Challenges with high-resolution regional earth system modelling on a stretched grid

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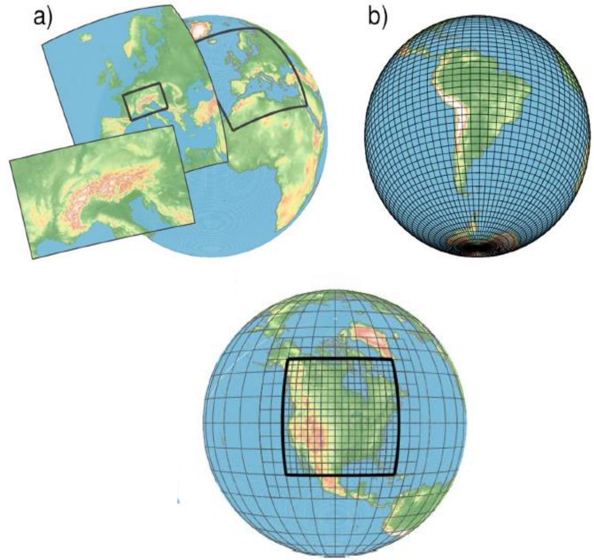
Regional climate modelling

- Different approaches have been traditionally used to simulate the climate at regional scales. The most well-known include:
  - Limited area model as a regional climate model (RCM)
  - High-resolution global atmospheric model (AGCM)

- An alternative approach is the variable resolution climate model (VR-GCM), where the resolution can be focused over a region of interest.

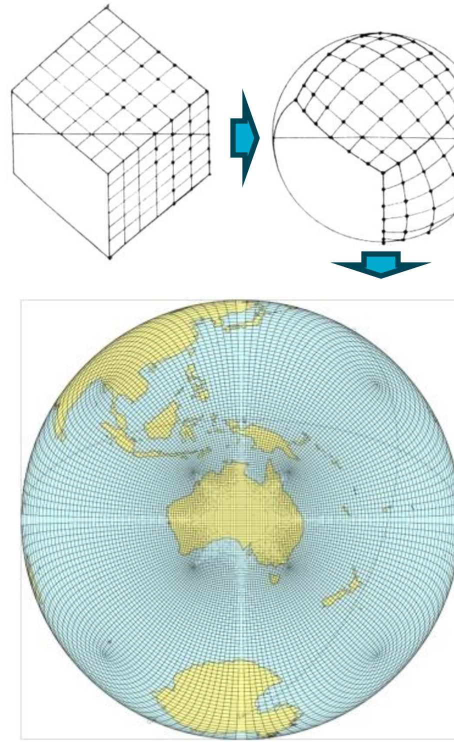
- This talk describes the CSIRO's VR-GCM called the Conformal Cubic Atmospheric Model (CCAM) and the experiment design used for simulating the regional climate for CORDEX Australasia.



Summary of different dynamical downscaling techniques for regional climate change projections adapted from Prein et al 2015. Limited area RCM (top left), high-resolution AGCM (top right) and variable resolution VR-GCM (bottom).

The Conformal Cubic Atmospheric Model

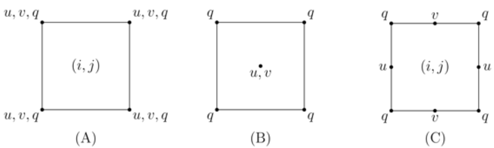
- CCAM is a non-hydrostatic, semi-implicit, semi-Lagrangian model based on a cubic grid (McGregor 2005)
- The cubic grid can be focused over a region using a Schmidt coordinate transform (Schmidt 1977), instead of using an unstructured grid.
- CCAM was part of the first generation of stretched grid models (Fox-Rabinovitz et al 2008), as well as being the first regional model based on a cubic grid.
- The model supports both mixed & double precision configurations, as well partial GPU support.



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

Reversibly staggered grid

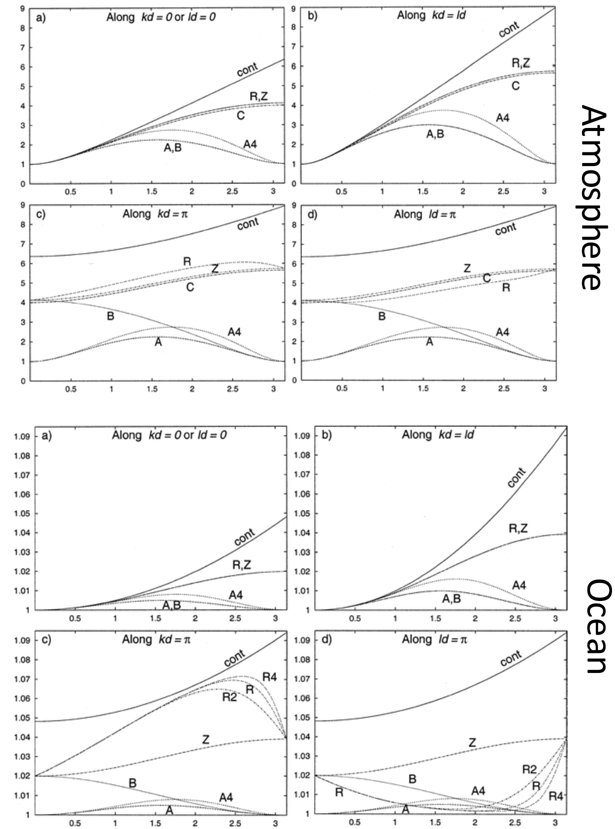
- The model also supports a reversibly staggered grid that pivots between the Arakawa A and C grids to improve the dispersive properties of the model.



- The reversible staggering is based on a generalized Vandermonde method.

- The reversibly staggered R grid generally performs similarly to the Arakawa C grid in the atmosphere case.

- The method can also improve the dispersive properties in the ocean case, although care needs to be taken when approaching coastlines.



Dispersive behaviour in the atmosphere case (λ/d=2, top) and the ocean case (λ/d=0.1, bottom) for various Arakawa grids as well as the reversibly staggered grid R. Reproduced from McGregor 2005b.

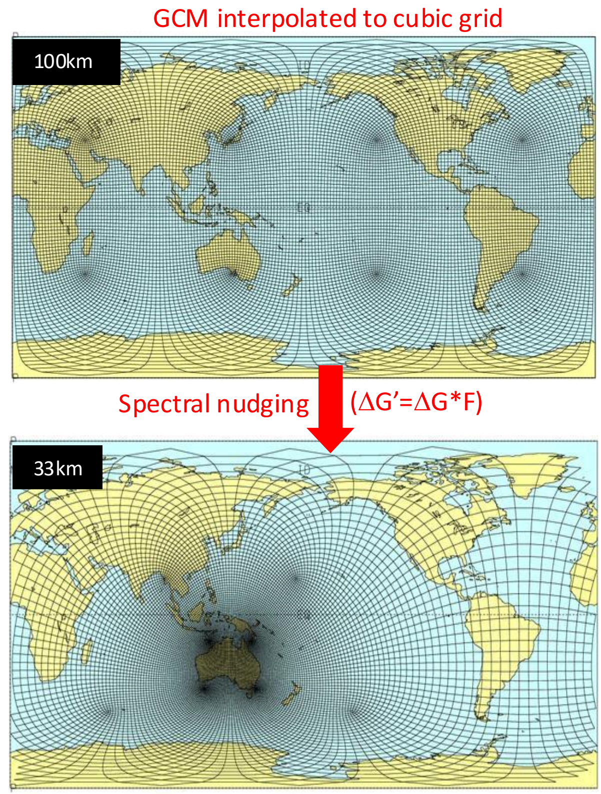
Spectral nudging

- Since CCAM does not have lateral boundaries, then use spectral nudging when downscaling and ensemble of CMIP GCMs. This constrains the behaviour of the regional simulation at large wavelengths to agree with the host GCM.

- We use a Gaussian filter with a relatively large length-scale of 3,000km to nudge winds and air temperature above 850hPa, as well as surface pressure (Thatcher and McGregor 2009). A convolution approach was found to work well with the variable resolution cubic grid.

- Relatively large jumps in resolution are possible (i.e., no lateral boundaries), but limited by the wavelengths resolved by the host GCM.

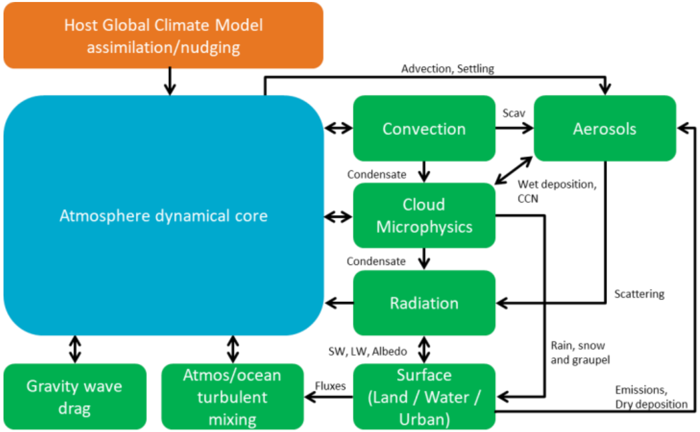
- The specific humidity is not nudged, allowing for a more consistent behaviour for clouds and condensate.



Example of nesting with CCAM using spectral nudging based on a convolution.

Variable resolution physical parameterisations

- CCAM's physical parameterisations include:
  - New double moment cloud microphysics (Zhao et al 2021)
  - Convection (McGregor 2003 or Grell-Freitas 2020)
  - CABLE land-surface model (Kowalczyk et al 2013)
  - GFDL radiation (Freidenreich and Ramaswamy 1999, Schwarzkopf and Ramaswamy 1999)
  - k-ε turbulence closure for boundary layer mixing (Hurley 2007)



Schematic of interactions between CCAM atmospheric parametrisations.

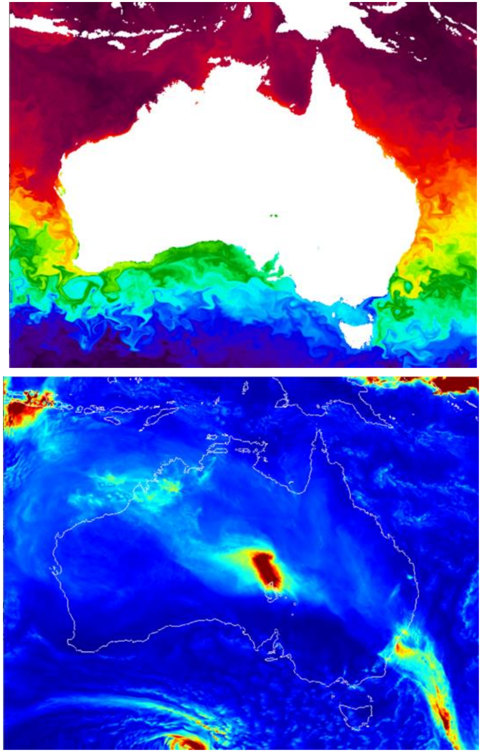
- However, since CCAM employs a variable resolution grid, then there is also a need for some parameterisations to be scale aware. Similar to Boutle et al 2014, these include:
  - Convection with an effective time-scale.
  - Cloud microphysics particularly for cloud fraction.
  - Boundary layer turbulent mixing with a scale-aware counter gradient term.

- The current parameterisations appear robust over typical resolutions simulated by an RCM. Nevertheless, scale-aware parameterisations remain an active area of research.

Regional Earth System Modelling

- Some RCMs are progressively incorporating regional earth system components, although a standard experimental protocol for CORDEX simulations does not yet exist.

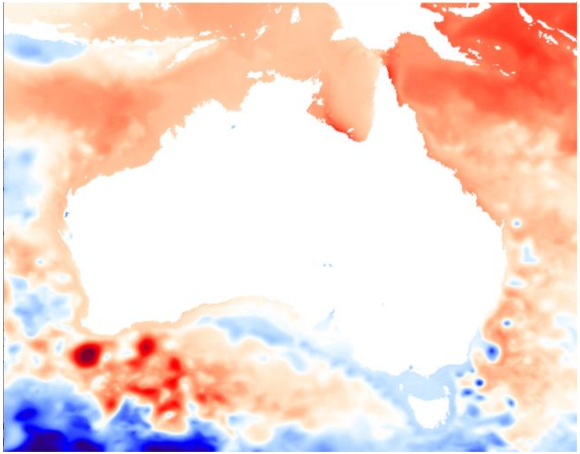
- In the case of CCAM, we have focused on:
  - Prognostic aerosols (single moment), with direct and indirect feedbacks to radiation and cloud microphysics (Horowitz et al 2017).
  - Coupled in-line ocean model, replacing prescribed SSTs and large lakes (Thatcher et al 2015).
  - River routing to support the freshwater inflows for the ocean model.
  - Terrestrial carbon cycle with CASA-CNP (e.g., changes in LAI) (Wang et al 2015).



Example output from CCAM ocean SSTs (top) and total aerosol 550nm optical depth (bottom).

Regional atmosphere-ocean coupling

- Rather than use a traditional coupling approach, we have instead explored the use of a CCAM in-line, hydrostatic, Boussinesq ocean model (Thatcher et al 2015).
- This approach allows for closer integration of the atmosphere and ocean turbulent mixing, enabling coupling every time-step. But also locks the atmosphere and ocean into a common grid that limits flexibility (e.g., along coastlines).
- Atmosphere-ocean-ice coupling is then achieved using a Sherman-Morrison formula that decomposes the turbulent mixing into two implicit tridiagonal matrix problems.
- The CCAM reversibly staggered grid also helps with the dispersive properties of the ocean model, although special treatment is required near coastlines.



Plot of SSH from the 4km ocean simulation, depicting ocean eddies forming off the Australian coastline.

$$(A' + u\,v^T)t = d$$

$$A'y = d$$

$$A'q = u$$

$$t = y - \left\{\frac{v^T y}{1 + v^T q}\right\} q$$

Sherman-Morrison formula used for atmosphere-ocean-ice coupling in CCAM.

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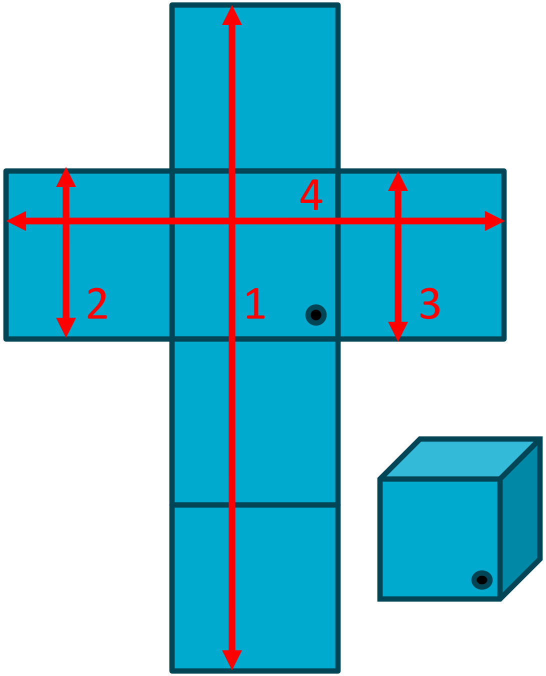
Spectral nudging and ESM components

- Spectral nudging can also be used to constrain the CCAM ocean, where the convolution approach works well with irregular coastlines.
- For our current CORDEX simulations, we use spectral nudging to constrain SSTs by perturbing the ocean mixed layer at a 1,000 km length-scale.
- Other spectral nudging configurations can be used, depending on the availability of host GCM data (e.g., potential temperature and salinity below the mixed layer).
- A similar approach can also be used for aerosols, or other ESM components. However, for CORDEX we currently only nudge aerosols when multiply nesting.



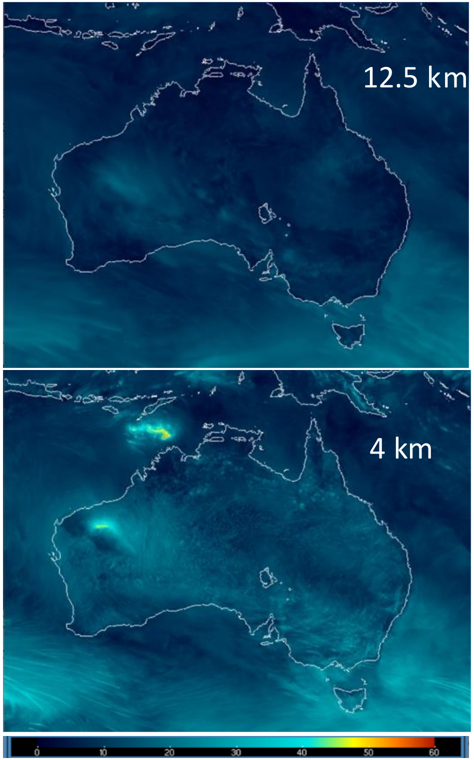
Schematic describing the implementation of spectral nudging using multiple 1D convolutions. This approach reduces the cost from $O(N^4)$ to $O(N^3)$, is flexible for irregular regions like oceans and scales effectively for GPUs.

Australian convective-scale simulations

- CCAM is currently testing 4km convective-scale simulations for Australia as part of the Australian Climate Service (CCAM-4).

- Simulations can run up to 24,576 cores for approximately 2 simulation years per day (C768 L54/48 S=3) with mixed precision.

- Additional changes made to CCAM-4 include:
  - Updated land-surface datasets (particularly for improving urban areas) and a revised representation of CMIP land-use change.
  - Experimenting with CABLE ground water model (Decker and Zeng 2009), as well as including lateral transport (Fan et al 2007).
  - Adjustments to cloud microphysics and surface fluxes for representing tropical cyclones.



Comparison of maximum daily wind gusts in CCAM-12 (top) and CCAM-4 (bottom) downscaling ERA5 on the 1st January 2014.

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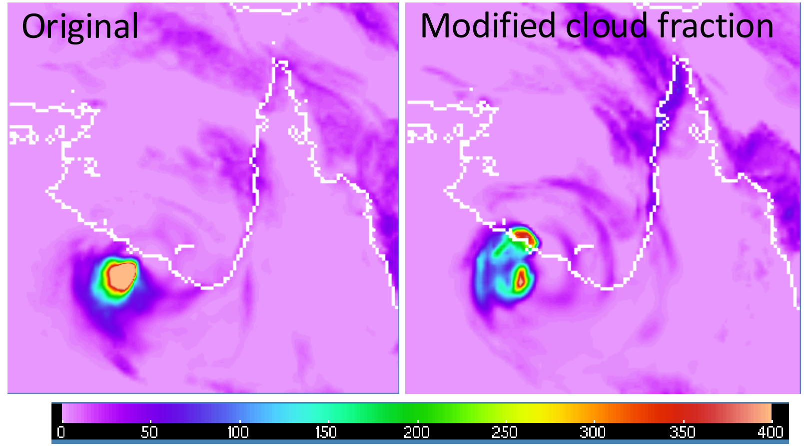
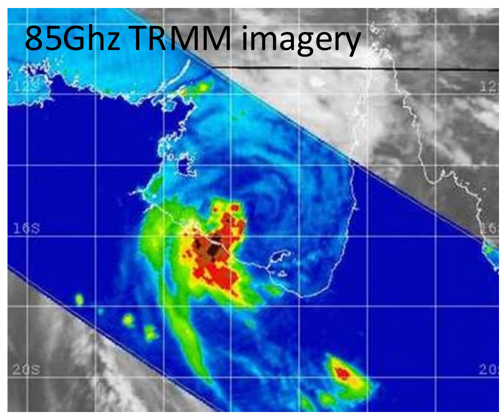
Improving cyclones at convective scales

- Our initial CCAM-4 simulations showed that extreme rainfall associated with cyclones was significantly overestimated.
- This issue appears to be related to the parameterisation of the cloud fraction, with significant improvement after modifying the scale-aware component.
- More careful treatment of surface fluxes for high wind speeds also helped to improve the representation of cyclones (e.g., Moon et al 2006).





Example of over prediction of extreme rainfall associated with tropical cyclones. Observed rainfall is approximately 335mm/day. Results are sensitive to the parameterisation of cloud fraction.

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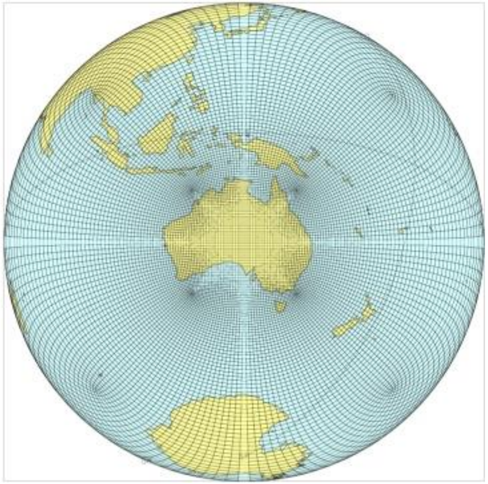
Conclusions

- This talk describes the Conformal Cubic Atmosphere model used for simulate the regional climate with a variable resolution cubic grid.
- We have found the stretched grid to be a flexible design when including RESM components, avoiding the need to provide lateral boundaries for aerosols or the ocean.
- Physical parameterisations need to work robustly across a range of grid scales, including for the grey zone when simulating at convective scales.
- Computation speed is competitive with other dynamical models, despite the stretched grid and coupled design.
- But we are still in the process of refining the experiment design with CCAM-4, based on preliminary results.



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Thank you

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