Cloud climatology and cloud-controlling factors

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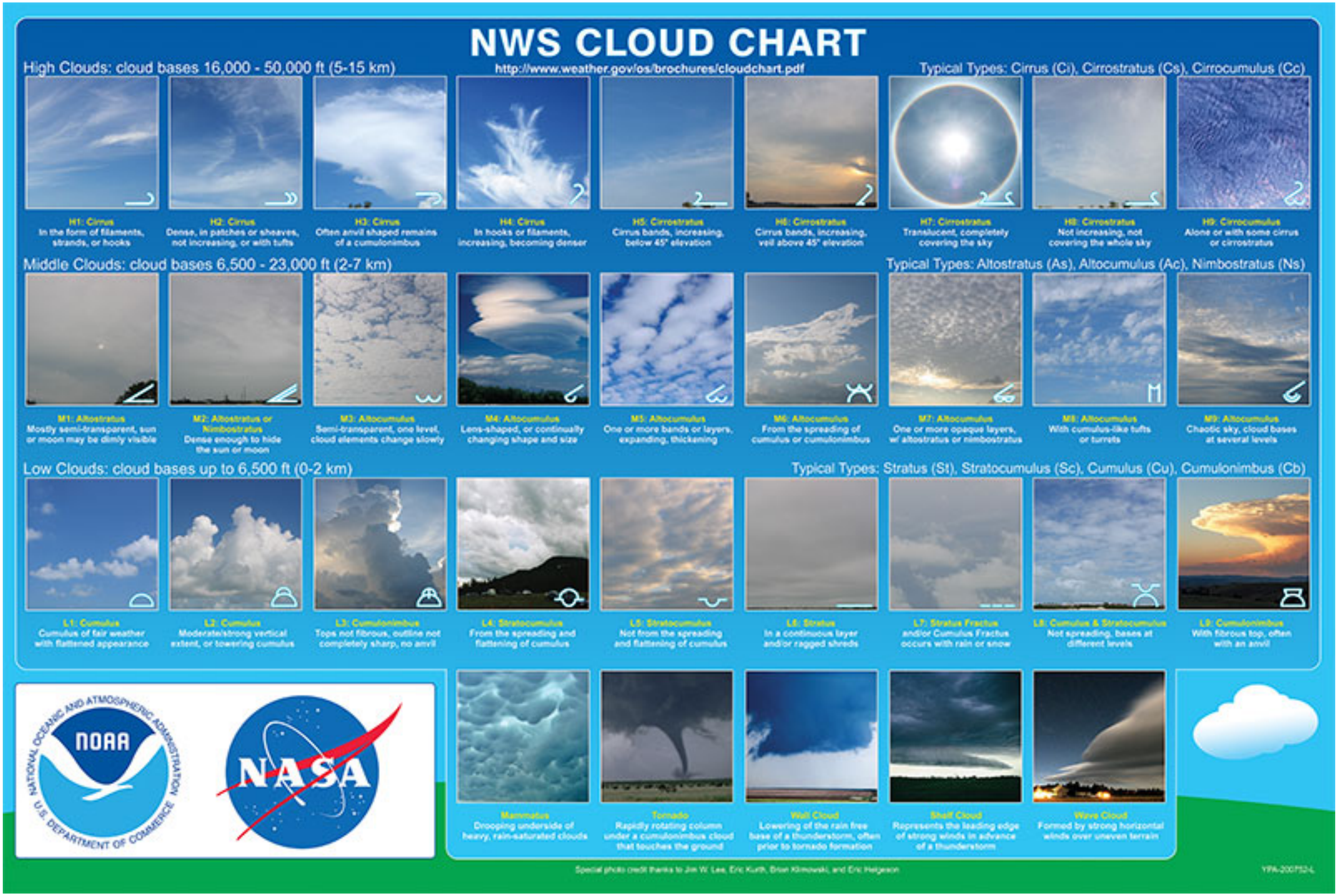
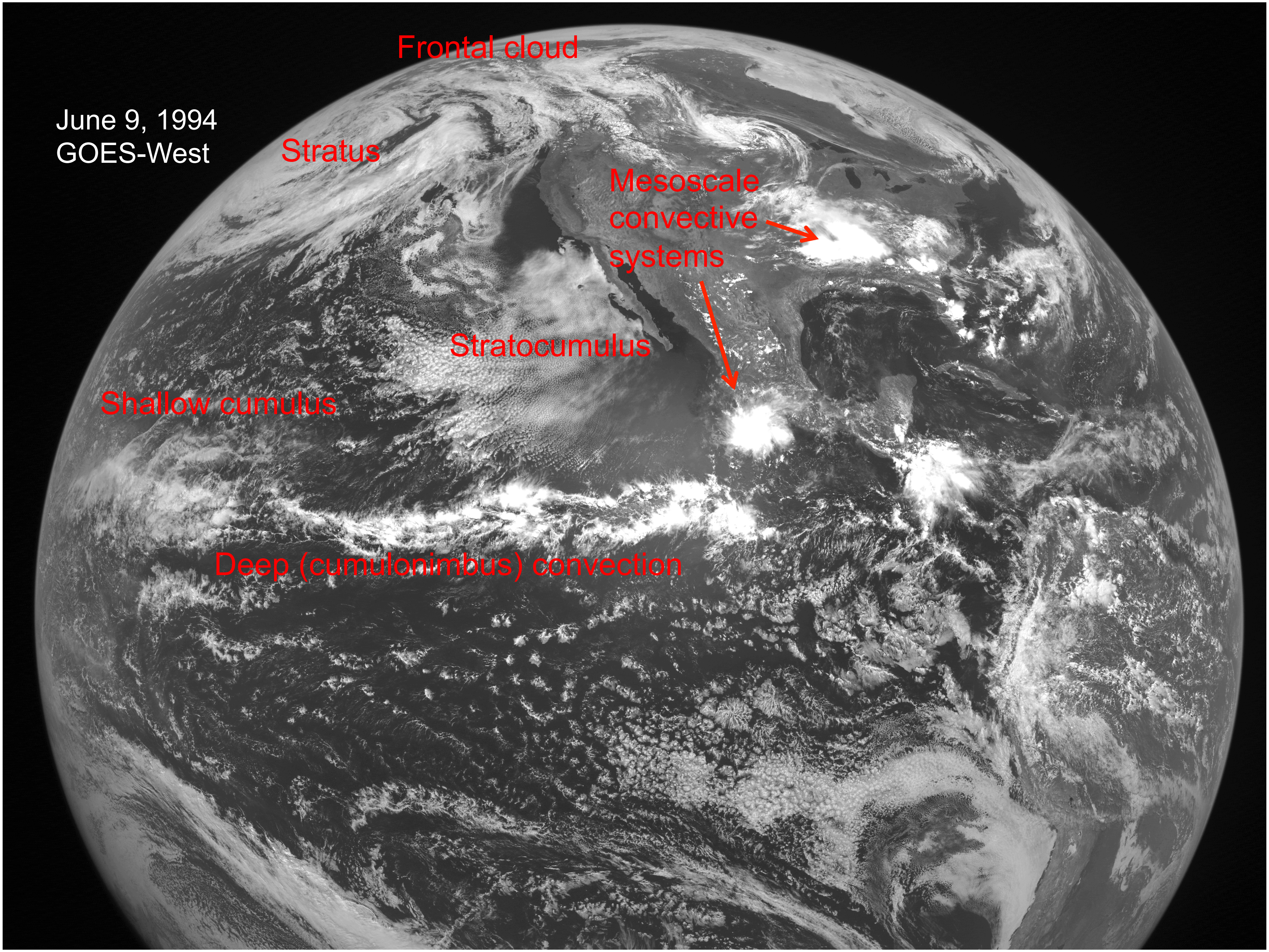
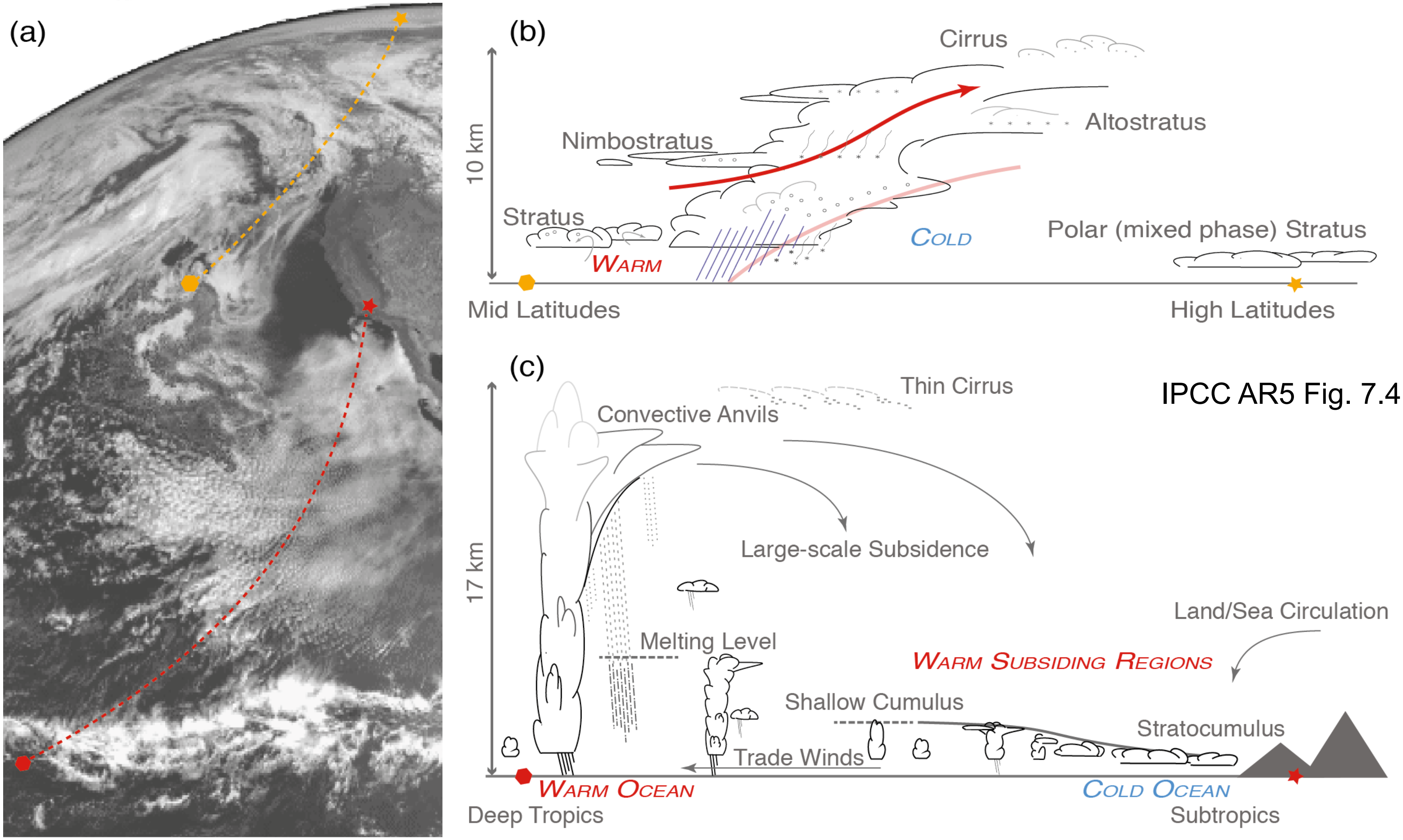
Reference: IPCC AR5, Chapter 7.3

Diverse cloud types, diverse formation mechanisms




June 9, 1994
GOES-West
Frontal cloud
Stratus
Mesoscale
convective
systems
Stratocumulus
Shallow cumulus
Deep (cumulonimbus) convection

Different cloud types for different synoptic settings



Clouds form when air cools or moistens, usually via ascent and adiabatic cooling. But this can happen in many ways on many scales.

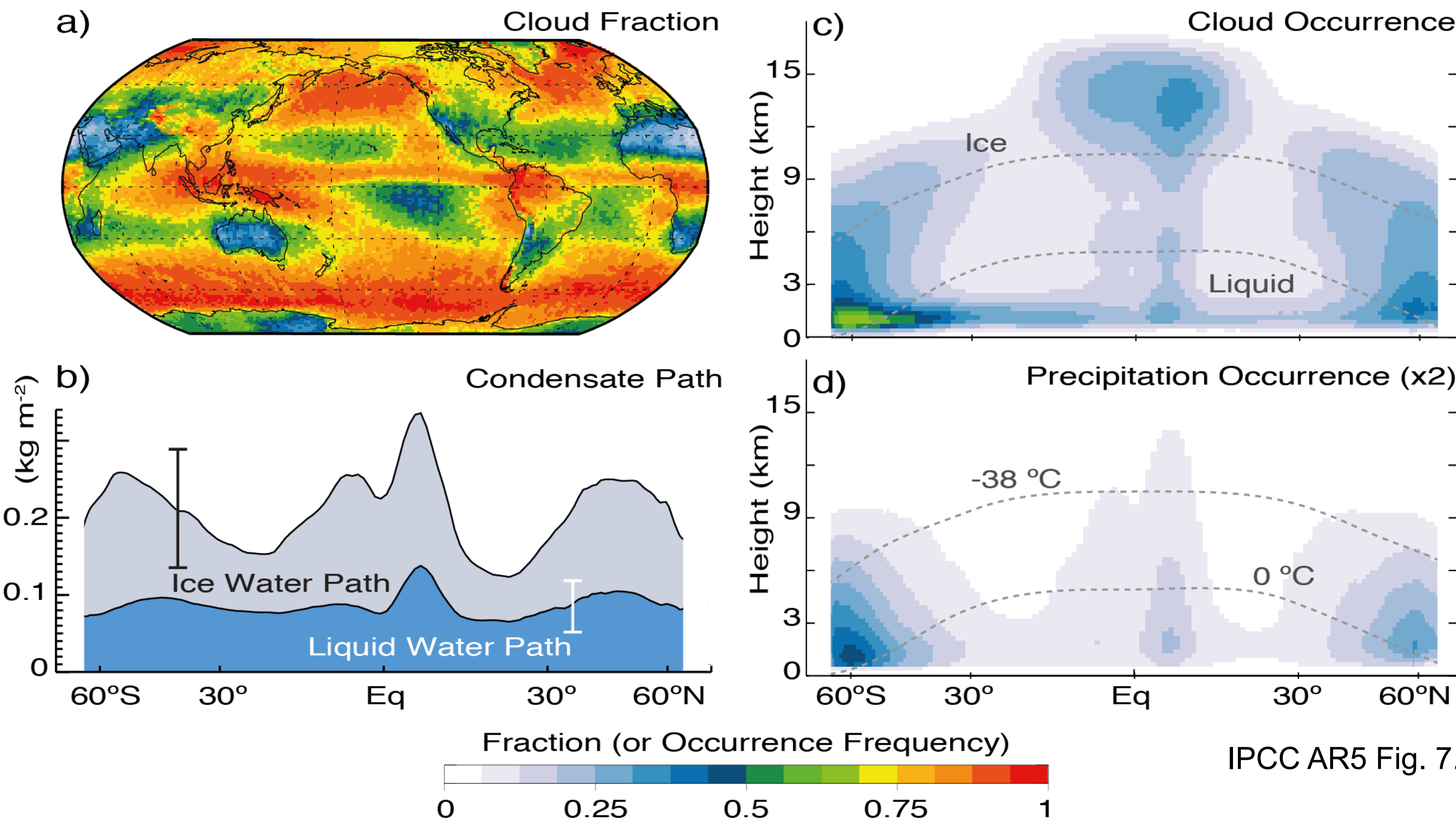
Cloud observations

- Surface-based
  - visual observations of cloud amount/type (1950+)
  - ceilometer
  - downwelling radiation
  - active remote sensing (radar/lidar)
- Satellite
  - broadband solar/IR (1980s+)
  - multi-wavelength and microwave (1990s+)
  - active remote sensing (2000s+)

Clouds are highly variable on all time and space scales, so global or near-global trends are difficult to robustly detect.

Measurement drifts have often induced spurious trends.

Satellite-observed distribution of clouds and precipitation



IPCC AR5 Fig. 7.5

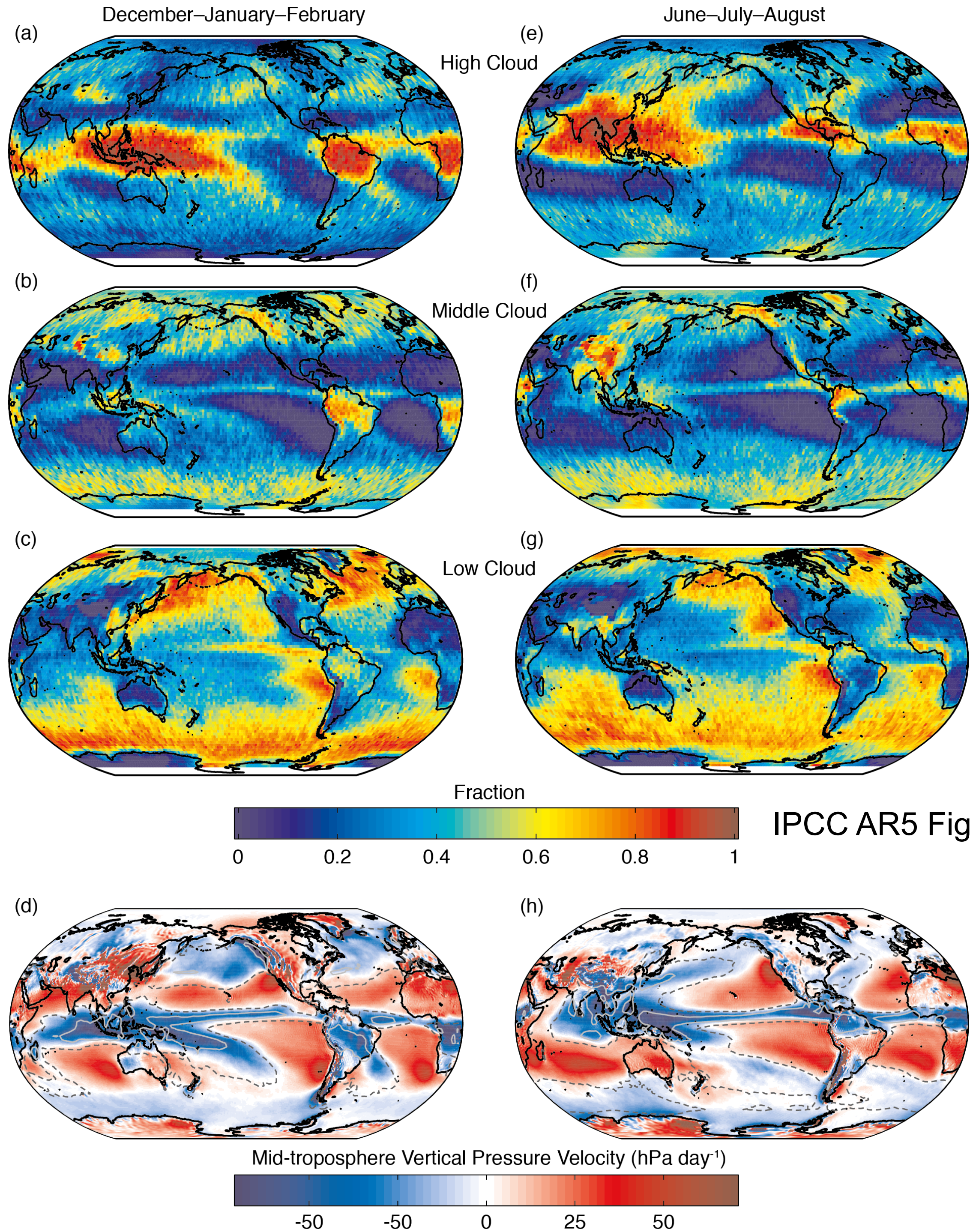
From CloudSat radar, Calipso lidar, passive microwave

Seasonal cycle of clouds and circulation

High (<400 hPa) and middle (400-700 hPa) clouds in regions of mean ascent

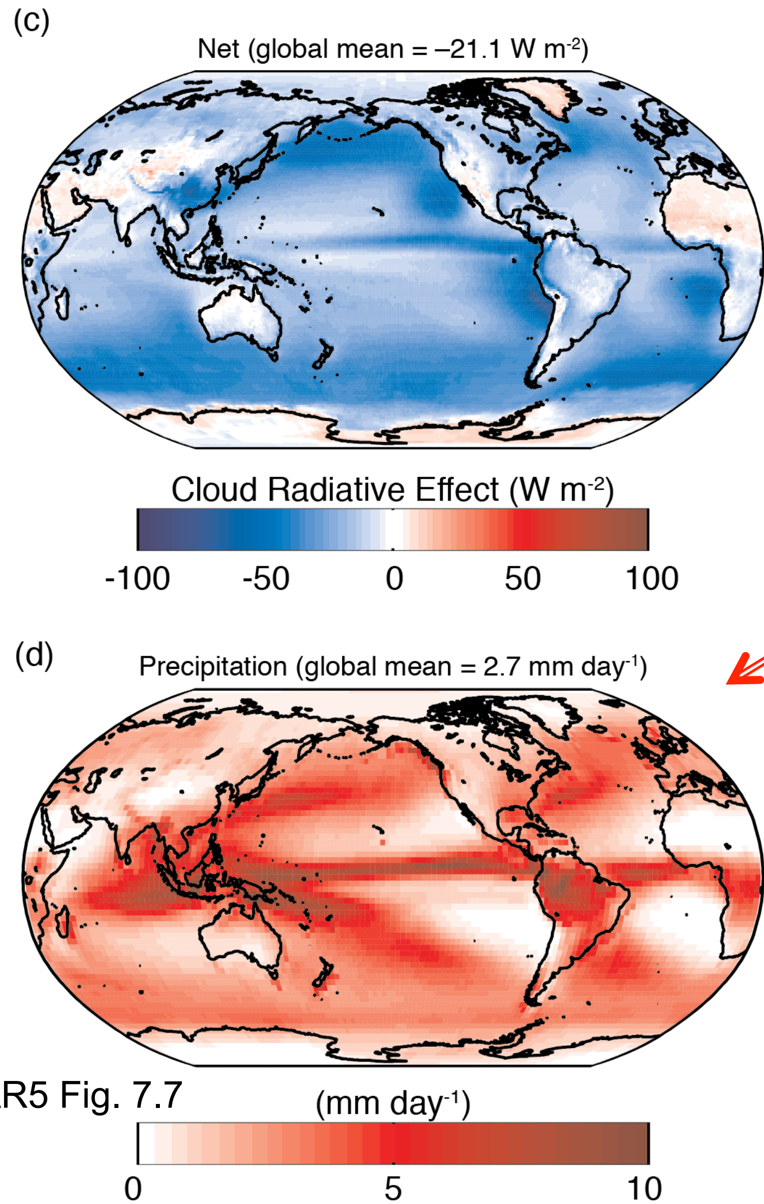
Low clouds (>700 hPa) favor cool oceans

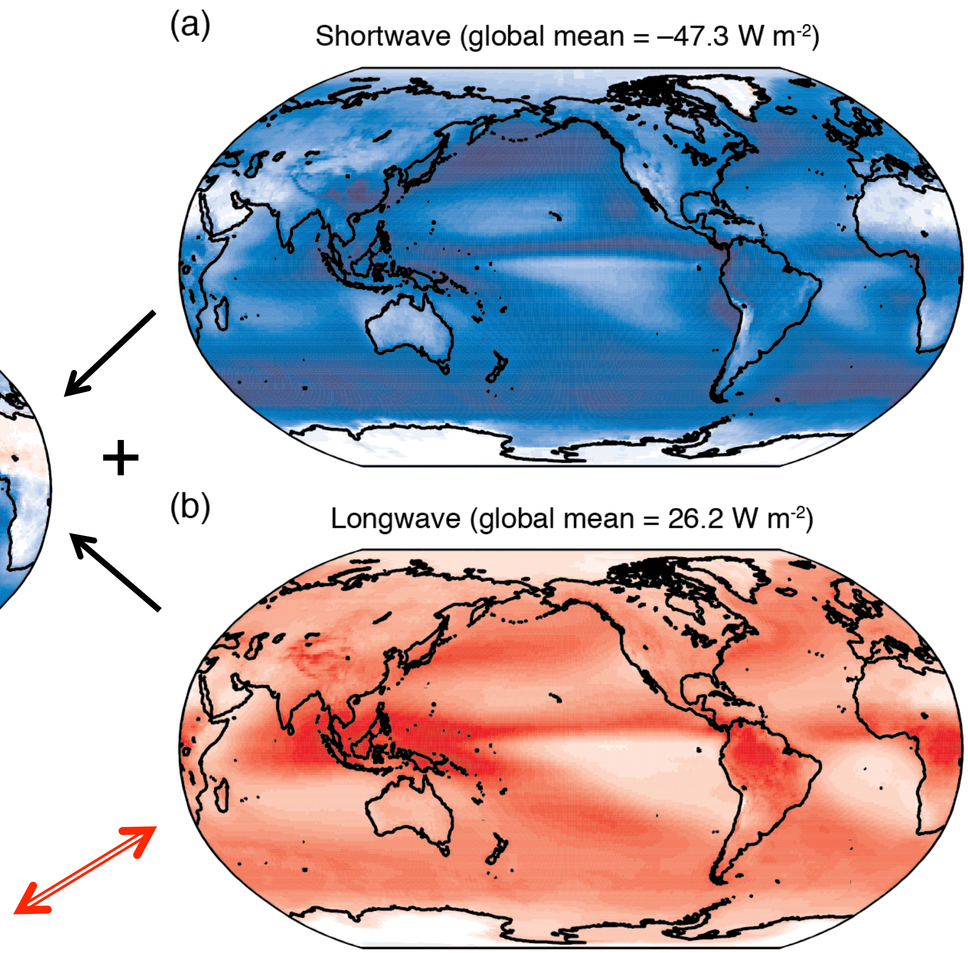
Precipitation strongly correlated with mean ascent



IPCC AR5 Fig. 7.6

Clouds and radiation





IPCC AR5 Fig. 7.7

SWCRE = RSW_{clr} – RSW < 0

…depends on cloud optical thickness, fraction (& surface albedo)

LWCRE = OLR_{clr} – OLR > 0

…depends on cloud fraction, emissivity and height (& humidity, CO_2)

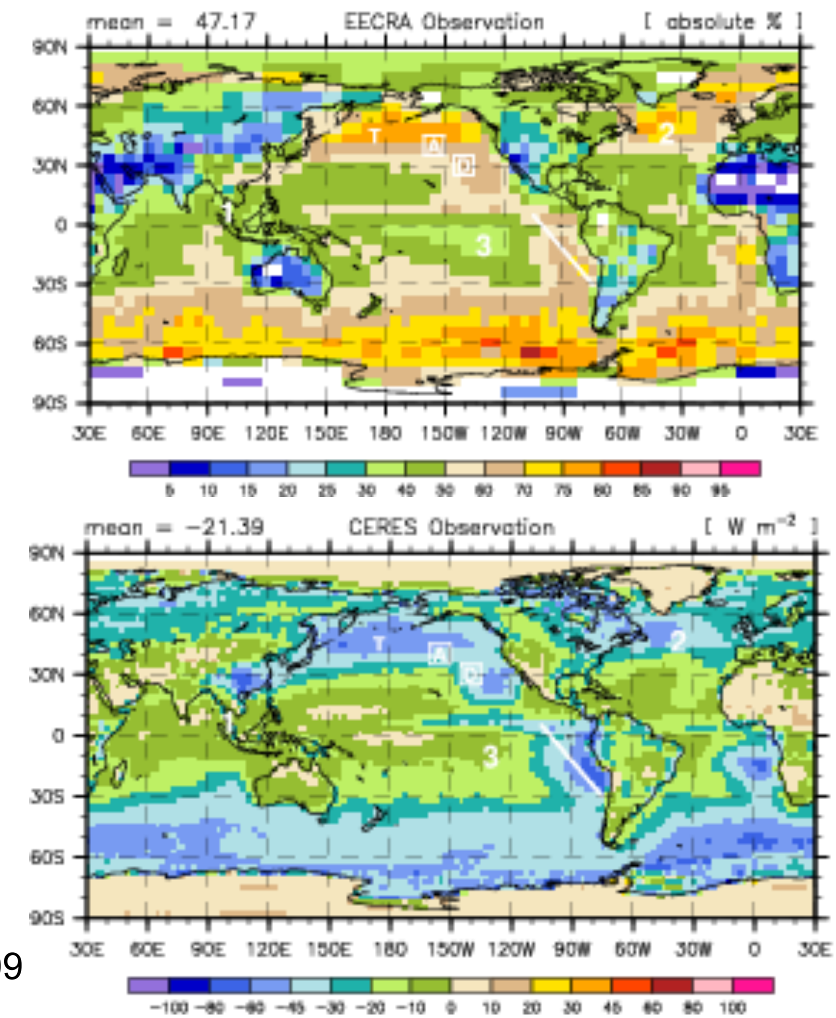
Net CRE = SWCRE + LWCRE

Boundary-layer cloud amount and net cloud radiative effect

Low cloud amount (%)

correlated with…

Net CRE [W m^{-2}]



Park and Bretherton 2009

Net CRE= extra radiative energy absorbed by atmosphere+surface due to the presence of clouds

BL clouds reflect sunlight but are too warm to much affect outgoing longwave radiation, producing a negative SWCRE and little LWCRE, for negative net CRE. They are thus the 'climate refrigerators'.

- Marine boundary-layer cloud is the most radiatively important cloud type for the current climate.

Diverse cloud-controlling factors

- Relative humidity
- Large-scale or mesoscale ascent (esp. middle/high cloud)
- Wind/wind shear
- Orography
- SST/land surface type (turbulent fluxes)
- Conditional instability (cumulus convection)
- Stratification and inversions
- Radiative cooling
- Aerosol (CCN/INP)
- Temperature

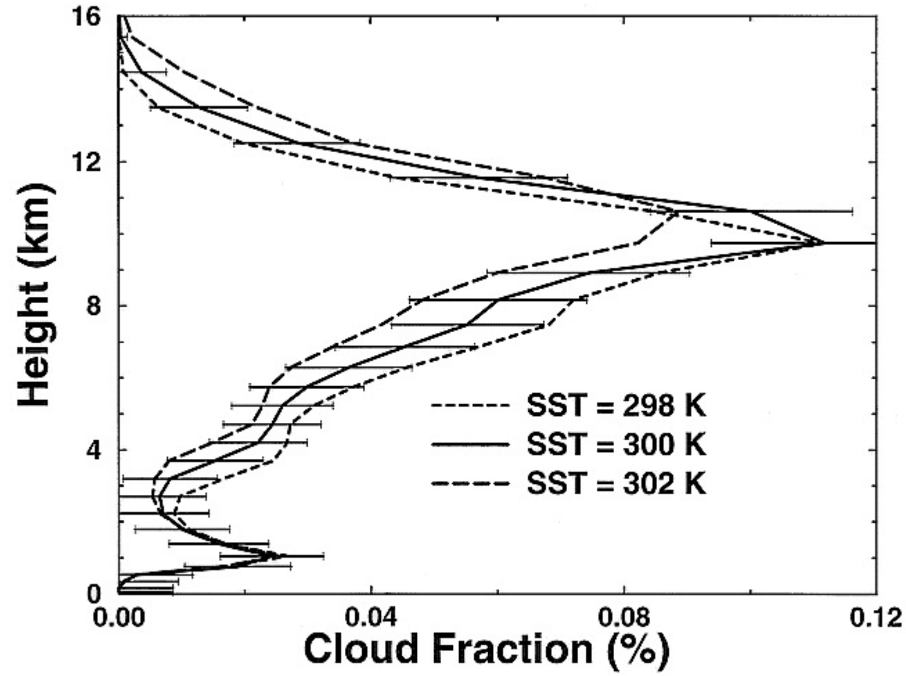
…

Clouds feed back on these controls through latent heating/ precipitation processes, radiative and aerosol feedbacks, etc.

Cloud distribution in radiative-convective equilibrium

Limited-area CRM simulations of radiative-convective equilibrium (Tompkins and Craig 1999):

- RCE for SST = 298, 300, 302 K; 45 days, 60 x 60 km x 21 km, Δx = 2 km, L35.
- Mid/high clouds rise following isotherms in a warmer climate.
- Also a shallow Cu population



Hartmann and Larson (2002): Fixed Anvil Temperature (FAT) mechanism – tropopause height and associated cirrus anvils are radiatively pinned to a temperature (~200 K) below which there is too little water vapor to be radiatively emissive.

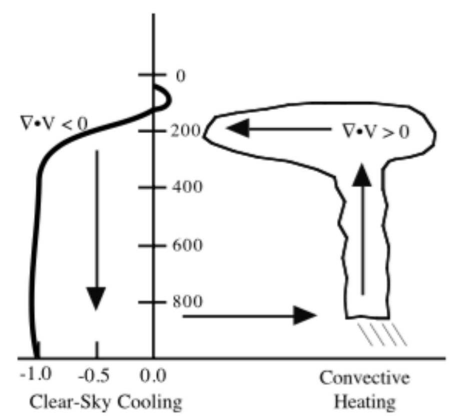
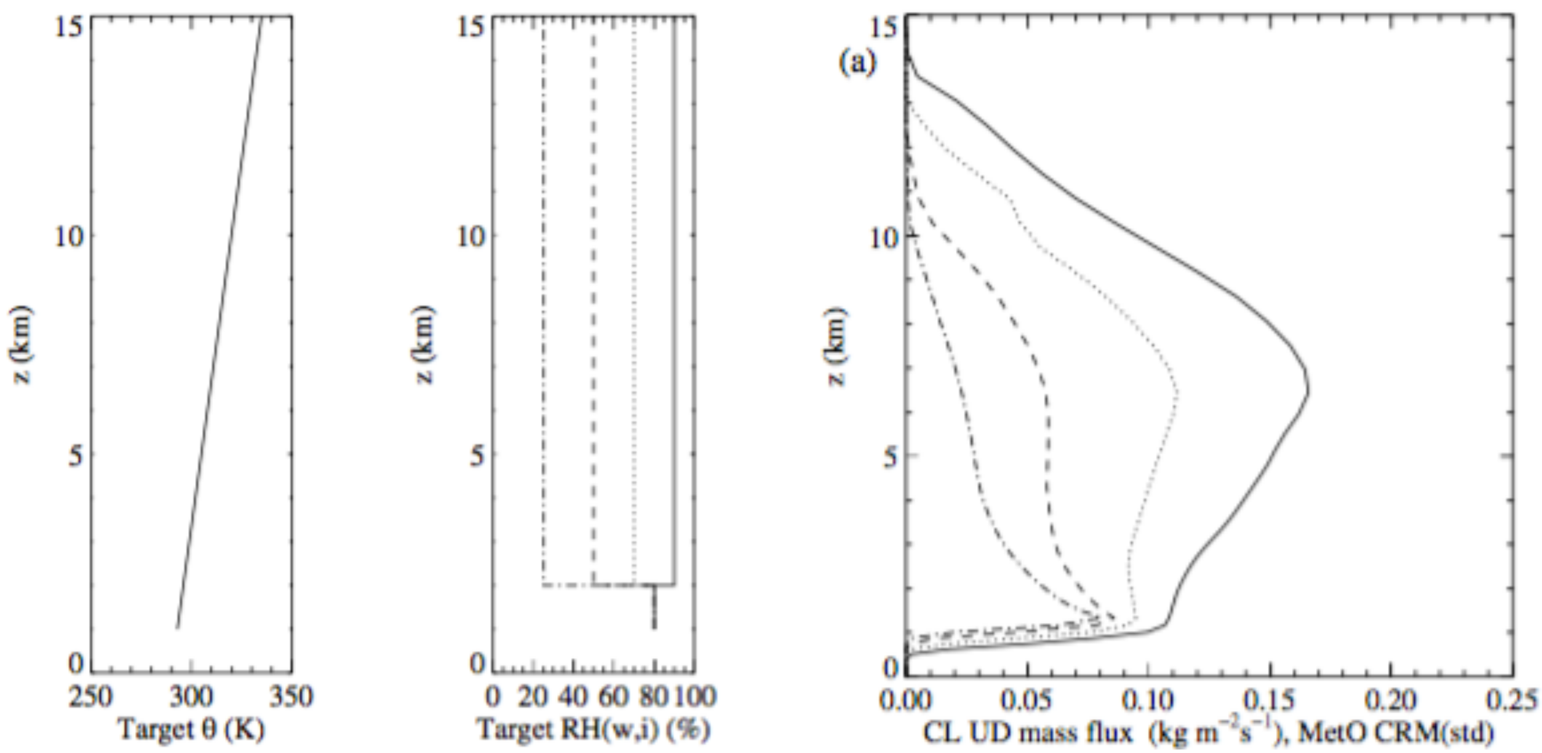


Figure 1. Schematic showing relation of clear sky radiative cooling to upper level divergence (∇oV) and convective anvil outflow.

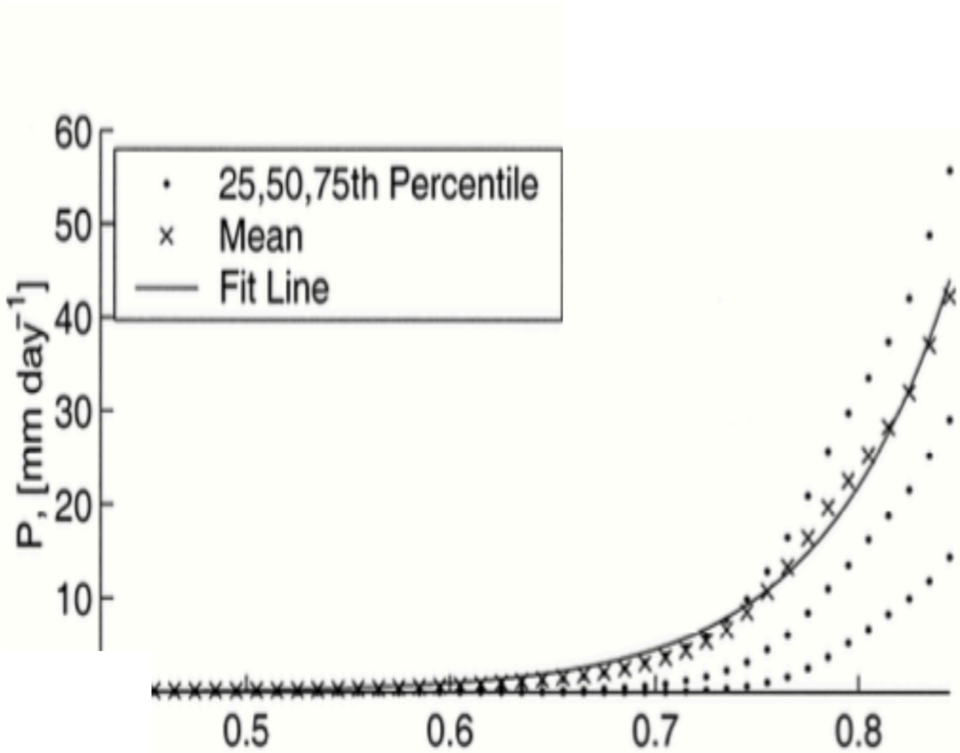
Tropical convective cloud vs. column humidity

- Even given conditional instability, due to entrainment dilution moist convection deepens only if the environment is moist.

S. H. DERBYSHIRE *et al.* 2004



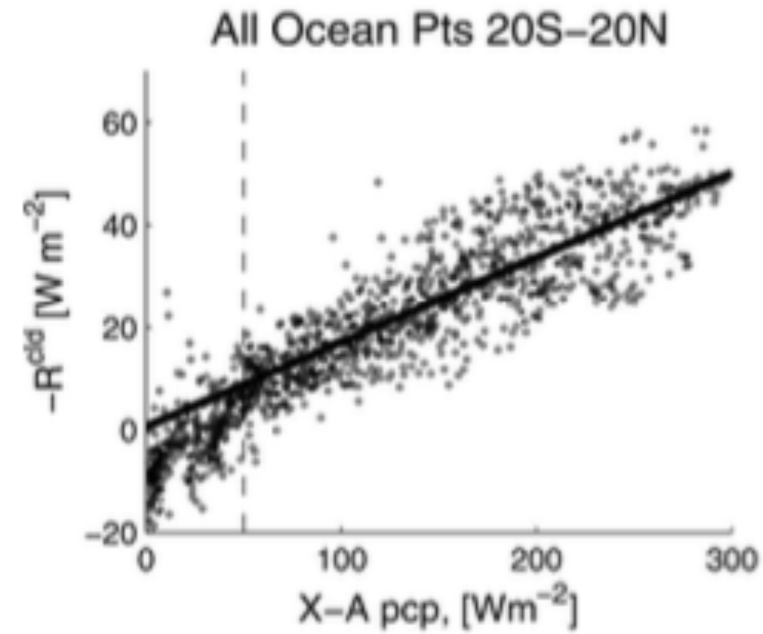
This leads to strong correlations between humidity, convection and high cloud in the tropics



CRH = WVP/WVP_{sat}

Daily precip vs. column relative humidity over tropical oceans, 2.5° x 2.5° grid boxes

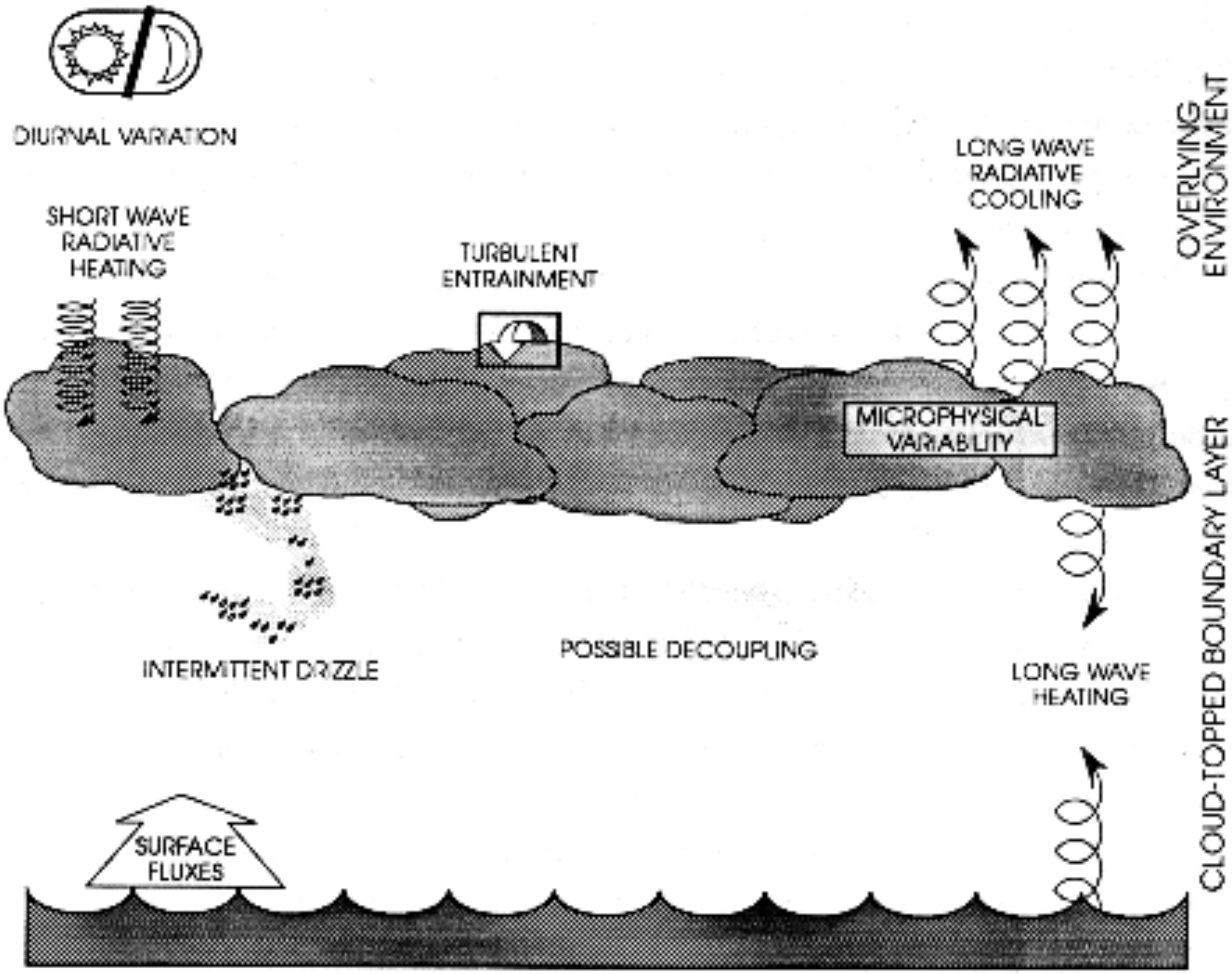
(Bretherton et al. 2004)



Atmospheric radiative heating due to cloud (proxy for high cloud), monthly means

(Peters and Bretherton 2005)

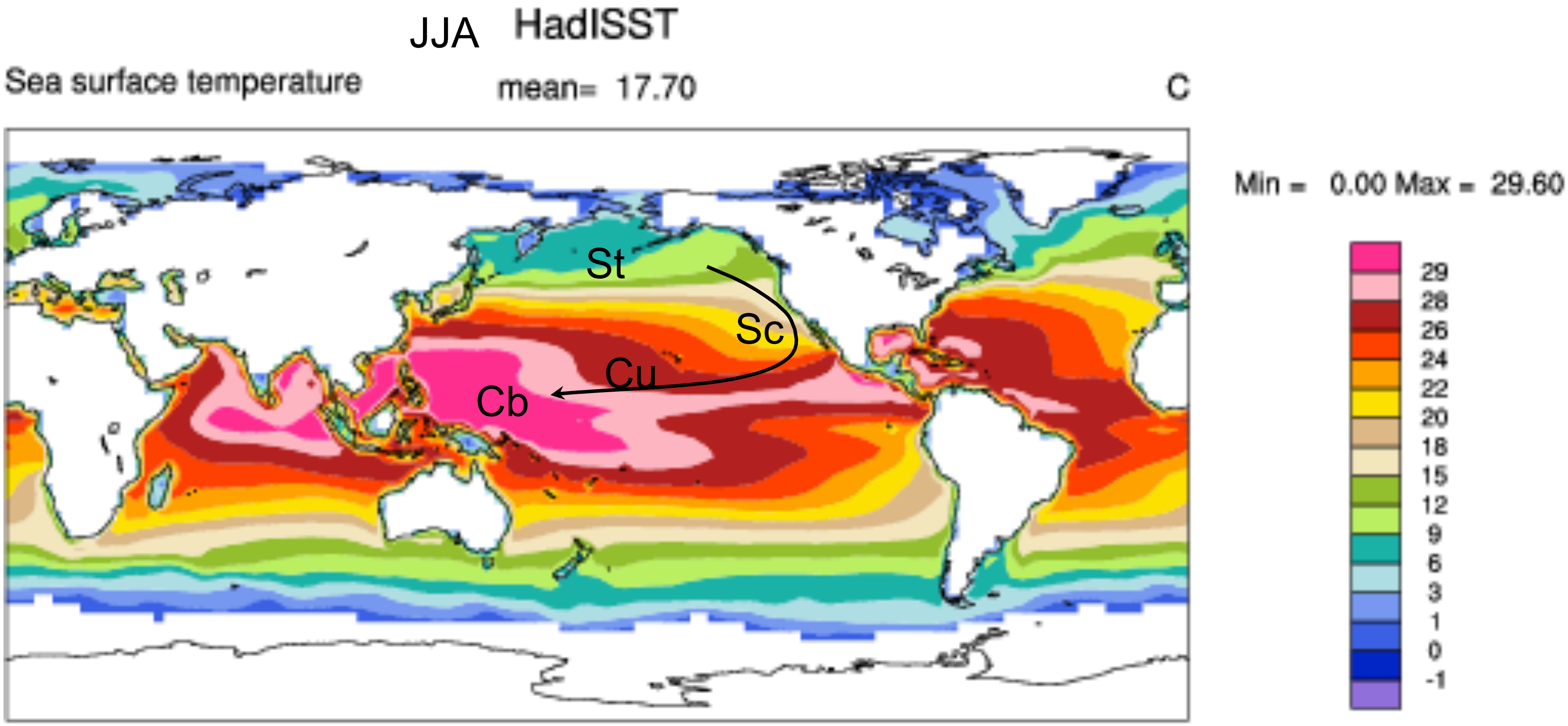
Low cloud processes



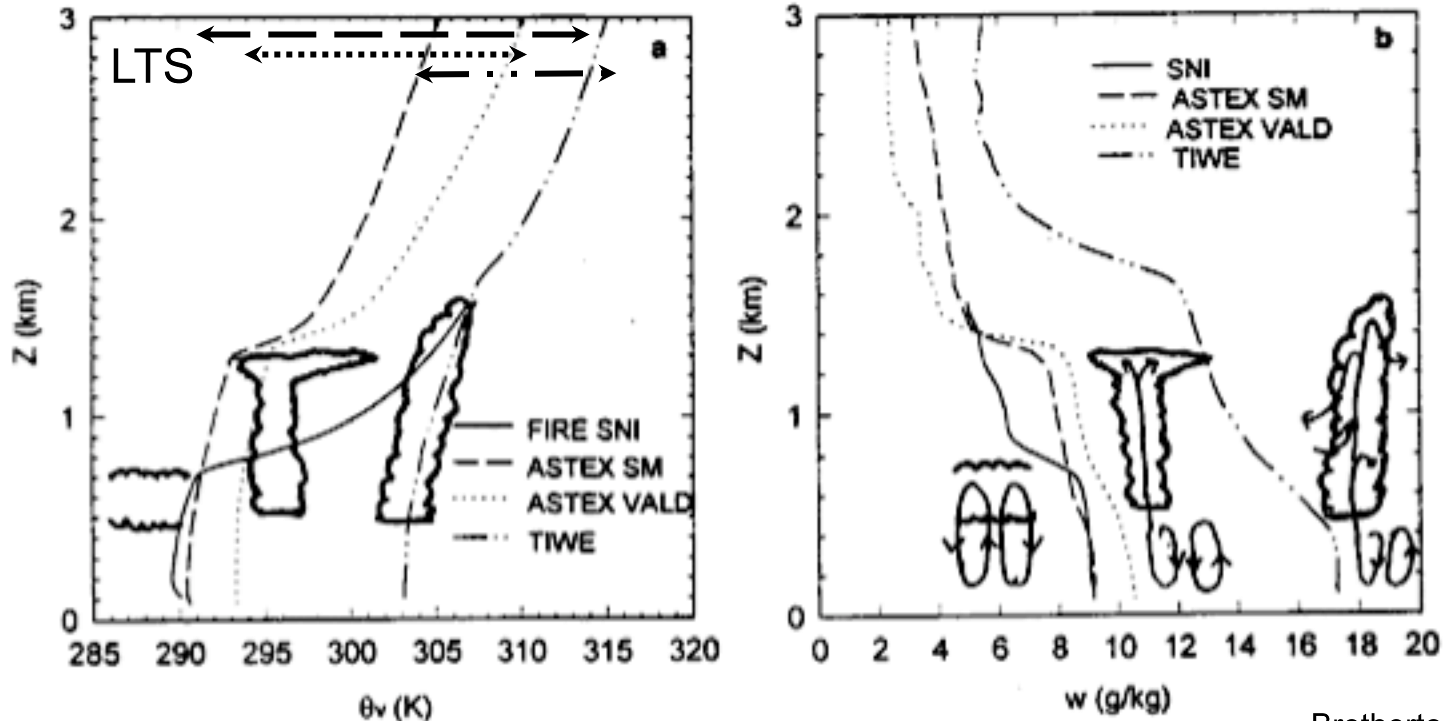
Siems et al. 1993

Marine low clouds

- Transition from Sc - shallow Cu - deep Cu as temperature of sea-surface rises compared to that of mid-troposphere.



Subtropical PBL soundings



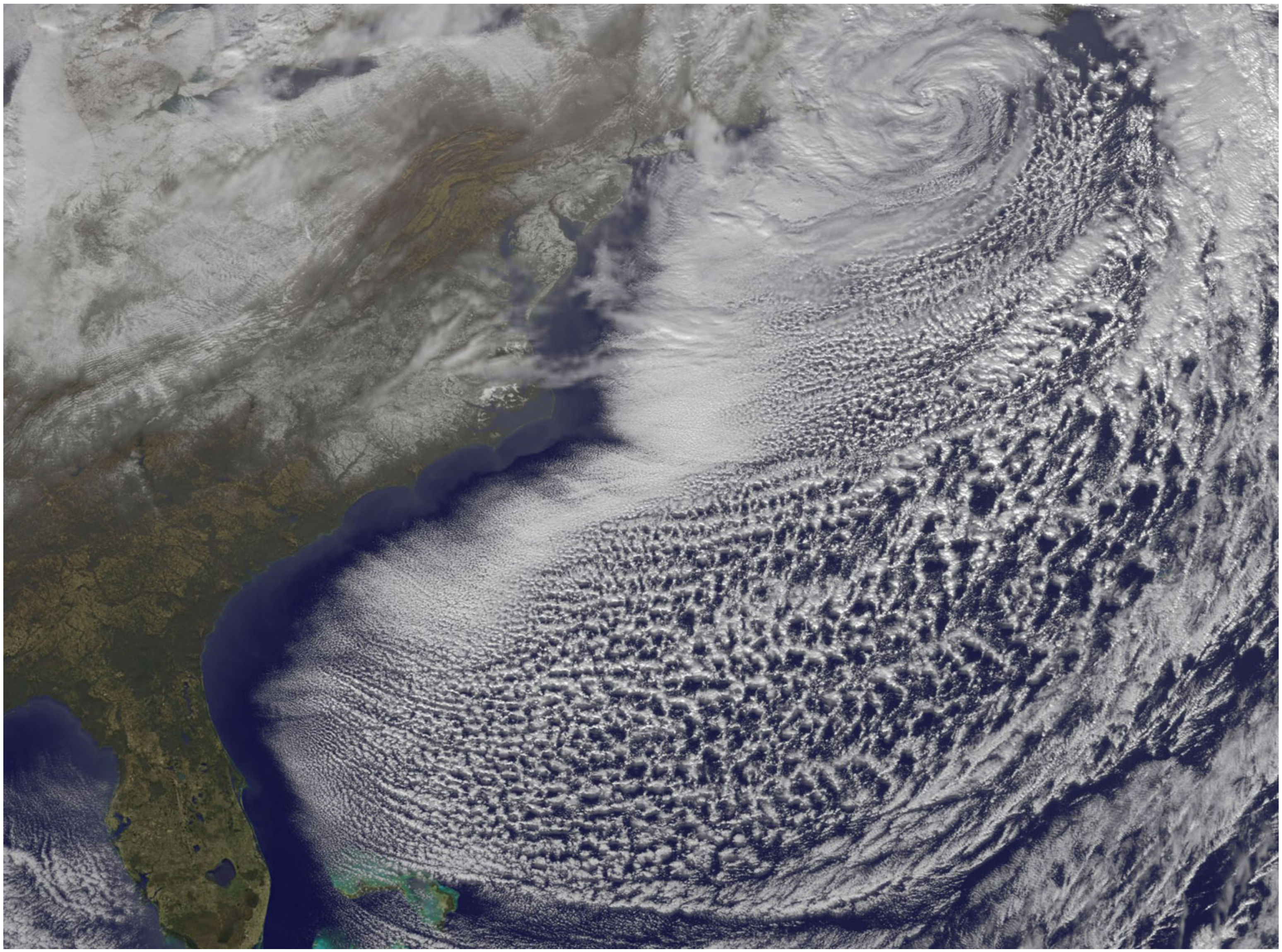
Bretherton 1997,
after Albrecht et al. 1995

Figure 3. Composite soundings of (a) θ_v and (b) q_t from four CTBL experiments from Albrecht *et al.* (1995). Sketches of the typical boundary layer cloud structure observed in (left to right) FIRE (July 1987, 33 N, 120 W, SST = 289 K, Cloud Fraction = 0.83), ASTEX (June 1992, SM: 37 N, 25 W, SST = 291 K, CF = 0.67; VALD: 28 N, 24 W, SST = 294 K, CF = 0.40),), and TIWE (December 1991, 0 N, 140 W, SST = 300 K, CF = 0.26) are overlaid. In (b), the air motions that accompany the clouds are also sketched.

- Sc and St clouds favored by strong, low inversions, which go with large lower tropospheric stability.

Same cloud evolution in midlat cold air outbreaks

- In this case, driven by strong surface heat fluxes



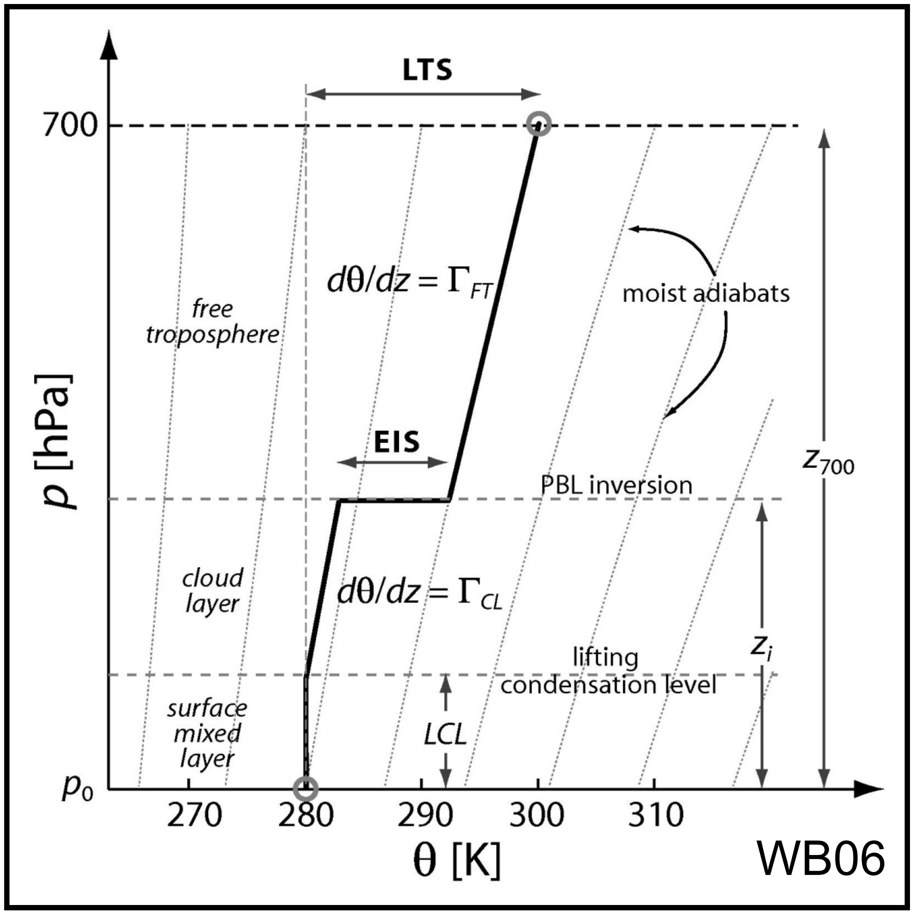
Stratification measures predict low cloud fraction

Lower tropospheric stability (Klein & Hartmann 1993)

$$LTS = \theta_{700} - \theta_{1000}$$

Estimated Inversion Strength (Wood & Breth 2006)

$$EIS = LTS - \Gamma_{ma,850}(z_{700} - z_{LCL})$$



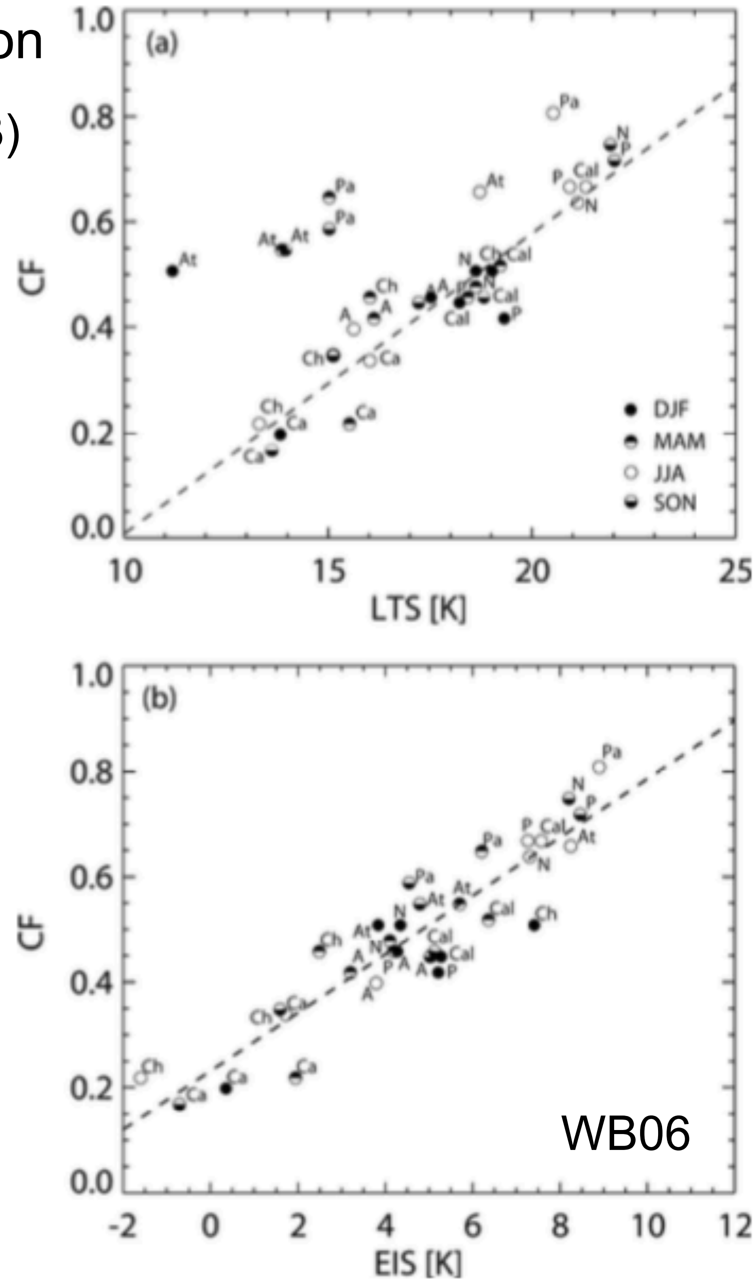
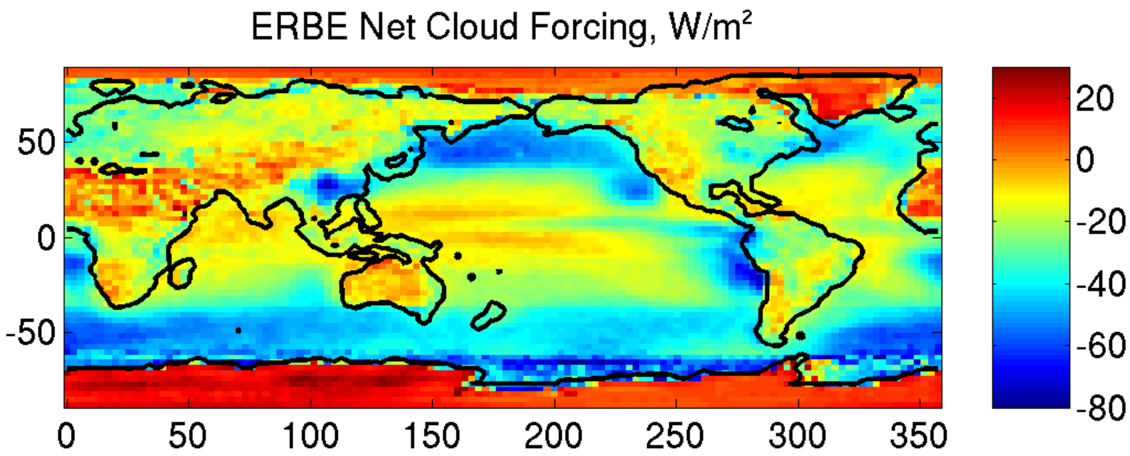
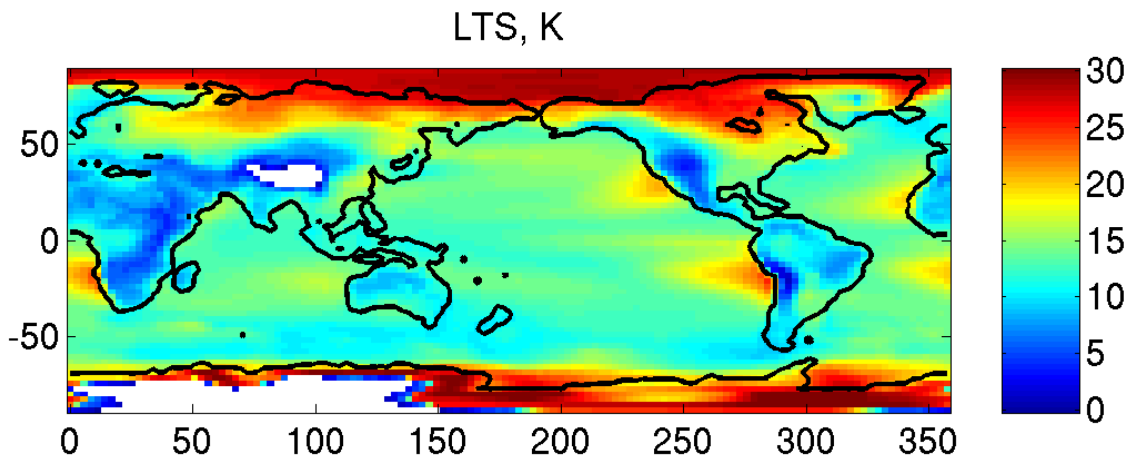


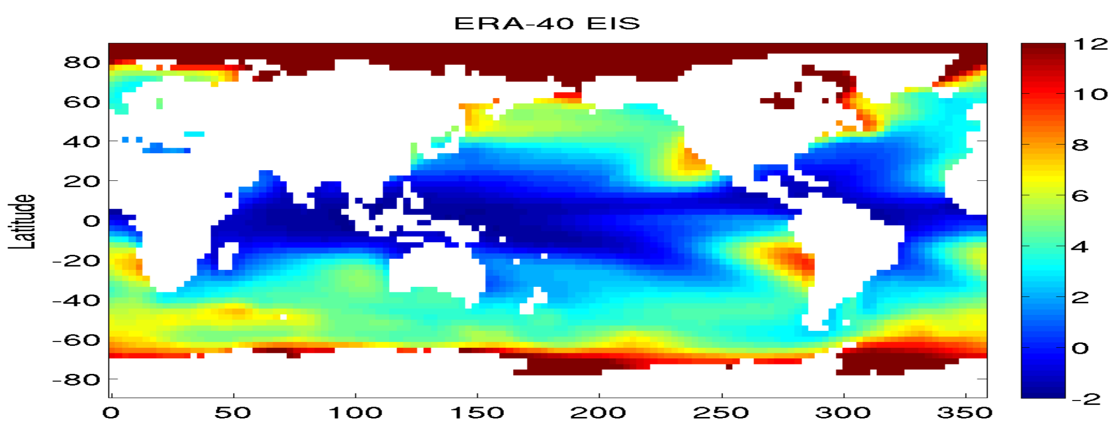
FIG. 6. Relationship between (a) LTS and low cloud amount, and (b) EIS and low cloud amount, for seasonal means at the locations described in Table 1. All seasons/regions where LTS > 10 K are plotted.



EIS correlated to low cloud everywhere, LTS correlated to low cloud in low latitudes



Lower tropospheric stability correlated with low-latitude marine low cloud
(Klein and Hartmann 1993)

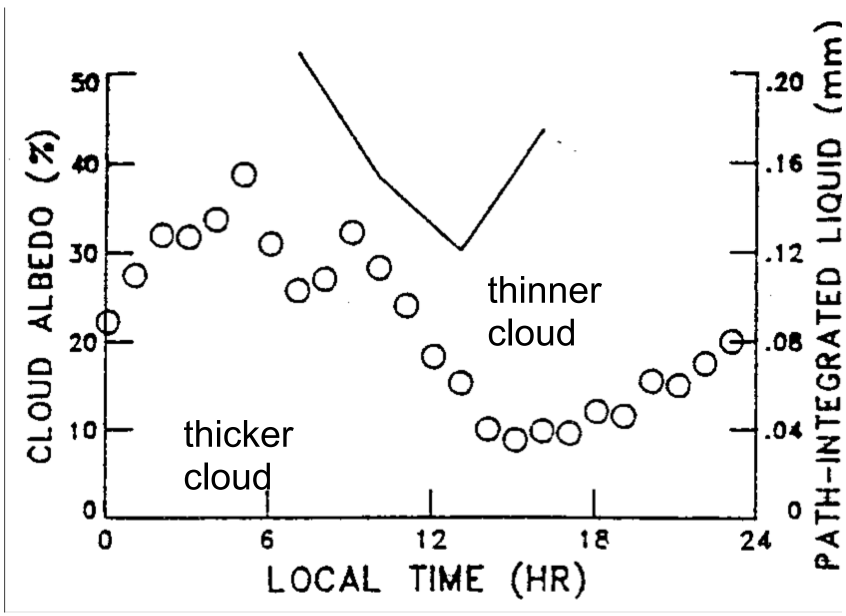


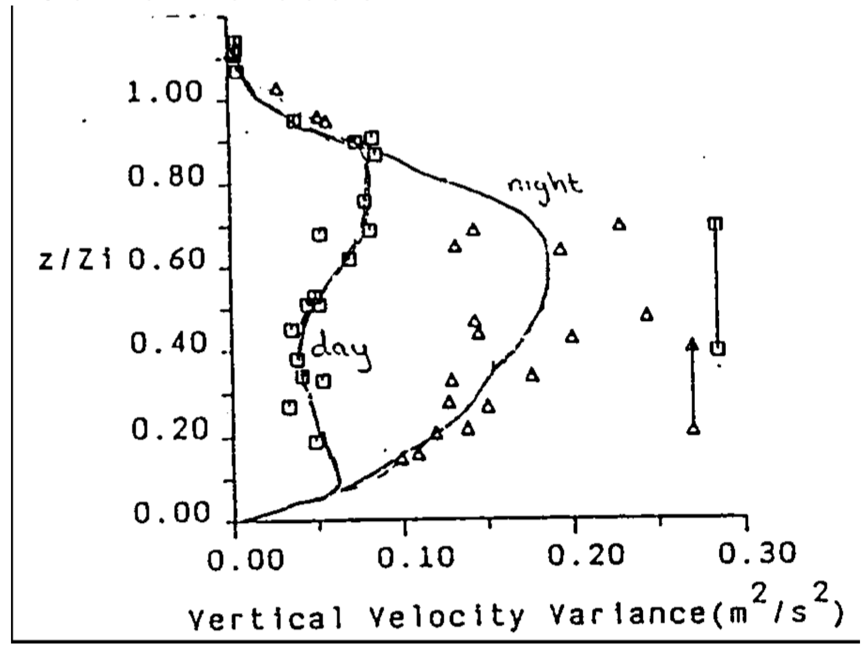
EIS also captures midlat BL cloud underlying a cooler free troposphere:
EIS is a more ‘temperature-invariant’ predictor of low cloud response to stratification change.

Radiative driving of marine low cloud

- Important to daytime thinning of marine stratocumulus cloud (via daytime absorption of sunlight, reduced upward turbulent moisture flux).

Stratocumulus off California coast



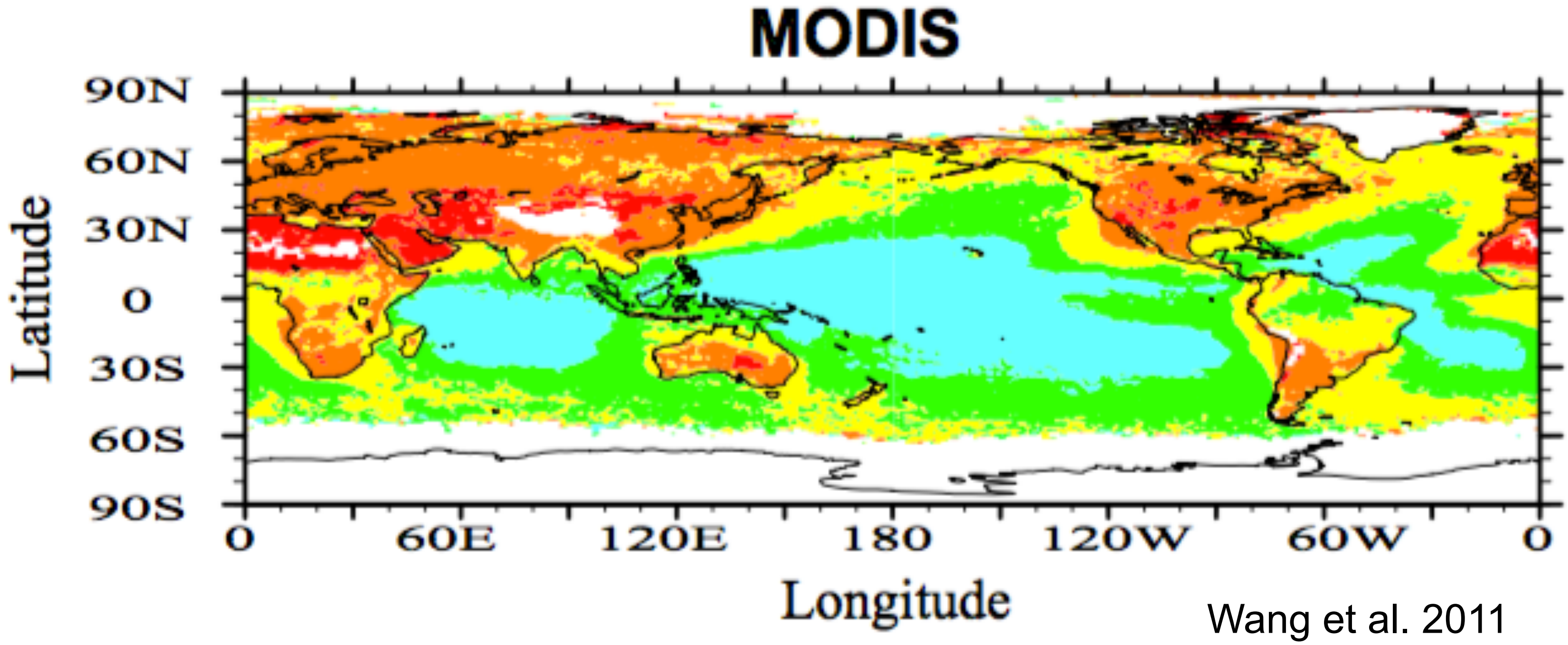


- More CO_2 and water vapor both increase downwelling longwave radiation and reduce longwave cooling of low cloud layers, reducing subtropical low clouds under greenhouse warming by decreasing their radiative driving.

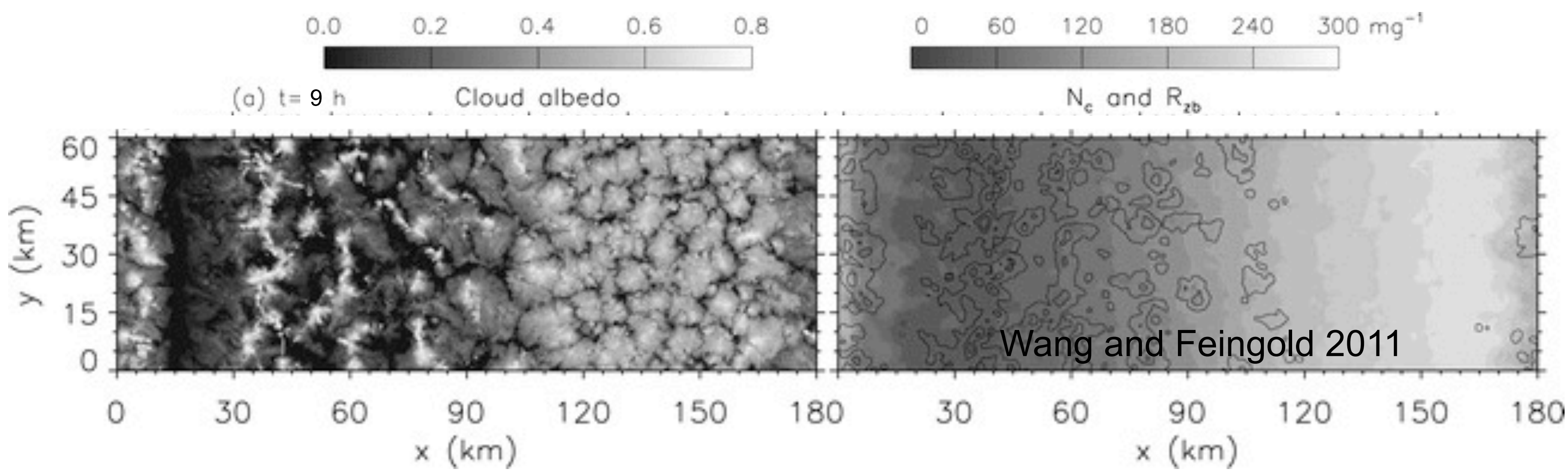
(Bretherton et al. 2013)

Aerosol and low cloud

Liquid-cloud droplet concentration (cm^{-3})
(subject to observational uncertainties!)

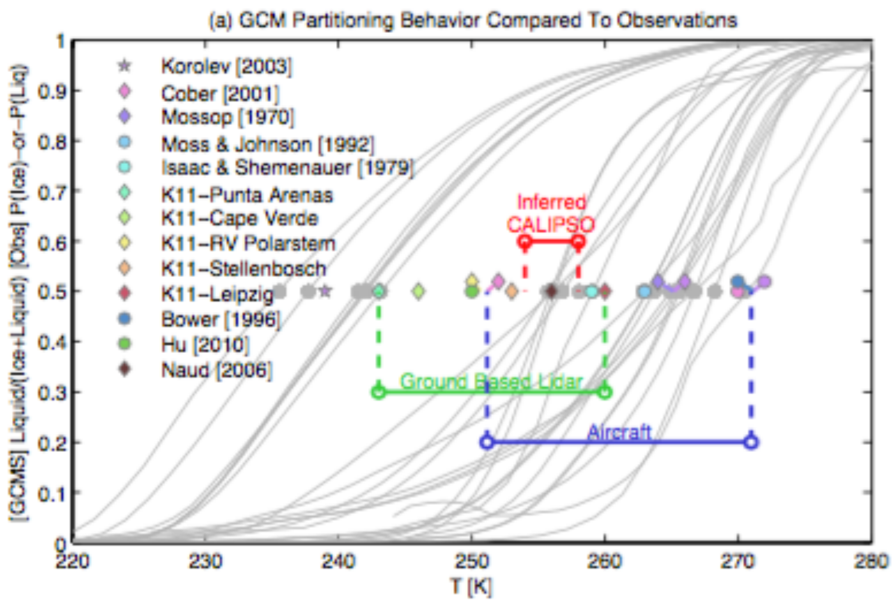


Wang et al. 2011

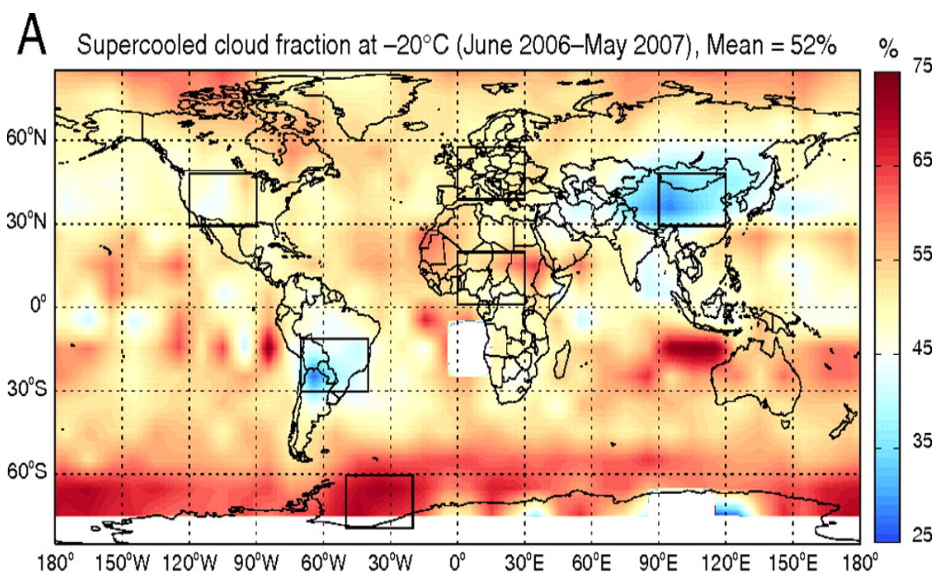


Wang and Feingold 2011

Supercooled liquid water



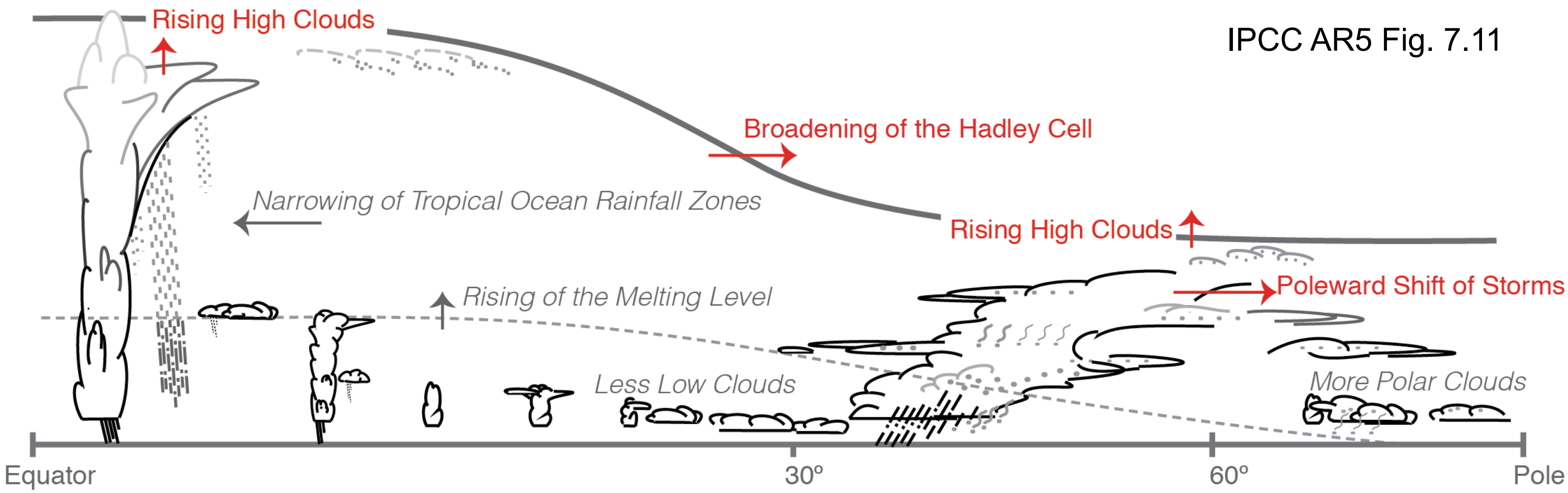
GCMs have diverse temperature ranges over which ice cloud transitions to liquid cloud (McCoy et al. 2016)



Fraction of cloud-tops at temperatures near -20˚C containing supercooled liquid water, retrieved using CALIPSO depolarization measurements (Choi et al. 2010b).

Supercooled liquid water raises cloud albedo and affects high-latitude cloud biases (Kay et al. 2016) and feedbacks (Tan et al. 2016). It is sensitive to ice nucleation, updraft strength, microphysical processes, etc.

Expected cloud responses to a warmer climate



- Overall cloud feedbacks on climate change likely positive
- More liquid cloud in polar regions
- Regional cloud changes will be strongly tied to circulation, SST, and land surface type (vegetation) changes.

Main points

- Middle and high clouds tied to ascent and precipitation
- Moist surfaces capped by strong inversion favor low clouds
- Low clouds radiatively cool the planet
- Tight feedbacks: clouds, turbulence, convection, radiation, sfc
- Aerosols and mixed phase are challenging complications.