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Development of a regional Earth system model using a variable resolution global grid

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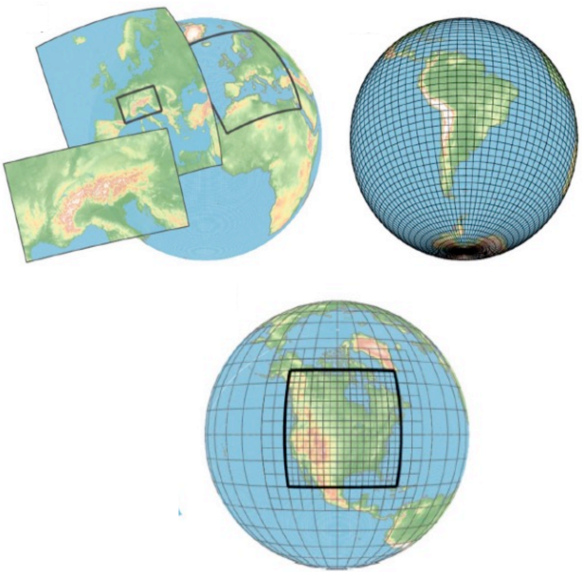
Stretched grid for regional climate modelling

- There are a range of methods for developing dynamical downscaling models, including:
  - Limited area Regional Climate Models (RCMs)
  - High-resolution Atmospheric General Circulation Models (AGCMs)
  - Stretched grid models (SGMs)

- Many submissions to CORDEX are based on limited area RCMs, but it is also possible to use a stretched grid approach that has different advantages and disadvantages.

- This talk describes the Conformal Cubic Atmospheric Model (CCAM), which is a stretched grid model with some regional earth system components that is contributing to a few CORDEX domains.

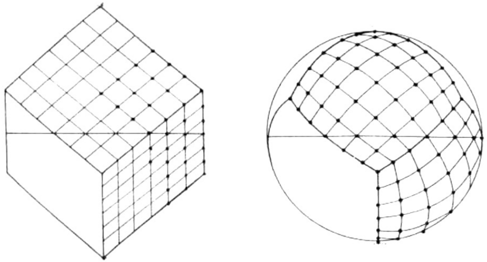


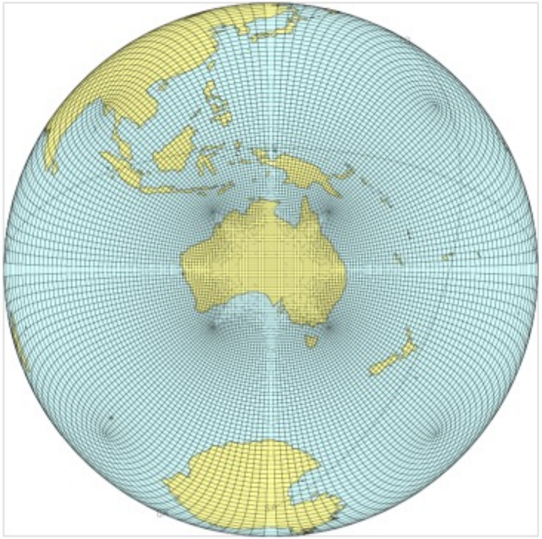
Summary of different dynamical downscaling techniques for regional climate change projections adapted from Prein et al 2015.

Introducing CCAM

- The Conformal Cubic Atmospheric Model (CCAM) is a semi-implicit, semi-Lagrangian atmospheric model based on a cubic grid. The model was original developed by John McGregor (2005a).
- The model development is lead from Australia, but with collaborators in South Africa, New Zealand, South America and Southeast Asia.
- CCAM is primarily developed for regional climate research. To this end CCAM includes some Earth system components including:
  - an in-line ocean,
  - prognostic aerosols and
  - terrestrial carbon cycle.
- CCAM is open-source model

https://confluence.csiro.au/display/CCAM/Getting+started

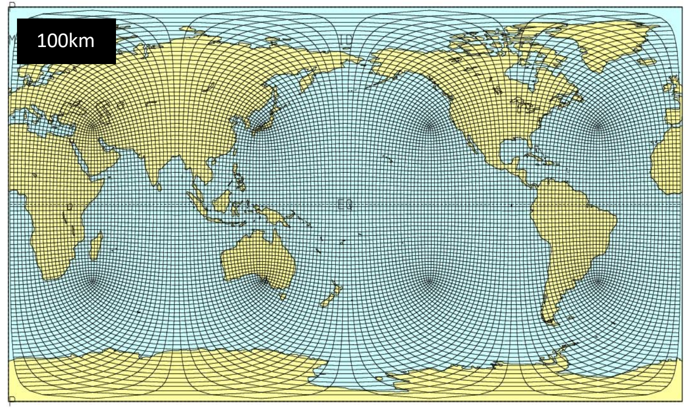


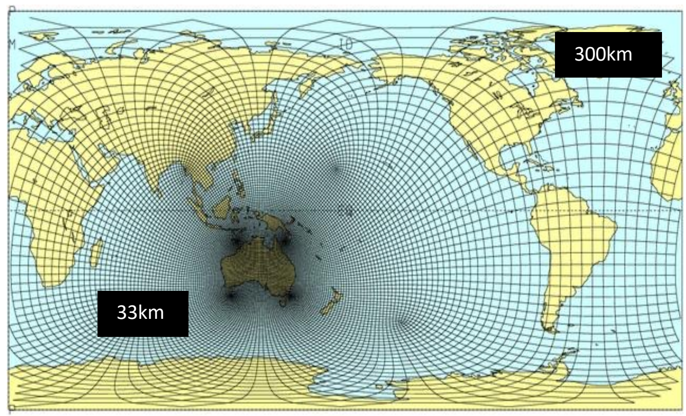


Example of the CCAM stretched grid with a high-resolution region centred over Australia.

Schmidt transform

- CCAM employs a conformal cubic grid*, and can focus its grid over a region using a Schmidt transform (Schmidt 1977).
- This coordinate transformation approach can make it easier to avoid some numerical issues (e.g., avoid reflections), but also has a loss of resolution to counterbalance the high-resolution region.
- This design also makes it easier to implement other features such as a reversibly staggered grid (McGregor 2005b) and spectral nudging (see later).
- CCAM was part of the early generation of stretched grid models (Fox-Rabinovitz et al 2008).





Alternative projection of the CCAM grid showing the redistribution of grid points after the Schmidt coordinate transformation is applied.

* - This grid is in the process of being updated with a gnomic grid.

Spectral nudging for stretched grid

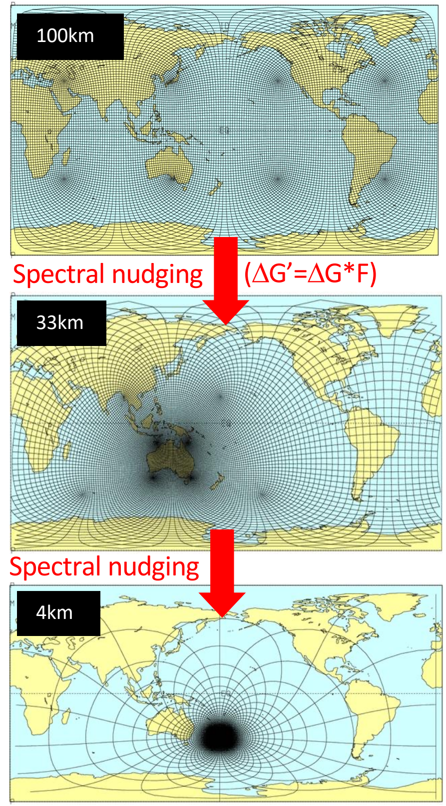
- Since CCAM does not have lateral boundaries, then we cannot use them to constrain the simulation to follow a particular host GCM.

- Instead CCAM can be run in an SST-only forcing mode (e.g., similar to AMIP, Hoffman et al 2016) or it can be run with spectral nudging (Thatcher and McGregor 2009).

- We have adopted a convolution approach to spectral nudging (optimised for the cubic grid). Typically, we perturb large wavelengths (> 3,000km) and can be wider than the high-resolution region.

- CCAM is selective as to which variables are nudged and at what levels. For example, CCAM does not nudge water vapour, and only nudges air temperature and winds above 850hPa.

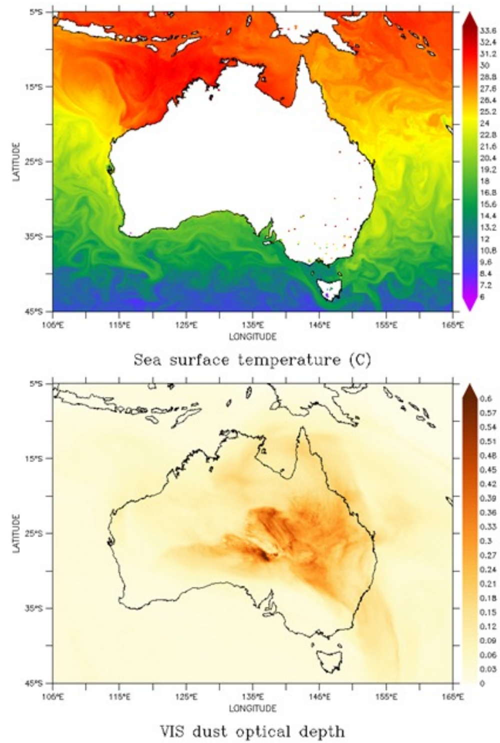
- Multiple nesting is possible with this approach with greater than 1:4 steps in resolution, although the host GCM must resolve the required wavelengths and frequency of nudging is important for highly stretched grids.



Example of multiple nesting with CCAM using spectral nudging

Towards Regional Earth System Modelling

- CCAM includes some Earth system model components that have been implemented with the stretched grid*:
  - An in-line Boussinesq ocean model with z-* coordinate (Thatcher et al 2015).
  - Prognostic aerosols including direct and indirect feedbacks (sulphur cycle, carbonaceous, dust and sea-salt) (Horowitz et al 2017).
  - Terrestrial carbon cycle (with feedbacks into the biosphere) (Wang et al 2015).
- Prognostic aerosols has been implemented with an emissions forced model and no lateral boundaries. Spectral nudging can optionally be used for background aerosol concentrations.
- Earth system components can then be implemented without necessarily requiring additional data from GCMs.



Example output from CCAM ocean and aerosol models showing SSTs and 550nm aerosol optical depth for dust.

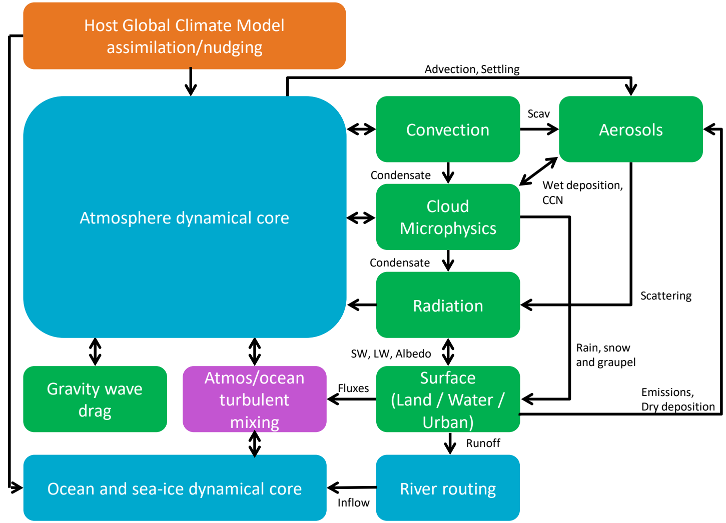
* - A regional atmospheric chemistry component is also being developed based on the CSIRO Chemical Transport Model (CTM).

CCAM's in-line ocean model design

- Atmosphere-ocean coupling is based on combining the turbulent mixing into a single implicit parameterisation (i.e., a k-ε closure in this case). This approach allows coupling every time-step and helps to implicitly conserve momentum fluxes.

- However, this approach requires the atmosphere and ocean grids to be aligned to a common grid, which is more appropriate for a regional climate model (Thatcher et al 2015)*. No explicit coupler is involved.

- Simulation speed is still satisfactory (e.g., 8 sim years per day at 12.5km) despite an inhomogeneous distribution of ocean points across computing nodes.

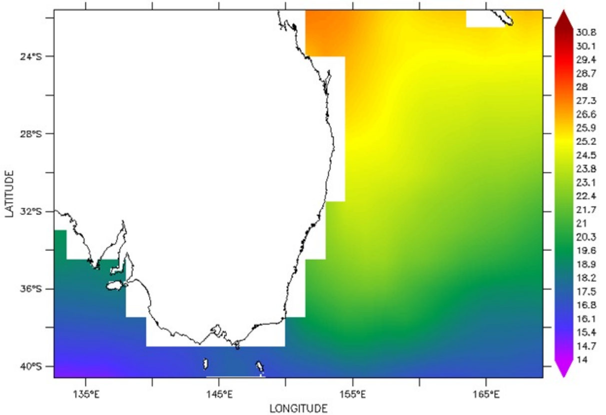


Schematic of CCAM model components with the implicit atm-ocn turbulent mixing shown in purple.

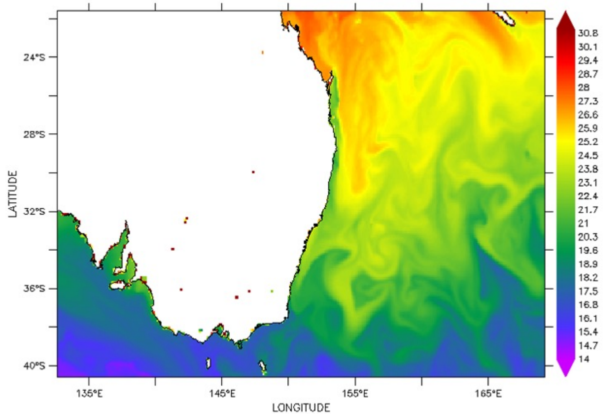
* - There are examples of this approach with global atmosphere models, but it is less common with regional modelling.

Spectral nudging for the ocean

- The ocean model is constrained to agree with the host GCM by using spectral nudging, modified to account for irregular coastlines.
- The ocean currents, potential temperature, salinity and surface height can be constrained with GCM data (e.g., below the mixed layer depth).
- Alternatively, we can also partially constrain the ocean temperature over the mixed layer based on differences in the SSTs with the host GCM at large wavelengths (> 1,000 km).
- This second option can be useful when there is some ambiguity about the source of ocean data (e.g., atmosphere only reanalyses).



ERAI Sea surface temperature (C)



CCAM Sea surface temperature (C)

Scale-aware physical parametrisations

- A requirement with the stretched grid approach is that some form of (pragmatic) scale-aware physical parameterisations are required (i.e., O(1km) – O(100km), including the grey zone).

- In the case of CCAM, scale-aware parameterisations are used for*:
  - Convection with an effective time-scale that depends on grid spacing.
  - Cloud microphysics where the variance of moisture in the grid-box depends on grid spacing.
  - Boundary layer turbulent mixing where the counter gradient is weakened as the grid resolution decreases below the boundary layer height (Boutle et al 2014).

- This is still an active research area for CCAM, but current results appear to operate without the introduction of significant biases or degradation in performance.

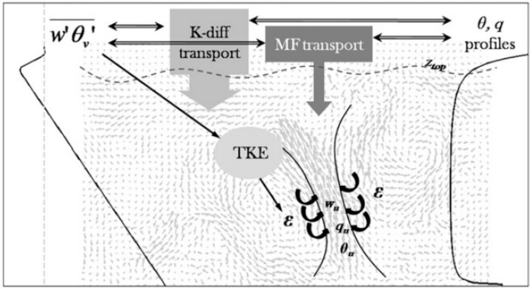


Figure from Witek et al 2010 showing LES simulation of turbulent boundary layer eddies. The scale-aware parameterisation weakens the large eddies which have sizes comparable to the boundary layer height.

$$\overline{u'w'} = -K\frac{\partial u}{\partial z},$$

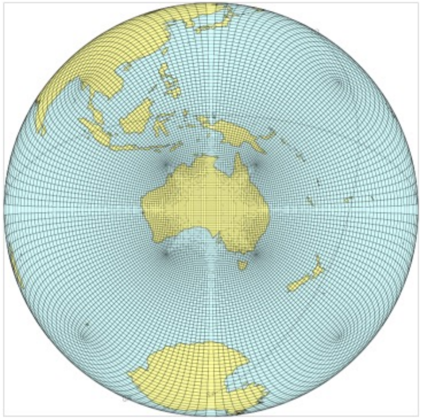
$$\overline{v'w'} = -K\frac{\partial v}{\partial z},$$

$$\overline{w'\theta_v'} = -K\left(\frac{\partial \theta_v}{\partial z} - \boxed{\gamma\theta_v}\right)$$

* - Ideally gravity wave drag could also be scale-aware.

Conclusions

- This talk describes the Conformal Cubic Atmosphere model used for climate downscaling with a stretched cubic grid.
- The absence of lateral boundaries can be replaced with a wavelength constraint using spectral nudging.
- We have implemented some Earth system components on the variable resolution grid.
  - Emissions based prognostic aerosol model (without requiring lateral boundaries).
  - In-line ocean model where the model can be constrained by SST differences and the ocean is implicitly coupled to the atmosphere with turbulent mixing.
- But a challenge for the stretched grid approach is the need to improve scale-aware physical parameterisations.



Thank you

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