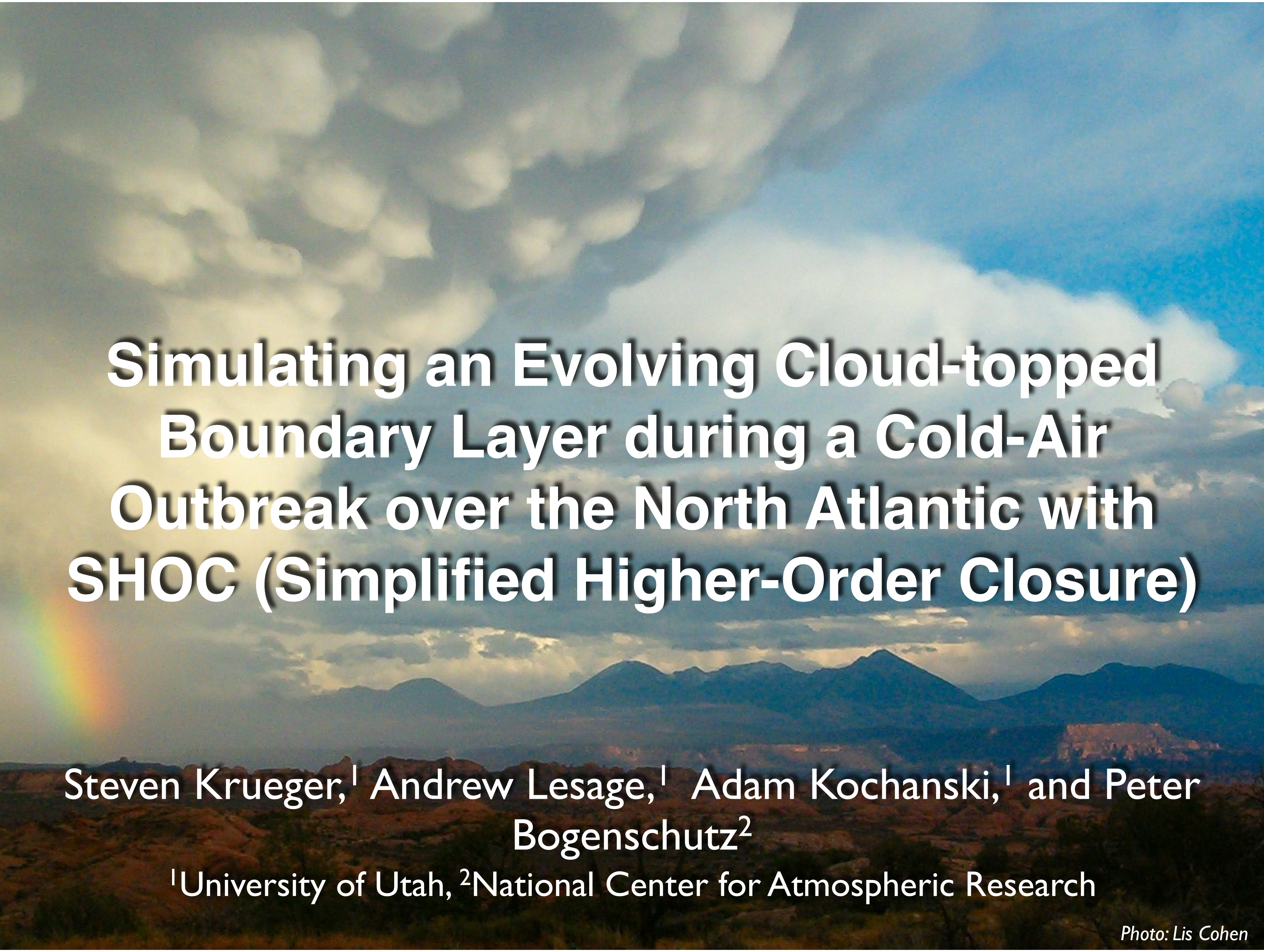

Simulating an Evolving Cloud-topped Boundary Layer during a Cold-Air Outbreak over the North Atlantic with SHOC (Simplified Higher-Order Closure)

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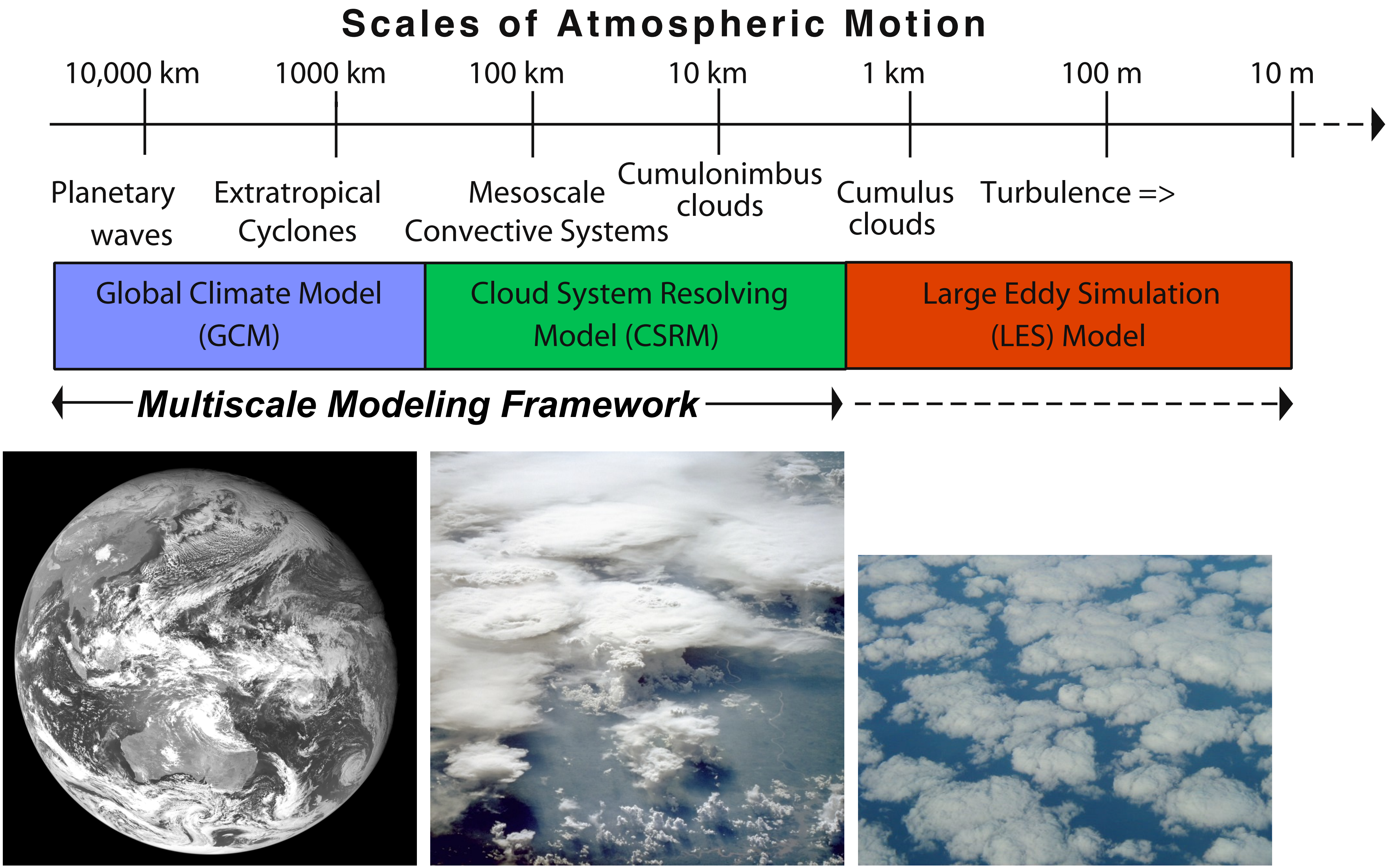
[1]University of Utah, [2]National Center for Atmospheric Research

Photo: Lis Cohen


Scales of Atmospheric Motion
10,000 km
1000 km
100 km
10 km
1 km
100 m
10 m
Planetary waves
Extratropical Cyclones
Mesoscale Convective Systems
Cumulonimbus clouds
Cumulus clouds
Turbulence =>
Global Climate Model (GCM)
Cloud System Resolving Model (CSRM)
Large Eddy Simulation (LES) Model
Multiscale Modeling Framework

Boundary layer clouds in cloud-system-resolving models (CSRMs)

- One approach for better representing SGS clouds and turbulence is the *Assumed PDF Method.*

- This method parameterizes SGS clouds and turbulence in a unified way.

- It was initially developed for boundary layer clouds and turbulence.

- It is a very promising method for use in coarse-grid CRMs.

Steps in the Assumed PDF Method

The Assumed PDF Method contains 3 main steps that must be carried out for each grid box and time step:

(1) Prognose means and various higher-order moments.

(2) Use these moments to select a particular PDF member from the assumed functional form.

(3) Use the selected PDF to compute many higher-order terms that need to be closed, e.g. buoyancy flux, cloud fraction, etc.

Our PDF includes several variables

We use a three-dimensional PDF of vertical velocity, w, total water (vapor + liquid) mixing ratio, q_t, and liquid water potential temperature, θ_l :

$$P = P(w, q_t, \theta_l)$$

This allows us to couple subgrid interactions of vertical motions and buoyancy.

Randall et al. (1992)

SHOC (*Simplified Higher-Order Closure*)

$$\overline{\theta_l'^2}, \overline{q_t'^2}, \overline{w'^2}, \overline{w'\theta_l'}, \overline{w'q_t'}, \overline{q_t'\theta_l'}, \overline{w'^3}$$

- Typically requires the addition of several prognostic equations into model code (Golaz et al. 2002, Cheng and Xu 2006, 2008) to estimate the turbulence moments required to specify the PDF.

- Our approach is called *Simplified Higher-Order Closure* (SHOC) (Bogenschutz and Krueger 2013):

    - Second-order moments diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)

    - Third-order moment diagnosed using algebraic expression of Canuto et al. (2001)

    - All diagnostic expressions for the moments are a function of prognostic SGS TKE.

Bogenschutz, P. A., and S. K. Krueger, 2013: A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models. J. Adv. Model. Earth Syst., 5, 195–211

We implemented SHOC in SAM (*System for Atmospheric Modeling*), a 3D CRM developed by Marat Khairoutdinov.

Khairoutdinov, M. F., and D.A. Randall, 2003: Cloud-resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties and sensitivities. *J. Atmos. Sci.*, **60**, 607-625.

Summary

- SHOC includes these desirable features:
  - A diagnostic higher-order closure with assumed double Gaussian joint PDF.
  - A turbulence length scale that depends on SGS TKE and large-eddy length scales.
  - It can realistically represent many boundary layer cloud regimes in models with dx ~ 0.5 km or larger, with virtually no dependence on horizontal grid size.
  - It is economical, with potential for easy portability to other explicit-convection models.

CONSTRAIN: A cold-air outbreak case

This cold air outbreak case is based on observations taken during the U. K. Met Office CONSTRAIN campaign over the North Atlantic on January 31, 2010 and associated NWP simulations.

As cold air advects over warmer seas, stratocumulus changes to mixed-phase cumulus over a 14-hour period.

(http://appconv.metoffice.com/cold_air_outbreak/constrain_case/home.html)

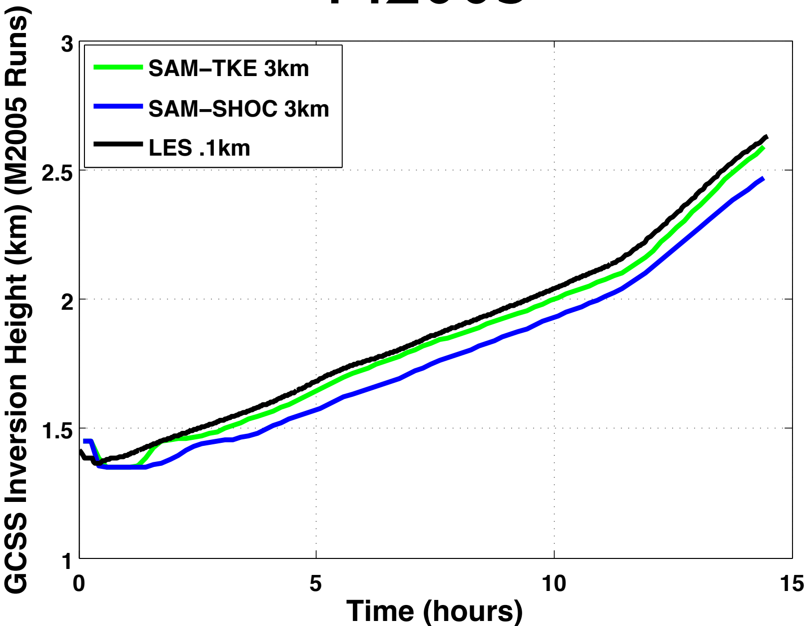
SHOC Perfomance

- Various horizontal grid sizes: 0.5, 1, 3, 8 km
- Vertical grid size = 100 m
- Domain size = 96 km x 96 km
- LES benchmarks: horizontal grid size = 100 m, vertical grid size = 50 m, domain size = 32 km x 32 km or larger.

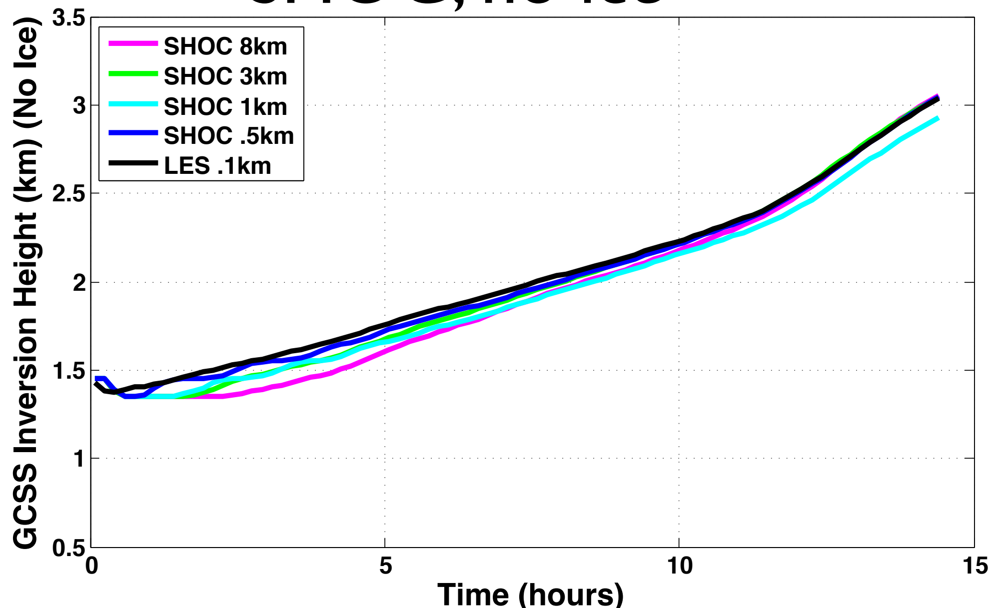
Case	Microphysics	Radiation	Cloud	Precip.	Liquid Water	Ice	Ice Sed.
Full Physics	1M						
M2005	2M						
No Ice	1M						
No Sed	1M						

Inversion Height

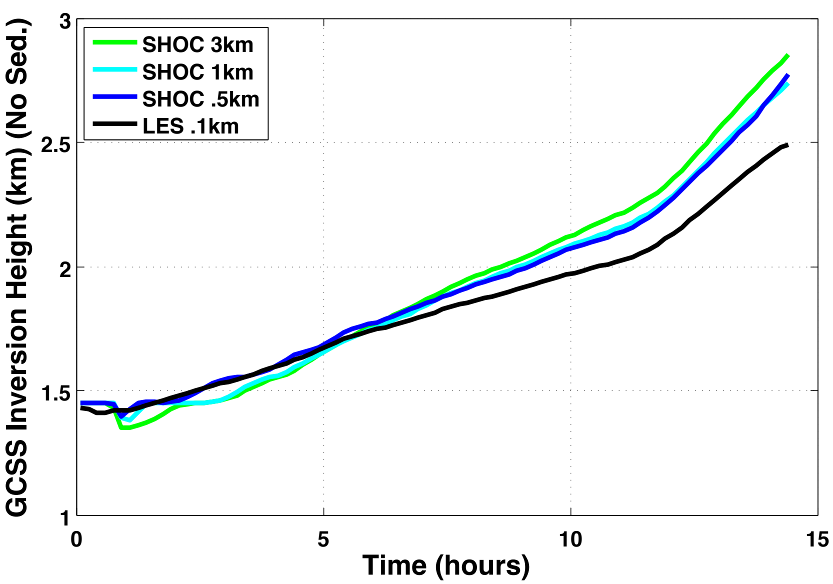
M2005



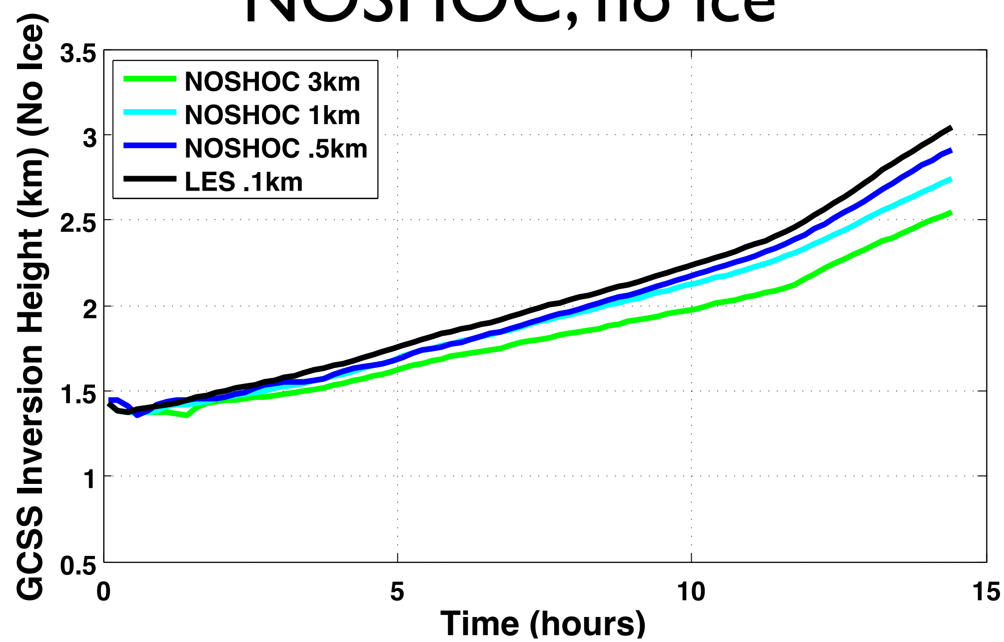
SHOC, no ice



SHOC, no sed.

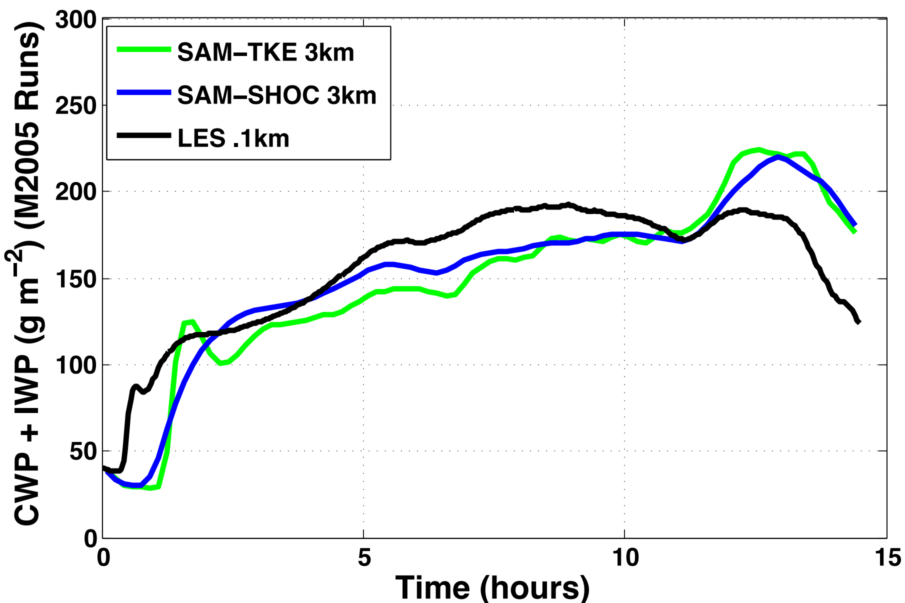


NOSHOC, no ice

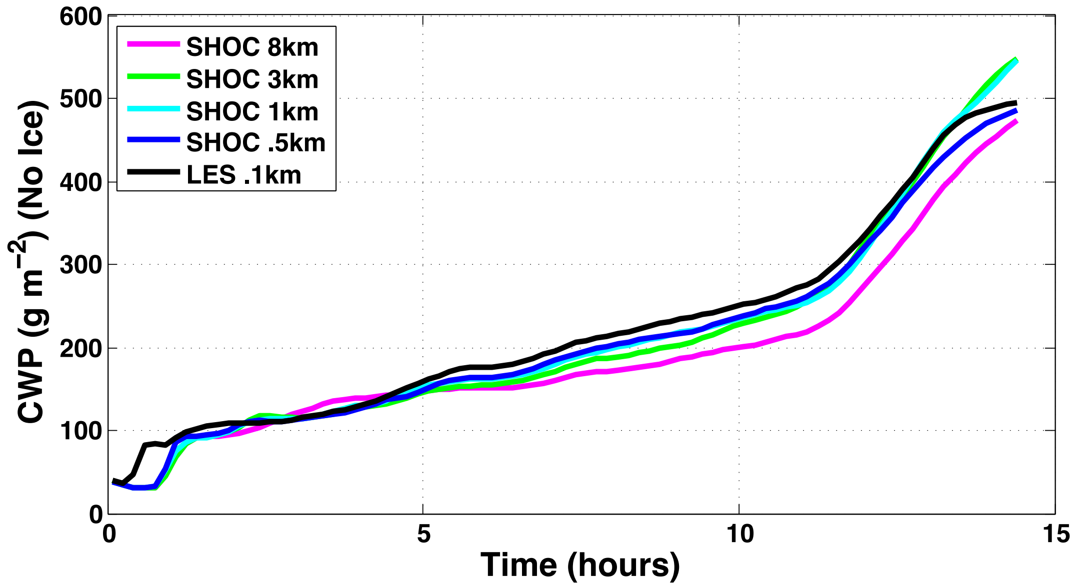


CWP + IWP

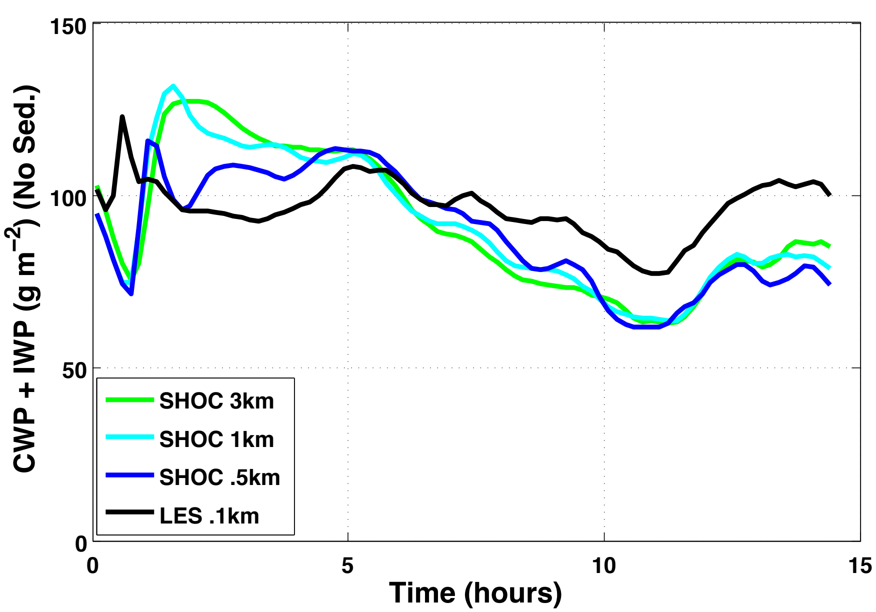
M2005



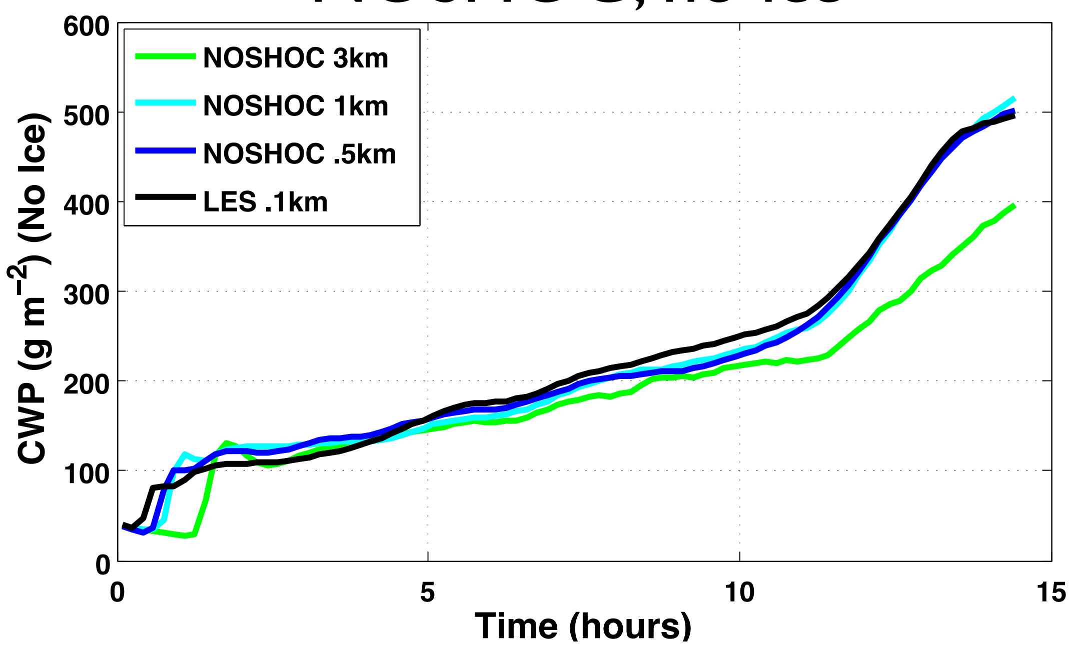
SHOC, no ice



SHOC, no sed.

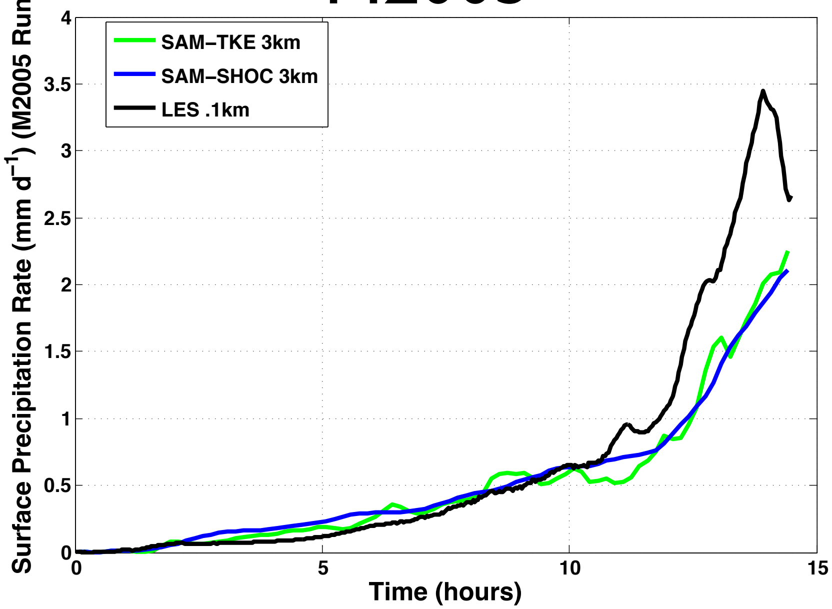


NOSHOC, no ice

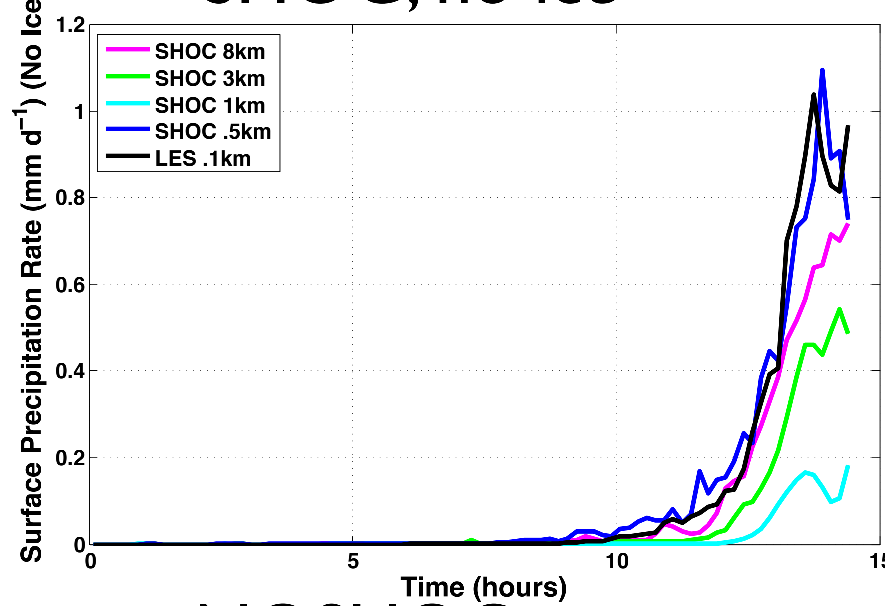


Surface Precipitation

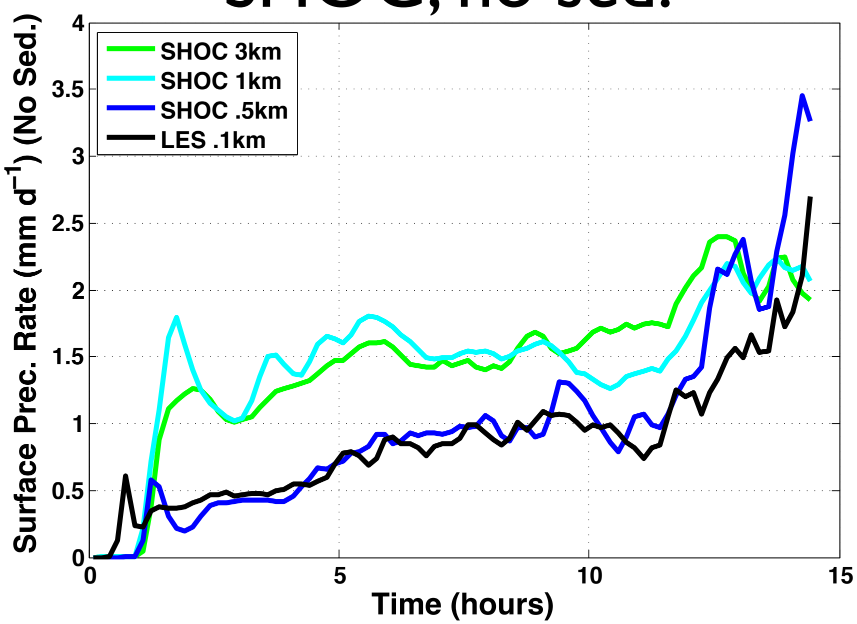
M2005



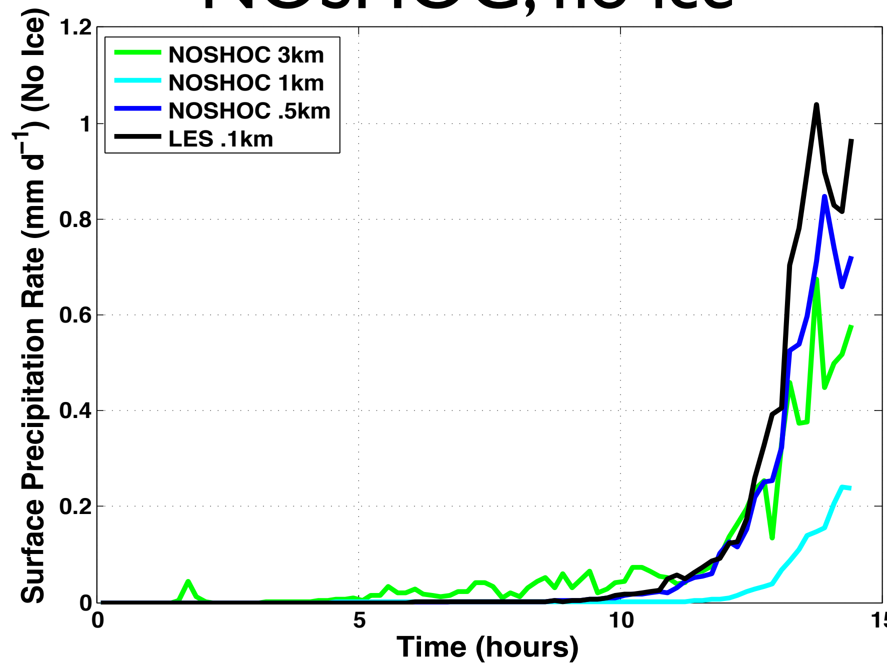
SHOC, no ice



SHOC, no sed.

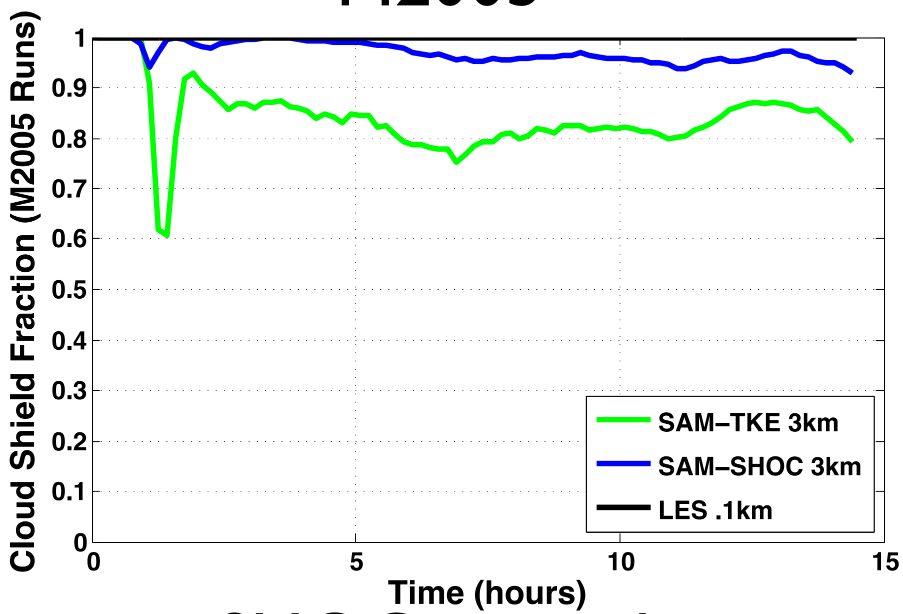


NOSHOC, no ice

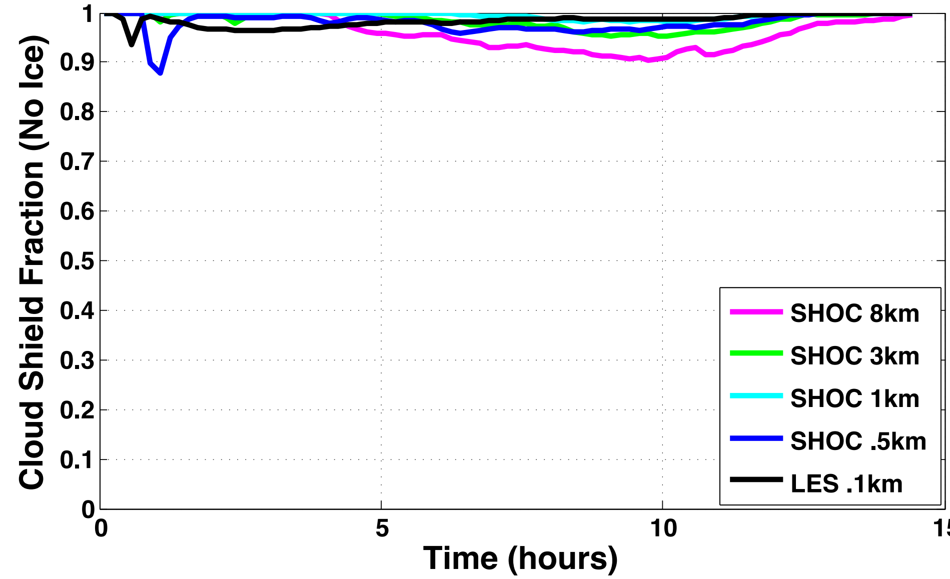


Shaded Cloud Fraction

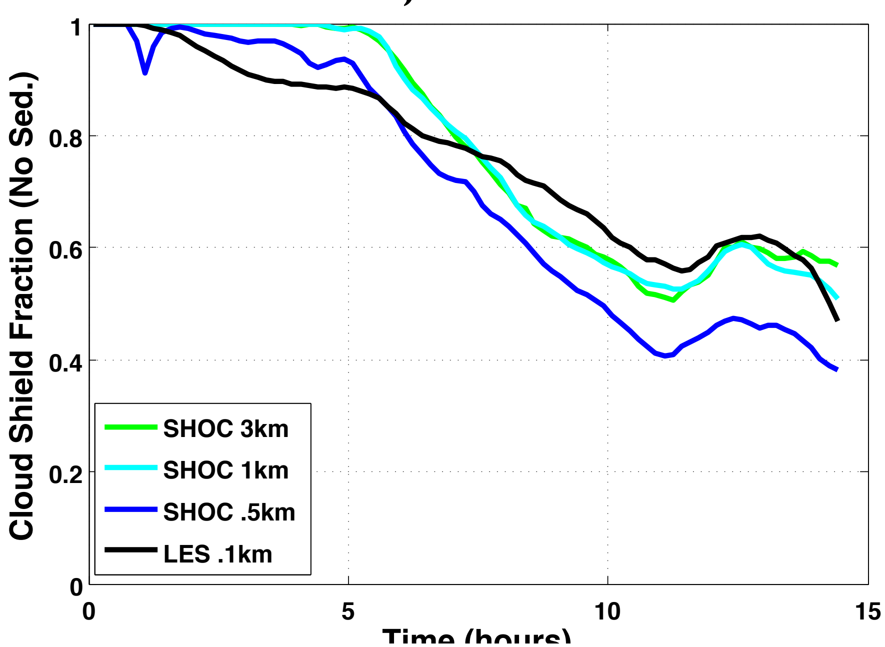
M2005



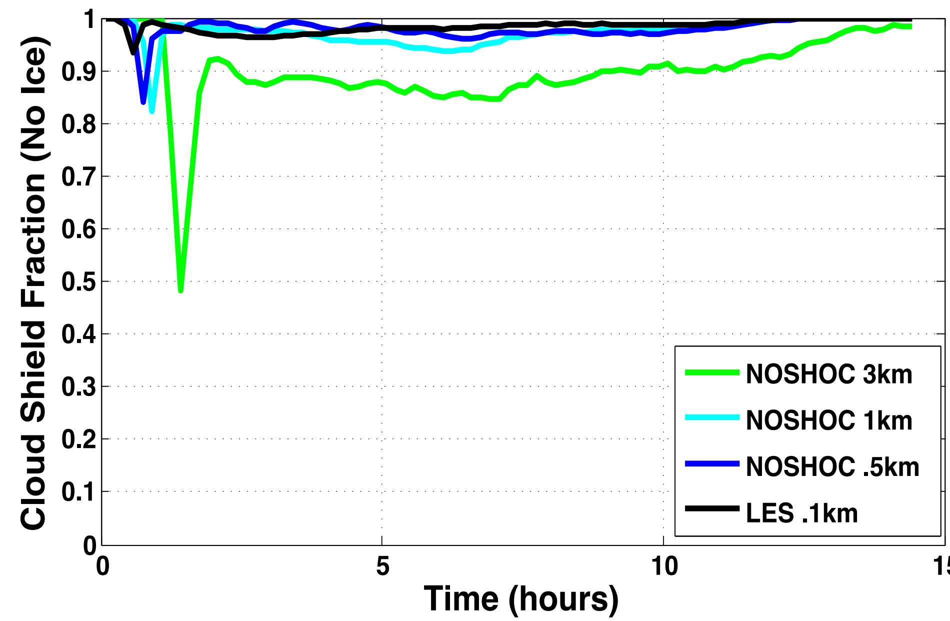
SHOC, no ice



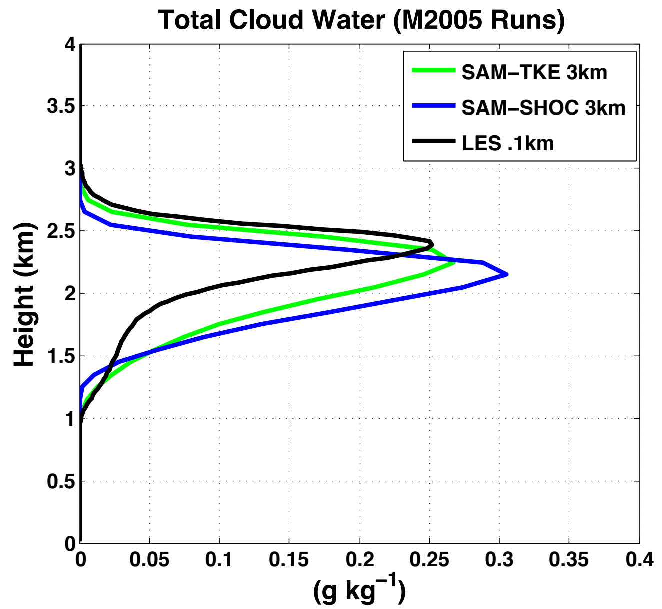
SHOC, no sed.



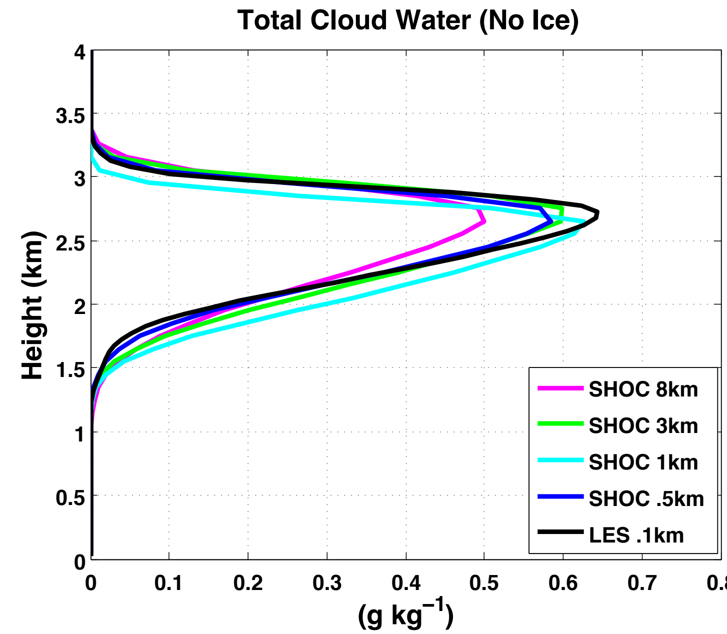
NOSHOC, no ice



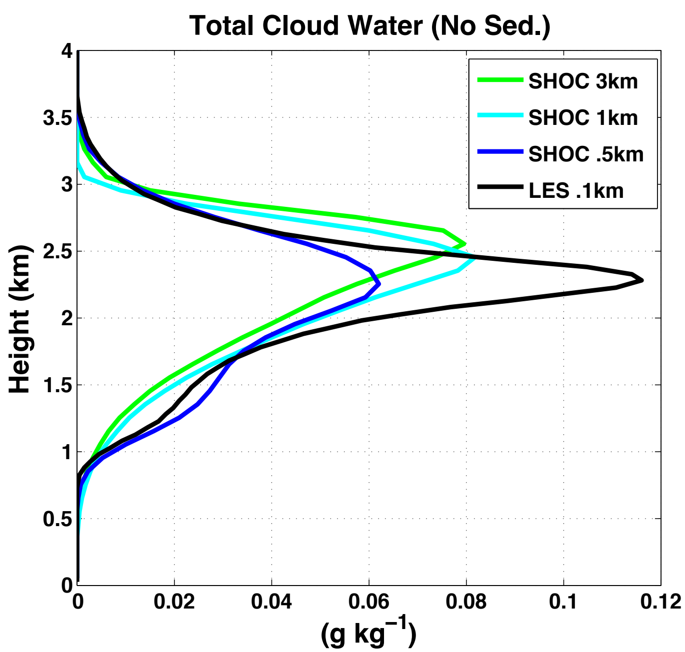
Cloud Water + Ice



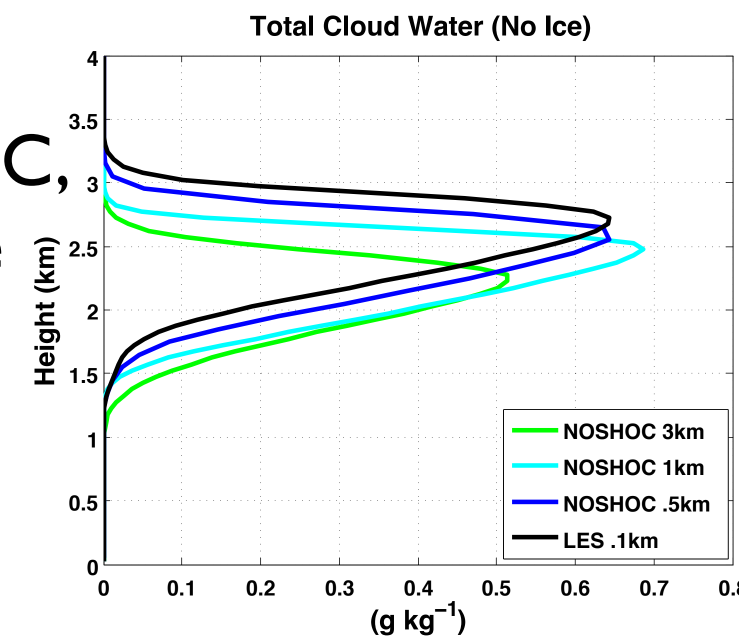
M2005



SHOC, no ice



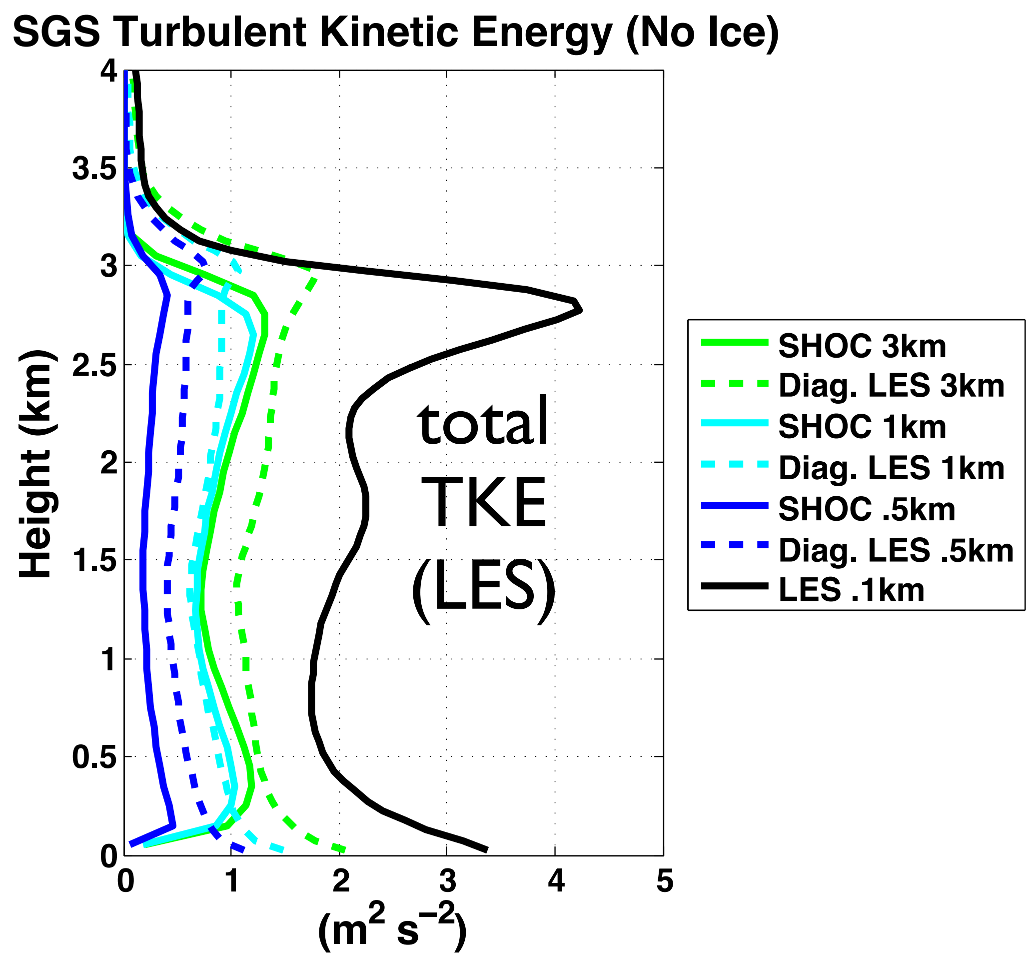
SHOC, no sed



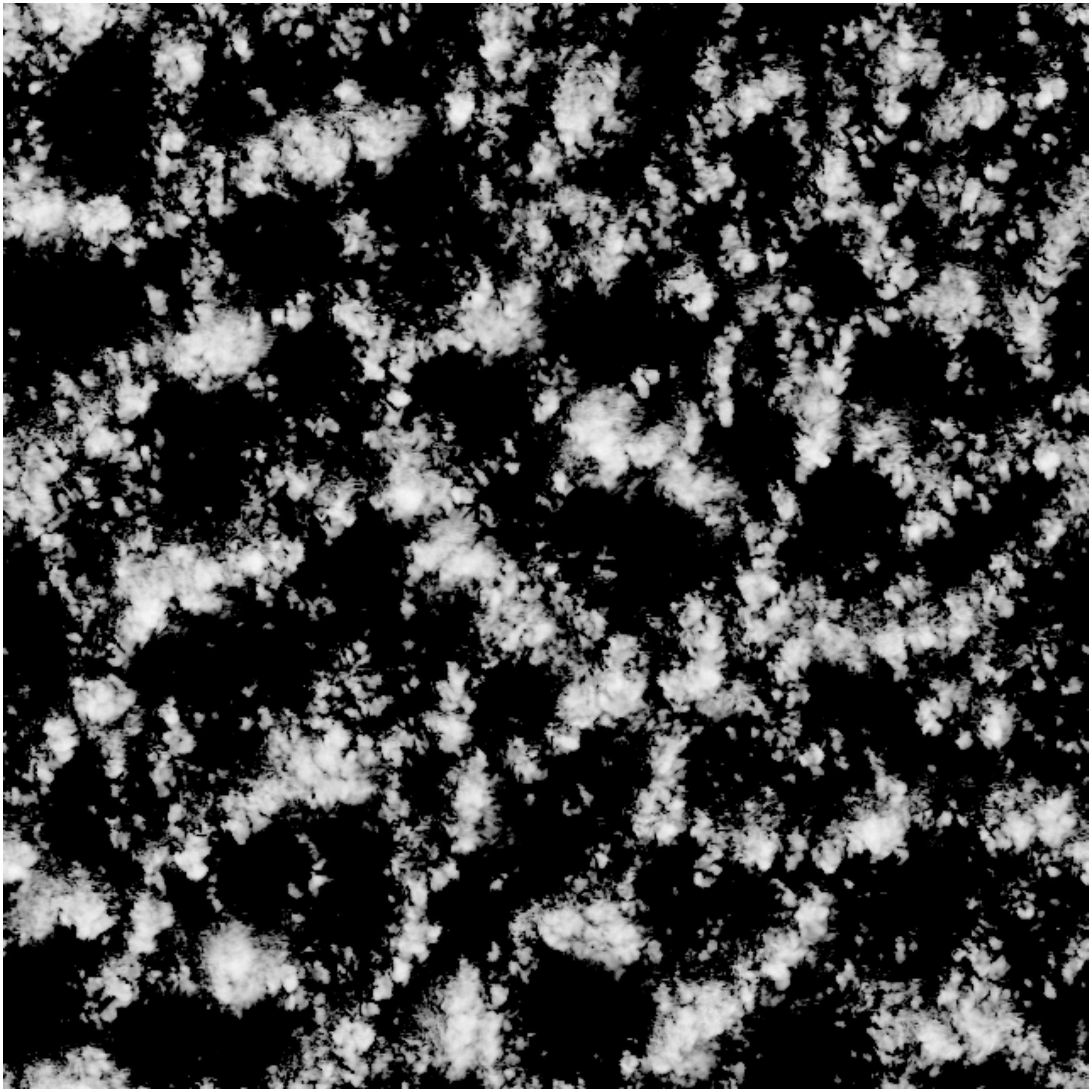
NOSHOC, no ice

SHOC Perfomance Summary

- Compared to LES, SAM-SHOC performs well, but so does SAM without SHOC. Why?
- Even for a 3-km grid size, most of the TKE is resolved, so the turbulence closure is not very important in this case.



Cloud Water Path (LES: 64 km x 64 km domain)



(Full Physics)

Sensitivity to physical processes

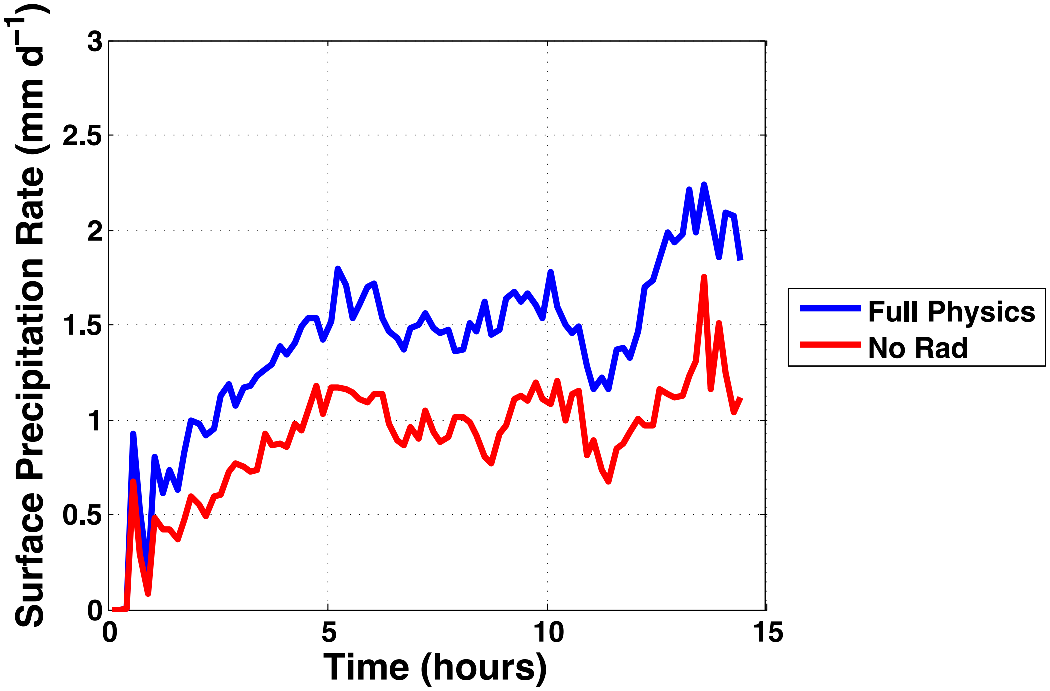
LES Cases

Case	Microphysics	Radiation	Cloud	Precip.	Liquid Water	Ice	Ice Sed.
Full Physics	1M						
M2005	2M						
No Rad	1M						
No Rad/Pcp	1M						
No Pcp	1M						
No Ice	1M						
Ice Only	1M						
Ice, No Sed	1M						
No Sed	1M						
Ice, No Sed/Rad/Pcp	1M						
No Rad/Pcp/Cld	1M						
No Ice/Rad/Pcp	1M						

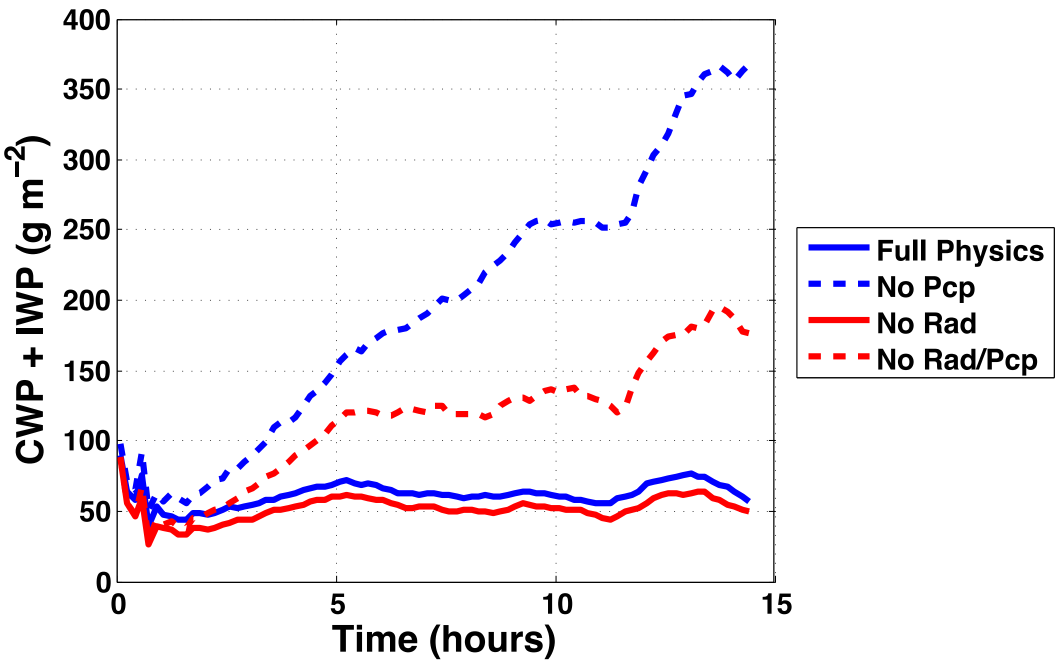
Sensitivity to physical processes

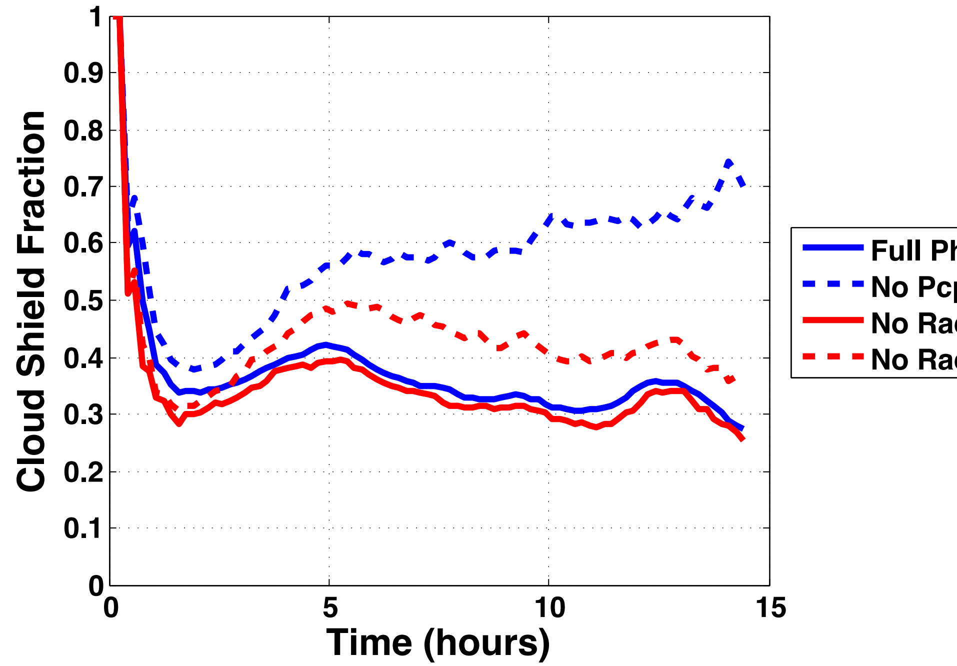
- Precipitation and Radiation
- Sedimentation of cloud ice
- Ice-phase microphysics
- Double-moment microphysics

Precipitation and Radiation

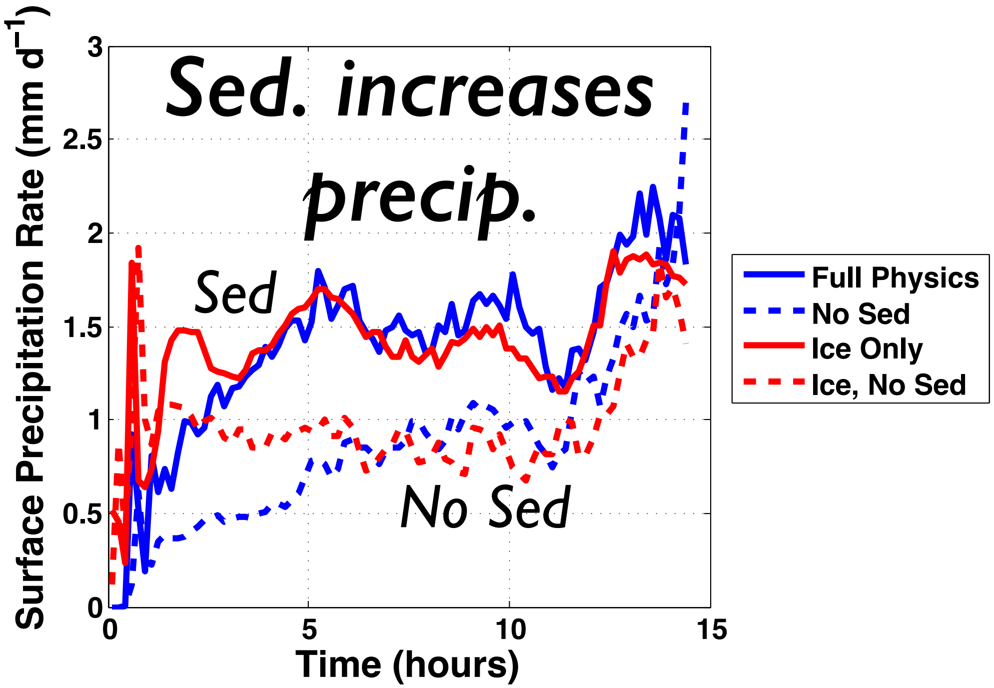


- With Pcp, Rad increases Pcp rate, but does not affect clouds.
- Without Pcp, Rad greatly increases clouds.
- Pcp greatly decreases clouds.

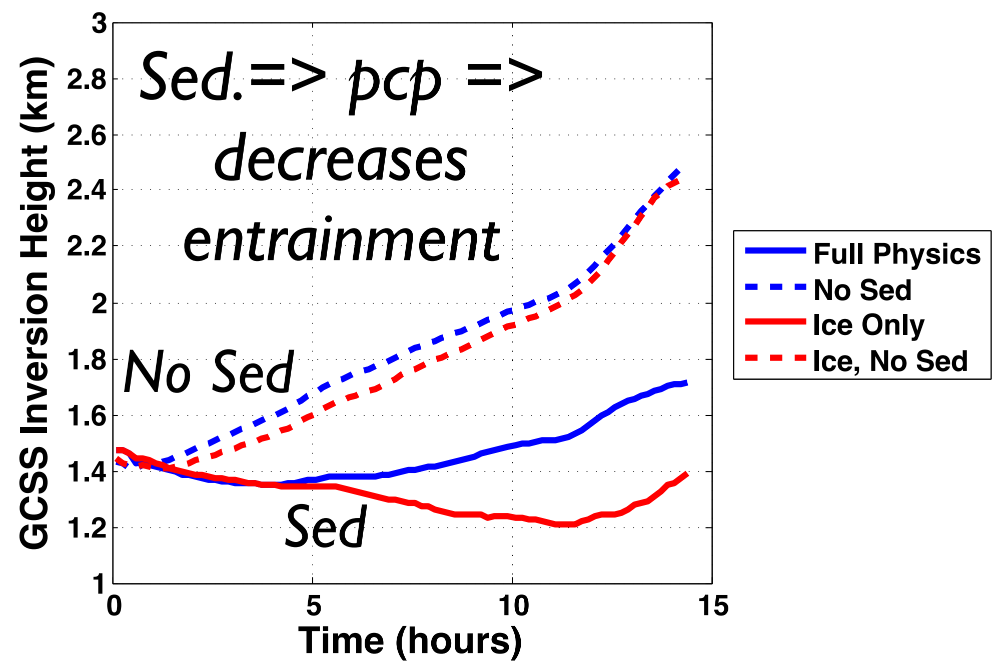




Sedimentation of cloud ice

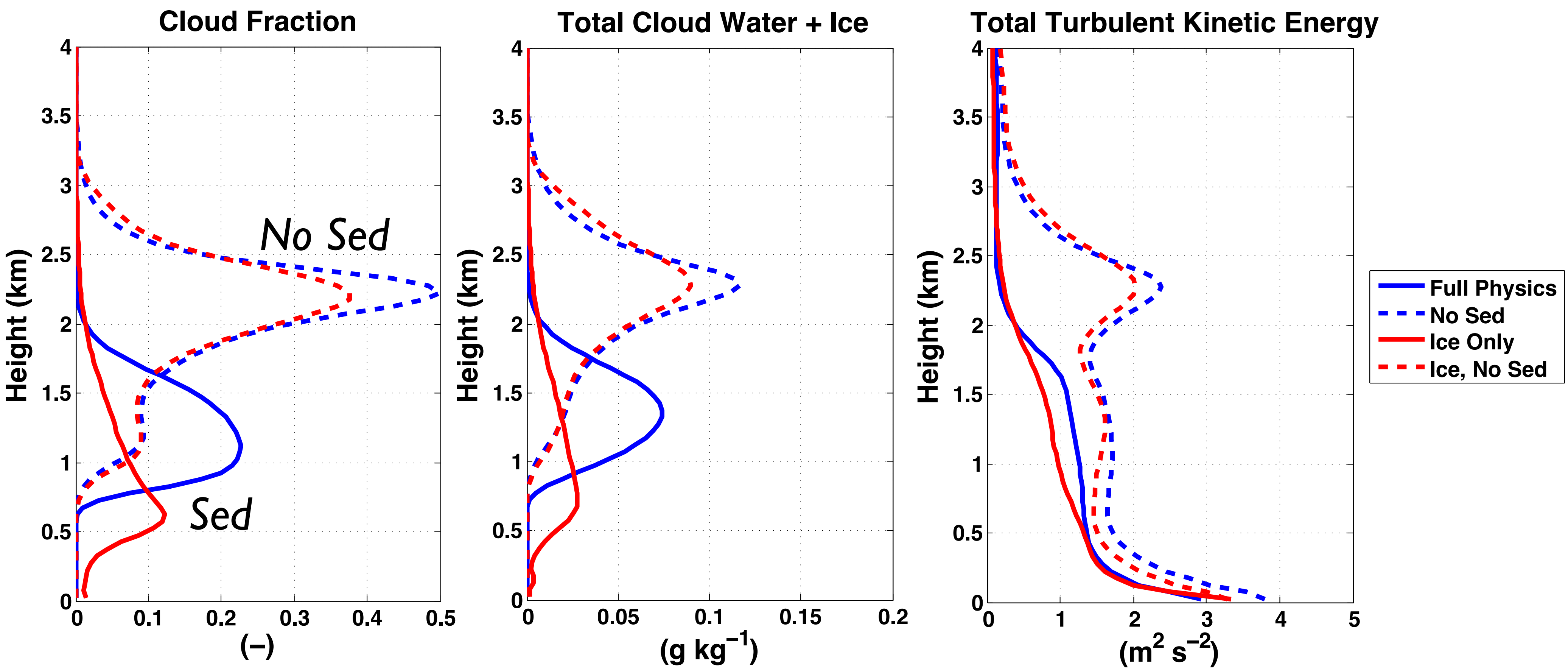


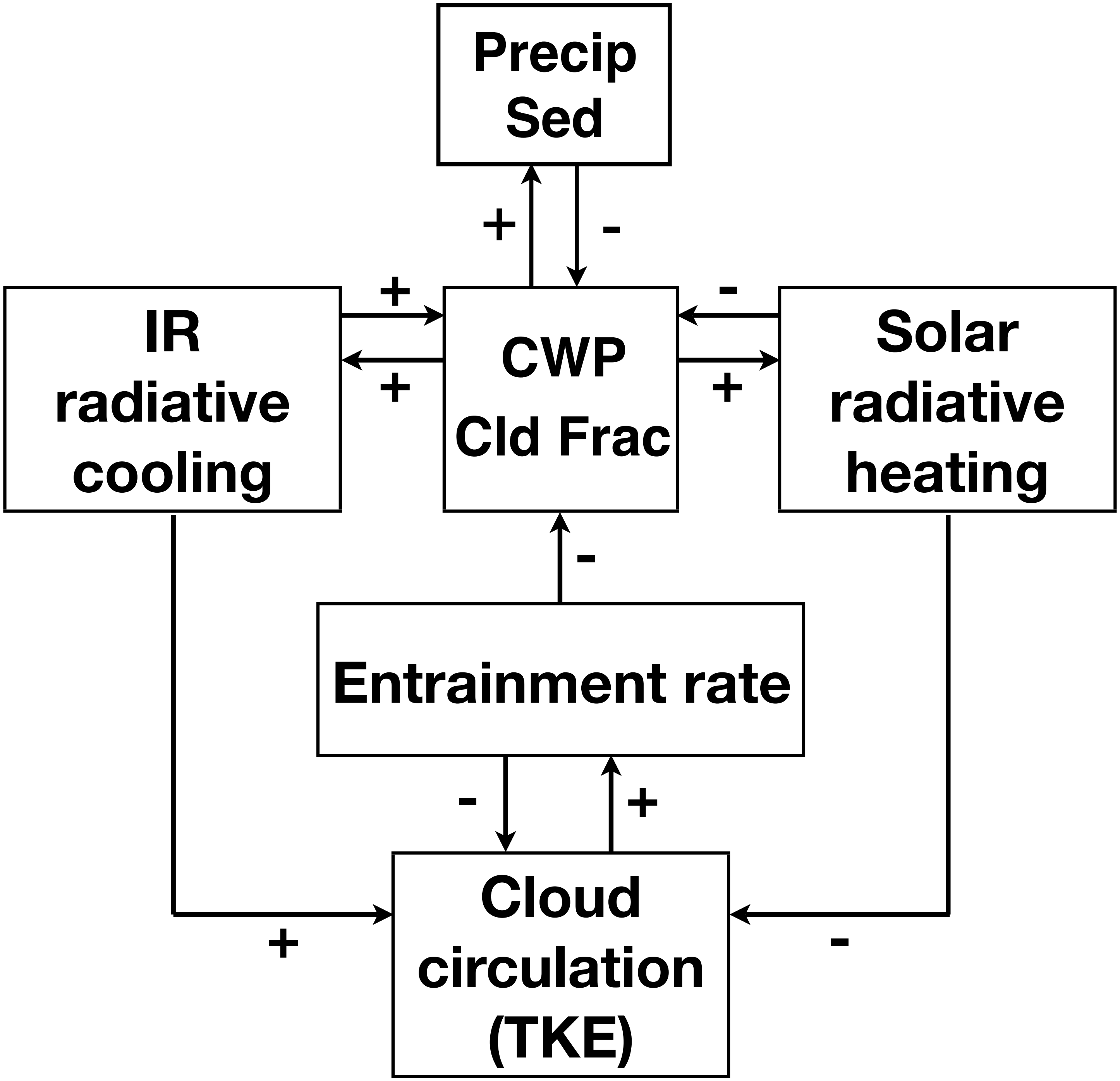
Sed.=> pcp => decreases cloud amount



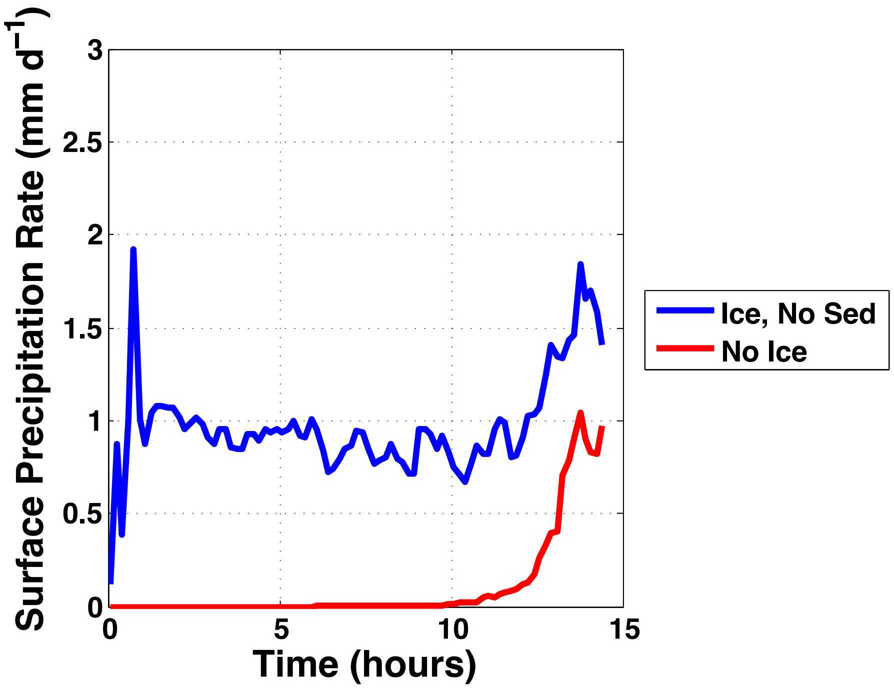
Sedimentation of cloud ice

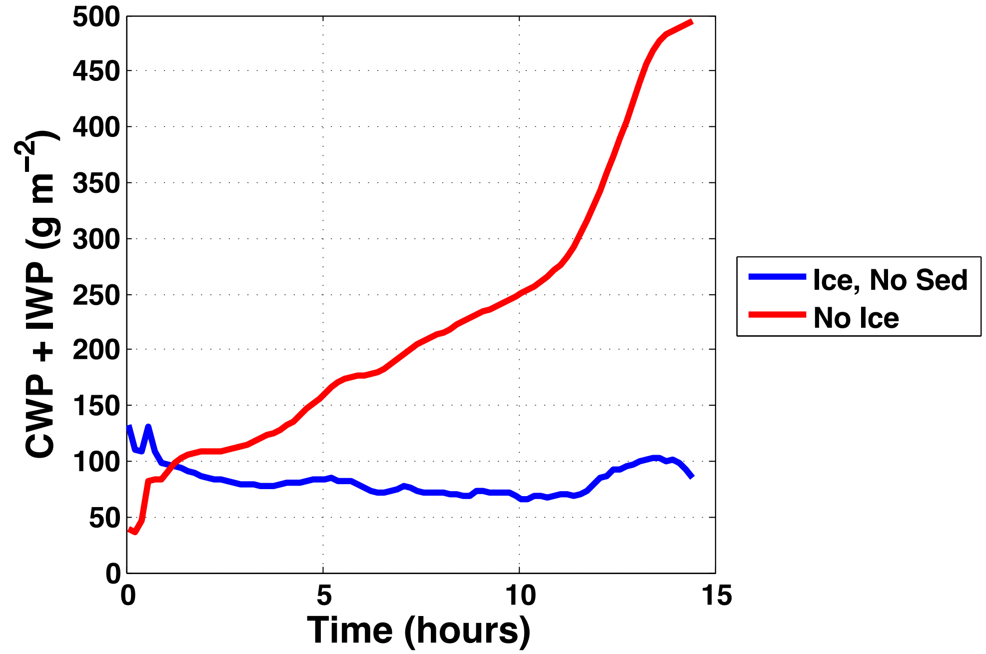
No sed => less pcp => more cloud => more entrainment




Precip
Sed
+
-
IR
radiative
cooling
+
+
CWP
Cld Frac
-
+
Solar
radiative
heating
-
Entrainment rate
-
+
Cloud
circulation
(TKE)
+
-

Ice-phase microphysics

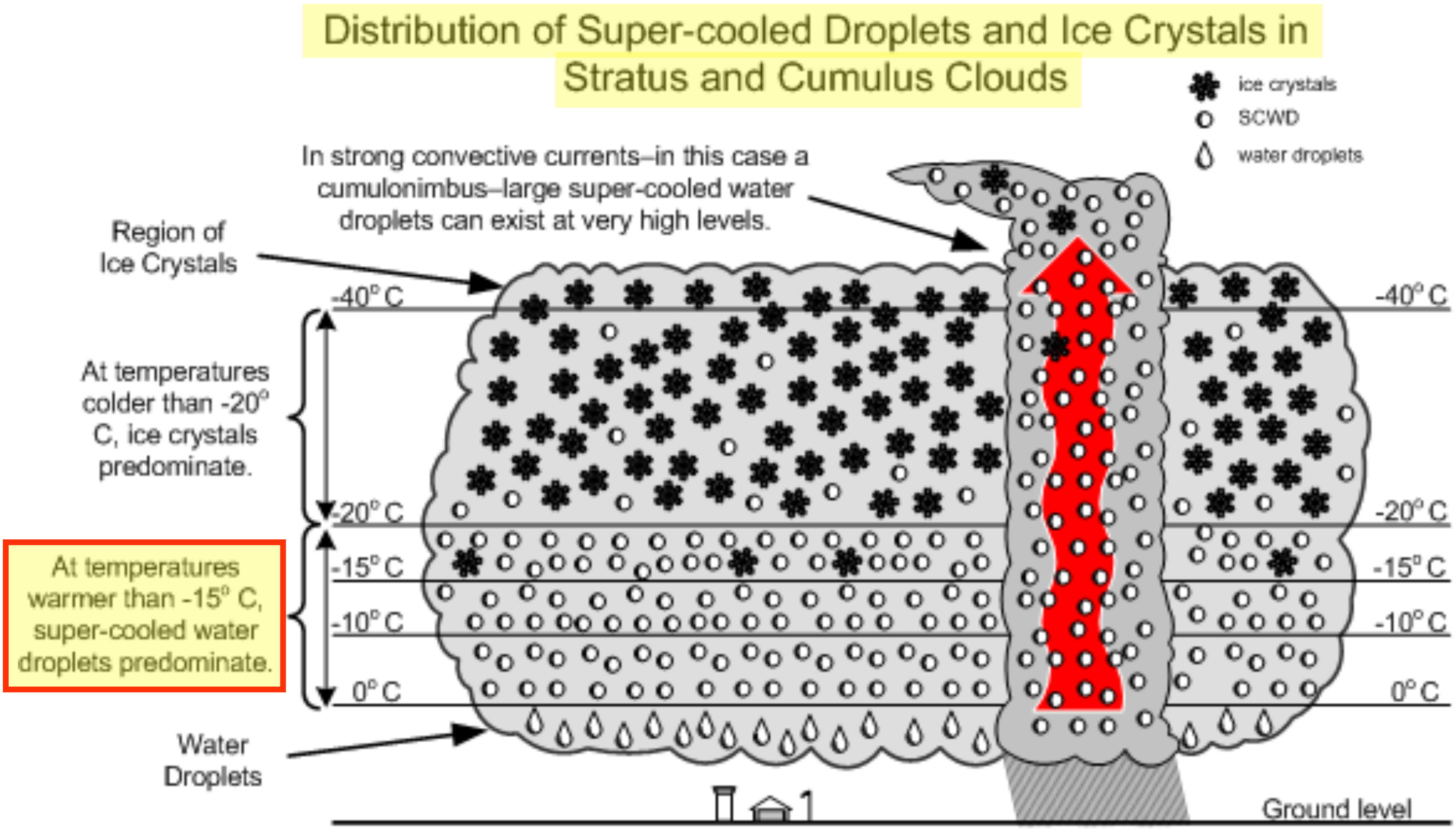




Without ice, precip. onset is delayed.

IWP is less with precip.

Double-Moment Microphysics

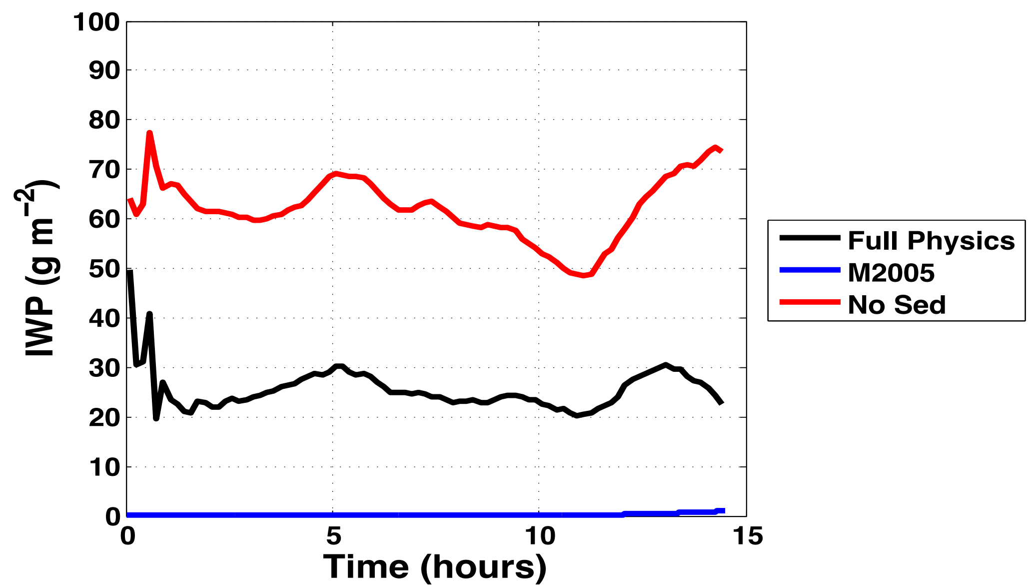


Based on depiction found in *Air Command Weather Manual*, Fig. 9-3

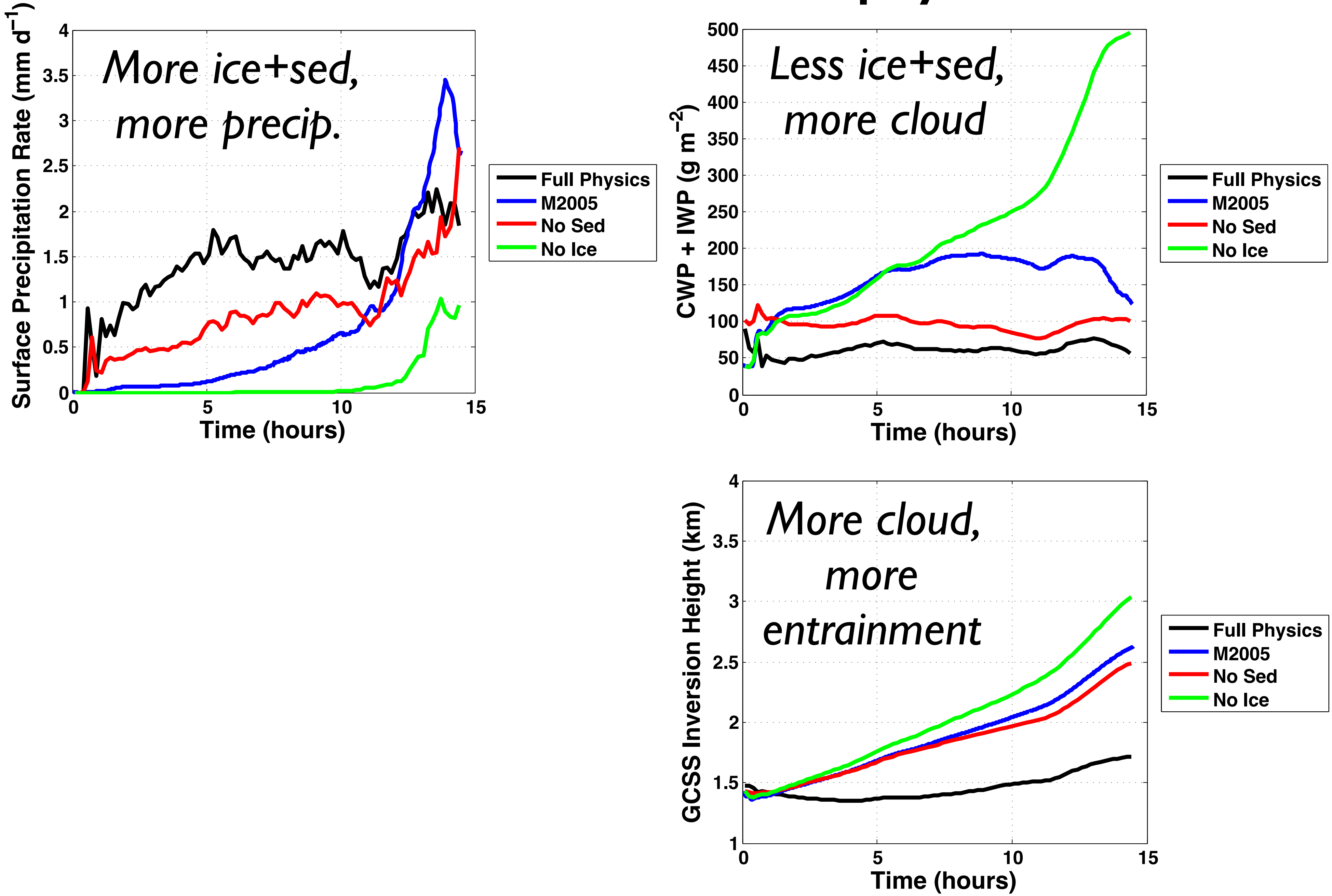
Double-Moment Microphysics

Morrison et al. (2005)

M2005 has almost no ice.
*Only **Full Phys** and*
No Sed have ice.



Double-Moment Microphysics



Summary of LES Comparisons

- SAM one-moment microphysics (unrealistically) produces cloud ice instead of supercooled cloud water.
- Morrison et al. (2005) double-moment microphysics (more realistically) produces supercooled cloud water instead of cloud ice.
- Precip. is greater with cloud ice and cloud ice sedimentation.
- Precip. reduces cloud cover and CWP+IWP.

- Radiation tends to increase cloudiness and precip.

- Because precip. tends to decrease cloudiness, the net effect of radiation on cloudiness is small in the presence of precip., but large without precip.

- More cloudiness produces greater entrainment.