Limitations on ever-higher resolution and adaptive mesh refinement

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Dynamics Research

Plan

1. Motivation.
2. High resolution modelling.
3. High resolution NWP.
4. Global NWP.
5. Climate.
6. Conclusions and questions.

Higher resolution

In short-range (i.e deterministic) NWP , higher resolution -> more skill

... but is higher resolution always cost-effective?

Doubling horizontal resolution requires 2x for each direction and for the time step.

Computer power increases that amount every 5 years (or so) so in real terms it’s free!

Global model resolution

The highest resolution operational models are now around 25km.

year	2010	2015	2020	2025	2030
res(km)	25	12.5	5	2.5	1
cpu x	1	8	128	1000	10000

Typically we allow about 6 minutes for a 1 day forecast

1 year forecast would only take around 36 hours, 10 years a couple of weeks.

If we can take around 16 weeks then could double resolution.

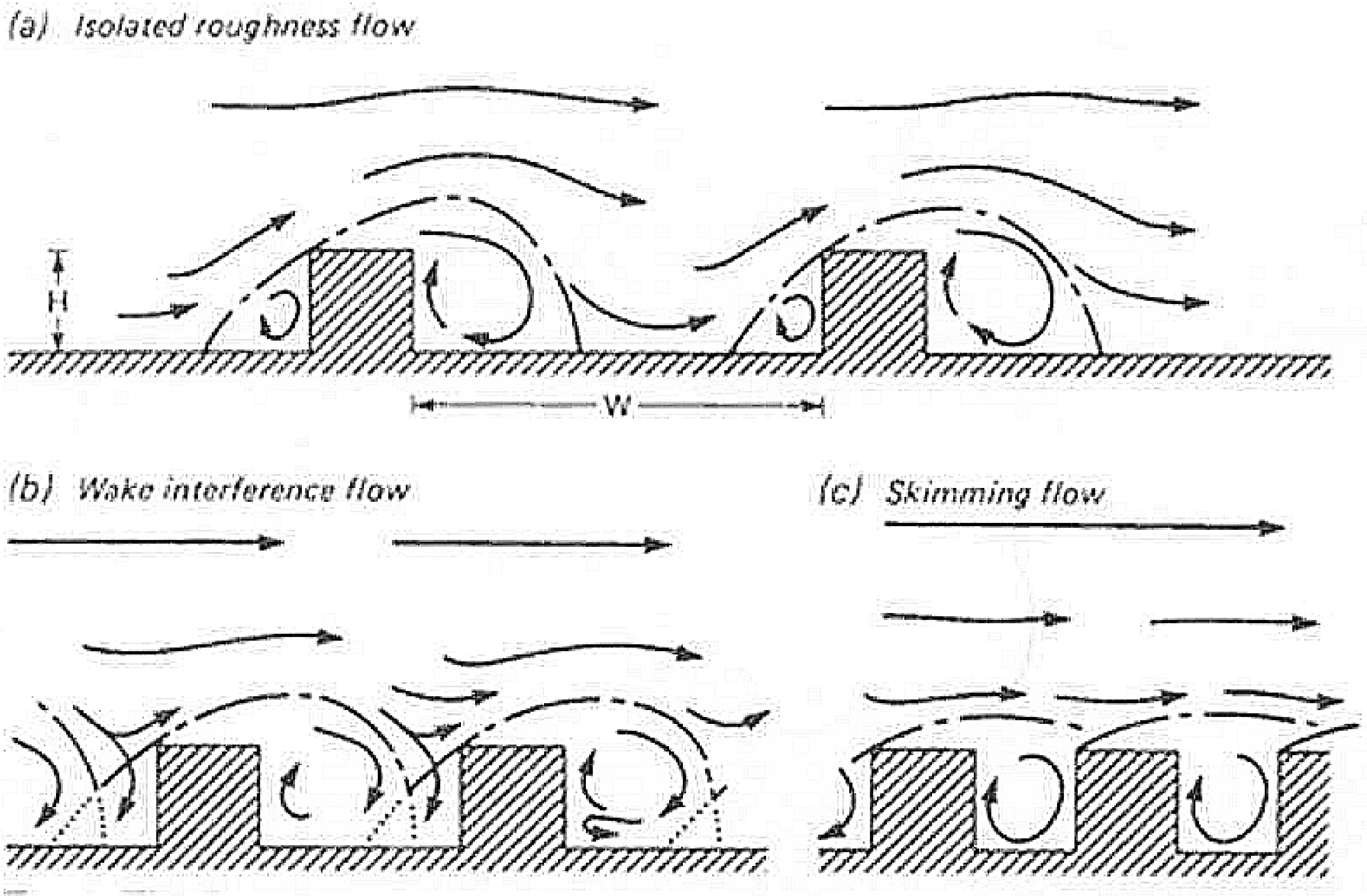
....but other demands on computer time such as more processes (carbon cycle, aerosols, chemistry) and to validate a climate model would need to run for at least a couple of centuries.

CFD - flow over obstacles

- Employ finite elements/AMR to refine (unstructured) grid around obstacle and in disturbed flow. Coarse resolution for steady/undisturbed flow.
- Use similar approach for flow around buildings.
- Obstacles $\sim 10m$, highest resolution grid length $\sim 1m$.
- $1km^2$ domain using $1m$ resolution requires 10^6 points in horizontal. Far fewer if using mesh refinement only where needed.
- Explicit representation of edges/corners?
- What about features that present a challenge for grid-refinement? e.g. large tree near a building.
- Wind tunnel comparisons; no meteorology and dry.

Larger domain - urban scale modelling

- Air quality and airport models.
- How do we cope with a domain size of $10km^2$ with variable building density, orography and vegetation?
- Even with AMR, cannot afford to reduce grid-size to $\sim 1m$ but perhaps can do $\sim 10m$.
- Flow around each obstacle now not modelled directly; finer details of the flow are not resolved.
- Interested in moist meteorology. Need parametrizations for surface roughness, turbulence, radiative forcing (diurnal cycle), cloud microphysics (for visibility if not for precipitation).
- AMR useful in adapting grid to more important features and/or processes.


(a) Isolated roughness flow
H
W
(b) Wake interference flow
(c) Skimming flow

Under resolved flows

- For environmental flows over complex terrain, often unable to resolve all features or details of flows.
- Terrain and coasts “fractal-like”. Increasing resolution introduces new features.
- Insufficient resolution for many features.
- AMR still useful in adapting grid to more important features and/or processes. e.g. 1km resolution used for part (say 1/4) of UK 4km domain where convection is expected.

High resolution NWP

- 1-10km resolution. Needs to be non-hydrostatic.
- Parametrization of convection a problem; assume ensemble of plumes.
- If a parametrization is used there is a tendency for convection to be too widespread and too frequent.
- If convection is explicit updraughts (vertical velocities of several metres per second or more) develop at the grid-scale which is unphysical (and should be unacceptable).
- Real updraughts $< 1km$. Numerical convergence studies suggest convergence in model behaviour at around $100 - 200m$.

Short-range NWP

- Short-range (i.e deterministic, 1-2 days) NWP somewhat easier than longer range global NWP or climate modelling. Stop before errors become too large.
- Limited area models (LAMs) constrained by driving data (lateral boundary conditions, lbcs).
- Increasing resolution gives more local detail near the surface and increased skill of near surface quantities (screen temperature, 10m wind, visibility, precipitation).
- In short-range (i.e deterministic) NWP some success using AMR.

Short-range NWP

- At larger scales lower resolution global model usually more skillful then LAMs. Why?
- LAMs need lbcs from lower resolution driving model. Errors at boundaries. Outflow of small scale information needs to be damped (similar problem for AMR with rapid resolution change).
- LAM domain not large enough to contain synoptic scale structures.
- Analysis (initial conditions) does not contain small scale information. Observation density at small scales is even lower than at large scales.
- Difficult to improve small scale analysis without compromising large scales.
- Global models usually better tuned than LAMs. Sample size is larger - larger number of regimes.

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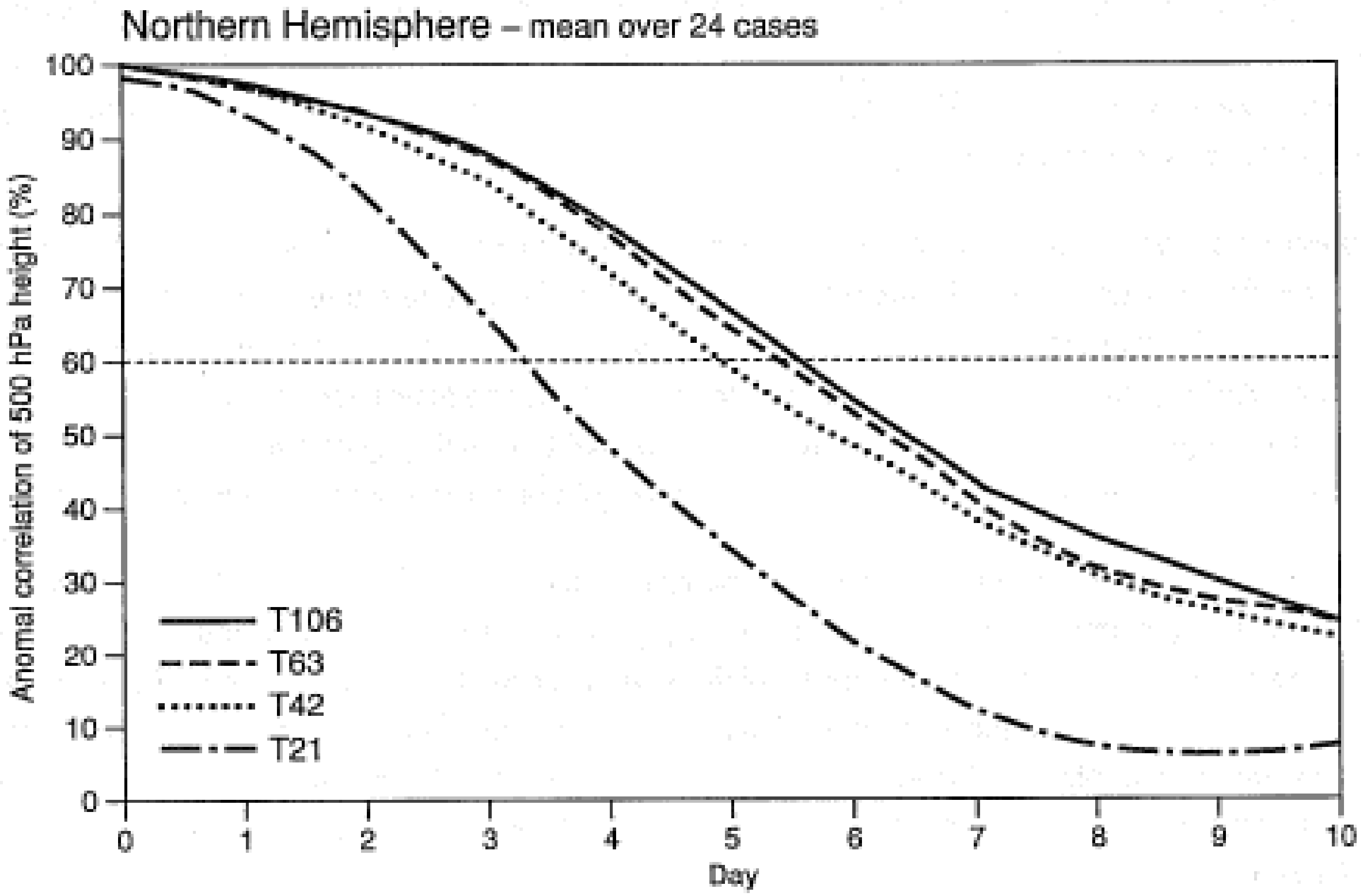

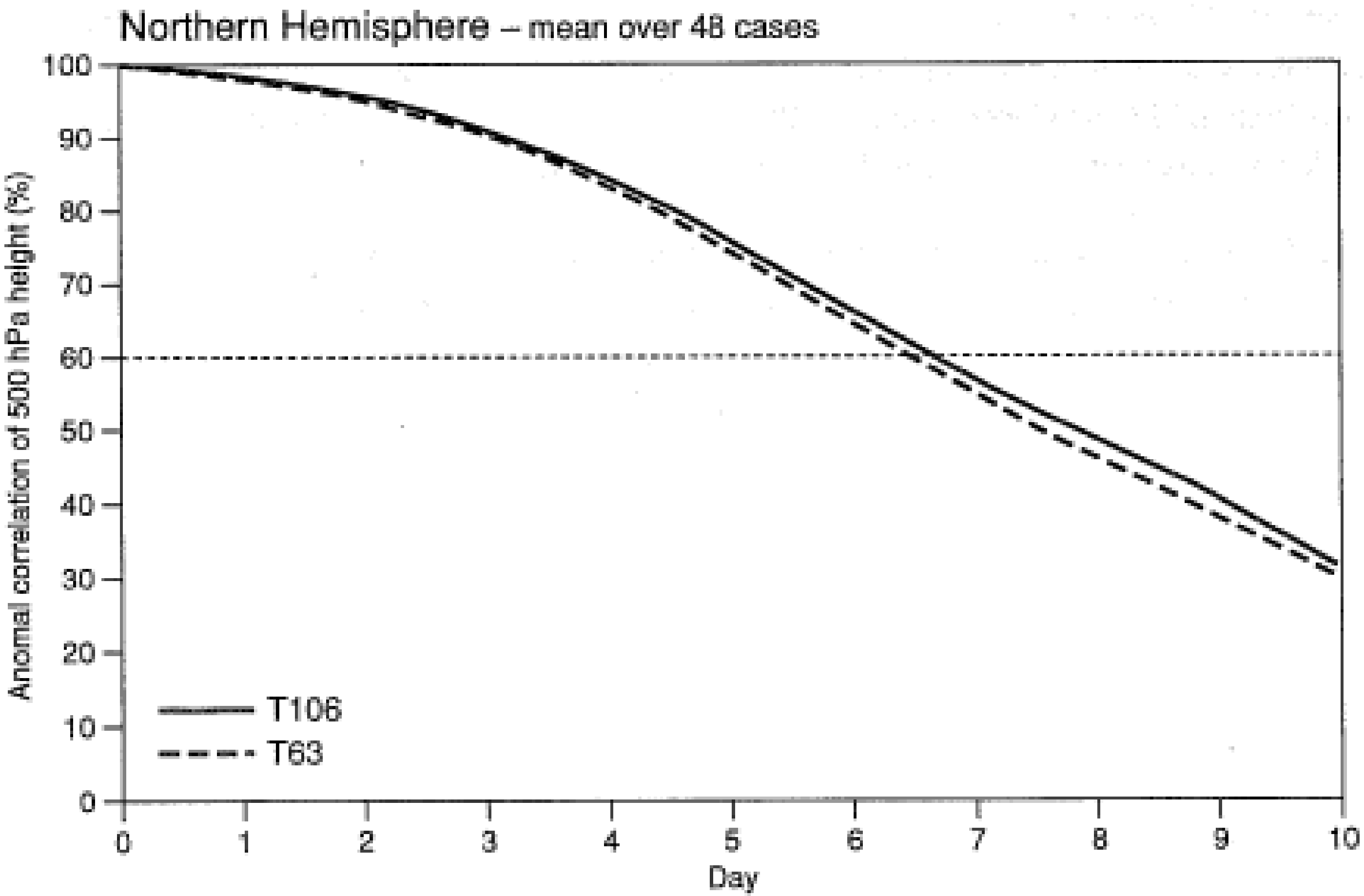

Northern Hemisphere – mean over 48 cases
Anomal correlation of 500 hPa height (%)
100
90
80
70
60
50
40
30
20
10
0
T106
T63
0
1
2
3
4
5
6
7
8
9
10
Day

T319vT159

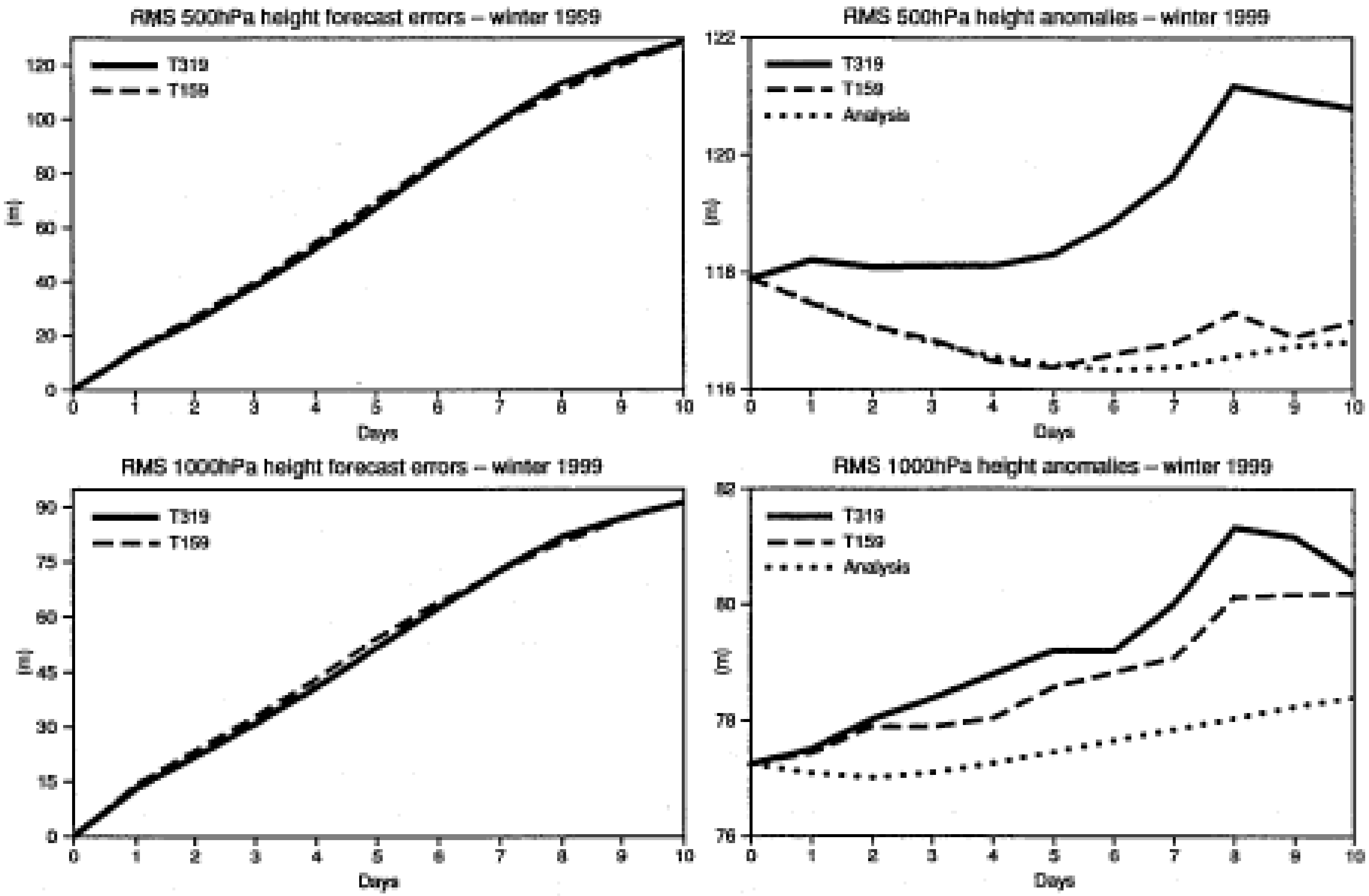

Fig 1.2 Root-mean-square errors (left) and anomalies (right) of 500 hPa (upper) and 1000 hPa (lower) height, computed over the extratropical Northern Hemisphere for the period 1 December 1998 to 28 February 1999. Errors and anomalies are shown for T319 (red, solid) and T159 (blue, dashed) resolutions, and the anomalies of the variational analyses are also shown.

Data assimilation

Data assimilation at higher resolution results in higher skill over the deterministic range.

1. Better first guess (smaller background errors)
2. More information can be extracted from observations (particularly for higher vertical resolution).

BUT

1. At very high resolution observation density is generally low.
2. Can range of scales for analysis be extended to the smaller scales without compromising the larger scales?

Systematic errors

- Modelling errors and missing processes.
- Parametrizations need to account for processes at or below the truncation scale.
- Parametrizations use prognostic variables, ancillary data and empiricism/sub-modelling.

Parametrizations

- Radiation, large-scale cloud and precipitation generally not a problem as resolution increases.
- Drag processes, boundary-layer and convection harder to tune.
- Convection a problem below 10km. Explicit convection alone is NOT acceptable until resolved scale is well below 1km. Grid-scale convection updraughts are at the grid scale (or larger!) which is unphysical. For short-range NWP explicit convection + some limiting works but unlikely to be adequate for longer runs (CASCADE might tell us).
- The use of damping and/or diffusion are acceptable in reducing systematic errors overall. However, it is not acceptable to reduce some systematic errors at the expense of the variability.

Climate model resolution

- Mid-latitude NWP suggests that around 100km might be enough

BUT

1. TROPICS
2. Is there something fundamentally wrong (sub-optimal) in how the sub-grid processes are parametrised and coupled with the dynamics?

Small scales

- In modelling of environmental flows, near the truncation limit, there are always under-resolved details.
- These details may not be important in determining regional climate.
- If the flap of a butterfly's wings can change the weather somewhere can it change the climate? i.e. do small scale processes affect regional climate?
- Weather is determined by disturbances in the atmospheric flow.
- Climate is determined by boundary forcing.
- Grey area in-between weather and climate - short-term climate (monthly/seasonal forecasts) determined by patterns of variability.

Not just initial conditions

- Changes in the weather, and patterns of variability, occur all the time but the global climate has not changed over the last millennium. However, there have been some regional climate changes (e.g. expanding deserts, Greenland?).
- If small-scale processes could change the climate of a region then since there have been countless events at those scales would more regional climate changes have occurred?
- Perhaps small-scale processes can lead to the change the climate of a region but it happens very rarely. This would be very difficult to capture by any single model run (or small ensemble) however accurate.
- This is reassuring since it implies that the small scale variability does not change the climate, otherwise over the last millennium (say) the huge number of random changes would probably have led to significant fluctuations in the climate system.
- It may also be the reason why stochastic physics may work.

Variability

The global atmospheric circulation is observed to have a small number of patterns of variability on various time scales. (MJO, ENSO, NAO)

A climate modelling system needs to be able to reproduce the larger scale, long-lived patterns with the appropriate amplitude and frequency.

How do these patterns form?

Does what happens at small scales force these patterns?

Hypothesis

- Sub-grid scale details are not important for time scales longer than predictability time scale.
- Only require effects of sub-grid scales at truncation scale.

Conclusions and questions

- Running a climate model at 1km horizontal resolution (anywhere or everywhere) may not be worthwhile.
- Regional climate models as downscaling tools may be useful.
- High resolution models of some processes may also be needed (e.g. modelling of the larger glaciers such as Western Antarctic and Greenland).

Adaptive mesh refinement (AMR) - modelling issues

- Refinement strategies. Criteria (gradients, features, location, process) and cost.
- Spurious wave reflection and refraction from mesh inhomogeneity (Information propagating from high to low resolution)
- Maintaining balances where appropriate (geostrophic, hydrostatic, normal modes etc)
- Parametrizations scaling
- Monotonicity (non-negative constituents) and conservation

SYSTEMATIC ERRORS - TAYLOR DIAGRAM