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Subtropical Turbulence and Clouds

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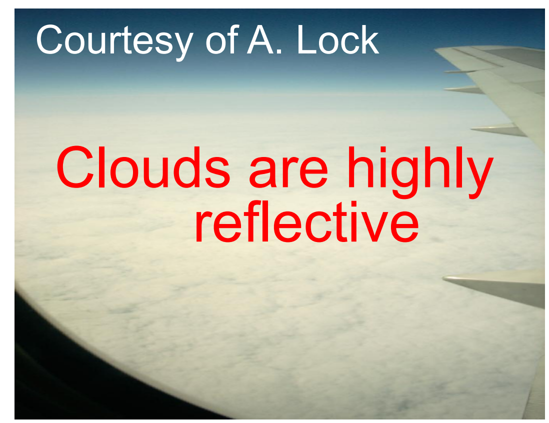
Hawaii CF~10%



LA CF~100%

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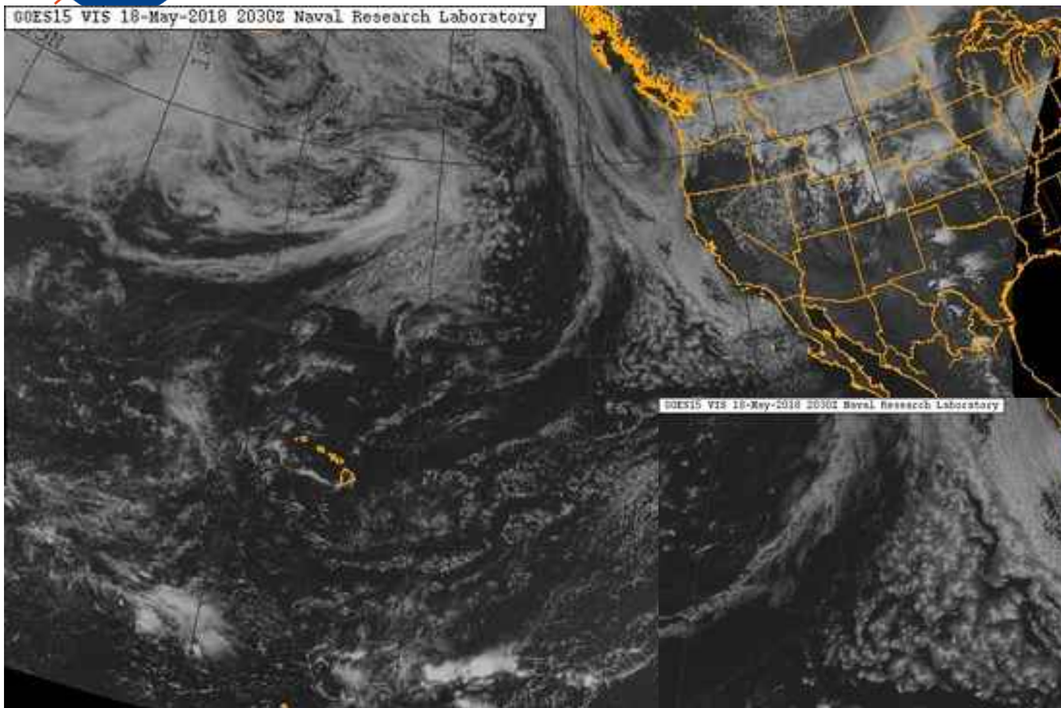
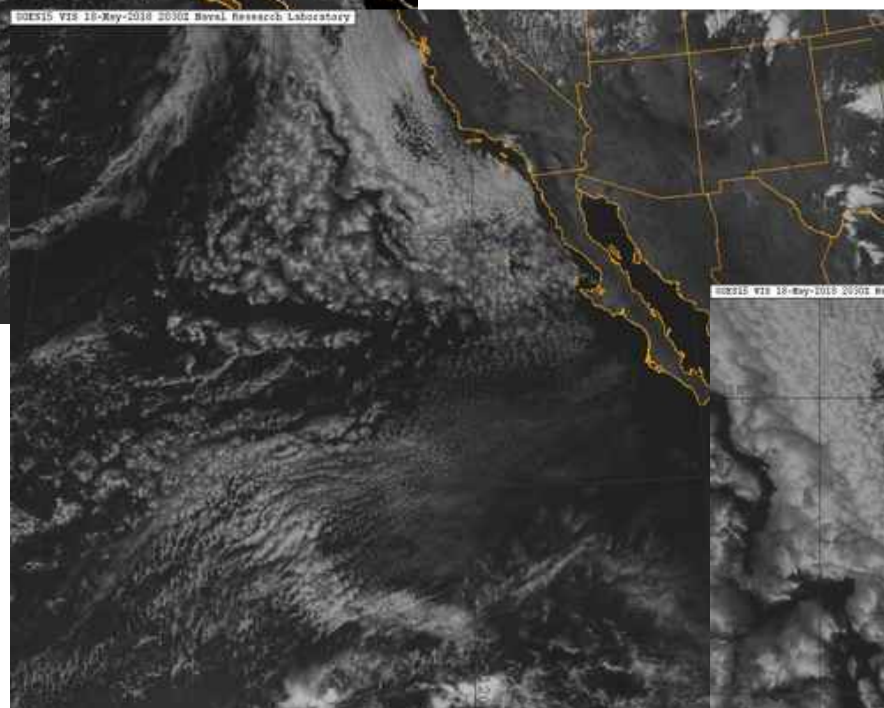
Sunday Afternoon …





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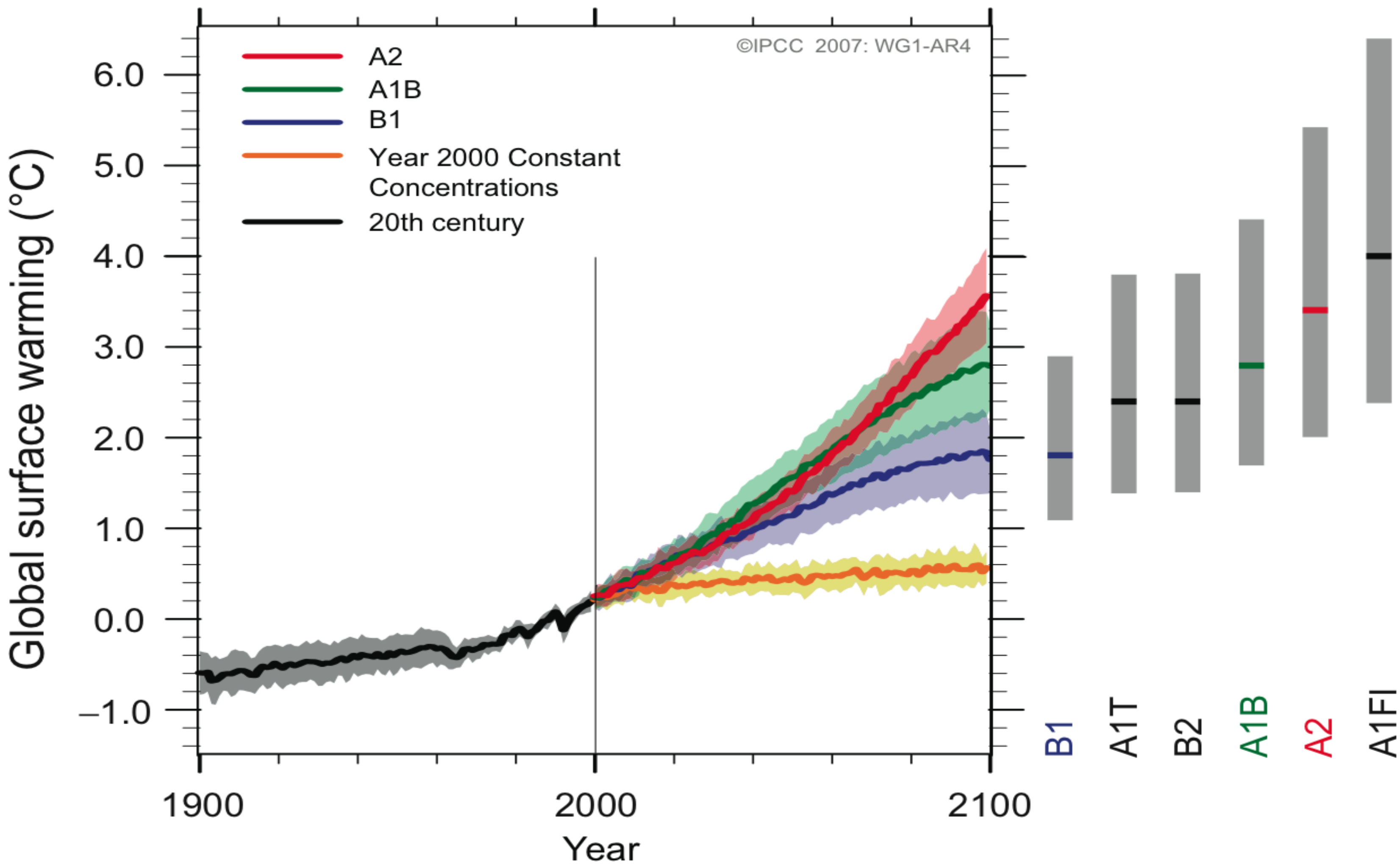
Climate Change Prediction

Multi-model Averages and Assessed Ranges for Surface Warming



Cloud modeling uncertainties and cloud interaction with radiation lead to significant uncertainties in climate prediction

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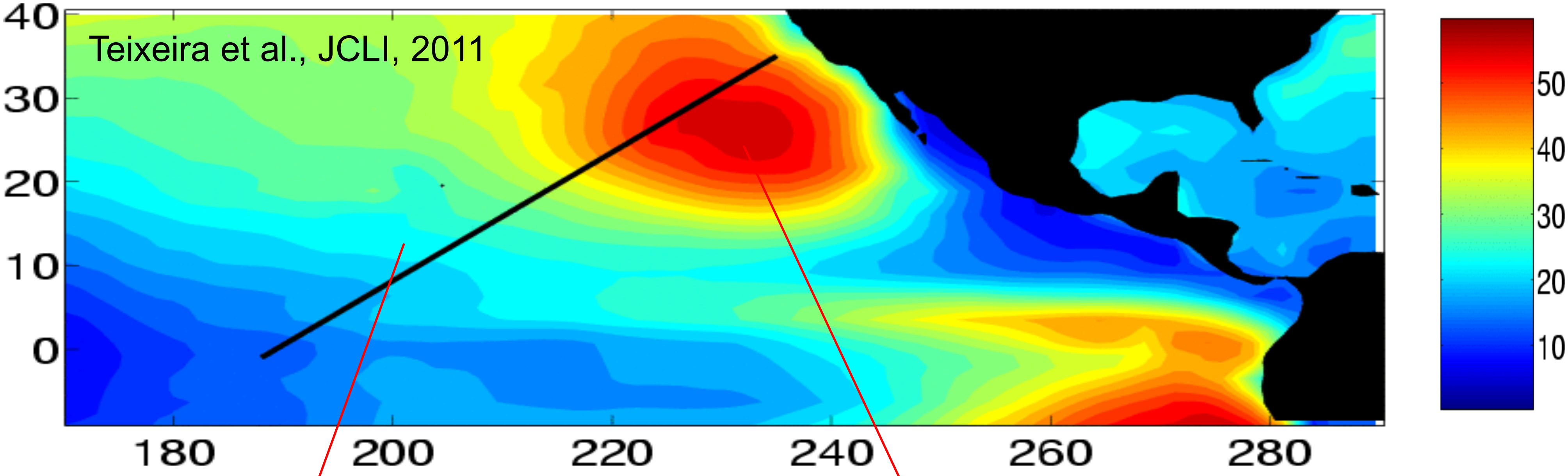
Subtropical Cloud Transition

ISCCP Low Cloud Cover (%)



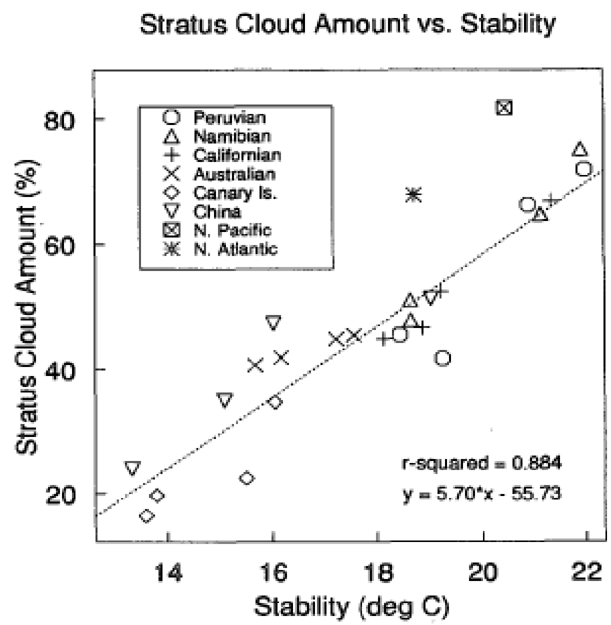
Highly reflective stratocumulus clouds (large cloud cover)

Cumulus cloud (virtually clear sky, much less reflection)

Hypothesis: Changes in the properties of stratocumulus-to-cumulus transition play a key role in cloud-climate feedbacks

Sc to Cu Transition: Key Questions

Which climatological factors control the climatological transition?



$\theta_{700} - SST$

Klein & Hartman, JCLI, 93

But starts with Neiburger, 1960s; Slingo, 1970s and 80s.

Which specific physical processes determine the cloud transition?

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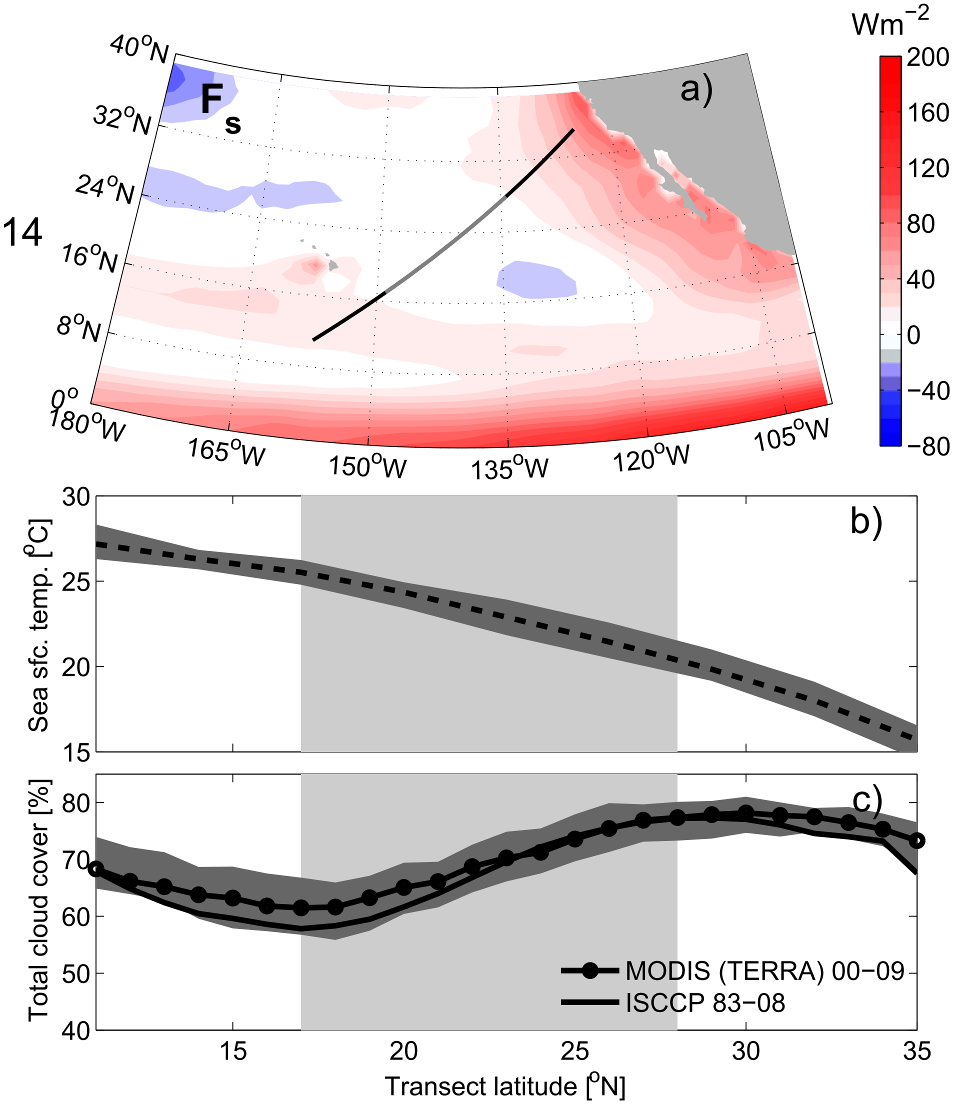
Climatological Surface Energy Balance

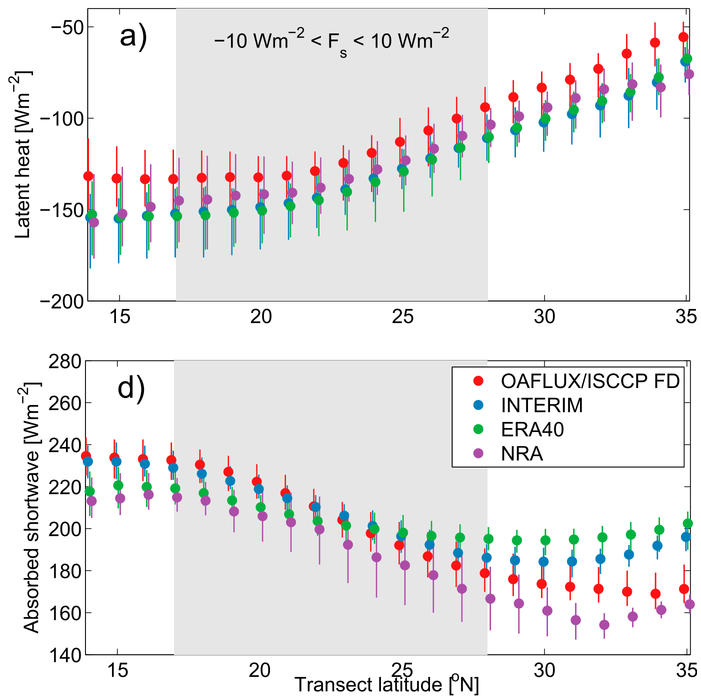
Karlsson & Teixeira, JCLI, 2014



ERA-Interim (1989–2007) climatological net surface energy flux (F_s)

In key transition region: $\mathrm{SW_{sfc}} + \mathrm{LW_{sfc}} + \mathrm{LH} + \mathrm{SH} \approx 0.$

Cloud Diagnostic Equation from Surface Energy Balance



Karlsson & Teixeira, JCLI, 2014

In essence: Increase of surface latent heat flux balanced by increase in surface SW radiation

➔ Cloud cover (a) equation:

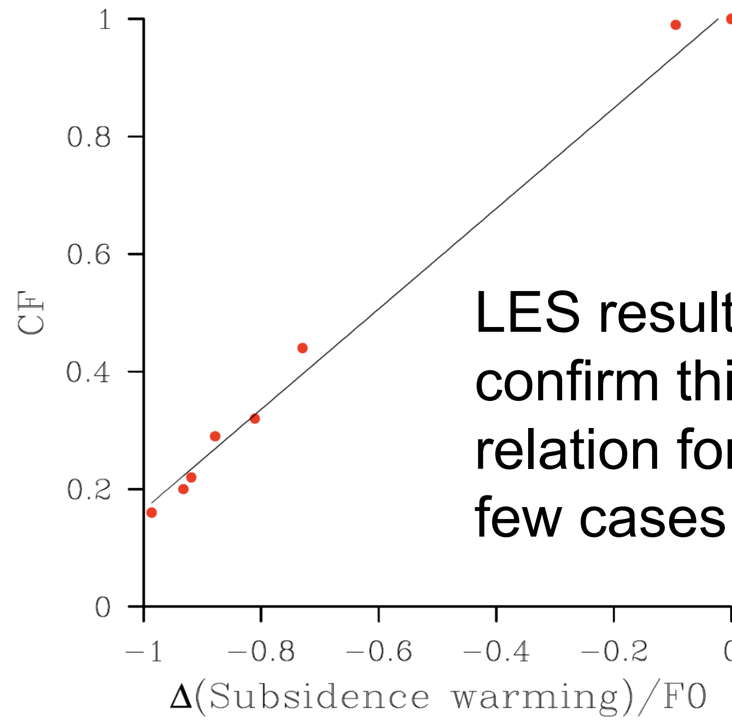
$$a = \frac{1}{\alpha_c} + \frac{\mathrm{LW} + \mathrm{LH} + \mathrm{SH}}{\gamma_{\mathrm{SW}}(1-\alpha_o)\alpha_c M_{\mathrm{atm}} \mathrm{SW}_{\mathrm{toa}}\downarrow}.$$

LTS Simple Model of the Transition

Empirical linear relation between cloud cover and Lower Tropospheric Stability (LTS) established for a while (e.g. Klein and Hartmann, 93)

LES + PBL energy balance leads to (1st order):

$$CF \sim \frac{hD}{F_0}(\theta_{700} - SST)$$



LES results confirm this relation for a few cases

Chung et al, JAS, 2012

Where:

CF – cloud cover

h – PBL height

D – large-scale divergence

F0 – LW flux divergence at cloud-top

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Simple Coupled Model

$$\begin{cases} CF = \alpha LTS + \beta \\ CF = \dfrac{1}{a_c} + \dfrac{LH + SH + LW}{\gamma_{SW}(1 - a_o) a_c M_{atm} SW_{toa}} \end{cases}$$

With $$LH = \rho L C_l \gamma_{Udq} U \left[q_s(SST) - RH q_s(T_a) \right]$$

- Two equations and two unknowns: SST and cloud cover
- Coupled model from (i) the linear LTS relation and (ii) the surface energy balance equation
- α and β have to be defined

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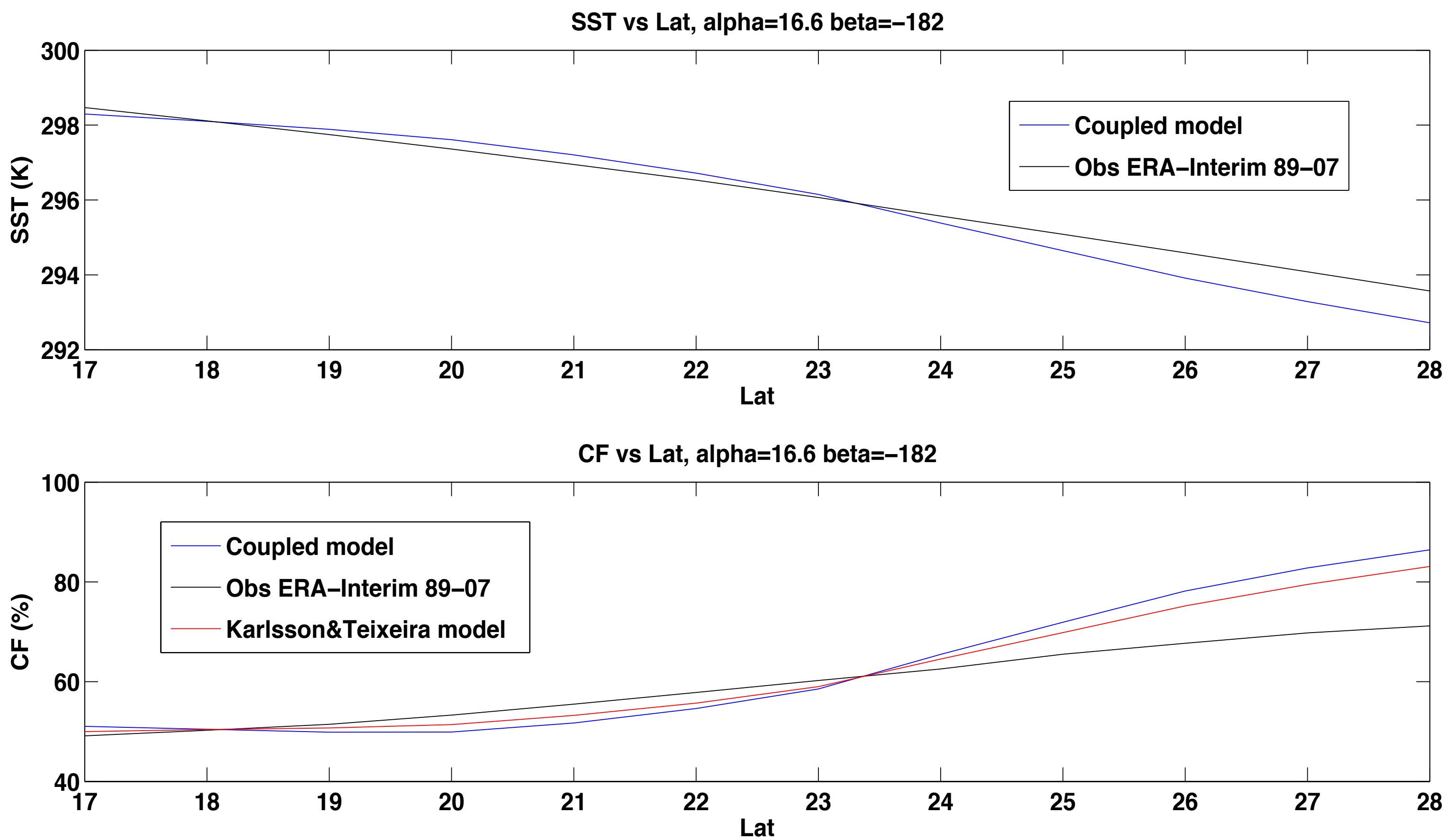
Simple Coupled Model with α and β from ERA-Interim



Cloud and SST changes are well described by coupled model using coefficients from ERA-Interim

Radet & Teixeira, 2018

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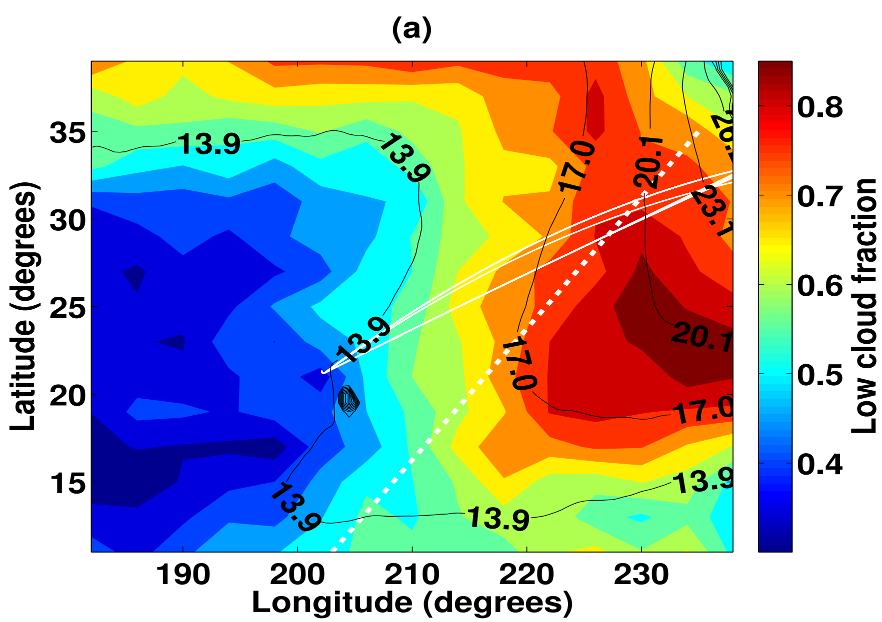
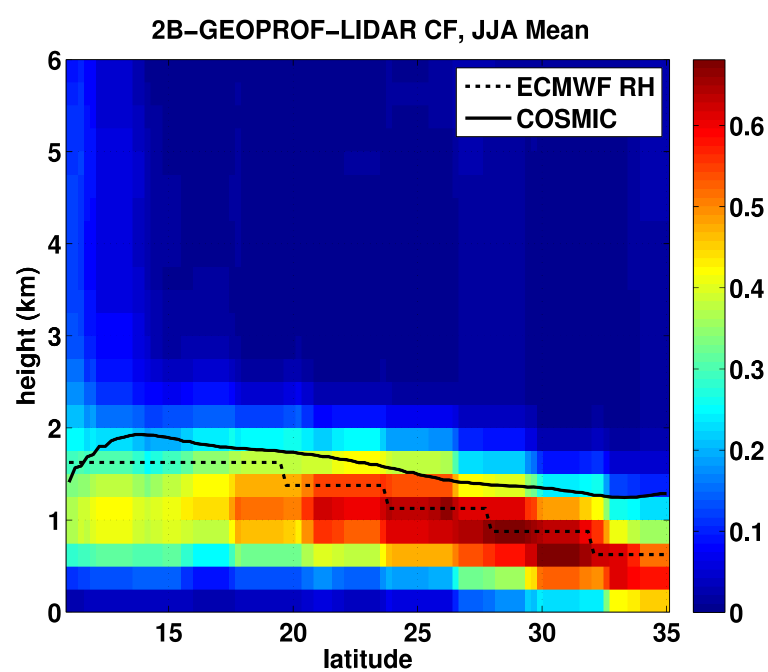
DOE Marine ARM GPCI Investigations of Clouds: MAGIC

One year [Sep. 2012-2013] deployment of ARM mobile facility on cargo ship between Los Angeles and Honolulu

Fig. 1. Horizon *Spirit* and possible locations for AMF2 operations.



Lewis & Teixeira, 2015



Kalmus et al, 2015

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MAGIC: Individual Cloud Transition Legs

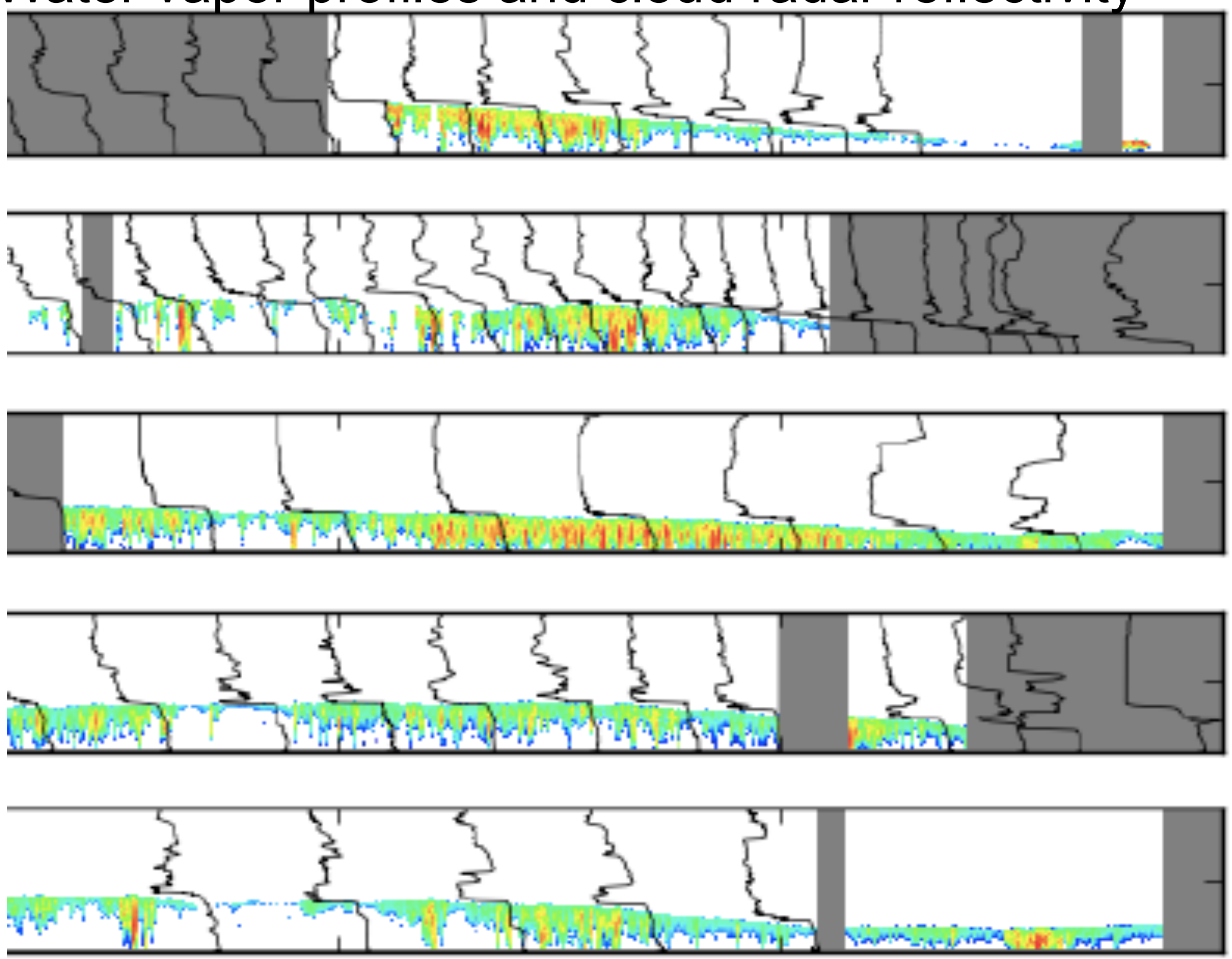
Kalmus et al, 2018

Diversity of cloud transition patterns

But

Also common key physical processes

Water vapor profiles and cloud radar reflectivity



Honolulu

LA

MAGIC: unique observational dataset depicting cloud transitions

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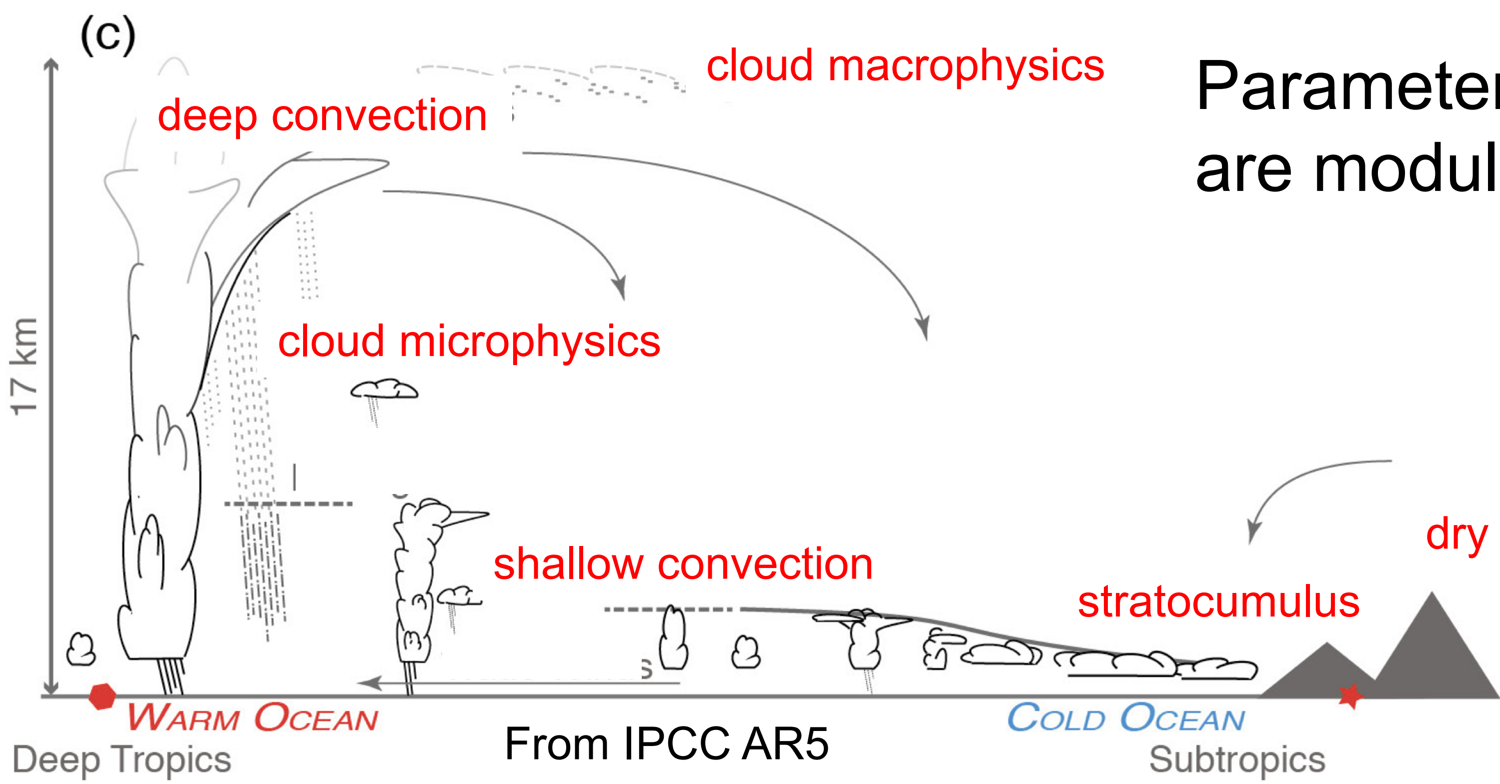
Turbulence, Clouds and Convection Parameterizations



From IPCC AR5

Parameterizations are modular

Artificial modularity leads to many problems: interfaces, transition

Key goal: Unified parameterization for boundary layer and convection

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Unified Approach: Eddy-Diffusivity/Mass-Flux (EDMF)

Dividing a grid square in two regions (updraft and environment) and using Reynolds decomposition and averaging leads to

$$\overline{w'\varphi'} = a_u \overline{w'\varphi'}_u + (1-a_u)\overline{w'\varphi'}_e + a_u(1-a_u)(w_u - w_e)(\varphi_u - \varphi_e)$$

where a_u is the updraft area. Assuming a_u<<*1* and w_e~*0* leads to

$$\overline{w'\varphi'} = \overline{w'\varphi'}_e + a_u w_u (\varphi_u - \overline{\varphi})$$

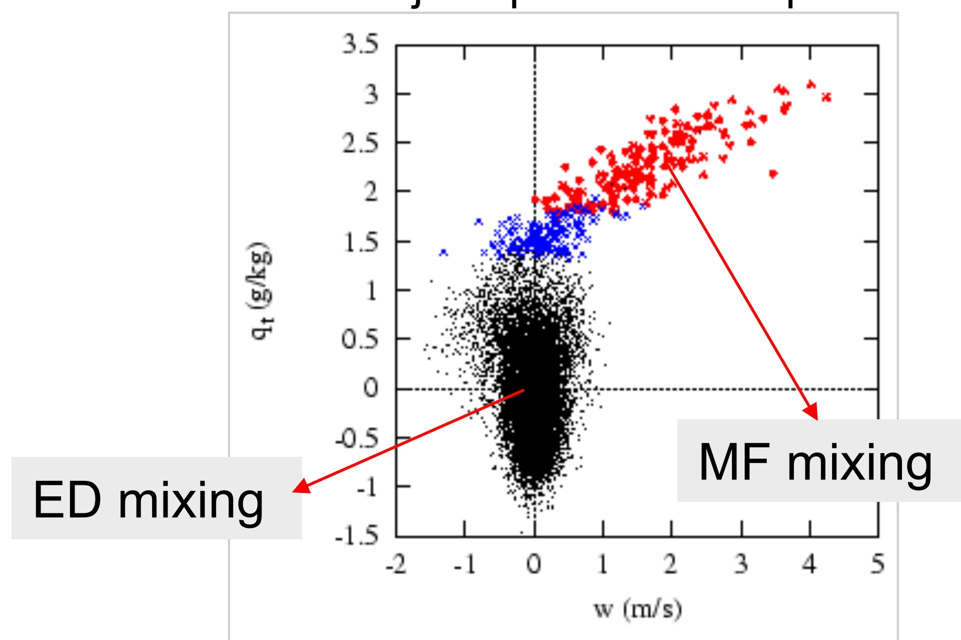
ED closure: assuming ED for 1st term and neglecting 2nd term

MF closure: neglecting 1st term and assuming $M = a_u w_u$

EDMF: $$\overline{w'\varphi'} = -k\frac{\partial \overline{\varphi}}{\partial z} + M(\varphi_u - \overline{\varphi})$$

Siebesma & Teixeira, 2000

Bimodal joint pdf of w and qt



EDMF represents different turbulence and convection scales

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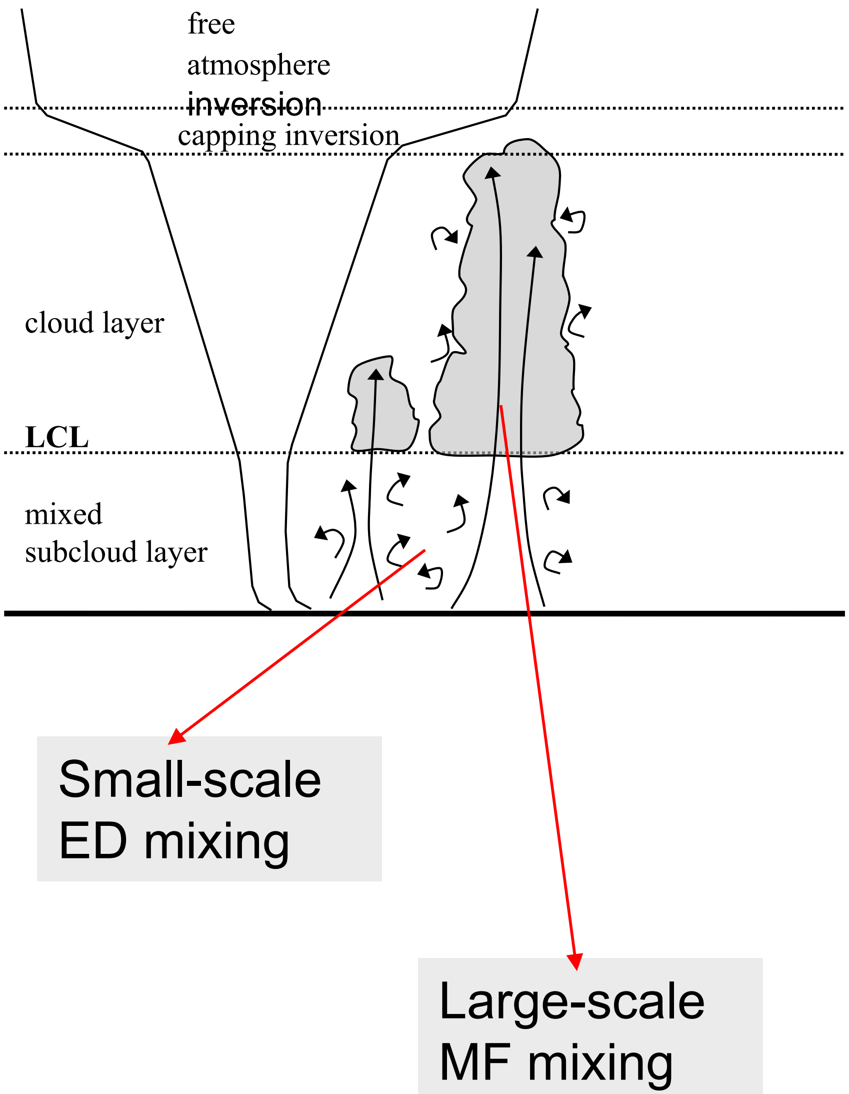
Mass-Flux Model for Plumes/Updrafts



1) Integrating over plume area
2) Assuming steady-state
3) Neglecting some sources/sinks

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon(\phi_u - \overline{\phi}) \text{ for } \phi \in \{\theta_l, q_t\}$$

$$M = \sigma_u w_u$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = -b\varepsilon w_u^2 + a\frac{g}{\theta_0}\left(\theta_{v,u} - \overline{\theta}_v\right)$$

σ_u is updraft/plume area fraction and is fixed for each plume in our approach

EDMF and moist convection: multiple plumes and stochastic entrainment

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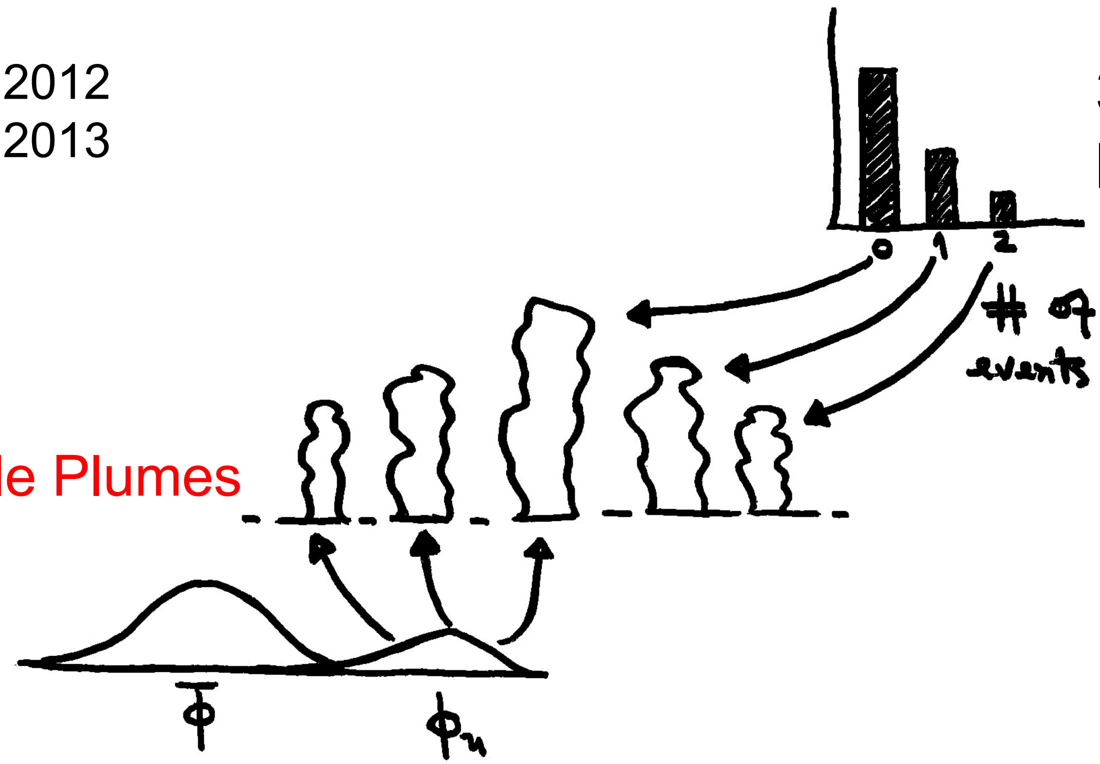
Suselj et al. JAS, 2012
Suselj et al. JAS, 2013



3) Stochastic lateral entrainment

Inspired by Romps & Kuang, JAS, 2010

Multiple Plumes

1) Parameterization of surface layer PDF of thermodynamics
2) Monte Carlo sampling of PDF to produce multiple plumes

Provides estimates of updraft area and avoids need for cloud base closure

New multiple-plume EDMF: plumes start from PDF of surface properties

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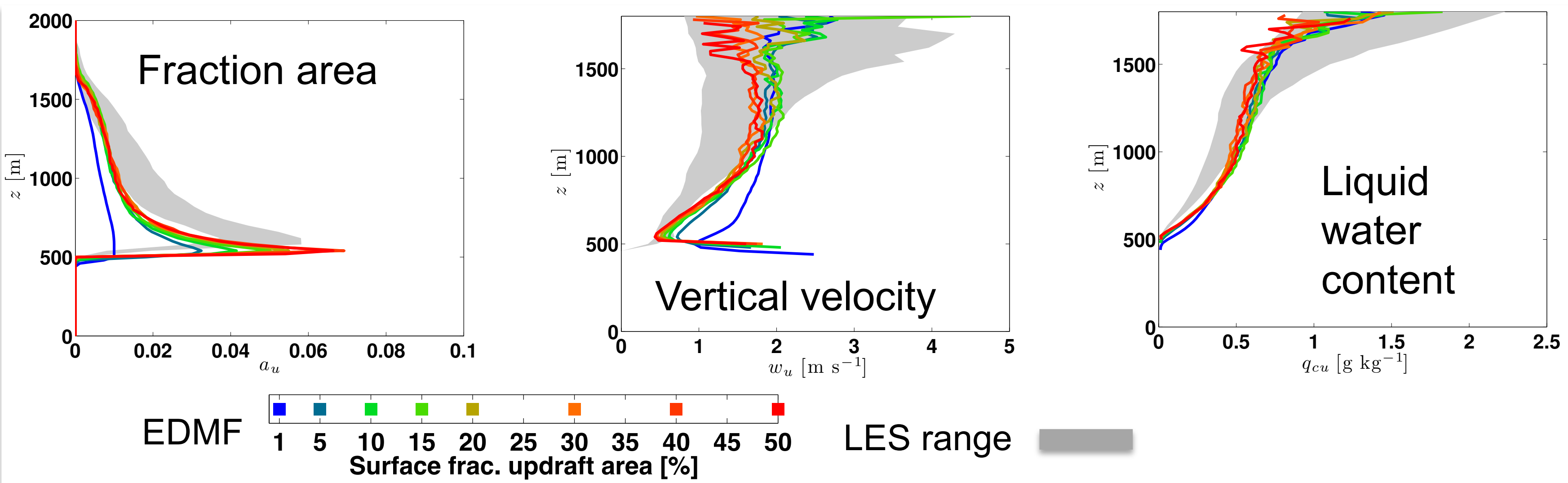
BOMEX: Comparison of EDMF moist updraft properties against LES results



Suselj et al, 2018

Low sensitivity of multiple-plume EDMF to surface updraft area

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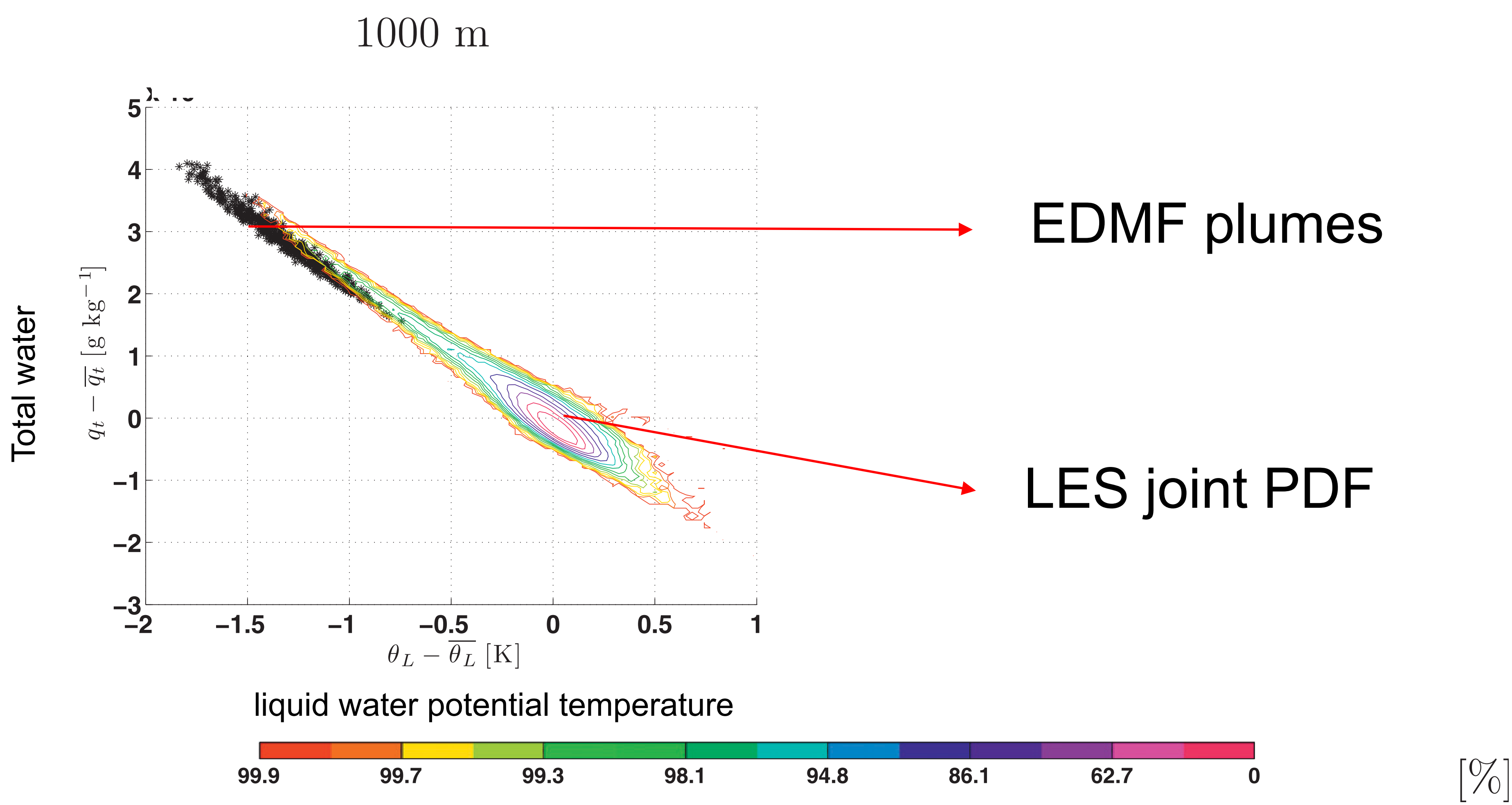
BOMEX: LES PDF vs EDMF plumes



EDMF multiple plumes represent skewed part of PDF

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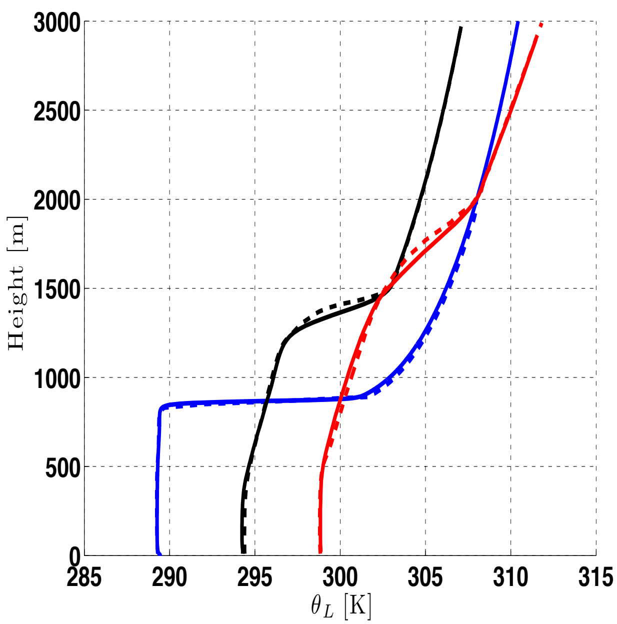
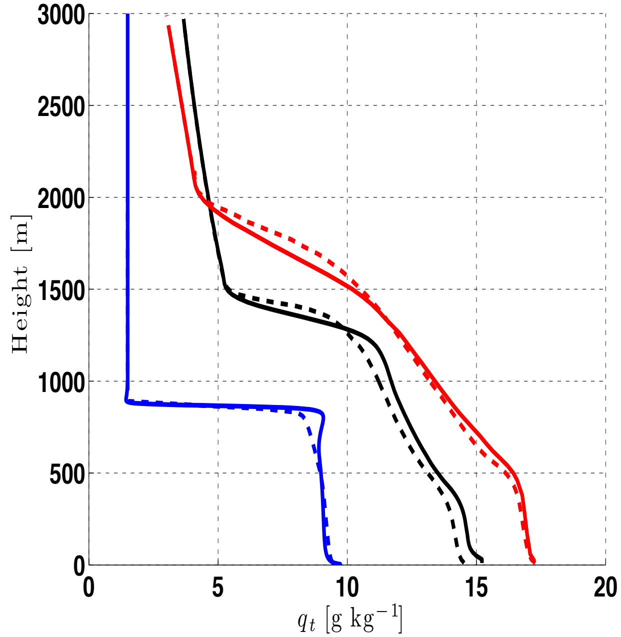
EDMF Results: Sc to Cu Transition

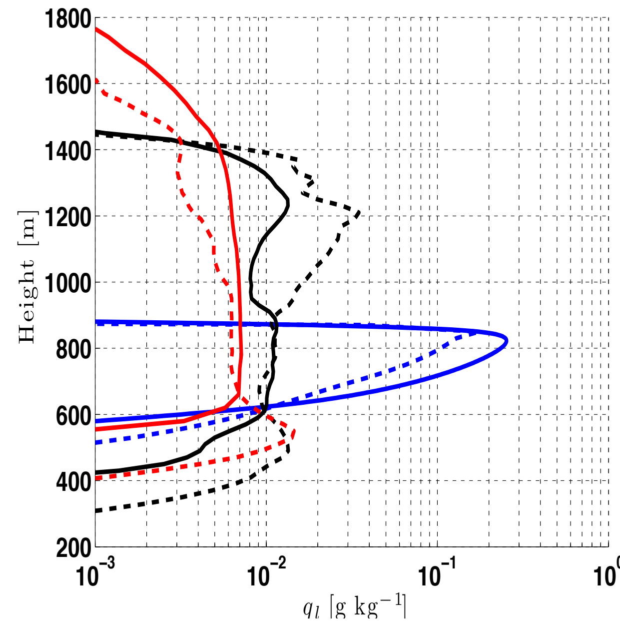
Liquid water potential temperature



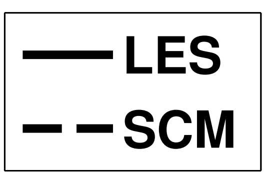
Total water



Liquid water



Suselj et al, 2013



EDMF is able to represent the vertical dynamics of the transition

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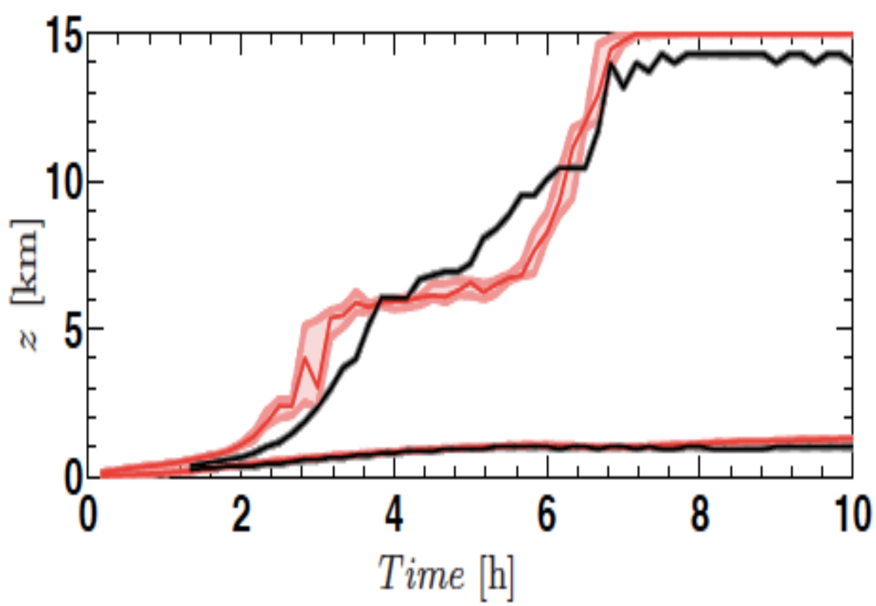
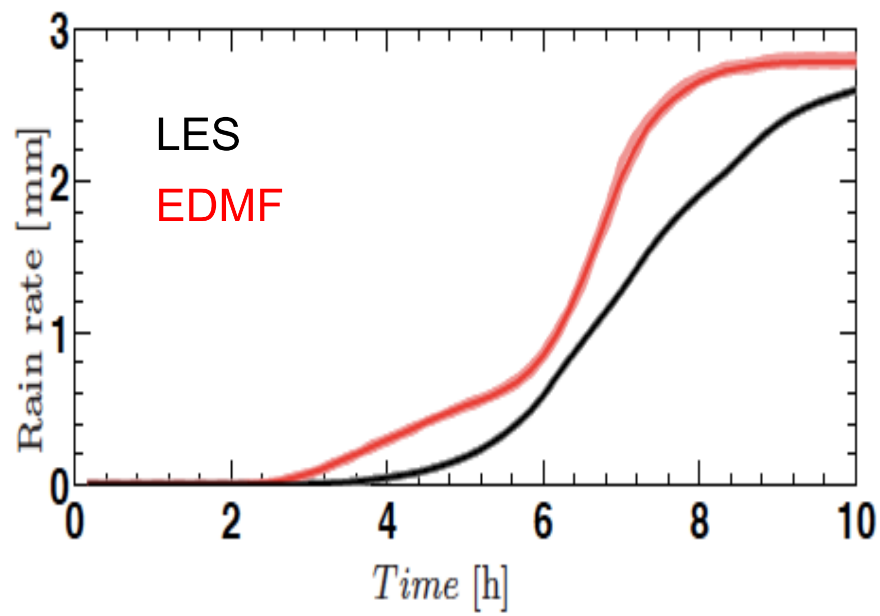
Diurnal cycle of precipitating convection over land - LBA

New fully unified (PBL + shallow + deep convection) EDMF evaluated for the LBA diurnal cycle of precipitating convection

Cloud base and top



Cumulative surface precipitation



Realistic transition with EDMF from shallow to deep convection

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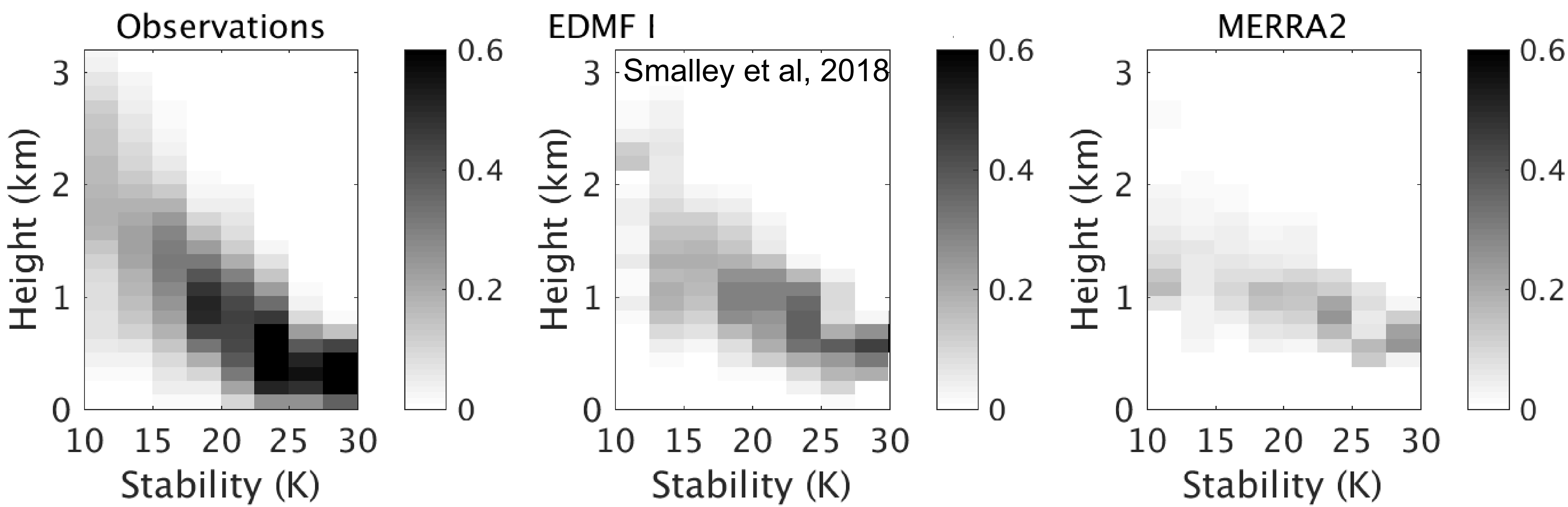
EDMF forced by Re-Analysis: realistic response to climatological forcing

500 EDMF SCM simulations (June 2007) between Los Angeles and Hawaii forced by large-scale fields from MERRA2



EDMF represents the physics of the cloud transition and leads to realistic response to climatological factors such as LTS

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Summary

- Sc-to-Cu transition will likely play key role in cloud-climate feedback
- Climate models cannot represent cloud transition realistically
- Surface energy balance equation in transition region leads to realistic simple model of cloud cover as a function of SST
- Simple coupled model (CC and SST) based on (i) surface energy balance and (ii) PBL energy balance (LTS relation)
- Shows that (to first order) SST and clouds are strongly and uniquely coupled in the Sc-to-Cu transition region
- EDMF approach reproduces thermodynamic structure of transition
- EDMF responds realistically to climatological forcing of transition