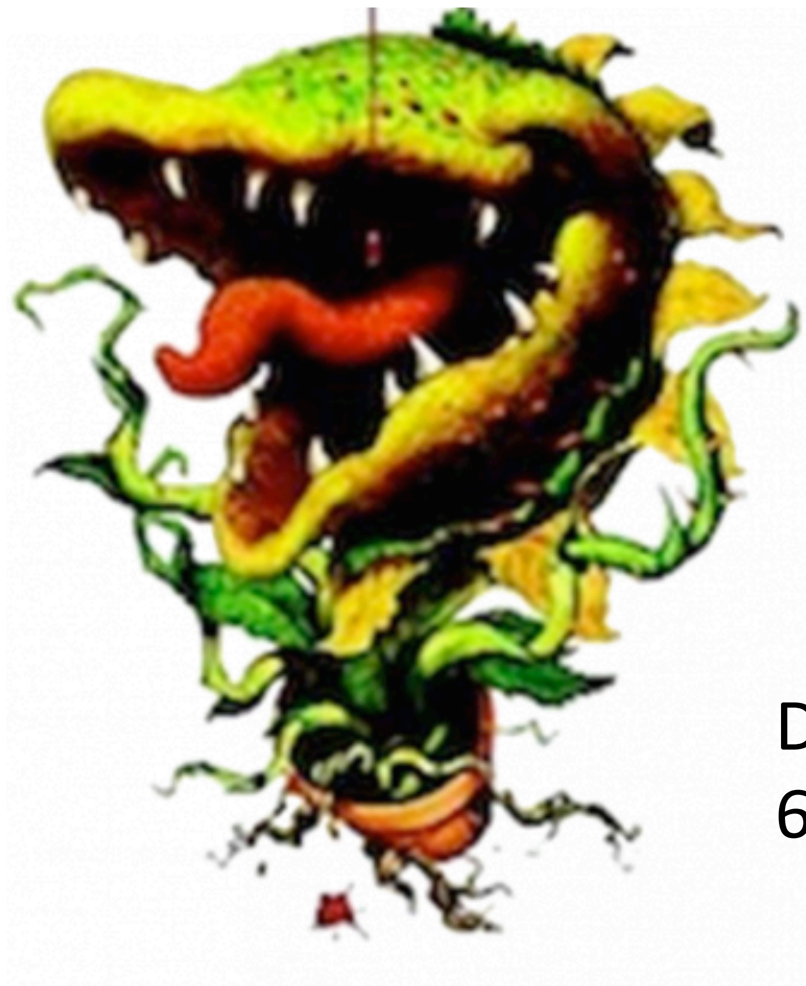
Resolution Sensitivity of Physical Parameterizations

By Peter Caldwell



With help from: Rich Neale, Phil Rasch, Chris Bretherton, Steve Klein, Chris Golaz, ...

DCMIP Meeting
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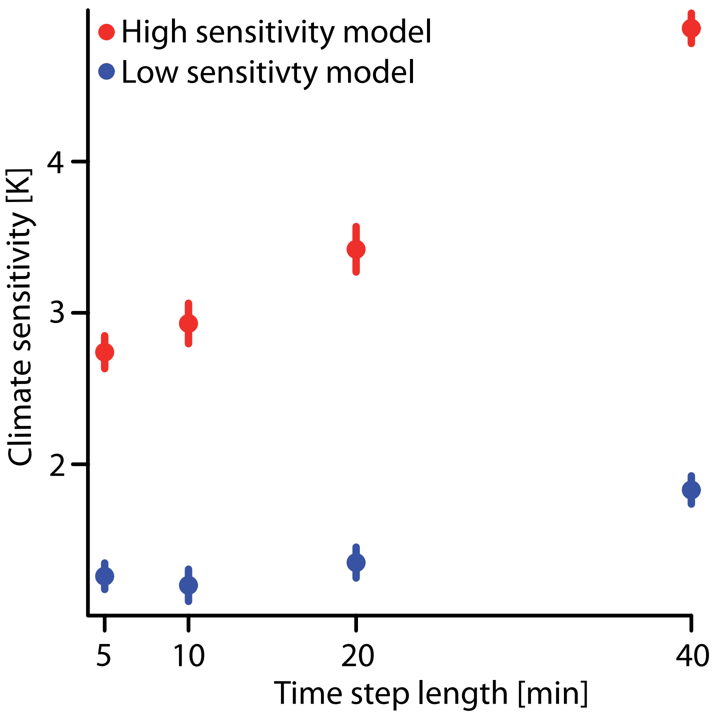
WHY SHOULD WE CARE?

- Resolution sensitivity and lack of convergence erode credibility of results
- If higher resolution vastly improves solutions, we are more likely to accept its expense
- Retuning our model to optimize performance at each resolution doesn't work with variable-resolution grids
- Changing resolution uncovers compensating errors

Equilibrium Climate Sensitivity

Our best index of the Earth's sensitivity to greenhouse gases is dependent on timestep!



Because changing parameter settings changes this sensitivity, we know the culprit is physics

Def: Equilibrium climate sensitivity = global-average surface temperature change after doubling CO_2 and letting the planet re-equilibrate

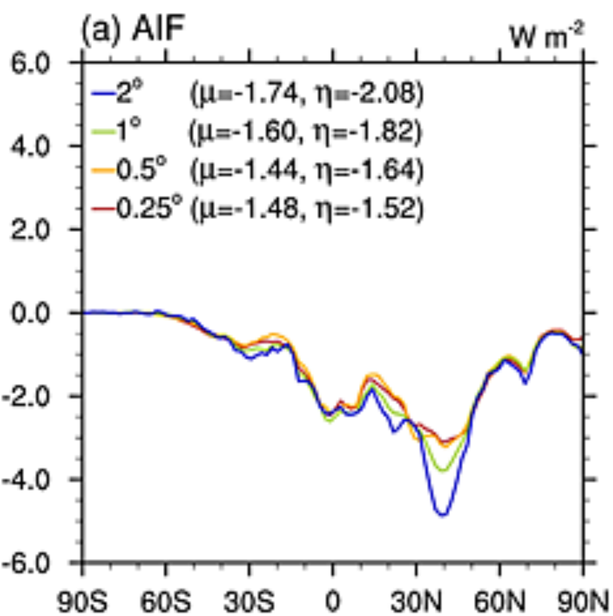
Fig: Impact of changing timestep on climate sensitivity in ECHAM5 model. High sensitivity and low sensitivity models differ only in values of a few tuning parameters from Klocke et al (2011). Figure Courtesy Daniel Klocke.

Aerosol Effects

Anthropogenic aerosol hinders our ability to estimate climate sensitivity from the historical record by cooling the planet. That cooling is also resolution dependent

For CAM5, Ma et al (2015) report:

- Anthropogenic emissions become more effective at creating cloud droplets (which increases cloud reflectivity) at finer Δx because anthropogenic aerosol number and SGS vertical velocity increase
- Extension of cloud lifetime by aerosol decreases at finer Δx because accretion (which increases with drop number) becomes more important



- **The net effect of these changes is that aerosol sensitivity decreases with Δx refinement**
  - this brings CAM5 better in line with observational estimates

Fig: Zonal-average aerosol Indirect Forcing (impact of anthropogenic aerosol on cloudiness-induced changes in top-of-atmosphere radiative balance) as a function of horizontal resolution. From Ma et al (2015) Fig. 3.

Aside: What are we talking about?

- Resolution sensitivity could refer to Δx, Δz, or Δt changes
  – they are related, but most people focus on Δx

- Sensitivity could mean:
  1. Does solution change at all?
  2. Does solution get better?
  3. ~~Is solution converging?~~ **Don't ask**
- Model could be:
  – ~~LES~~
  – ~~Weather~~
  – GCM

Mainly focusing on GCMs here

What Gets Better with Resolution?

- **<u>Topographic Precipitation/Snowpack/Streamflow</u>** (Pope and Stratton, 2002; Duffy et al 2003; Iorio et al, 2004; Smith et al, 2012; lots of others)
- **<u>Extreme Precipitation</u>** (Kiehl and Williamson, 1991; Déqué et al, 1994; Iorio et al, 2004; Wehner et al, 2010)
- **<u>Convective:Stratiform Rain Partitioning</u>**: Pope and Stratton, 2002; Hagemann et al, 2006; Bacmeister et al, 2014; Demory et al, 2014)
- **<u>Tropical/Extratropical Cyclones</u>** (Jung et al, 2006; Manganello et al, 2012; Jung et al 2012; Strachan et al, 2013; Bacmeister et al, 2014; Demory et al, 2014)
- **<u>Blocking</u>** (Matsueda and Palmer 2010; Jung et al, 2012; Berckmans et al, 2013)
- **<u>Variability</u>** (Stratton 1999; Hourdin et al, 2013)
- **<u>Sea Breeze Effects</u>** (Boyle and Klein, 2010; Schiemann et al, 2013)
- **<u>Vertical Moisture Gradient</u>** (Hagemann et al, 2006)

What do these features have in common?

What Gets Better with Resolution?

- **Topographic Precipitation/Snowpack/Streamflow** (Pope and Stratton, 2002; Duffy et al 2003; Iorio et al, 2004; Smith et al, 2012; lots of others)
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Ans: they are mostly related to improved topography or dynamics rather than parameterizations

Your mission:

Parameterize the effect of all subgrid processes and their interactions using available grid-scale variables

Outline

1. Including Unresolved Effects
   a. Cloud Fraction
   b. Hydrometeor Area Fraction
   c. Process Rates
   d. Covariances
   e. Vertical Overlap
   f. Radiation
   g. Vertical Grid Effects
   h. Convection
   i. Handoff between Convection and Large-Scale
2. Correct Response to Resolution Change
   a. Convection
   b. Microphysics
   c. Temperature
3. Conclusions/Discussion

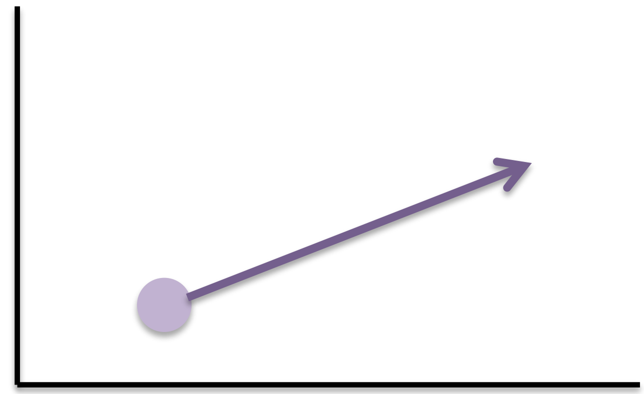


Fig: Like a Taylor series, we first 1). try to include SGS effects at all, then 2). we try to get the correct response to resolution change.

Def: SGS = sub-grid scale

Fractional Cloudiness

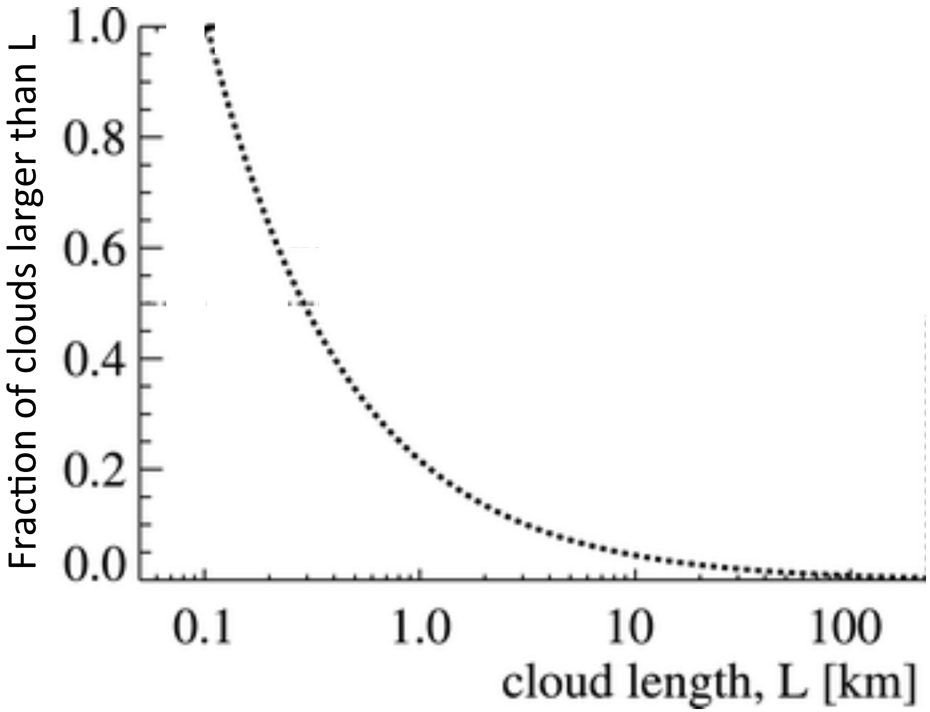


Fig: Fraction of global clouds of given size. From Wood and Field (2011) Fig 6.

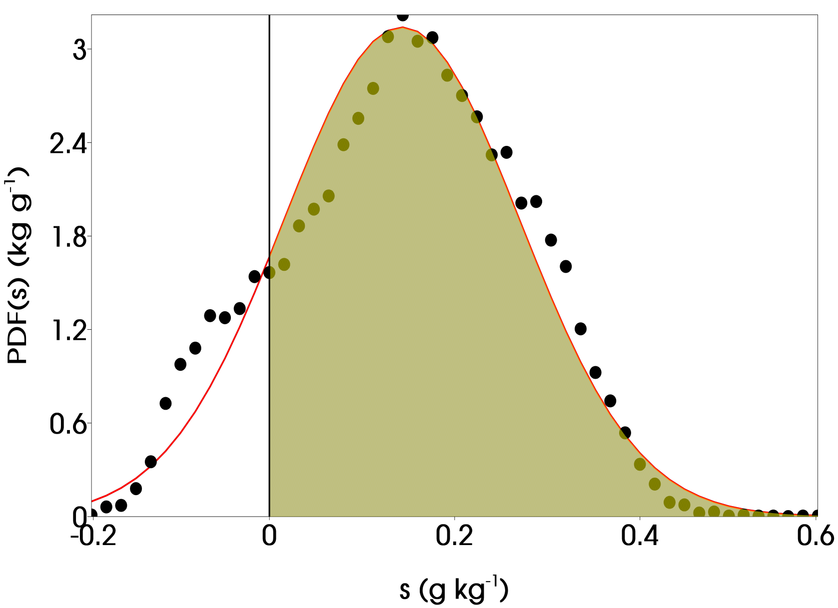
- High-resolution models (like LES or WRF) assume cells are 100% cloudy where cell-average relative humidity (RH) > 100% and are otherwise cloud-free
- Most clouds are smaller than 100 km (a typical GCM grid size), so models assume a *fraction* of each cell is cloudy

This is the simplest form of parameterized sub-grid variability

How to Parameterize Cloud Fraction?

Cloud fraction can be modeled prognostically, as an empirical fit to RH, or using an assumed PDF (below)

- SGS cloud variations imply subgrid humidity variations!
- Handling SGS cloudiness and condensate is the job of macro*physics*
- **Appropriateness of assumptions depends on resolution**



mixing ratio saturation mixing ratio

Let $s = q - q_s$. Then

$$\boxed{\text{Cloud Fraction} = \int_0^\infty PDF(s)\,ds}$$

$$\boxed{\text{Cloud Mass} = \int_0^\infty s \cdot PDF(s)\,ds}$$

Fig: Example PDF from ASTEX observations (dots) with Gaussian fit (line) and cloud fraction (shaded area).

Cloud Fraction is Not Enough

SGS variability in hydrometeors is also important

- Spreading rain over the cloud-free portion of cell causes too much evaporation and not enough autoconversion and accretion (see Fig)
- Models are still grappling with hydrometeor fraction parameterization

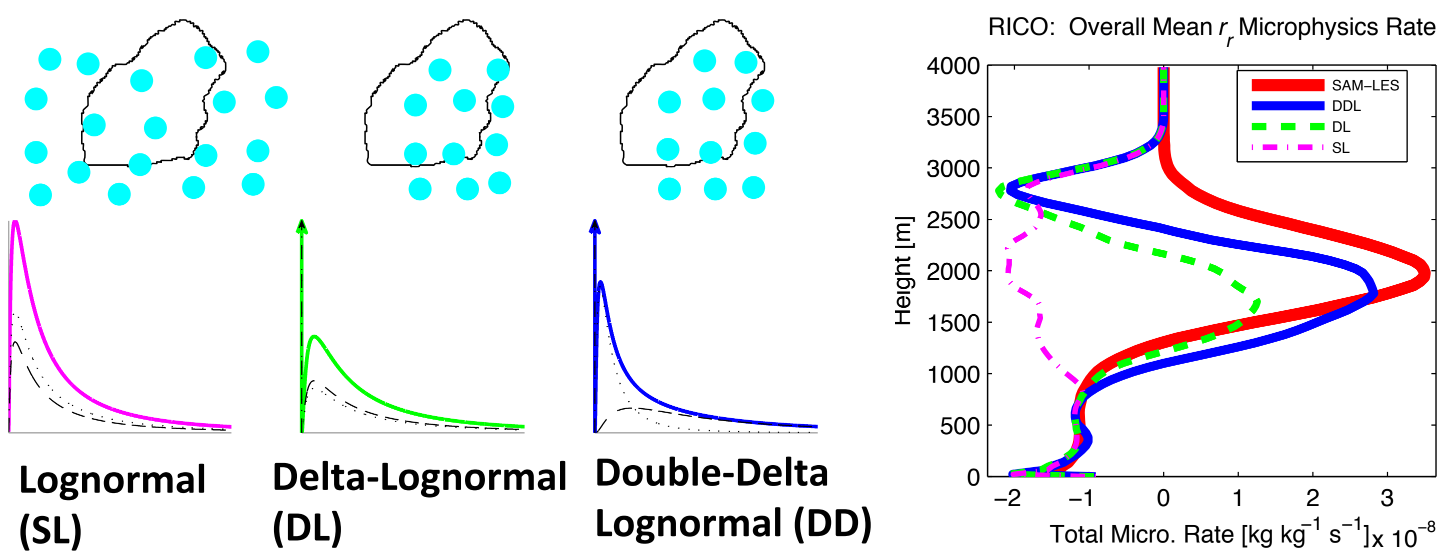


Fig: Left-hand panels show possible choices for CLUBB rain mass PDF. Right-hand panel shows impact of each choice on CLUBB single-column simulation of RICO (shallow convection) test case. From Fig 1 and 7 of Griffin and Larson (2015)

Inhomogeneity Affects Process Rates

Failure to include SGS variability in nonlinear processes causes large errors (see Fig)

- Nonlinear processes include:
  - optical depth for radiation
  - many aspects of microphysics
- Assumptions about subgrid structure are needed for:
  - cloudiness, humidity, cloud water, rain water, ice water, cloud drop number, cloud ice number, rain drop number, snow number, etc
- Vertical variability is usually ignored

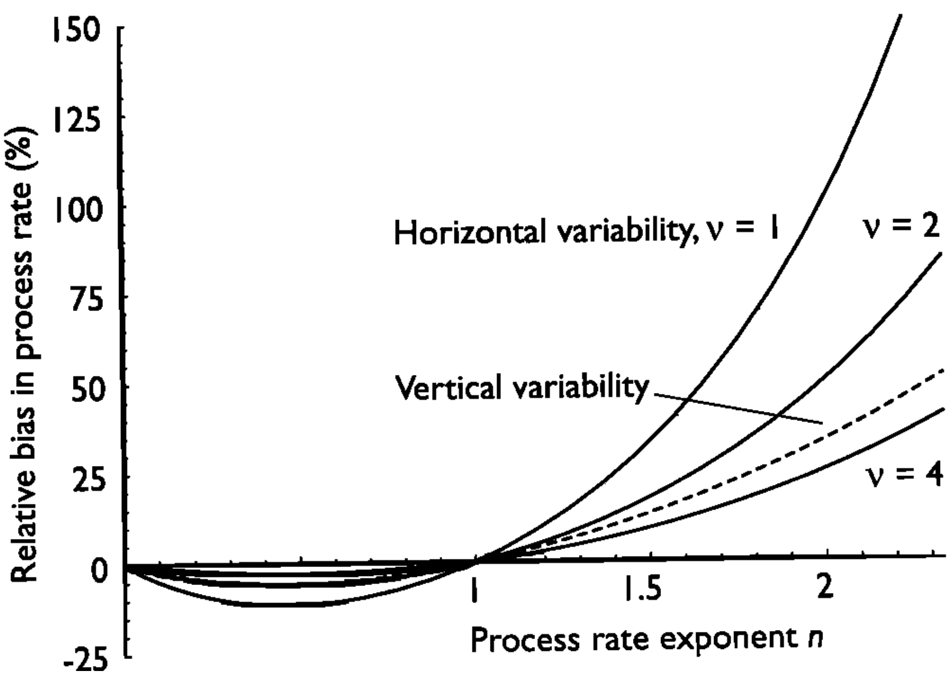
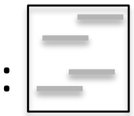
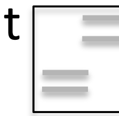
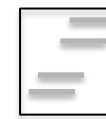


Fig: Bias in calculation of microphysical process $P \propto q^n$ due to neglecting sub-grid variability in q. Horizontal variability is modeled as a gamma distribution whose variations decrease with increasing ν. Vertical variations are assumed to be linear. From Fig 1 of Pincus and Klein (2000)

Vertical Overlap

Covariance between adjoining grid cells is also important

Popular methods of aligning clouds vertically are:

1. random: positioning of cloud within adjacent cells is uncorrelated: 
2. maximum-random: clouds in adjacent cells are maximally overlapped but clouds separated by clear sky are randomly overlapped: 
3. decorrelation lengthscale: correlation between layers decreases as a function of their distance: 

Random and maximum-random overlap have large resolution sensitivity (see Fig), yet the decorrelation lengthscale is often not used.

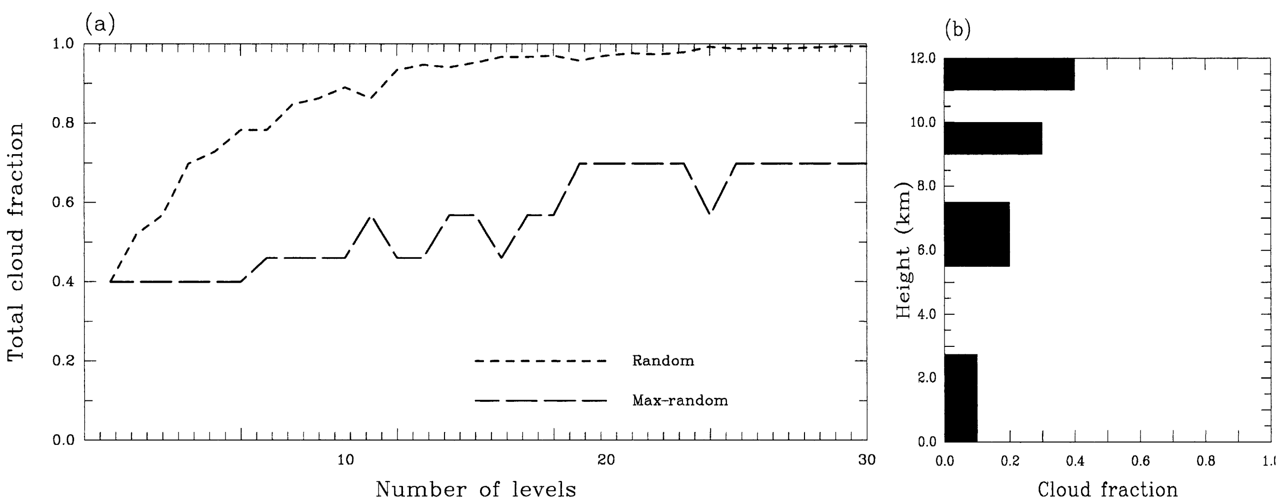


Fig: Total cloud fraction as a function of # of model levels for random and maximum-random overlap assumptions. From Fig. 1 of Bergman and Rasch (2002).

Subcolumns: the Solution?

- SGS variability and overlap in clouds can be included by drawing samples from an assumed PDF
- ~all modern radiation schemes do this (McICA)
- This method is currently being explored for CAM microphysics (Thayer-Calder et al (2015)

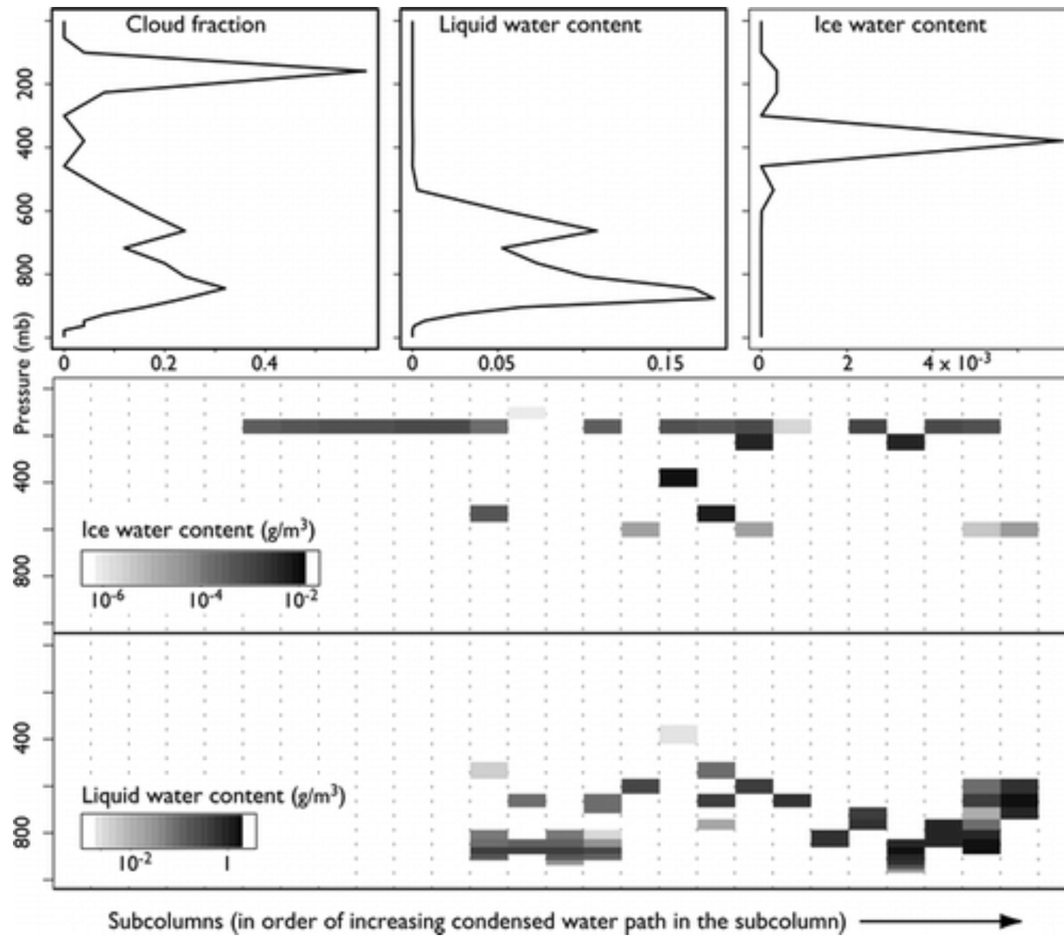


Fig: Illustration of liquid and ice content in subcolumns (bottom panels) generated from cell-average cloud fraction, liquid water content, and ice water content (top panels). From Fig. 1 of Pincus et al (2006)

Radiation

- Strong radiative cooling in the ~20 m below a cloud topped inversion is an important source of turbulence missed by coarse models (see Fig)
  - Some turbulence schemes explicitly handle cloud-top radiative cooling (e.g. Lock et al, 2000; Bretherton and Park, 2009)
- Radiation through the sides of clouds (3d effects) is also ignored
  - Cole et al (2005) show this to be a small effect

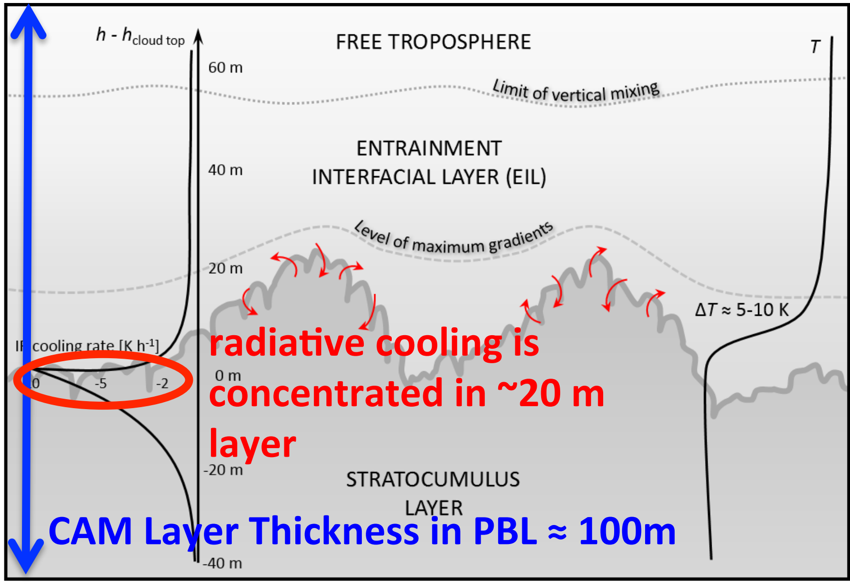


Fig: Diagram of stratocumulus cloud structure from https://www.uni-leipzig.de/~strahlen/web/research/en_index.php?goto=azoren

Convection

Convective parameterizations handle SGS vertical transport in condensing plumes... Their entire purpose is to compensate for inadequate resolution.

Typical assumptions (which fall apart at fine resolution):

- Updrafts occupy a small fraction of a column
- Compensating subsidence is contained within the convecting column
- Convective timescale is shorter than that of resolved forcing so the quasi-equilibrium assumption works
- There are many convective clouds within each grid cell
- Simple microphysics are sufficient
- Triggering comes from a model level rather than a geometric height

Handoffs between Schemes:

- The code exercised by explicit treatment of convective clouds (dynamics, macrophysics, and microphysics) is very different than that within convective schemes
  - Resolving convection causes weird sensitivities
  - For example, stratiform microphysics is sensitive to aerosol but convective schemes aren't (see Fig)

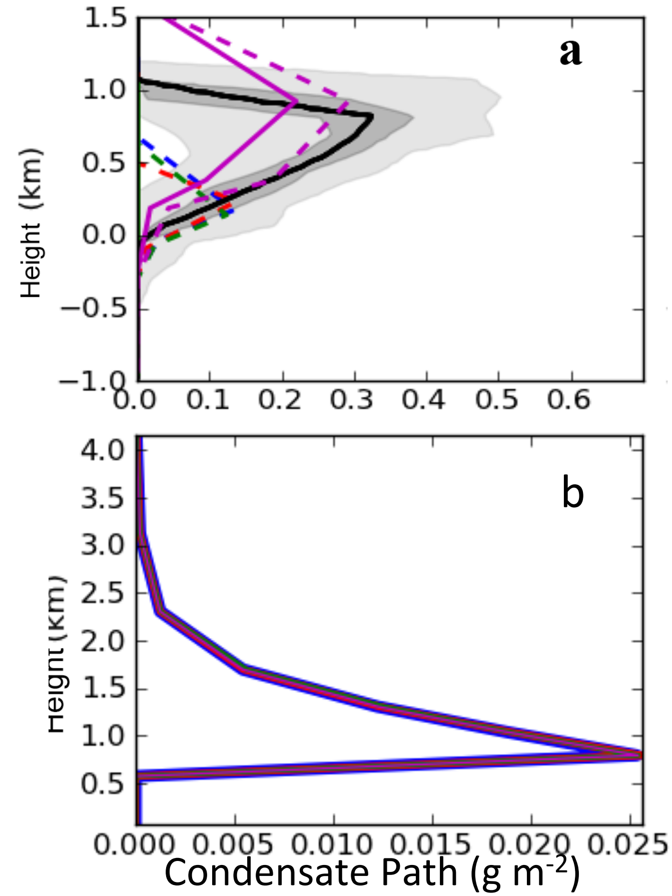


Fig: Impact of different aerosol treatments (colored lines) on condensate path for a). MPACE-B mixed-phase stratiform cloud case and b). RICO shallow convection case. From Habtezion and Caldwell (2014).

Definitions:

The ***gray zone*** is the set of resolutions where processes are partly resolved and partly parameterized

- Developing parameterizations for this regime is hard
- All parameterizations have a gray zone

Scale-aware parameterizations work correctly across the spectrum of resolutions

- they must naturally turn off as their process becomes resolved

Resolution Sensitivity of Convection

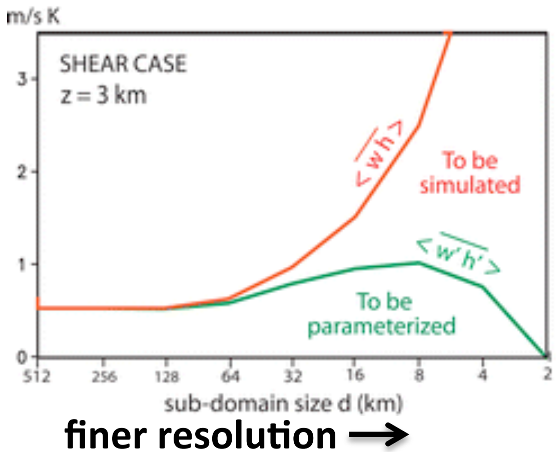


Fig: total moist-static energy (h) transport (in red) and sub-grid scale transport which must be parameterized (in green) based on averaging CRM data to the scales on the x-axis. Note results are taken over updrafts only. From Arakawa and Wu (2013) Fig. 6.

- Parameterized convection should turn off as resolution increases (left figure)
- It often doesn't (blue line in right figure)
- Arakawa and Wu (2013) and Xiao et al (2015) suggest ways to make convection scale-aware

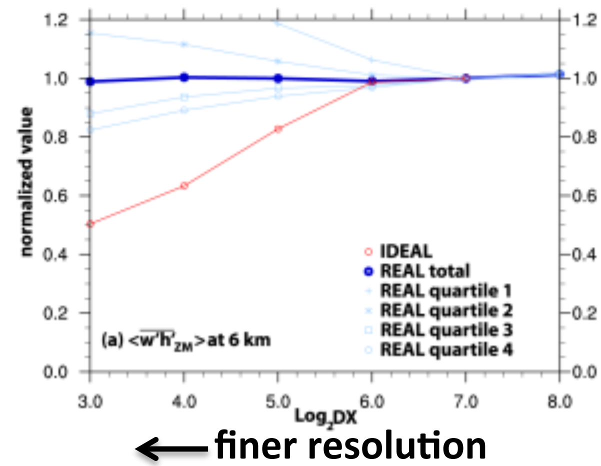
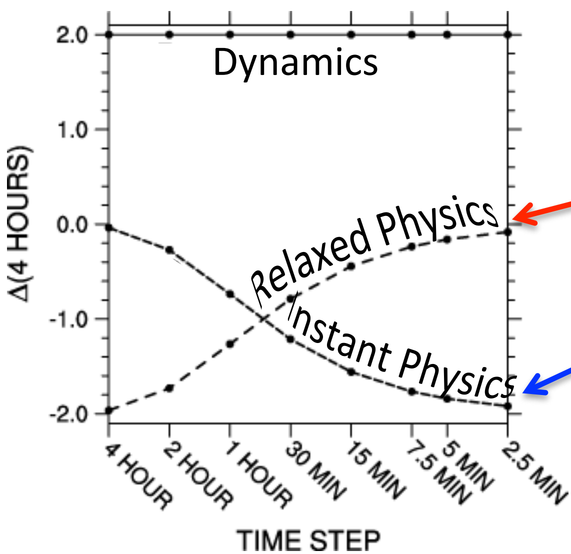


Fig: Parameterized h transport from Zhang-McFarlane convection scheme forced by CRM input. 'IDEAL' is case above, 'REAL' is temporally-varying. Results are averaged over entire grid. From Xiao et al (2015)

Method 1 for isolating resolution sensitivity: drive your parameterization with aggregated cloud-resolving model data

Example: Convective Timescale

Combining instantaneous processes and processes with a fixed timescale is a recipe for Δt sensitivity



Relaxation timescale >> Δt ⇒ relaxed processes shut off and instant physics must pick up the slack.

This causes massive (bad) changes in stability, vertical motion, and precipitation

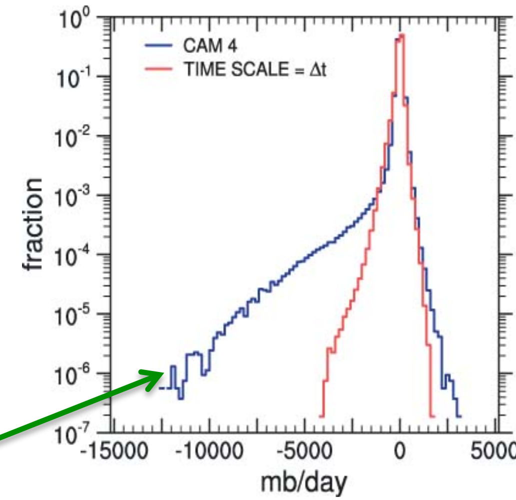


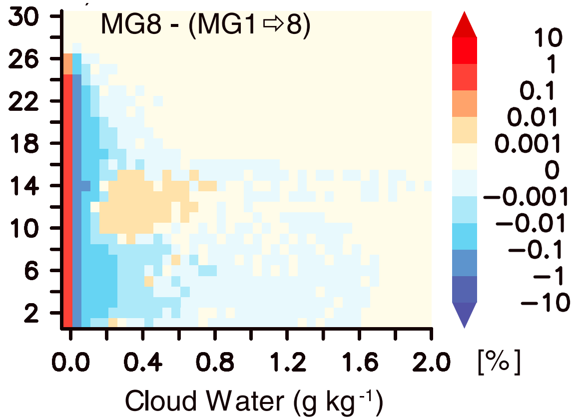
Fig: Change in q over 4 hours from a simple model combining physics relaxing to equilibrium w/ 1 hr timescale and instantly adjusting physics. From Williamson (2012)

Method 2: identify problems, track them to source

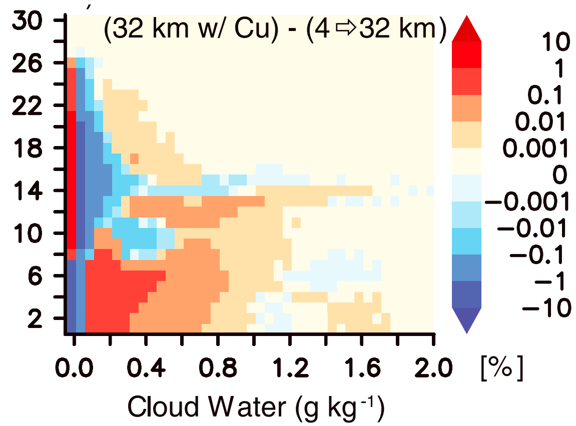
Fig: Vertical velocity in grid-point storm cell using default and reduced-timescale convection. From Williamson (2012)

Resolution Sensitivity of Microphysics

Effect of Coarsening Micro Only



Effect of Running at Coarser Res

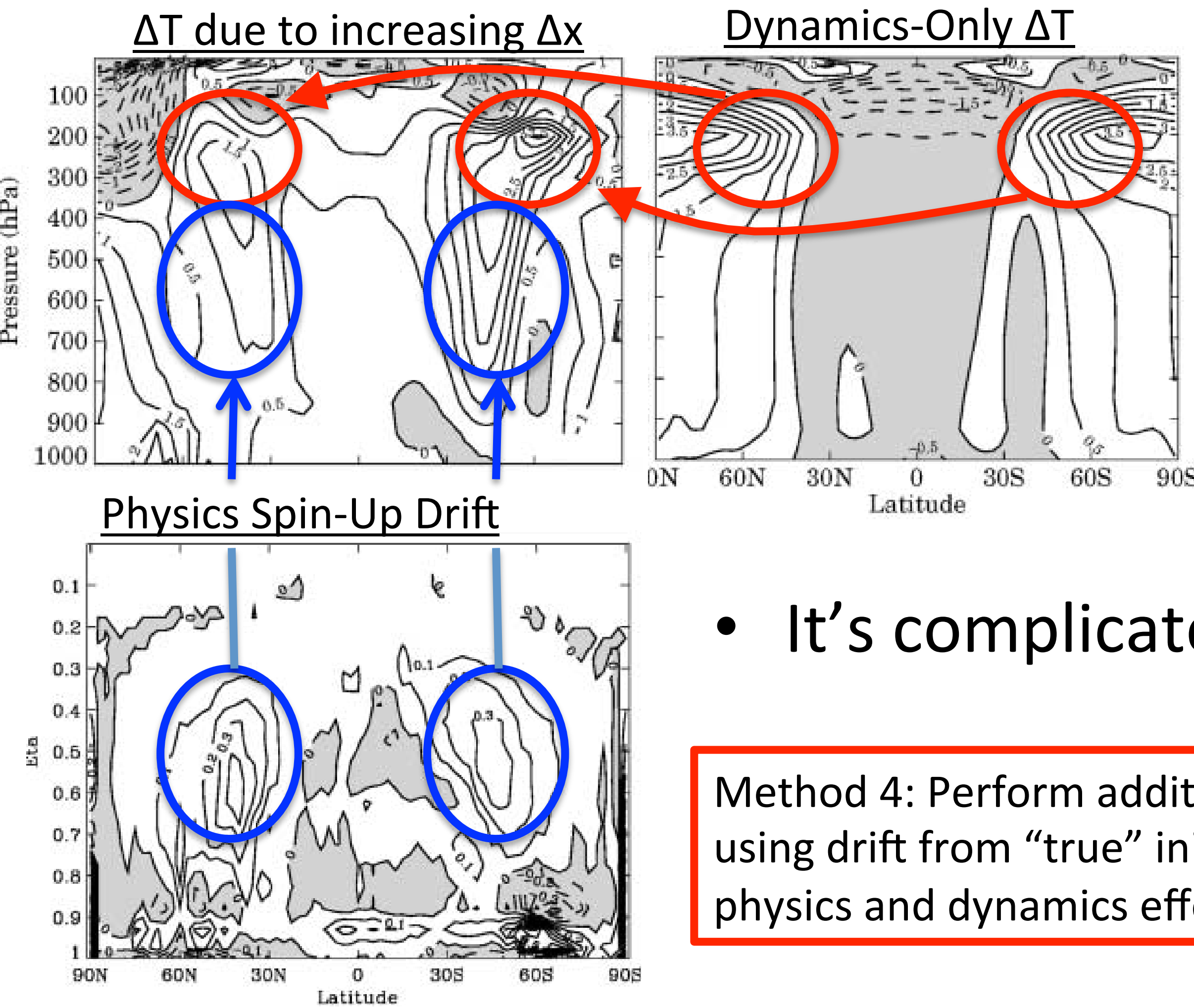


- Computing processes offline using coarsened data isolates individual process sensitivity
  - For Gustafson test case, microphysics is not the main source of CAM5 resolution sensitivity (top – bottom panels)
  - Microphysics decreases cloudiness at higher resolution

Method 3: run model at high resolution, call process of interest again diagnostically w/ coarser input

Fig: Change in PDF (in color) of cloud water (x axis) for each WRF-CAM model level (y axis) due to running the model at Δx=4 km instead of 32 km (top panel) or from offline microphysics calculations using 4 km data aggregated to 32 km (bottom panel). From Gustafson et al (2013) Figs 7 and 8. Simulations are for MC3E campaign at ARM Southern Great Plains site.

Tracking Down Sources Of Sensitivity



- The reason for temperature changes varies by region

- It's complicated!

Method 4: Perform additional simulations - particularly using drift from "true" initial conditions – to separate physics and dynamics effects.

Fig: Temperature (T) change in HadAM3 due to increasing Δx from N48 (~3°) to N144 (~1°). Panel a is net effect, panel b is effect in dynamics-only simulations, and panel c is the resolution effect of drift from ECMWF initialization values due to physics over the first day of simulation. on day-1 warming initialized from ECMWF. From Pope and Stratton (2002)

How to Deal With Resolution Sensitivity?

1. Use a global Cloud Resolving Model (CRM)
   a. NICAM team has done this, but can only afford short runs
2. Use superparameterization: replace column physics with a CRM, use coarse GCM for dynamics
3. Create parameterizations that are scale-aware
   a. Arakawa and Wu (2013) and Xiao et al (2015) provide scale-aware extensions for convection

Fig: to create a scale-aware model, first find a unicorn...

Lessons Learned:

- Physics parameterization affects things we care about (like climate sensitivity and aerosol effect)
- Physics is tasked with capturing SGS effects
  - this task is impossible/physics developers are heroes
  - there are a huge number of SGS effects to deal with
    - many of these are really hard/ignored in current models
- Scale-awareness is hard/work is ongoing
  - Identifying resolution sensitivity is easy. Figuring out why is hard
  - variable-resolution grids are problematic because of resolution-dependent parameters
    - parameterizing partially-resolved processes is particularly difficult
- Improved resolution sensitivity will come from trial + error and lots of hard thought
  - best practice = run all new parameterizations at doubled Δx, Δz, and Δt before acceptance?

The Resolution Paradox:

We *want* results to change as we increase resolution because otherwise the added expense would be pointless.

We *don't* want results to change as we coarsen resolution because that would mean our parameterizations are inadequate.


That's all Folks!

Covariances Matter

Process calculations also require covariances between variables

- Just keeping track of SGS variations in cloud quantities is not enough – covariances matter too (see Fig)
- There are a lot of covariances to keep track of (see table)
- Atmospheric models generally ignore these covariances
- Variances and covariances change as a function of resolution
  – at fine resolution, quantities are uniform across cell and SGS variations can be ignored

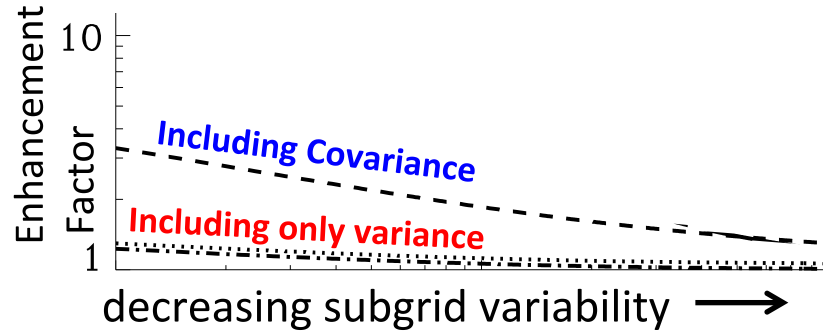


Fig: Fractional enhancement of accretion when covariance between cloud and rain water is included or excluded as a function of cloud water variability. Modified from Lebsock et al (2013)

	Variate						
	W	*QS*	*NS*	*QI*	*NI*	*QC*	*NC*
W	*1.00*	0.65	0.73	0.44	0.55	−0.01	0.34
QS	0.65	*1.00*	0.95	0.29	0.43	0.06	0.14
NS	0.73	0.95	*1.00*	0.49	0.60	0.04	0.21
QI	0.44	0.29	0.49	*1.00*	0.77	−0.08	0.39
NI	0.55	0.43	0.60	0.77	*1.00*	0.28	0.29
QC	−0.01	0.06	0.04	−0.08	0.28	*1.00*	0.09
NC	0.34	0.14	0.21	0.39	0.29	0.09	*1.00*

Table: Correlations between important microphysical variables from a mid-cloud layer of an ISDAC mixed-phase cloud LES simulation. Taken from Table 1 of Larson et al (2011)

Snapping to vertical levels

- Forcing cloud boundaries to lie on cell edges causes problems with coarse vertical resolution
  - Creates noise and large response to small changes
  - Making cloud-top the bottom (or top) of a stable layer causes under- (or over) prediction of liquid water path (Grenier and Bretherton (2001)
- The CAM5 turbulence scheme attempts to interpolate the inversion to avoid this (middle panel below)

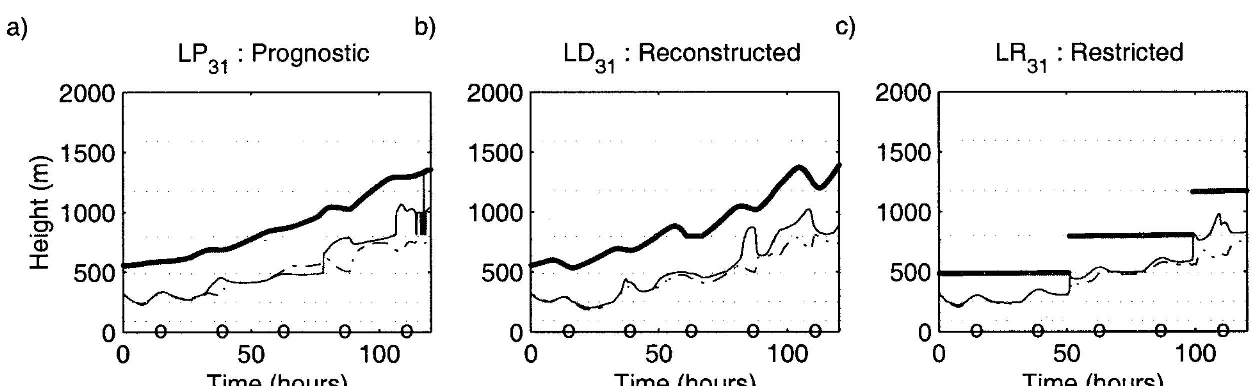


Fig: Cloud boundaries using different methods for calculating inversion height.From Grenier and Bretherton (2001) Fig 15.

Example: Turbulent Mountain Stress

- Turbulent Mountain Stress (TMS) is an enhancement to the surface drag parameterization meant to capture low-level drag from orography in CAM5.

⇒including TMS at high resolution degrades performance (see Fig)

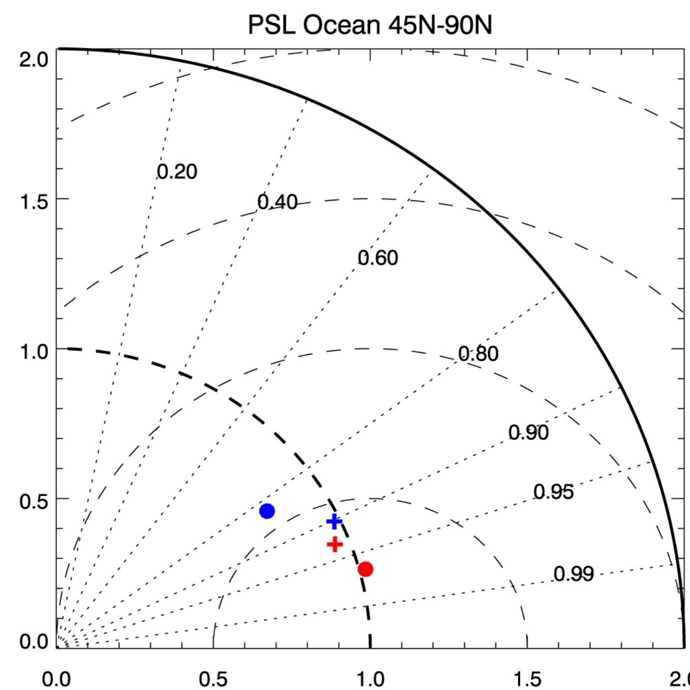
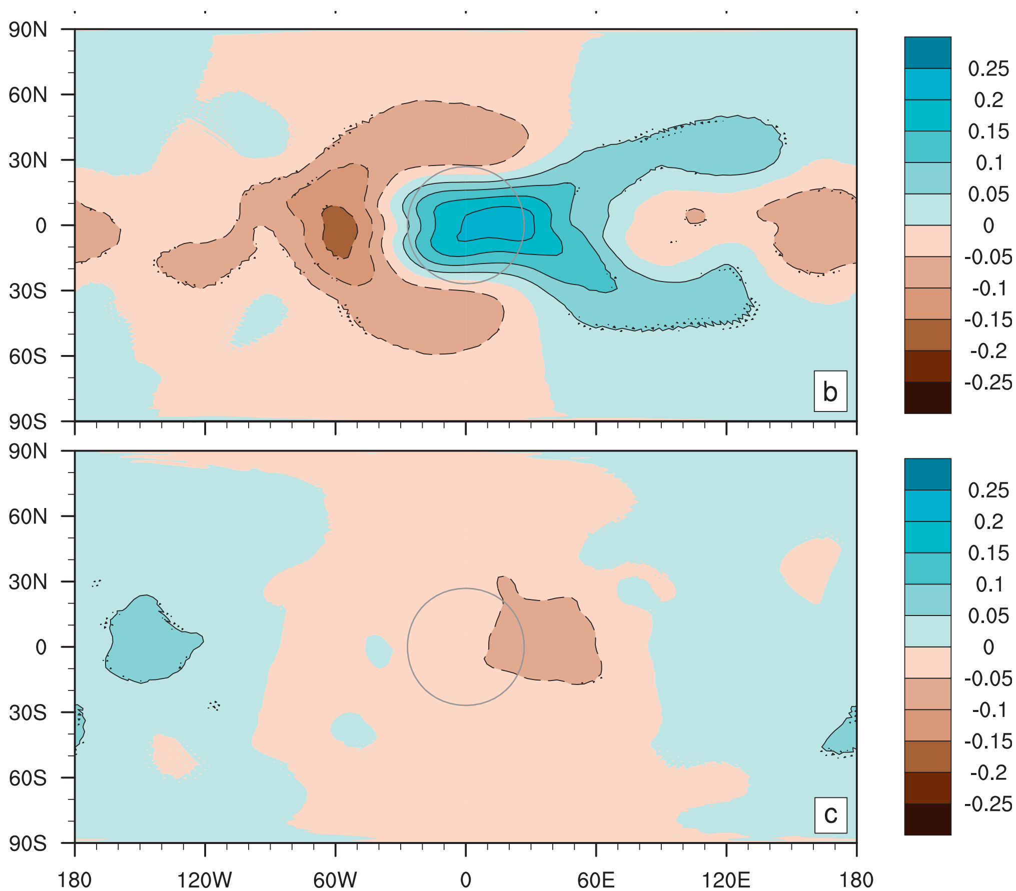


Fig: Taylor diagram for oceanic sea-level pressure at high northern latitudes. Blue symbols indicate CAM4 results and red symbols indicate CAM5 results. Filled circles show results for 0.9 × 1.25 resolution and crosses indicate 0.23 × 0.31 resolution. From Bacmeister et al (2014) Fig. 2.

Example: Variable Resolution

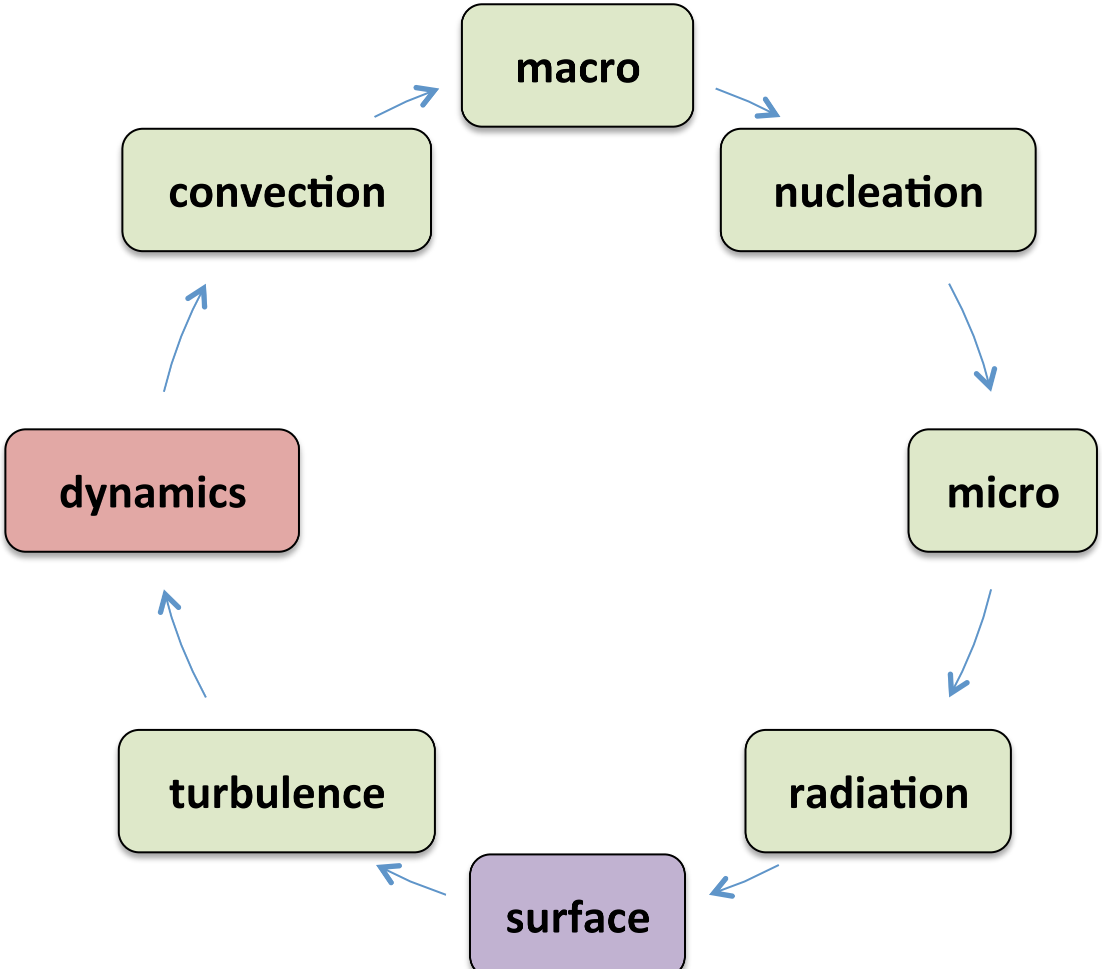
Climate models contain many parameters whose values are chosen to maximize skill for a particular resolution.



- Variable-resolution grids require a single tuning for multiple resolutions...
  - Getting rid of resolution-sensitive parameters is an active area of research
  - Is the cost:benefit of reformulating schemes worth it?

Fig: 200 mb eddy velocity potential for MPAS-A aquaplanet simulations with regional refinement in circled area. Panel A uses full physics and panel B uses Held-Suarez idealizations. From Rauscher et al (2013)

Processes in CAM5



Δx Sensitivity in CAM4 vs CAM5

- This is phys effect b/c all simulations run w/ same dynamics

- I don’t know why CAM5 is better in cloudiness and worse in rain than CAM4… figure this out before talk

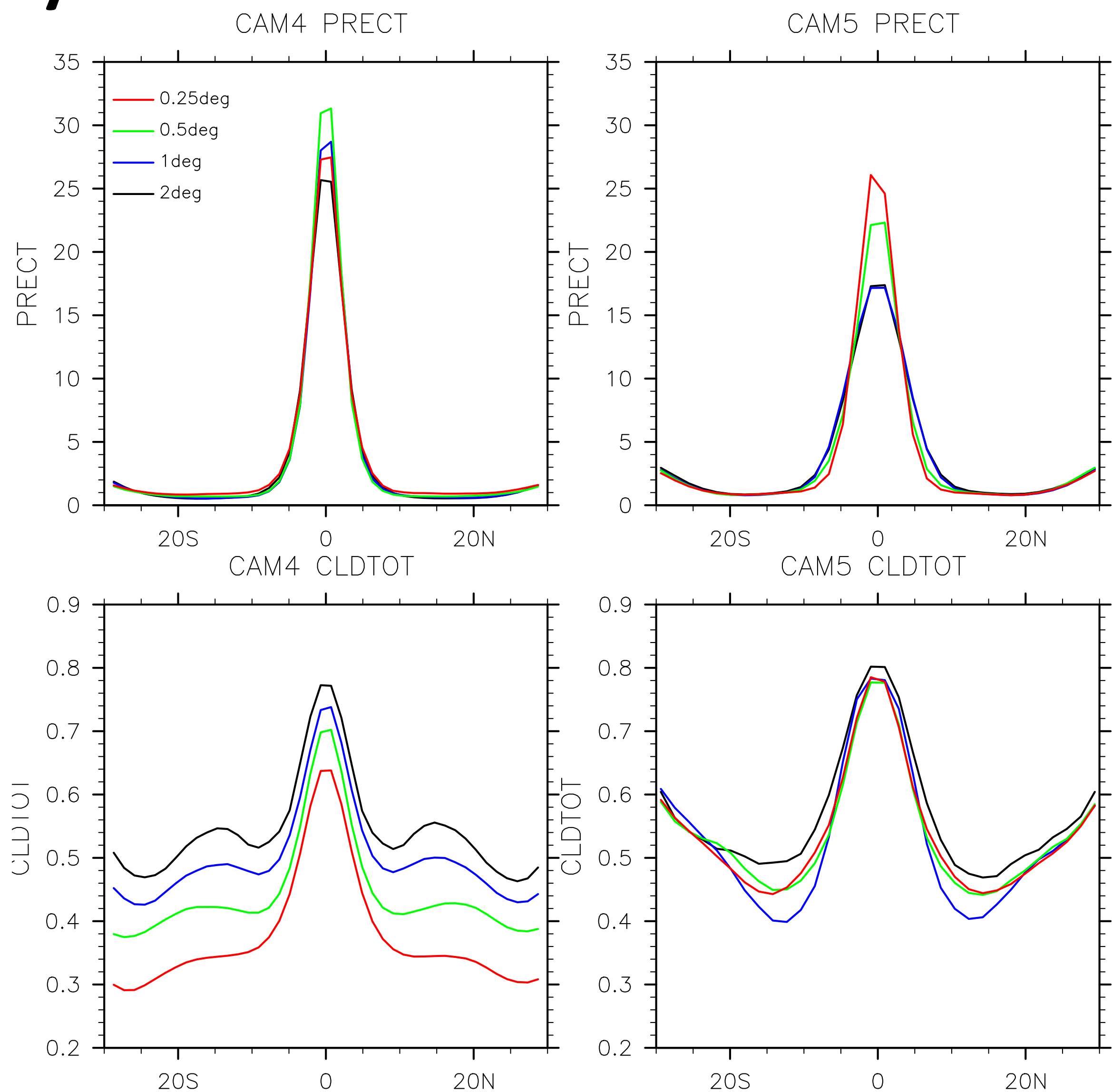


Fig: Stuff from aquaplanet simulations using CAM4 and CAM5 from Rich.

Sensitivity of CAM4 ShCu to Vert Res

- Point here is that Hack sucks. I don't understand the physical reason.
- Point out that UW ShCu starts its parcel calculations from average of bottom 2 layers rather than a geometric height?

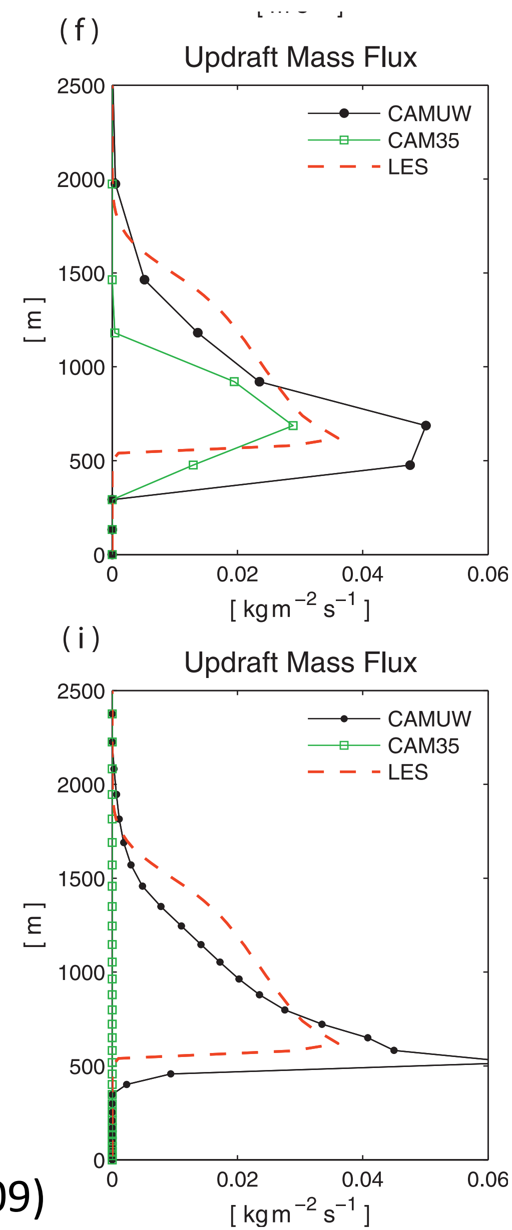


Fig: From Park and Bretherton (2009)