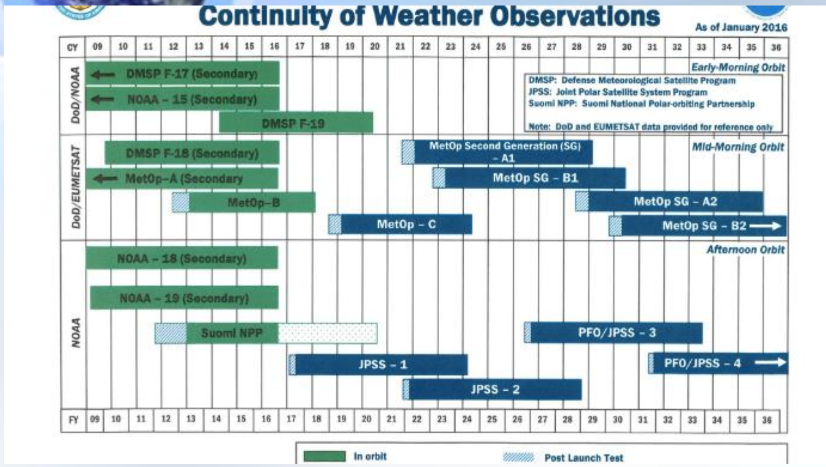
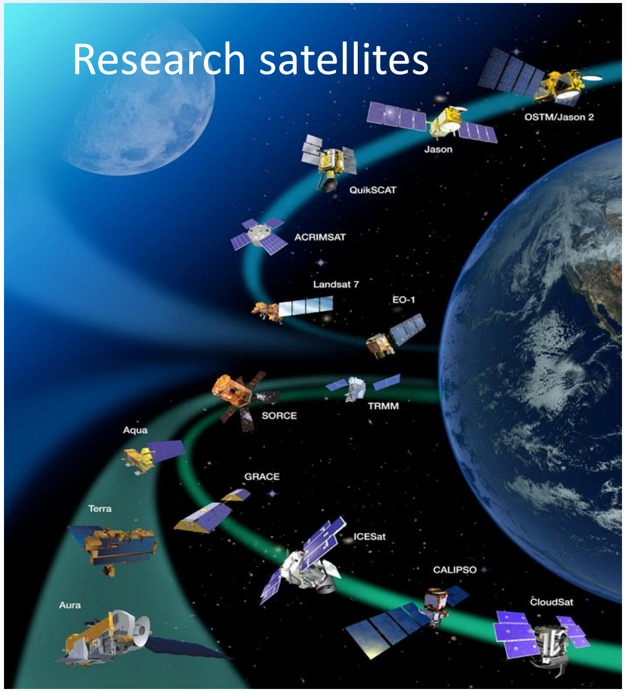
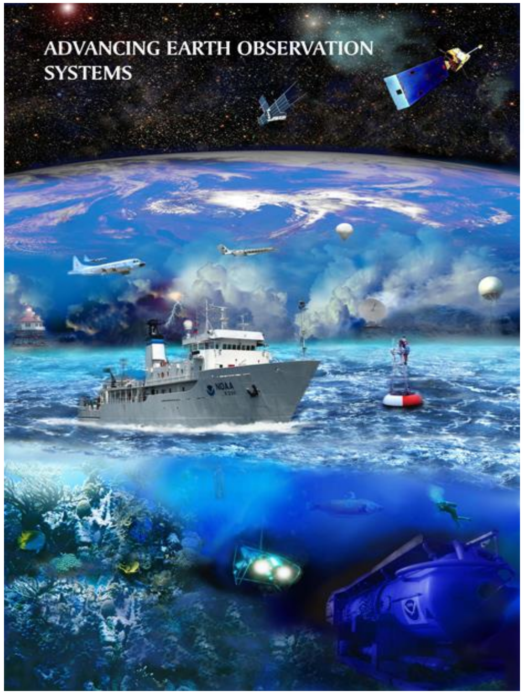
# Satellite Observations




Operational weather sat systems

Graeme Stephens




Variety of observational tools developed for global satellite observations , and many observations that are to be sustained over the coming decade but …

# Outline

- The NASA downscaling project  - lessons learned
- Sat obs capabilities today & challenges looming
- Exemplifying a ‘decade’ of progress
- A couple of examples of new ways to using data
- Model obs synergy
- Looking forward

# Assessing the Credibility of Dynamically-Downscaled Climate Projections: A NASA Pilot Study

Multi-Center NASA (JPL, GSFC, MSFC, AMES) Working Group

Downscaling Assessment Questions

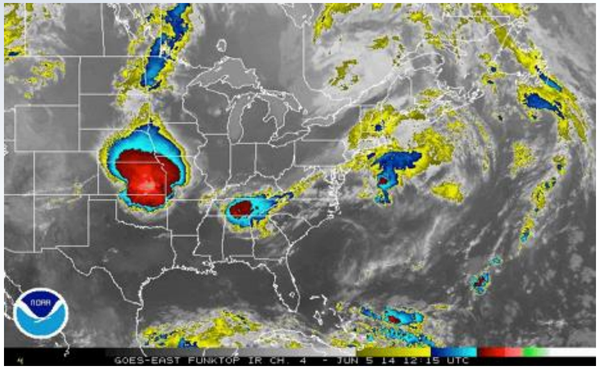
- Under ideal forcing conditions (e.g., high-quality re-analyses), how good is the RCM at replicating important weather and climate processes/phenomena?
- Under what conditions does downscaling (RCMs driven by GCMs) give valid results?
- Do high-resolution RCMs (5 km or finer) offer anything that can't be obtained via today's "high" but coarser resolution GCMs (25-50 km or coarser)?

# Downscaling Assessment

## Narrow Scope – Focus only on 3 Impactful Phenomena


**Northeast Wintertime Storms (NESs)**

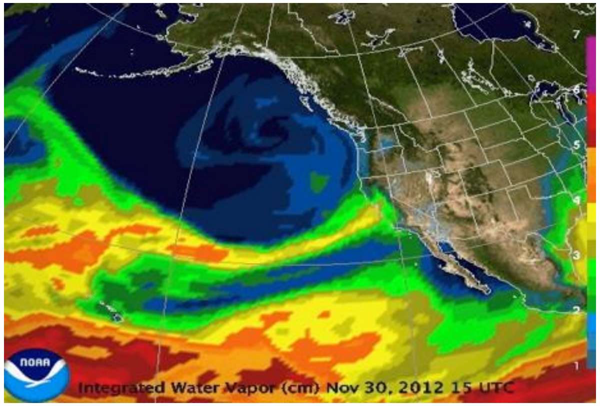
- Extreme precipitation/snowfall events
- Extreme wind events




**Midcontinent Summertime MCSs**

- Warm / Dry Climate Model Biases
- Extreme weather events

Resolution May Matter To The Proper Representation of The Impacts Of These Phenomena




**West Coast Wintertime Atmospheric Rivers (ARs)**

- Crucial for water resources/availability
- Associated with most flooding events

# Study Conclusions

- Based on the metrics developed, the study results do not show dramatic improvement of the downscaled fields compared to the reanalysis fields (which were at ~ 0.5 degree resolution)
- Performance metrics vary by season, region, variable, and phenomenon of interest.
- NU-WRF and M2R12K generally capture climatology (particularly winter). In numerous evaluations (though not all) they show some systematic improvement over MERRA-2. This is good!
- All simulations improved realism of the diurnal cycle relative to MERRA-2.
- Nudging usually improves performance metrics.
- Resolution seems to have marginal impact (a surprise!) but there are cases where higher resolution did systematically improve representation of precipitation.
- **Many evaluations were observation limited. When we get down to 4km even our “gold standard” observations don’t have the resolution and accuracy to support a robust evaluation of results.**

# Resolution - underscoring the challenge

| Variable | Sensor | Native (measurement) Resolution |
|---|---|---|
| T(z), q(z) | COSMIC | Δx~100s of km, ~daily, Δz<1km |
| | AIRS,IASI*<br>Poor boundary layer resolution | Δx~10km, twice daily, Δz~2km |
| Winds<br>ocean surface only | **Scatterometry** | Δx>10km, daily |

What the last two decades has revealed is the viability of active systems - just as 'affordable' and just as reliable

**Pros: Delivers vertical profiles and information that is much less ambiguous**

**Cons: narrow swath, limited coverage**

| | | |
|---|---|---|
| Water storage: Snow depth, density | ? | ? |
| Water storage: subsurface | GRACE | Δx>400km |
| Radiation budget | CERES | Δx~20km, twice daily |
| Clouds | MODIS,VIRS<br>**CloudSat/CALIPSO** | Δx~1km, daily<br>Δx~2km, no swath+ Δz~500m |

*** IASI to go on geostationary – sub-hourly**
**+ Data composited in space on 100s km, monthly**

# Thoughts

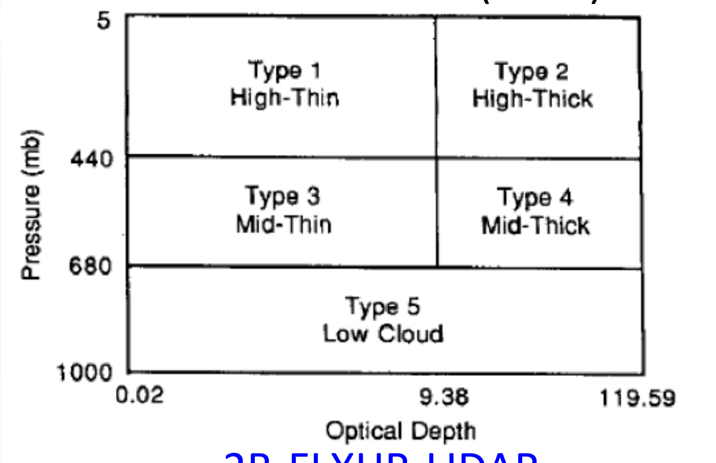
- We are at a point in time where the paradigm is shifting – model resolutions (e.g. CPMs) are now below the native resolutions of almost all satellite observations.
- It is unlikely that we will see fields of observed variables at resolutions now being produced by O(1km) models.
- Thus we are left to ponder do observations need to be at these same resolutions, if not then at what resolution and for what variables?
- How do we more effectively use the observations of today and of the future?

# Selected Progress

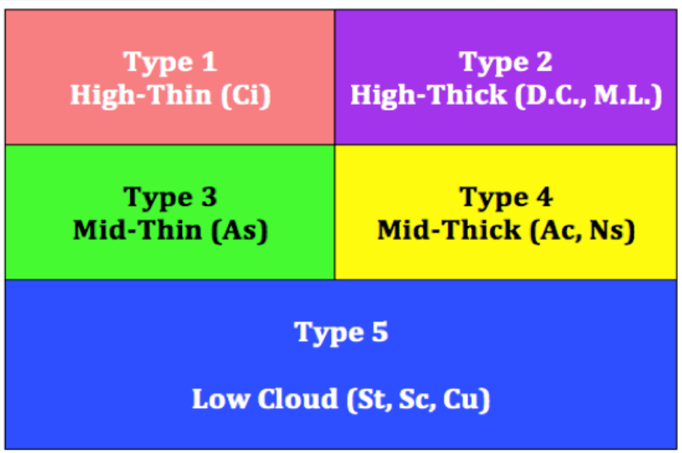
- Clouds ain't where we think the where this last 30+ years
- Dreary models – we know by how much and why and more or less how to fix them
- We know much more about the cloudy nature of convection& are beginning to understand what the broader Earth science implications
- We know we there is a SW southern ocean bias and how to fix it
- Frozen precipitation – we now have reasonable measures of it (at least in polar regions)

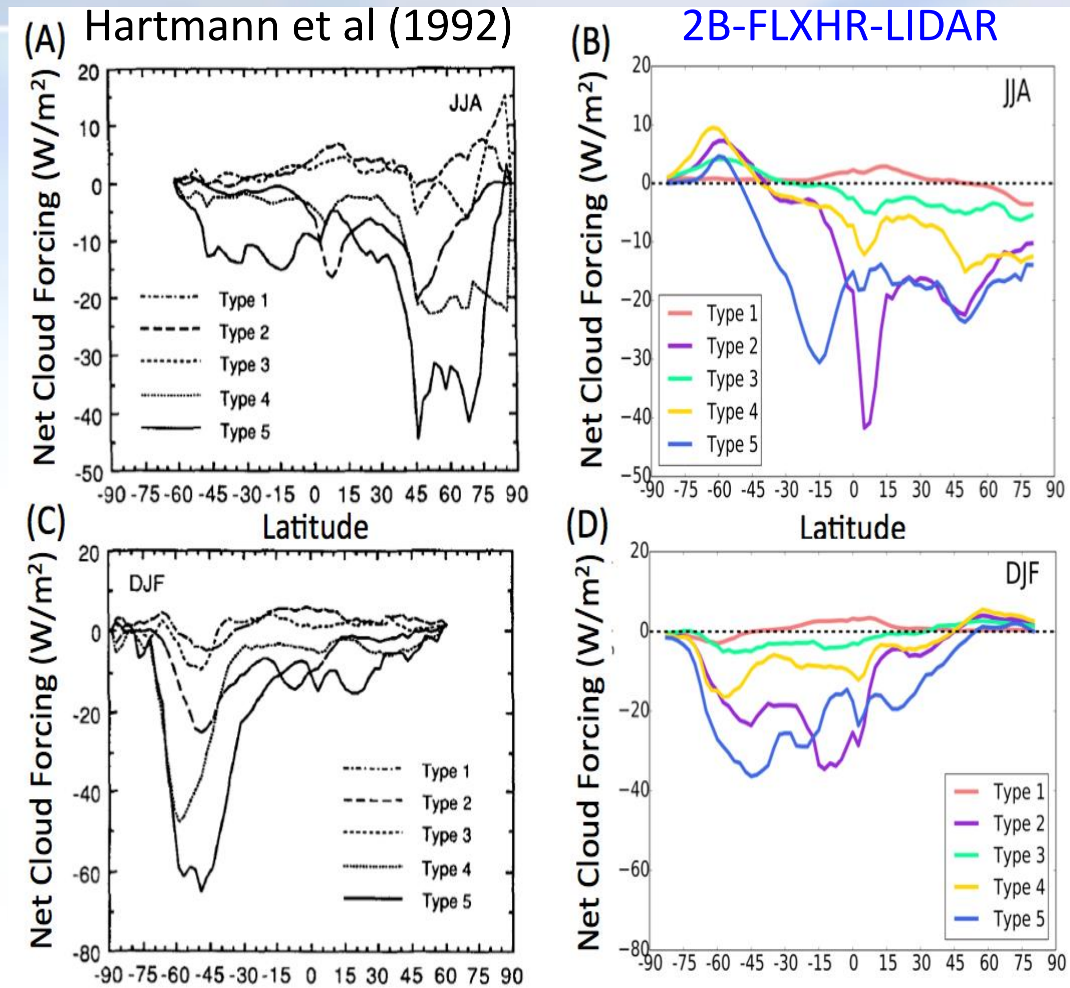
# Some highlights of progress over the past decade

Hartmann et al (1992)




2B-FLXHR-LIDAR




To be frank, passive climatologies of clouds mis-assign clouds in significant ways

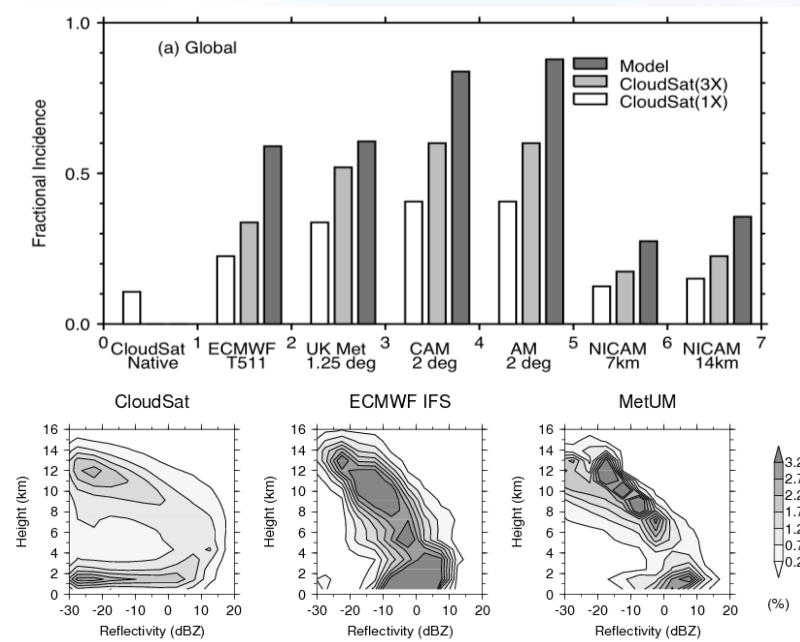
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D24211, doi:10.1029/2010JD014532, 2010

# Dreary state of precipitation in global models

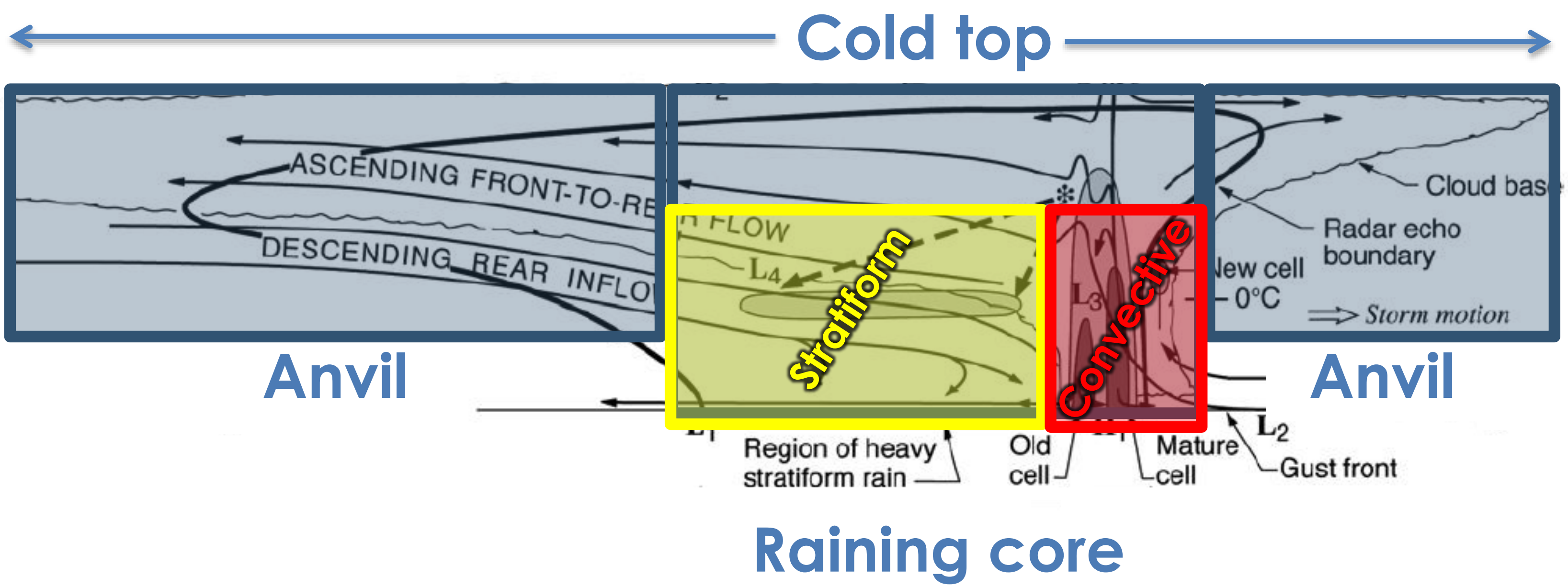
Graeme L. Stephens,[1] Tristan L'Ecuyer,[1] Richard Forbes,[2] Andrew Gettlemen,[3] Jean-Christophe Golaz,[4] Alejandro Bodas-Salcedo,[5] Kentaroh Suzuki,[1] Philip Gabriel,[1] and John Haynes[6]

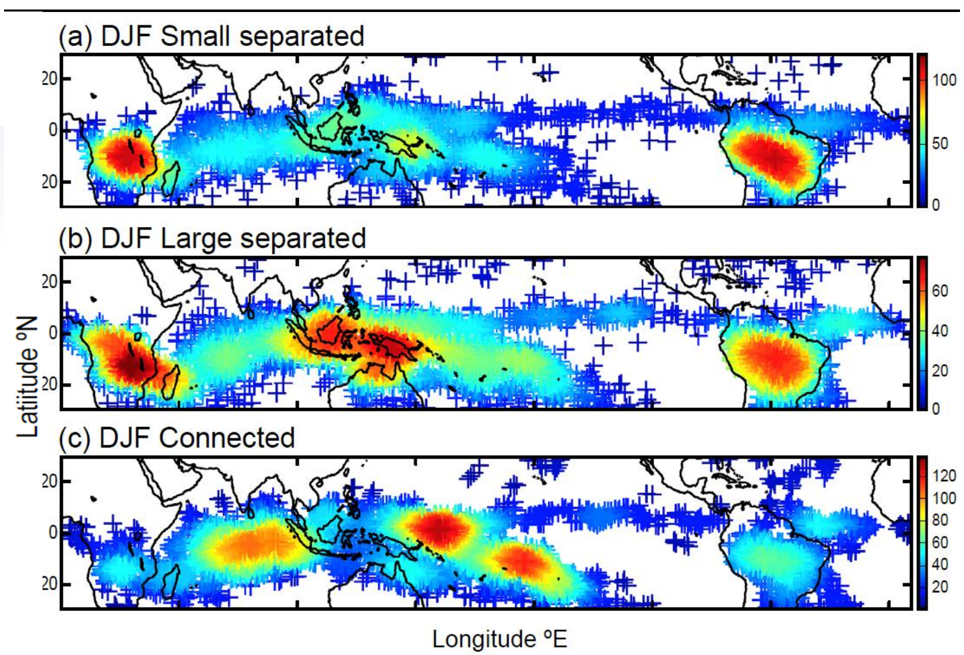
and models. We show that the time integrated accumulations of precipitation produced by models closely match observations when globally composited. However, these models produce precipitation approximately twice as often as that observed and make rainfall far too lightly. This finding reinforces similar findings from other studies based on surface

**The dreariness is not just a state of climate models but also of global CPMs??? So there is still 'physics' to be improved even as resolutions increase**



The shape of tropical deep convection




Smallest 25% (<12,000 km$^2$)

Largest 25% (>40,000 km$^2$)

“Superclusters” – produces the majority of the high clouds

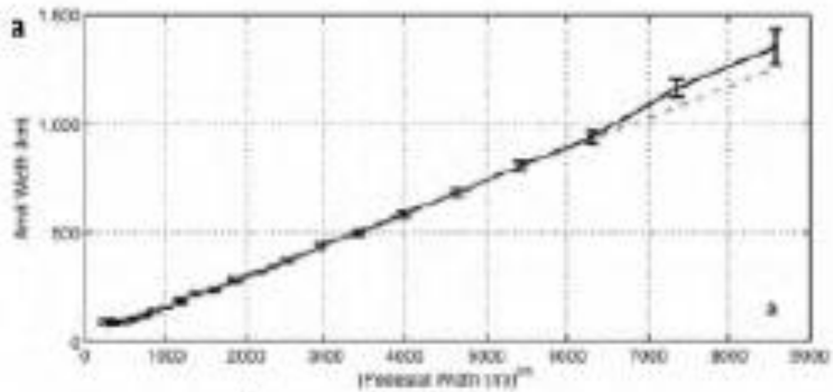
Yuan and Houze 2010

# The shape and size of deep convection

**Table J.10.3-1.** Means of various length scales as a function of the number of cores (with 25th and 75th percentiles in parentheses), as derived from CloudSat analyses by Igel & van den Heever [59]. "3+" cores signifies that the values are for clouds with 3 or more convective cores.

| Cores | Pedestal Width (km) | Anvil Width (km) | Cutoff Height (km) | Anvil Depth (km) |
|---|---|---|---|---|
| 1 | 11 (8, 13) | 95 (33, 119) | 7.2 (6.0, 8.3) | 6.4 (5.3, 7.3) |
| 2 | 20 (14, 25) | 121 (50,153) | 7.3 (6.0, 8.4) | 6.7 (5.7, 7.8) |
| 3+ | 116 (42, 148) | 335 (156, 449) | 7.1 (6.0, 8.1) | 7.7 (6.6, 8.8) |

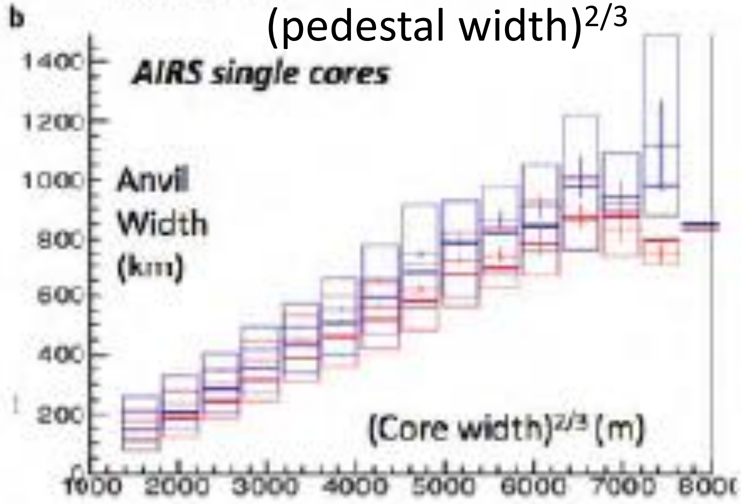
Anvil width





Inference from
2 dimensional
(x,z) data

(pedestal width)$^{2/3}$



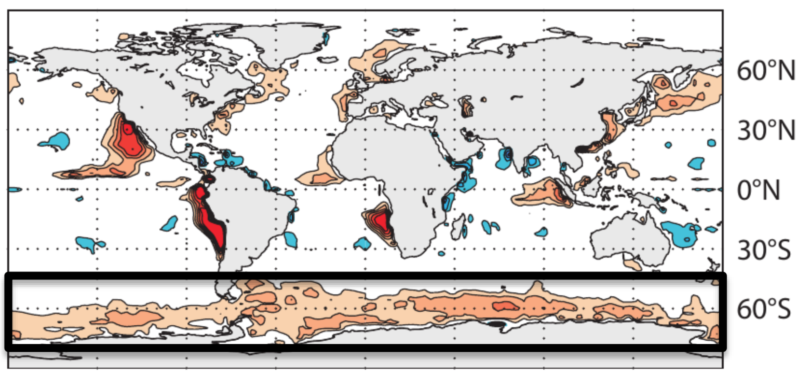

Inference from
2 dimensional
(x,y) data

# The Southern Ocean SW radiation bias

Forbes et al. 2016
(ECMWF Newsletter 146)

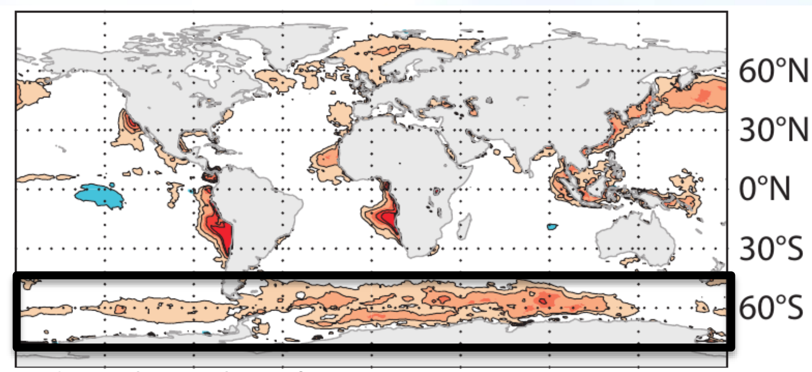
Annual mean 10-20 $Wm^{-2}$ TOA SW bias (too little reflection) over Southern Ocean

**ECMWF low resolution “climate” bias**

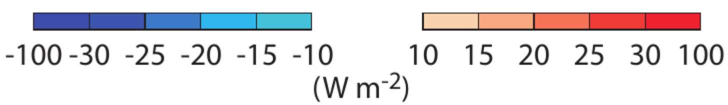



**dx=125 km 1 year forecast – CERES**

**ECMWF high resolution “analysis” bias**

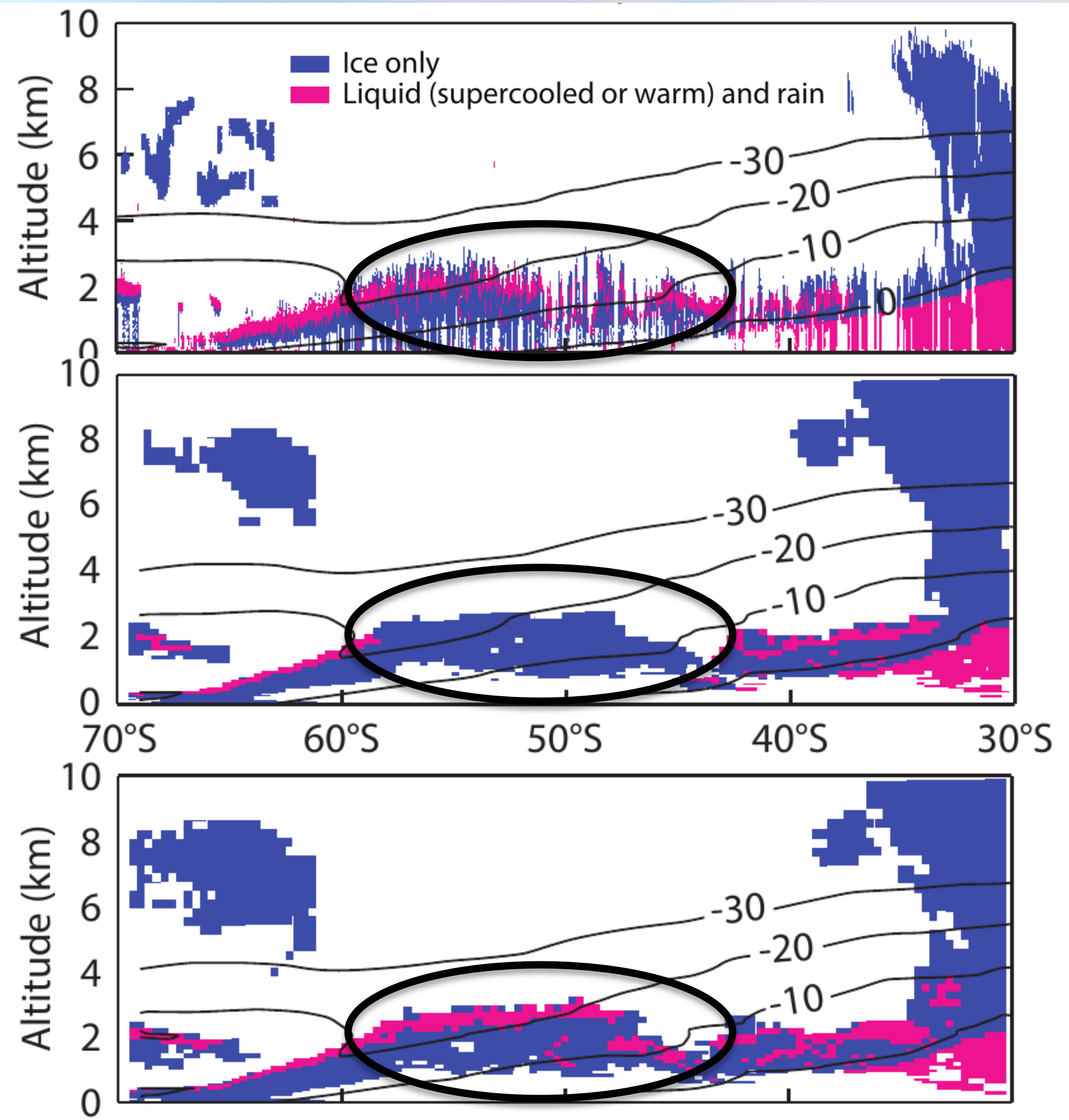



**dx=16 km 24 hour forecast – CERES**




ECMWF

# Supercooled liquid water now present at the tops of convective clouds in cold-air outbreaks




CALIPSO satellite lidar cloud phase

IFS along-track lidar forward modelled cloud phase

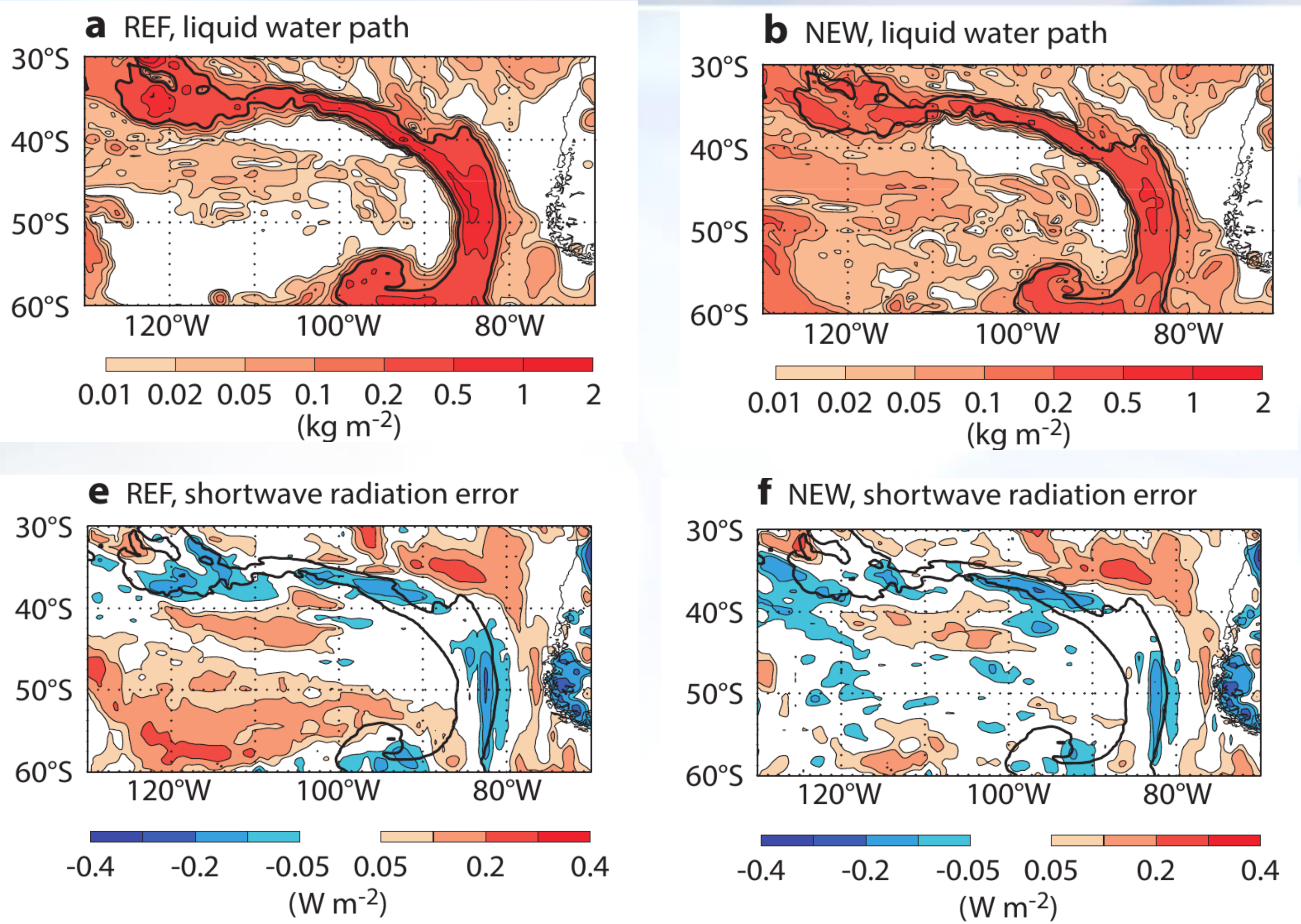
IFS with convection producing SLW below 600hPa

Forbes, pers comm

ECMWF

# More liquid water path (closer to SSMI/S) and SW radiation bias dramatically reduced!

24 hour forecast

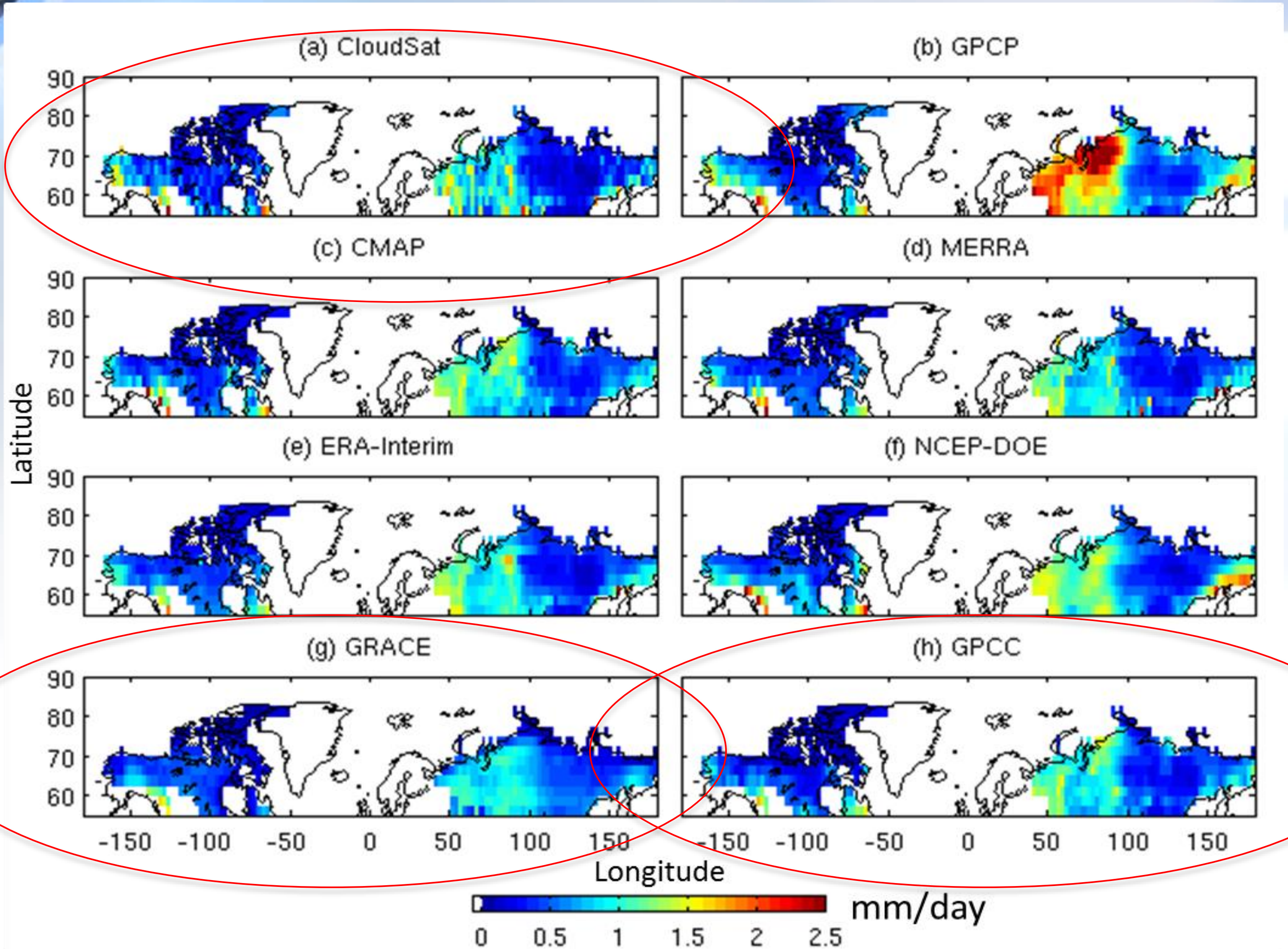



Forbes et al. 2016 ECMWF Newsletter 146

Also UKMO Bodas-Salcedo et al 2016

ECMWF

# Genuine progress on frozen precipitation




ECMWF

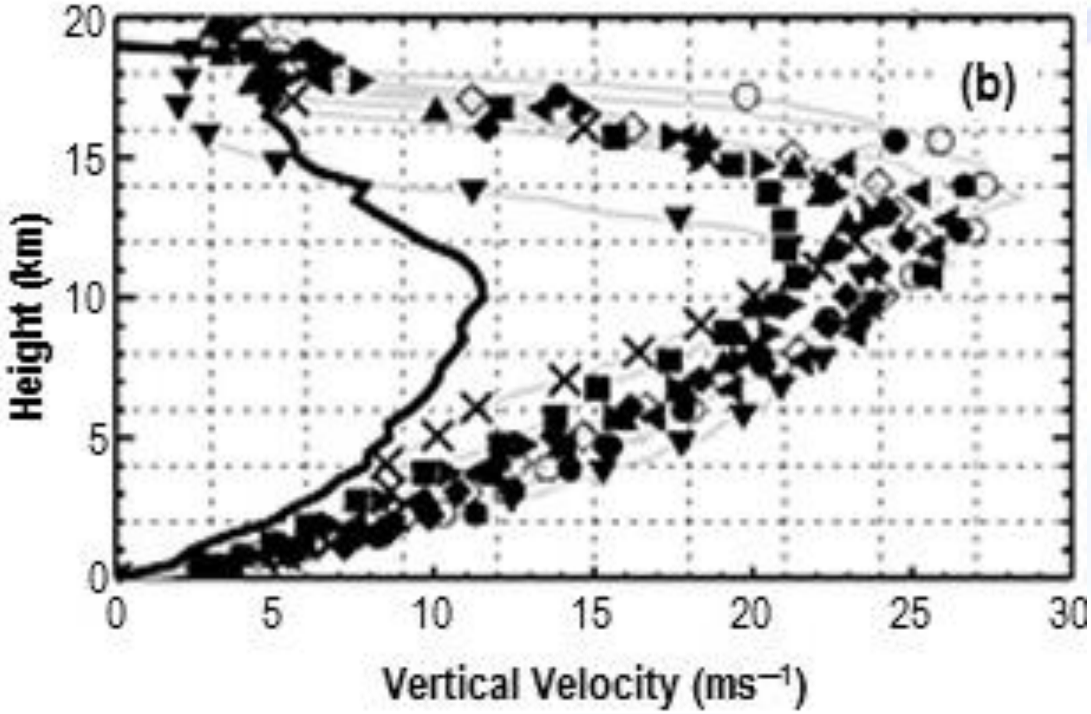
# New ways of using data – process oriented

Two examples

Deep convection

Warm rain

# CRM 'surrogate' observations of tropical deep convection

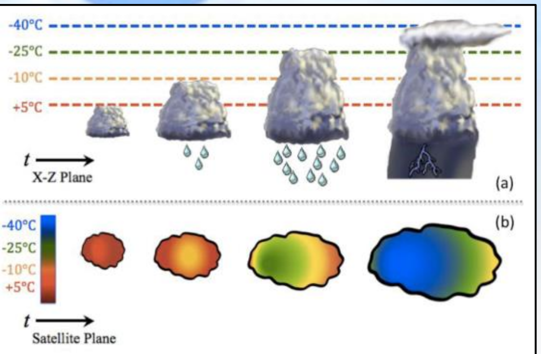



A. Varble, et al., "Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations: 1. Deep convective updraft properties," Journal of Geophysical Research: Atmospheres, vol. 119, pp. 13891-13918, 2014.

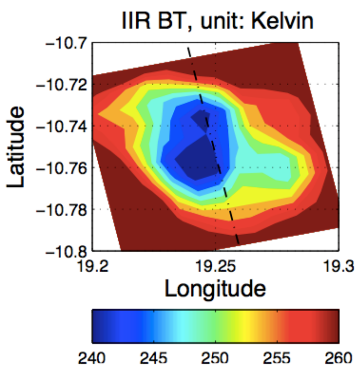
**Too anecdotal to suggest systemic problem with CRMs?**

# A-few glimpses of the puzzle

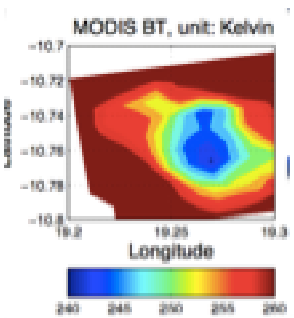
## Cloud-top w




$$w = \left(\frac{\partial T}{\partial z}\right)^{-1} \frac{dT_{BB}}{dt}$$



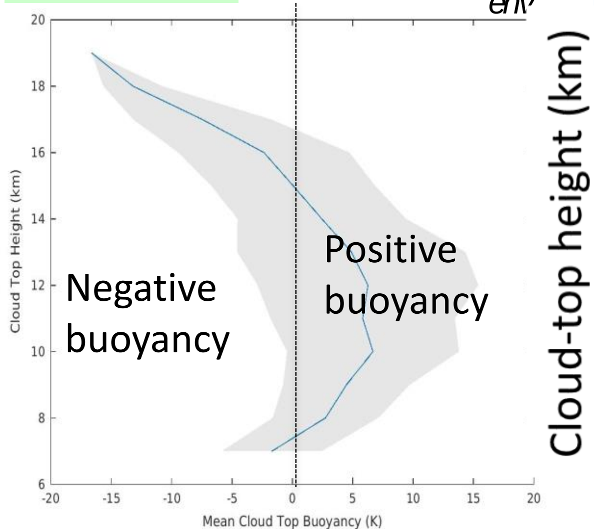

~2 min




Luo et al. (2014)

## Cloud-top buoyancy

$$B = g\frac{T_{parcel} - T_{env}}{T_{env}}$$

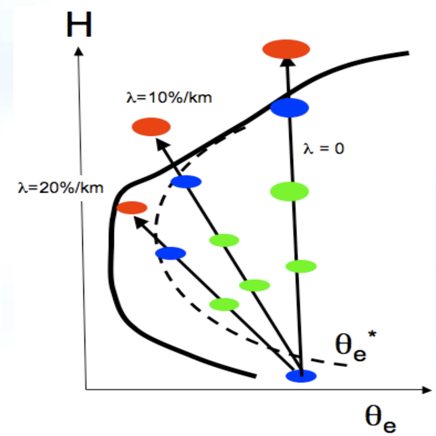



Cloud-top buoyancy (K)

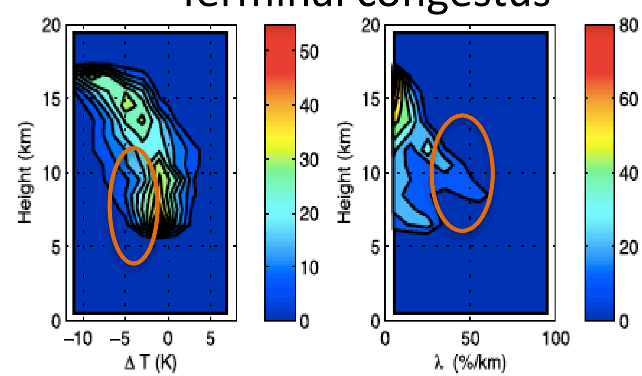
Luo et al. (2010); Wang et al. (2011)

## Entrainment

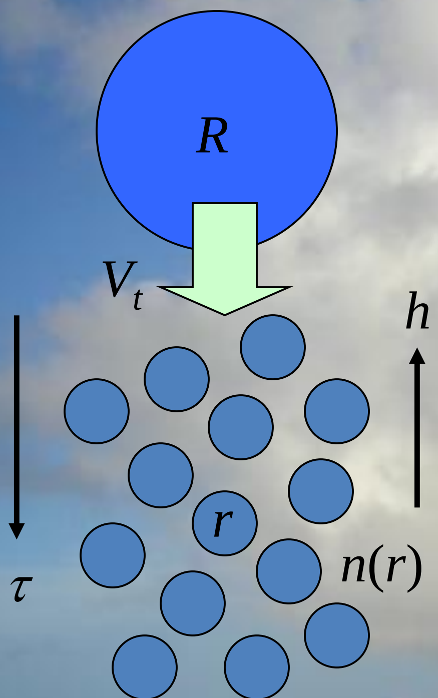
Entrainment: By estimating $\theta_e$ of convective top and placing it in the context of the ambient $\theta_e$ profile, we are able to calculate the entraining rate (using the entraining plume model)




Terminal congestus



# Observing the warm rain process globally




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

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

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

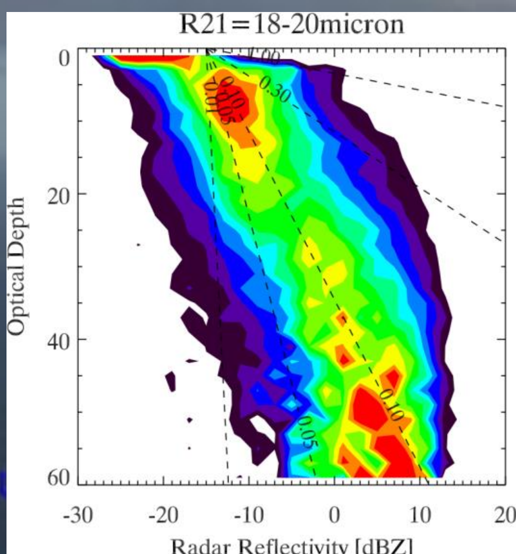
$$\frac{dZ_e}{Z_e} = \lambda \frac{dR}{R}$$

$$dt \approx -\frac{3}{2}\frac{1}{\rho_w}\frac{q_c}{R}\,dh$$

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

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

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

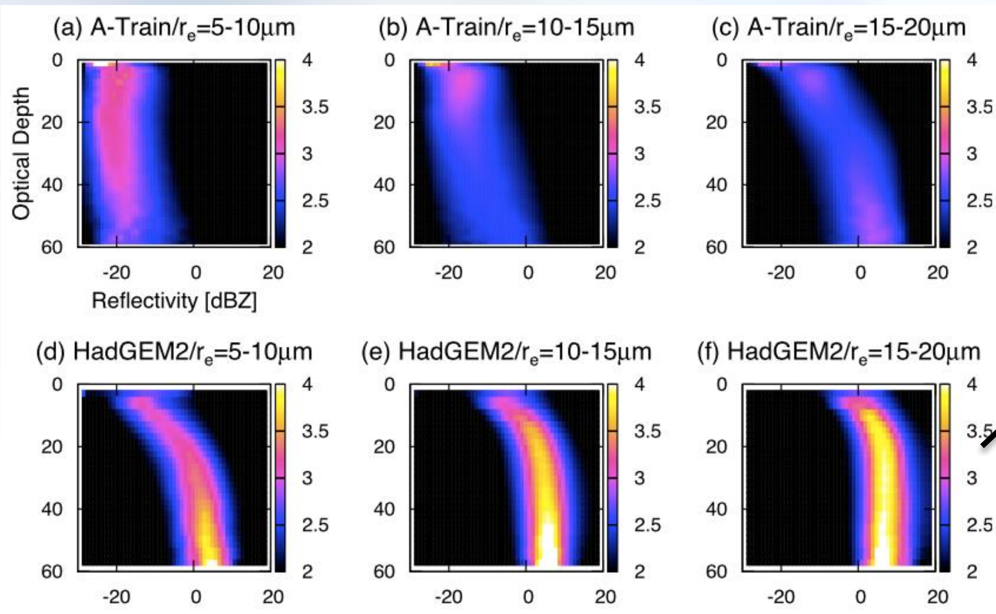


# Understanding processes - improving parametrizations
# Using observation synergy and modelling studies

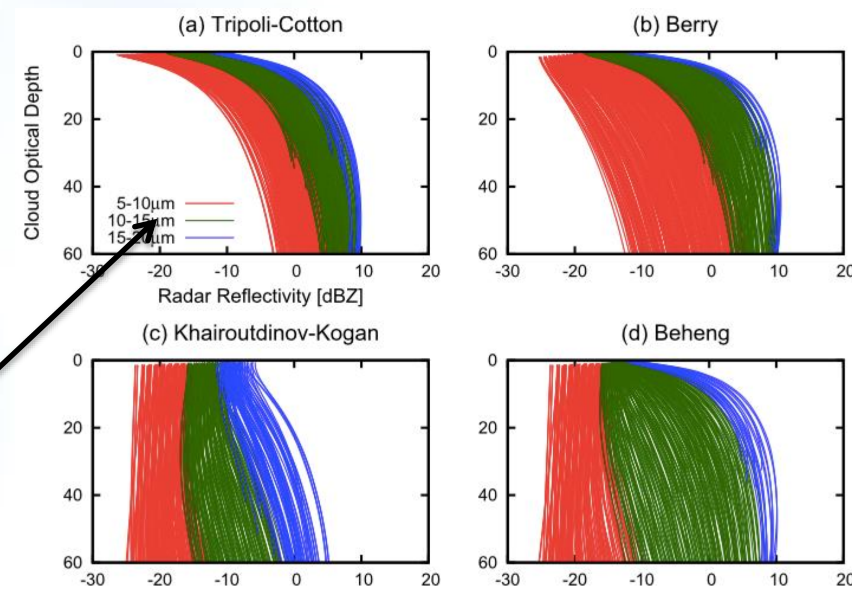
## Example: Warm-rain formation process using A-Train data, GCMs and process models.

Suzuki et al. 2015

Z vs Optical Depth for different $R_{eff}$ from CloudSat/MODIS and from the HadGEM2 model




Effect of different autoconversion parametrizations



# CRM

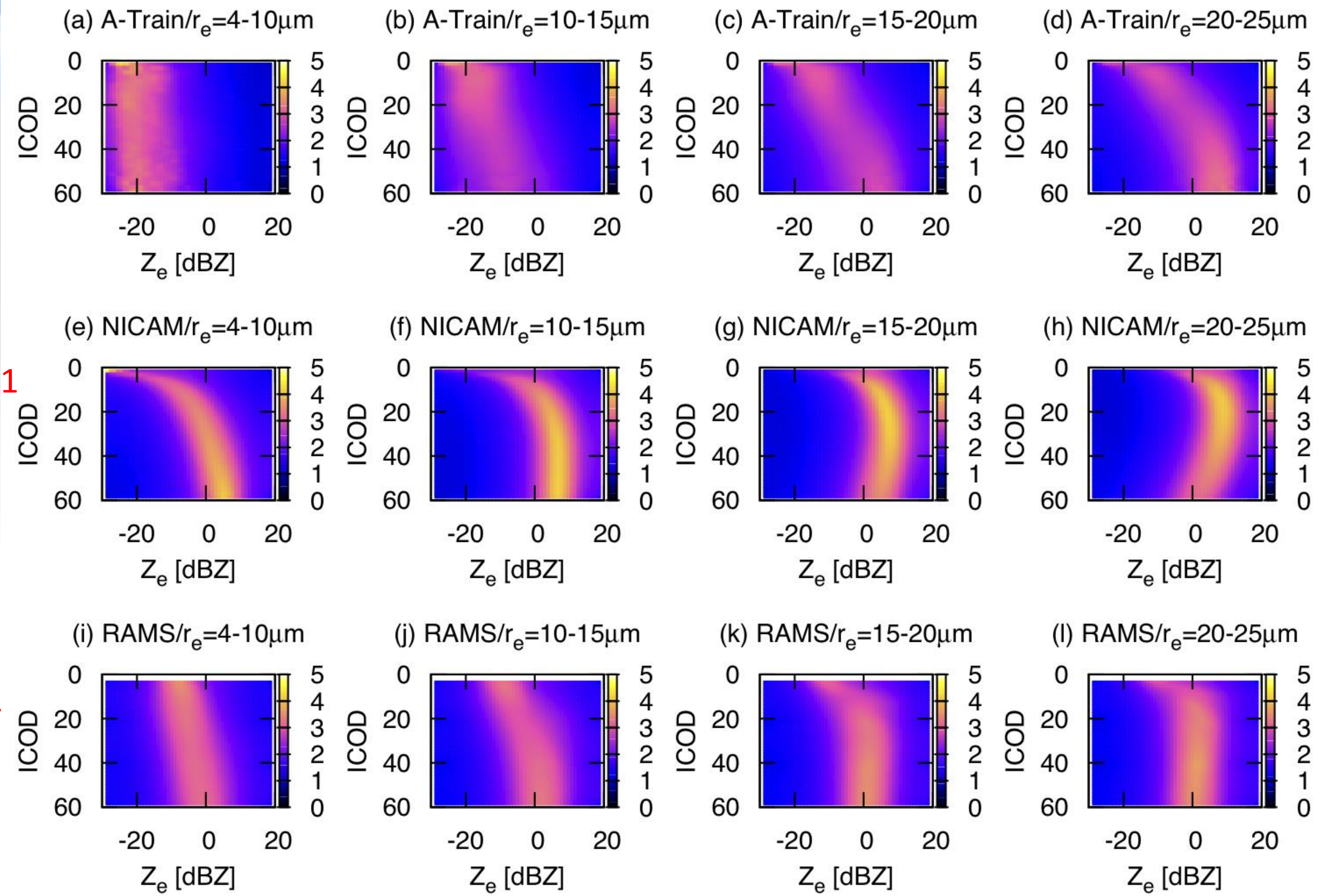
Suzuki *et al*. (JAS'11)

$R_e$=4-10mm　$R_e$=10-15mm　$R_e$=15-20mm　$R_e$=20-25mm

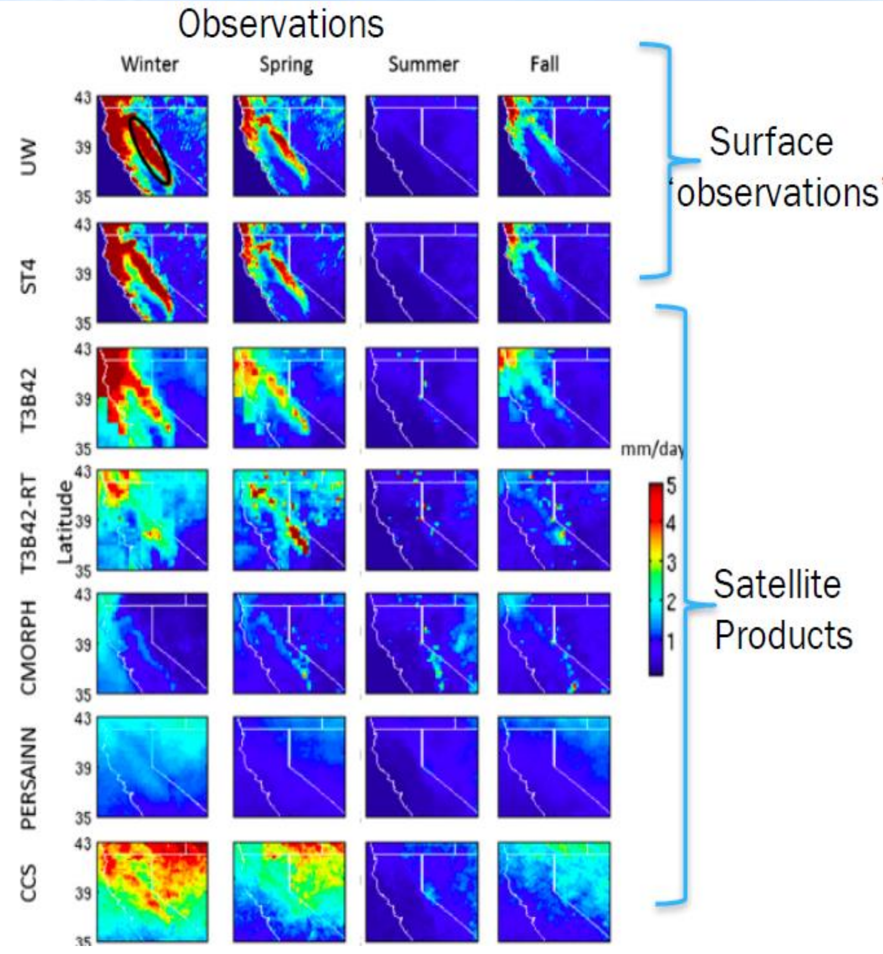
A-Train

NICAM(1-mom)

RAMS(2-mom)



# The challenge of Orographic Precipitation:




Behrangi et al. (JHM 2014)

## Some key challenges:

- **Capturing <u>orographic precipitation</u> remains a challenge for remote sensing of precipitation**
- **A large fraction of the precipitation falls in winter and as snow over mountains. Yet, <u>snow retrieval skill is limited</u> from space**
- **In practice <u>we don't determine precipitation phase from space</u>. It is based on established relationship between temperature and precipitation phase observed in stations. Given that temperature data is often from reanalysis and at coarse spatial resolution it can be a large source of uncertainty.**
- **High resolution modeling remains as a viable alternative to help**

Surface radar data challenges in orography

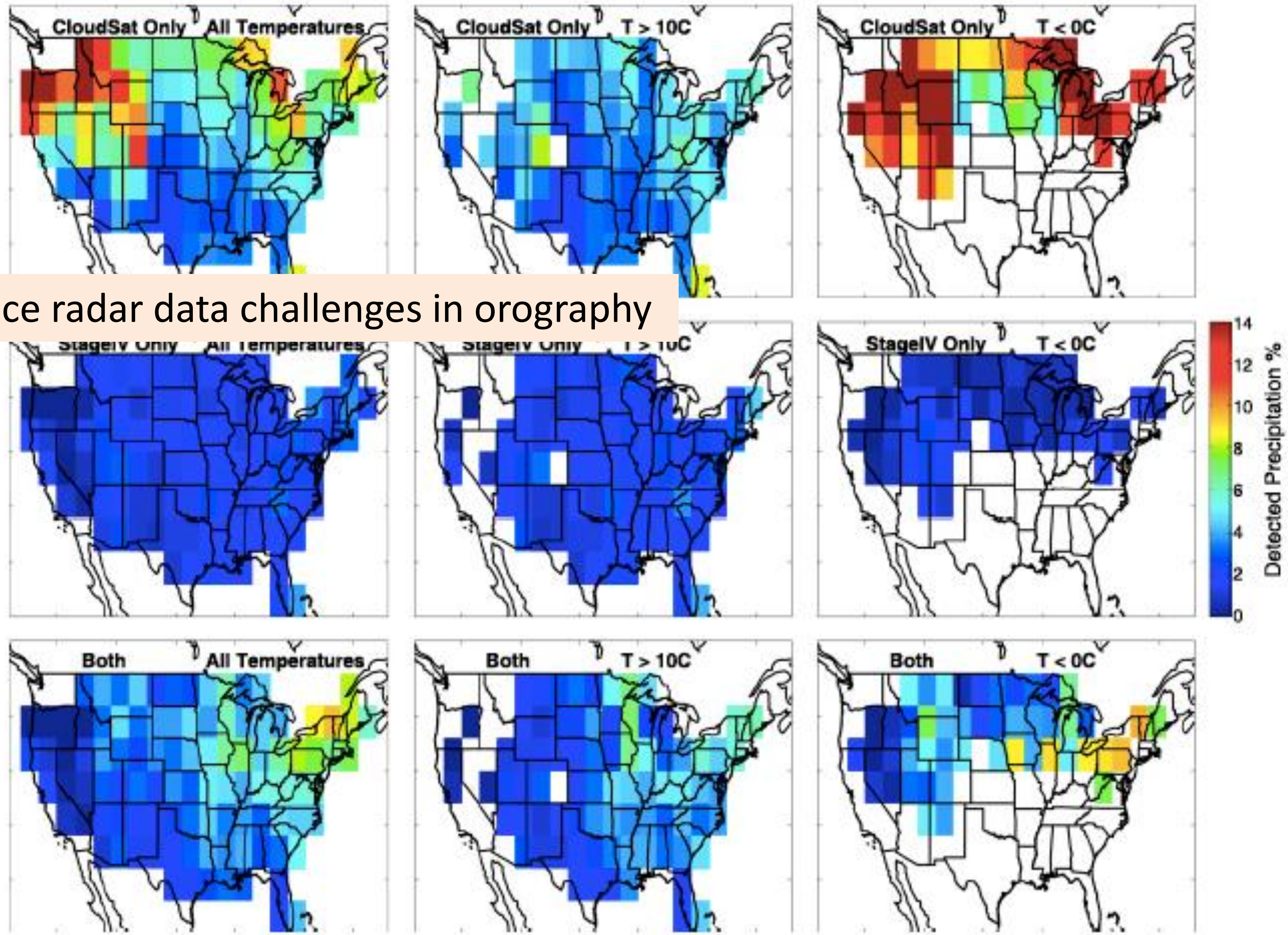
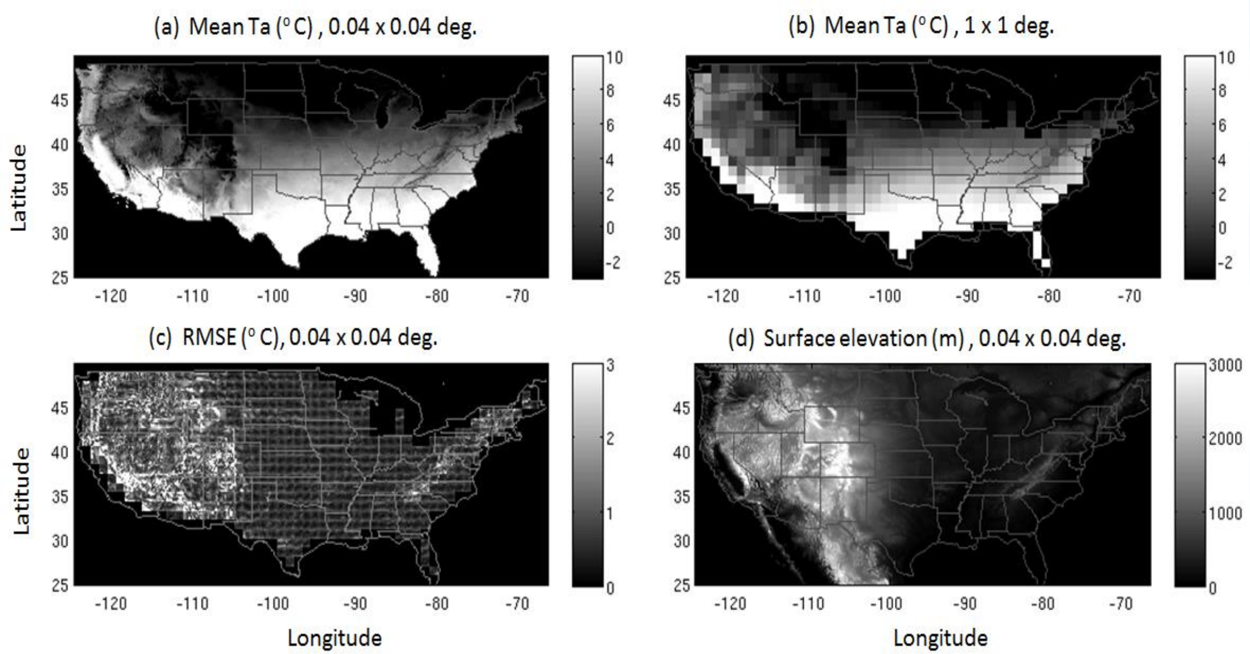
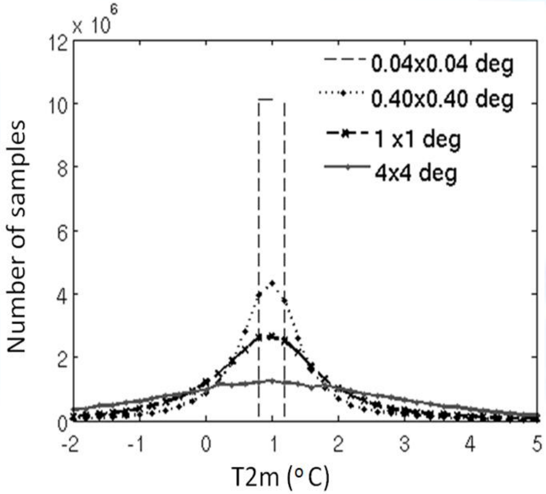



FIG. 4. Relative statistics for 48 months of collocated Stage IV and *CloudSat* precipitation detections. (left) Data from all temperatures;, (middle),(right) only data for which the 2-m near-surface air temperatures from ECMWF are >0°C and <0°C, respectively. Grid boxes are omitted if the corresponding *CloudSat* standard errors are found to be >25%, as computed by Eq. (1).

Smalley et al., 2015

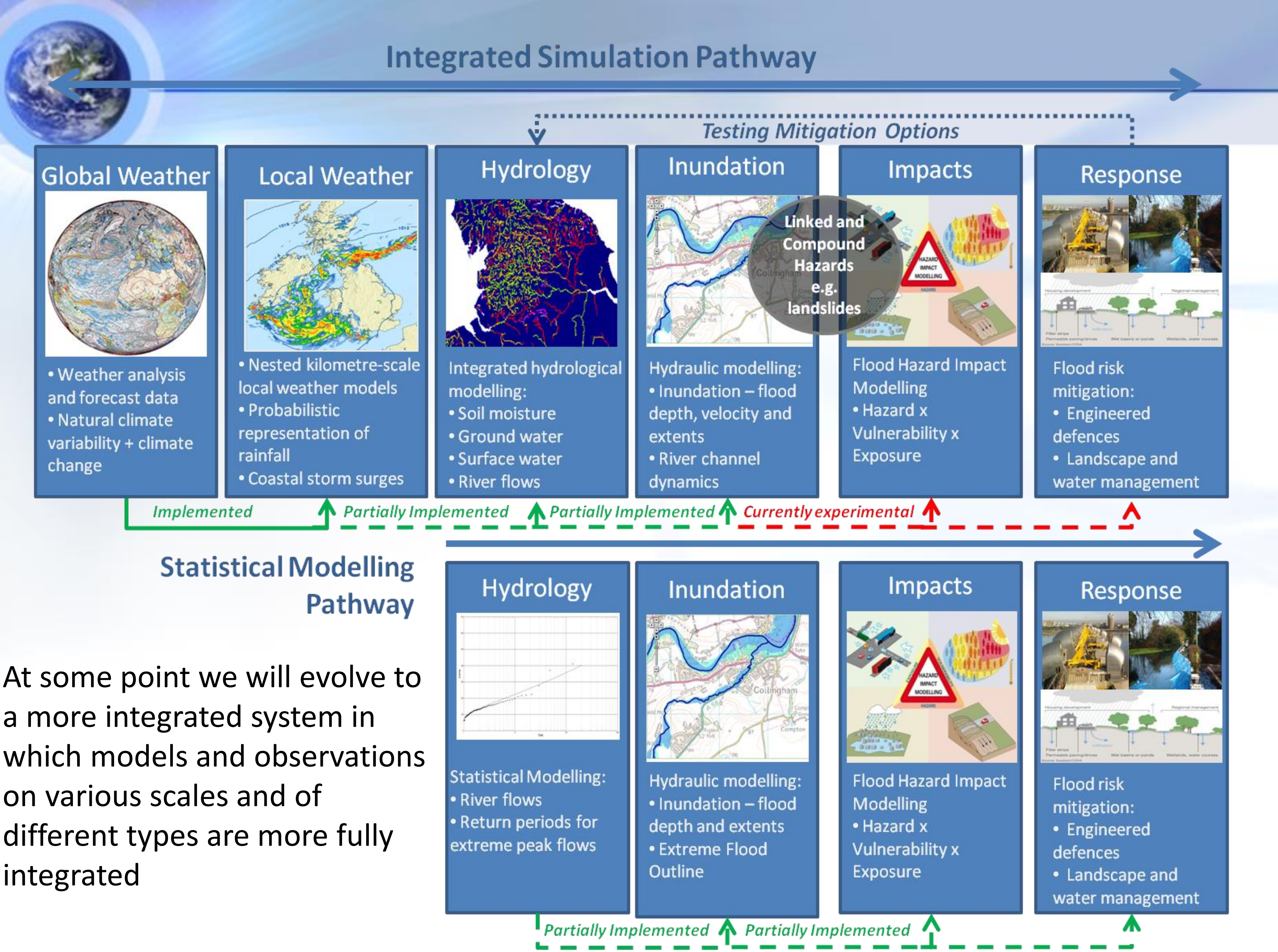
# Spatial resolution for improving observations



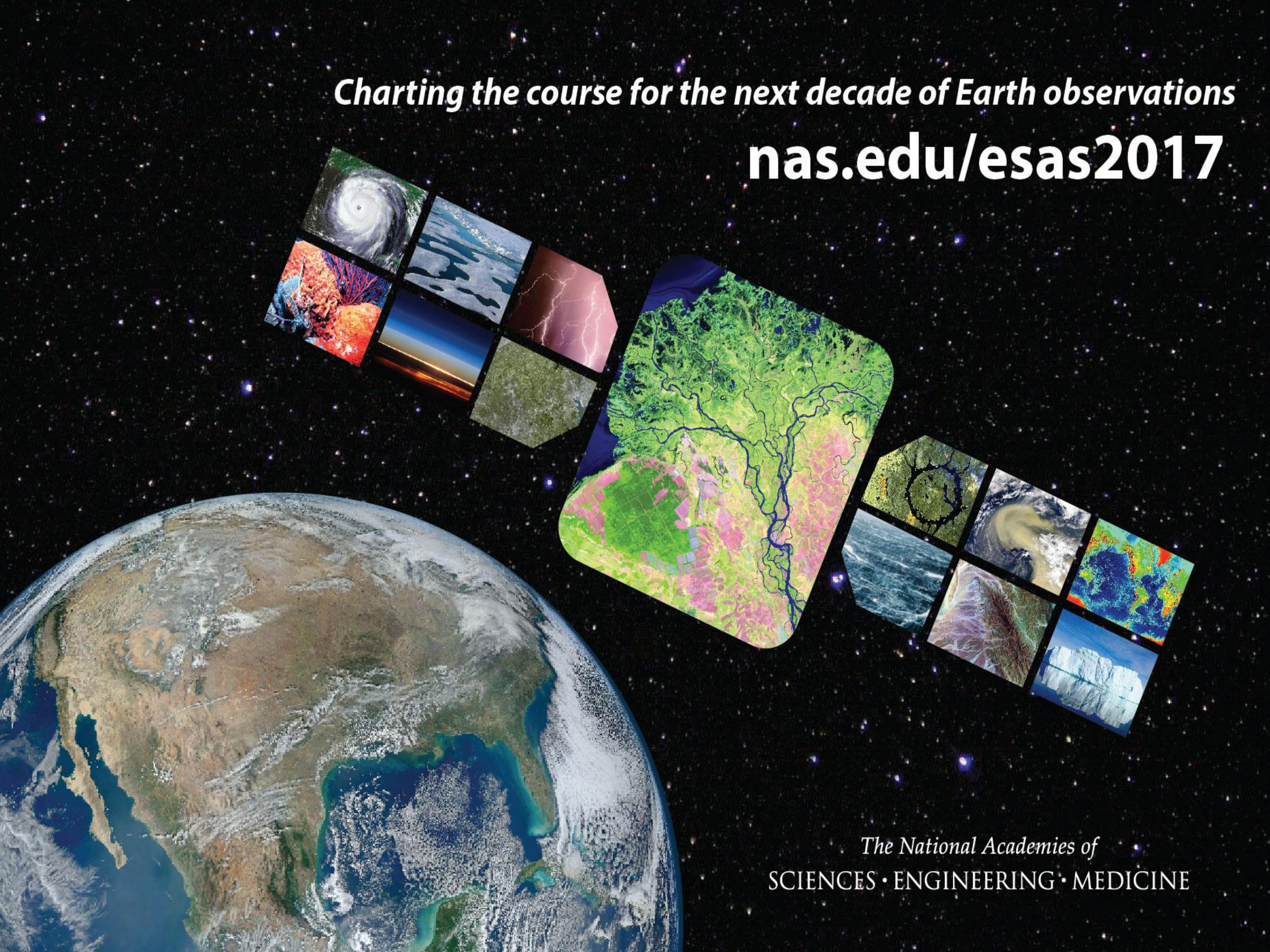




Moving from 0.4x0.4 deg. Resolution that is typical resolution of reanalyses to 0.04 x0.04 deg. we can experience about 3°C or higher error in temperature in topographically complex regions. The impact appears critical for many applications including snow-rain separation.

Behrangi et al. 2016 (submitted to *J. of water resources research*)




At some point we will evolve to a more integrated system in which models and observations on various scales and of different types are more fully integrated


Charting the course for the next decade of Earth observations
nas.edu/esas2017
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

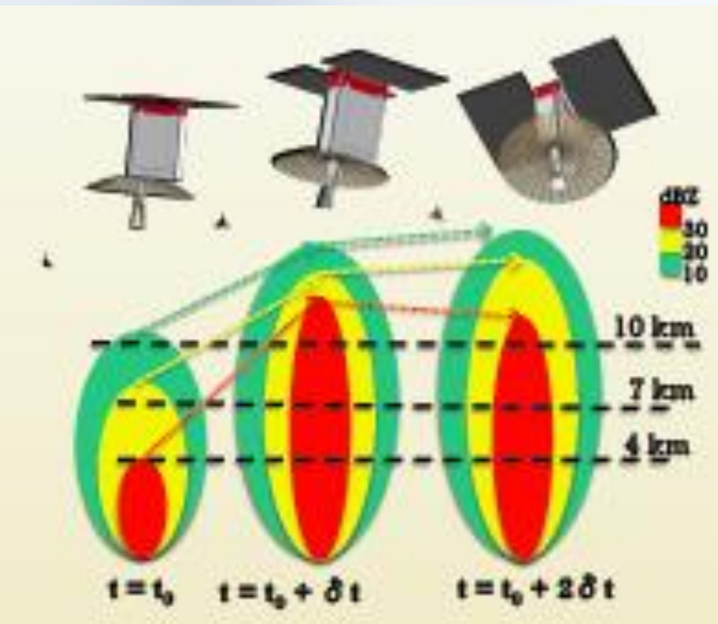
# ESAS 2017 Panels

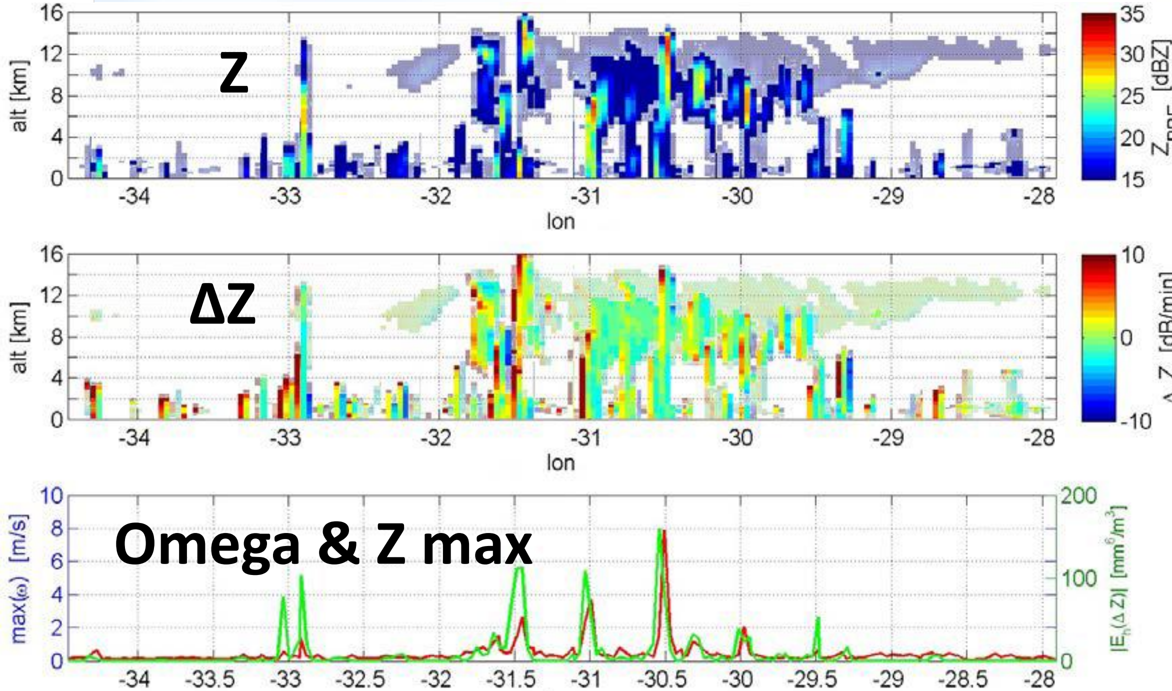
WORKING GROUPS (Tentative)

| | Weather: Minutes to Sub-seasonal | Climate Variability and Change | Marine & Terrestrial Eco-systems | Global Hydrological Cycle & Water Resources | Earth Surface & Interior |
|---|---|---|---|---|---|
| Extreme Events | | | | | |
| Water Cycle | | | | | |
| Carbon Cycle | | | | | |
| Technology & Innovations Cross-Cut | | | | | |
| Applications' Science Cross-Cut | | | | | |

Technology is advancing offering new ways to consider making measurements

Performance > GPM Ka




- Provides more accurate measures of condensed mass because biases get removed
- Provides methods to estimate mass flux, previously unthinkable

**Uncertainties in observed daily precipitation extremes over land**

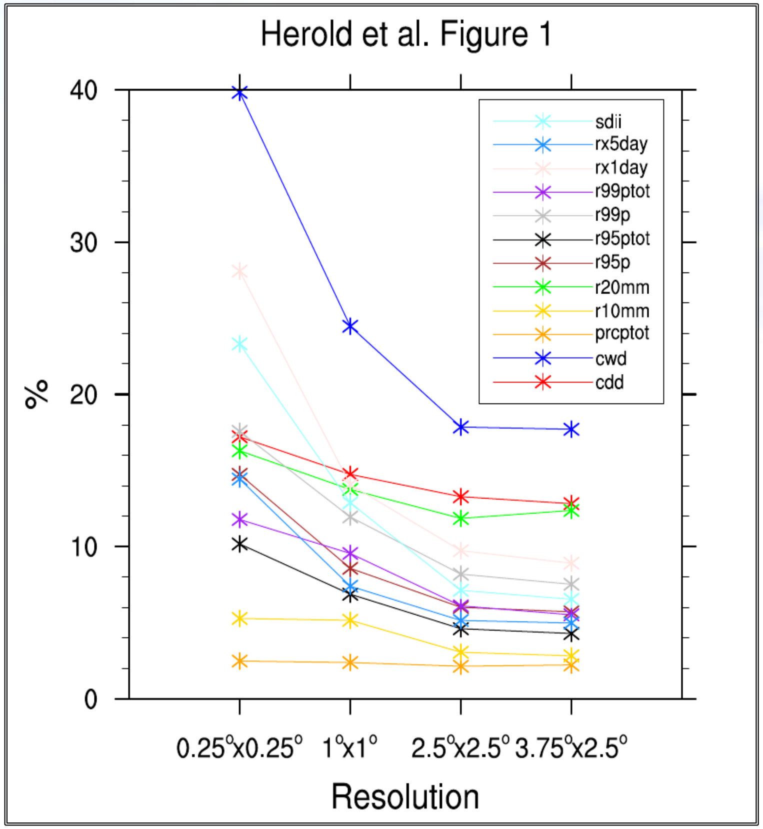
N. Herold*[1], A. Behrangi[2], L.V. Alexander[1]

[1]Climate Change Research Centre & ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia.

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA.

Submitted to JGR

- Generally, ***the more extreme a precipitation index is, the more sensitive it is to product and resolution choice.***
- ***A minimum resolution exists where observations exhibit agreement on extremes.*** Product sensitivity is prominent at resolutions of 1°x1° and finer. Thus inter-product differences will be particularly problematic when evaluating precipitation extremes in high resolution global climate models. This provides an insight on the finest resolution models should be evaluated at.




*Inter-product variability for each index at each resolution*

## INTENSE workshop

*Sub-daily rainfall extremes: data, processes and modelling*

**The Core, Newcastle upon Tyne, 13-15th September 2016**

# Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?

- Boundary layer?
- Convective transport?
- Entrainment/detrainment?
- Other?

Q2: What level of complexity in observations is really needed to advance our understanding and ability to model moist atmospheric processes?

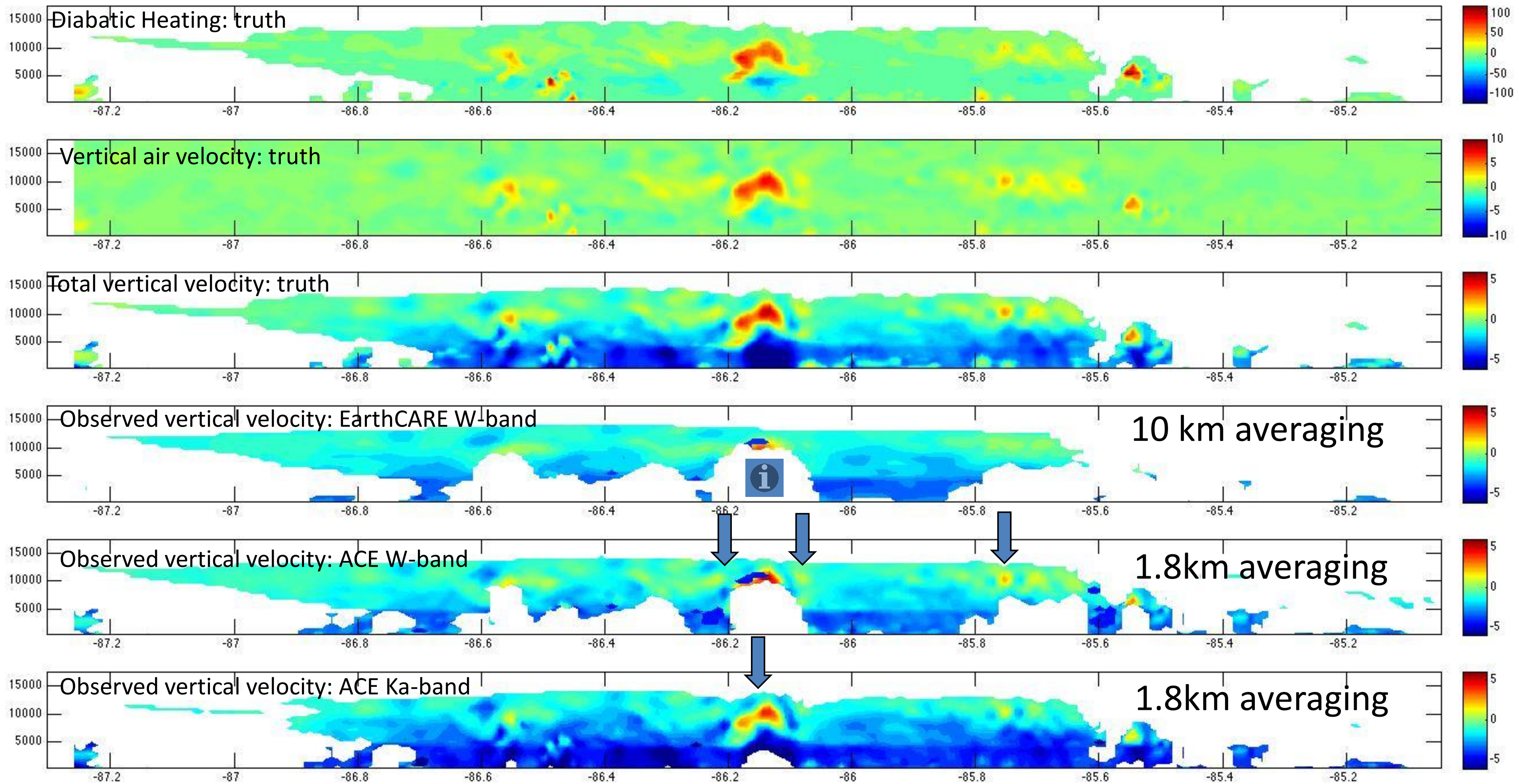
- Is information on bulk microphysics enough?
- Representativeness? Large volumes of coarse data (e.g. global) versus very small samples of higher resolved information?

Q3: Are we really making the most effective use of the observational capabilities we currently have?

- Assimilation of cloud/precipitation information?
- Use of simulators?
- Surface data & field expt data?
- Growing data records

**(Model) data without validation is merely rumour**

# Vertical motion measurement from space



# COPERNICUS SENTINELS

**SENTINEL-6 (Jason-CS)**
- 2020
- Radar altimeter
- 10 days
- Measure precision sea-surface height for ocean and climate studies

**SENTINEL-1**
Launch Date: 1A: Launched; 1B: 2016
Payload: All Weather Imaging Radar
Revisit time: 1-6 Days
Applications: Monitoring sea ice and the Arctic, Land Surface motion risks, disaster response

**SENTINEL-2**
- 2A: Launched; 2B: 2016
- Optical imaging sensor with 13 bands
- 2-5 days
- Monitoring land-use changes, agriculture and ecosystems, volcanoes and landslides

**SENTINEL-5**
- 2021
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer on Metop-SG A satellite
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate


**SENTINEL-3**
- 3A: Launched; 3B: 2017
- Radar altimeter, Sea/land surface temperature radiometer, sea/land colour imager
- 1-2 days (imagers); 27 days (altimeter)
- Sea-surface and land-ice topography, sea and land surface temperature and colour

**SENTINEL-5 precursor**
- 2016
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate

**SENTINEL-4**
- 2021
- Ultraviolet/visible/near-infrared spectrometer on MTG-S satellite
- Geostationary. Hourly coverage of Europe/North Africa
- Monitoring of air pollution, stratospheric ozone, solar radiation

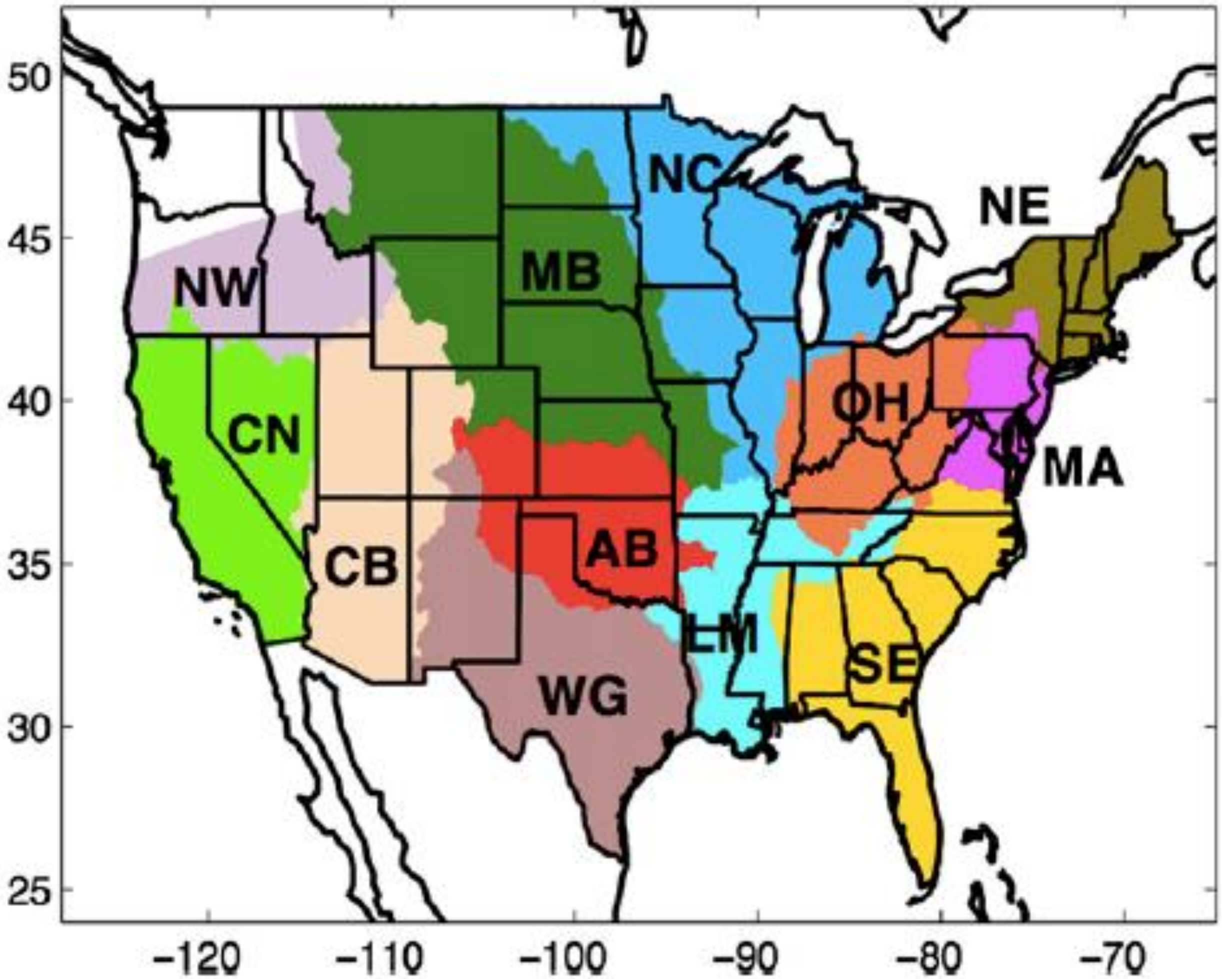



FIG. 1. Stage IV precipitation accumulation coverage for the Northwest (NW), California–Nevada (CN), Colorado Basin (CB), Missouri Basin (MB), Arkansas–Red Basin (AB), West Gulf (WG), North Central (NC), Lower Mississippi (LM), Ohio (OH), Northeast (NE), Middle Atlantic (MA), and Southeast (SE) RFC basins. Study coverage is limited to the CONUS.

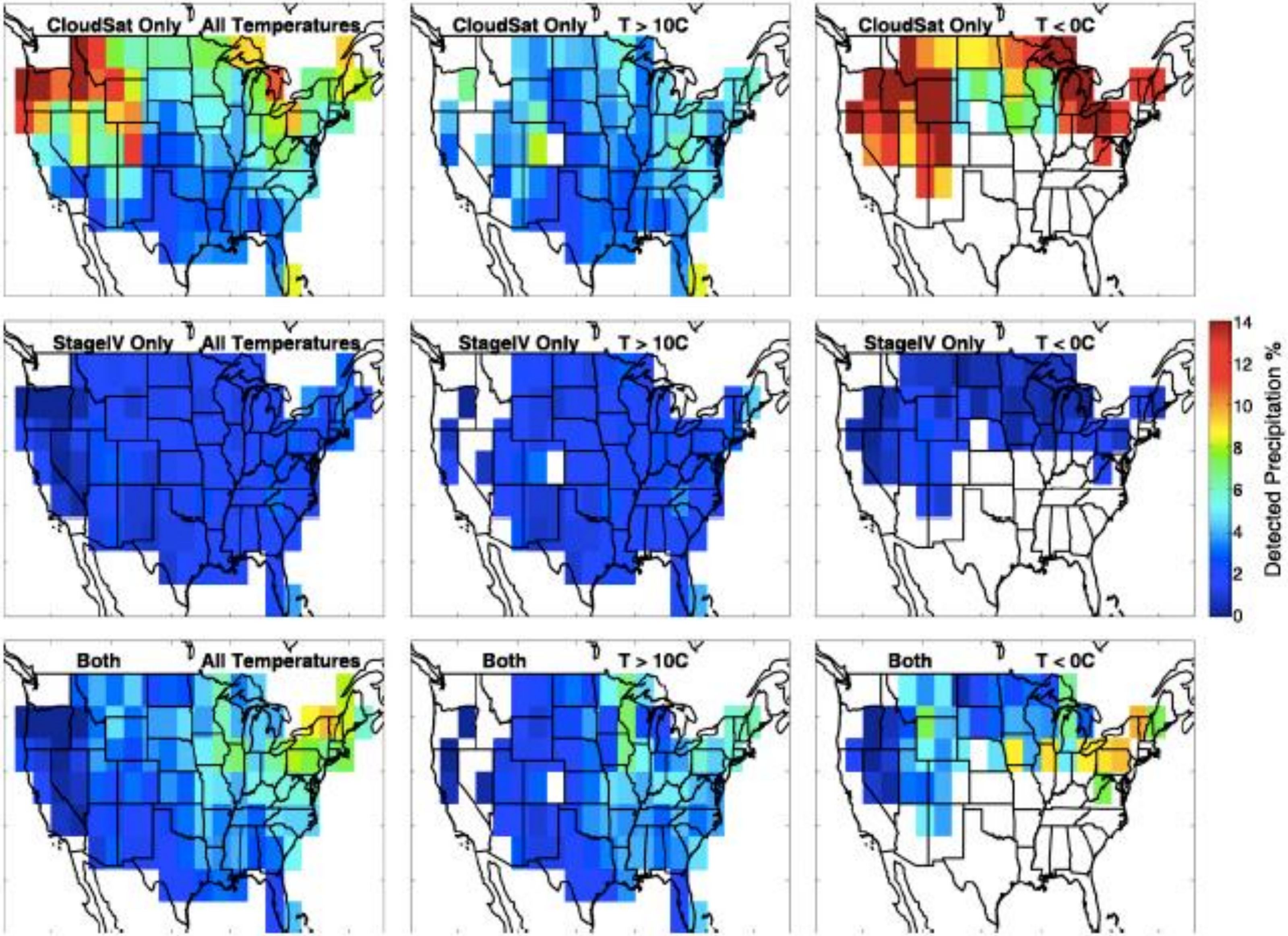
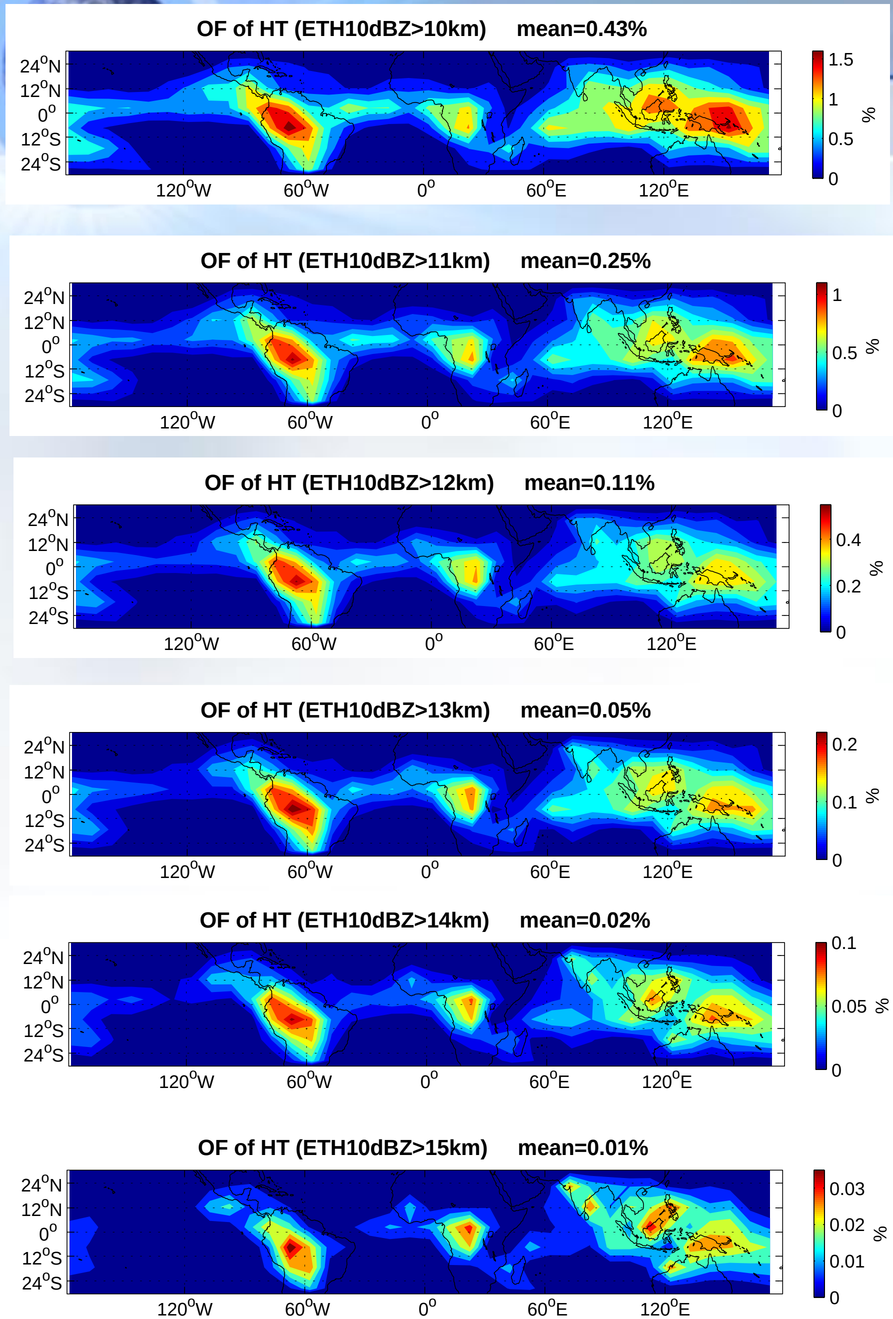
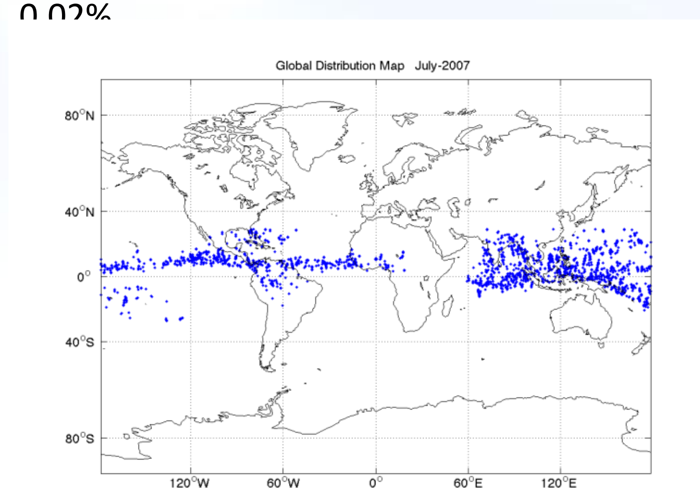
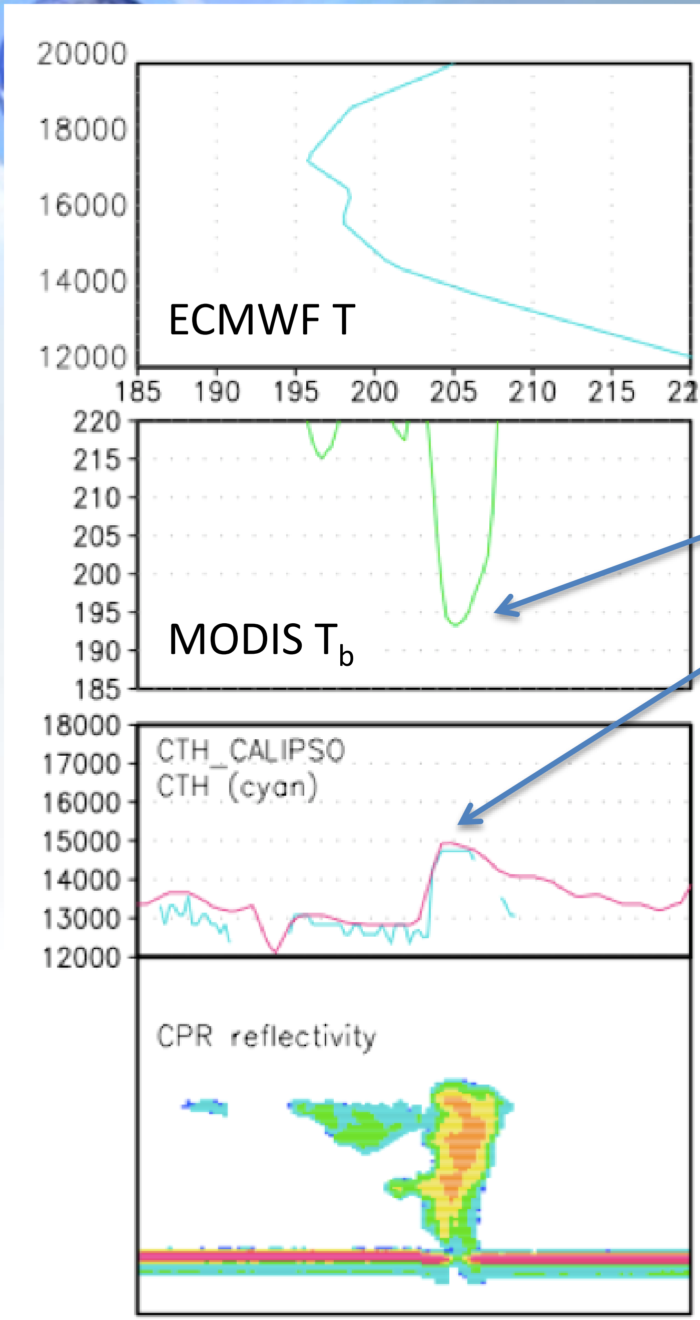



FIG. 4. Relative statistics for 48 months of collocated Stage IV and *CloudSat* precipitation detections. (left) Data from all temperatures;, (middle),(right) only data for which the 2-m near-surface air temperatures from ECMWF are >0°C and <0°C, respectively. Grid boxes are omitted if the corresponding *CloudSat* standard errors are found to be >25%, as computed by Eq. (1).




- Occurrence frequency of hot towers with different reference levels (from ETH10dBZ greater than 10 to 15km).
- This maps illustrate how the occurrence frequency of HT will changes over weaker HT (e.g., larger entrainment) to stronger H HT (e.g., small entrainment).
- The assumption of 14km is closed to the statistics given by Rieh and Malkus (1979) whose coverage of HT over 30S-30N is 0.02%






$$C_pT + gz + L_vq$$

Cloud-top MSE ($T_b$ has been corrected for non-blackbody effect)

$$B \equiv g\frac{T_{parcel} - T_{env}}{T_{env}}$$

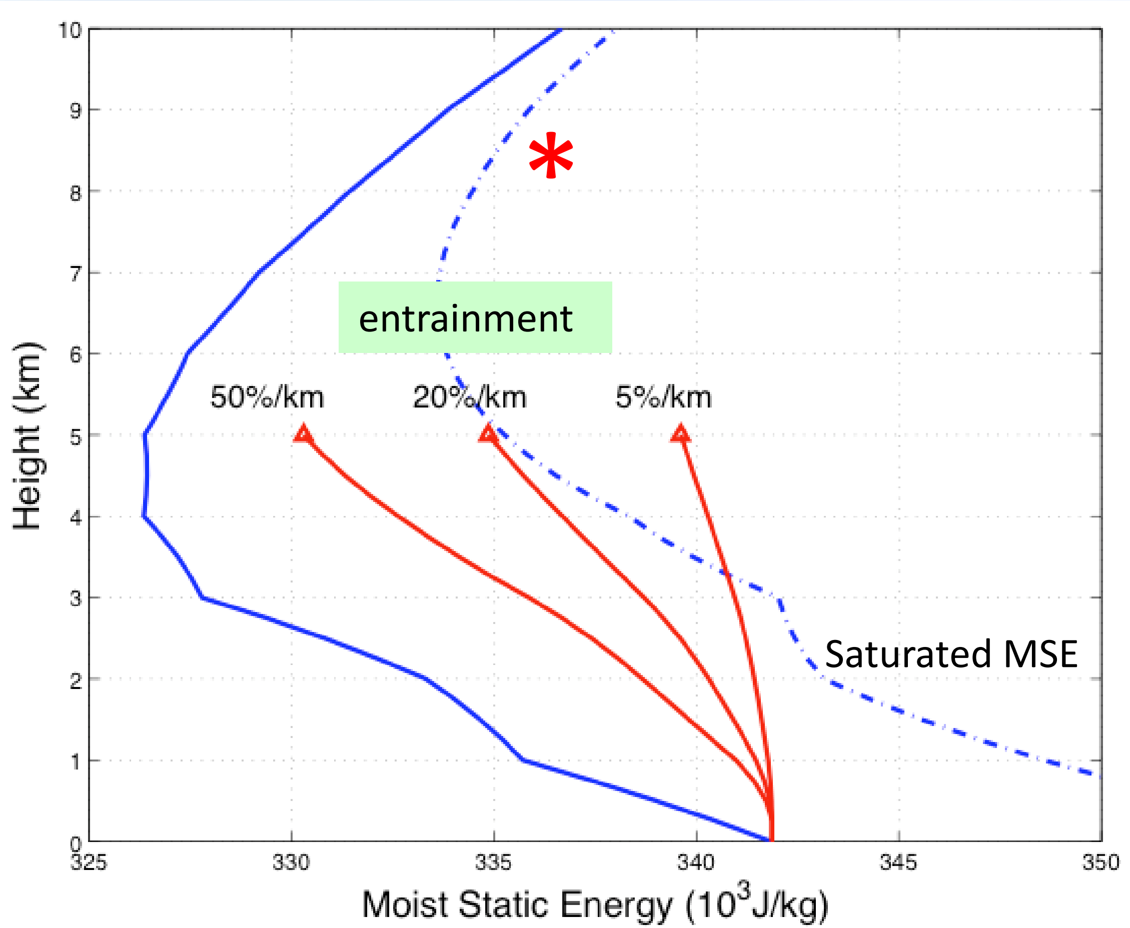
$T_{parcel}$=193 K; $T_{env}$=198 K

Negatively buoyant!

Luo et al. (2010)

Integrate this equation from PBL upward to the observed cloud top height. Iterate λ until the calculated MSE matches the observed MSE. Then that's the inferred entrainment rate

$$\frac{dF}{dz} = /\,(F' - F)$$

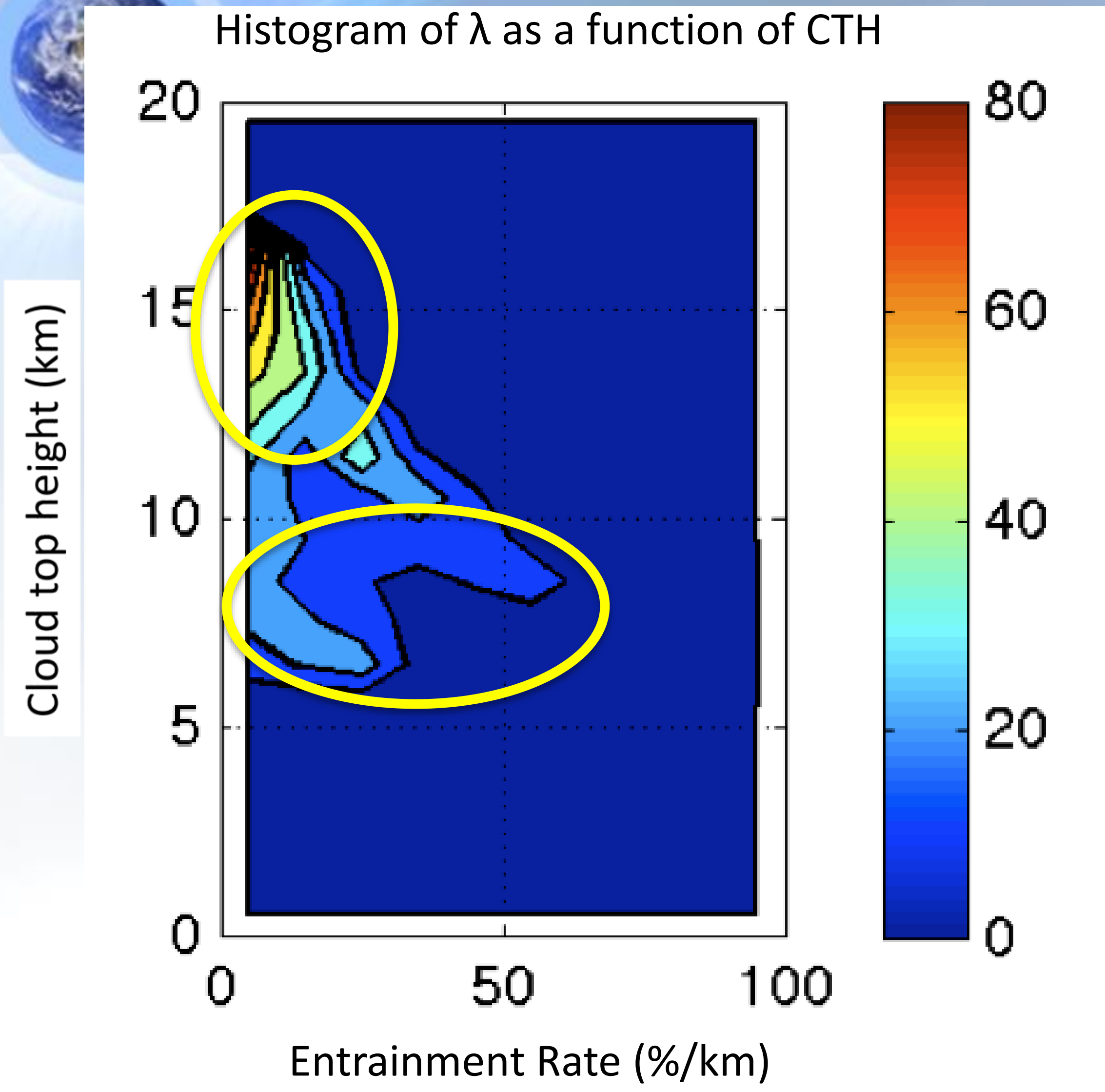


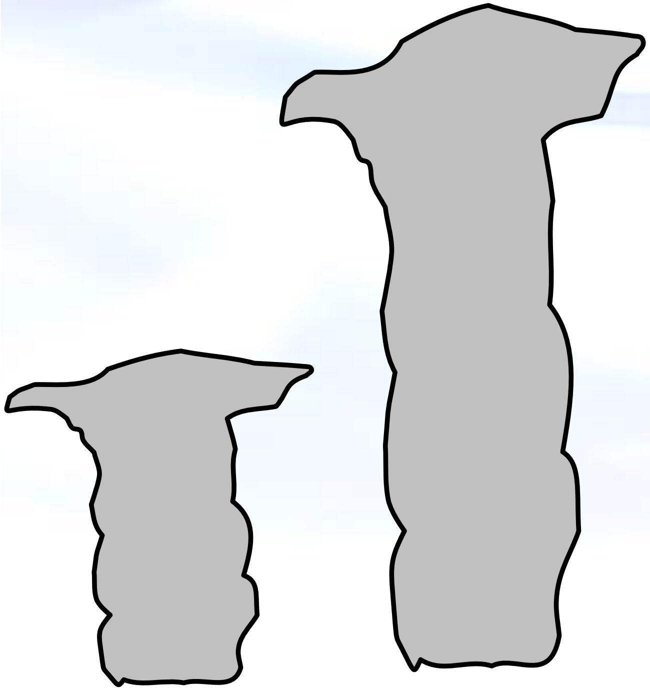

Caveat: 1) Assuming the environment (50 km) MSE represents that of the cloud base, 2) using the bulk entraining plume model

Energy boost from ice nucleation is ignored for now, but could be included using CloudSat IWC product

Luo et al. (2010)

# Entrainment rate

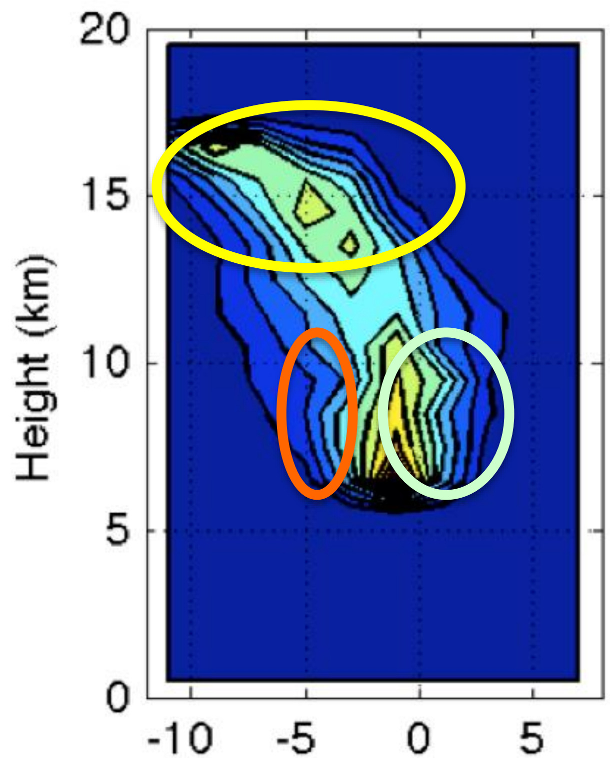


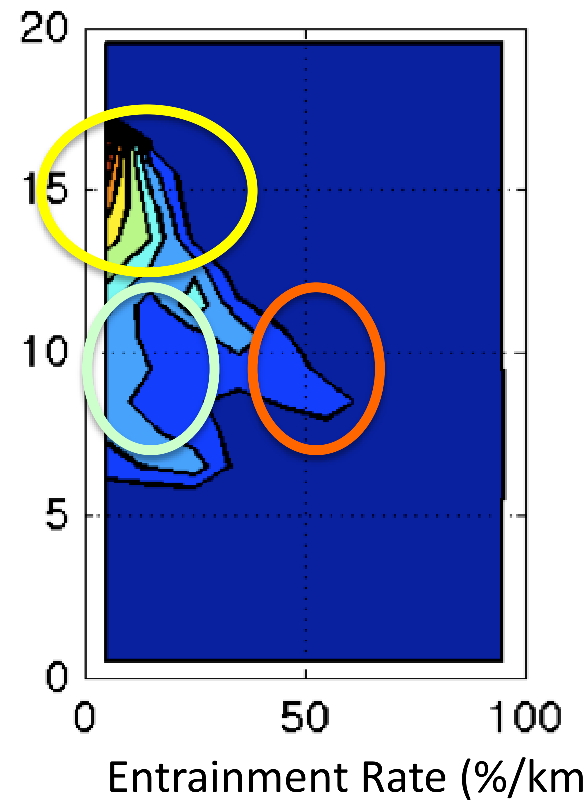
Luo et al. (2010)

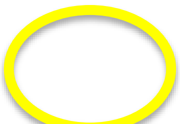
Buoyancy

Entrainment rate

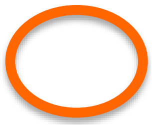



$\Delta T = T_{parcel} - T_{env}$ (K)

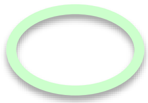


Deep convection:
B <0 & λ < 10%/km



"Terminal" cumulus congestus:
B < 0 & λ up to 50%/km



"Transient" cumulus congestus:
B > 0 & λ ~ 10%/km

Luo et al. (2010)

# Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?

- Boundary layer?
- Convective transport?
- Entrainment/detrainment?
- Other?

Q2: What level of complexity in observations is really needed to advance our understanding and ability to model moist atmospheric processes?

- Is information on bulk microphysics enough?
- Representativeness? Large volumes of coarse data (e.g. global) versus very small samples of higher resolved information?

Q3: Are we really making the most effective use of the observational capabilities we currently have?

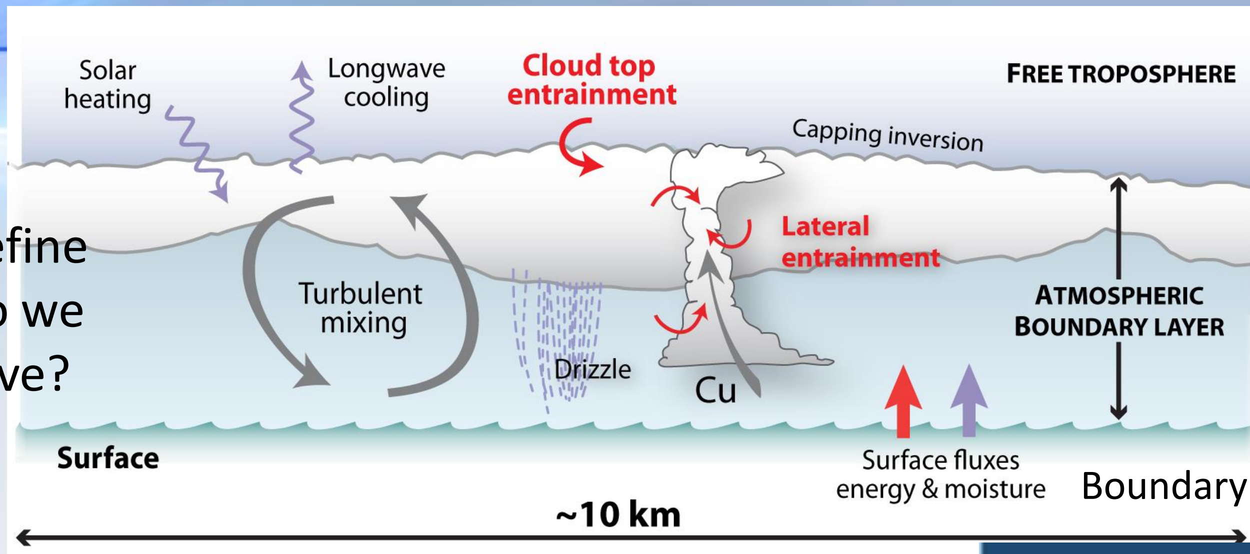
- Assimilation of cloud/precipitation information?
- Use of simulators?
- Surface data & field expt data?
- Growing data records

**(Model) data without validation is merely rumour**

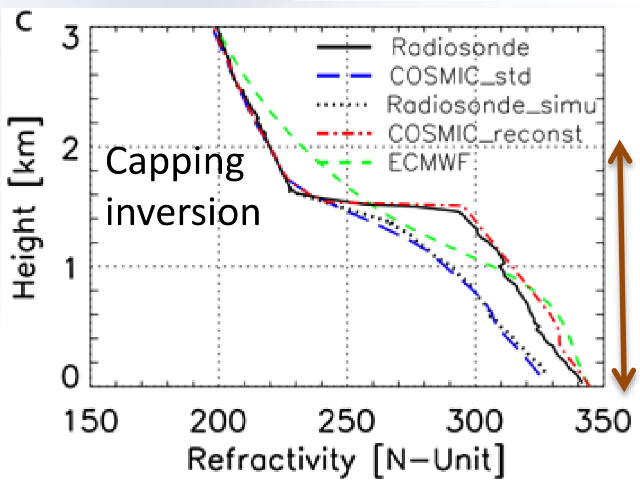
- The boundary layer
- Warm clouds
- Mixed phased clouds
- Convection
- Aerosol and ‘degrees of freedom’
- Heating distributions (radiative and latent heating)
- Polar clouds and precipitation
- Prospects for the decade ahead

# 1) The Boundary Layer

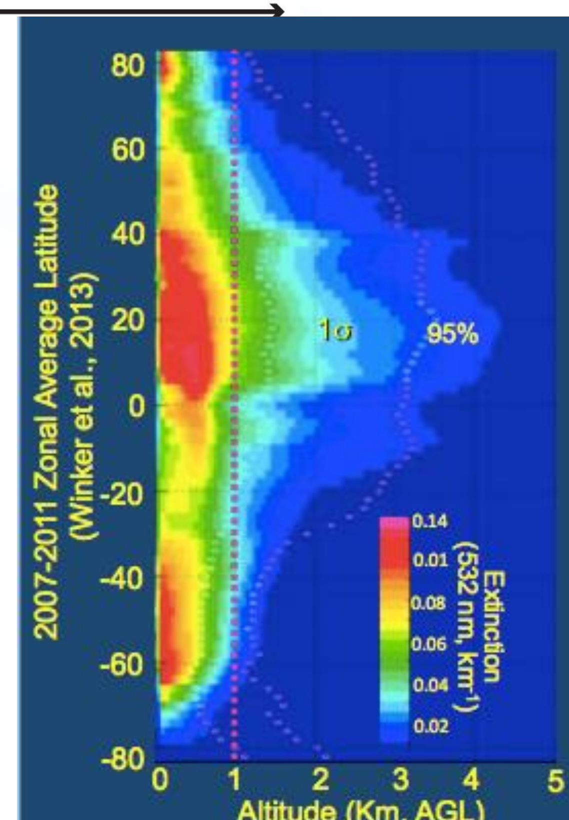
How do we define it and what do we want to observe?



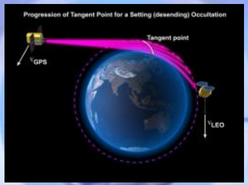

Boundary Layer Processes




So if we really want to study the primary physical drivers of aerosol science instead of the aftermath, we absolutely need good PBL measurements (Reid, 2016, CC 10 year anniversary).




BL height resolved variables: T,q,v, fluxes, cloud macro and microphysics….

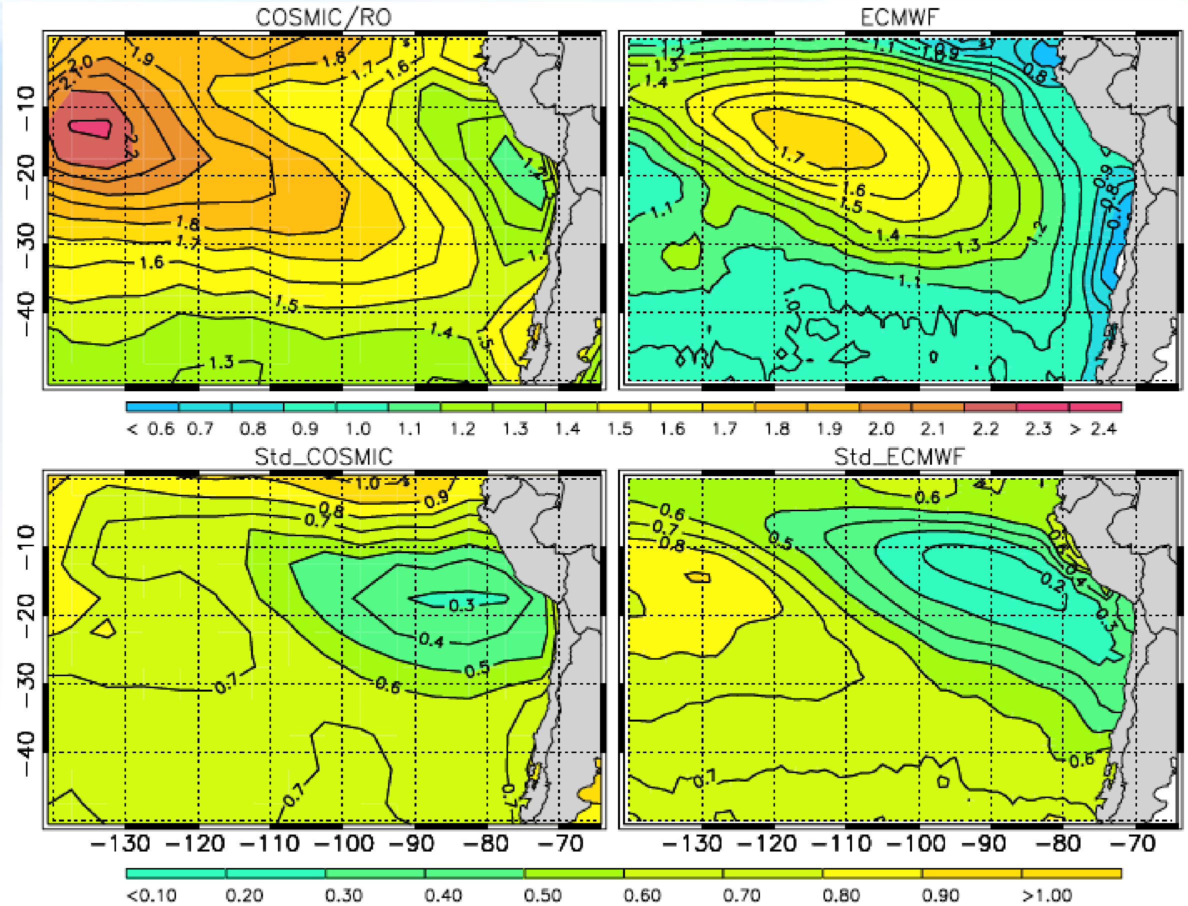


# Atmospheric Boundary Layer Height

## Eastern Pacific Stratocumulus Region

Mean height

Height variability (std)

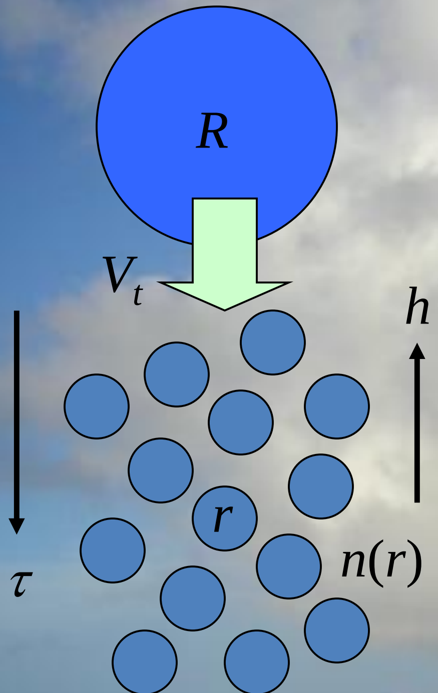



VOCALS campaign region

ECMWF analyses (TL799L91). Period: Sept-Nov 2007-2009.


F. Xie, D. L. Wu, C. O. Ao, A. J. Mannucci, and E. R. Kursinski (2012) “Advances and limitations of atmospheric boundary layer observations with GPS occultation over southeast Pacific Ocean” Atmos. Chem. Phys., 12, 903–918, 2012 doi:10.5194/acp-12-903-2012.

# 2) Observations of warm cloud processes




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

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

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

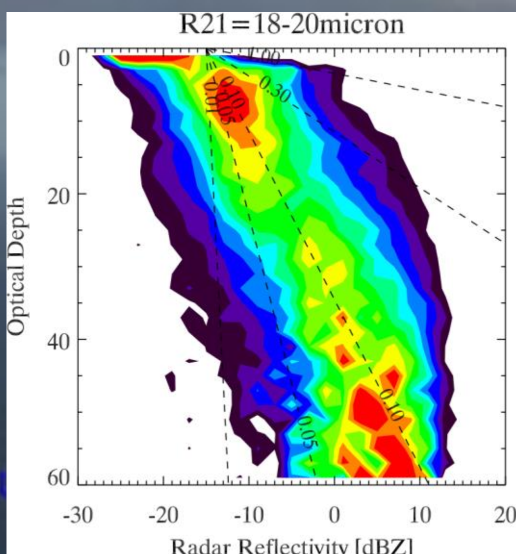
$$dh = -V_t(R)dt$$

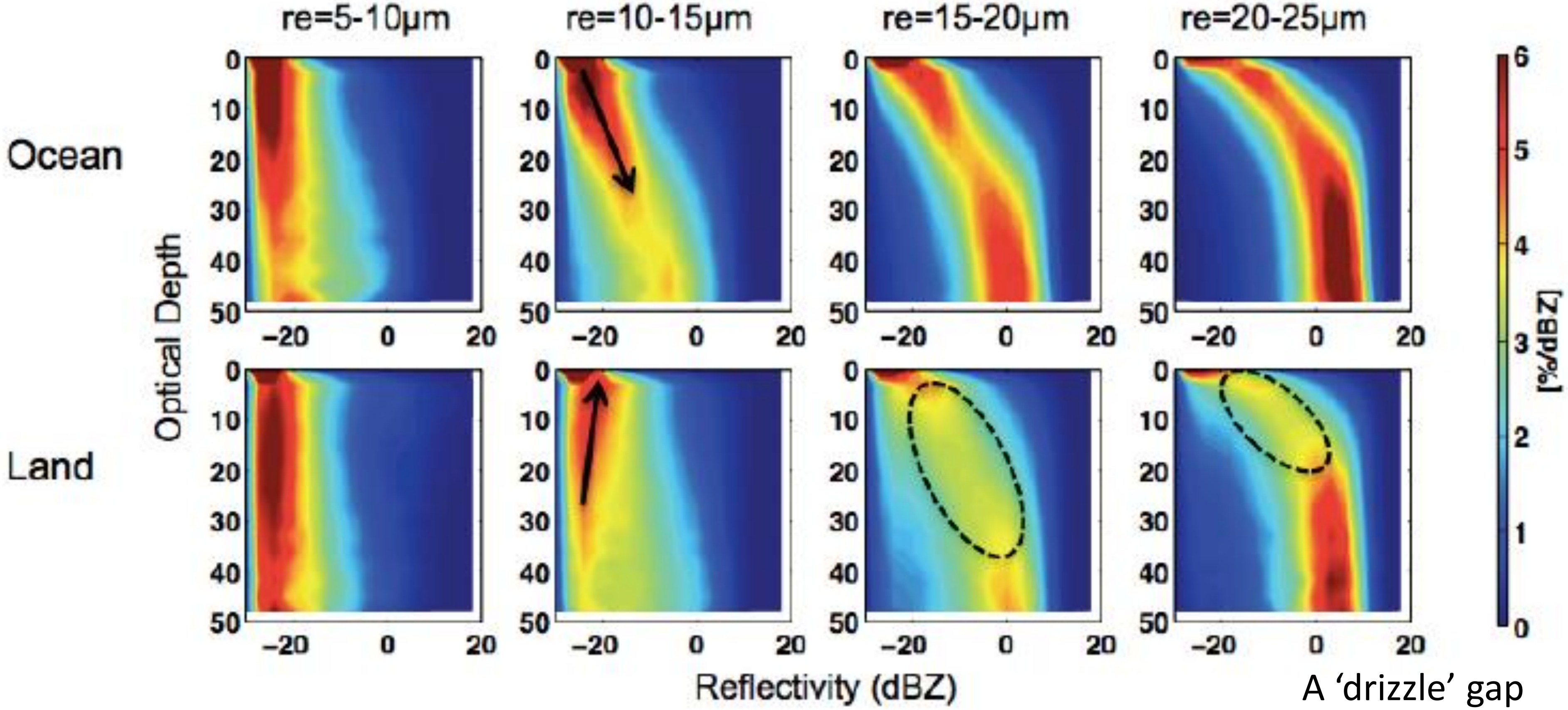
$$\frac{dR}{dh} = -\frac{E_c}{4\rho_w} q_c \qquad \frac{dR}{R} = -\frac{E_c}{4\rho_w}\frac{q_c}{R} dh$$

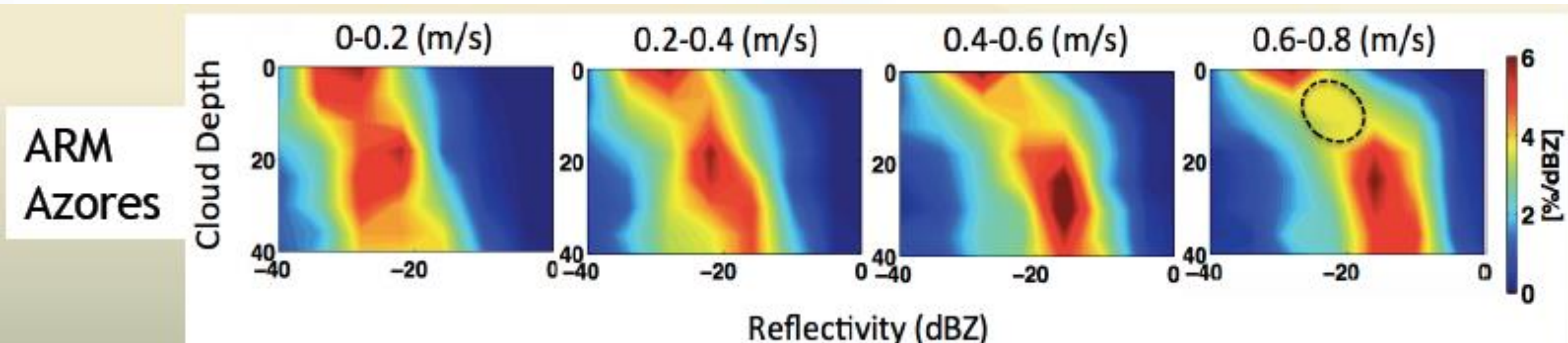
$$\frac{dZ_e}{Z_e} = \lambda \frac{dR}{R}$$

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

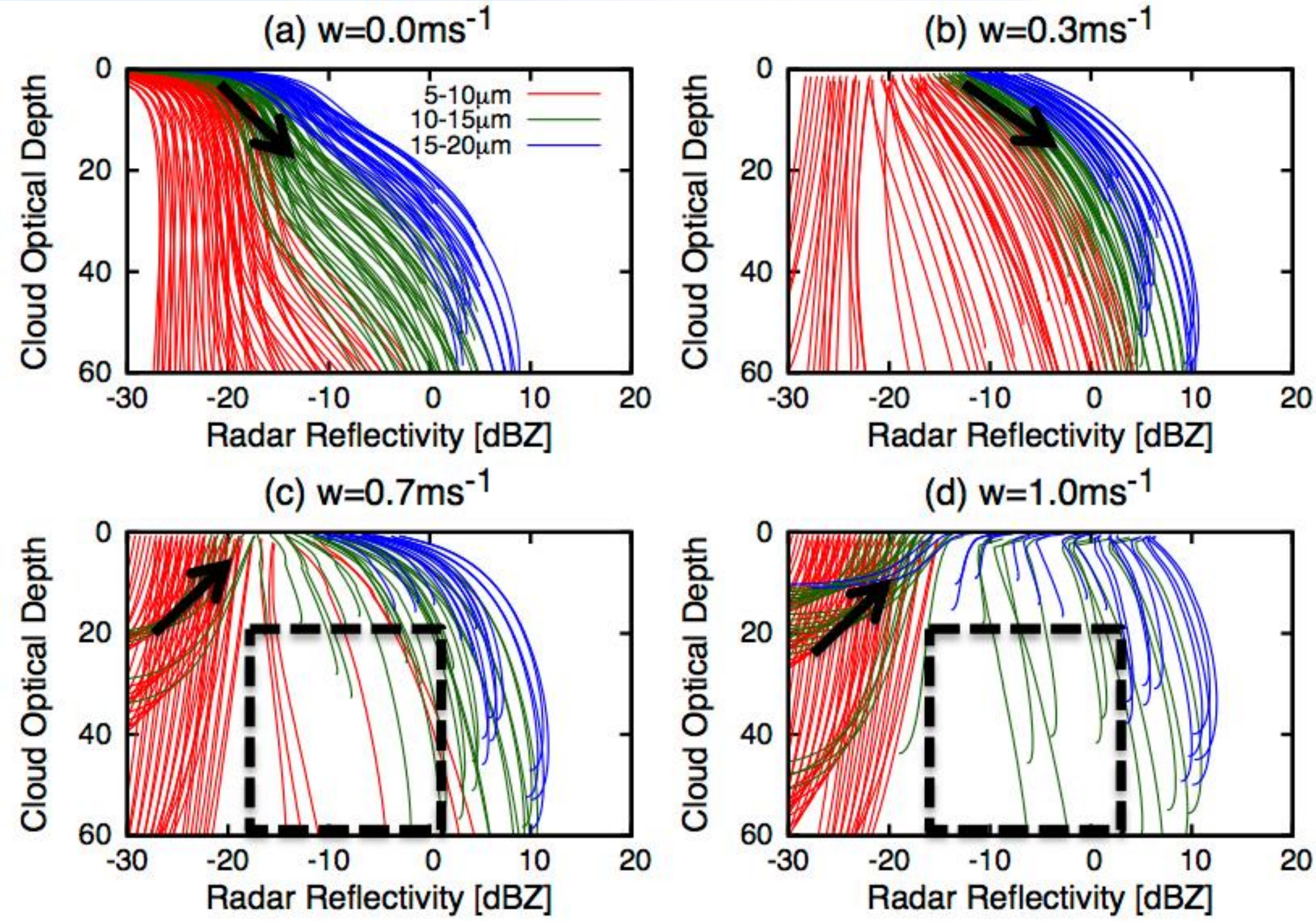
$$\frac{d\ln Z_e}{dt} \approx \frac{\lambda}{6} E_c$$




re=5-10μm
re=10-15μm
re=15-20μm
re=20-25μm
Ocean
Land
Optical Depth
Reflectivity (dBZ)
[%/dBZ]
A 'drizzle' gap


ARM
Azores
0-0.2 (m/s)
0.2-0.4 (m/s)
0.4-0.6 (m/s)
0.6-0.8 (m/s)
Cloud Depth
Reflectivity (dBZ)
[%/dBZ]

# Spectral bin models captures this drizzle gap

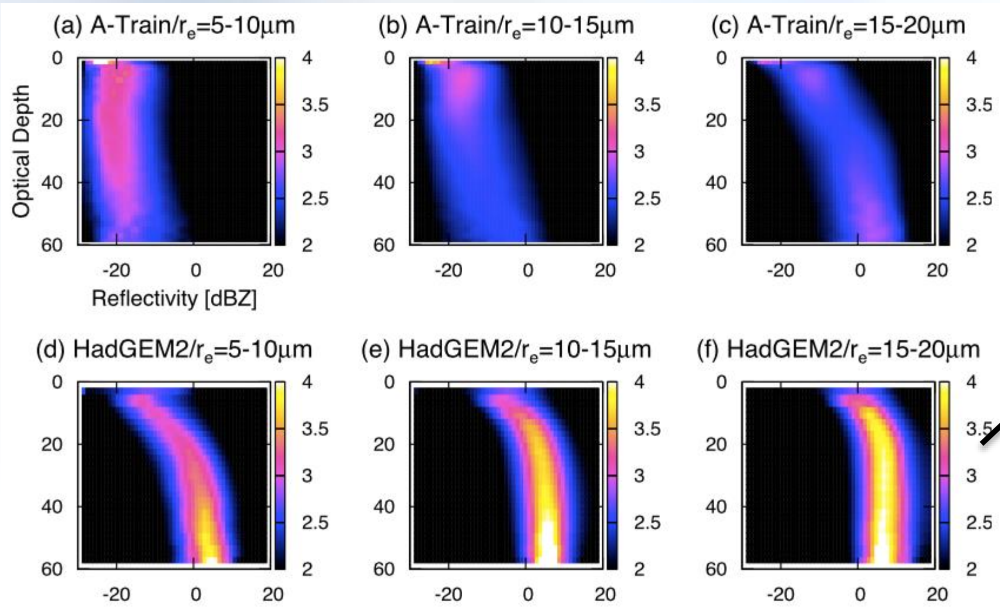


# Understanding processes - improving parametrizations Using observation synergy and modelling studies

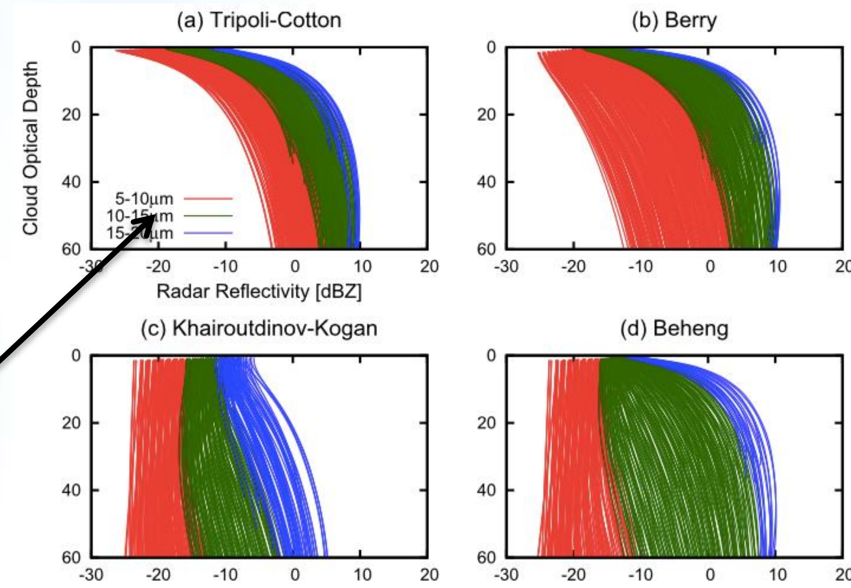
## Example: Warm-rain formation process using A-Train data, GCMs and process models.

Suzuki et al. 2015

Z vs Optical Depth for different $R_{eff}$ from CloudSat/MODIS and from the HadGEM2 model




Effect of different autoconversion parametrizations

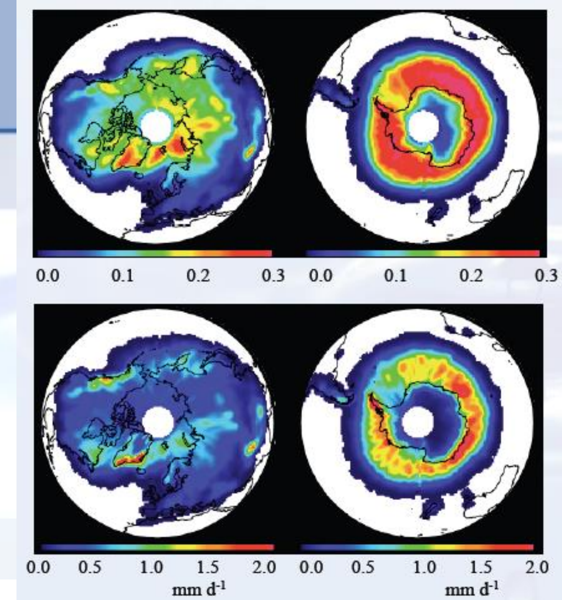



ECMWF

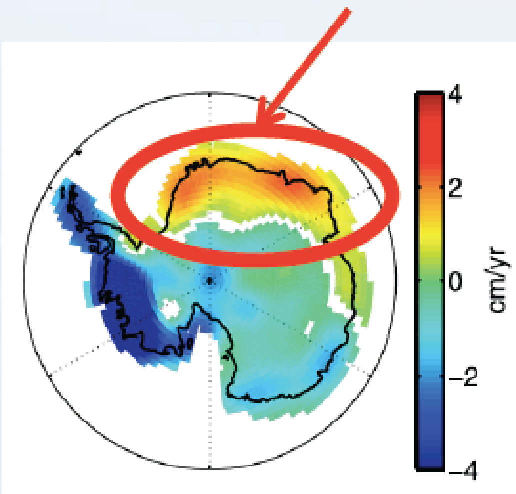
# Polar precipitation

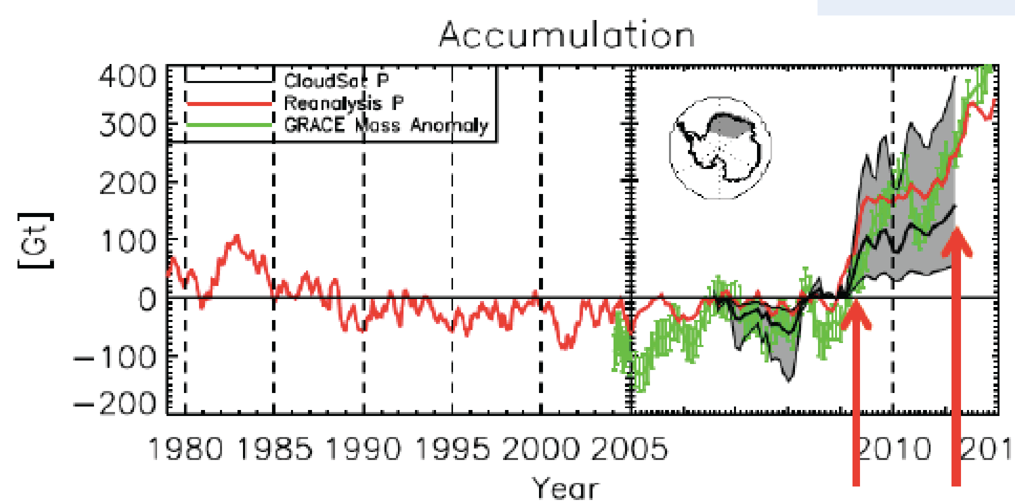
Global Mean = 62 mm $yr^{-1}$

(By comparison it rains ~ 1000 mm yr-1)




Mass trend (2004-2011) from GRACE ~0.32 mm/year sea level rise.



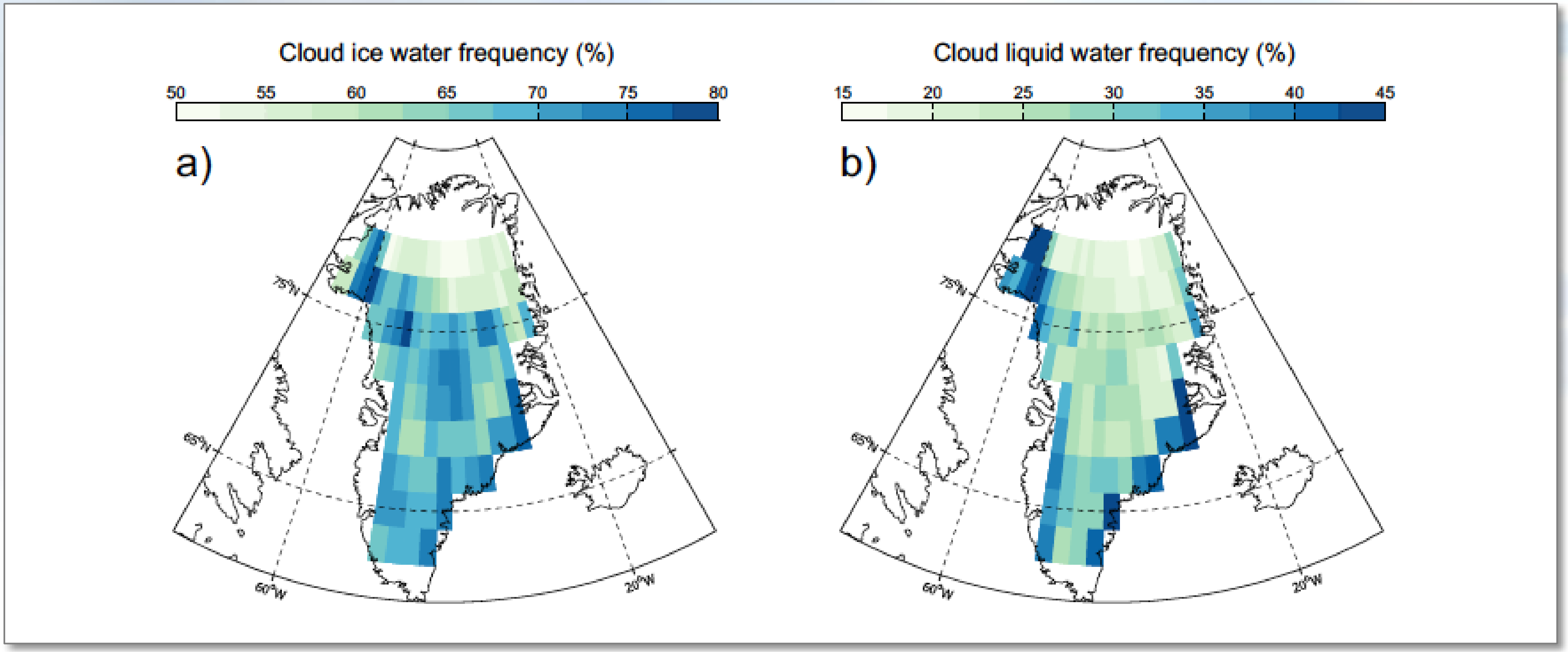




Storm Events

Boening et al., 2012;2016

- 5 warm and moist storms account for unprecedented mass gain.

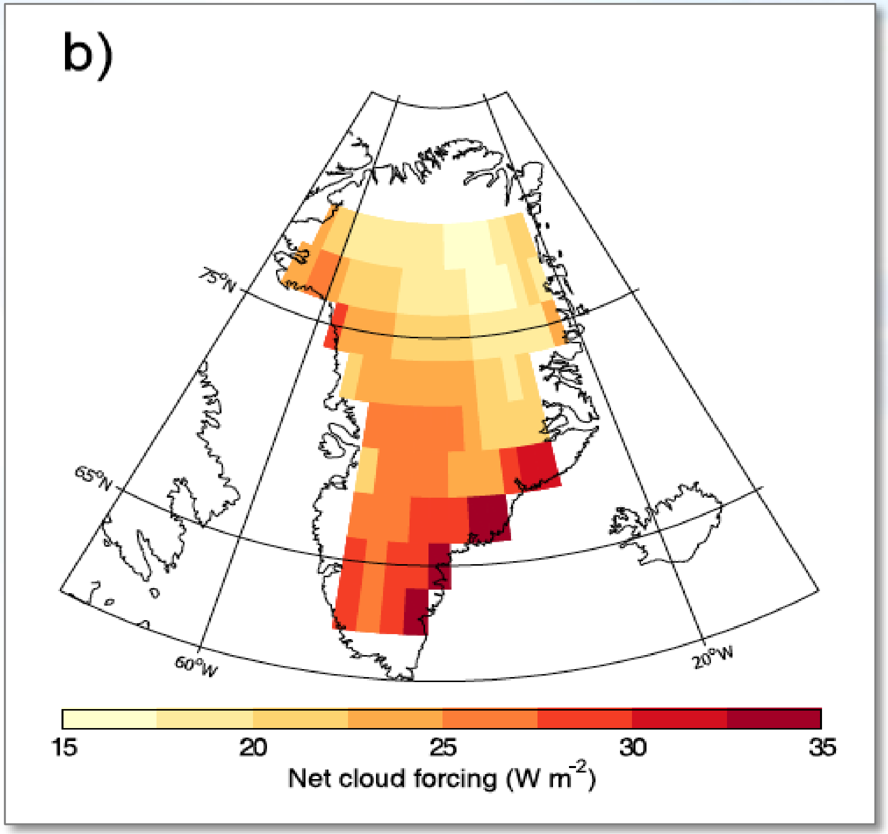
# Role of Clouds in Ice Sheet Melt




- On average, more than 40% of the clouds over the Greenland Ice Sheet contain super-cooled liquid water (70% in summer, 25% in winter).

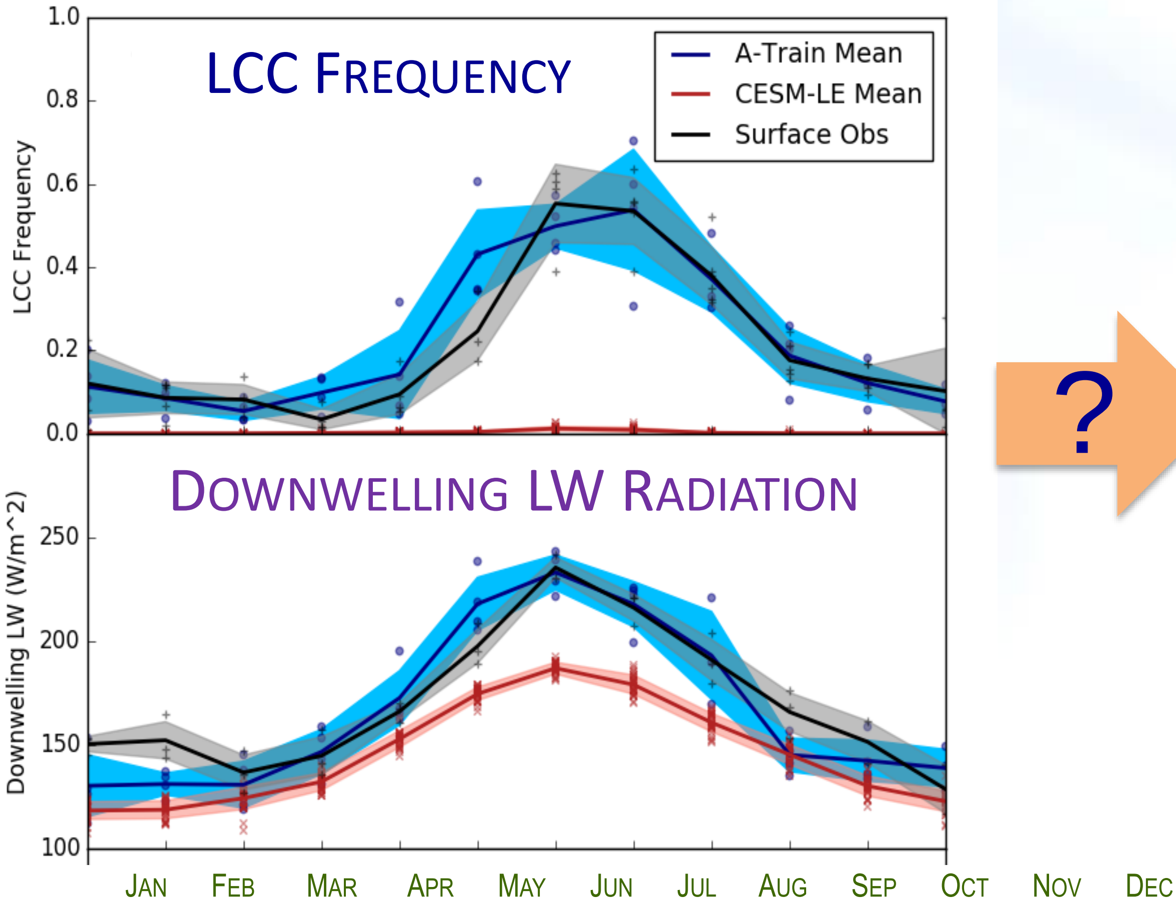
# Implications for Sea Level Change

- Clouds enhance the net surface radiation on the ice sheet by an average of nearly 30 ± 6 $Wm^{-2}$ relative to clear conditions.
- Unfrozen liquid droplets account for HALF of this forcing.
- This is enough energy to melt up to 90 Gt of ice each year.
- Surface modeling suggests that this effect results in about 25 Gt of additional runoff each year after warming and sublimation are accounted for.

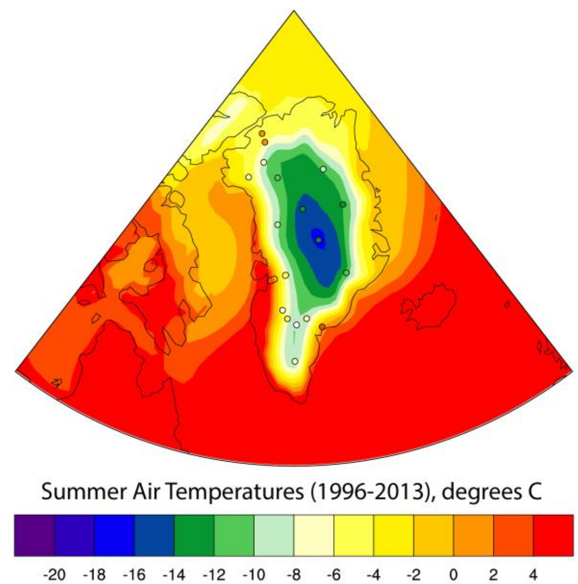



van Tricht et al., *Nature Comm*. (2016)

# Low clouds and model biases in surface temperature




?




Greenland is too cold in CESM (Kay pers com).

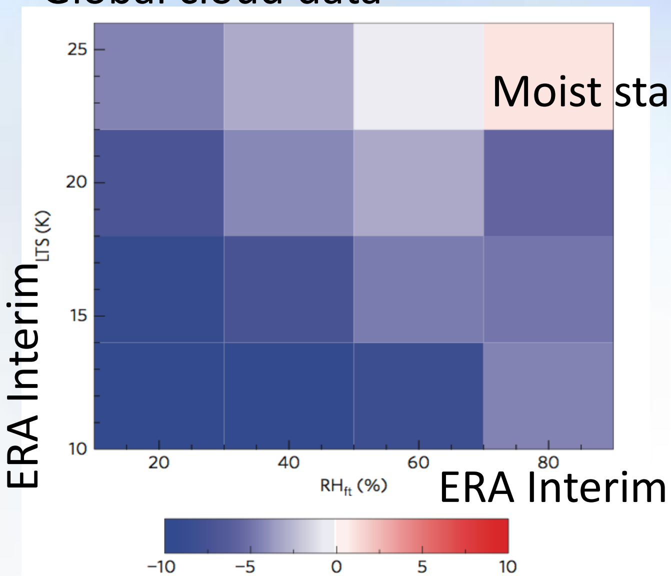
# 4) Deep Convection

# Aerosol and (a lack of) DOF

# Whats missing GCMs – insufficient DOF that buffer the system

$$\frac{\Delta \tau}{\tau} = -\frac{\Delta R_e}{R_e} + \frac{\Delta LWP}{LWP} \propto \frac{\Delta \alpha}{\alpha}$$

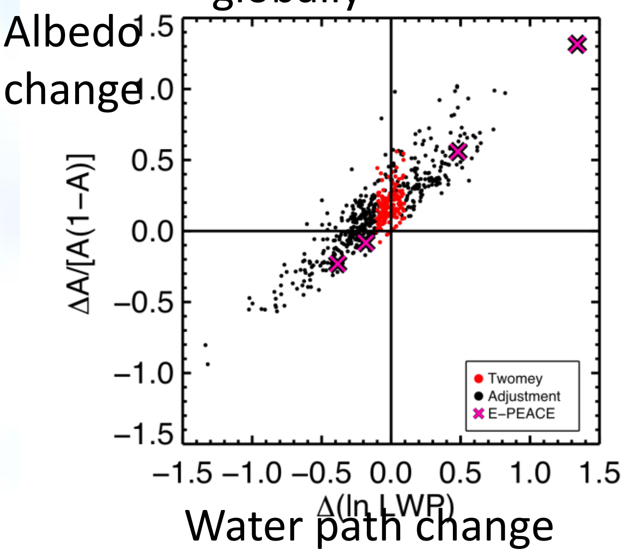
Global cloud data



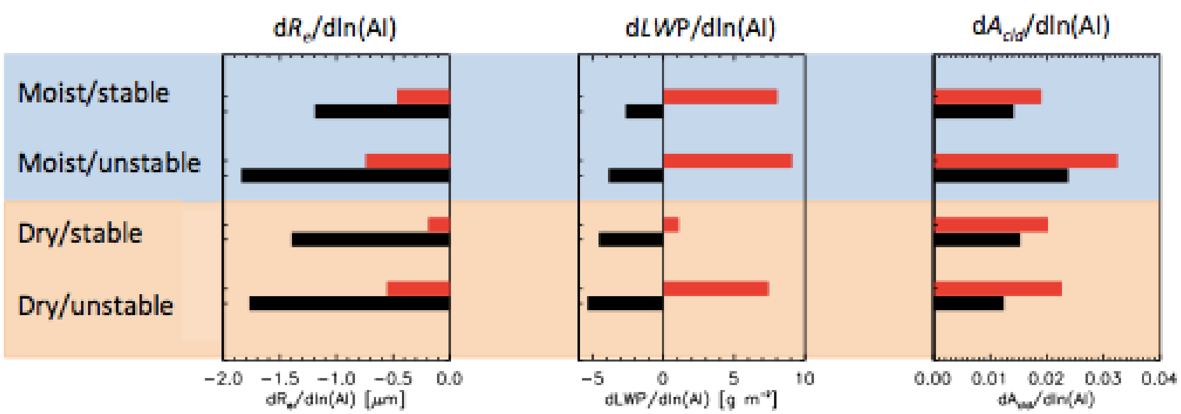

**Moist/dry**: RH above cloud top higher/lower than 40%.
**Stable/Unstable**: LTS ($\Theta_{700mb} - \Theta_{sfc}$) larger/lower than 17K.

The ‘Twomey’ effect- cloud responses are more complicated than that

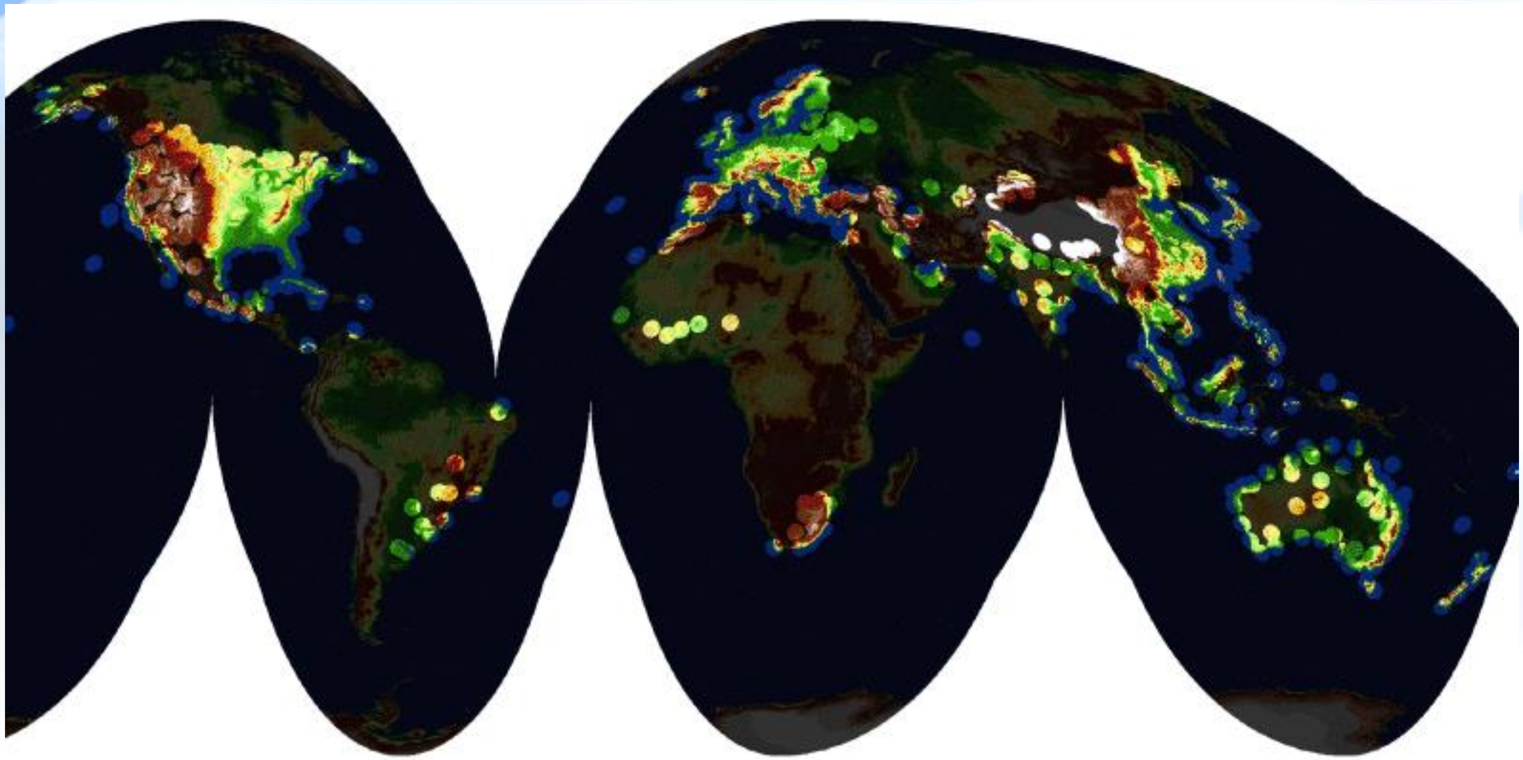
1000’s of ship track data accumulated globally




Non-raining (82.6 %)
Raining (17.4 %)



# New data sources - World wide weather radar coverage > 800 systems listed by Heistermann et al., 2013



Heistermann et al. (2013), HESS

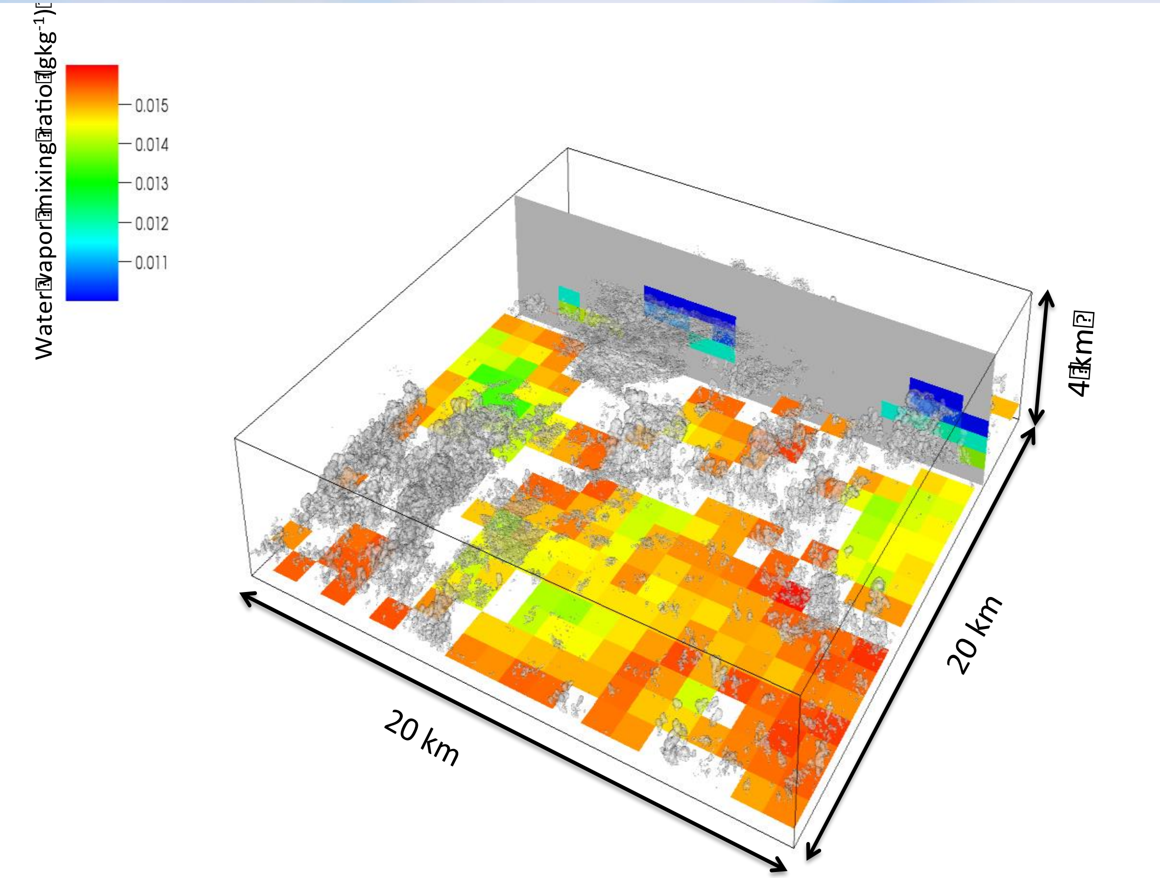
**Europe, UK:** Nimrod, OPERA, EUMETNET 17 countries,

**Northern Germany**: Precipitation and Attenuation Estimates from a High Resolution Weather Radar Network (PATTERN)

**US: NEXRAD** (**Nex**t-Generation **Rad**ar), network of 160 high-resolution S-band Doppler weather radars

# New technology, new approaches, new dimensions

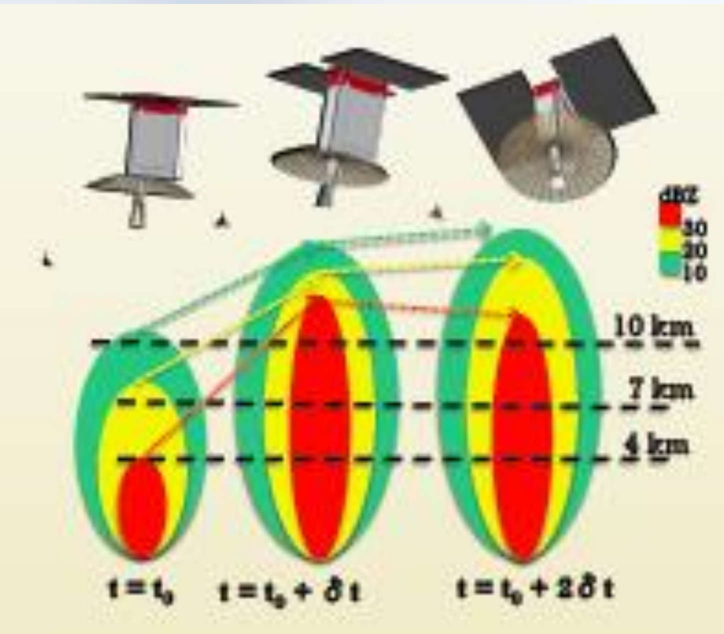
In-cloud profiling of temperature, humidity

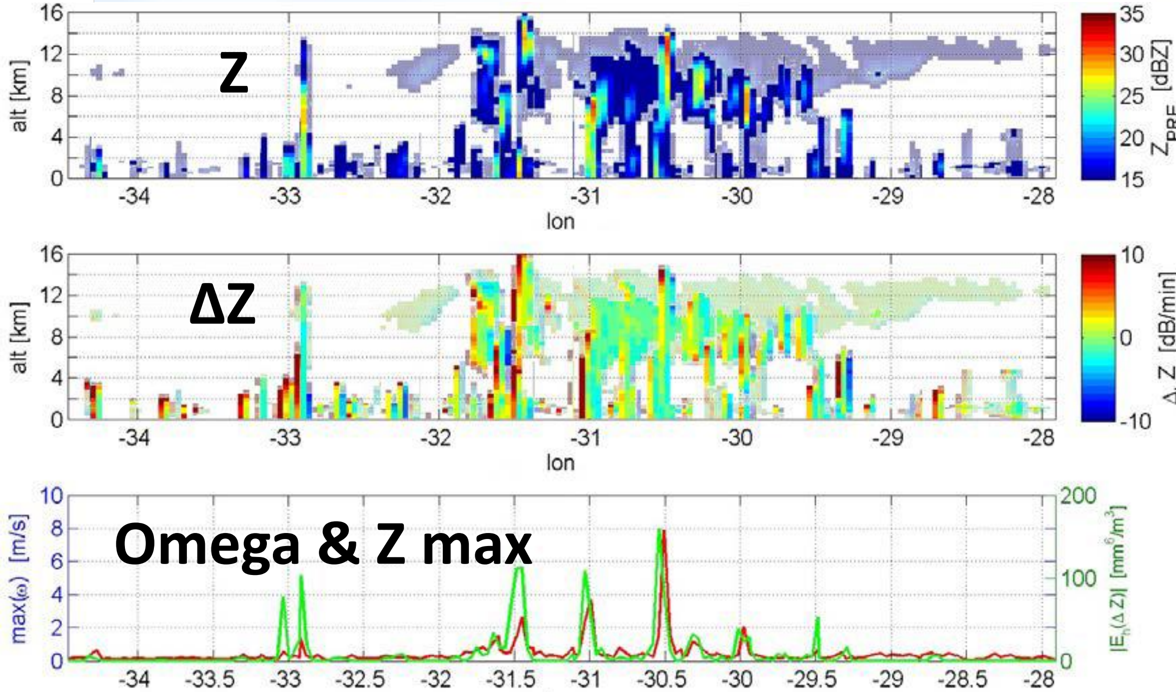



Atmospheric Boundary Layer Thermodynamic Structure: Blending Infrared and Radar Observations

Results from a large-eddy simulation of a cumulus show the key characteristics of the measurements proposed: A differential absorption radar on LEO provides water vapor profiles within cloudy areas along a ‘curtain’ (grey in figure) with resolution on the order 1.0x1.0x0.5 $km^3$. An IR sounder provides the 3D context of temperature and water vapor structure by sampling the adjacent clear sky regions with resolution of order 1x1 $km^2$.

Performance > GPM Ka




- Provides more accurate measures of condensed mass because biases get removed
- Provides methods to estimate mass flux, previously unthinkable

# Questions to ponder

Q1: What are the glaring observational gaps that obstruct progress in understanding and modeling the moist atmosphere?

- Boundary layer?
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- Entrainment/detrainment?
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- Surface data & field expt data?
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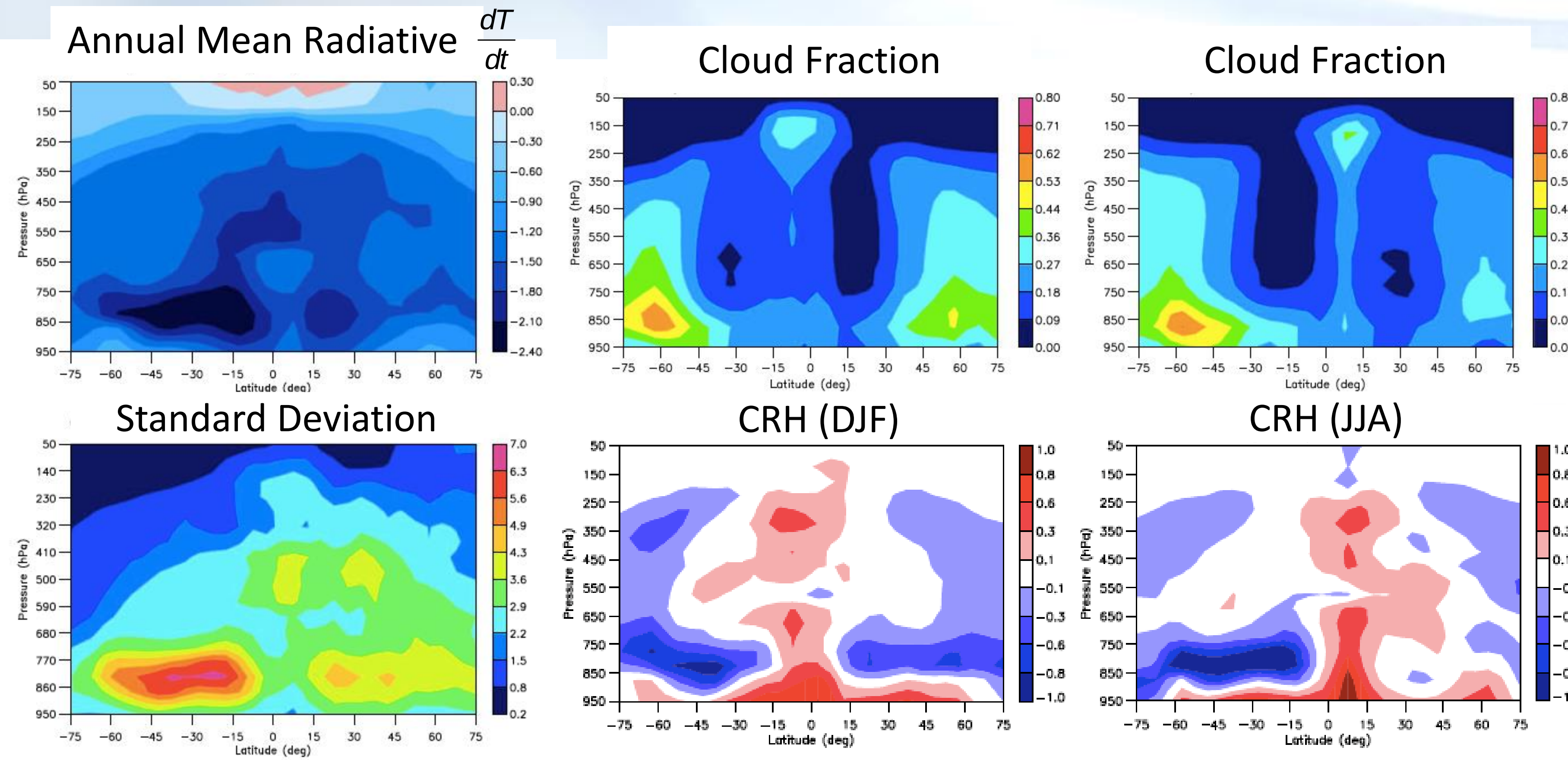
# Adding The Vertical Dimension




Haynes et al., *Geophys. Res. Letters* (2013)