Simulating the Earth System with filtered Navier Stokes Equations

10th CHPC National Meeting

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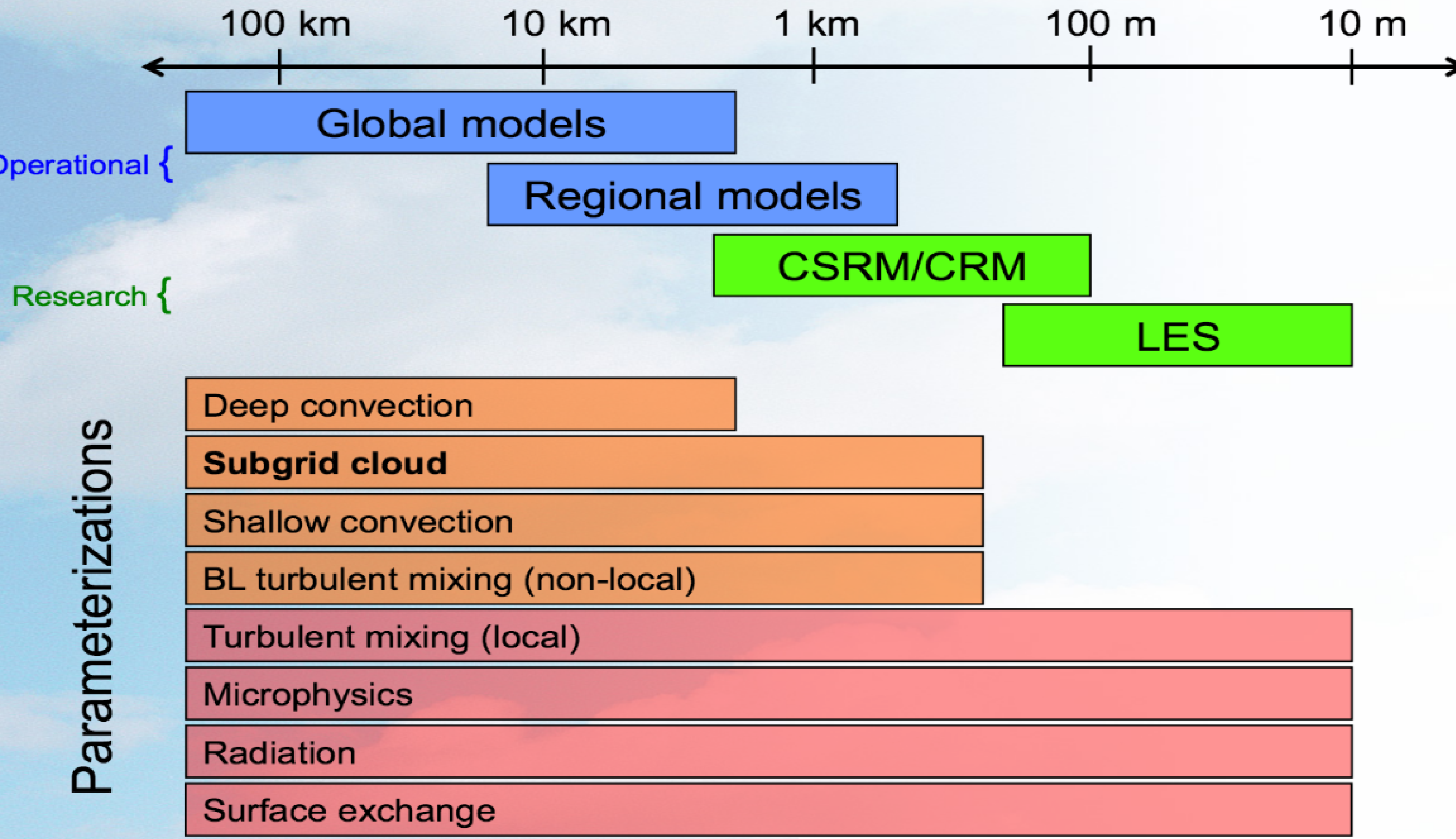
Atmospheric Modelling



Basic Equations of motion

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\nabla p - fkXv - gk + \mathcal{F}$$

$$\frac{D\theta}{Dt} = \dot{\mathcal{H}}$$

$$\frac{D\rho}{Dt} = -\rho\nabla .V$$

$$\frac{Dq_x}{Dt} = S_x, x = 1,2,\ldots.n$$

$$\frac{\bar{D}\bar{u}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x} + f\bar{v} - \left[\frac{\partial \overline{u'u'}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right]$$

$$\frac{\bar{D}\bar{v}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \left[\frac{\partial \overline{u'v'}}{\partial x} + \frac{\partial \overline{v'v'}}{\partial y} + \frac{\partial \overline{v'w'}}{\partial z}\right]$$

$$\frac{\bar{D}\bar{w}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial z} + g - \left[\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{v'w'}}{\partial y} + \frac{\partial \overline{w'w'}}{\partial z}\right]$$

$$\frac{\bar{D}\bar{\theta}}{Dt} = \dot{\mathcal{H}} - \left[\frac{\partial \overline{u'\theta'}}{\partial x} + \frac{\partial \overline{v'\theta'}}{\partial y} + \frac{\partial \overline{w'\theta'}}{\partial z}\right]$$

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0$$

$$\frac{D\overline{q_x}}{Dt} = \overline{S_x} - \left[\frac{\partial \overline{u'q_x'}}{\partial x} + \frac{\partial \overline{v'q_x'}}{\partial y} + \frac{\partial \overline{w'q_x'}}{\partial z}\right]$$

- Prime terms are subgrid terms that are parameterised using resolved terms(bar terms)

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Large Eddy Modelling

Simulations

- Convective atmosphere
  - Constant sensible heat flux : 30 and 241Wm^{-2}
  - Constant temp of 290 and 300K up to 1km, and a sharp jump of 8K is imposed over a depth of 100m near the top of the BL.
  - 1K amplitude perturbations, 4 hour simulations
- Domain size: 4.8 km x 4.8 km
  - Δx: 10m, 20m, 40m, 80m and 160m.
- Domain size: 9.6 km x 9.6 km
  - Δx: 25m, 50m, 100m, 200m and 400m.

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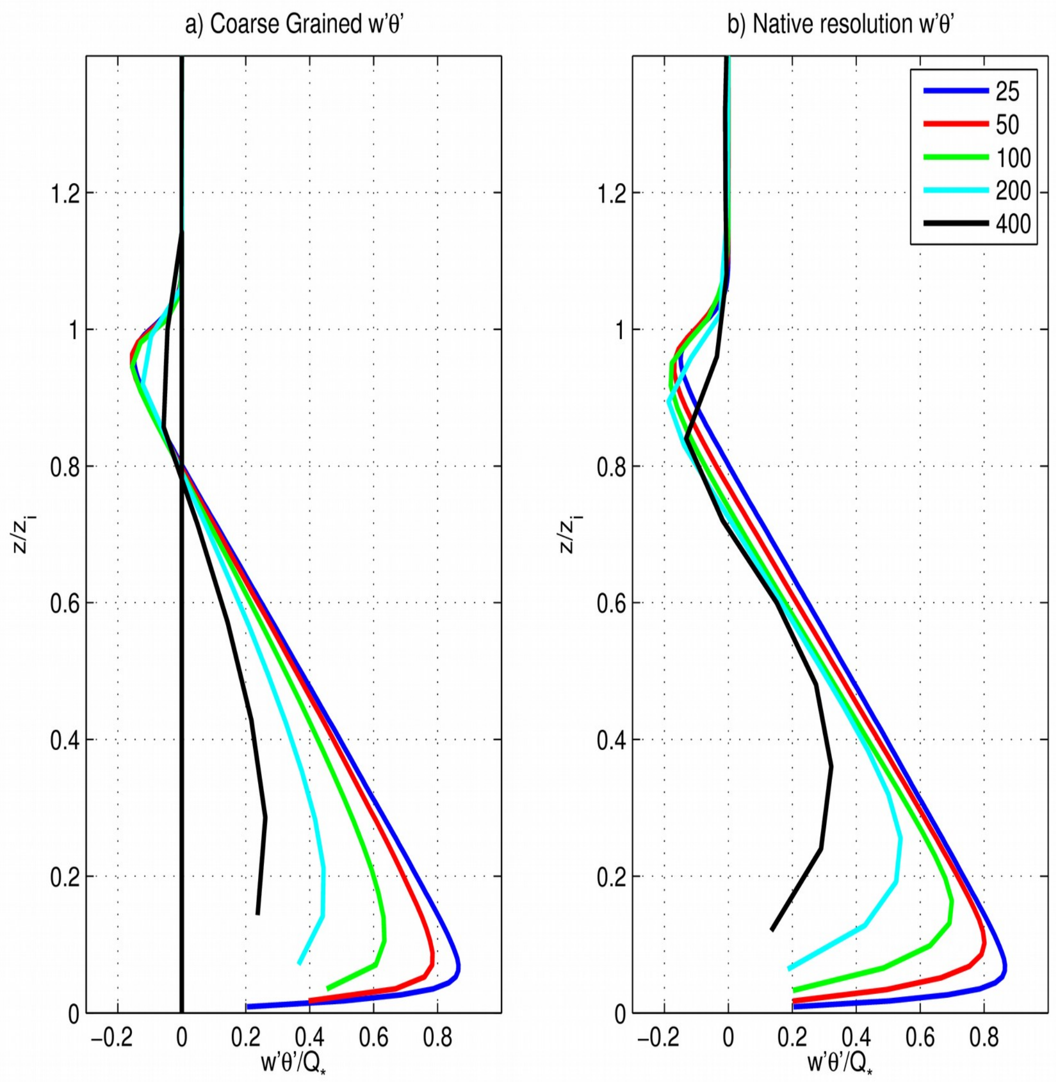
Resolved Potential temperature flux



- Decrease with height to a minimum
- Negative region = entrainment zone
- Minimum – lower height with low resolution
- CG data is more converged below zi

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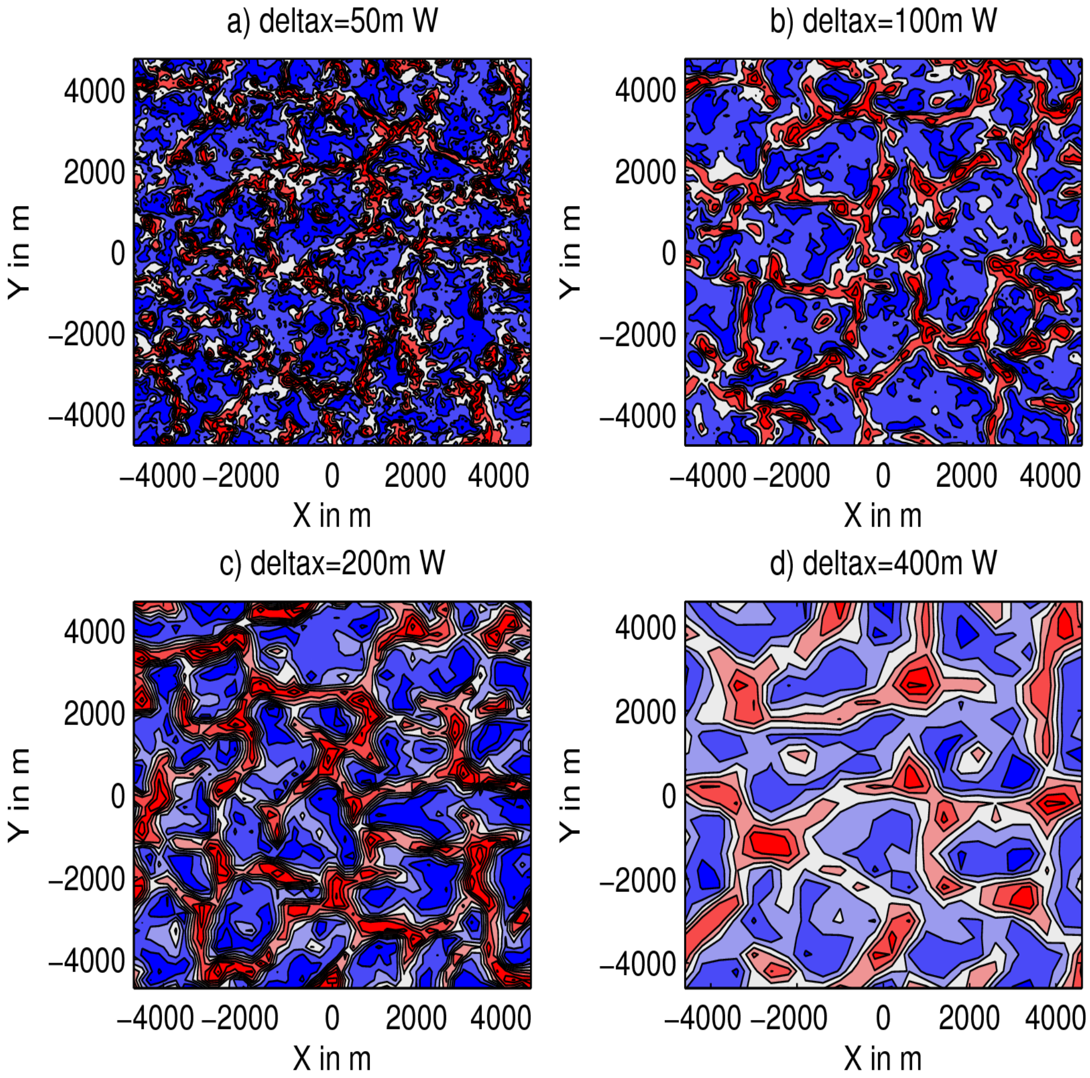
Grid spacing dependence



- Lower resolution – less detail
- Subgrid processes are parametrized
- Assumptions in parametrizations dependent on resolution

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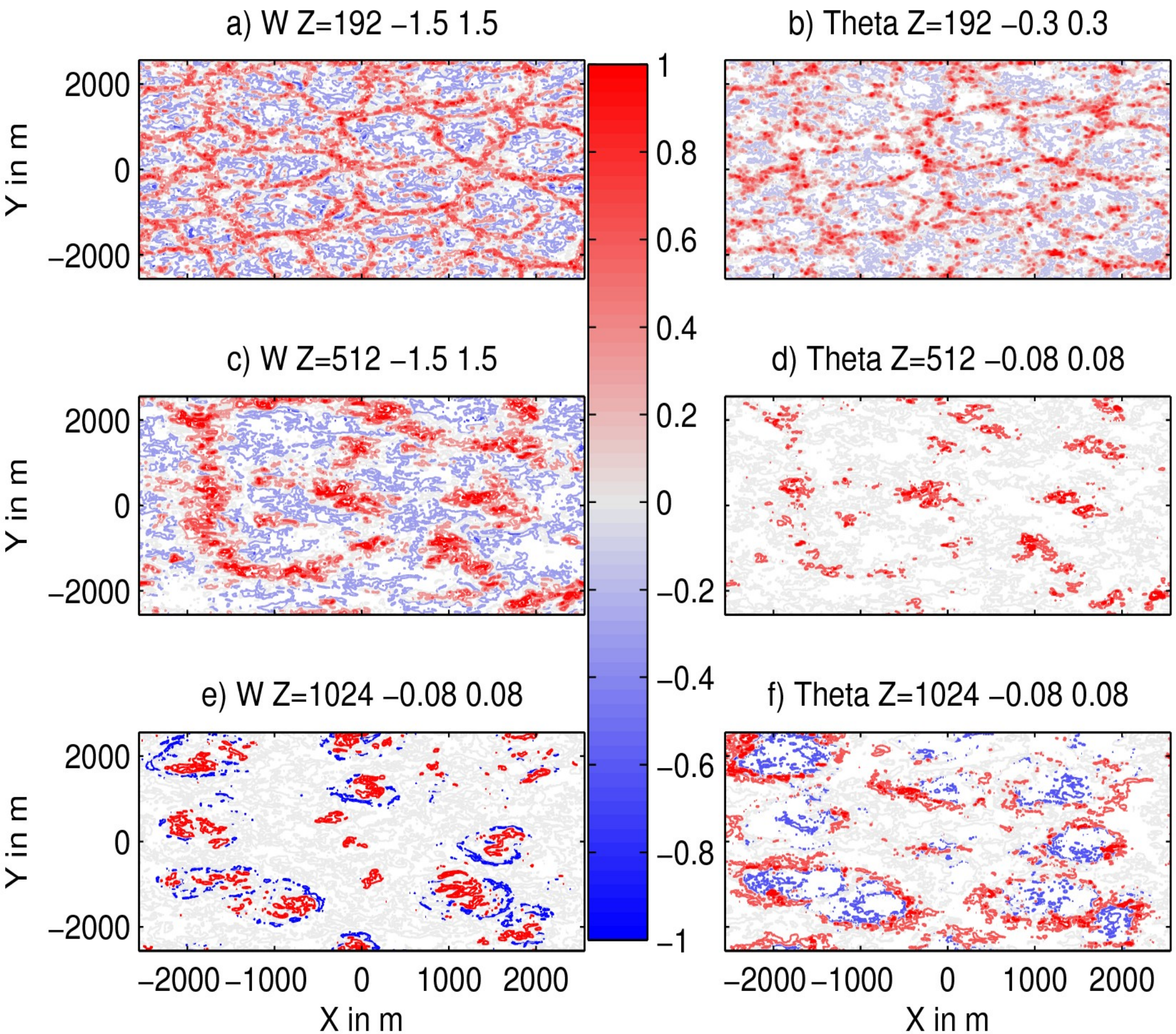
Atmospheric processes



- Thermals rise
- Join those in adjacent regions to form larger structures.
- Closer to BL height – negative theta' associated with positive w'

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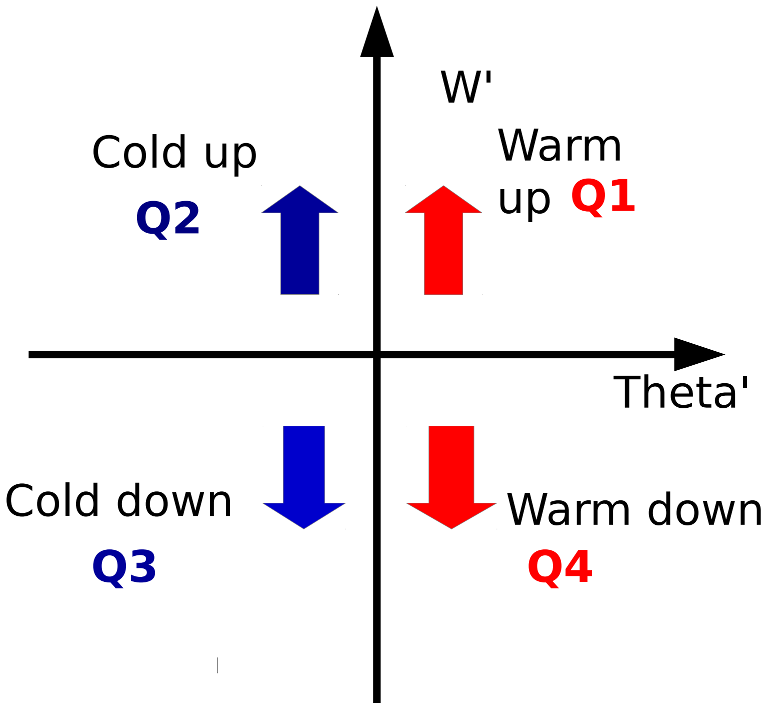
Temperature flux Quadrant analysis



- Disentangle the temperature flux.
- e.g.Sullivan et al., 1998; Coceal et al 2007, Park and Baik 2014
- Theta'>0,W'>0 : Q1
- Theta'<0,W'>0 : Q2
- Theta'<0,W'<0 : Q3
- Theta'>0,W'<0 : Q4
- Number of events and contribution of each quadrant to the total flux.

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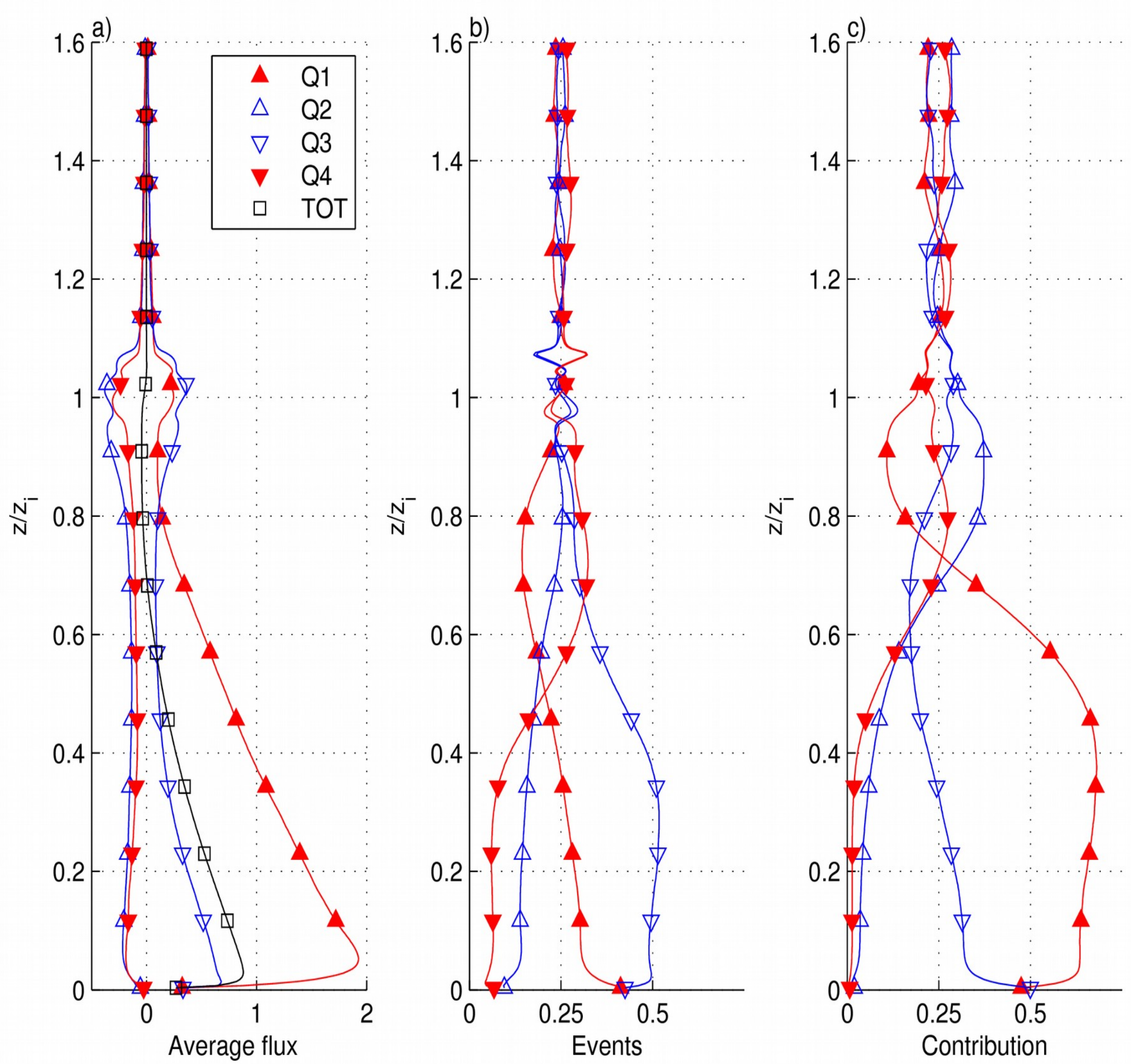
Processes at high resolution



- Thermals rise – mix with environment-get colder
- Some join Q3 closer to the surface, most become Q2
- Q2 – bigger contribution theta'w'
- More Q4 events close to inversion layer- entrainment – contribution is about ¼.

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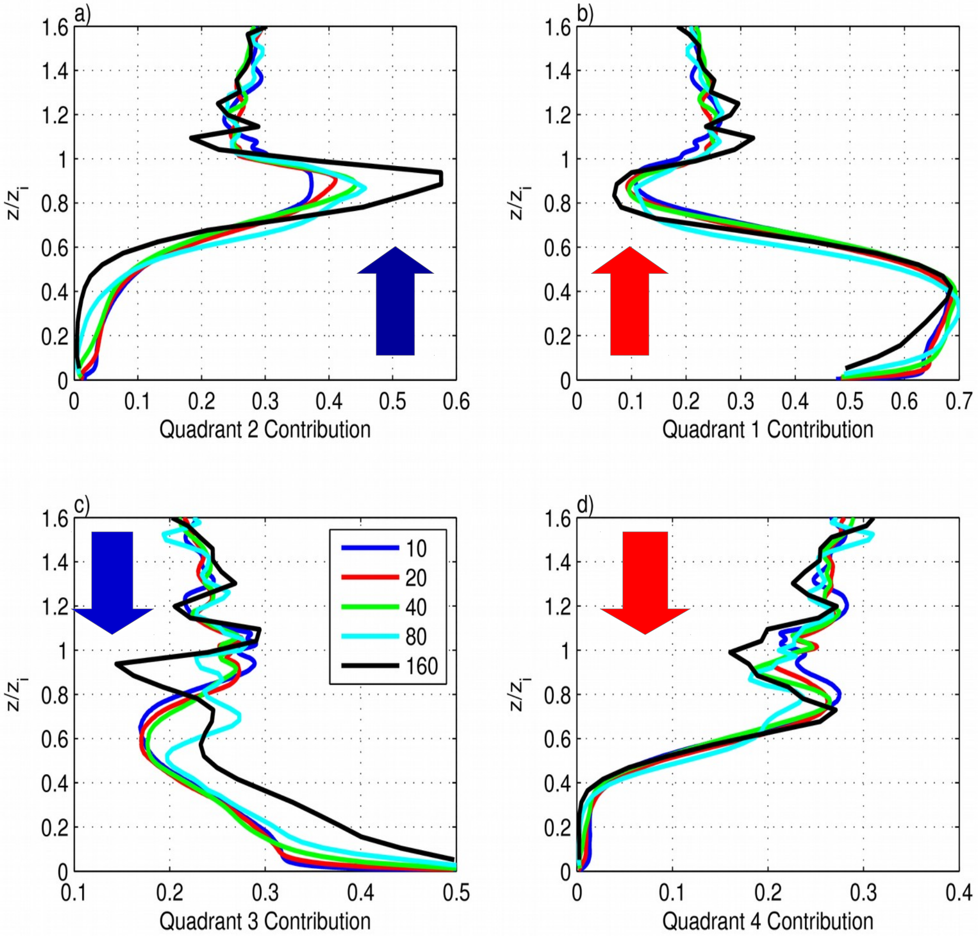
Contribution – resolution dependence

- Low resolution – smaller Q1 contribution to mid-BL
- Smaller change from Q1 to Q2 – mixin
- Big contribution of Q2 to flux – smaller mixing.
- Bigger contribution of entrainment in high resolution simulations.
- Q2 lines according to resolution close to inversion layer
- Q2 represents thermals which get colder due to mixing but manage to maintain their momentum.
- Sullivan and Patton profile



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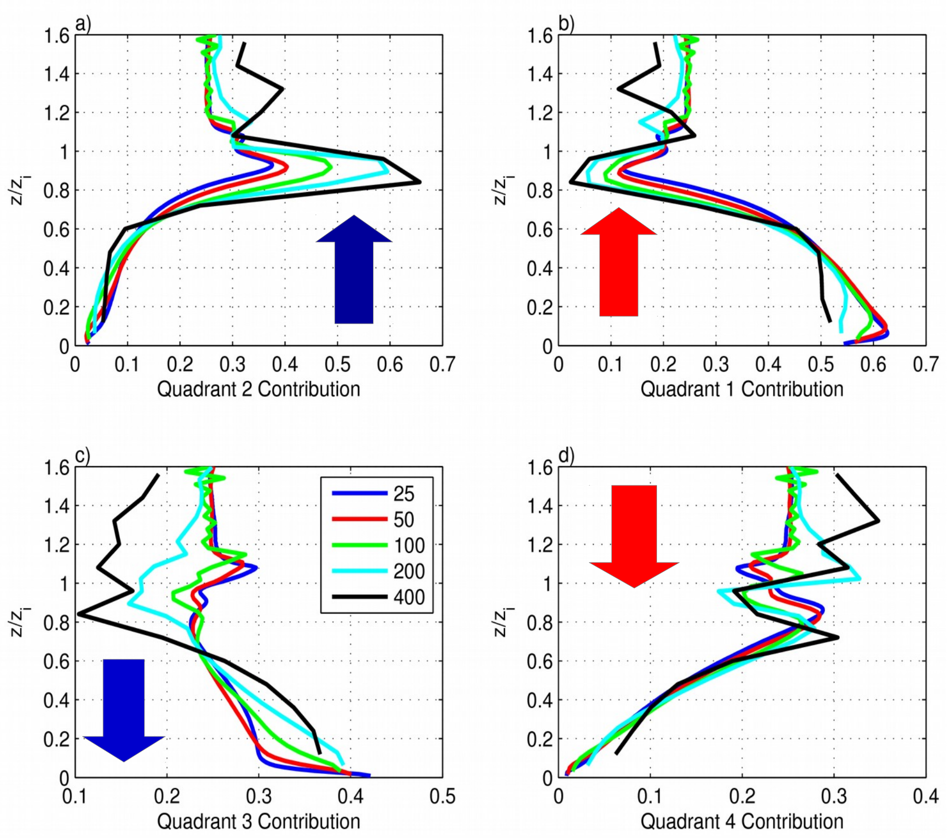
Contribution - Sullivan



- Change in contribution with grid length capture ok in Q1 and Q3
- Peak in Q2 and Q4 below BL height at lower height
- Q3 and Q1 contributions substantially smaller
- Q2 contribution much larger than the rest with increased grid length

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Concluding remarks - LES

- Different subgrid models being tried to resolve the problem as yet – big research topic.
- LES used for research purposes.
- Use of LES models for operations – not far off
- Effects of changing the grid spacing visible in inertial subrange, as well as grey-zones.

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CCAM Modelling

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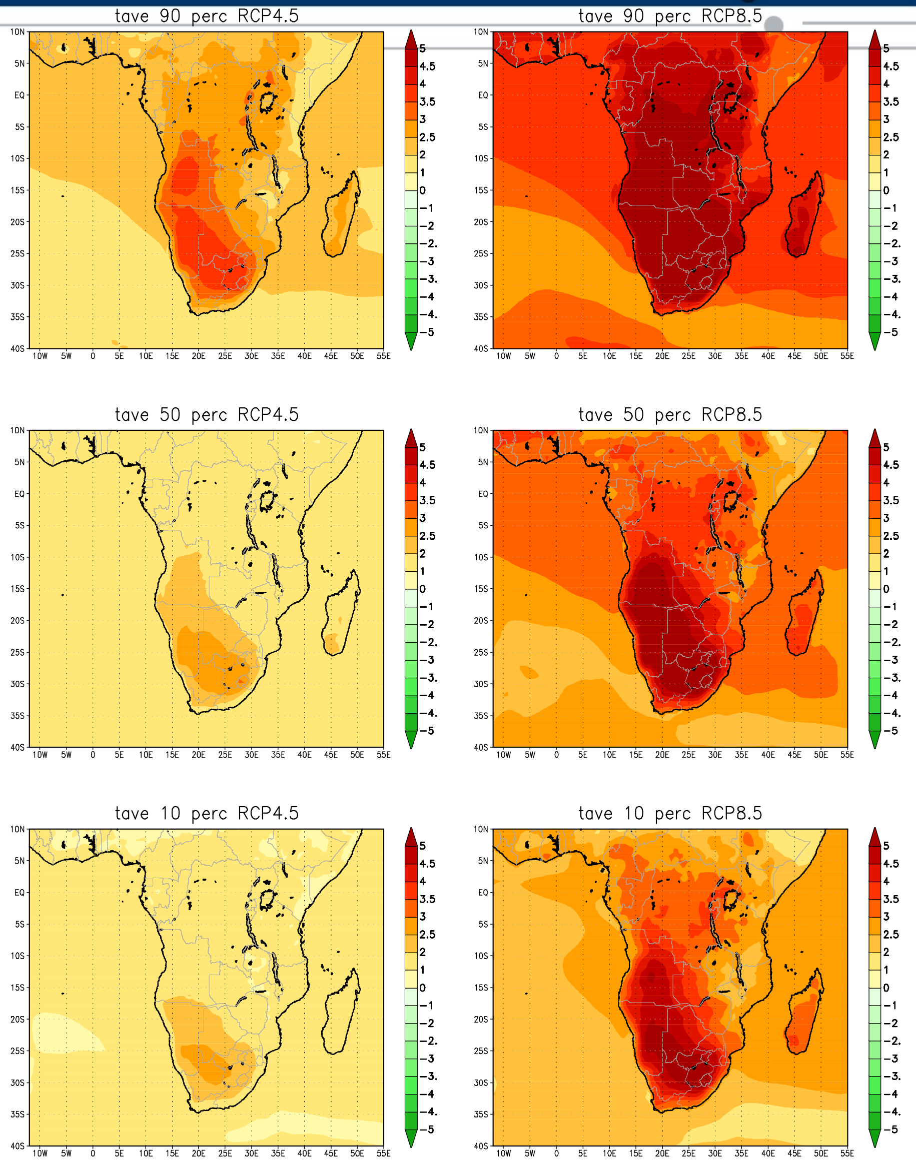
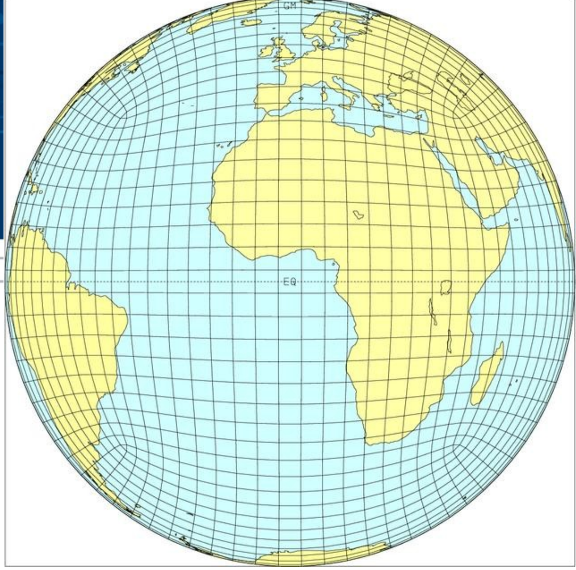
CCAM model

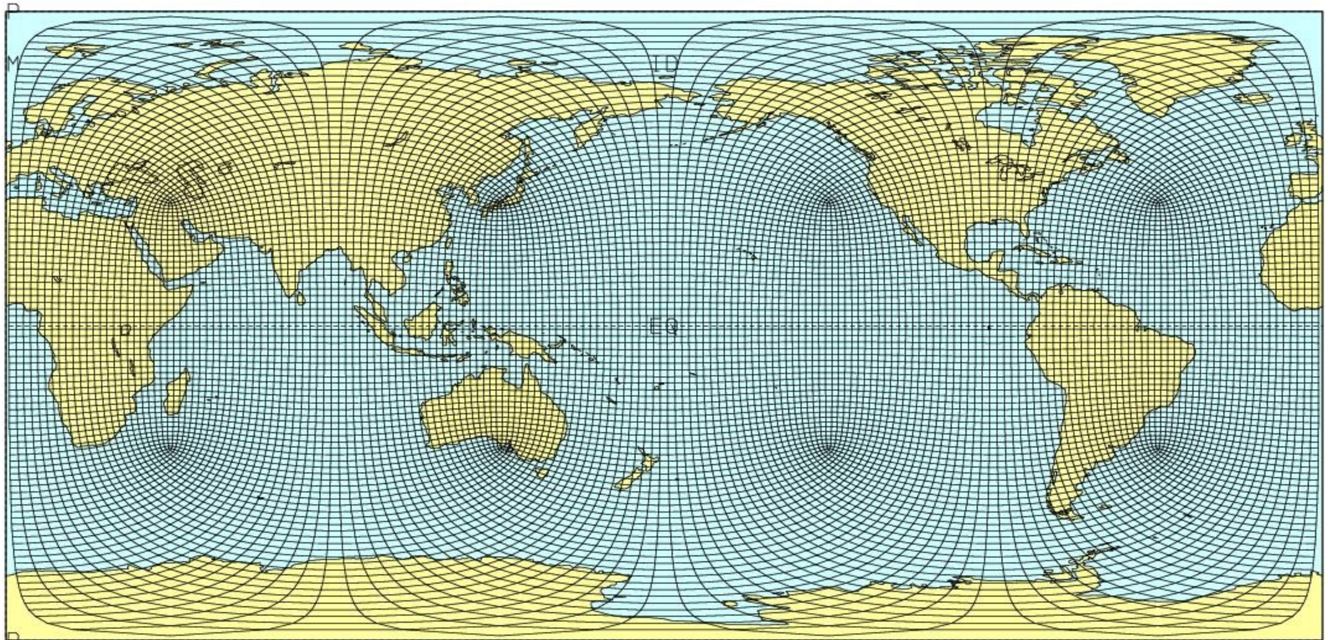
- Used for
  - Numerical Weather Prediction,
  - Seasonal Forecasting
  - Multi-decadal simulation
- Scaling tests: 1 month simulation
  - C768 – 13km
  - C384 – 26km
  - C192 – 50km
  - C96 - 100km



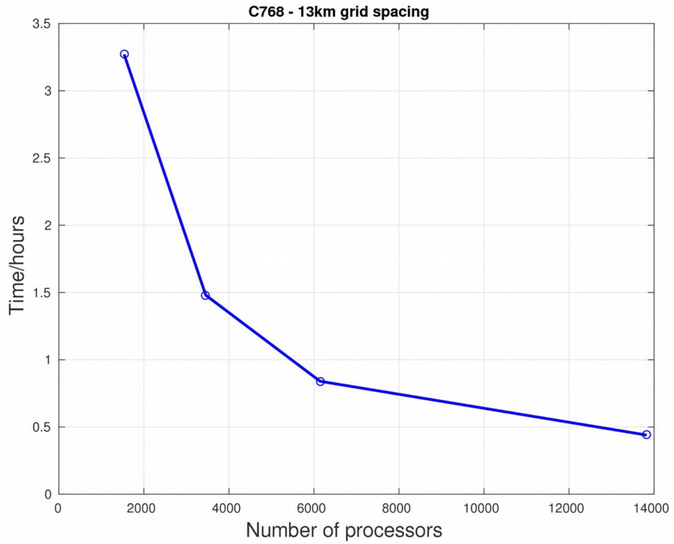
CCAM grid

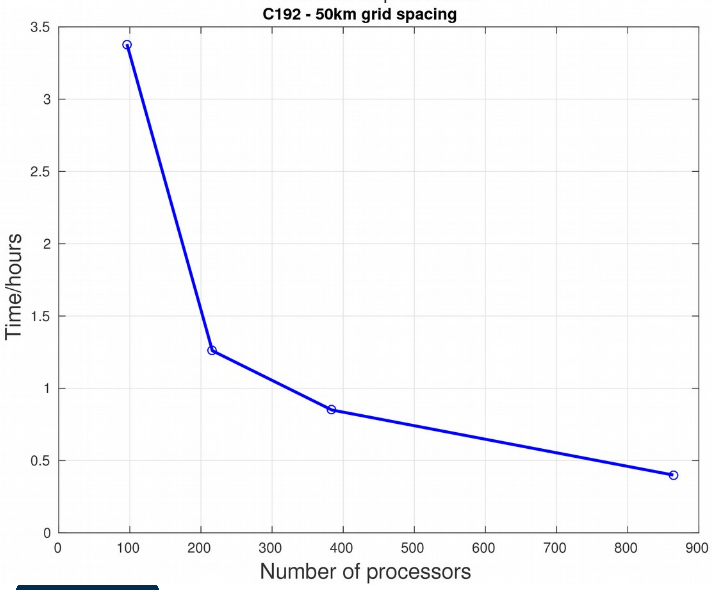


- Cube – based GCM
- Grid decomposition choices:
  - Uniform – not restrictive on # of procs
    Requires more MPI message passing.
  - **Face – only works for factors or multiples of six**



Scaling tests





C96 - 100km		C768 - 13km	
nproc	hours	nproc	hours
96	3.38	1536	3.27
216	1.27	3456	1.48
384	0.85	6144	0.83
864	0.4	13824	0.45

- To produce 1 month simulation with 13km grid spacing globally in less than 30 mins requires 13824 processors for atmosphere only

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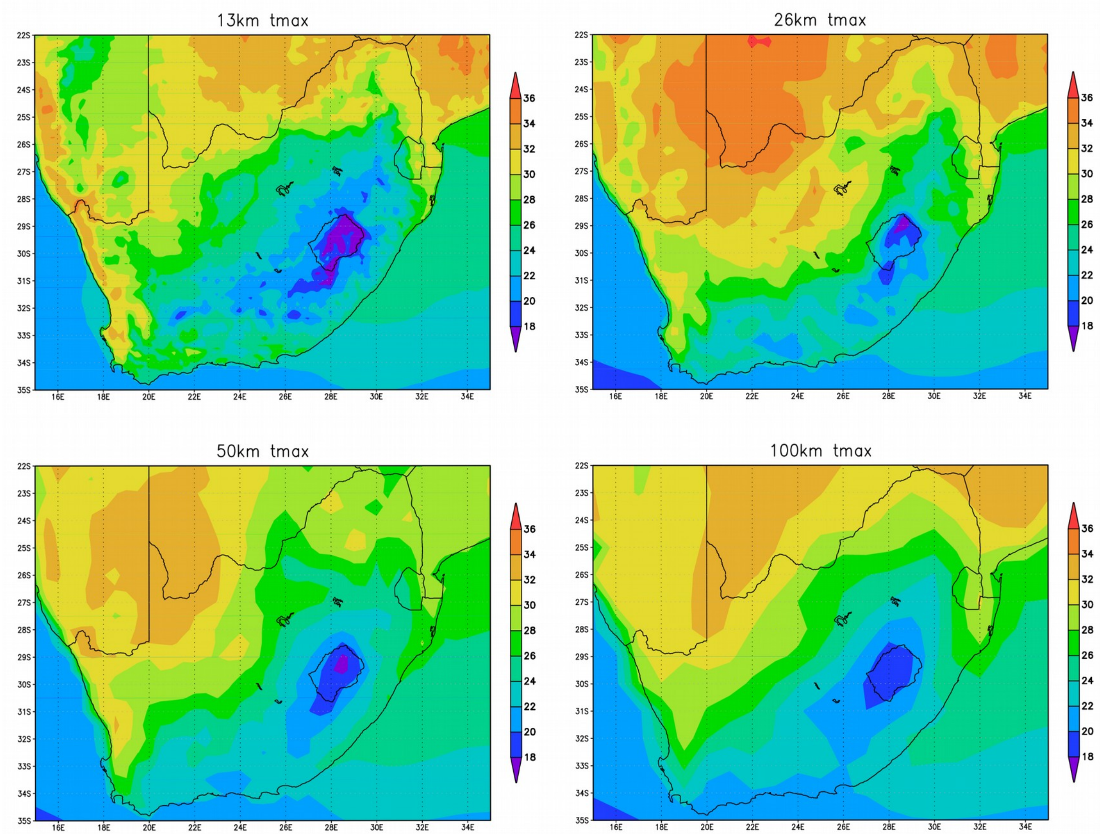
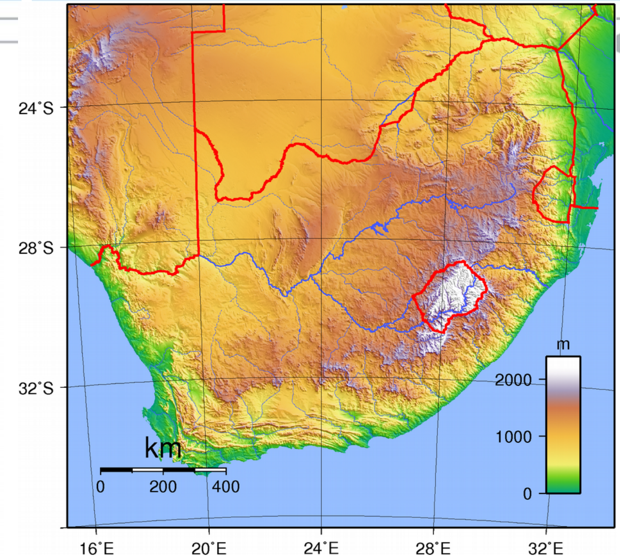
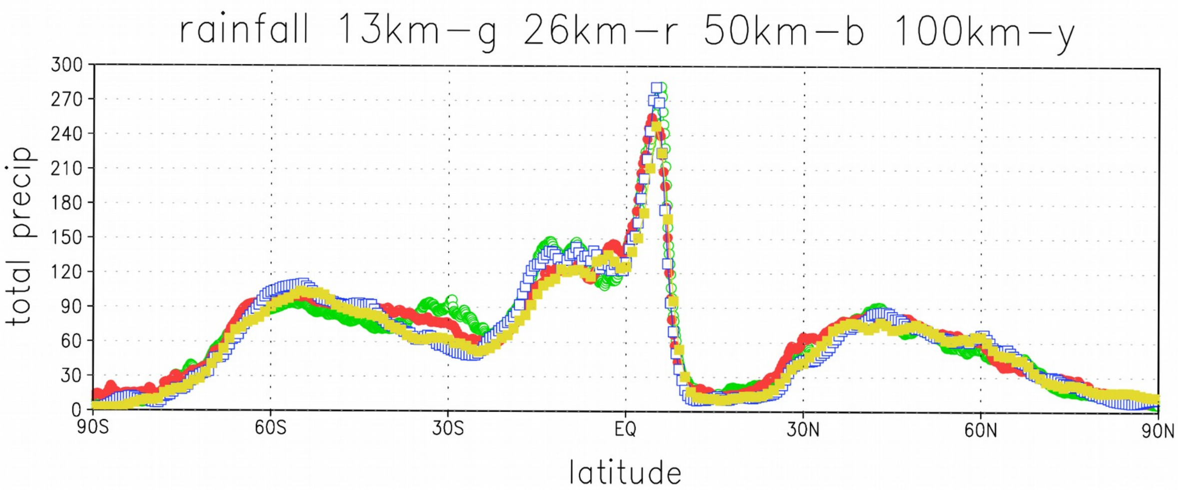
Maximum Temperature

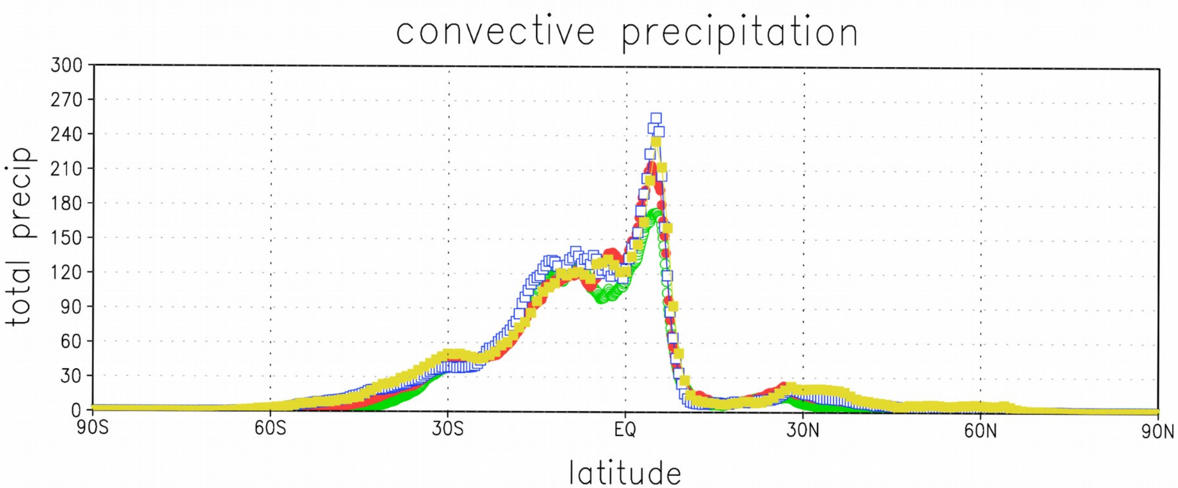




- High resolution correspond to topography map

Global rainfall





- Small differences in simulated amounts.
- More convective rainfall over tropics.

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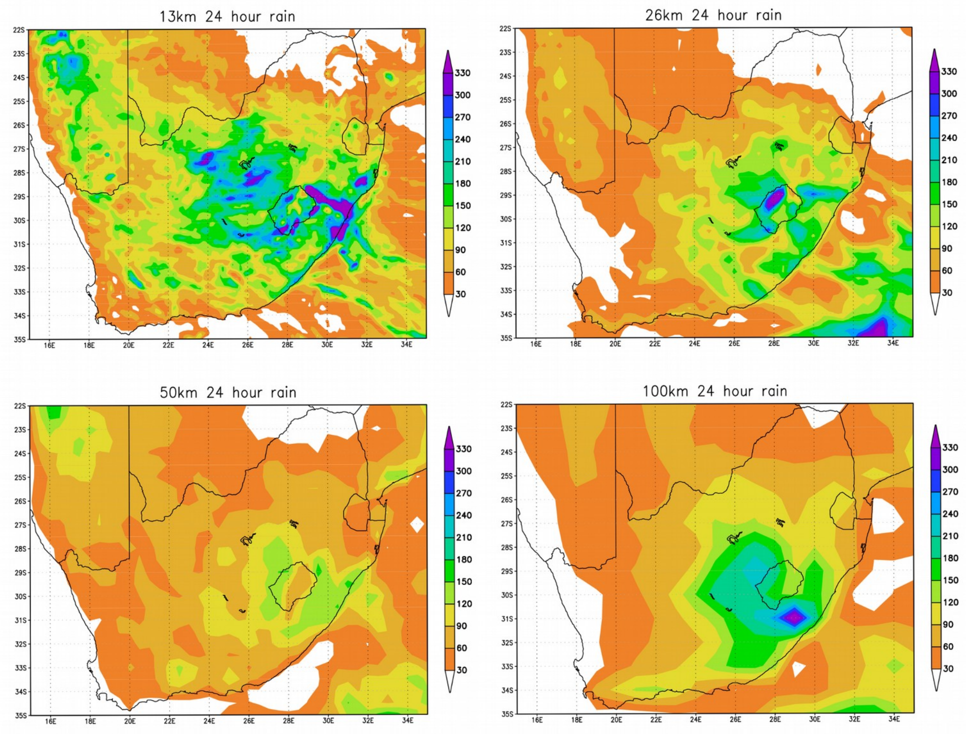
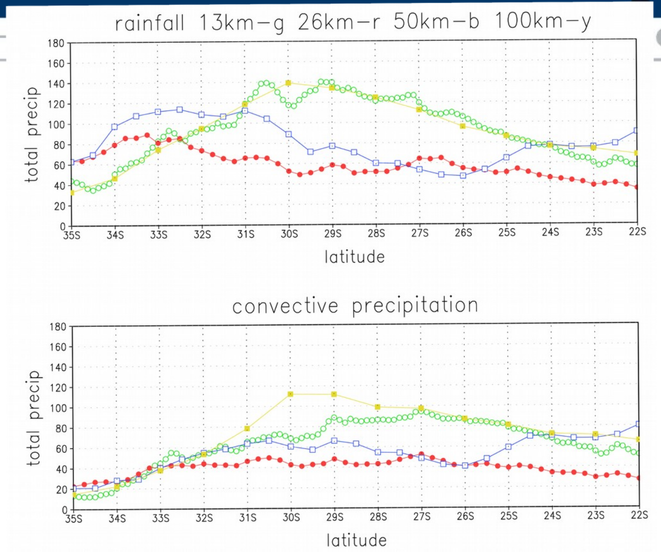
Rainfall – South Africa





- More detail with high resolution
- 100km matched by 13km

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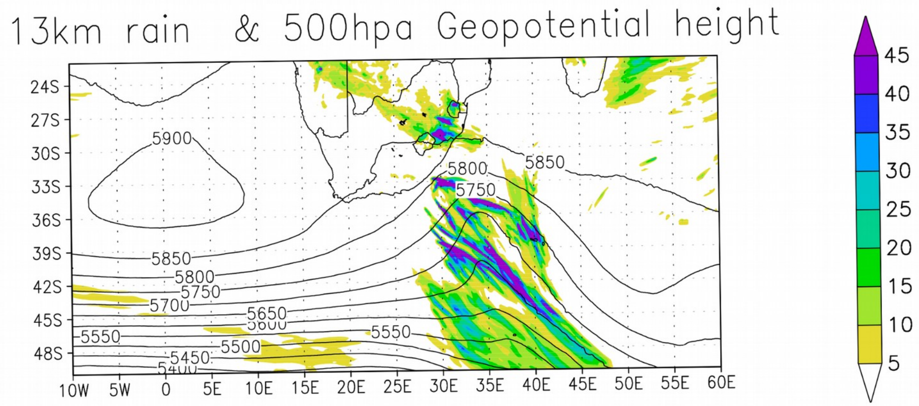
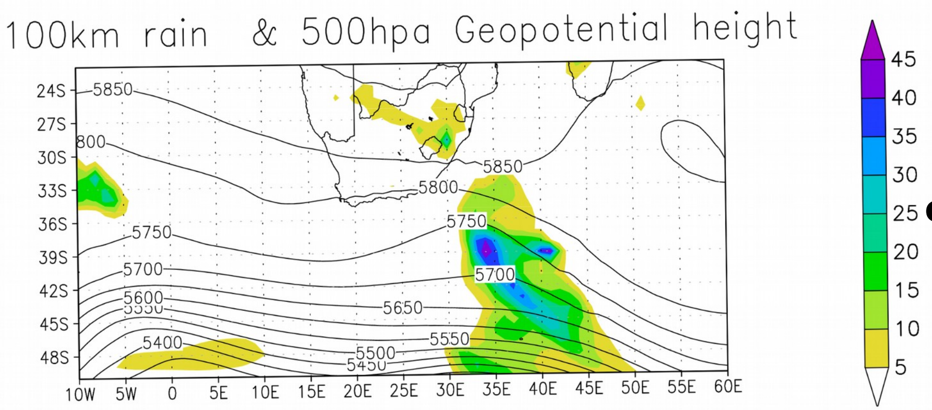
Synoptic control subgrid processes





- Parametrization – determine relationship of subgrid processes to large scale processes.
- Large synoptic systems give rainfall

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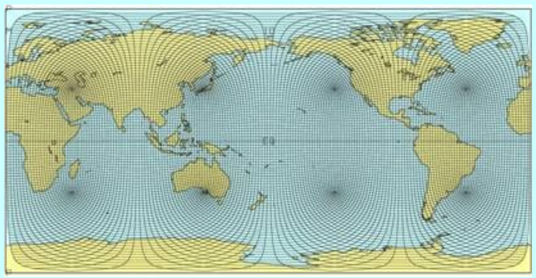
Climate Change Experimental design

Regional Climate Modelling Flow of Events: CSIR ensemble of projections

Bias-adjust SSTs (Reynolds Climatology)

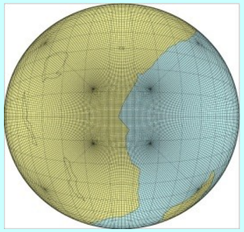
Downscaling using CCAM in 2 stages

Simulation period 1960-2100
6 CGCMs downscaled



Global simulations, quasi-uniform C192 resolution (~ 50 km) for the Coordinated Regional Downscaling Experiment (CORDEX)

SSTs, sea-ice, atmospheric nudging



Very high-resolution simulations over areas of interest (8 km resolution)

Further downscaling to 1 km resolution over smaller areas is feasible

Regrid from CCAM to lat-lon grid

Application modelling, climate change impact studies, climate change adaptation strategies and policy making

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Concluding remarks

- The grid spacing has a big effect on simulations.
- Subgrid models are responsible for most of the uncertainty in simulations.
- Increase in grid spacing at multi-decadal timescales possible because of CHPC machines.
- CCAM scales well
- Variable Resolution Earth System Model (VRESM) - Busy writing Variable-resolution Cube Ocean Model (VCOM) in parallel – using CCAM as benchmark.

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