CMIP Low Cloud Feedback Interpreted Through a Mixed-Layer Model

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CFMIP Meeting, Exeter 6/6/11

Prepared by LLNL under Contract DE-AC52-07NA237344.

UCRL: LLNL-PRES-484756

Motivation:

- GCM disagreement is largest for low clouds
  - because low clouds depend sensitively on small-scale processes which are hard to parameterize
- Problems due to cloud physics, not dynamics (?)
  - dynamics better resolved than cloud physics
  - Cloud changes are dominated by thermodynamic rather than dynamic changes (e.g. Bony et al, Clim Dyn 2004)

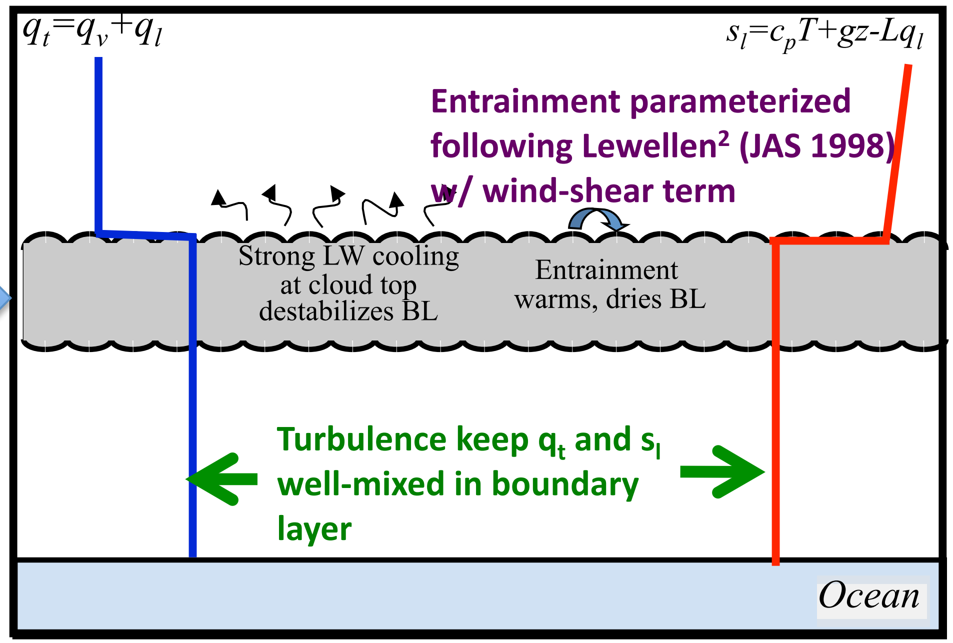
Hypothesis: a limited area model forced by output from various GCMs will produce more consistent, physically-defensible low-cloud changes.

Approach:

Mixed Layer Model (MLM)

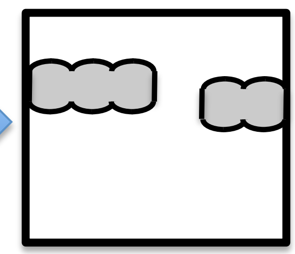
CMIP model output (or reanalysis)

1. Get daily SST, surface pressure, winds, free-tropospheric T, q, and subsidence, advection of BL T and q from GCM output



2. Run MLM to equilibrium using GCM model forcing for each day

Cloud fraction, LWP, etc

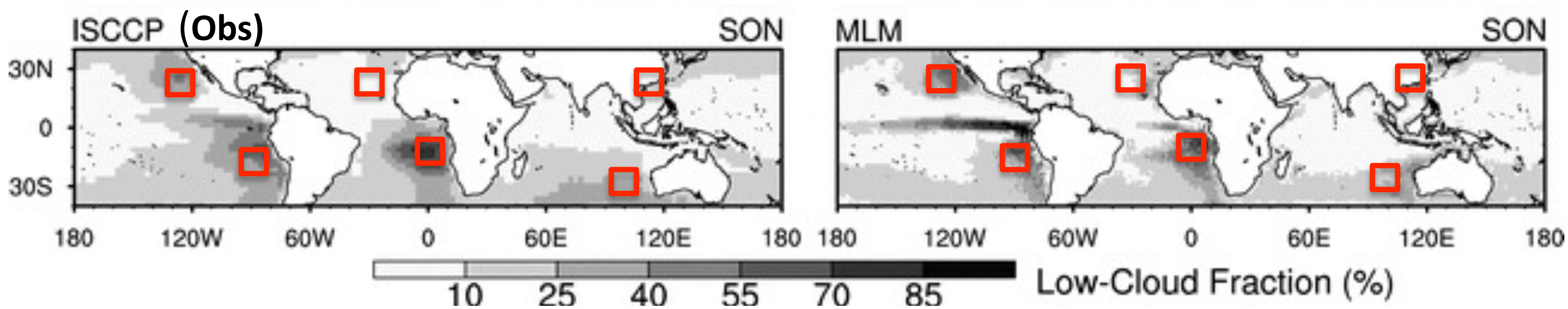


3. Calculate cloud fraction as % of time cloudy MLM solution is found (Zhang et al, JClim 2009)

Benefits:
1. MLM is simple and easy to interpret
2. Existent local model studies do not assess forcing uncertainty or variability
   - exception=Lauer et al (JClim 2010) regional model forced by 3 GCMs

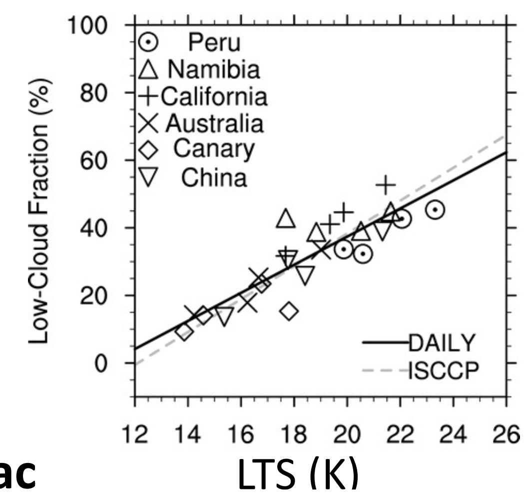
Model Validation:

When forced by ERA40 for 1990-2001, this approach reproduces the observed geographical distribution of cloud and the observed low-cloud vs. LTS relationship



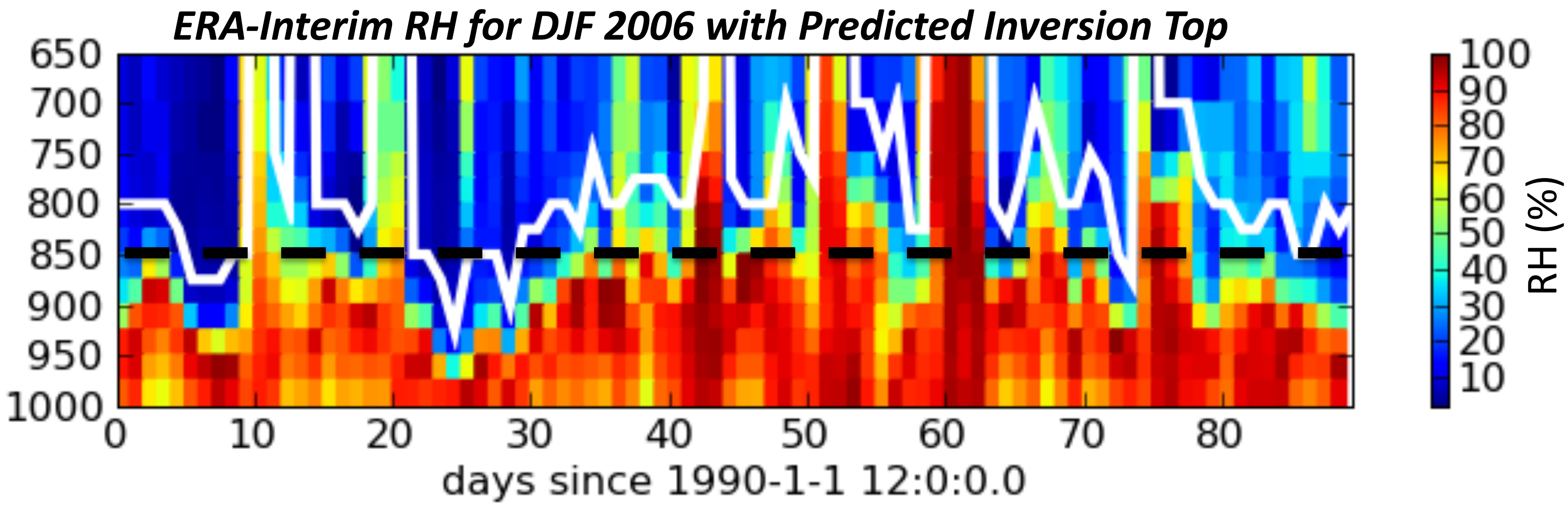
Sept-Nov low cloud observed from ISCCP and from the model. Red boxes denote the 6 Sc regions identified in Klein + Hartmann (JClim 1993) and used below.

- **Results decent, but equatorial and near-coast values are overpredicted**
  - **Not equilibrated due to sharp upstream gradients**
- **The observed LTS vs cld frac relation is nicely reproduced**
- **Comparing ISCCP obs and ERA-Interim-forced MLM cldfrac for 2006, approach has poor daily skill ($r^2 \approx 0.2$), decent weekly skill ($r^2 \approx 0.5$), and good seasonal skill ($r^2 \approx 0.8$)**



Modeled and observed relation between LTS and cloud fraction using each season for each region as a data point.

Forcings from GCMs



Compiling MLM forcings from GCM data is generally easy but:

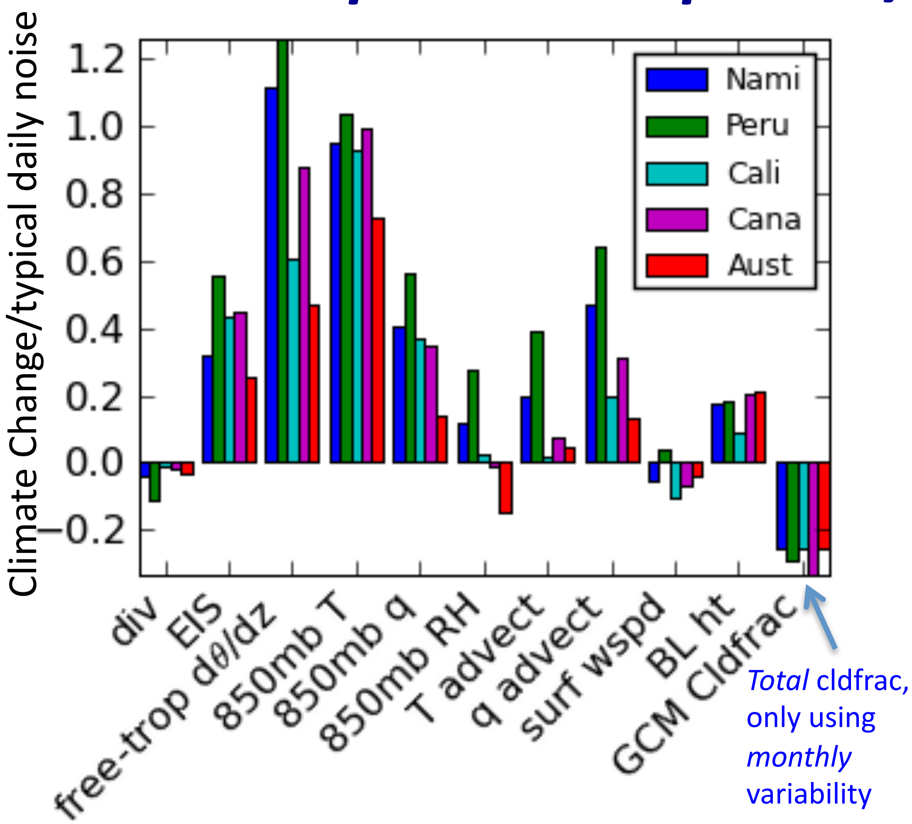
1. Free-tropospheric boundary conditions require inversion height estimation since BL depth changes with time (see graphic)

2. ∇SST and ∇q_s(SST) are good predictors of T and q gradients; BL depth advection is not computable, $v \bullet \nabla z_i$=0.49mm/day is assumed

3. Subsidence is computed assuming constant divergence (using 10m winds)

Forcing Changes

Do GCMs produce expected/consistent forcing changes?

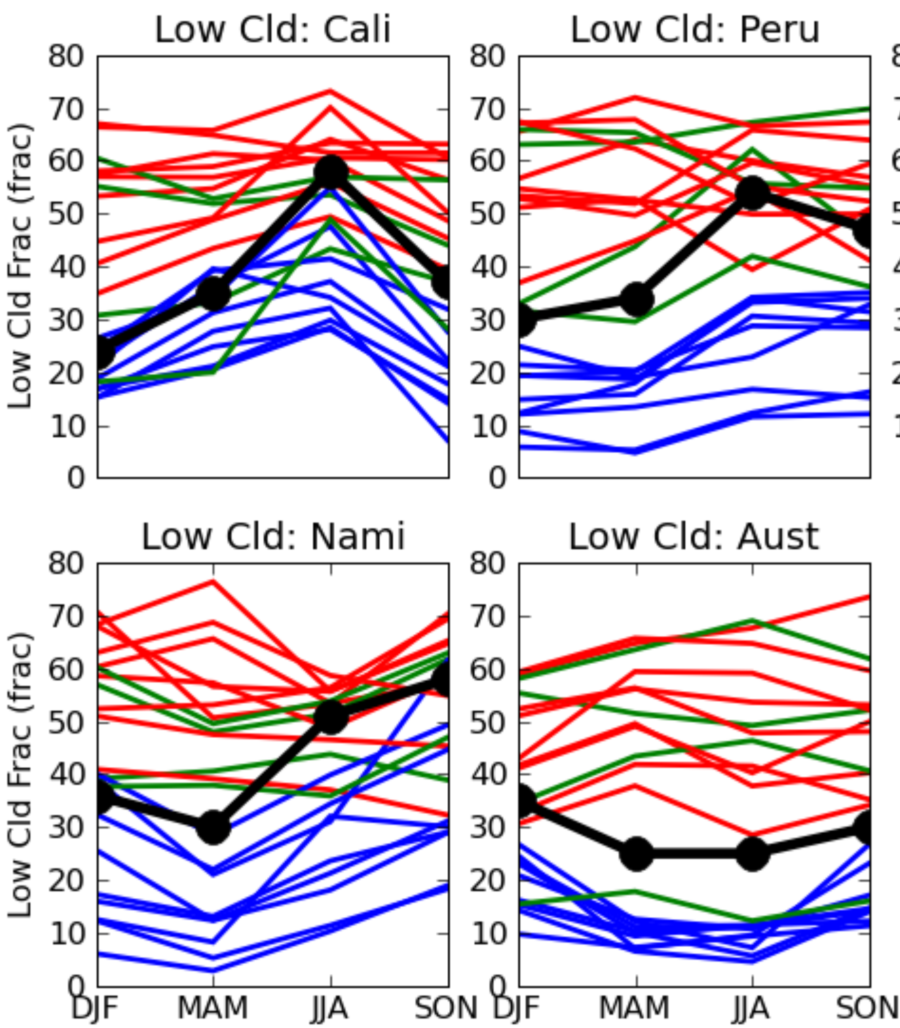


Inter-model average change in MLM forcings between 20th century (1981-2000) and A1B (2081-2100) runs normalized by the standard deviation of current-climate data (with annual cycle removed).

- Divergence decreases but change < daily noise
- T, q, EIS, and dθ/dz changes large & positive
- Advection increases, particularly for q
- BL ht robustly increases

Results: Current-Climate

Does the MLM improve current-climate prediction?



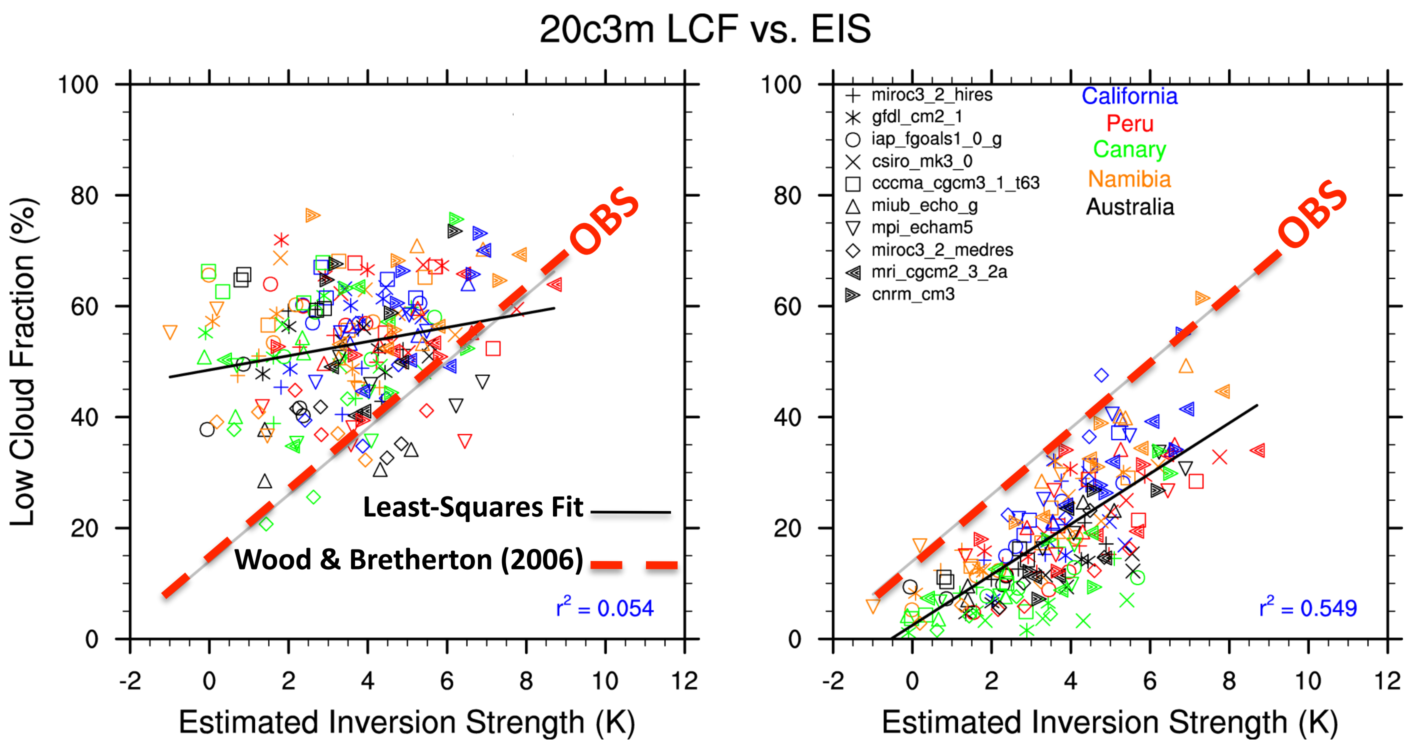
Seasonal cycle **of GCM total cldfrac**, **GCM low-cldfrac assuming random overlap** (where available), **MLM cldfrac**, and **ISCCP 1990-2000 pres > 680mb**.

- MLM under-predicts, GCM overpredicts
- MLM improves seasonal and regional pattern

- Conclusions independent of whether GCM total cldfrac or random-overlap of monthly 3d fields below σ=0.7 is used

Results: Current Climate

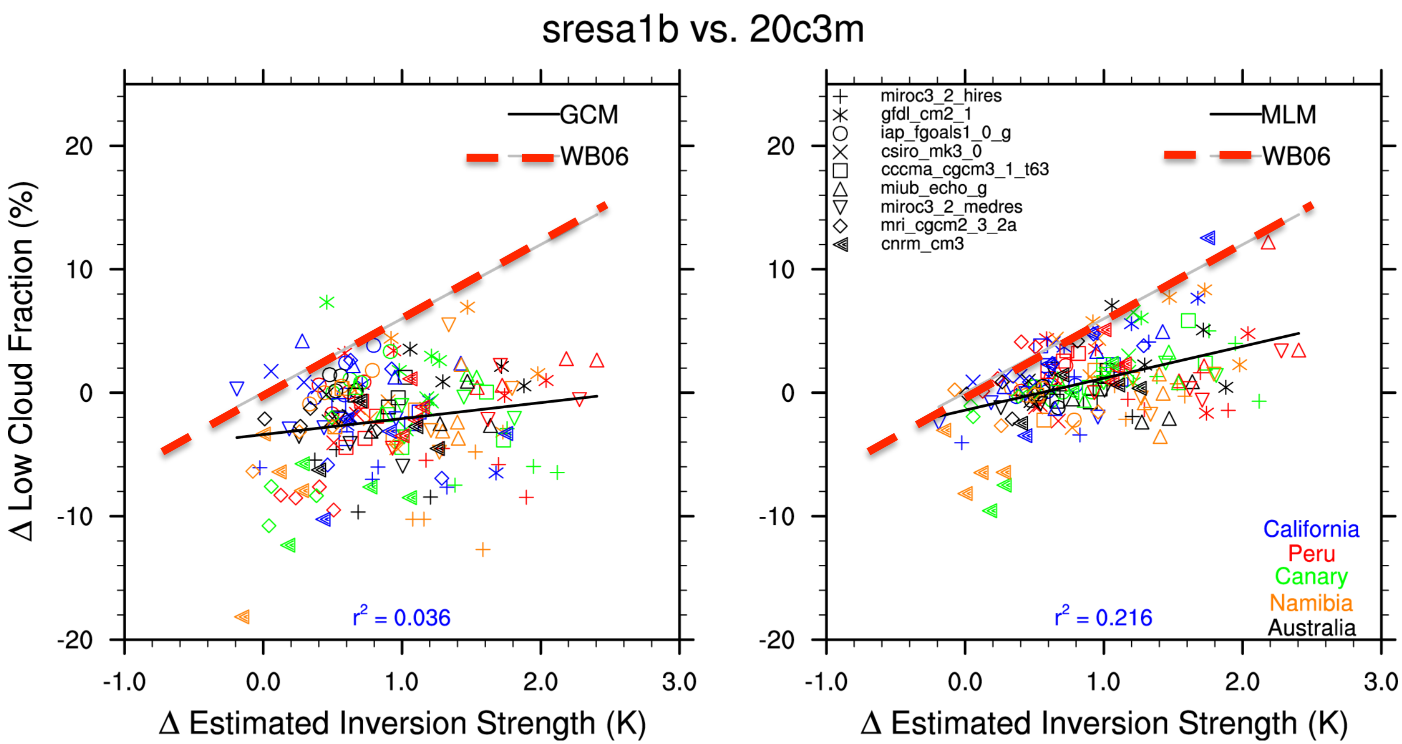
Do the models capture the observed stability/cldfrac relation?



- **MLM dcld/dEIS across models, regions, and seasons is very good**
- **GCMs results are poor because of low regional, seasonal variation**

Results: EIS as a Climate-Change Predictor

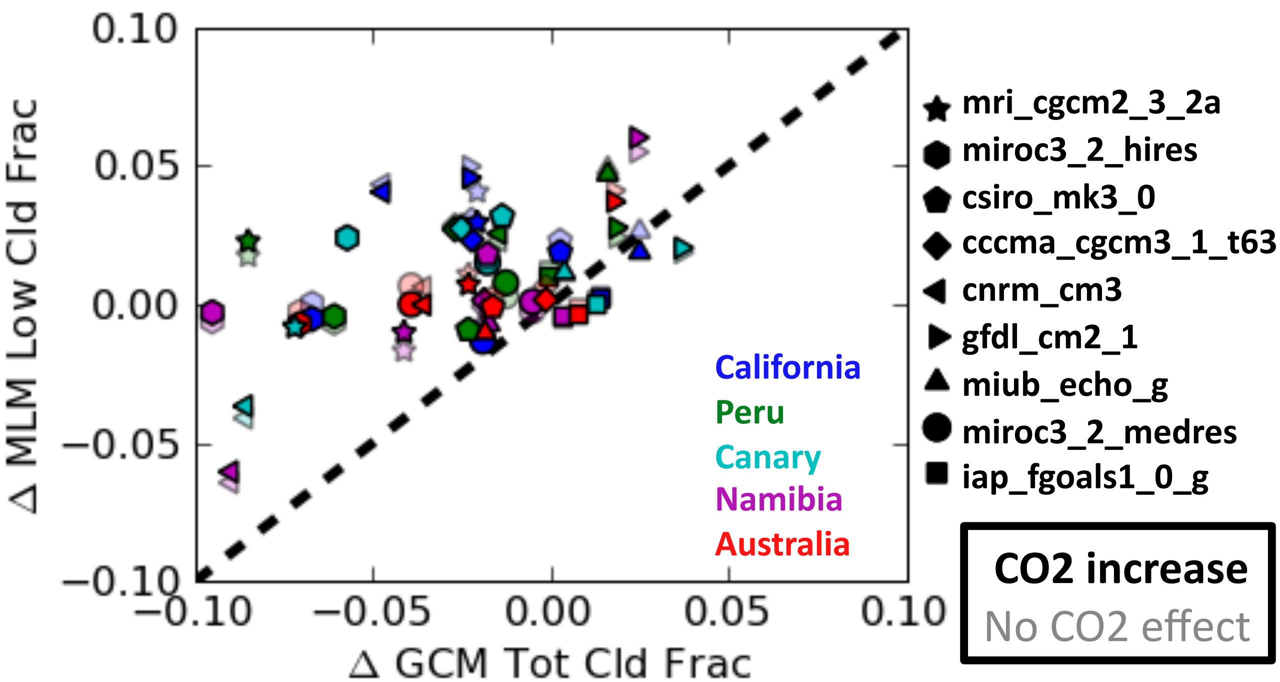
Does the observed EIS/cldfrac relation explain future change?



- **EIS is marginal for GCM Δcld, better for MLM Δcld**
  - **EIS is a better predictor for GCMs when averaged over region, season (not shown)**
- **Current-climate dcld/dEIS *slope* is a poor predictor of future climate**

Results: MLM vs GCM cldfrac

Does the MLM alter our predictions of low cloud change?

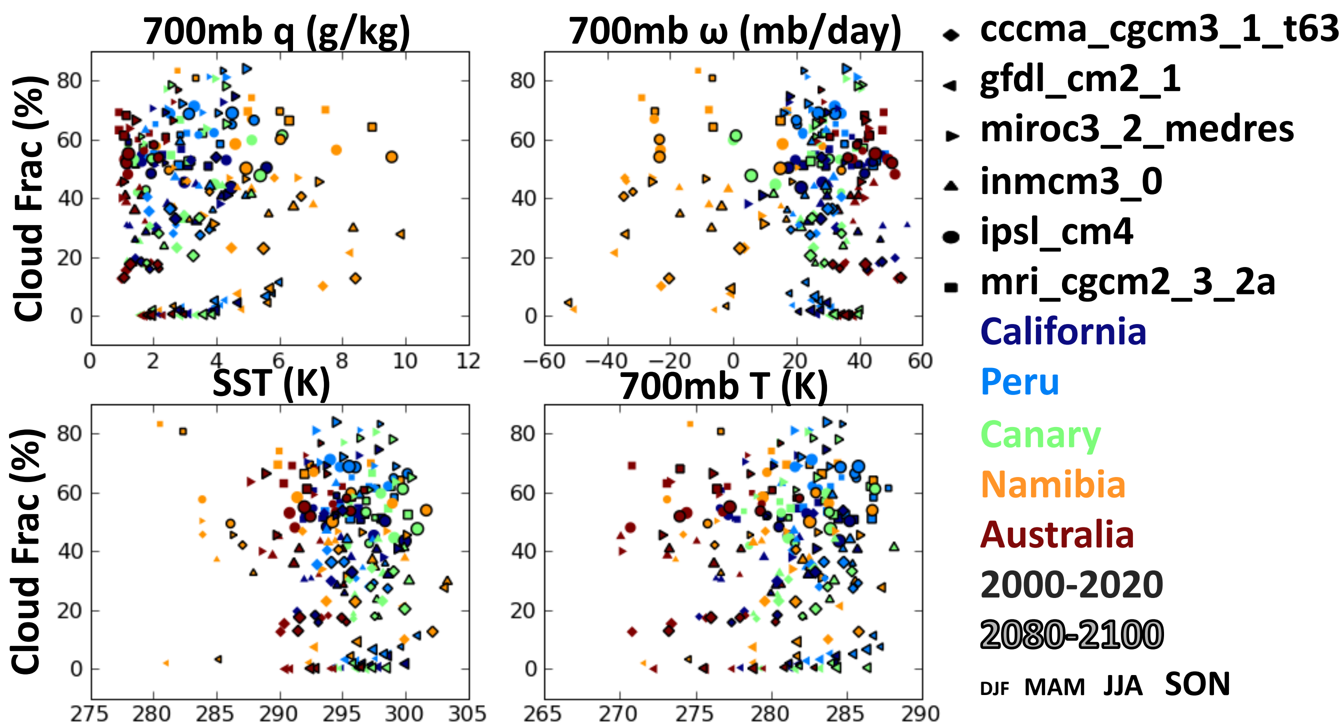


Low cloud climate change signal from MLM vs GCMs. Climate change is 20c3m yrs 1981-2000 vs sresa1b yrs 2081-2100 with BL radiative cooling reduced 4 W/m² to mimic CO2 doubling.

- **Cloud change more positive in MLM (since pts above 1:1 line)**
- **Direct CO2 effect has little influence**
- **MLM does reduce inter-model spread (since spread in y< spread in x)**
- **MLM and GCM clouds only weakly correlated (ie pts don't lie parallel to 1:1 line)**

Imprinting

Do models with less low cloud have conditions which discourage low cloud in the MLM?



Low cloud fraction (from monthly data using random overlap) vs forcing variables where imprinting may be expected. Datapoints are 20 yr averages stratified by model, region, season, and date.

No.

- *Change* in variables is also not related to cloud changes

Conclusions

1. The MLM captures seasonal and regional cldfrac differences which CMIP3 GCMs miss
2. Interpreting GCM results through a MLM does reduce inter-model spread
3. GCM low cloud bias does not imprint onto the MLM

Future Directions:

- Examine other variables (LWP, PBL depth, etc)
- Explore (lack of) connection between MLM and GCM results
- Identify aspects of GCM forcings which lead to spread in MLM results (through sensitivity tests)
- Check if results for CMIP5 are similar


Thanks!
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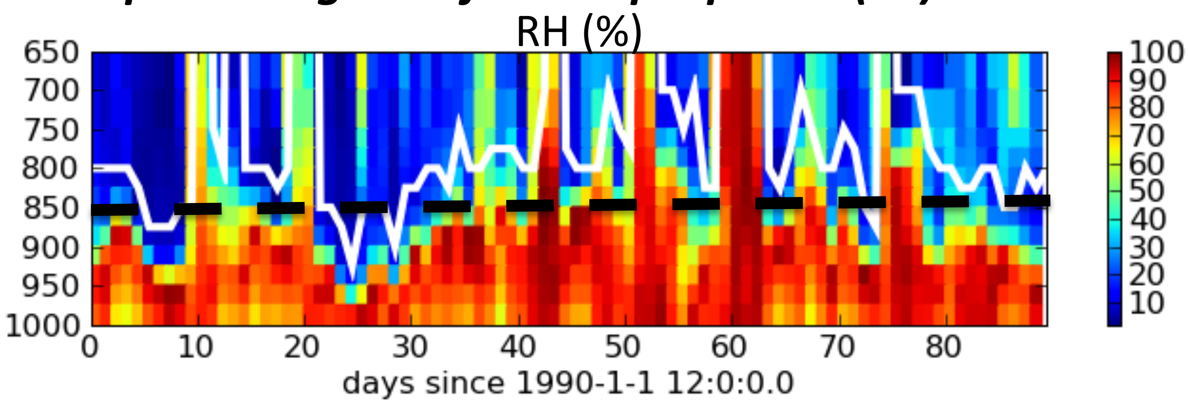
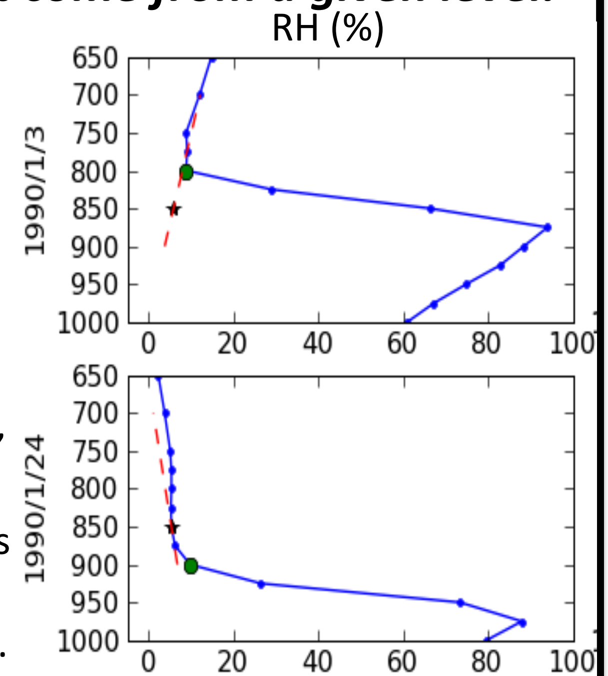
Forcing

Forcings from GCMs

***1.* BL depth changes so free-tropospheric (FT) values can't come from a given level.**





Above: RH profiles from ERA-Interim show 850mb is often in the BL at 30N, 130.5W during winter. White line=predicted inversion top.

Right: Inversion top (green dot) = the level of max(d^2RH/dp^2). Least-squares regression is used to find FT slope (red line), which is used to get a FT value if 850mb is found to be in the BL. FT values of T and q are found in this way.

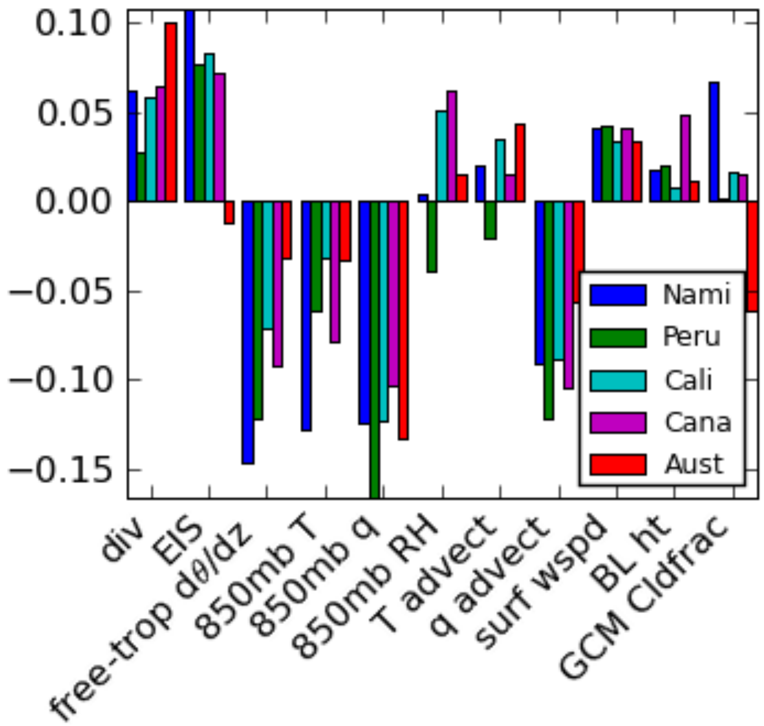
2. *Horizontal advection is unavailable from CMIP data or simple models.*

- Testing with ERA-Interim suggests that using ∇SST and ∇q_s(SST) works quite well
- Advection of BL height is challenging and we ended up using $v \bullet \nabla z_i$=0.49mm/day

3. Daily-resolution subsidence is also not available

- Subsidence is computed assuming constant divergence (calculated from 10m winds)

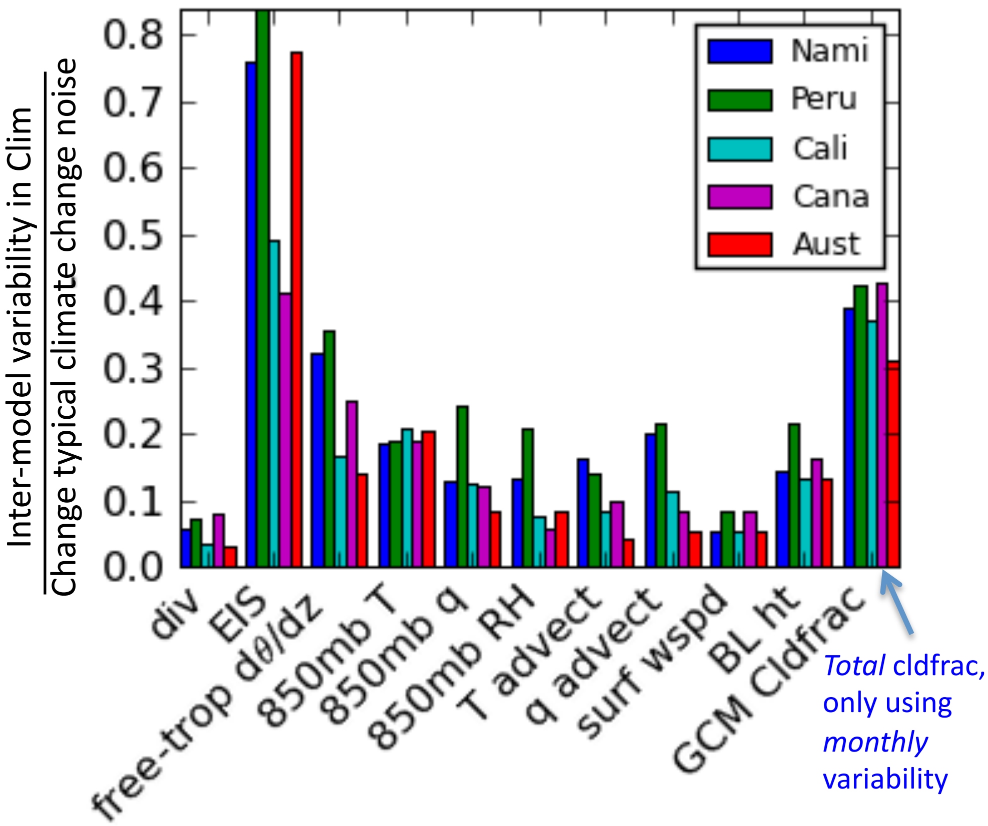
Forcing: Changes in Daily Variability



Inter-model average change in standard deviation of MLM forcing between 20th century (1981-2000) and A1B (2081-2100) runs normalized by the standard deviation of current-climate data. Annual cycle removed.

Forcing Changes

Is inter-model forcing variability *actually* less than cldfrac variability?



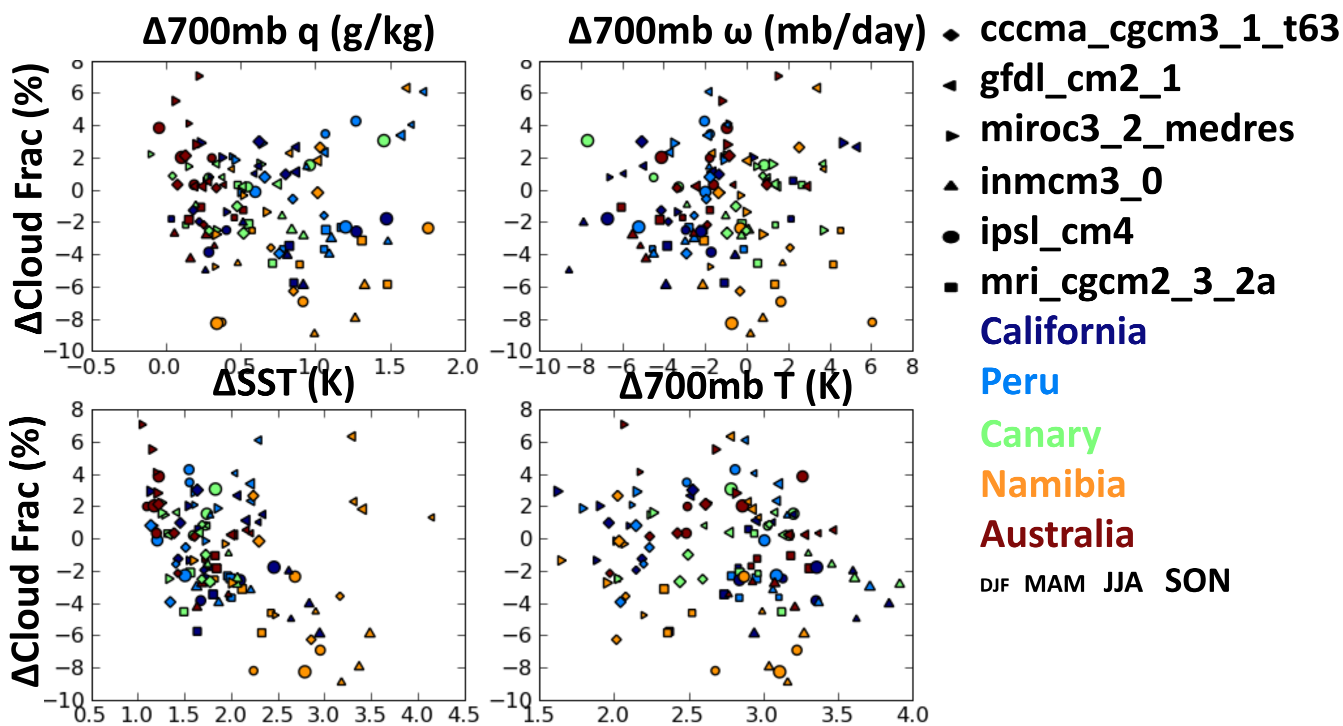
Standard deviation across models of variable change for 2080-2100 – 1980-2000 normalized by the inter-model average standard deviation of current-climate data (with annual cycle removed).

- GCMs differences in cldfrac changes > in all other variables except EIS even when daily variability is omitted

⇒Inter-model spread in GCM-predicted cloud is generally bigger than spread in forcings

Imprinting

Is the *change* in forcing variables controlled by the *change* in cloud fraction?



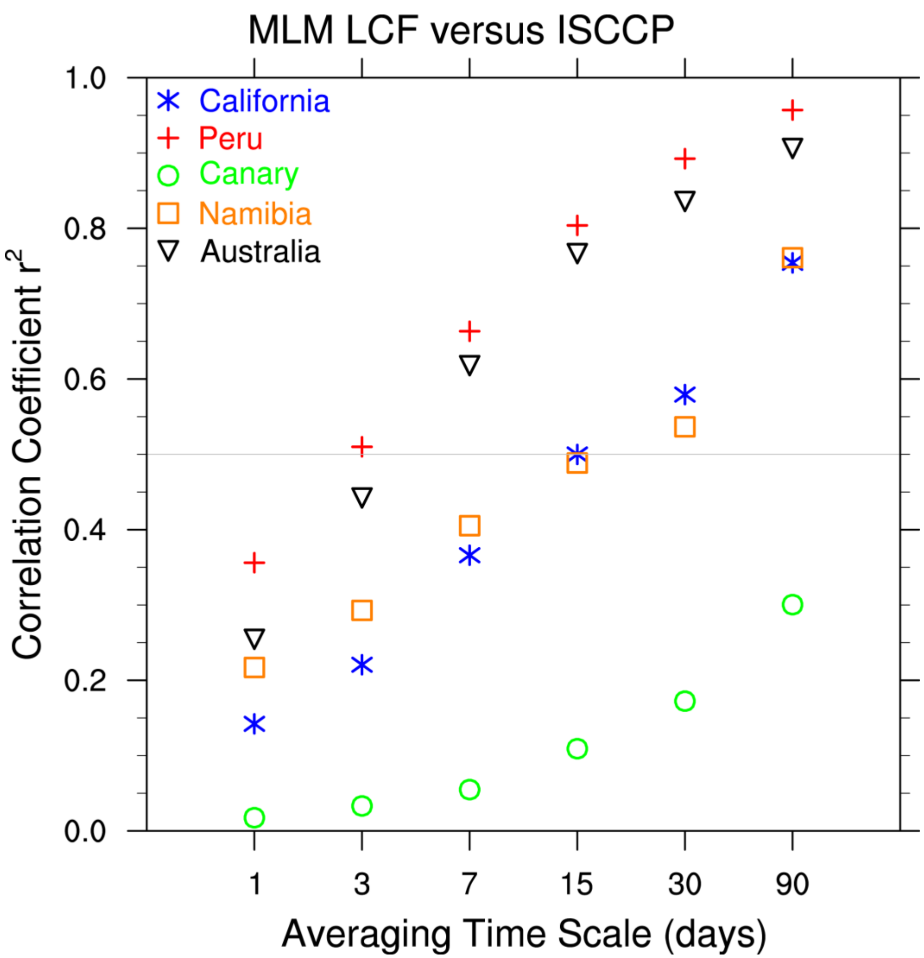
Change (defined as 2080-2100 – 2000-2020) in low cloud fraction vs change in forcing variables.

No.

Model Validation

Model Validation

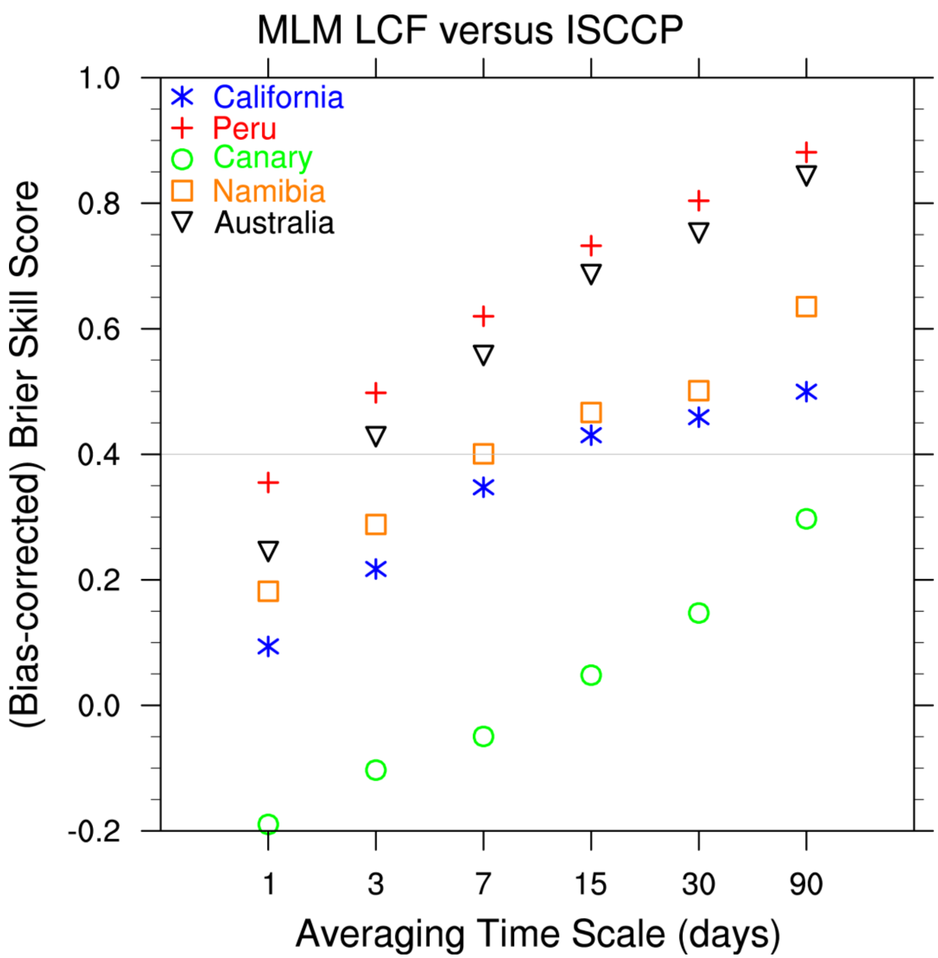
MLM theory based on short timescales so model should have skill at these scales. Does it?



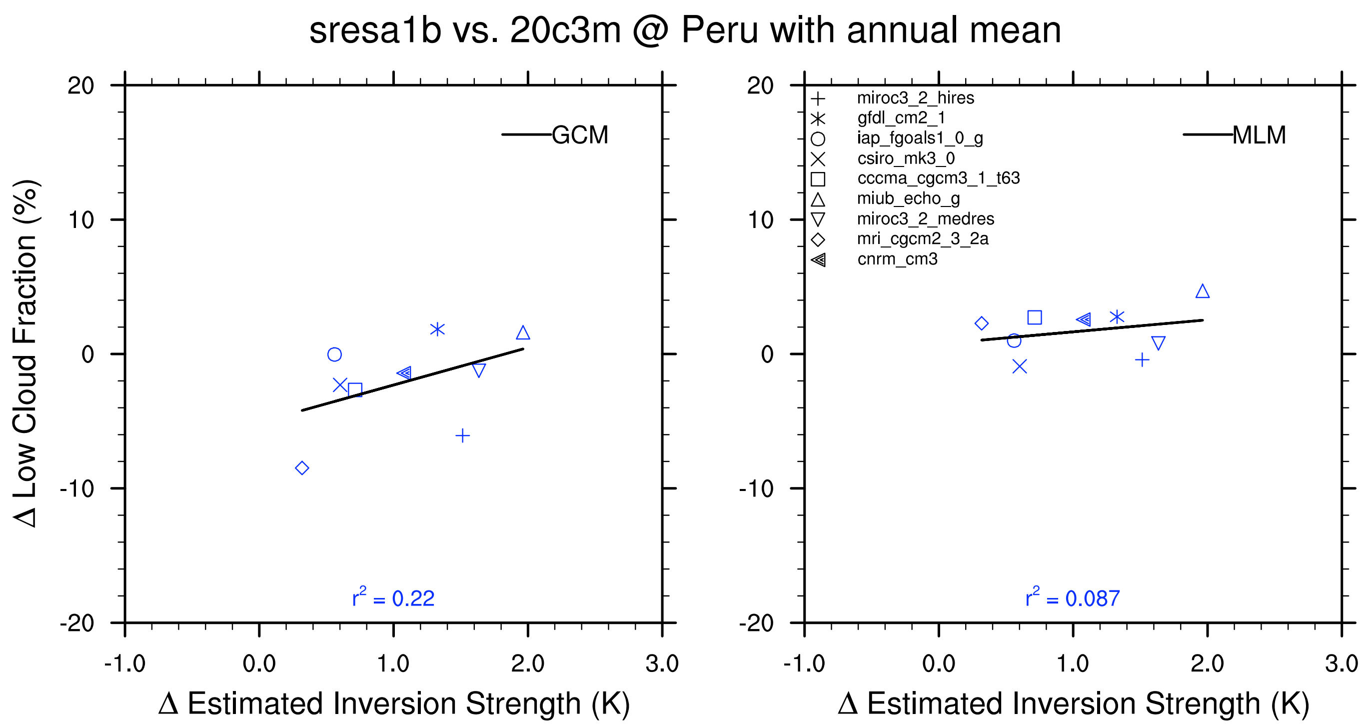
Correlation between regional-average cloud fraction from the MLM forced by 2006 ERA-Interim and from ISCCP data as a function of temporal averaging period.

- Canary region tends to be decoupled ⇒ MLM poor
- MLM has low skill at daily scale, decent at weekly+
    - Large forcing and obs error at daily scale erode short-term skill
    - synoptic (~weekly) scale is well predicted

Mixed layer model forecast ability

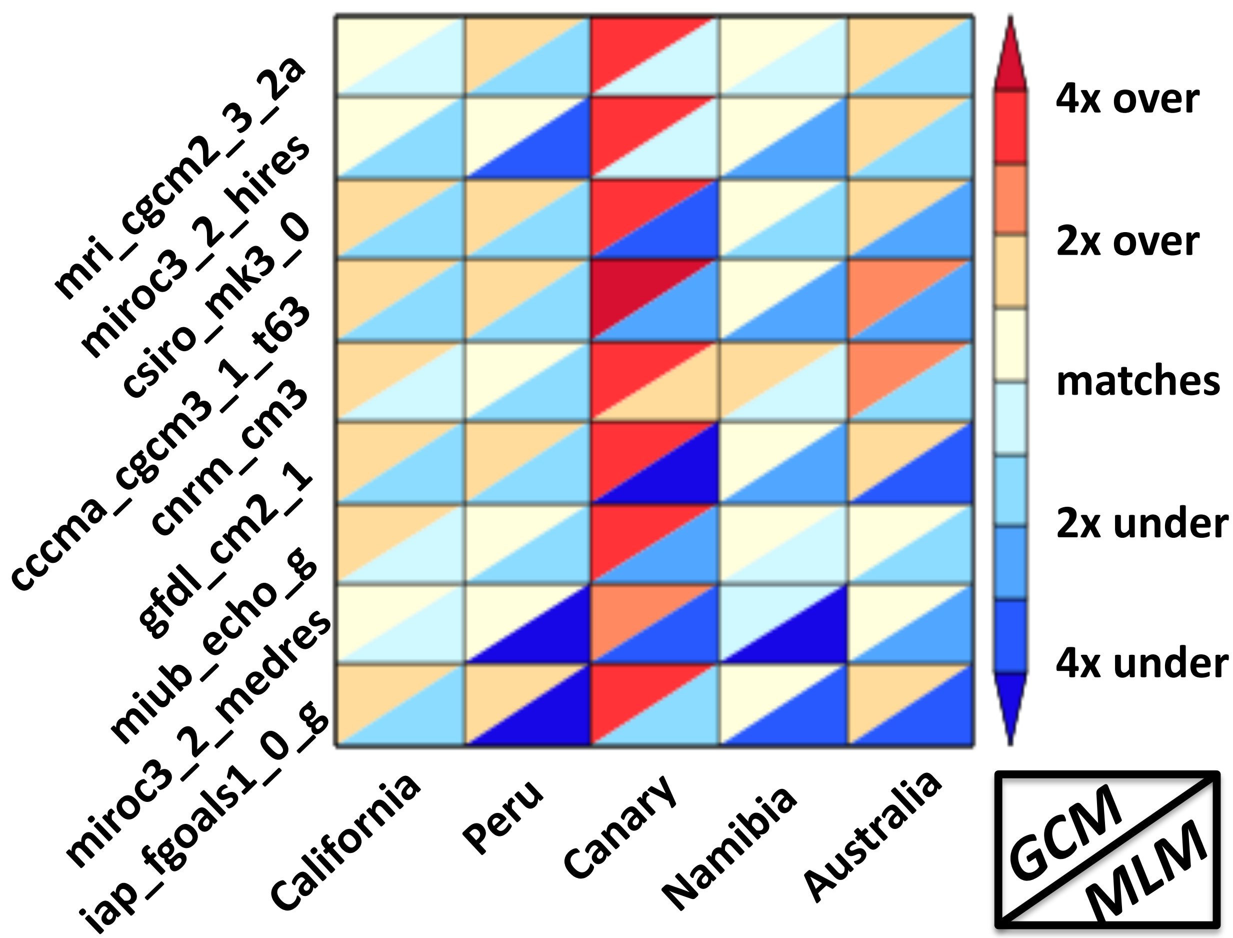


Results: EIS as a Predictor – Averaging Effect



GCM skill improves when seasonal and regional differences (which are generally not captured) are removed.

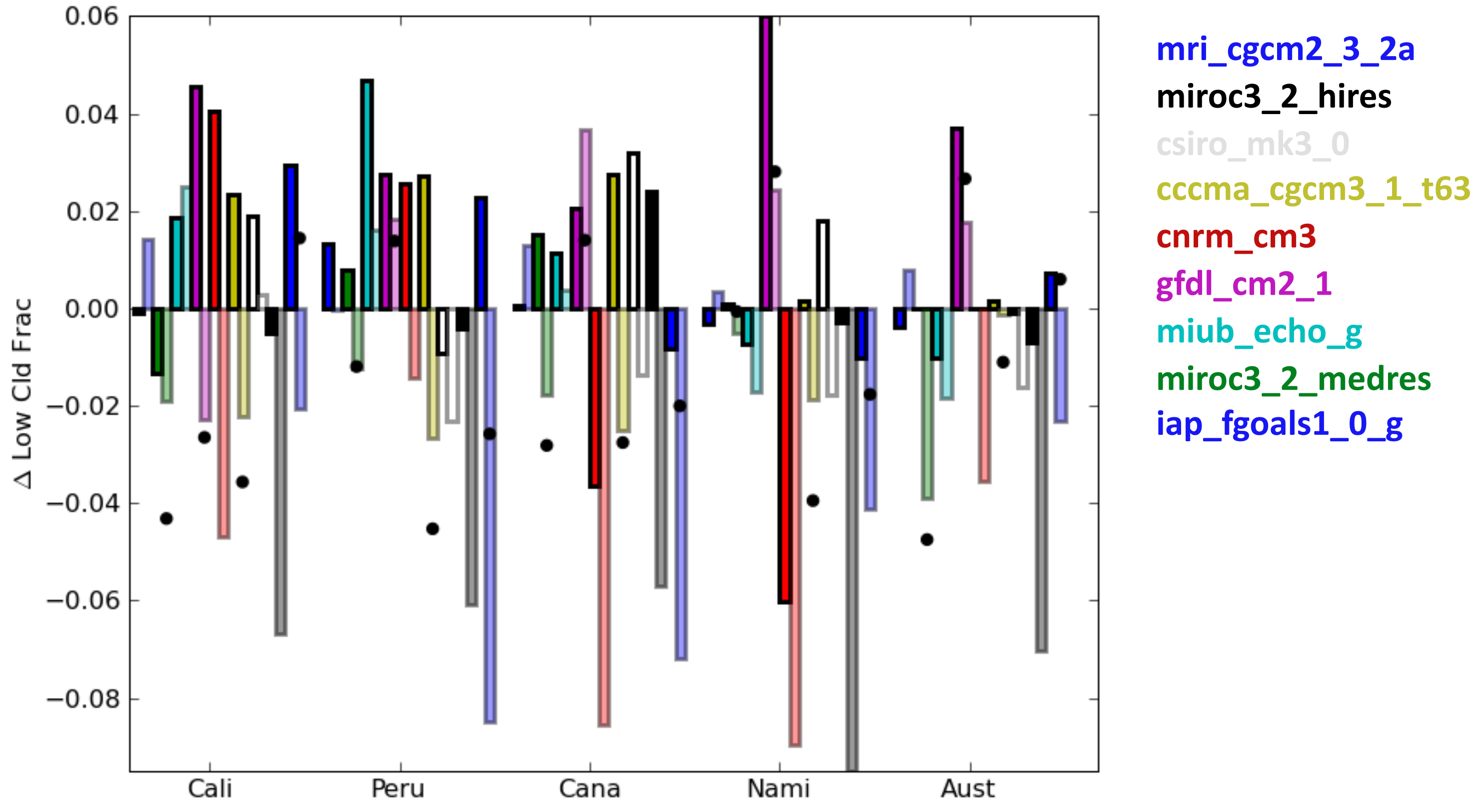
Present-Day Mean Low-Cloud Skill



Ratio of modeled to ISCCP-observed annual-ave low cldfrac for 1980-2000 conditions

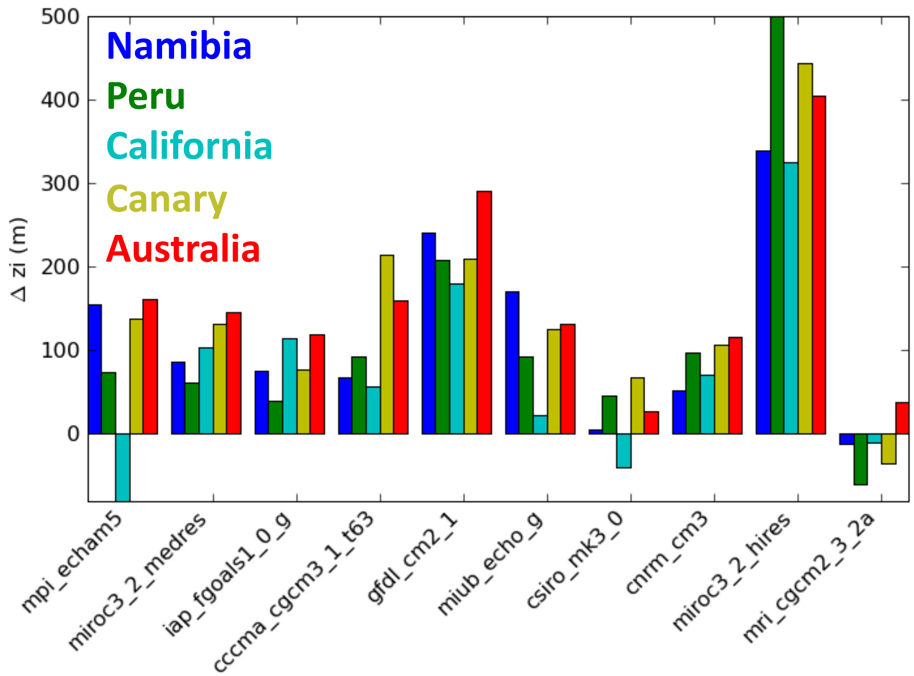
- **GCMs overpredict, MLMs underpredict**
  - **GCMs do poorly for Canary**
  - **miroc_medres and iap have conditions hostile to MLM**
- **GCM and MLM values are not correlated**
  - **suggests imprinting not a problem**
- **California always well simulated!**


Climate Change Signals



Change in low cloud fraction by region and model. MLM output=more solid colors, GCM output = faded colors. GCM output = total cloud. Where present, dots = GCM value using random overlap instead.

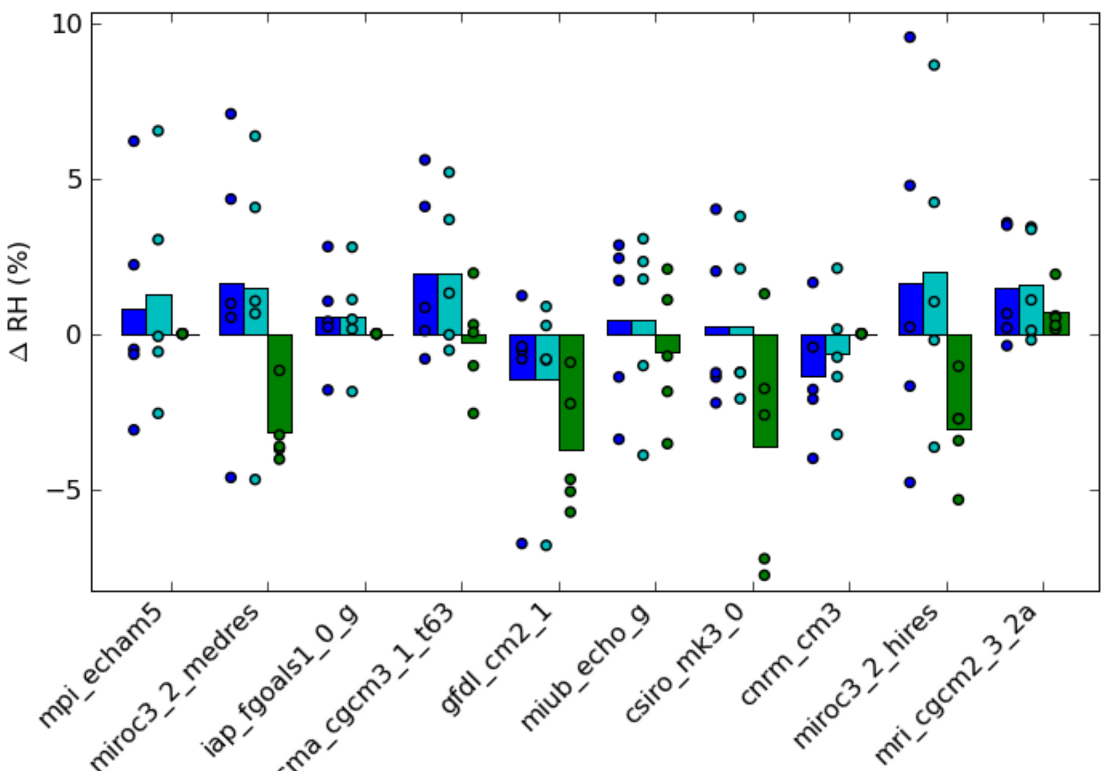
Climate Change signal in BL depth



Change in diagnosed inversion height from CMIP3 models (2080-2100 vs 1980-2000)

- GCM BL depth increases in most models, regions.

RH Changes – Methodology Choice

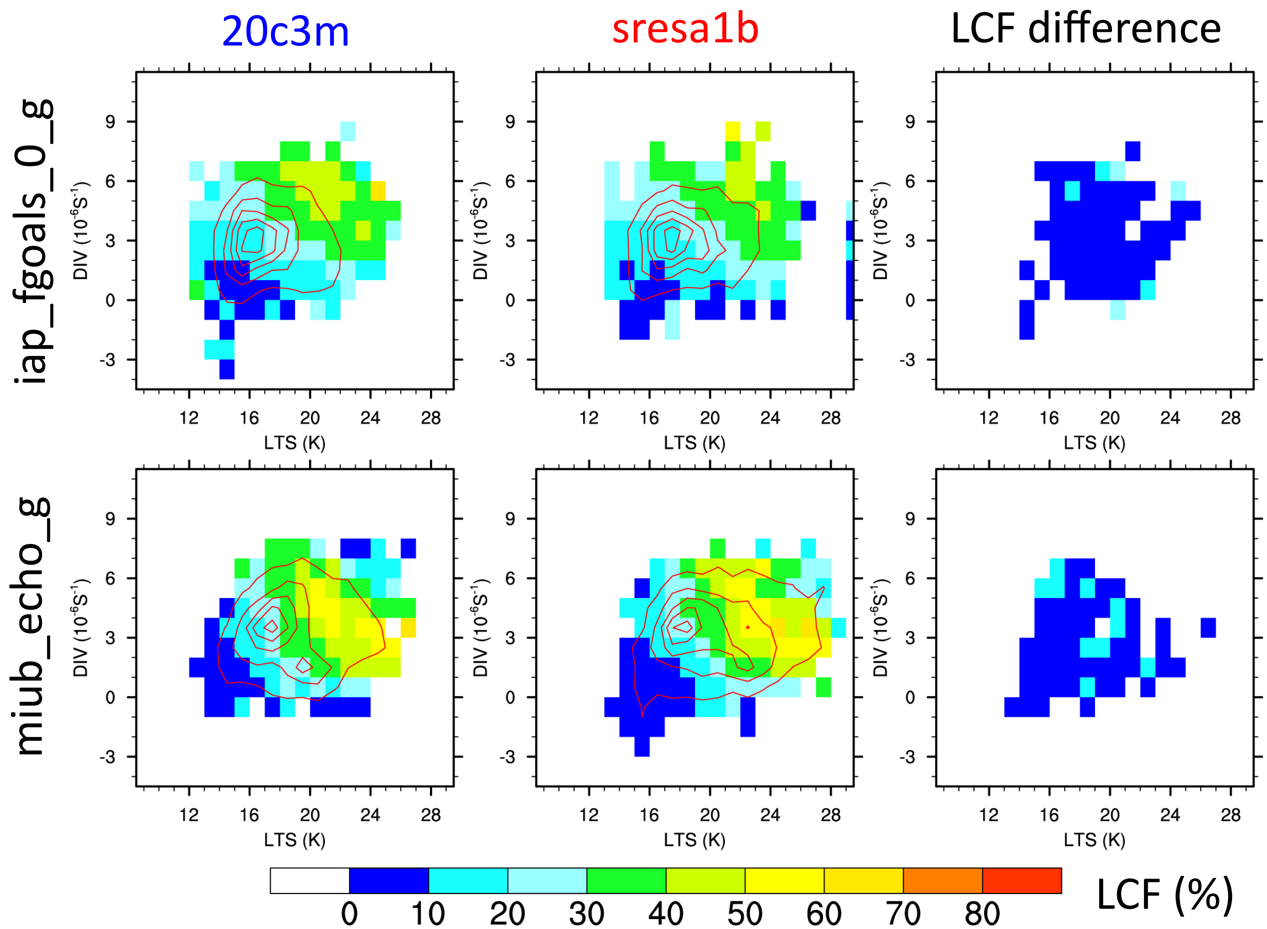


Blue=RH from daily free-trop corrected 850mb values, light blue=RH from climatological free-trop-corrected T and q, and green=RH from climatological *uncorrected* T and q. Bars are averages over regions, dots are individual regional values.


Sources of Intermodel Difference

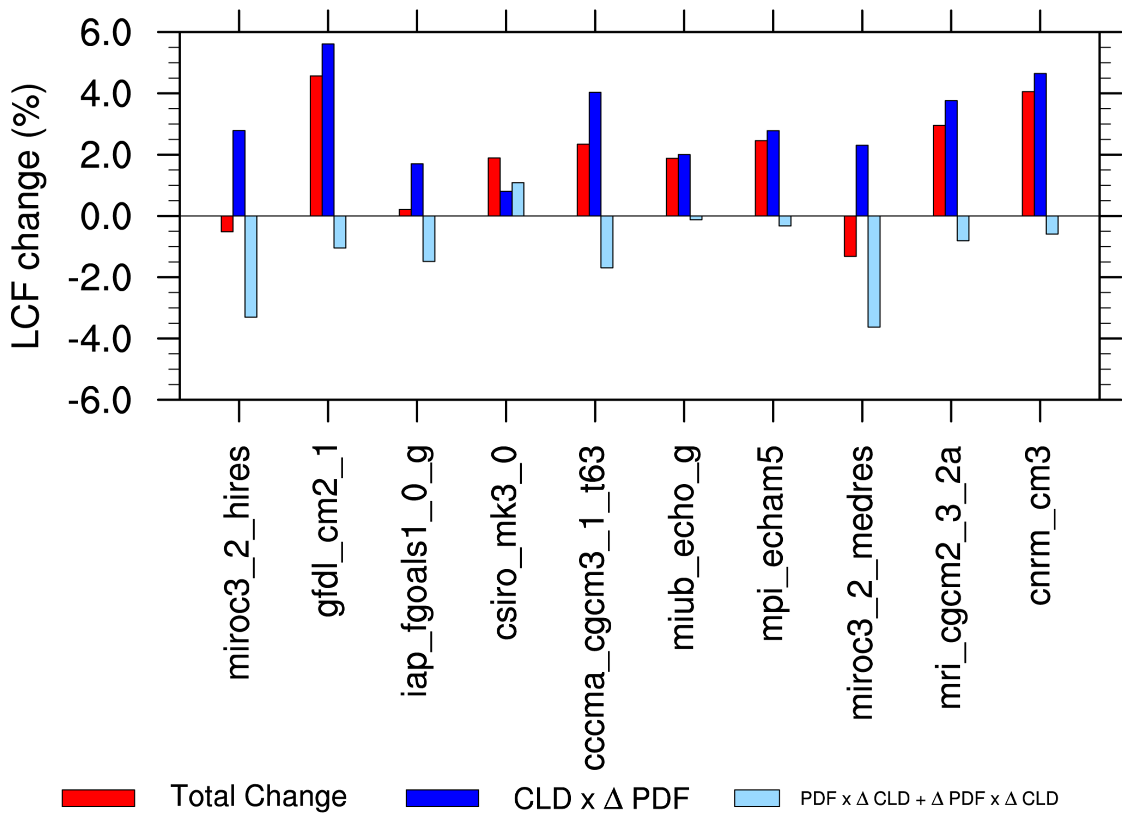
MLM LCF conditioned on joint PDF of LTS and Divergence

- **MLM cloud fraction is largely set by LTS and div (since colors invariant)**
  - **cloud changes due to changes in PDF of LTS and div**
- **LTS dependency on prev slide explained by breadth of LTS distribution here.**



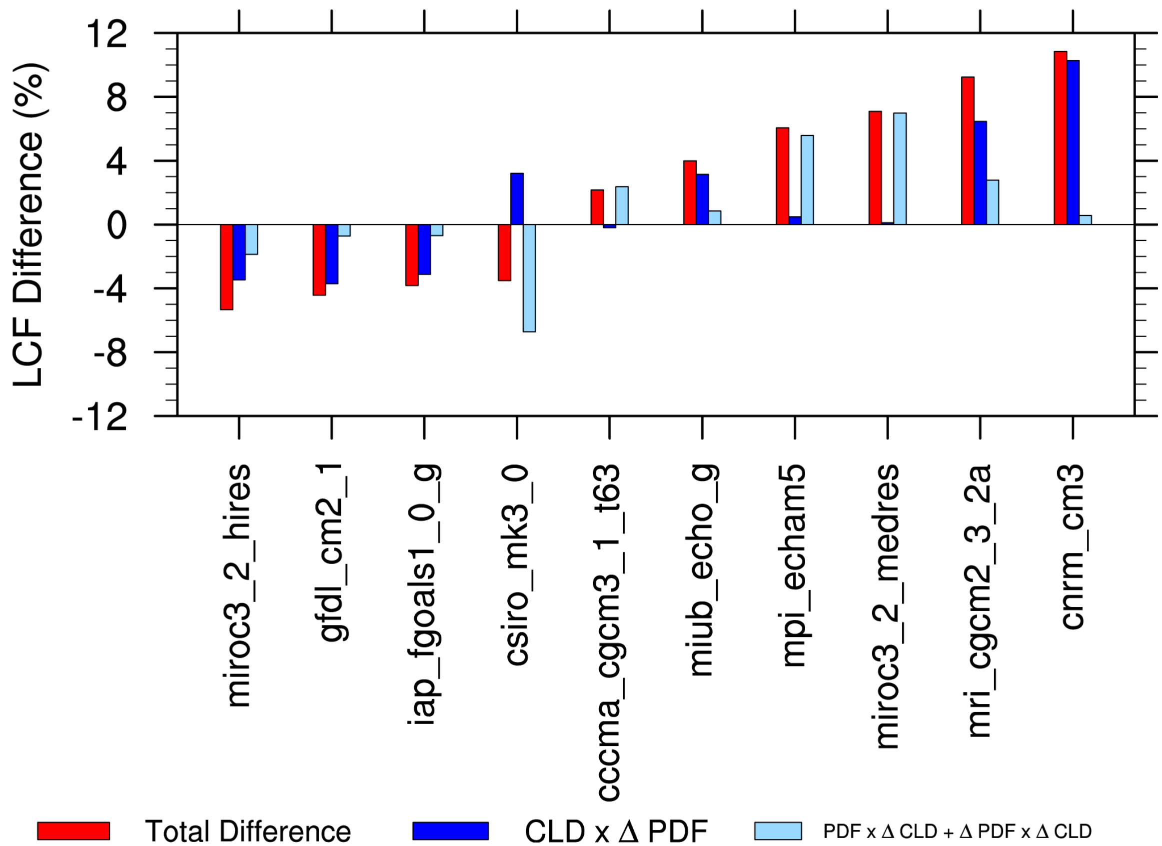
MLM cloud fraction (colors) and joint PDF of monthly mean LTS and divergence (contours) for California region.

What determines a Model's low cloud response to climate change



- EIS and div (dark blue) explain most of the total cloud change for 6/10 models, but other factors (light blue) are important for many models.
- EIS and div increase cloud (averaging over other quantities), while other factors reduce cloud.
- Mean cloud fraction is not a strong indicator of cloud change or whether it can be explained by EIS and div or not.

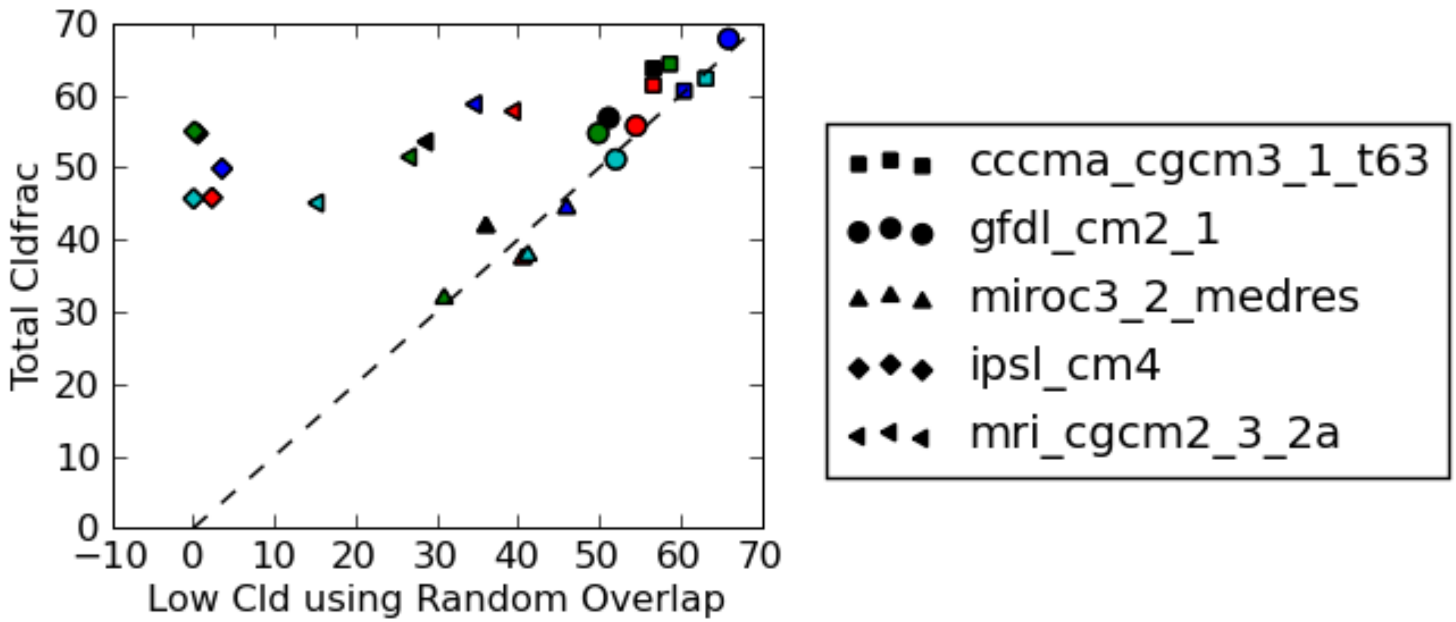
What Determines Inter-Model Spread for Current climate MLM cldfrac



- EIS and div again explain differences for 6/10 models
  - 4 of these 6 are the same as prev slide.

- Models with *really* different low clouds are that way because of different EIS,div occurrence. More average models have differences explained by other factors.

GCM Total vs Low Cloud for Sc regions



•GCM total cloud ≈ random-overlap low cloud for 3 of the 5 models where this can be checked