The impact of parametrized convection on cloud feedback.

Mark Webb, Adrian Lock (Met Office)

Thanks also to Chris Bretherton (UW), Sandrine Bony (IPSL),Jason Cole (CCCma), Abderrahmane Idelkadi (IPSL), Sarah Kang (UNIST), Tsuyoshi Koshiro (MRI), Hideaki Kawai (MRI), Tomoo Ogura (NIES), Romain Roehrig (CNRM), Yechul Shin (UNIST), Thorsten Mauritsen (MPI), Steve Sherwood (UNSW), Jessica Vial (IPSL), Masahiro Watanabe (AORI), Matthew Woelfle (UW), Ming Zhao (GFDL).

CFMIP Meeting, Monterey, June 2015

Selected Process On/Off Klima Intercomparison Experiment (SPOOKIE)

Aims

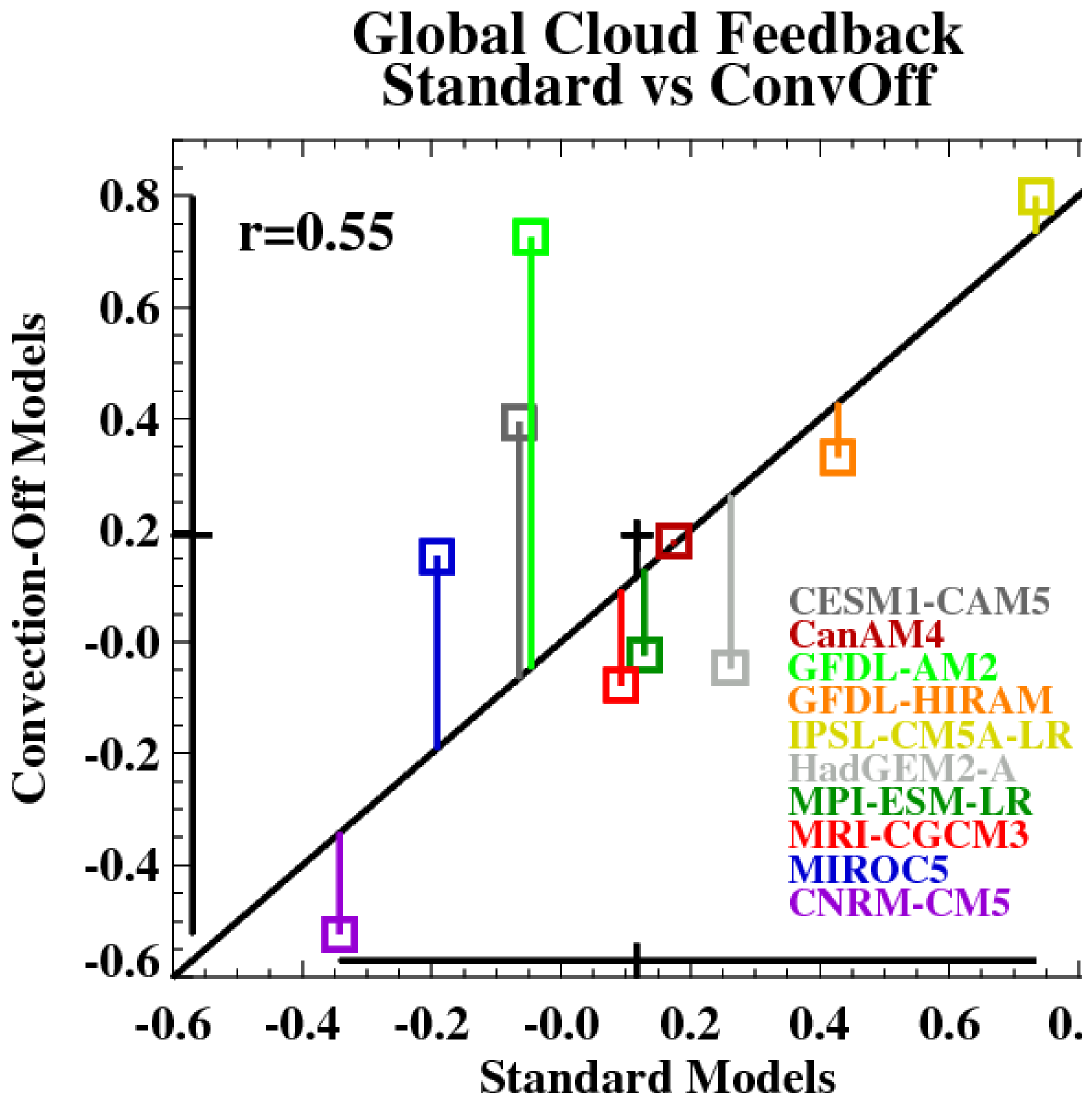
- Establish the relative contributions of different areas of model physics to inter-model spread in cloud feedbacks

Approach

- Repeat CFMIP-2 AMIP/AMIP Uniform +4K SST perturbation experiments
- Switch off or simplify different model schemes in turn

Pilot Experiments

- Start by switching off convective parametrization



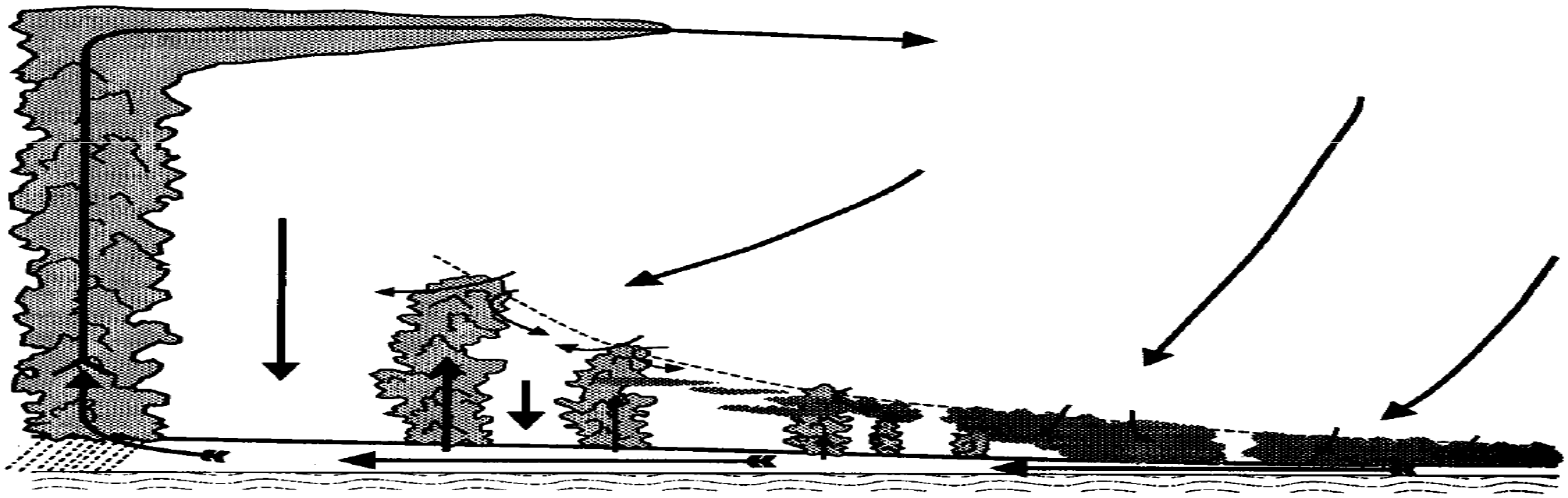
The Cloud Radiative Effect (CRE) is the difference in the net downward radiation at the top of the atmosphere with and without clouds.

Here we diagnose the cloud feedback as the change in net CRE between amip and amip4K divided by the change in global surface temperature.

This includes the climatological 'cloud masking' effect on the non-cloud feedbacks.

Organisation of tropical cloud regimes

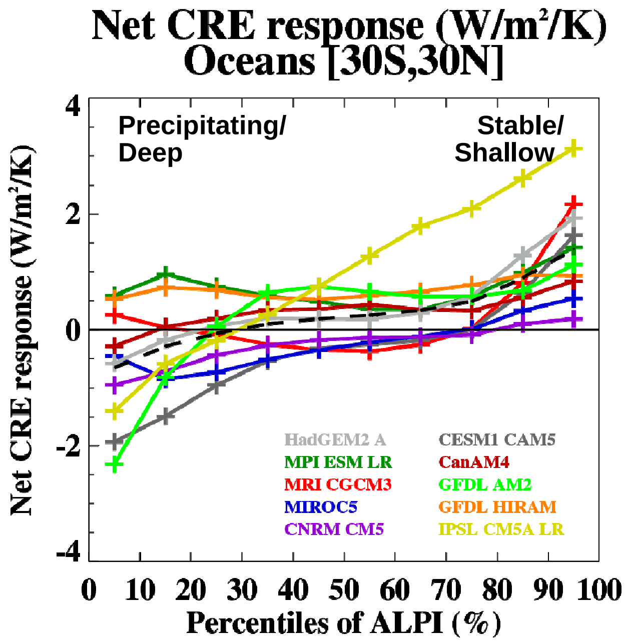
Deep Convection **Trade Cumulus** **Stratocumulus**



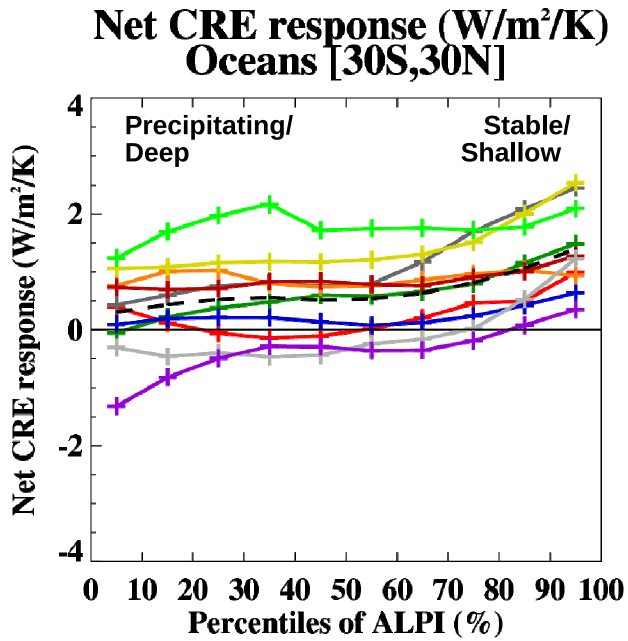
Schematic from Emanuel (1994)

amip4K Cloud Feedbacks over 30^{O}N/S Oceans

Standard



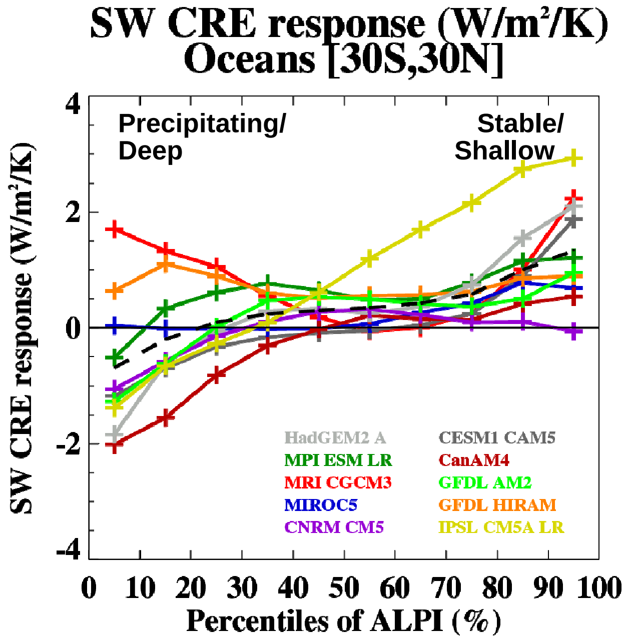
ConvOff



We sort cloud regimes in the tropics using a composite index based on precipitation rate and Lower Tropospheric Stablity (LTS). We call this the Angular LTS/Precipitation Index (ALPI).

amip4K Cloud Feedbacks over 30^{O}N/S Oceans

Standard



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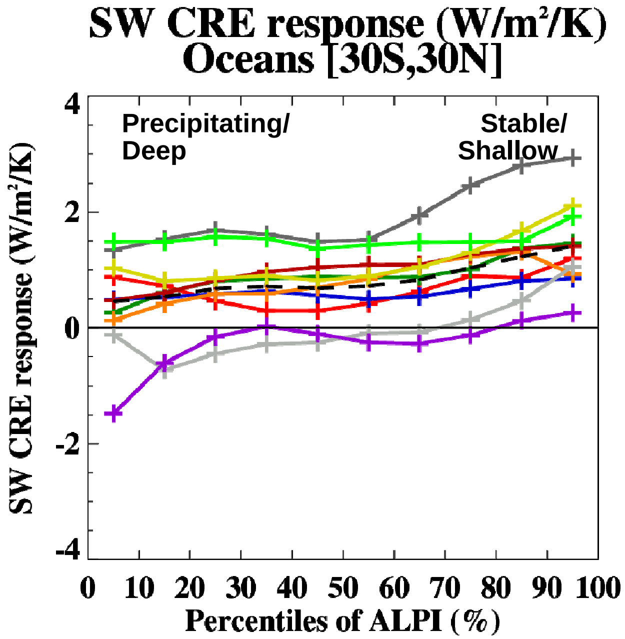
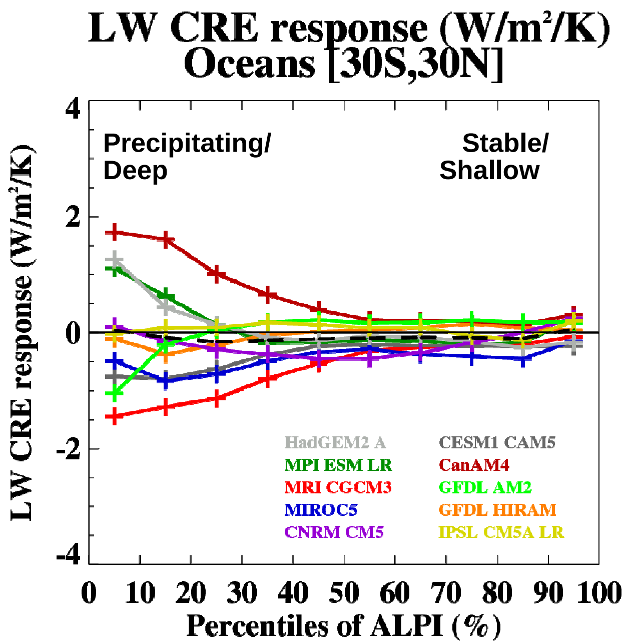


amip4K Cloud Feedbacks over 30^{O}N/S Oceans

Standard



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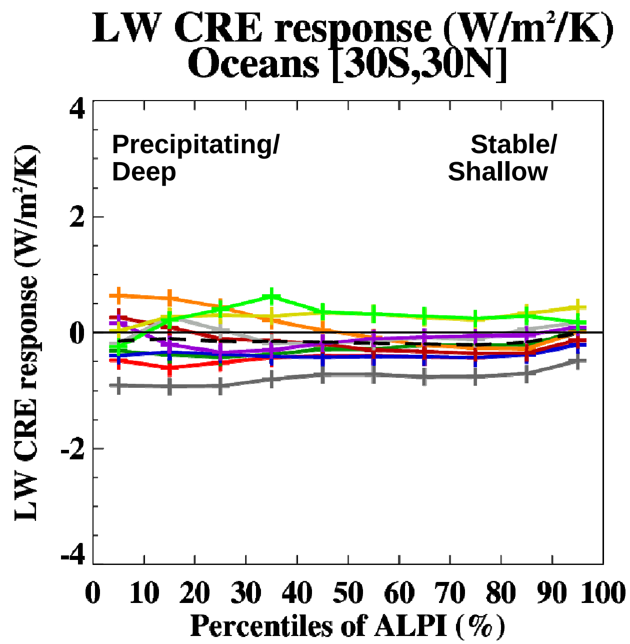
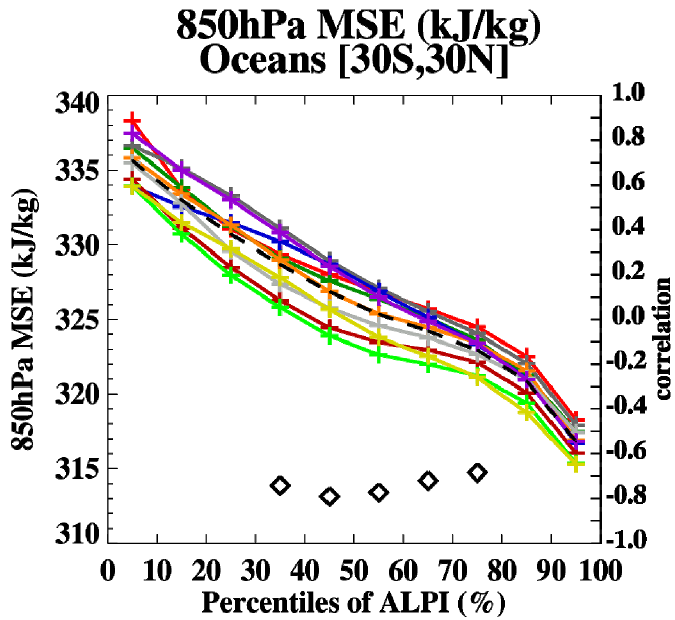
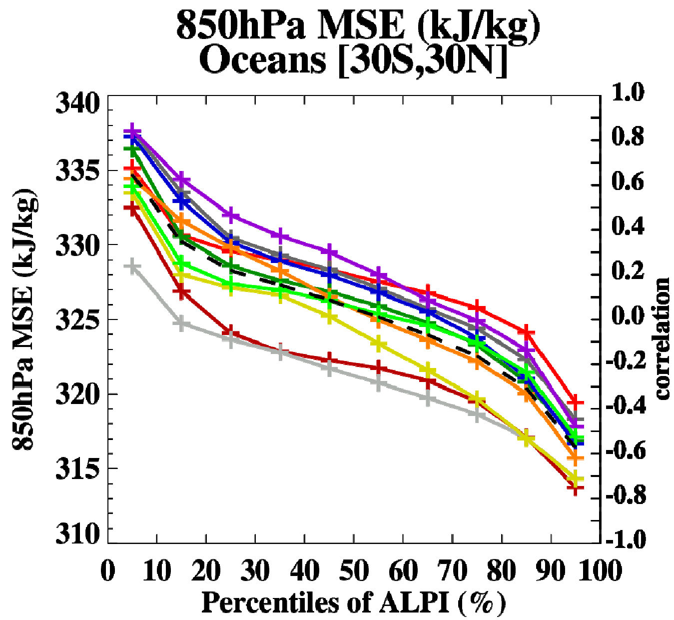


Standard Models



Precipitating/ Deep | **Stable/ Shallow**

ConvOff Models



Precipitating/ Deep | **Stable/ Shallow**

Black diamonds mark significant correlations with the net cloud feedbacks in same regime

Grey squares mark significant correlations with the net cloud feedback area averaged over tropical oceans

Moist Static Energy (MSE) is a measure of the energy in a parcel of air, including sensible heat due to temperature, latent heat due to water vapour and potential energy due to height.

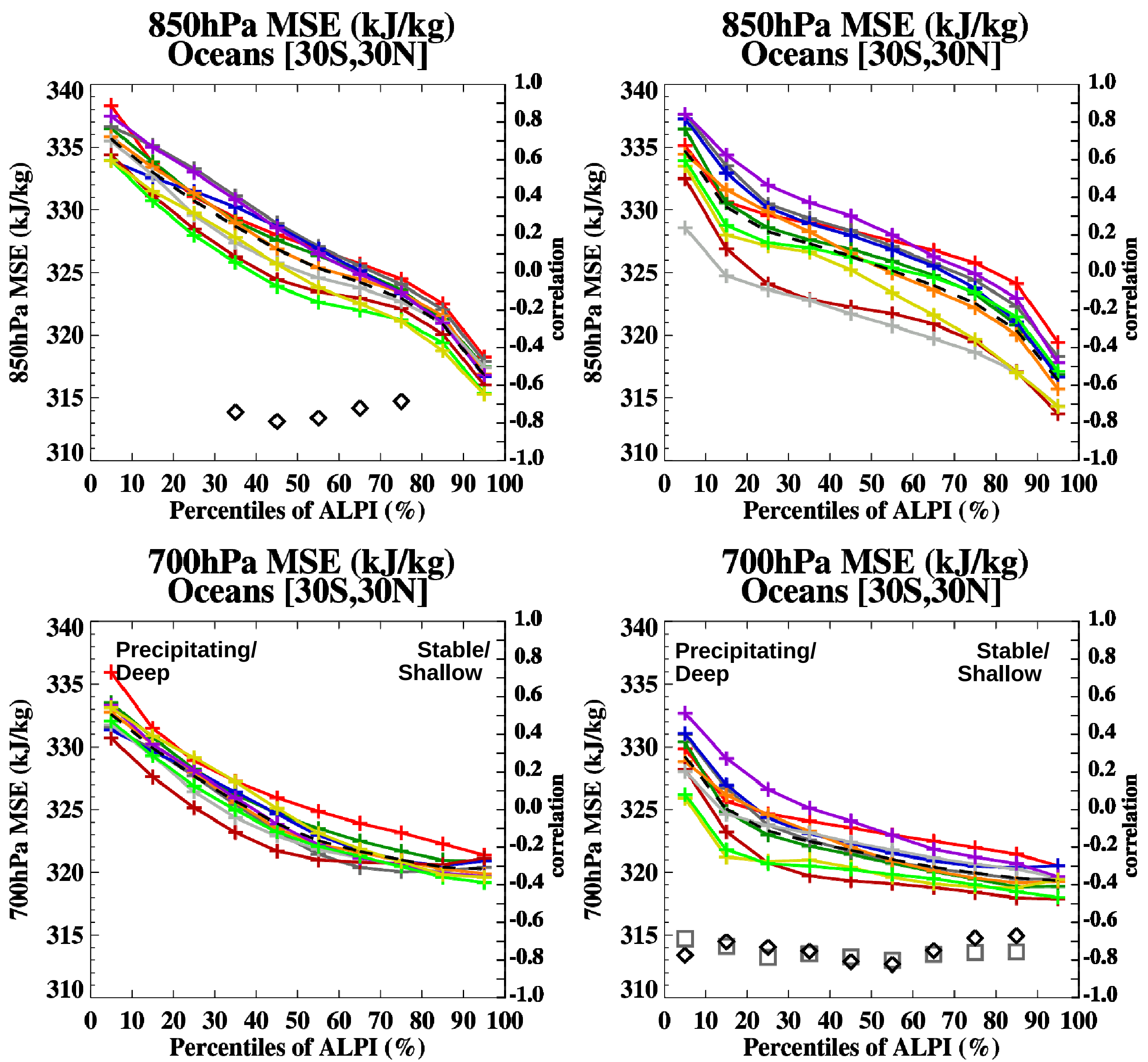
$$MSE = C_P T + L_v q + gz$$

C_P is the specific heat of air at constant pressure
L_v is the latent heat of vaporization
g is the acceleration due to gravity

T is temperature
q is the specific humidity
z is the height above the surface

Standard Models

ConvOff Models



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Why might models with less MSE near the top of the PBL have more positive cloud feedbacks?

Met Office

- Sherwood et al. 2014 and Zhao 2014 argue that precipitation efficiency plays an important role in cloud feedback.
- Sherwood et al. 2014 defines the bulk precipitation efficiency in terms of the upward transport of water vapour from the boundary layer to the free troposphere required to maintain a given surface precipitation rate.
- In GCMs such transports are due to ‘lower tropospheric mixing’ by small scale processes such as parametrized convection or turbulence and by large scale mixing associated with the resolved large scale circulation.
- Sherwood et al. 2014 argue that models with stronger lower tropospheric mixing will have a stronger drying of the boundary layer, and that this drying effect will strengthen more in the warming climate, resulting in stronger low cloud reductions and more positive cloud feedbacks.
- Reduced MSE near the top of the PBL in higher sensitivity models could then be a consequence of stronger lower-tropospheric mixing in accordance with the arguments of Sherwood et al.

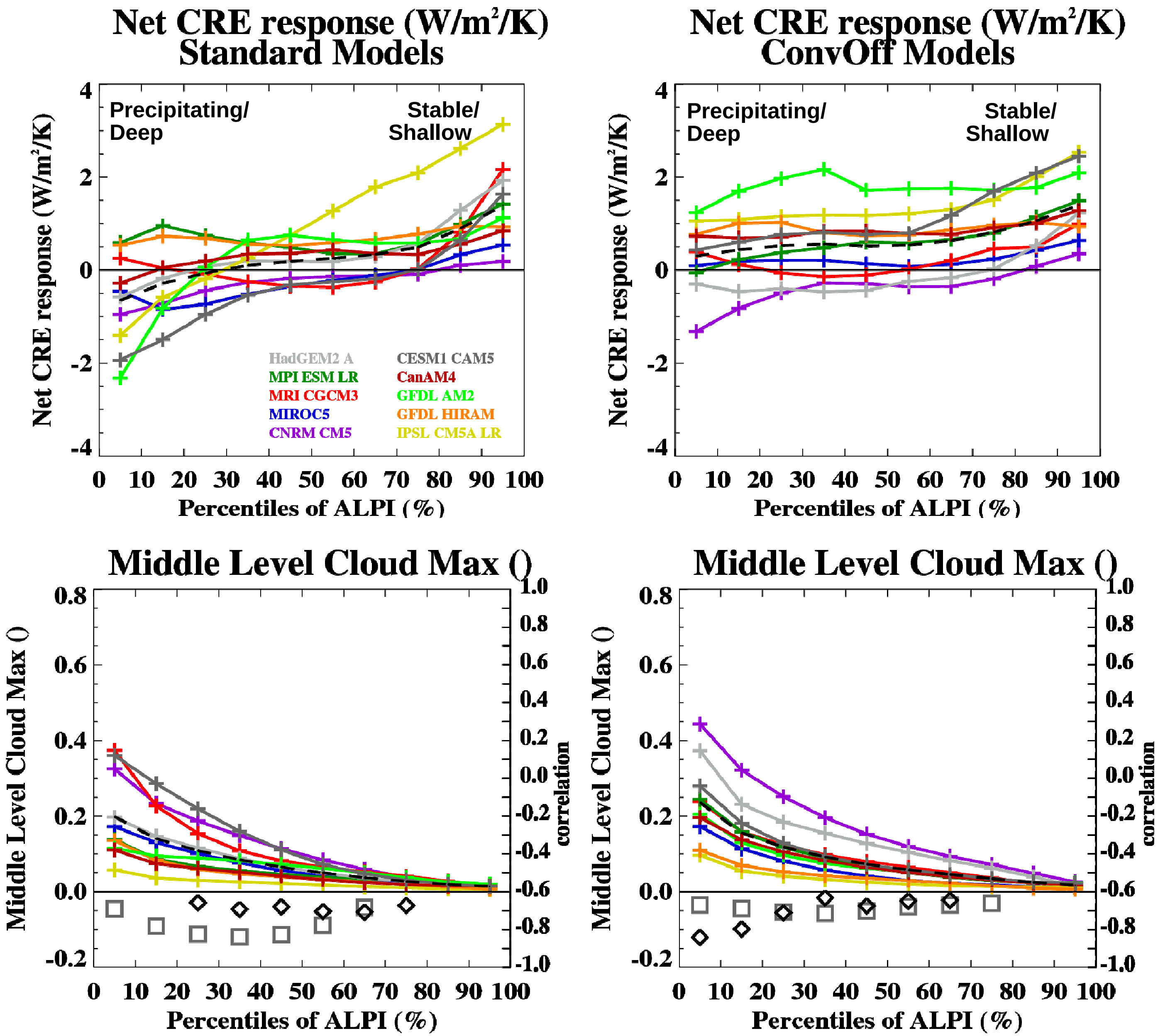
Met Office

What processes other than parametrized convection regulate lower tropospheric mixing?

- Inter-model differences in parametrized convection and its precipitation efficiency cannot explain the overall range in cloud feedbacks in the models examined here.
- Zhao, 2014 defines precipitation efficiently slightly differently to Sherwood et al. and makes a distinction between precipitation efficiency associated with convective schemes and large scale cloud/precipitation schemes.
- Might inter-model spread in lower tropospheric mixing and cloud feedback instead be explained by inter-model differences in the precipitation efficiency associated with the large scale cloud and precipitation schemes?

Standard

ConvOff



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Why might less present-day mid-level cloud lead to more positive low cloud feedback?

Met Office

- In radiative-convective equilibrium, convection adjusts to provide enough heating to balance longwave radiative cooling in the free troposphere.
- Models which easily form precipitating clouds in the mid troposphere will rain out efficiently to the surface.
- Models which form mid level clouds less easily will need to condense higher up to provide the required latent heat release in the free troposphere.
- Precipitation from higher clouds has further to fall and more time to evaporate, offsetting latent heating and requiring a stronger upward transport of water vapour to maintain the surface precipitation rate.
- Hence having less mid level cloud in models might result in stronger lower tropospheric mixing, an enhanced drying of the PBL in the warmer climate, and more strongly positive cloud feedbacks.

Testing our ideas – future experiments.

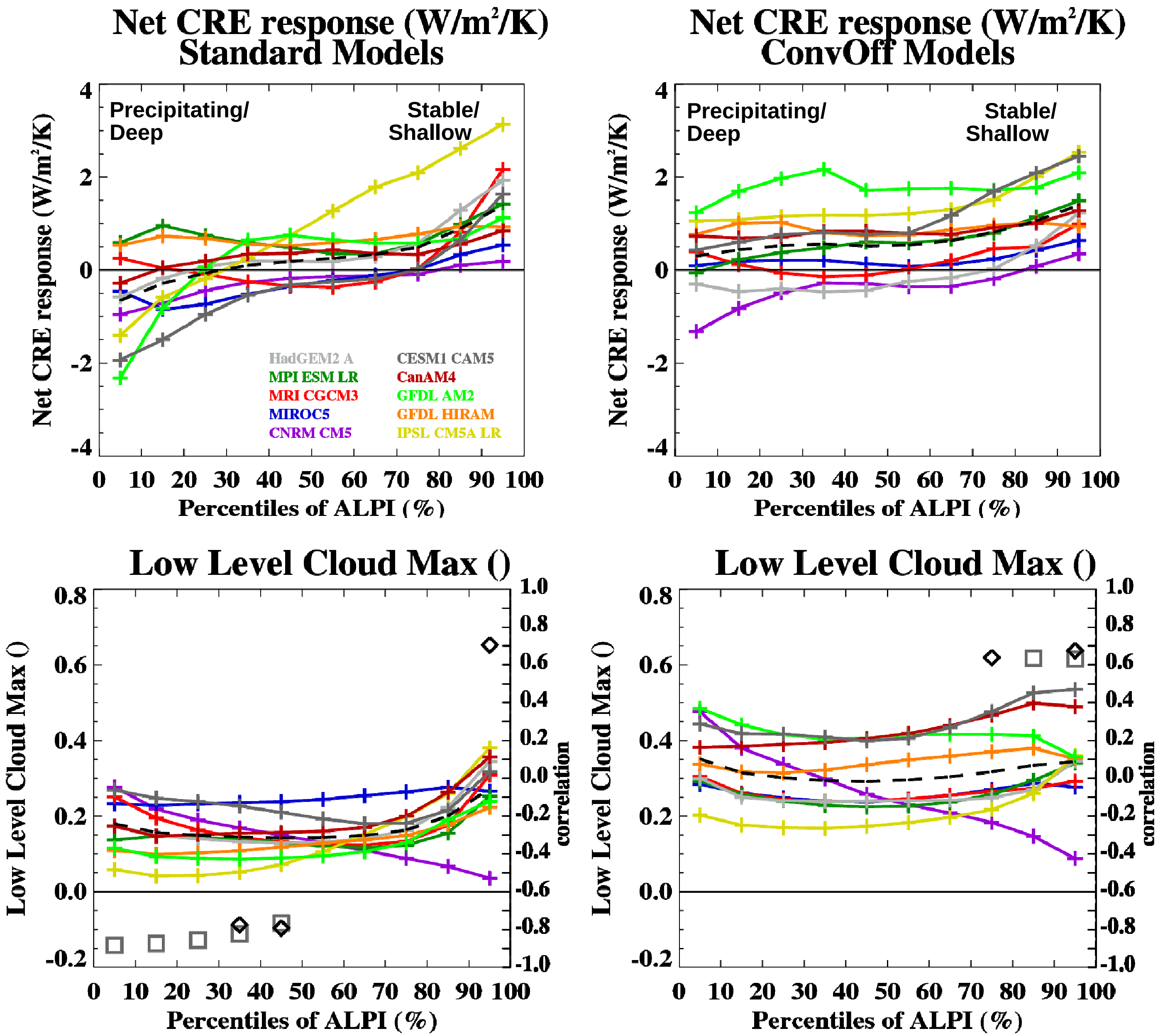
Met Office

- The large scale precipitation efficiency in models could be reduced by modifying the cloud microphysics to make it harder to rain from mid-level clouds.
- Alternatively, cloud condensation at mid levels could be suppressed by re-evaporating cloud water.
- Reducing ice fall speeds would also reduce precipitation efficiency.
- If the ideas outlined above are correct, then these experiments would be expected to reduce precipitation efficiency, increase upward transports of water vapour and boundary layer drying, reduce MSE near the top of the boundary layer and strengthen positive low level cloud feedbacks.

Summary

- ConvOff experiments reproduce positive subtropical cloud feedback.
- They show strong convergence in tropical deep convective longwave cloud feedbacks but increased spread in net cloud feedback in the trades.
- Differences in parametrized convection can have a substantial impact on global cloud feedback in some models, but do not explain the overall range.
- Higher sensitivity models in both standard and ConvOff ensembles have:
    - Less moist static energy near boundary layer top
    - Less mid-level cloud in trades / deep convection regimes
- We have developed some ideas which may explain these results and will test them in future process suppression experiments.
- Such experiments could form the basis for SPOOKIE phase 2.

Supplementary Slides



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Met Office

How might low cloud fraction regulate shallow cloud feedback?

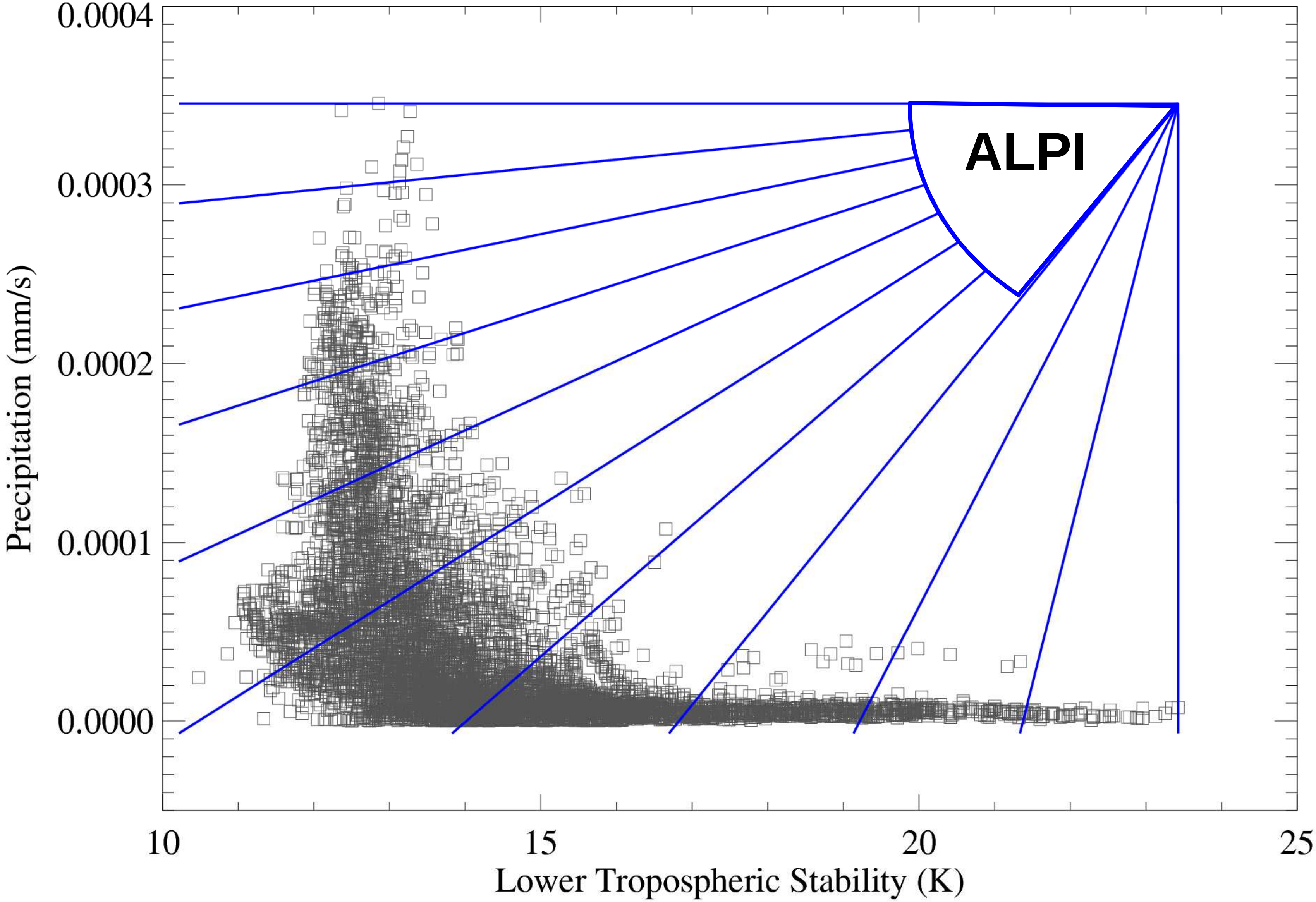
- Brient and Bony (2012) proposed a ‘beta feedback’ in which radiative cooling from low clouds increases relative humidity and enhances cloud amount.

- A stronger beta effect would be expected to increase low level cloud fraction and also to amplify any low cloud fraction feedback.

- Brient and Bony (2012) tested this idea in versions of the IPSL models by making clouds transparent to radiation.

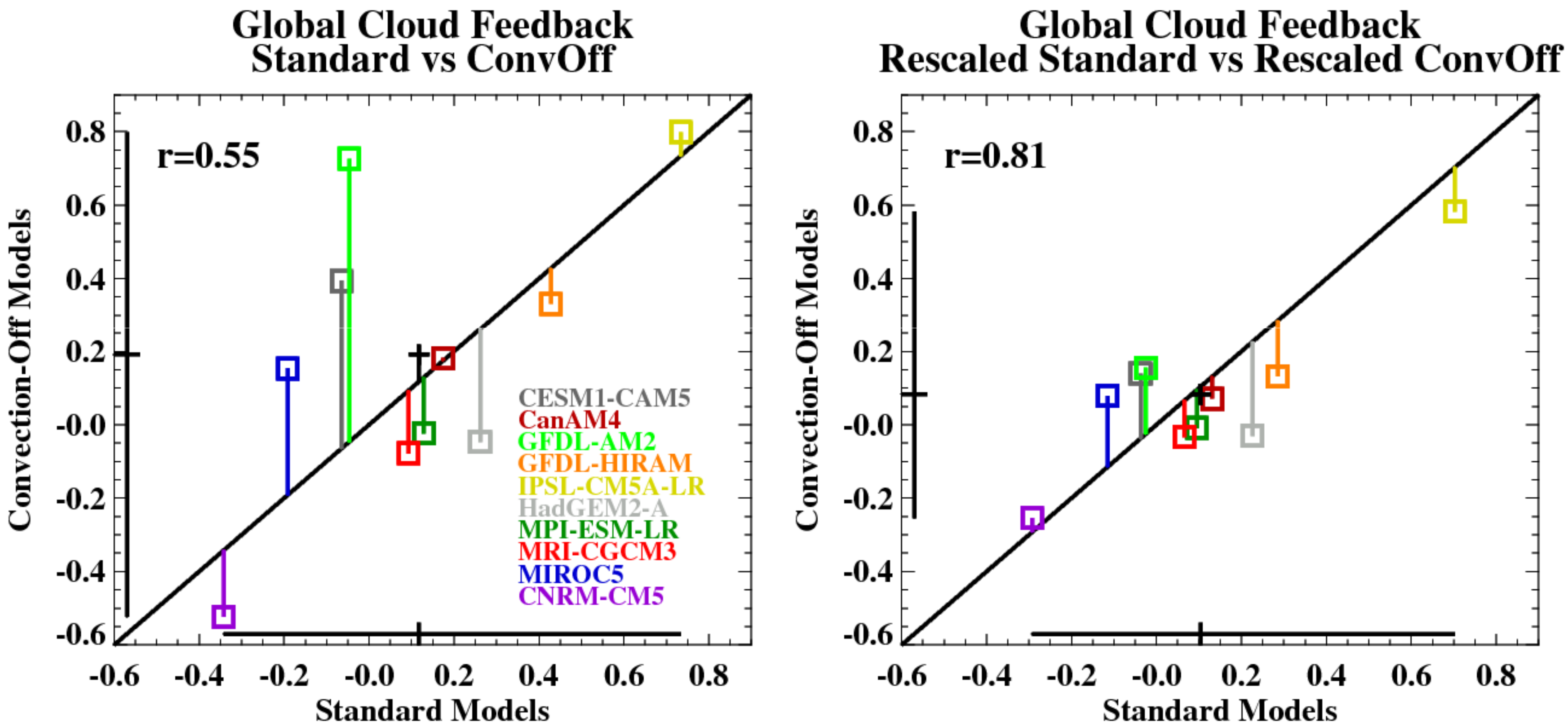
- Experiments to make clouds transparent to longwave radiation are proposed for CMIP6/CFMIP-3. These will allow importance of the beta effect for the shortwave cloud feedback to be assessed across models.

Angular LTS/Precipitation Index (ALPI)



Global Mean Cloud Feedback ($Wm^{-2}K^{-1}$)

(Including cloud masking)

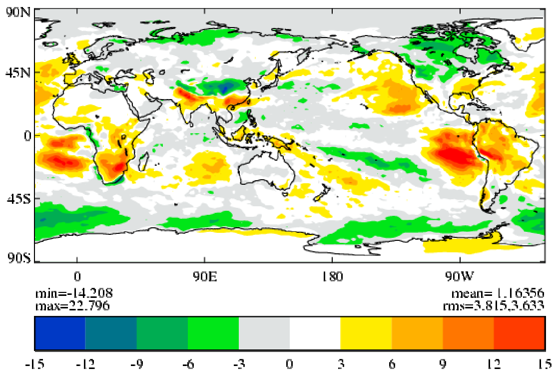


We can attempt to 'bias correct' the cloud feedbacks by applying a scaling factor of $NCRE_{OBS}/NCRE$ where NCRE is the global mean Net Cloud Radiative Effect.

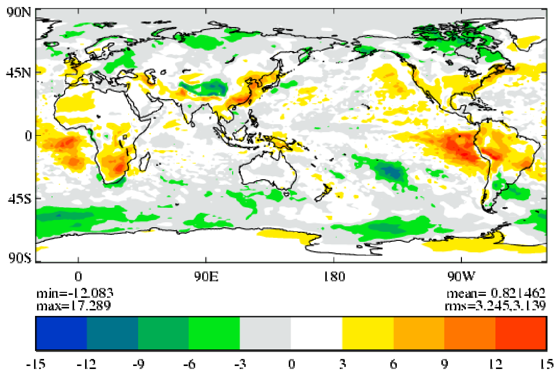
How do deep vs shallow convective regions affect cloud feedback?

Net Cloud Feedback

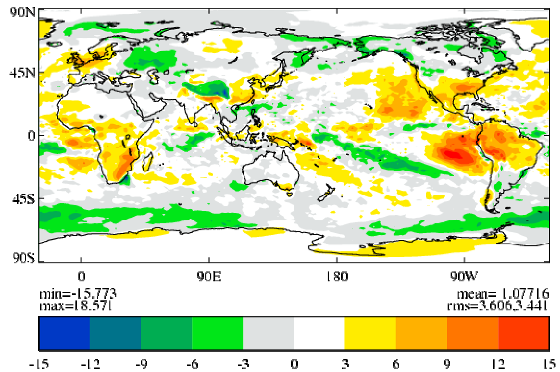
Standard HadGEM2-A



Conv Off Subtropics SST 290-300K/294-304K



Conv Off Deep SST > 300K/304K



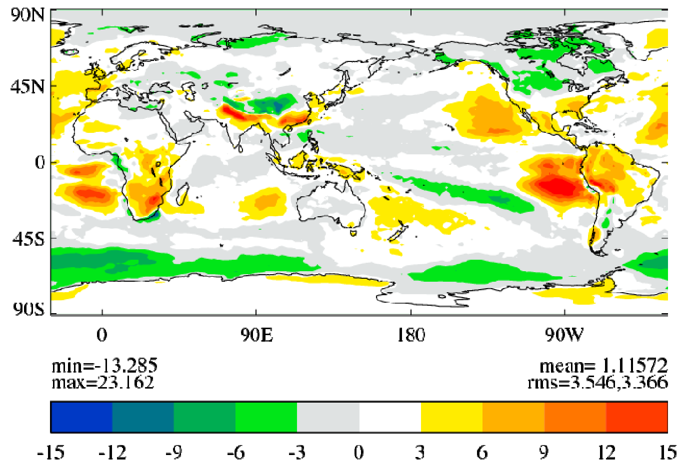
More ideas for SPOOKIE phase II

Understand reasons for convective parametrization differences

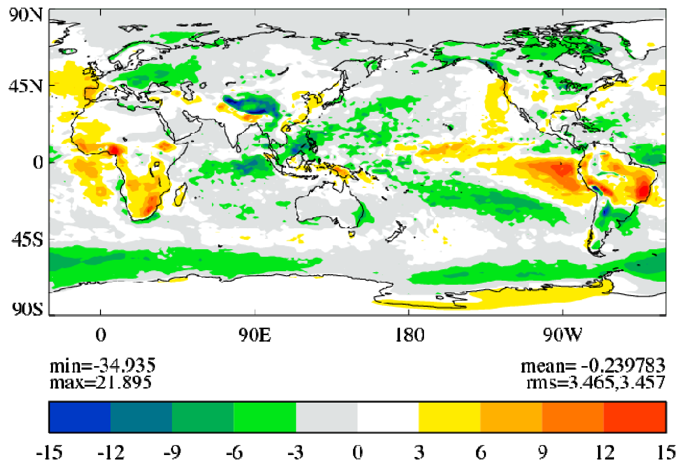
- Many studies have shown sensitivity of cloud feedback to lateral entrainment in deep convection (e.g. Rougier et al. 2009).
    - We can run with no convective entrainment/detrainment
- Details of convective precipitation microphysics can also affect cloud feedback via detrainment – e.g. threshold vs fractional conversion of convective cloud water to precipitation (Zhao 2014)
    - Can rain out all convective cloud water without evaporation (precip efficiency=1)
    - Can switch off convective precipitation (precip efficiency=0)

HadGEM2-A Convection Experiments
amip 4K CRE Response

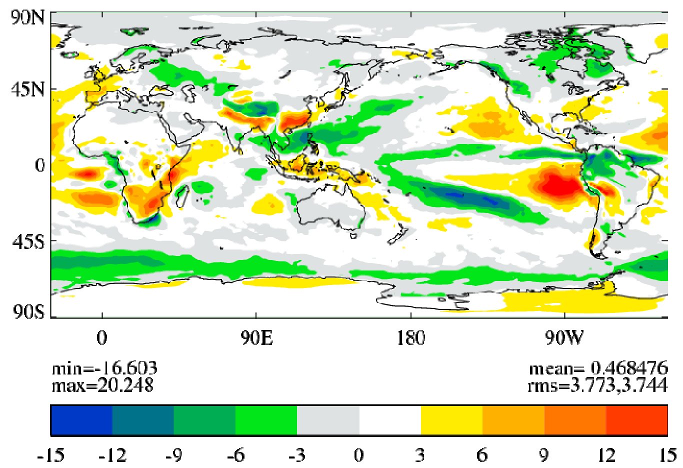
Standard Model



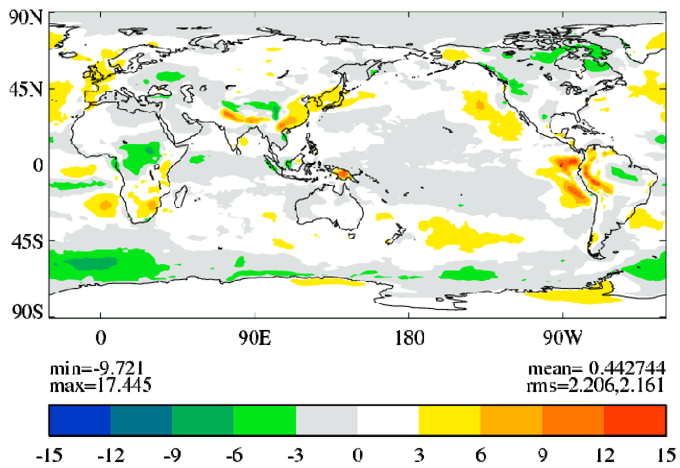
Convection Off



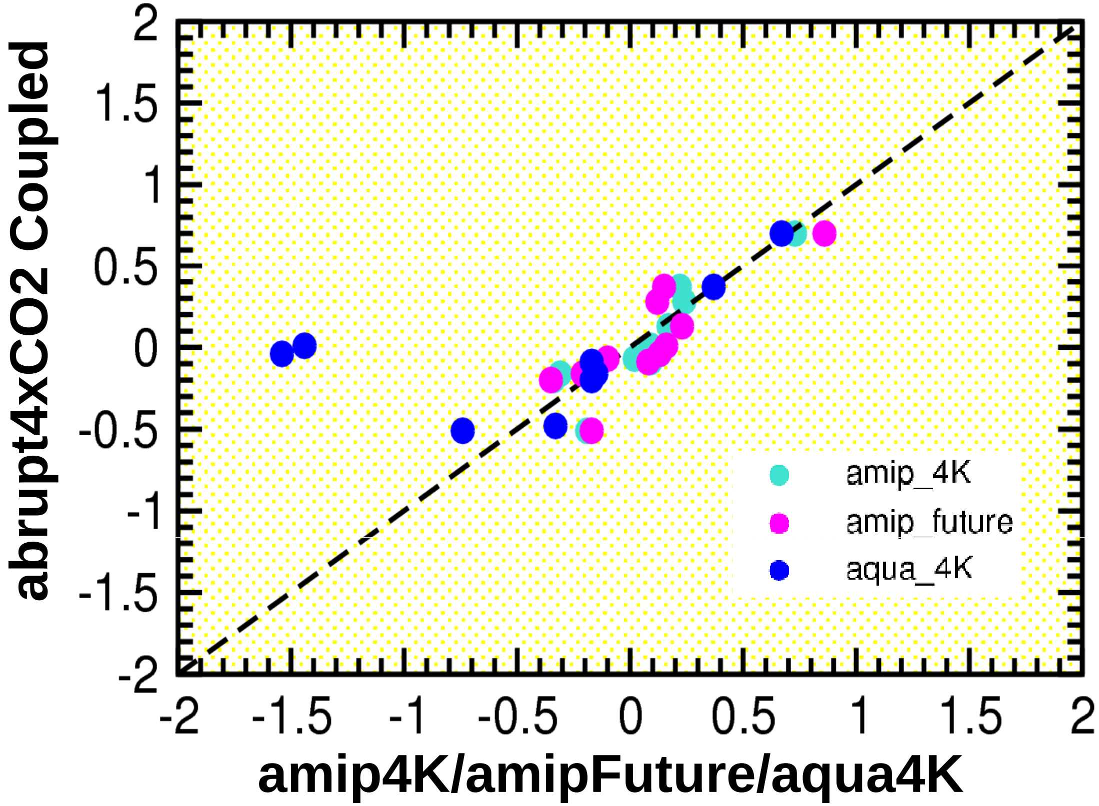
Weak Conv Precip Efficiency



Strong Conv Precip Efficiency

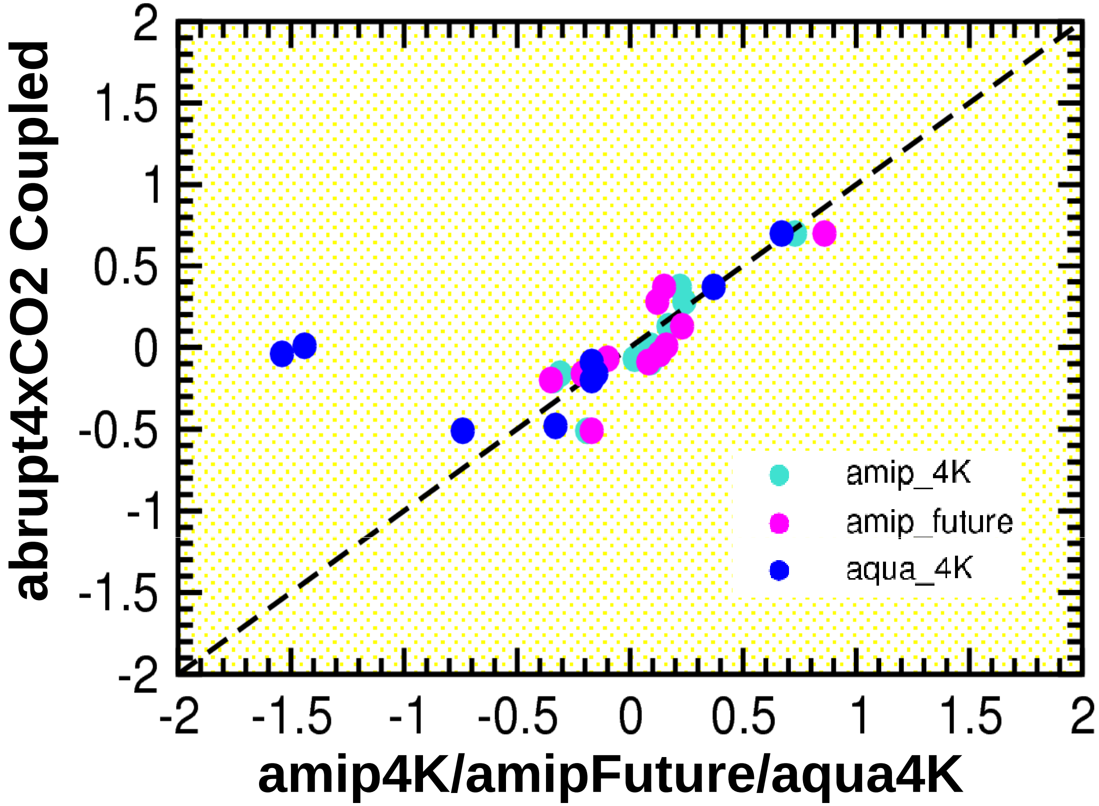


Global Mean Cloud Feedback ($Wm^{-2}K^{-1}$)



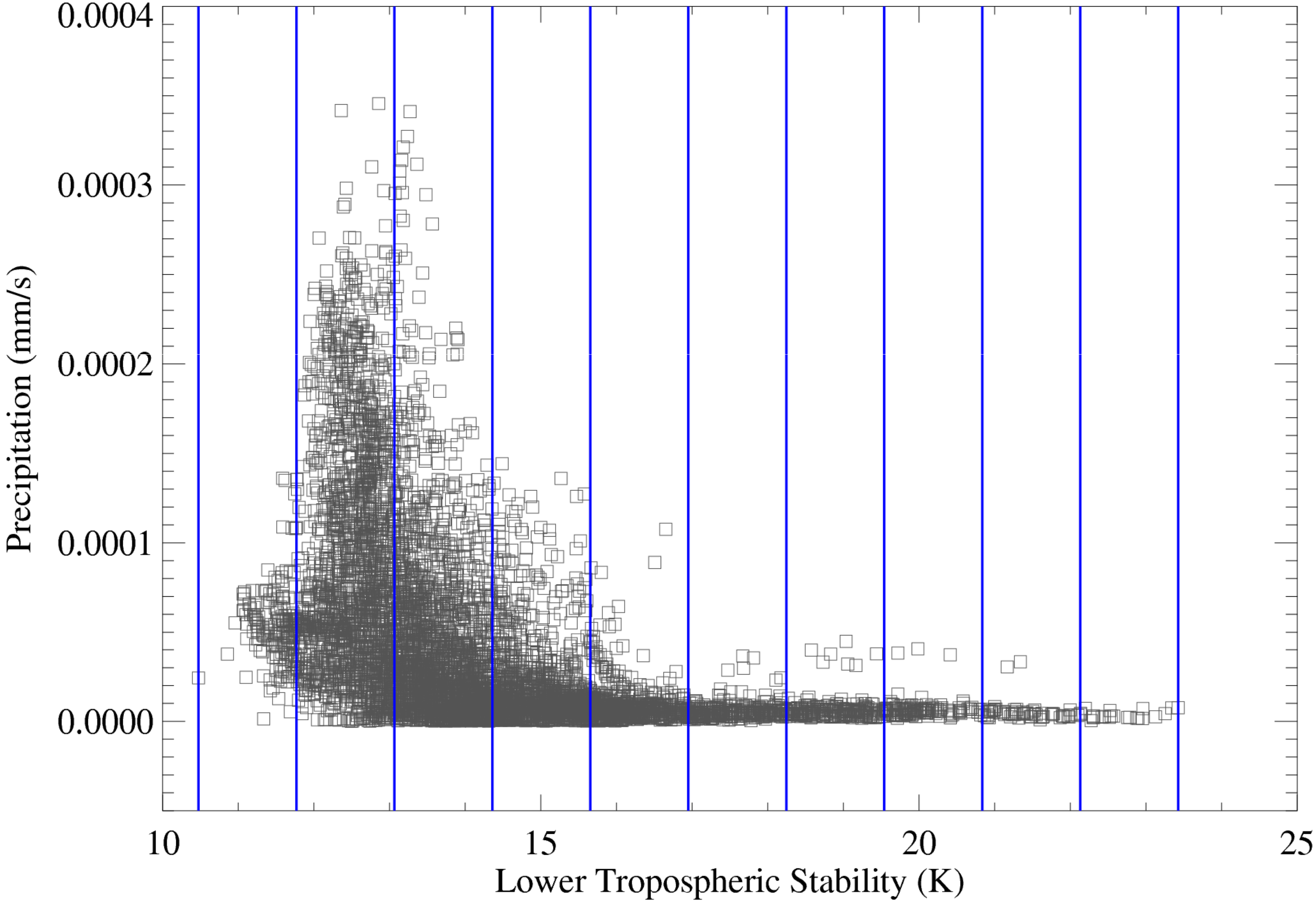
Ringer, Andrews and Webb, GRL, 2014

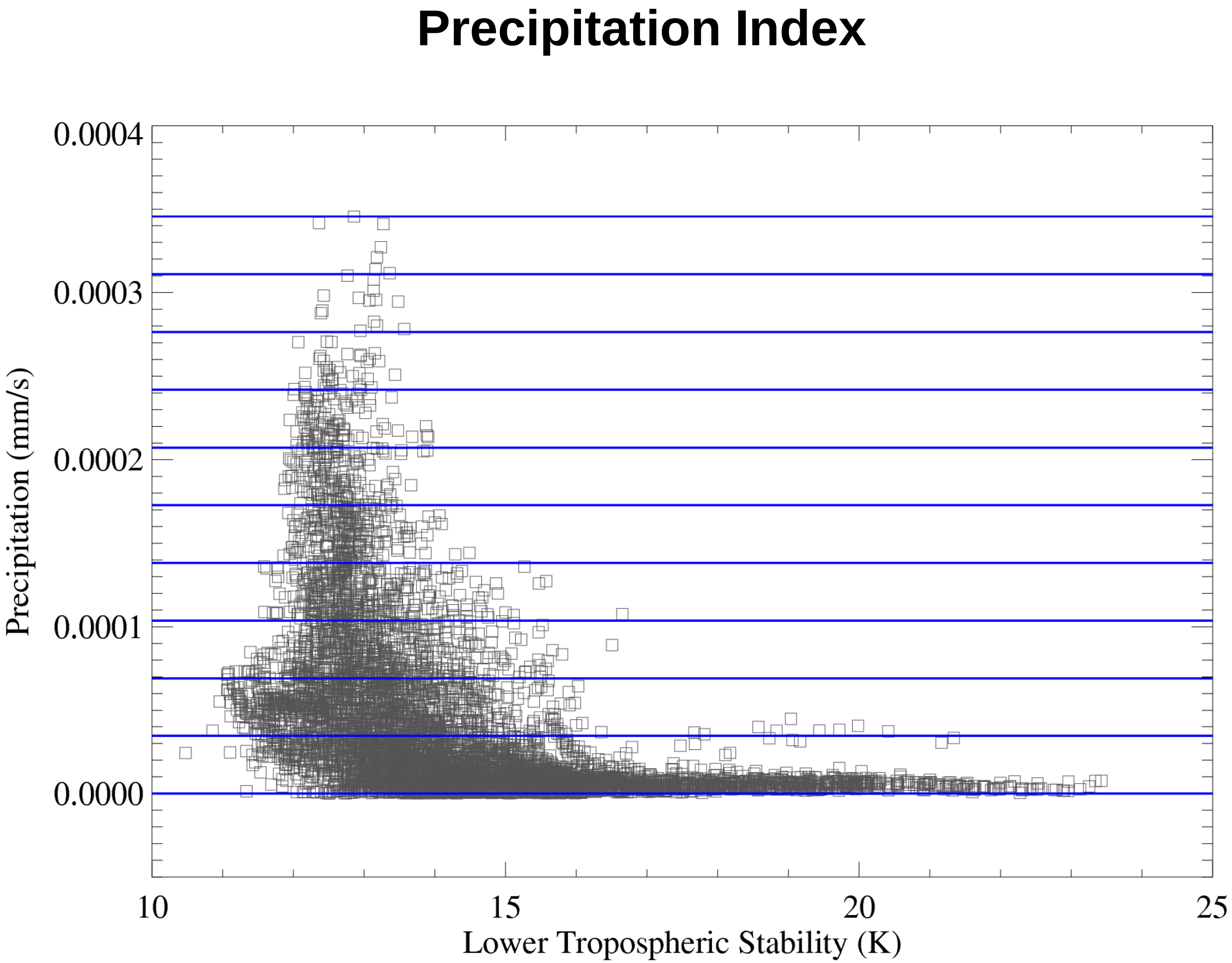
Global Mean Cloud Feedback ($Wm^{-2}K^{-1}$)



- This provides a new opportunity to investigate and understand the physical mechanisms responsible for different cloud feedbacks in relatively computationally inexpensive experiments
- What approach should we take to exploit this opportunity?

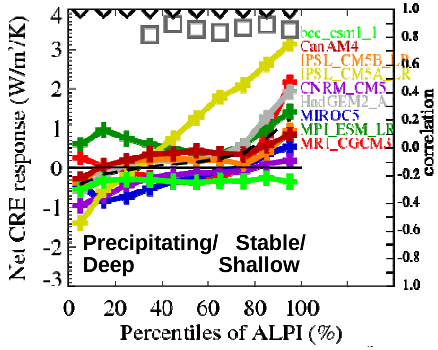
Lower Tropospheric Stability (LTS) Index

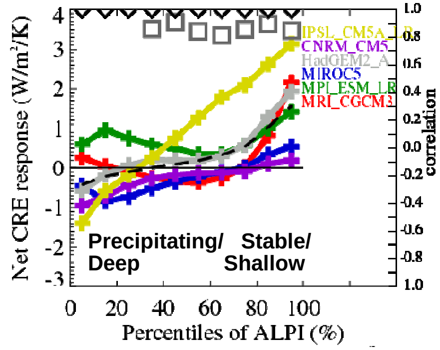



Precipitation Index
Precipitation (mm/s)
0.0004
0.0003
0.0002
0.0001
0.0000
10
15
20
25
Lower Tropospheric Stability (K)

amip4K cloud feedbacks over tropical oceans [30^{O}N/S]

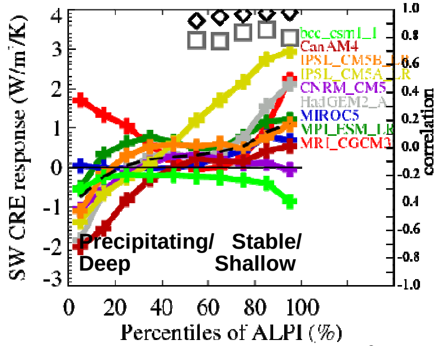
All Standard Models | **SPOOKIE Standard models**

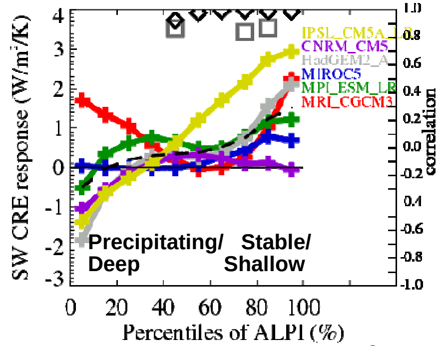




Net Cloud Feedback*

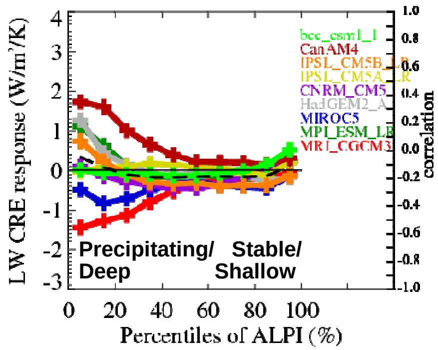
Black diamonds mark significant correlations with the net cloud feedbacks in same regime

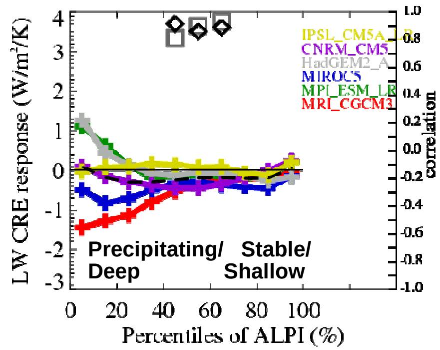




Shortwave Cloud Feedback*

Grey squares mark significant correlations with the net cloud feedback area averaged over tropical oceans



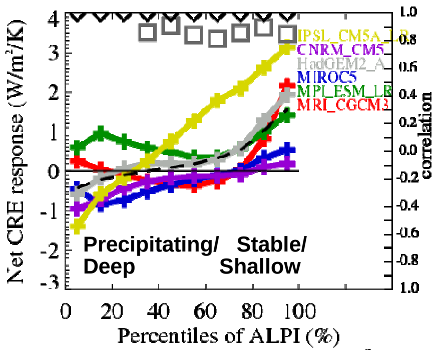


Longwave Cloud Feedback*

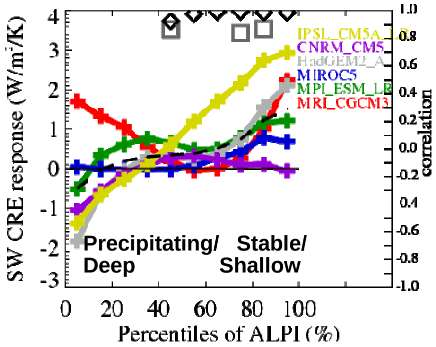
*Includes cloud masking

amip4K cloud feedbacks over tropical oceans [30^{O}N/S]

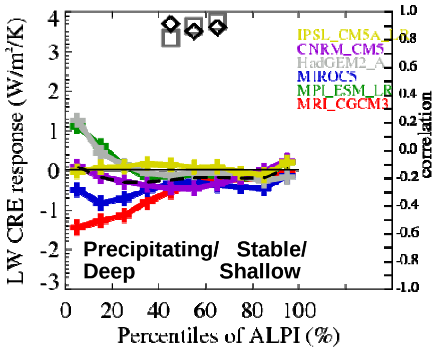
SPOOKIE
Standard models



Net Cloud Feedback*



Shortwave Cloud Feedback*



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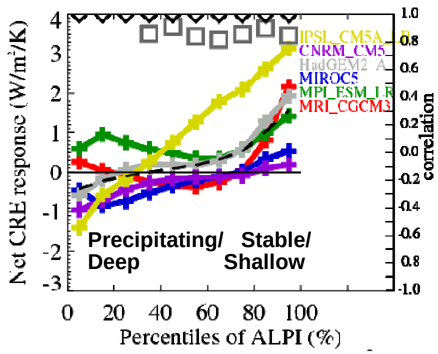
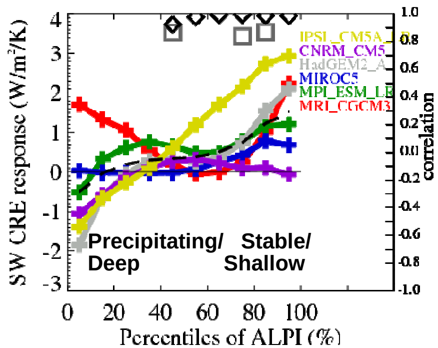
amip4K cloud feedbacks over tropical oceans [30^{O}N/S]

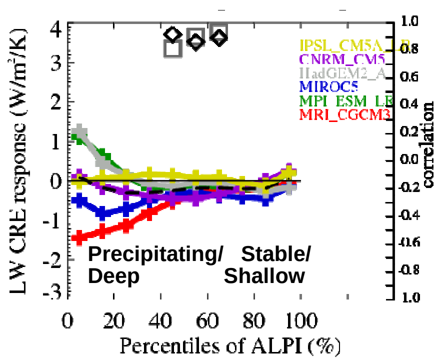
SPOOKIE
Standard models



Net Cloud Feedback*



Shortwave Cloud Feedback*



Longwave Cloud Feedback*

***Includes cloud masking**

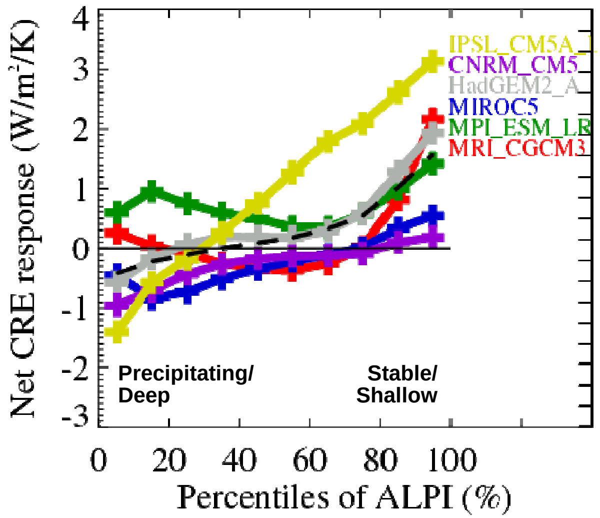
Or can the spread be traced to emergent properties of the climate system?

- Cloud biases projecting onto cloud feedbacks: Williams and Webb *Cli Dyn* 2009, Yokohata et al *J Clim* 2010, Trenberth and Fasullo *J Clim* 2010.
  - Can we bias correct clouds in models?

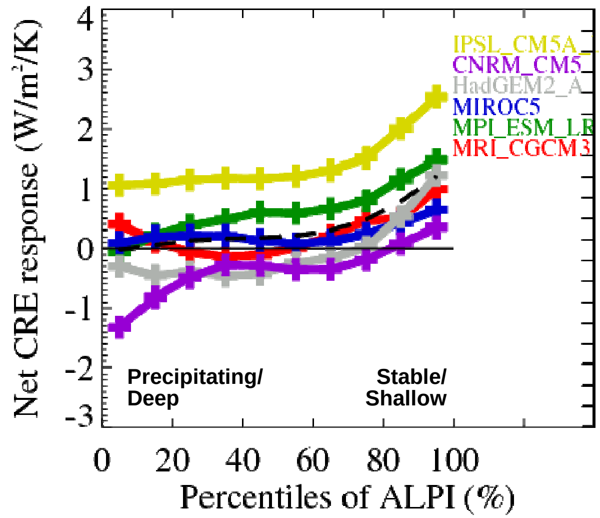
- Large scale biases in atmospheric temperature and humidity structure/circulation strength/depth: e.g. Sherwood et al *Nature* 2014 *Fasullo and Trenberth* Science 2012, Volodin *Izvestia* 2008.
  - Can we nudge models to observations and see the impact on feedbacks?

amip4K Cloud Feedbacks over 30^{O}N/S Oceans

SPOOKIE
Standard models



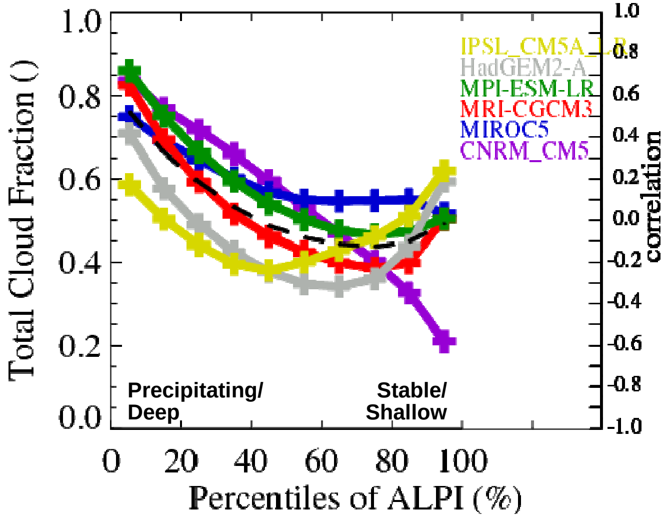
SPOOKIE
ConvOff models

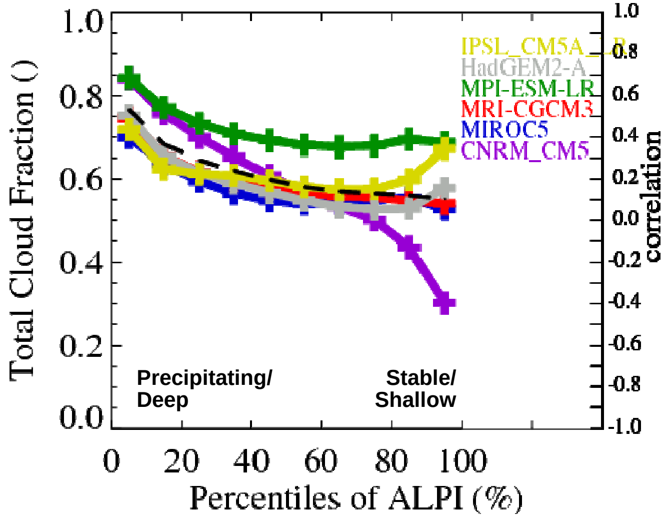


Net Cloud Feedback*

*Includes cloud masking

Present Day Total Cloud Fraction ()





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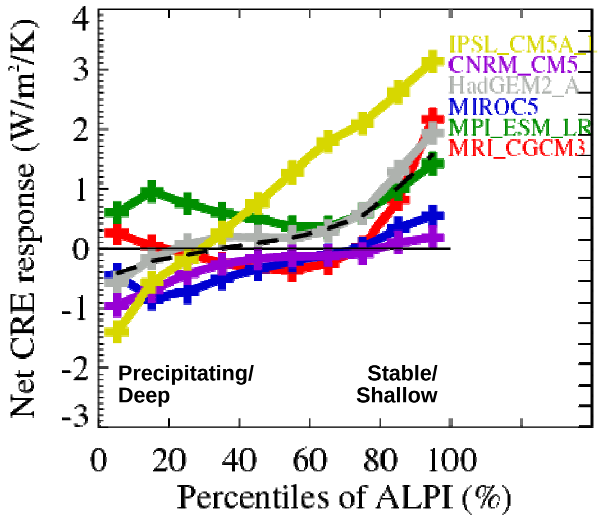
amip4K Cloud Feedbacks over 30^{O}N/S Oceans

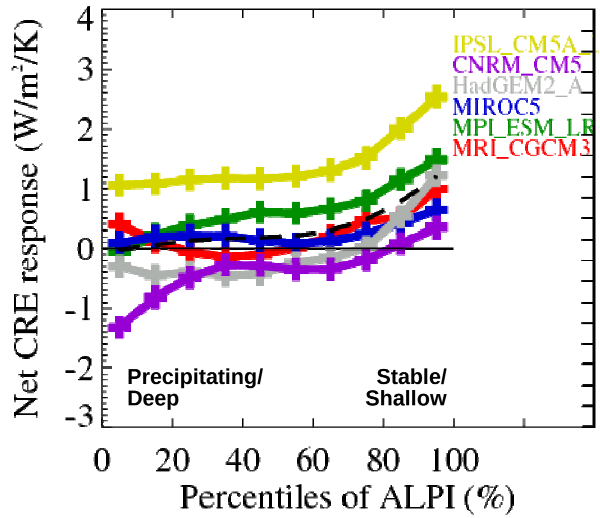
SPOOKIE Standard models



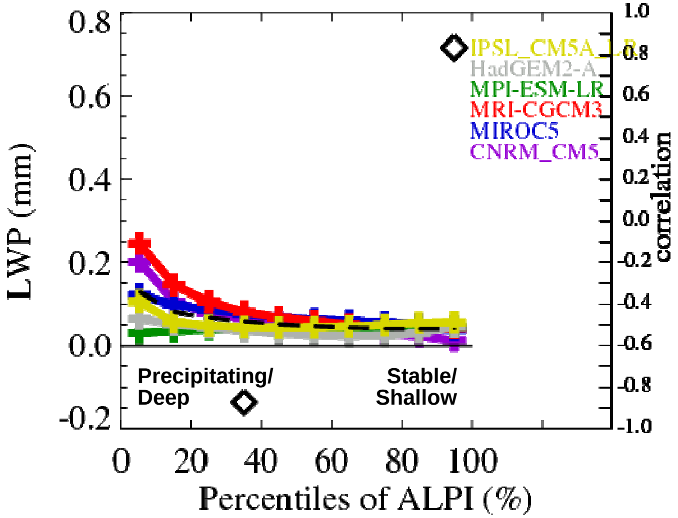
Net Cloud Feedback*

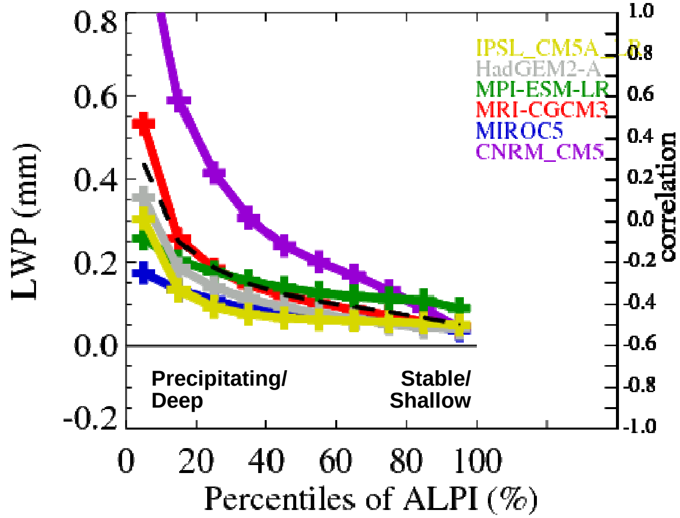
*Includes cloud masking

SPOOKIE ConvOff models



Present Day Liquid Water Path (mm)





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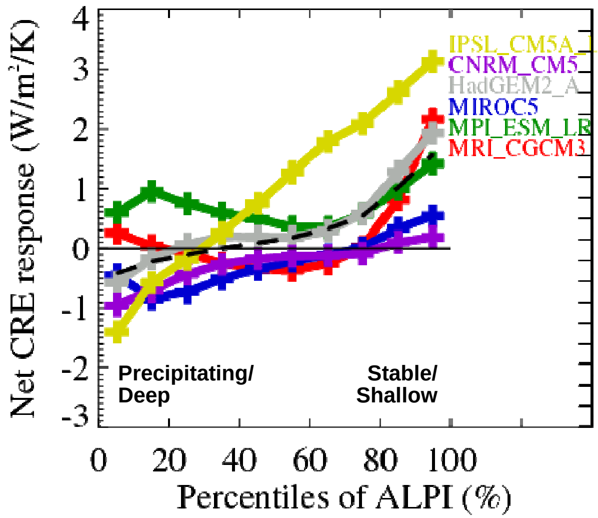
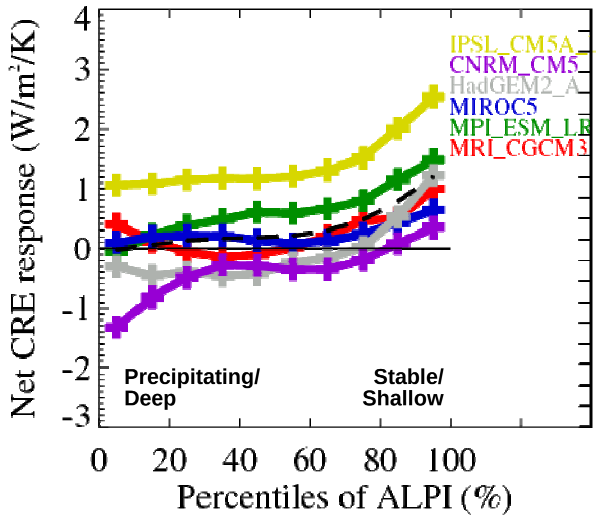


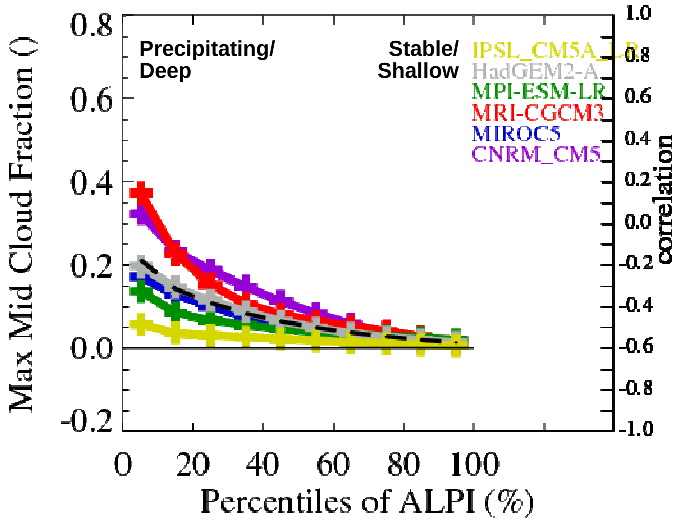
Net Cloud Feedback*

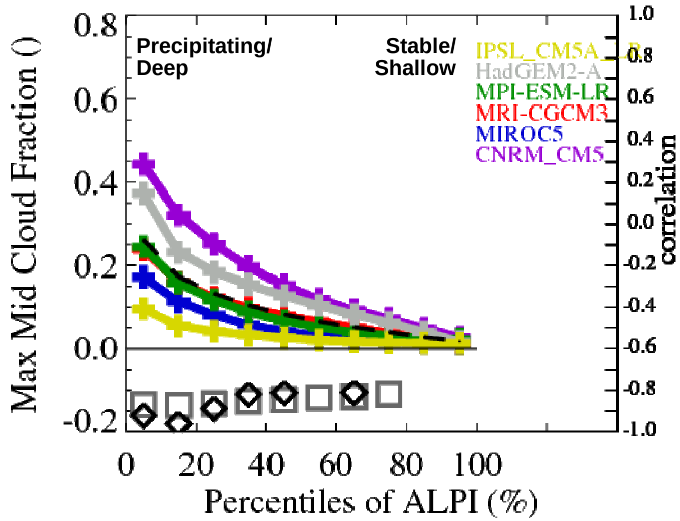
*Includes cloud masking

SPOOKIE
ConvOff models



Present Mid Level Cloud (Max 680-440 hPa)



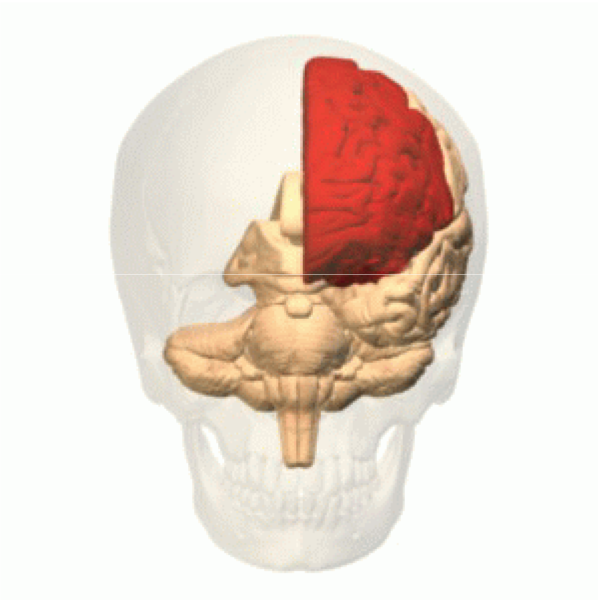


Black diamonds mark significant correlations with the net cloud feedbacks in same regime

Grey squares mark significant correlations with the net cloud feedback area averaged over tropical oceans

Understanding the human brain:

a useful analogy for understanding cloud feedbacks?



http://en.wikipedia.org/wiki/File:Frontal_lobe_animation.gif

- Much work on understanding the human brain has revolved around the study of cognitive impairments in people who have suffered disease or injury to specific areas.
- Famous cases include that of Phineas Gage, a railway worker who suffered personality changes following accidental damage to his prefrontal cortex.
- Can we better understand the physical mechanisms of cloud feedbacks by removing or simplifying different components of climate models?

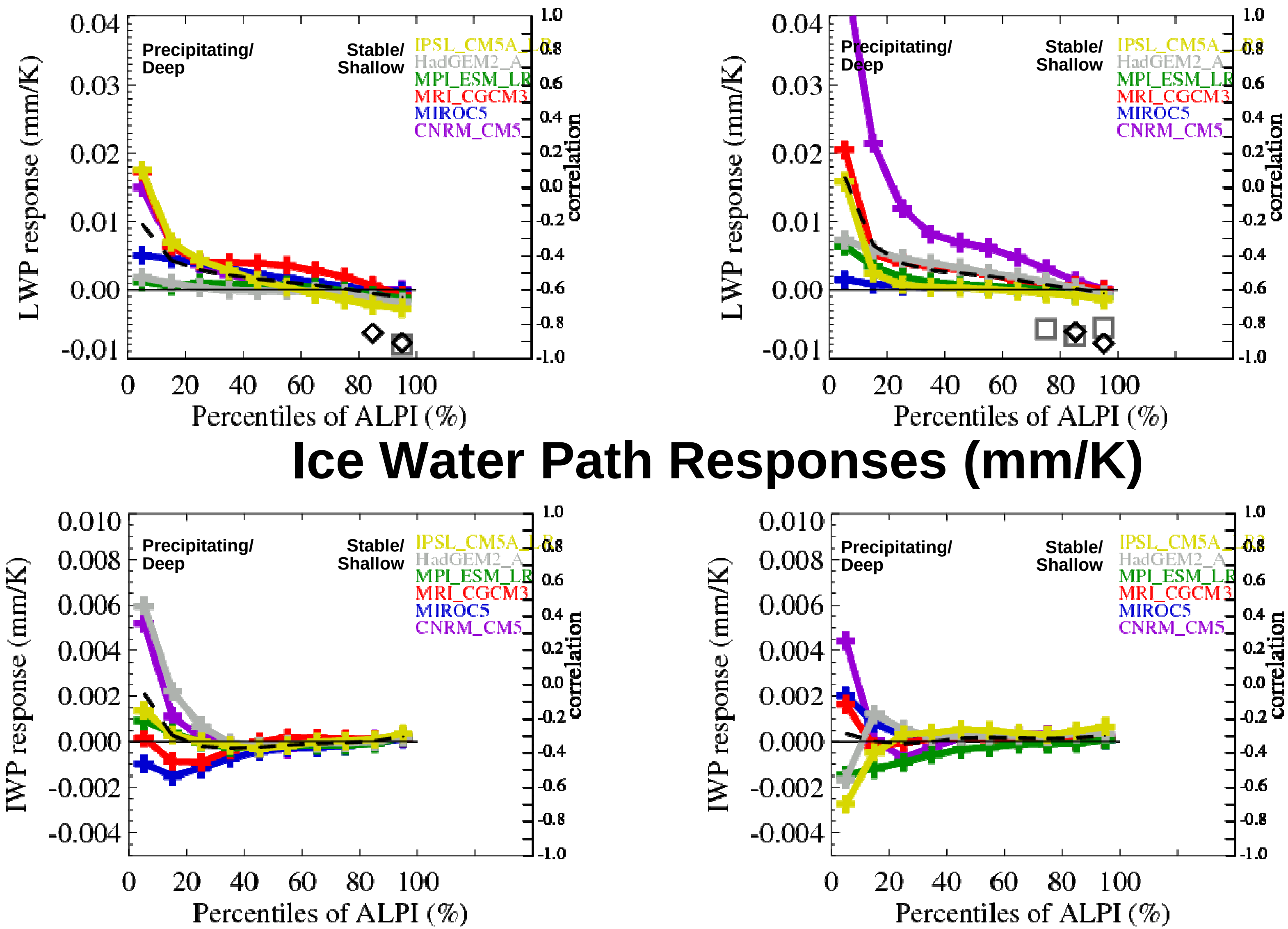
Background

- The radiative feedbacks of clouds on climate change differ widely between climate models
- Our understanding of the physical mechanisms underlying the different model responses is still very limited, which makes it difficult to assess their credibility
- The Cloud Feedback Model Intercomparison Project (CFMIP) has in recent years demonstrated that much of the spread in cloud feedback in coupled atmosphere-ocean climate models can be reproduced in idealised atmosphere-only experiments forced with specified SSTs
- This provides a new opportunity to investigate and understand the physical mechanisms responsible for different cloud feedbacks in relatively computationally inexpensive experiments
- What approach should we take to exploit this opportunity?

SPOOKIE
Standard models

SPOOKIE
ConvOff models

Liquid Water Path Responses (mm/K)



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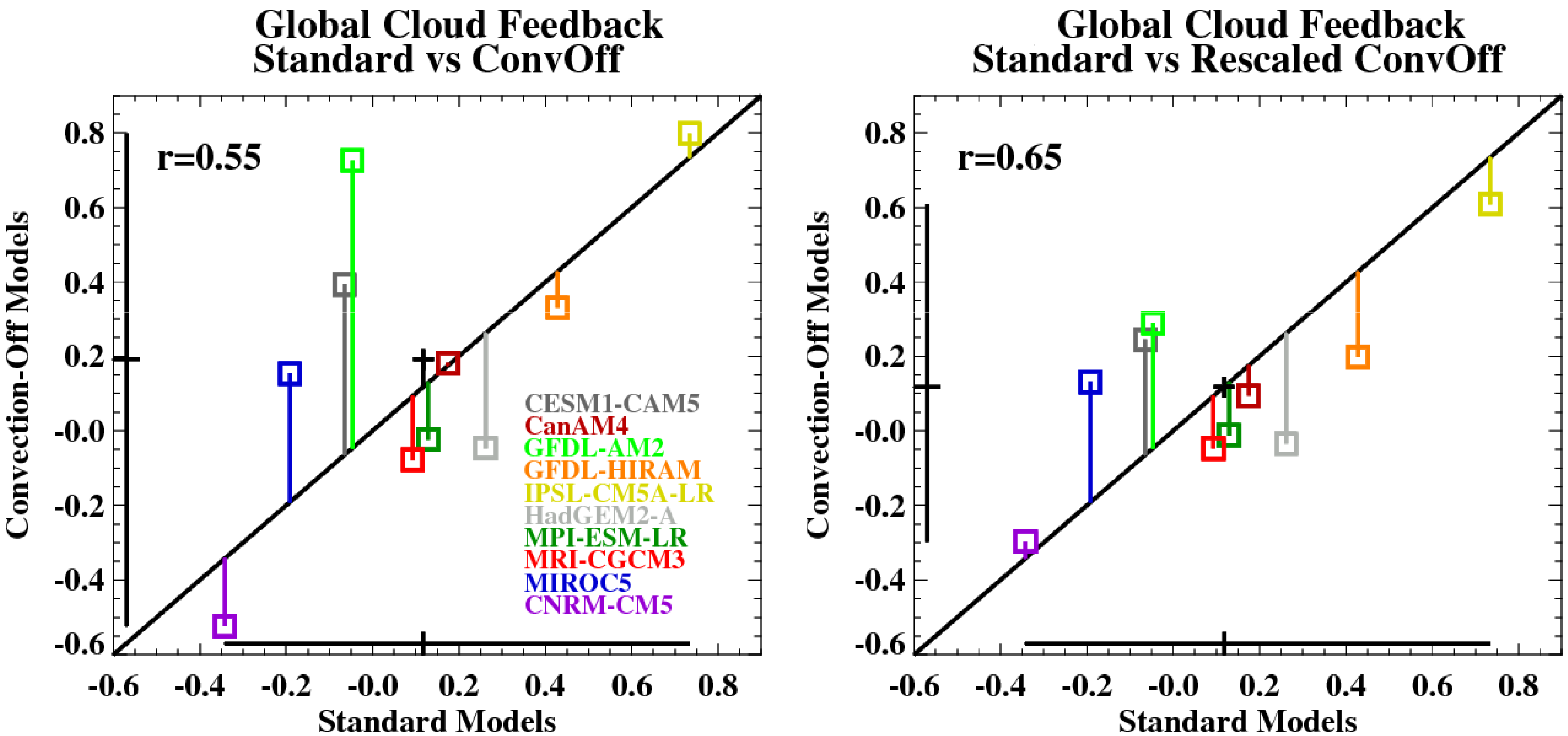
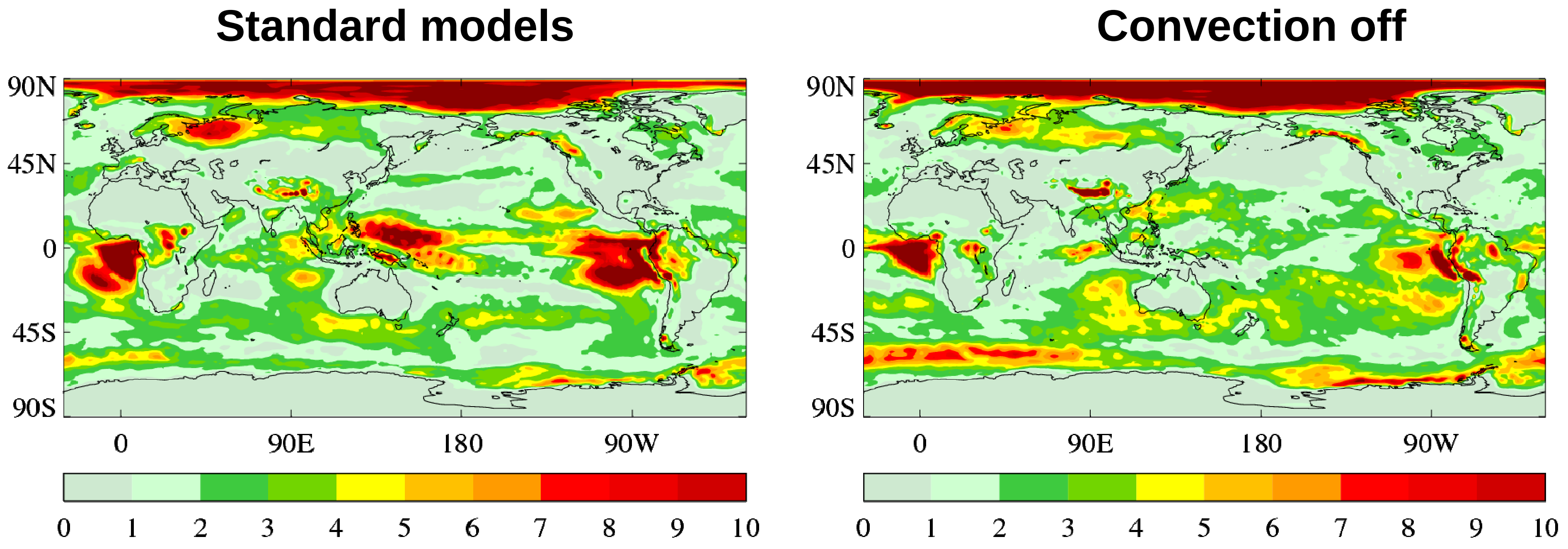
Global Mean Cloud Feedback ($Wm^{-2}K^{-1}$)

(Including cloud masking)

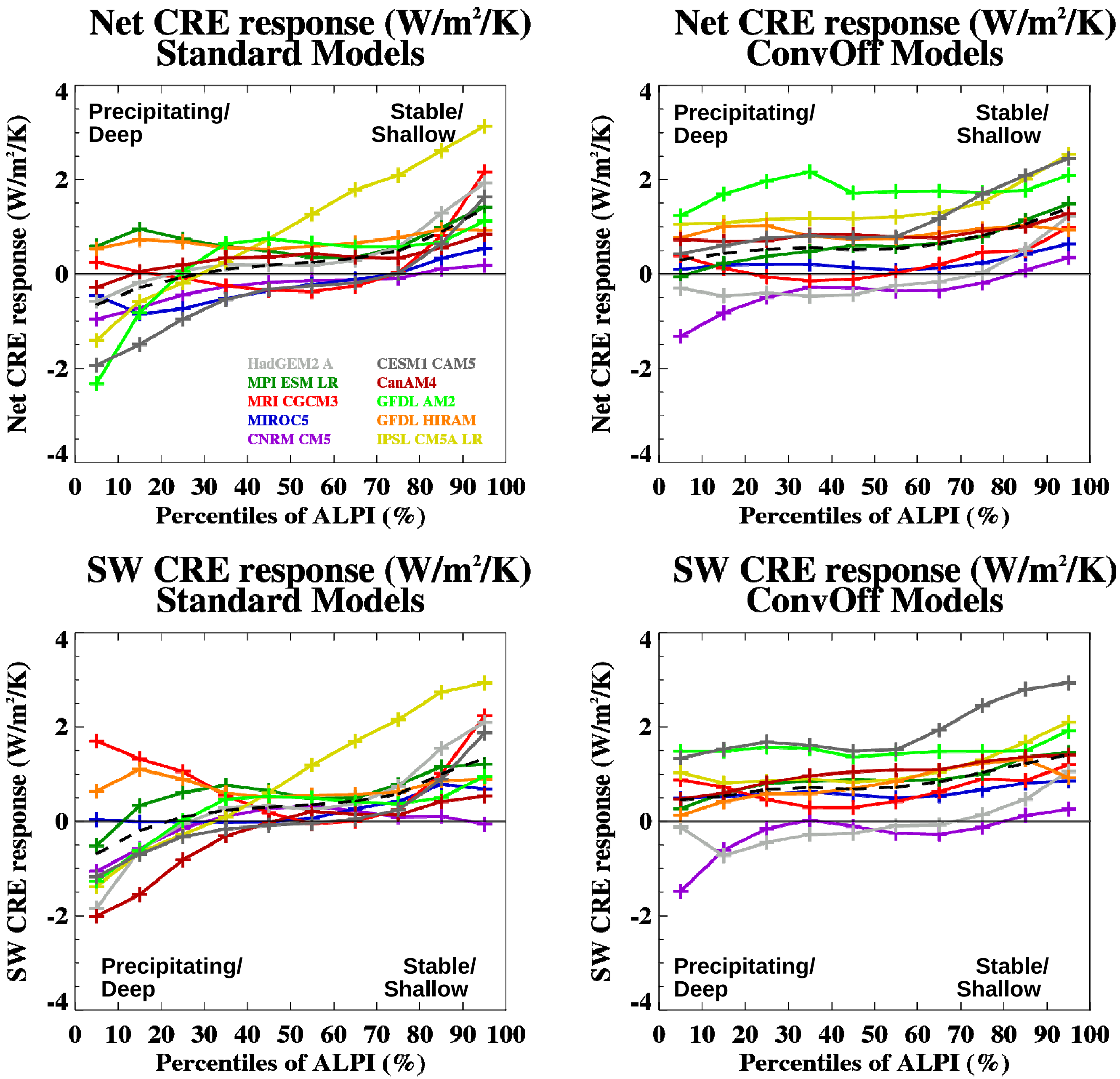


How does convection affect inter-model spread in cloud feedback?

Ensemble variance of amip4K Net Cloud Feedback



amip4K Cloud Feedbacks over 30^{O}N/S Oceans



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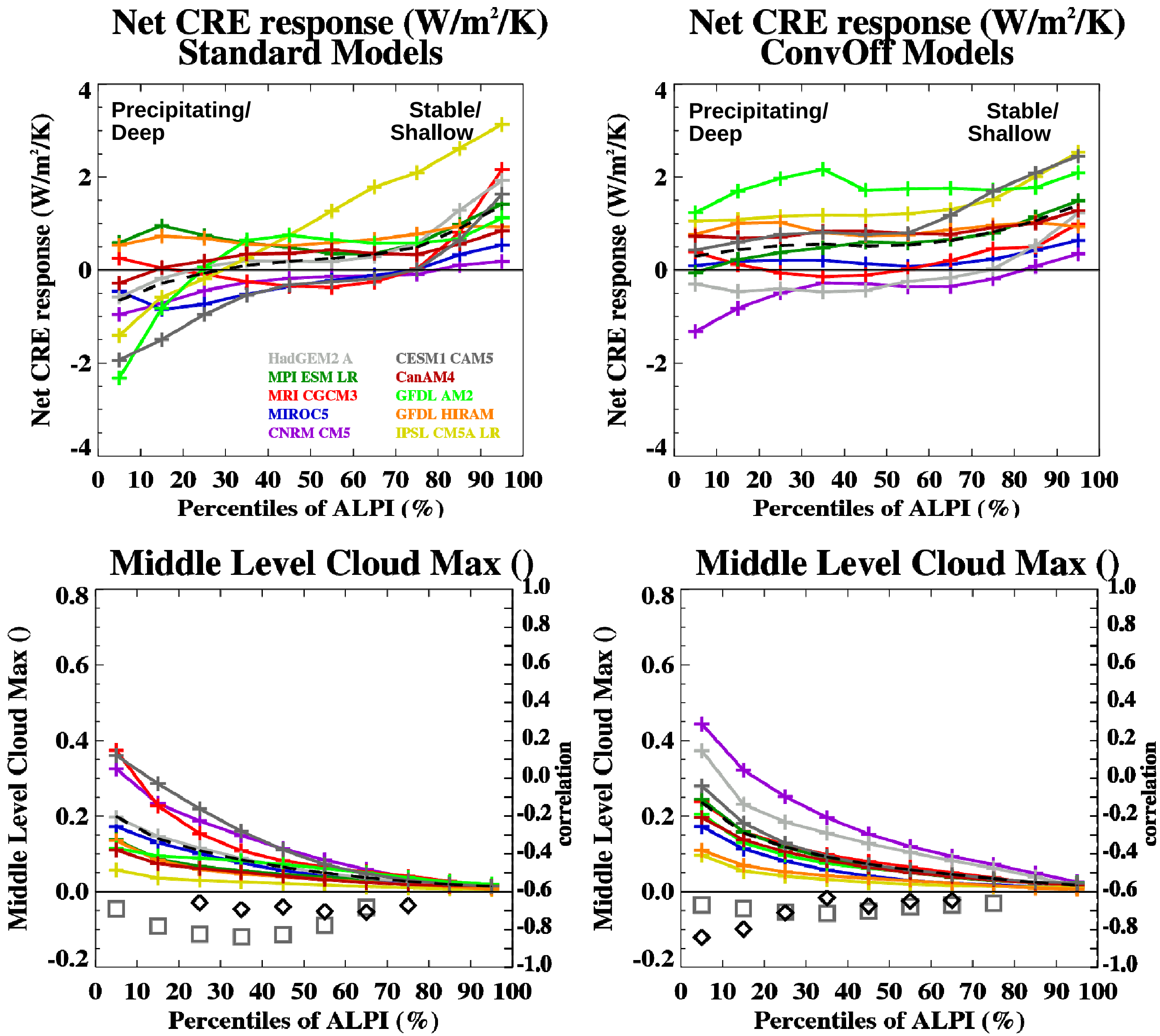

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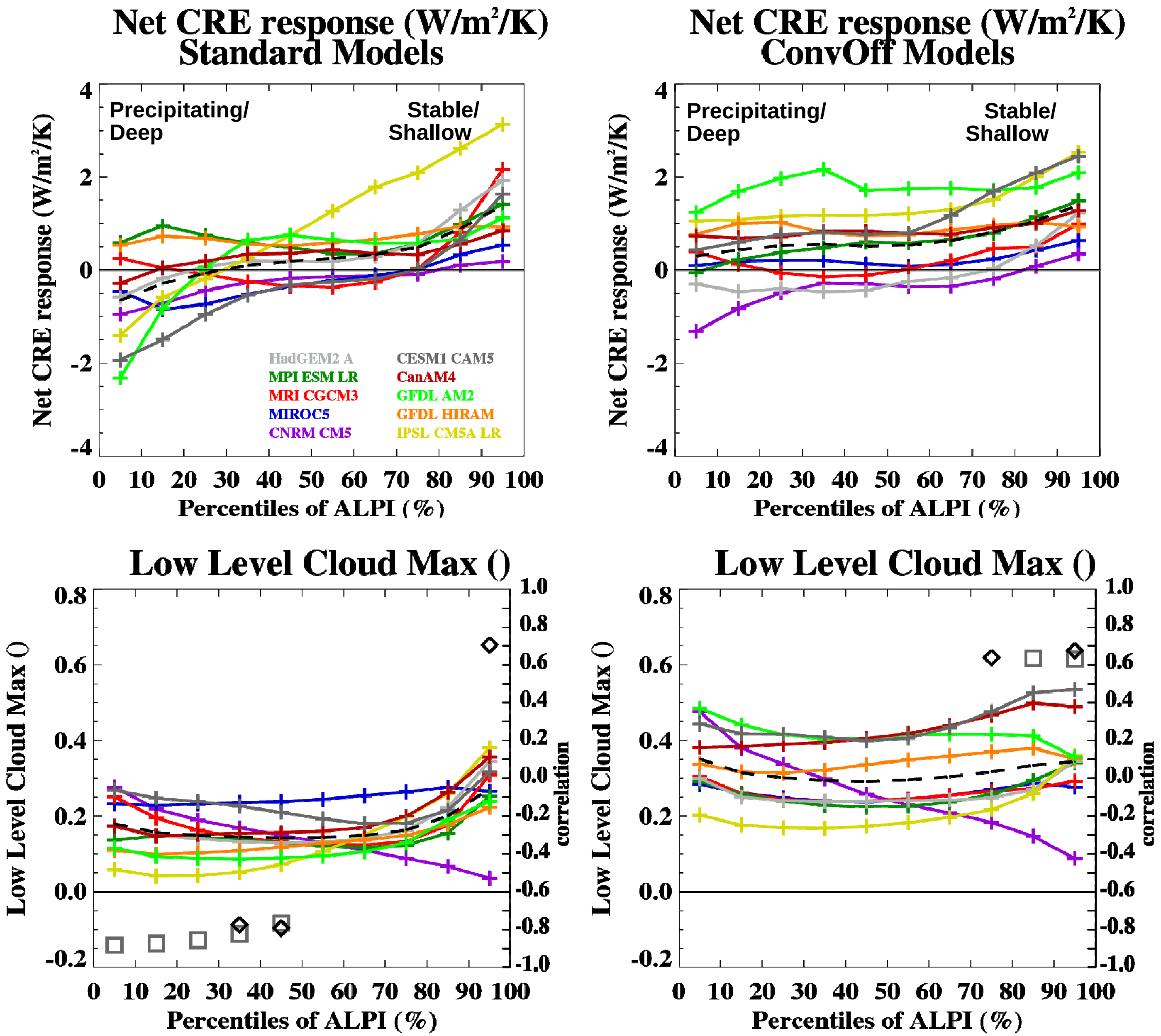

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What other processes other than convection could drive spread in global cloud feedback and how could we simplify them?

- Cloud schemes: Qu et al. *(*2014), Brient and Bony (2012):
  - Diagnose cloud fraction as a simple function of RH?
  - Fix cloud radiative properties?

- Boundary layer/surface schemes: Jones, Bretherton and Blossey *(*2014):
  - Implement a simple diffusive PBL scheme?
  - Suppress or standardise cloud top entrainment?

- Warm/cold/mixed phase microphysics: e.g. Rougier et al. (2009).
  - Implement a simple precipitation scheme?
  - Rain out to the surface when saturation reached?

- Resolution: e.g. Bushell and Martin *Cli Dyn 1999.*
  - Run models with consistent/fine vertical resolution in the PBL?

- Alternatively could there be 'emergent properties' of the climate system which regulate cloud feedbacks via a range of interacting processes?

Convection-off (ConvOff) experiments: what do we expect to see?

- Zhang et al. (2013) argue that positive subtropical feedback is caused by enhanced entrainment of dry air into the boundary layer from the free troposphere in models with active shallow convection.

    - If this is the sole cause of positive subtropical feedback, then convoff feedbacks will be neutral or negative.

- Sherwood et al. (2014) argue that positive shallow cloud feedback (and much of its spread) is related to the strength of lower tropospheric mixing by convection and large scale circulations.

    - Hence some reduction in magnitude and spread of cloud feedback would be expected in the absence of convective parametrization

Could differences in large-scale precipitation efficiency contribute to spread in cloud feedback?

- Might instead large scale precipitation efficiency be the dominant control of the vertical flux of water vapour in deep convective regions?
- Large scale precipitation efficiency will depend on various aspects of cloud parametrization/cloud microphysics.
- Models that can form clouds and condensate more easily at low levels in ascending regions of the tropics may find it easier to rain out to the surface, and hence have stronger large scale precipitation efficiencies.
- Models which condense over a greater depth at higher levels where water contents are smaller might precipitate less easily and evaporate more. There also will be more opportunity for precipitation to evaporate before reaching the surface, resulting in weaker precipitation efficiencies.
- Such models would be expected to dry the boundary layer more and moisten the free troposphere more, and this effect would be expected to strengthen with the hydrological cycle as the climate warms.

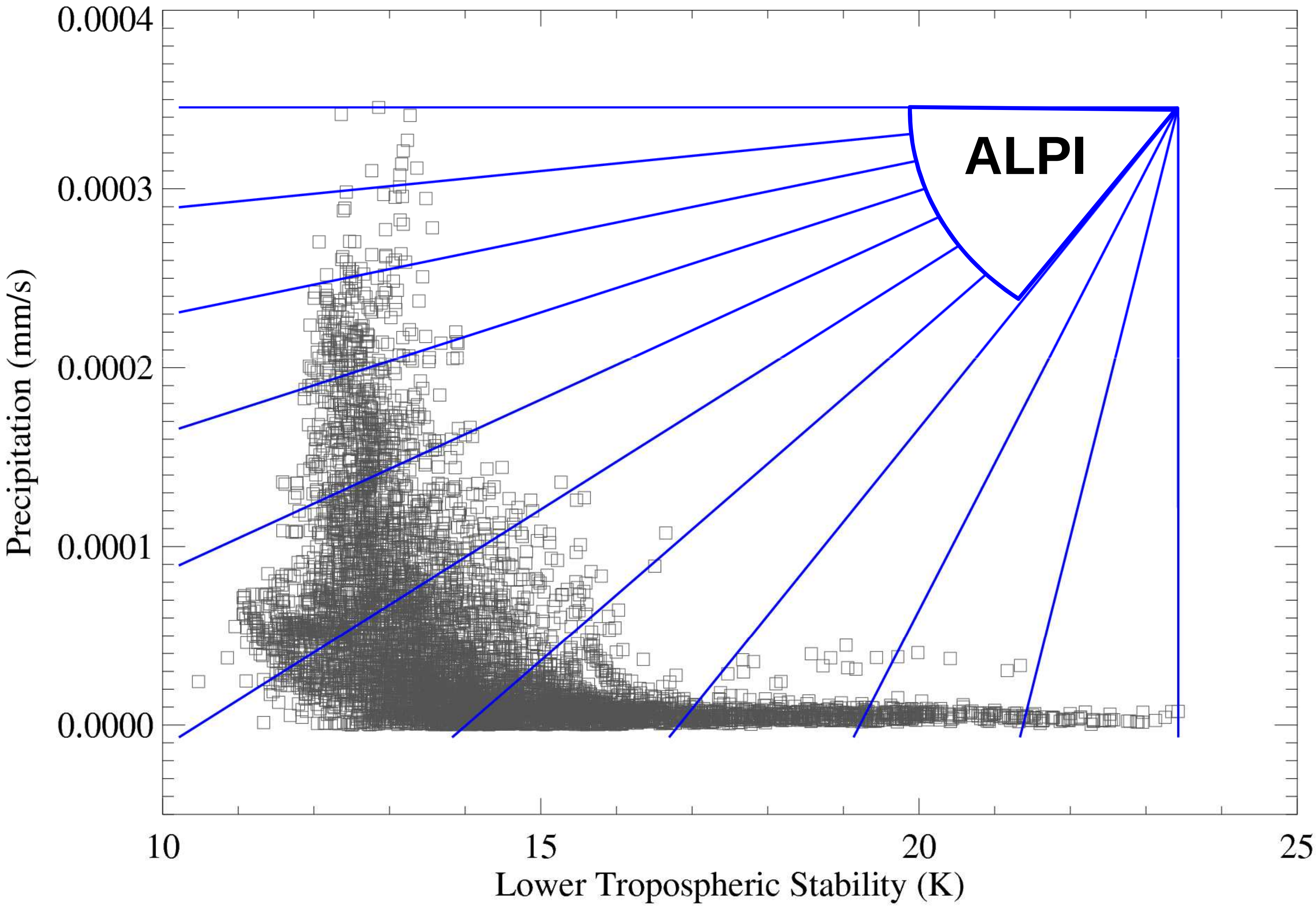
Could differences in large-scale precipitation efficiency contribute to spread in cloud feedback?

- Sherwood et al. 2014 argued that enhanced drying of the tropical boundary layer will dry low cloud regions resulting in stronger low cloud reductions.

- Alternatively it is possible that the additional moistening of the free troposphere might propagate to the subtropics and encourage the breakup of low level clouds by inhibiting radiative cooling of the subtropical boundary layer.

- Studies with LES have demonstrated that an enhanced free-tropospheric greenhouse effect can reduce turbulent mixing and cloudiness in the subtropical boundary layer - e.g. Bretherton et al. (2013).

Angular LTS/Precipitation Index (ALPI)



Background

Met Office

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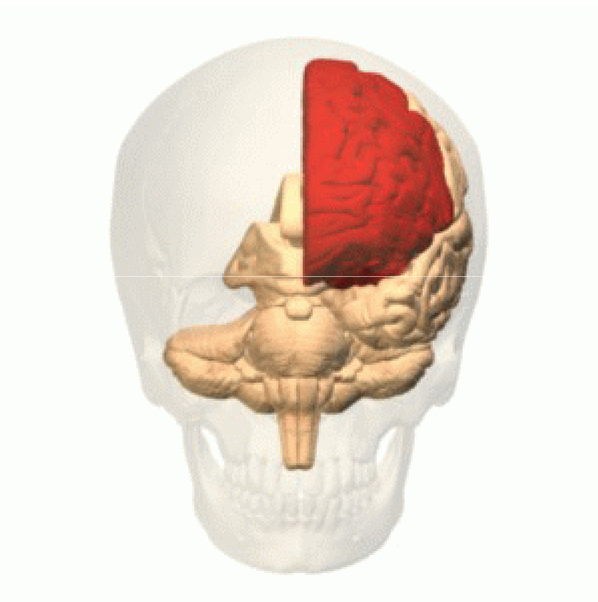

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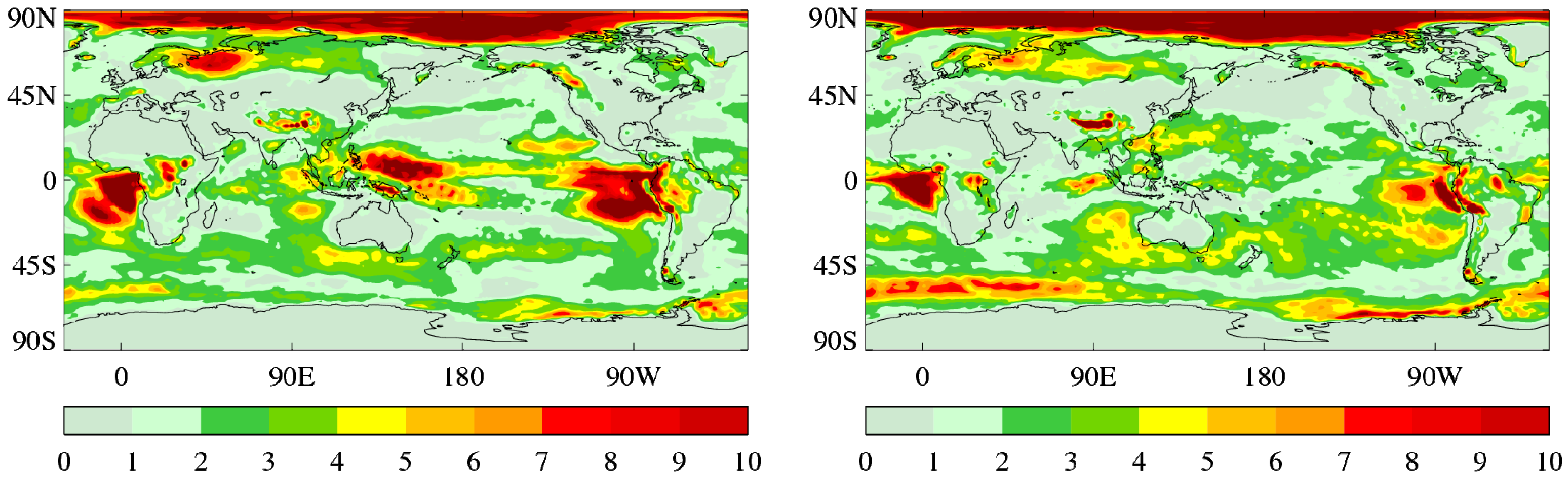
Ensemble variance of amip4K Net Cloud Feedback

Standard models **Convection off**



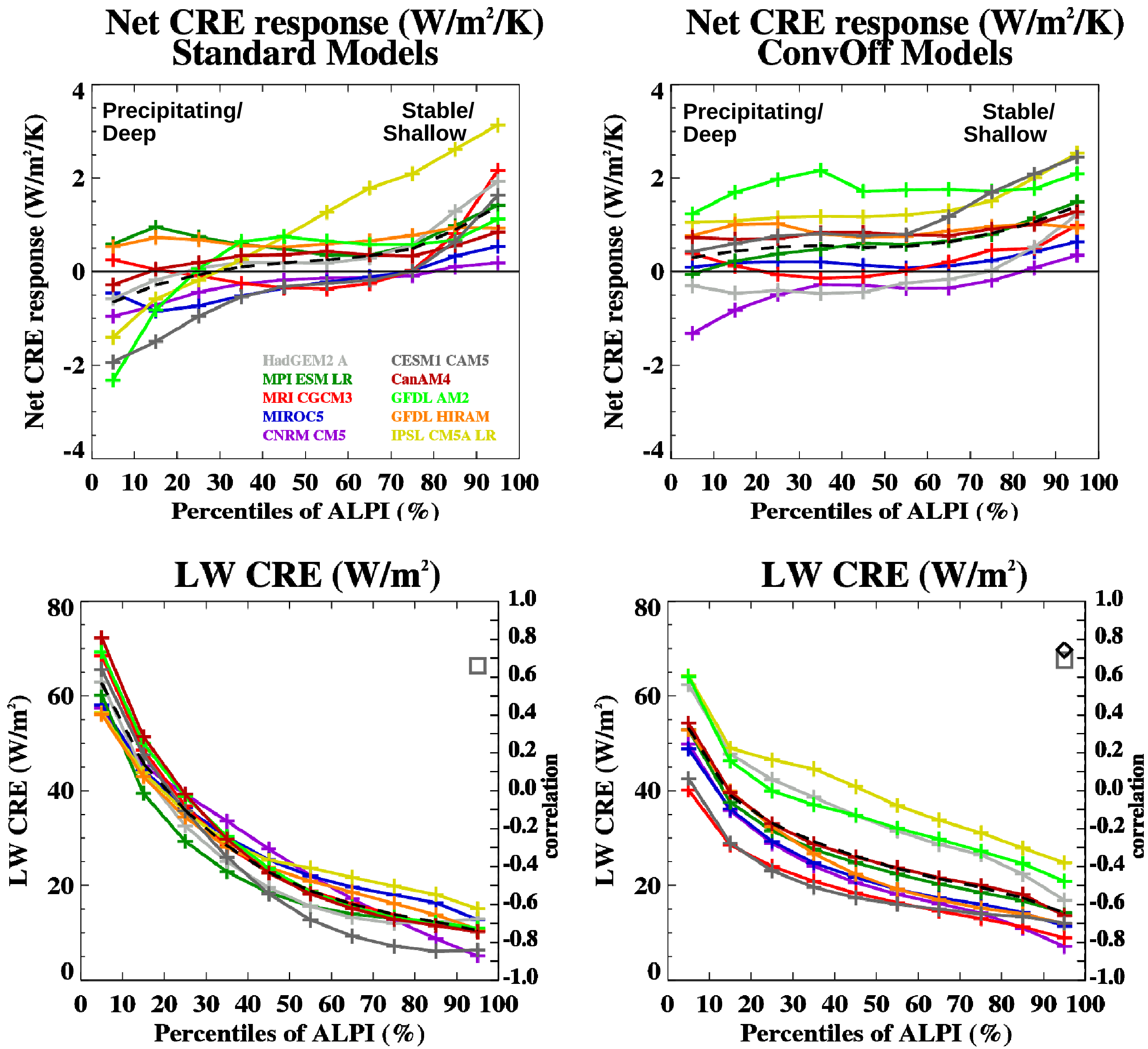
How might cirrus cloud regulate shallow cloud feedback?

- Models with weaker precipitation efficiencies and stronger vertical transports of water vapour might produce more or thicker cirrus clouds above shallow cloud regimes.

- Could this somehow encourage the breakup of low level clouds in the warmer climate by affecting the circulation or the downwelling longwave flux?

- We can test the idea that the radiative effects of cirrus influence the low cloud feedback by making cirrus transparent to longwave radiation.

amip4K Cloud Feedbacks over 30ON/S Oceans



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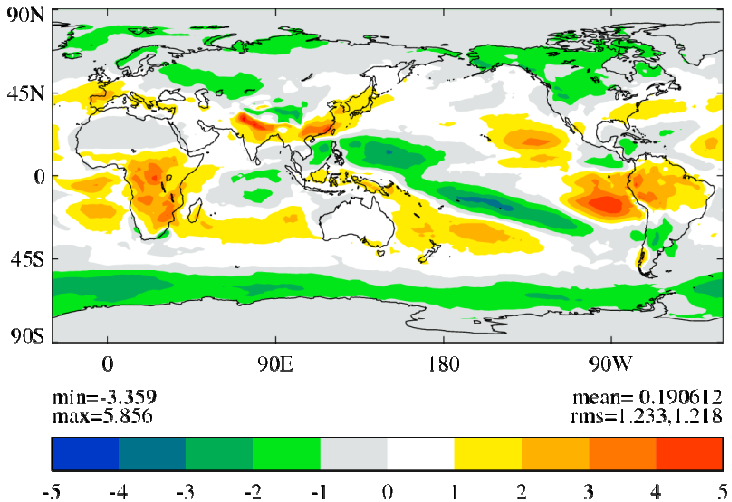
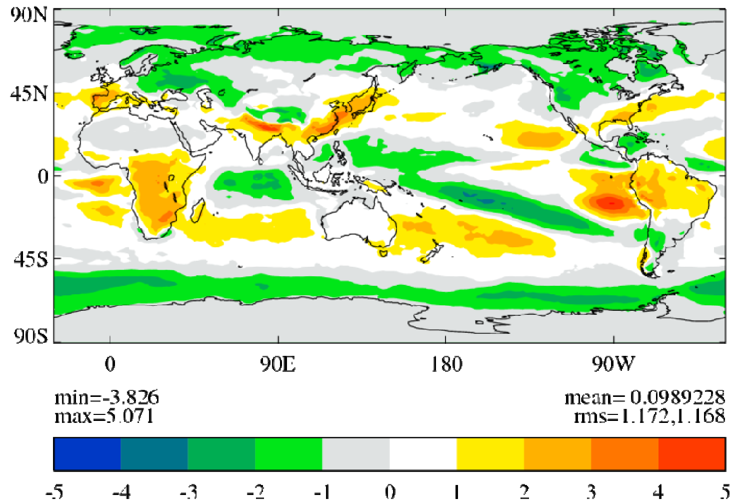
HadGEM2-A amip4K Shortwave Cloud Feedback

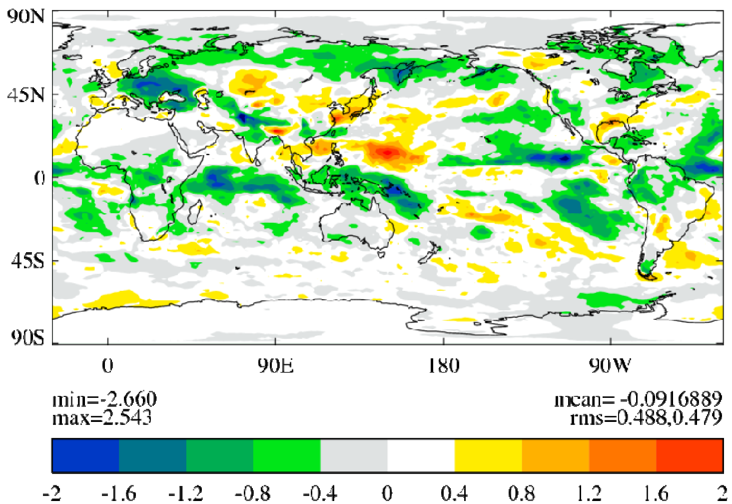
Standard HadGEM2-A



HadGEM2-A with invisible cirrus



HadGEM2-A with invisible cirrus
minus Standard version



Making cirrus clouds transparent to radiation decreases the shortwave cloud feedback parameter by just 0.1 $Wm^{-2}K^{-1}$ – not that big an effect compared to the overall range of 1.1 $Wm^{-2}K^{-1}$