Subtropical Stratocumulus Processes and Feedbacks: The Role of Large-Scale Dynamics

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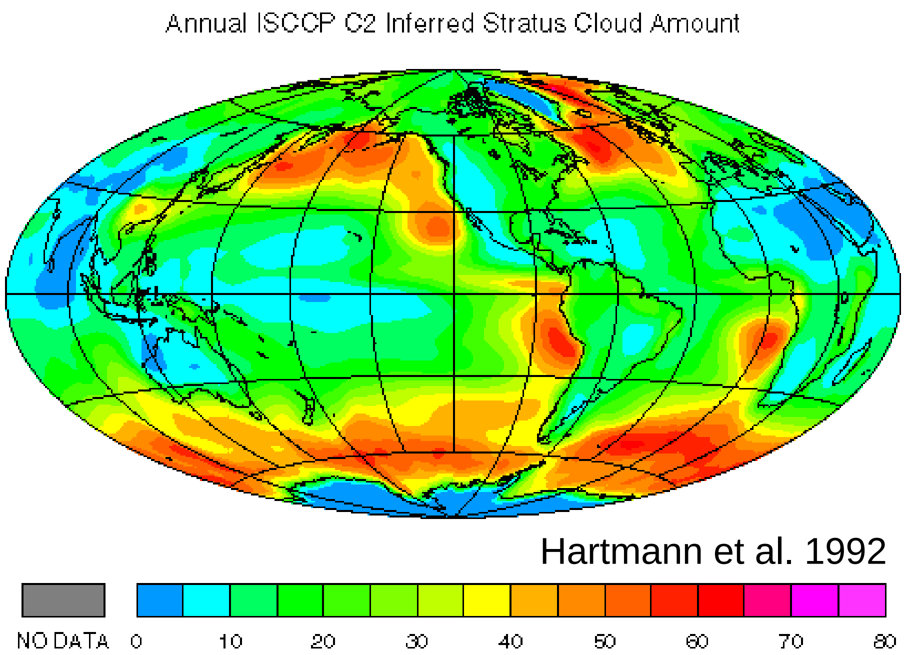
Introduction and Motivation

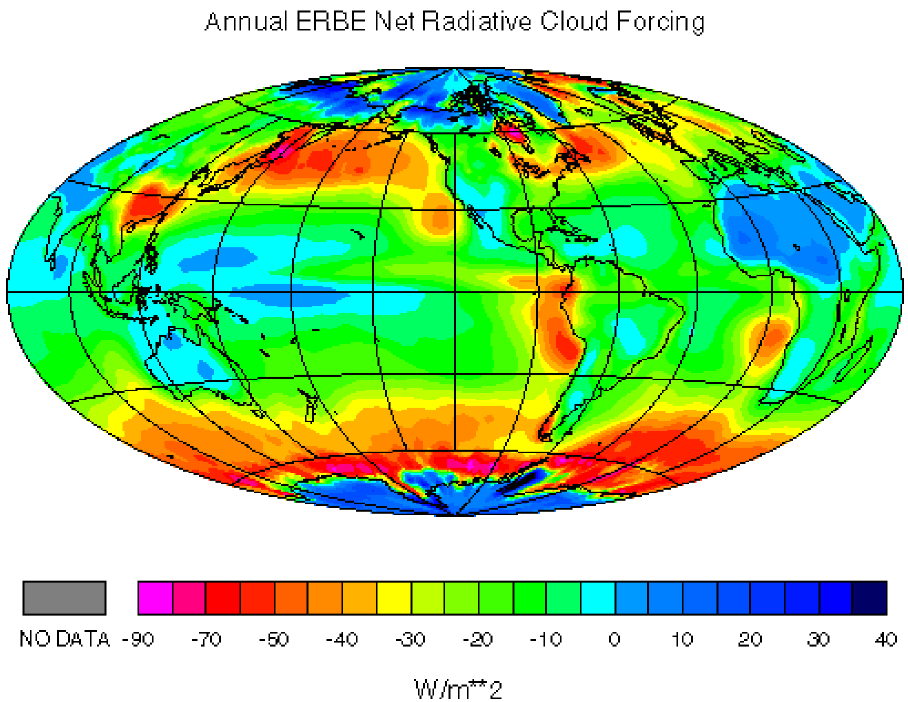
4th IPCC: Key Uncertainties

- “Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty [to climate sensitivity].”
- “Surface and satellite observations disagree on total and low-level cloud changes over the ocean.”
- “Large uncertainties remain about how clouds might respond to global climate change.”
- “Cloud feedbacks are the primary source of intermodel differences in equilibrium climate sensitivity…”

Low-Level Cloud and Net Radiation



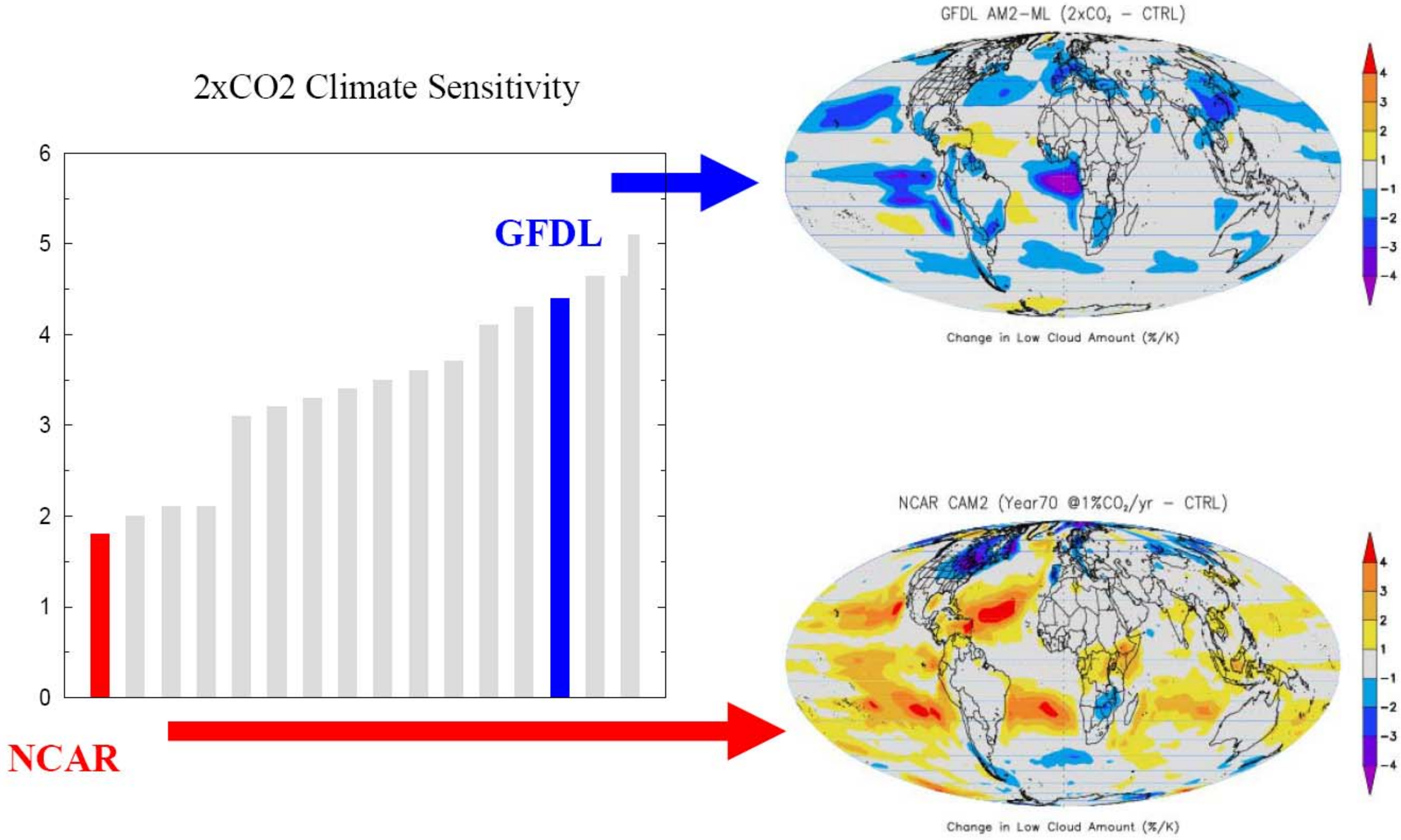
Hartmann et al. 1992



Cloud with tops below 680 mb (less than 3 km)

Low-level clouds and especially marine stratocumulus cool the planet (solar reflection by clouds greater than greenhouse effect of clouds)

Simulated Cloud Change for 2×CO_2



Courtesy of Brian Soden

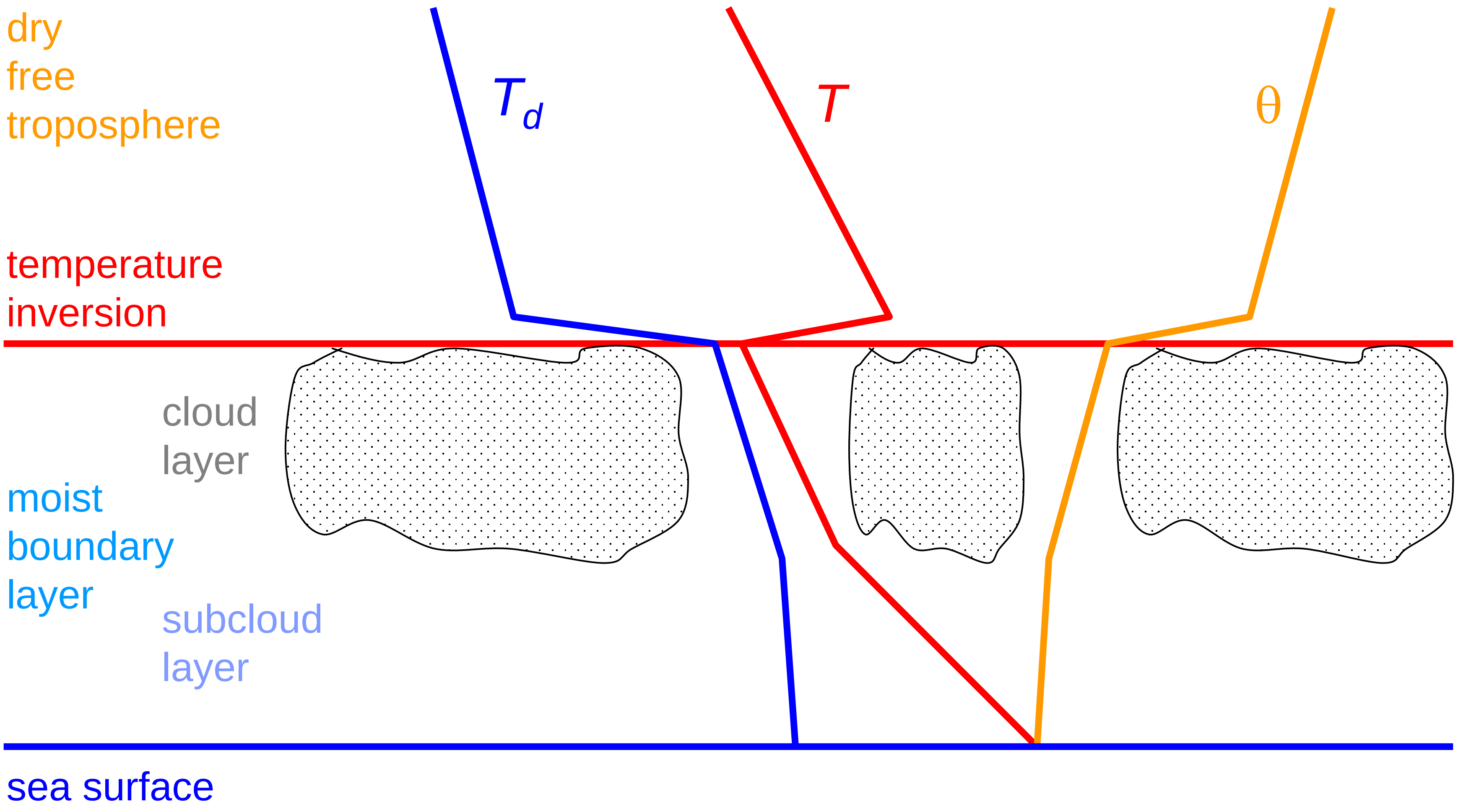
Models predict different signs of cloud change

Why is Cloud Simulation Difficult?

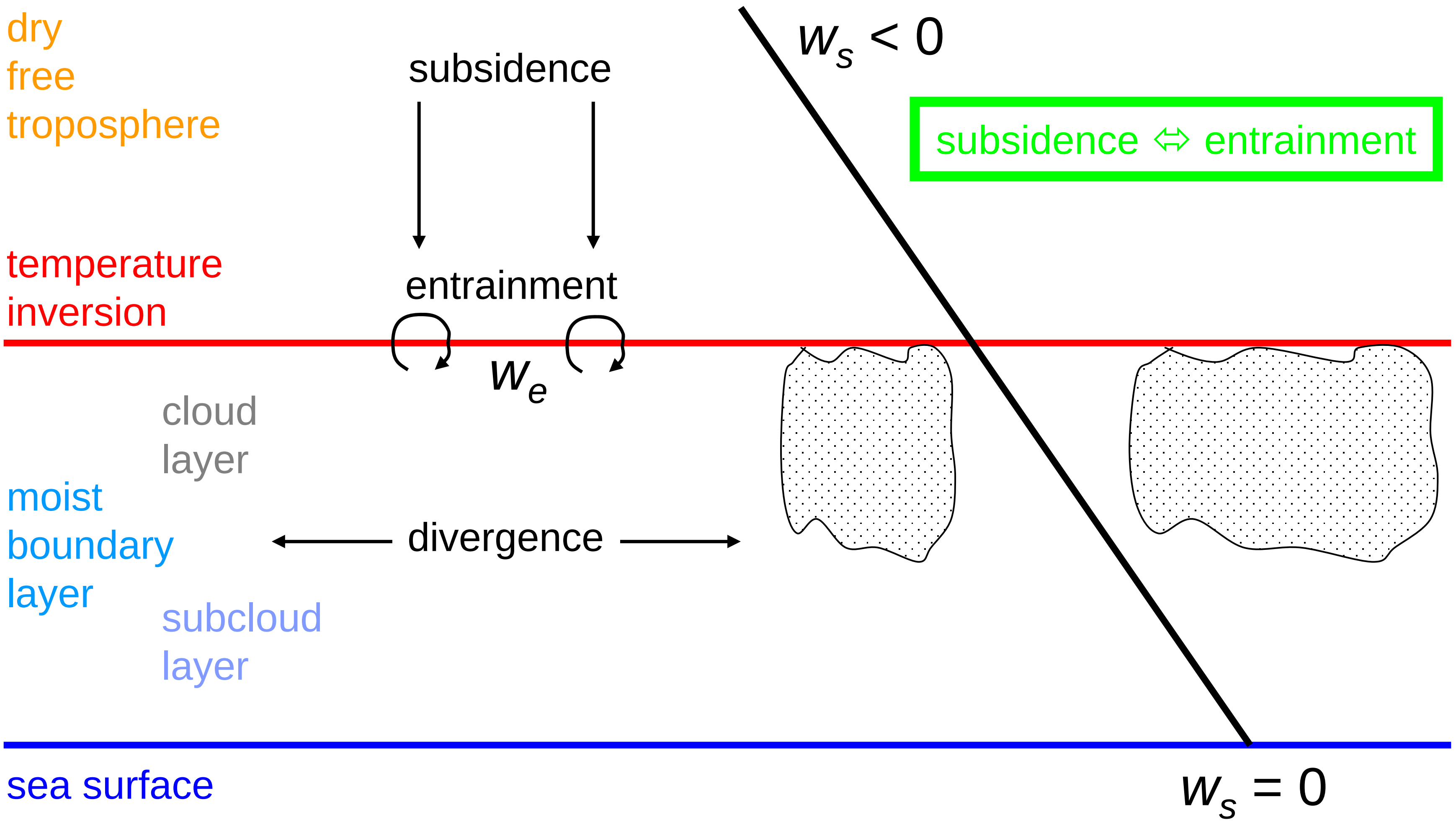
- Cloud distribution in boundary layer is controlled by small-scale processes
- Shallow convection, turbulence, entrainment, and radiative cooling are closely interacting
- Parameterizations in terms of resolved-scale processes are too crude and disconnected

Background Material

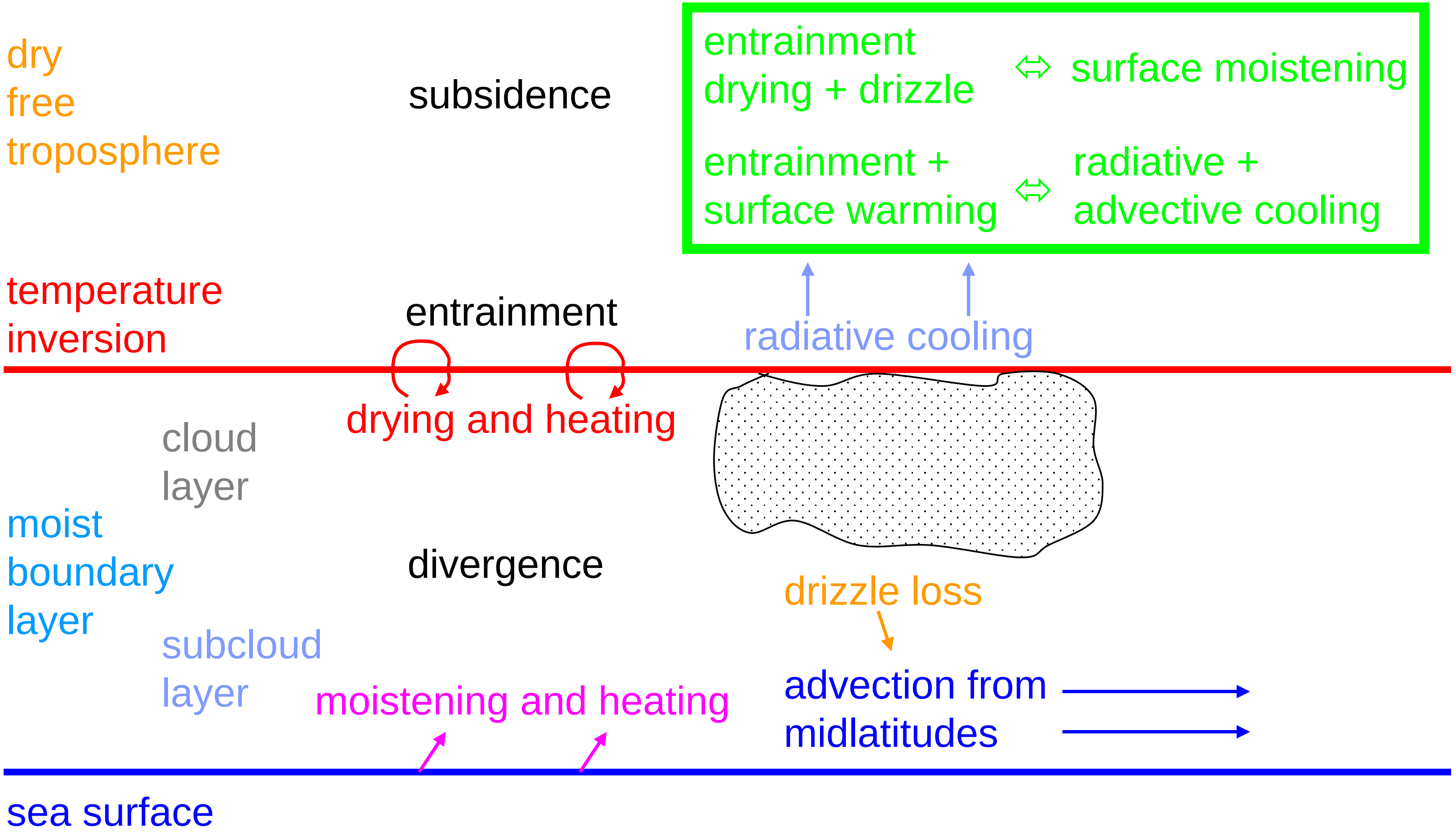
Subtropical Marine Boundary Layer



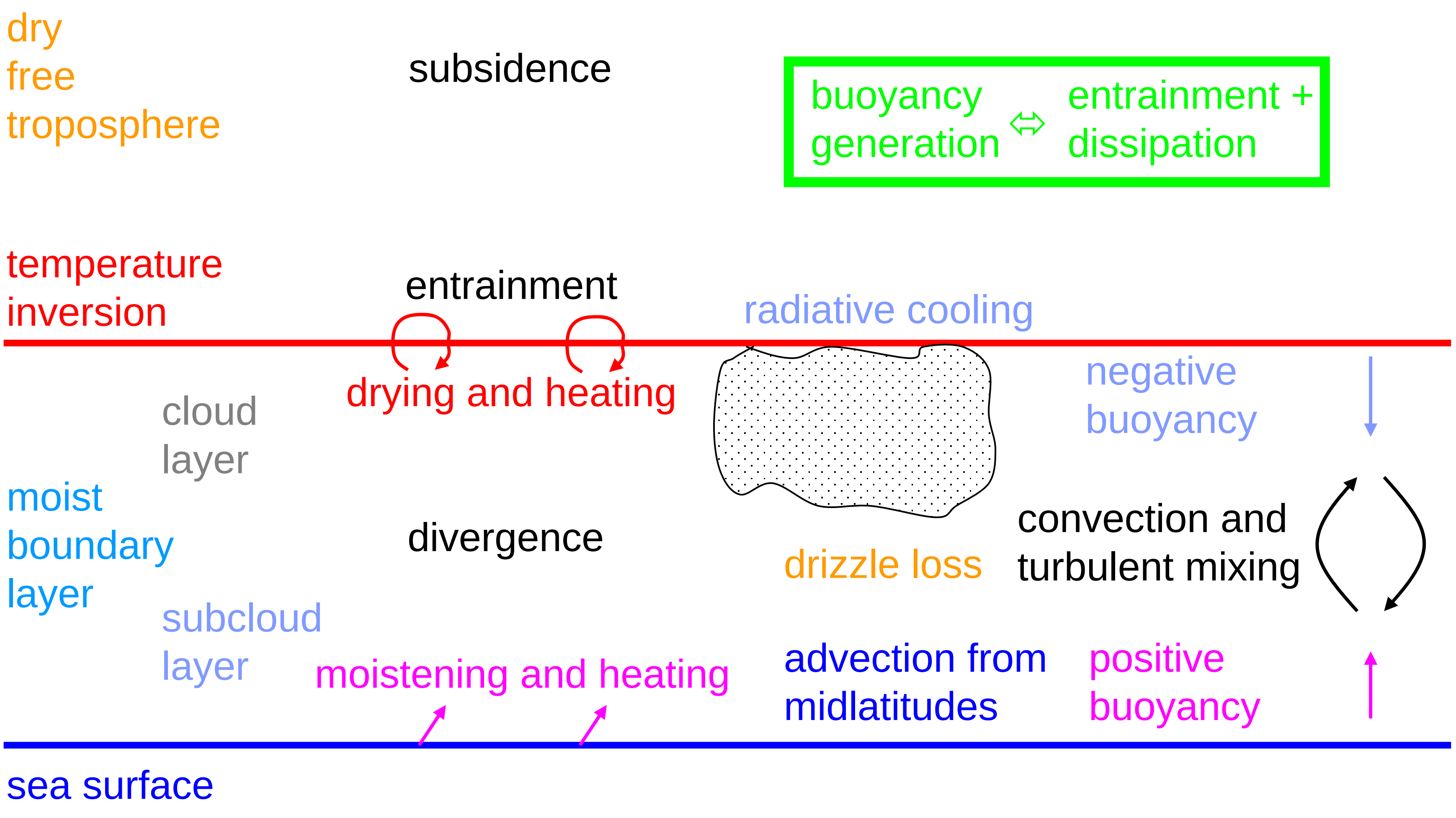
Subtropical Marine Boundary Layer



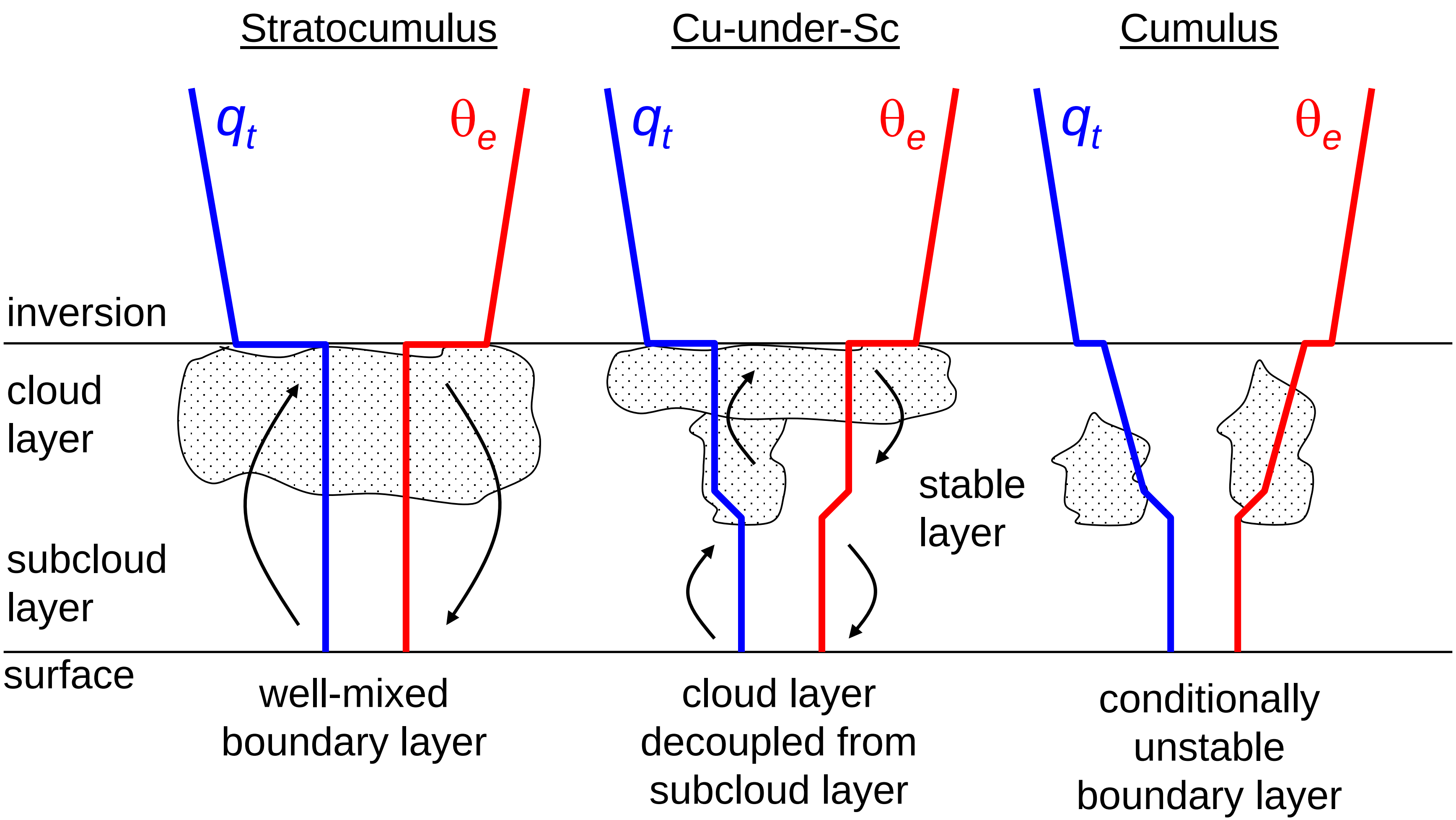
Subtropical Marine Boundary Layer



Subtropical Marine Boundary Layer



Boundary Layer Structure and Clouds



What Promotes Decoupling?

- Entrainment of warm air stratifies boundary layer

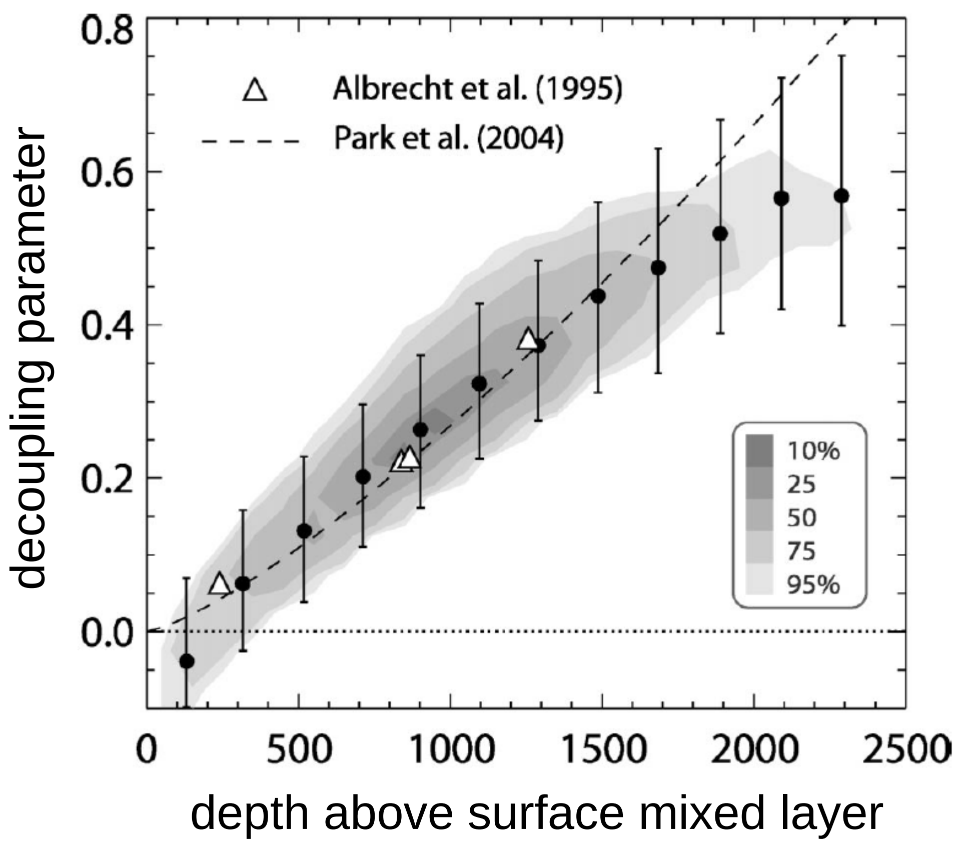
  except for condition of CTEI
- Daytime solar heating of cloud layer

  diurnal effect
- Drizzle condensation in cloud layer and evaporation in subcloud layer

  potentially influenced by anthropogenic aerosol

What Promotes Decoupling?

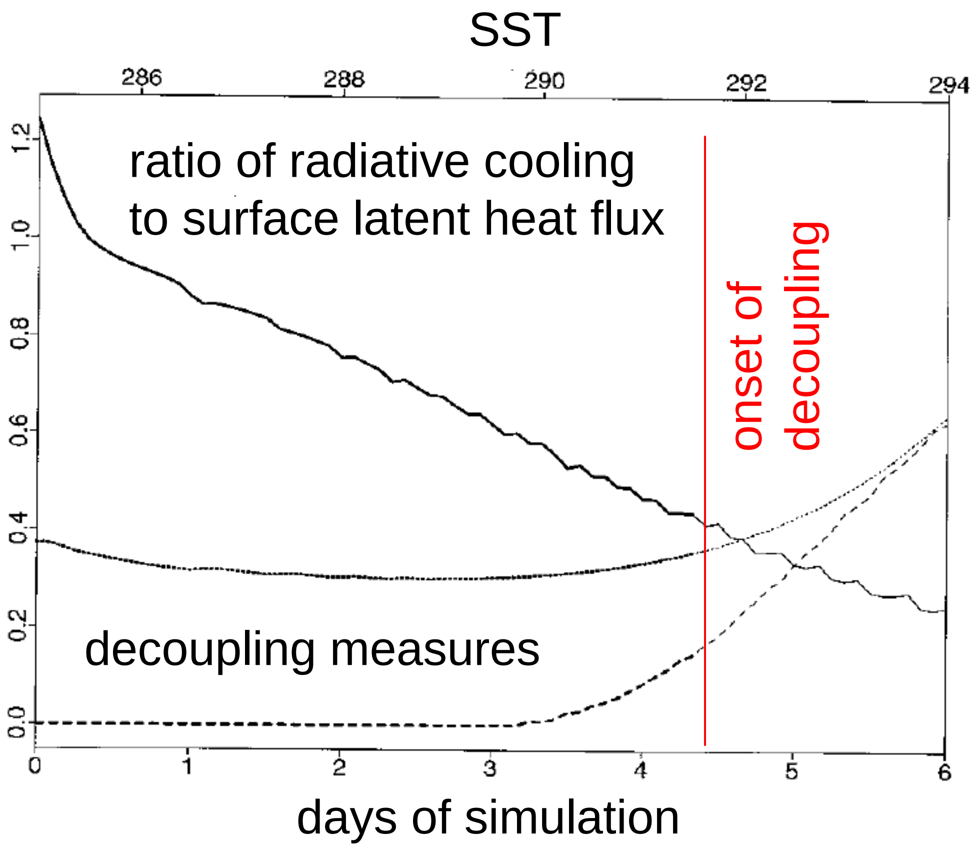
- Deeper boundary layer



from Wood and Bretherton (2004)

What Promotes Decoupling?

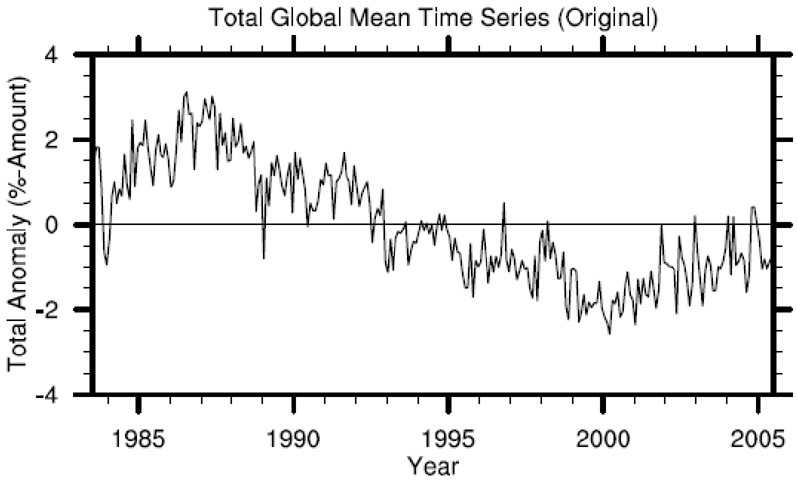
- Surface heat flux stronger than radiative cooling

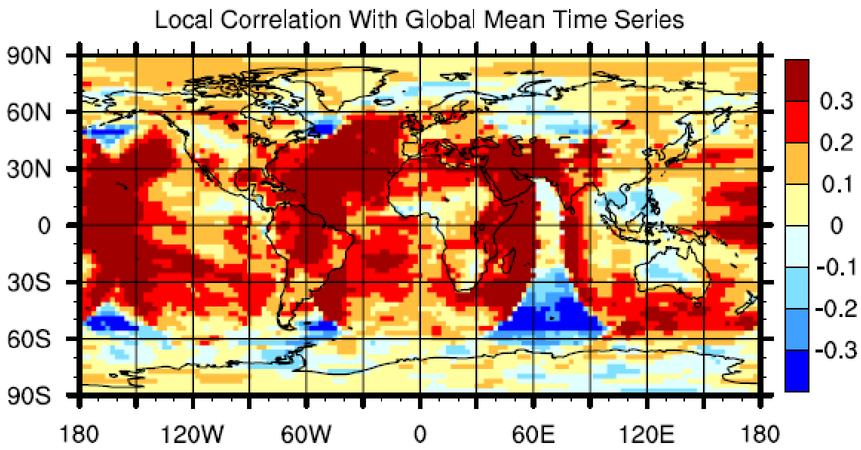


from Bretherton and Wyant (1997)

Observed Multidecadal Relationships

Artifacts Dominate Cloud Record



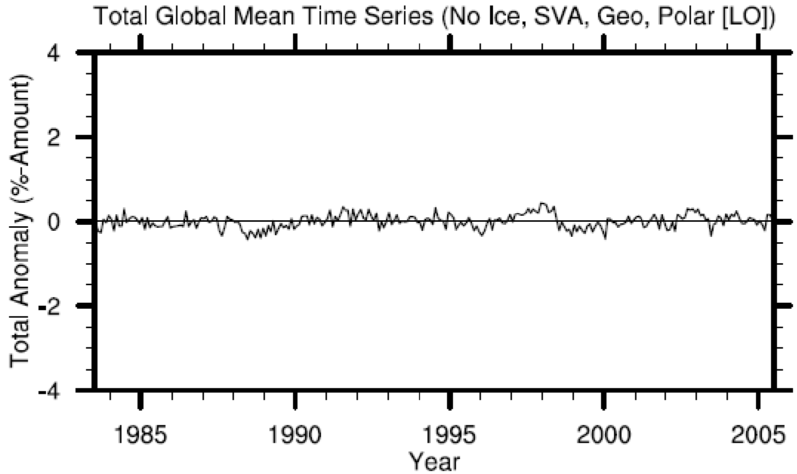


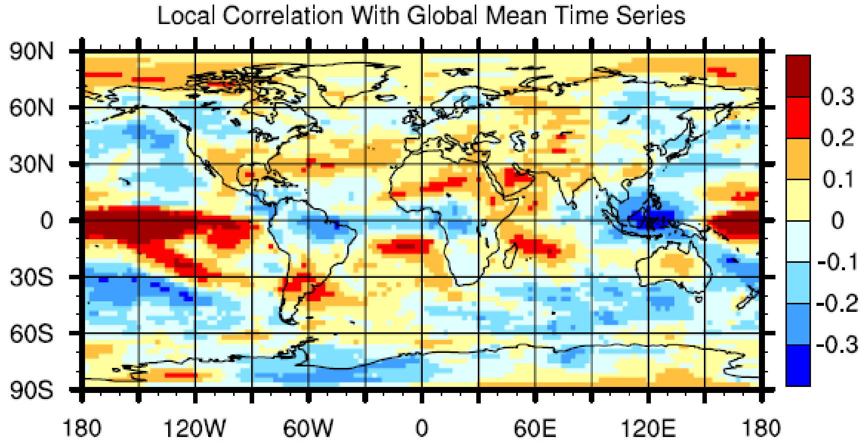
ISCCP cloud amount is dominated by artifacts on multidecadal time scales caused by:

changes in satellite view angle (Evan et al. 2007)

imperfect calibration of geostationary satellites

But This Can Be Corrected





ISCCP total cloud amount after statistical removal of artifacts via linear regression:

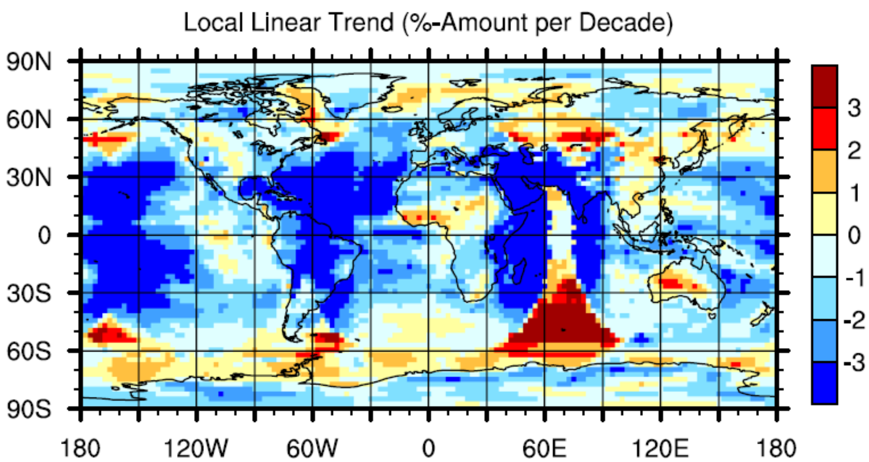
satellite view angle

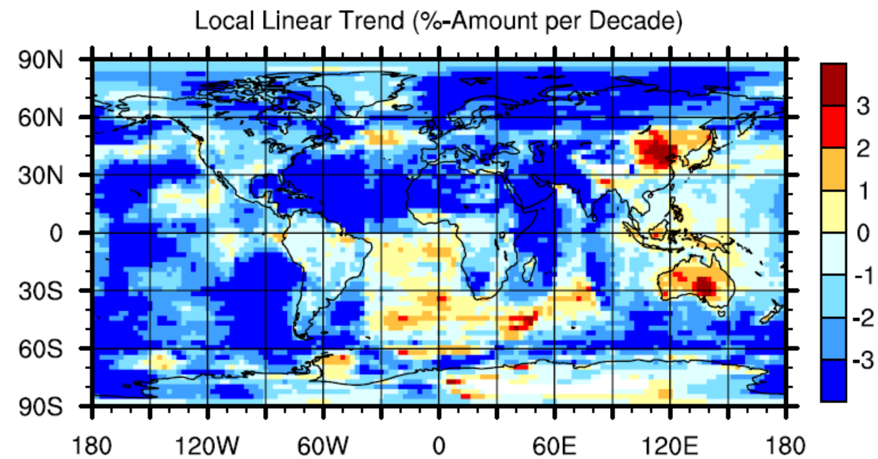
average normalized anomaly within view of a geostationary satellite

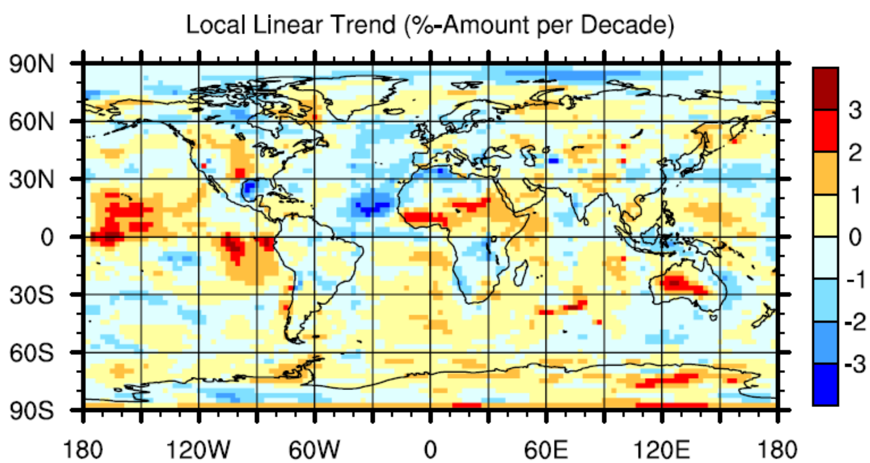
Before and After Cloud Trends

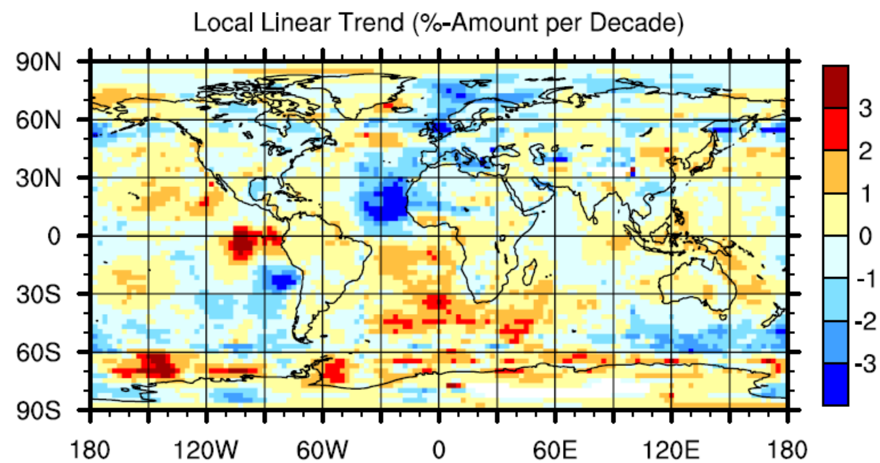
total cloud

low-level cloud



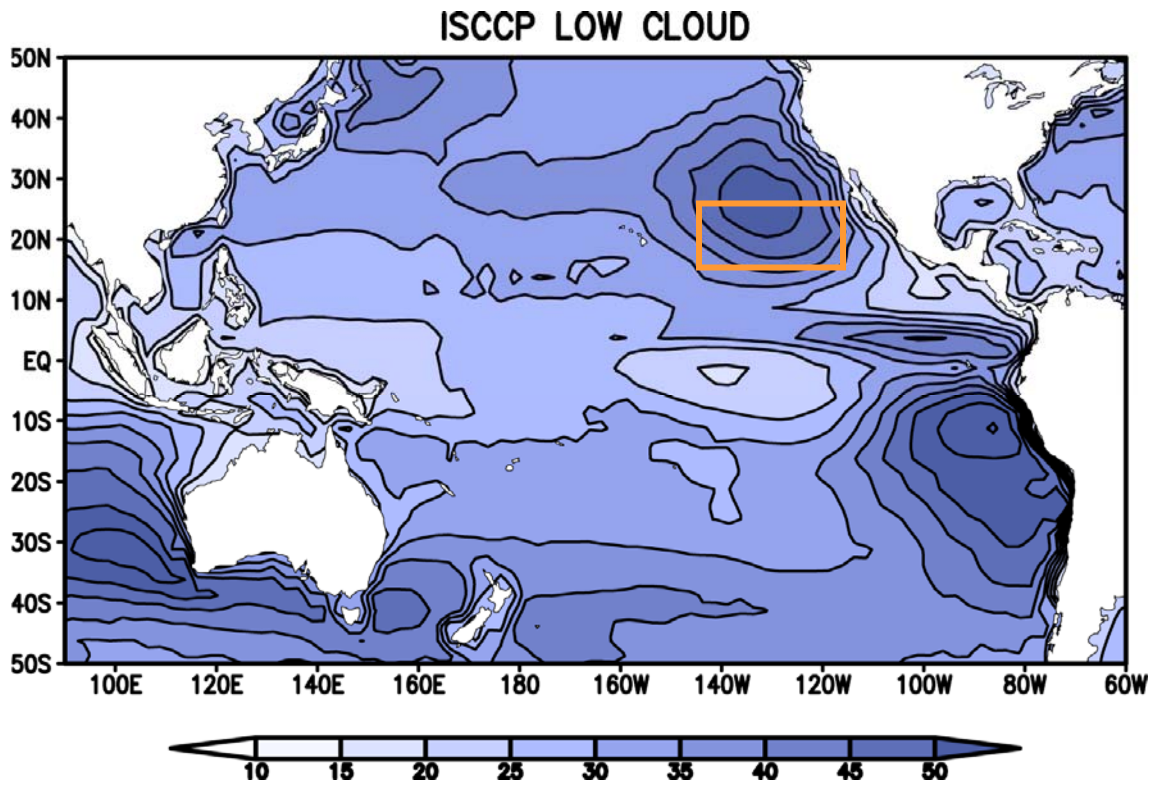






NE Pacific Decadal Variability

How is cloud variability related to SST and circulation?

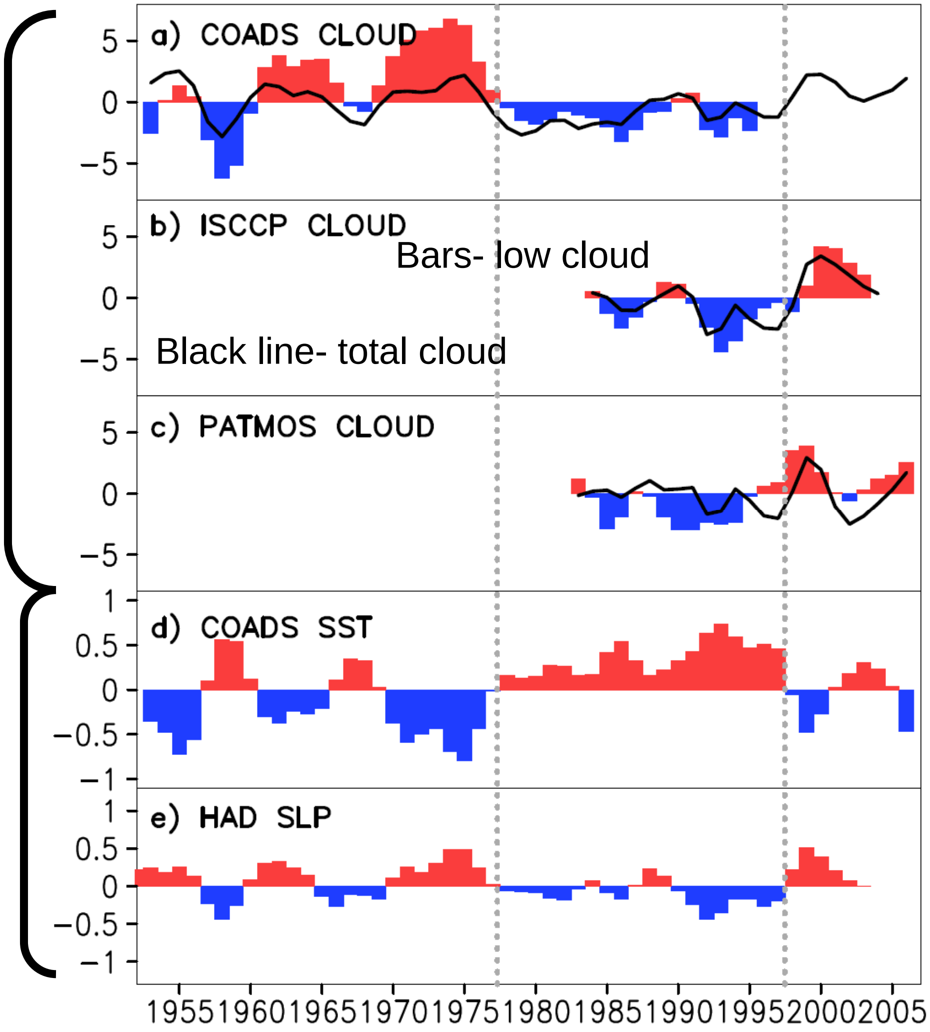


NE Pacific Decadal Variability

Similar variations in three independent cloud datasets

Cloud fluctuations coincide with regional SST and SLP changes

- 1976 'shift'
- Late 1990's 'shift'

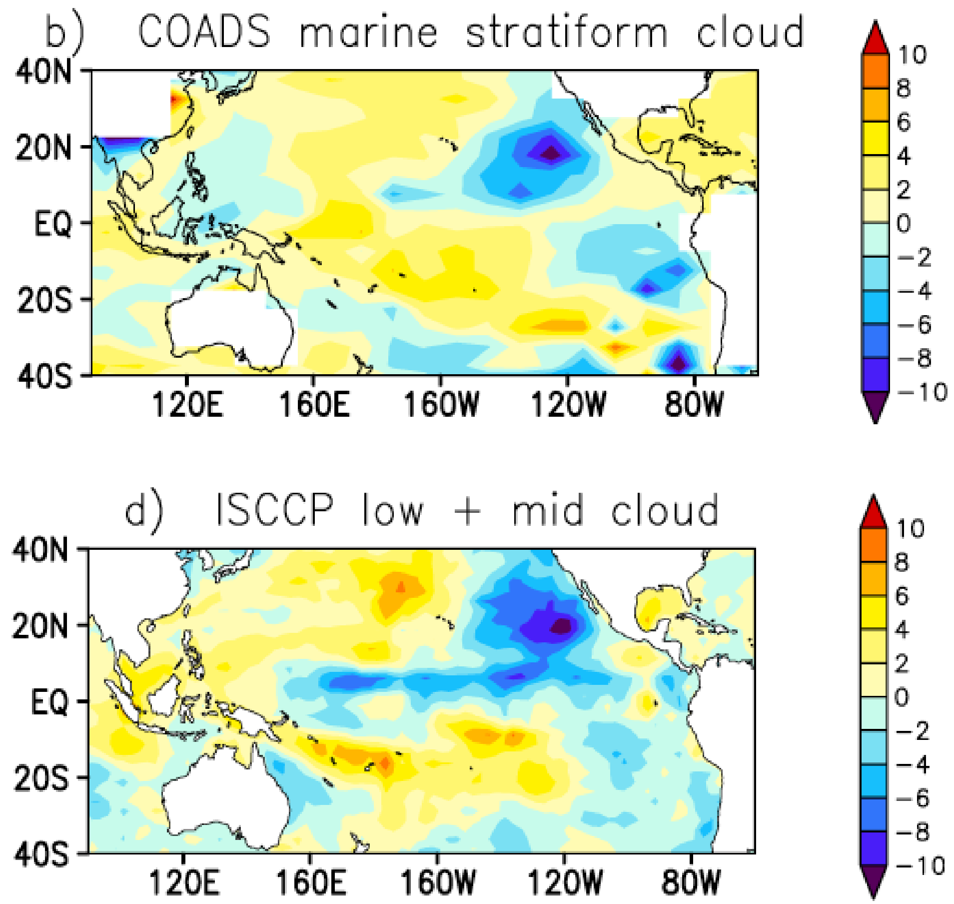


Spatial Structure of Cloud Change

COADS and ISCCP show less low-level cloud cover over NE and SE subtropical Pacific when NE Pacific SST is warm

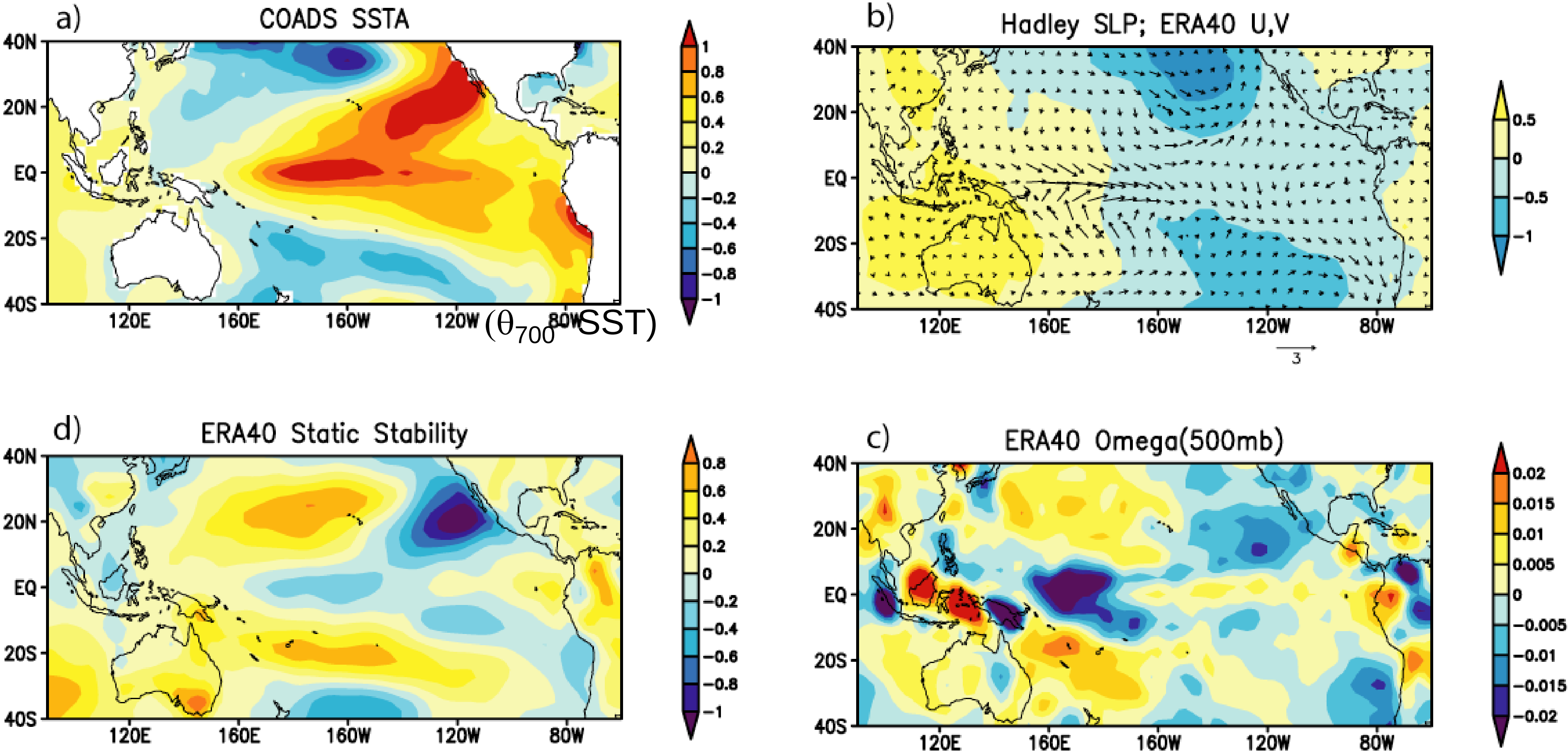
PATMOS pattern is similar (not shown)

Regression of low cloud on NE Pacific SST



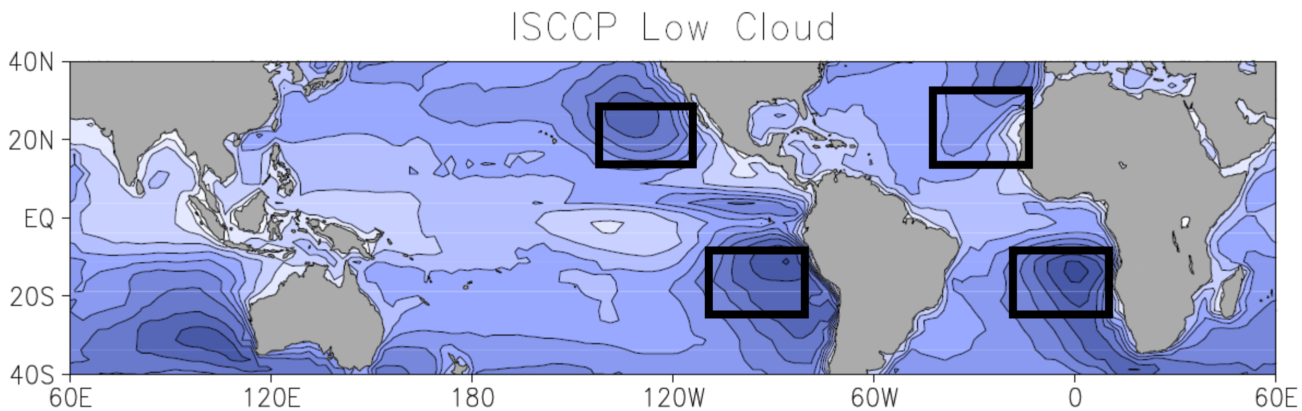
Structure of Meteorological Change

Regression on NE Pacific SST



lower tropospheric static stability (LTS) = θ_{700} - θ_{SST}

Cloud-Meteorological Correlations



ISCCP low cloud amount	SST	LTS	SLP	ω_{500} (NCEP)
NE Pacific	**-0.85**	**0.65**	**0.71**	**0.42**
SE Pacific	**-0.53**	**0.65**	0.40	0.38
NE Atlantic	**-0.72**	**0.44**	**0.60**	**0.78**
SE Atlantic	**-0.52**	**0.51**	**0.58**	0.37

*Significant correlations (based on t-statistic) at the 95% level are shown in **bold**.

Co-Meteorological Correlations

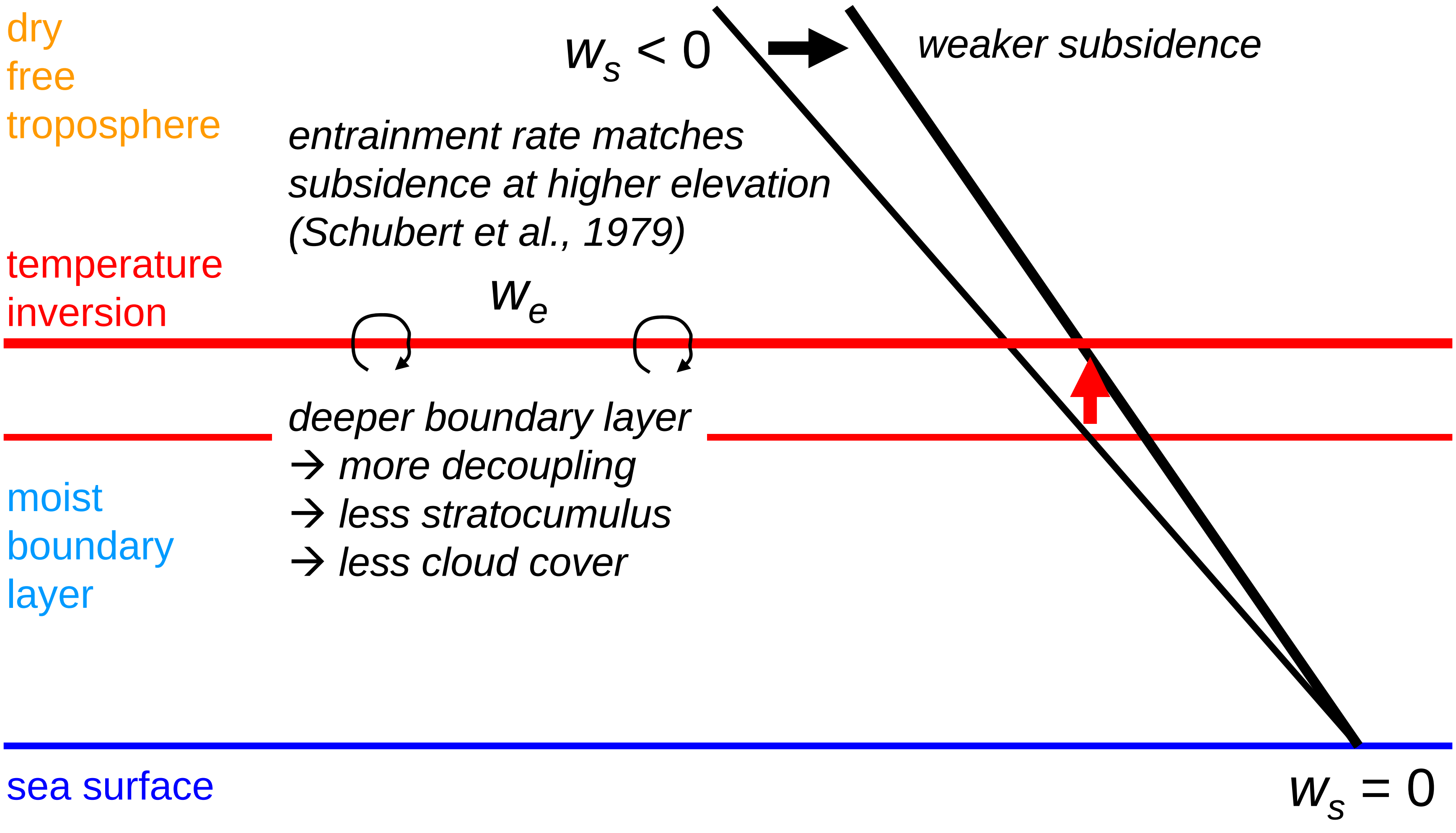
NE PACIFIC	**SST**	**LTS**	**SLP**	ω_{500}
SST	**1**	**-0.8**	**-0.7**	**-0.36**
LTS		**1**	**0.71**	**0.63**
SLP			**1**	**0.42**
ω_{500}				**1**

Results are similar for other regions.

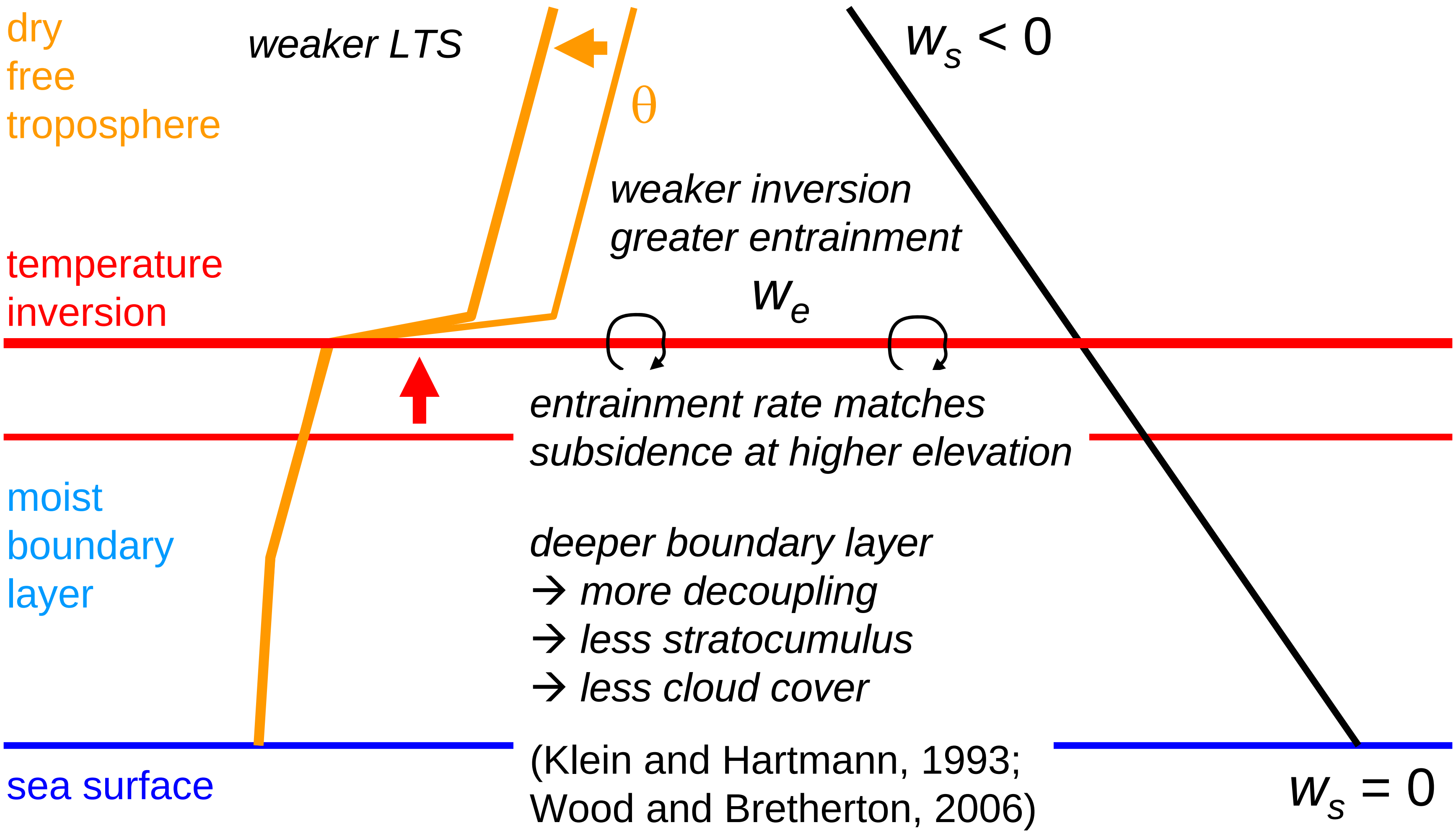
All values are significant at the 95% level based on t-statistic

Mechanisms Driving Relationships

Subsidence and Cloud



LTS and Cloud



SLP and Cloud

- SLP is positively correlated with LTS, divergence, and pressure vertical velocity

- Lower subtropical SLP is associated with weaker trade winds
- Weaker trade winds produce less advection from upwind stratocumulus regions
- Cloud cover locally decreases in downwind region

SST and Cloud

- Warmer SST contributes to weaker LTS

- Warmer SST produces greater latent heat flux
- Greater latent heat flux favors more decoupling
- More decoupling promotes less stratocumulus and less cloud cover

Cloud Feedbacks

- Less cloud cover warms the ocean and weakens LTS

- Less cloud cover reduces radiative cooling of the boundary layer

  → Weaker pressure gradient and trade winds (Ma et al. 1996, Nigam 1997)

  → Weaker subsidence warming

Cloud Feedbacks and Climate

In eastern subtropical oceans…

- Surface cloud radiative warming anomalies are larger than latent heat cooling anomalies
- Ocean dynamical forcing is weak (Hazeleger et al., 2004)
- Cloud feedbacks may promote persistence of SST anomalies and enhance decadal variability

- What about global warming?

Model Simulations

Are CMIP3 Simulations Realistic?

- Do the models reproduce the correct sign of the observed correlation for all parameters?
- Examine total cloud correlation because low-level cloud usually not archived
- The preceding test is a necessary (but not sufficient) condition for a credible low-level cloud feedback
- Will examine CMIP5 archive when available

Are CMIP3 Simulations Realistic?

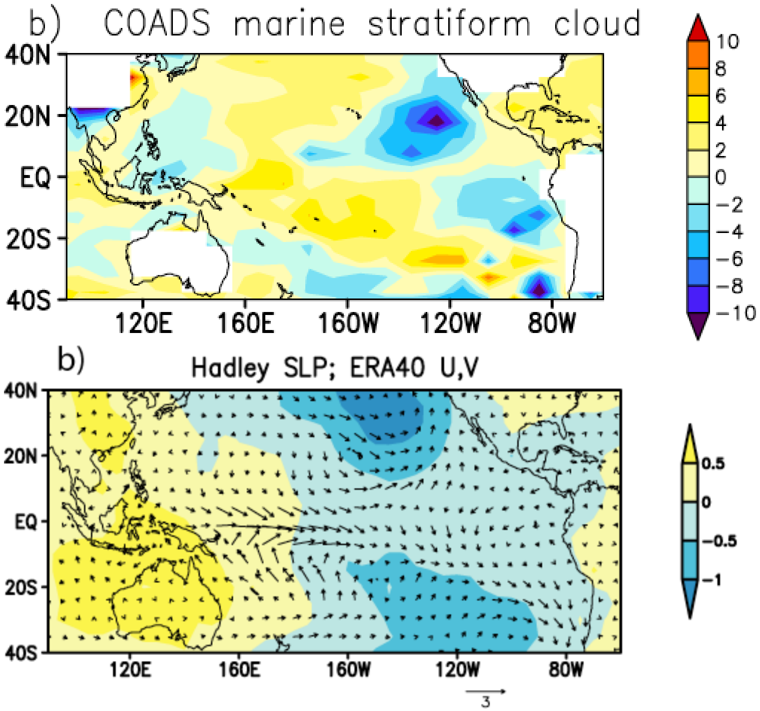
Only two models (HadGEM1 and INMCM3) reproduced the correct sign of all observed correlations

INMCM3 had strongly empirical cloud schemes and produced a very unrealistic mean tropical climate

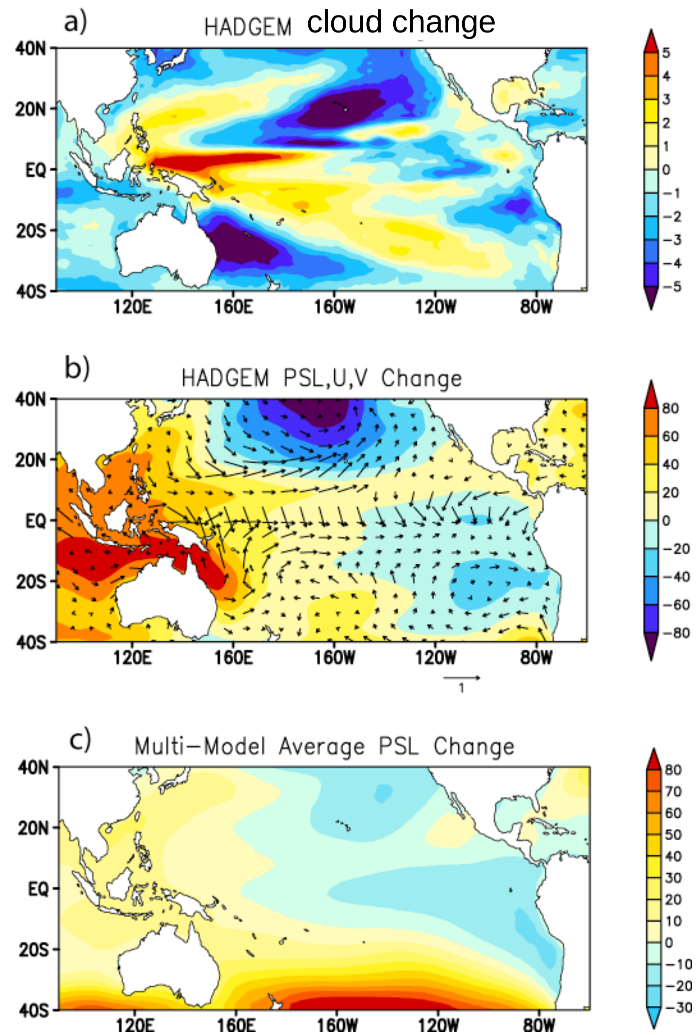
	SST	LTS	SLP	ω 500
Observations				
ISSCP-corrected total	**-0.75**	0.44	**0.80**	0.30
ISCCP-corrected low + mid	**-0.91**	**0.81**	**0.89**	**0.70**
COADS total	**-0.74**	0.35	**0.73**	0.53
COADS MSC	**-0.82**	0.42	**0.74**	**0.70**
Models with the correct cloud-meteorology relationships				
ukmo_hadgem1	**-0.81**	**0.84**	**0.65**	**0.39**
inmcm3_0	**-0.77**	**0.37**	**0.58**	0.14
Models that simulate the wrong sign r(cloud, ω 500)				
mri_cgcm2_3_2a	**-0.60**	0.21	**0.35**	**-0.58**
gfdl_cm2_0	**-0.69**	0.06	**0.52**	**-0.42**
ncar_ccsm3_0	**-0.66**	**0.48**	**0.63**	-0.18
Models that simulate the wrong sign r(cloud, SLP)				
miroc3_2_hires	**-0.91**	**0.54**	-0.03	-0.10
Models that simulate the wrong sign (or close to zero) r(cloud, LTS)				
cccma_cgcm3_1_t63	**-0.86**	0.01	**0.52**	0.20
cccma_cgcm3_1	**-0.80**	-0.08	**0.35**	-0.14
cnrm_cm3	**-0.73**	-0.24	**0.54**	**-0.54**
ipsl_cm4	**-0.53**	-0.16	0.25	**-0.32**
ukmo_hadcm3	**-0.44**	-0.17	**0.33**	**-0.43**
gfdl_cm2_1	**-0.31**	**-0.38**	0.05	**-0.56**
mpi_echam5	-0.23	**-0.44**	0.06	**-0.70**
miroc3_2_medres	-0.13	-0.08	-0.04	**-0.67**
Models that simulate the wrong sign r(cloud, SST)				
giss_aom	0.12	**-0.63**	**-0.39**	**-0.67**
iap_fgoals1_0_g	0.22	**-0.43**	-0.24	**-0.89**
giss_model_e_h	0.34	0.10	0.10	**-0.81**
giss_model_e_r	**0.39**	-0.04	0.003	**-0.58**

HadGEM1 2×CO_2 Change

Observed Decadal



2×CO_2 Simulation



2×CO_2 cloud and circulation changes
resemble observed decadal
cloud and circulation changes

HadGEM1 2×CO_2 Change

- HadGEM1 SLP change resembles multimodel mean, suggesting it is robust
- HadGEM1 cloud and SLP changes resemble observed NE Pacific patterns, suggesting similar mechanisms apply
- This implies a regional positive subtropical stratocumulus feedback under global warming

  but…

- LTS change is different sign from observed

Tropical LTS and Regional Dynamics

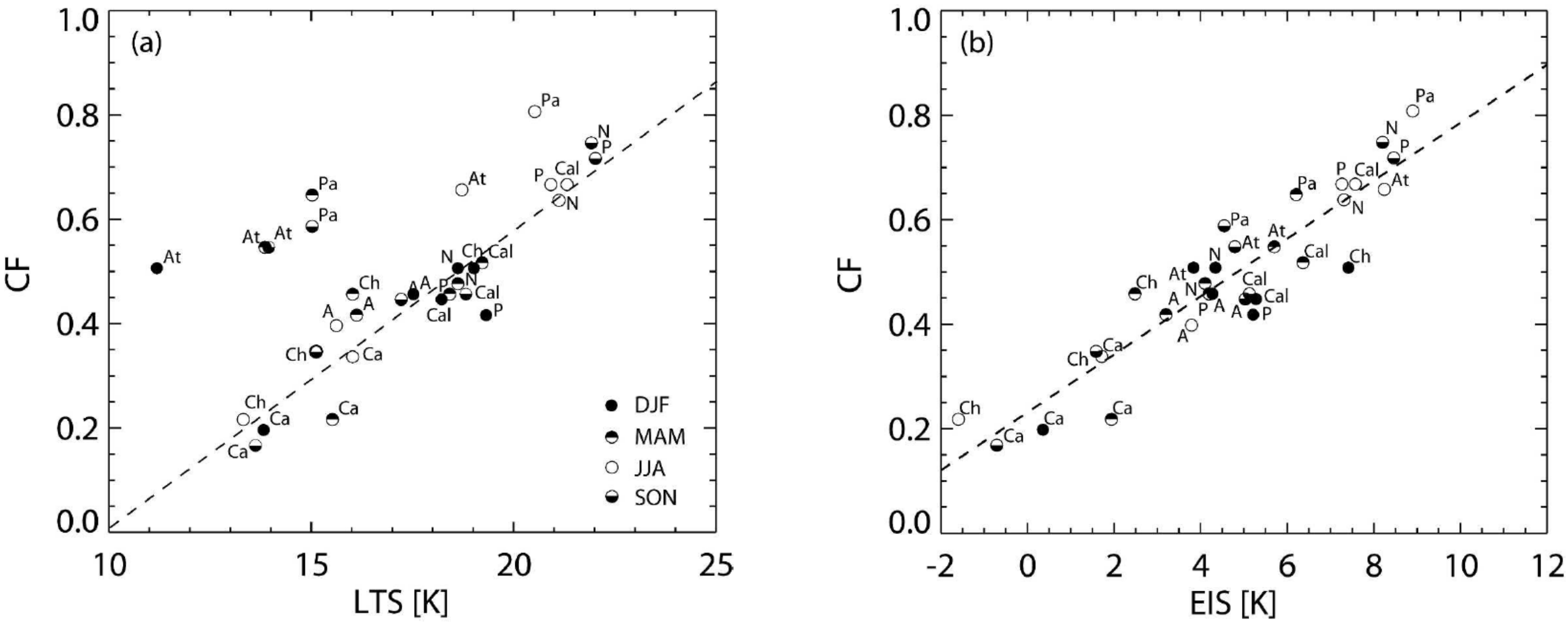
Increased LTS for Global Warming

- Moist adiabatic lapse rate in deep convection regions decreases for warmer SST
- The decreased lapse rate is communicated throughout the tropical free troposphere
- LTS increases in subtropical regions
- Stronger LTS promotes more stratocumulus and more cloud cover (Miller 1997; Medeiros et al., 2008)

  Is the last step correct?

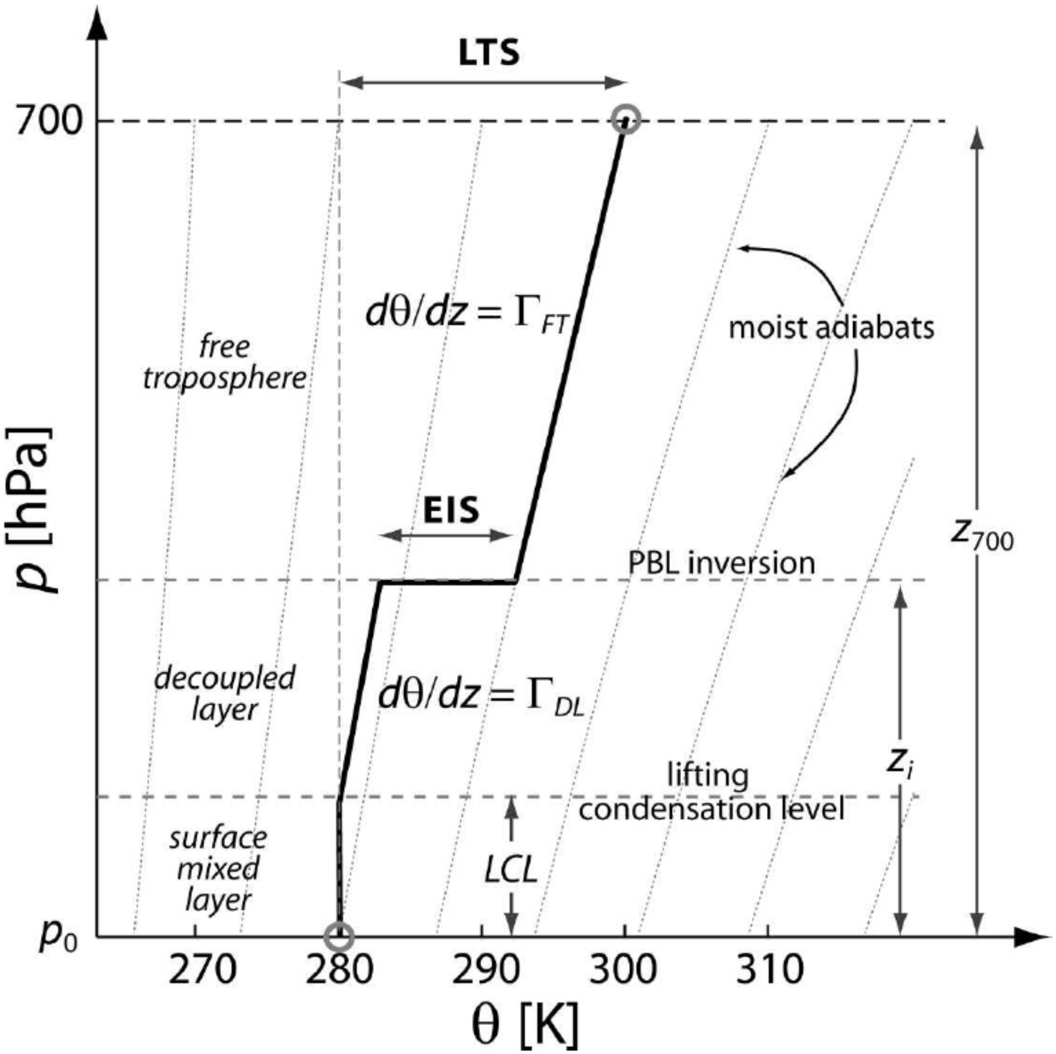
LTS and EIS

Estimated inversion strength (EIS) takes into account the temperature dependence of the moist adiabatic lapse rate (Wood and Bretherton 2006)



Climatological low-level cloud cover has higher correlation with EIS than LTS

LTS and EIS



In a warmer climate, EIS does not change as much as LTS because *d*θ/*dz* between inversion and 700 hPa is larger (WB 2006)

→ Much smaller impact on cloud!

LTS and Subsidence

What is the relationship between LTS and subsidence?

- Dynamical control of LTS?
- Thermodynamical control of subsidence?

Dynamical Control of LTS?

- Stronger subsidence produces warming through greater vertical temperature advection
- Because subsidence rate increases with height, warming increases with height (e.g, stronger LTS)
- Consistent with positive observed correlation between ω_{500} and LTS

Thermodynamic Control of Subsidence

- Stronger LTS associated with weaker lapse rate
- Less subsidence needed for vertical temperature advection to balance tropospheric radiative cooling

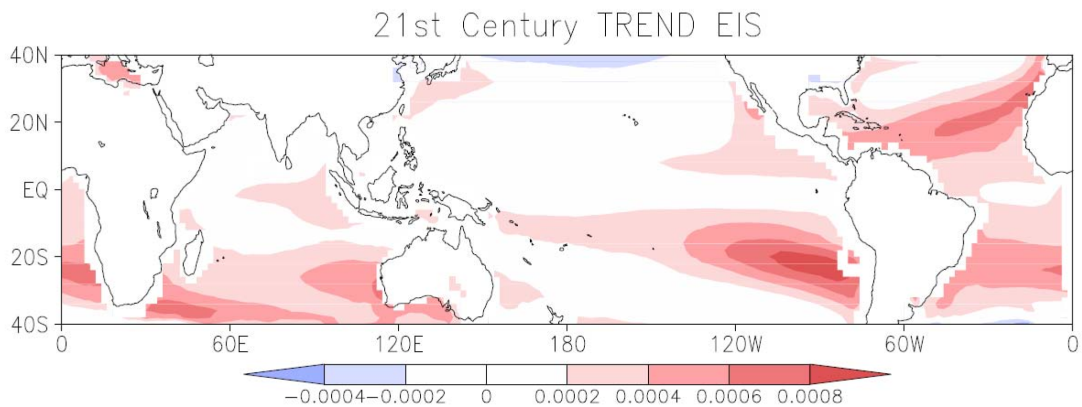
  But…

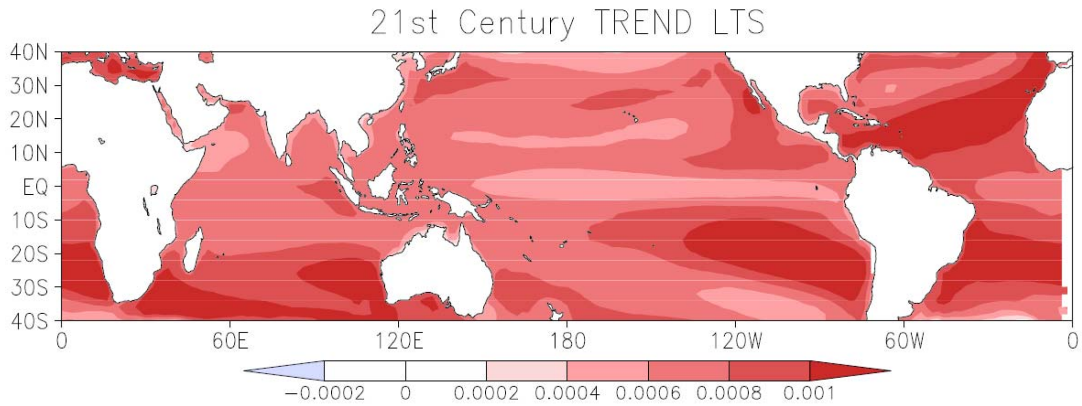
- Negative correlation between ω_{500} and LTS not regionally observed on multiyear time scales
- Regional dynamics may differ from tropical mean circulation change under global warming

Multimodel Trend in LTS and EIS

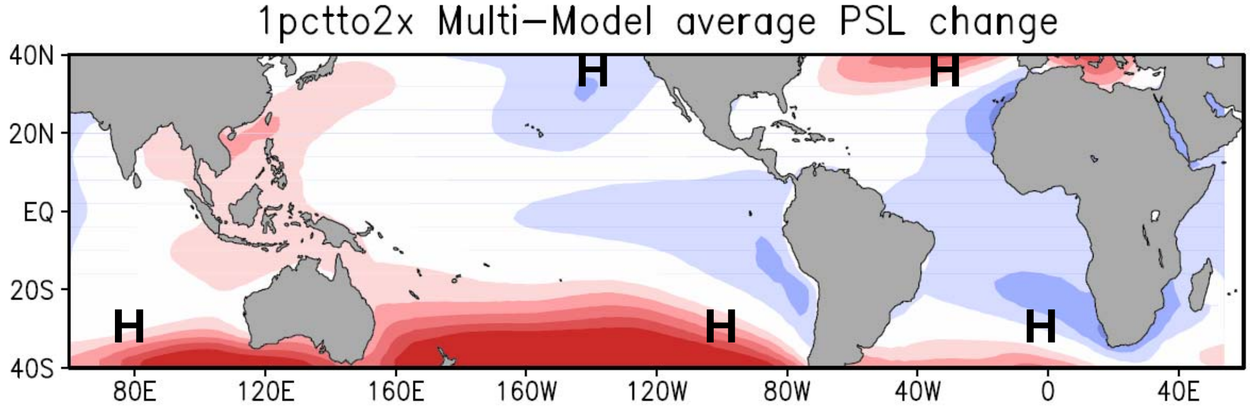
Much smaller trends in EIS than LTS

Positive EIS trends due to less SST warming than elsewhere





Multimodel Trend in SLP



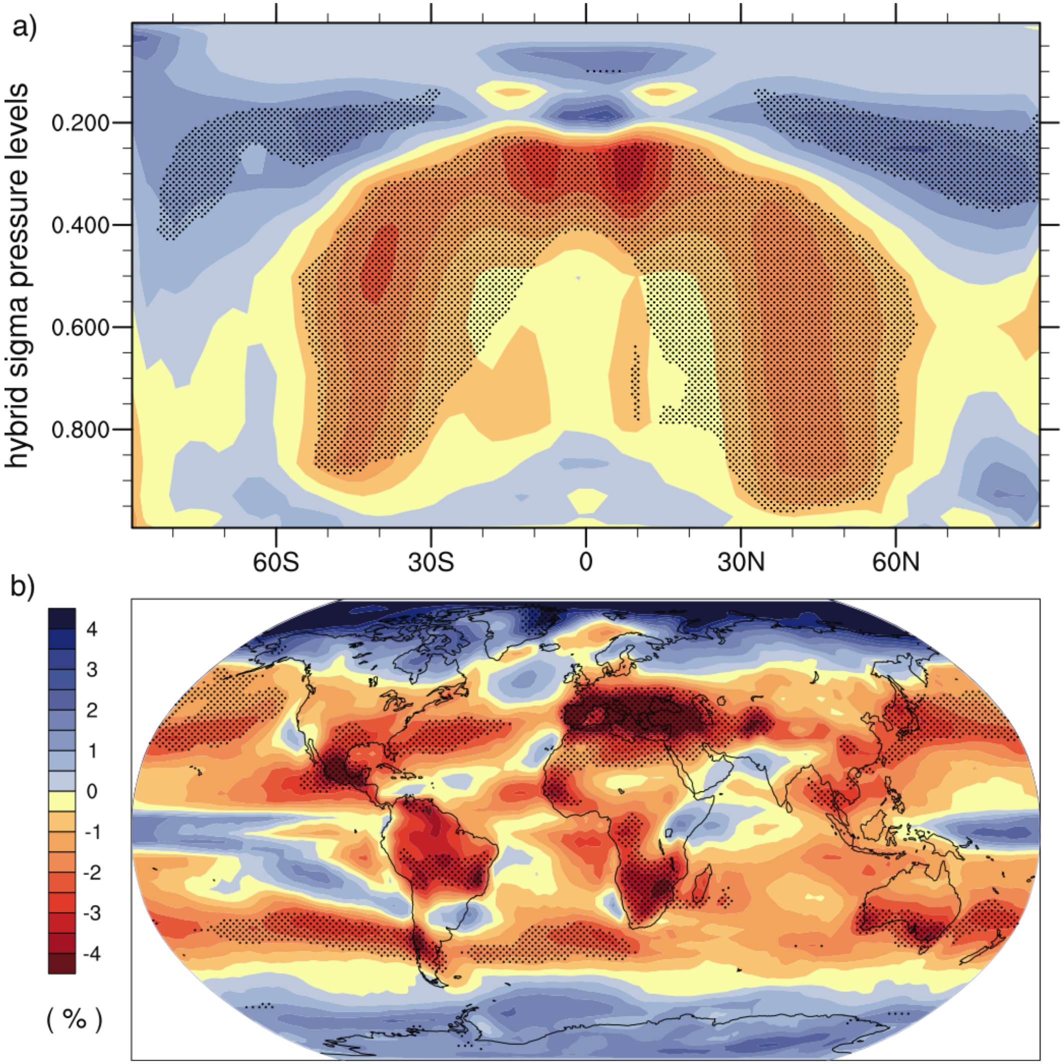
H indicates locations of annual mean subtropical anticyclone centers

Increased trade winds in eastern subtropical regions other than NE Pacific

More evaporation, reduced SST warming, stronger EIS

More cloud cover?

Multimodel Trend in Total Cloud



Low-latitude trends dominated by high-level cloud changes

Not really consistent with EIS and circulation trends

Adapted from Fig. 10.10 of IPCC AR4, courtesy of Steve Klein

Hypotheses

“Tropical Mean” Cloud Hypotheses

- Changes in moist adiabatic lapse rate with will have little impact on EIS and thus little impact on low-level cloud cover *(no negative feedback)*
- Weaker tropical mean subsidence with unchanged EIS will promote a deeper BL and less low-level cloud cover *(positive feedback)*
- Warmer tropical mean SST and reduced cloud top radiative cooling will promote decoupling and less cloud cover *(positive feedback)*

Regional Cloud Hypotheses

- Regional circulation trends will have a bigger impact on low-level clouds than tropical mean trends *(varying regional cloud changes)*
- Circulation changes may offset warmer SST effects on clouds
- Clouds exert a positive feedback on regional SST and circulation *(we will do modeling experiments)*

Conclusions

- Regional circulation has a large impact on subtropical low-level cloud variability
- Clouds appear to exert a positive feedback on regional circulation and SST on decadal and probably longer time scales
- Models should reproduce multiple observed relationships between meteorology and cloud as a necessary (but not sufficient) condition for a credible subtropical cloud feedback