Low-Level Cloud Feedback Estimated from CERES Co-Variability with Meteorology

Joel Norris and Ryan Scott (SIO/UCSD)
Tyler Thorsen (NASA LaRC)

Spring CERES Science Team Meeting

May 8, 2019

Outline

- Ten-year retrospective
- Prior work
- Challenges and solutions
- Cloud response to meteorology
- Radiative effects method
- Radiative response to SST
- Regional radiative response
- Estimation of climate feedback
- Discussion and summary

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- Ten-year retrospective – *how far have we come? How far has Joel come?*
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Clouds in the Climate System:
Why is this such a difficult problem, and where do we go from here?

Joel Norris
Scripps Institution of Oceanography

CERES Science Team Meeting

April 29, 2009

Why is this a difficult problem?

- We have no stable system to monitor global cloudiness and radiation on multidecadal time scales

- Cloud and radiation measurements are insufficiently integrated with associated meteorological processes

- Wrong priorities in climate modeling efforts

Where do we go from here? (1)

- Develop a stable observational system to monitor global cloudiness and radiation on decadal time scales
- Correct (to the extent possible) the historical cloud and radiation record

– this includes reprocessing data long after a mission has ended

– integrate satellite and non-satellite datasets (surface observations, ocean heat content, reanalysis meteorology)

Where do we go from here? (2)

- Integrate meteorological conditions with cloud and radiation measurements

  – detailed information of cloud properties is not sufficient to characterize processes and feedbacks

  – daily rather than monthly data is fundamental

- Understand that the instantaneous cloud and radiation state results from a history of meteorological processes

  – coincident cloud and meteorological correlations may not show true relationships

Where do we go from here? (3)

- Assimilate cloud and radiation measurements into global models for best integration

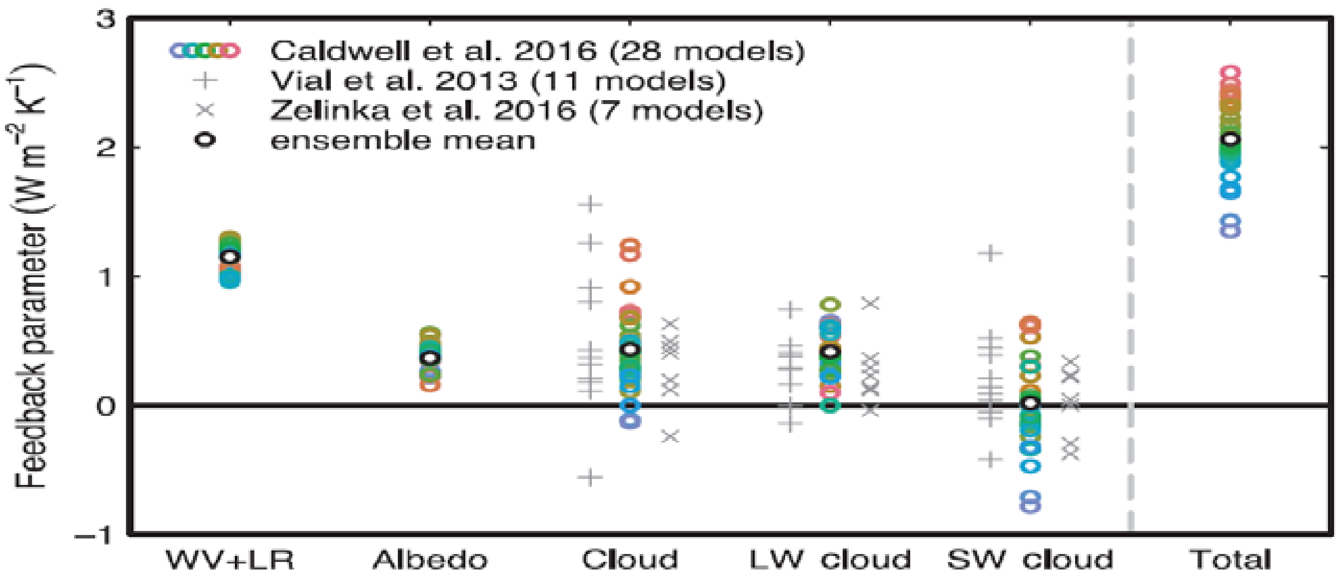
  – *this is a very difficult task due to model cloud biases*

- Focus on essential cloud, convection, and turbulence parameterization development

  – *it doesn't make sense to add aerosol indirect effects when basic cloud processes are not credible*

Cloud Feedbacks in Recent Climate Models

- Cloud feedbacks are still greatest source of disagreement among models about climate sensitivity



Plot from Ceppi et al. (2017)

Cloud Feedbacks in Recent Climate Models

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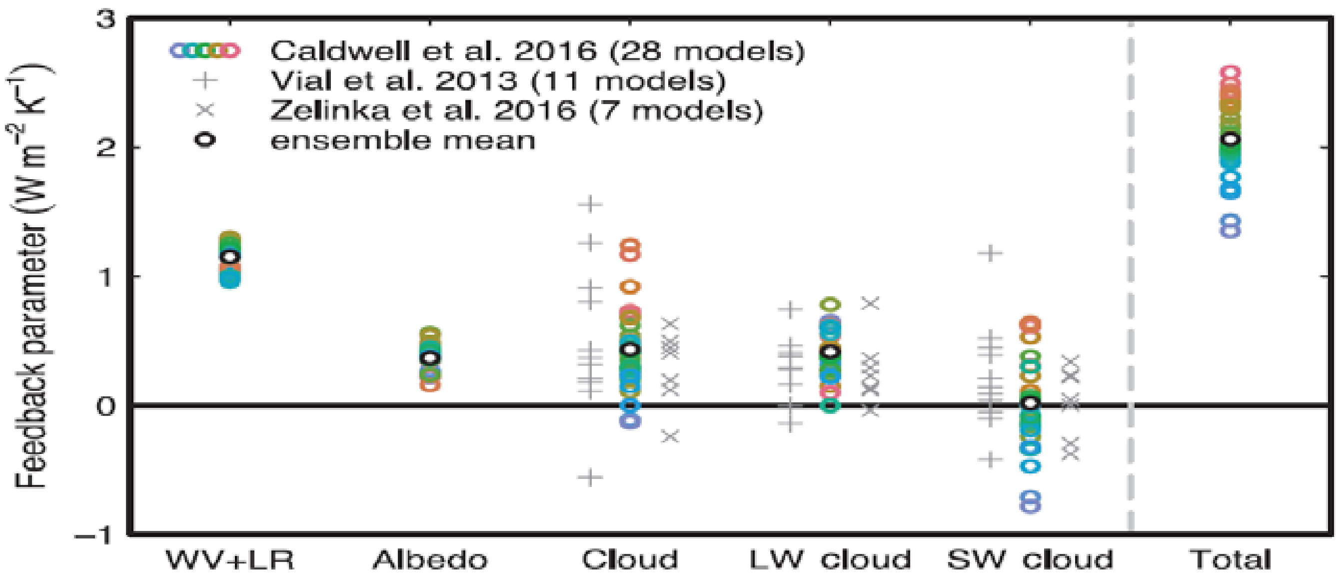
- SW cloud feedback causes the most inter-model disagreement



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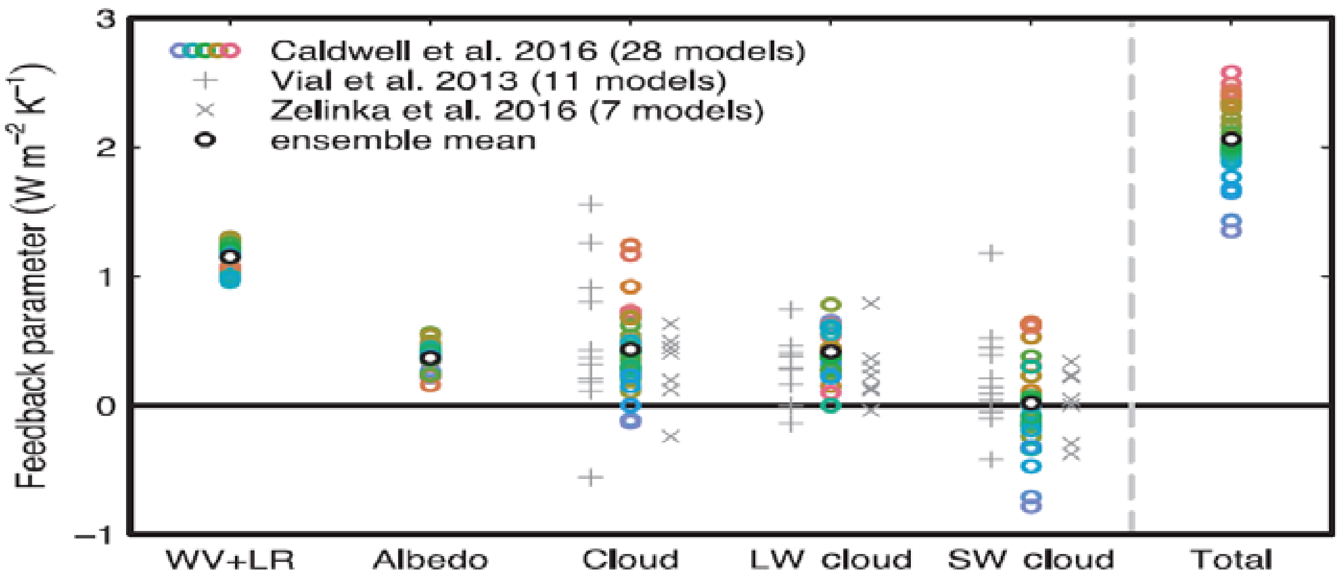

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Cloud Feedbacks in Recent Climate Models

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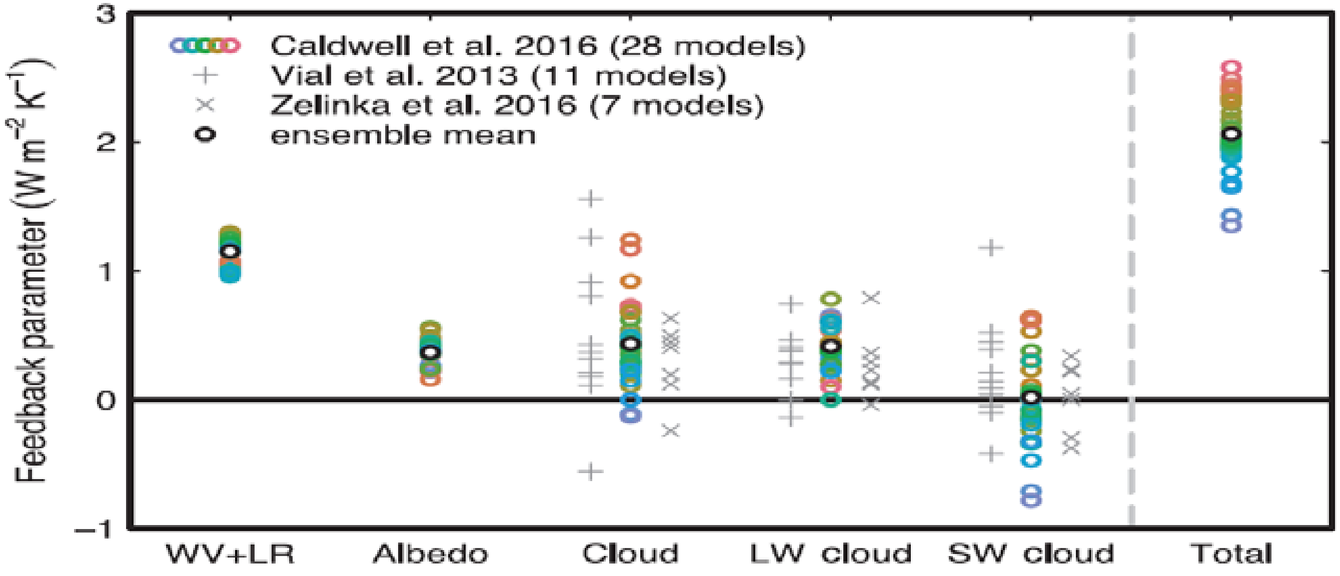
- SW cloud feedback causes the most inter-model disagreement
- SW cloud feedback primarily arises from low-level clouds
- Climate models inconsistently and incorrectly simulate low-level cloudiness



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Estimating Low-Level Cloud Feedback

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- Climate models *disagree* about low-level cloud response to changes in meteorological "controlling factors"

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- Climate models *agree* about how meteorological "controlling factors" will change due to global warming

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Solution:

- Multiply observed cloud response to model-projected change in controlling factors – *Myers and Norris (2016)*

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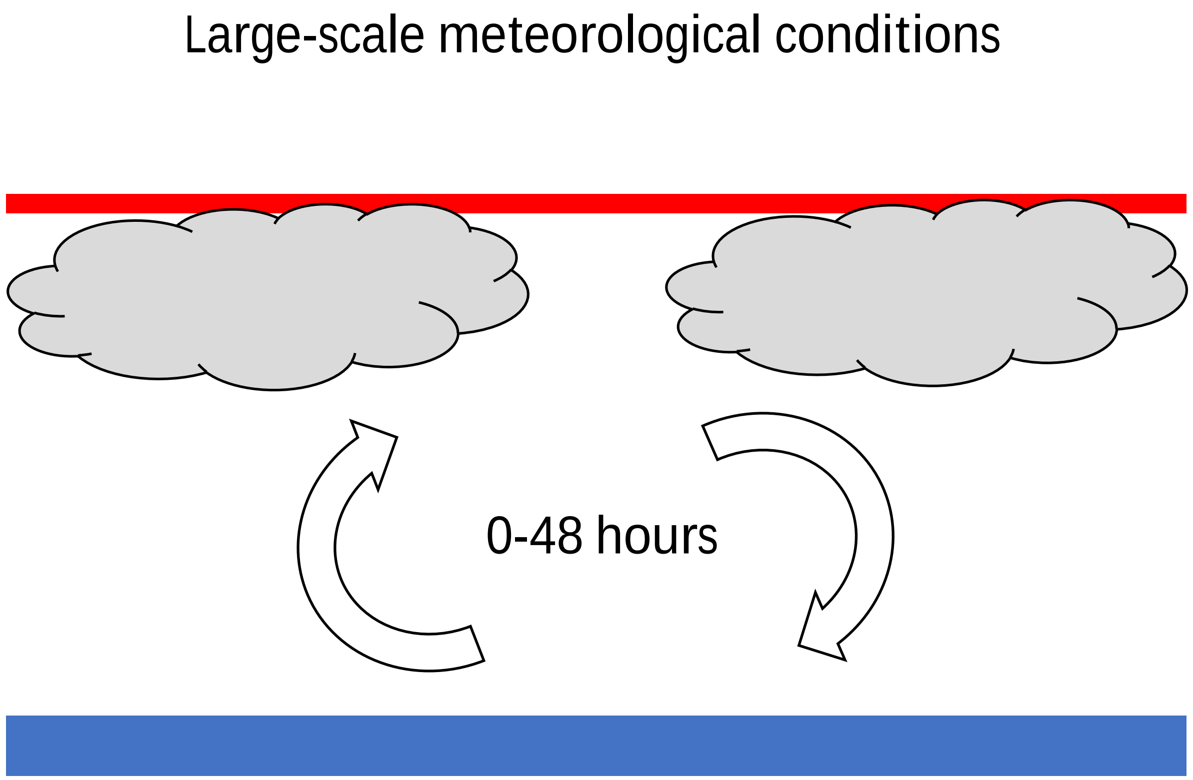
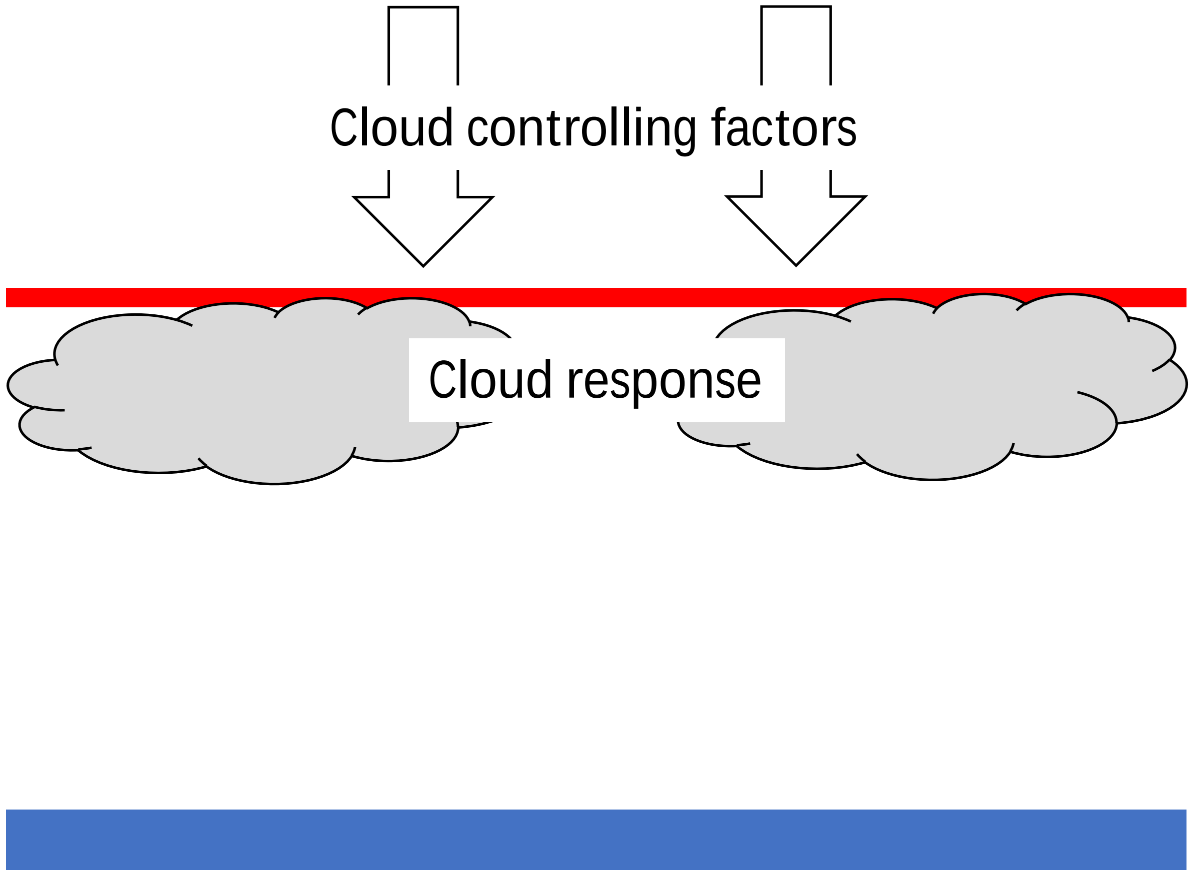
Conceptual Model

- Low-level clouds occur in the marine boundary layer
- Clouds respond on time scales of 0-48 hours to changes in large-scale meteorological conditions outside the boundary layer
- Clouds radiative forcing of the atmosphere and ocean outside the boundary layer occurs at time scales much longer than 2 days



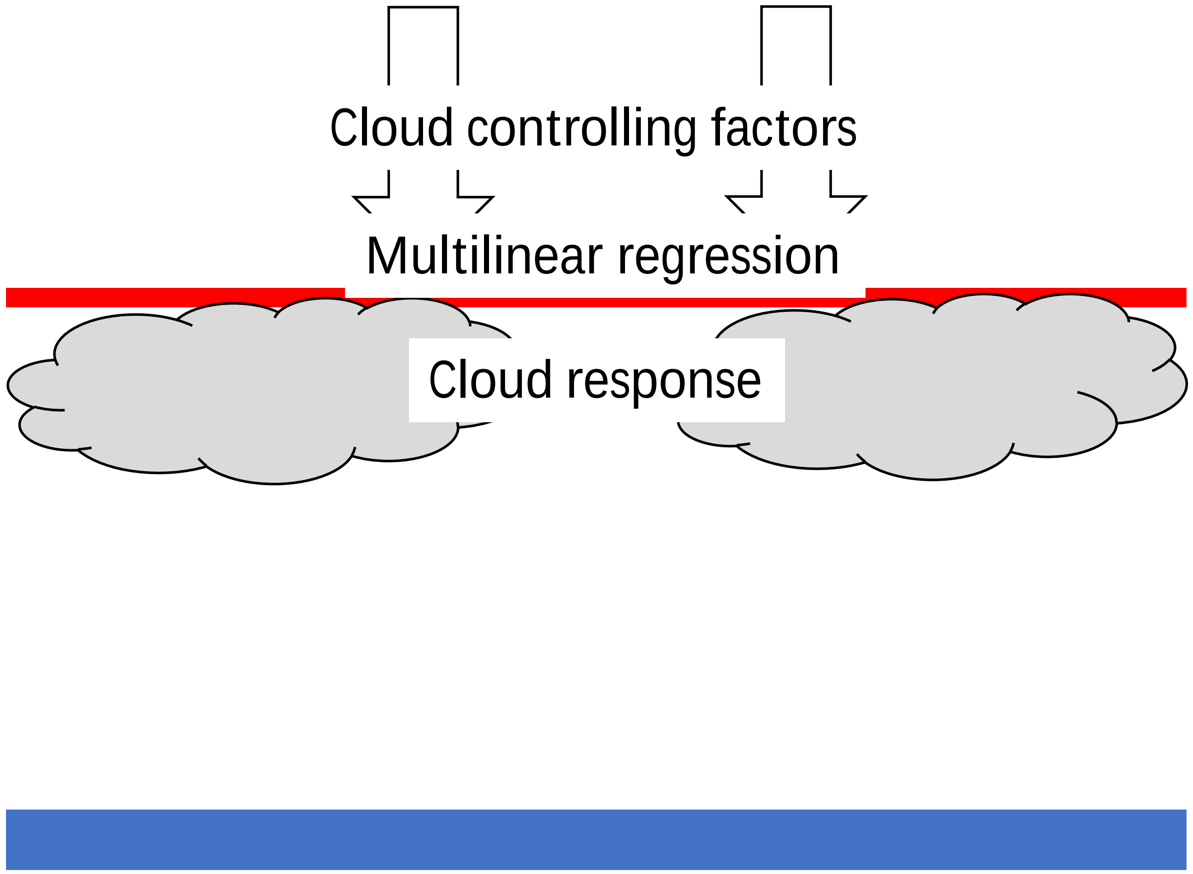
Conceptual Model

- When averaged over more than a few days, low-level clouds are in equilibrium with large-scale meteorological conditions
- Co-variability represents cloud response to changing large-scale meteorological conditions
- Large-scale meteorological conditions can be represented by several “cloud-controlling factors”



Conceptual Model

- Cloud response to large-scale meteorology can be empirically determined by multilinear regression on cloud controlling factors
- Multilinear regression provides “partial derivatives” to distinguish specific and independent influence of each controlling factor on cloud
- Important since controlling factors co-vary differently with each other on interannual and climate change time scales



Myers and Norris (2016) Method

Leading order Taylor expansion®

$$\Delta SW = \frac{\partial SW}{\partial SST}\Delta SST + \frac{\partial SW}{\partial EIS}\Delta EIS + \frac{\partial SW}{\partial RH_{700}}\Delta RH_{700}$$

$$+ \frac{\partial SW}{\partial SSTadv}\Delta SSTadv + \frac{\partial SW}{\partial \omega_{700}}\Delta \omega_{700}$$

SW = SW cloud radiative effect

SST = sea surface temperature

EIS = estimated inversion strength

RH_{700} = 700 hPa relative humidity

w_{700} = 700 hPa pressure vertical velocity

SSTadv = –V·ÑSST = advection over the SST gradient

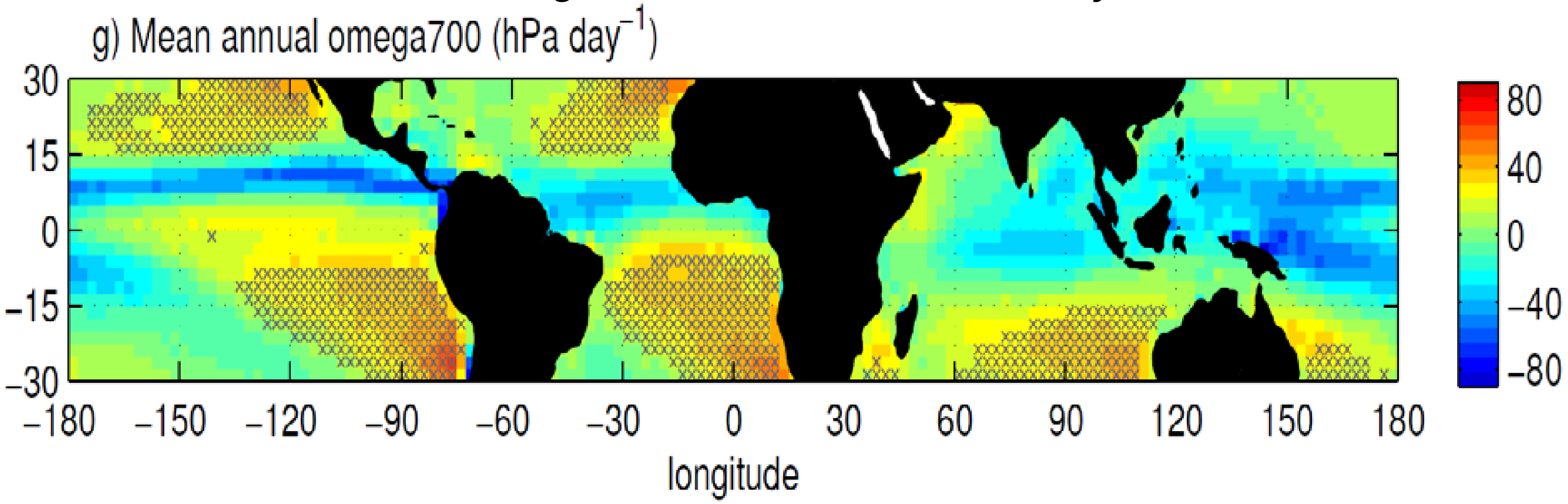
- SW cloud response coefficients (red) obtained from multilinear regression on satellite and reanalysis data
- Changes in controlling factors caused by global warming (blue) obtained from climate model projections for 4xCO2 warming

Myers and Norris (2016) Analysis Domain

Low-latitude ocean grid boxes where monthly mean subsidence always occurs

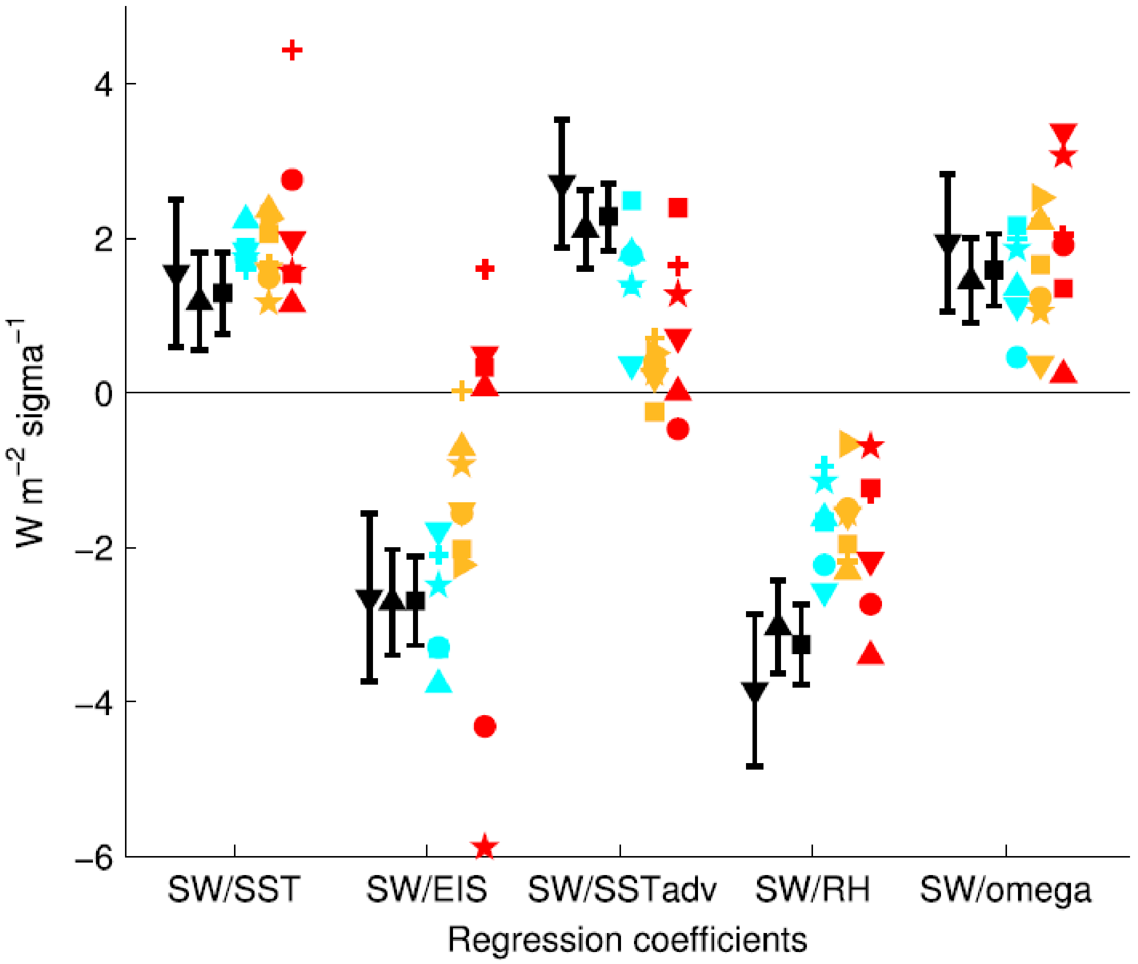
- Minimizes confounding effects of high clouds
- But more weighting on stratocumulus and less weighting on trade cumulus
- Neglects midlatitude low-level cloud

hatching indicates domain of analysis



SW Cloud Response to Controlling Factors

- Calculated via multilinear regression applied to monthly anomalies
- Climate models exhibit great disagreement with observations and each other



Plot from Myers and Norris (2016)

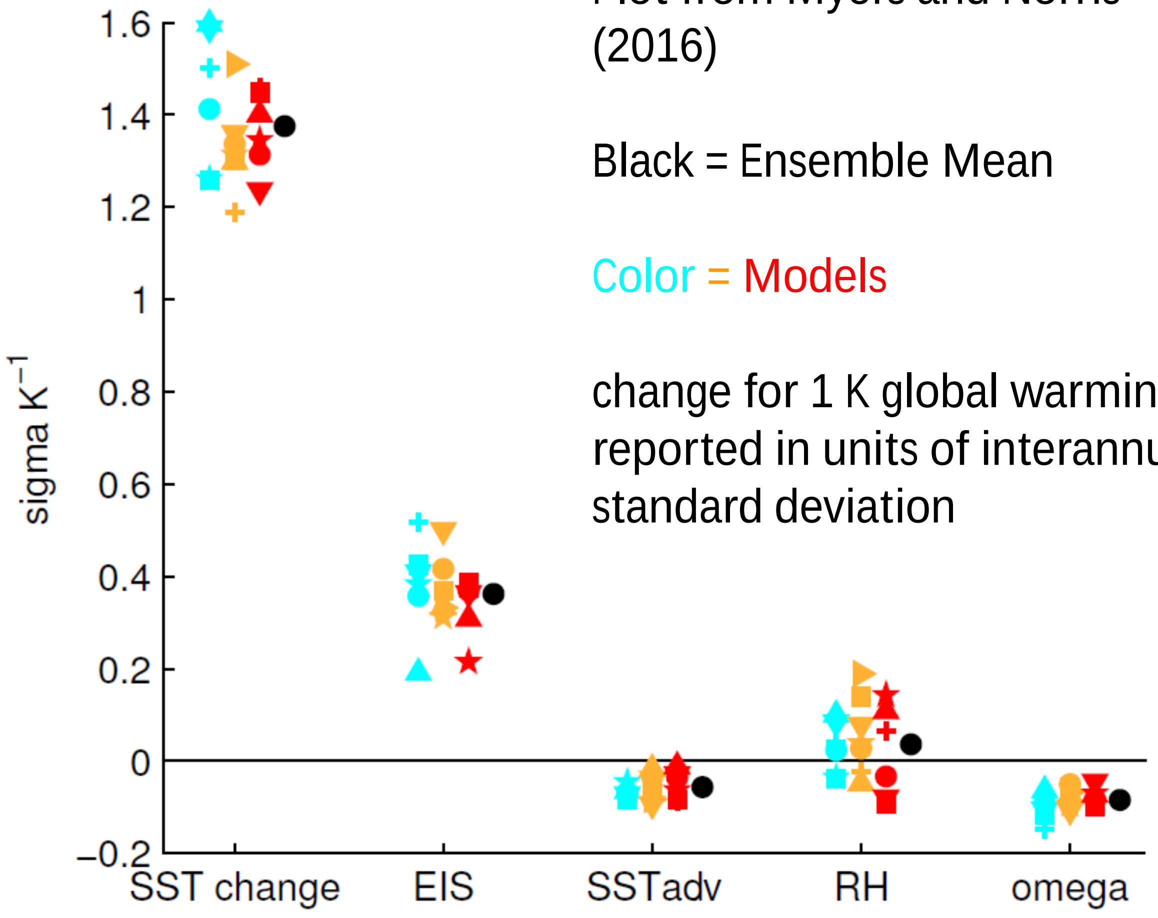
Black = coefficients from observed monthly anomalies

Color = coefficients from climate model monthly anomalies

Units: W m^{-2} per interannual standard deviation of meteorological parameter

Changes in Controlling Factors for 4xCO2

- Climate models agree about changes in meteorological controlling factors



Plot from Myers and Norris (2016)

Black = Ensemble Mean

Color = Models

change for 1 K global warming reported in units of interannual standard deviation

Estimated SW Cloud Feedback

- Actual SW cloud feedback produced by climate models for 4xCO2 spans a large range of positive and negative values

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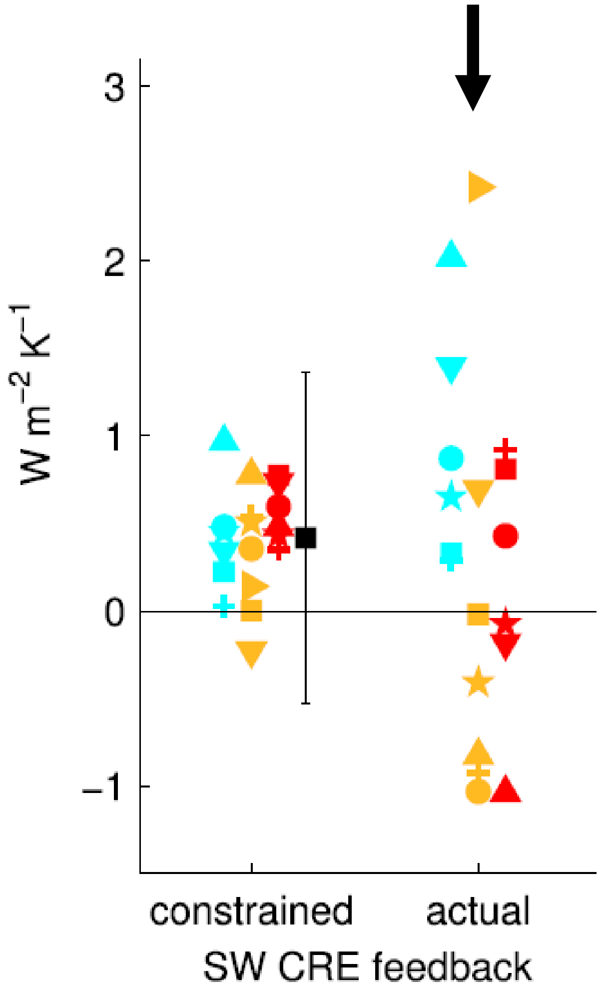

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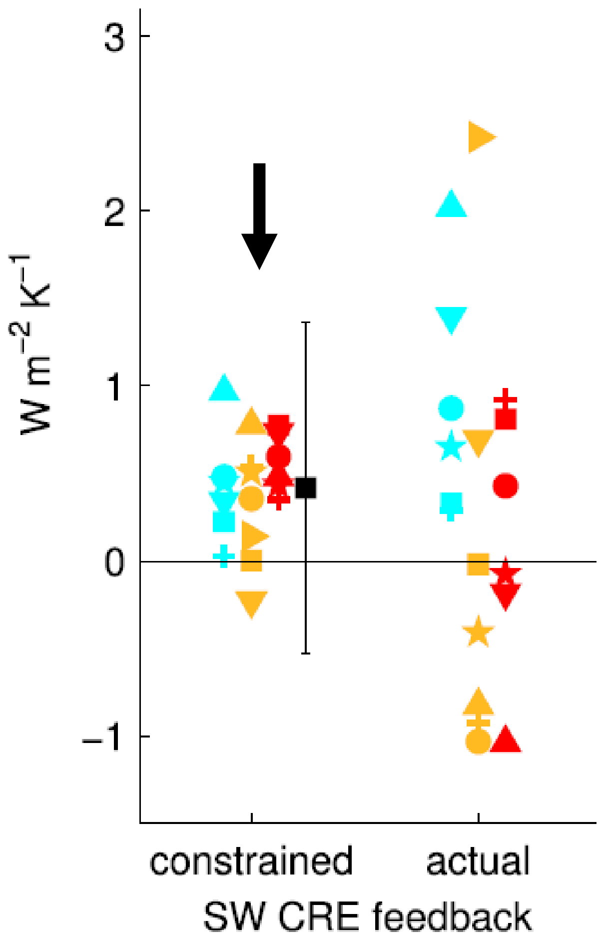
- Estimated SW cloud feedback has much smaller range of values
- About +0.4 W m^{-2} K^{-1} for low-level clouds over ocean

  (+0.25 W m^{-2} K^{-1} scaled globally)



Shortcomings of Myers and Norris (2016)

- Examined limited area of ocean
- Assumed no mid- and high-level clouds were present
- Attributed characteristics of (mostly) subtropical stratocumulus to all low-level clouds over ocean

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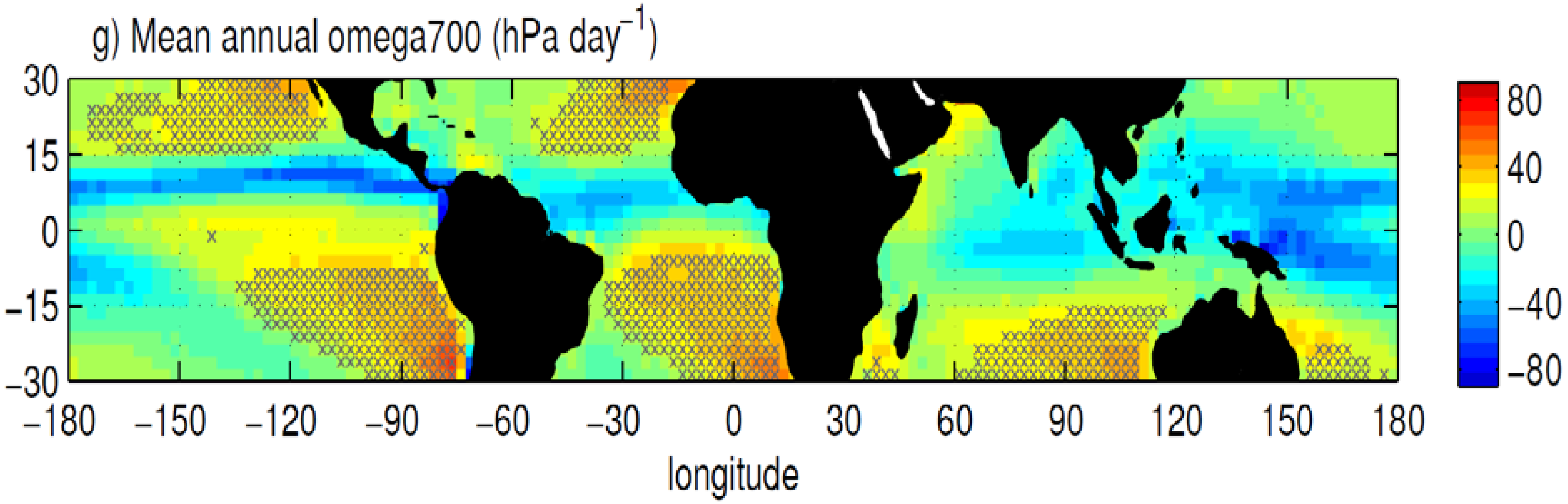

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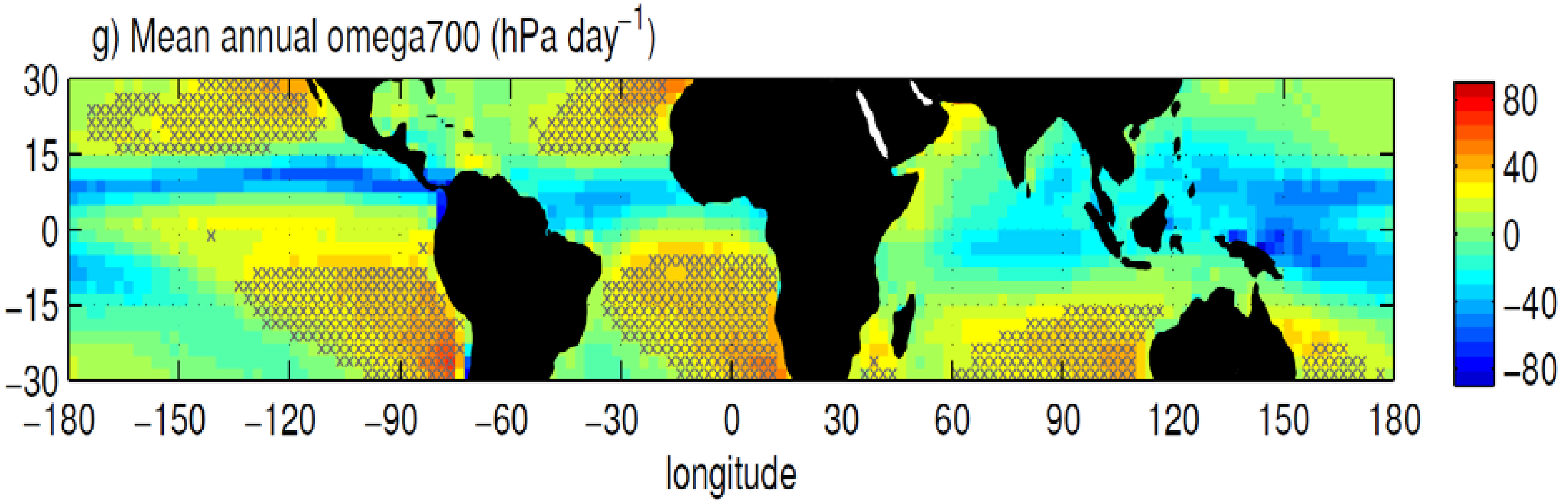
Need global ocean analysis that addresses mid- and high-level cloud presence



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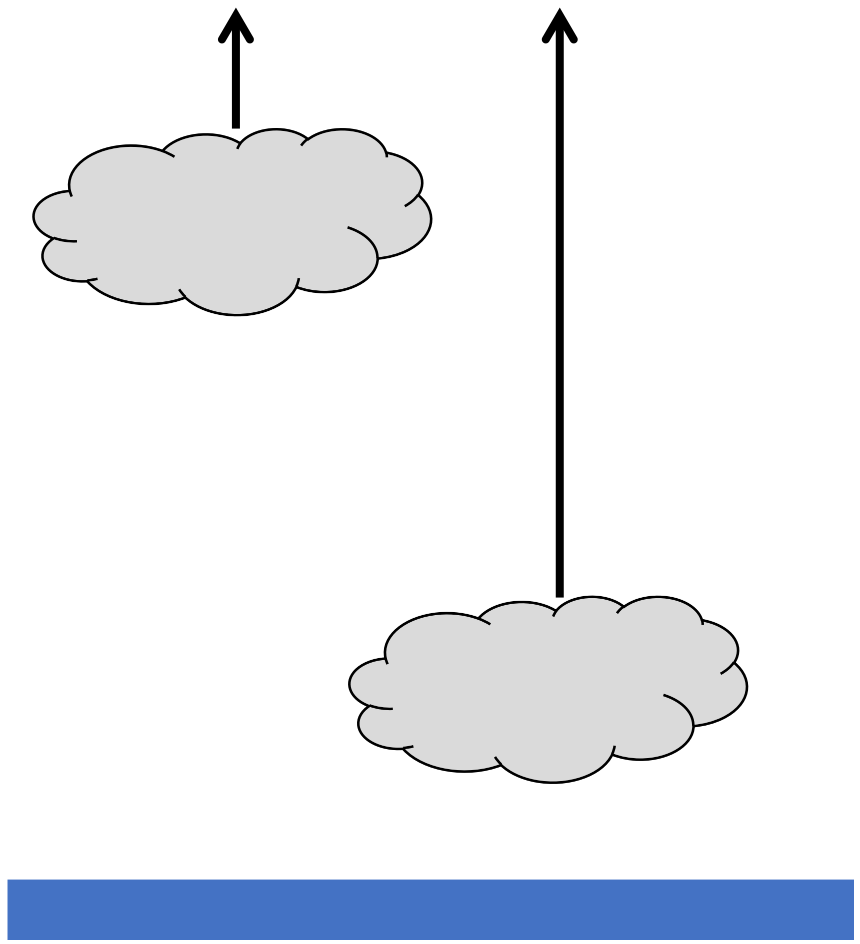
Challenges to Applying Method Globally

Challenge

Need to distinguish radiative effects of low-level clouds from radiative effects of higher clouds



Challenges to Applying Method Globally

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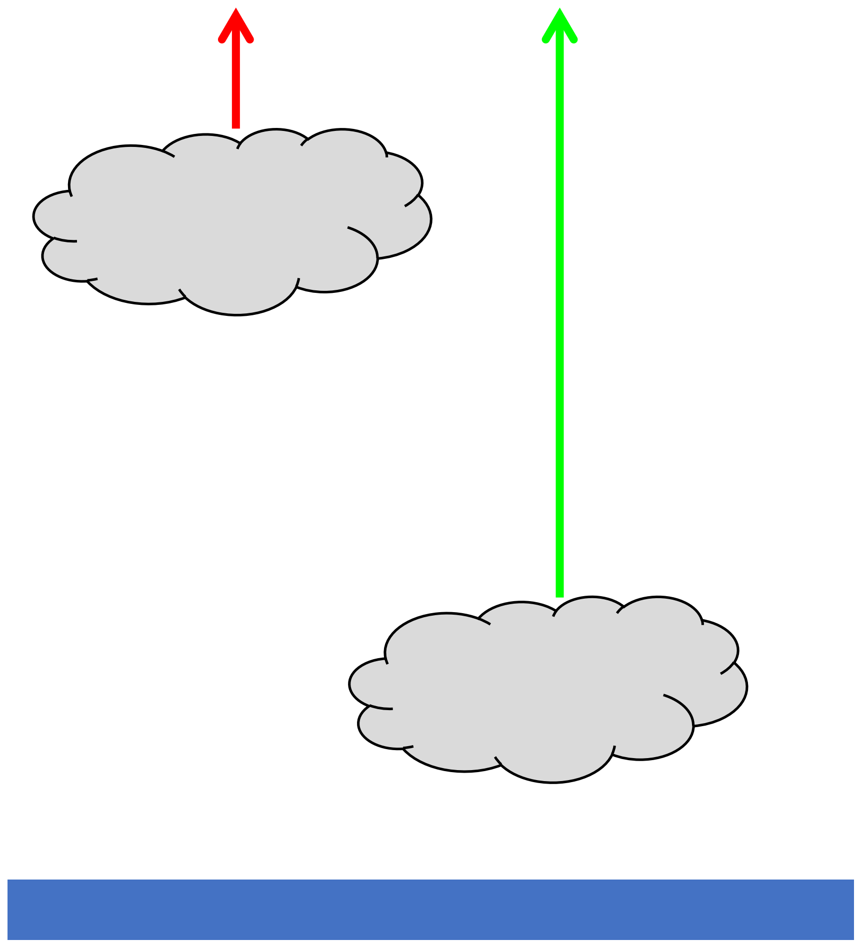
Solution

CERES Partial Radiative Perturbation (Thorsen et al. 2018)



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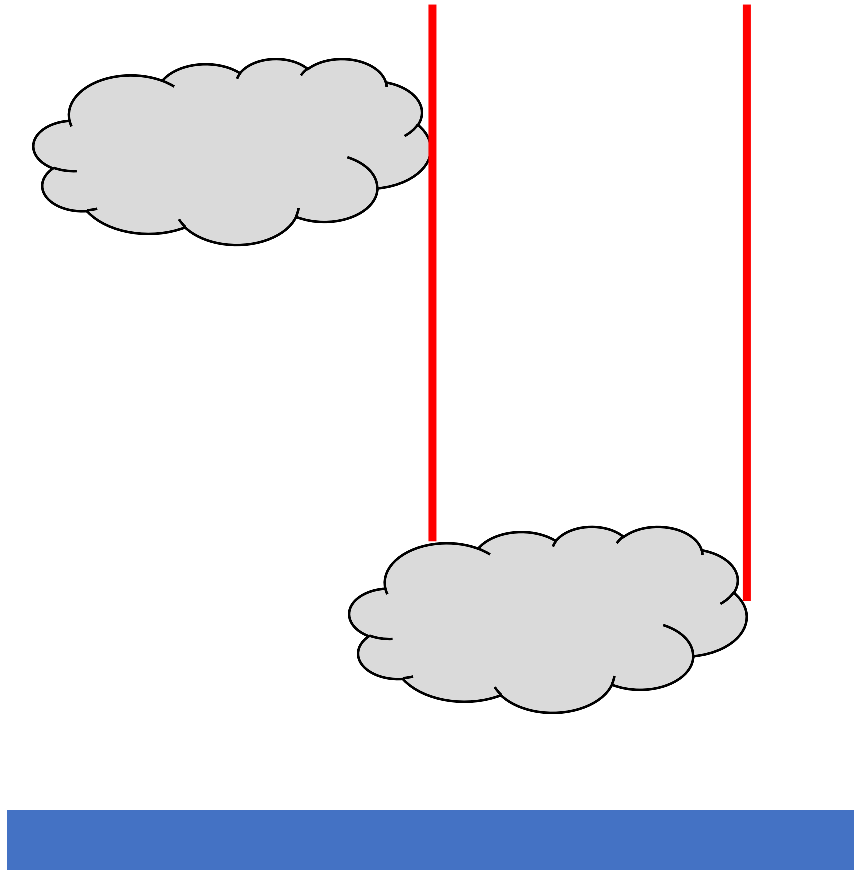

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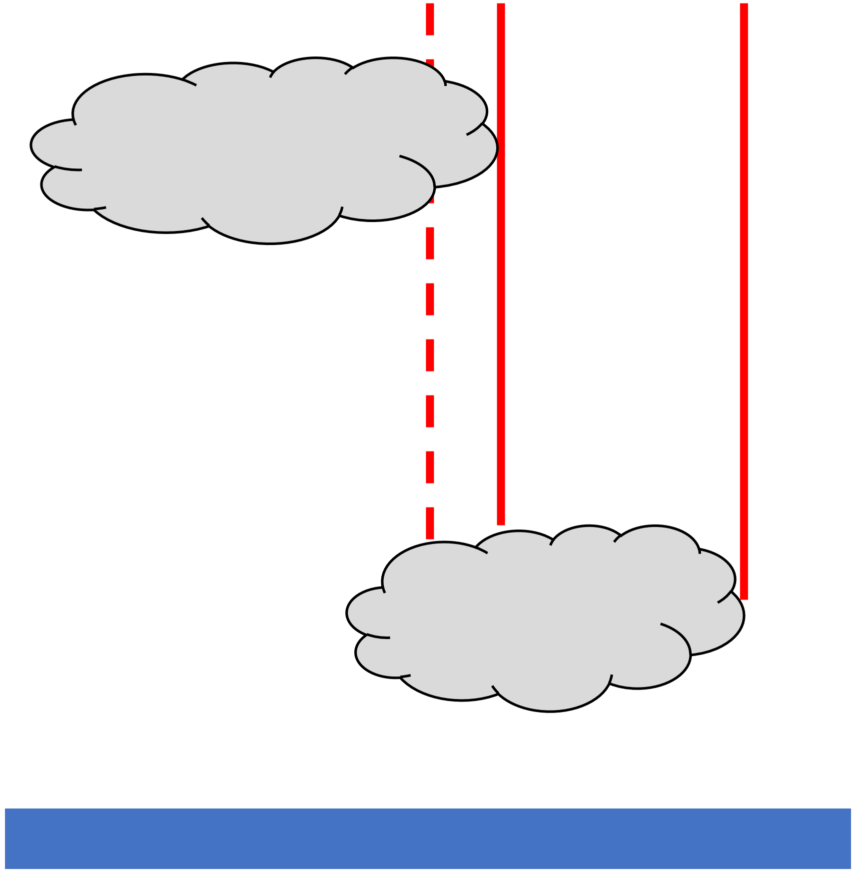

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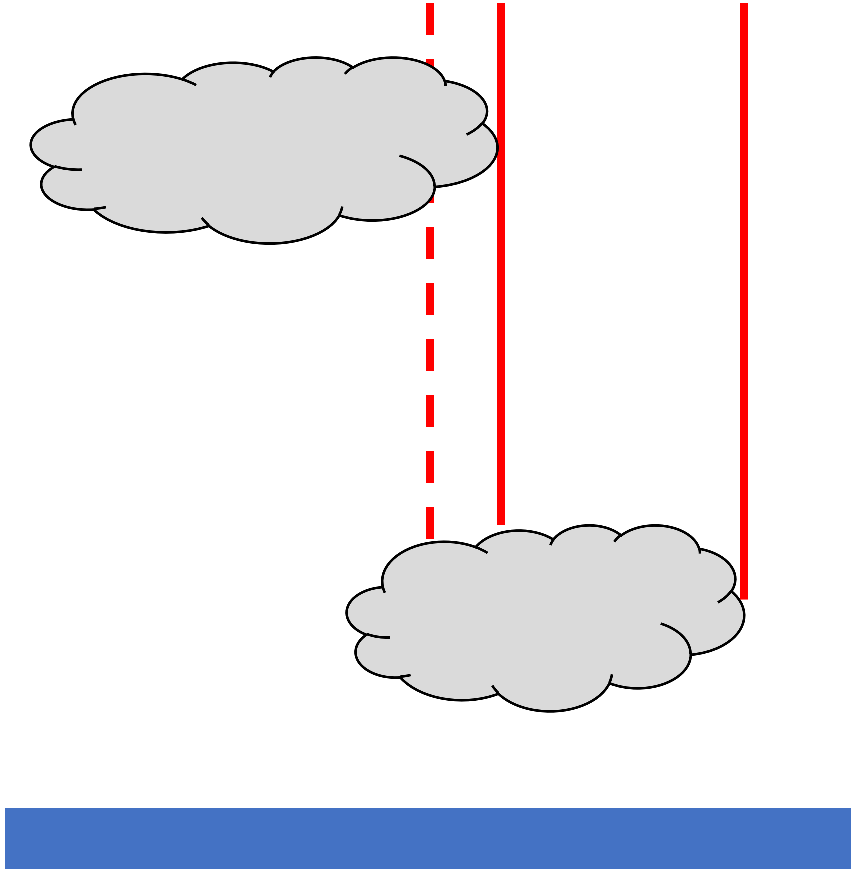
Two new approaches



Approach 1: Adjust for Obscuring Upper Cloud

L = fractional area of grid box covered by **low-level cloud** viewed by satellite

U = fractional area of grid box covered by **upper-level** (mid+high) **cloud**

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$$L_n = \frac{L}{1-U}$$

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Climatology (overbar) and anomaly (prime)

ignore 2nd-order terms (small)

$$\overline{L_n} = \frac{\bar{L}}{1 - \bar{U}} \qquad L'_n = \frac{L' + U'\overline{L_n}}{1 - \bar{U}}$$

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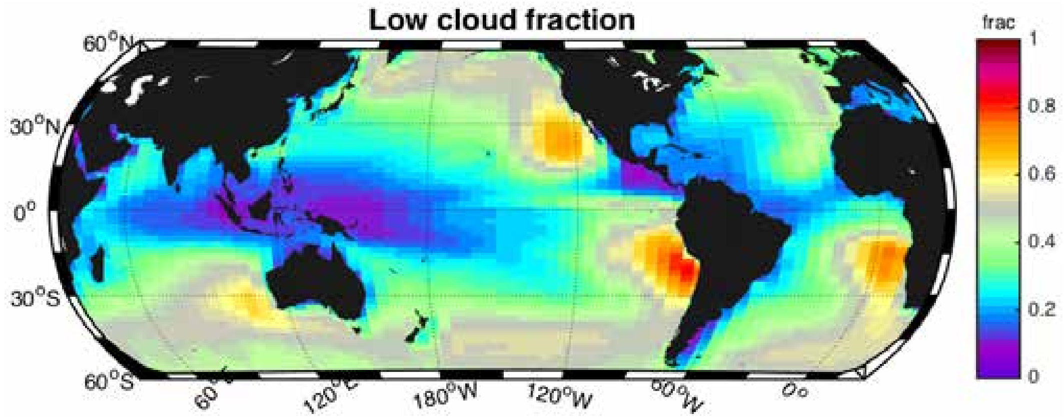
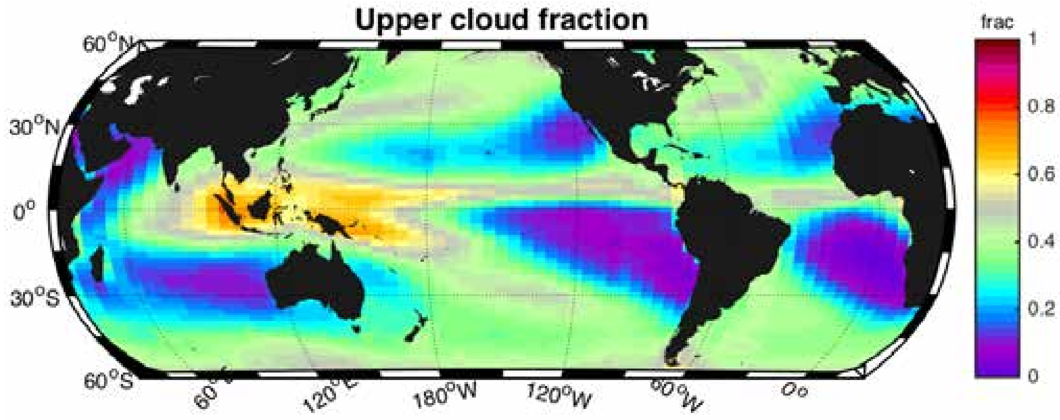
$$\overline{L_n} = \frac{\overline{L}}{1 - \overline{U}} \qquad L_n' = \frac{L' + U'\overline{L_n}}{1 - \overline{U}}$$

fraction of upper cloud anomaly that overlaps low cloud – add this to low cloud anomaly reported by satellite

Approach 1: Adjust for Obscuring Upper Cloud





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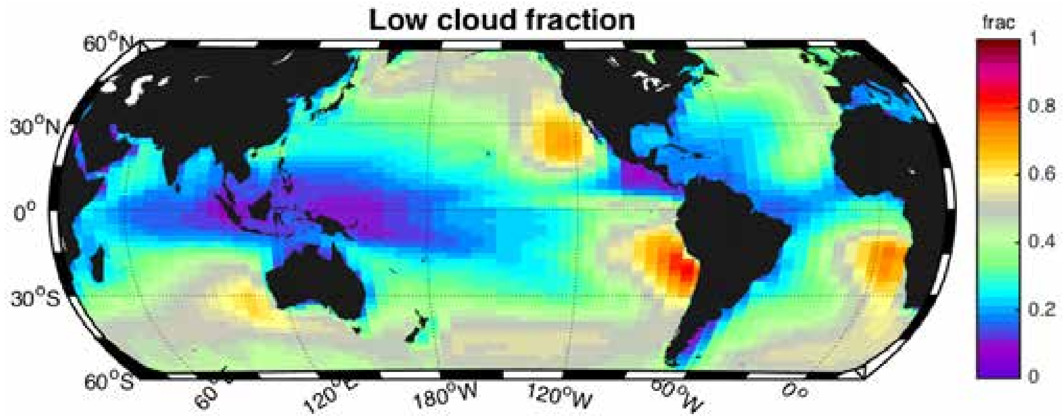

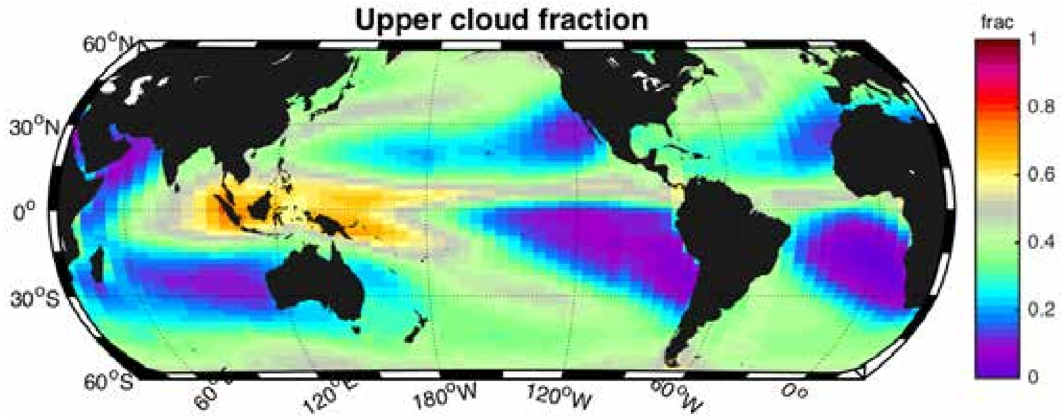

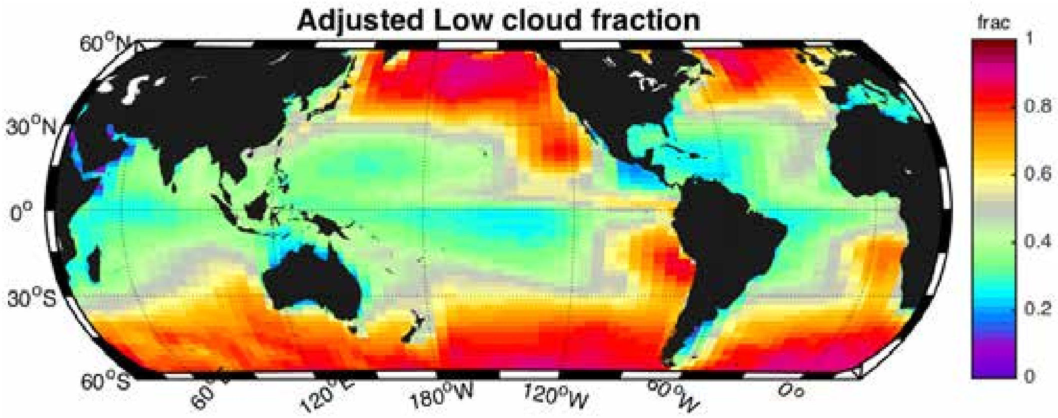

Approach 2: Use Upper Cloud as a Predictor

- Let ***U*** be a predictor of ***L*** along with the meteorological parameters in the calculation of multilinear regression coefficients

$$\Delta L = \frac{\partial L}{\partial SST}\Delta SST + \frac{\partial L}{\partial EIS}\Delta EIS + \frac{\partial L}{\partial RH_{700}}\Delta RH_{700}$$

$$+ \frac{\partial L}{\partial SSTadv}\Delta SSTadv + \frac{\partial L}{\partial \omega_{700}}\Delta \omega_{700} + \frac{\partial L}{\partial W_s}\Delta W_s$$

$$+ \frac{\partial L}{\partial U}\Delta U$$

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- Let ***U*** be a predictor of ***L*** along with the meteorological parameters in the calculation of multilinear regression coefficients
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- Meteorological coefficients will then represent partial derivative response with upper cloud obscuration held constant
- *Do not include **U** as a predictor of low-level cloud change for 4xCO2 warming*

$$\Delta L = \frac{\partial L}{\partial SST}\Delta SST + \frac{\partial L}{\partial EIS}\Delta EIS + \frac{\partial L}{\partial RH_{700}}\Delta RH_{700}$$

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Multilinear Regression Coefficients

<u>Approach 1</u>

- Non-obscured low-level cloud fraction anomalies ***L_n′***
- Effects of upper-level cloud removed prior to regression

$$\Delta L_n = \frac{\partial L_n}{\partial SST}\Delta SST + \frac{\partial L_n}{\partial EIS}\Delta EIS + \frac{\partial L_n}{\partial RH_{700}}\Delta RH_{700}$$

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Approach 2

- Satellite-viewed low-level cloud fraction anomalies L'
- Effects of upper-level cloud removed using upper cloud as a predictor in regression

$$\Delta L = \frac{\partial L}{\partial SST}\Delta SST + \frac{\partial L}{\partial EIS}\Delta EIS + \frac{\partial L}{\partial RH_{700}}\Delta RH_{700} + \frac{\partial L}{\partial SSTadv}\Delta SSTadv + \frac{\partial L}{\partial \omega_{700}}\Delta\omega_{700} + \frac{\partial L}{\partial W_s}\Delta W_s + \frac{\partial L}{\partial U}\Delta U$$

Multilinear Regression Coefficients

- Will have greater confidence if the two approaches yield similar coefficients

$$\Delta L_n = \frac{\partial L_n}{\partial SST}\Delta SST + \frac{\partial L_n}{\partial EIS}\Delta EIS + \frac{\partial L_n}{\partial RH_{700}}\Delta RH_{700} + \frac{\partial L_n}{\partial SSTadv}\Delta SSTadv + \frac{\partial L_n}{\partial \omega_{700}}\Delta\omega_{700} + \frac{\partial L_n}{\partial W_s}\Delta W_s$$

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Multilinear Regression Coefficients

- Will have greater confidence if the two approaches yield similar coefficients
- ***L***

$$\frac{\partial L}{\partial EIS} \leftrightarrow (1-\bar{U})\frac{\partial L_n}{\partial EIS}$$

$$\Delta L_n = \frac{\partial L_n}{\partial SST}\Delta SST + \frac{\partial L_n}{\partial EIS}\Delta EIS + \frac{\partial L_n}{\partial RH_{700}}\Delta RH_{700} + \frac{\partial L_n}{\partial SSTadv}\Delta SSTadv + \frac{\partial L_n}{\partial \omega_{700}}\Delta\omega_{700} + \frac{\partial L_n}{\partial W_s}\Delta W_s$$

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Multilinear Regression Coefficients

- Will also have greater confidence if observed coefficients are consistent with expected physical processes

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Multilinear Regression Coefficients

- Will also have greater confidence if observed coefficients are consistent with expected physical processes
- Surface wind speed is added as a predictor to distinguish effects of wind speed from SST gradient in SSTadv.

$$\Delta L_n = \frac{\partial L_n}{\partial SST}\Delta SST + \frac{\partial L_n}{\partial EIS}\Delta EIS + \frac{\partial L_n}{\partial RH_{700}}\Delta RH_{700}$$

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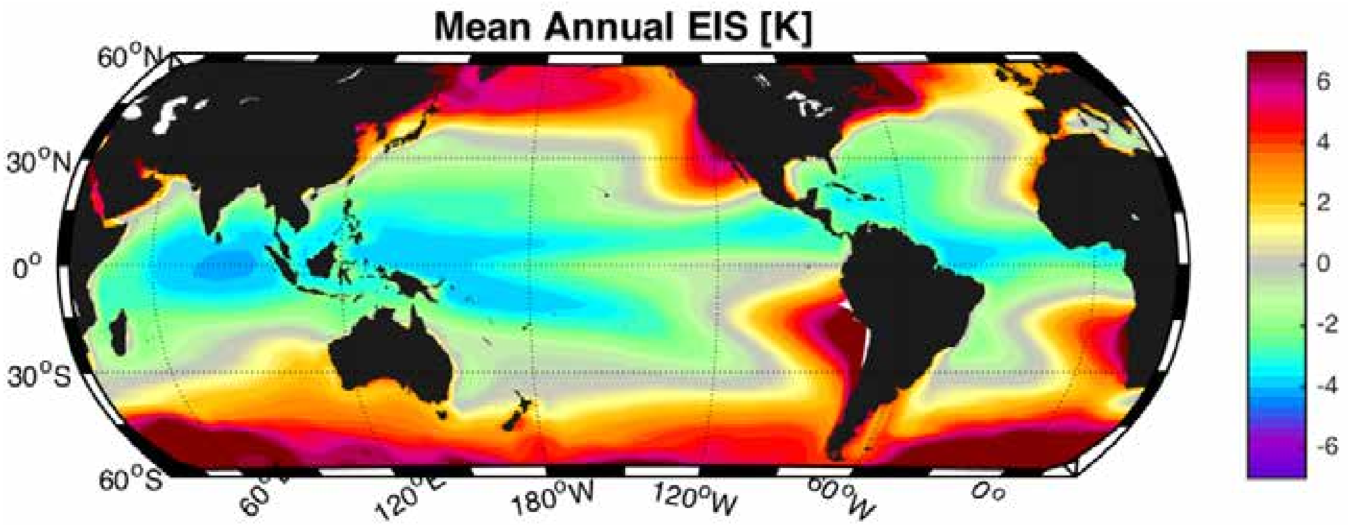
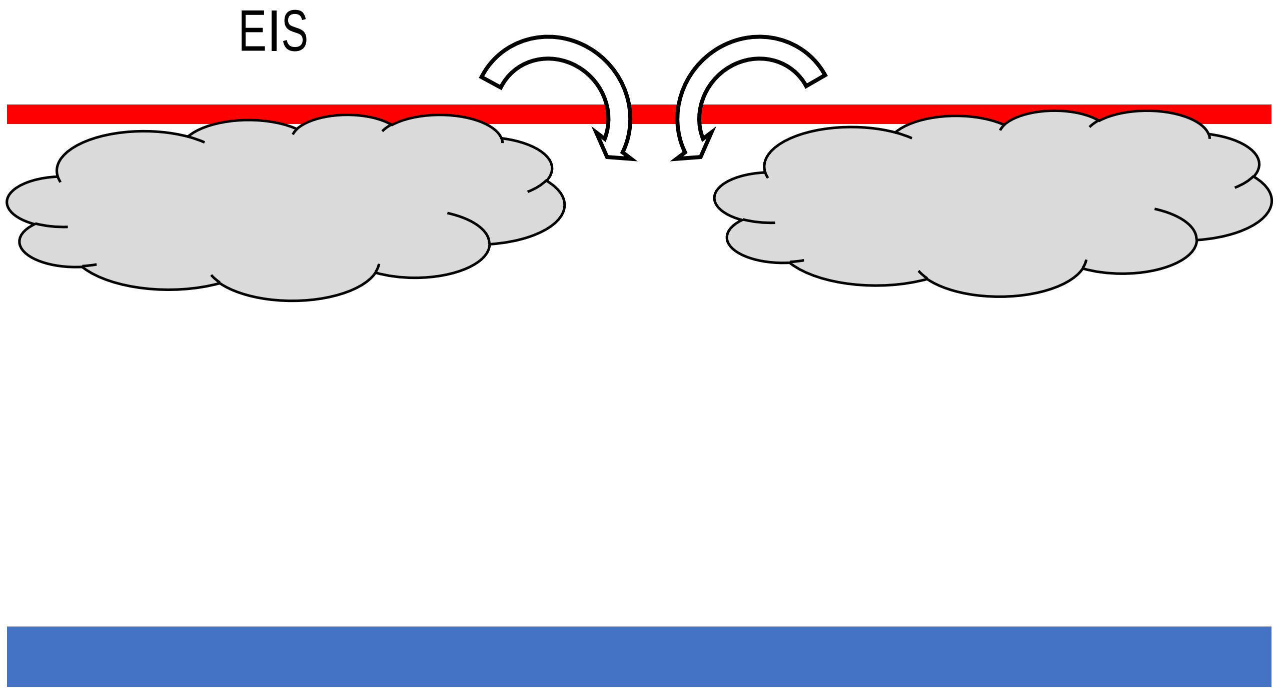
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)



Expected Low Cloud Response to EIS

Entrainment of air through the capping inversion dries and warms the boundary layer

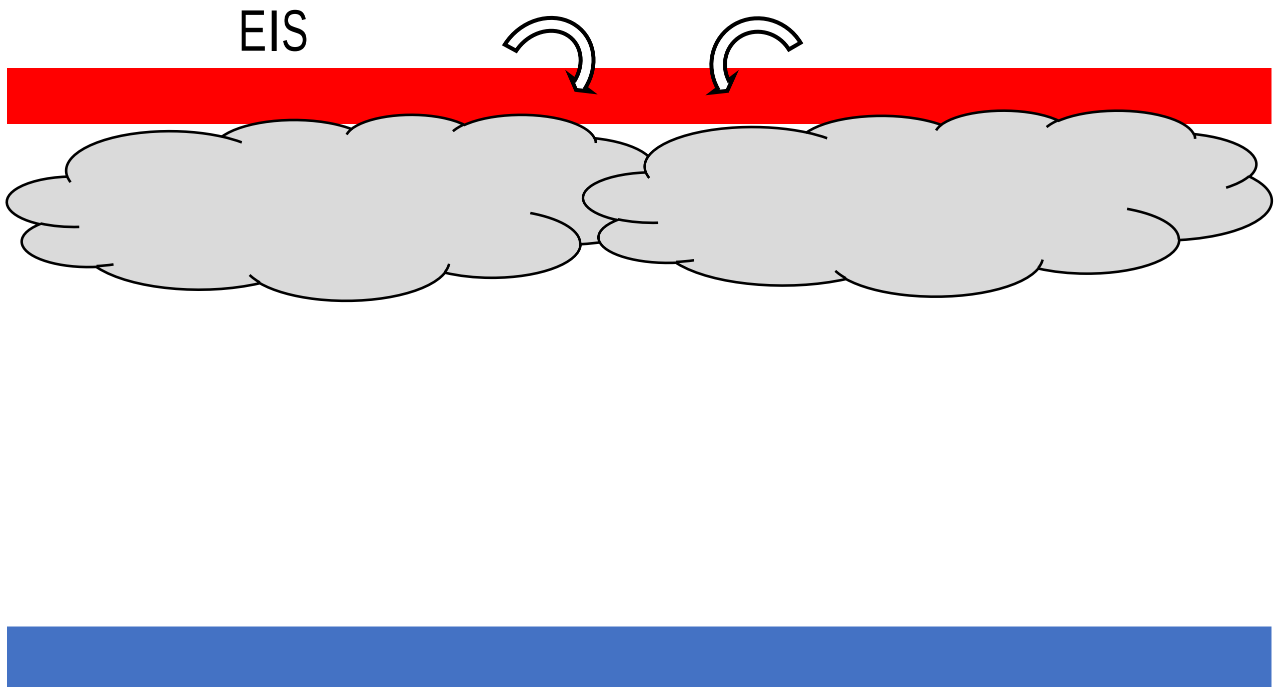


Expected Low Cloud Response to EIS

Entrainment of air through the capping inversion dries and warms the boundary layer

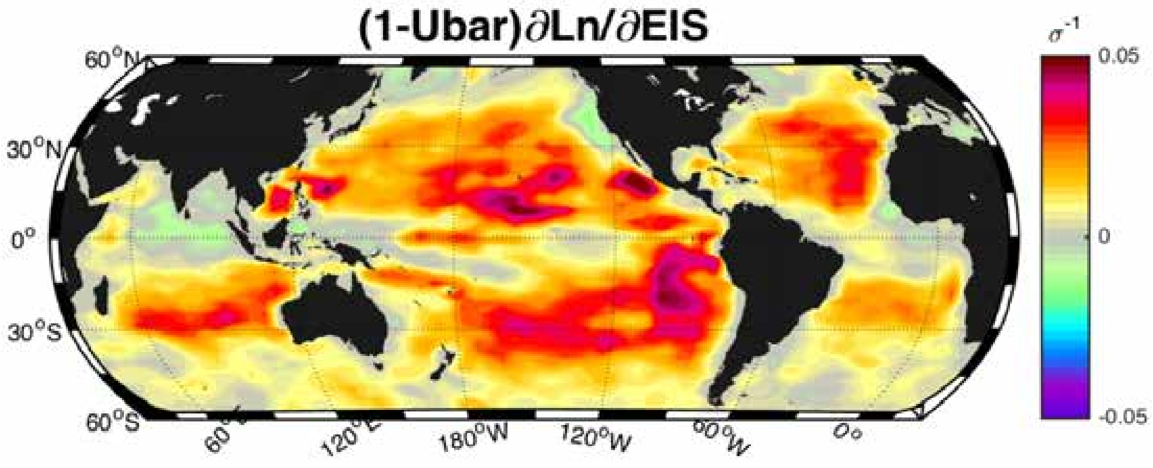
<u>*If the inversion strengthens*</u>

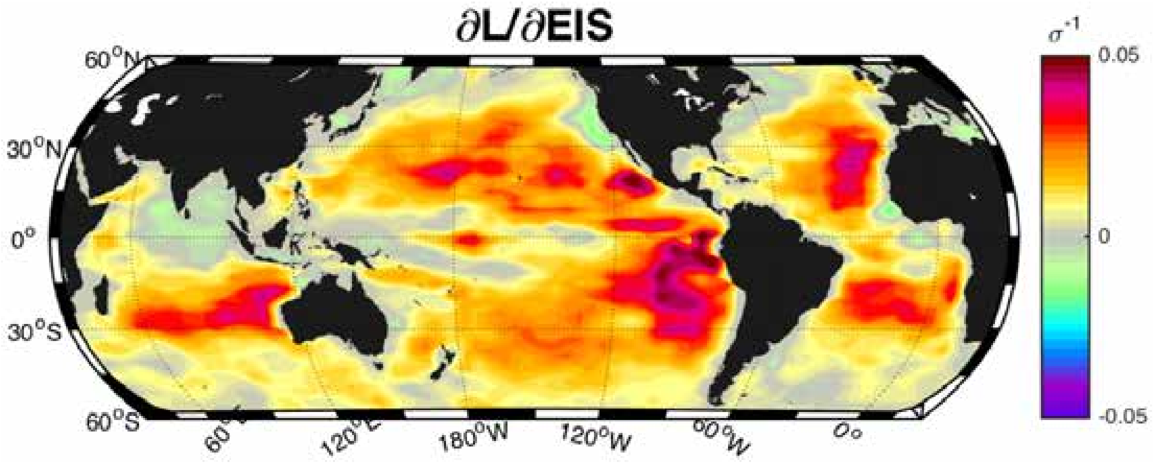
- Entrainment decreases
- Low-level cloudiness increases
- Less SW is absorbed by climate system



Observed Low Cloud Response to EIS

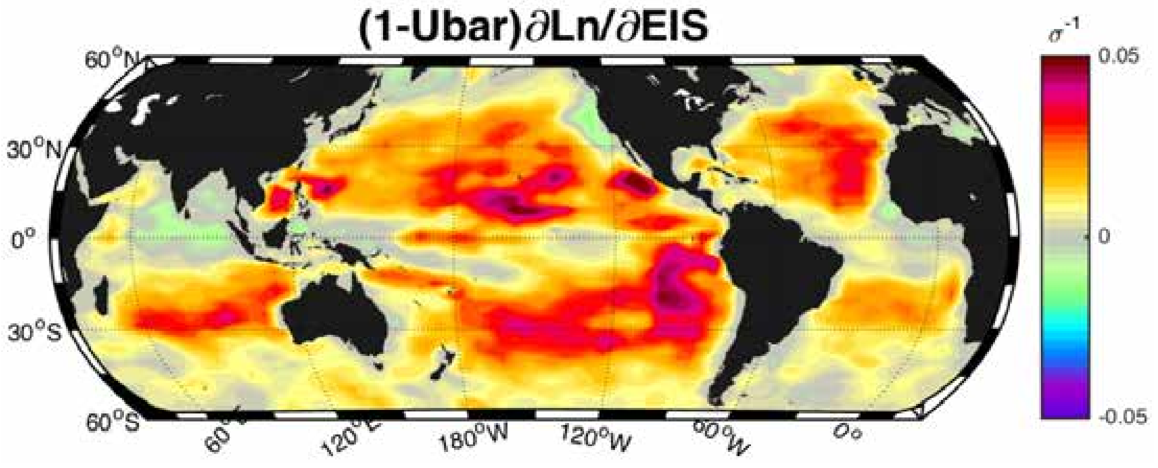
- Increased low-level cloudiness for stronger EIS almost everywhere
- Slightly larger response in eastern subtropical ocean regions

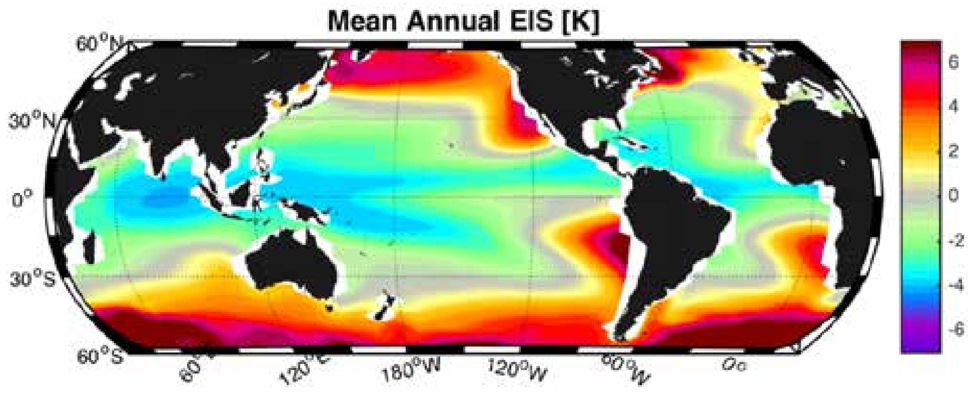


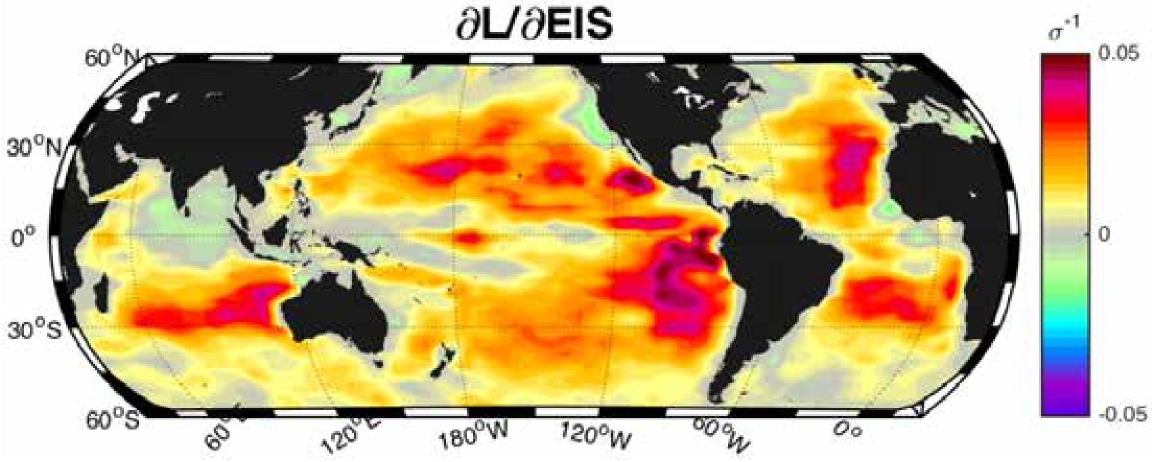


Observed Low Cloud Response to EIS

- Increased low-level cloudiness for stronger EIS almost everywhere
- Slightly larger response in eastern subtropical ocean regions
- Weak negative or zero response in deep convective regions where EIS is weakest and capping inversion is absent

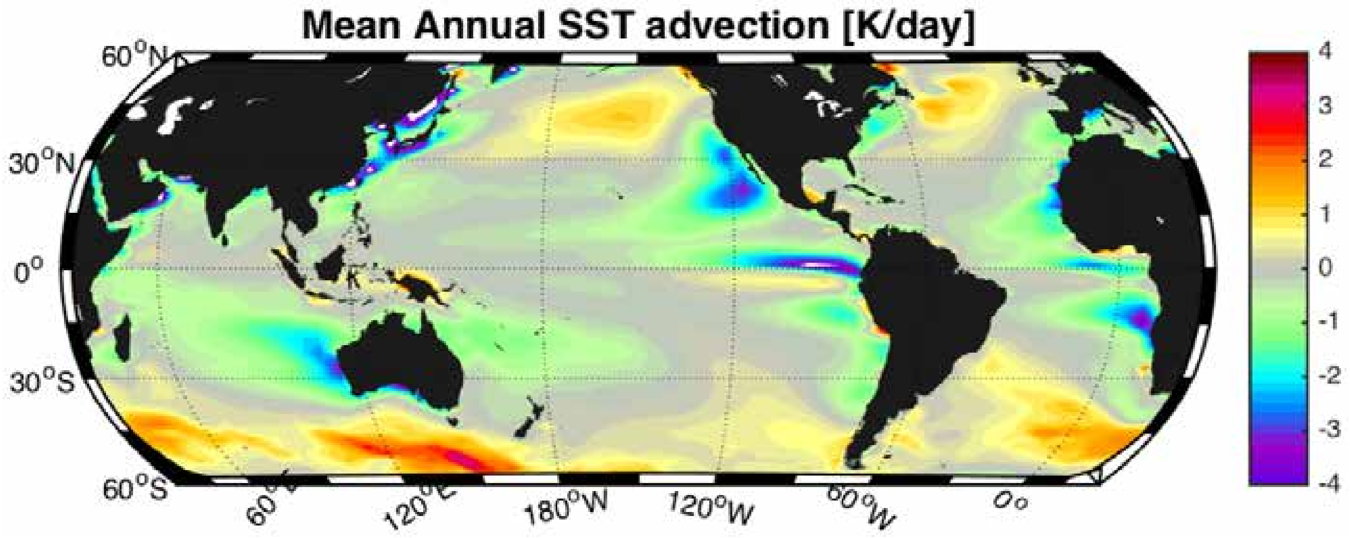






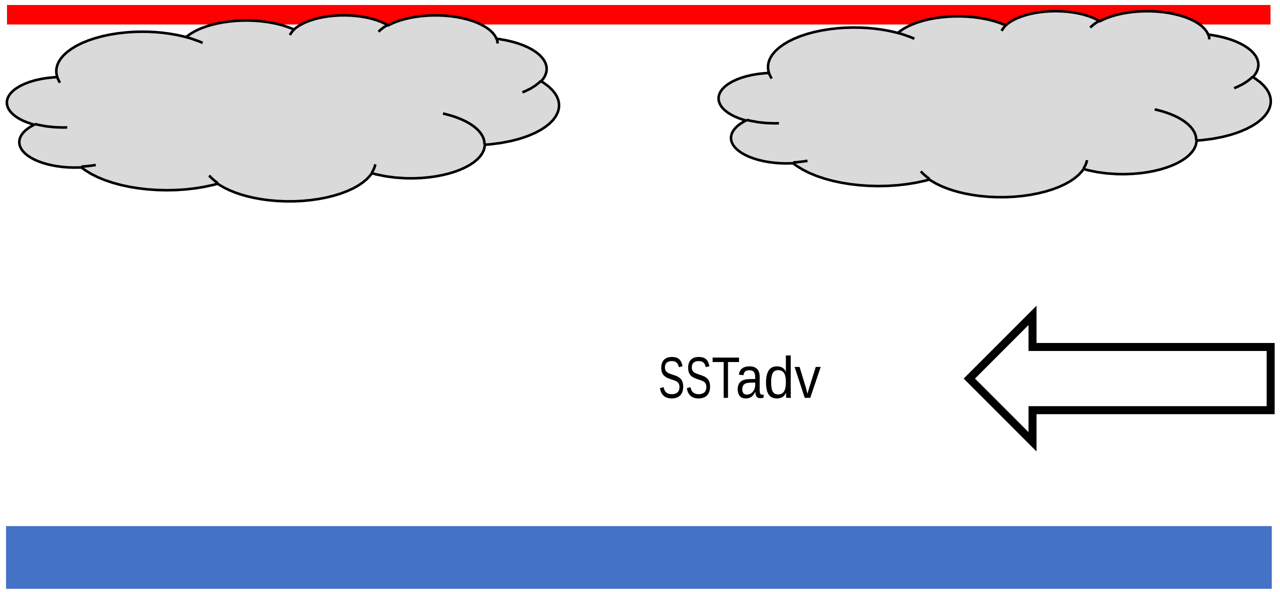
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)
- Advection over SST gradient (SSTadv)



Expected Low Cloud Response to SSTadv

Near-surface stratification varies according to the advection of the boundary layer over a SST gradient

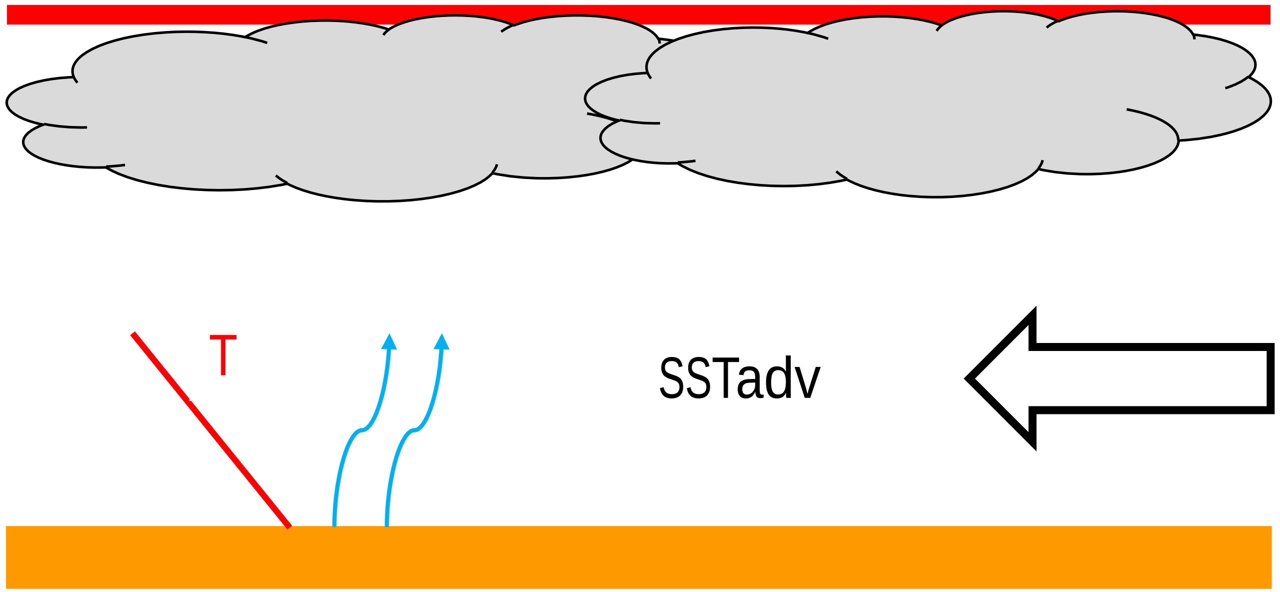


Expected Low Cloud Response to SSTadv

Near-surface stratification varies according to the advection of the boundary layer over a SST gradient

__If cold advection strengthens__

- Cooler air over warmer water
- Near-surface instability increases
- More upward mixing of moisture
- Low-level cloudiness increases
- Less SW is absorbed by climate system

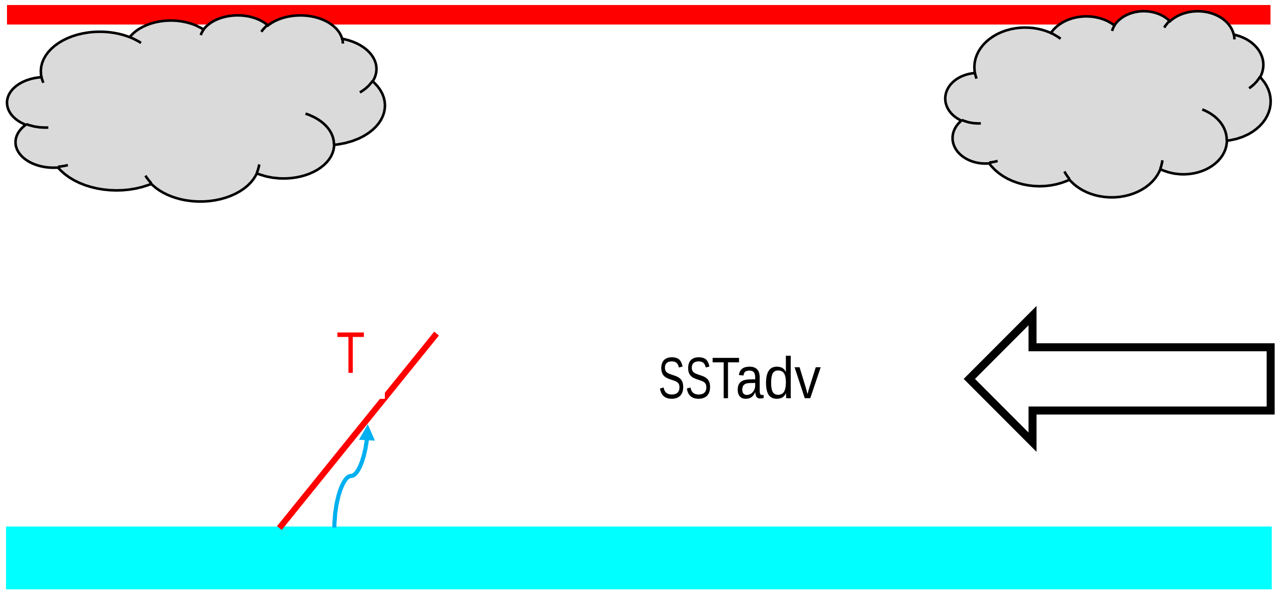


Expected Low Cloud Response to SSTadv

Near-surface stratification varies according to the advection of the boundary layer over a SST gradient

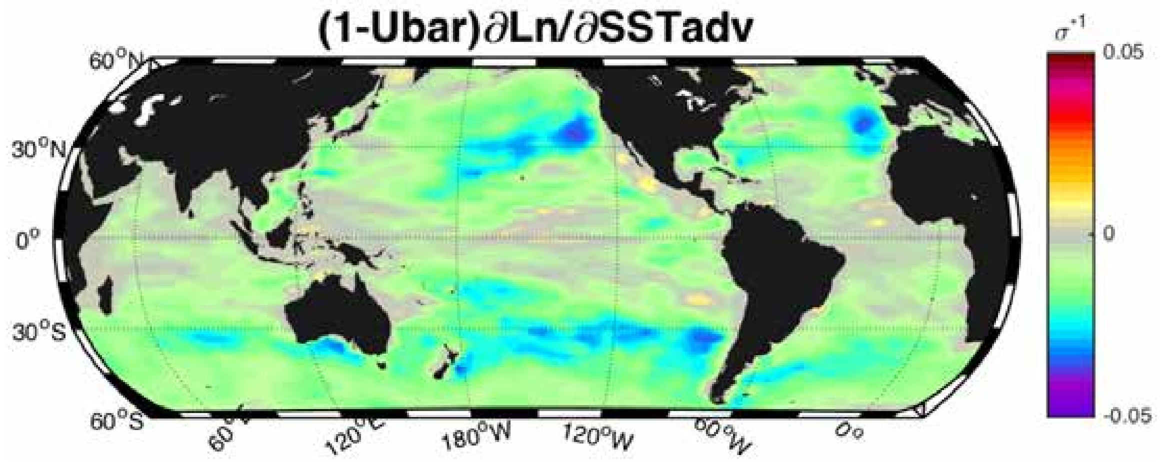
If warm advection strengthens

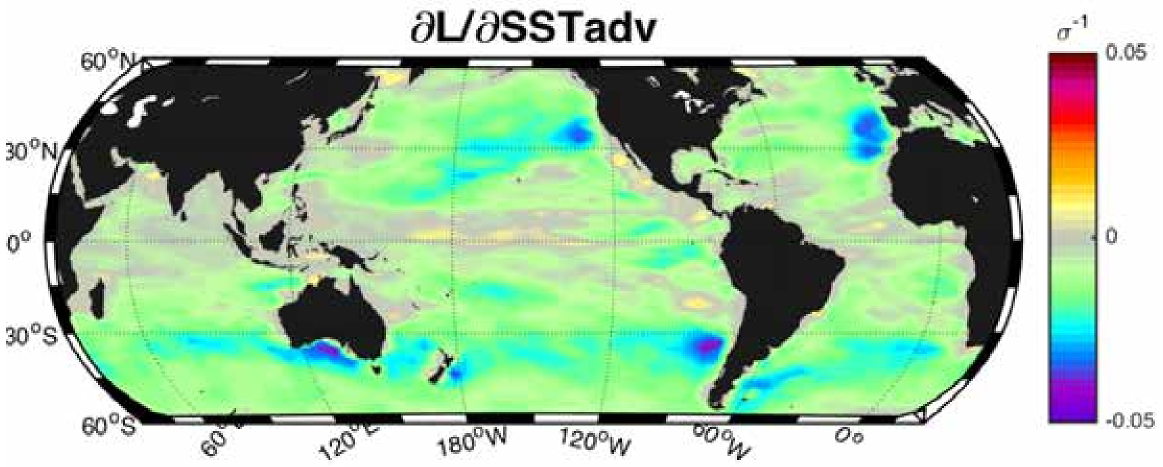
- Warmer air over cooler water
- Near-surface stability increases
- Less upward mixing of moisture
- Low-level cloudiness decreases
- More SW is absorbed by climate system



Observed Low Cloud Response to SSTadv

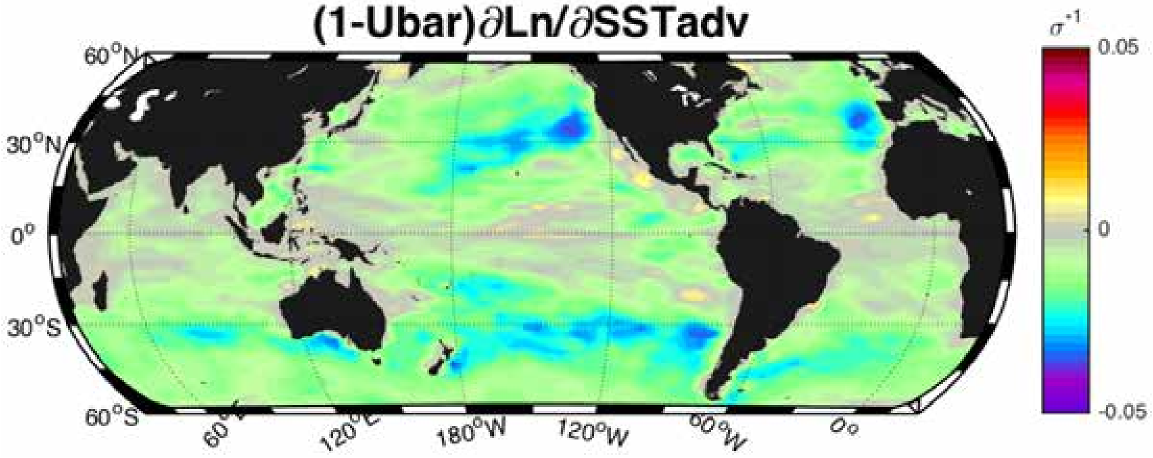
- Increased low-level cloudiness for stronger (negative) cold advection almost everywhere
- Weak positive or zero response at lowest latitudes

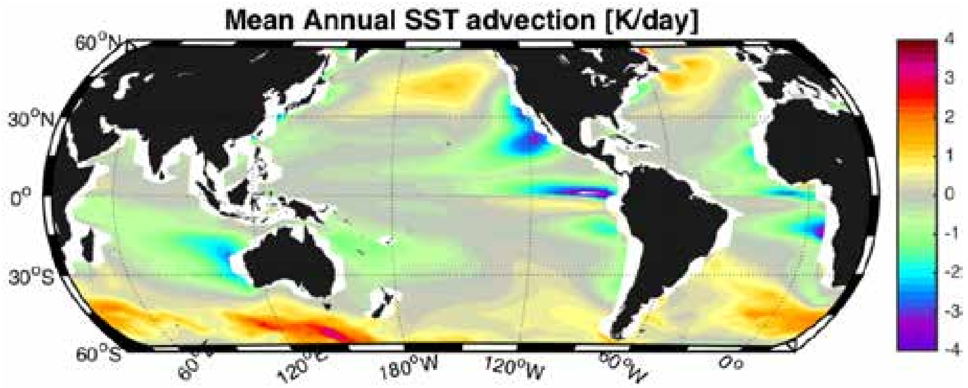


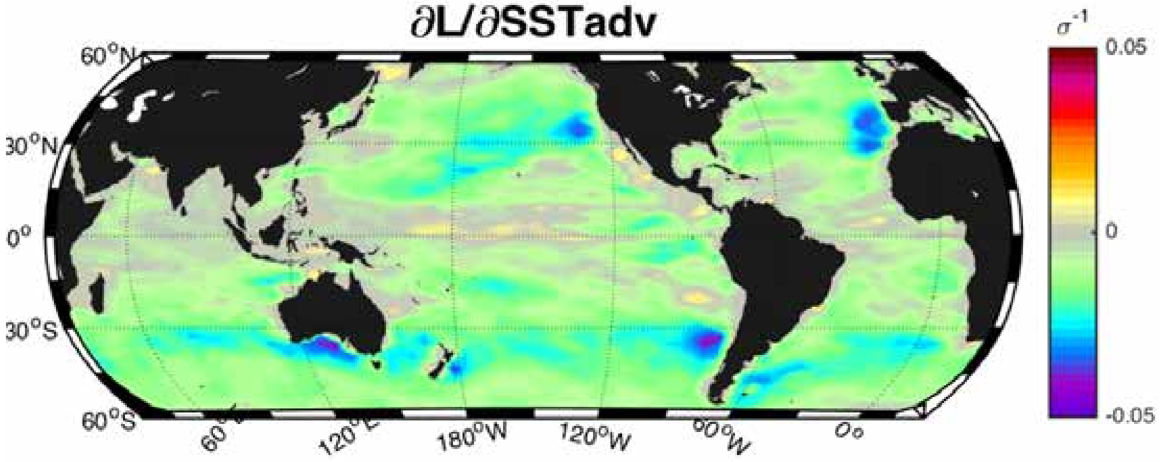


Observed Low Cloud Response to SSTadv

- Increased low-level cloudiness for stronger (negative) cold advection almost everywhere
- Weak positive or zero response at lowest latitudes
- Larger response along subtropical-midlatitude SSTadv transition zone

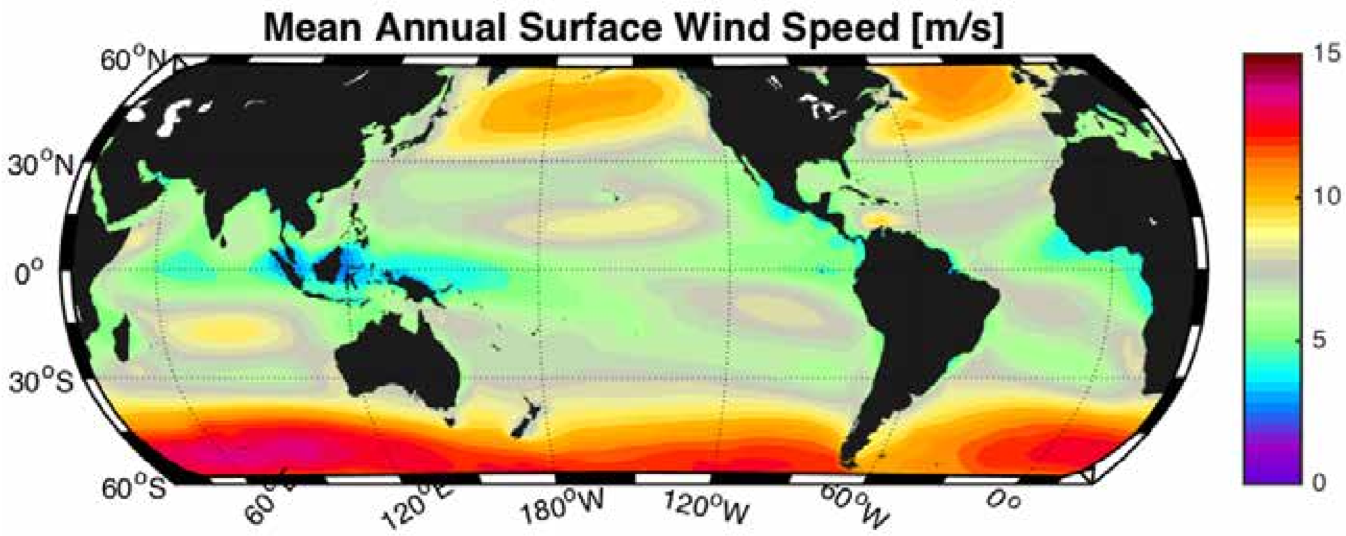






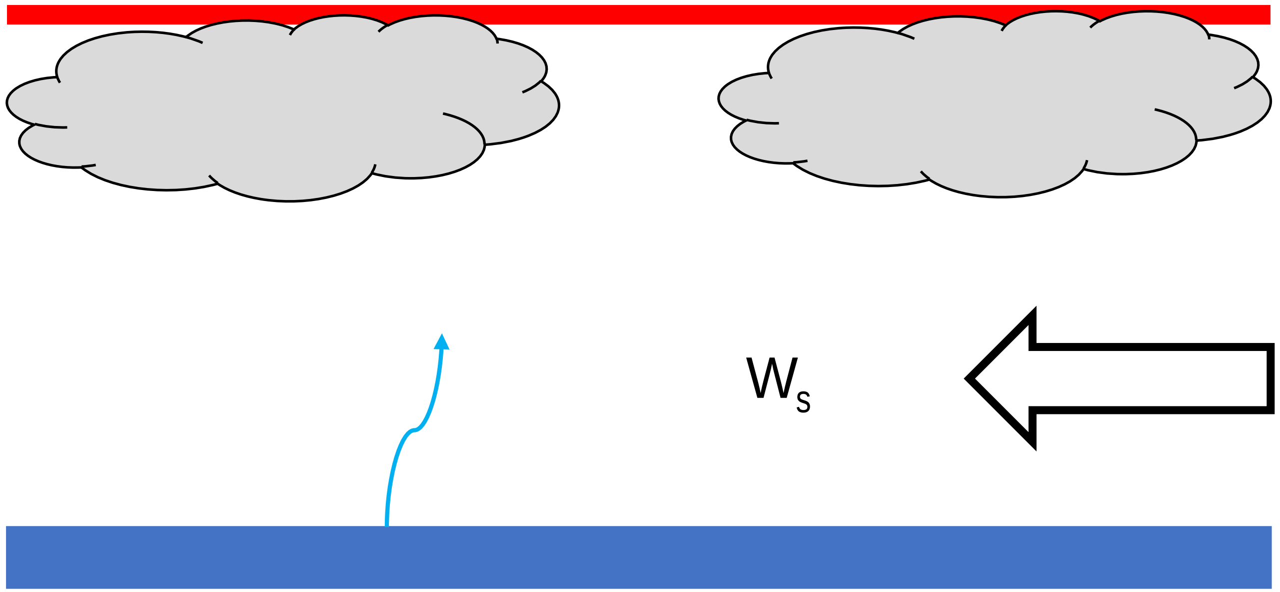
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)
- Advection over SST gradient (SSTadv)
- Surface wind speed (W_s)



Expected Low Cloud Response to W_s

Surface moisture flux increases with wind speed

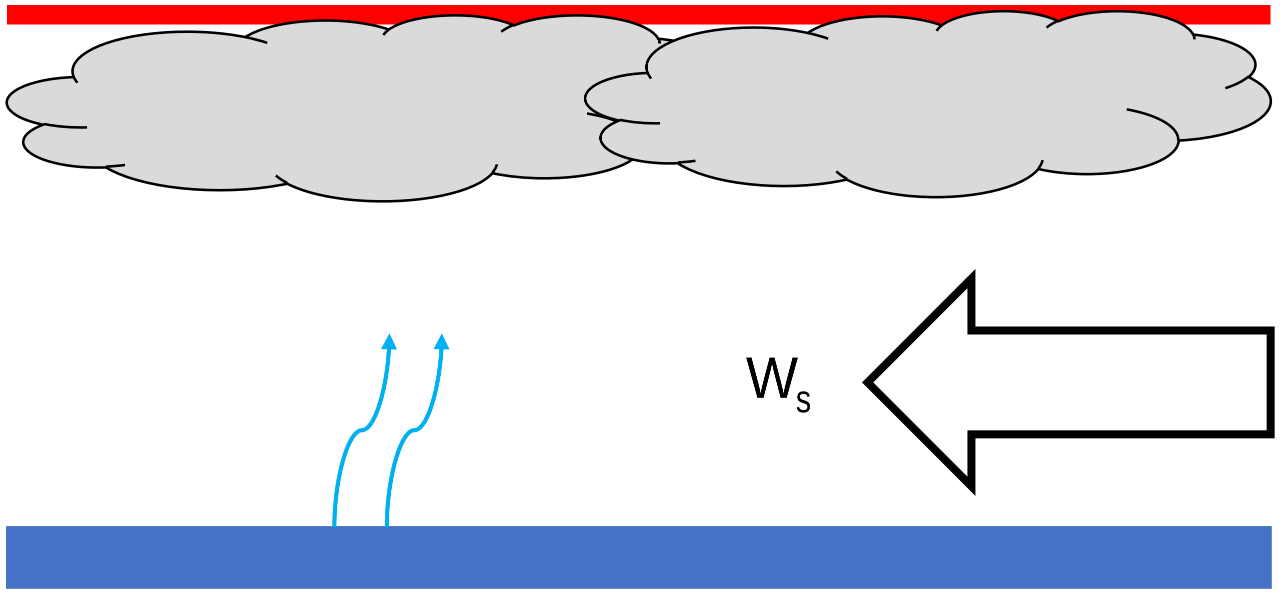


Expected Low Cloud Response to W_s

Surface moisture flux increases with wind speed

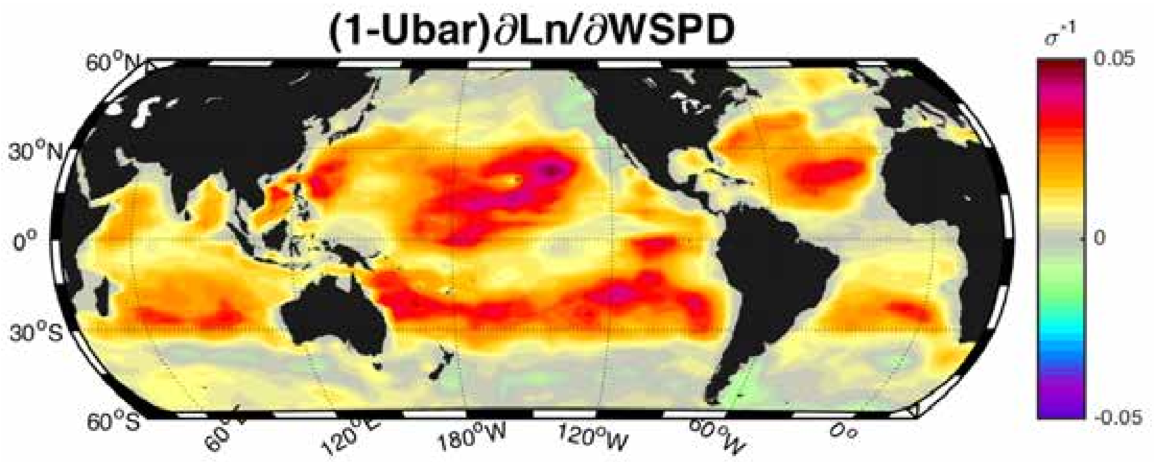
If surface wind speed strengthens

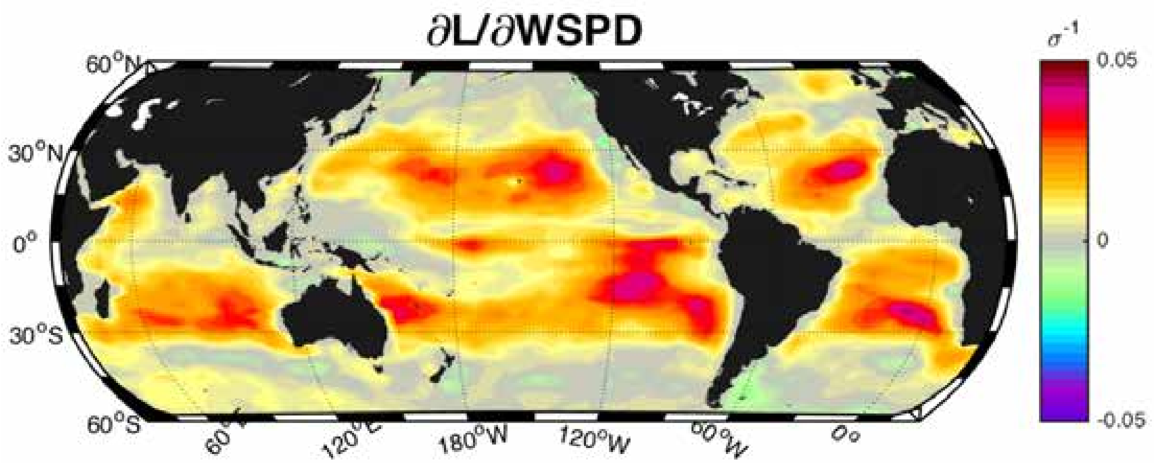
- More upward mixing of moisture
- Low-level cloudiness increases
- Less SW is absorbed by climate system



Observed Low Cloud Response to W_s

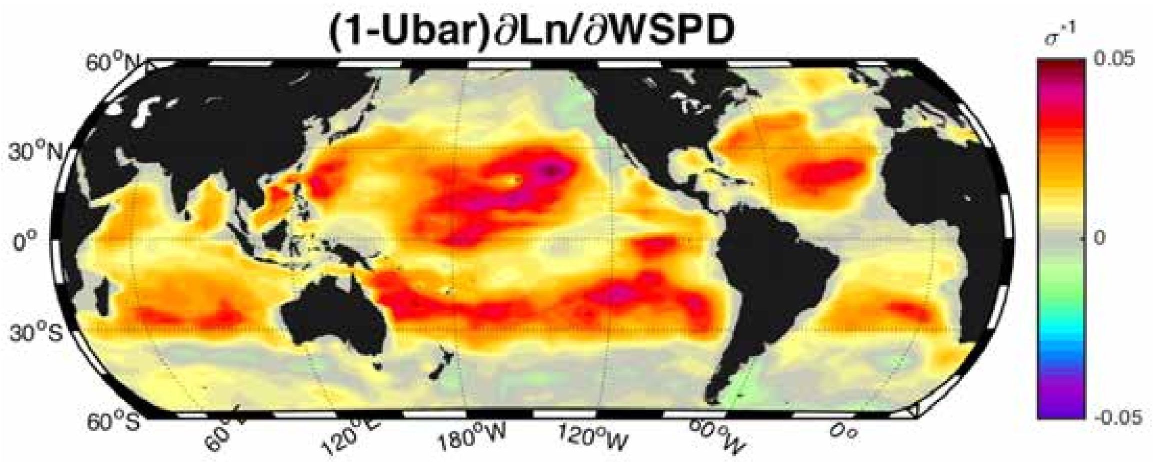
- Increased low-level cloudiness for stronger surface wind at low latitudes

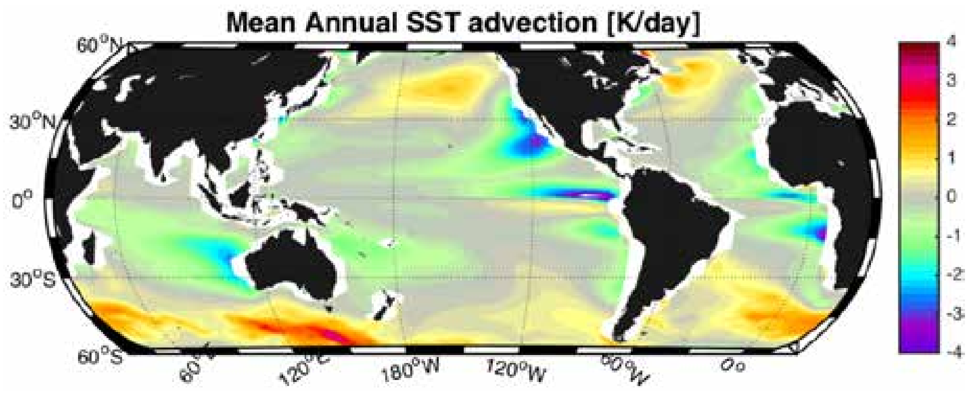


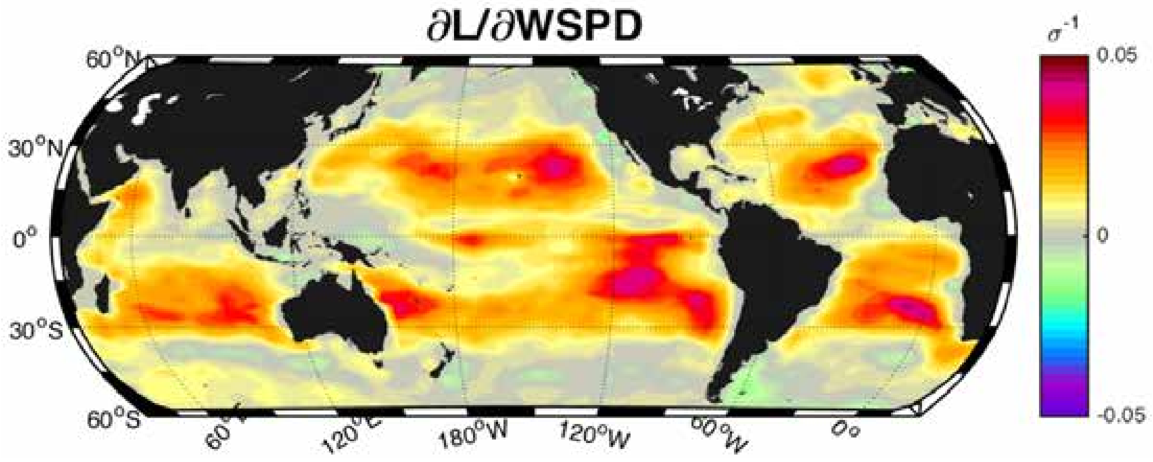


Observed Low Cloud Response to W_s

- Increased low-level cloudiness for stronger surface wind at low latitudes
- Weak negative or zero response at middle latitudes (warm advection, cold SST)

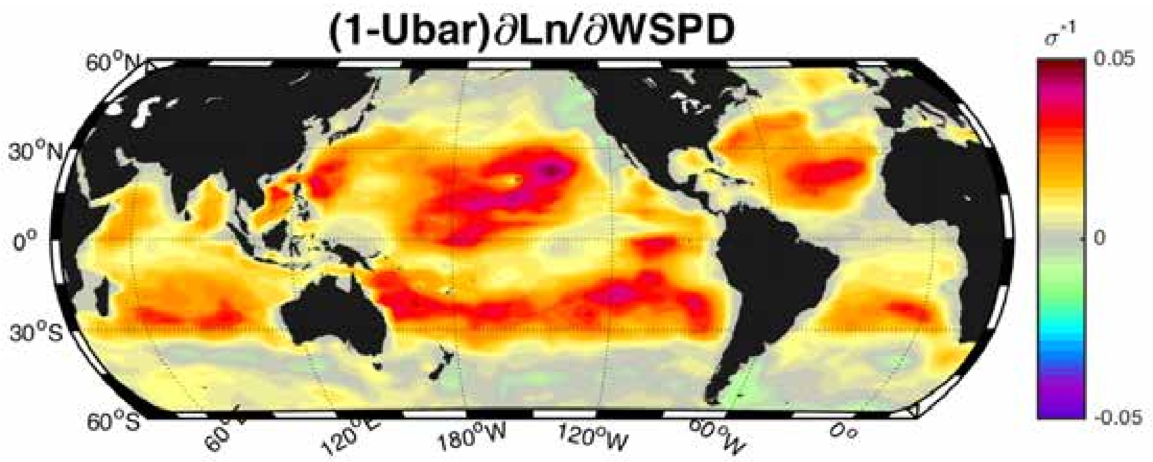


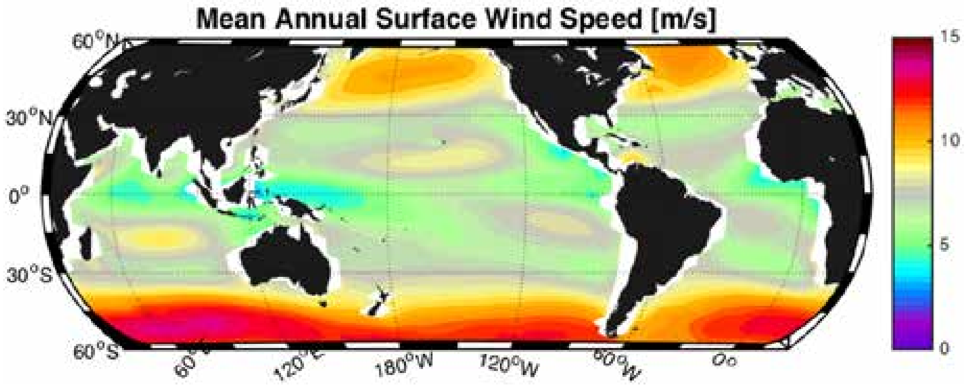


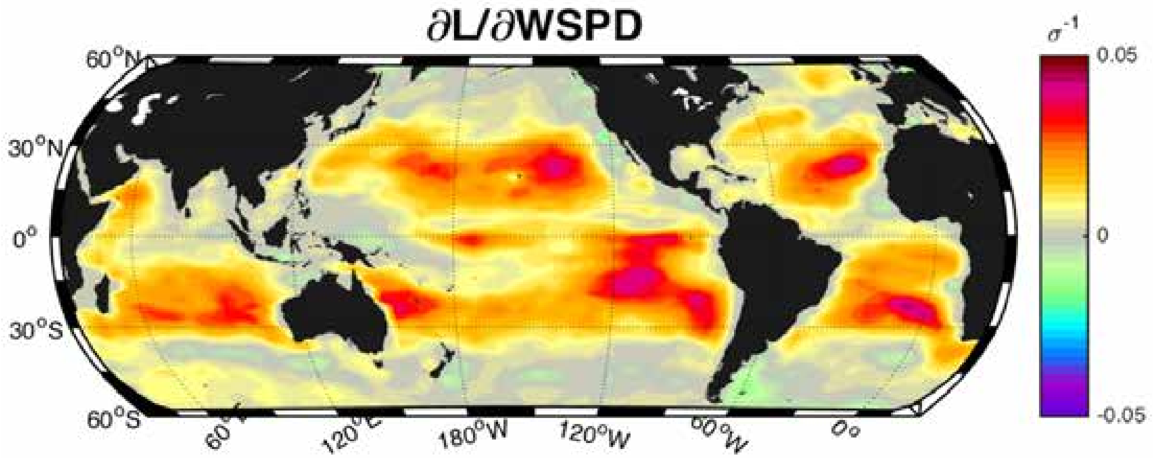


Observed Low Cloud Response to W_s

- Increased low-level cloudiness for stronger surface wind at low latitudes
- Weak negative or zero response at middle latitudes (warm advection, cold SST)
- Weak negative or zero response in deep convective regions (weak wind)

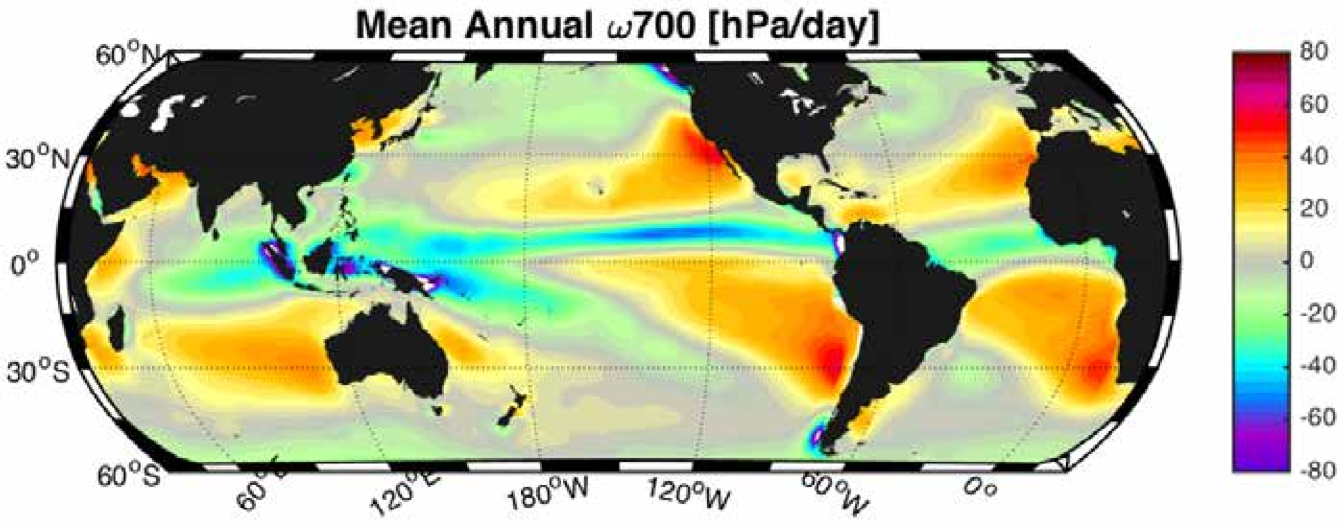






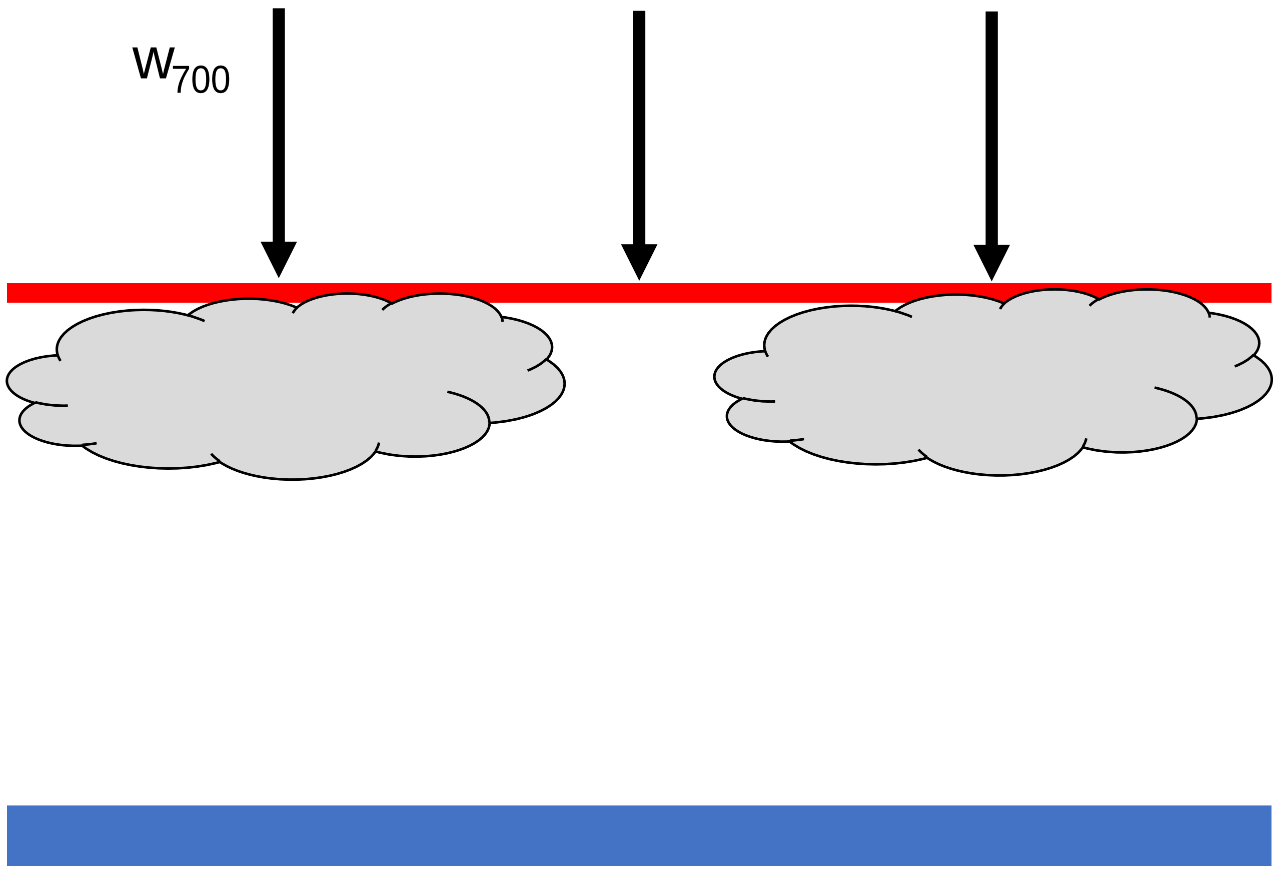
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)
- Advection over SST gradient (SSTadv)
- Surface wind speed (W_s)
- Vertical velocity at 700 hPa (w_{700})



Expected Low Cloud Response to w_{700}

Low-level cloud is capped by a subsidence inversion

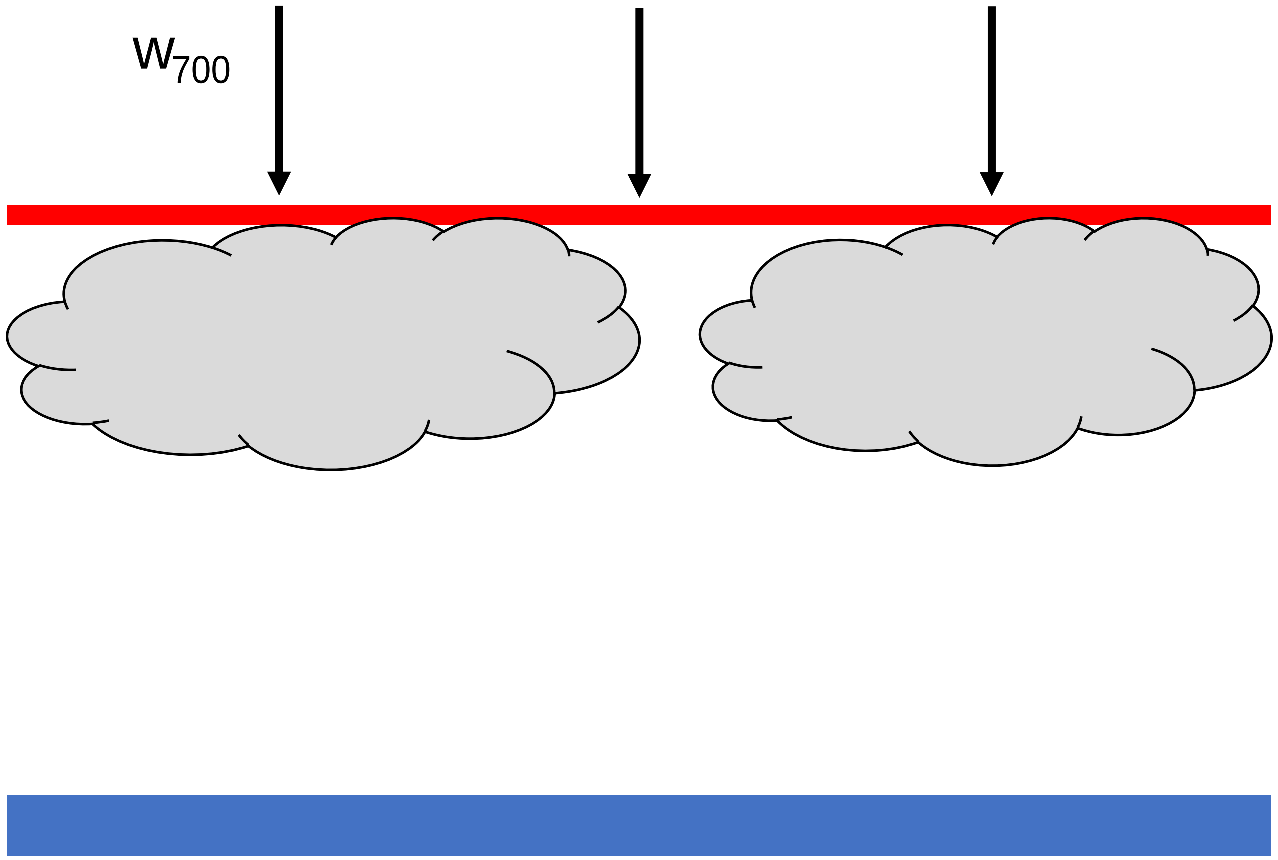


Expected Low Cloud Response to w_{700}

Low-level cloud is capped by a subsidence inversion

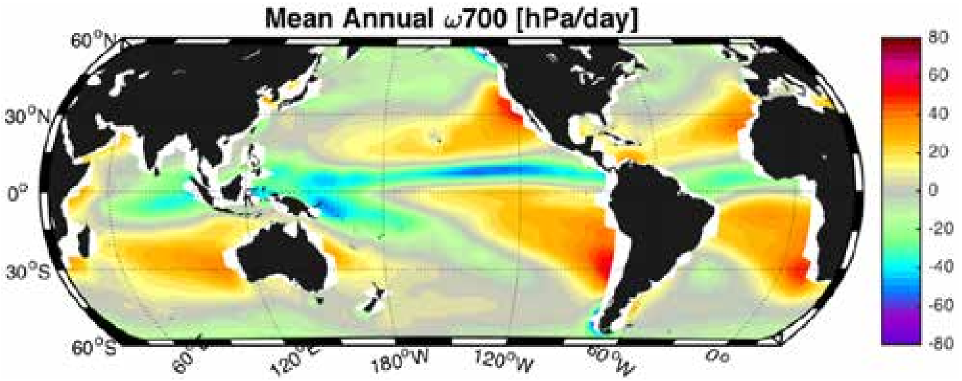
<u>If subsidence weakens</u>

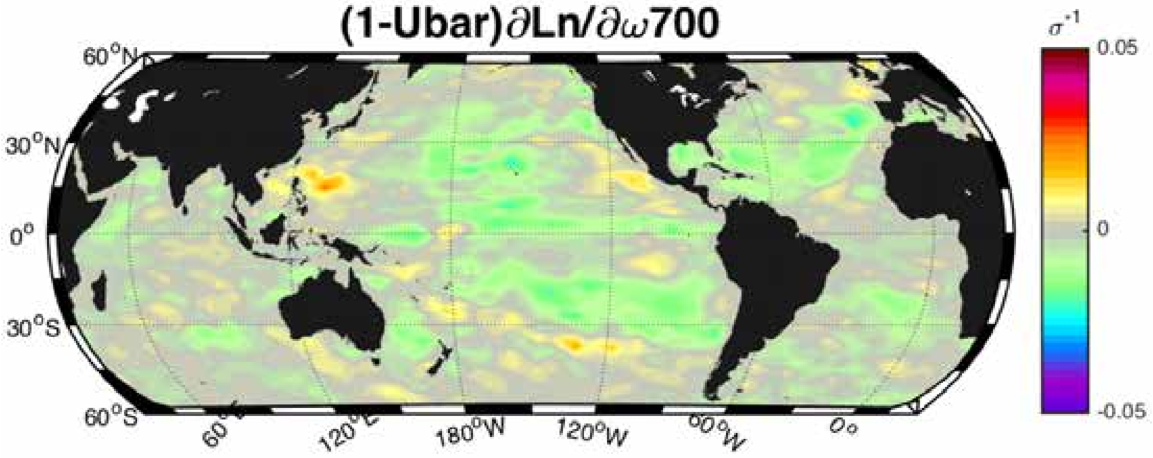
- Low-level cloud top rises
- Low-level cloudiness increases
- Less SW is absorbed by climate system

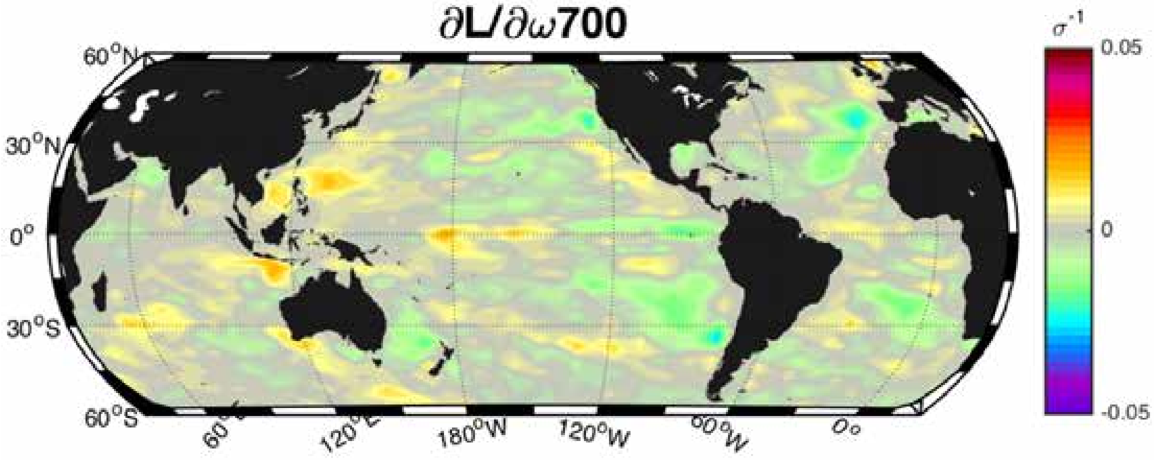


Observed Low Cloud Response to w_{700}

- Slight tendency for increased low-level cloudiness for weaker subsidence in subsidence regime

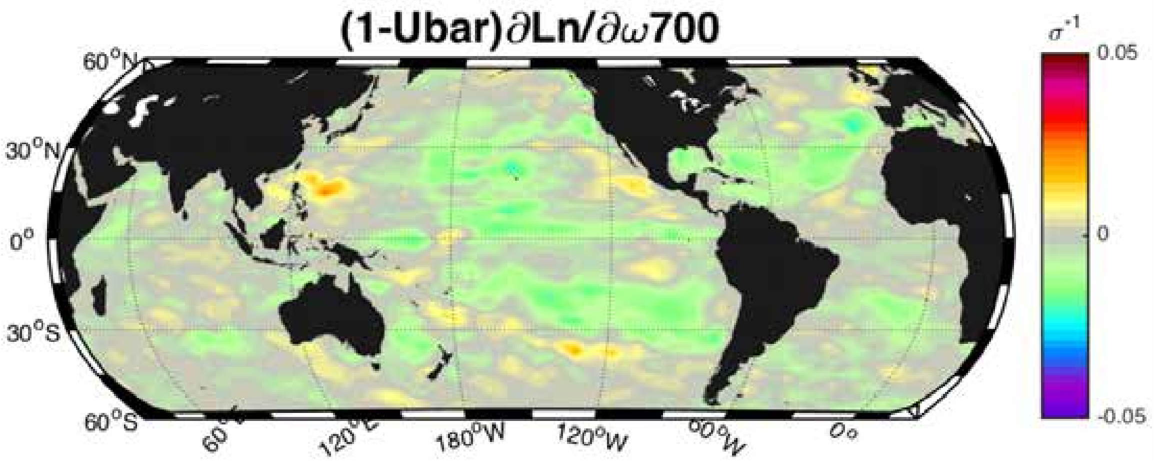


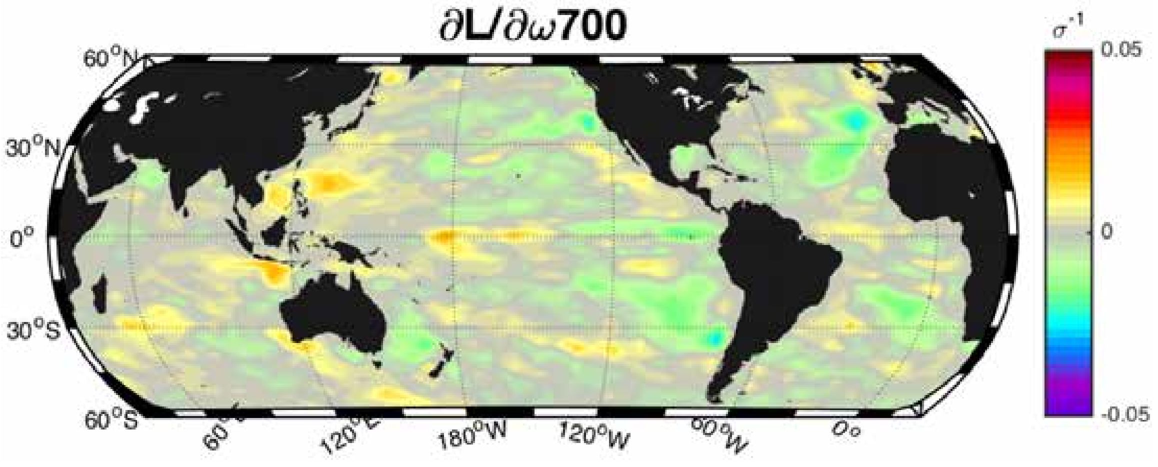




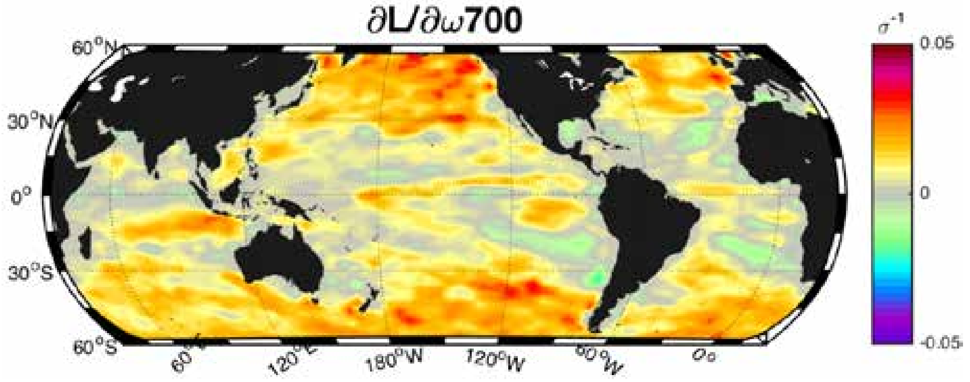
Observed Low Cloud Response to w_{700}

- Slight tendency for increased low-level cloudiness for weaker subsidence in subsidence regime
- If obscuring effects of upper clouds are not taken into account, then satellite-viewed low-level cloud is reduced when ascent occurs



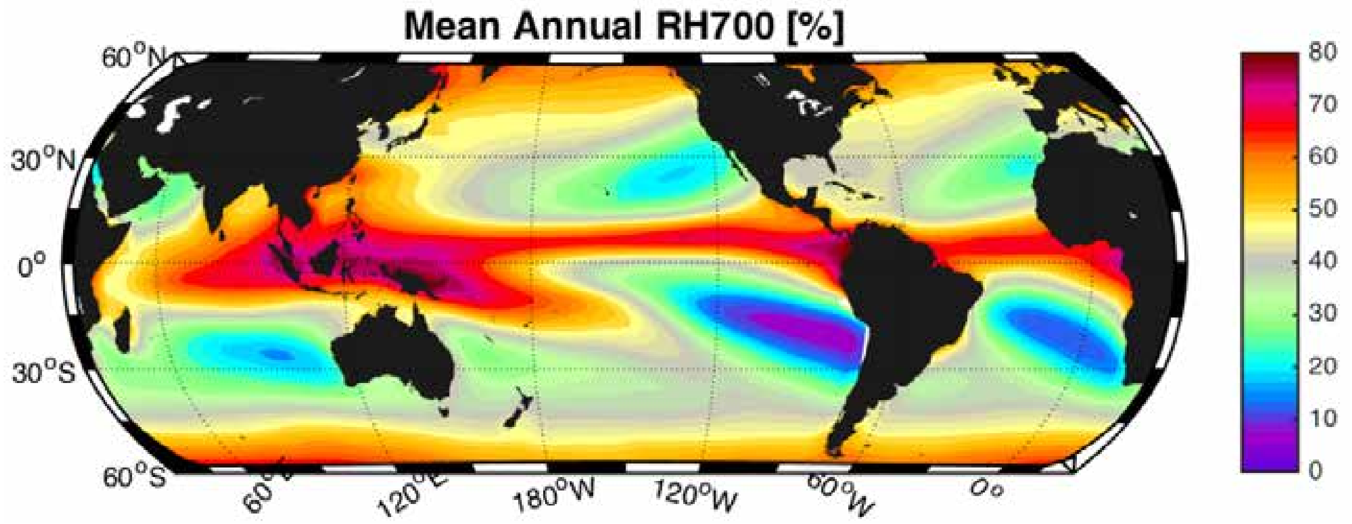


Upper level cloud not a predictor



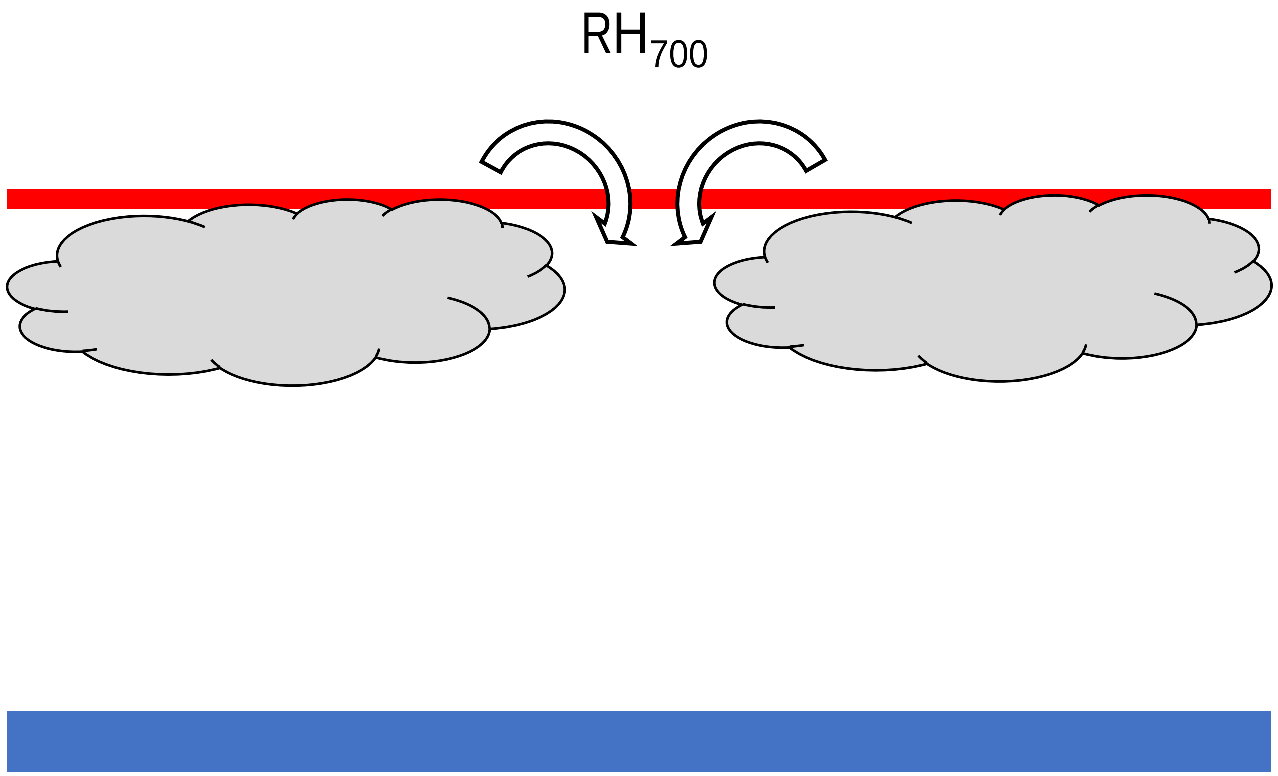
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)
- Advection over SST gradient (SSTadv)
- Surface wind speed (W_s)
- Vertical velocity at 700 hPa (w_{700})
- Relative humidity at 700 hPa (RH_{700})



Expected Low Cloud Response to RH_{700}

Entrainment of air from the free troposphere dries the boundary layer



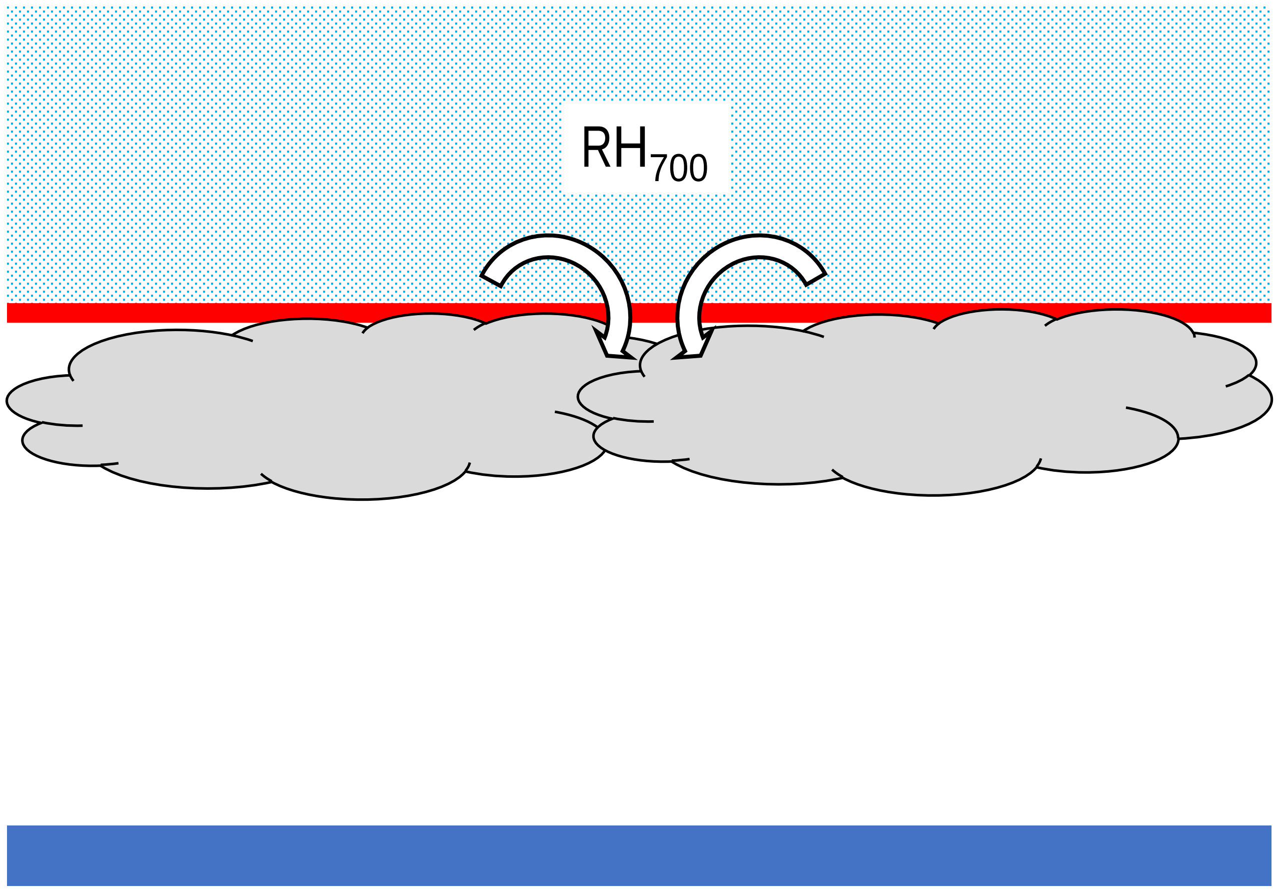
Expected Low Cloud Response to RH_{700}

Entrainment of air from the free troposphere dries the boundary layer

<u>*If the troposphere humidifies*</u>

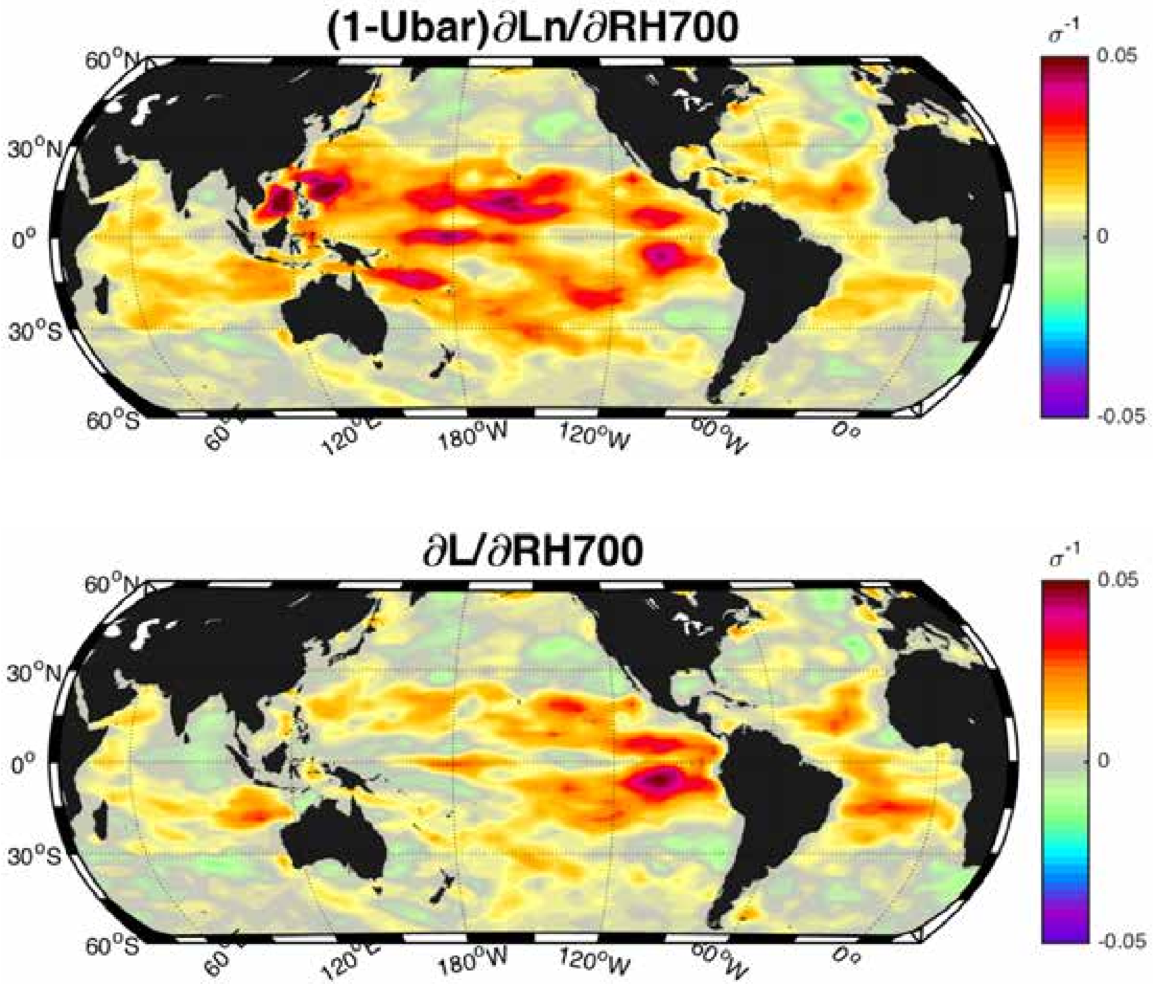
- Entrainment drying decreases
- Low-level cloudiness increases
- Less SW is absorbed by climate system

(also more LW emitted downward toward cloud, but appears to be a secondary effect)



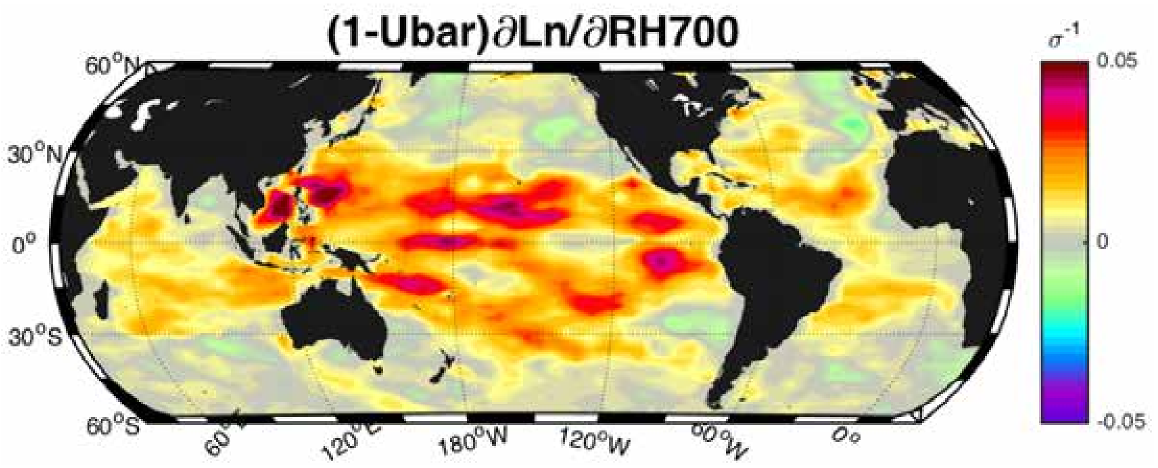
Observed Low Cloud Response to RH_{700}

- Increased low-level cloudiness for greater humidity above boundary layer at low-latitudes (warmer SST)

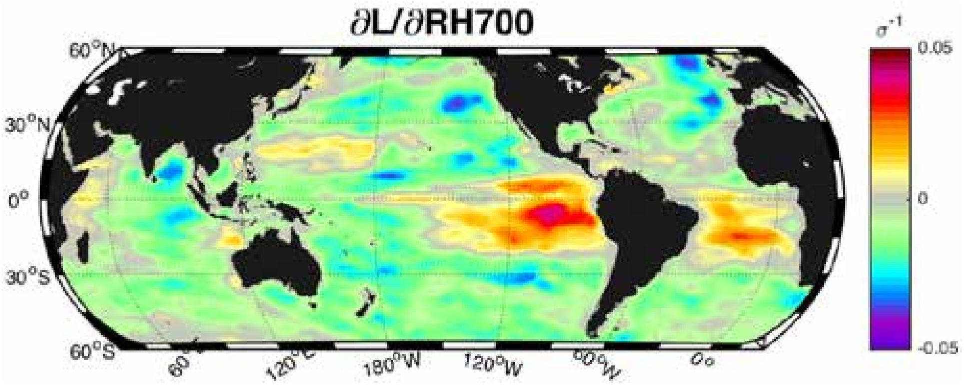


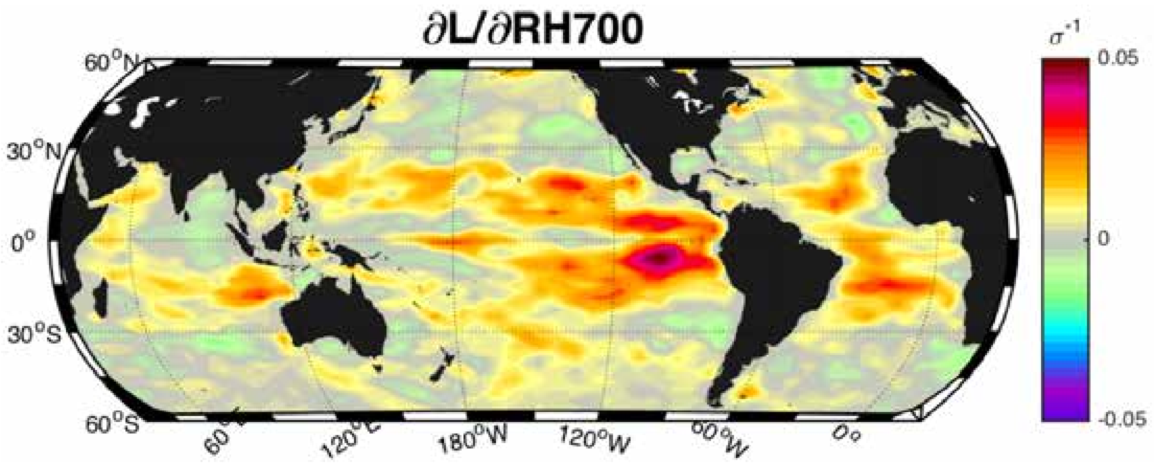
Observed Low Cloud Response to RH_{700}

- Increased low-level cloudiness for greater humidity above boundary layer at low-latitudes (warmer SST)
- If obscuring effects of upper clouds are not taken into account, then satellite-viewed low-level cloud is reduced when free-tropospheric humidity is greater



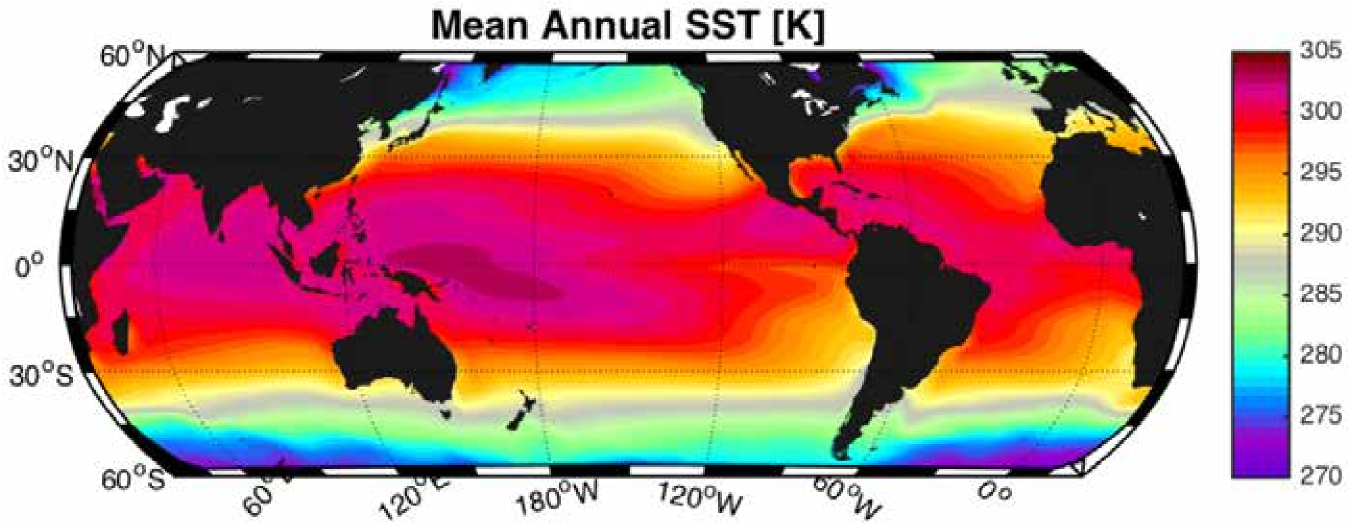
Upper level cloud not a predictor





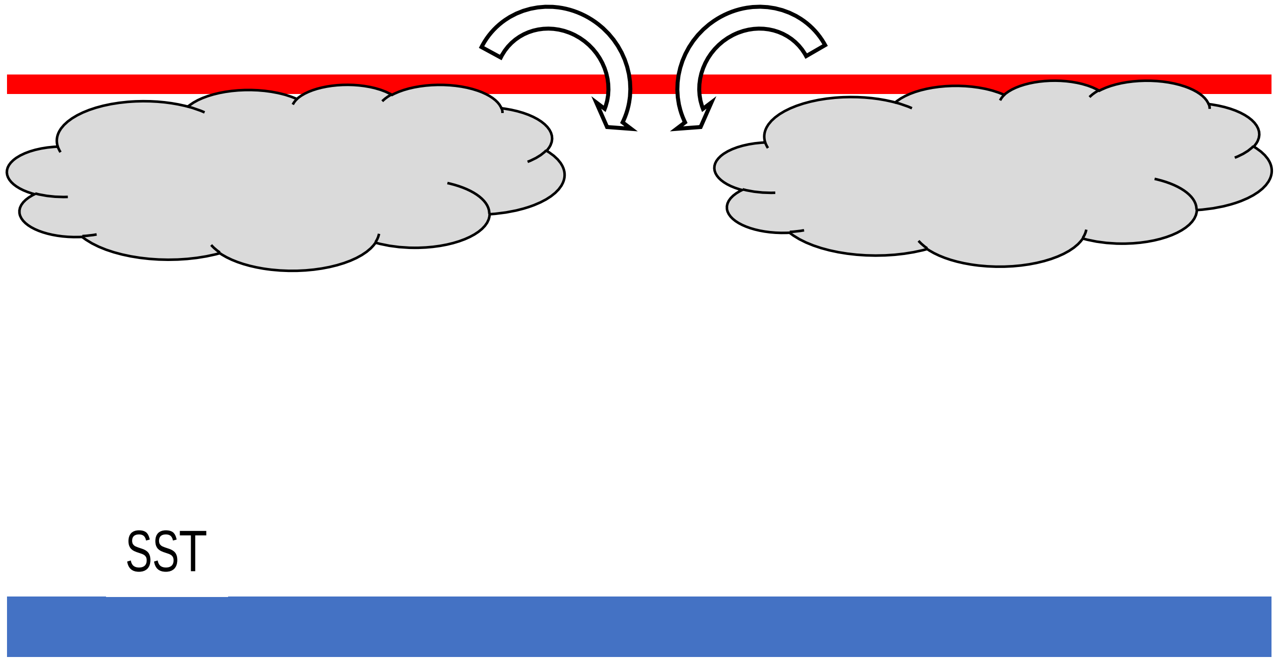
Meteorological Controlling Factors

- Estimated Inversion Strength (EIS)
- Advection over SST gradient (SSTadv)
- Surface wind speed (W_s)
- Vertical velocity at 700 hPa (w_{700})
- Relative humidity at 700 hPa (RH_{700})
- Sea surface temperature (SST)



Expected Low Cloud Response to SST

Turbulence in the boundary layer drives the entrainment that dries and warms the boundary layer

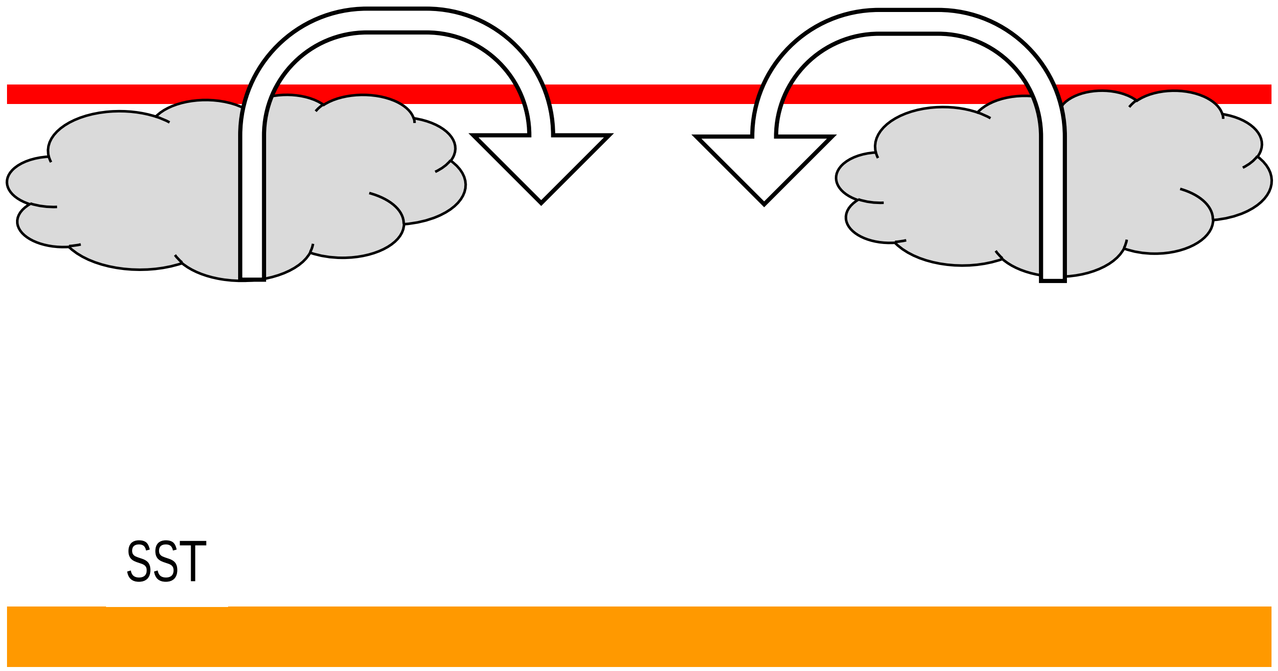


Expected Low Cloud Response to SST

Turbulence in the boundary layer drives the entrainment that dries and warms the boundary layer

<u>If SST increases</u>

- Cloud latent heating increases
- Turbulence increases
- Entrainment increases
- Low-level cloudiness decreases
- More SW is absorbed by climate system



Expected Low Cloud Response to SST

Turbulence in the boundary layer drives the entrainment that dries and warms the boundary layer

__If SST increases__

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- Turbulence increases
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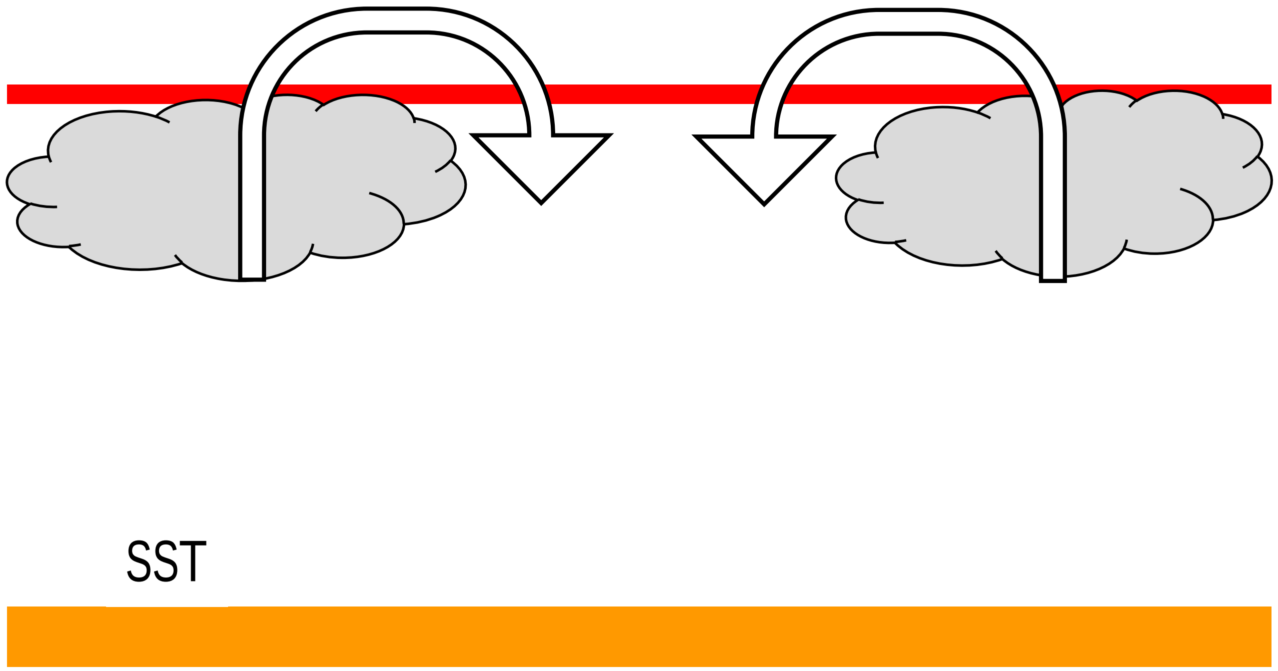
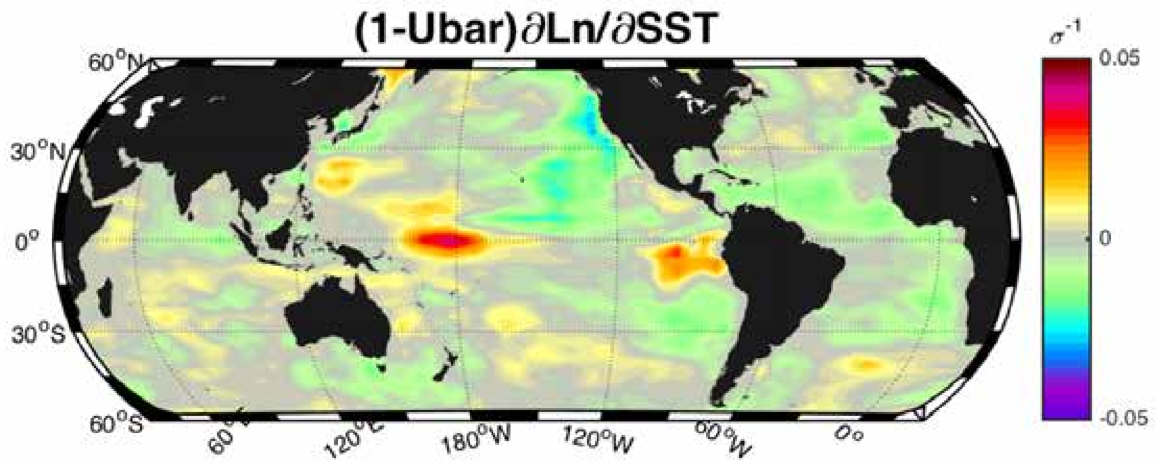
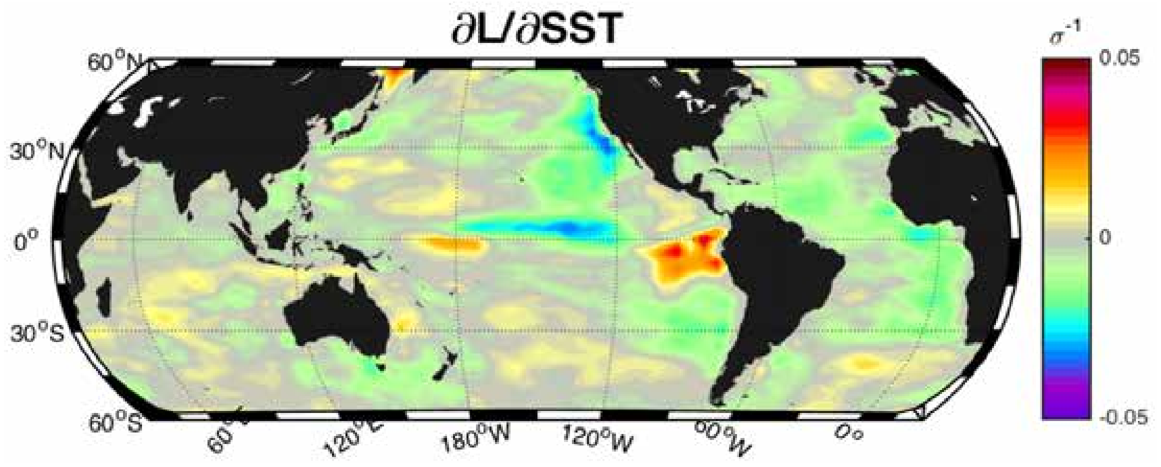
Is this true beyond the subtropical stratocumulus regime?



Observed Low Cloud Response to SST

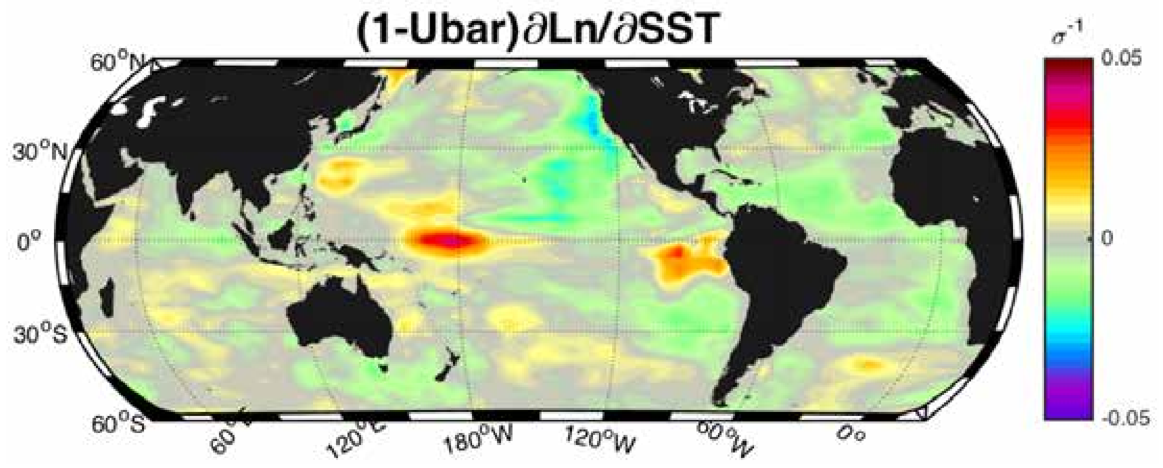
- Decreased low-level cloudiness for warmer SST in stratocumulus regimes

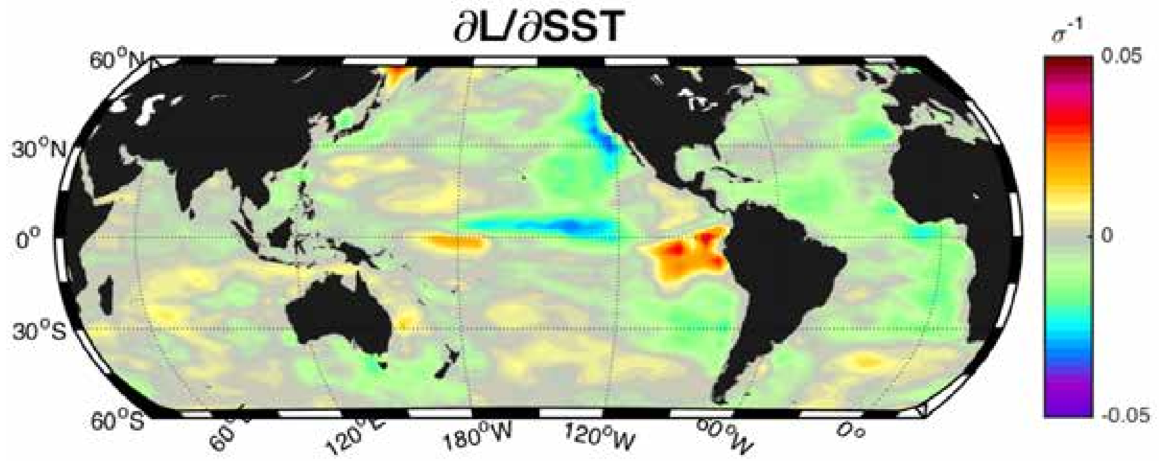




Observed Low Cloud Response to SST

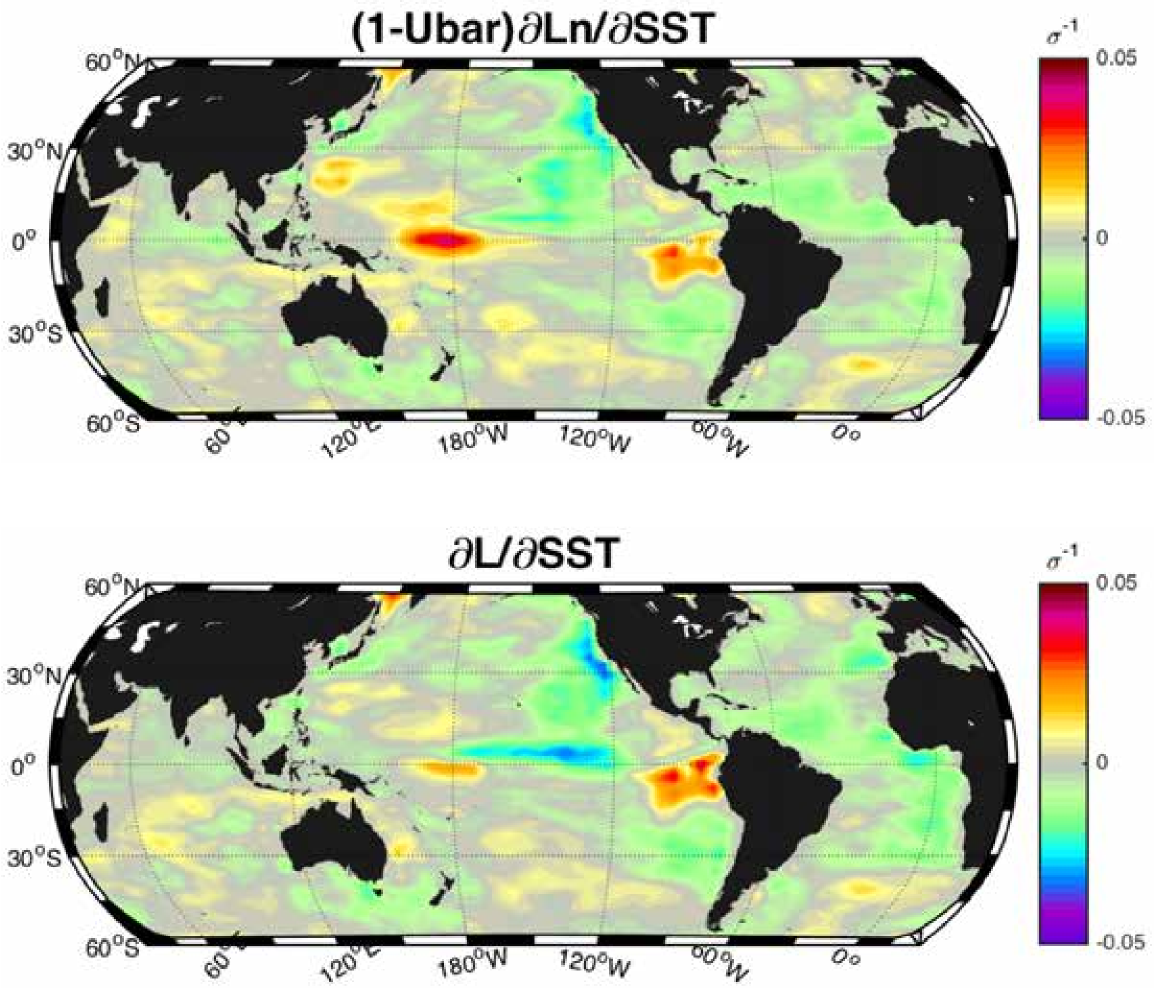
- Decreased low-level cloudiness for warmer SST in stratocumulus regimes
- Increased low-level cloud for warmer SST south of eastern cold tongue





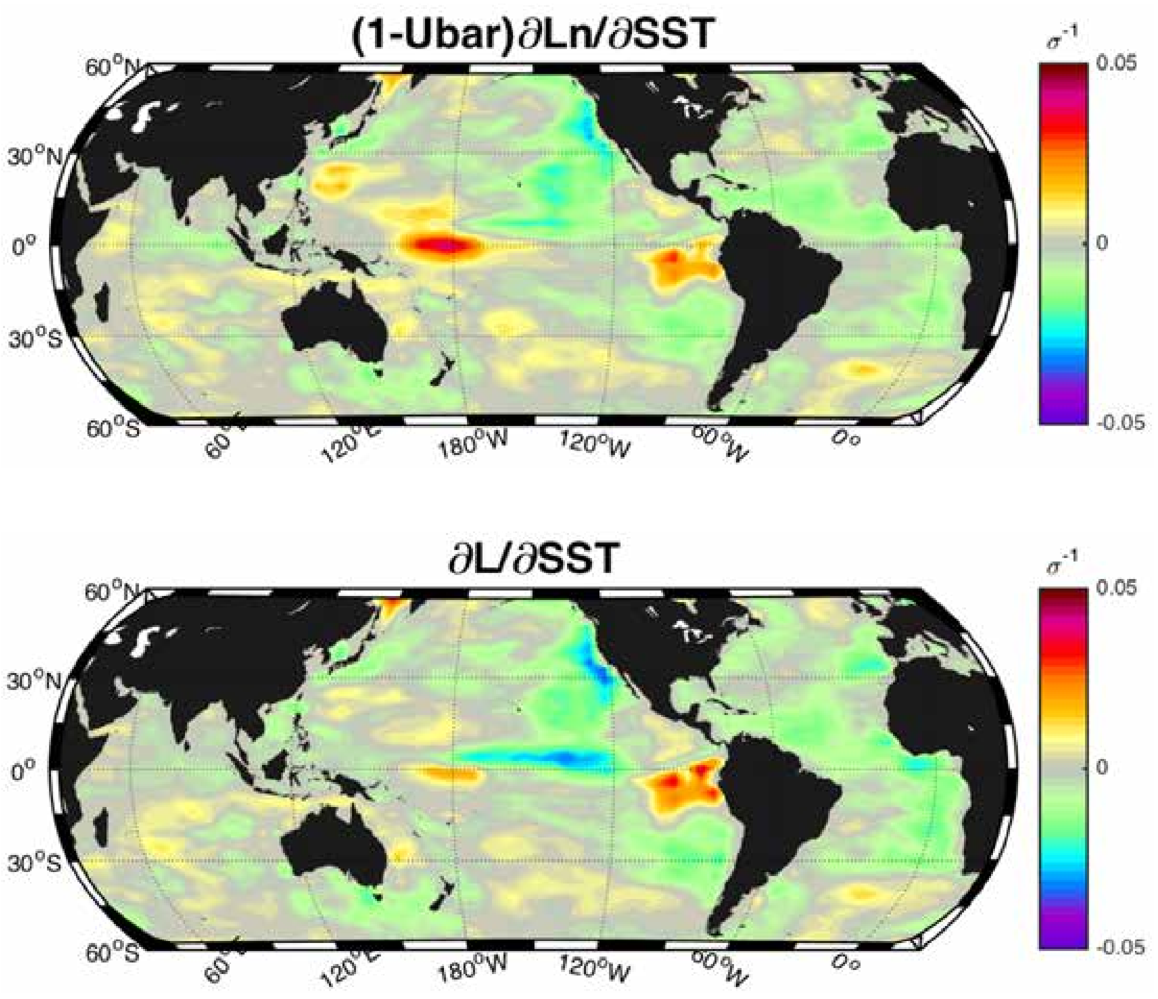
Observed Low Cloud Response to SST

- Decreased low-level cloudiness for warmer SST in stratocumulus regimes
- Increased low-level cloud for warmer SST south of eastern cold tongue
- Strong positive coefficient in western equatorial Pacific may be artifact of obscuration adjustment in deep convective region



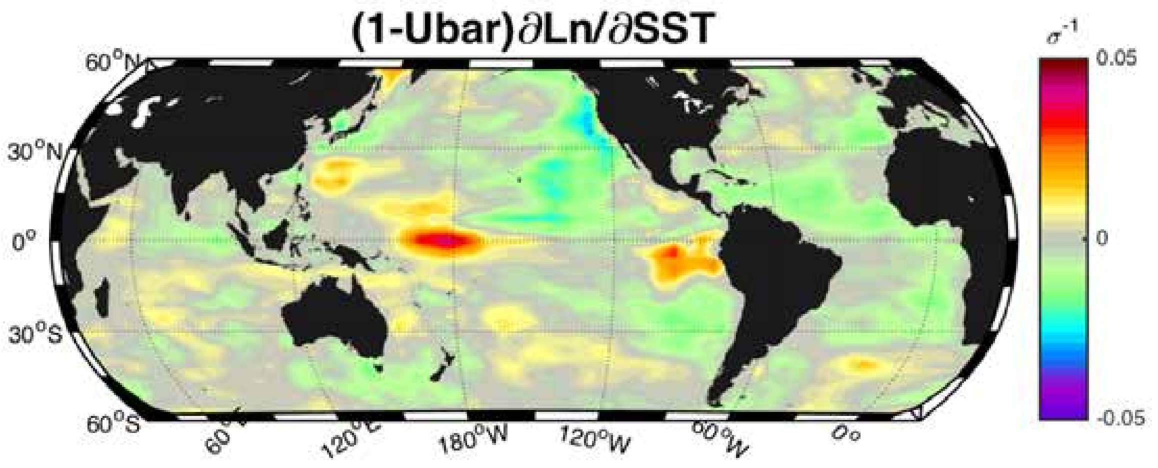
Observed Low Cloud Response to SST

- Decreased low-level cloudiness for warmer SST in stratocumulus regimes
- Increased low-level cloud for warmer SST south of eastern cold tongue
- Strong positive coefficient in western equatorial Pacific may be artifact of obscuration adjustment in deep convective region
- Mixture of weak positive, weak negative, and near-zero coefficients elsewhere

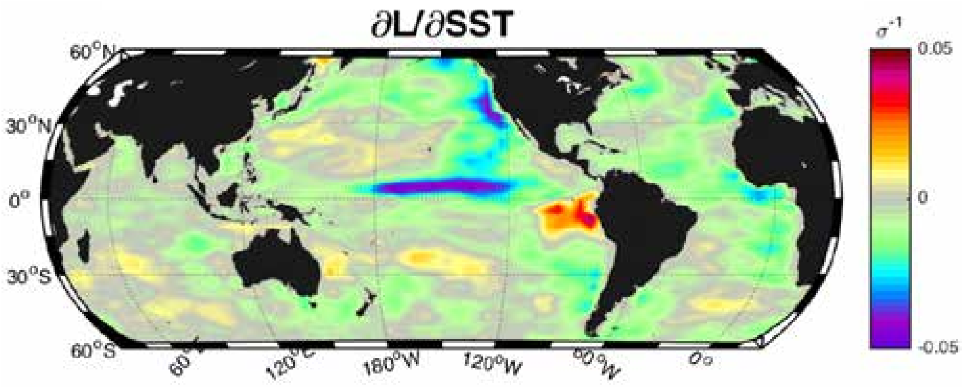


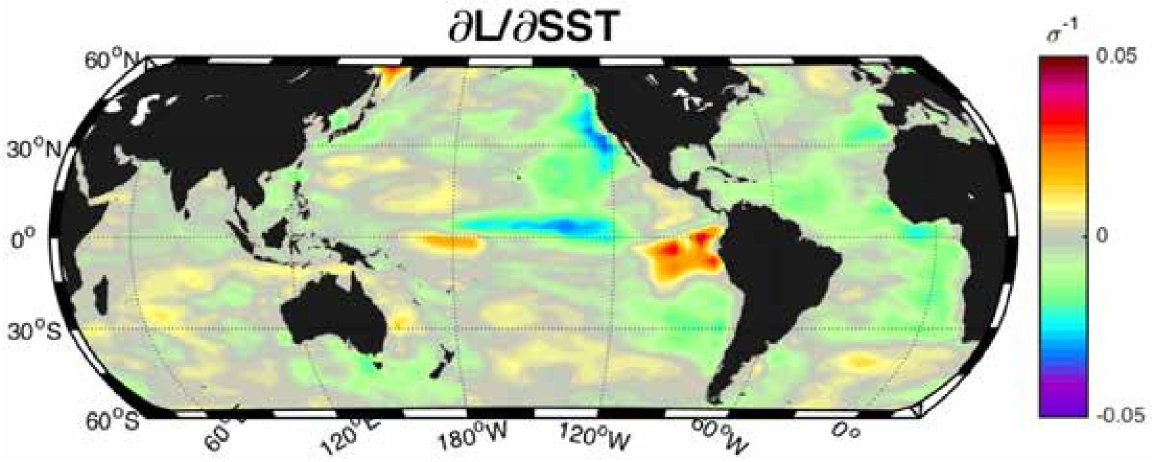
Observed Low Cloud Response to SST

- If obscuring effects of upper clouds are not taken into account, then greater and more widespread reduction of satellite-viewed low-level cloud for warmer SST
- Could lead to overestimate of positive low-level cloud feedback



Upper level cloud not a predictor





Outline

- Ten-year retrospective – *how far have we come? How far has Joel come?*
- Prior work – conceptual model and *Myers and Norris (2016)*
- Challenges and solutions – *confounding impact of upper-level cloud*
- Cloud response to meteorology – *physical processes and observed response*
- Radiative effects method – *calculation of radiative impact of cloud response*
- Radiative response to SST
- Regional radiative response
- Estimation of climate feedback
- Discussion and summary

Radiative Effects of Cloud Change

SW_{all} = TOA SW radiation flux averaged over cloudy and clear areas of the grid box

SW_{clr} = TOA SW radiation flux from clear areas of the box

SW_{CRE} = TOA SW cloud radiative effect

f_{cld} = fractional area of grid box covered by **all clouds**

SW_{ovc} = TOA SW radiation flux from cloudy areas of the grid box (as if overcast)

Radiative Effects of Cloud Change

$\boldsymbol{SW_{all}}$ = TOA SW radiation flux averaged over cloudy and clear areas of the grid box

$\boldsymbol{SW_{clr}}$ = TOA SW radiation flux from clear areas of the box

$\boldsymbol{SW_{CRE}}$ = TOA SW cloud radiative effect

$\boldsymbol{f_{cld}}$ = fractional area of grid box covered by **all clouds**

$\boldsymbol{SW_{ovc}}$ = TOA SW radiation flux from cloudy areas of the grid box (as if overcast)

$$SW_{all} = SW_{clr} - SW_{CRE}$$

Radiative Effects of Cloud Change

SW_{all} = TOA SW radiation flux averaged over cloudy and clear areas of the grid box

SW_{clr} = TOA SW radiation flux from clear areas of the box

SW_{CRE} = TOA SW cloud radiative effect

f_{cld} = fractional area of grid box covered by **all clouds**

SW_{ovc} = TOA SW radiation flux from cloudy areas of the grid box (as if overcast)

$$SW_{all} = SW_{clr} - SW_{CRE}$$

$$SW_{ovc} = -\frac{SW_{CRE}}{f_{cld}}$$

Radiative Effects of Cloud Change

SW_{all} = TOA SW radiation flux averaged over cloudy and clear areas of the grid box

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$$SW_{all} = SW_{clr} + SW_{ovc}\, f_{cld}$$

Radiative Effects of Cloud Change

$\boldsymbol{SW_L}$ = TOA SW radiation flux from areas with low-level cloud (as if overcast)

$\boldsymbol{SW_U}$ = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

Radiative Effects of Cloud Change

SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

SW_U = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

$$SW_{all} = SW_{clr} + SW_L\, L + SW_U\, U$$

Radiative Effects of Cloud Change

SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

SW_U = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

$$SW_{all} = SW_{clr} + SW_L\, L + SW_U\, U$$

$$SW_{all} = SW_{clr} + SW_L(1 - U)L_n + SW_U\, U$$

Radiative Effects of Cloud Change

SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

SW_U = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

$$SW_{all} = SW_{clr} + SW_L\, L + SW_U\, U$$

$$SW_{all} = SW_{clr} + SW_L(1-U)L_n + SW_U\, U$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}\, L' + SW'_L\, \overline{L} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}(1-\overline{U})L'_n + SW'_L(1-\overline{U})\overline{L_n} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

ignore 2nd-order terms (small)

Radiative Effects of Cloud Change

SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

SW_U = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

$$SW_{all} = SW_{clr} + SW_L\, L + SW_U\, U$$

$$SW_{all} = SW_{clr} + SW_L(1-U)L_n + SW_U\, U$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}\, L' + SW'_L\, \overline{L} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}(1-\overline{U})L'_n + SW'_L(1-\overline{U})\overline{L_n} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

radiative anomaly from changes in low-level cloud fraction

radiative anomaly from changes in low-level cloud optical thickness, etc.

Radiative Effects of Cloud Change

SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

SW_U = TOA SW radiation flux from areas with upper-level cloud (as if overcast)

$$SW_{all} = SW_{clr} + SW_L\, L + SW_U\, U$$

$$SW_{all} = SW_{clr} + SW_L (1-U) L_n + SW_U\, U$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}\, L' + SW'_L\, \overline{L} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

$$SW'_{all} = SW'_{clr} + \overline{SW_L}(1-\overline{U}) L'_n + SW'_L (1-\overline{U})\overline{L_n} + \overline{SW_U}\, U' + SW'_U\, \overline{U}$$

radiative anomaly from changes in low-level cloud fraction

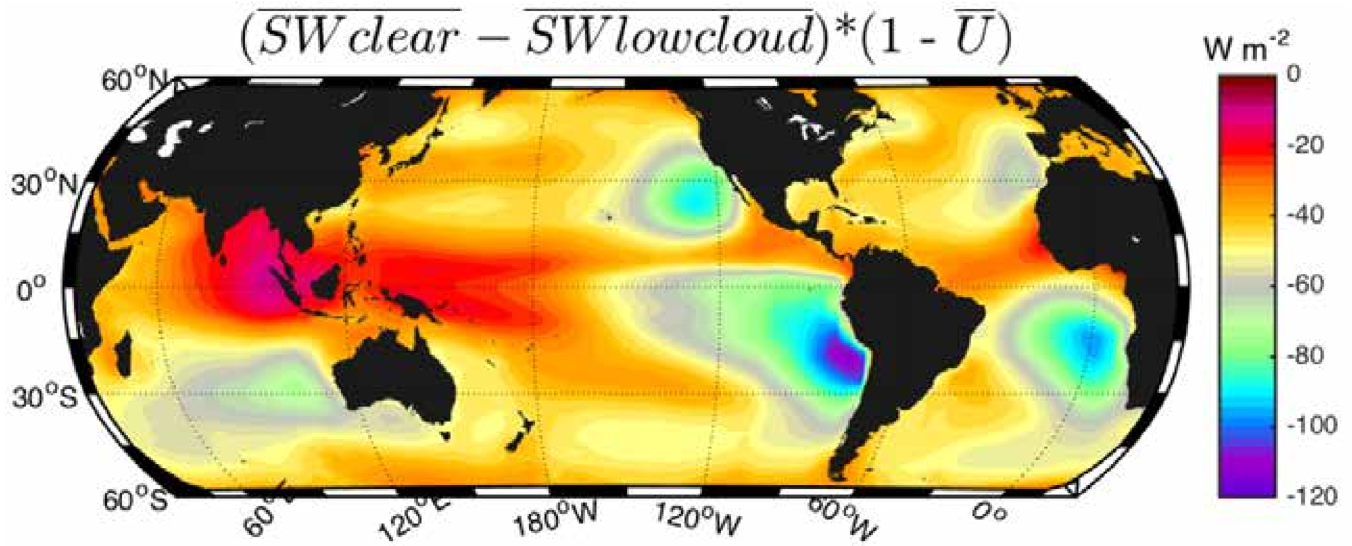
radiative anomaly from changes in low-level cloud optical thickness, etc. – ***small, so ignore***

Radiative Effects of Low Cloud Change

***SW**$_L$* = TOA SW radiation flux from areas with low-level cloud (as if overcast)

$\overline{SW_L}(1-\overline{U})$

radiative scaling for changes in low-level cloud fraction not obscured by higher clouds



Radiative Effects of Low Cloud Change

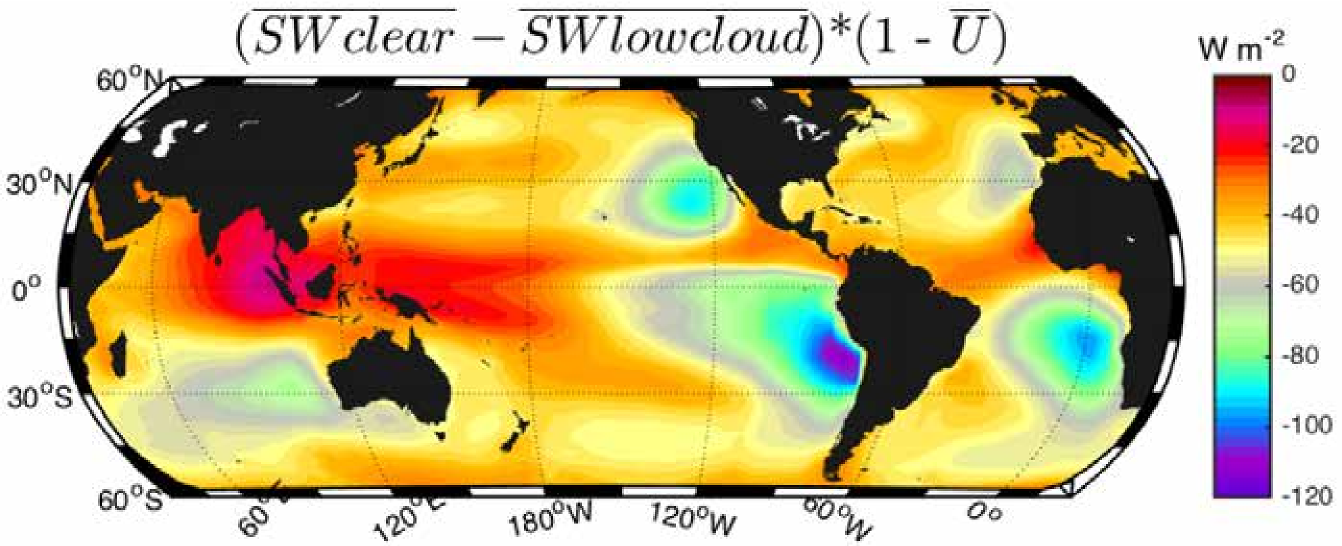
SW_L = TOA SW radiation flux from areas with low-level cloud (as if overcast)

$\overline{SW_L}(1 - \overline{U})$

radiative scaling for changes in low-level cloud fraction not obscured by higher clouds

multiply ***L_n*** *cloud response coefficients by this scaling*

multiply **L** *cloud response coefficients without* **(1 – *U*)**



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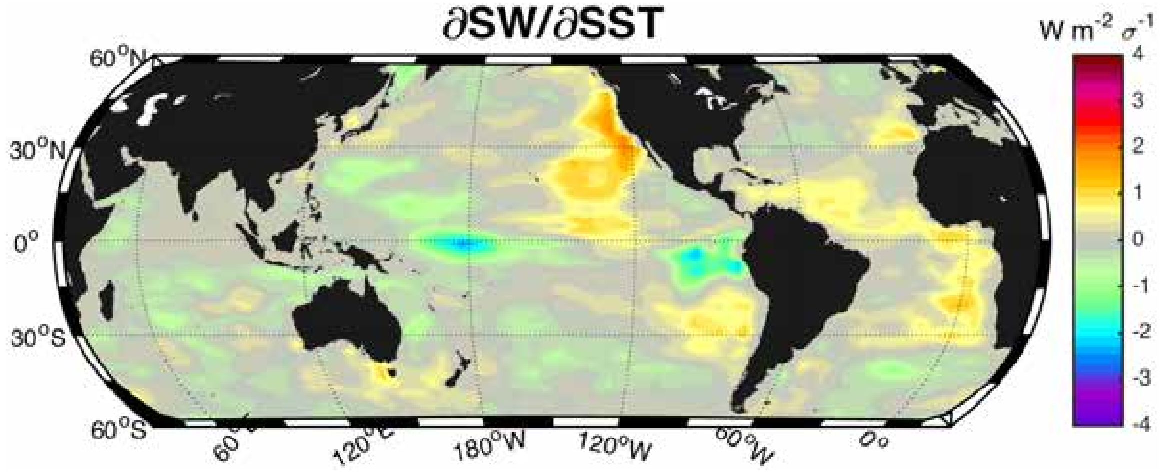
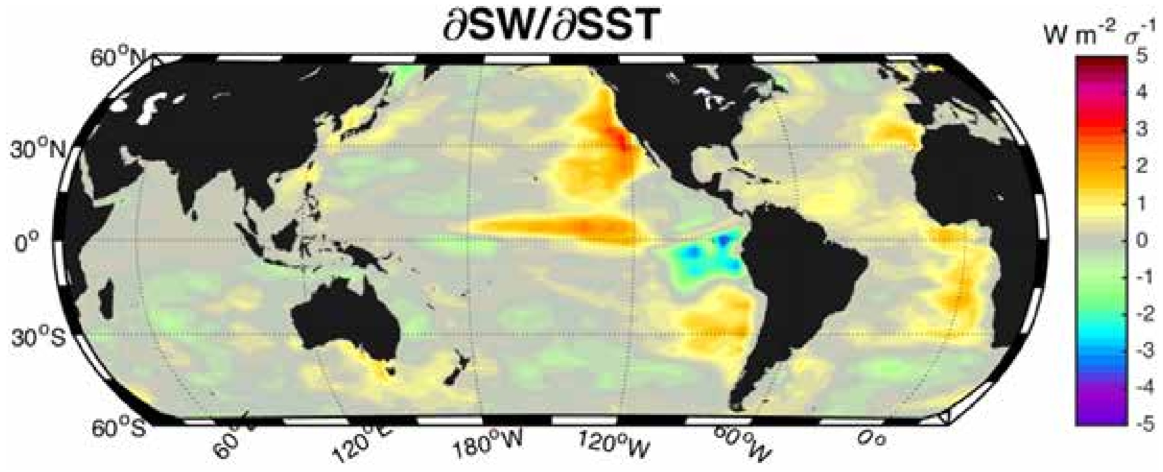
SW Low Cloud Radiative Response to SST

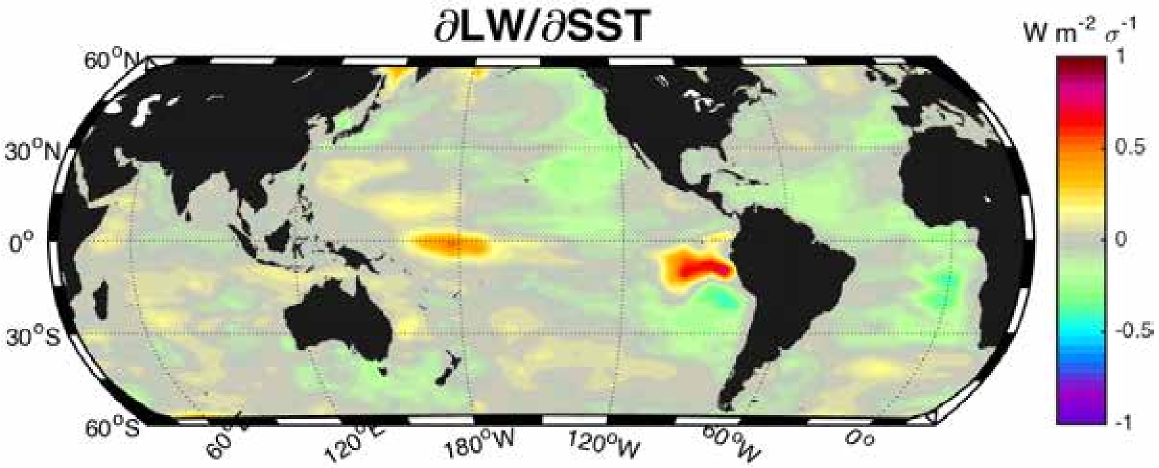
- Increased SW absorption for warmer SST in stratocumulus regimes
- Decreased SW absorption for warmer SST south of eastern cold tongue
- Warmer SST has near-zero effect on SW absorption over most other regions of the global ocean

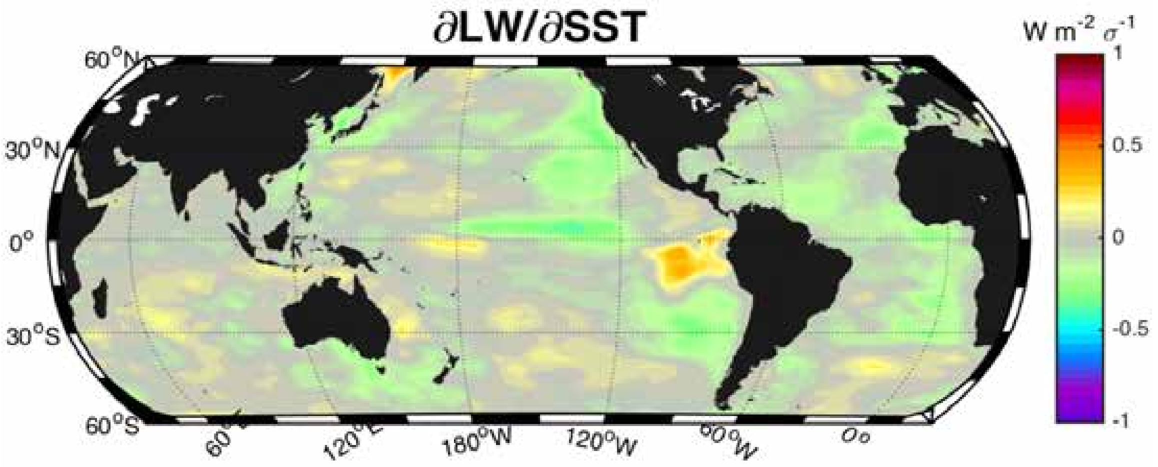




LW Low Cloud Radiative Response to SST

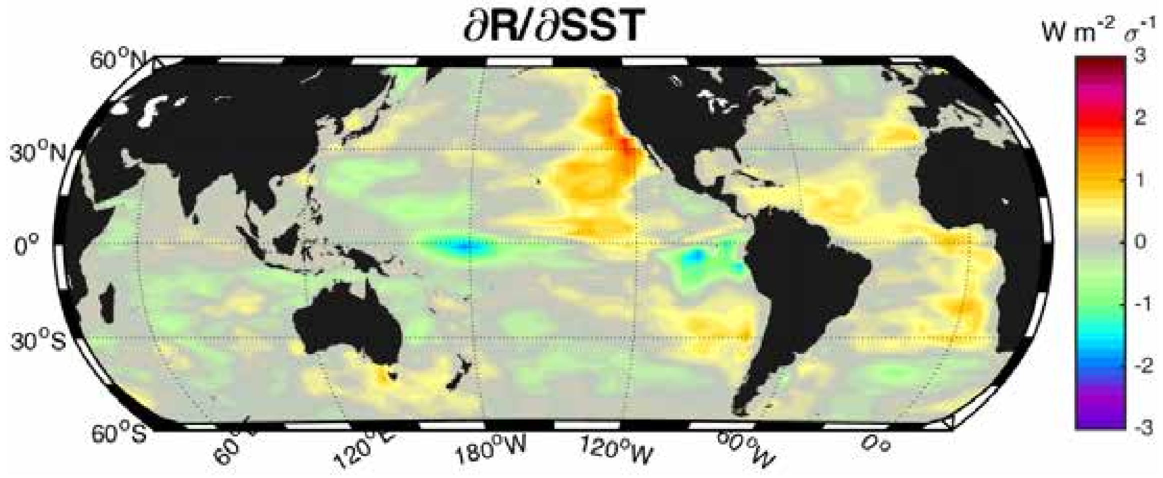
- Pattern of LW cloud response has opposite sign to SW response but weaker magnitude (note smaller scale)

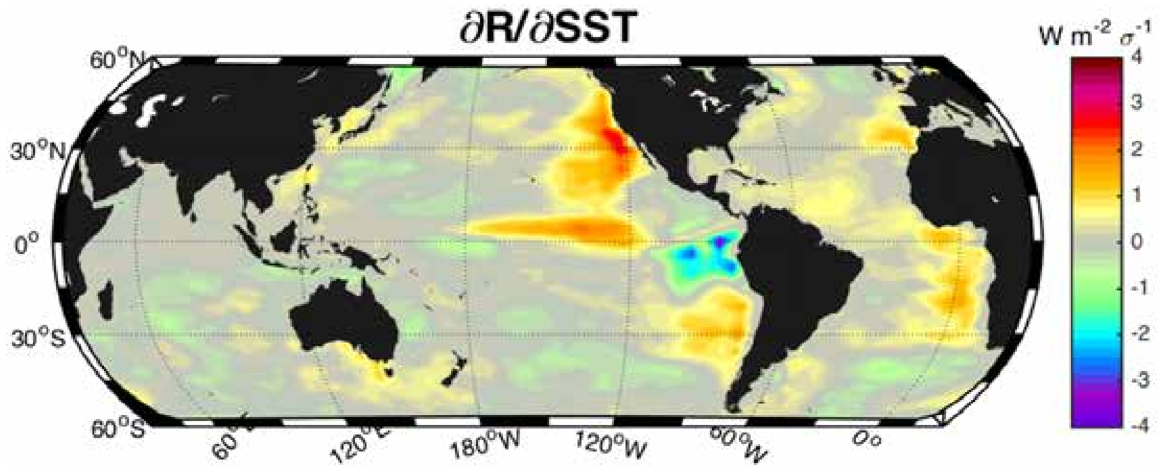




Net Low Cloud Radiative Response to SST

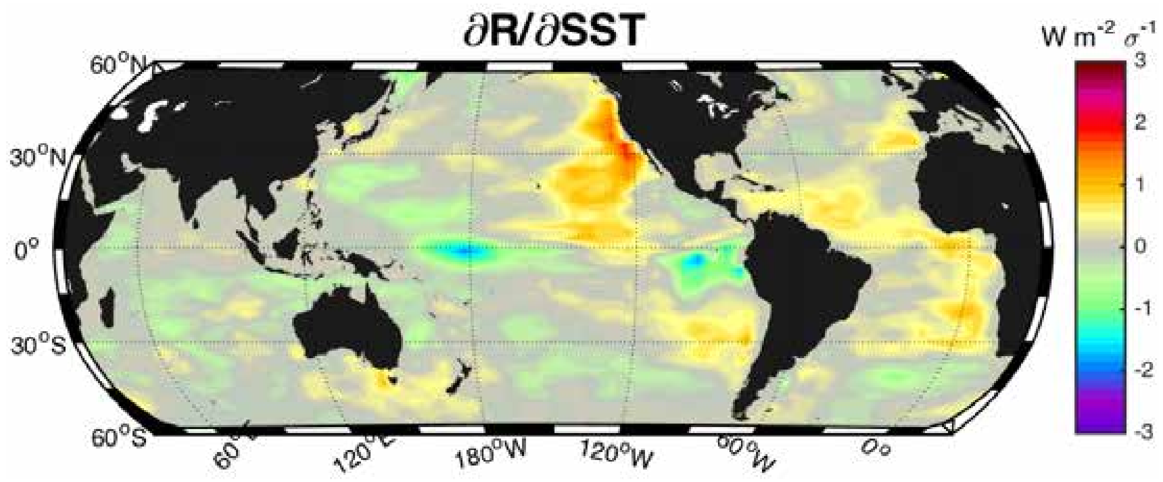
- More energy retained by climate system for warmer SST in stratocumulus regions
- Less energy retained by climate system for warmer SST south of eastern equatorial cold tongue
- Warmer SST has near-zero effect on net energy retained by climate system over most other regions of the global ocean
- Results of Myers and Norris (2016) may not be globally applicable



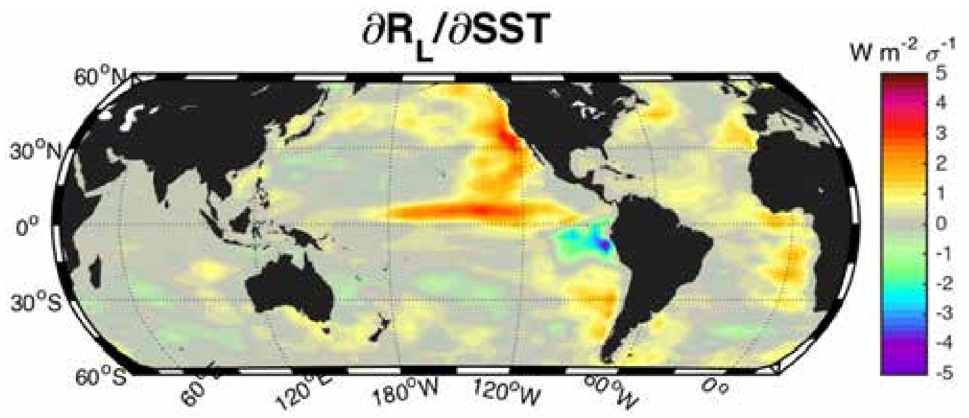


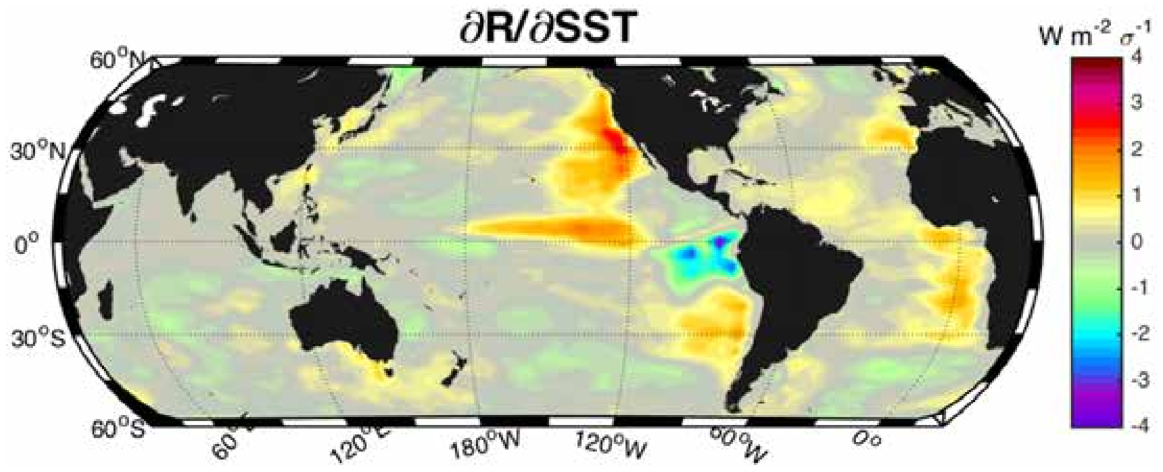
Net Low Cloud Radiative Response to SST

- If obscuring effects of upper clouds are not taken into account, then more energy retained by the climate system for warmer SST
- Could lead to overestimate of positive low-level cloud feedback



Upper level cloud not a predictor





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Define Regions for Averaging

Subsidence stratocumulus

- Cold advection

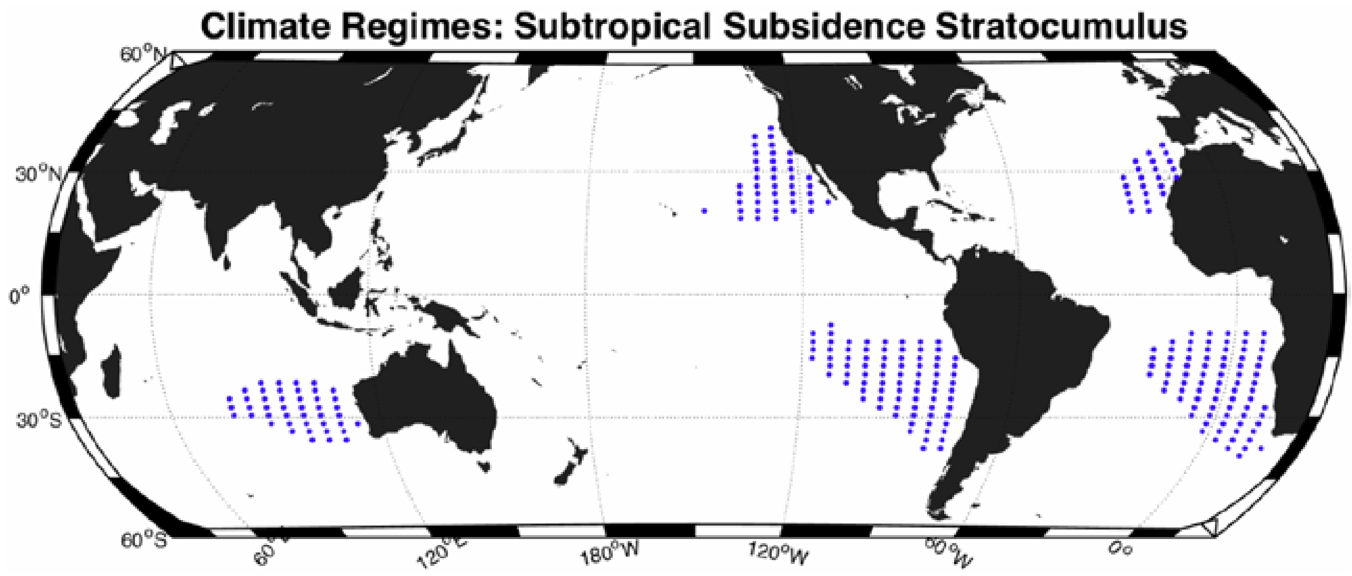
  SSTadv < 0 K day^{-1}

- Strong subsidence

  w_{700} > 25 hPa day^{-1}

- Strong inversion

  EIS > 0.5 K



Define Regions for Averaging

Trade cumulus

- Cold advection

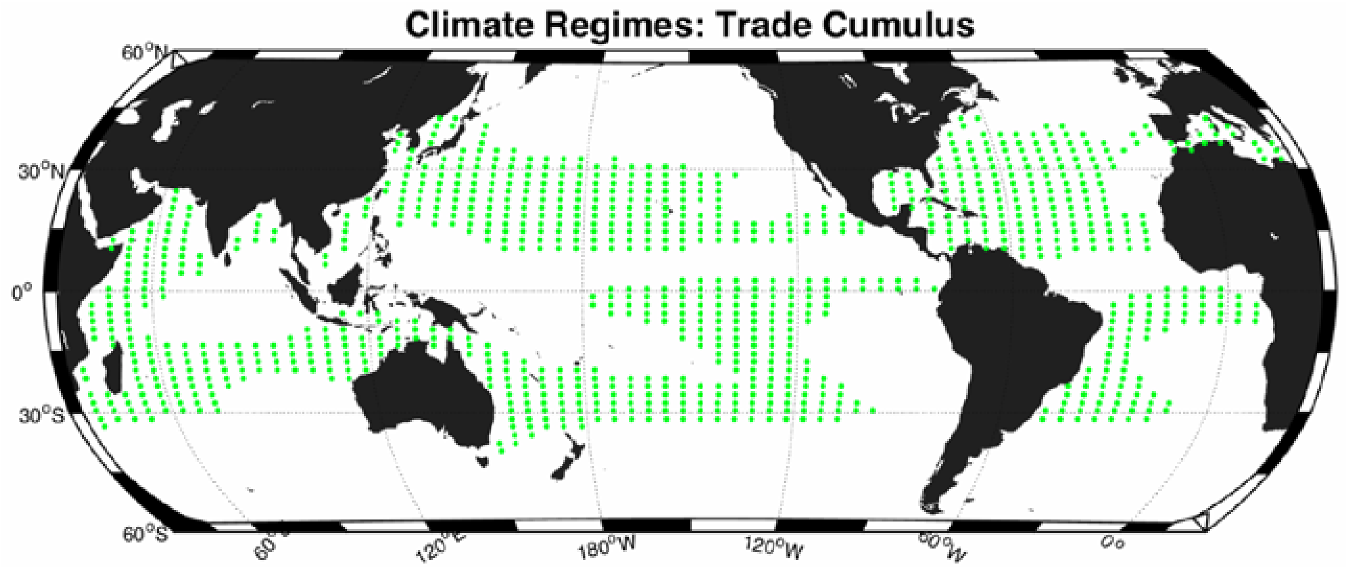
  SSTadv < 0 K day^{-1}

- Weak subsidence

  $-5 < w_{700} < 25$ hPa day^{-1}

- Weak inversion

  $-2 <$ EIS < 0.5 K



Define Regions for Averaging

<u>Deep convection</u>

- Ascent

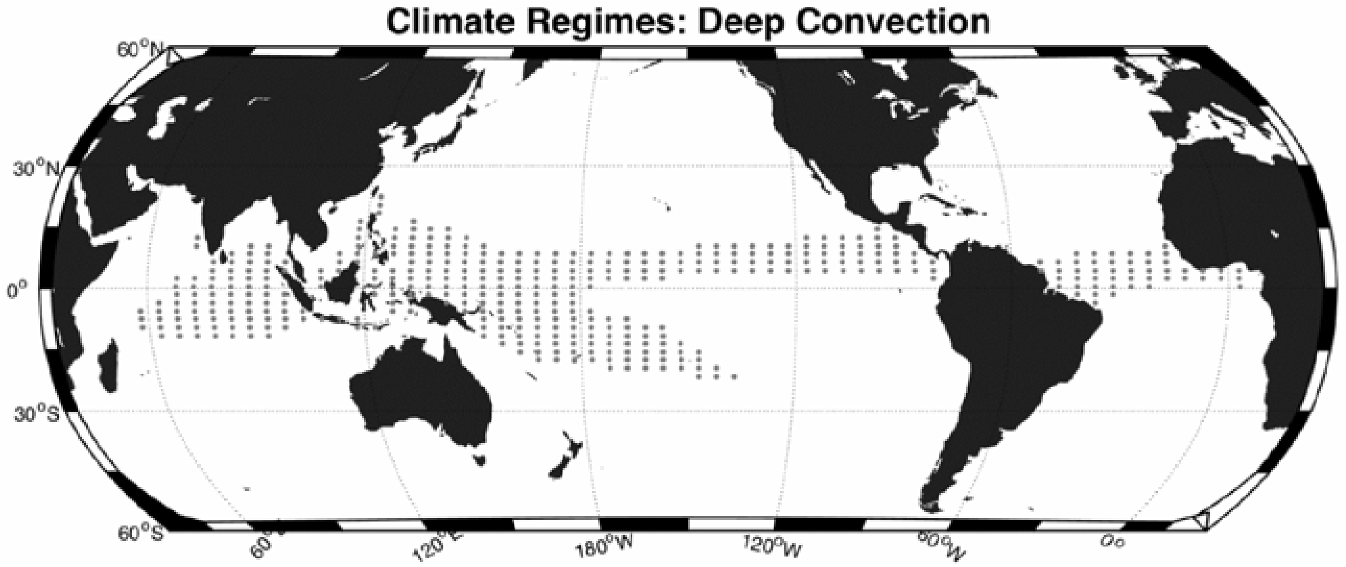
  $w_{700} < -5$ hPa day^{-1}

- No inversion

  EIS < −2 K

- Tropical

  latitude < 30°



Define Regions for Averaging

Midlatitude

- Warm advection

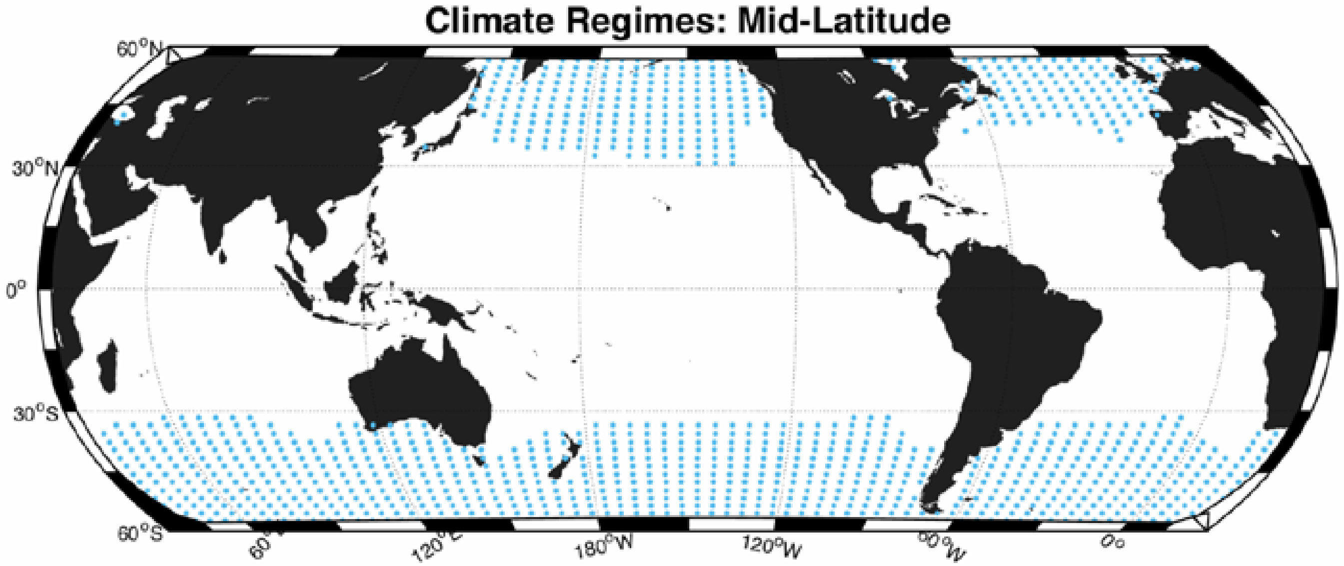
  SSTadv > 0 K day^{-1}

- *And/or* ascent

  $w_{700} < 0$ hPa day^{-1}

- Stable

  EIS > 0 K



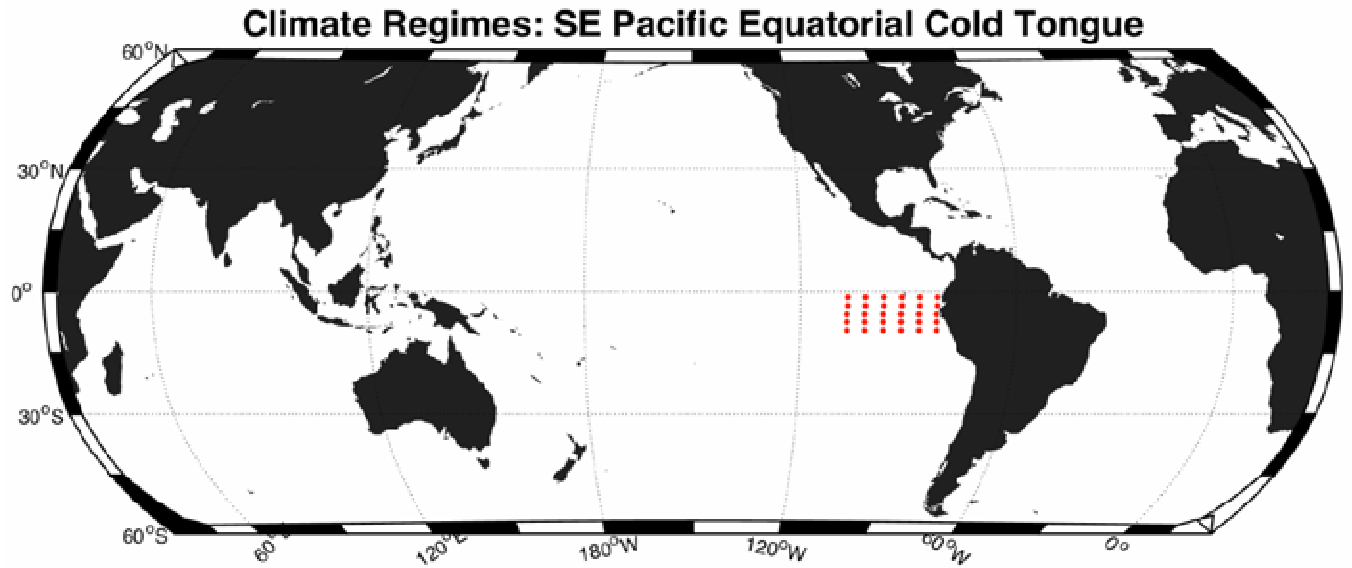
Define Regions for Averaging

Southeastern Pacific cold tongue

- General area of warm advection

  10°S < latitude < 0°

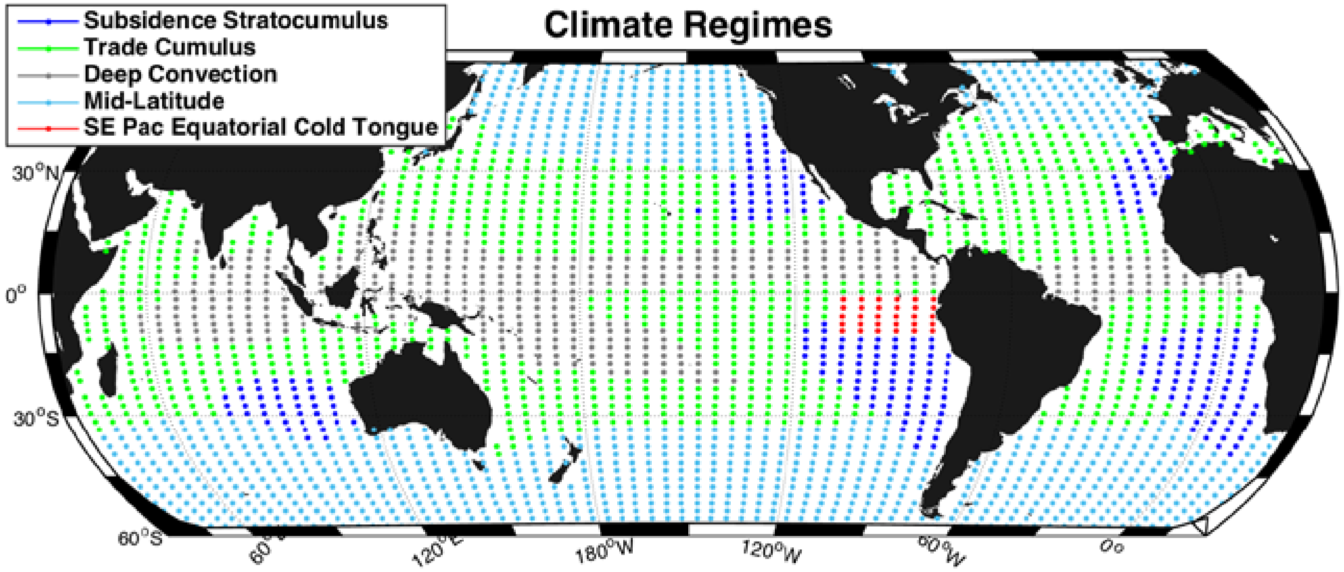
  80°W < longitude < 110°W



Define Regions for Averaging

All regions

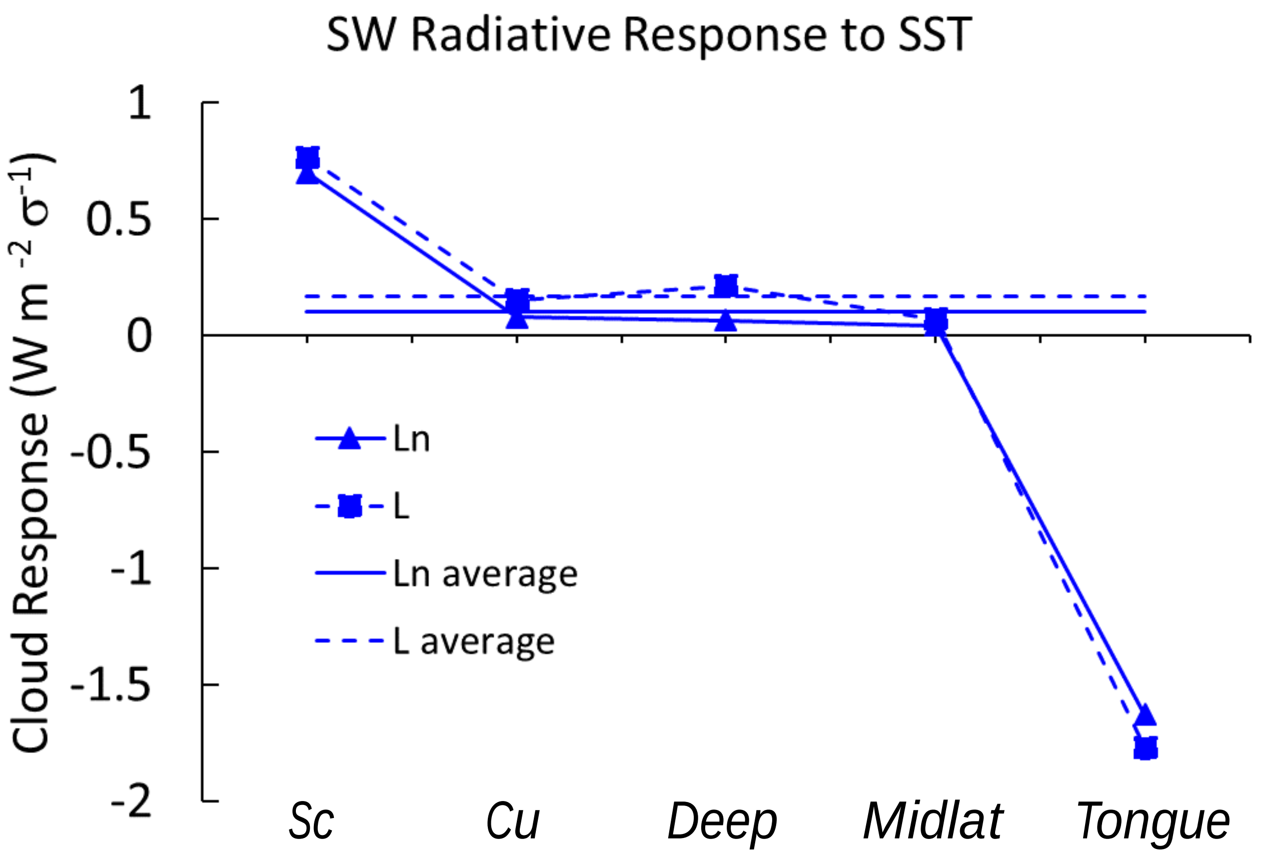
- Subtropical stratocumulus
- Trade cumulus
- Deep convection
- Midlatitude
- Southeastern Pacific cold tongue



Regional Low Cloud Radiative Response (SST)

For warmer SST…

- Stratocumulus regions have largest increase in SW absorption
- Southeastern cold tongue has large decrease in SW absorption
- Trade cumulus, deep convective, and midlatitude regions have very weak increase in SW absorption
- Average ocean has very weak increase in SW absorption



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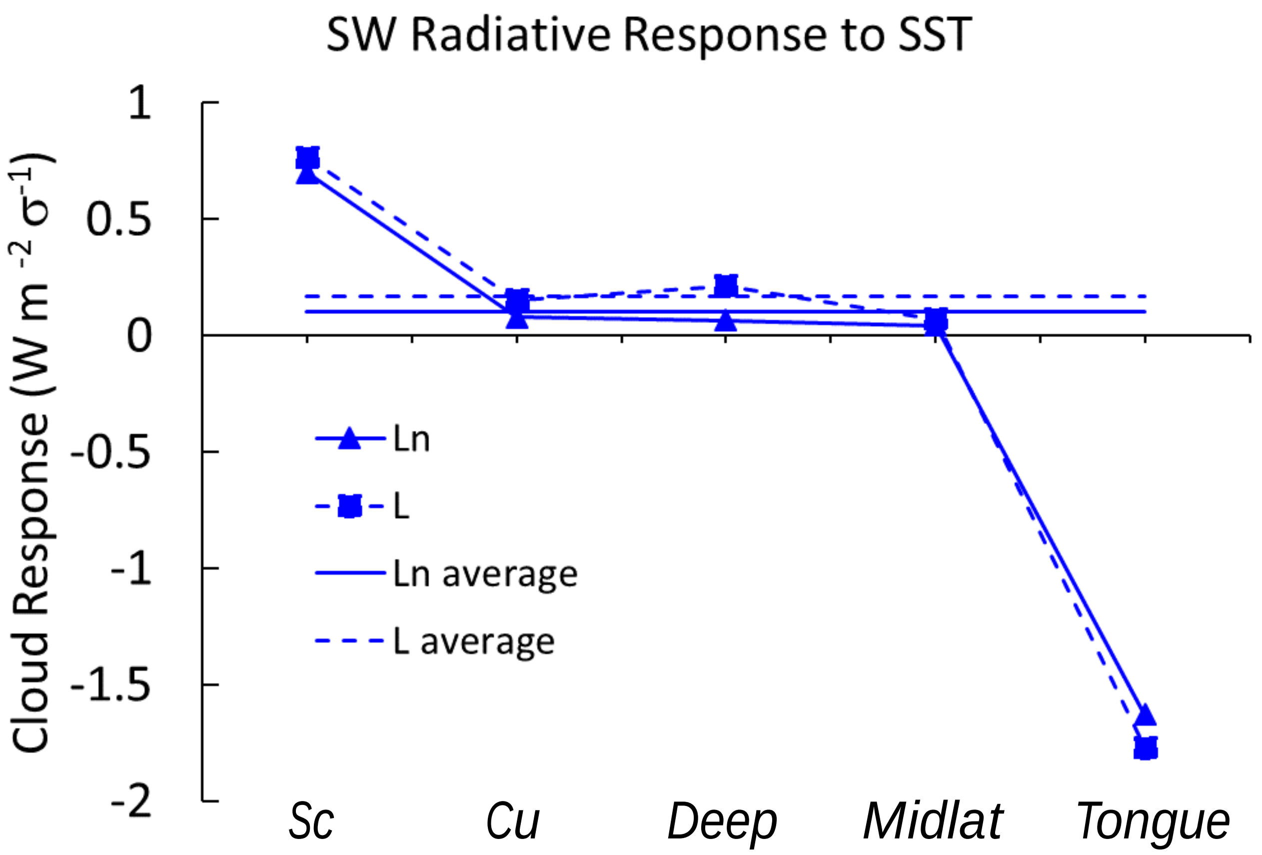
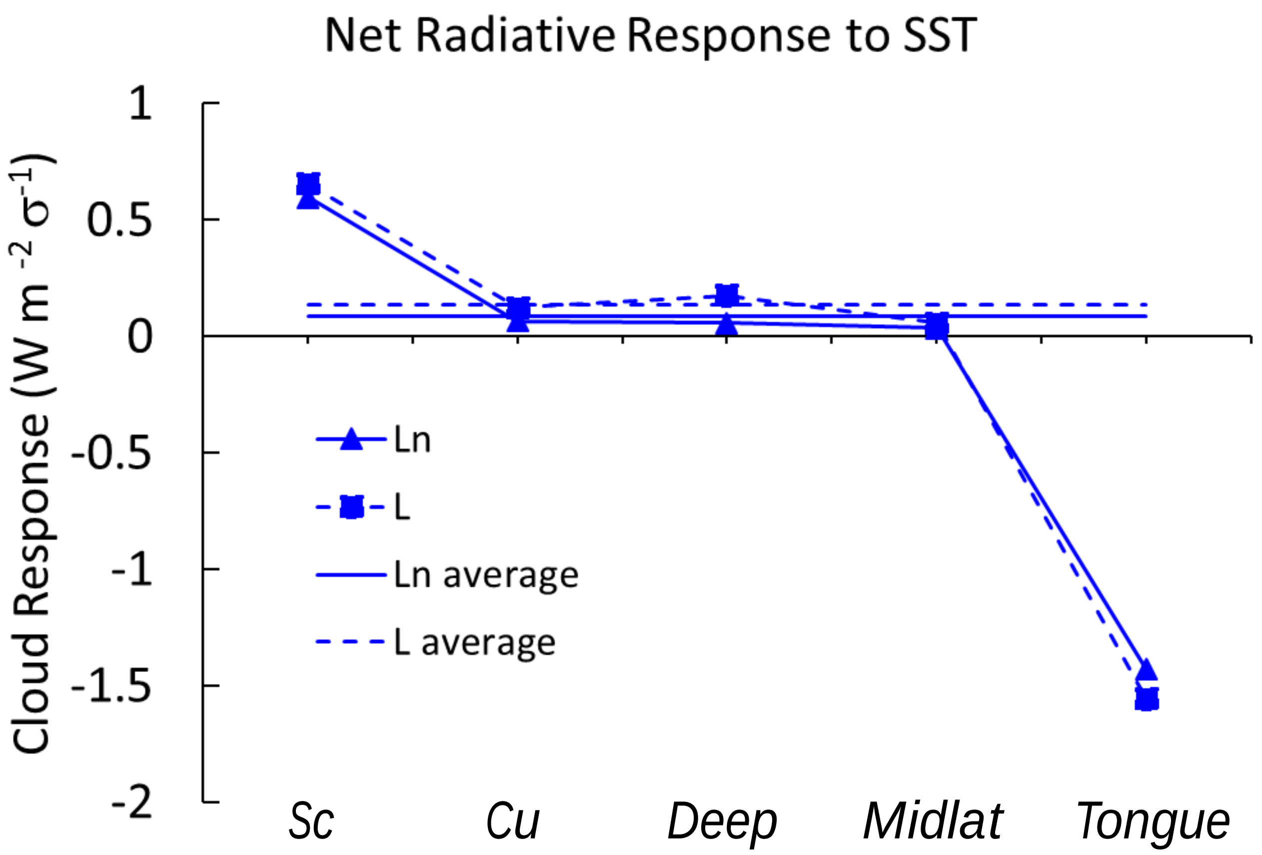
Results of Myers and Norris (2016) are not globally applicable



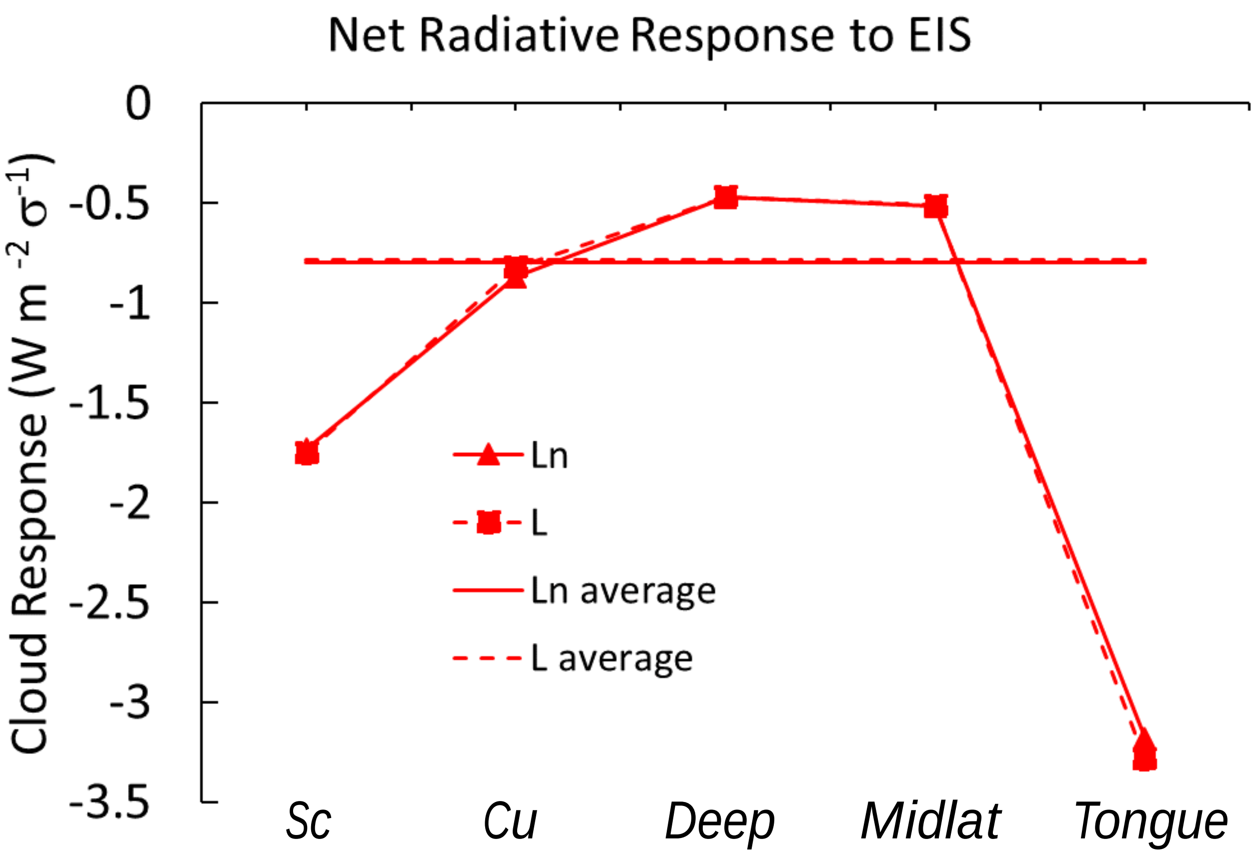
Regional Low Cloud Radiative Response (SST)

- Net energy gain by climate system due to warmer SST
- This is very slightly weaker than SW absorption due to very small offsetting effect of LW



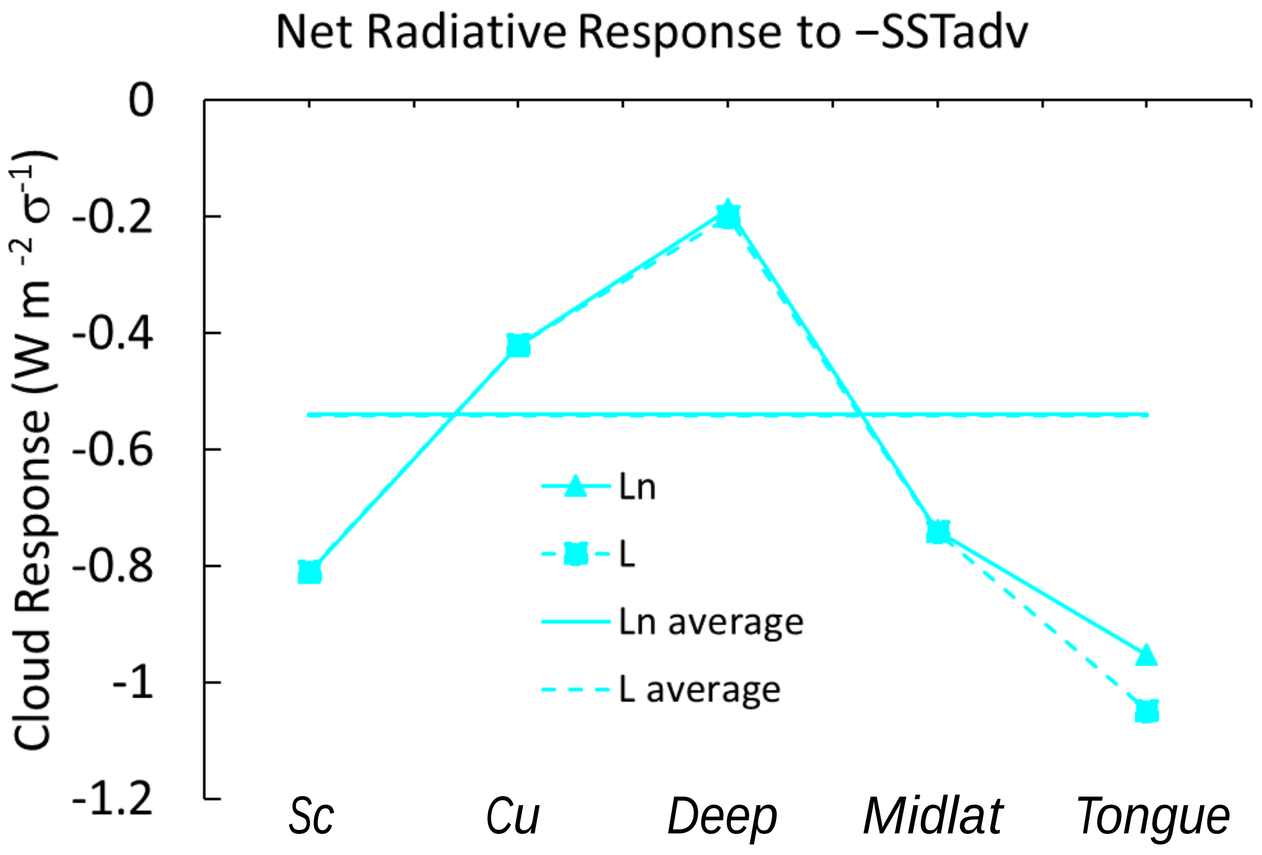
Regional Low Cloud Radiative Response (EIS)

- Net energy loss by climate system due to stronger inversion
- Cloud response is larger for regions with a trade inversion



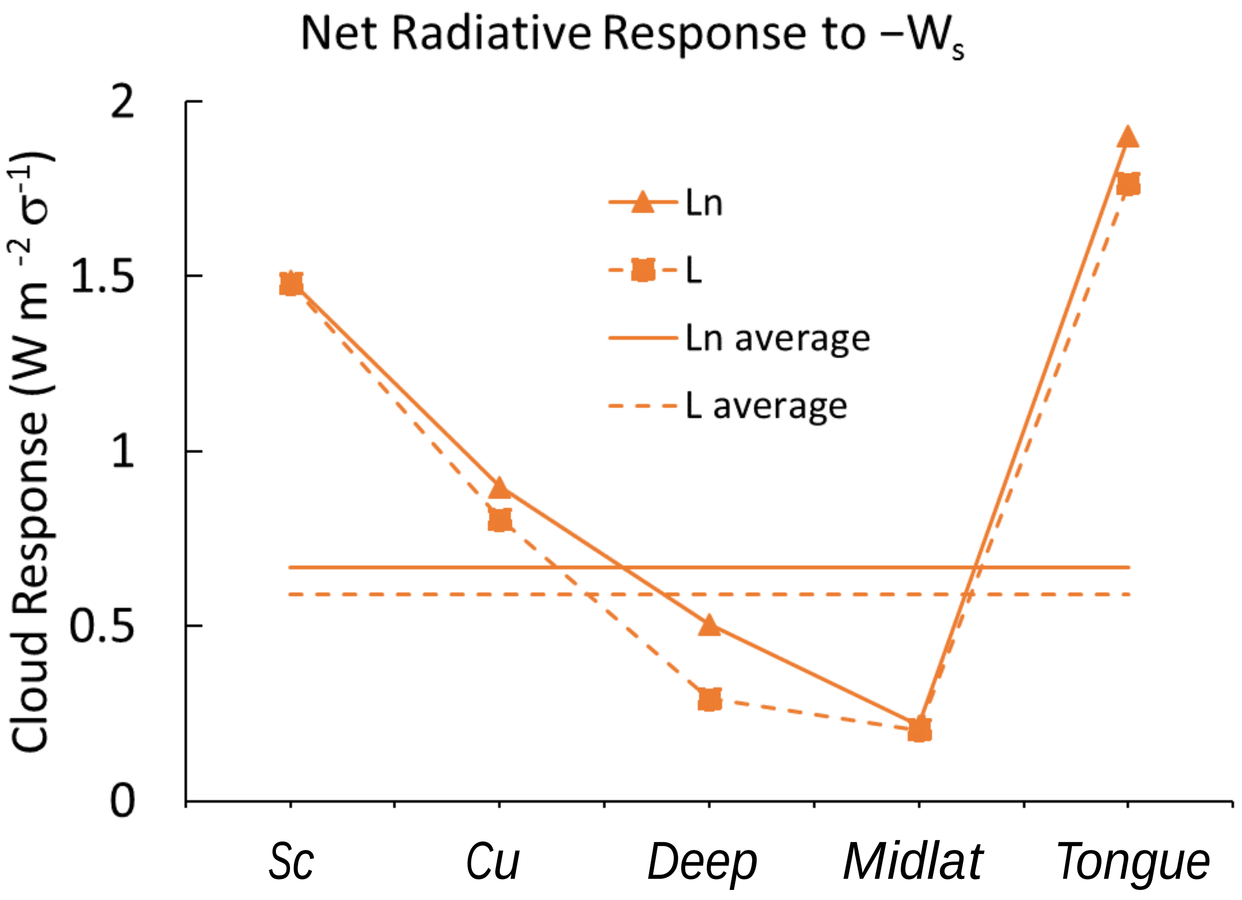
Regional Low Cloud Radiative Response (SSTadv)

- Net energy loss by climate system due to stronger cold advection
- Cloud response is larger for regions with stronger SST gradients



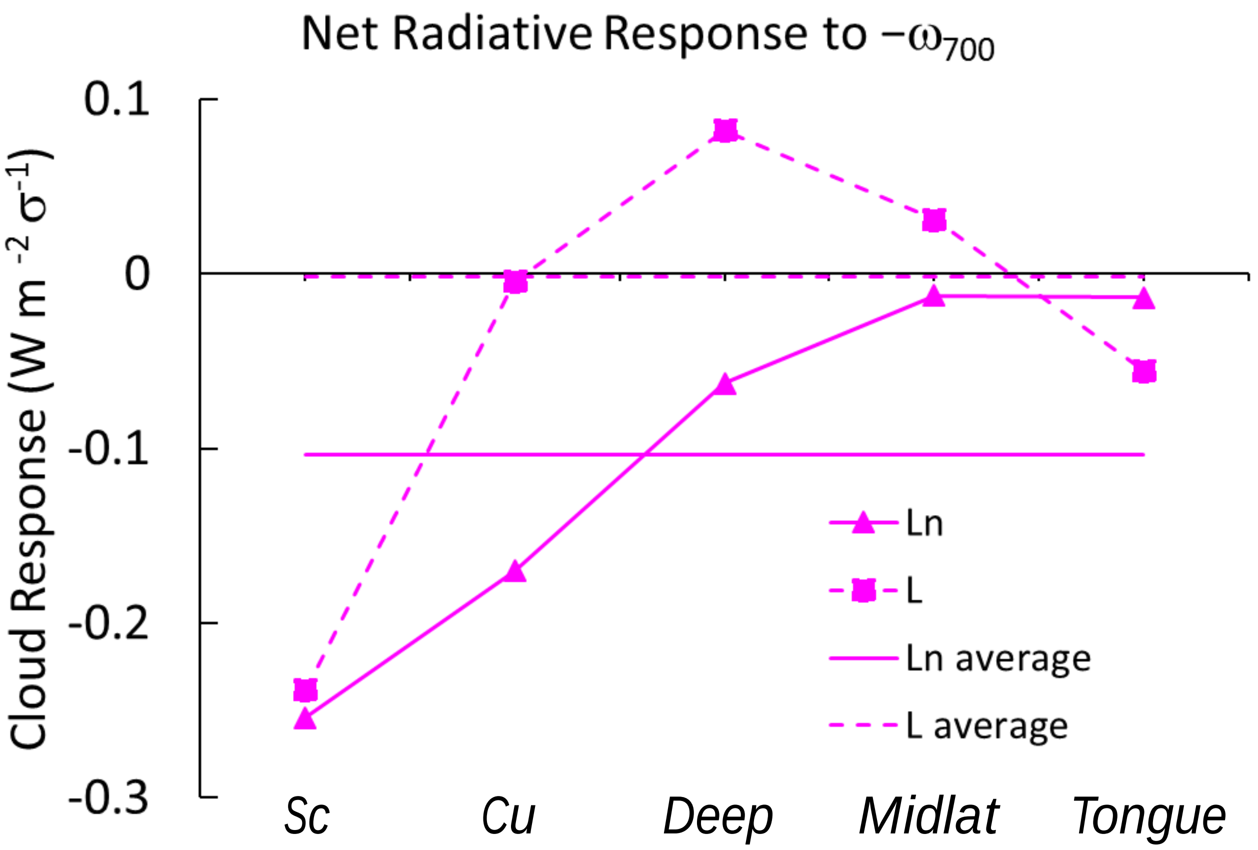
Regional Low Cloud Radiative Response (W_s)

- Net energy gain by climate system due to weaker surface wind
- Cloud response is larger for trade wind regions



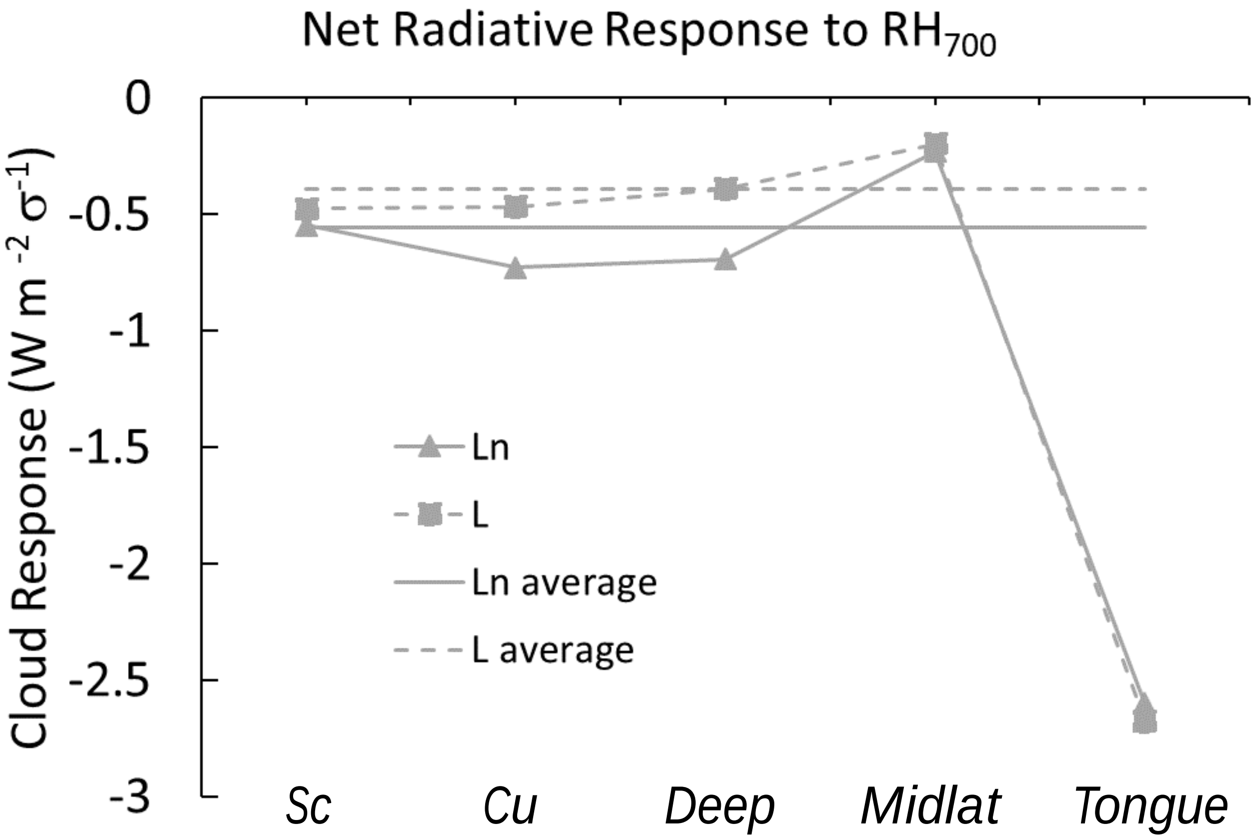
Regional Low Cloud Radiative Response (w_{700})

- Very small or zero net energy loss by climate system due to weaker subsidence (note axis scale)
- Disagreement between two methods for handling obscuration may result from weak signal
- Cloud response is larger for regions dominated by subsidence



Regional Low Cloud Radiative Response (RH_{700})

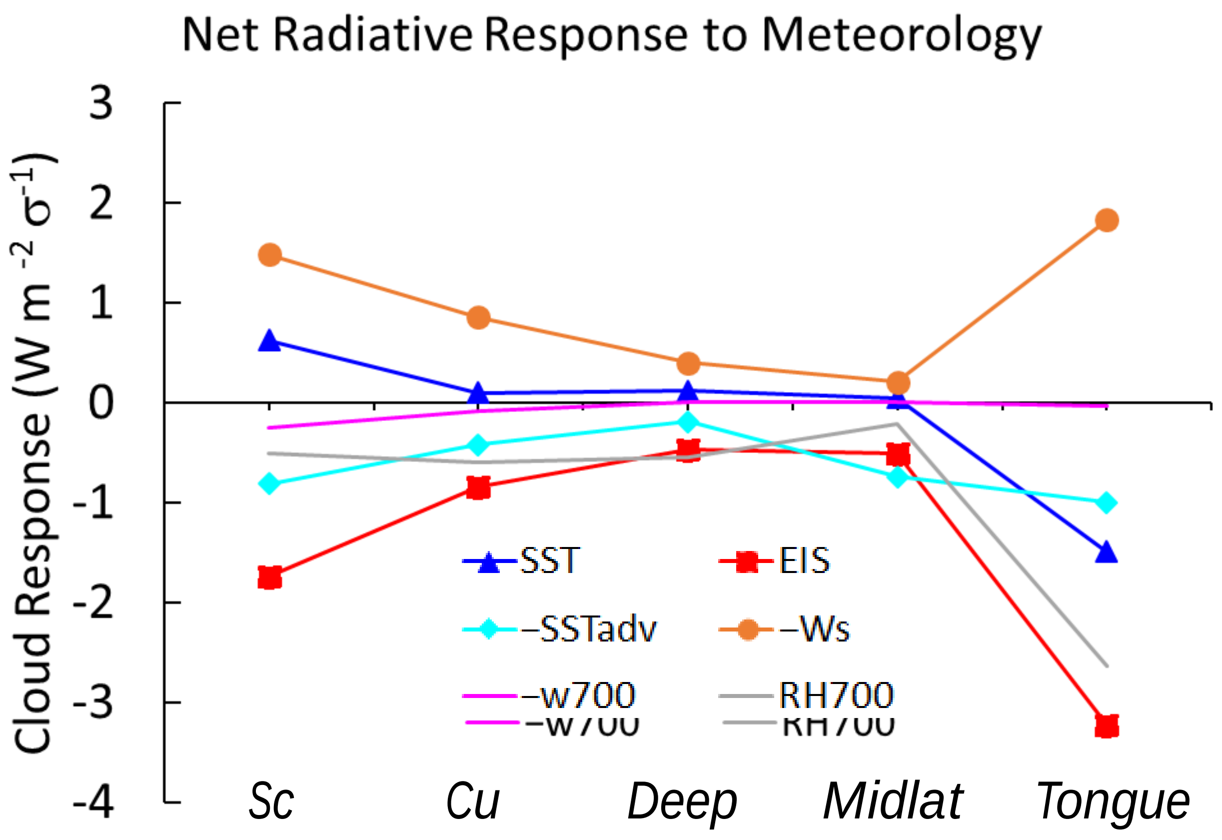
- Net energy loss by climate system due to greater relative humidity above the boundary layer
- Cloud response is much larger south of the eastern equatorial cold tongue where there is near-surface stratification



Regional Low Cloud Radiative Response (All)

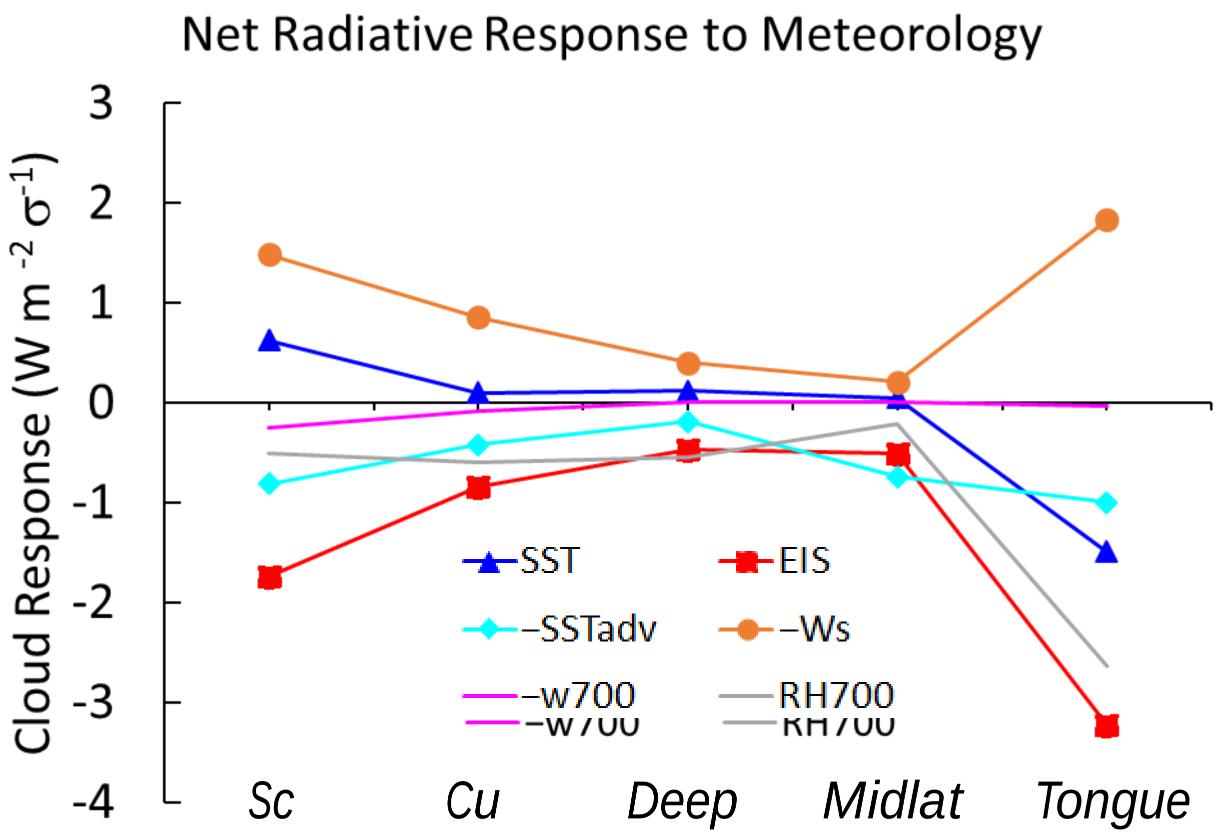
For a meteorological monthly anomaly of typical magnitude…

- Largest cloud radiative response for inversion strength and surface wind speed
- Smallest cloud radiative response for subsidence
- Small cloud radiative response in deep convective and midlatitude regions may be partly due to obscuration by higher clouds



Regional Low Cloud Radiative Response (All)

What about meteorological changes occurring with global warming?



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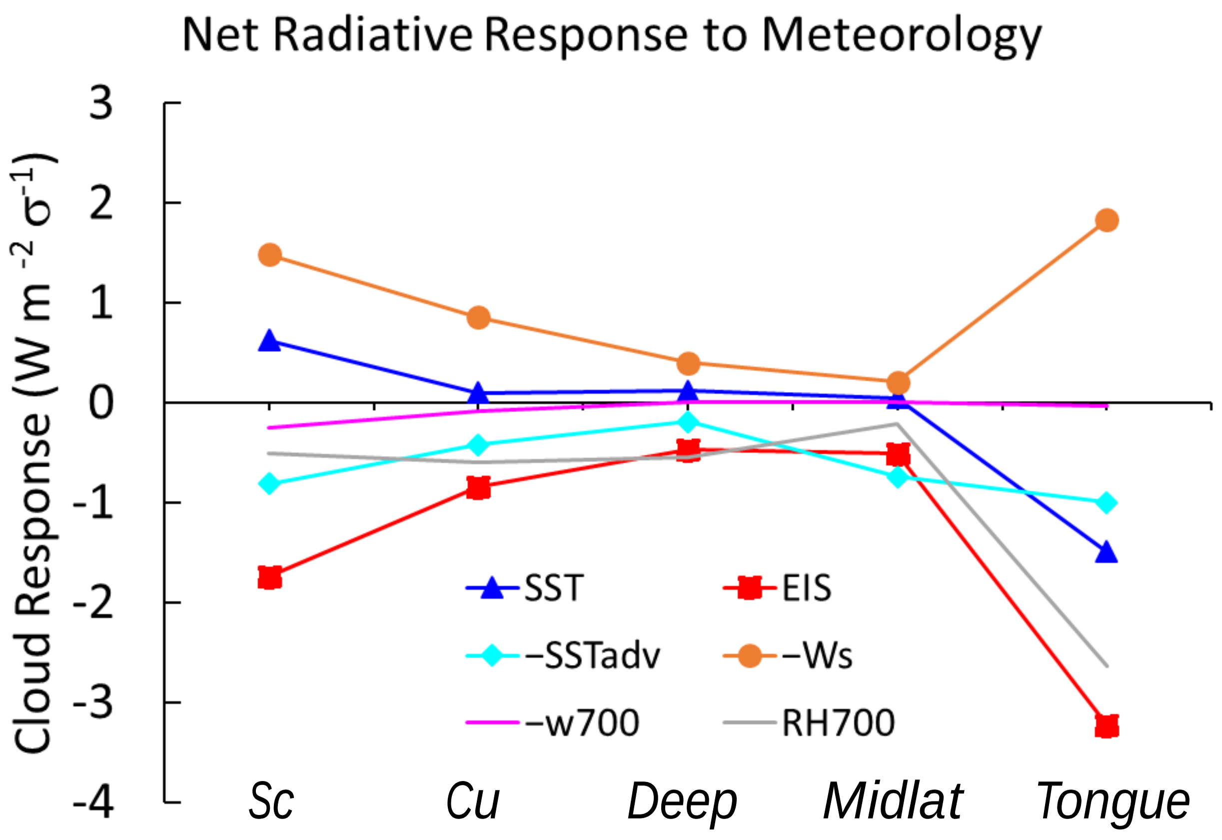
Low-Level Cloud Feedback on Climate

Myers and Norris (2016) suggests the following changes will occur per degree global warming…

(all relative to typical monthly anomaly)

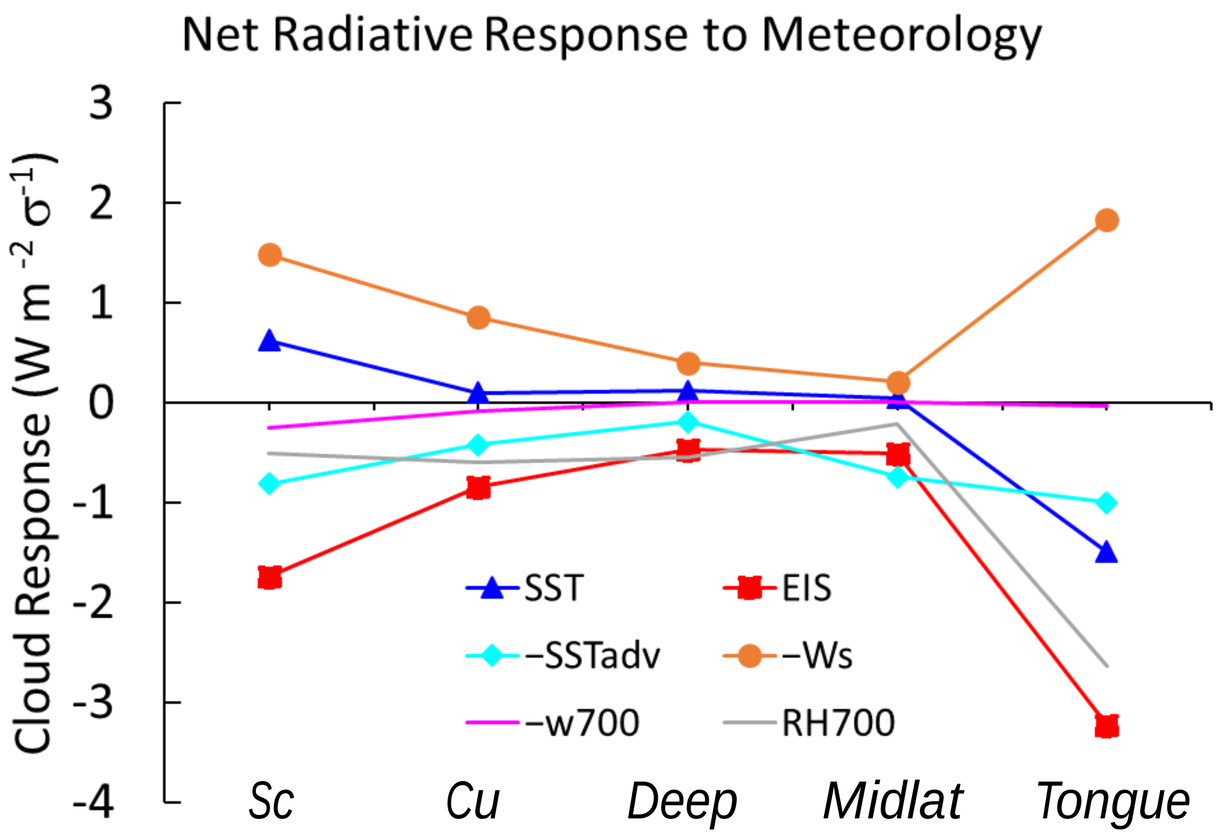


Low-Level Cloud Feedback on Climate

Myers and Norris (2016) suggests the following changes will occur per degree global warming…

(all relative to typical monthly anomaly)

- 1.4× warmer SST

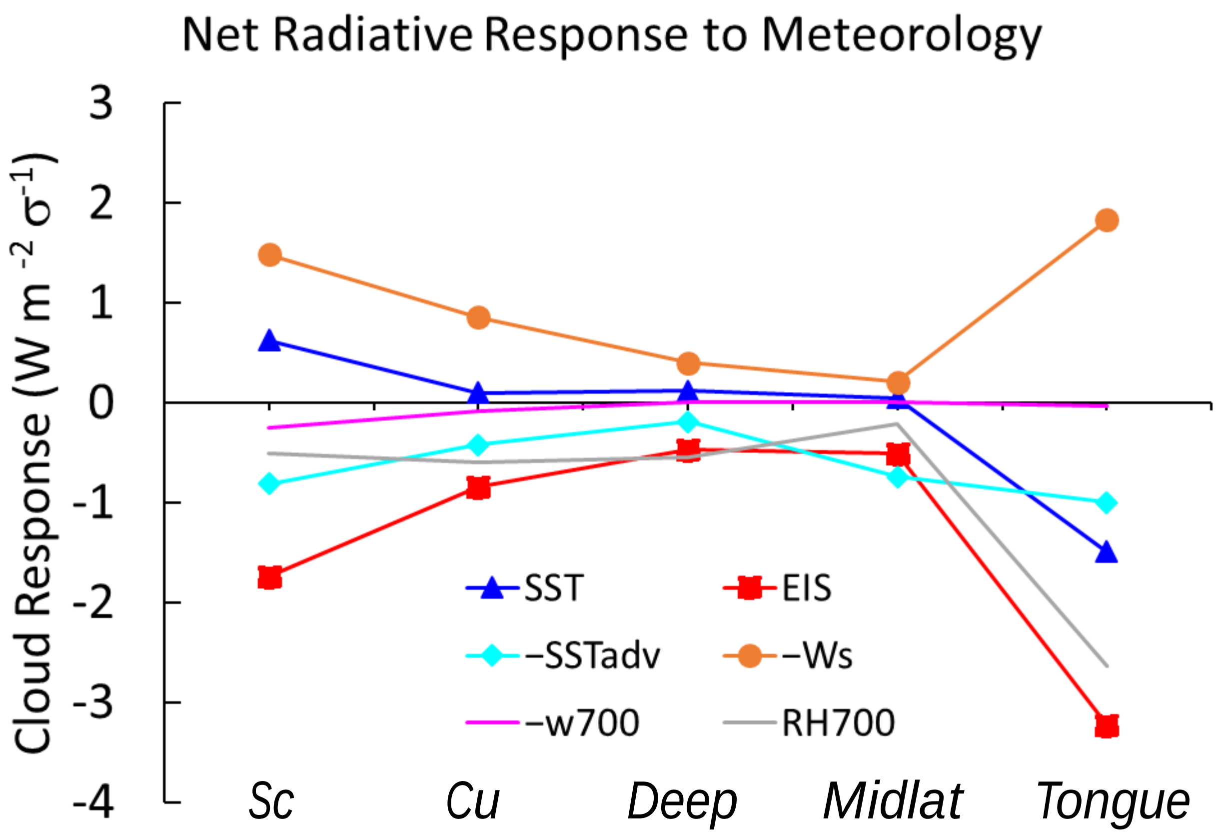


Low-Level Cloud Feedback on Climate

Myers and Norris (2016) suggests the following changes will occur per degree global warming…

(all relative to typical monthly anomaly)

- 1.4× warmer SST
- 0.35× stronger inversion

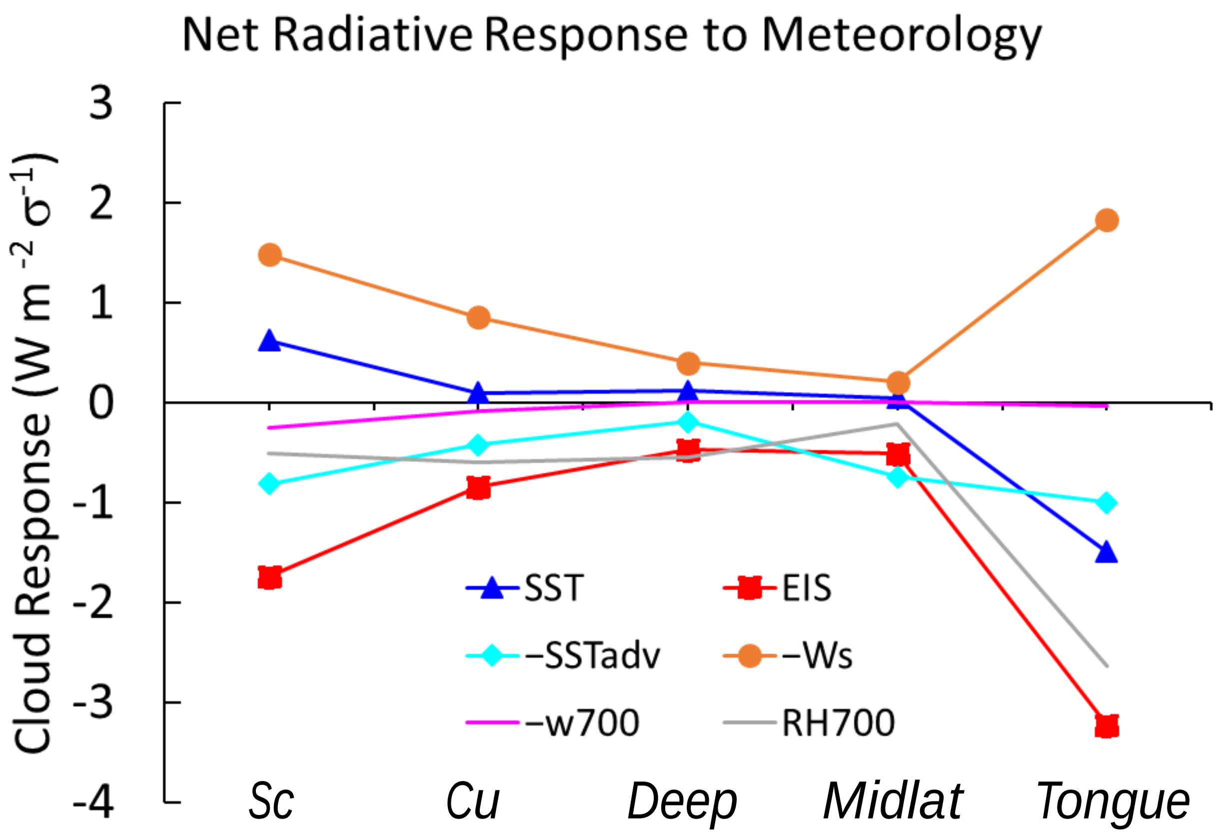


Low-Level Cloud Feedback on Climate

Myers and Norris (2016) suggests the following changes will occur per degree global warming…

(all relative to typical monthly anomaly)

- 1.4× warmer SST
- 0.35× stronger inversion
- 0.05× stronger SST advection
- 0.1× weaker surface wind
- 0.1× weaker subsidence
- 0.05× greater RH_{700}



Low-Level Cloud Feedback on Climate

Myers and Norris (2016) suggests the following changes will occur per degree global warming…

Obtained for subsidence regions; assumed to be globally uniform

- 1.4× warmer SST
- 0.35× stronger inversion
- 0.05× stronger SST advection
- 0.1× weaker surface wind
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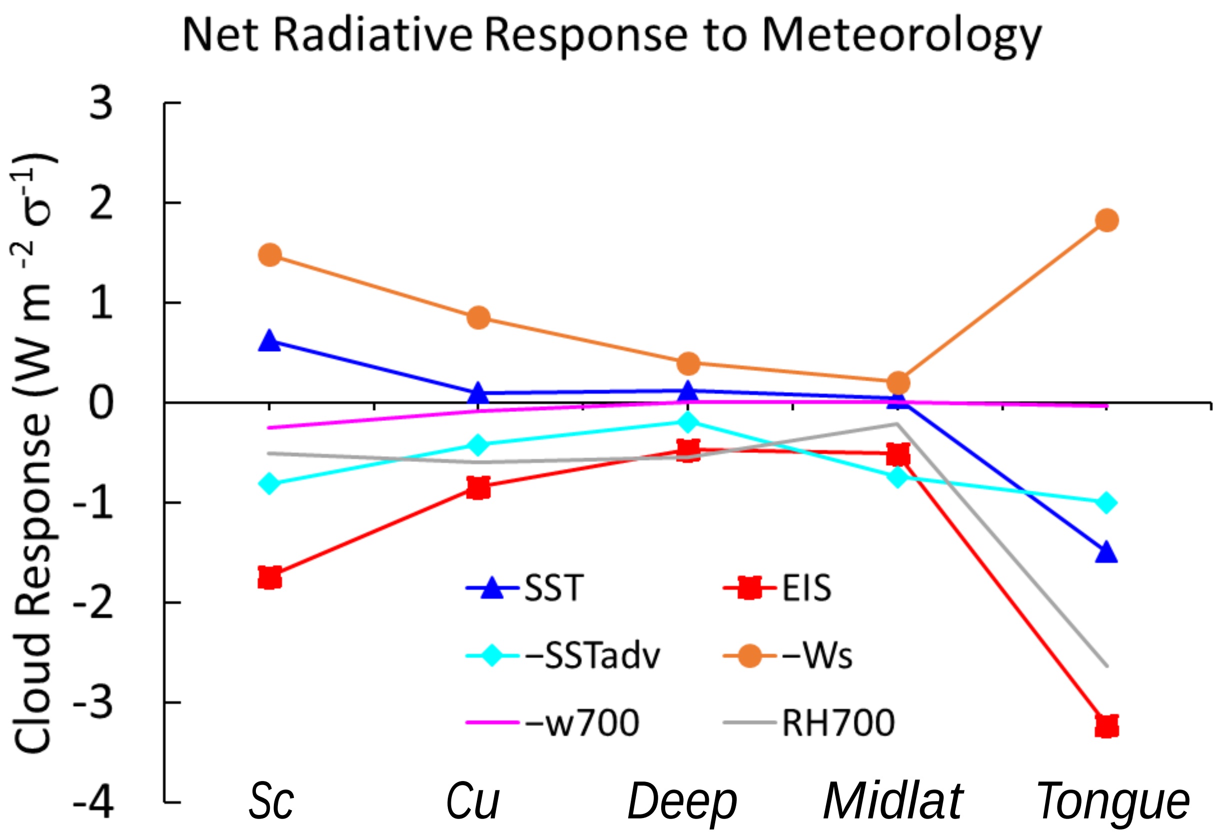
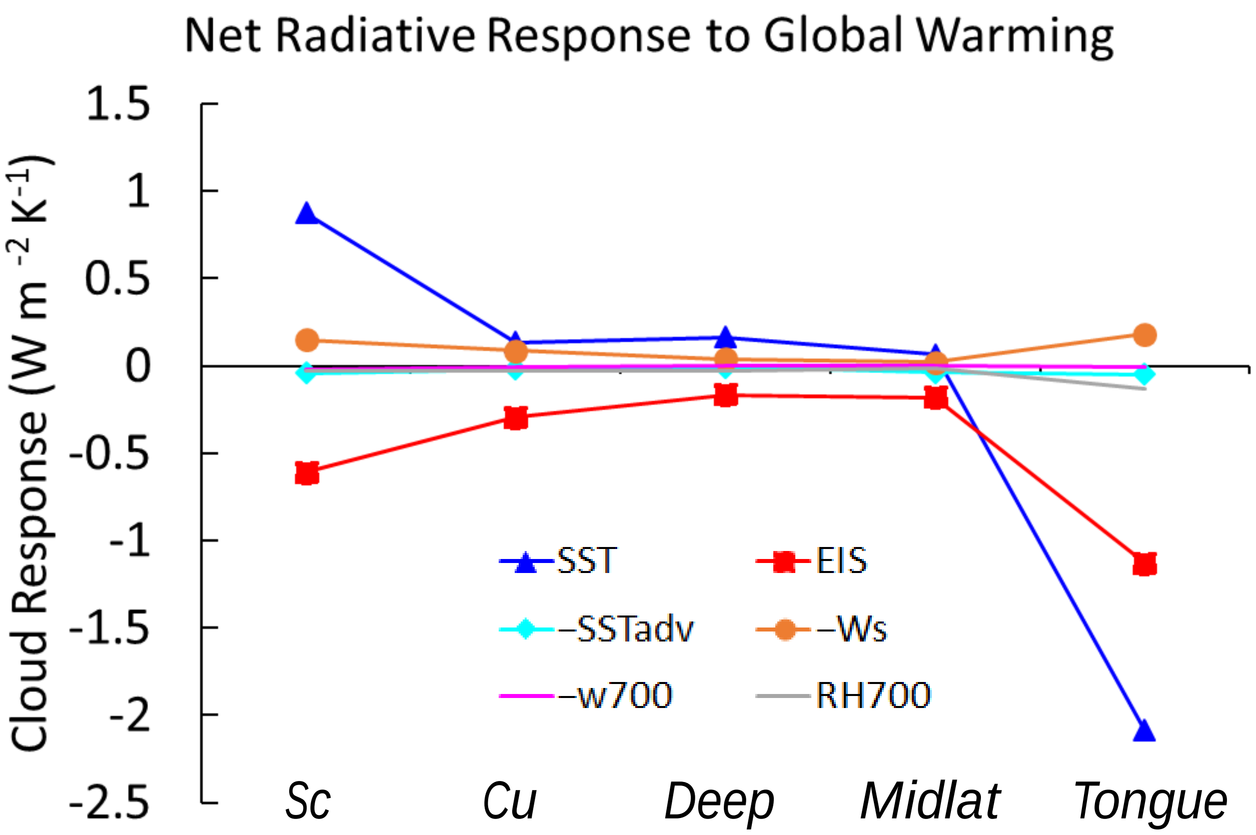
- 0.05× greater RH_{700}



Low-Level Cloud Feedback on Climate

- Positive low-level cloud feedback from warming SST *(except cold tongue)*
- Negative low-level cloud feedback from strengthening inversion
- Effects of other meteorological changes are small



Low-Level Cloud Feedback on Climate

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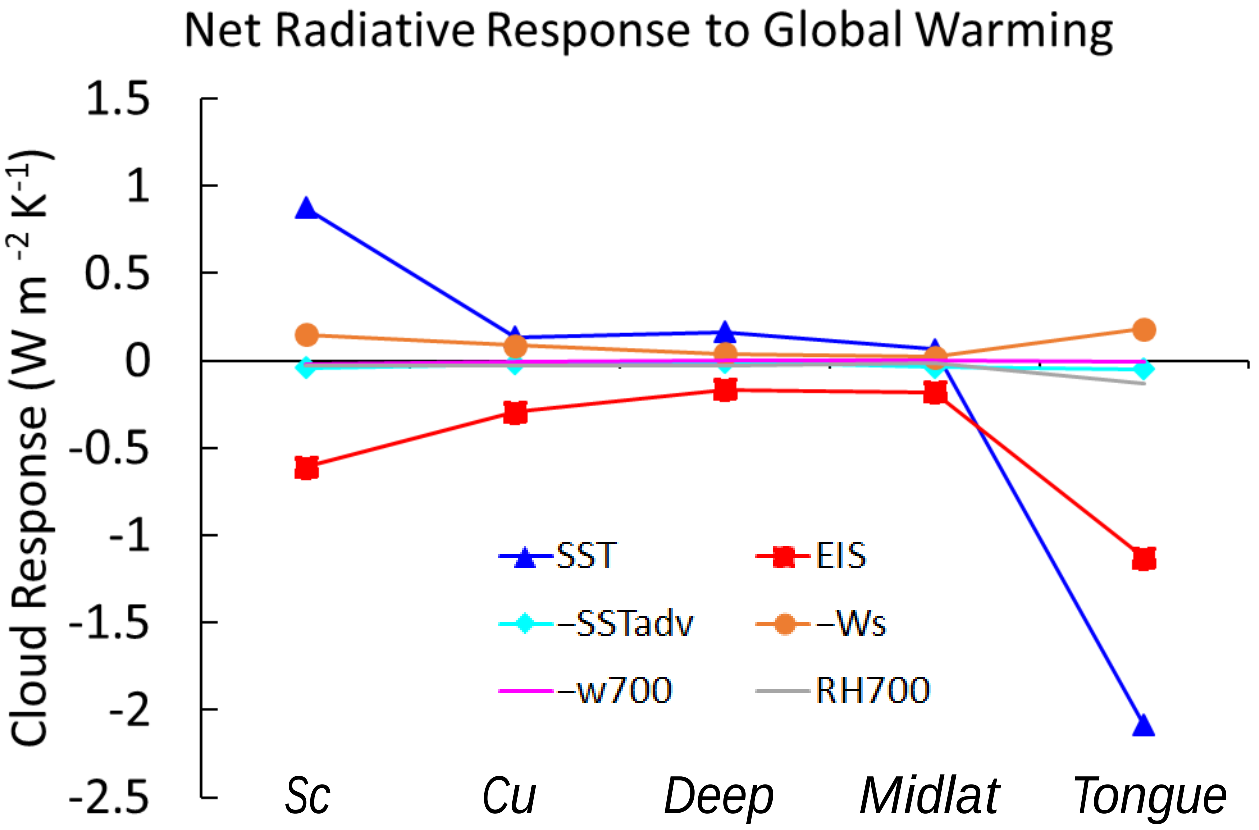
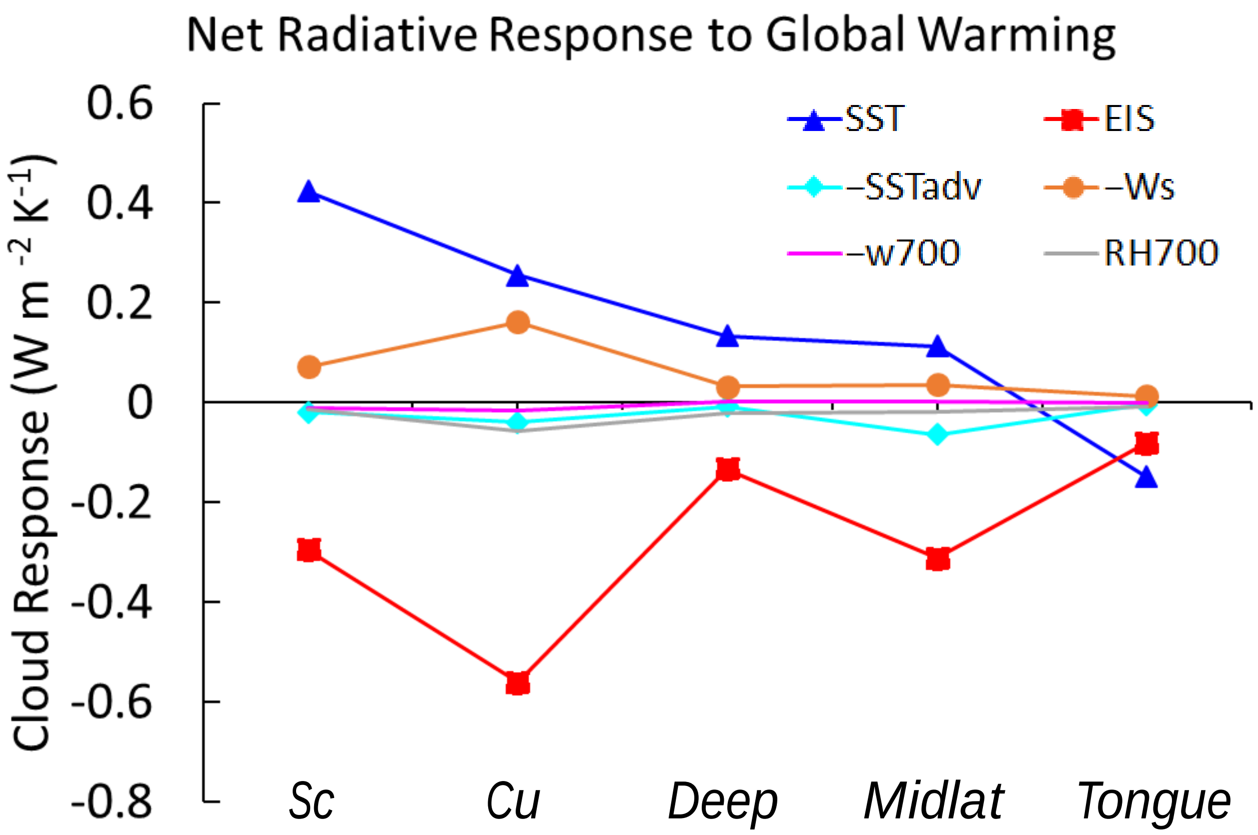
What about differing areal sizes of climate regimes?



Low-Level Cloud Feedback on Climate

After adjustment according to area covered by each climate regime…

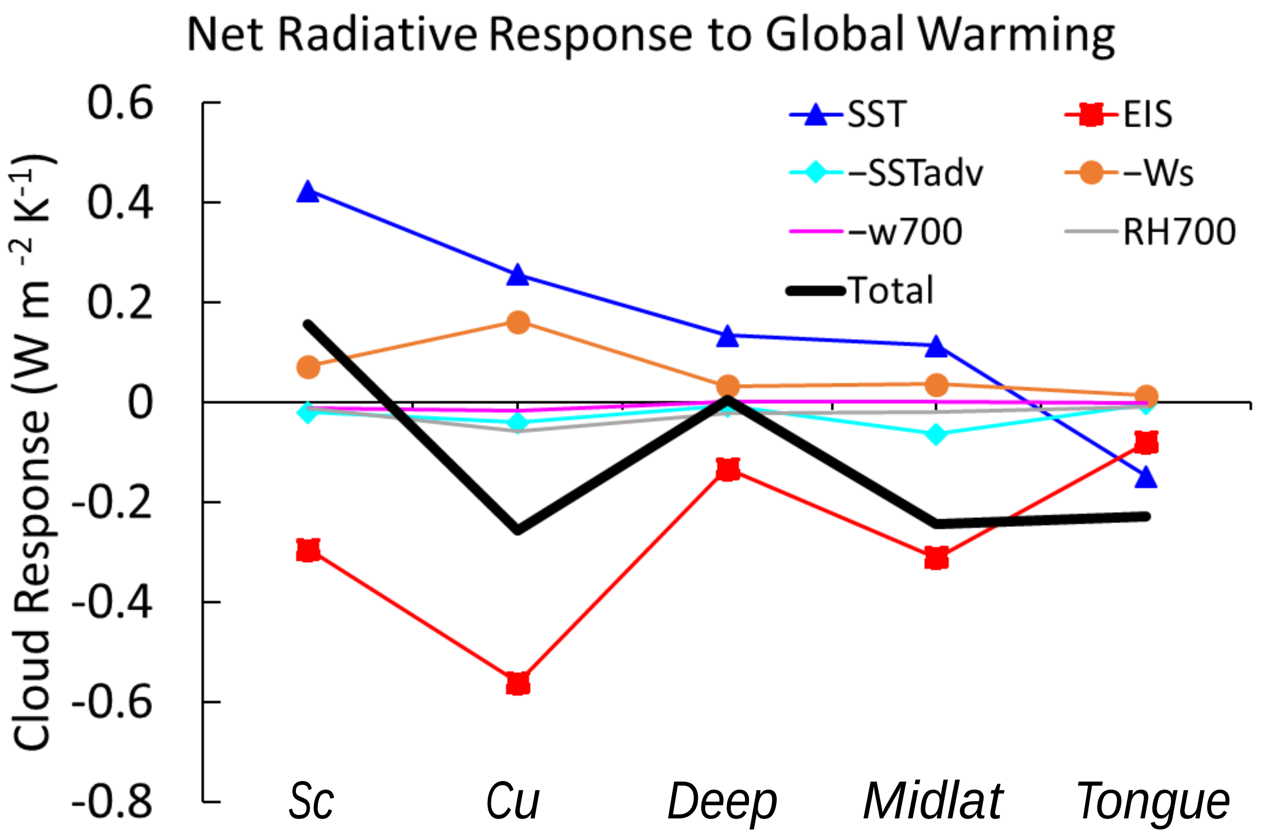
- Stratocumulus regime is relatively less important
- Cold tongue regime is much less important



Low-Level Cloud Feedback on Climate

The total low-level cloud feedback is

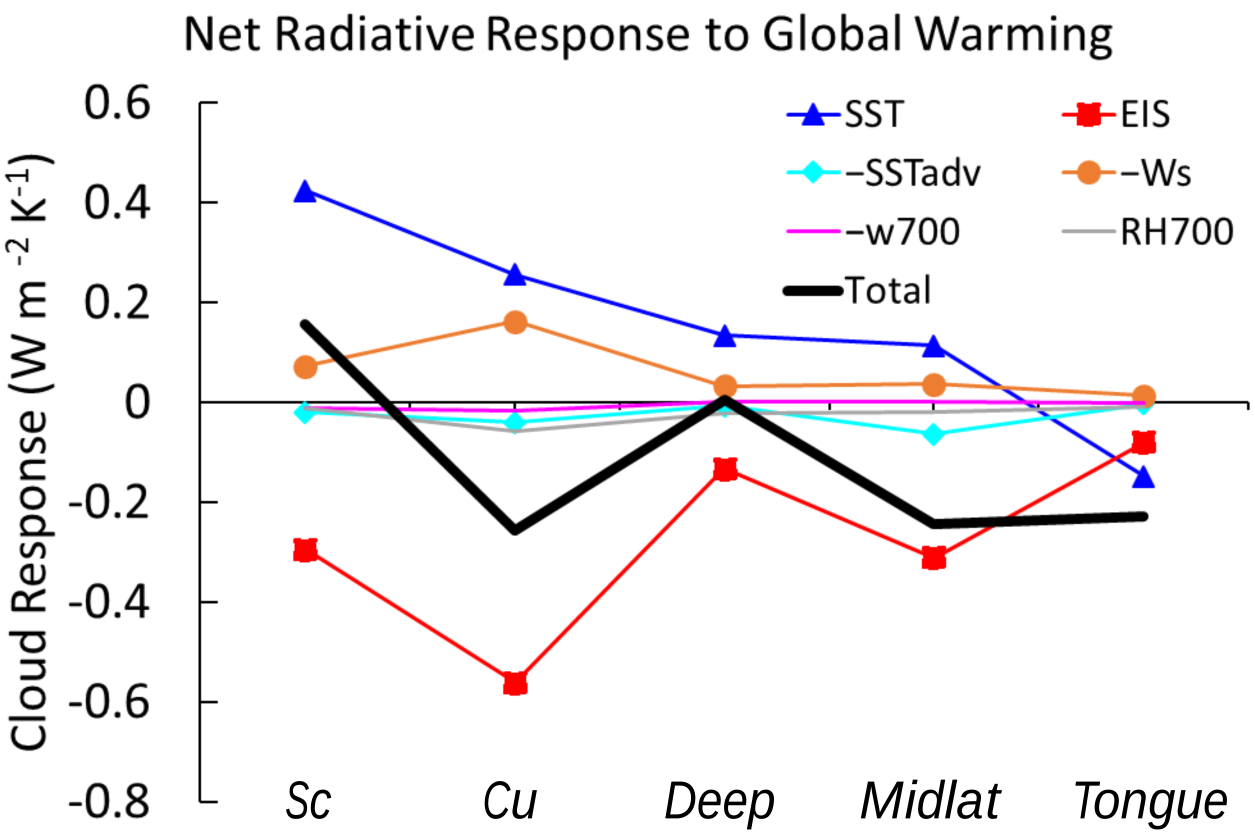
- Positive for stratocumulus regime
- Negative for trade cumulus, midlatitude, and southeastern Pacific cold tongue regimes
- Zero for deep convection regime



Low-Level Cloud Feedback on Climate

The total low-level cloud feedback is

- Positive for stratocumulus regime
- Negative for trade cumulus, midlatitude, and southeastern Pacific cold tongue regimes
- Zero for deep convection regime
- About −0.1 W m $^{-2}$ averaged over the global ocean
- About −0.06 W m $^{-2}$ prorated globally – *essentially zero*



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- Discussion and summary – shortcomings, uncertainties, and conclusions

Known Shortcomings

Did not examine changes in cloud optical thickness

- Data are available
- Low-level cloud optical thickness feedback likely reinforces cloud fraction feedback

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Did not examine changes in cloud optical thickness

- Data are available
- Low-level cloud optical thickness feedback likely reinforces cloud fraction feedback

Projected 4xCO2 changes in SST and EIS from subsidence regime may not apply globally

- SST warming probably larger outside of stratocumulus regions
- EIS strengthening probably weaker outside of stratocumulus regions
- Estimated low-level cloud feedback is likely too negative

Uncertainties

Adjustment of low-level clouds for obscuring upper clouds assumes zero correlation

- Strong agreement between two approaches is reassuring
- Low and upper clouds probably preferentially co-occur in deep convective regions
- But deep convective region not so important due to widespread obscuration

Uncertainties

Adjustment of low-level clouds for obscuring upper clouds assumes zero correlation

- Strong agreement between two approaches is reassuring
- Low and upper clouds probably preferentially co-occur in deep convective regions
- But deep convective region not so important due to widespread obscuration

Monthly means average over daily variability, especially at midlatitudes

- Can be investigated using multi-day means

Uncertainties

Adjustment of low-level clouds for obscuring upper clouds assumes zero correlation

- Strong agreement between two approaches is reassuring
- Low and upper clouds probably preferentially co-occur in deep convective regions
- But deep convective region not so important due to widespread obscuration

Monthly means average over daily variability, especially at midlatitudes

- Can be investigated using multi-day means

What is the uncertainty range for coefficients derived from multilinear regression?

- Can be calculated using standard methods

Conclusions

Satellite combined with meteorology helps provide the best low cloud feedback estimate

- Empirical observation of cloud response to meteorological forcing
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Subtropical stratocumulus exerts a strong positive feedback, but…

- Not representative of trade cumulus and midlatitude cloud
- Only covers a relatively small area of Earth

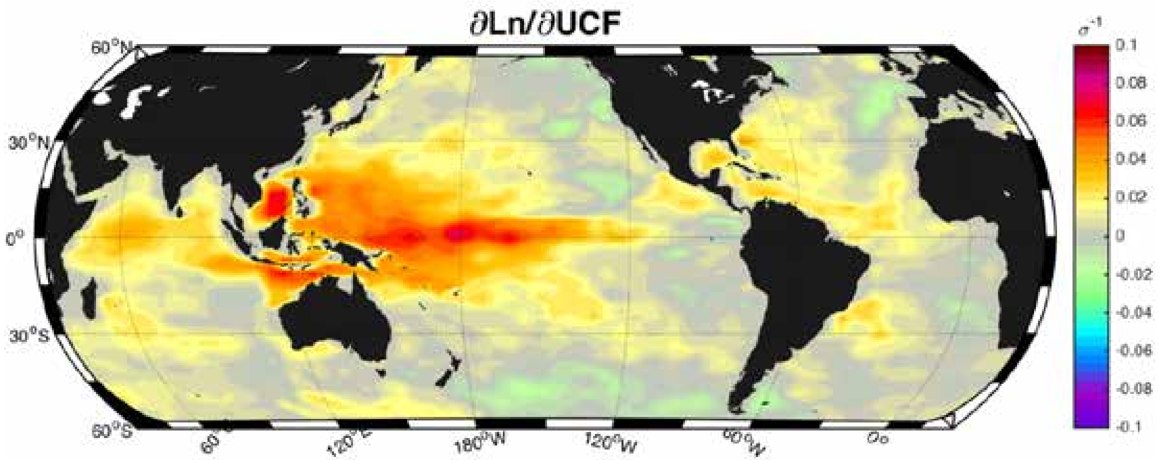
See you in 10 years!

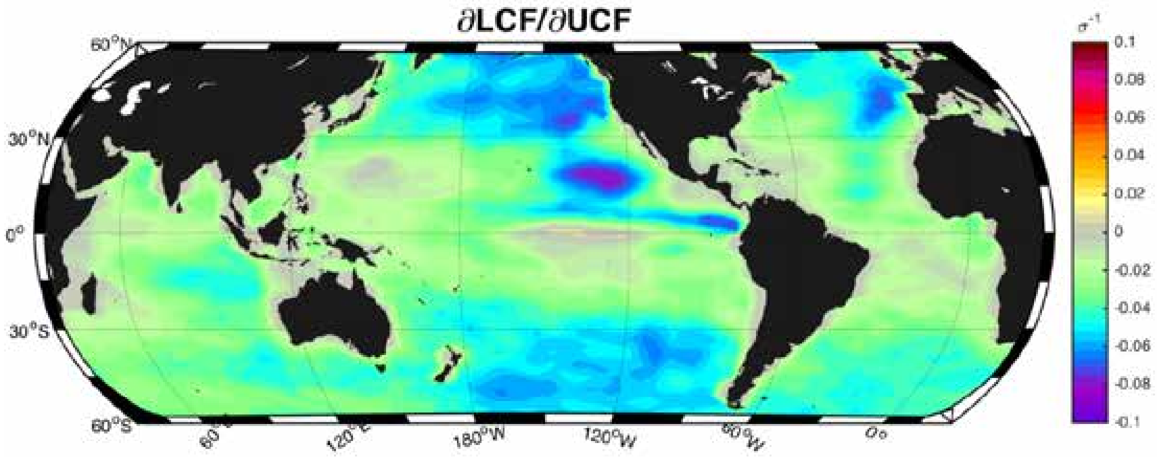
(and sooner)

Extra Slides

Observed Low Cloud Response to Upper Cloud

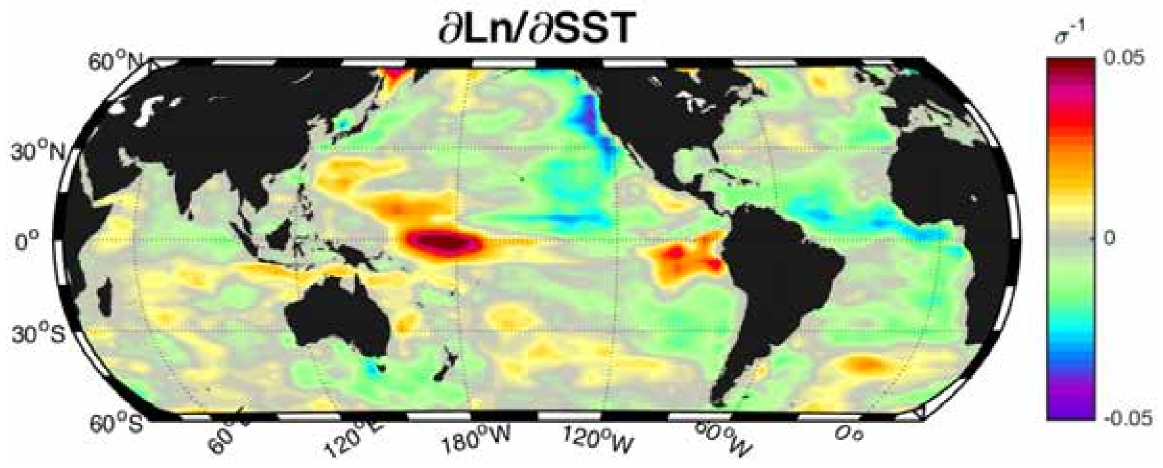
- ***L_n′*** has near-zero response to upper cloud as a predictor over most of global ocean, as expected if there is no correlation between ***L_n′*** and ***U′***
- ***L_n′*** increases with upper cloud in western tropical Pacific, suggesting that actual low-level cloud increases with upper-level cloud in that region
- ***L′*** decreases in response to upper cloud as a predictor over most of global ocean, as expected if increasing upper-level cloud obscures more low-level cloud





Adjusted Low Cloud Response to SST

Without ***U'*** as a predictor



With ***U'*** as a predictor