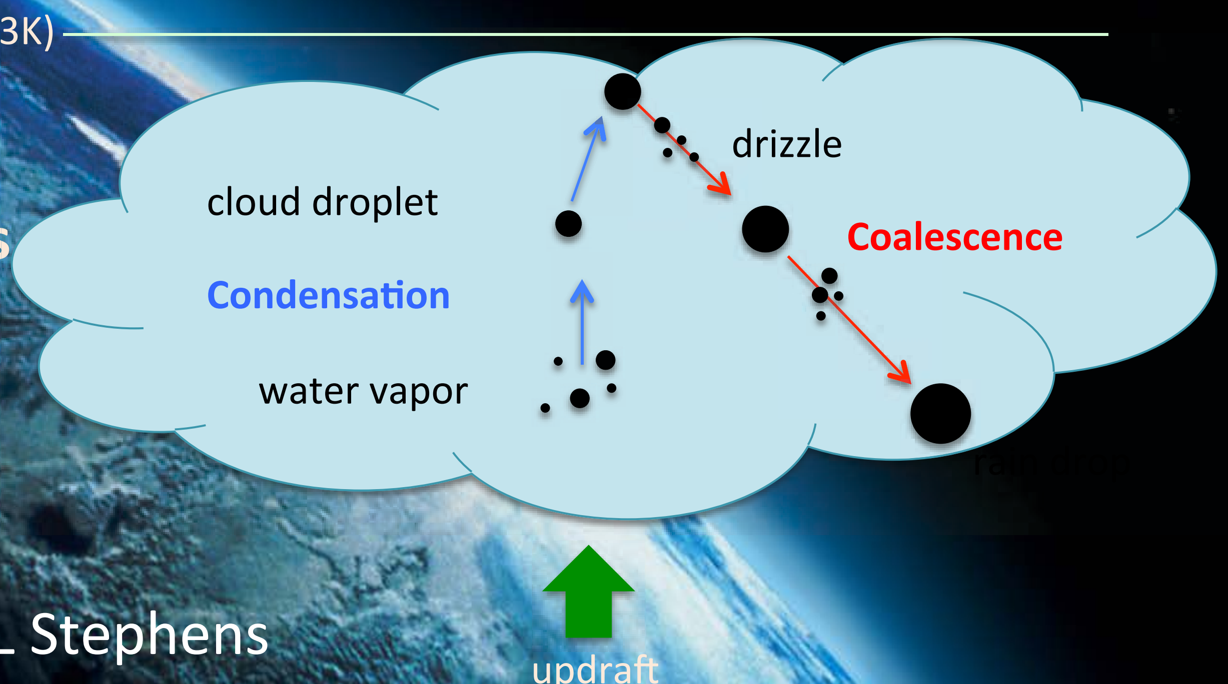
Process understanding of the connections between radiation, clouds, aerosol and precipitation

Macrophysics versus microphysics

- **Warm, shallow clouds**
- **Mixed phase & Cold clouds**
- **Radiation challenges**
- **Convection**



Graeme L Stephens
1. Jet Propulsion Lab, CalTech
2. Uni of Reading & UKMO

GEWEX PROES - Process Evaluation Studies (under development)

This grew out of the 2014 obs4mip meeting where participants felt the issue of using obs more intelligently to probe process understanding was missing in obs4mip II

PROES is developing into a WCRP cross cut activity

- Upper Tropospheric Clouds & Convection (UTCC) lead Stubenrauch and Stephens
- Ice mass balance (lead Larour, Sophie Nowicki), GEWEX with CLiC
- Radiative Kernels for Climate (lead Soden)
- Mid-lat storms (lead Tselioudis, Jakob)
- Soil moisture climate (lead Sonia Seneviratne)

PROES is about using observations to examine processes and my talk today underscores aspects of this CPT-like mentality applied to low, warm clouds

Global Water-Energy balance dilemma

Water and energy don't balance - To achieve a balance we are forced to make adjustments to our best estimate fluxes

At the TOA this is done wrt the observed ocean heat uptake (e.g. Loeb et al., 2012)

At the surface, two philosophical pathways have been followed

1) **Small adjustment to turbulent fluxes – Big decrease to radiation - what is the missing sink of radiant energy?**
2) **Big increase to turbulent fluxes- Small adjustment to radiation - where is the missing source of water?**

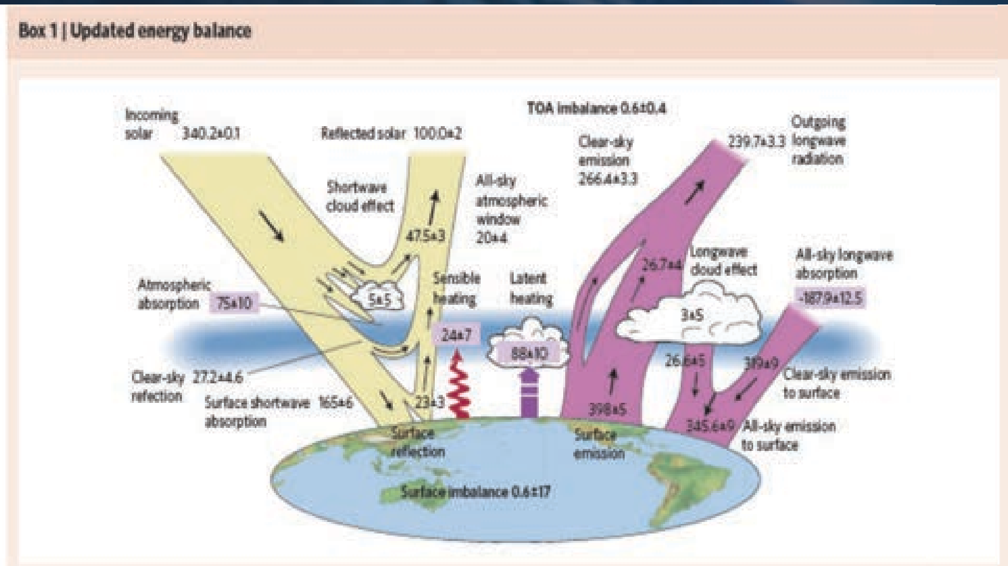
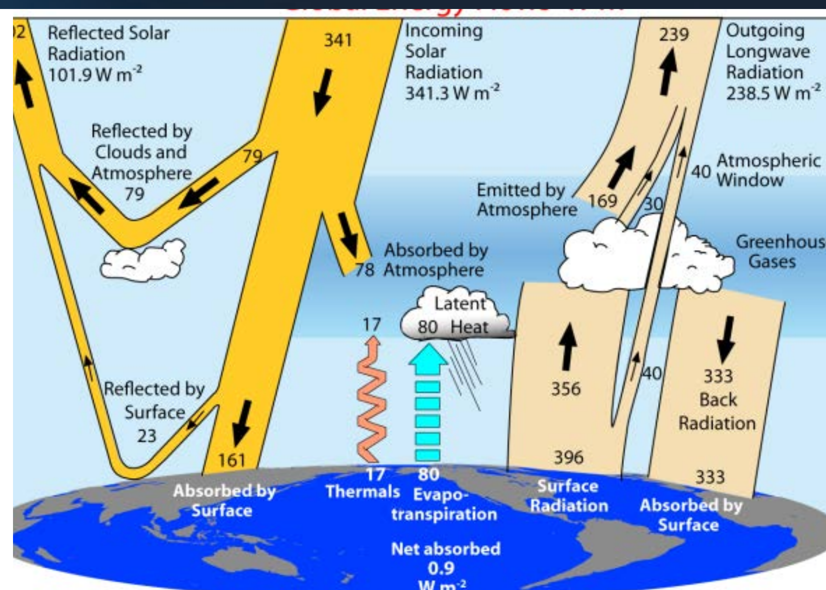


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.

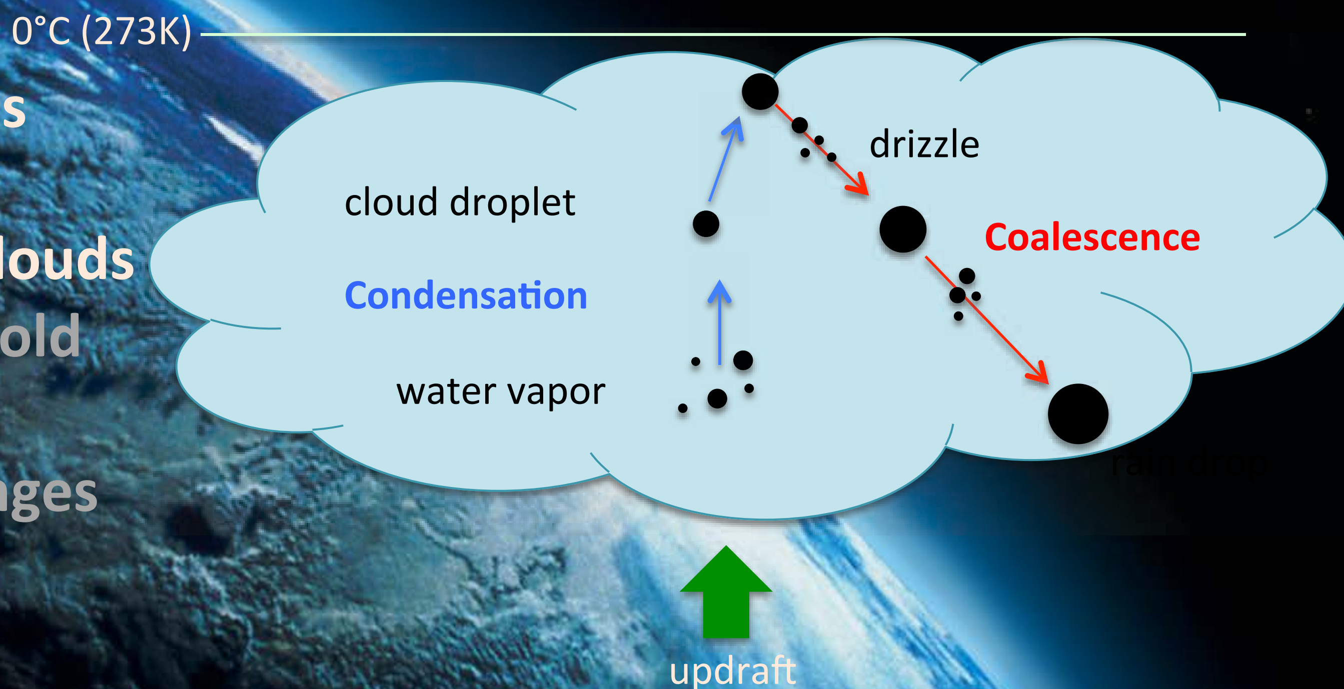


Stephens et al., 2012

Some Challenges in understanding the connections between radiation, clouds, aerosol and precipitation

Macrophysics versus microphysics

- **Warm, shallow clouds**
- **Mixed phase & Cold clouds**
- **Radiation challenges**
- **Convection**



Cloud albedo

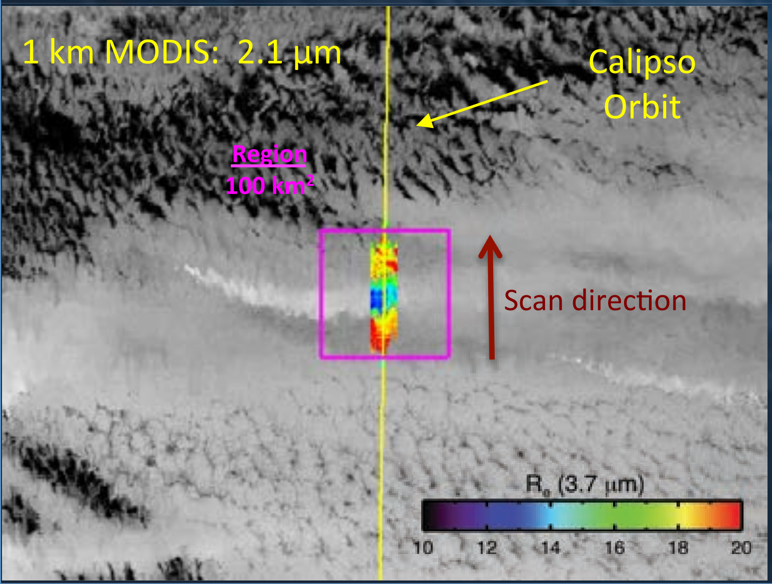
Largely microphysics perspective

Twomey (1976) introduced

$$\tau = C_1 w^{2/3} N^{1/3} h$$

Stephens (1978) introduced

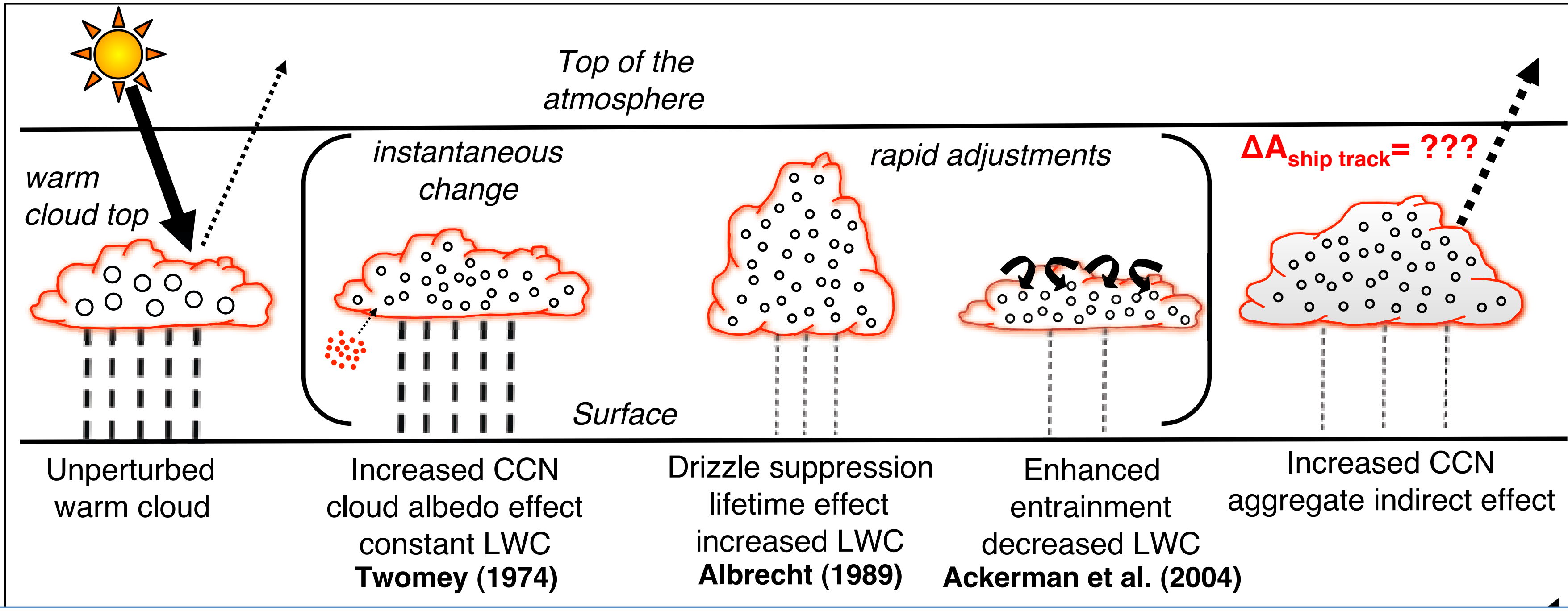
$$\tau = C_2 \frac{LWP}{r_e}$$



Largely macrophysics perspective

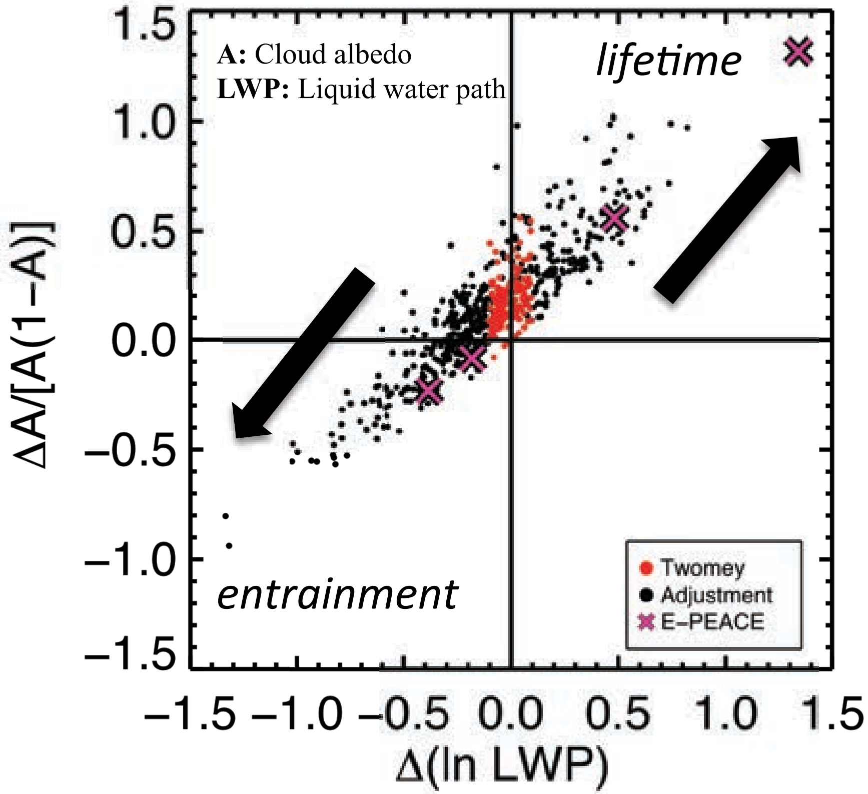
"Ship tracks have been called the Rosetta Stone of aerosol-cloud-climate interactions because they serve as a striking example of the effects of increased CCN on the albedo of marine stratiform clouds."
Ackerman et al., (1995)

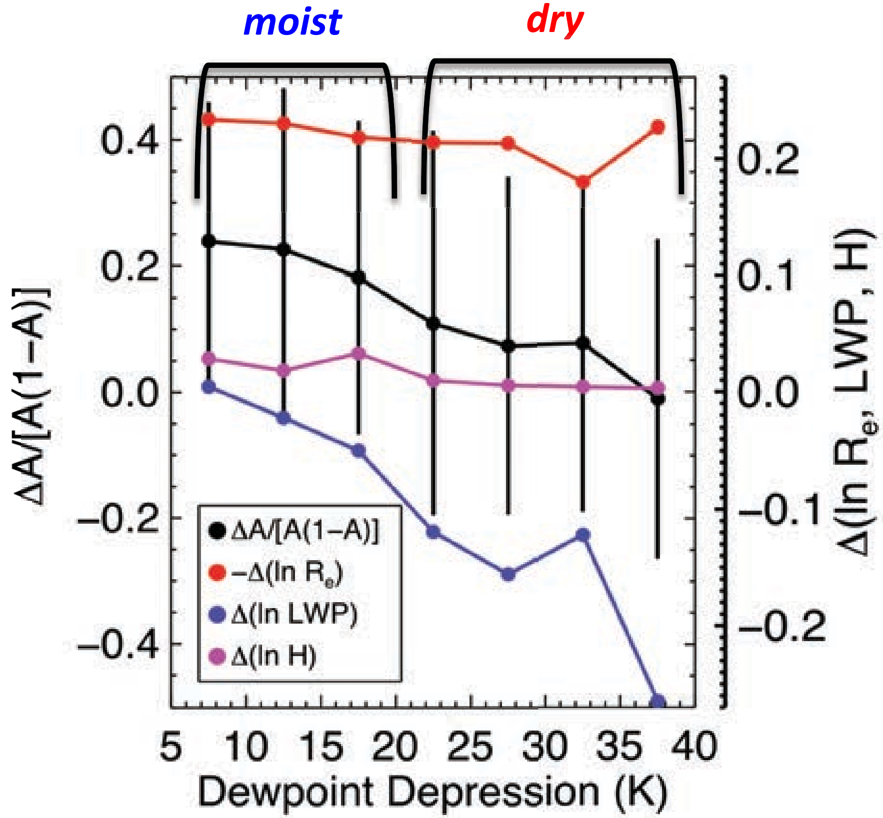
Indirect Effect Schematic Diagram for *Warm* & *Cold* Clouds



Cloud Albedo

$$\tau = \frac{3}{2}\frac{LWP}{r_e} \qquad \frac{\Delta\tau}{\tau} = \frac{\Delta LWP}{LWP} - \frac{\Delta r_e}{r_e}$$



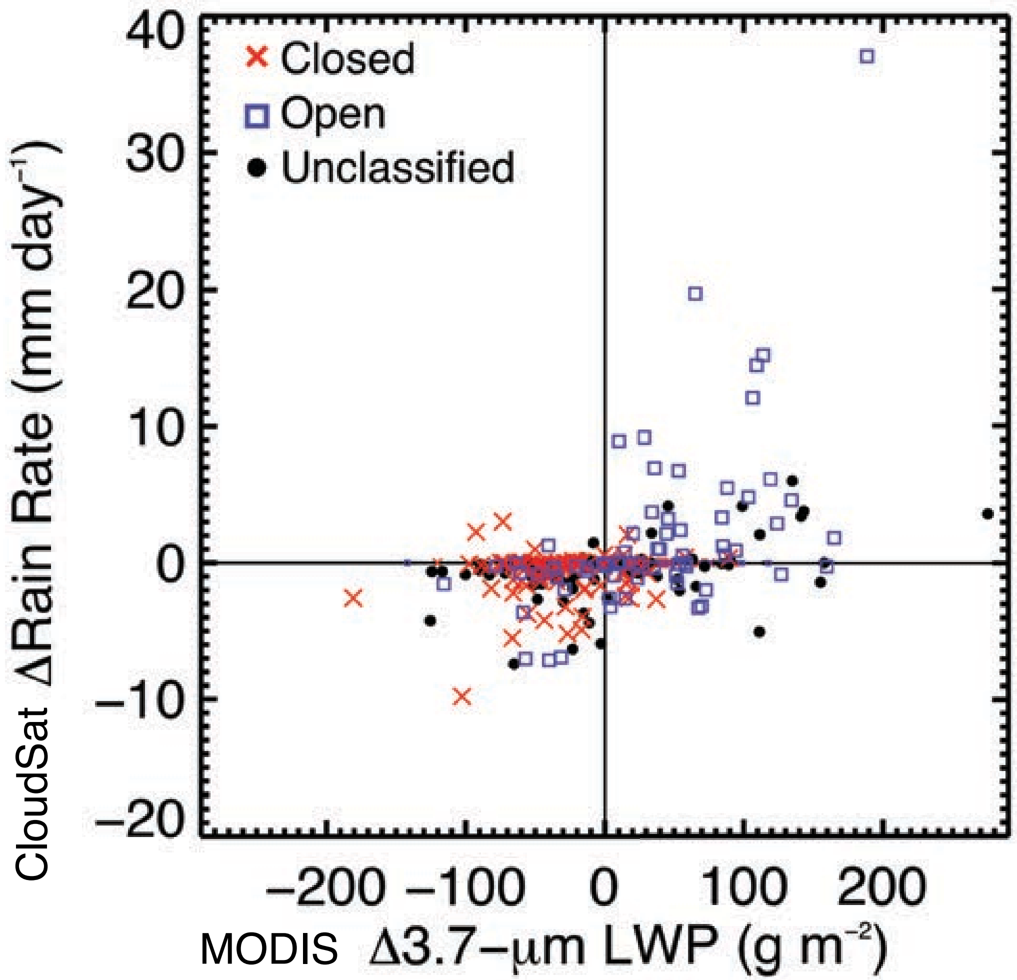


- Differences in liquid water path primarily determine the strength and sign of the aerosol indirect effect.
- Humidity above cloud tops is responsible for the differences in LWP.
- E-PEACE results are in general agreement with A-Train observations.

Chen et al. (2013)

Does suppressed drizzle lead to liquid increased water path?

(as suggested by Albrecht, [1989], and many others…)



Christensen and Stephens (2012)

Answer: rarely, in less than 10% of ship tracks.

→ Suggests more entrainment into polluted clouds resulting in less LWP and drizzle.

How often is rainfall suppressed?

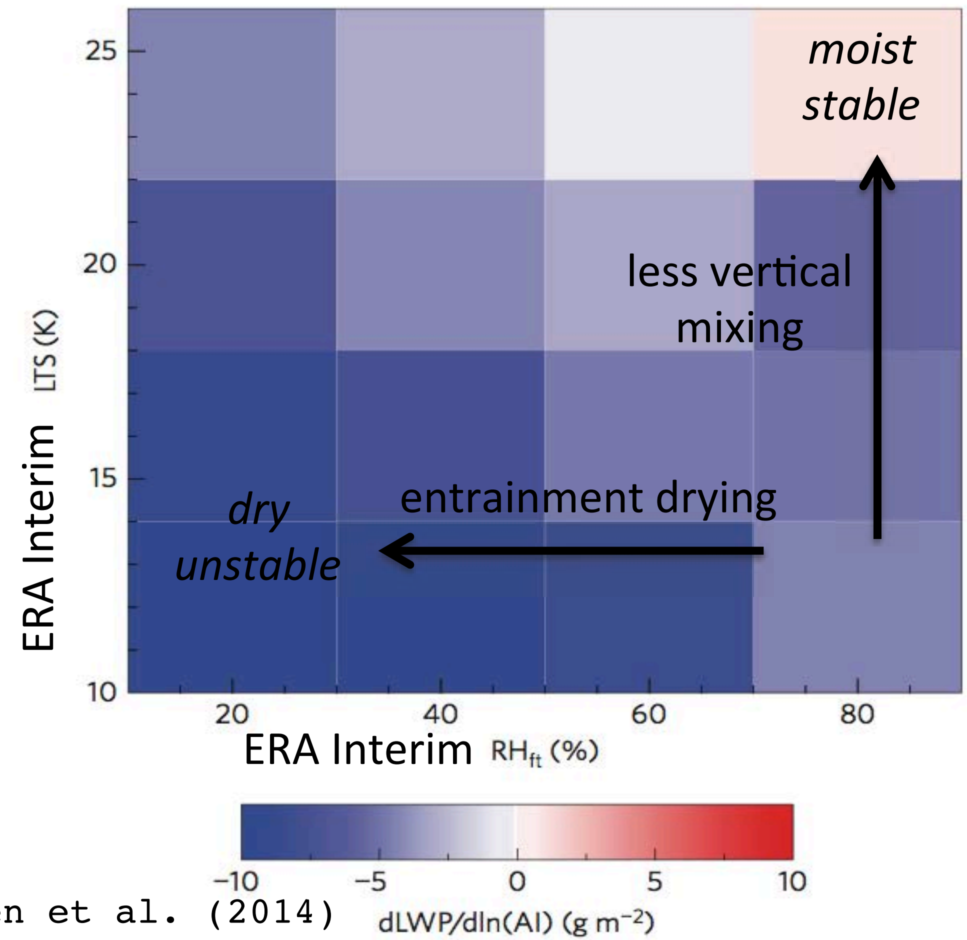
Answer: **72% of the time**

***Closed Cells:* 85% & Open *Cells:* 50%**

To what extent is cloud albedo affected by these processes?

Global A-Train Observations

Liquid Water Path Response



Chen et al. (2014)

LTS: Lower Troposphere Stability (LTS = $\Theta_{700mb} - \Theta_{surface}$)
RH$_{ft}$: Free-troposphere Humidity (relative humidity above cloud top)
LWP: Liquid Water Path (MODIS)
AI: Aerosol Index (MODIS)

Data

- 4 years of collocated A-TRAIN observations using CERES, MODIS, CALIPSO, and CloudSat instruments.
- Over 5 million carefully screened retrievals (single layer low-level warm phase cloud) 60°S to 60°N.
- Aerosol (MODIS) properties are averaged over 1° regions.

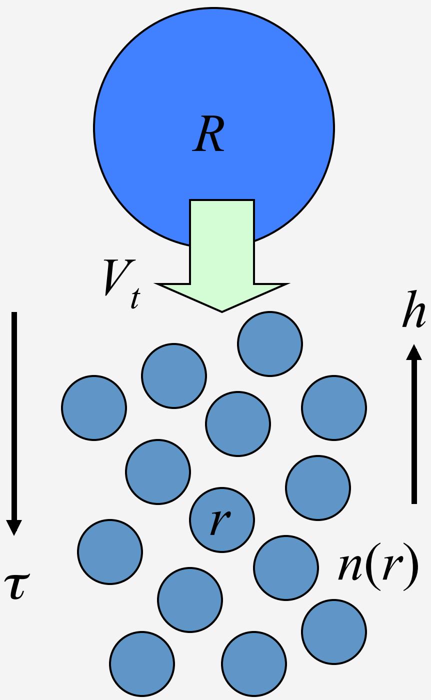
Results

- Entrainment/drying effect is largest in dry and unstable conditions.
  - Consistent with ship track assessment and the LES simulations performed by Ackerman et al. (2004) & Chen et al. (2011).
- Co-variability of LTS and RH$_{ft}$ *buffer* the liquid water path response to increasing aerosol concentration.

How do aerosol changes on cloud properties and cloud fraction impact the global aerosol indirect forcing?

Insight into cloud to rain processes

Continuous collection model



$$r_e = \frac{\int n(r) r^3 dr}{\int n(r) r^2 dr}$$

$$q_c = \rho_w \frac{4}{3}\pi \int n(r) r^3 dr$$

$$\frac{dR}{dt} = \frac{E_c V_t(R)}{4\rho_w} q_c$$

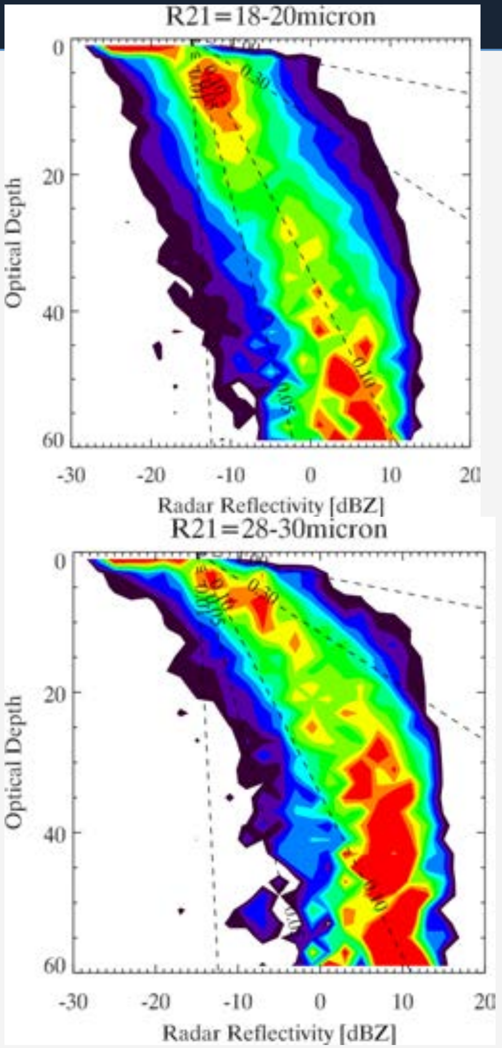
$$dh = -V_t(R) dt$$

$$\frac{dR}{dh} = -\frac{E_c}{4\rho_w} q_c \qquad \frac{dR}{R} = -\frac{E_c}{4\rho_w}\frac{q_c}{R} dh$$

$$\frac{dZ_e}{Z_e} = \lambda \frac{dR}{R} \quad (\lambda = 3\sim 6)$$

$$d\tau \approx -\frac{3}{2}\frac{1}{\rho_w}\frac{q_c}{R} dh$$

$$\boxed{\frac{d\ln Z_e}{d\tau} \approx \frac{\lambda}{6} E_c}$$

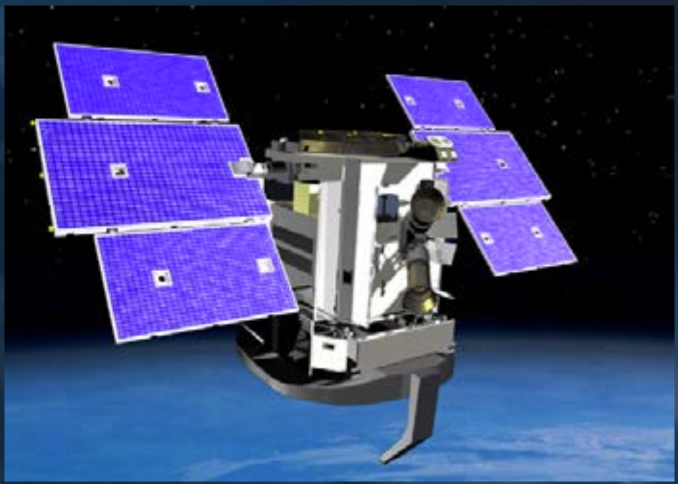


Suzuki *et al*. (JAS 2010)

The slope in CFODD is a gross measure of drop collection efficiency E_c.

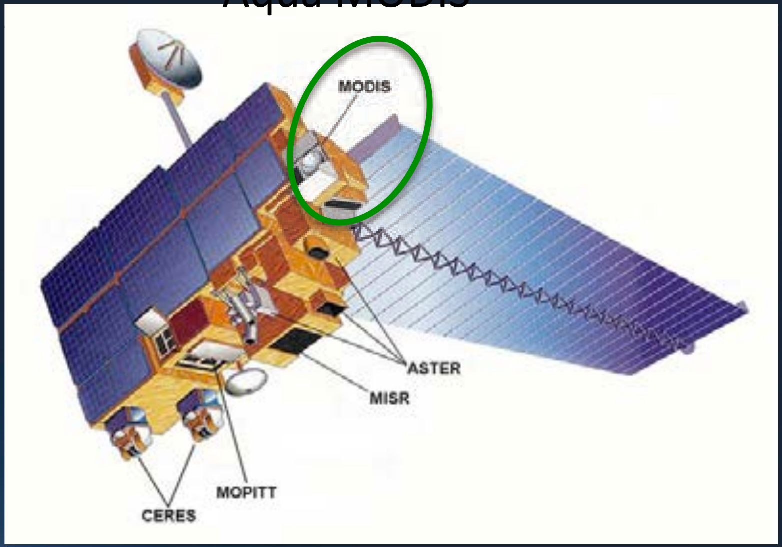
Data: A-Train Satellite Observation

Rain/drizzle



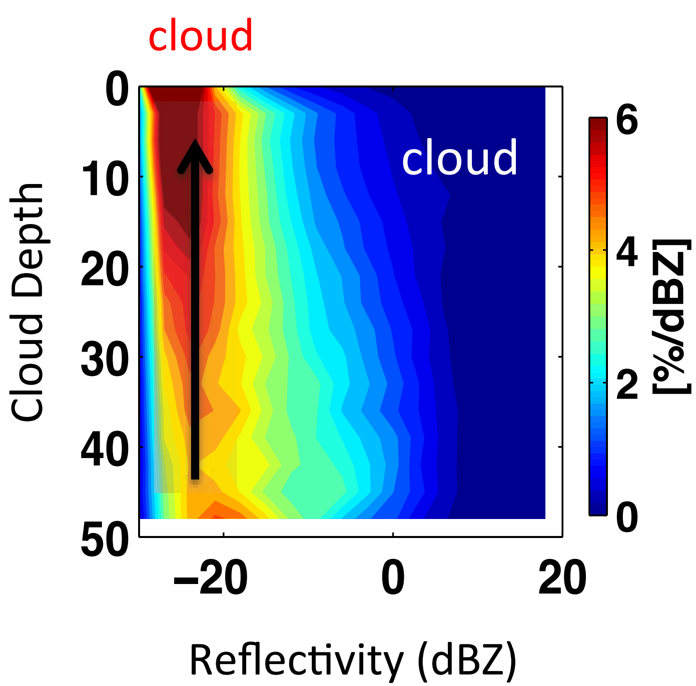
Cloud

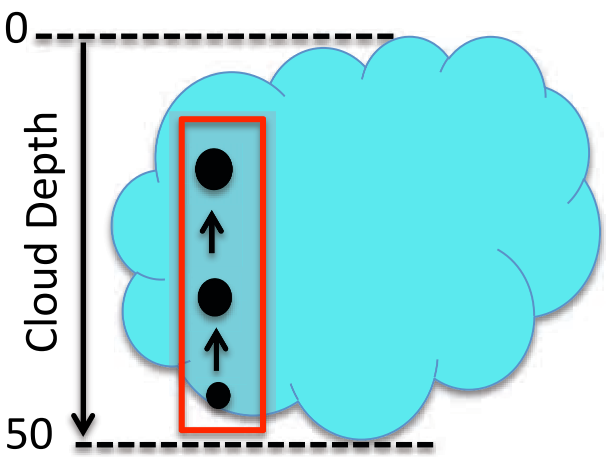
Aqua MODIS



Method: Contour Frequency of Optical Depth Diagram (CFODD)

Cloud top particle size
5-10µm





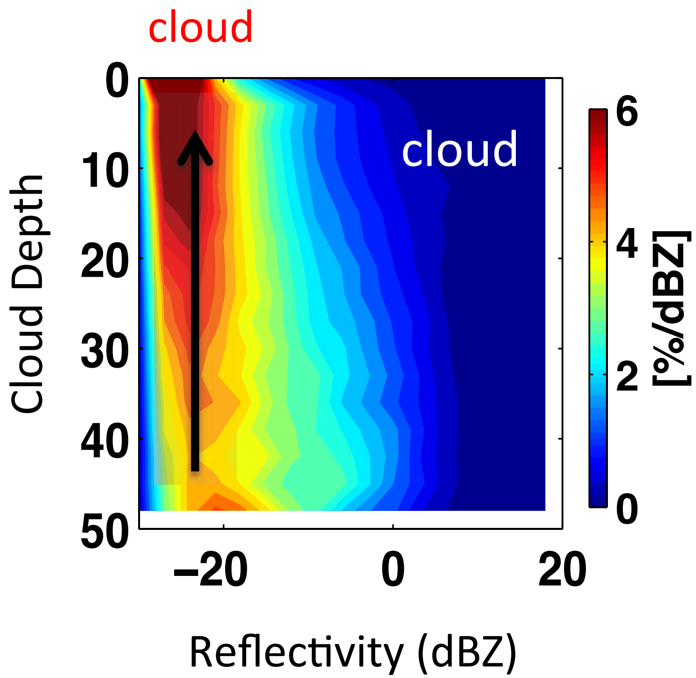
cloud mode (<-15dBZ) ➔ drizzle mode (>-15dBZ & <0dBZ) ➔ rain mode (>0dBZ)

❖ Stage of condensation

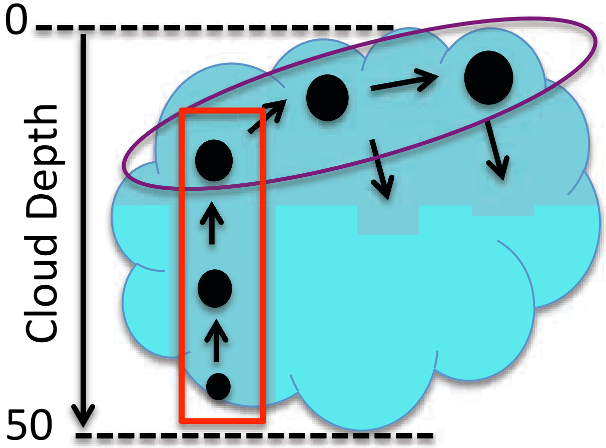
Method: Contour Frequency of Optical Depth Diagram (CFODD)

5-10μm

10-15μm

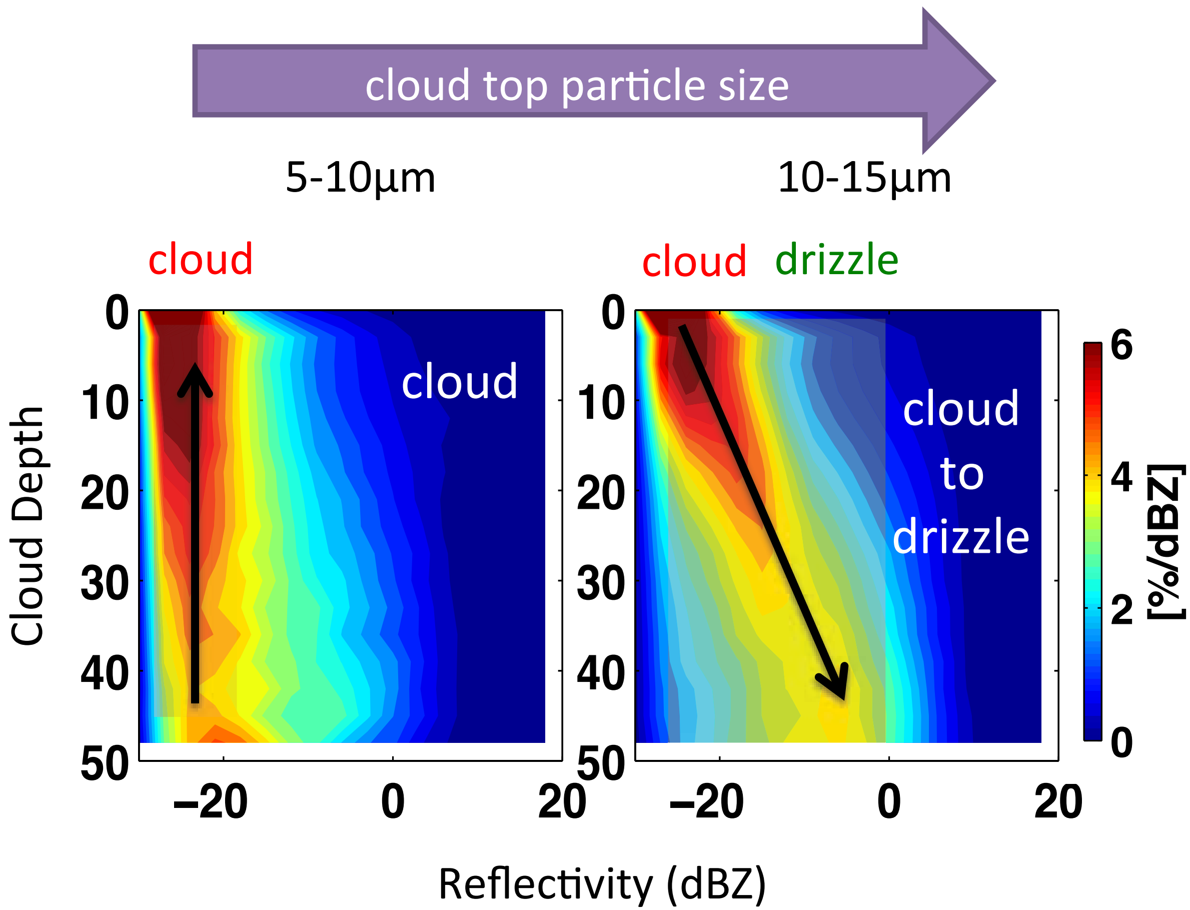


- As clouds age, cloud top particles grow

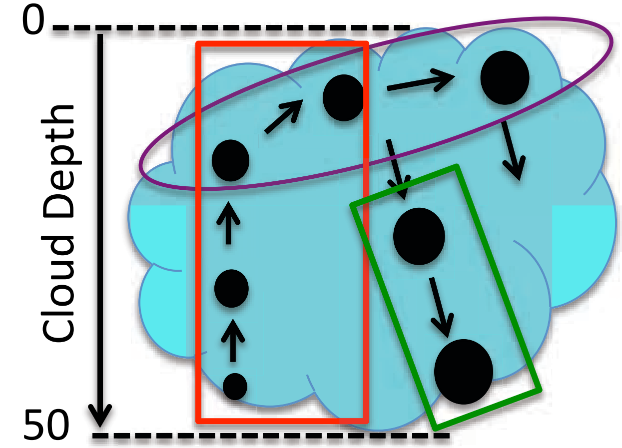


cloud mode (<-15dBZ) ➔ drizzle mode (>-15dBZ & <0dBZ) ➔ rain mode (>0dBZ)

Method: Contour Frequency of Optical Depth Diagram (CFODD)



- As clouds age, cloud top particle grows



cloud mode (<-15dBZ) ➔ drizzle mode (>-15dBZ & <0dBZ) ➔ rain mode (>0dBZ)

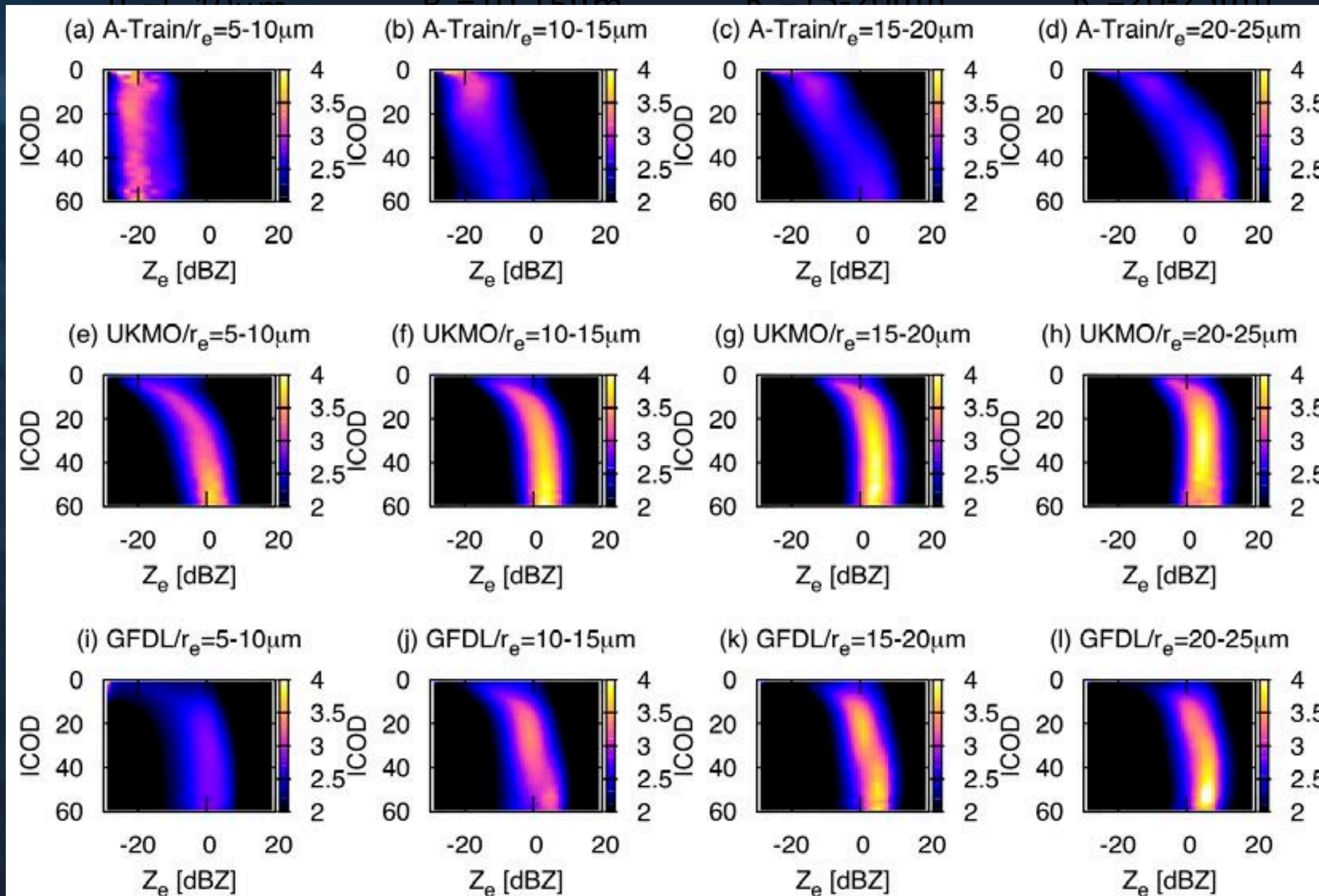
- Stage of coalescence

Obs versus global GCMS

A-Train

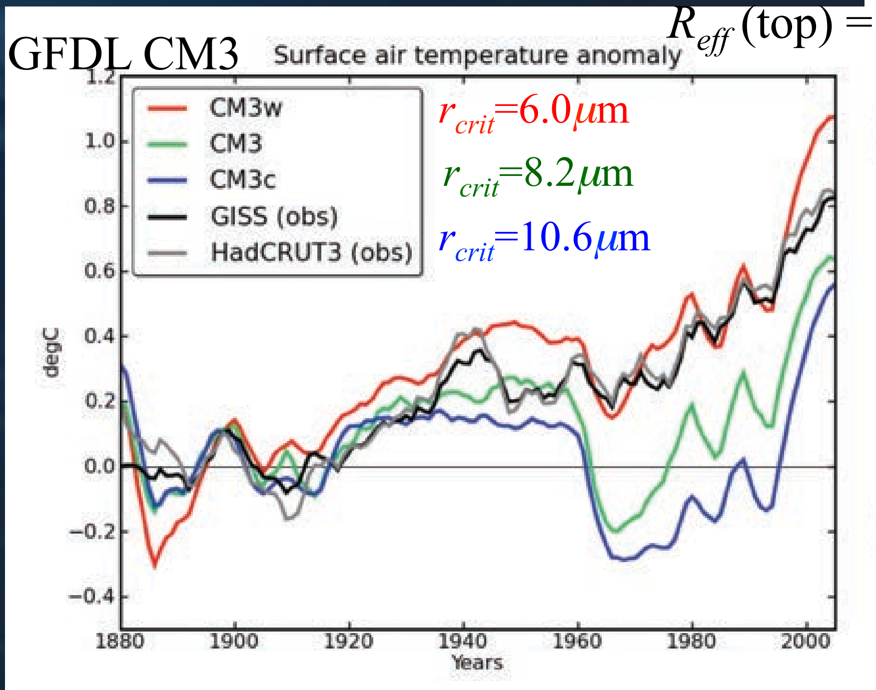
UKMO

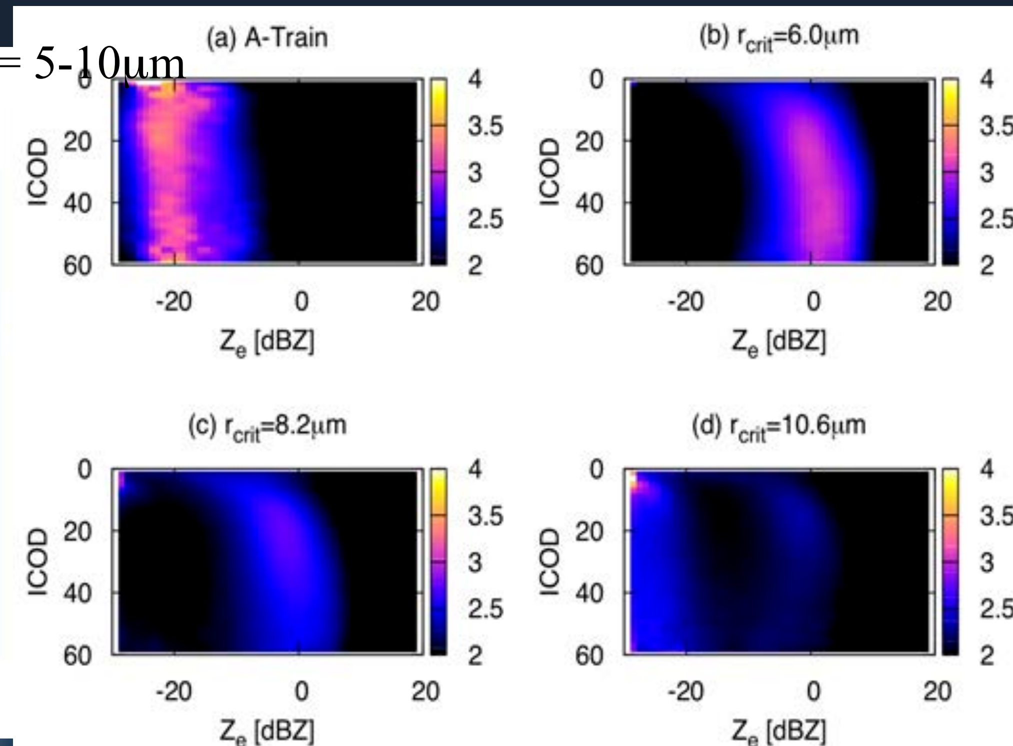
GFDL



This is an example of PROES-like use of observations to probe processes

One example of process influence on model





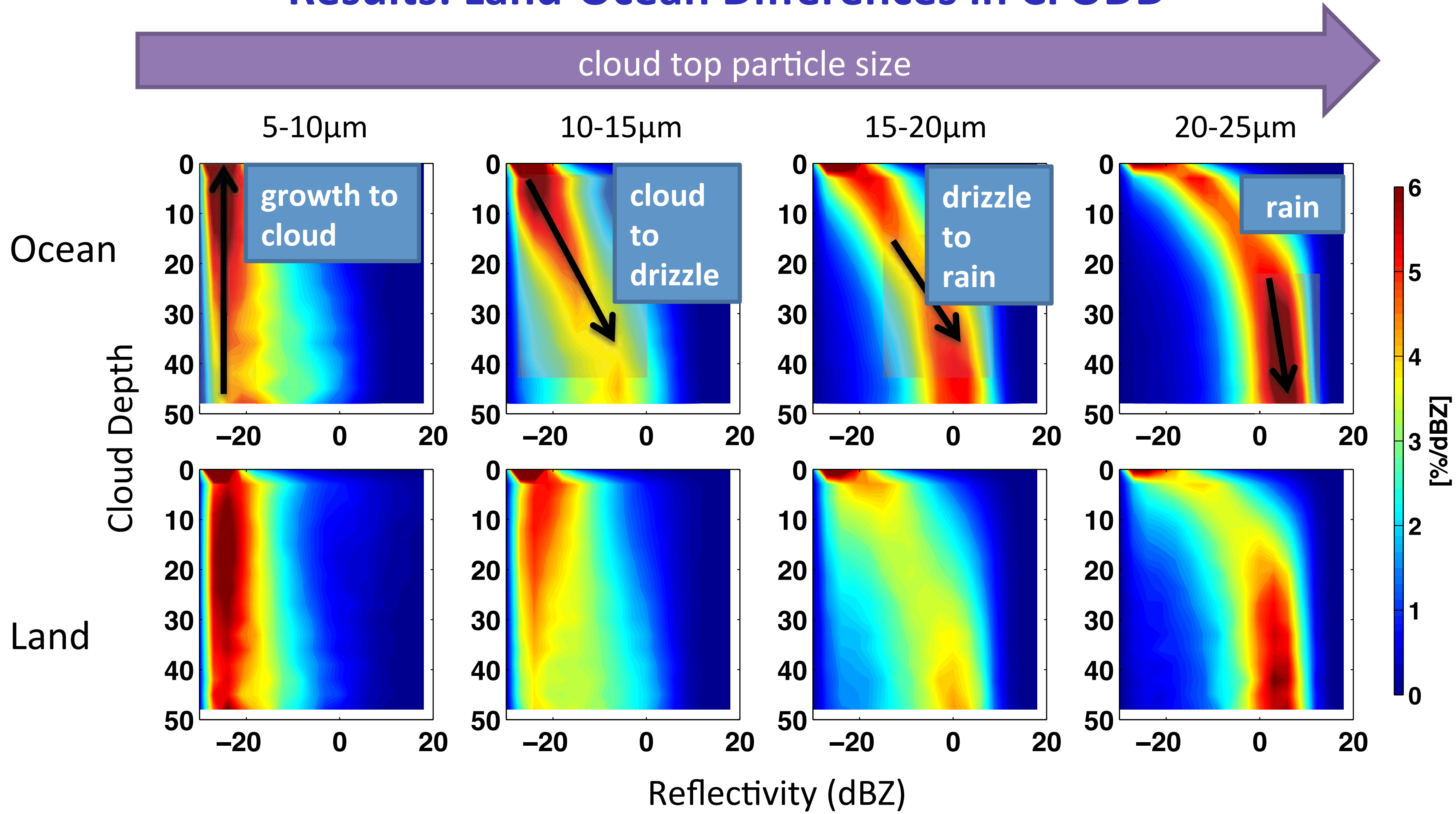
Golaz et al (2013)

- ✓ Historical temperature change simulations are sensitive to the details of how warm precipitation is triggered
- ✓ The most realistic warm rain initiation produces the *worst* simulation.
- ✓ Small changes in reflected energy appear to force a transition into a different regime that appears to be triggered by the Mt Agung eruption in early 1960s.

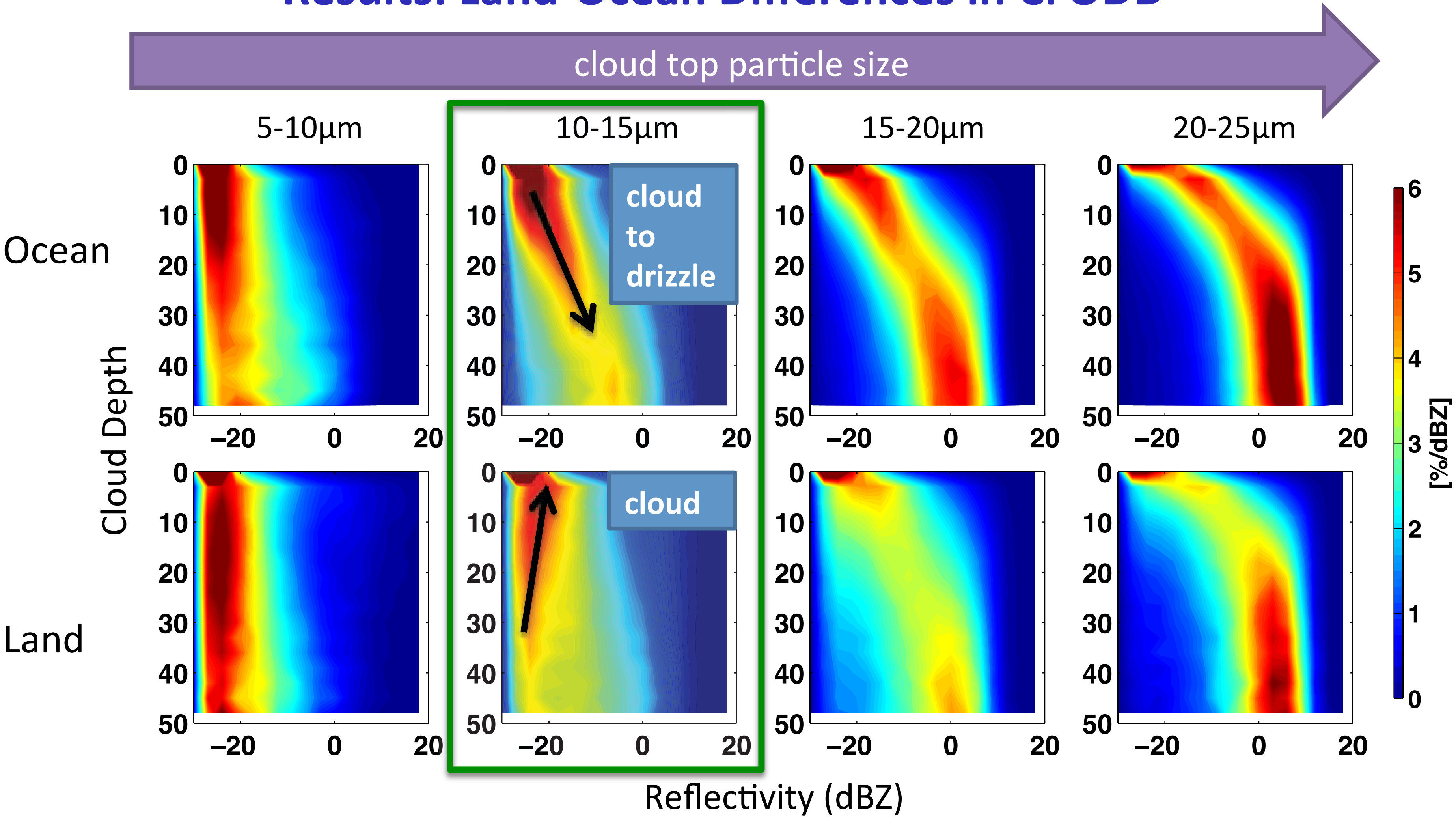
Land versus ocean contrasts in Cloud-to rain processes

Hanii Takahashi (in prep)

Results: Land-Ocean Differences in CFODD

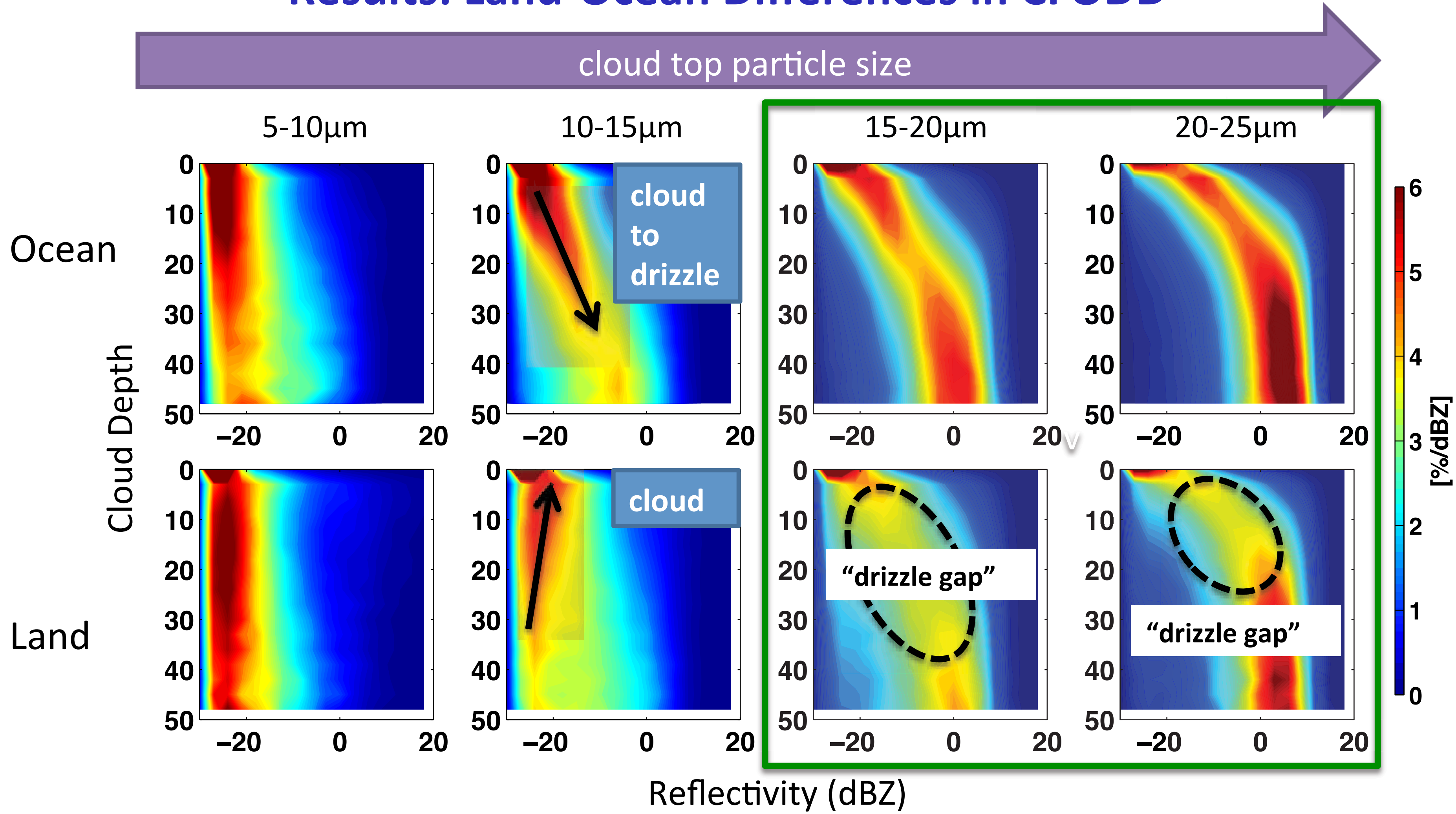


Results: Land-Ocean Differences in CFODD



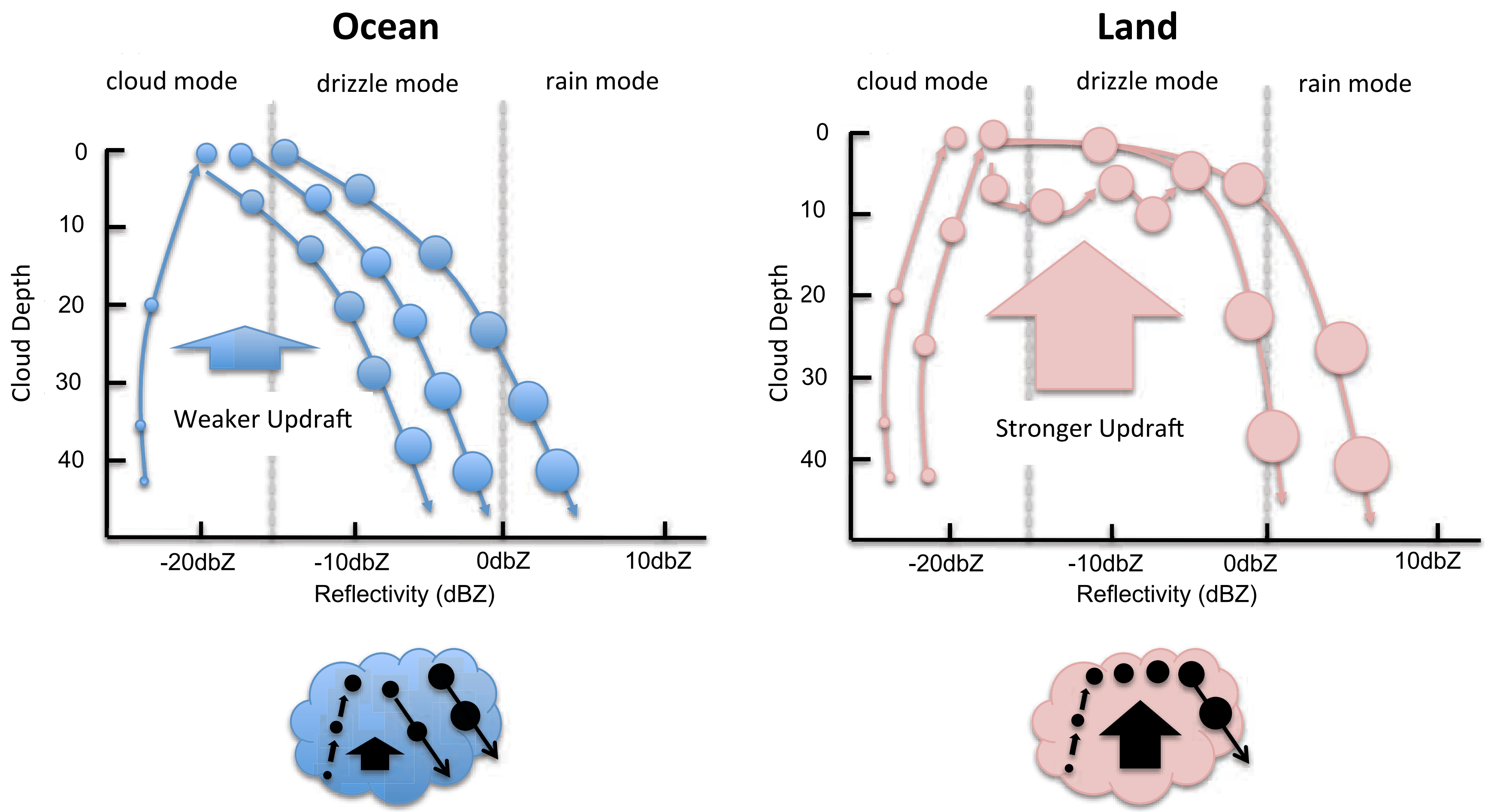
- Particles start to fall sooner over ocean.

Results: Land-Ocean Differences in CFODD



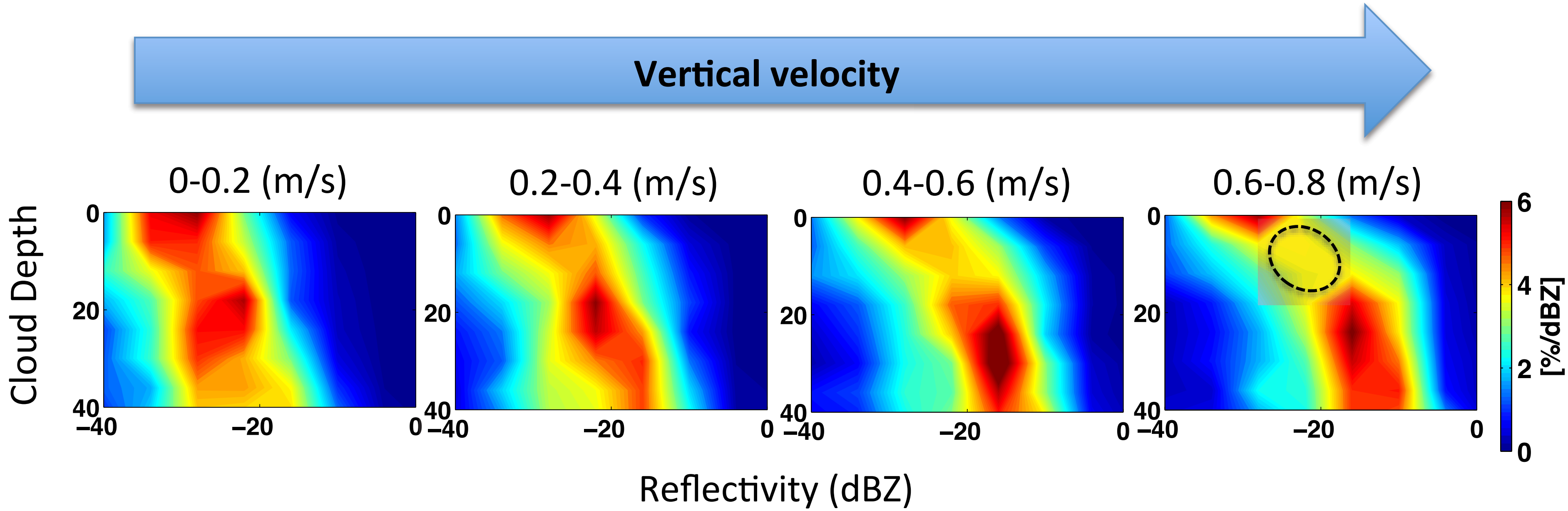
- Particles start to fall sooner over ocean.
- A "drizzle gap" can be seen over land (drizzle suppression).

Hypothesis: The land-ocean differences are due to the land-ocean differences in the intensity of updrafts



- Particles start to fall sooner over ocean.
- Drizzle suppression can be seen over land.

Test : ARM Ground-Based Measurement (and cloud model simulation)



- ARM Cloud Radar has Doppler velocity.
- "Drizzle gap" starts to appear when vertical velocity is stronger.

Summary& closing comments

- The radiative properties of clouds are primarily shaped by their macrophysical properties.
- Direct microphysical influences seem to be smaller and subtlely play out through influences on macrophysical adjustments.
- Anecdotally, the way cloudy air moves and mixes with its environment seems to be a dominant control of these macro-properties and thus to cloud-radiation-aerosol properties.
- We have some tools to probe cloud-radiation processes in growing detail that clearly impact model development, and more are to be developed under PROES. Ironically, the 8000lb gorilla is convection and our 'obs-based process tools' are primitive.

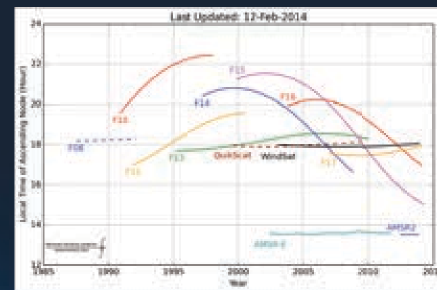
Multi-sensor Advanced Climatology for Liquid Water Path (MAC-LWP)

Input Sensors

TABLE 1. Properties of microwave sensors used in this work.

Sensor	Platform	Dates employed	ECT range (LT)	Orbit	Footprint (km)
SSM/I	F8	Jan 1988–Dec 1991	0615	Polar	32
SSM/I	F10	Dec 1990–Nov 1997	1942–2226	Polar	32
SSM/I	F11	Dec 1991–May 2000	1700–1938	Polar	32
SSM/I	F13	May 1995–Dec 2005	1739–1833	Polar	32
SSM/I	F14	May 1997–Dec 2005	2049–1908	Polar	32
SSM/I	F15	Dec 1999–Dec 2005	2133–2042	Polar	32
AMSR-E	*Aqua*	Jun 2002–Dec 2005	1330	Polar	12
TMI	TRMM	Dec 1997–Dec 2005	Varies	Equatorial	13

Orbital Drift



Fit Function

$$\mathrm{LWP}(Y_i, t_i) = \overline{\mathrm{LWP}}(Y_i) + A_1 \cos\omega(t_i - T_1) + A_2 \cos 2\omega(t - T_2) + n(t).$$

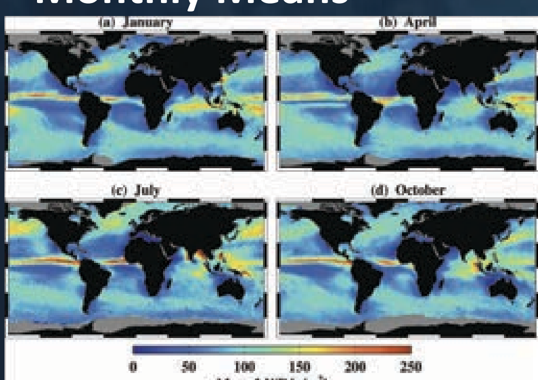
Benefits

1. Consistent inter-calibrated input data set
   - Based on Remote Sensing Systems Version 7 water path retrievals. SSM/I , AMSR-E, AMSR2, and TMI
   - Satellites are Inter-Calibrated at the radiance level
   - Common algorithm applied to all sensors with only minor variation in channel set.
2. No systematic regional/diurnal *sampling* biases (unlike optical)
3. Fit procedure accounts for diurnal and semi-diurnal cycle to remove the effects of orbital drift. Assumes that diurnal cycle is stationary
4. Explicit uncertainty estimation

Limitation

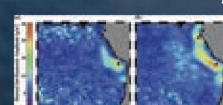
1. Must be bias corrected. Precipitation related biases are particularly difficult. (ongoing work)

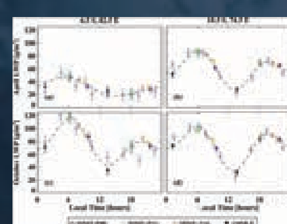
Monthly Means



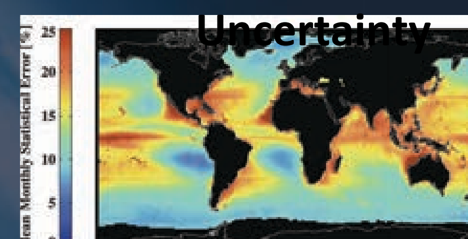
Diurnal Cycle

Lebsock, Teixeira, ODell, Elsaesser,



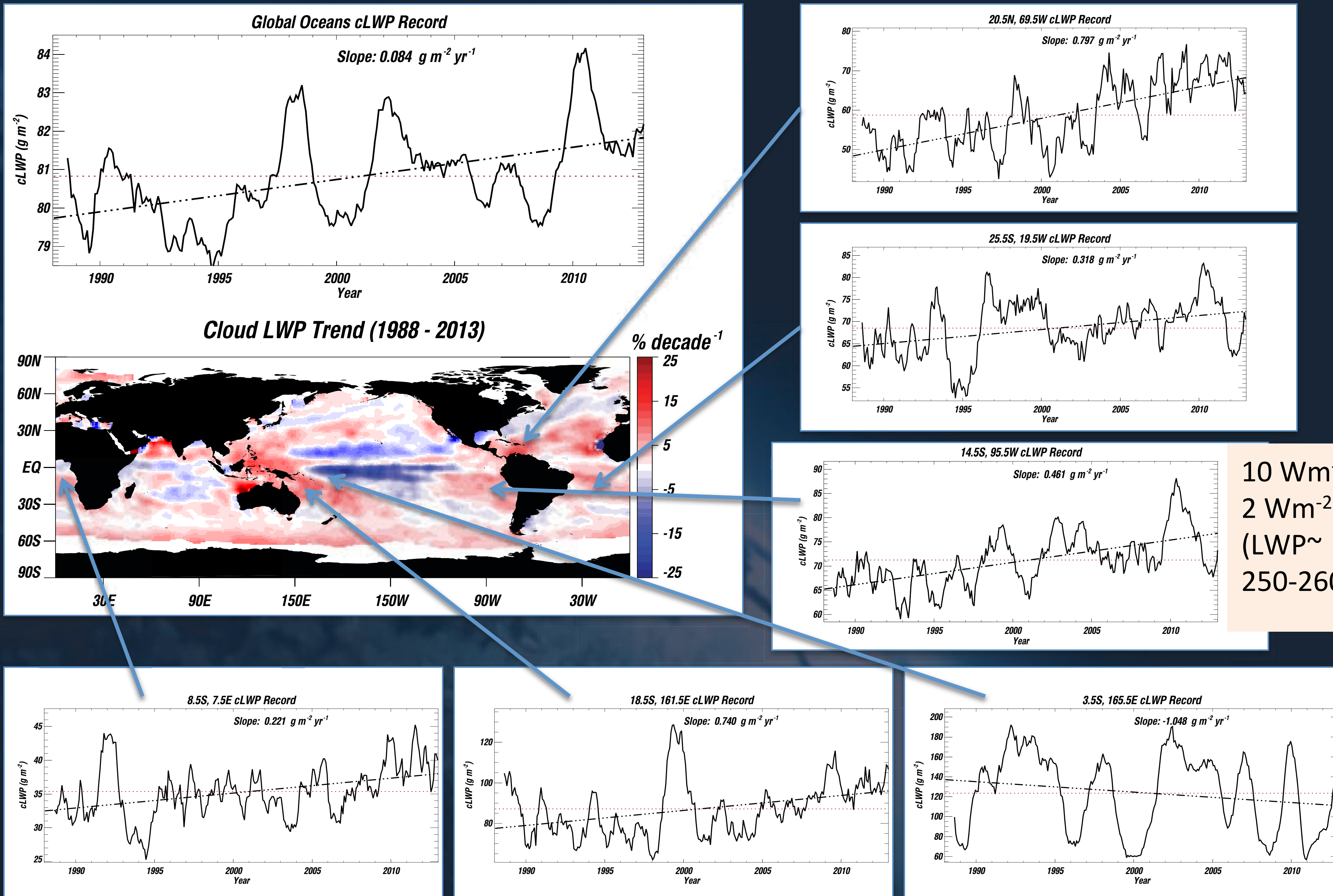


Uncertainty



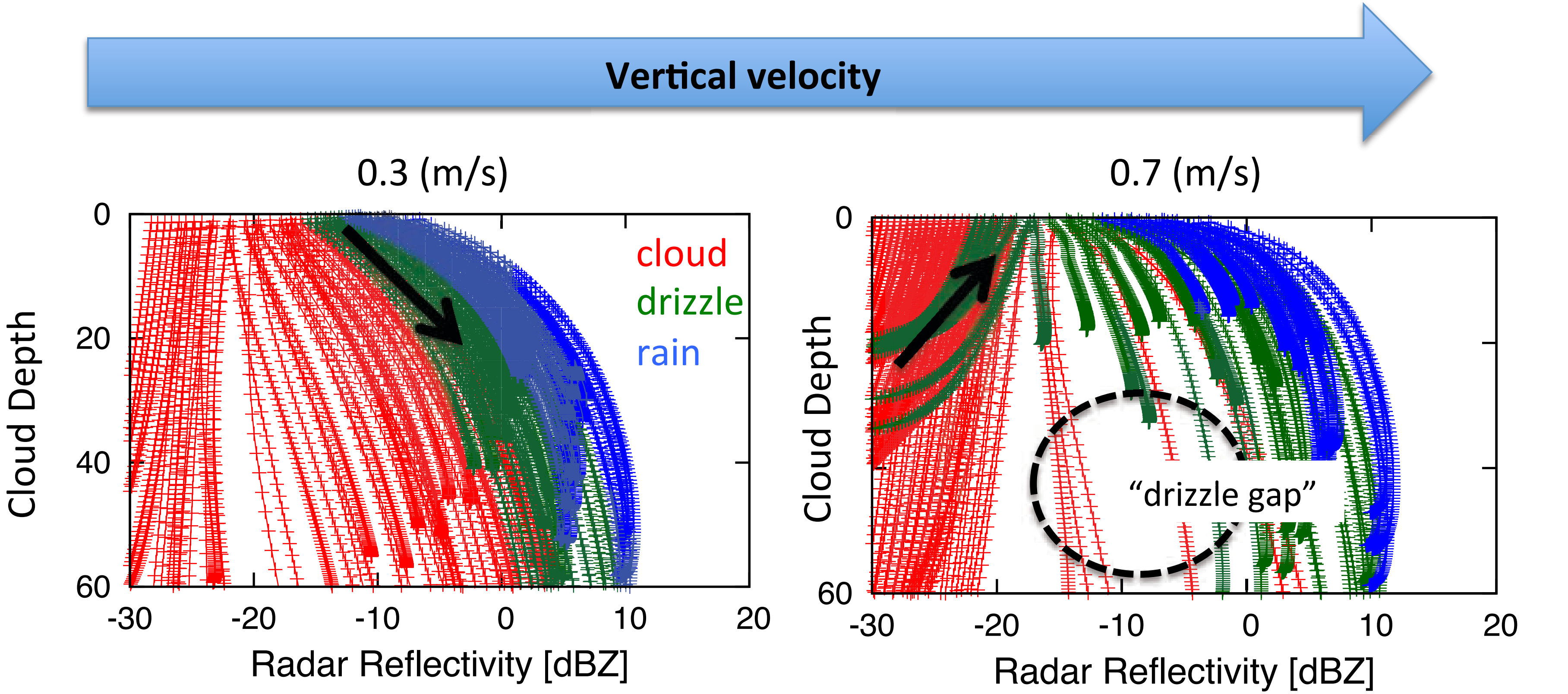
The resulting climate data record – Elsaesser et al., 2014; Lebsock et al., 2104 (in prep)

Cloud Liquid Water Path Trends



10 Wm^{-2}
2 Wm^{-2}
(LWP~
250-260)

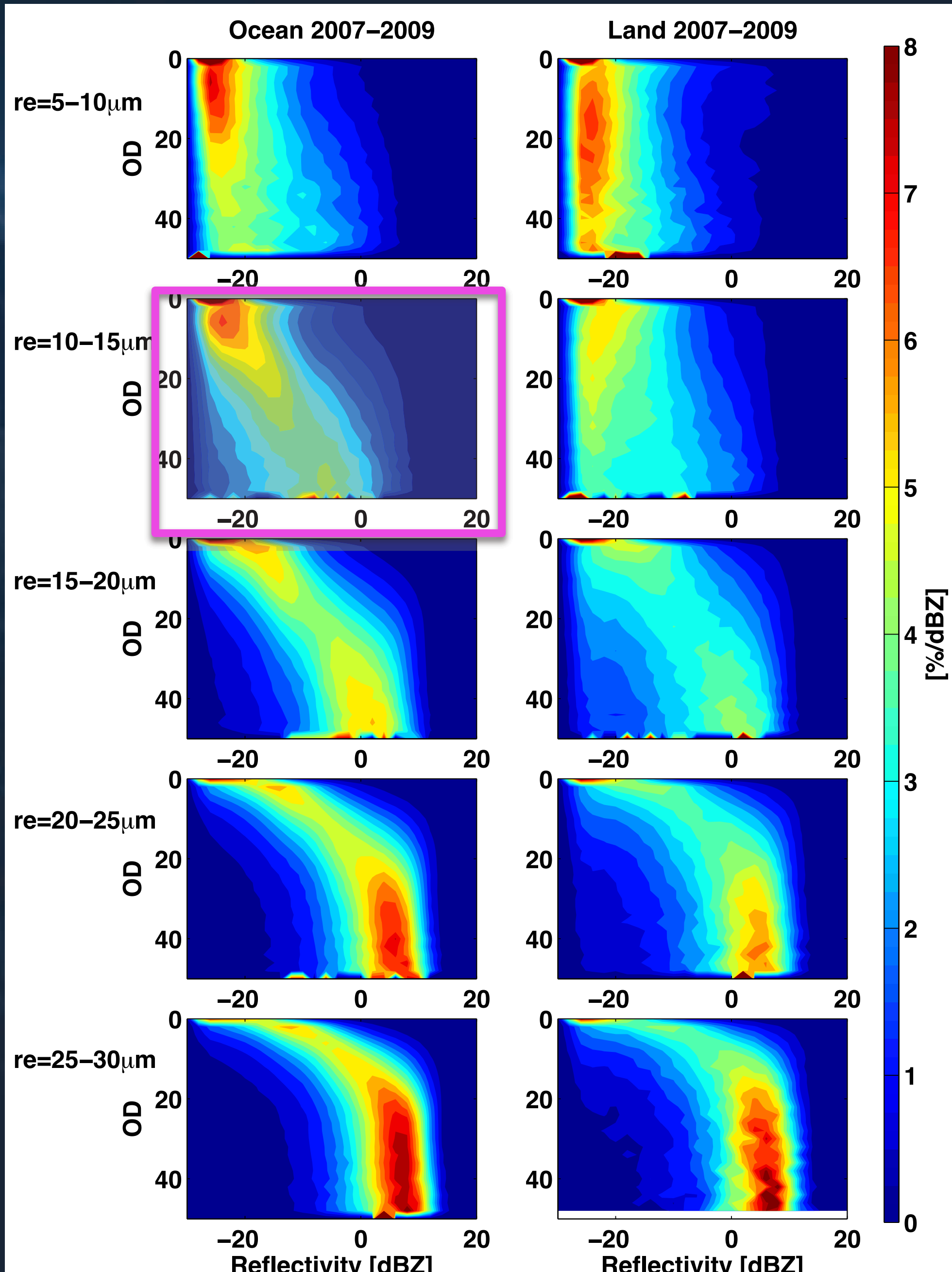
Testing Our Hypothesis II : Model Simulation



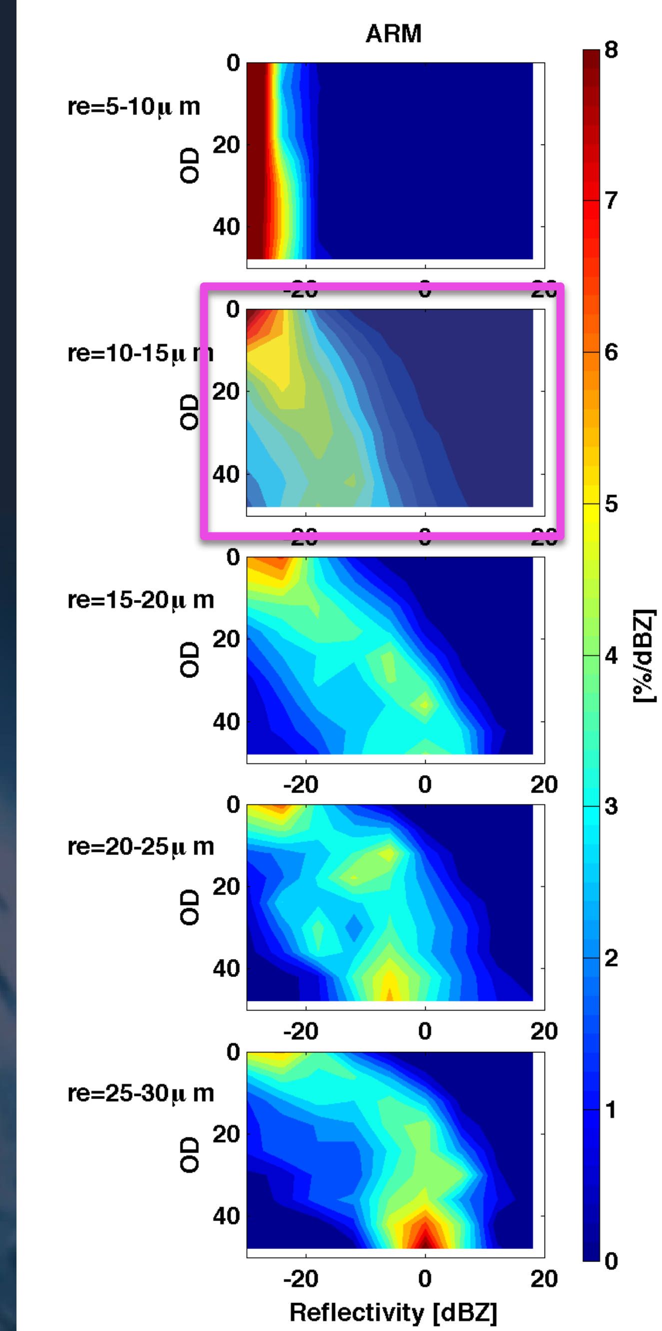
- Particles start to fall sooner over weak updraft.
- Physical model confirmed the nature of the “drizzle gap”.

Takahashi et al., 20015 in prep

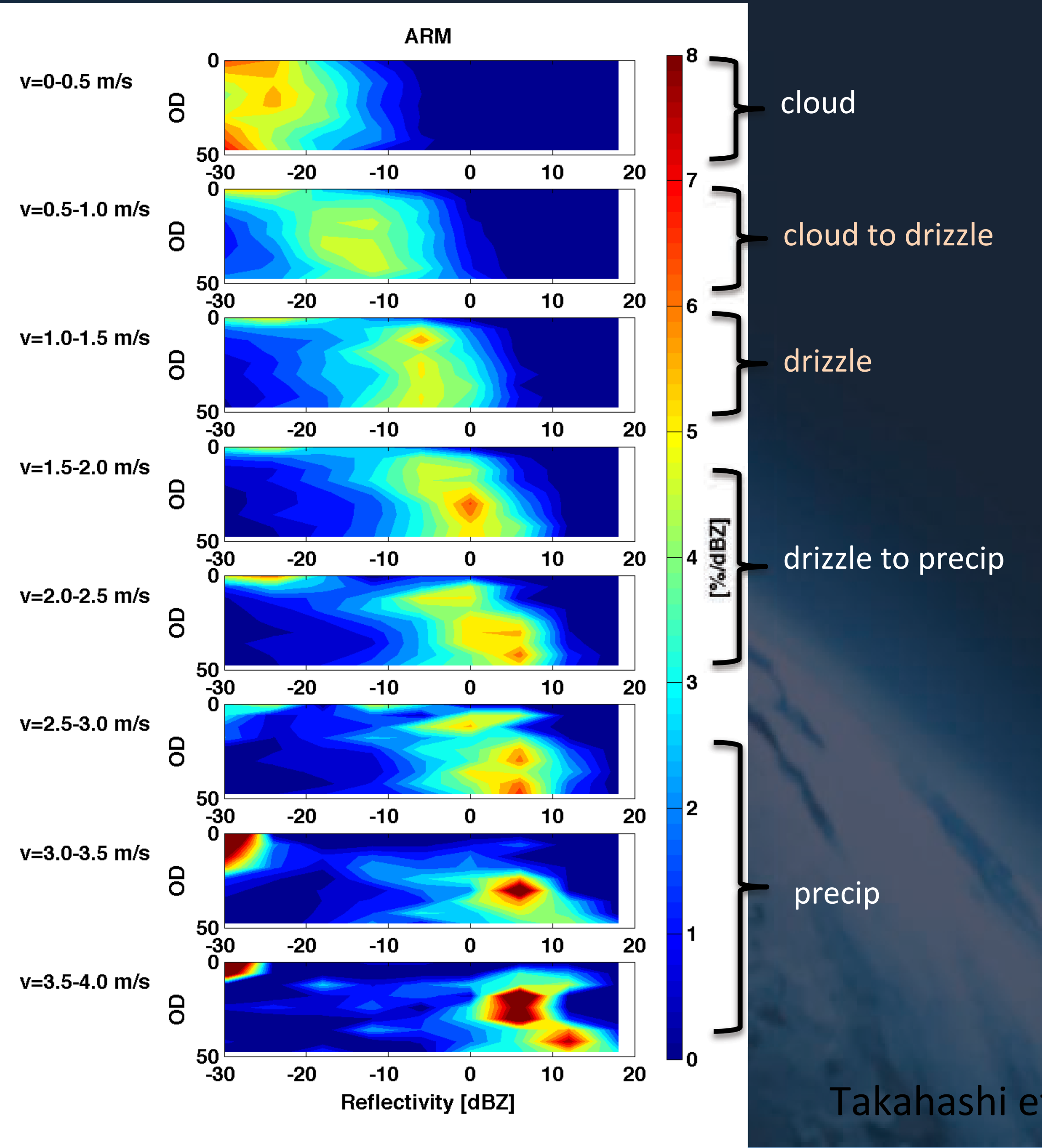
A-Train



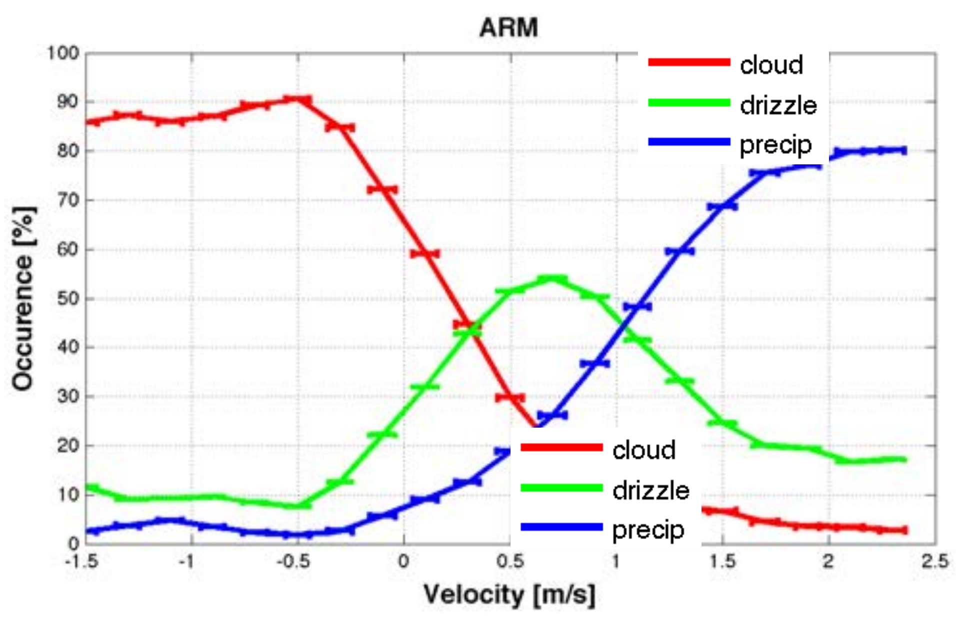
ARM (GRW)



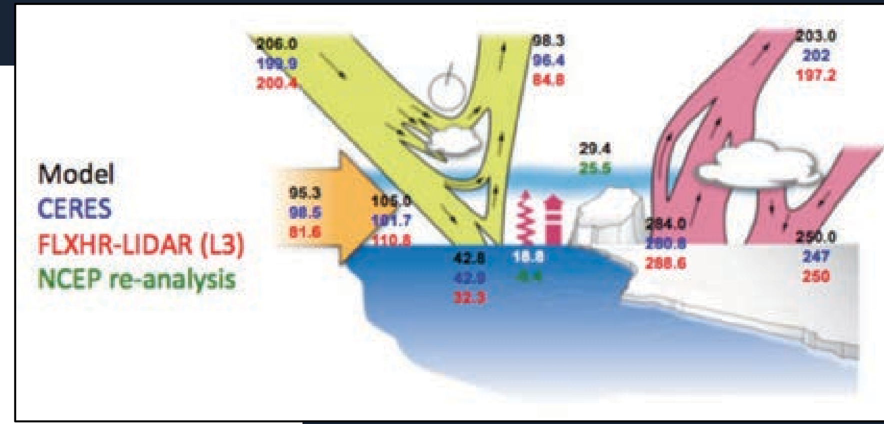
Instead of using effective radius, we can see the cloud-drizzle-precip process by using velocity (0.5 m/s bin)

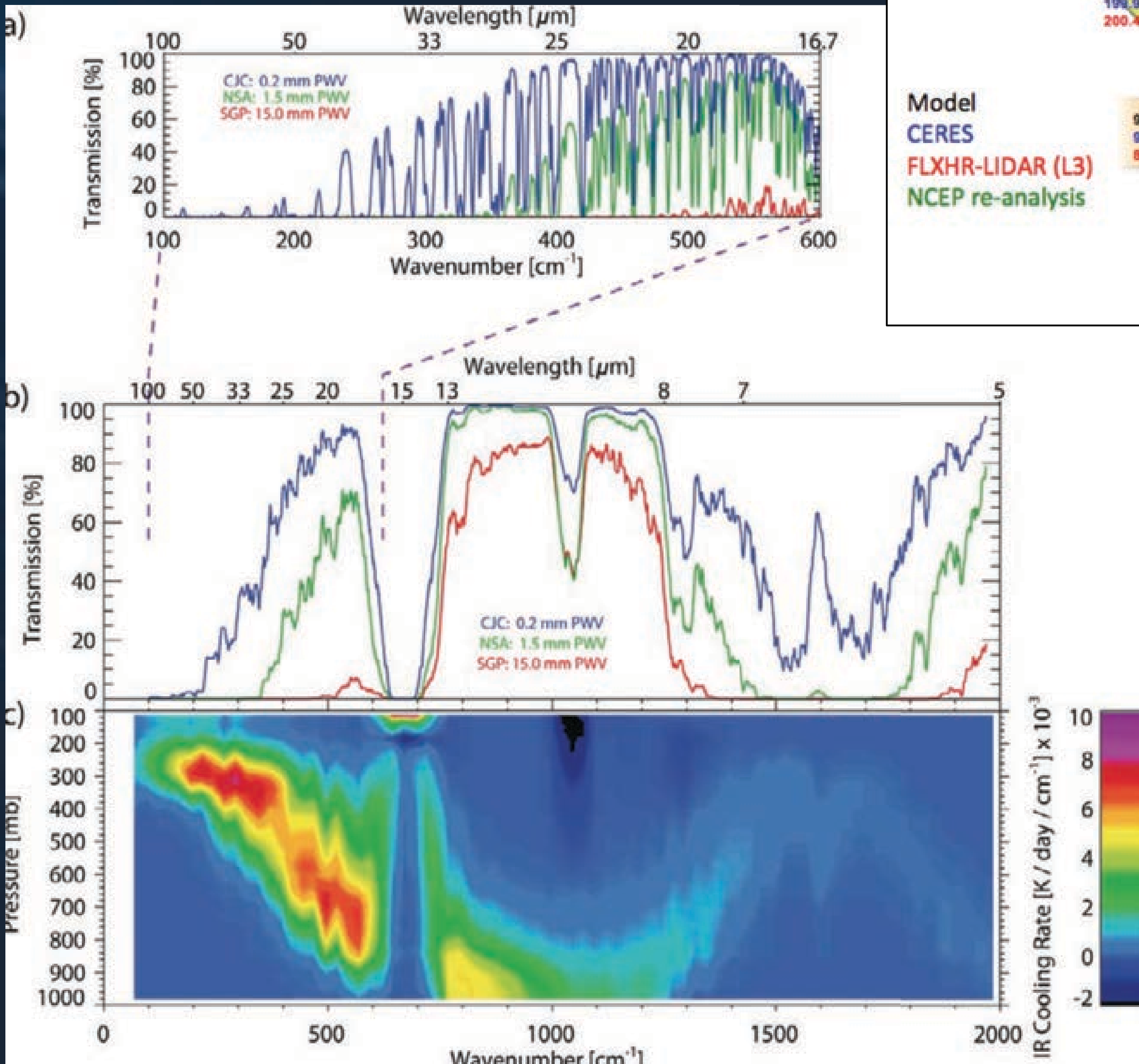


Takahashi et al. 2015 (in prep)


ARM
cloud
drizzle
precip
cloud
drizzle
precip
Occurence [%]
Velocity [m/s]
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

Energy balance of Arctic





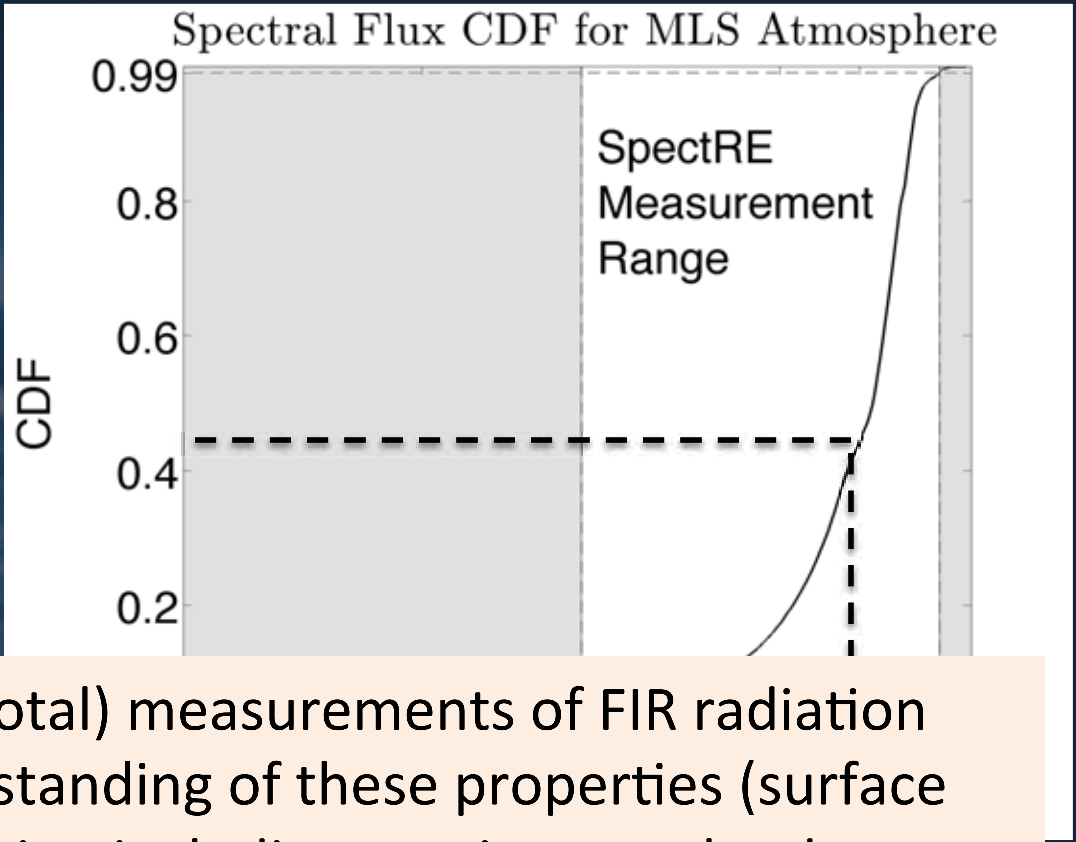
Far IR, λ> 15 μm

Mid IR, λ< 15 μm

Changes to the emission from cold, dry regions of the planet (polar regions, UT) are increasingly dominated by FIR.

Challenge 2: The Far IR (e.g. Harries et al., 2009;Rev. Geophys., 46, *RG4004, doi:* 10.1029/2007RG000233.)

45-59% of energy emitted from Earth occurs at FIR wavelengths – and a even greater fraction of the energy change associated with warming comes from FIR



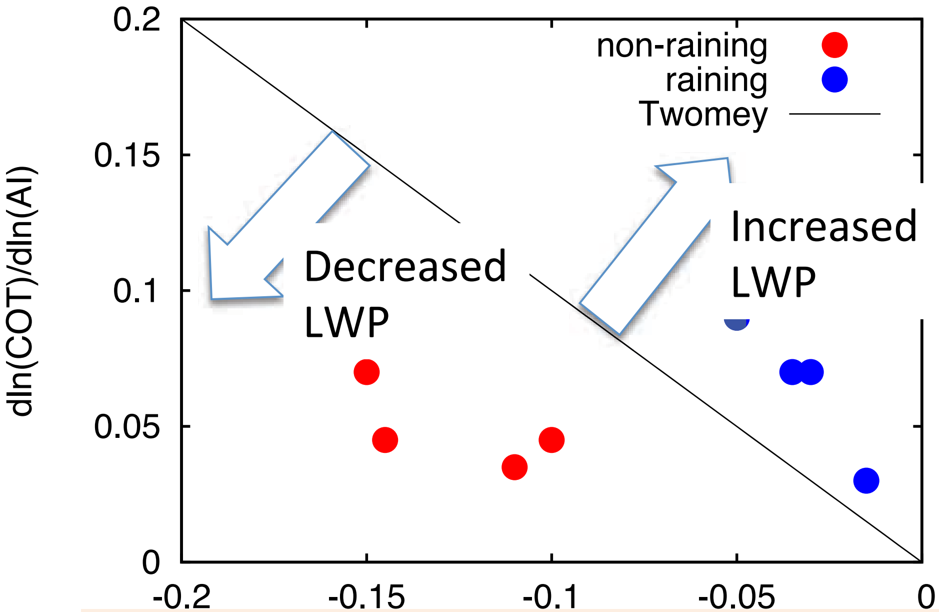
We have very few (anecdotal) measurements of FIR radiation properties and our understanding of these properties (surface emission, spectral absorption including continuum, cloud properties,…) is mostly untested. Simply extrapolating from MIR knowledge is problematic (e.g. Feldman et al., 2014)

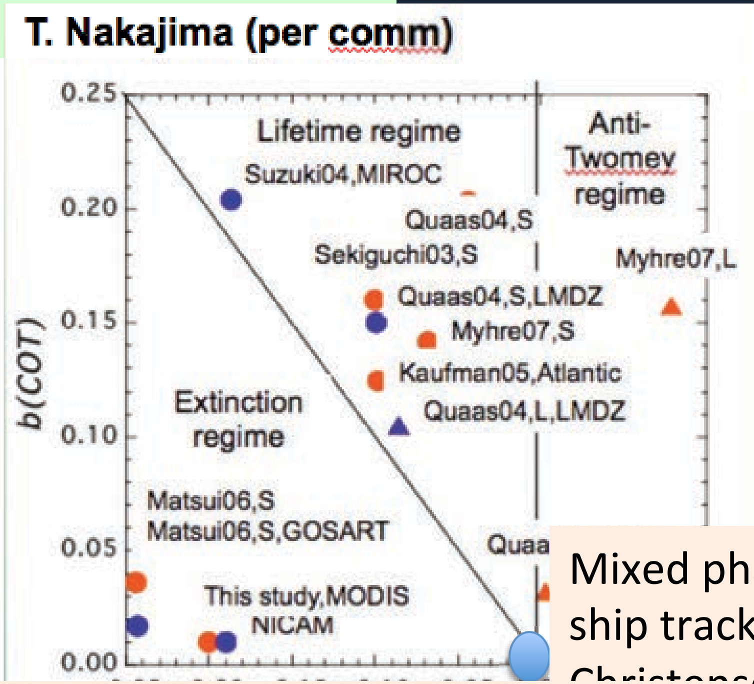
$$\Delta F \propto b(COT)\Delta \ln N_a \qquad \text{radiative response (forcing)}$$

$$b(COT) = -b(CDR) + b(LWP)$$

$$b(X) = \frac{d \ln X}{d \ln N_a}, X = (CDR, COT, LWP)$$

$$COT = \tau, CDR = r_e$$



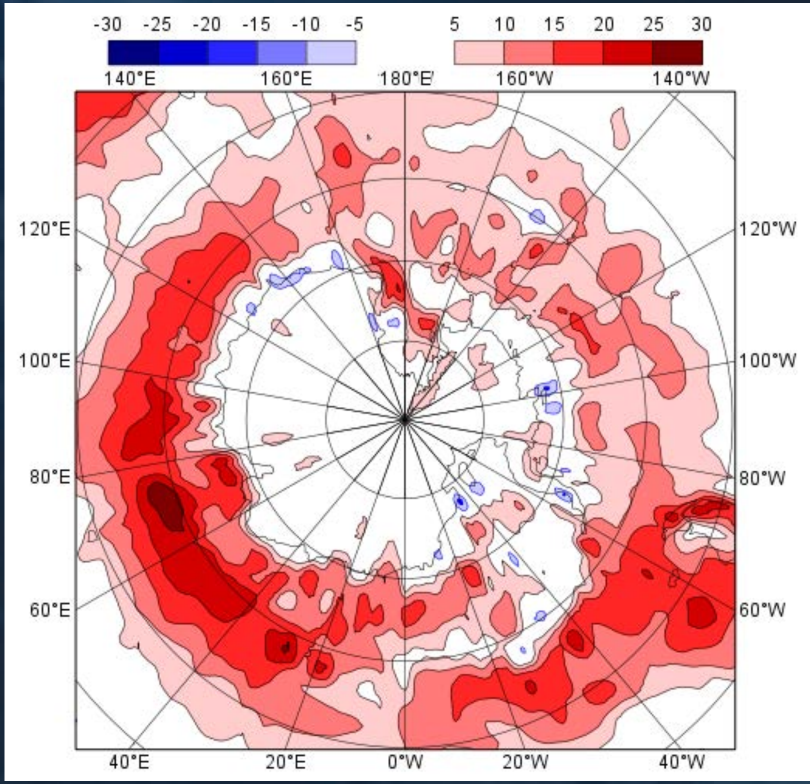


Mixed phase, ship track study Christensen et

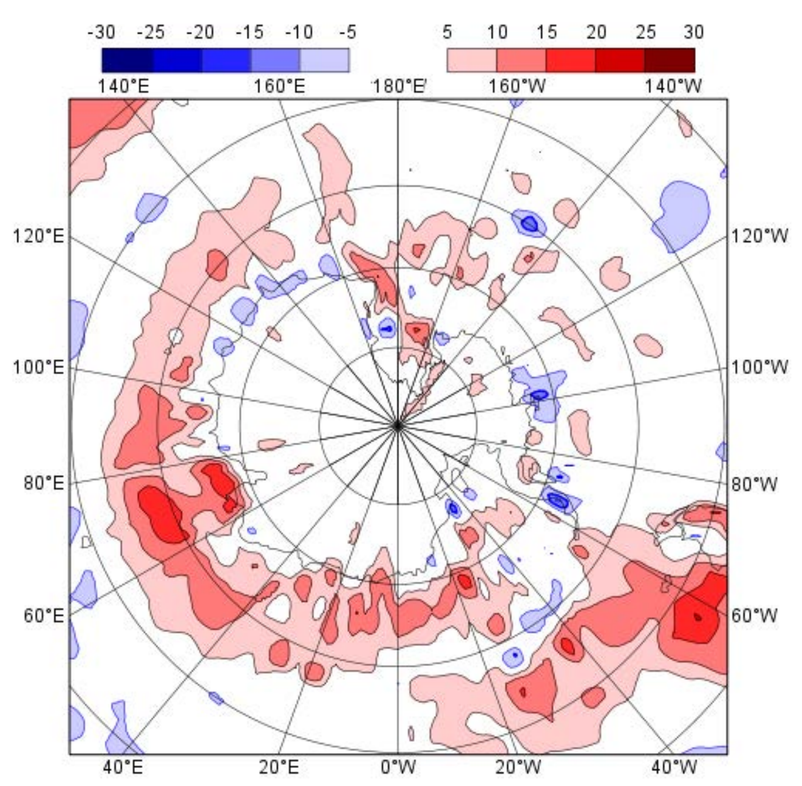
To reiterate, processes that govern the water budget of clouds determine the aerosol indirect effect & getting the cloud to rain transition right is a critical step toward getting these effects right, e.g. Suzuki et al., 2014; Golaz et al., 2013

Importance of supercooled liquid water for the ECMWF model Southern Ocean cloud-radiation bias

Annual mean net TOA SW difference, IFS (T159 "climate" resolution) free-running simulation versus CERES-EBAF



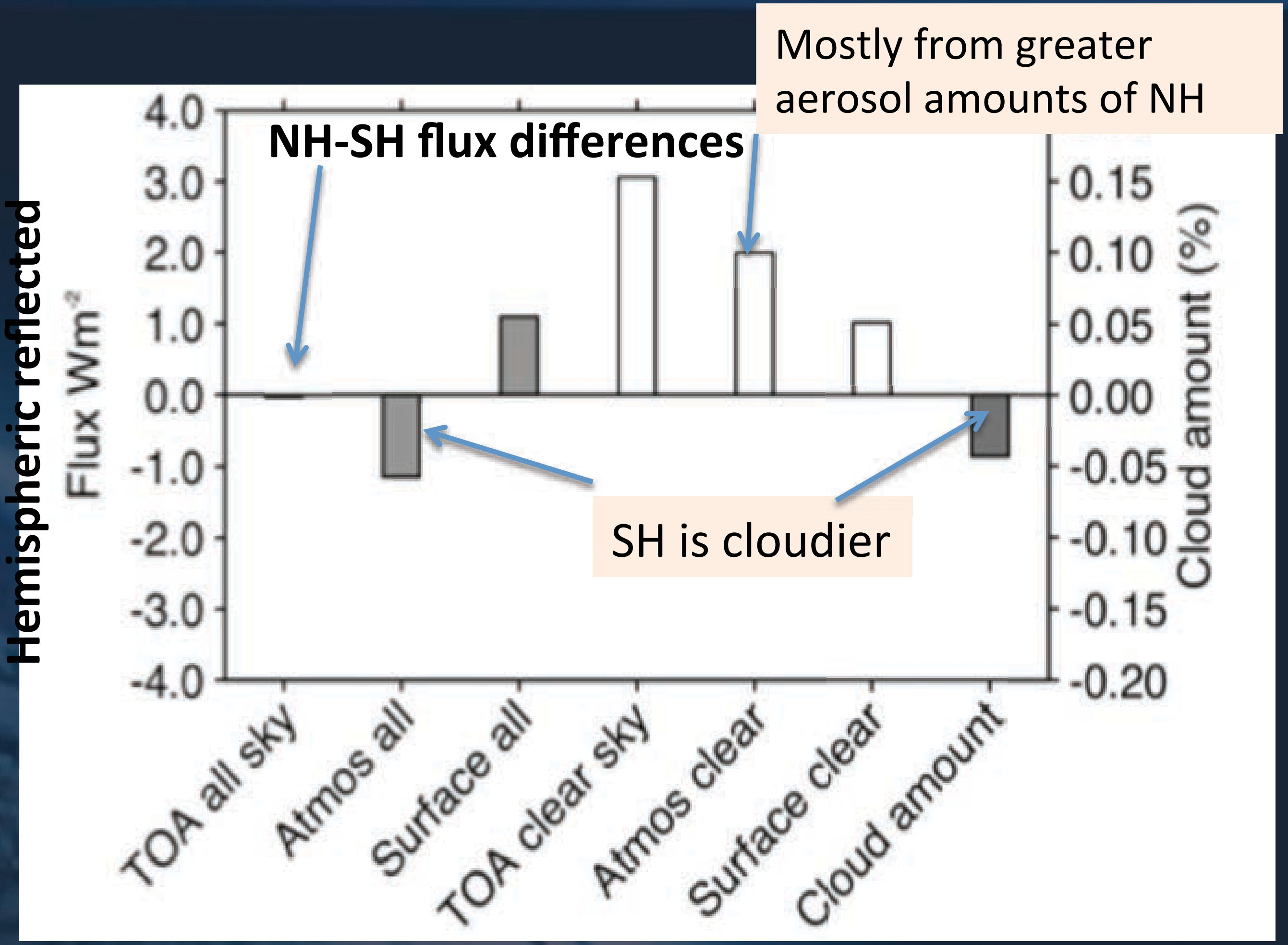
Current model version (40r1)



With increased supercooled liquid water production from "cold air" shallow/mid-level top convection

Richard Forbes, ECMWF

Challenge 6: Large scale controls – regional responses



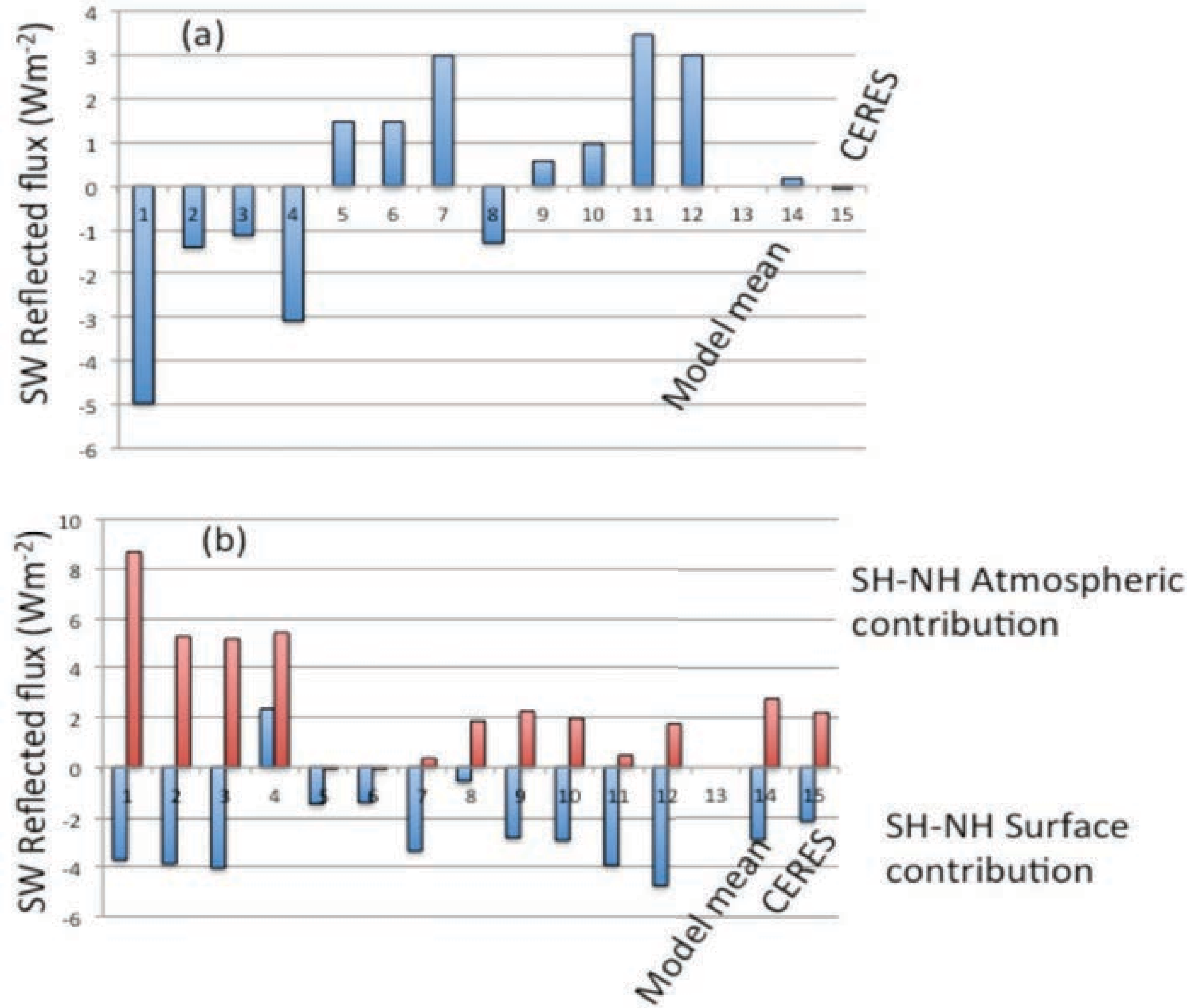
Although the hemispheres are structurally different, the reflected flux is identical (~0.1Wm^{-2}) : VonderHaar&Suomi, 1969; Voigt et al., 2012;Stephens et al., 2014

CMIP5 analysis

1) There is a general lack of hemispheric symmetry in models

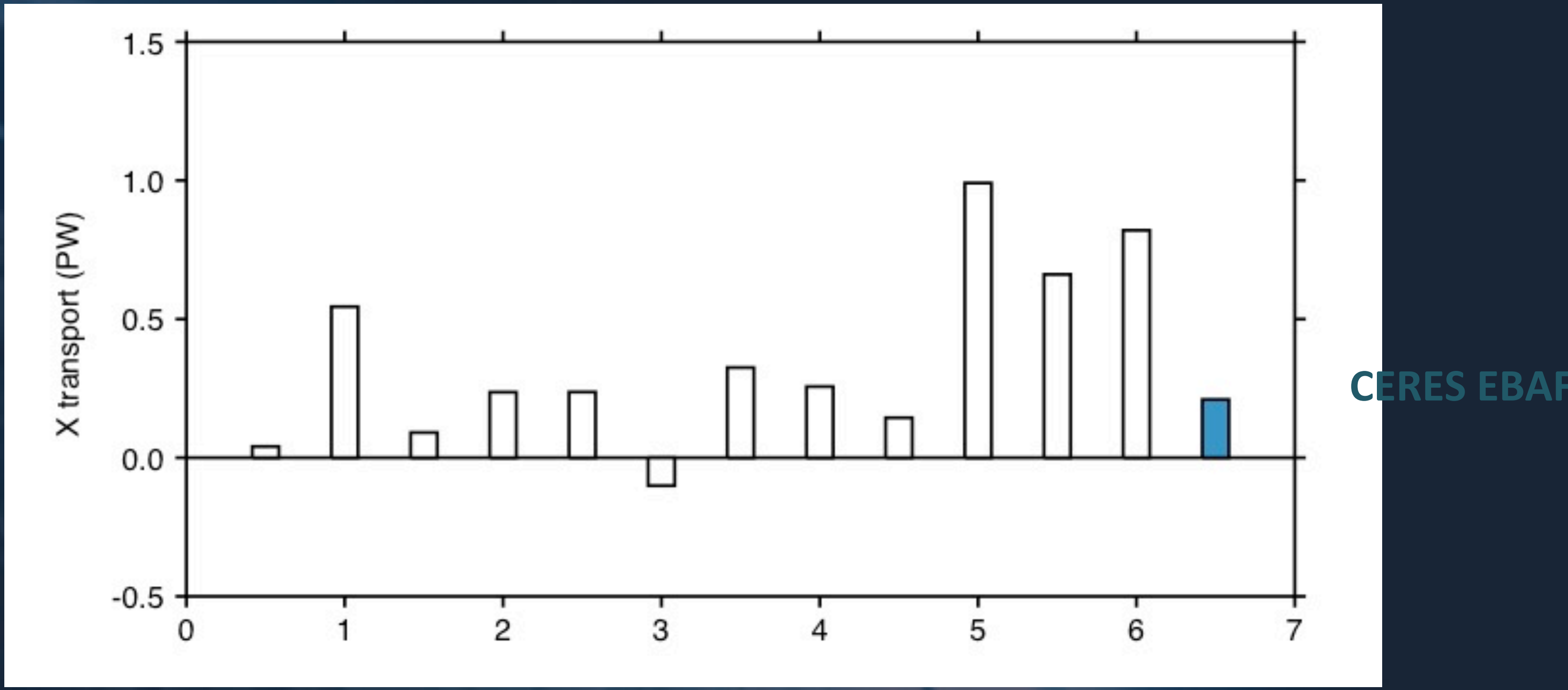
2) The reasons for this vary – in some models the SH clouds are too bright, others these clouds aren't bright enough & yet in others the surface is too bright

NH-SH



Stephens et al., 2014

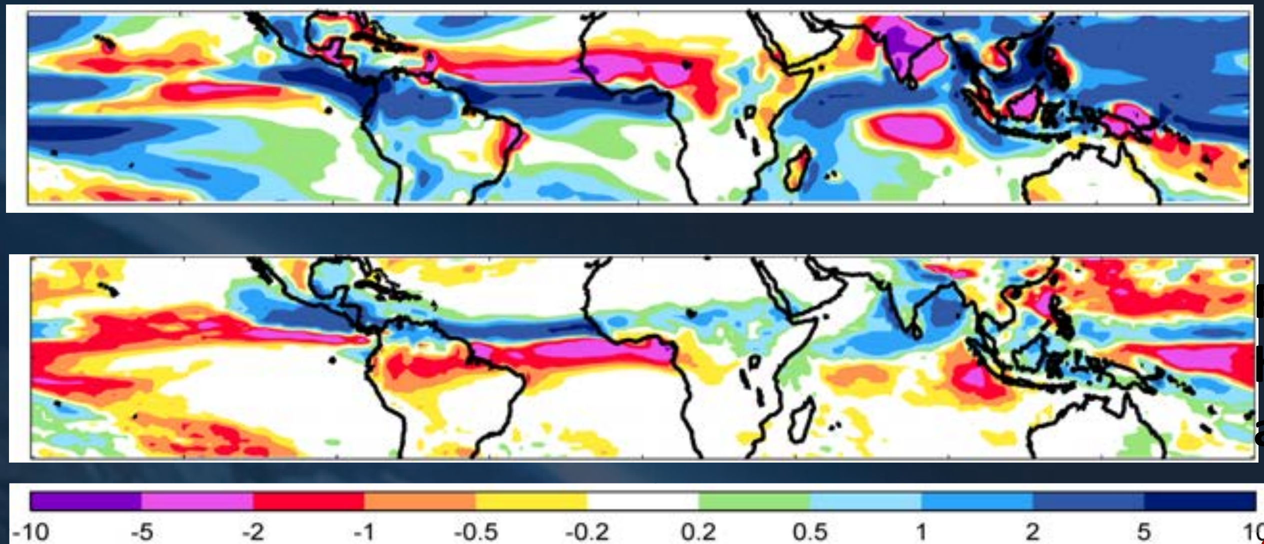
A time-mean symmetrical energy balance implies a time mean zero X equatorial heat transport



CMIP5 models

The observed slight hemispheric asymmetry (SH >NH ~ 0.6Wm-2 and mostly in OLR) implies a SH to NH net transport - the atmosphere pumps heat one way(NH-SH) and the oceans the other

Hemispheric Albedo Symmetry experiments
X transport changed from 0.8PW to 0.4PW



Precip bias HadGEM2-ES minus GPCP

Precip change when hemispheric albedos are equilibrated

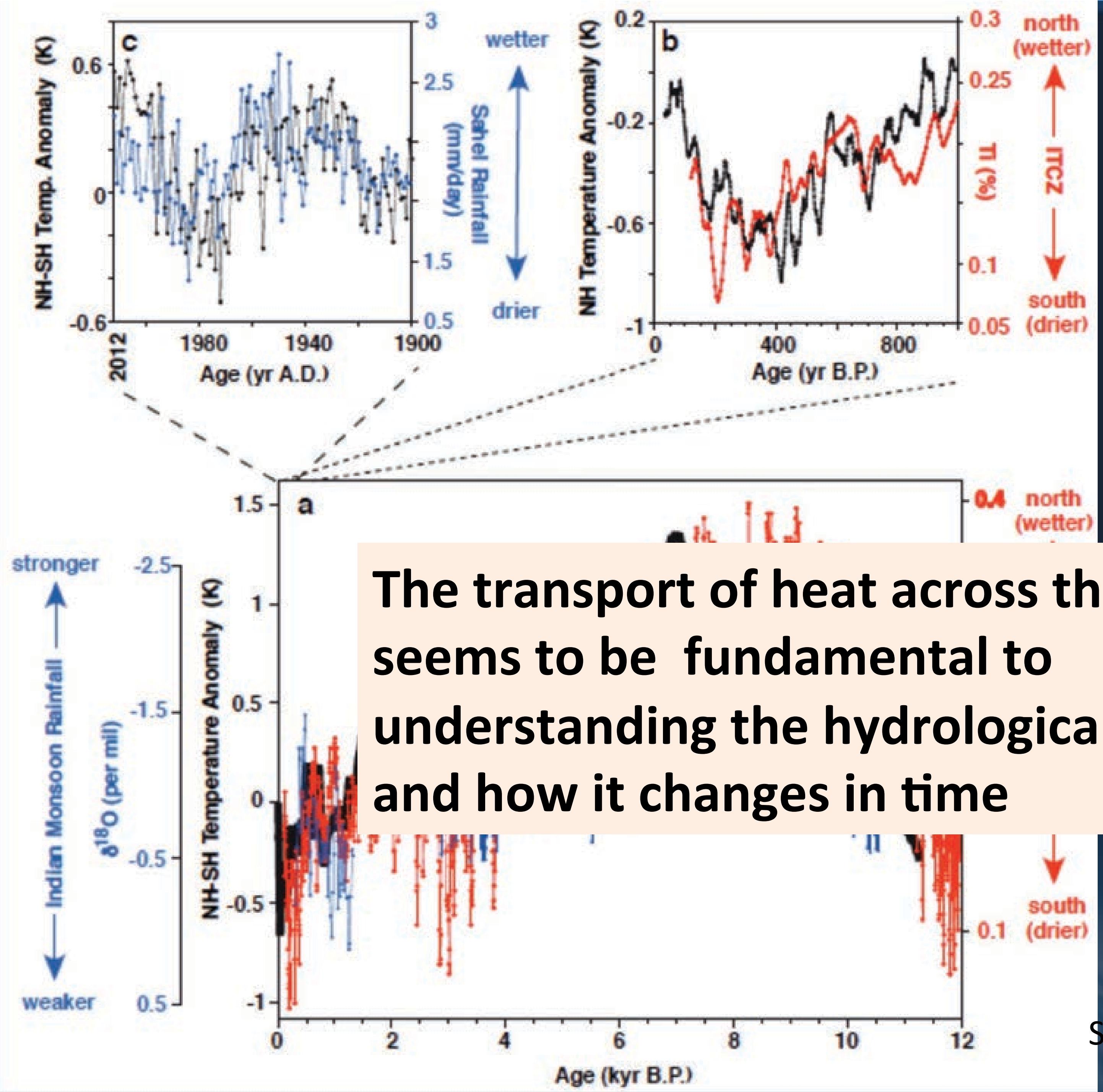
mm/day

Bias ratio

Key areas affected by monsoonal precipitation

Geographic Region	DJF	MAM	JJA	SON
North Africa	0.64	0.47	0.54	0.17
South Asia	1.05	2.59	0.67	0.70
Amazonia	0.86	0.90	0.73	0.72
South East Asia	1.17	0.35	0.80	0.96

Haywood et al., 2014

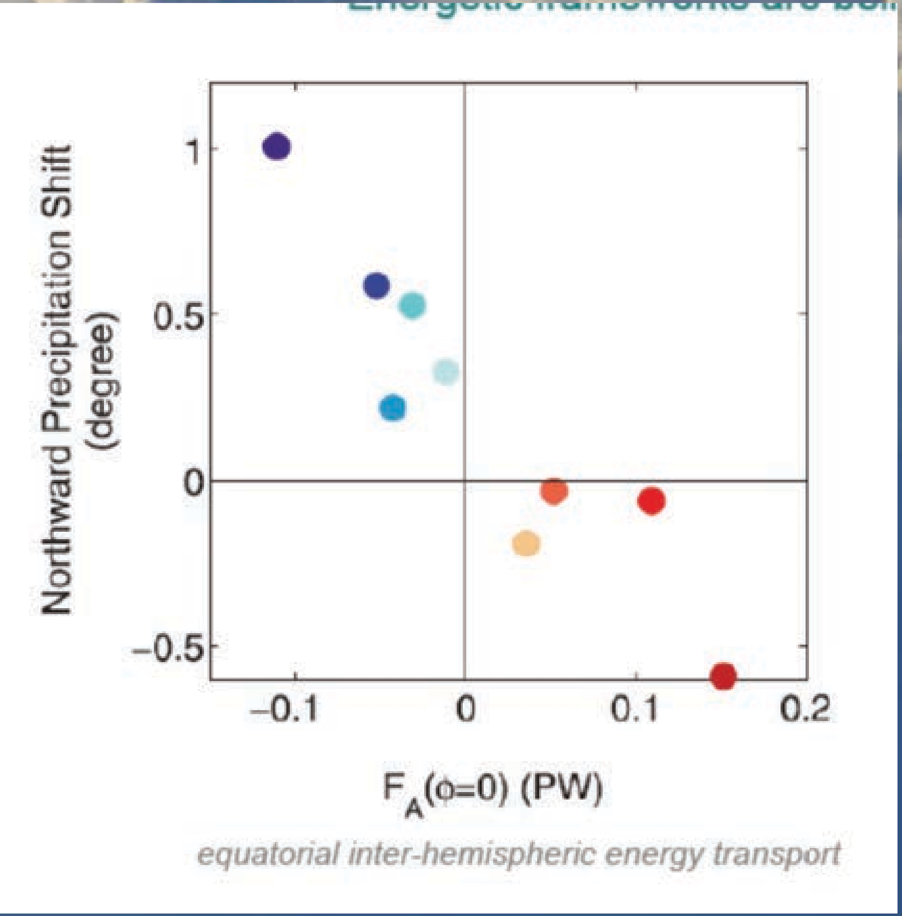


The transport of heat across the equator seems to be fundamental to understanding the hydrological cycle and how it changes in time

Schneider et al., 2014

A grand challenge: CONVECTION

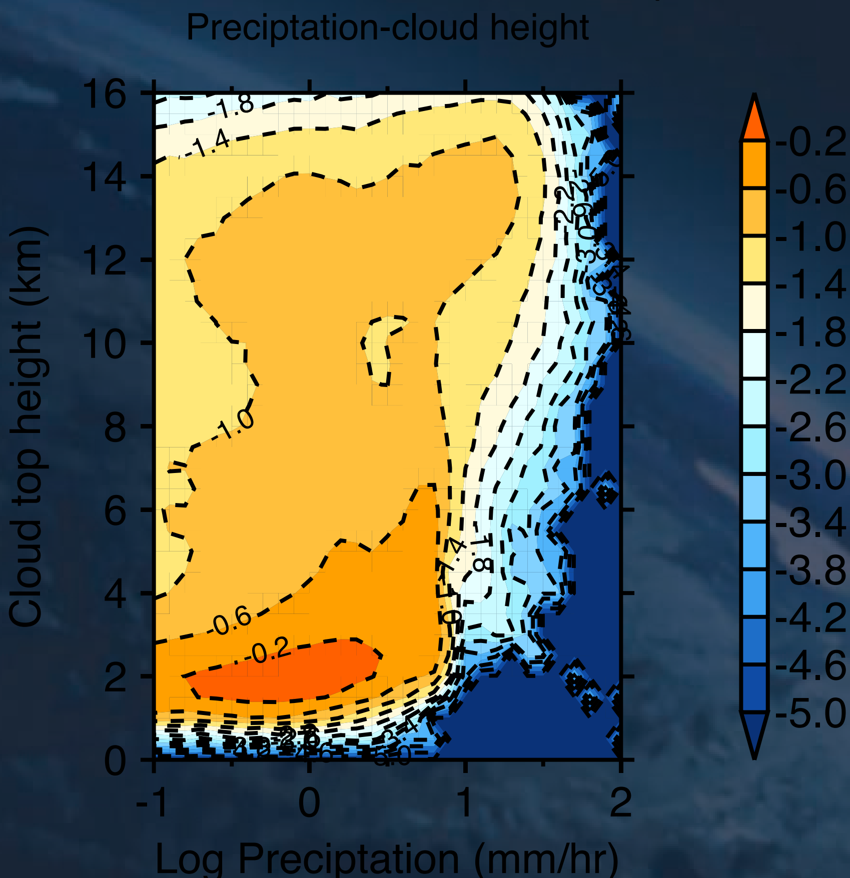
The WCRP clouds/climate GC questions
Q1: How will storm tracks change in the future?
Q2: What controls the position and strength of tropical convergence zones?
Q3: Is convective aggregation important for climate?
Q4: How does convection contribute to cloud feedbacks?



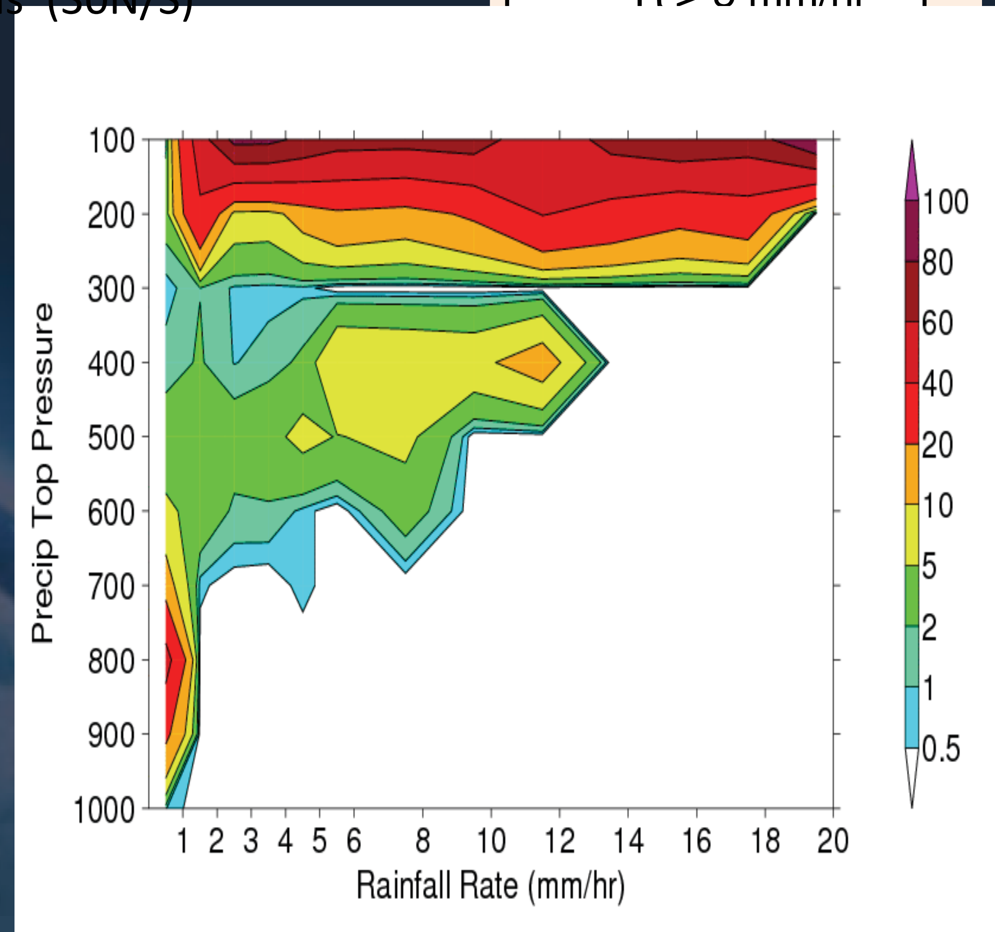
Kang et al., 2009

Work in progress with R. Forbes, ECMWF

Tropical oceans (30N/S)



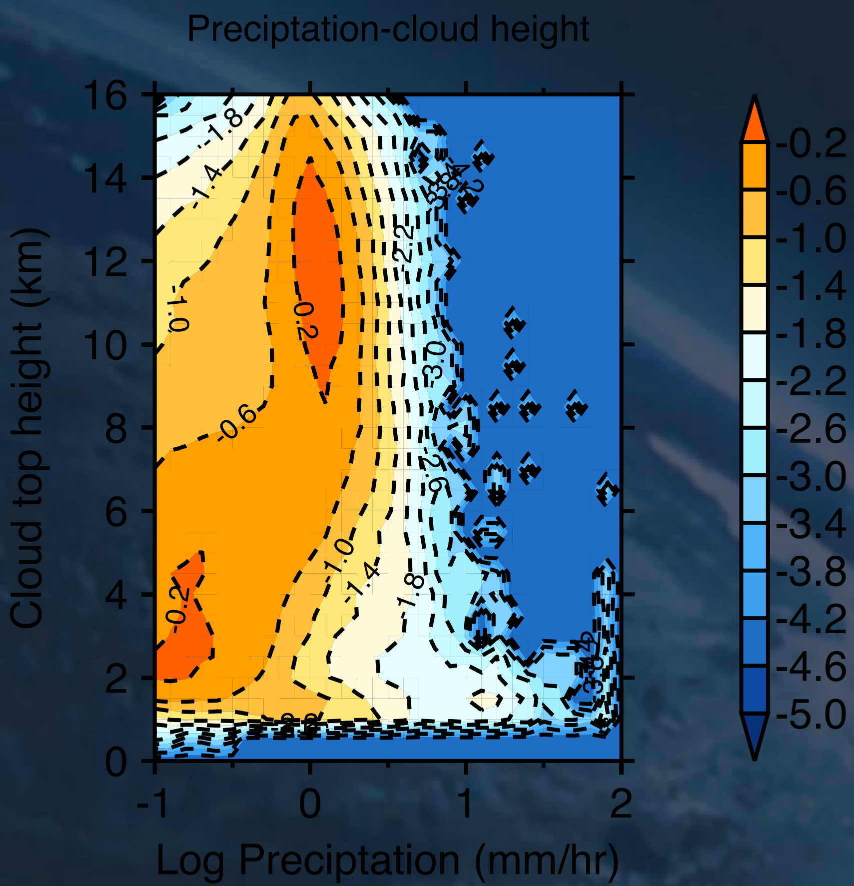
R > 5 mm/hr

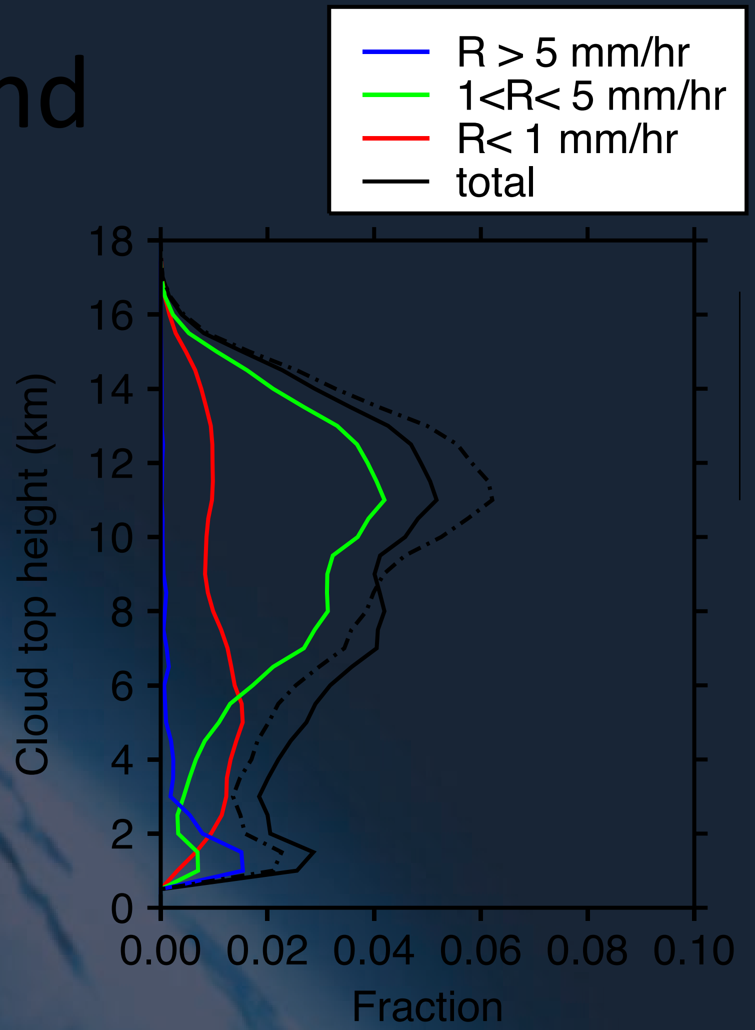


of total
accumu

48% of total annual accumlated precip comes from clouds with tops < 8km

Tropical land





Closing Remarks:

Other related challenges :

- **Observations, convection, snowfall**
- **Models - Higher resolution & convective-resolving**
- **Observing, quantifying and understanding extremes**

The previous generation was greatly concerned with the dynamics of pressure systems and talked about highs and lows. Today we have not lost interest in these systems but we tend to look upon them as circulation systems. This change in attitude has led to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems.

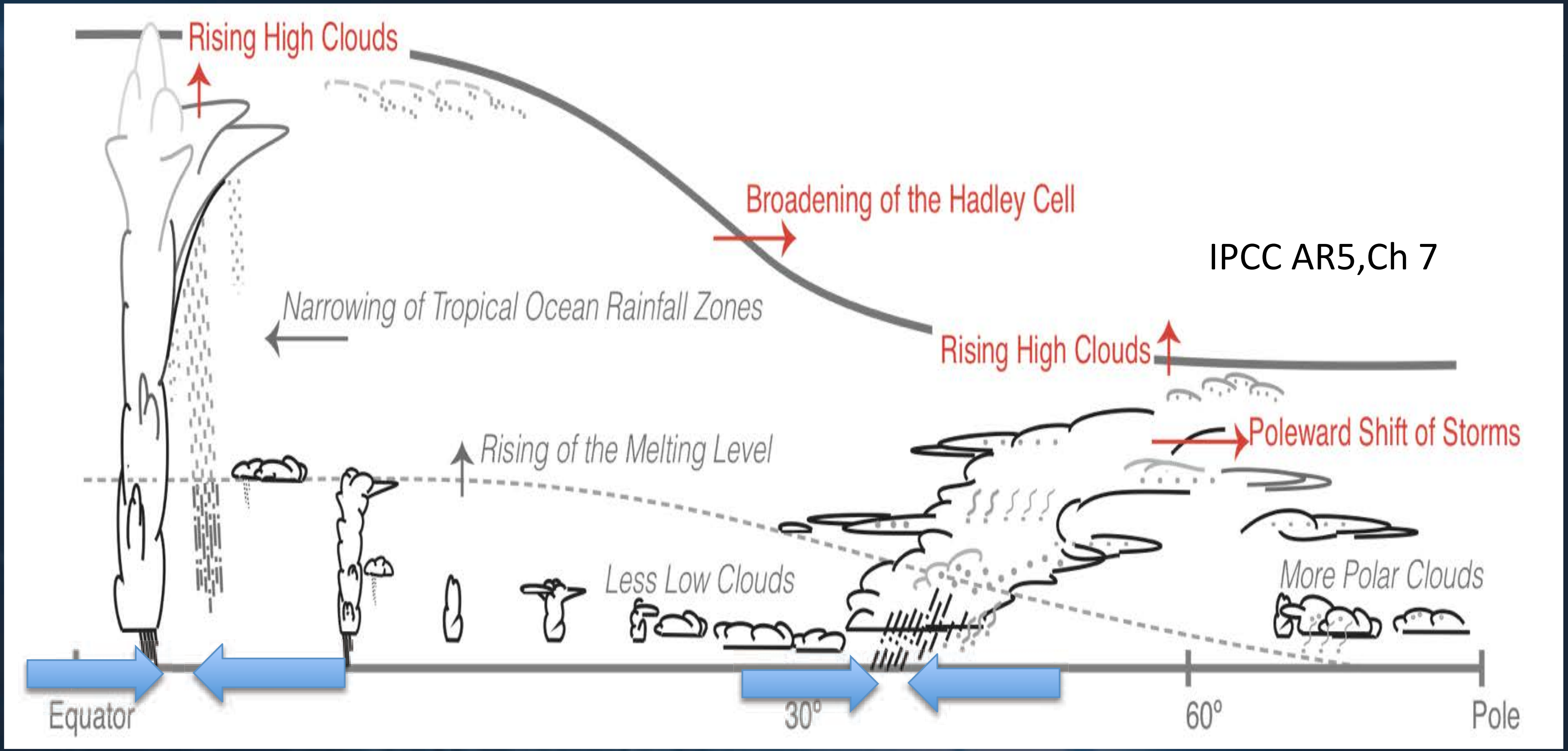
Our fundamental challenge is to build a quantitative understanding of these water systems and their interactions within the broader Earth system

Lorenz, 1970.

Outline:

- Global -Energetic controls on precipitation
- Regional - wet wetter/dry drier
- Storm-scale –superadiabatic
- Cloud radiation/convection/precipitation feedbacks
- Upper tropospheric moistening and the SuperGreenhouse Effect

2) Regional changes: The wet wetter and dry drier (WWDD) paradigm



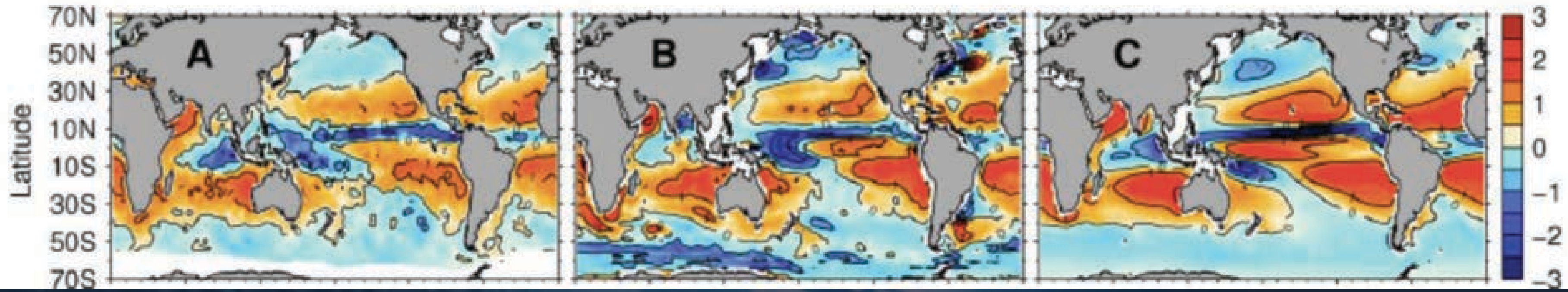
$\mathrm{q} \bullet \nabla \mathrm{v}$ $\mathrm{q} \bullet \nabla \mathrm{v}$

$$\frac{1}{q}\frac{\Delta q}{\Delta t} \sim 7\% / K$$

Fundamental question; are regional changes in precipitation fundamentally determined by a combination of C-C and circulation shifts and are the latter predictable?

Oceans

Changes to the saltiness of the oceans supports the notion that wet areas get wetter and the dry areas drier. Is this wetting merely following water vapor changes within main convergence zones?



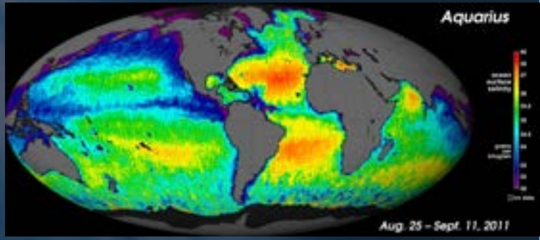
Evaporation –minus precipitation

Salinity

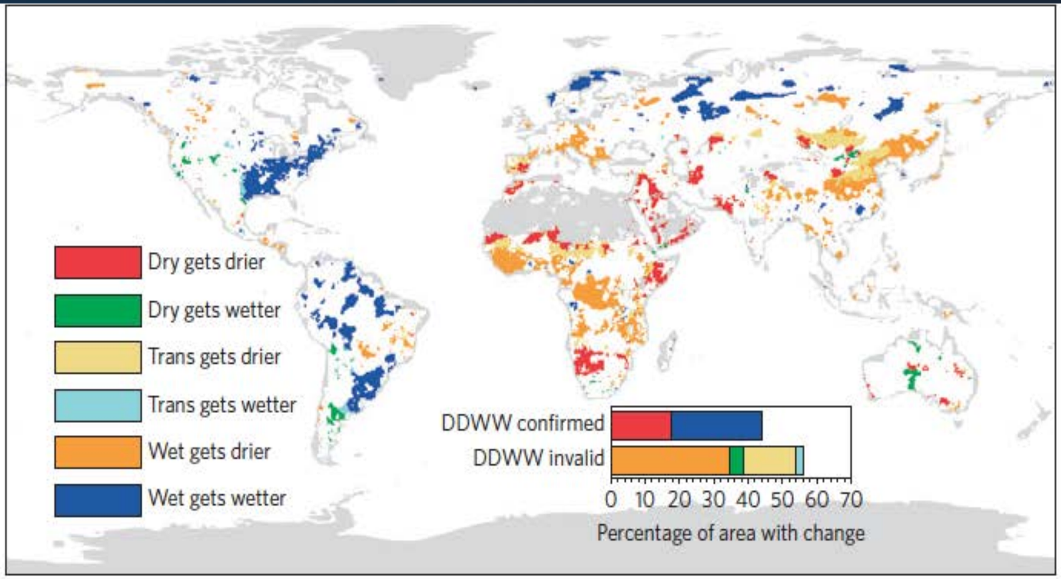
Durack et al. 2011
Change in Salinity over 50 years

These look a like

First global map of salinity from Aquarius, Launched in 2011



Wet wetter/dry drier is far too simplistic a description of water change



(Greve et al. 2014, Nature Geoscience)

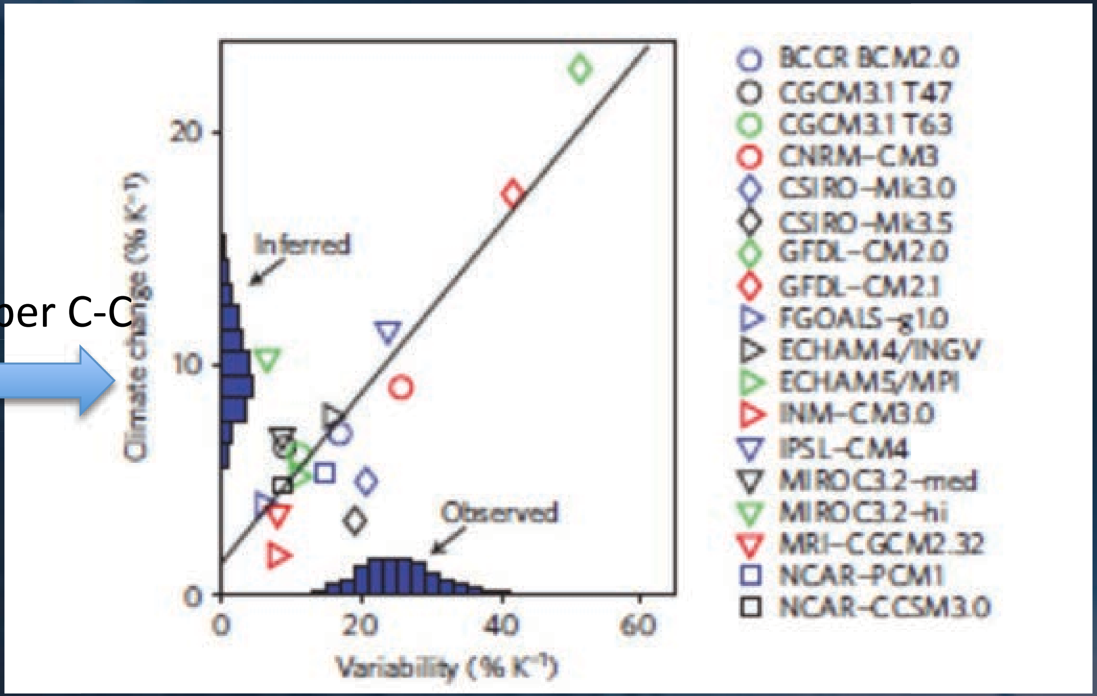
Assessment of changes in drought over land (comparison of 1948-1968 and 1985-2005 periods, annual changes)

4 P datasets, 11 Ep datasets, 7 E datasets

Few regions with robust changes
No clear support for "dry gets drier, wet gets wetter" paradigm

Ocean trends apparently do not apply on land

Super CC



Super C-C

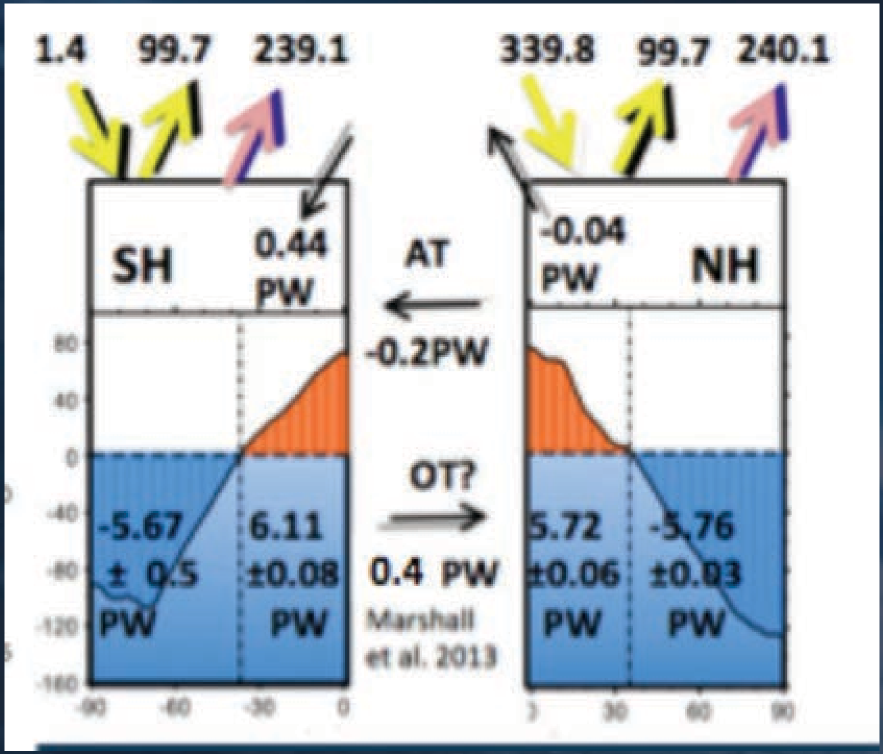
OGorman, 2012

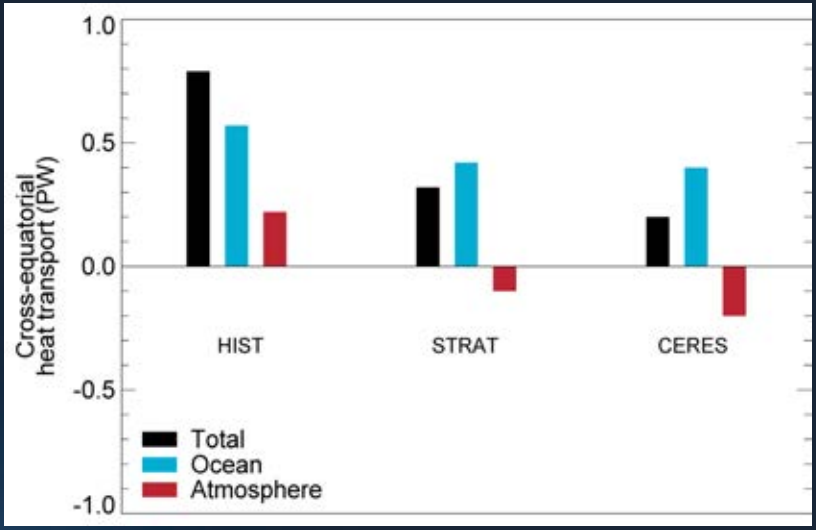
Tropical precipitation changes due to climate variability is a surrogate for precip changes under climate change.

Precipitation extremes are super CC, also Kendon et al., 2014

The hemispheric balance/imbalance and the main tropical rainbelts

Observed hemispheric, annual mean radiation balance



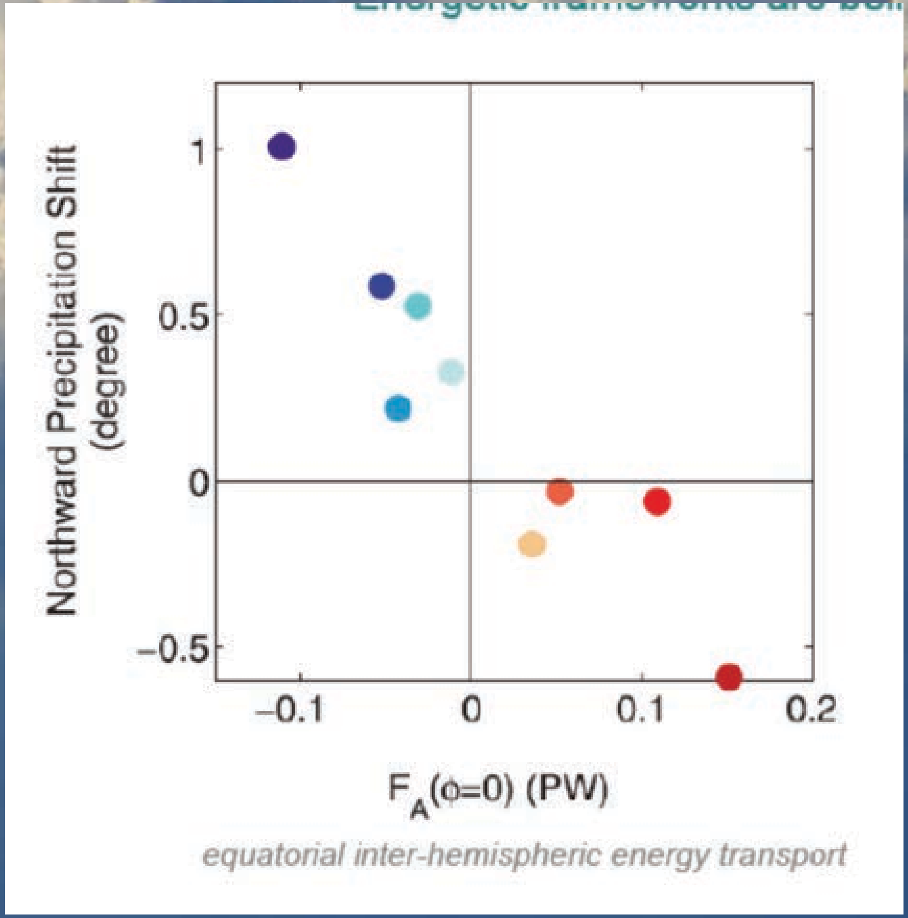


Model expts with HadGEM, Haywood et al., 2015

The radiation (im)balance of hemispheres fundamentally sets the cross equatorial transport of heat (and moisture) that influence the tropical rain belts

A grand challenge: CONVECTION

The WCRP clouds/climate GC questions
Q1: How will storm tracks change in the future?
Q2: What controls the position and strength of tropical convergence zones?
Q3: Is convective aggregation important for climate?
Q4: How does convection contribute to cloud feedbacks?



Kang et al., 2009

Two concepts Clouds -radiation → convection feedbacks

Differential heating/cooling: I horizintal

Gray 1973

(i) Disturbed undisturbed radiative heating; Gray and Jacobsen, 1977; Raymond, 2000; Mapes, 2002

Think of this as a self-sustaining of the convectively disturbed regions and reinforcing of the clear sky – a positive feedback (+)

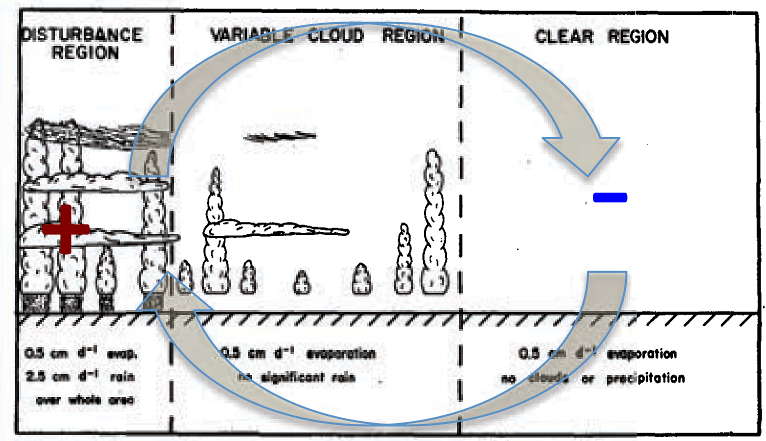
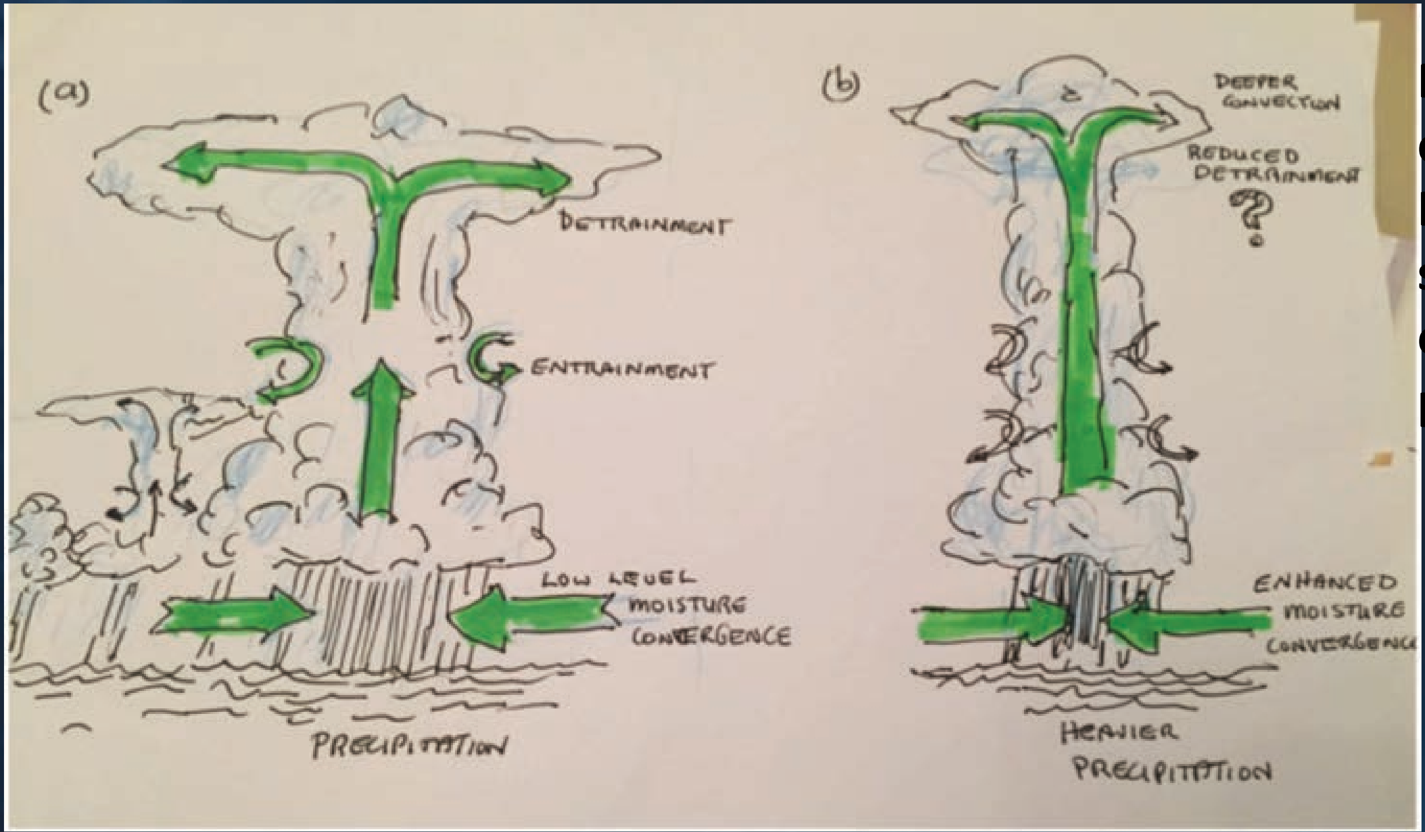


FIG. 2. Schematic of cloudiness in the cloud cluster disturbance and its environment.

Differential heating/cooling: II vertical

(i) Destabilization by strong cloud top radiative cooling – Webster and Stephens, 1980; Tao 1996; Xu and Randall, 1995 (positive feedback)

(ii) Stabilization by upper tropospheric heating of cirrus anvils – Fu et al., 1995; Stephens et al., 2003; Slingo and Slingo, 1988;Lebsock et al., 2010 (negative feedback)



Reduced high cloud???- (IRIS), less IR heating, strengthened convection and precipitation

Present

Future

Moisture Supply 7%/K

Precipitation super CC; >7%/K?

Climate sensitivity and the IRIS effect

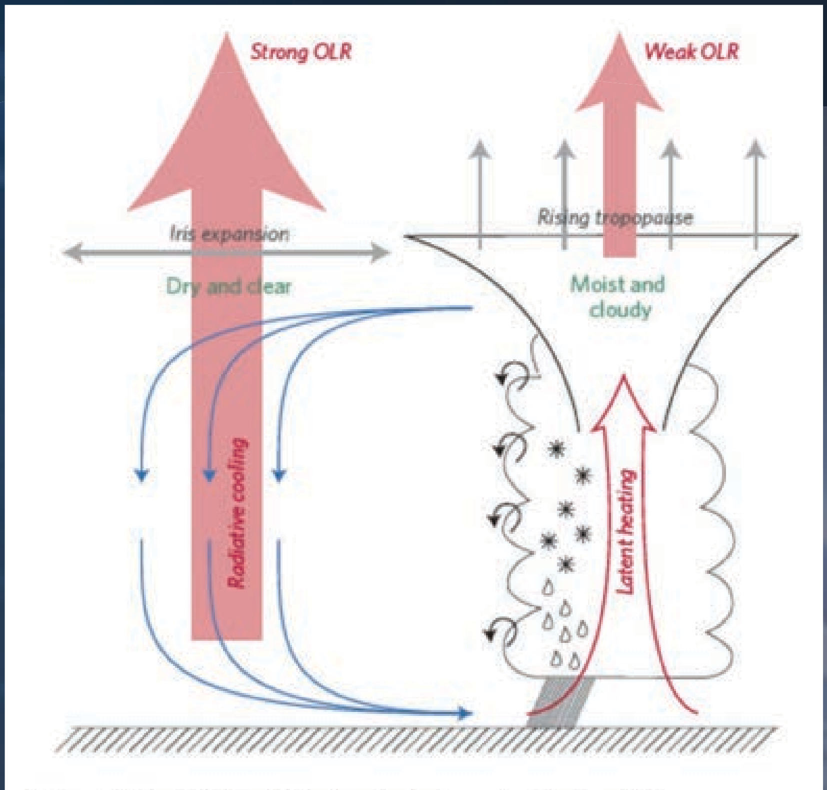
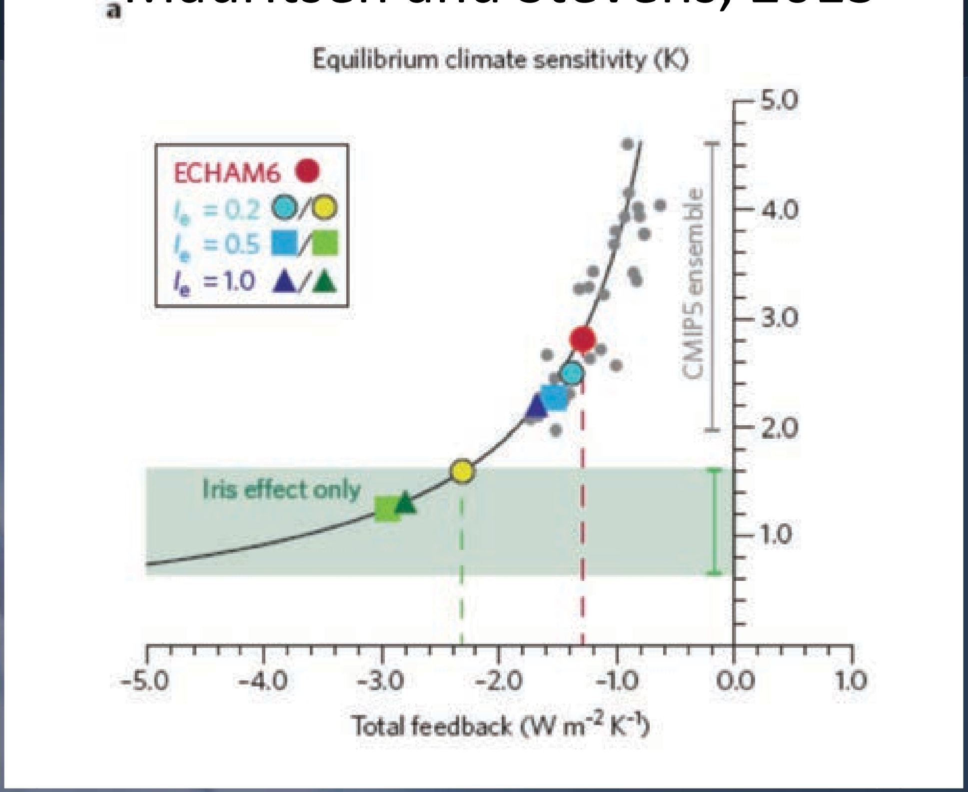


Figure 1 | Illustration of the tropical atmospheric circulation.

Mauritsen and Stevens, 2015



Clearly the convectively produced high clouds can effect both the climate and hydrological sensitivities – increasing strength of the IRIS effect lowers the ECS but enhances the hydrological sensitivitiy

GEWEX PROES UTCC (Stubenrauch (LMD and Stephens)

1) Scientific Motivation: How does convection affect UTC ? And how does UTC affect convection?

2) Goal: To understand the relation between convection, UTC and the radiative heating , & provide observational based metrics of this relationship as a way of evaluating detrainment processes in models

relate convective strength to properties of high clouds
Test hypothesis that majority of UT heating is from thinner clouds

Tools & steps:

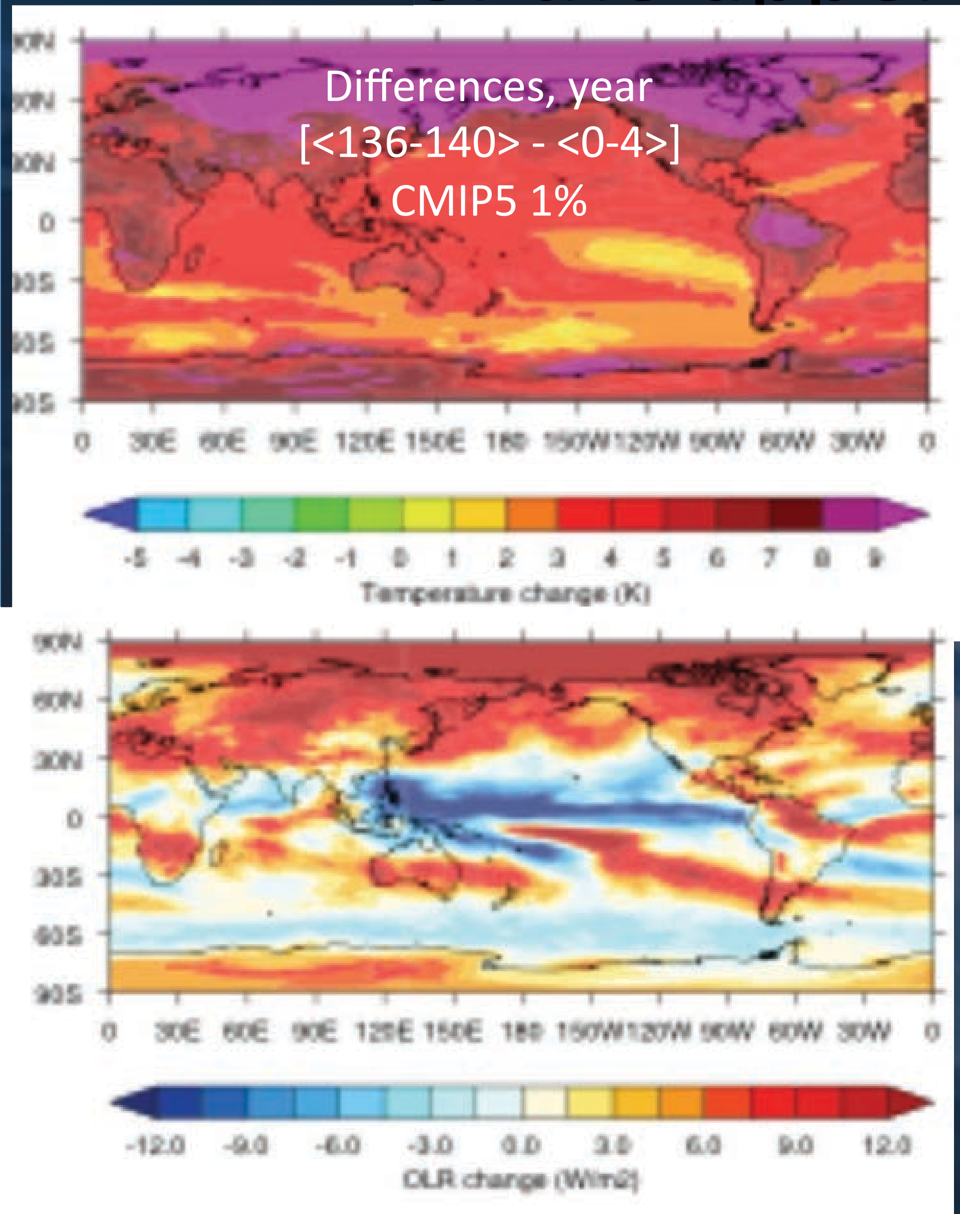
- **Develop/study proxies of convective strength from the A-Train** (e.g. colocate **CloudSat** *(Takahashi & Luo 2012, 2014)*, **AIRS**)
- **determine horizontal extent & cloud types** (convect core, CiAnvil, thin Ci) **from AIRS, IASI**

& study multi-layering from CALIPSO-CloudSat per cloud type

study life cycle of convective systems (MeghaTropiques, geostationary, AIRS-IASI)

GEWEX UTCC PROES (Process Evaluation Study) -> 1. meeting 16 Nov 2015, Paris
(coord. Stubenrauch & Stephens)

Convection and the moistening of the upper troposphere

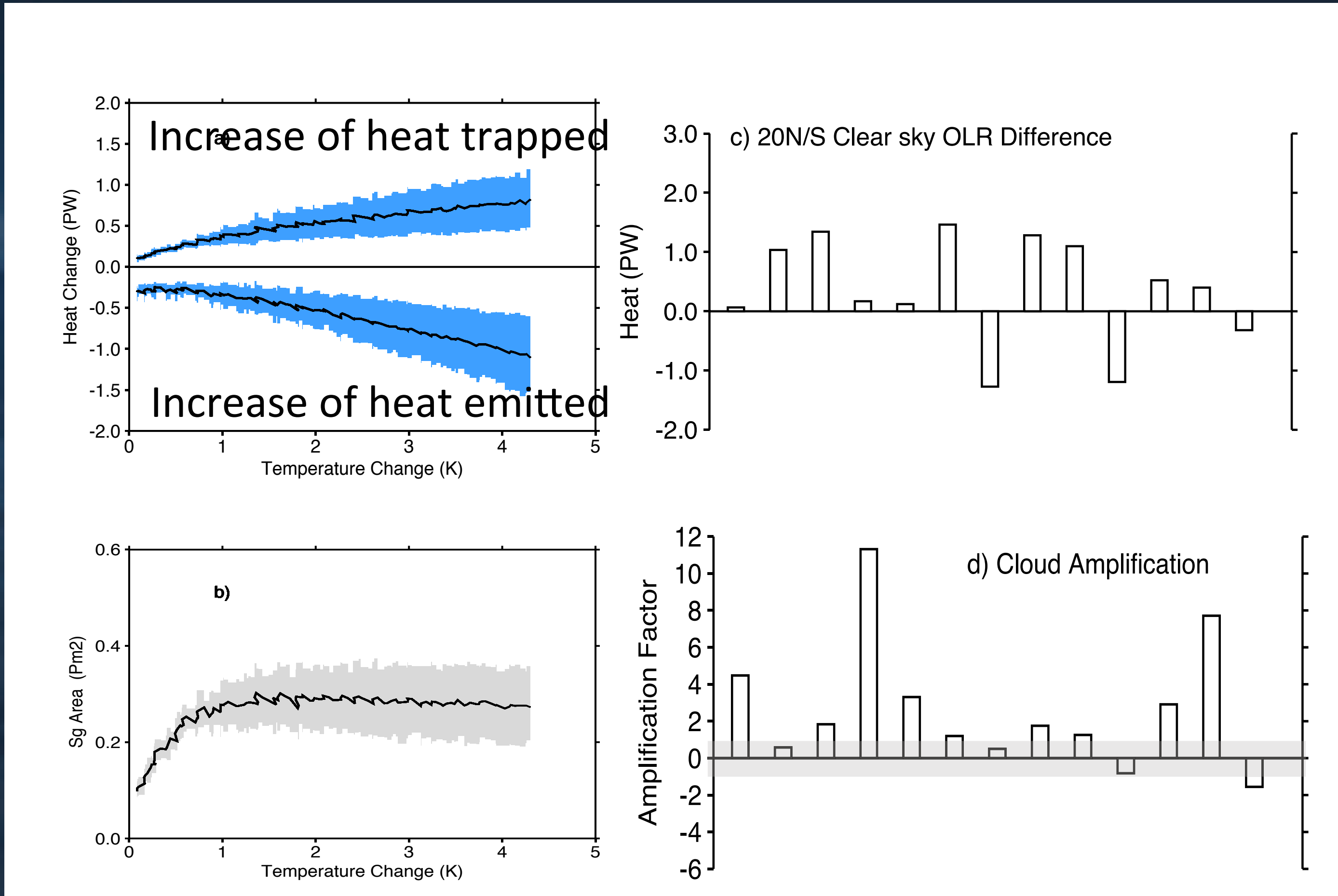


$$G = \sigma(SST)^4 - OLR$$

$$\frac{dSGE}{dSST} > 4\sigma SST^3$$

$$\frac{dOLR}{dSST} < 0$$

(e..g. Valero et al., 1997)



$$-\left[OLR_{end} - OLR_{begin} < 0\right]$$

$$-\left[\frac{OLR_{all,end} - OLR_{all,begin}}{OLR_{clr,end} - OLR_{clr,begin}}\right]$$

- Super greenhouse effect (SGE) is a term used here to refer to those regions of the planet that trap increasingly more heat than can be radiated to space as warming occurs.
- This places an onus on horizontal transport to move heat away from these regions in order to maintain a stable climate.
- The clear-sky SGE is a dominate source of heat build up in tropical latitudes in climate change experiments and is dominated by processes that moisten the low latitude upper troposphere associated with deep convection.
- the radiant energy exchange that defines it is strongly associated with emission in the far IR.

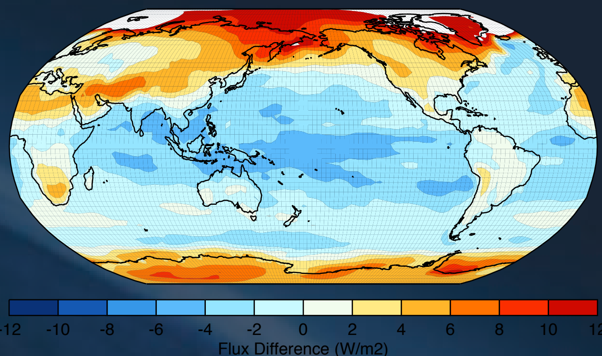
Summary

- Global -Energetic controls on precipitation & role of cloud radiative processes
- Regional - wet wetter/dry drier paradigm
- Storm-scale –superadiabatic
- Cloud radiation/convection/precipitation feedbacks involving high clouds (e.g. IRIS and other concepts) & the focus of the GEWEX PROES UTCC
- Upper tropospheric moistening by deep convection and enhanced heat trapping via the Super Greenhouse Effect

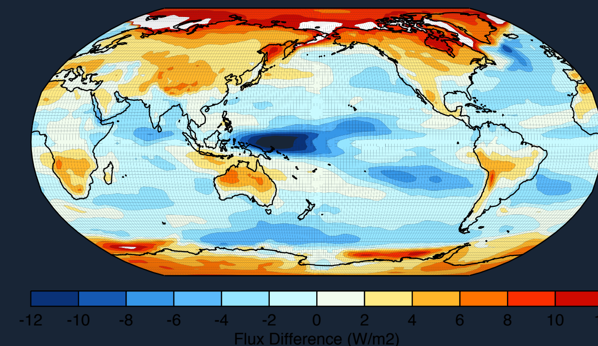
The SGE in CMIP5 1%/yr experiments
Clear-sky OLR differences [<136-140> - <0-4>]

CMIP5
1%/yr
experiments

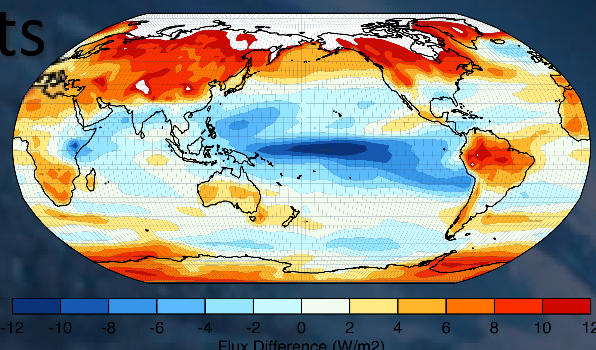
bcc



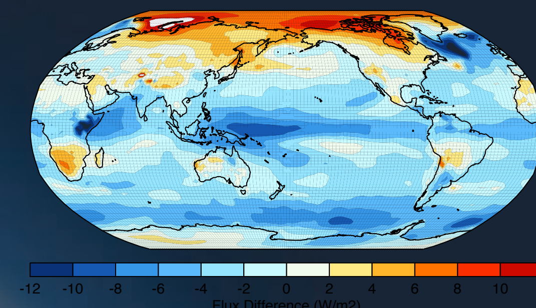
gfdl



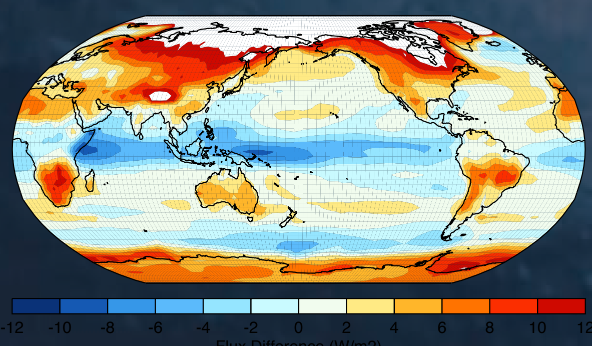
cnrncm5



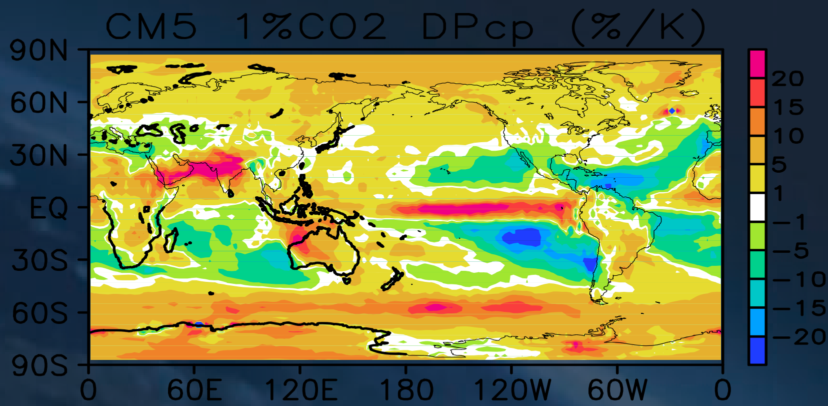
HadGEM

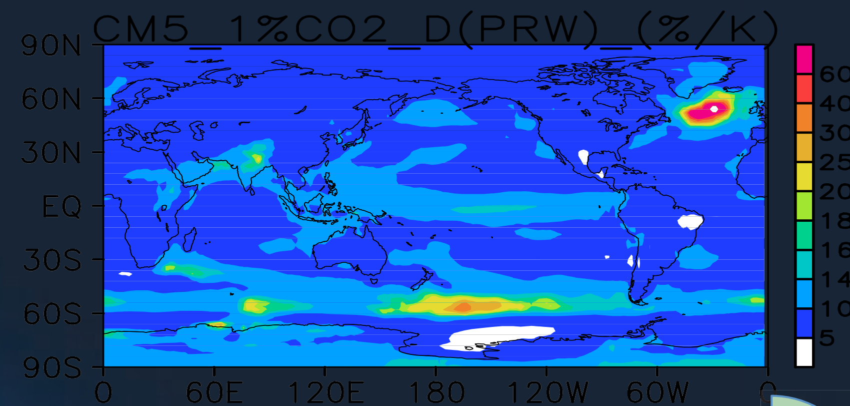


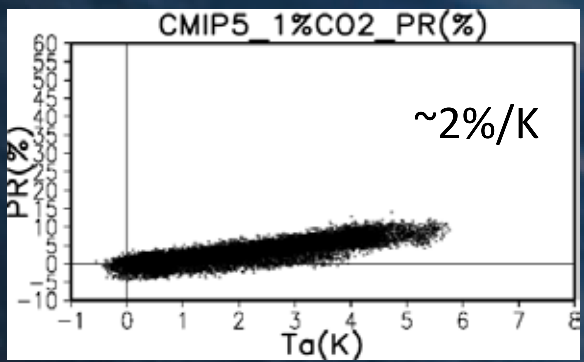
mpi

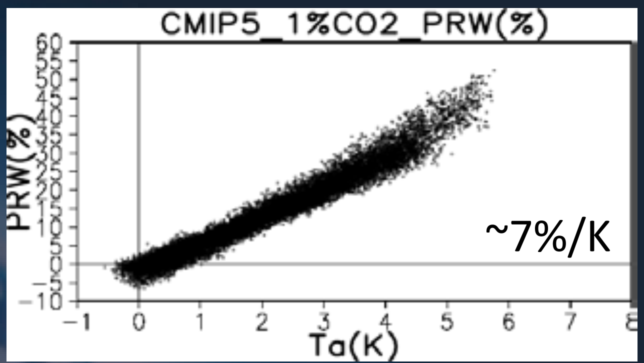


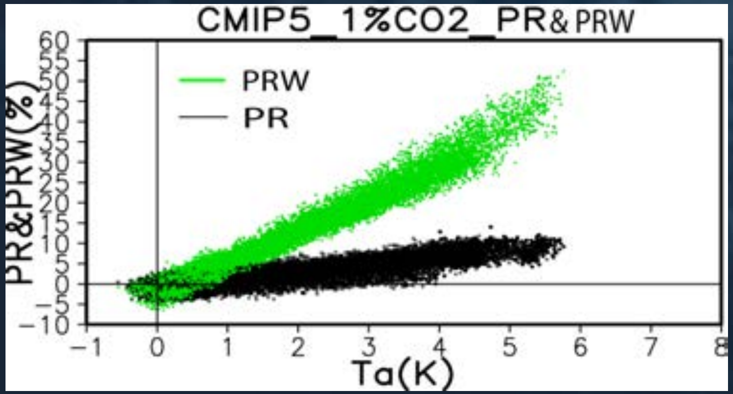
Here we consider the regions of SGE as where OLR decreases in a warming world. These regions aren't simply defined by a fixed SST threshold

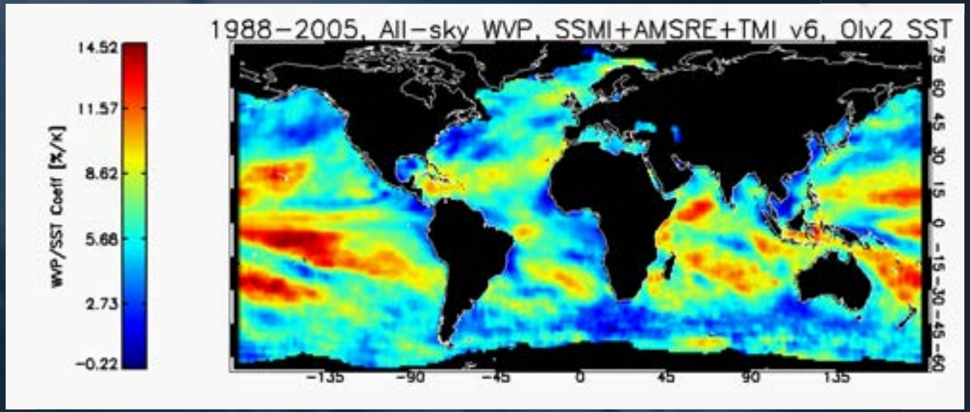

CM5 1%CO2 DPcp (%/K)
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
20
15
10
5
1
−1
−5
−10
−15
−20


CM5_1%CO2_D(PRW)_(%/K)
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
60
40
30
25
20
18
16
14
10
5


CMIP5_1%CO2_PR(%)
~2%/K
PR(%)
Ta(K)


CMIP5_1%CO2_PRW(%)
~7%/K
PRW(%)
Ta(K)


CMIP5_1%CO2_PR&PRW
PRW
PR
PR&PRW(%)
Ta(K)

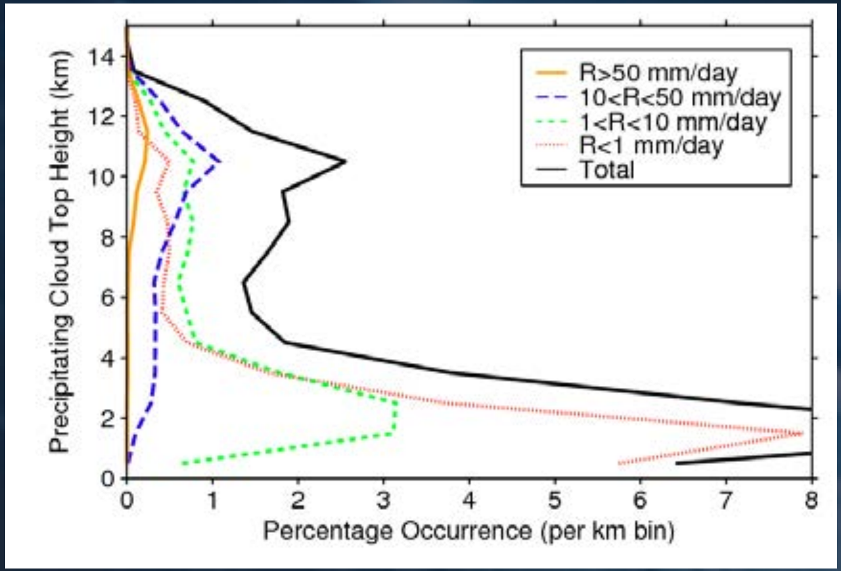

1988−2005, All−sky WVP, SSMI+AMSRE+TMI v6, OIv2 SST
WVP/SST Coeff [%/K]
14.52
11.57
8.62
5.68
2.73
−0.22

The Cloudy Nature of Southern Ocean Precipitation

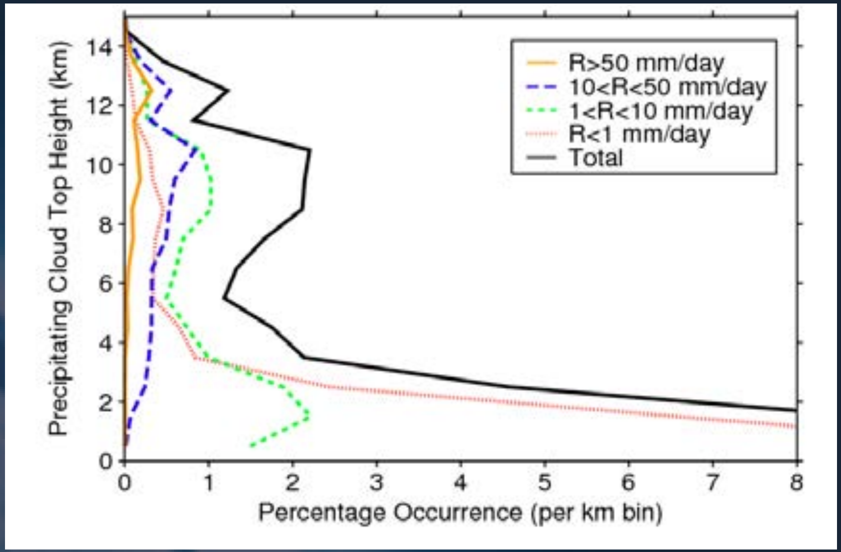
Graeme L Stephens (JPL)
Richard M Forbes (ECMWF)

Characterising Southern Ocean precipitation 30S-60S as a function of precipitating cloud top height

SH Winter



SH Summer

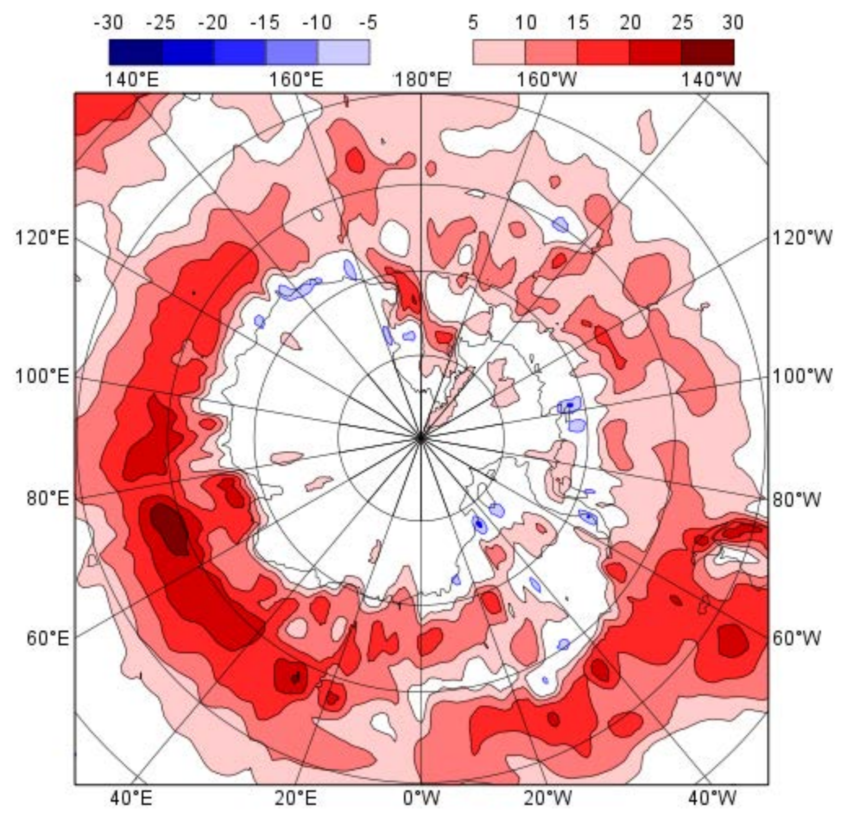


Radiation ↔ Cloud ↔ Precipitation

- Need to consider all aspects together
- Identifying systematic errors in one can lead to improvements in another
- Example of identifying supercooled liquid water bias in the ECMWF operational model analysis system, leading to reduction of long-standing SW radiation bias over the Southern Ocean for all time ranges (short-range forecasts to climate).

Southern Ocean solar radiation systematic error in the ECMWF IFS

Annual mean net TOA SW difference, IFS (T159 “climate” resolution)
1-year free-running simulation versus CERES-EBAF

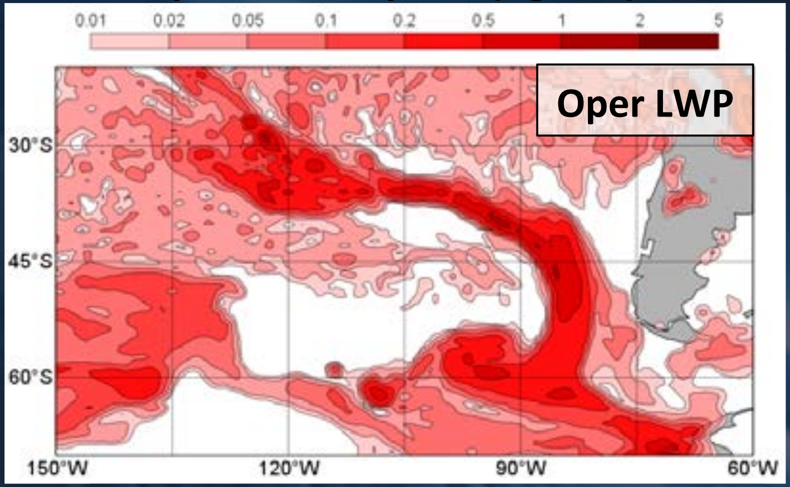


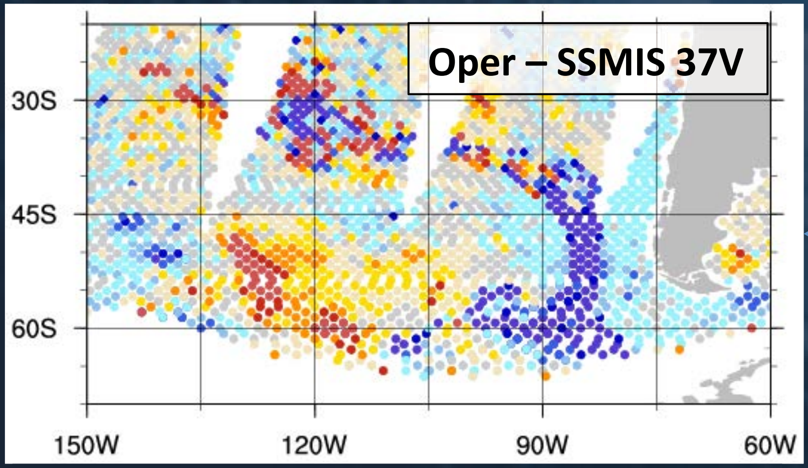
Significant top-of-atmosphere reflected shortwave radiation bias over the Southern Ocean (too little reflection) in the ECMWF IFS model (for all forecast times). Annual mean spatial average bias south of 50S about 10 Wm-2, with peak about 30Wm-2, and locally much larger in SH summer season (DJF)

Reducing supercooled liquid water systematic errors

Case study: Southern Ocean 24 Aug 2013

Operational ECMWF model liquid water path (kg m^{-2})





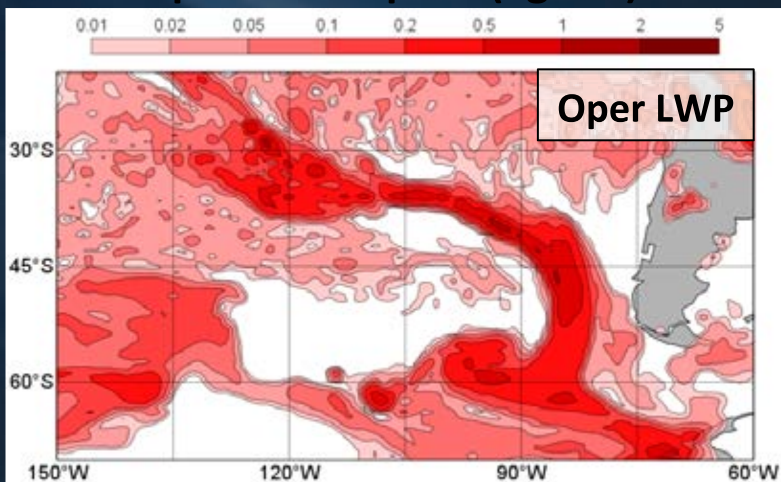
MODIS visible image of front / cold sector

Comparing SSM/IS 37V observations with values simulated from the model fields in the analysis suggest an excess of liquid water in the front and a deficiency of liquid water in the cold air convection behind

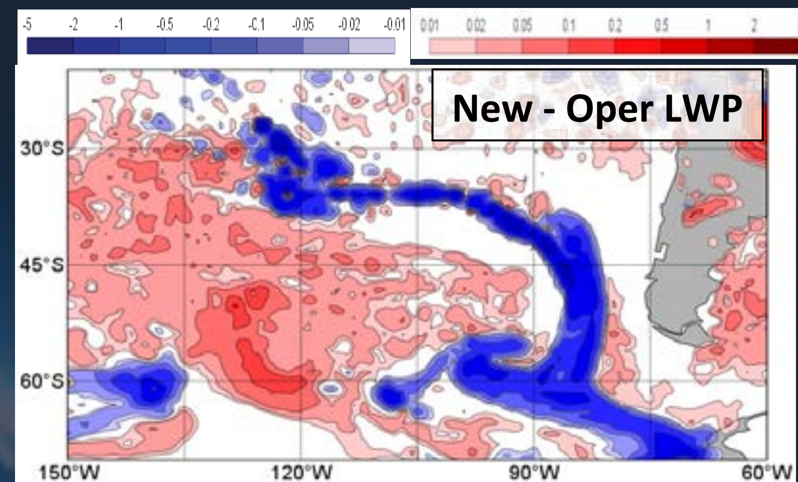
Reducing supercooled liquid water systematic errors

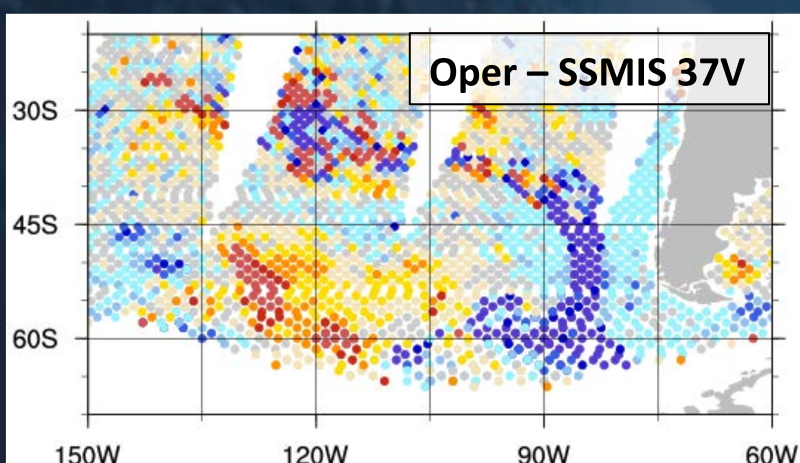
Case study: Southern Ocean 24 Aug 2013

Operational ECMWF model liquid water path (kg m^{-2})



Model (NEW) liquid water path (kg m^{-2})



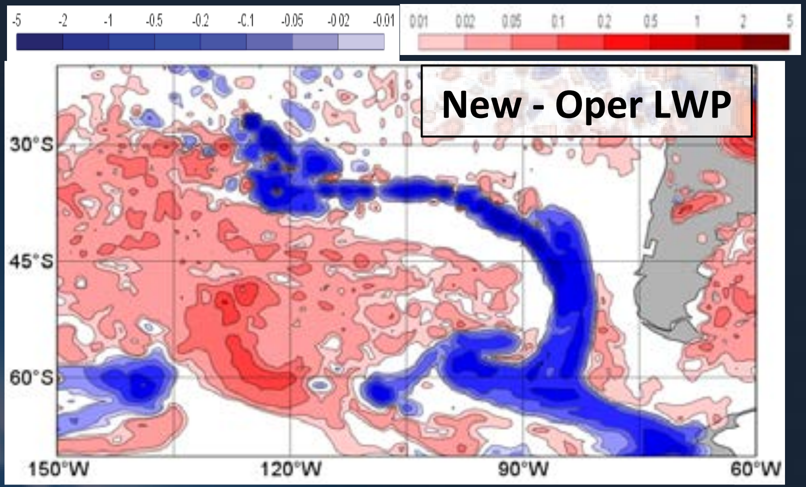


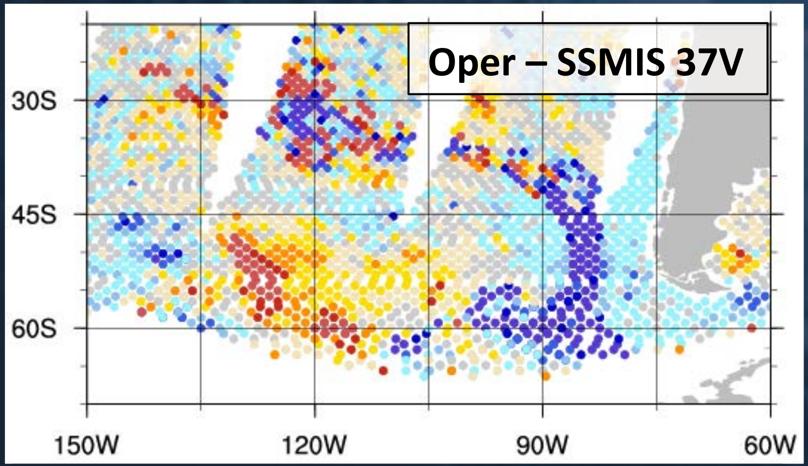
Changes to the physical processes determining super-cooled liquid water reduce values of LWP in frontal zones and increase LWP in the cold air convection regions

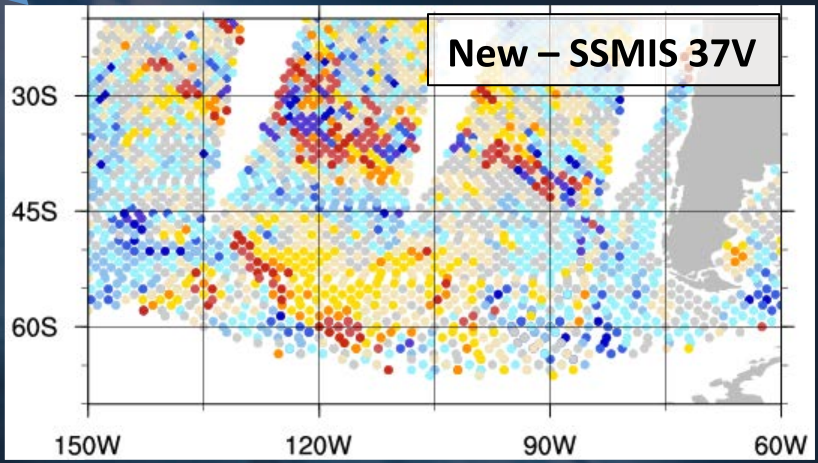
Reducing supercooled liquid water systematic errors

Case study: Southern Ocean 24 Aug 2013

New model version compared with SSM/IS 37V observations, significantly reduced differences in the front and cold air convection regions



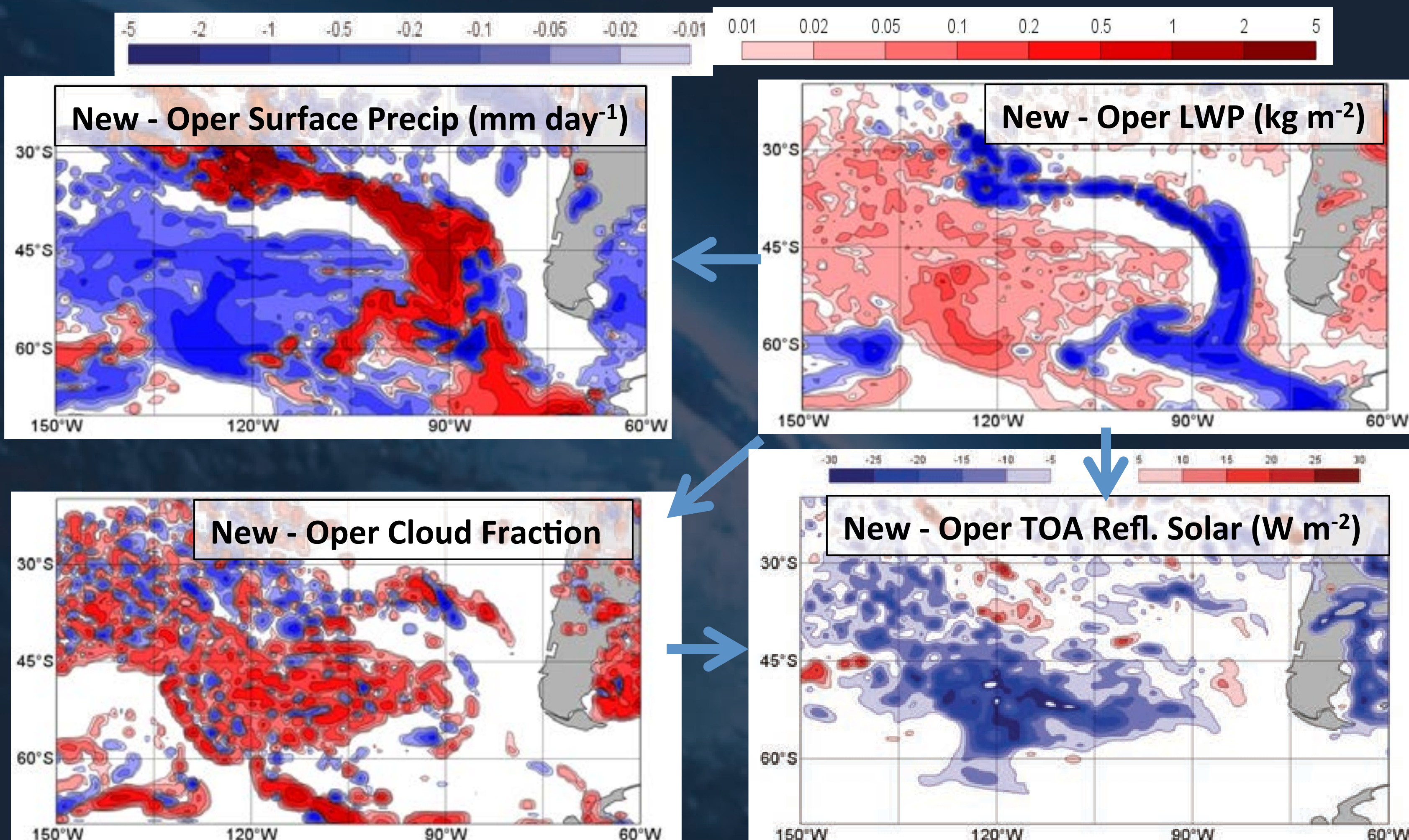




Reducing supercooled liquid water systematic errors

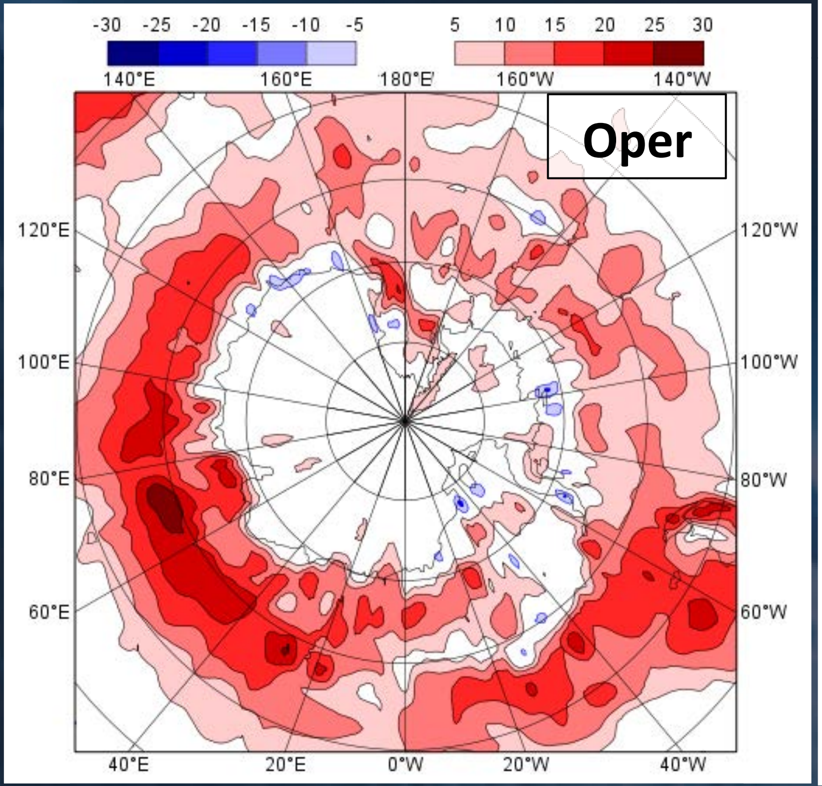
Case study: Southern Ocean 24 Aug 2013

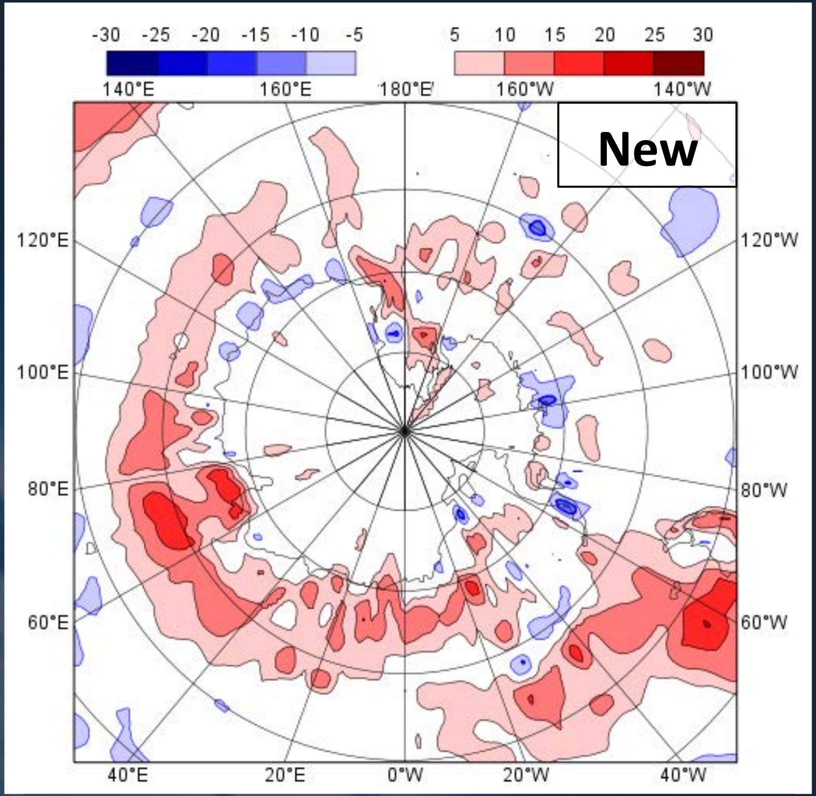
Changes to **supercooled liquid water** path also change **precipitation** and **cloud cover** and importantly, decrease **reflected solar radiation** in the cold air convection



Impact on high-latitude SW radiation systematic errors

Annual mean net TOA SW difference, IFS (T159 "climate" resolution) free-running simulation versus CERES-EBAF



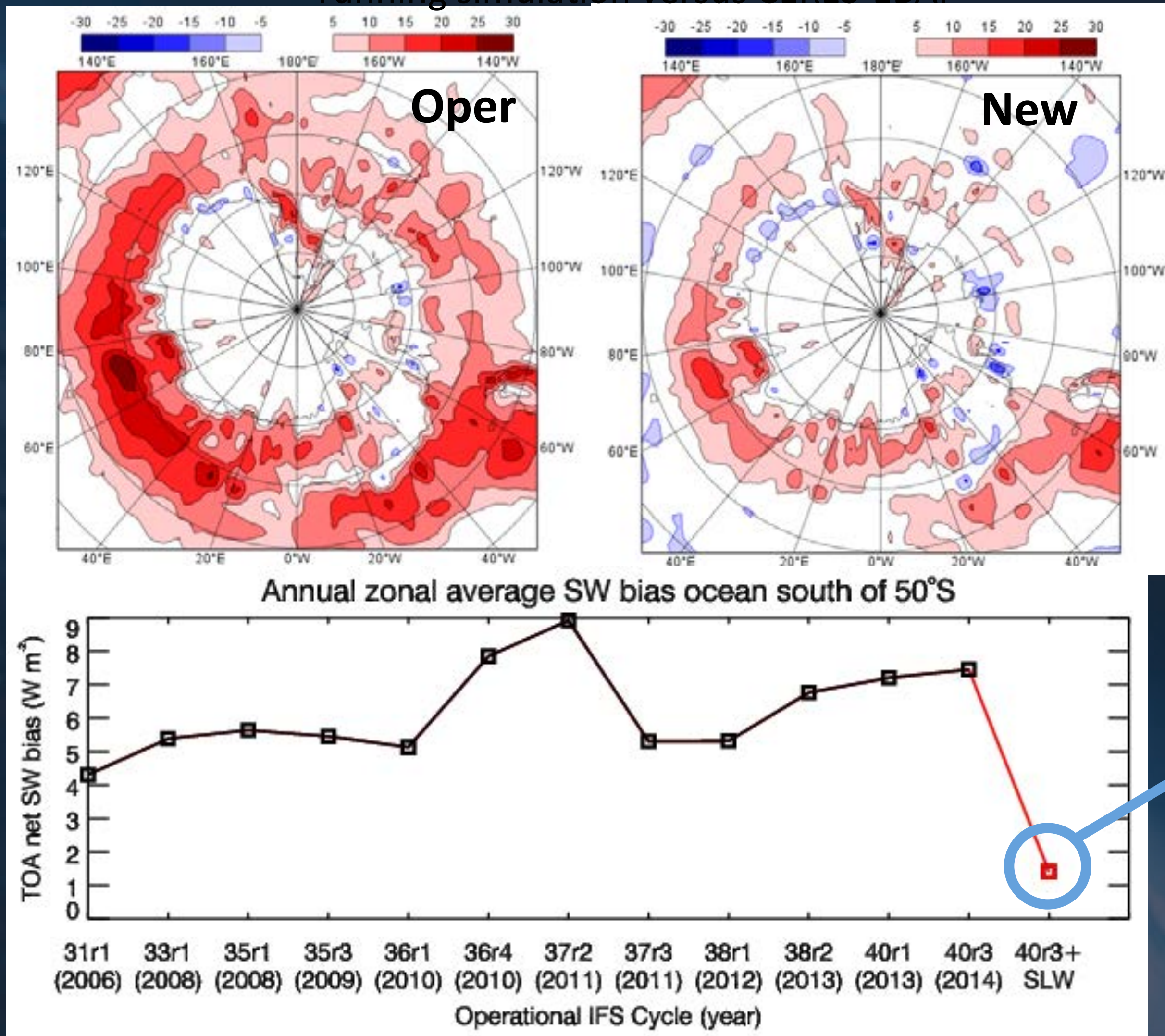


With physics changes to supercooled liquid water guided by SSMIS first guess departures…. significantly reduces Southern Hemisphere systematic shortwave radiation bias in the forecast model…

Extra Slides

Impact on high-latitude radiation systematic errors

Annual mean net TOA SW difference, IFS (T159 “climate” resolution) free-running simulation versus CERES-EBAF

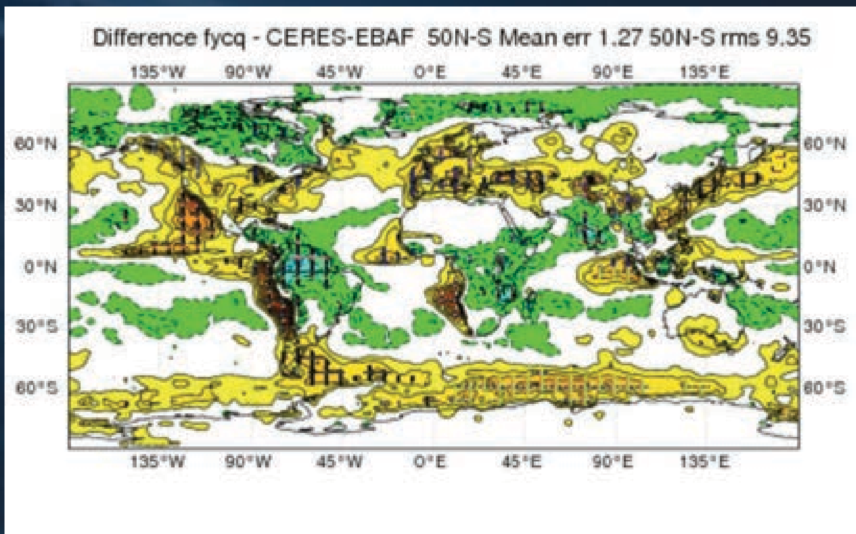


With physics changes to supercooled liquid water guided by SSMIS first guess departures.... significantly reduces Southern Hemisphere systematic shortwave radiation bias in the forecast model...

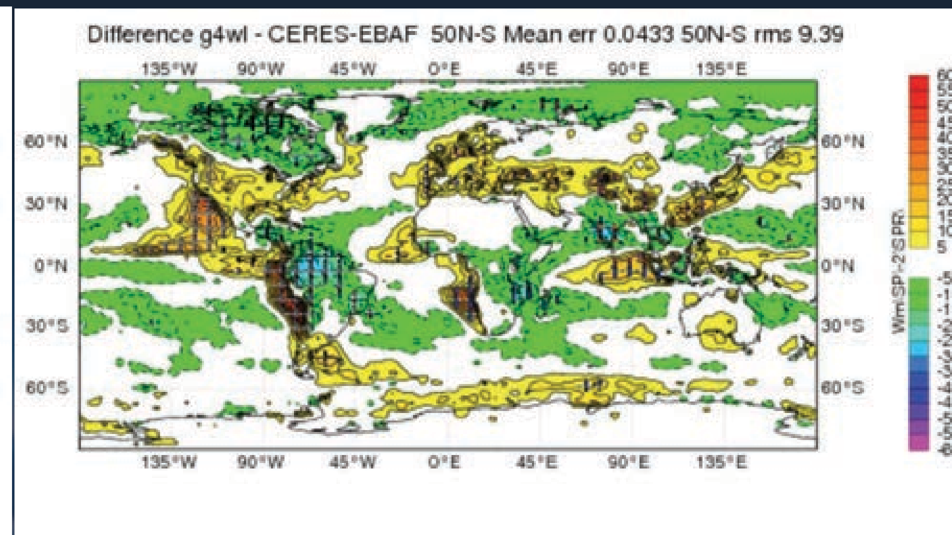
...lowest Southern Hem. shortwave radiation error by far compared with at least last ~10 years IFS cycles!

Impact of SLW physics changes on 1 year climate (T159) net TOA shortwave cloud forcing (IFS minus CERES-EBAF) annual mean…

Reference

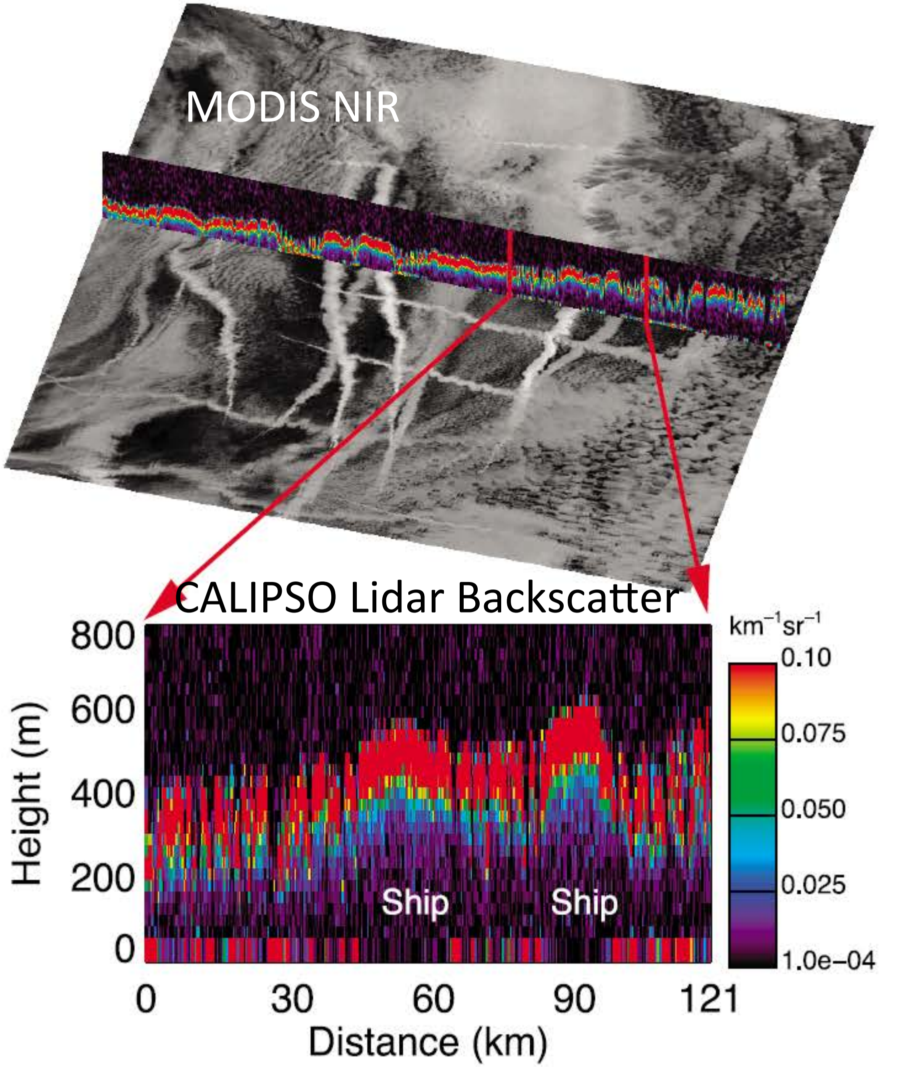


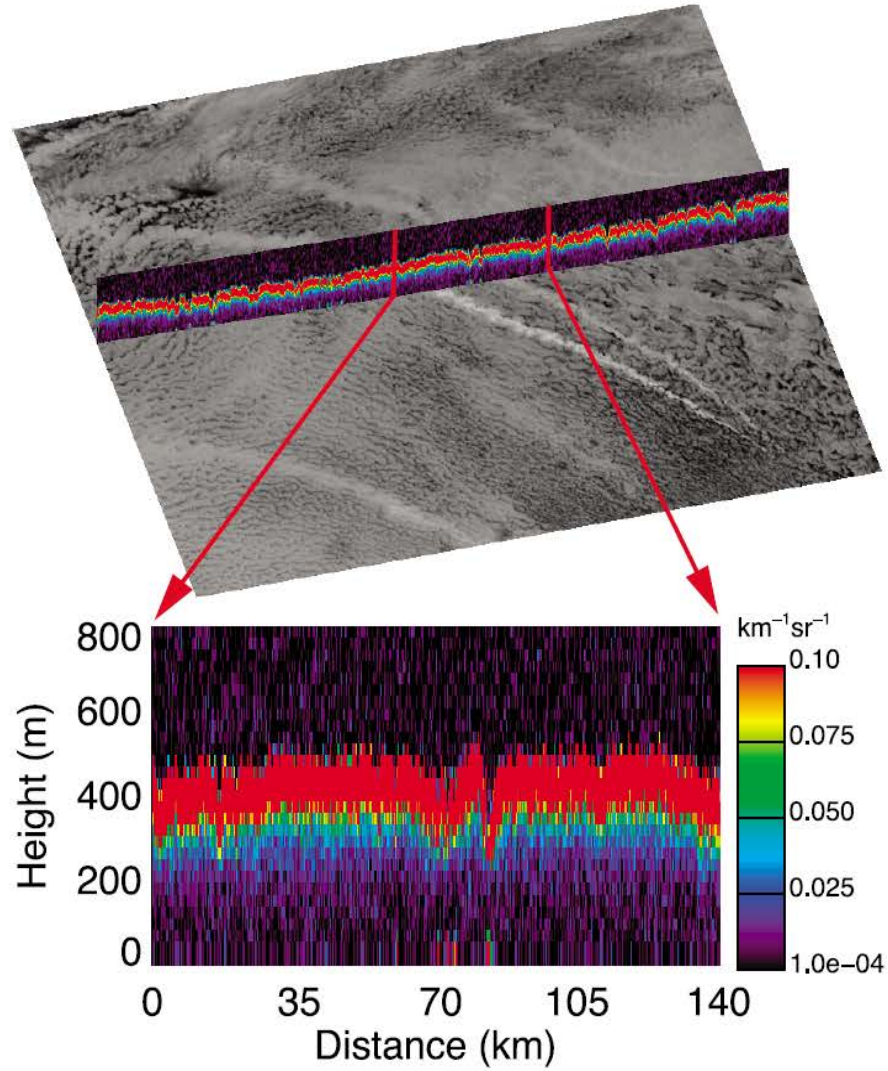
New



Significant impact over Southern Ocean and North Pacific/Atlantic Oceans without degradation in the Tropics/sub-tropics (rms 50N-50S very similar)

Evidence of Cloud Deepening



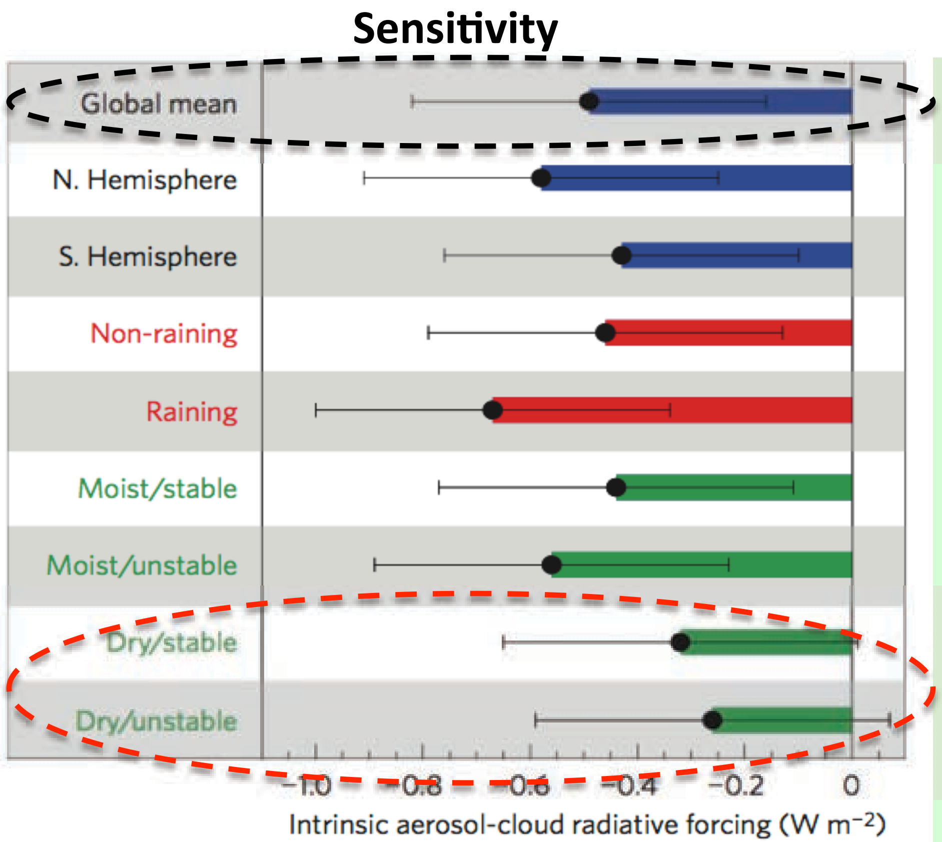


Open cells: 16% increase in cloud top height, +42% increase in liquid water path

Closed cells: no change in cloud top height, 6% decrease in liquid water path

Christensen and Stephens (2011)

Global Aerosol Indirect Forcing



Indirect Forcing Estimates:

- Intrinsic = **−0.49±0.33 W/m²**
- Extrinsic = **−0.46±0.31 W/m²**

> −0.95 W/m²

Summary

•Environmental condition and cloud type exert strong controls on the aerosol indirect effect sensitivity at both local (e.g., ship tracks) and global scales.

•*For observational studies:* it's imperative to isolate aerosol indirect effects by environmental conditions and, improve cloud albedo, aerosol, precipitation rate, and infrared sounding retrievals.

•*For modeling studies:* feedbacks involving entrainment, drizzle, and surface coupling should be incorporated into GCM's to improve estimates of the aerosol indirect forcing.

$$\frac{dC_{SW}}{d\ln(AI)} = \left[\underbrace{\overline{c_m} \left(\frac{dA_{clr}}{d\ln(AI)} - \frac{dA_{cld}}{d\ln(AI)} \right)}_{\textbf{intrinsic effect}} + \underbrace{\overline{(A_{clr} - A_{cld})} \frac{dc_f}{d\ln(AI)}}_{\textbf{extrinsic effect}} \right] \overline{F^{\downarrow}}$$

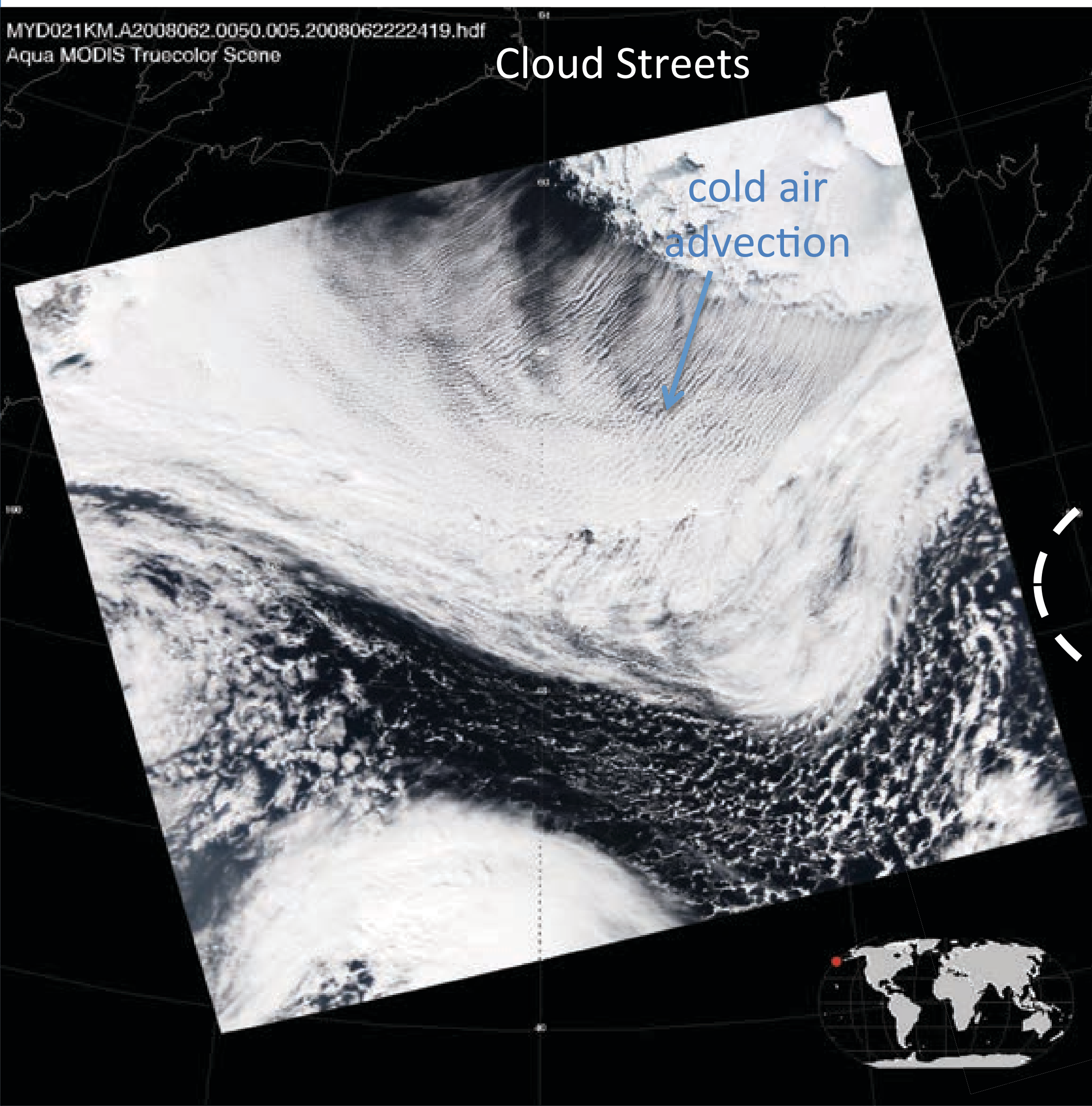
intrinsic effect
aerosol changes on cloud properties

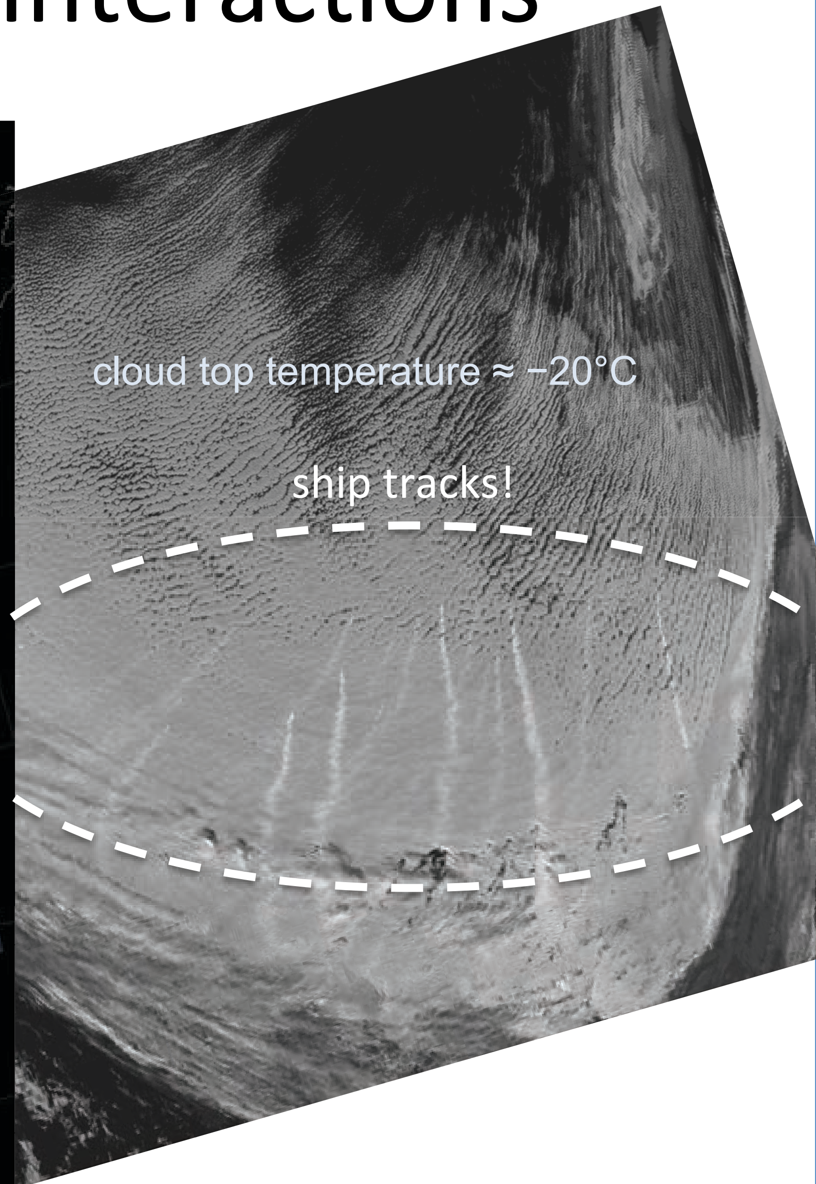
extrinsic effect
impact of aerosol on cloud fraction

Chen et al. (2014), Nat. Geosci.

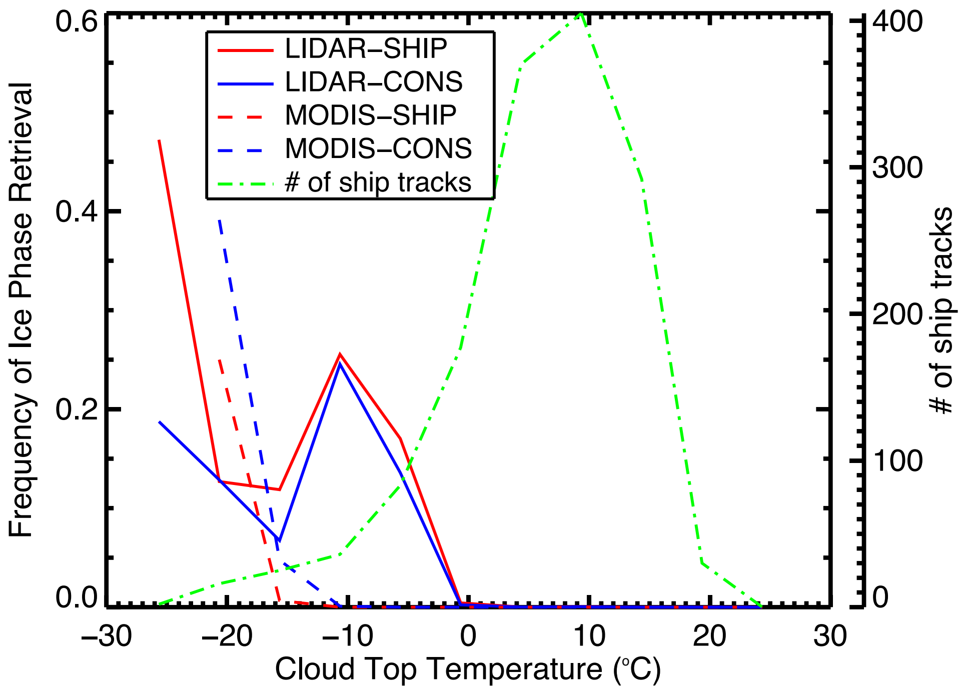
C_{SW}: Shortwave Cloud Forcing (CERES)
A_{clr}: clear-sky albedo (CERES)
A_{cld}: cloudy sky albedo (CERES)
c_f: cloud cover fraction over CERES footprint
c_m: annual mean marine warm cloud coverage
AI: Aerosol index (MODIS)

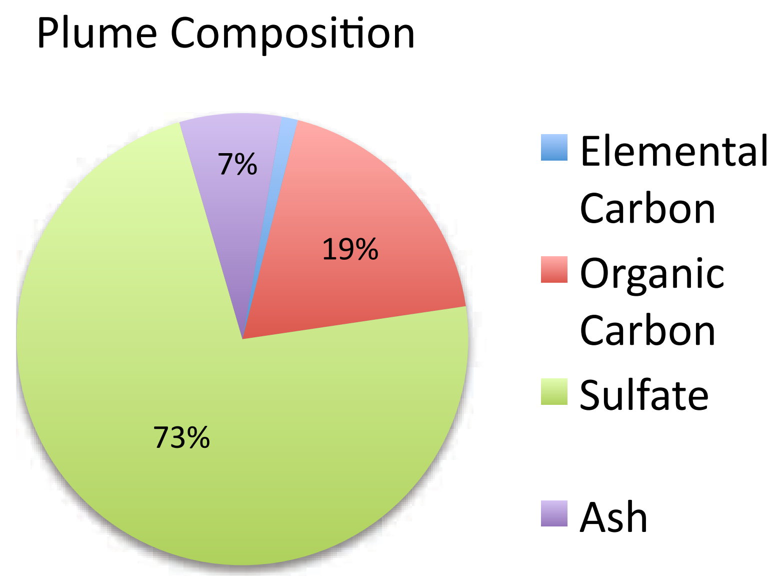
Aerosol-Ice Cloud Interactions





Aerosol Glaciation Effect Observed in Ship Tracks

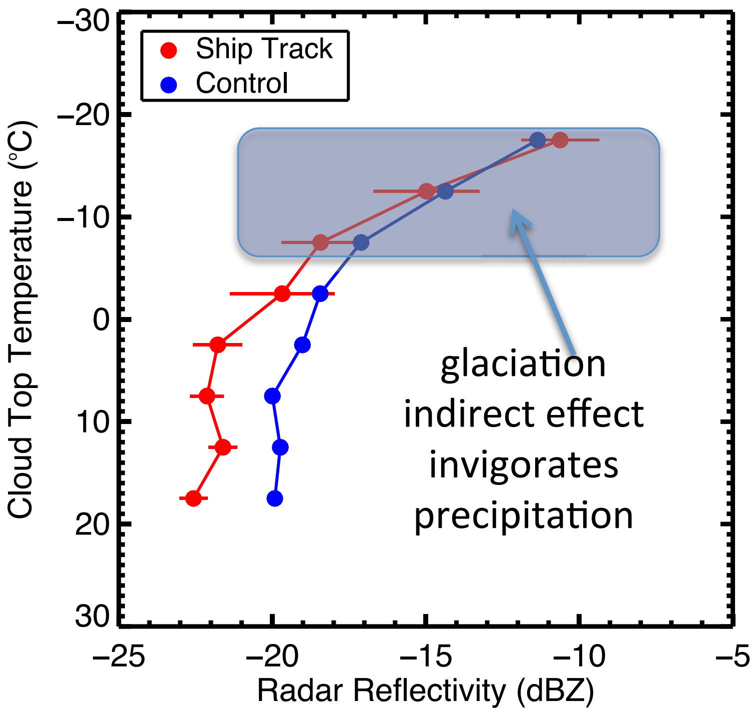


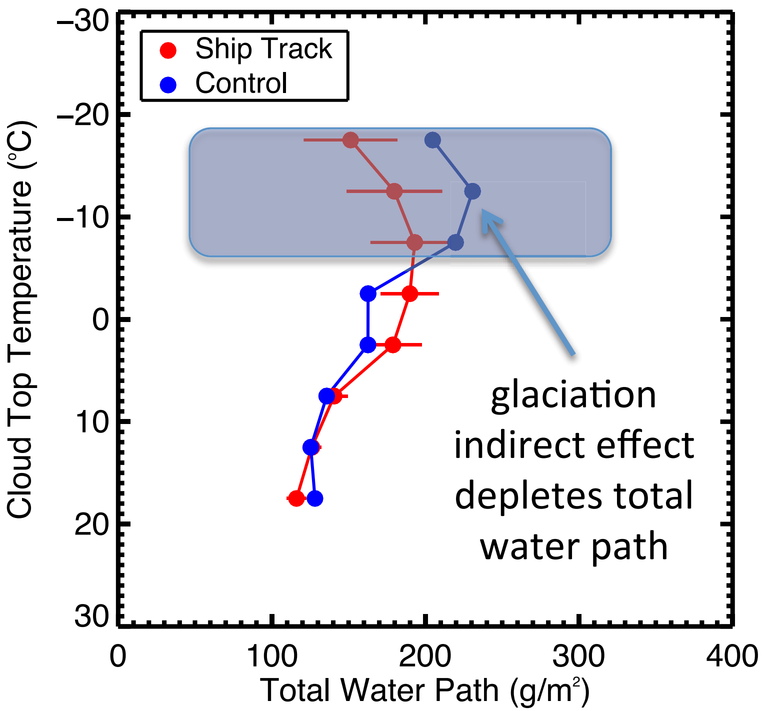


Diesel-powered ship burning low-grade marine fuel oil (Agrawal et al., 2008)

- Frequency of ice clouds increase as cloud top temperature decreases.
- Local maximum ice frequency occurs at −10°C.
  - Secondary ice production by the Hallett and Mossop (1974) mechanism is efficient between −10°C to −4°C.
- Polluted clouds contain more ice (~15% increase in lidar observations) than adjacent clouds.
  - Local increase in ice nuclei from ship exhaust (~25%) enhances contact & immersion freezing of cloud drops.

Aerosol Glaciation Effect Observed in Ship Tracks

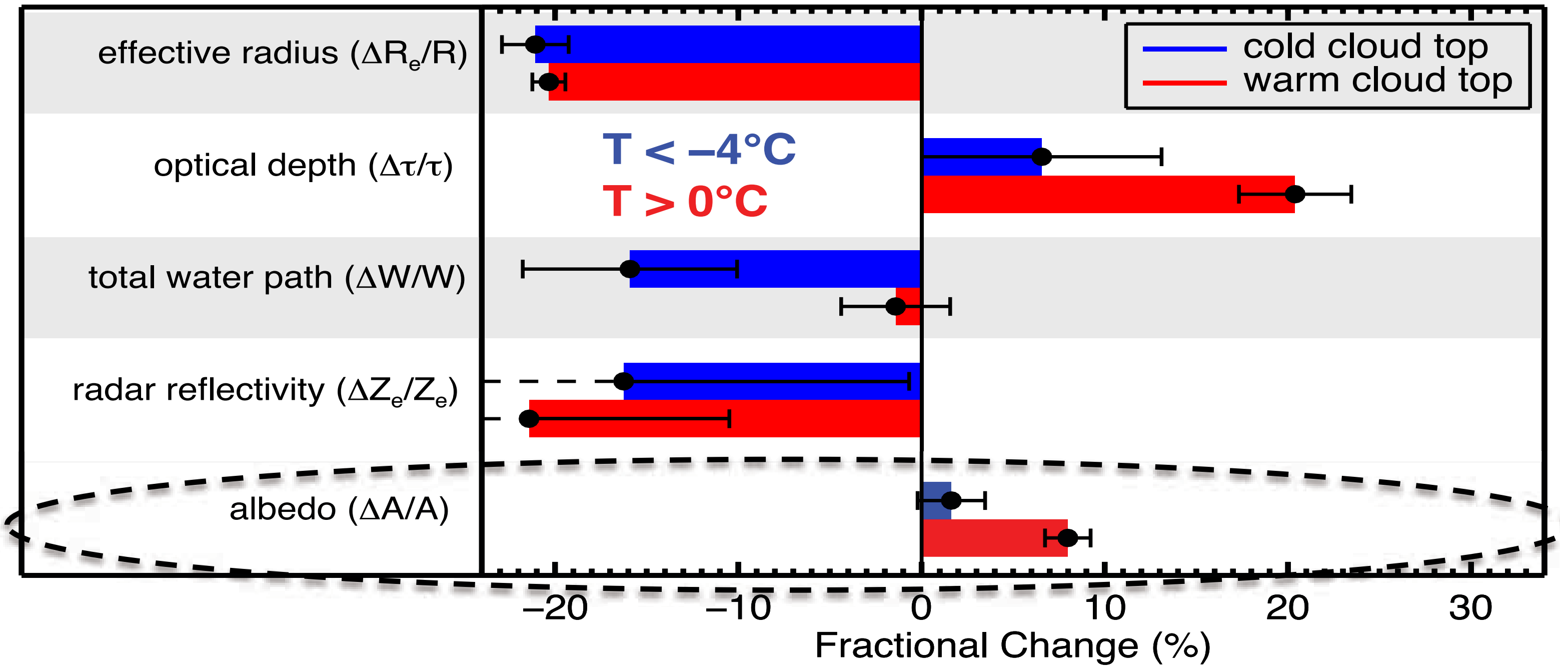


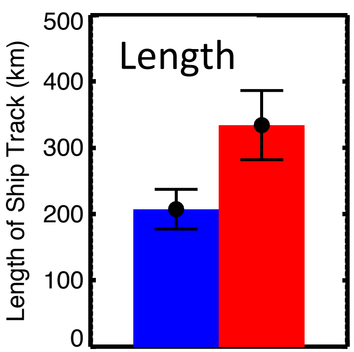


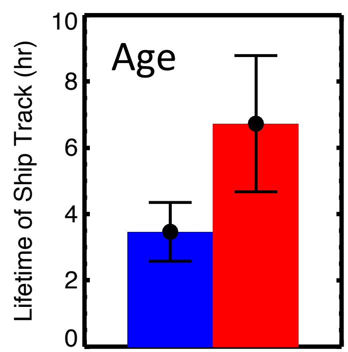
- Radar reflectivity is strongly influenced by the size/number of precipitation-sized particles.
- Aerosol effect on suppressing precipitation decreases with cloud top temperature.
  - More ice in polluted clouds invigorate particle growth and precipitation rates.
- Total water path is significantly depleted in mixed-phase clouds due to the glaciation indirect effect.

Indirect Effect Responses for *Warm* and *Mixed-phase* Clouds

Differences: polluted – unpolluted







Main Result

1) Liquid clouds are 5 times more susceptible to increases cloud albedo and . . .
2) persist ~2hours longer than mixed-phase clouds.
   – This suggests that aviation aerosol alters the properties of mixed-phase clouds through the glaciation indirect effect.

Implications and Future Work

The implications of these results are twofold:

1) Emissions from ships are expected to increase throughout the Arctic as sea-ice continues to melt giving way to direct and sought after transportation routes between countries (Corbett et al., 2010).
   – Increased shipping will unlikely provide any significant counter balancing cooling influence over the prone and already warming polar region.

2) Assessments of aerosol indirect forcing commonly overlook the proportion of low-clouds that contain ice.
   – These clouds are ***abundant*** accounting for roughly 25% of marine low-cloud!
   – Global assessments using satellite data are likely biased and overestimate the indirect effect by neglecting ubiquitous mixed-phase clouds.

Future Work

- It is imperative to incorporate mixed-phase clouds in observation-based studies to improve the estimate of the overall strength of aerosol indirect effects on climate.
  – Extend study to globe using the JPL COMPARES (COMPrehensive ARctic Energy budget dataSet) dataset which combines satellite, reanalysis, and ground base observations into a common framework.
- Results presented here offer unique guidance on how mixed-phase cloud processes should be incorporated in models under the influence of changing aerosol.
- Improve ice nucleation processes and feedbacks involving entrainment and drizzle in GCM's with the goal to decrease the uncertainty of the aerosol indirect forcing and the impacts of climate change.