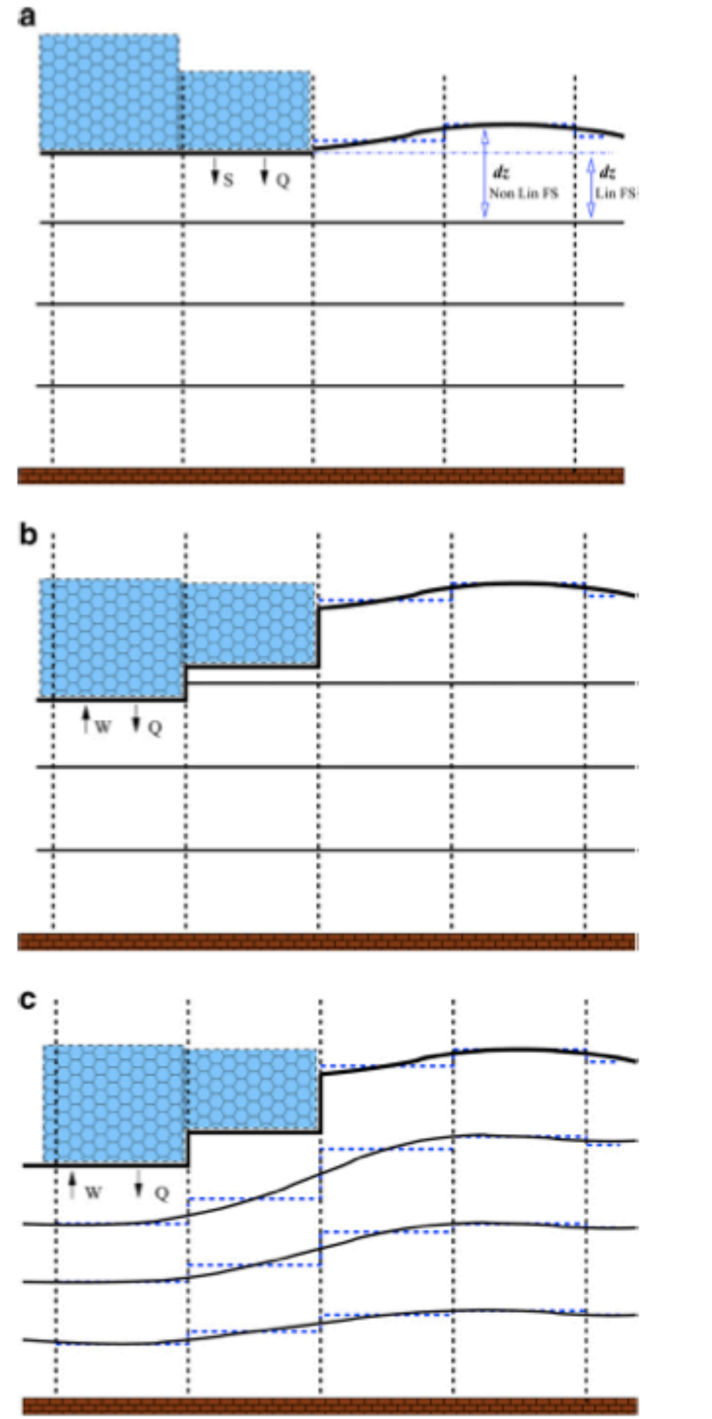
$$\begin{pmatrix} z = -H \\ w = -\vec{v}_h \cdot \nabla H \end{pmatrix} \Leftrightarrow \begin{pmatrix} z^* = -H \\ w^* = -\vec{v}_h \cdot \nabla H \end{pmatrix}$$

$$\begin{pmatrix} z = \eta \\ w = D_t \eta - (P - E) \end{pmatrix} \Leftrightarrow \begin{pmatrix} z^* = 0 \\ w^* = \dfrac{-H}{H + \eta}(P - E) \end{pmatrix}$$

Application to sea ice and coupled problem (Campin et al. 2008)

- avoids the difficult issue of vanishing levels under thick ice
- Non-linear sea surface even with sea ice → real freshwater flux treatment globally

- achieve perfect conservation of fresh water, heat and salt, as shown in extended integration of coupled ocean sea ice atmospheric model



Ocean (z-coordinate)

$$D_t\vec{v}_h + f\hat{k}\times\vec{v}_h + \tfrac{1}{\rho_o}\nabla_z p = \vec{F}$$

$$\partial_z p + g\rho = 0$$

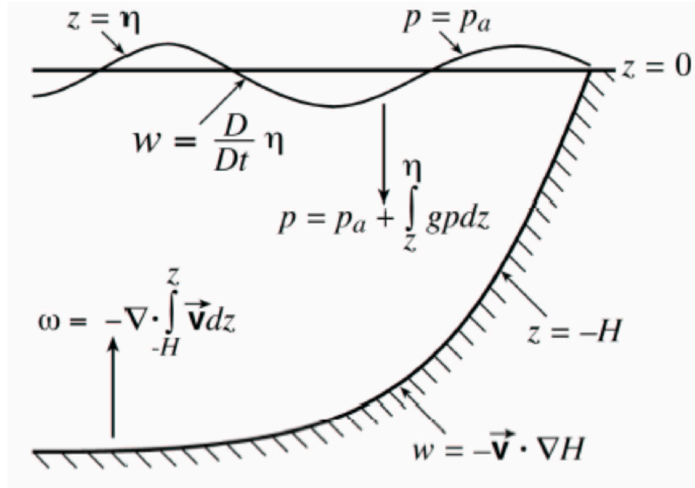
$$\nabla_z\cdot\vec{v}_h + \partial_z w = 0$$

$$\partial_t\eta + \nabla\cdot(H+\eta)\vec{v}_h = P - E$$

$$D_t\theta = Q_\theta$$

$$D_t s = Q_s$$

$$\rho = \rho(s,\theta,p)$$



Isomorphism between ocean and atmosphere

Variables:

Z ←→ P

P ←→ Φ

ρ ←→ α

w ←→ ω

Θ

S ←→ q

H+η ←→ p_s

Atmosphere (p-coordinate)

$$D_t\vec{v}_h + f\hat{k}\times\vec{v}_h + \nabla_p\Phi = \vec{F}$$

$$\partial_p\Phi + \alpha = 0$$

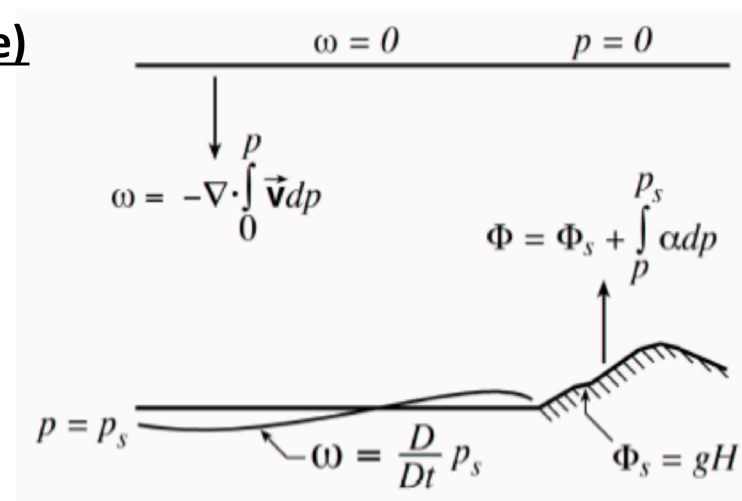
$$\nabla_p\cdot\vec{v}_h + \partial_p\omega = 0$$

$$\partial_t p_s + \nabla\cdot p_s\langle\vec{v}_h\rangle = 0$$

$$D_t\theta = Q_\theta$$

$$D_t q = Q_q$$

$$\alpha = \tfrac{\partial\Pi}{\partial p}\theta$$



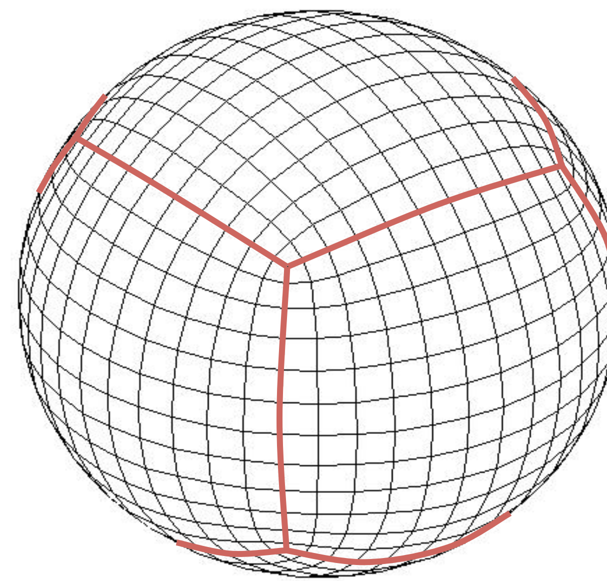
Isomorphism between ocean and atmosphere

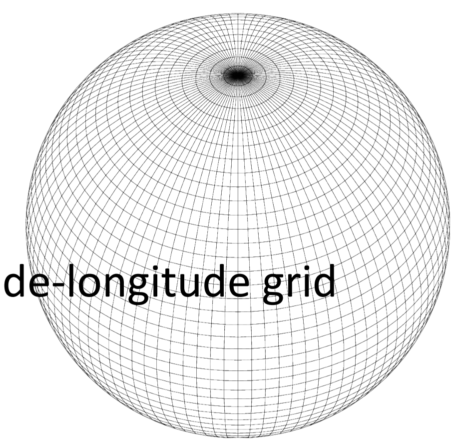
- MITgcm is both an ocean and an atmospheric model

- Development for ocean → "almost" done for atmosphere and vice-versa
  → ex: p* coordinate available for atmosphere (analogous to z*)

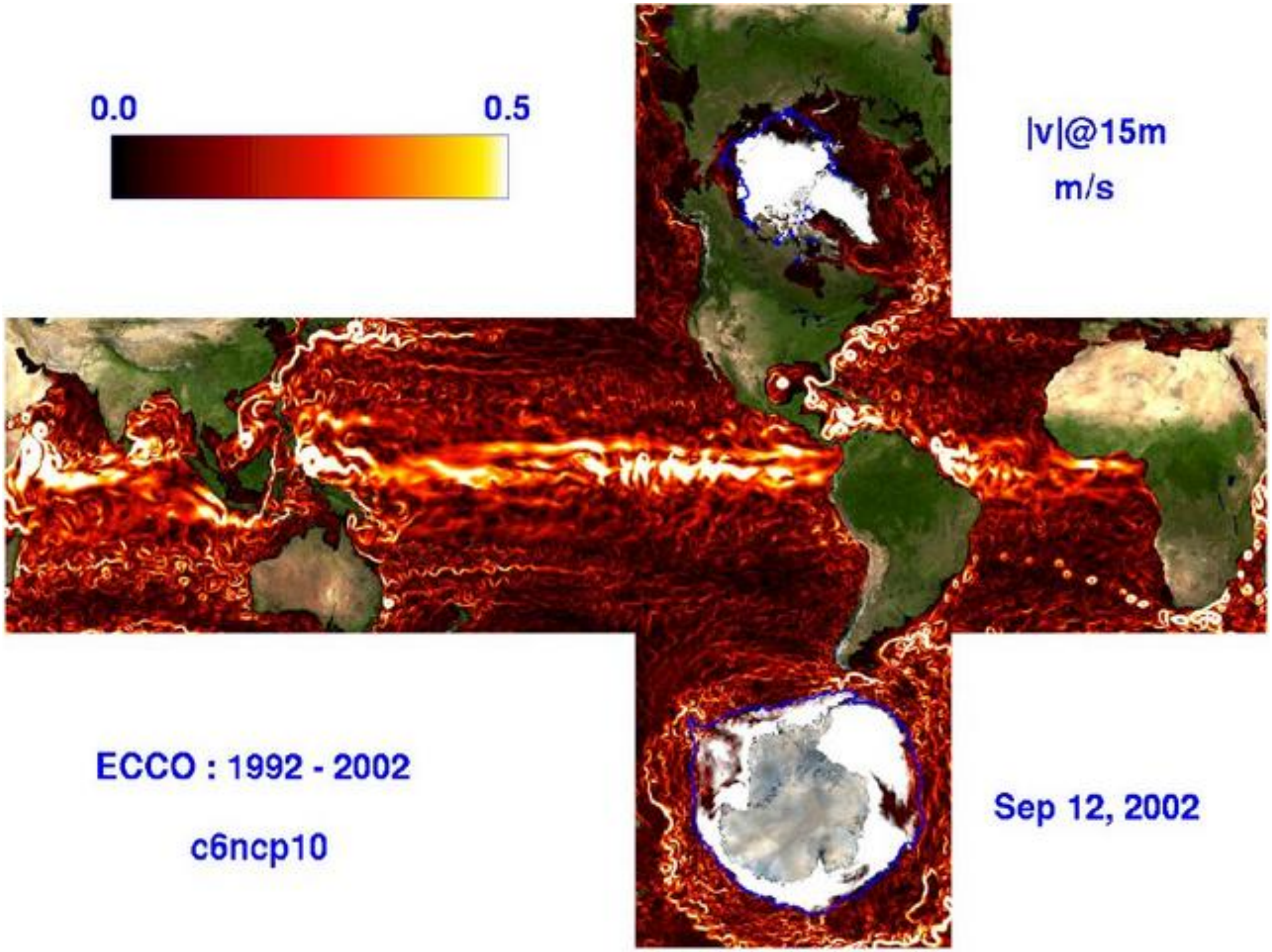
- Possibility for a non-Boussinesq ocean (pressure coordinate ocean)

- Combined with cubed-sphere: easy and conservative coupling (Campin et al. 2008)



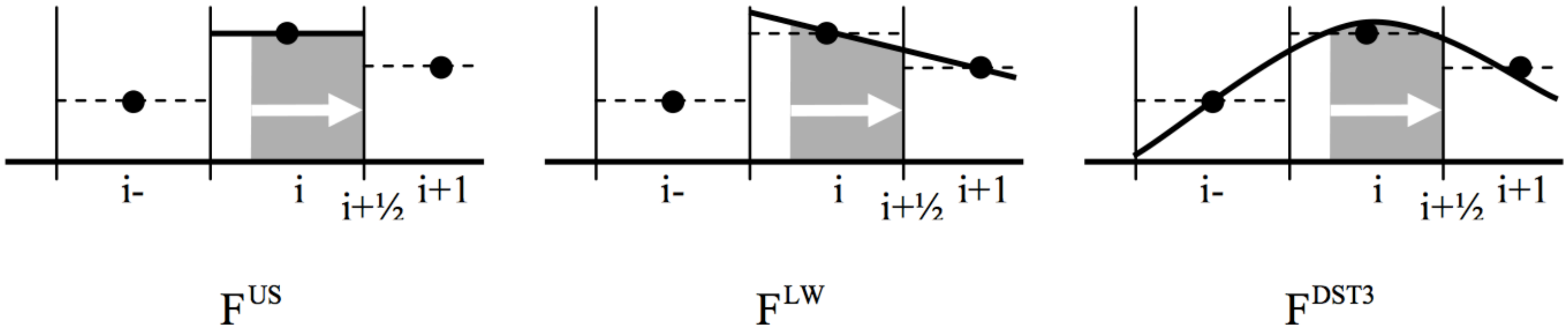


Latitude-longitude grid

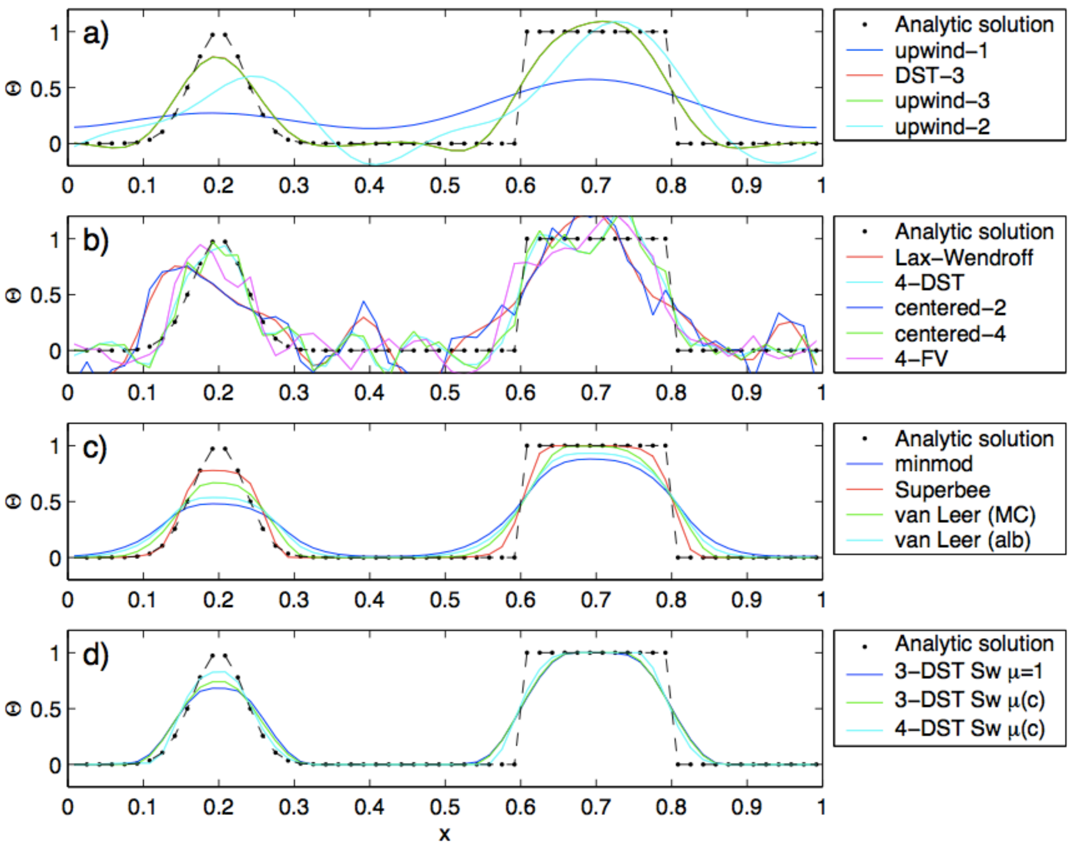


https://www.youtube.com/watch?v=liohY282oi8

Advection schemes



$$F^{US}_{i+\frac{1}{2}} = u\theta^n_i$$
$$F^{LW}_{i+\frac{1}{2}} = F^{US}_{i+\frac{1}{2}} + \tfrac{1}{2}u(1\text{-}C)\left(\theta^n_{i+1} - \theta^n_i\right)$$
$$F^{DST3}_{i+\frac{1}{2}} = F^{LW}_{i+\frac{1}{2}} - \tfrac{1}{6}u(1-C^2)\left(\theta^n_{i+1} - 2\theta^n_i + \theta^n_{i-1}\right)$$



- Advection schemes exploit finite volume method
- Compute flux through faces
- There are many advection schemes number?

Accurate modeling of the adiabatic ocean interior in Z-coordinate model

David Ferreira, Chris Hill, Ryan Abernathey, Jean-Michel Campin, John Marshall and Nicolas Barrier

• Diapycnal mixing in the mid-depth ocean is weak $O(10^{-5})\ m^2s^{-1}$ (Ledwell et al. 93 & 98, DIMES)

• In z-coordinate model, advection generates large spurious diapycnal diffusivity, often in excess of $10\text{-}30 \times O(10^{-5})\ m^2s^{-1}$ (Griffies et al. 2000)

However – result is sensitive to numerical scheme used. What if we revisit with schemes that are designed for high accuracy e.g. Prather (JGR, 1986) second order moments

Estimating spurious mixing in models is complicated

→ Use two methods

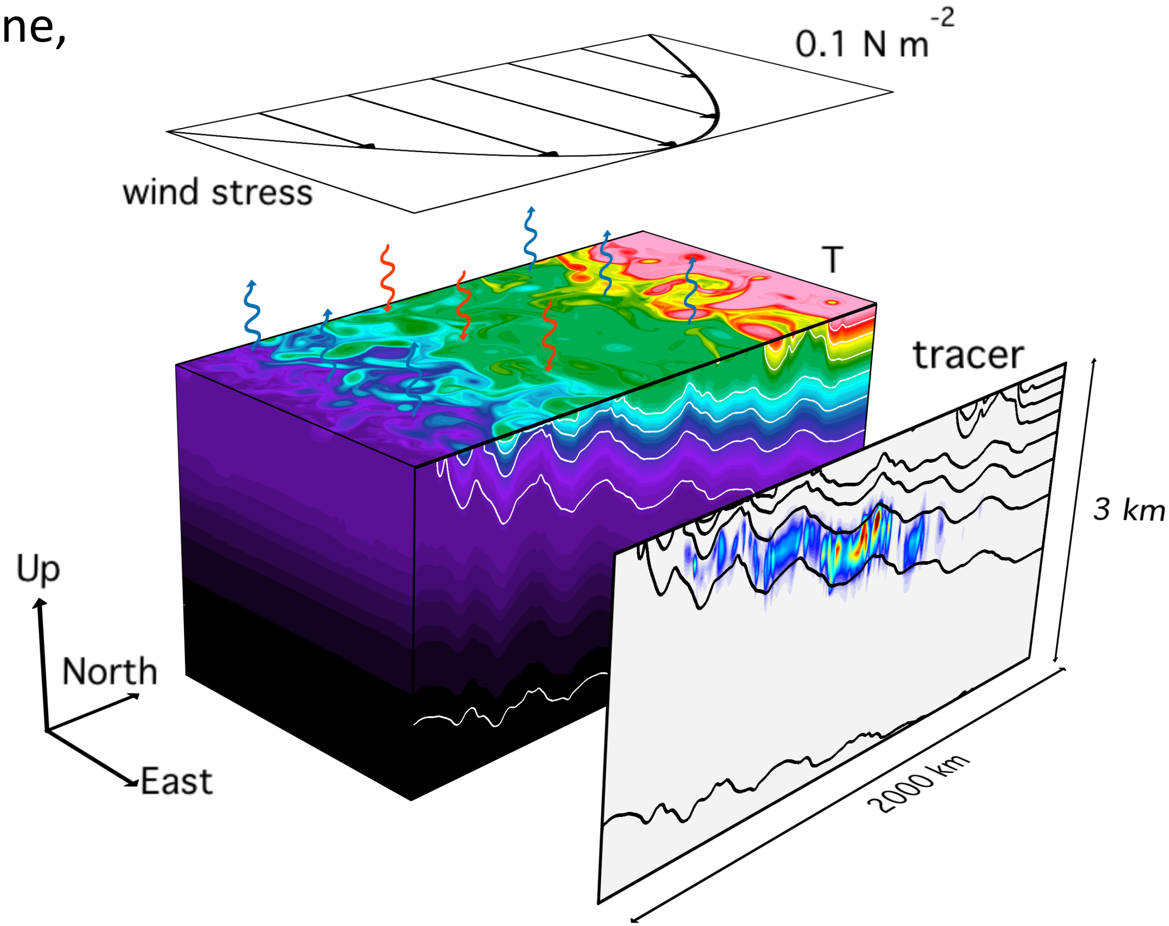
- Griffies et al. spindown (active tracer)
- Tracer release (passive tracer)

Experimental setup

MITgcm

Periodic "ACC" channel:

- 1000 km long by 2000 km wide,
- wall to south, sponge and T profile to north,
- zonal wind stress, sinusoidal heating/cooling,
- linear EOS, Δx=Δy=5 km, β-plane,
- spun up to equilibrium

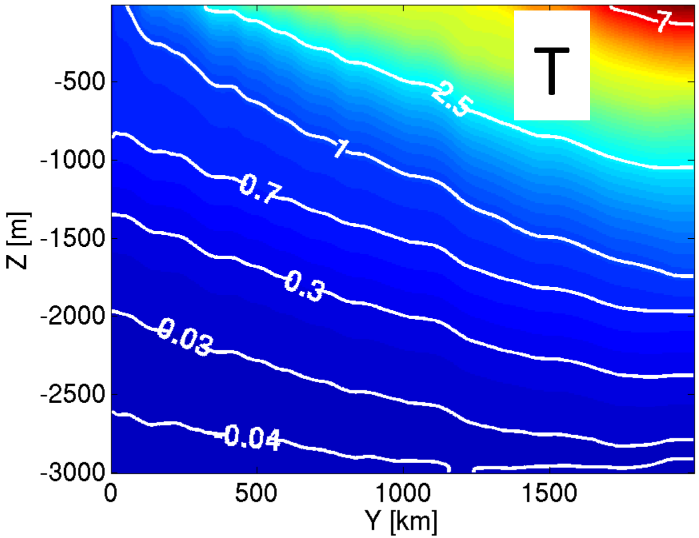


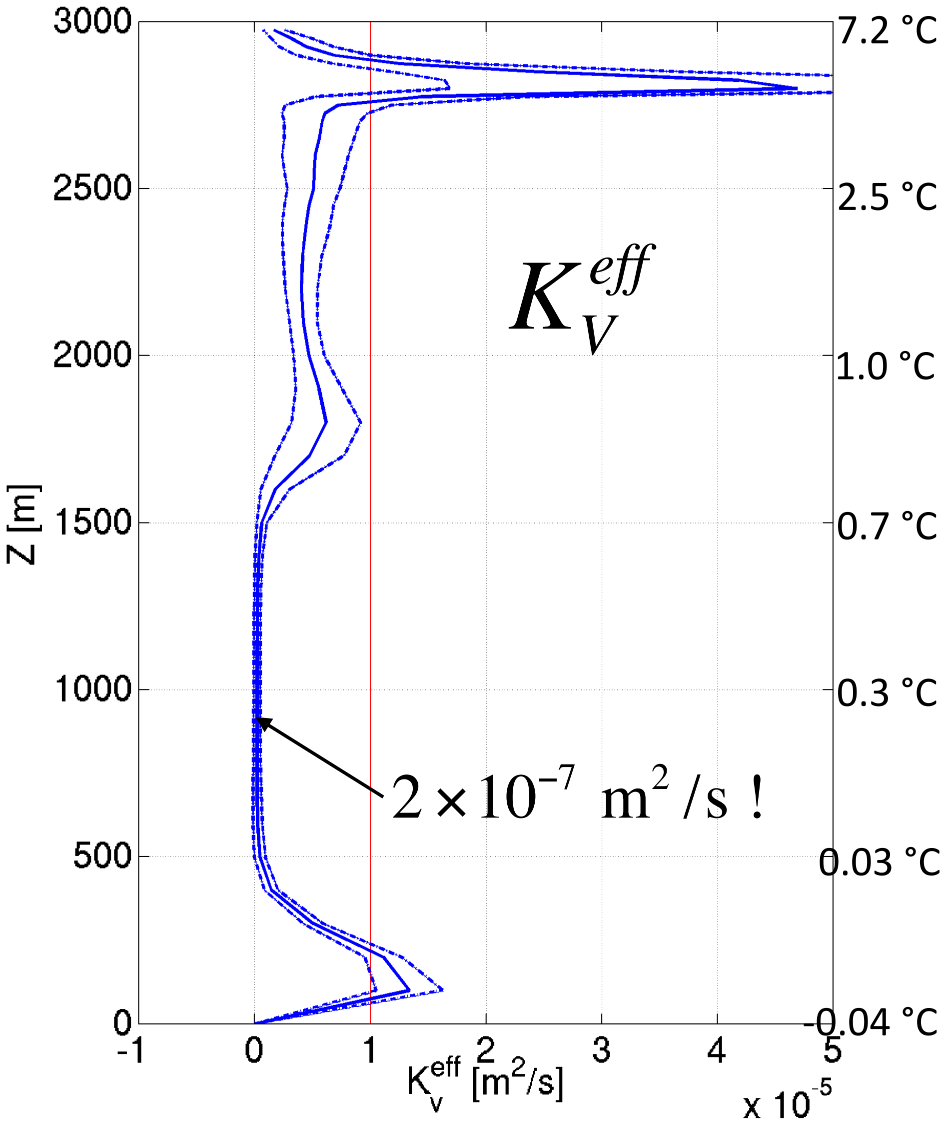
The "Griffies et al." method

300 levels of 10 m

1 – spin up
2 – turn off all forcings
3 – monitor T(z,t)
4 – diagnose K_v

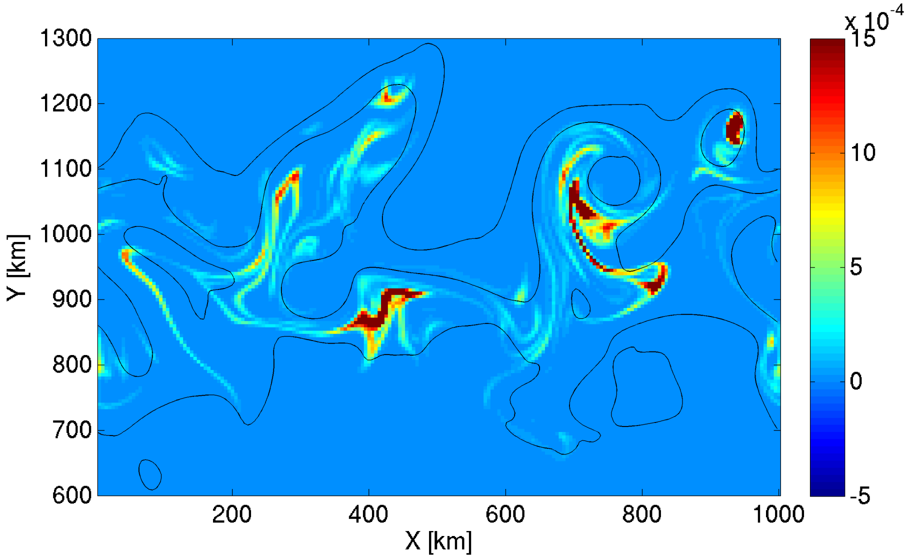
Prather advection scheme with $K_H = K_V = 0$ on temperature





The "Ledwell et al." method

Release of a dye at ~900 m

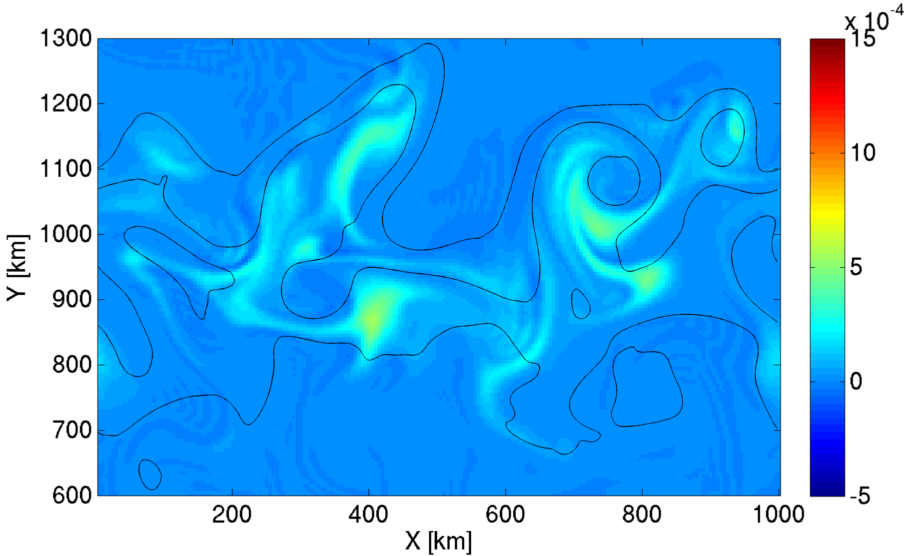


Prather

$$K_H = K_V = 0$$

Tracer distribution after 150 days

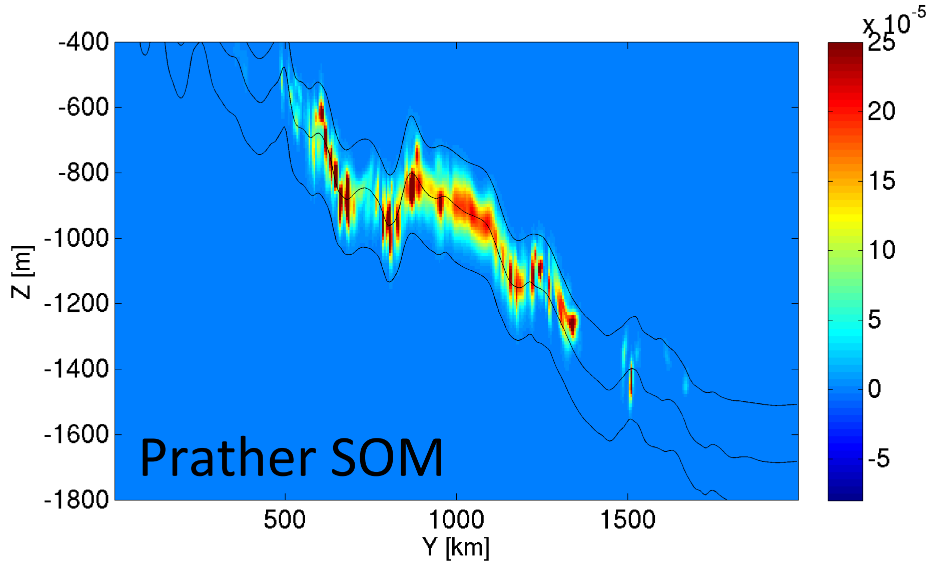
Same flow field!

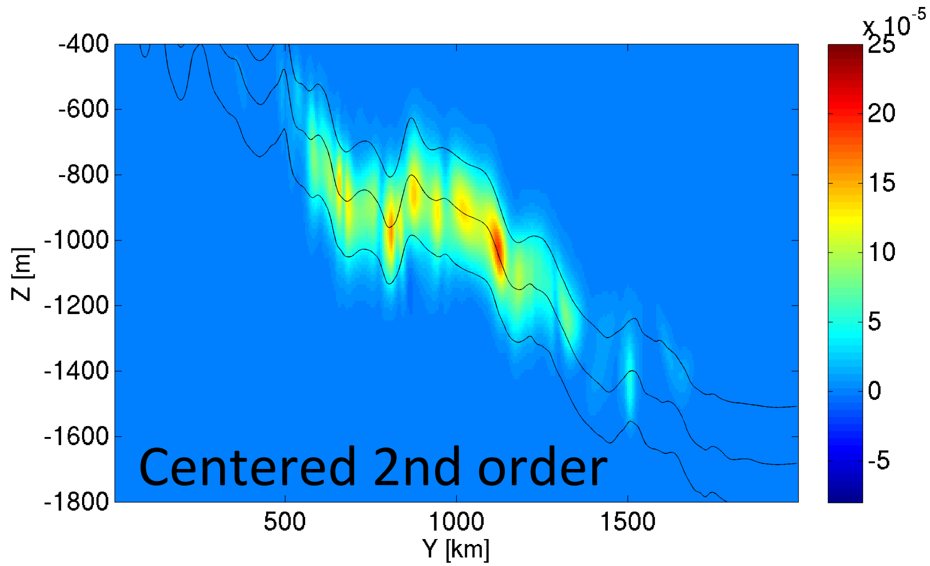


Centered 2nd order

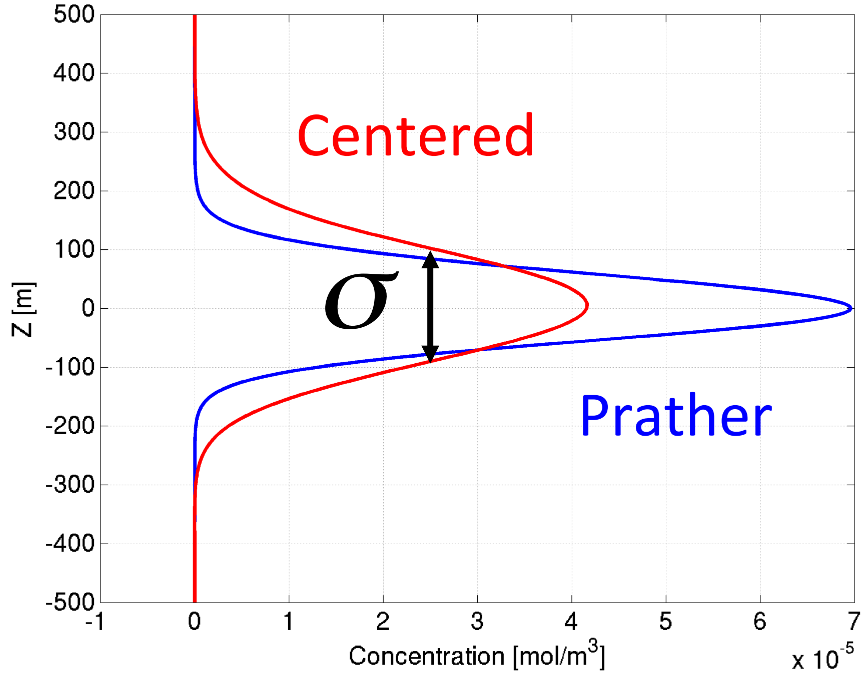
$$K_H = 30 \text{ m}^2/\text{s},\ K_V = 10^{-5}\text{m}^2/\text{s}$$

Meridional section: 225 days after release





Reconstructed Tracer profile at 225 days

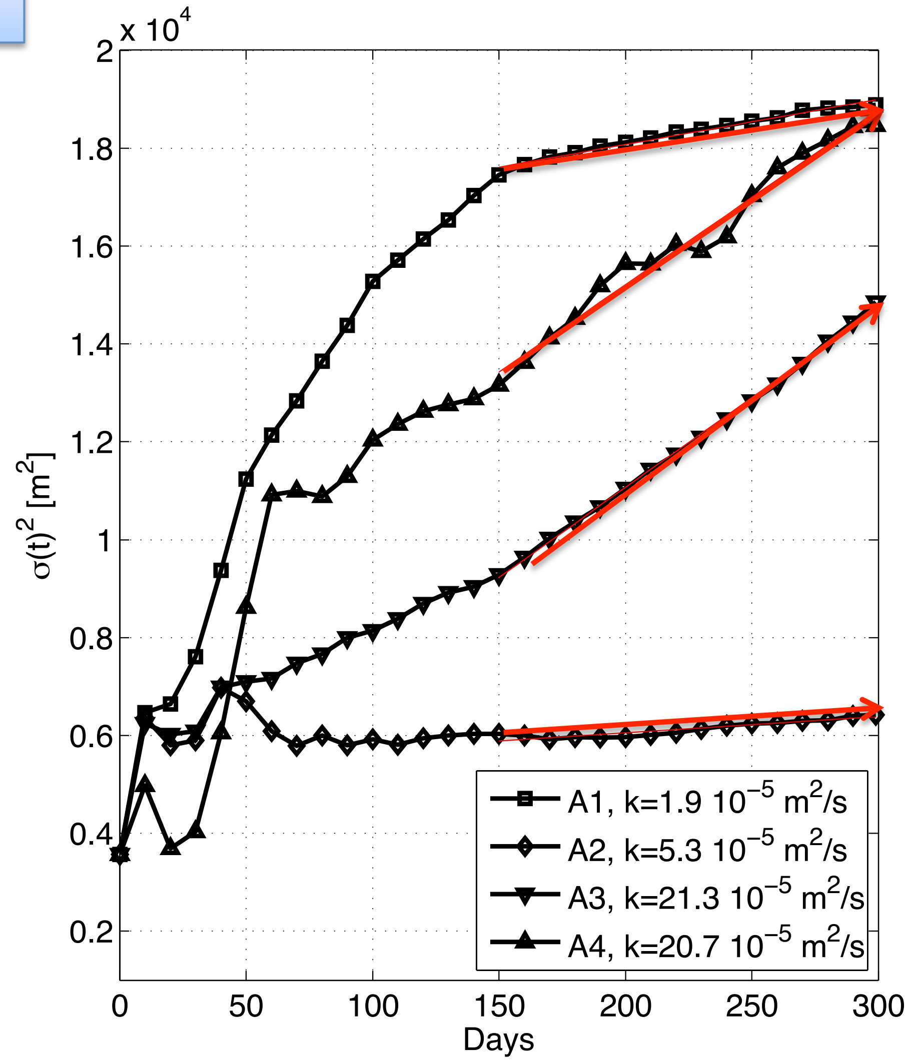


Time-evolution of Gaussian width

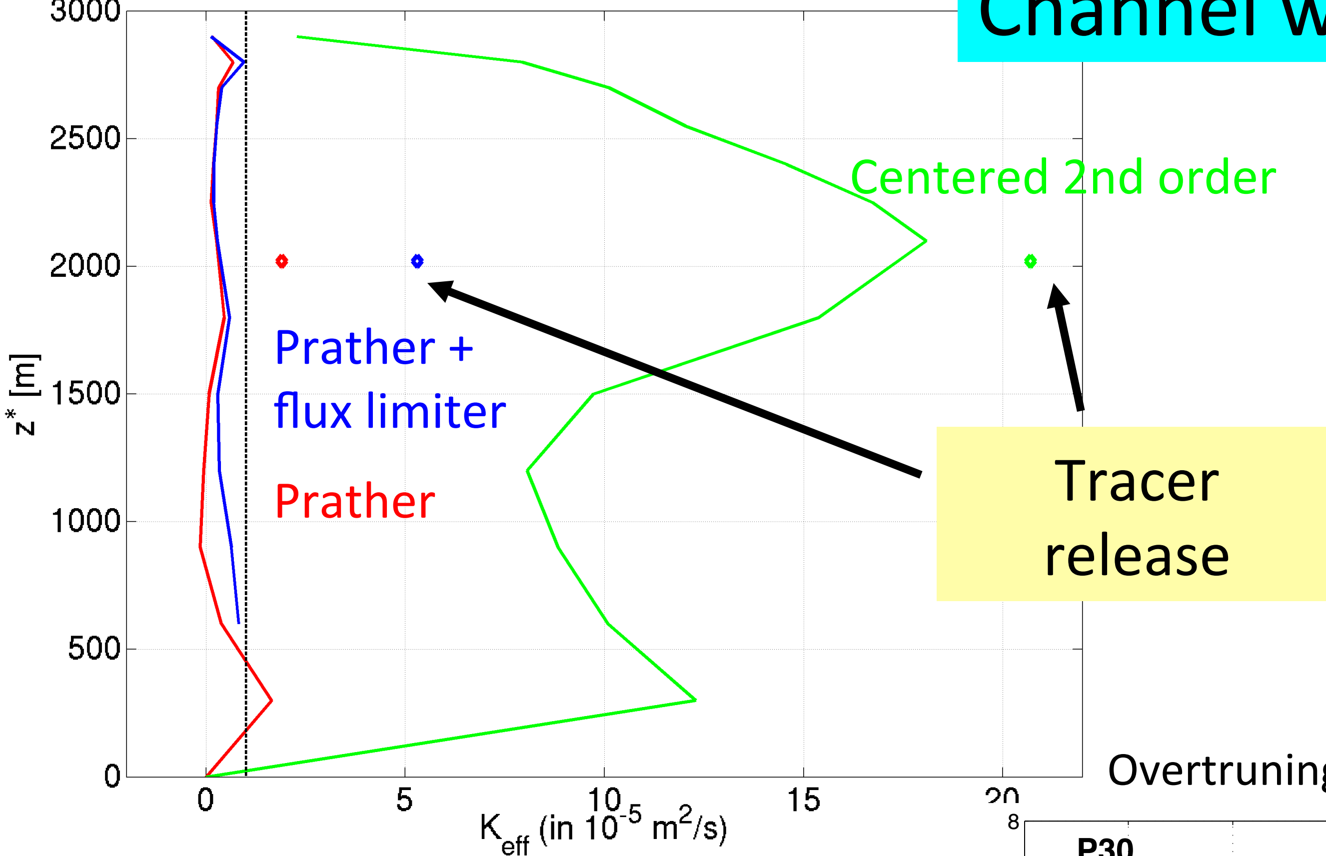
$$K_V^{eff} = \frac{1}{2}\frac{d\sigma^2}{dt}$$

Prather
$0.4 \times 10^{-5} \mathrm{m}^2/\mathrm{s}$
Consistent with Griffies method

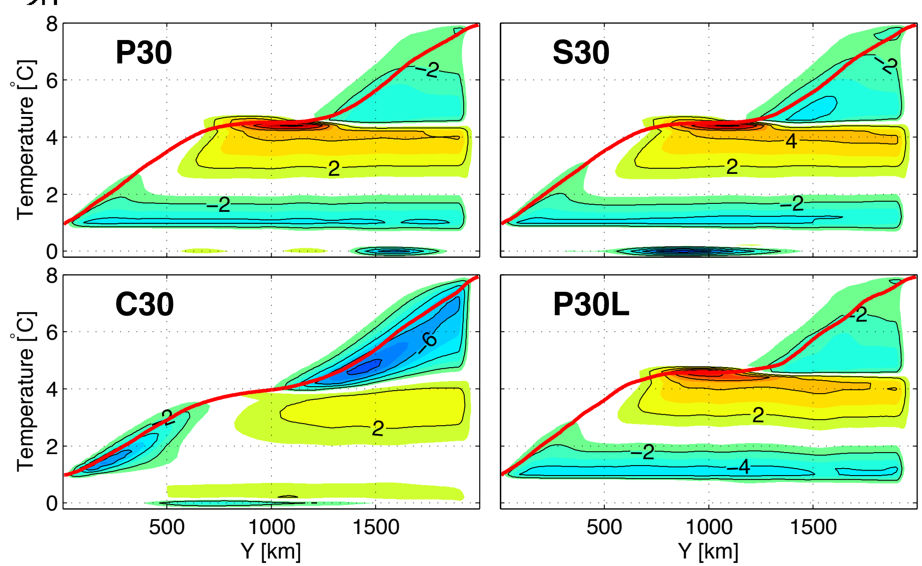
Centered
$16 \times 10^{-5} \mathrm{m}^2/\mathrm{s}$



Channel with 30 levels



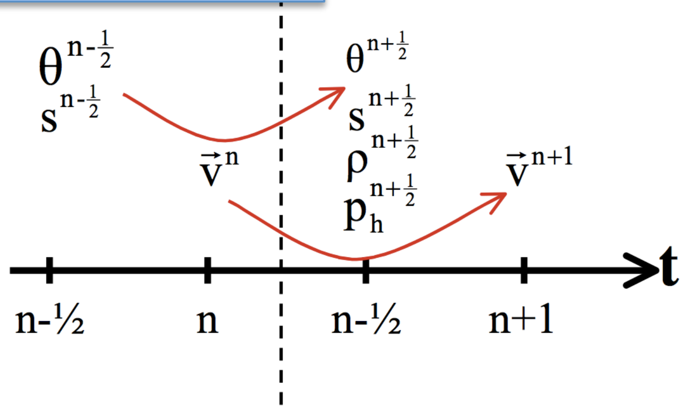
Overtruning in Temperature classes



Possible to maintain a quasi adiabatic ocean interior in a vigorous eddying regime (at least numerical mixing << observed mixing)

More than one option for time-stepping:

Ex:
- staggered time step
- Adams-Bashford
- Crank-Nicholson



Other options in formulation:

- Deep atmosphere
- Mass sources within fluid
- Anelastic
- etc .

Vector Invariant form of equation

$$\partial_t \vec{v} + (2\vec{\Omega} + \vec{\zeta}) \wedge \vec{v} - b\hat{r} + \vec{\nabla}B = \vec{\nabla}\cdot\vec{\tau}$$

Multiple schemes

- Implicit/explicit treatment of diffusion/viscosity
- Various schemes for Coriolis terms,
- Etc …

Passive tracer
Lagrangian floats

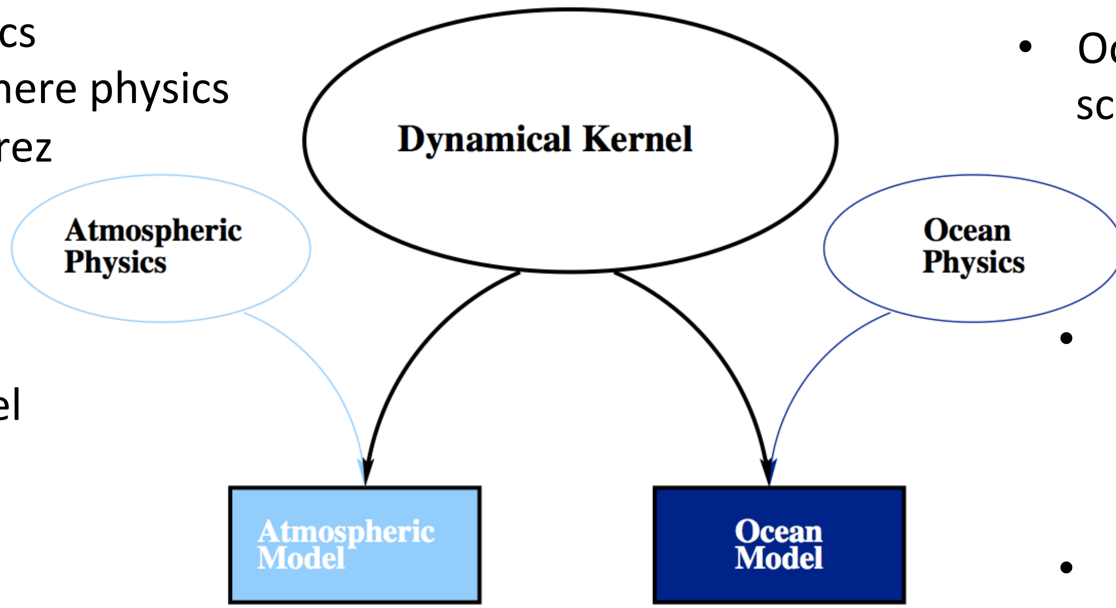
- Advection schemes
- Temporal scheme
- Free surface
- Hydrostatic/non-hydrostatic
- Cartesian/spherical-polar/ curvilinear

- GM/Redi parameterization

+ tapering schemes
+ advective/skew …

- SPEEDY physics
- Grey atmosphere physics
- Held and Suarez

- Ocean mixed layer schemes (5)



- Land model

- Viscosity (harmonic, biharmonic, Smagorinksy, and Leith scheme)
- Shapiro filter

Cryosphere:

- Thermodynamics sea ice models (2)

+ Hibler 79 rheology

- Ice shelf model
- Ice stream (land ice) model

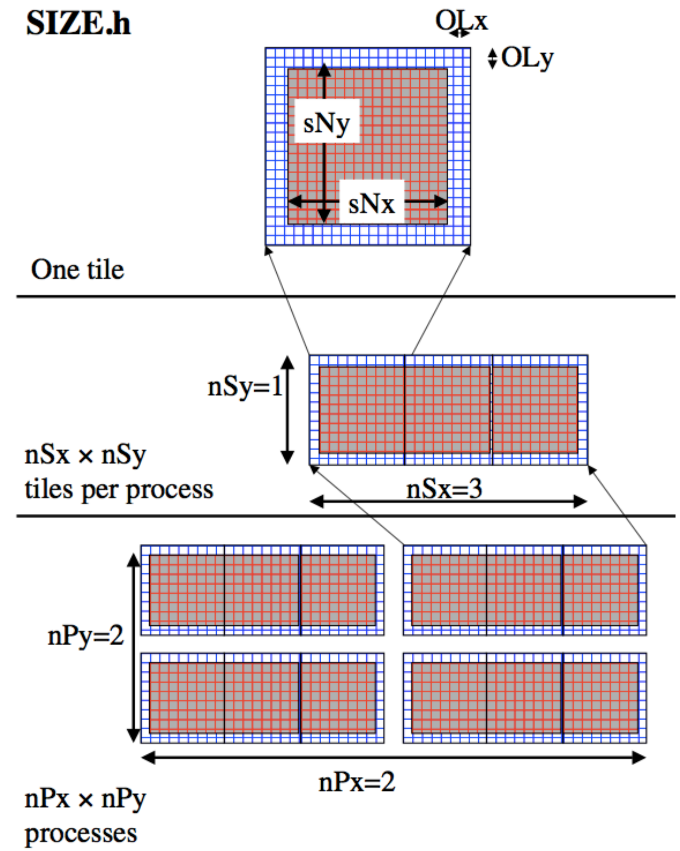
- Biogeochemistry packages:

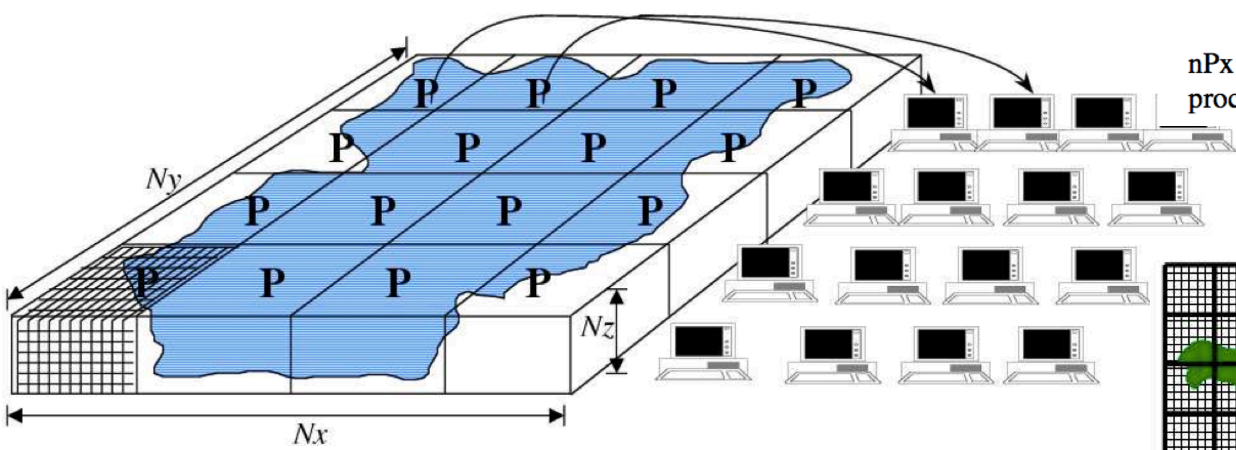
DIC, Bling, Darwin

- Adjoint/Tangent linear model with Automatic differentiation

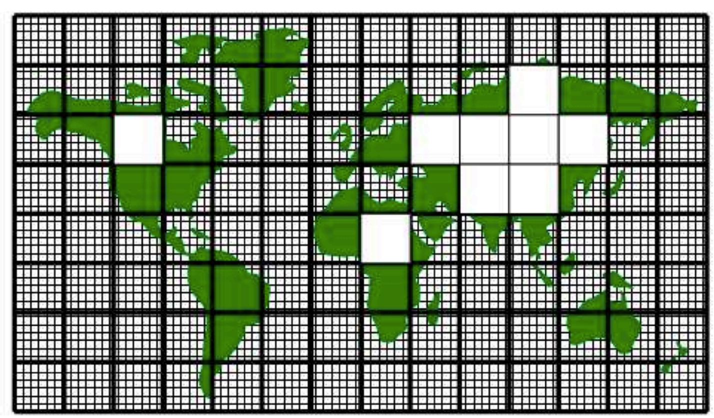
Two dimensional decomposition of the domain
→ MPI, multithreading

→ Runs on a variety of platforms, including many HPC centers



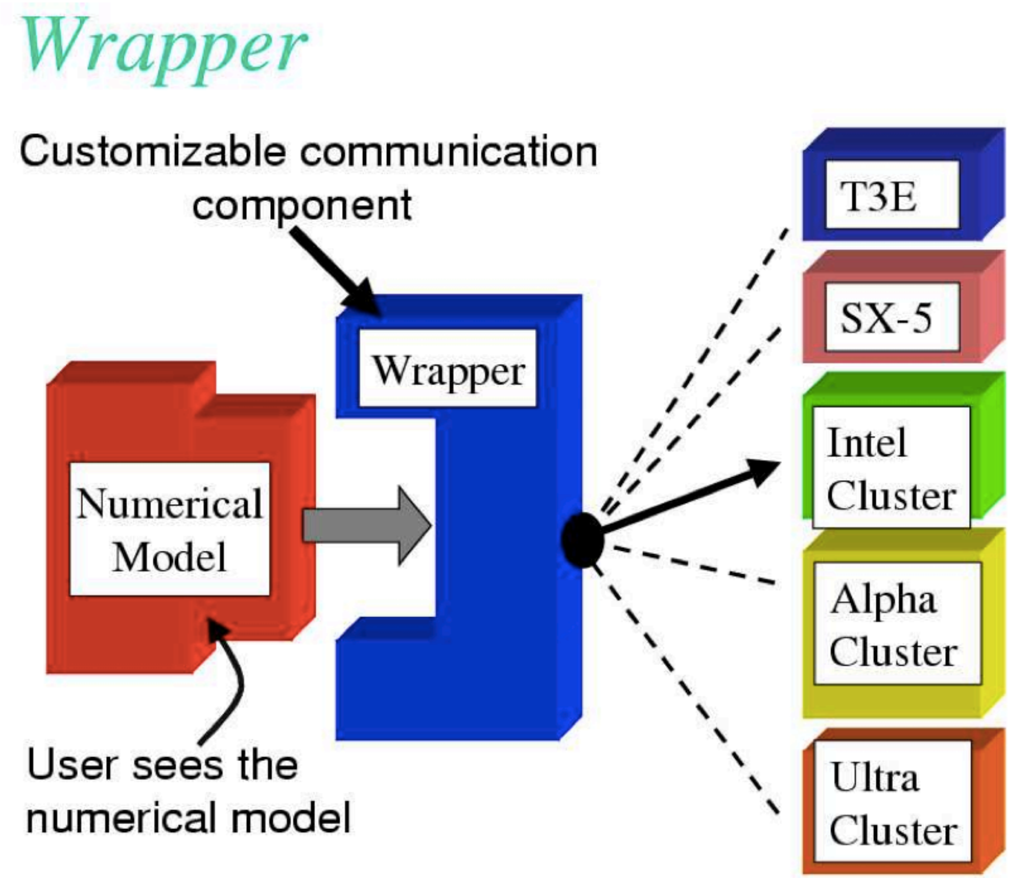


Possibility of blank tiles



The WRAPPER takes care of everything

→ as transparent as possible to the users



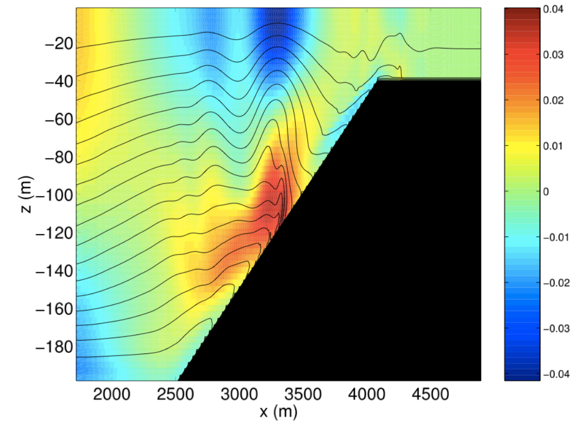
- The machine consists of one or more logical processors.
- Each processor operates on tiles that it owns.
- A processor may own more than one tile.
- Processors may compute concurrently.
- Exchange of information between tiles is handled by the machine (WRAPPER) not by the application.

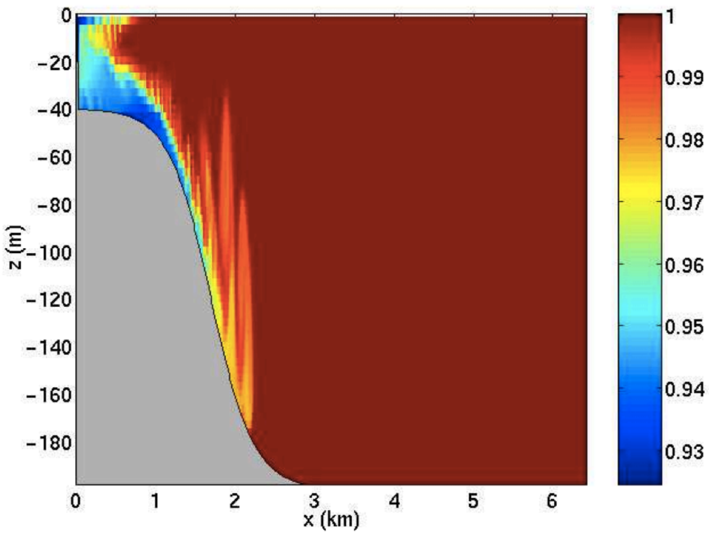
Outputs

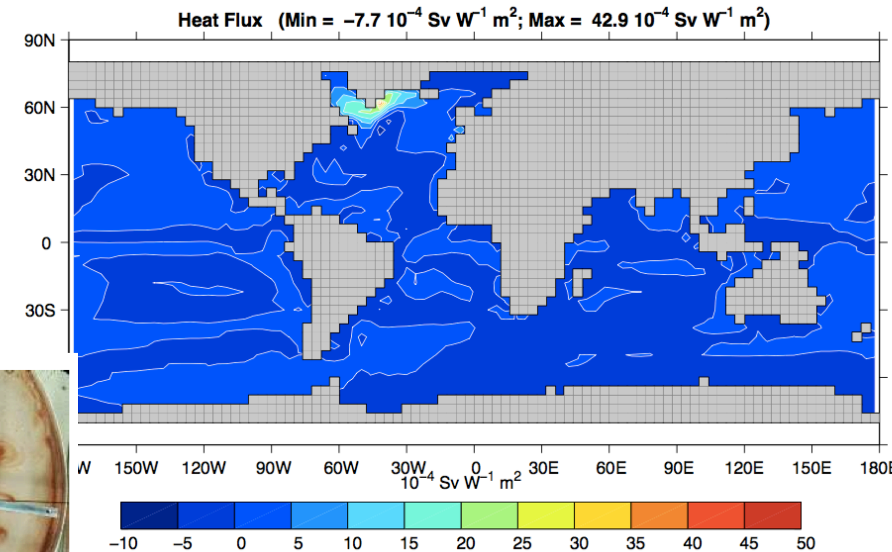
- "Diagnostics" packages offer flexible solutions for outputs
  - → list of variables bundled (or not) is files
  - → output frequency can be set independently for each bundle of outputs
  - → Allows subsampling in the vertical
  - → Snapshots or time-averages
  - → A variable can be outputed multiple time with different choices
  - → easy to implement new outputs
  - → time-series of spatially averages variable
- Output in binary format or netcdf format

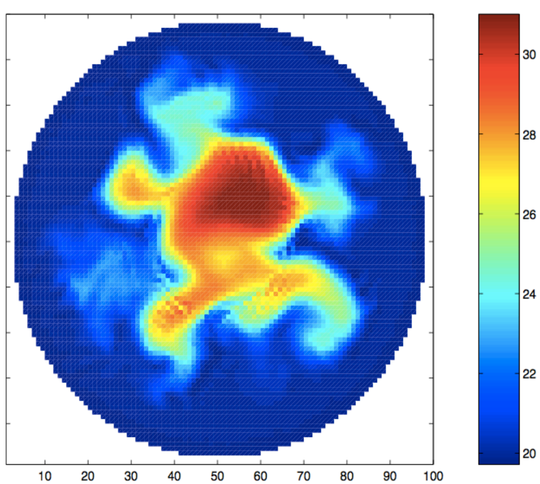
```
&DIAGNOSTICS_LIST
 fields(1:2,1) = 'UVEL    ','VVEL    ',
  levels(1:5,1) = 1.,2.,3.,4.,5.,
  filename(1) = 'diagout1',
 frequency(1) = 86400.,
 fields(1:2,2) = 'THETA   ','SALT    ',
  filename(2) = 'diagout2',
 fileflags(2) = ' P1     ',
 frequency(2) = 3600.,
&

&DIAG_STATIS_PARMS
&
```

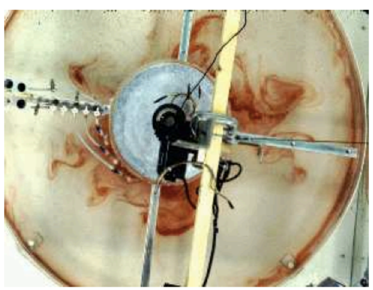
Examples of applications











Adjoint/tangent linear

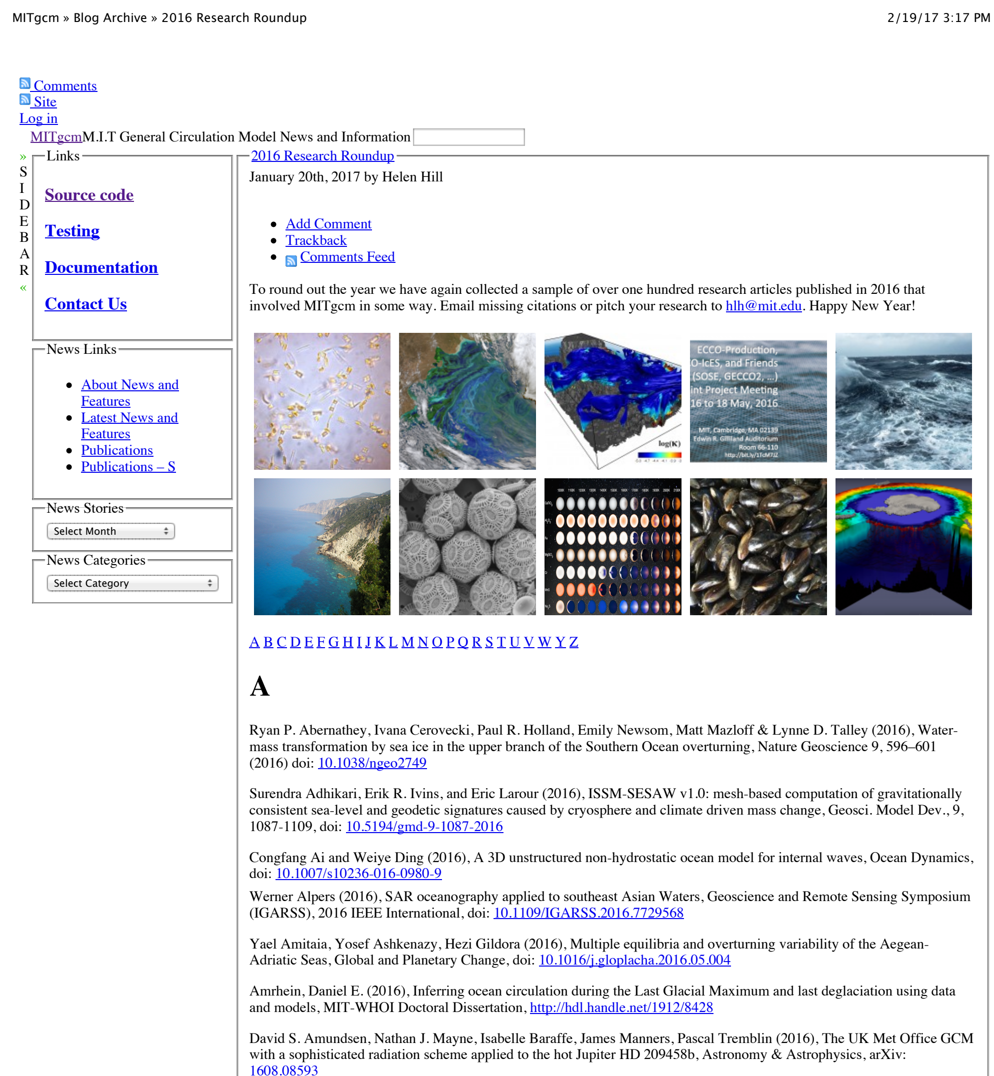
Global ocean circulation model at 1/60 of a degree horizontal resolution

http://maps.actualscience.net/MITgcm_llc_maps/llc_4320/vorticity/

Credit: Ryan abernathey (Columbia), Chris Hill (MIT), Dimitri Menemenlis (JPL)

On the user side

- Code freely available on MITgcm website
- www.mitgcm.org
- Version control with CVS
- About 500 users (MITgcm-support list), probably an underestimate
- Model comes with about 70 pre-set experiments
- As well as numerous optimization file (gfortran, ifort, cray fortran, etc.)
- And examples to use MPI, OpenMP, netcdf libraries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2016 Research Roundup

January 20th, 2017 by Helen Hill

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To round out the year we have again collected a sample of over one hundred research articles published in 2016 that involved MITgcm in some way. Email missing citations or pitch your research to hlh@mit.edu. Happy New Year!

ECCO-Production, O-IcES, and Friends (SOSE, GECCO2, ...) int Project Meeting 16 to 18 May, 2016

A B C D E F G H I J K L M N O P Q R S T U V W Y Z

A

Ryan P. Abernathey, Ivana Cerovecki, Paul R. Holland, Emily Newsom, Matt Mazloff & Lynne D. Talley (2016), Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning, Nature Geoscience 9, 596–601 (2016) doi: 10.1038/ngeo2749

Surendra Adhikari, Erik R. Ivins, and Eric Larour (2016), ISSM-SESAW v1.0: mesh-based computation of gravitationally consistent sea-level and geodetic signatures caused by cryosphere and climate driven mass change, Geosci. Model Dev., 9, 1087-1109, doi: 10.5194/gmd-9-1087-2016

Congfang Ai and Weiye Ding (2016), A 3D unstructured non-hydrostatic ocean model for internal waves, Ocean Dynamics, doi: 10.1007/s10236-016-0980-9

Werner Alpers (2016), SAR oceanography applied to southeast Asian Waters, Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International, doi: 10.1109/IGARSS.2016.7729568

Yael Amitaia, Yosef Ashkenazy, Hezi Gildora (2016), Multiple equilibria and overturning variability of the Aegean-Adriatic Seas, Global and Planetary Change, doi: 10.1016/j.gloplacha.2016.05.004

Amrhein, Daniel E. (2016), Inferring ocean circulation during the Last Glacial Maximum and last deglaciation using data and models, MIT-WHOI Doctoral Dissertation, http://hdl.handle.net/1912/8428

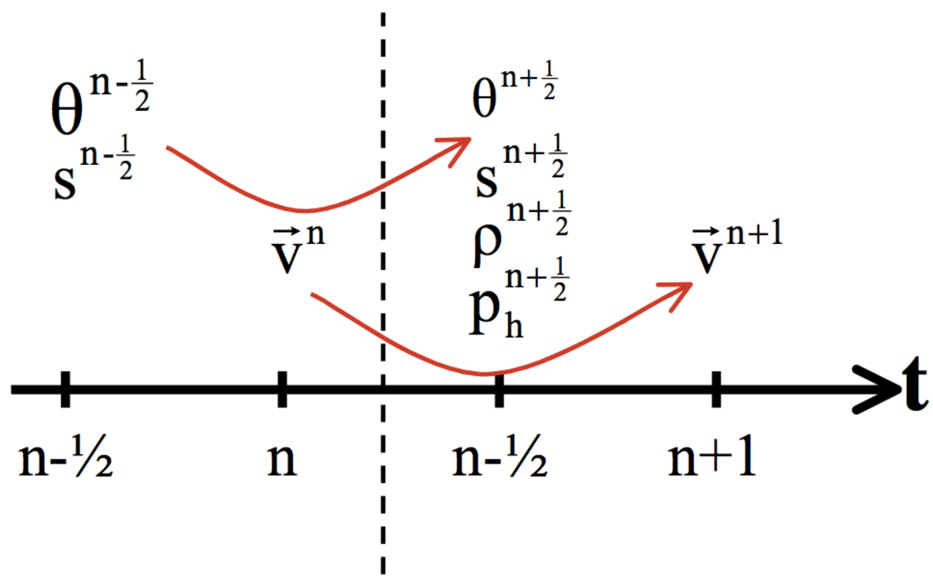
David S. Amundsen, Nathan J. Mayne, Isabelle Baraffe, James Manners, Pascal Tremblin (2016), The UK Met Office GCM with a sophisticated radiation scheme applied to the hot Jupiter HD 209458b, Astronomy & Astrophysics, arXiv: 1608.08593

Development

- About 10 people contribute actively to the development
  → Jean-Michel Campin (MIT), Chris Hill (MIT)
  → Gael Forget (MIT), Patrick Heimbach (Texas),
  → Martin Losch (Bremehaven)
  → Matt Mazlov et al. (Scripps)
  → Dimitri Mennemenlis (JPL)
  → Stephany Dutkiewizc, Oliver Jahn (MIT)
  → Dan Goldberg (Edinburgh)
  + other less active

- Users often contributes to the code development

<u>Funding</u>:
→ NASA and NSF funding (ECCO project, and other science proposals)
→ Very little funded direct development of the model



$\theta^{n-\frac{1}{2}}$
$s^{n-\frac{1}{2}}$
$\vec{v}^n$
$\theta^{n+\frac{1}{2}}$
$s^{n+\frac{1}{2}}$
$\rho^{n+\frac{1}{2}}$
$p_h^{n+\frac{1}{2}}$
$\vec{v}^{n+1}$
t
n-½
n
n-½
n+1

- Modular, comes with numerous example experiments, runs on a number of machines

- Key aspects of the code:
  - Shaved/partial cells
  - Isomorphism between ocean and atmosphere
  - Deep anelastic, 3d full Coriolis
  - Non-hydrostastic/hydrostatic

- General structure WRAPPER, parallelization, MPI, multithreading