



Hierarchical Development

Increasing Marine Stratocumulus Cover to Reduce
Ocean Heating in a Global Model

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Model Development at ECCO

- Hierarchical System Development (HSD) primer
- HSD in action:
 - SST biases in global coupled predictions
 - Building a new boundary layer scheme
 - Impact on predictions of stratocumulus clouds
- Application of HSD to other problems

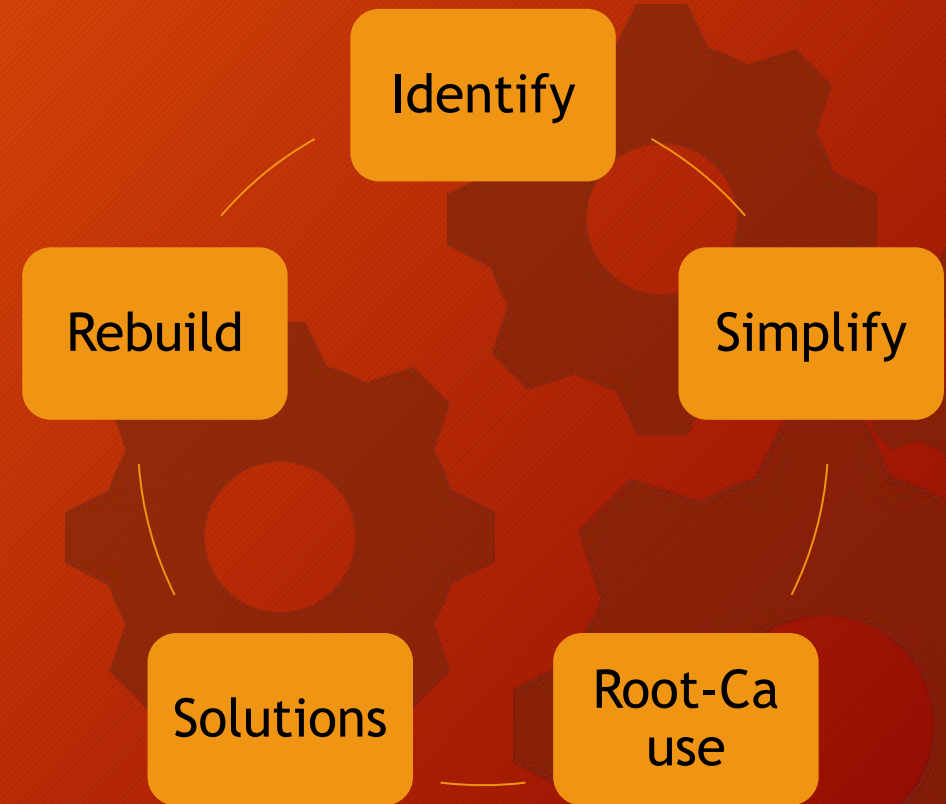


Stratocumulus clouds from the [Cloud Appreciation Society](#).

Hierarchical System Development

The HSD workflow follows steps:

1. Identify problems in a complex system
2. Reduce dimensionality by introducing constraints
3. Complete a root-cause analysis in the low-order system
4. Identify and introduce potential solutions
5. Reintroduce complexity



Goals of HSD

Prioritized

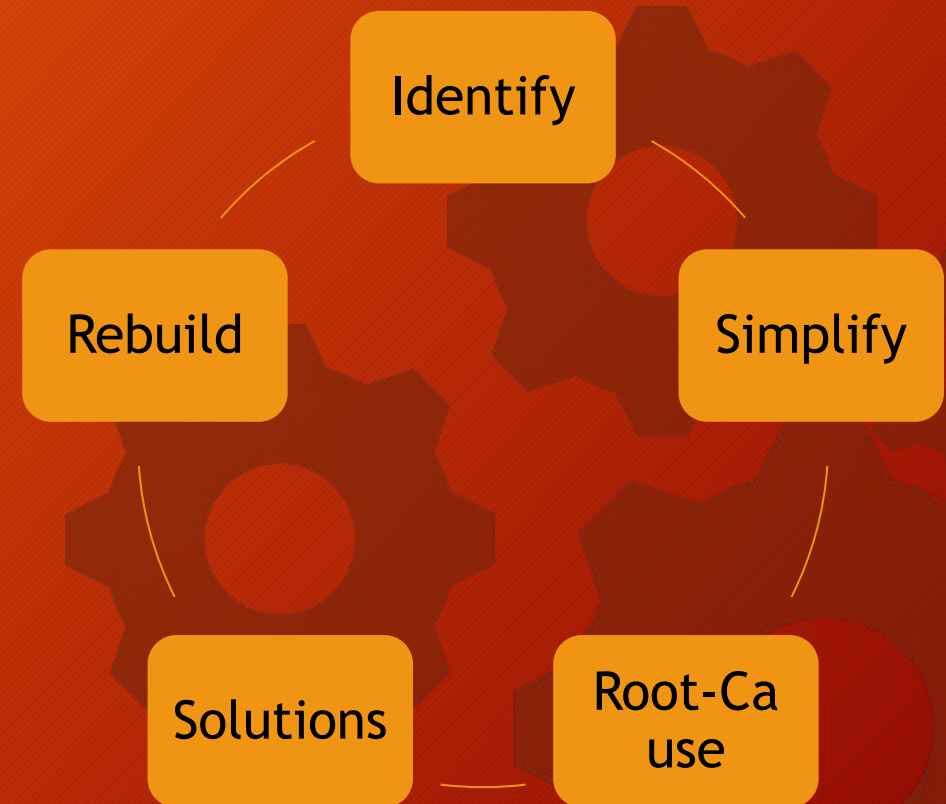
- Working on important / user-relevant problems
- Strategic approach to model development

Efficient

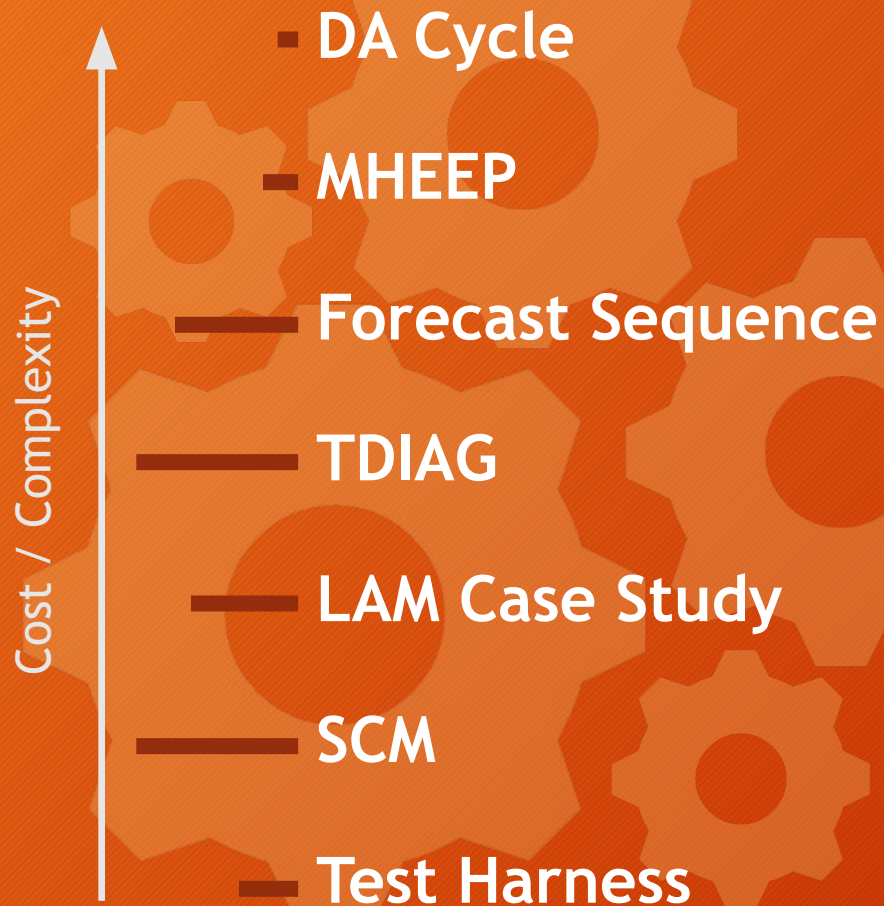
- Optimize use of limited development resources
- Confirm sensitivity as complexity reintroduced

Constrained

- Develop process-level understanding
- Avoid introducing compensating errors



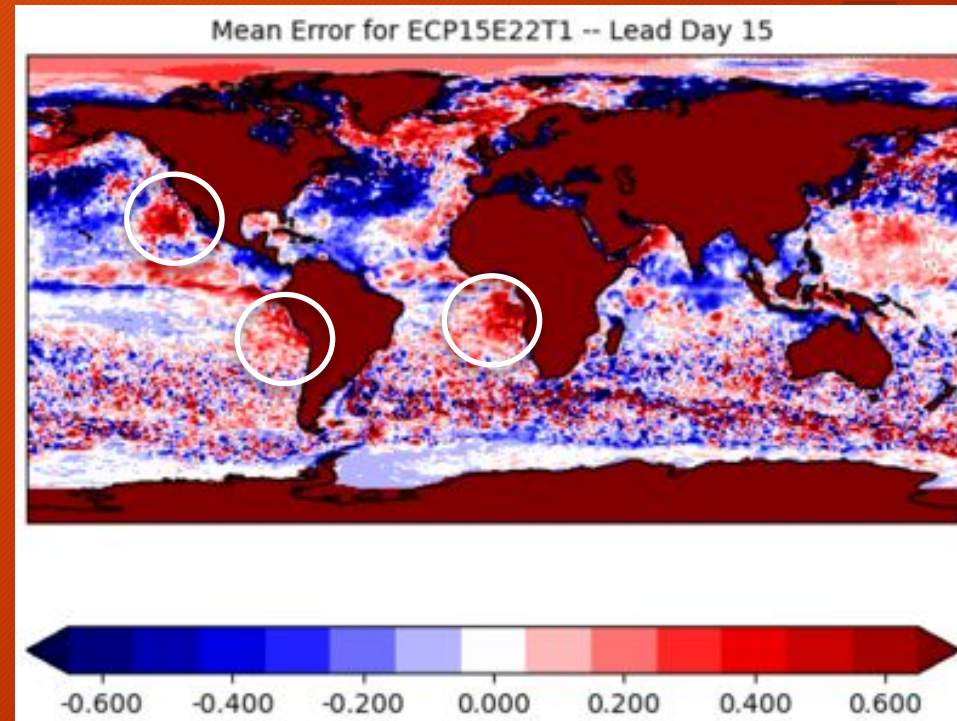
Implementation of HSD at ECCC



- We use a hierarchy of model complexity to implement HSD at ECCC
- Each step in the hierarchy:
 1. Increases our ability to understand problems at the process level
 2. Eliminates degrees of freedom
 3. Reduces computational cost and turnaround time
- Projects will use different combinations of these steps

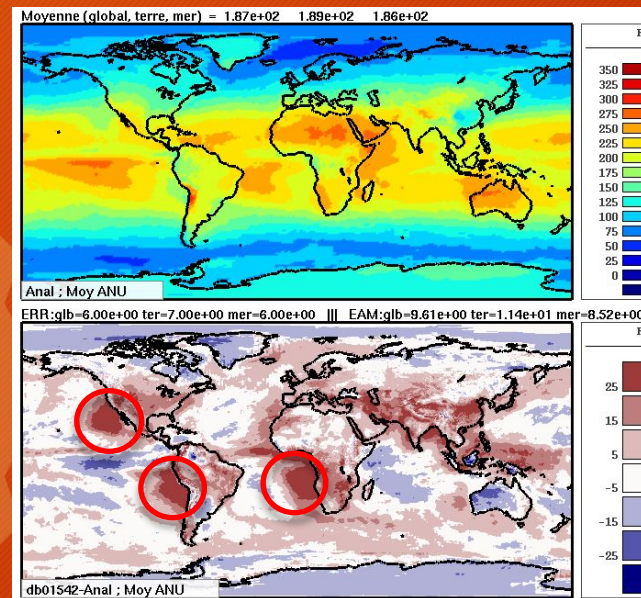
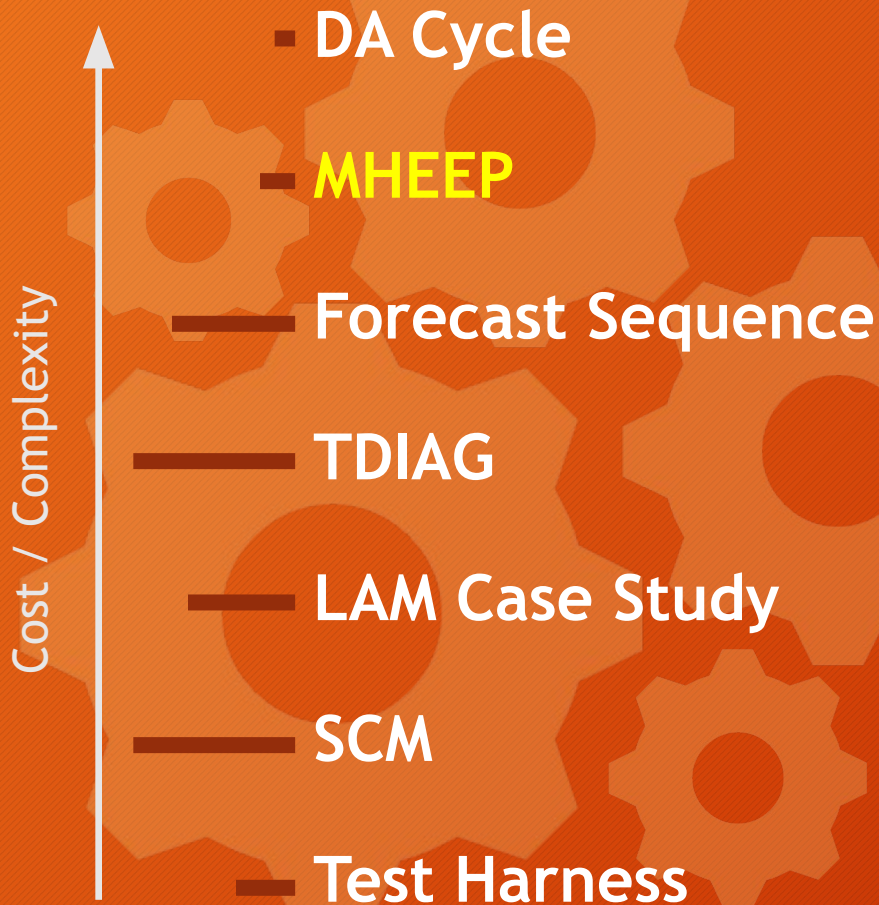
HSD Example: Stratocumulus Clouds

- Global deterministic and ensemble forecasts at ECCO are coupled to NEMO/CICE
- Ocean-model developers report overly warm sea surface temperatures (SSTs) in maritime stratocumulus (Sc) regions
- Seasonal cycle to the error, but it is persistent from run-to-run



Mean SST error for July-August 2022 after 15 d in the operational global ensemble prediction system.

Sc Clouds in MHEEP (Model Climate)



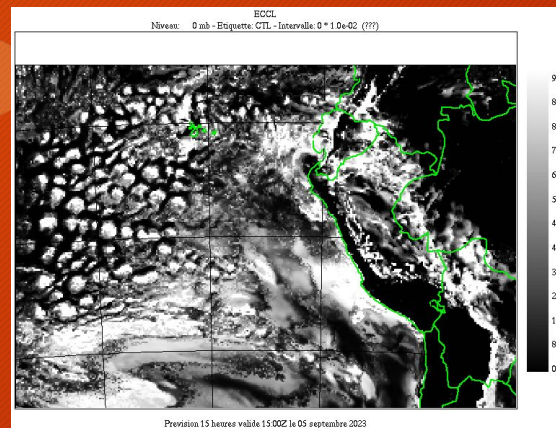
Annual-mean surface solar radiation from OAflux (top) and difference model-obs (bottom).

Excessive annual-mean surface solar radiation is diagnosed in the AMIP-type MHEEP protocol with forced SSTs.

This is evidence of an atmospheric problem and gives us an evaluation metric.

Sc Clouds in a Small LAM

- Cost / Complexity ↑
- DA Cycle
 - MHEEP
 - Forecast Sequence
 - TDIAG
 - LAM Case Study**
 - SCM
 - Test Harness



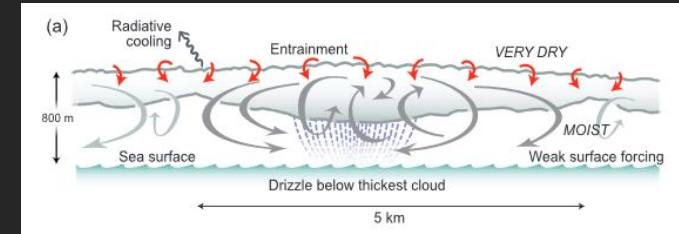
Observed (top) and LAM-predicted low-level cloud cover (bottom) after 15h in a small LAM.

Missing Sc cloud cover is reproduced in a short-integration LAM on a global grid subdomain.

This configuration will be used to test changes in the 3D model.

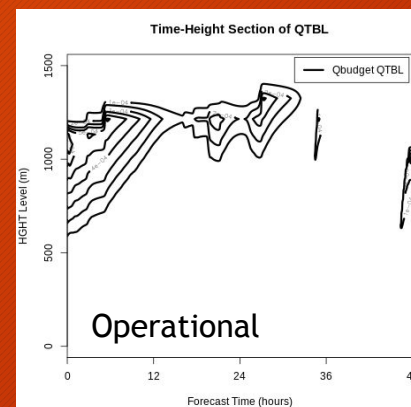
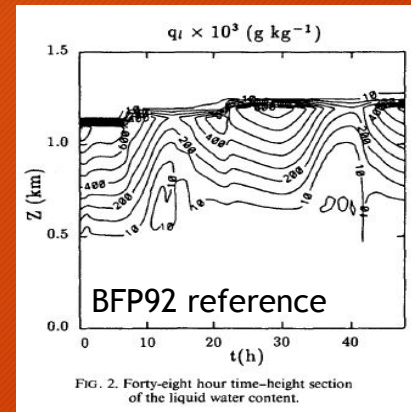
Convective “blobs” are a secondary objective.

Sc Clouds in the SCM



Marine Sc schematic (Wood 2012).

- Cost / Complexity ↑
- DA Cycle
 - MHEEP
 - Forecast Sequence
 - TDIAG
 - LAM Case Study
 - **SCM**
 - Test Harness



Condensate in BFP92 (top) and operational configuration (bottom).

An idealized protocol (Bechtold et al. 1992) is introduced in the SCM.

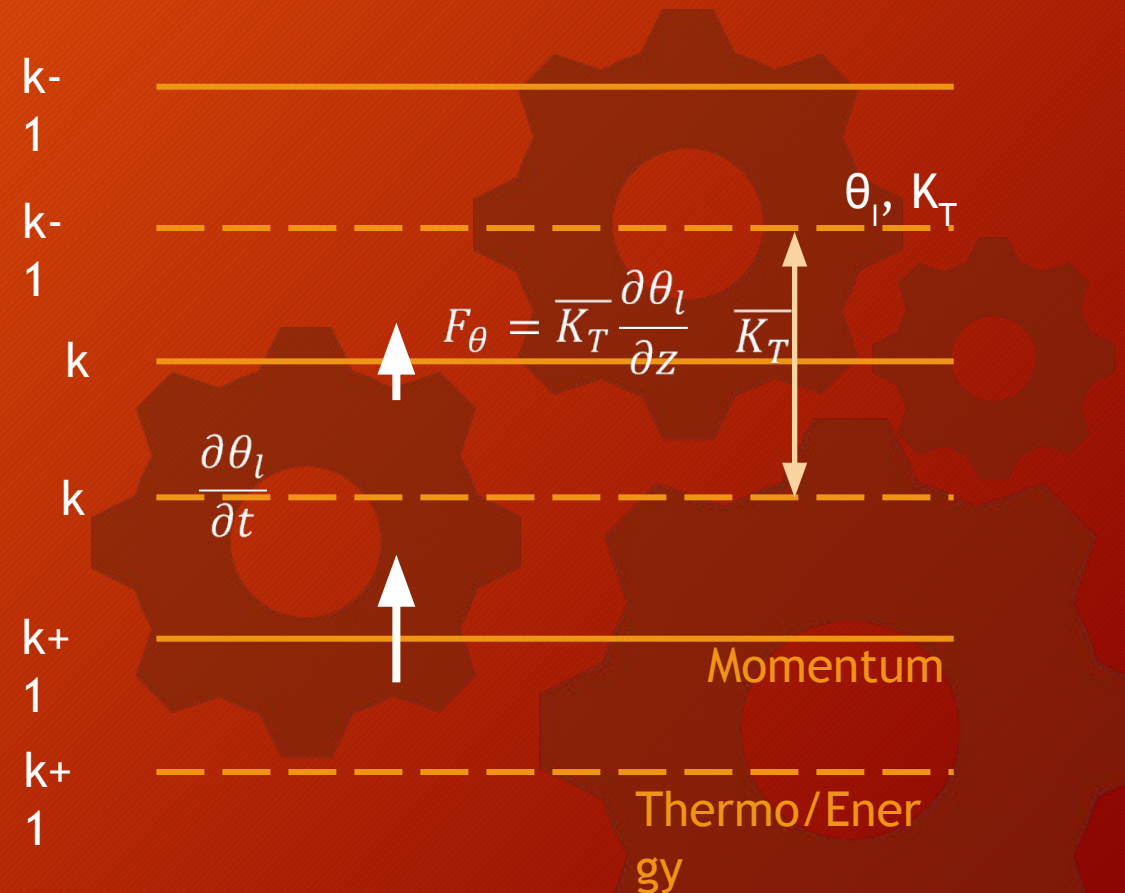
The operational configuration is unable to maintain a stable Sc deck.

Weak forcing provides an ideal testbed.

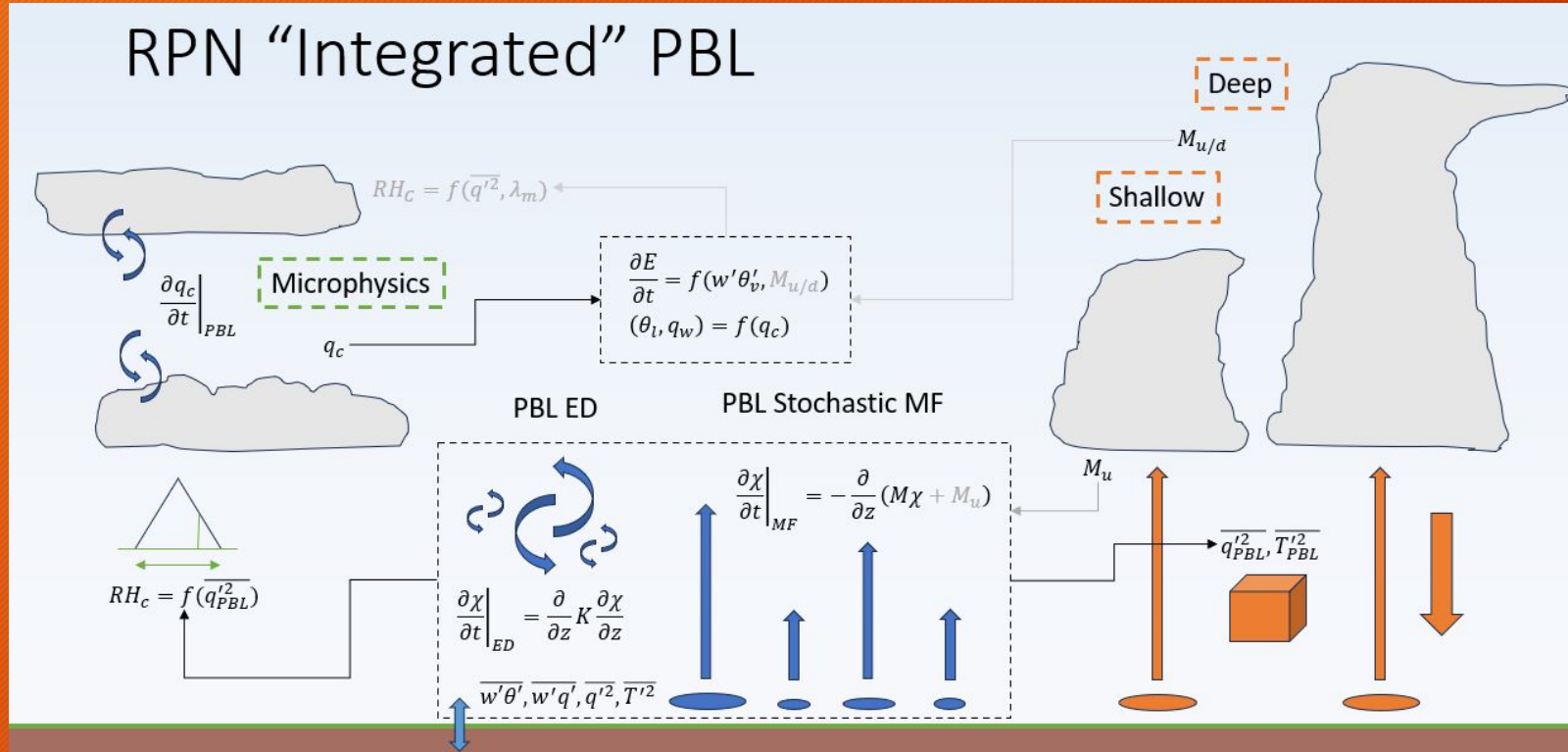
Root Cause: Numerical Entrainment

$$\begin{aligned}\frac{\partial \theta_l}{\partial t} &= -\frac{\partial}{\partial z} K_T \frac{\partial \theta_l}{\partial z} \\ &= \frac{\partial F_\theta}{\partial z}\end{aligned}$$

- The model's staggered vertical discretization means that the eddy diffusivity for heat (K_T) must be averaged to compute turbulent flux
- Averaging across the inversion at the top of Sc overestimates mixing
- Instability of the cloud layer and growth in cloud height are signs of this excess entrainment



A New Boundary Layer Scheme



Schematic of connections between schemes within the physics suite.

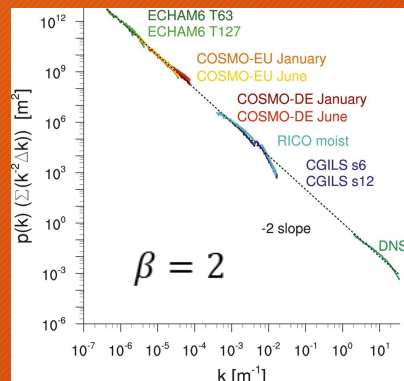
Discretization avoids K interpolation by design.

Turbulence-informed microphysics scheme is responsible for all non-convective clouds, including Sc.

A New Boundary Layer Scheme

A new nonlocal mixing length based on parcel conservation of θ_l sustains buoyancy fluxes in the Sc cloud layer.

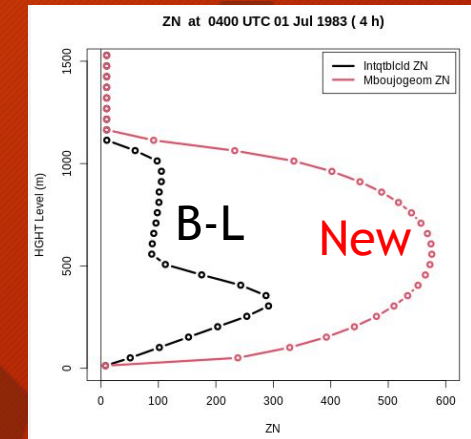
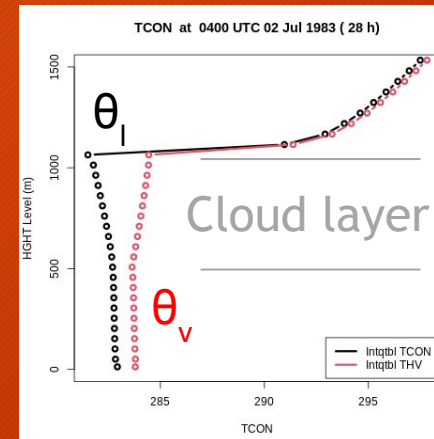
This has a large impact on the TKE budget and Sc maintenance.



Moisture variance power spectrum (from Schemann et al. 2013).

Power-law rescaling of turbulence-computed subgrid-scale variances (q , T , Tq) underpins a scale-aware cloud fraction estimate.

$$\sigma_s = \left(\frac{\Delta x}{\delta x_{ref}} \right)^{\frac{\beta-1}{2}} (c_1 \lambda \lambda_d)^{\frac{1}{2}} \left[a^2 \left(\frac{\partial \bar{q}_t}{\partial z} \right)^2 + b^2 \left(\frac{\partial \bar{\theta}_l}{\partial z} \right)^2 - 2ab \frac{\partial \bar{q}_t}{\partial z} \frac{\partial \bar{\theta}_l}{\partial z} \right]^{1/2}$$



Sc Clouds in the SCM with RPNInt

Cost / Complexity

- DA Cycle
- MHEEP
- Forecast Sequence
- TDIAG
- LAM Case Study
- SCM**
- Test Harness

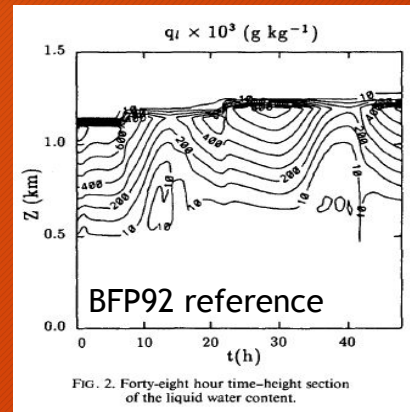
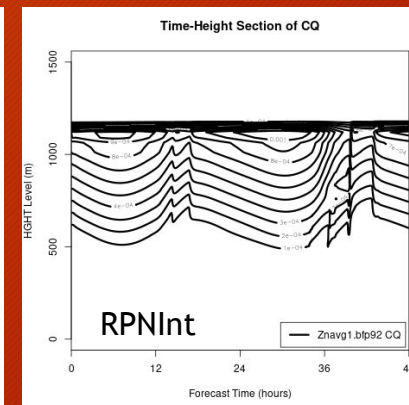
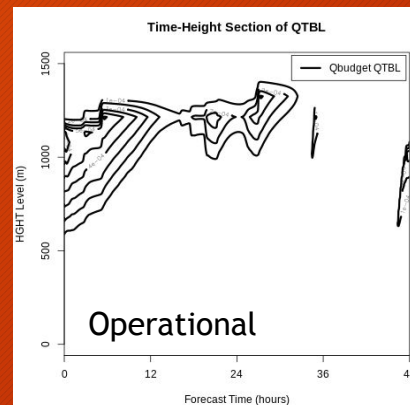


FIG. 2. Forty-eight hour time-height section of the liquid water content.

The RPNInt scheme is able to maintain a stable Sc layer throughout the BFP92 integration.



Condensate in BFP92 (top) and SCM configurations as labelled.

The scheme's TKE budget closely follows the reference (not shown).

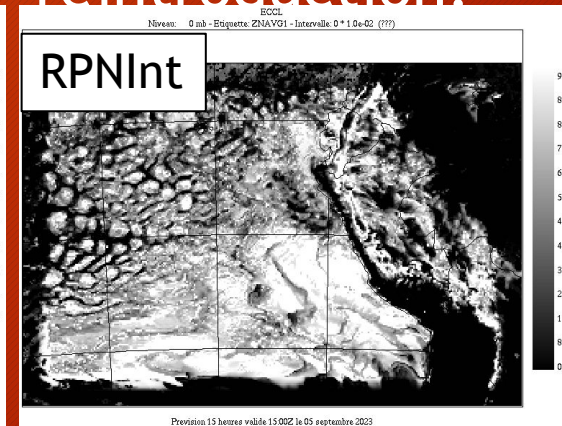
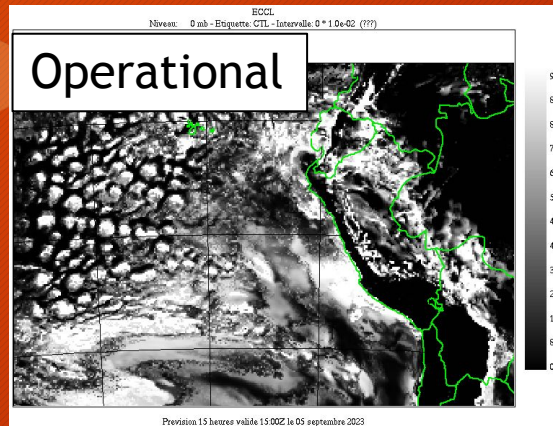
Sc Clouds in a Small LAM

Cost / Complexity

- DA Cycle
- MHEEP
- Forecast Sequence
- TDIAG
- LAM Case Study**
- SCM
- Test Harness



A solid Sc deck is maintained in the small-LAM step of HSC complexity reintroduction.

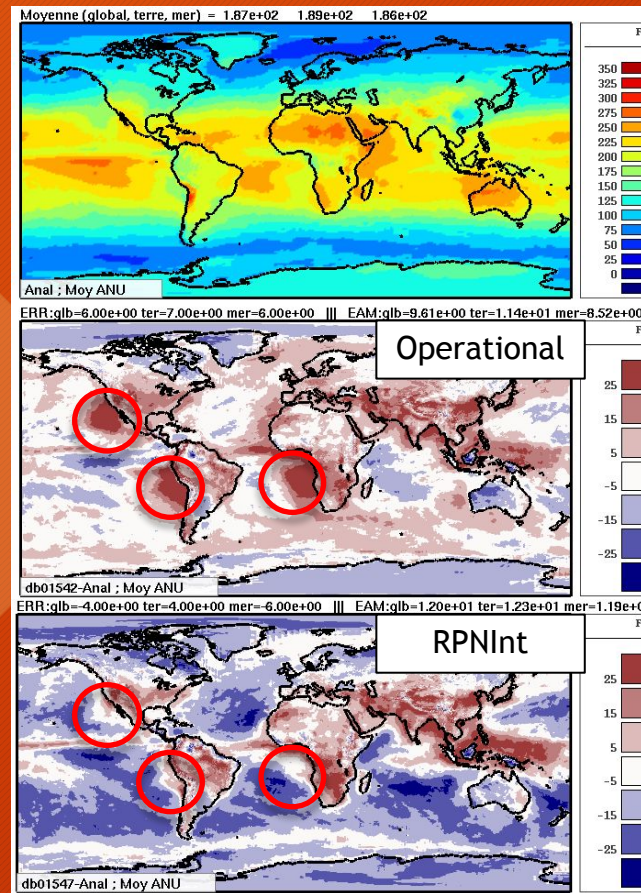


Observed (top) and LAM-predicted low-level cloud cover after 15h in a small LAM for configurations as labelled.

Sc Clouds in MHEEP (Model Climate)

Cost / Complexity

- DA Cycle
- MHEEP**
- Forecast Sequence
- TDIAG
- LAM Case Study
- SCM
- Test Harness



Excessive downwelling solar flux in Sc regions is eliminated; however, tuning albedo in TDIAG led to overprediction of low cloud.

Reduction in variance rescaling appears promising (in progress).

Mean surface solar radiation from OAflux (top) and difference model-obs (below).

Discussion: Where did HSD get us?

Identify

Rebuild

Simplify

Solutions

Root-Cause

- Identified Sc error in operational global coupled systems
- A simplified low-cost model reproduces the problem
- Root-cause analysis to identify numerical entrainment
- Solution in the form of a new boundary layer scheme that is tightly integrated with cloud microphysics
- Iterations between HSD steps will help to rebalance the system to (hopefully) improve the global energy budget