Numerics of the new Earth System Model at the CSIR

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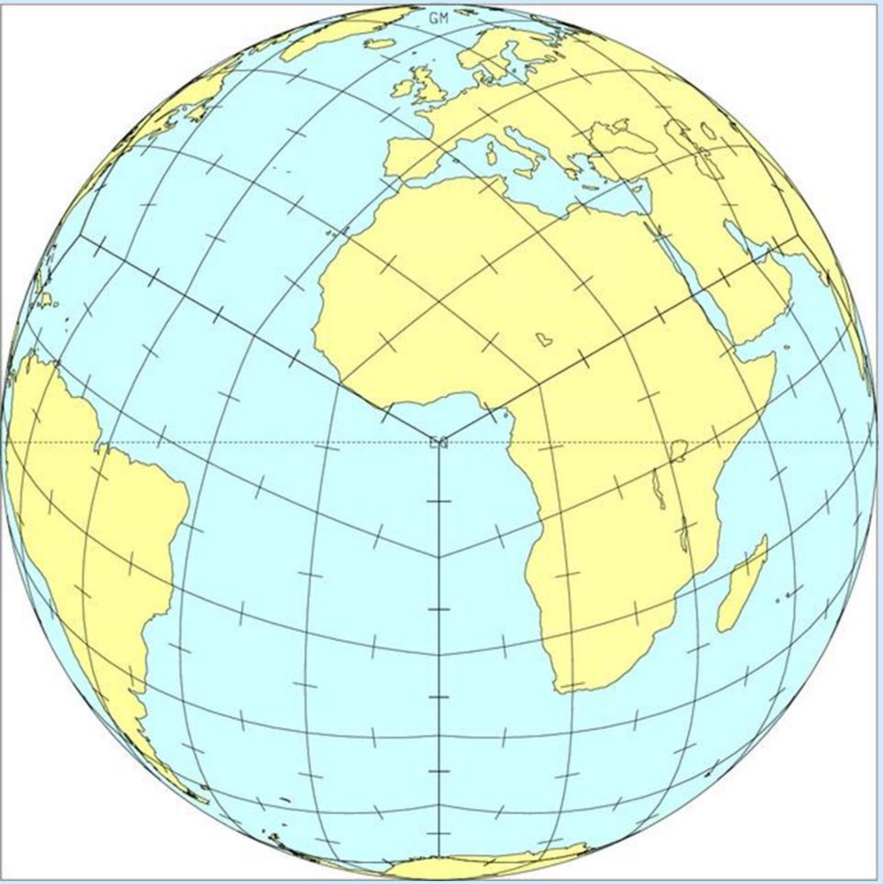
With numerous contributions from John McGregor (CSIRO)

our future through science

Variable-resolution Earth System Model (VrESM)



The Variable-resolution Earth System Model (VrESM): A CSIR-CSIRO collaboration

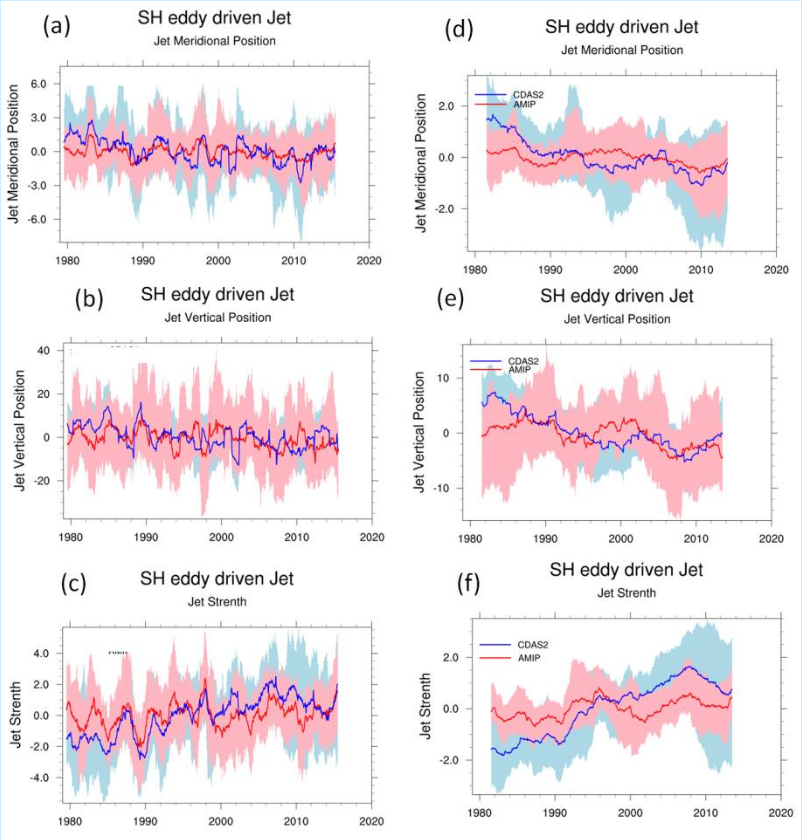
- First African-based ESM, developed through an African lens
- Atmospheric component: Conformal-cubic atmospheric model (CCAM) of CSIRO (Australia)
- Ocean component: Variable-cubic ocean model (VCOM) of CSIR (South Africa)
- Land-component: CSIRO Atmosphere-Biosphere Land Exchange model (CABLE)
- Ocean biochemistry: PISCES (from LOCEAN)
- Cube-based grid: options available for conformal-cubic, equi-angular gnomonic cubic or equal area (UJ); quasi-uniform 50 km res grid in horizontal;
- **New** ocean model VCOM and also CCAM never applied in CMIP before!

VrESM CMIP6 simulations

- Key VrESM areas of focus:

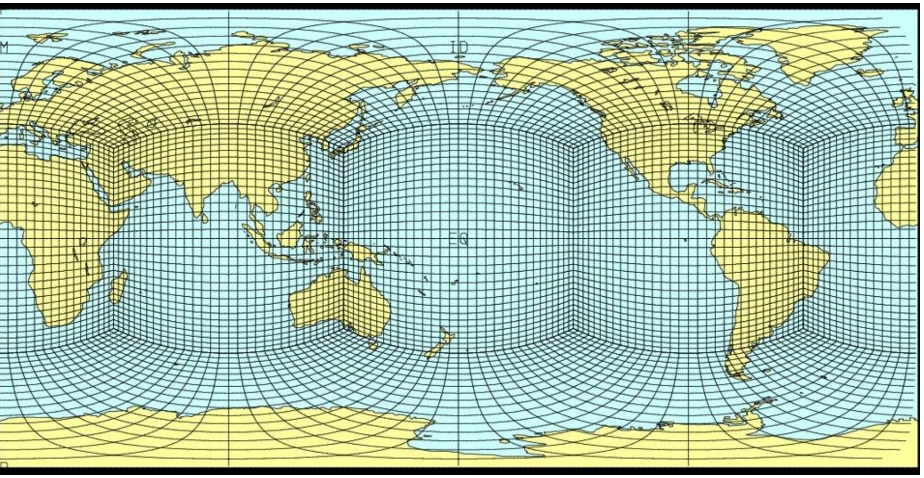
\- numerics on cube-based grids; convective rainfall parameterisation – African focus; southern African biomass burning aerosols and Atlantic Sc cloud deck; parameterisations for plant-functional types in African savannahs; parameteriations for Southern Ocean sub-mesoscale eddies and carbon fluxes

- VrESM DECK and historical runs are to be submitted by May 2018.
- VrESM ScenarioMIP is to be submitted by September 2018.
- VrESM is also to contribute to CMIP, HighresMIP and PMIP in 2019
- VrESM development is led by Francois Engelbrecht (CSIR, South Africa; fengelbrecht@csir.co.za)

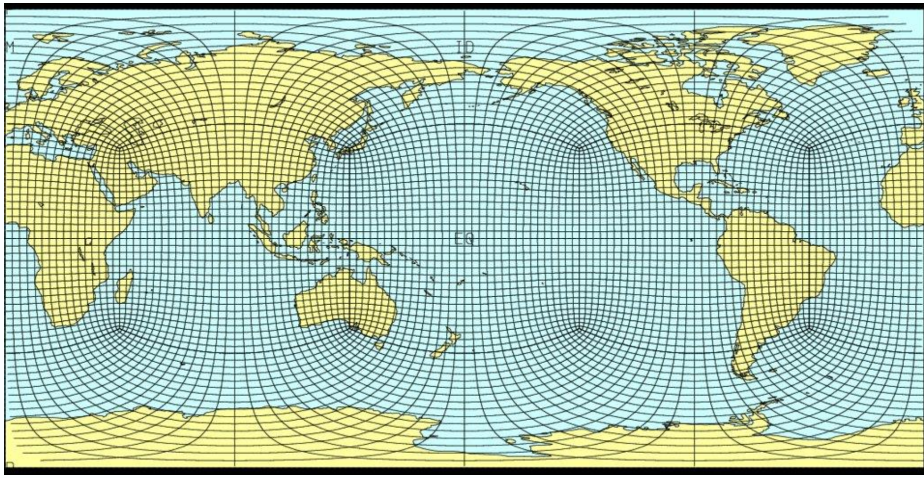


Time evolution of the SH jet stream meridional position (a), vertical position (b) and strength (c) in CMIP6 AMIP simulations (red) and NCEP reanalysis (blue) for 1-yr running mean daily anomalies. The corresponding 5-yr running mean anomalies are shown in (d) to (f)

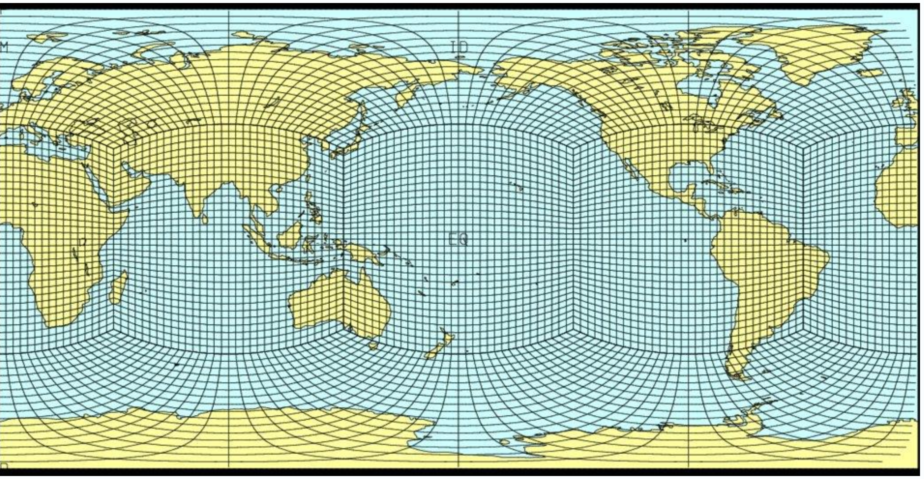
Alternative cubed-sphere grids



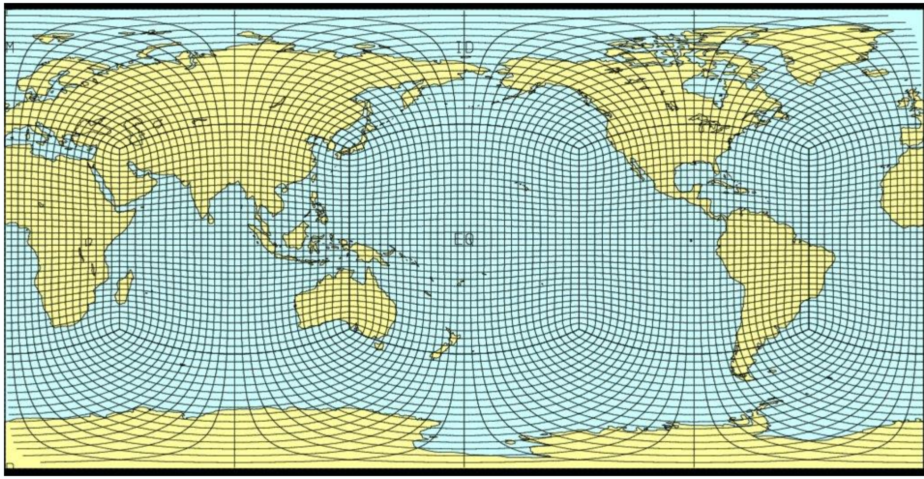
Original Sadourny gnomonic grid



Conformal cubic grid



Equi-angular gnomonic grid

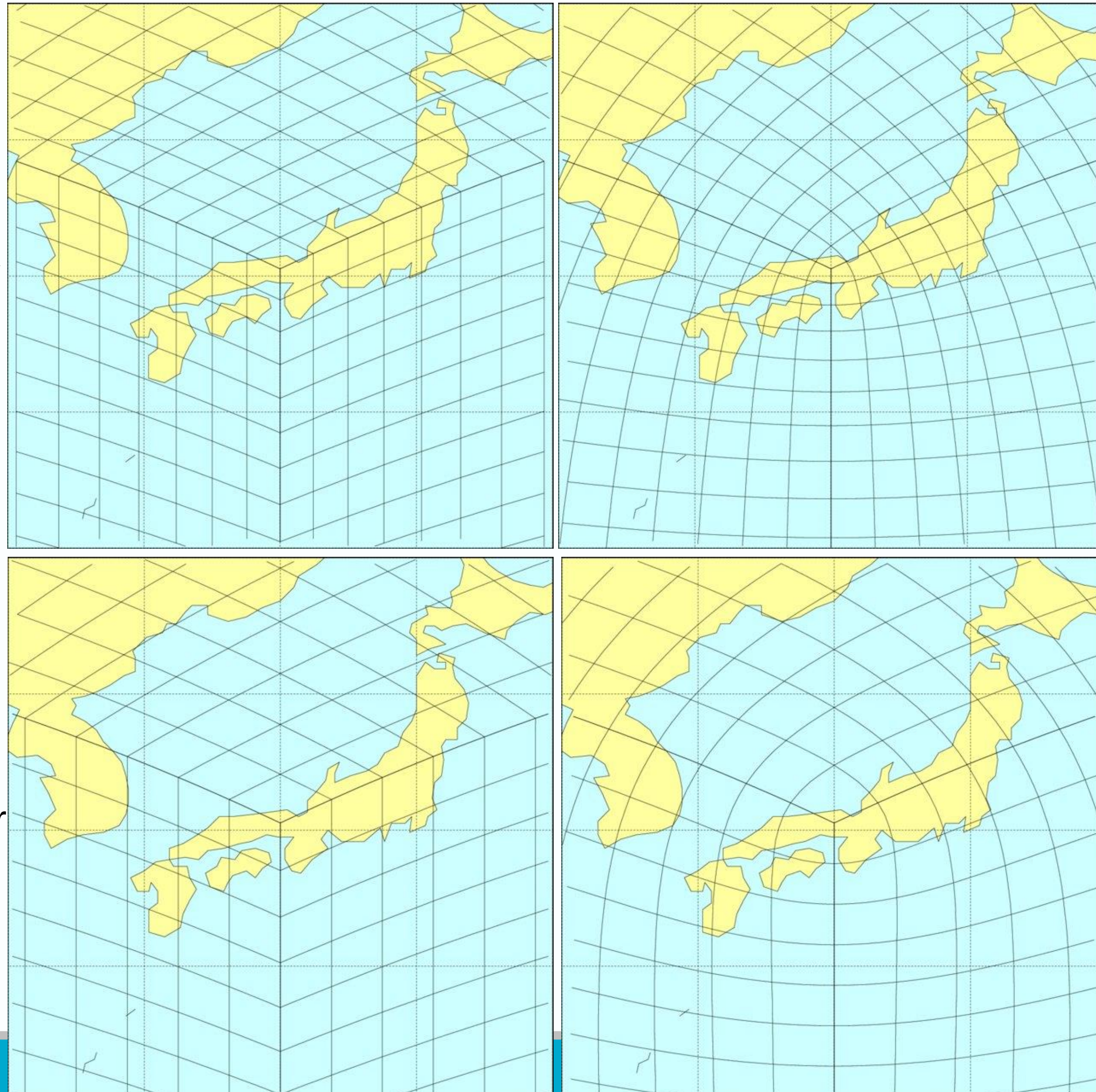


Uniform Jacobian (equal area) grid

All grids shown at C32 resolution

UJ-grid seems to have been independently developed by Jim Purser (NOAA) and Motohiko Tsugawa (JAMSTEC)

Vertex views of C48 grids



Sadourny

Conformal cubic

Equi-angular

Equal-area
Uniform Jacobian
(Purser/Tsugawa)

CCAMe – equal-area dynamical core

- very similar numerics to CCAM, but formulated on the (non-orthogonal) equal-area grid
- employs covariant and contravariant wind components, used for advection, etc.
- provides uniform resolution
- semi-Lagrangian, semi-implicit time-stepping
- reversible staggering transforms the contravariant winds to the staggered positions needed for calculating divergence and gravity-wave terms
- requires a larger stencil for the Helmholtz equation (whilst also using vertical eigenvector decomposition)
    - presently using SOR with many iterations
    - straightforward to solve using multigrid
- can use CCAM special treatments near orography and for nonhydrostatic treatment

VCOM dynamical core

- Formulated on equal-area (uniform Jacobian) grid
- Provides uniform resolution
- Flux form formulation of the Boussinesq equations
- 2D Le Veque (1996) advection
- forward-backward (F-B) split-explicit solver for gravity waves
- reversible staggering transforms the contravariant (and covariant) winds to the staggered positions needed for calculating divergence and gravity-wave terms
- Fox-Kemper parameterisation for mixing induced by sub-mesocale eddies

Variable-cubic Ocean Model (VCOM)

$$\frac{\partial u_\alpha}{\partial t} = (f+\zeta)\,E_{\alpha\beta}u^\beta - K_{;\alpha} - w\frac{\partial u_\alpha}{\partial z} - \frac{1}{\rho_0}p_{;\alpha} + F_\alpha, \quad (1)$$

$$\frac{\partial \theta}{\partial t} = -(\theta u^\alpha)_{;\alpha} - \frac{\partial w\theta}{\partial z} + D_\theta, \quad (2)$$

$$\frac{\partial s}{\partial t} = -(su^\alpha)_{;\alpha} - \frac{\partial ws}{\partial z} + D_s, \quad (3)$$

$$\frac{\partial w}{\partial z} = -u^\alpha_{;\alpha} \quad (4)$$

$$\frac{\partial p}{\partial z} = -g\rho. \quad (5)$$

$$u_i = \overline{V}\cdot\bar{a}_i, \quad (6)$$

$$\overline{V} = u^i\bar{a}_i, \quad (7)$$

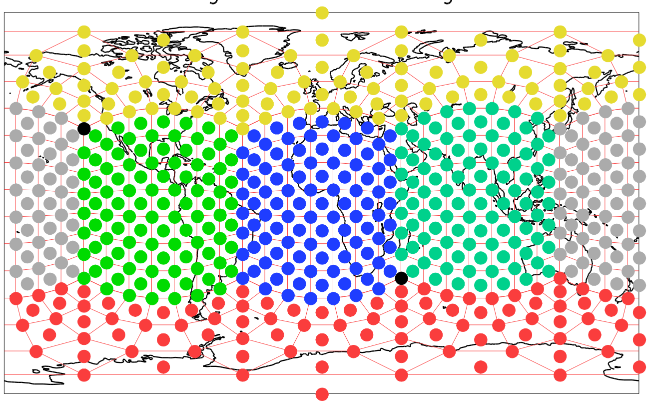
$$u^\beta = g^{\alpha\beta}u_\alpha, \quad (8)$$

$$G = \sqrt{g_{11}g_{22} - g_{12}g_{21}}. \quad (9)$$

$$\overline{a}_1 = \frac{\partial \overline{M}}{\partial x^1} = \frac{R}{r}\left[1 - \frac{(x^1)^2}{r^2}, \frac{x^1R}{r^2}, -\frac{x^1x^2}{r^2}\right]; \quad (17)$$

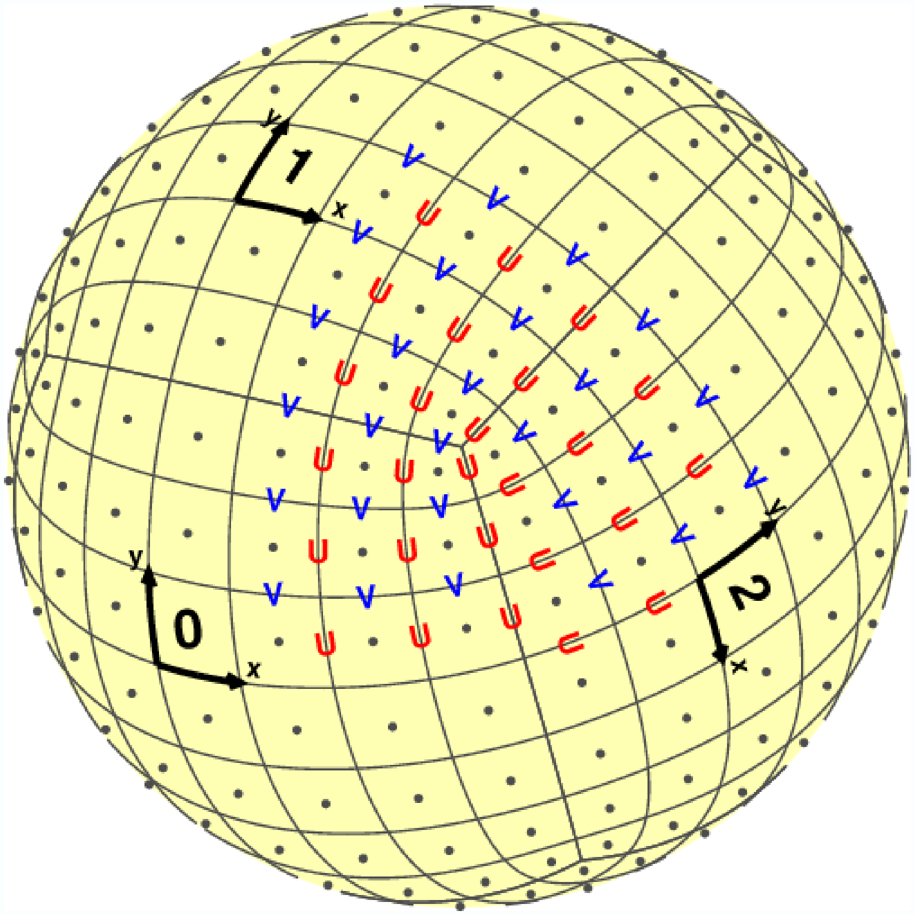
$$\overline{a}_2 = \frac{\partial \overline{M}}{\partial x^2} = \frac{R}{r}\left[-\frac{x^1x^2}{r^2}, \frac{Rx^2}{r^2}, 1 - \frac{(x^2)^2}{r^2}\right]. \quad (18)$$

$$g_{ij} = \frac{\partial \overline{M}}{\partial x^1}\cdot\frac{\partial \overline{M}}{\partial x^2} = \overline{a}_i\cdot\overline{a}_j = \frac{R^2}{r^4}\begin{bmatrix} R^2 + (x^2)^2 & -x^1x^2 \\ -x^1x^2 & R^2 + (x^1)^2 \end{bmatrix}. \quad (19)$$



VCOM follows Tsugawa et al. (2008) but on equi-angular grid

Location of variables in grid cells



All variables are located at the centres of quadrilateral grid cells.

In CCAM, during semi-implicit/gravity-wave calculations, u and v are transformed reversibly to the indicated C-grid locations.

Produces same excellent dispersion properties as spectral method (see McGregor, MWR, 2006), but avoids any problems of Gibbs' phenomena.

2-grid waves preserved. Gives relatively lively winds, and good wind spectra.

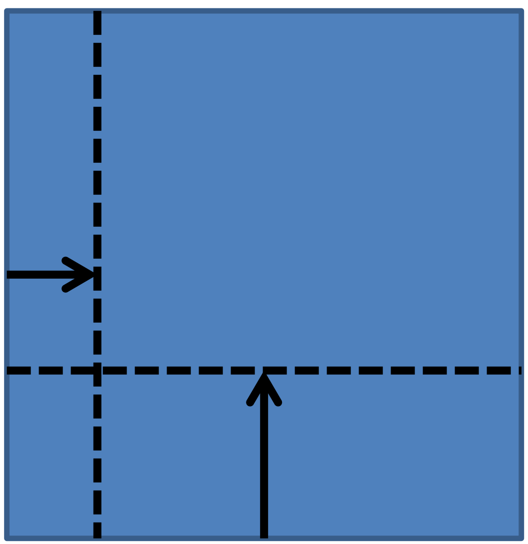
VCOM advection: 2D Le Veque (1996)

Low-order and high-order fluxes combined using MC-limiter
Cartesian components (U,V,W) of horizontal wind are advected

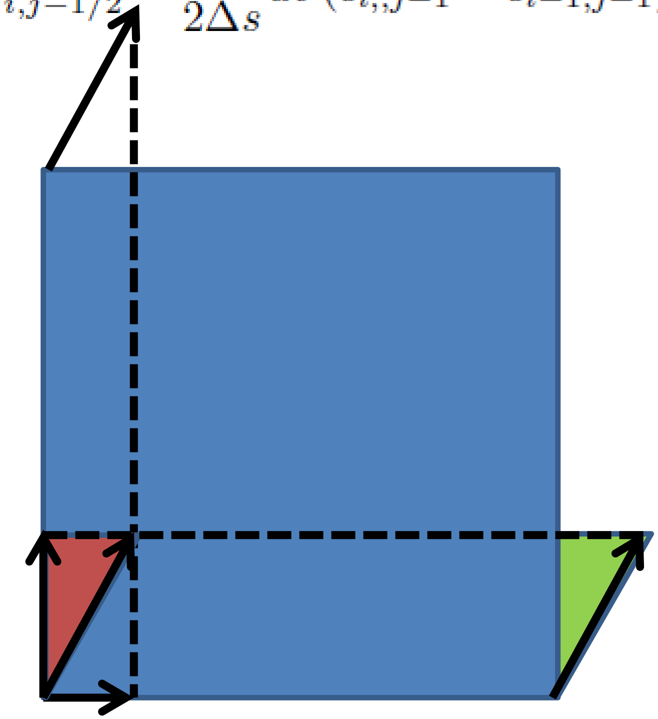
$$c^{t+\Delta t}_{i,j} = c^t_{i,j} = \frac{\Delta t}{\Delta s}\left[F^t_{i+1/2} - F^t_{i-1/2} + G^t_{i,j+1/2} - G^t_{i,,j-1/2}\right]$$

$$G^{ctu}_{i,j-1/2} = G^t_{i,j-1/2} - \frac{\Delta t}{2\Delta s} uv \left(c_{i,,j-1} - c_{i-1,j-1}\right)$$

$$G^t_{i,j-1/2} = vc_{i,,j-1}$$

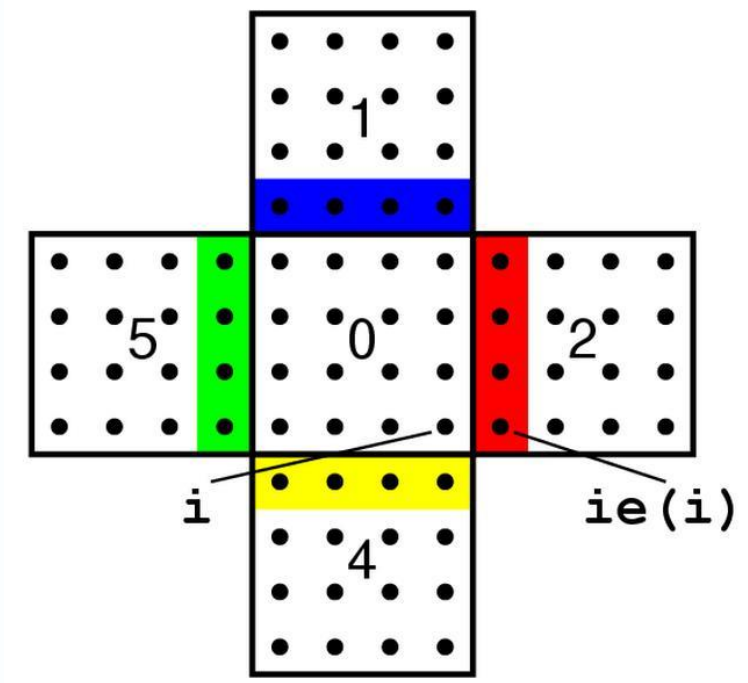


Standard upwind methods transmit fluxes parallel to coordinate axis

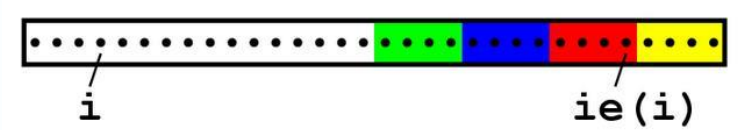


Transmission of fluxes in reality takes place parallel to the velocity vector

Message Passing (MPI) implementation



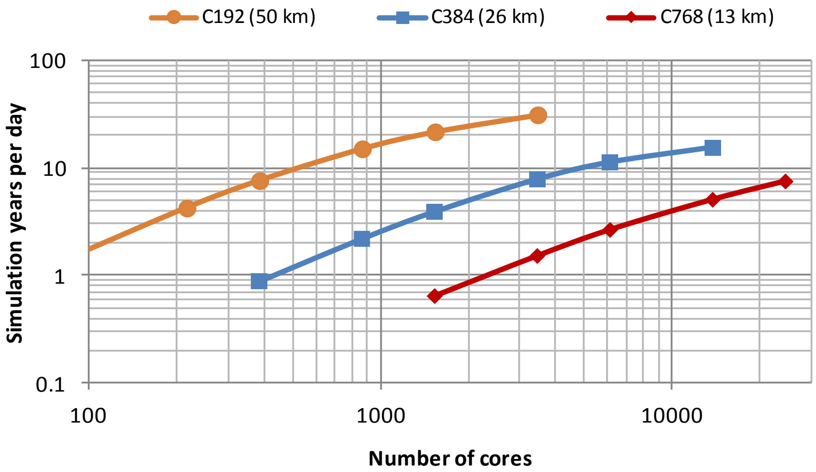
Original



Remapped region 0

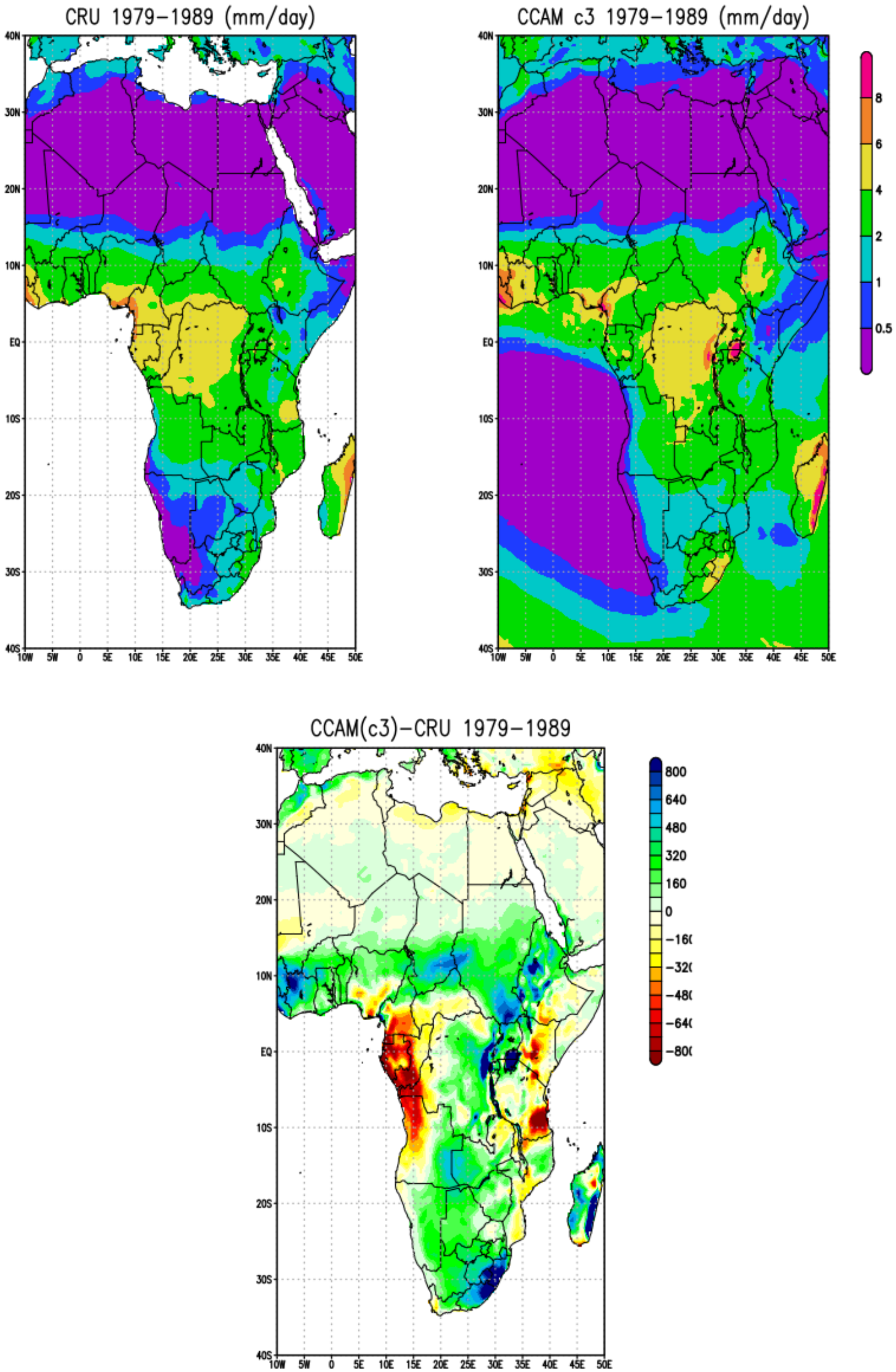
Remapping of off-processor neighbour indices to buffer region
Indirect addressing is used extensively in CCAM
- simplifies coding

HPC and code-scalability

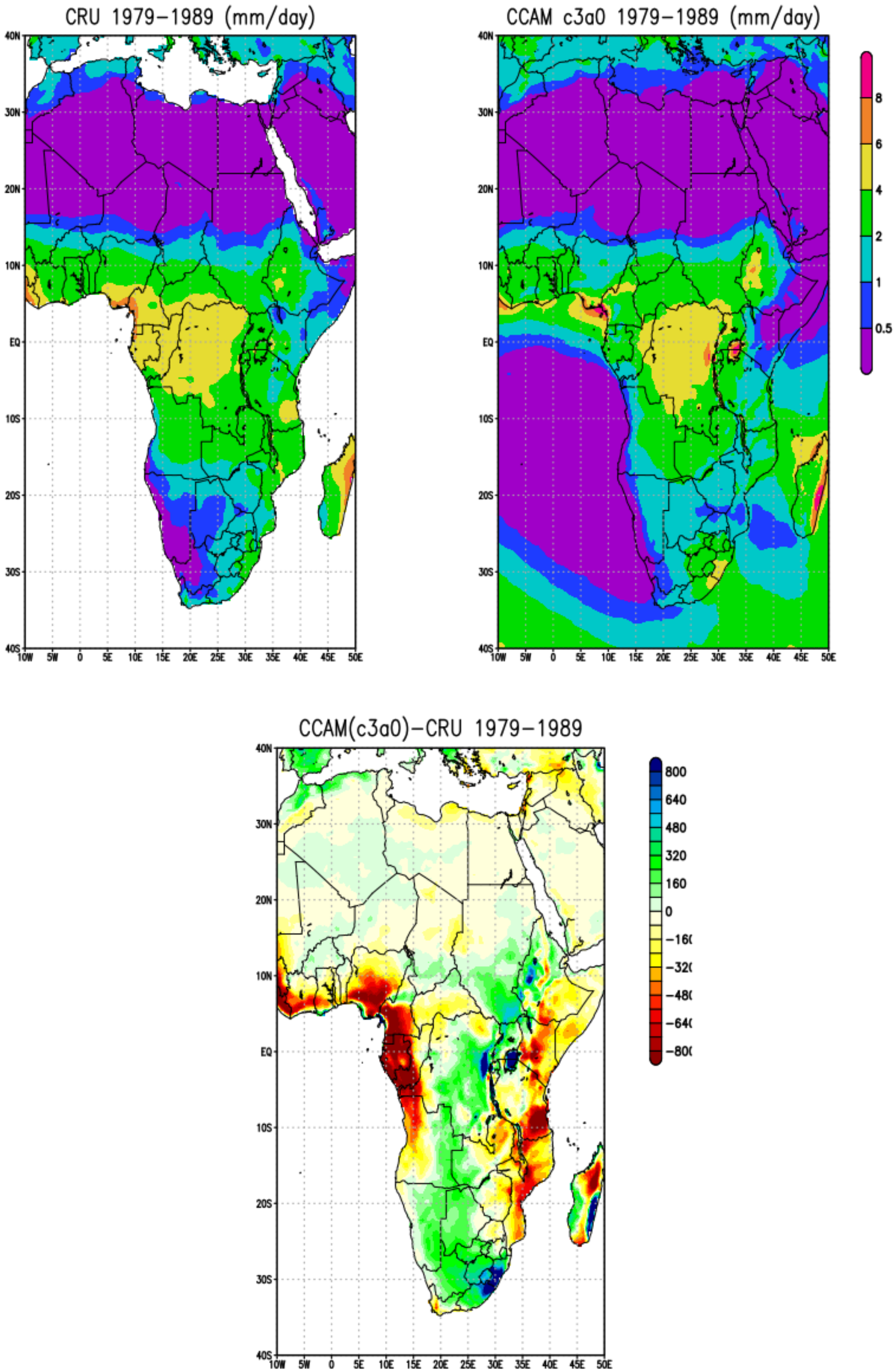


CCAM-TOM (CSIRO) scaling with 35 atmosphere levels and 30 ocean levels, suggesting excellent simulation speed for computing resources

- Computer clusters available to the project include the CHPC in South Africa (30 000 + CPUs – VRESM allocation is currently ~ 3 000 000 core hours per quarter);
- The VRESM design has achieved some comparable resolution and computing times with less than 10% of the cores required by some more traditional coupling approaches.
- CSIR NRE data servers and CHPC VRESM allocated space currently amounts to 1500 TB



Present-day observed (left) and simulated (right) annual rainfall totals over Africa; corresponding model bias (mm; bottom)



Present-day observed (left) and simulated (right) annual rainfall totals over Africa; corresponding model bias (mm; bottom) – prognostic aerosol scheme switched off