Constraining Long-Term Boundary Layer Cloud Feedback with Interannual Observations

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Constraining BL Cloud Feedback

Challenge:

- BL clouds have a strong radiative impact due to solar reflection and weak greenhouse effect

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- Climate models *disagree* on BL cloud response to changes in meteorological "controlling factors"
- Climate models *agree* on how meteorological "controlling factors" will change due to global warming

- ***Solution:*** multiply observed cloud response to controlling factors to model-projected change in controlling factors

Constraining BL Cloud Feedback

Leading order Taylor expansion®

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

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

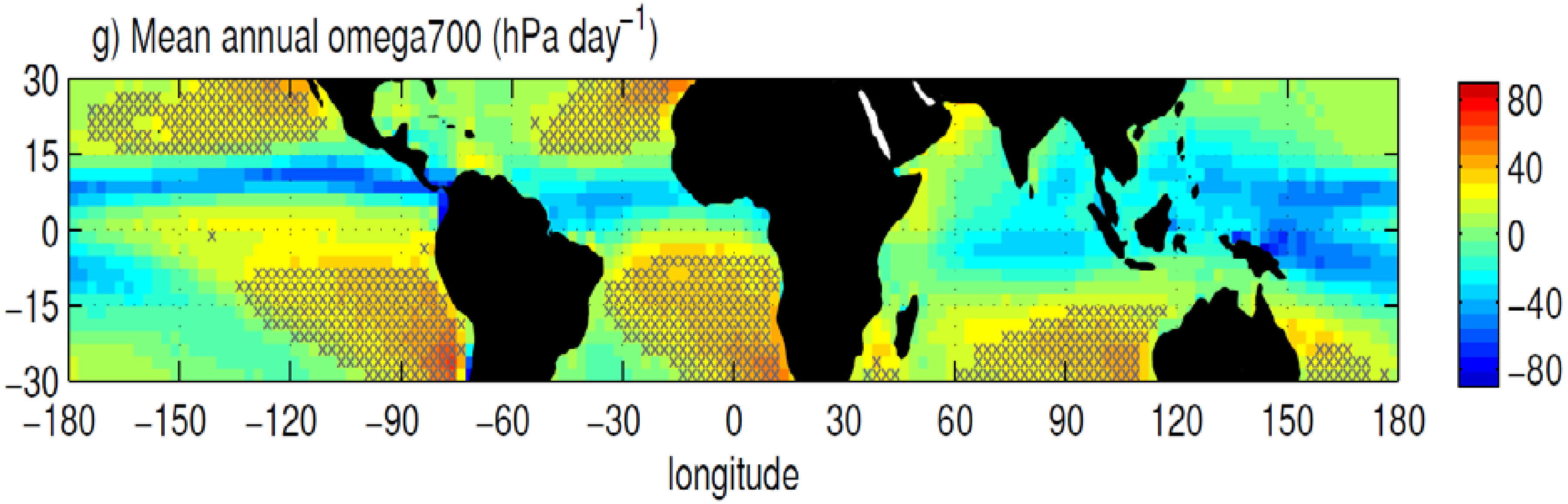
- SW cloud response coefficients (red) obtained from multi-linear regression on satellite and reanalysis data
- Changes in controlling factors caused by global warming (blue) obtained from climate model projections for 4xCO2 warming

Analysis Domain

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

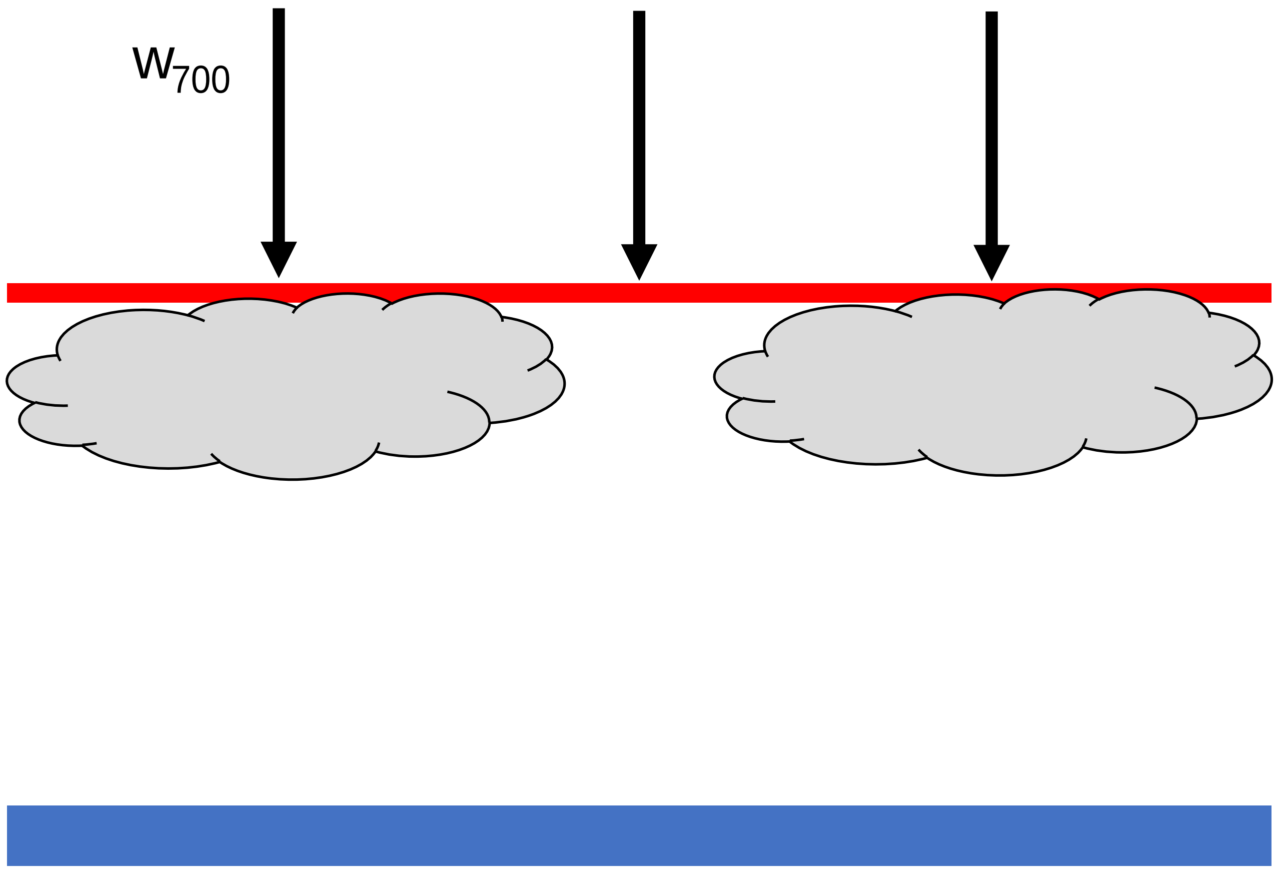
- Minimizes confounding effects of high clouds
- But more weighting on stratocumulus and less weighting on trade cumulus
- Neglects land and midlatitude BL cloud

hatching indicates domain of analysis



BL Cloud Response to Controlling Factors

BL cloud is capped by a subsidence inversion

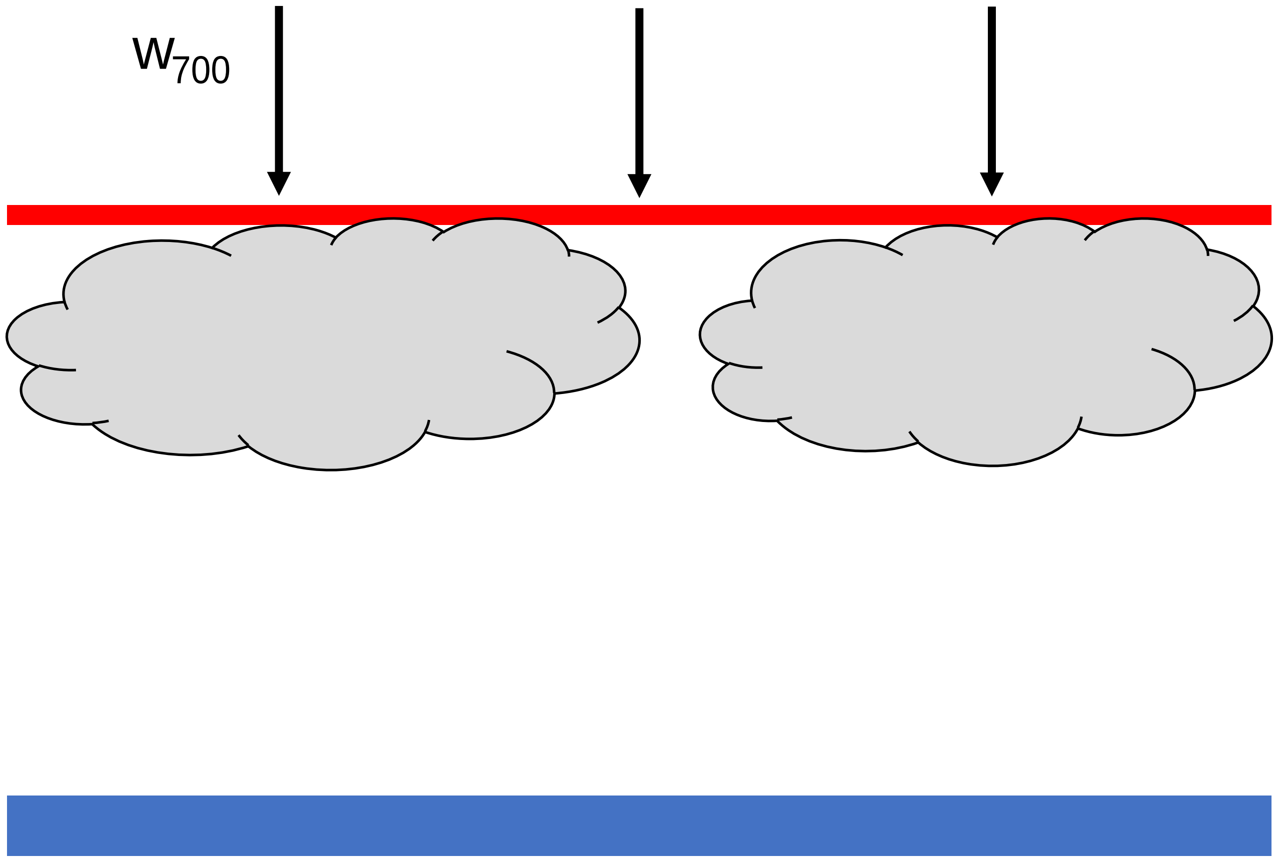


BL Cloud Response to Controlling Factors

BL cloud is capped by a subsidence inversion

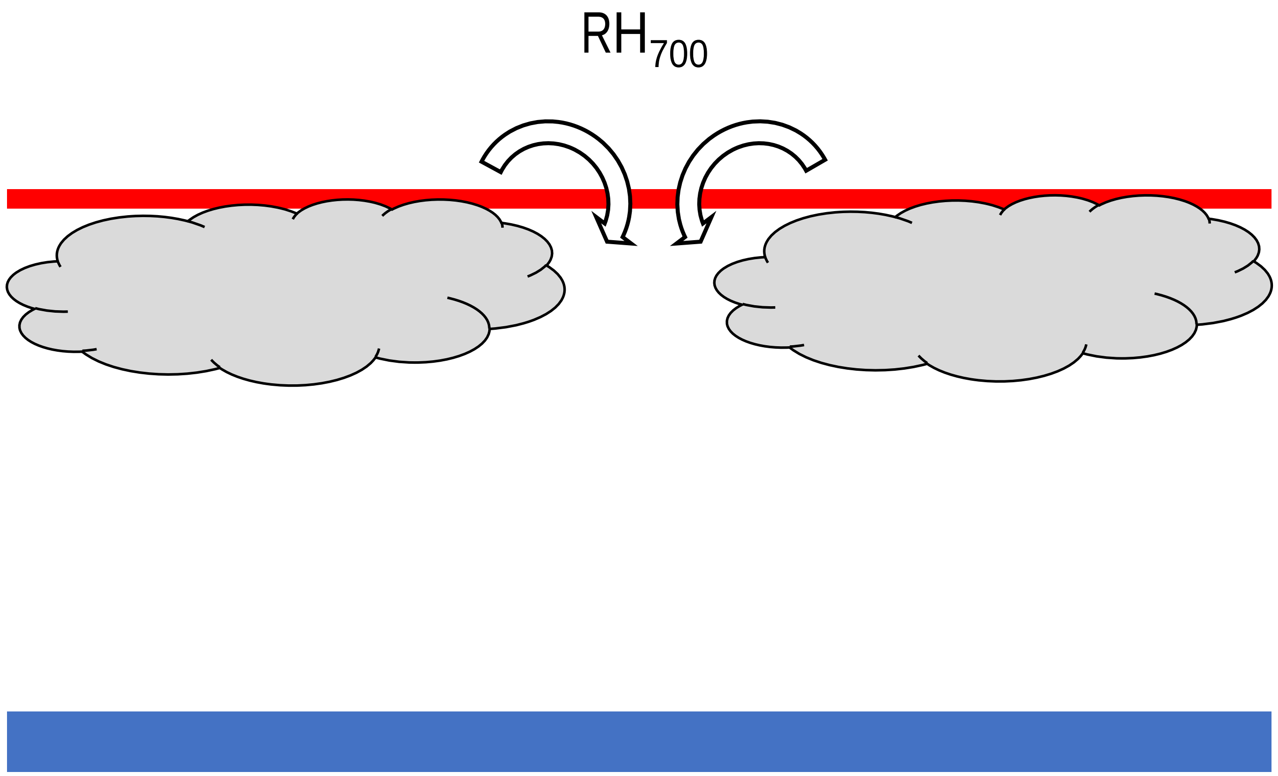
If subsidence weakens

- BL top rises
- BL cloudiness increases
- Less SW is absorbed by climate system



BL Cloud Response to Controlling Factors

Entrainment of air from the free troposphere dries the BL



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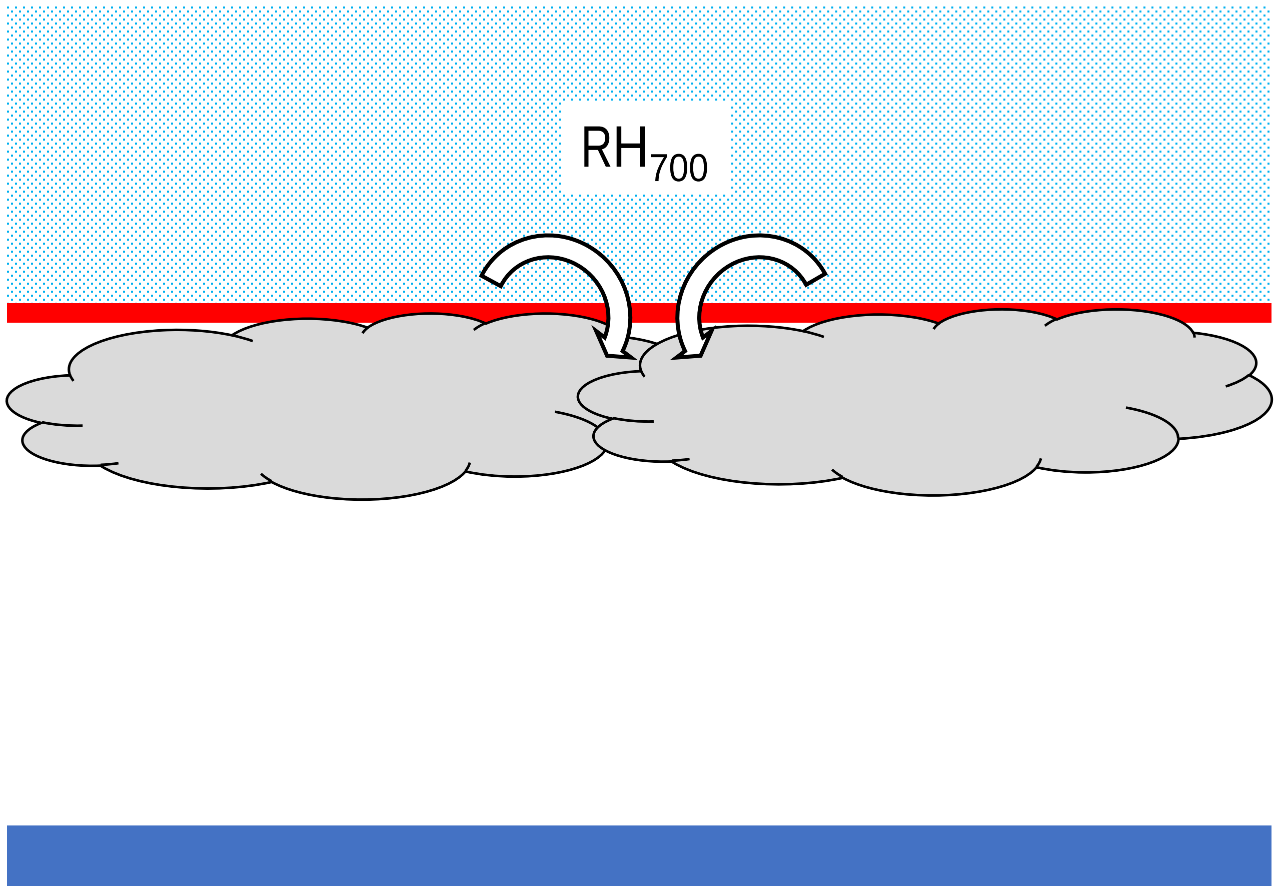


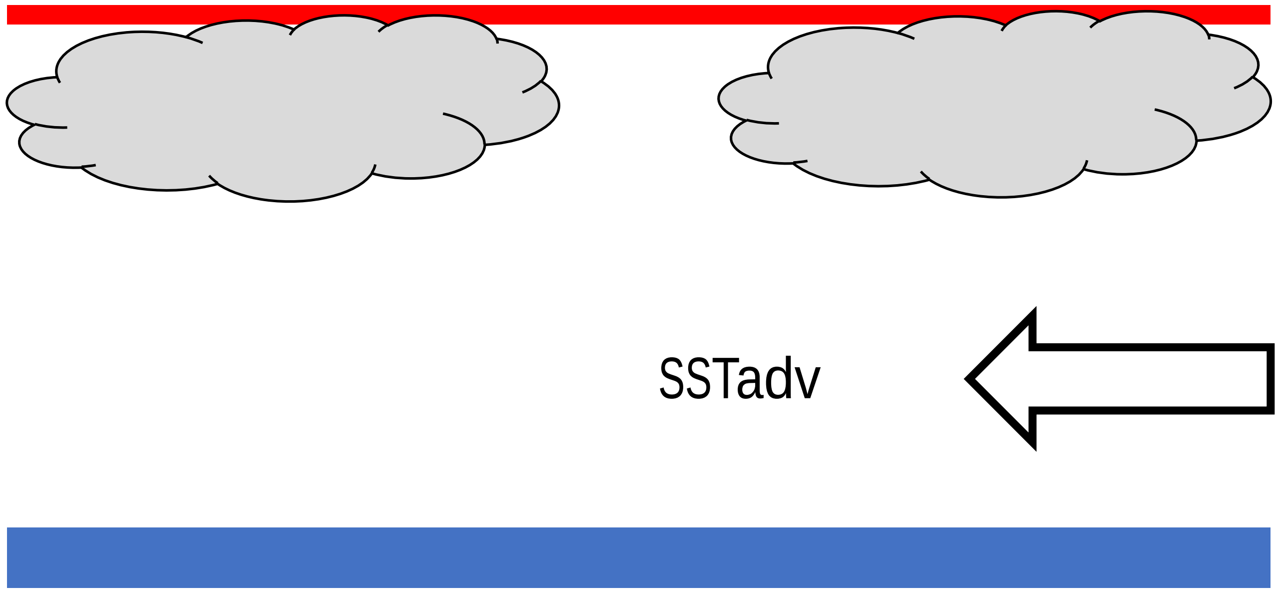
If the troposphere humidifies

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

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

BL Cloud Response to Controlling Factors

BL clouds occur where trade winds advect the BL over increasingly warmer water

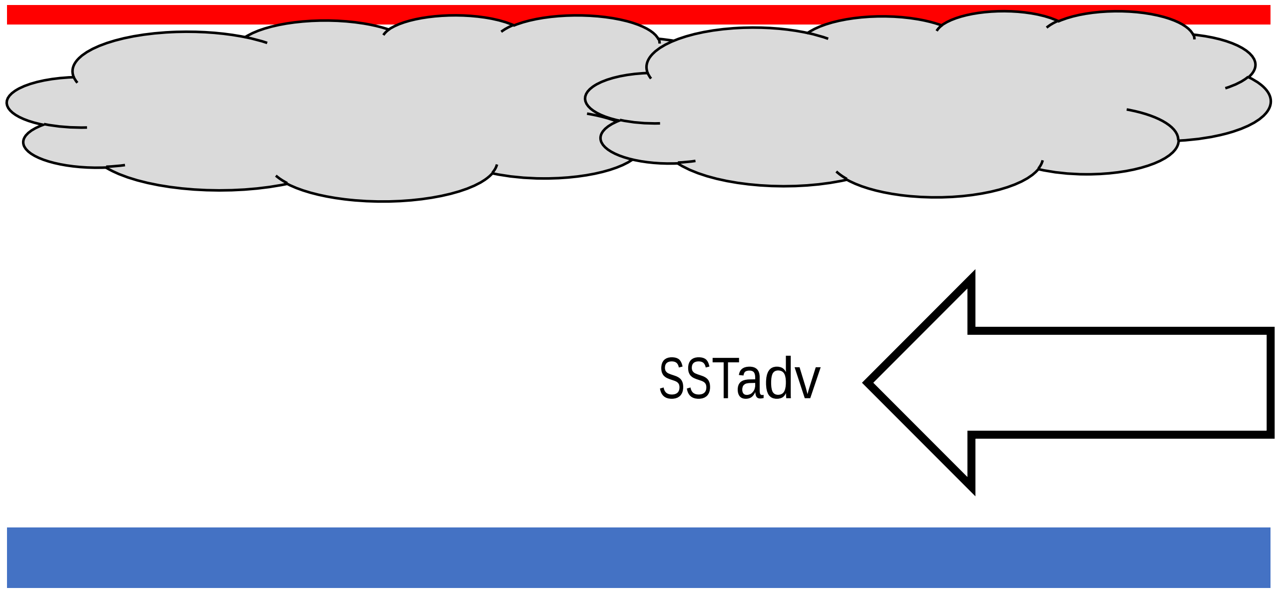


BL Cloud Response to Controlling Factors

BL clouds occur where trade winds advect the BL over increasingly warmer water

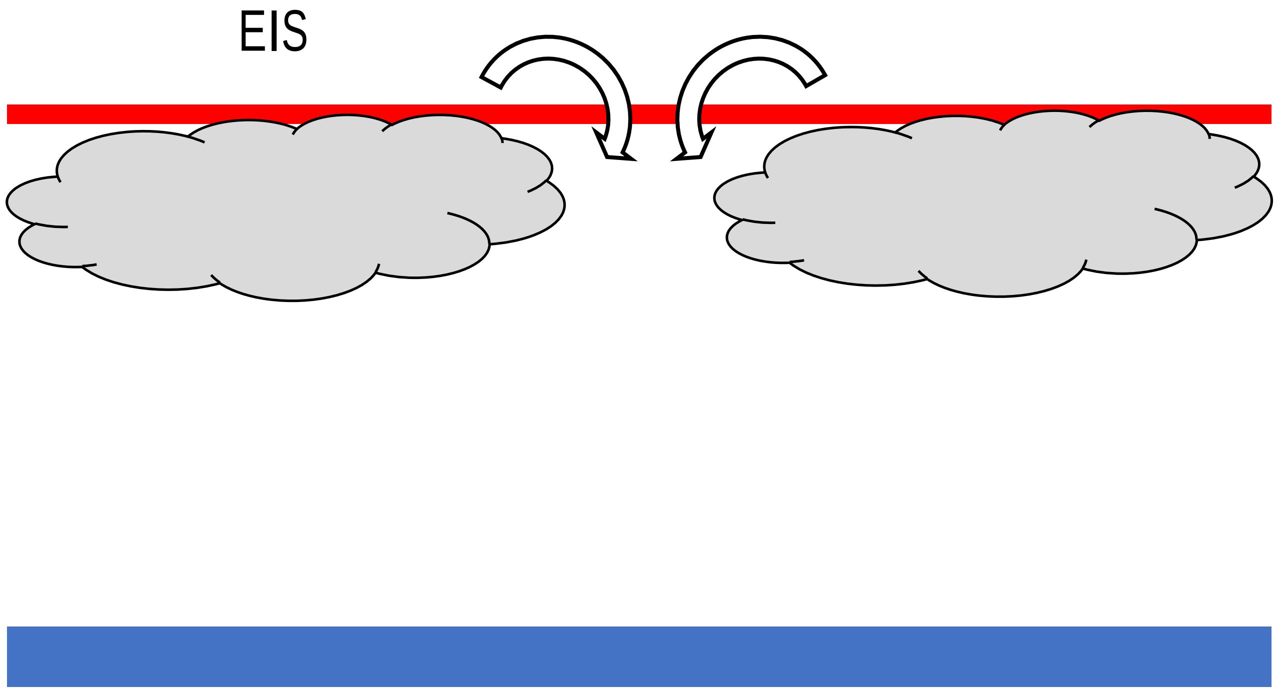
If cold advection strengthens

- BL cloudiness increases
- Less SW is absorbed by climate system
- Not merely due to greater evaporative flux
- Mechanism not well-understood



BL Cloud Response to Controlling Factors

Entrainment of air through the capping inversion dries and warms the BL



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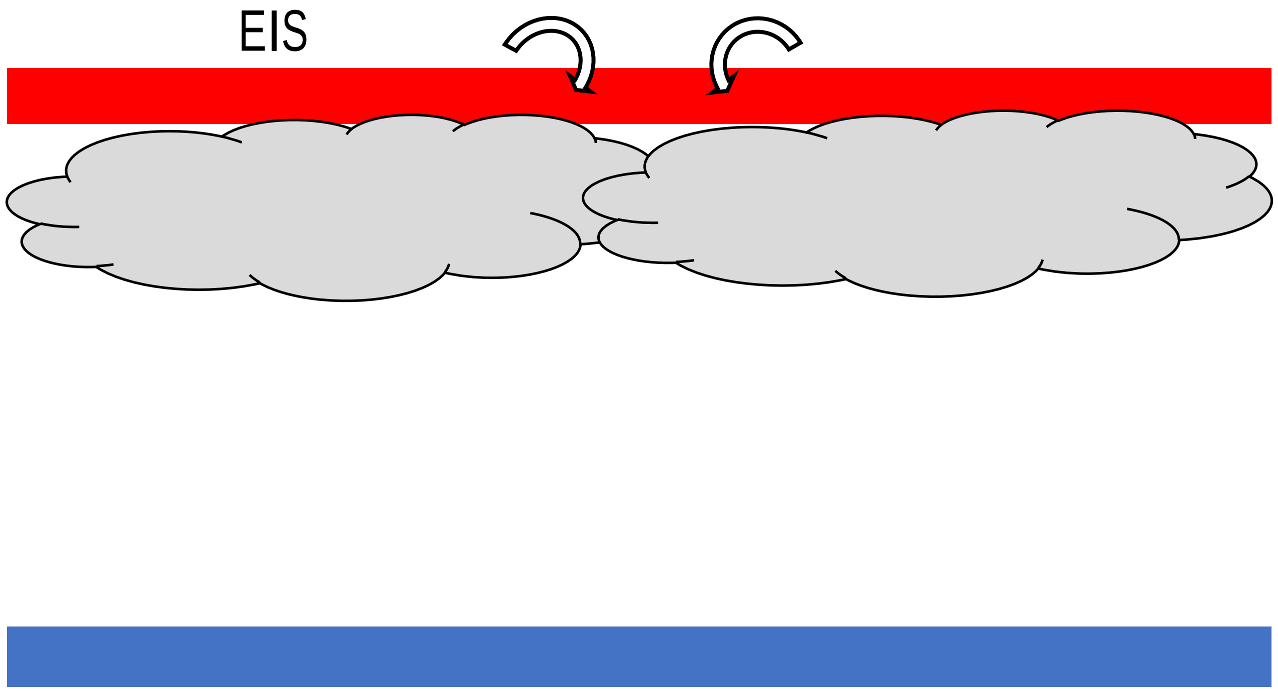
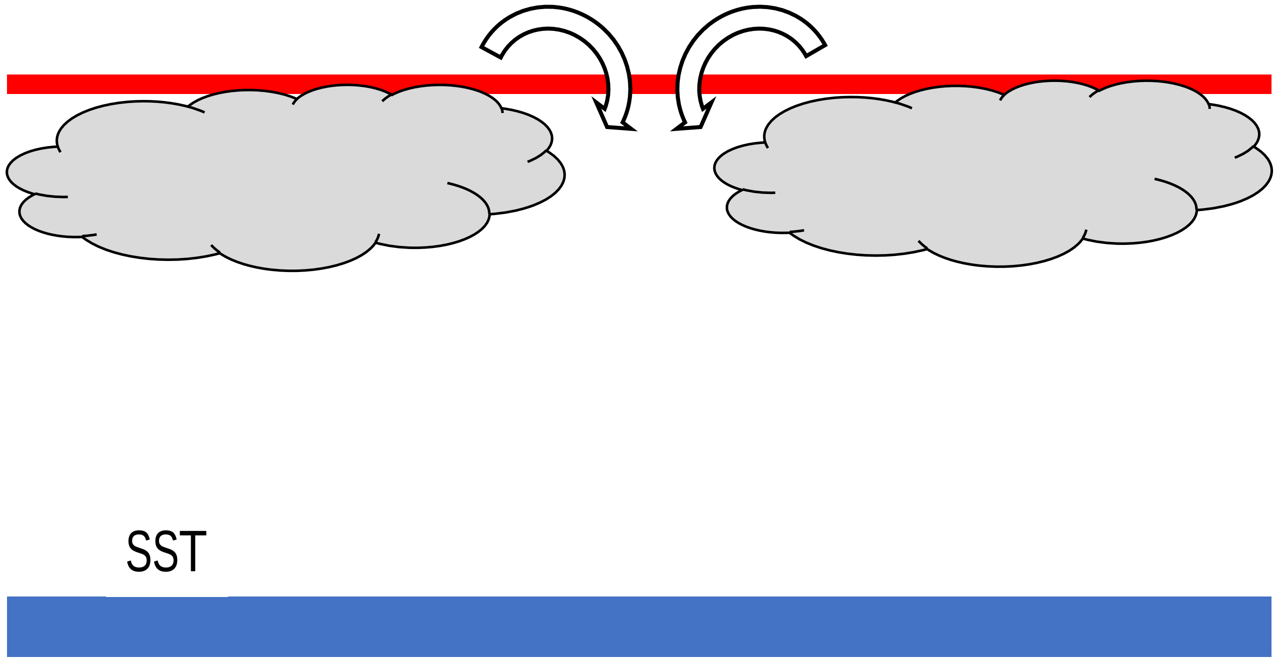


<u>If the inversion strengthens</u>

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

BL Cloud Response to Controlling Factors

Turbulence in the BL drives the entrainment that dries and warms the BL

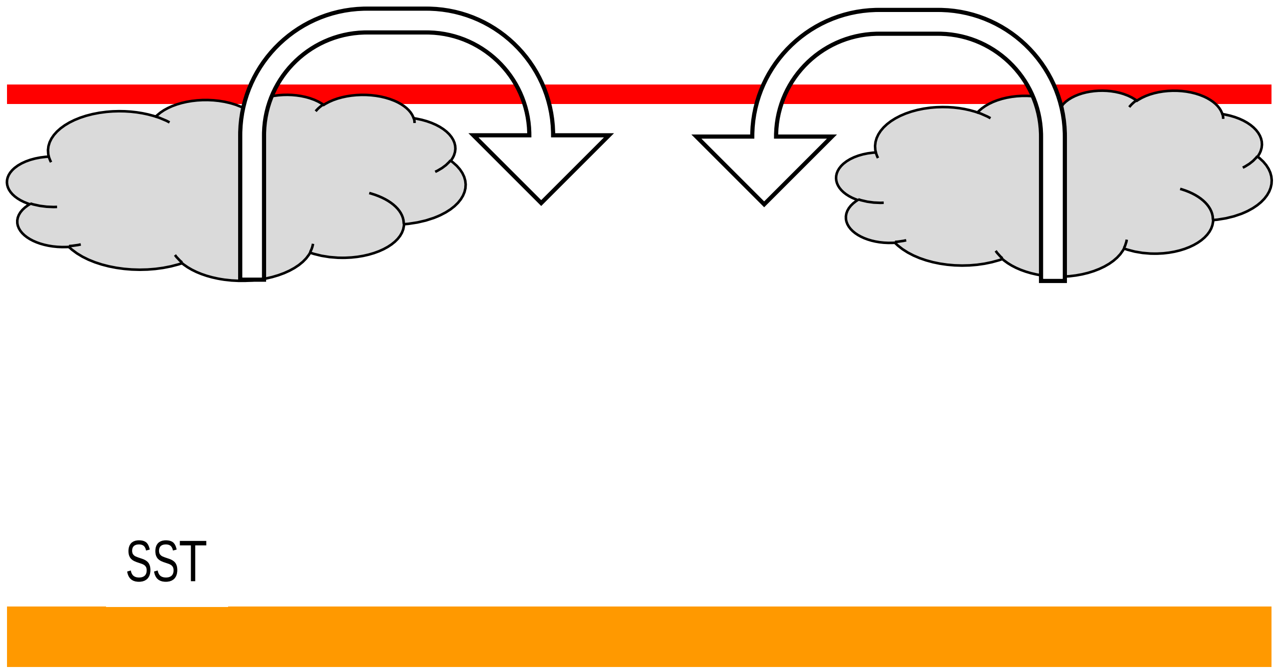


BL Cloud Response to Controlling Factors

Turbulence in the BL drives the entrainment that dries and warms the BL

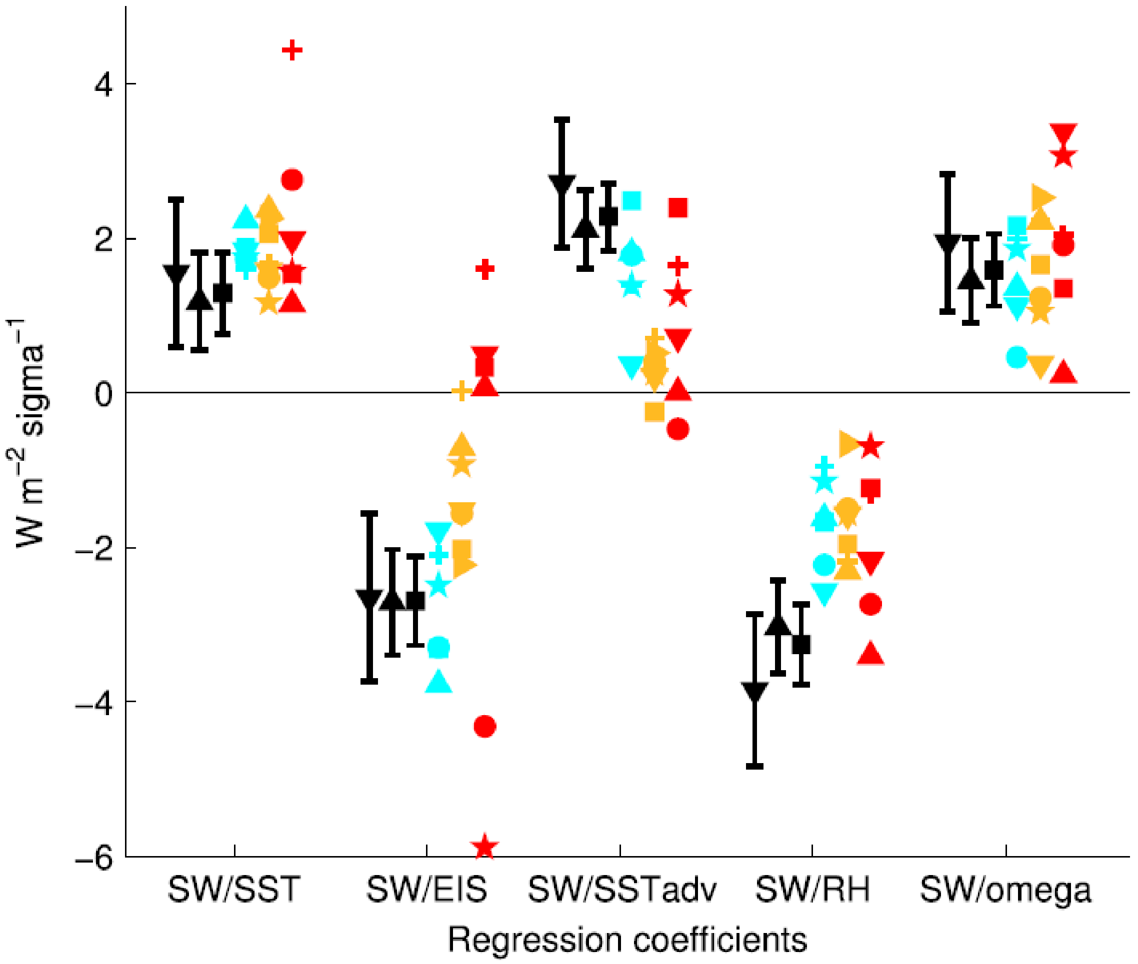
<u>*If SST increases*</u>

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



SW BL Cloud Response to Controlling Factors

- Observed SW cloud response to typical anomalies in the five controlling factors has similar magnitude



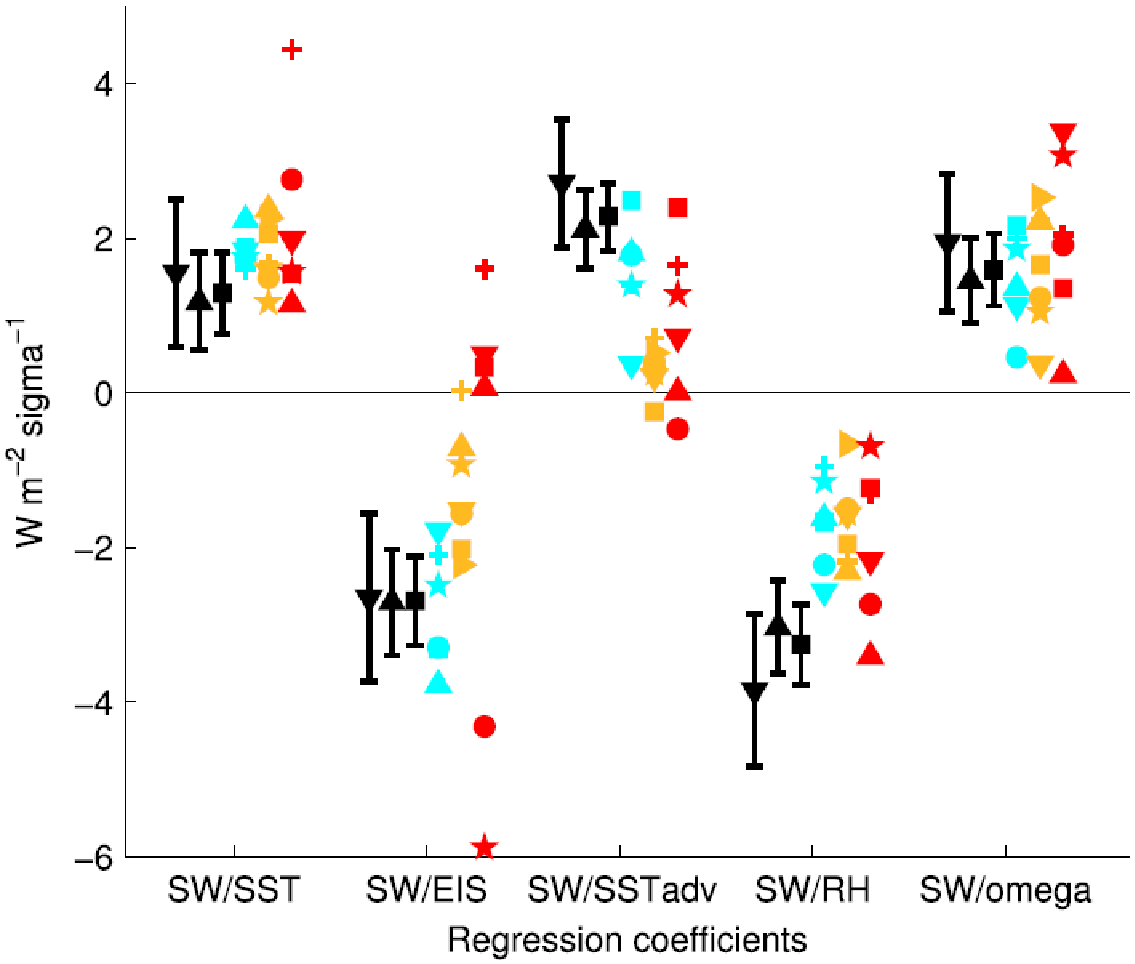
Plot from Myers and Norris (2016)

Black = coefficients from observed monthly anomalies

Color = coefficients from climate model monthly anomalies

SW BL Cloud Response to Controlling Factors

- Observed SW cloud response to typical anomalies in the five controlling factors has similar magnitude
- Climate models exhibit great disagreement with observations and each other



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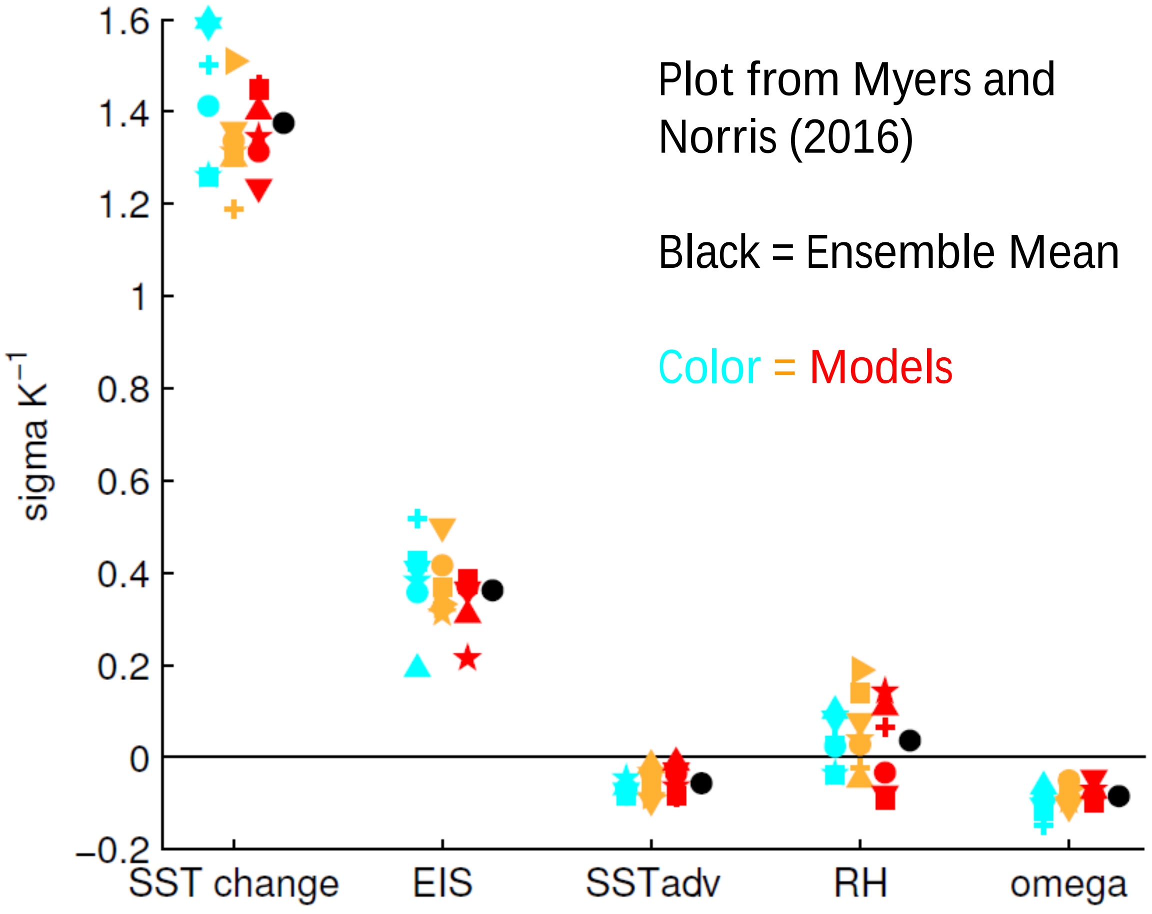
Changes in Controlling Factors for 4xCO2

Climate models agree about changes in meteorological controlling factors



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Changes in Controlling Factors for 4xCO2

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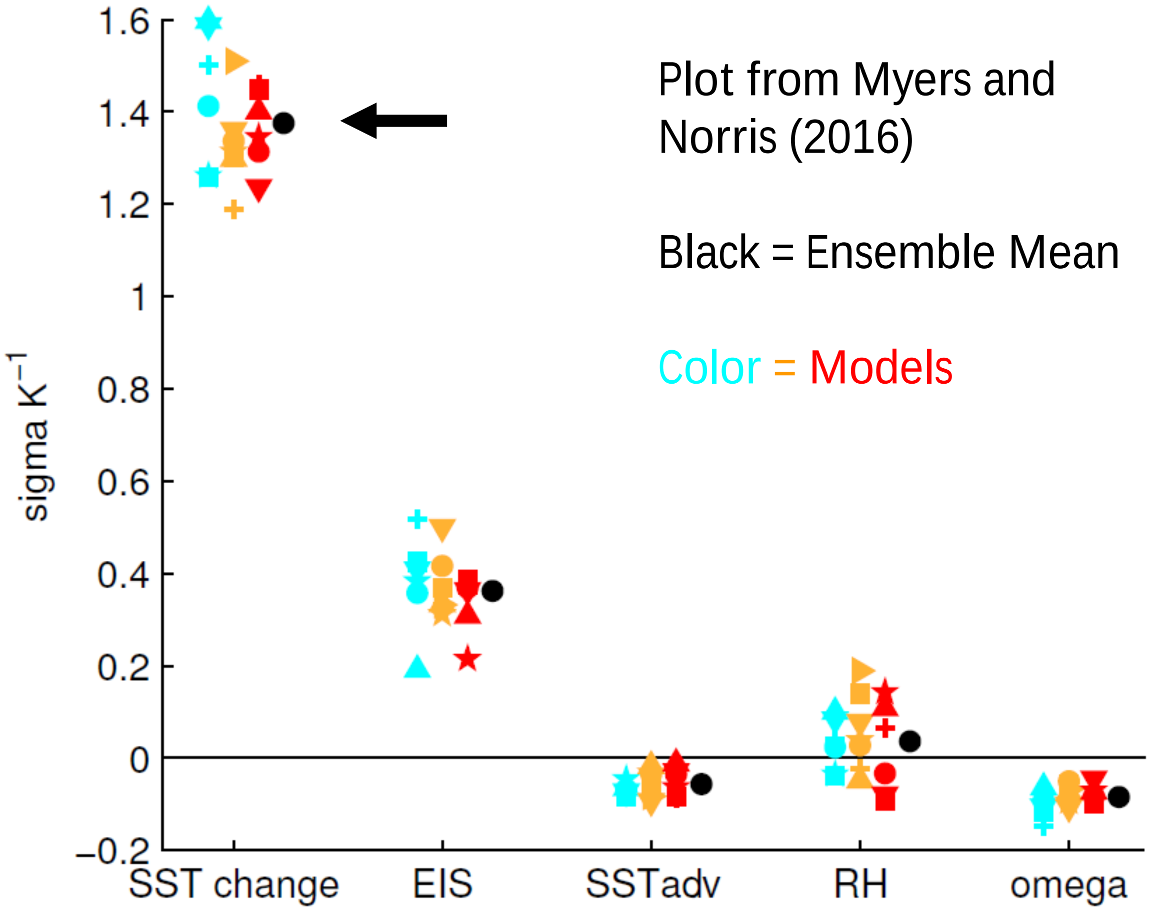
- Large warming of SST



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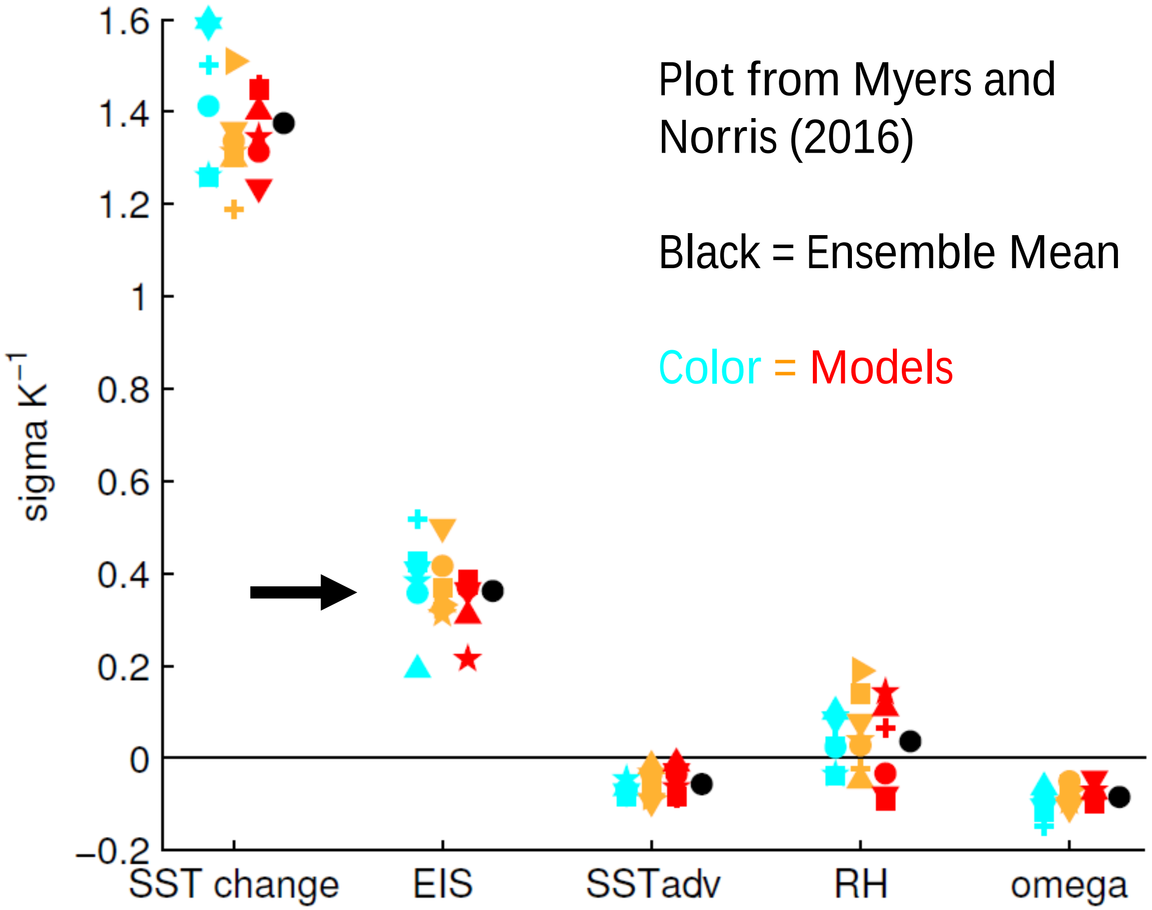

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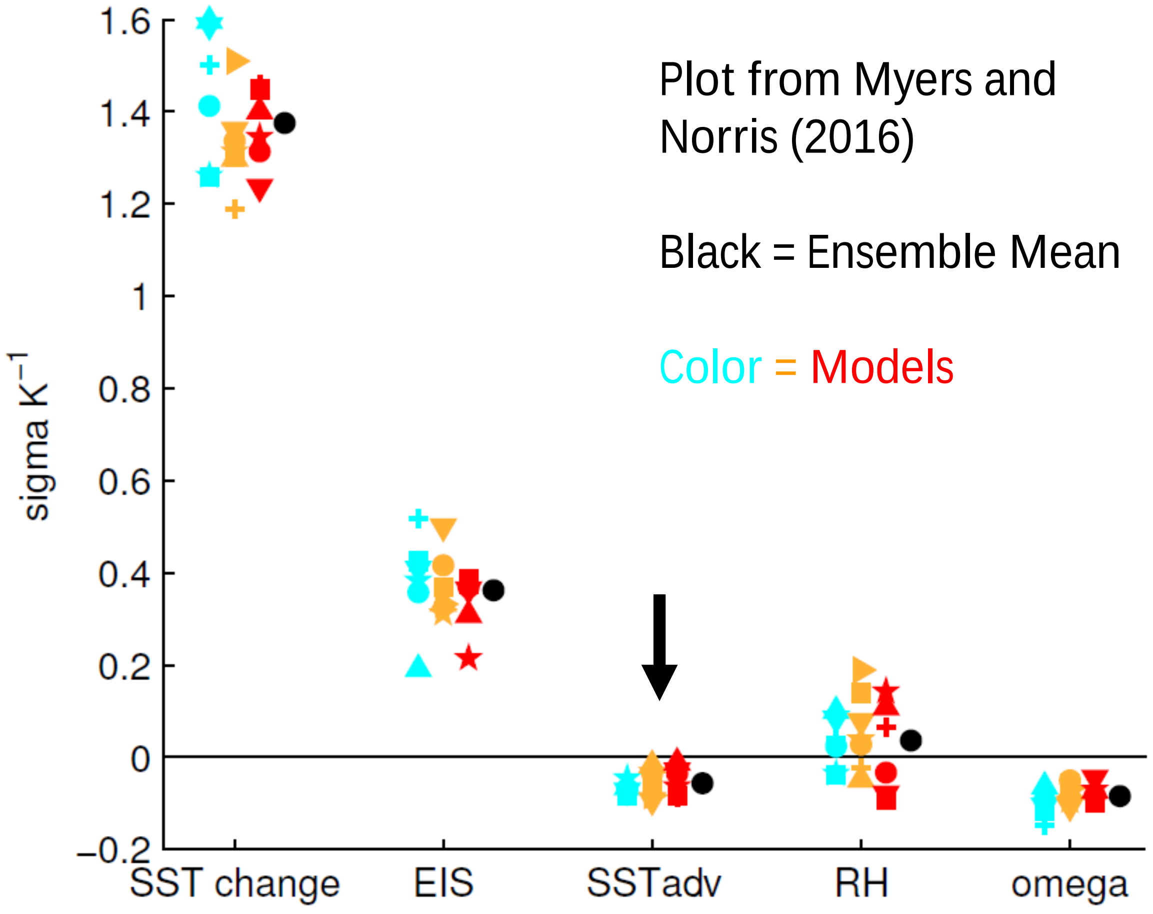
Changes in Controlling Factors for 4xCO2

Climate models agree about changes in meteorological controlling factors

- Large warming of SST
- Small strengthening of inversion
- Very small strengthening of cold advection over SST gradient



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Changes in Controlling Factors for 4xCO2

Climate models agree about changes in meteorological controlling factors

- Large warming of SST
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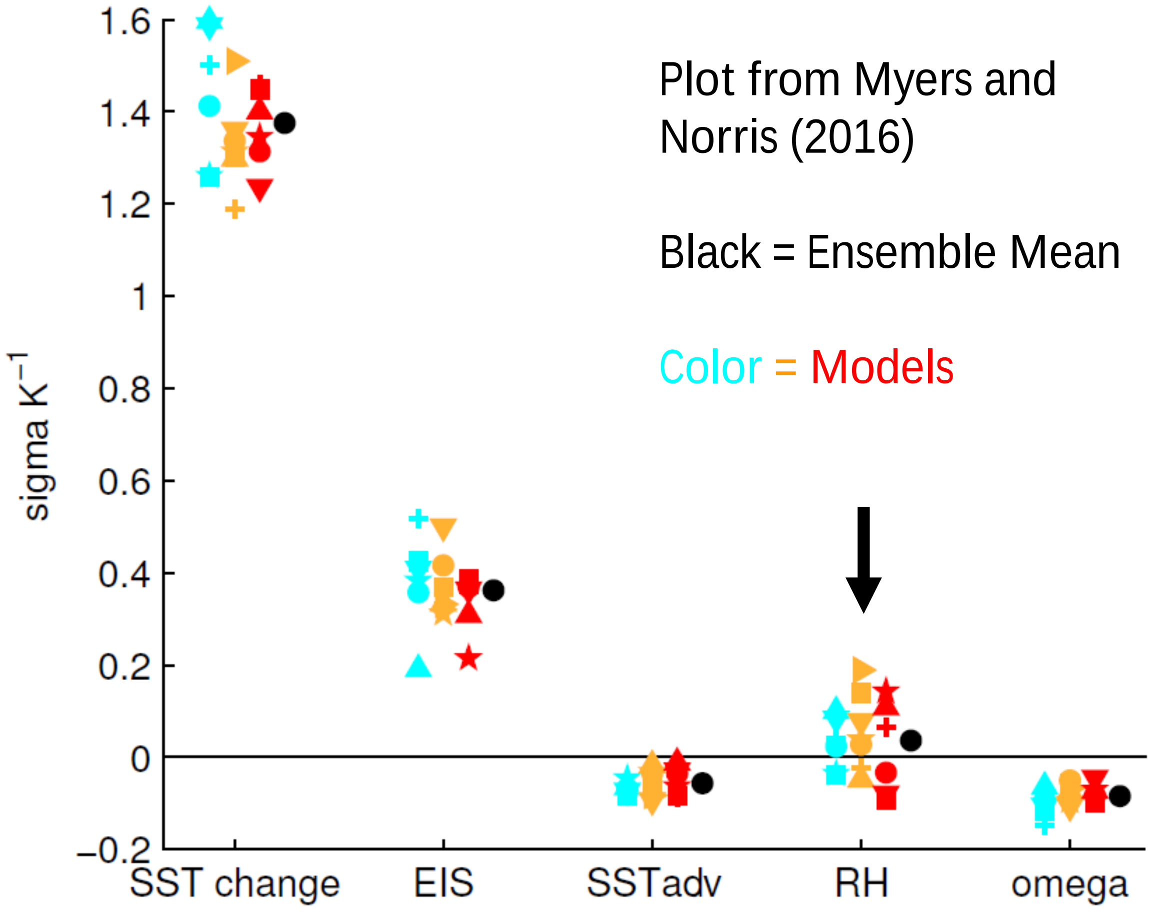
- Very small increase or decrease in relative humidity above BL



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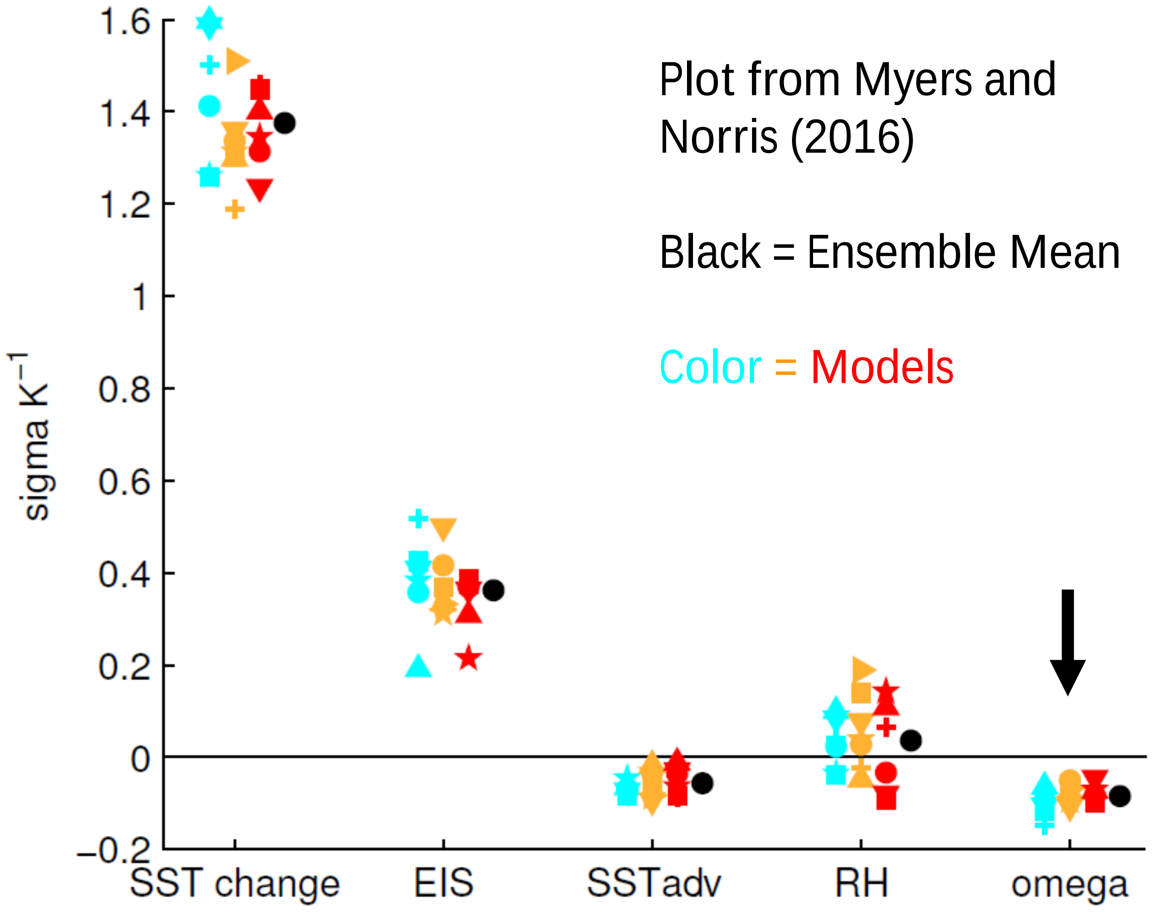

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Constrained SW BL Cloud Feedback

Constrained cloud feedback from changes in controlling factors caused by 4xCO2

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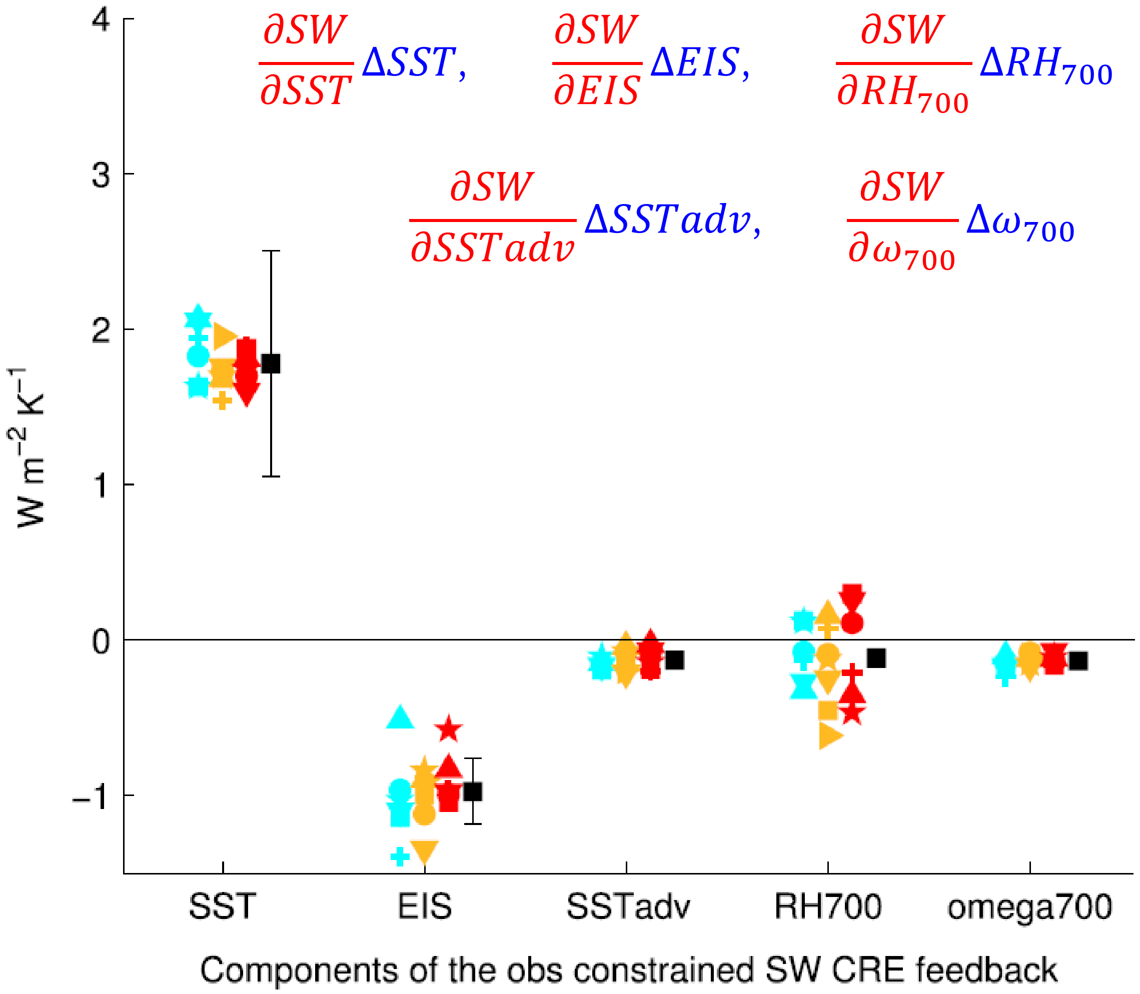
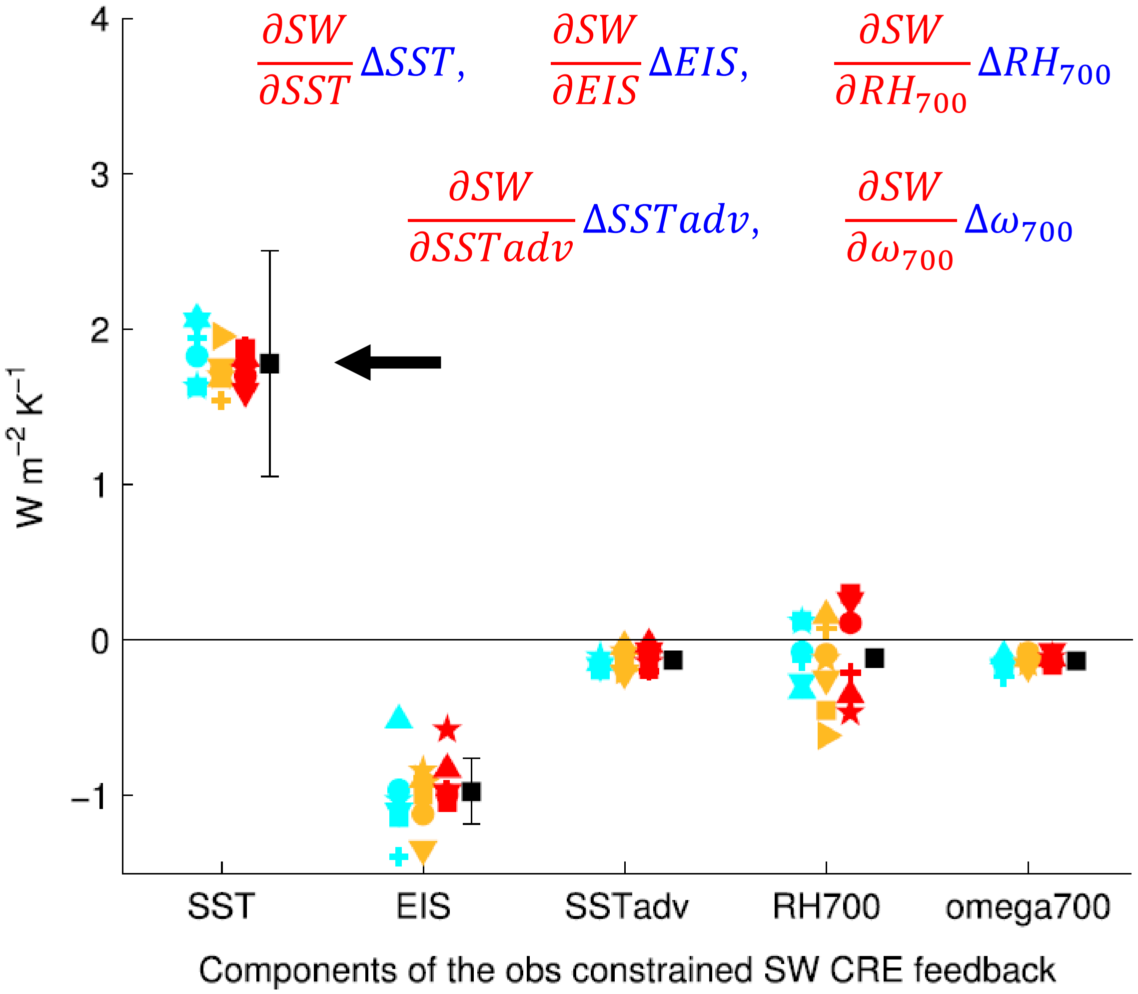


Constrained SW BL Cloud Feedback

Constrained cloud feedback from changes in controlling factors caused by $4xCO2$

- Increase in SW absorption due to cloud reduction in response to warmer SST



Constrained SW BL Cloud Feedback

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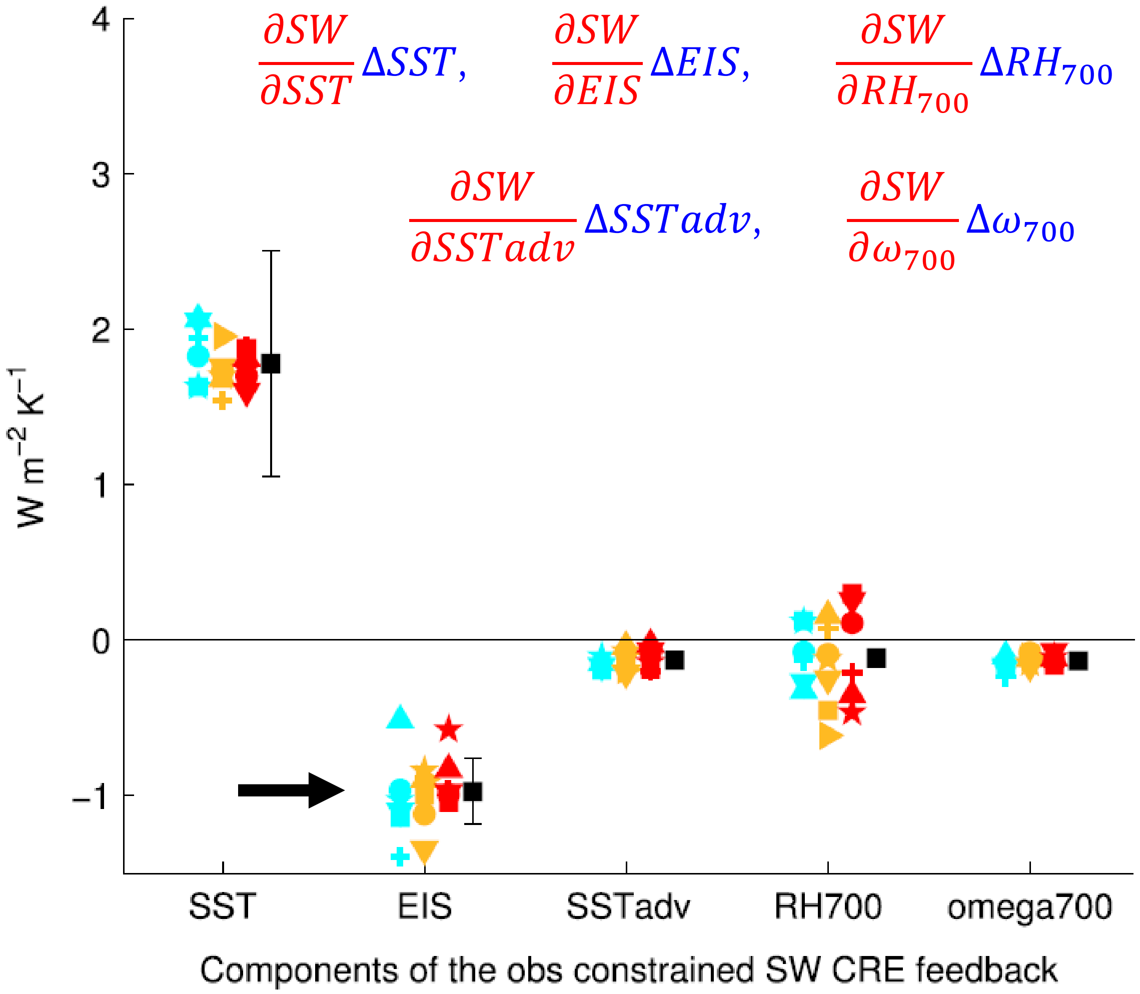
- Increase in SW absorption due to cloud reduction in response to warmer SST

partially offset by

- smaller decrease in SW absorption due to cloud enhancement in response to stronger inversion



Constrained SW BL Cloud Feedback

Constrained cloud feedback from changes in controlling factors caused by 4xCO2

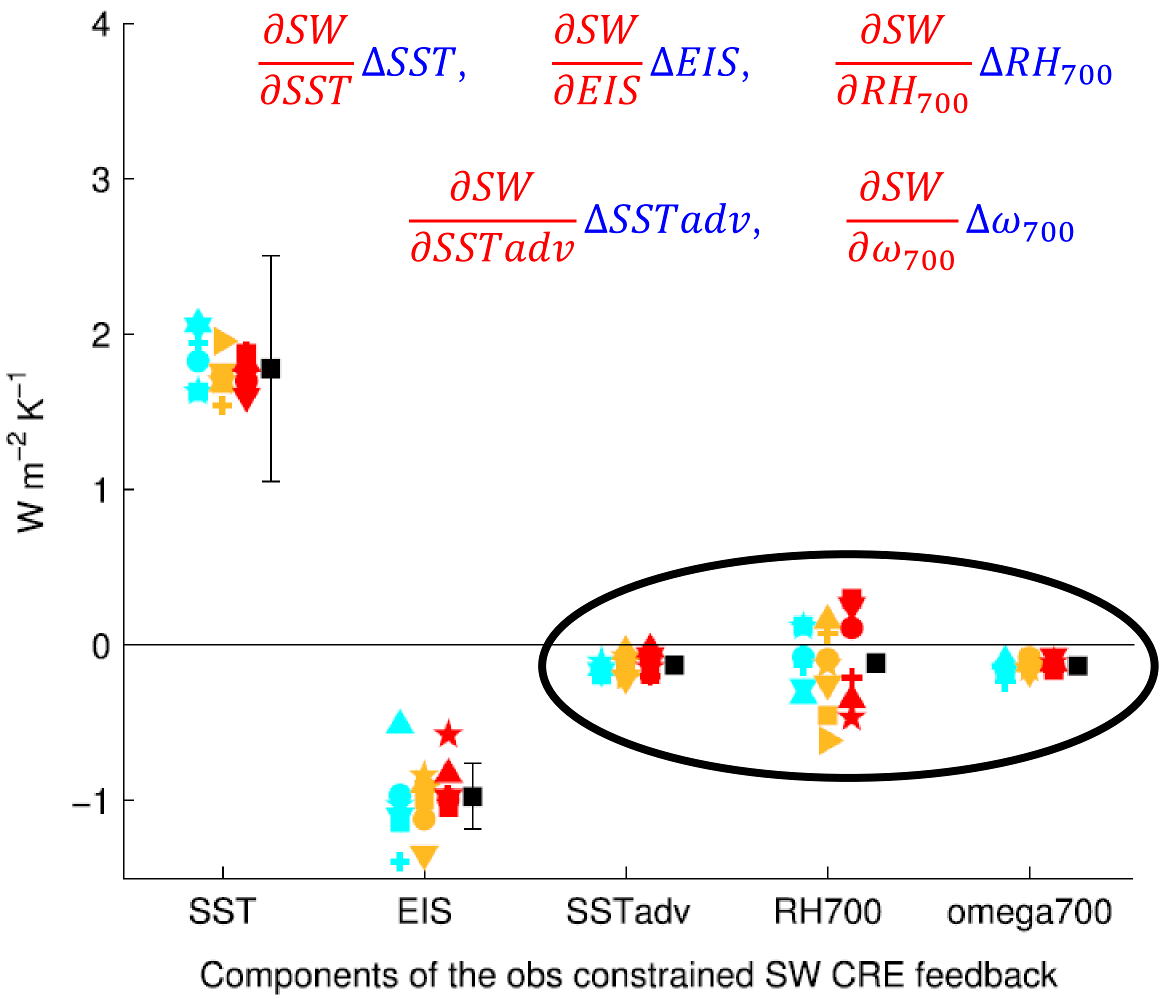
- Increase in SW absorption due to cloud reduction in response to warmer SST

partially offset by

- smaller decrease in SW absorption due to cloud enhancement in response to stronger inversion

and

- very small decreases in SW absorption due to cloud enhancement in response to other factors



Constrained SW BL Cloud Feedback

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

Plot from Myers and Norris (2016)

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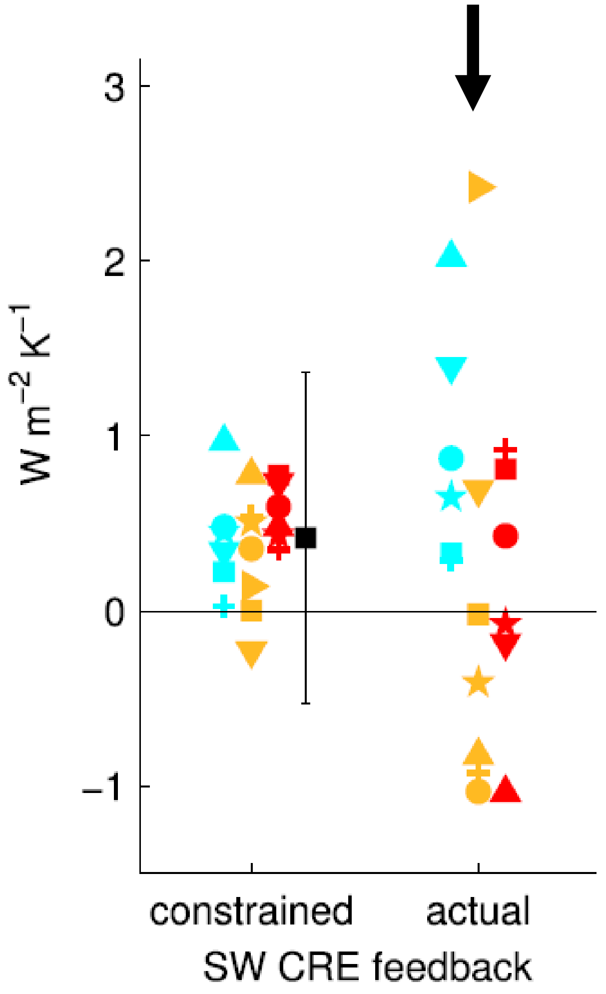

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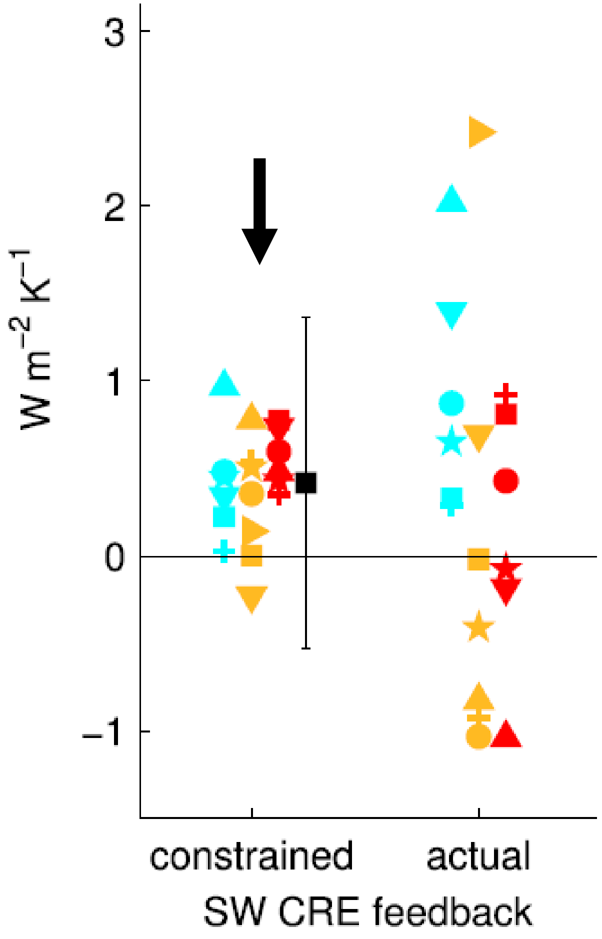
$$\Delta SW = \frac{\partial SW}{\partial SST}\Delta SST + \frac{\partial SW}{\partial EIS}\Delta EIS + \frac{\partial SW}{\partial RH_{700}}\Delta RH_{700}$$

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

- Constrained SW cloud feedback has much smaller range of values



Two Questions

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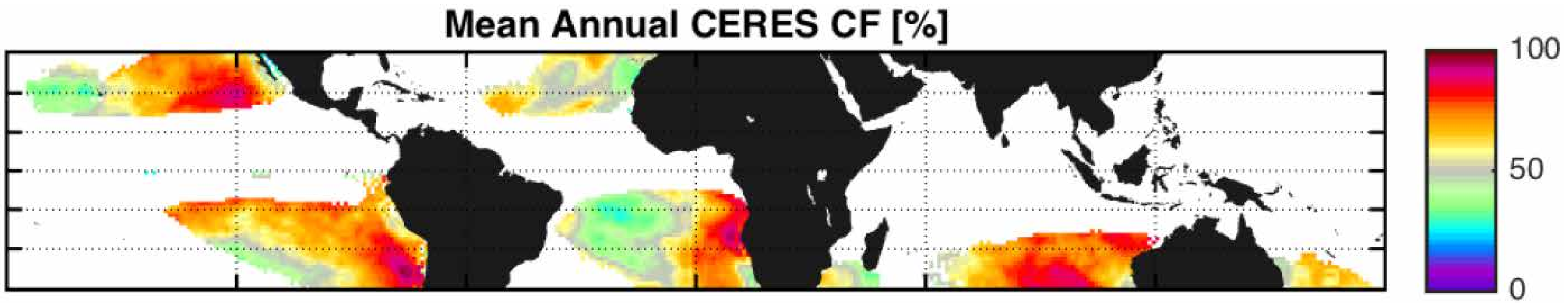
Is the BL cloud response to changes in meteorological controlling factors uniform across BL cloud regimes?

- Initial results

Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

Regime	Cloud Fraction (%)
Core Sc	78
Transition-to-Cu	45



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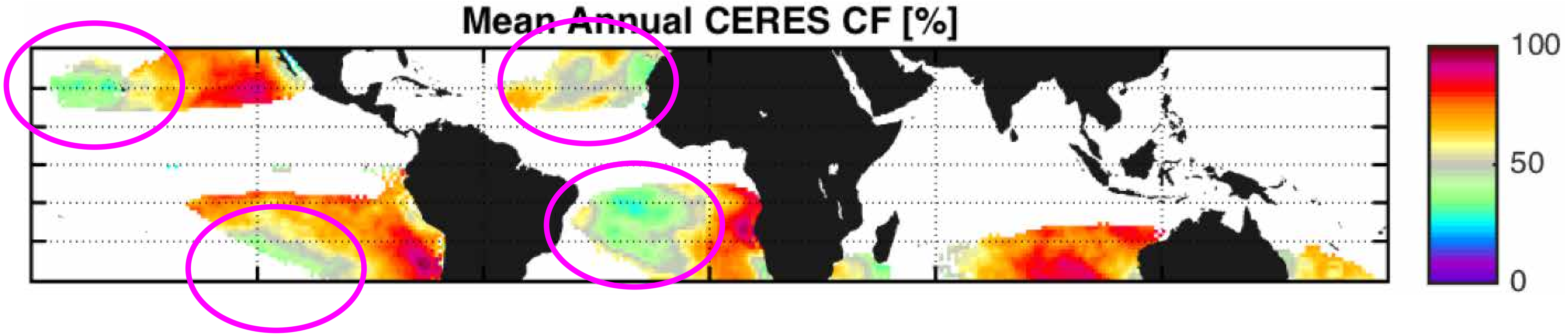
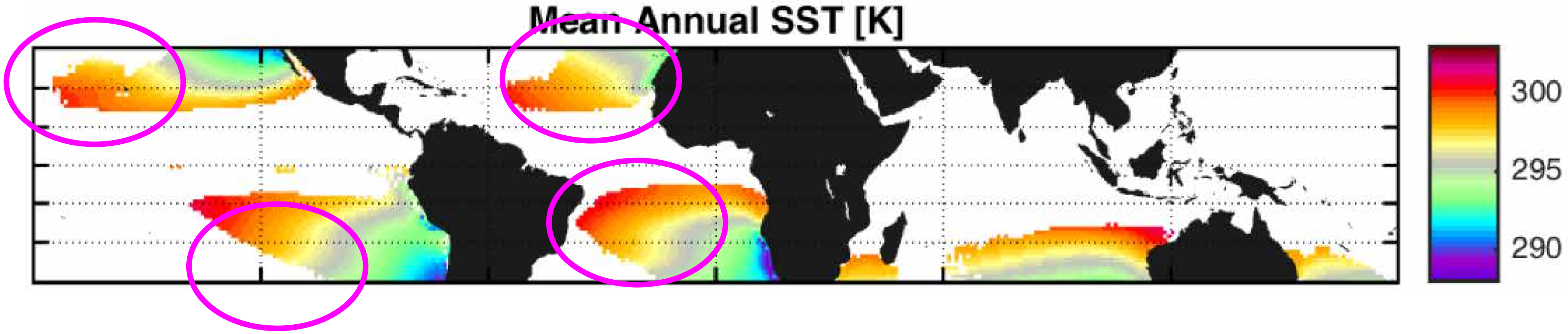


Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

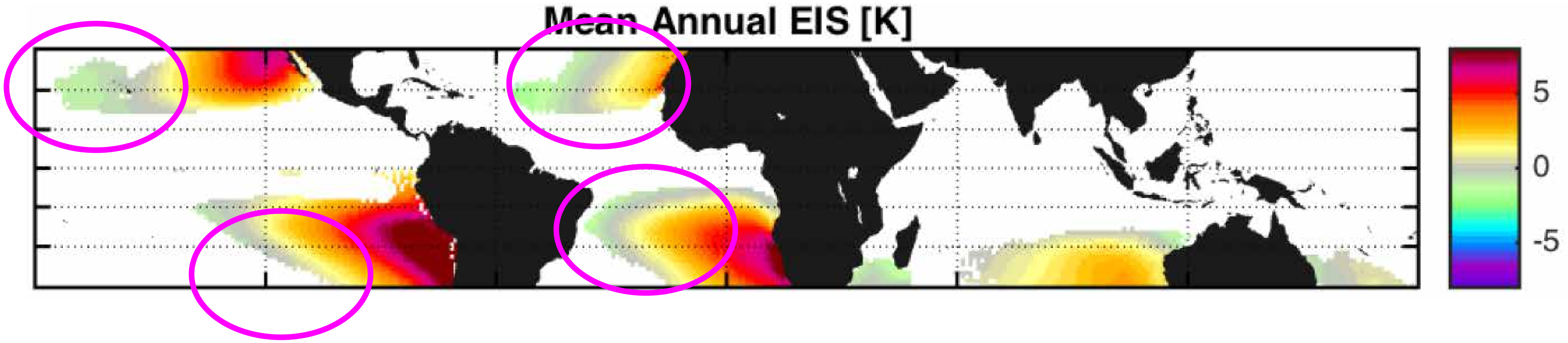
Regime	Cloud Fraction (%)	SST (K)
Core Sc	78	295.7
Transition-to-Cu	45	297.4



Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

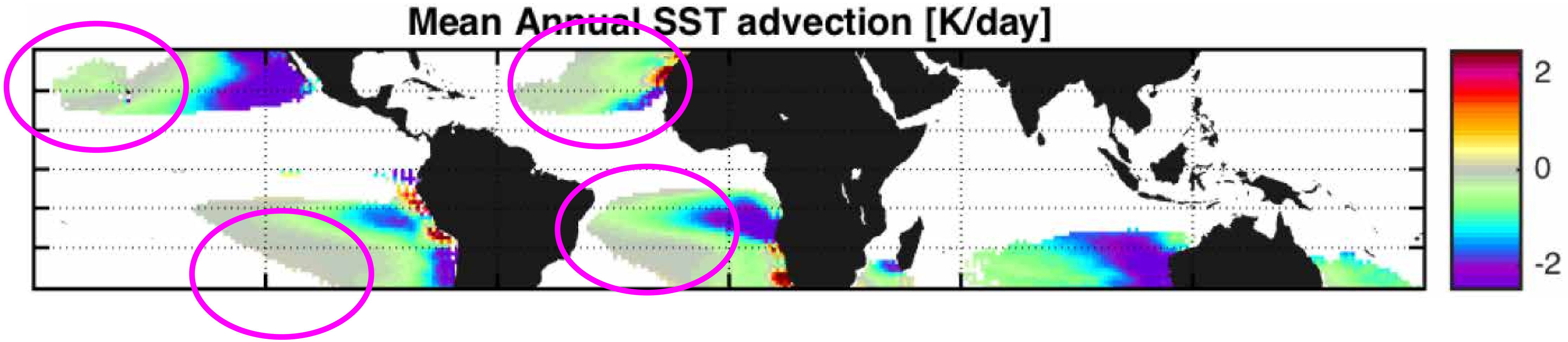
Regime	Cloud Fraction (%)	SST (K)	EIS (K)
Core Sc	78	295.7	3.6
Transition-to-Cu	45	297.4	1.0



Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

Regime	Cloud Fraction (%)	SST (K)	EIS (K)	SSTadv (K dy^{-1})
Core Sc	78	295.7	3.6	−1.3
Transition-to-Cu	45	297.4	1.0	−0.3



Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

Regime	Cloud Fraction (%)	SST (K)	EIS (K)	SSTadv (K dy^{-1})	RH_{700} (%)	w_{700} (hPa dy^{-1})
Core Sc	78	295.7	3.6	−1.3	24	33
Transition-to-Cu	45	297.4	1.0	−0.3	26	28

Compared to the Core Sc regime, the Transition-to-Cu regime has:

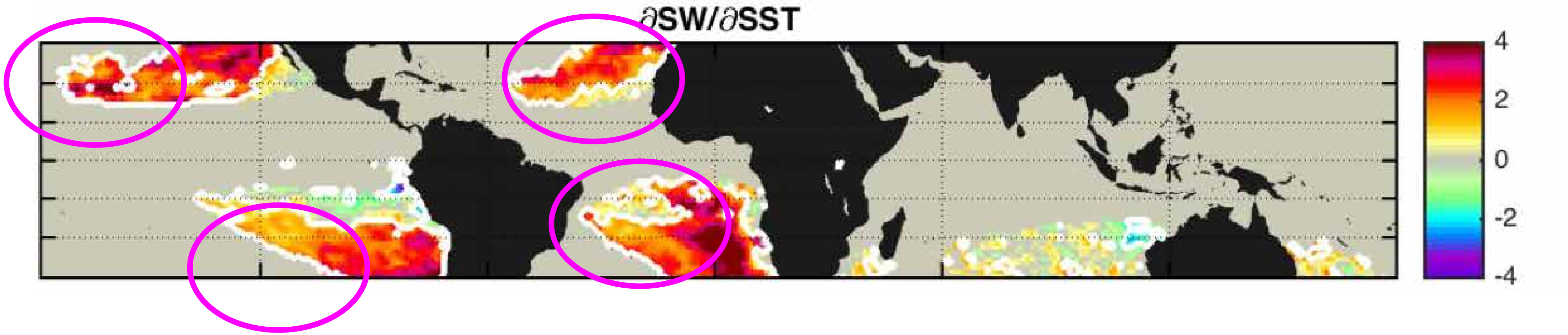
- warmer SST
- weaker capping inversion
- weaker cold advection over the SST gradient
- similar relative humidity and subsidence above the BL

Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} sigma^{-1})

Regime	$\frac{\partial SW}{\partial SST}$
Core Sc	1.3
Transition-to-Cu	1.8

SW cloud response more sensitive to SST change in Transition-to-Cu regime?

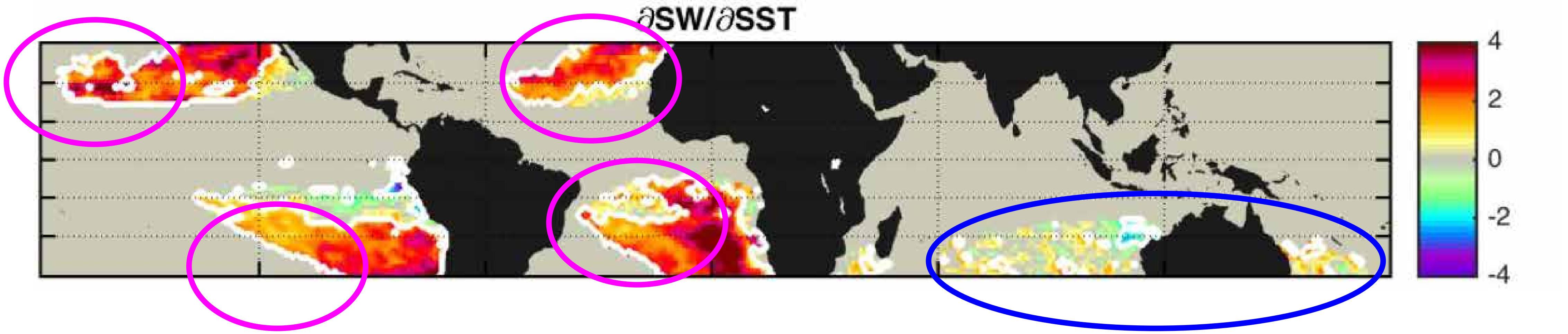


Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} $sigma^{-1}$)

Regime	$\frac{\partial SW}{\partial SST}$
Core Sc	1.3
Transition-to-Cu	1.8

SW cloud response to SST around Australia is really different

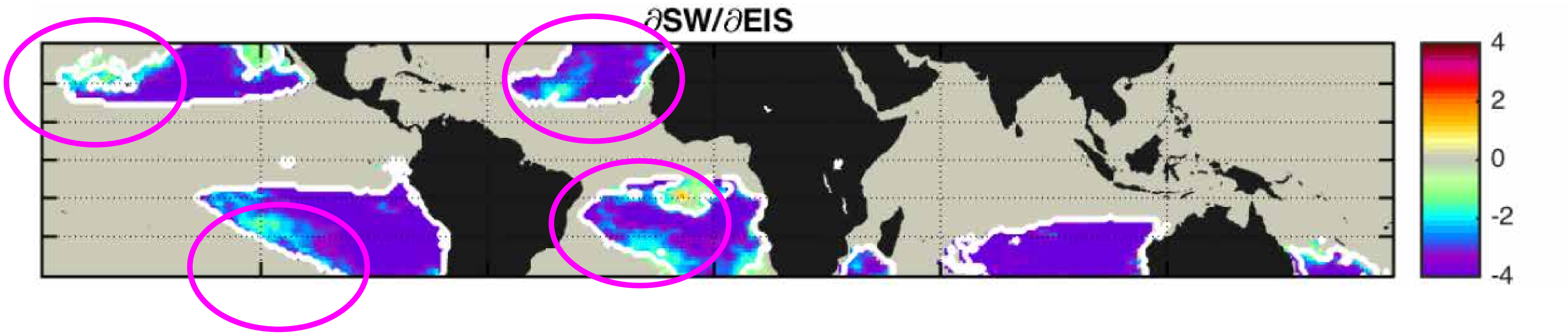


Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} $sigma^{-1}$)

Regime	$\frac{\partial SW}{\partial SST}$	$\frac{\partial SW}{\partial EIS}$
Core Sc	1.3	−4.2
Transition-to-Cu	1.8	−2.8

Weaker SW cloud response to EIS strengthening in Transition-to-Cu regime



Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} $sigma^{-1}$)

Regime	$\frac{\partial SW}{\partial SST}$	$\frac{\partial SW}{\partial EIS}$	$\frac{\partial SW}{\partial SSTadv}$	$\frac{\partial SW}{\partial RH_{700}}$	$\frac{\partial SW}{\partial \omega_{700}}$
Core Sc	1.3	−4.2	0.9	−3.6	0.4
Transition-to-Cu	1.8	−2.8	2.4	−3.7	1.2

SW cloud response to changes in advection over the SST gradient and subsidence

- Systematically varies with cloud regime
- Not important for 4xCO2 SW cloud feedback because changes in advection and subsidence are very small

Summary

- SW BL cloud feedback can be better constrained by multiplying the observed cloud response to controlling factors to model-projected change in controlling factors

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Summary

- SW BL cloud feedback can be better constrained by multiplying the observed cloud response to controlling factors to model-projected change in controlling factors
- The SW BL cloud feedback for 4xCO_2 is positive due to reduced cloudiness caused by warmer SST that is partially offset by enhanced cloudiness caused by a stronger inversion
- Changes in advection over the SST gradient, subsidence, and humidity above the BL have large impacts on cloudiness on monthly time scales but are unimportant for 4xCO_2.

Summary

- SW BL cloud feedback can be better constrained by multiplying the observed cloud response to controlling factors to model-projected change in controlling factors
- The SW BL cloud feedback for 4xCO2 is positive due to reduced cloudiness caused by warmer SST that is partially offset by enhanced cloudiness caused by a stronger inversion
- Changes in advection over the SST gradient, subsidence, and humidity above the BL have large impacts on cloudiness on monthly time scales but are unimportant for 4xCO2.
- The cloud response to warmer SST is generally similar across “classic” stratocumulus regions but differs for other regions of climatological subsidence

Future Work

- Develop better understanding of factors controlling SW BL cloud response for regimes other than “classic” stratocumulus

Challenges

  - Presence of high cloud
  - Synoptic variability
  - Land surface

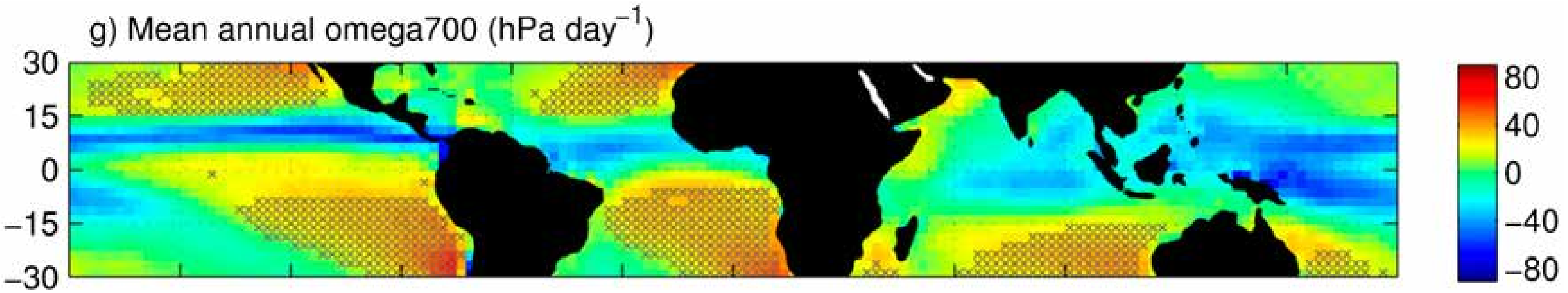
Thank You!

Extra Slides

Geography and Radiative Effects of BL Cloud

BL clouds

- Preferentially occur in areas of subsidence (analysis region marked with ´)



Geography and Radiative Effects of BL Cloud

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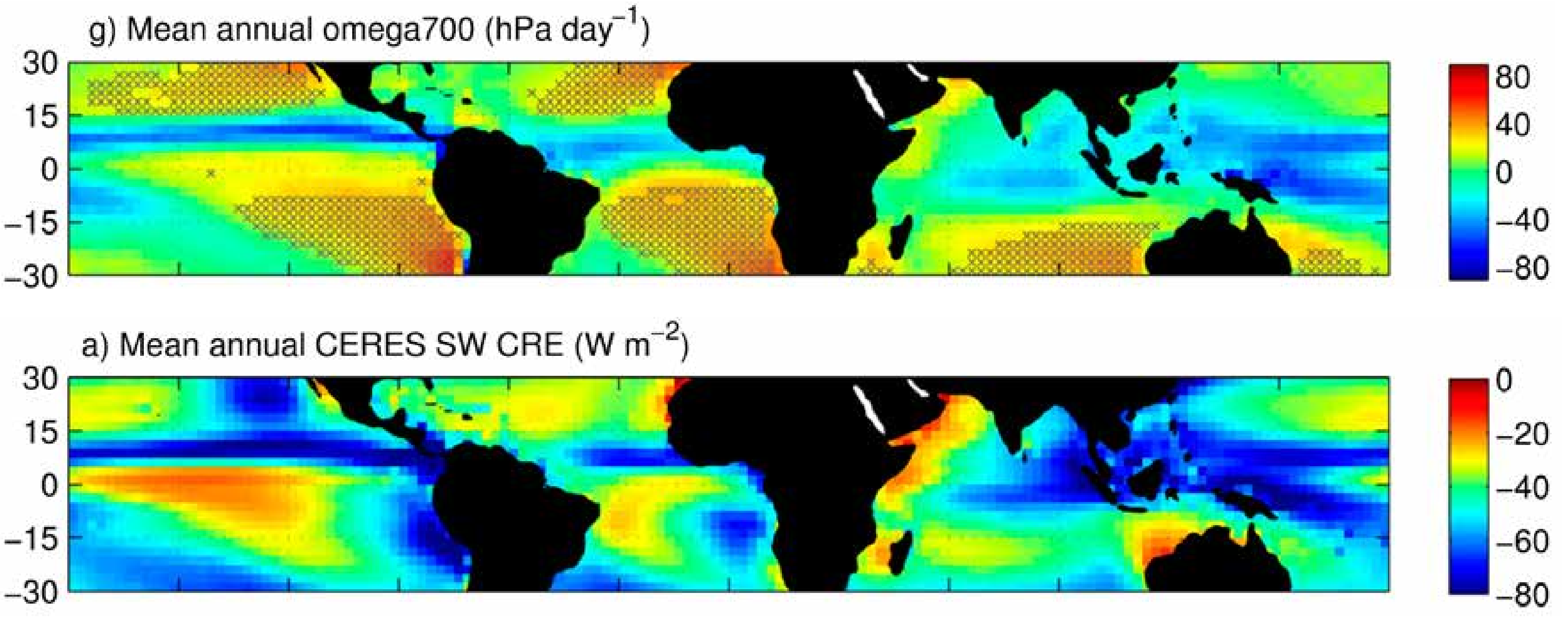
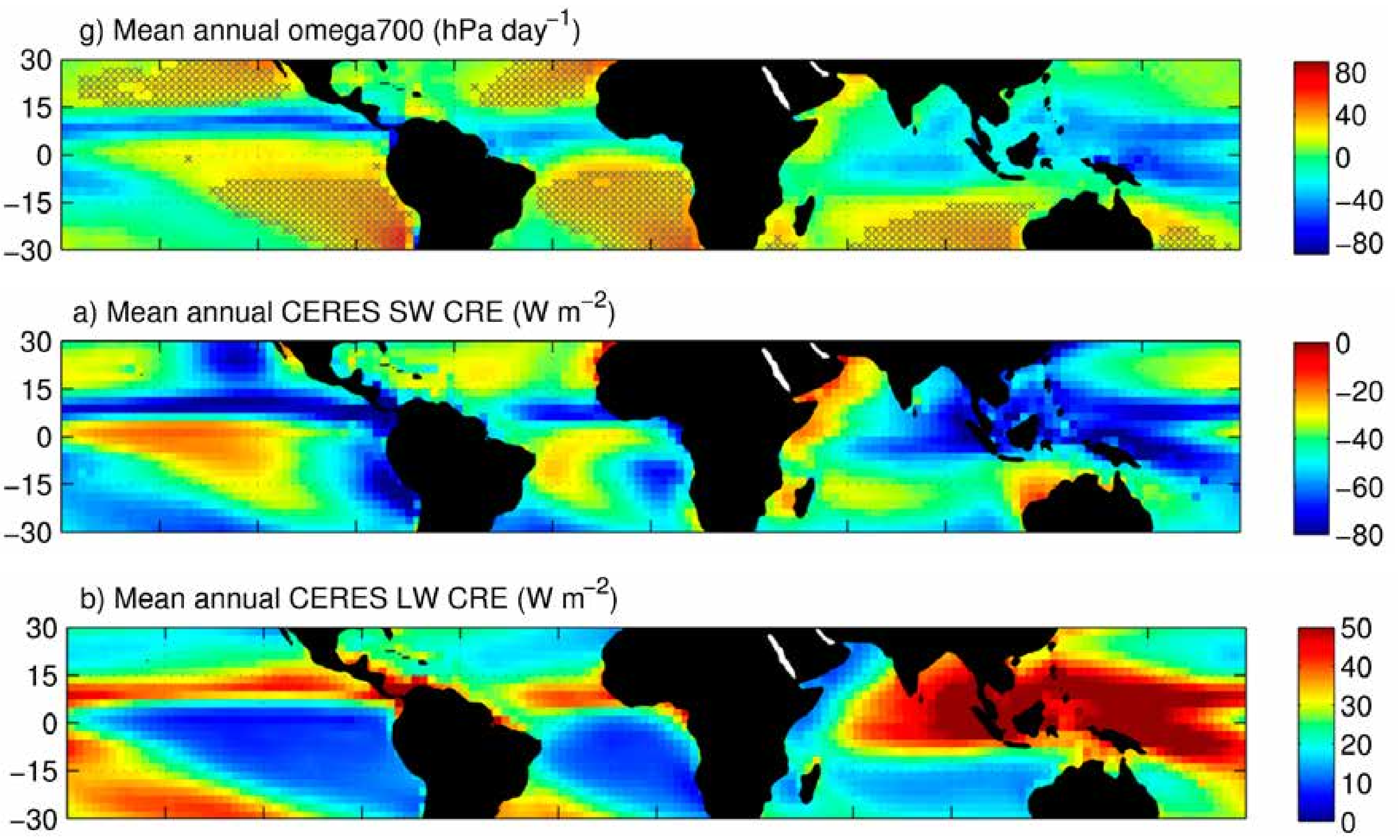
- Preferentially occur in areas of subsidence (analysis region marked with ´)
- Strongly reflect shortwave (SW) radiation and have large negative SW cloud radiative effect (CRE)



Geography and Radiative Effects of BL Cloud

BL clouds

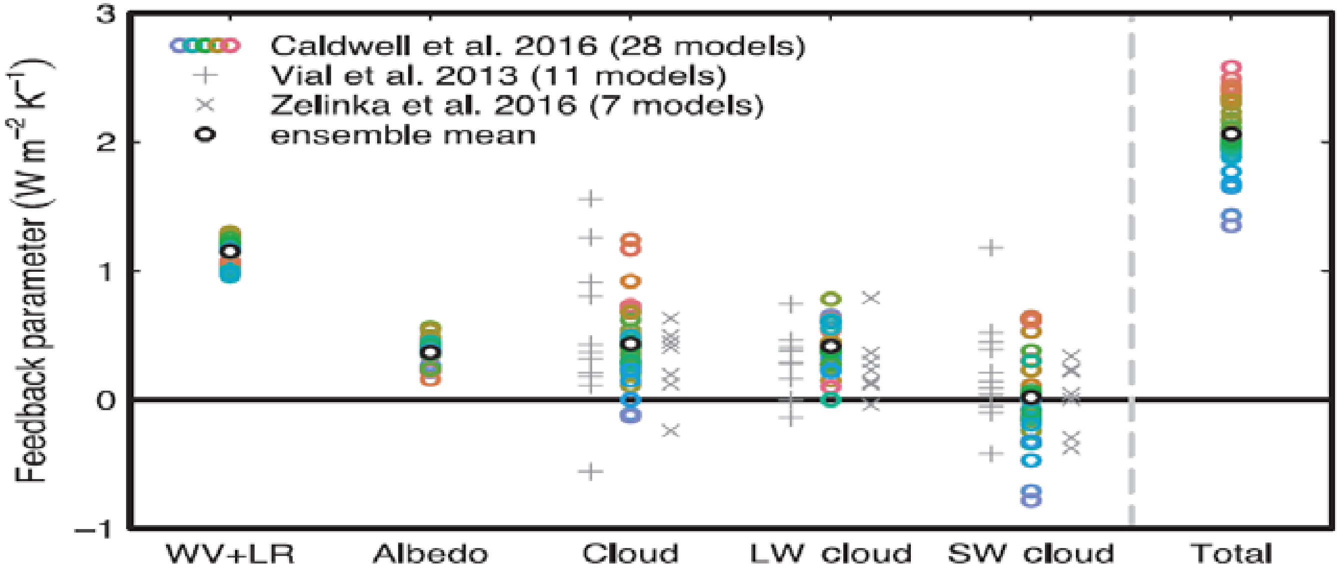
- Preferentially occur in areas of subsidence (analysis region marked with ´)
- Strongly reflect shortwave (SW) radiation and have large negative SW cloud radiative effect (CRE)
- Weakly retain longwave (LW) radiation and have small positive LW CRE



Plots from Myers and Norris (2015)

SW Cloud Feedbacks in Climate Models

- SW cloud feedback (primarily from BL clouds) causes the most inter-model disagreement about climate sensitivity

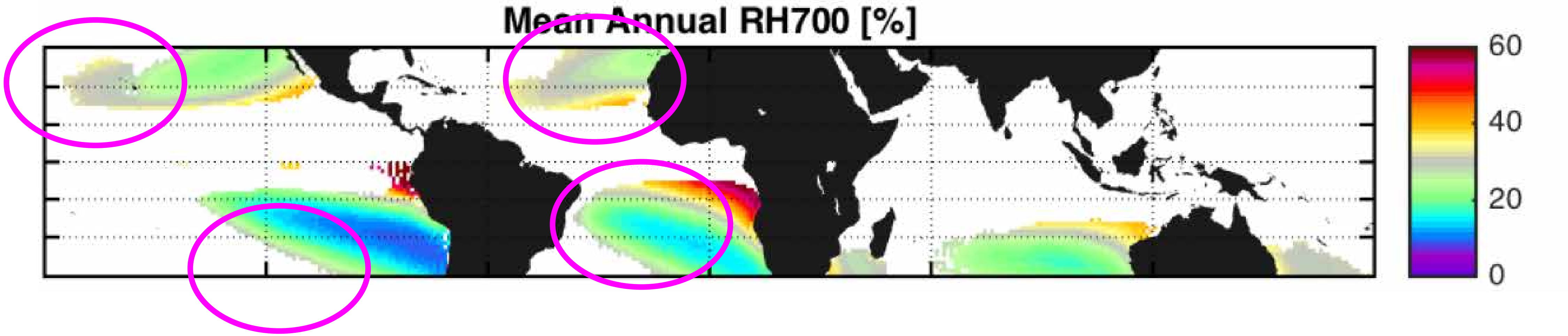


Plot from Ceppi et al. (2017)

Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

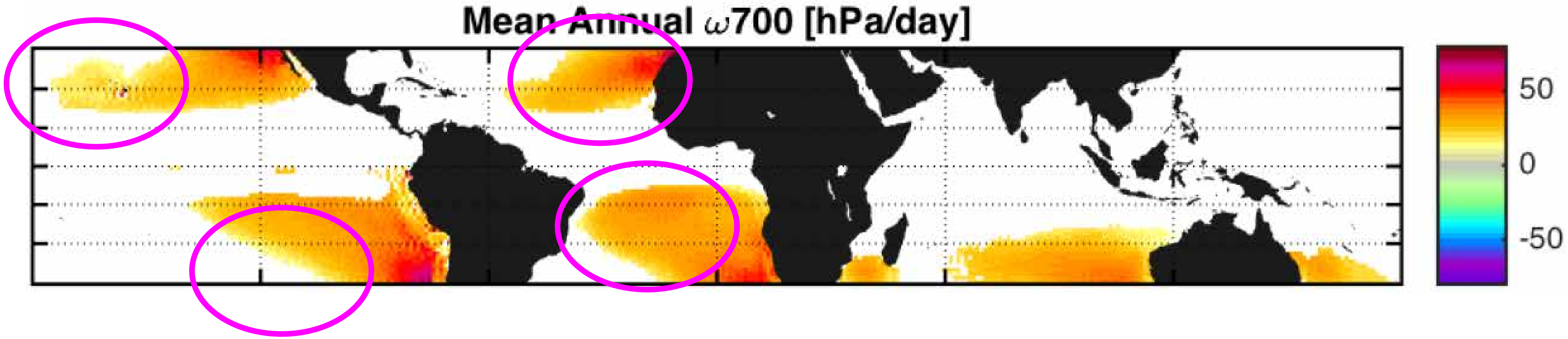
Regime	Cloud Fraction (%)	SST (K)	EIS (K)	SSTadv (K dy^{-1})	RH_{700} (%)
Core Sc	78	295.7	3.6	−1.3	24
Transition-to-Cu	45	297.4	1.0	−0.3	26



Core Sc and Transition-to-Cu Regimes

Divide grid boxes into upper and lower thirds according to climatological cloud fraction

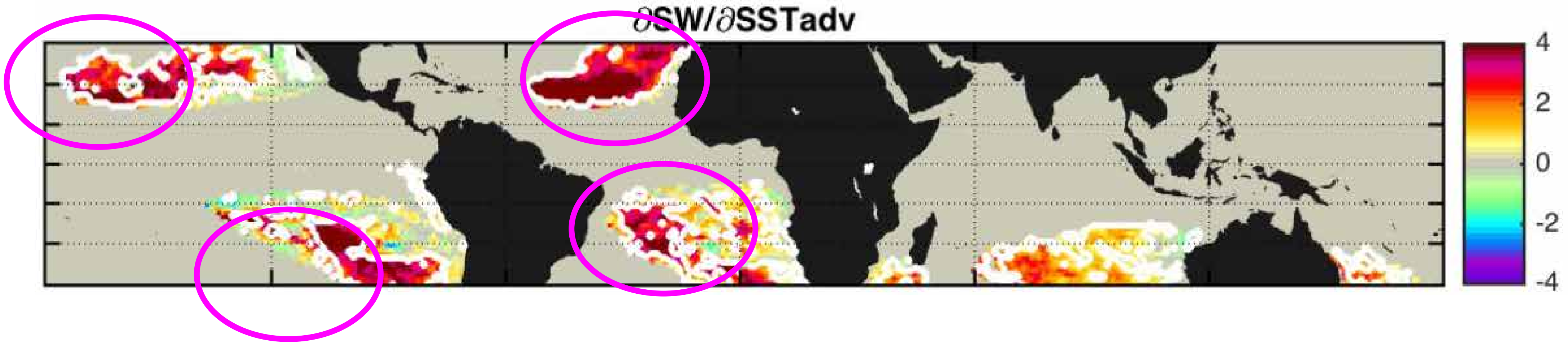
Regime	Cloud Fraction (%)	SST (K)	EIS (K)	SSTadv (K dy^{-1})	RH_{700} (%)	w_{700} (hPa dy^{-1})
Core Sc	78	295.7	3.6	−1.3	24	33
Transition-to-Cu	45	297.4	1.0	−0.3	26	28



Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} $sigma^{-1}$)

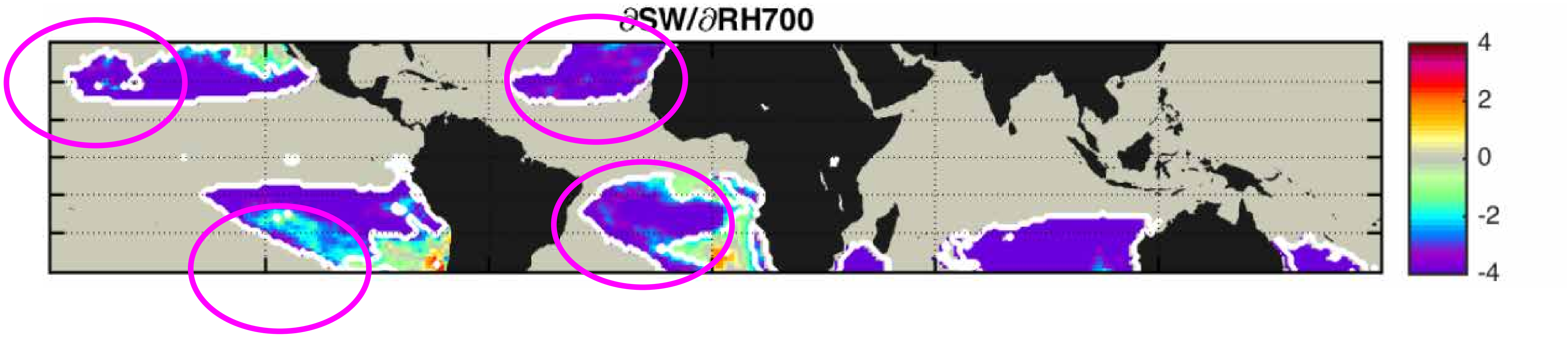
Regime	$\frac{\partial SW}{\partial SST}$	$\frac{\partial SW}{\partial EIS}$	$\frac{\partial SW}{\partial SSTadv}$
Core Sc	1.3	−4.2	0.9
Transition-to-Cu	1.8	−2.8	2.4



Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} sigma^{-1})

Regime	$\frac{\partial SW}{\partial SST}$	$\frac{\partial SW}{\partial EIS}$	$\frac{\partial SW}{\partial SSTadv}$	$\frac{\partial SW}{\partial RH_{700}}$
Core Sc	1.3	−4.2	0.9	−3.6
Transition-to-Cu	1.8	−2.8	2.4	−3.7



Core Sc and Transition-to-Cu Regimes

Observed SW cloud response to typical anomaly in controlling factor (units: W m^{-2} sigma^{-1})

Regime	$\frac{\partial SW}{\partial SST}$	$\frac{\partial SW}{\partial EIS}$	$\frac{\partial SW}{\partial SSTadv}$	$\frac{\partial SW}{\partial RH_{700}}$	$\frac{\partial SW}{\partial \omega_{700}}$
Core Sc	1.3	−4.2	0.9	−3.6	0.4
Transition-to-Cu	1.8	−2.8	2.4	−3.7	1.2