Ocean-Atmosphere Coupled Energy Budgets of Tropical Convective **Discharge-Recharge Cycles**

Brandon Wolding

WCO3 Workshop

September, 2023

Photo: Alexander Gerst
Intern. Space Station

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Collaborators

Juliana Dias

NOAA
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Collaborators

Adam Rydbeck

Naval Research Lab Mississippi

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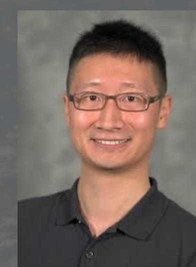
UCLA

Emily Riley-Dellaripa

CSU

Xingchao Chen



Penn State University

Isabel McCoy

University of Miami

Ocean-Atmosphere Coupled Energy Budgets of Tropical Convective Discharge-Recharge Cycles

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Most directly builds on work by:

Inoue and Back 2017, Inoue et al. 2021, Maithel and Back 2022 → Convective discharge-recharge cycles

Raymond et al. 2009 → GMS

Rydbeck et al. 2022 → Ocean-atmosphere energy budgets

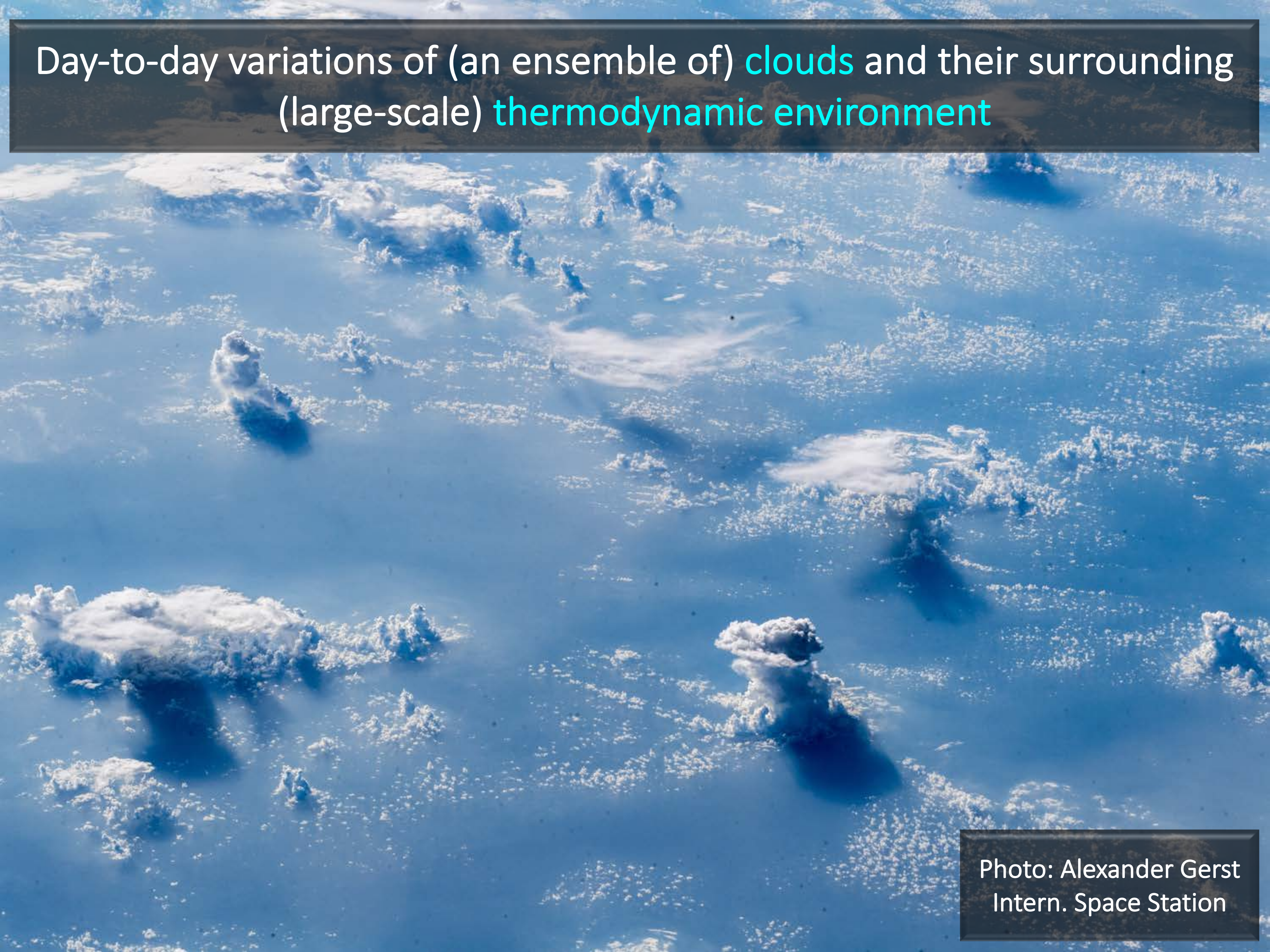
Mapes and Neale 2011 → Organizational feedbacks

Inspired by many others including:

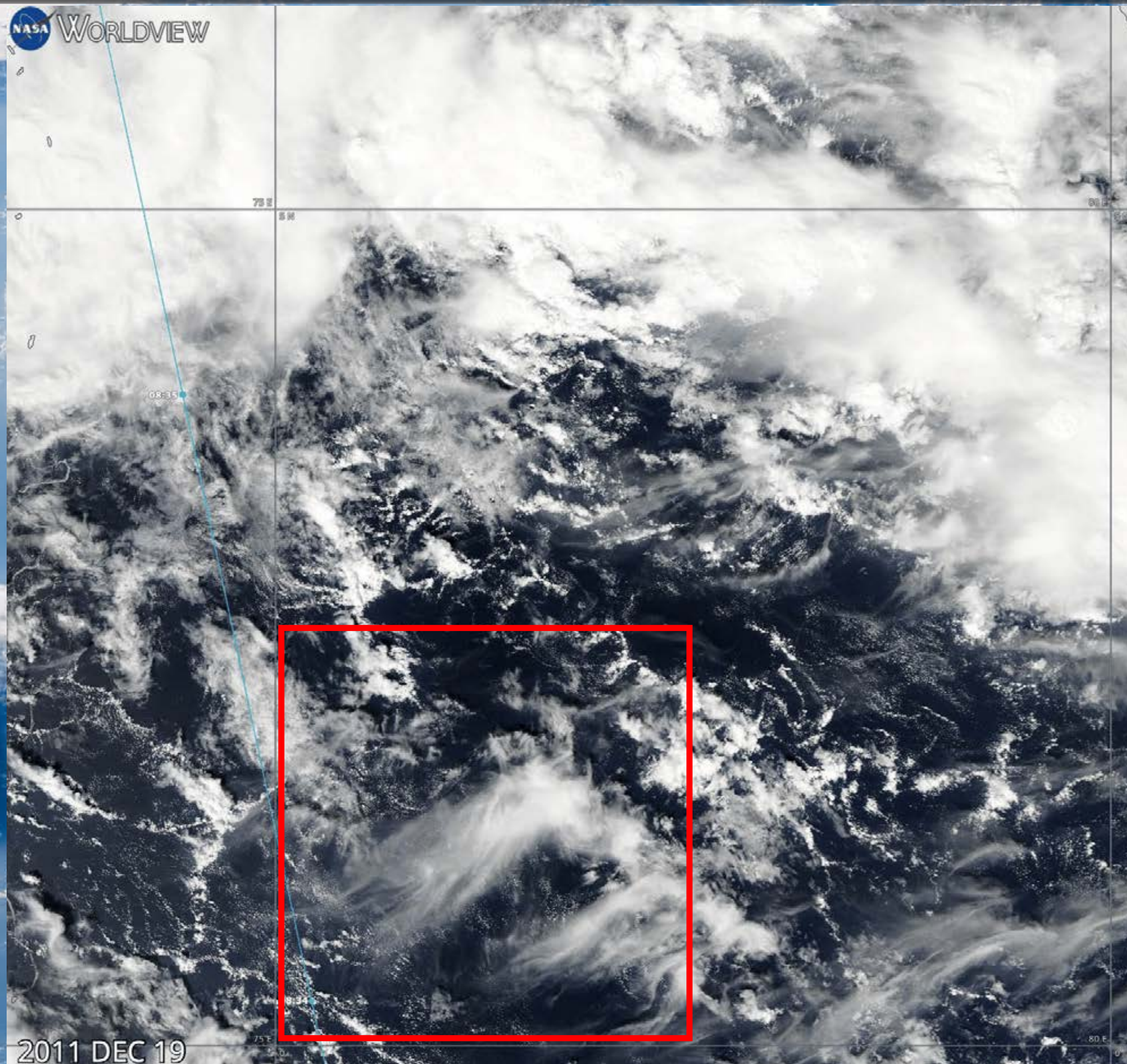
Bretherton, Neelin, Held, Peters, Holloway, Ahmed, and Schiro

Sessions, Sobel, Fuchs, Maloney, Adames, Chikira, Johnson, Ciesielski, and Ruppert

Schumacher, Houze, Moncrieff, Chidong Zhang, DeMott, and many many others


Day-to-day variations of (an ensemble of) clouds and their surrounding (large-scale) thermodynamic environment
Photo: Alexander Gerst
Intern. Space Station

Day-to-day variations of (an ensemble of) clouds and their surrounding (large-scale) thermodynamic environment



Roadmap for Today's Presentation

1.) Introduce entraining plume model computation of vert. integrated buoyancy $\langle \boldsymbol{B} \rangle$

2.) Identify and define convective discharge-recharge cycles

3.) Characterize the cloud population of discharge-recharge cycles

4.) Ocean-atmosphere energy budgets of discharge-recharge cycles

Indian Ocean and Western Pacific, oceans only

Daily average 2.5 degree data

IMERG precipitation and ERA5 thermodynamics

2001-2015 or available subset

Mean and seasonal cycle removed from energy budget terms

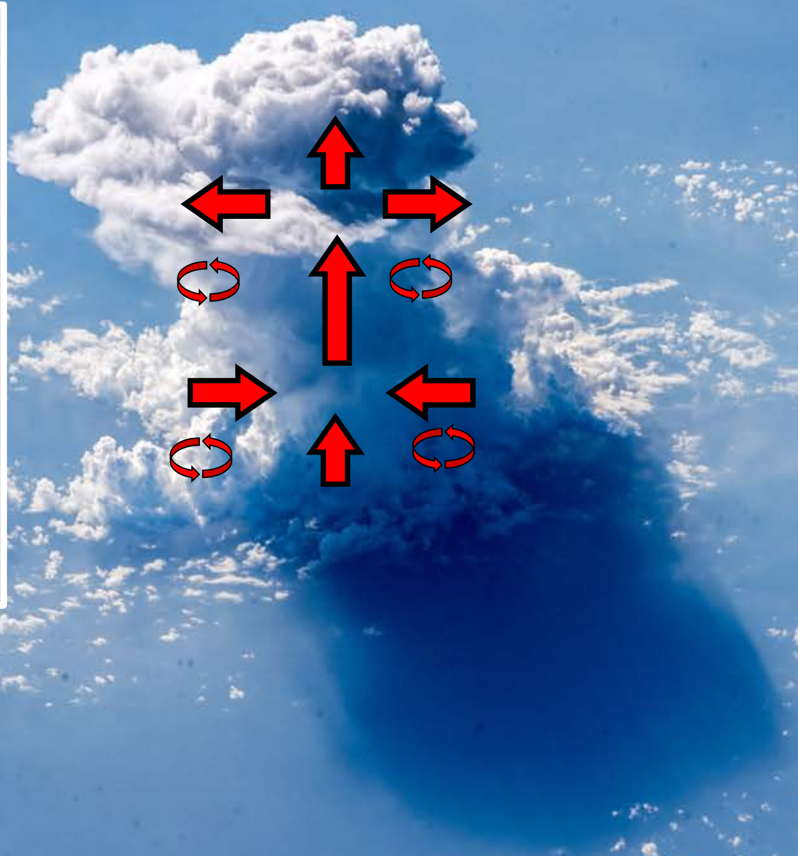
Lower Tropospheric Vertically Integrated Buoyancy $\langle B \rangle$

Calculating:

1.) Entraining CAPE (integrated measure of buoyancy)

restricted to

2.) 1000 hPa – 600 hPa, below the freezing level (~575 hPa, ~4.5km)



Lower Tropospheric Vertically Integrated Buoyancy $\langle B \rangle$

1.) **Initialized at 1000 hPa** using large-scale average **T and q profiles**

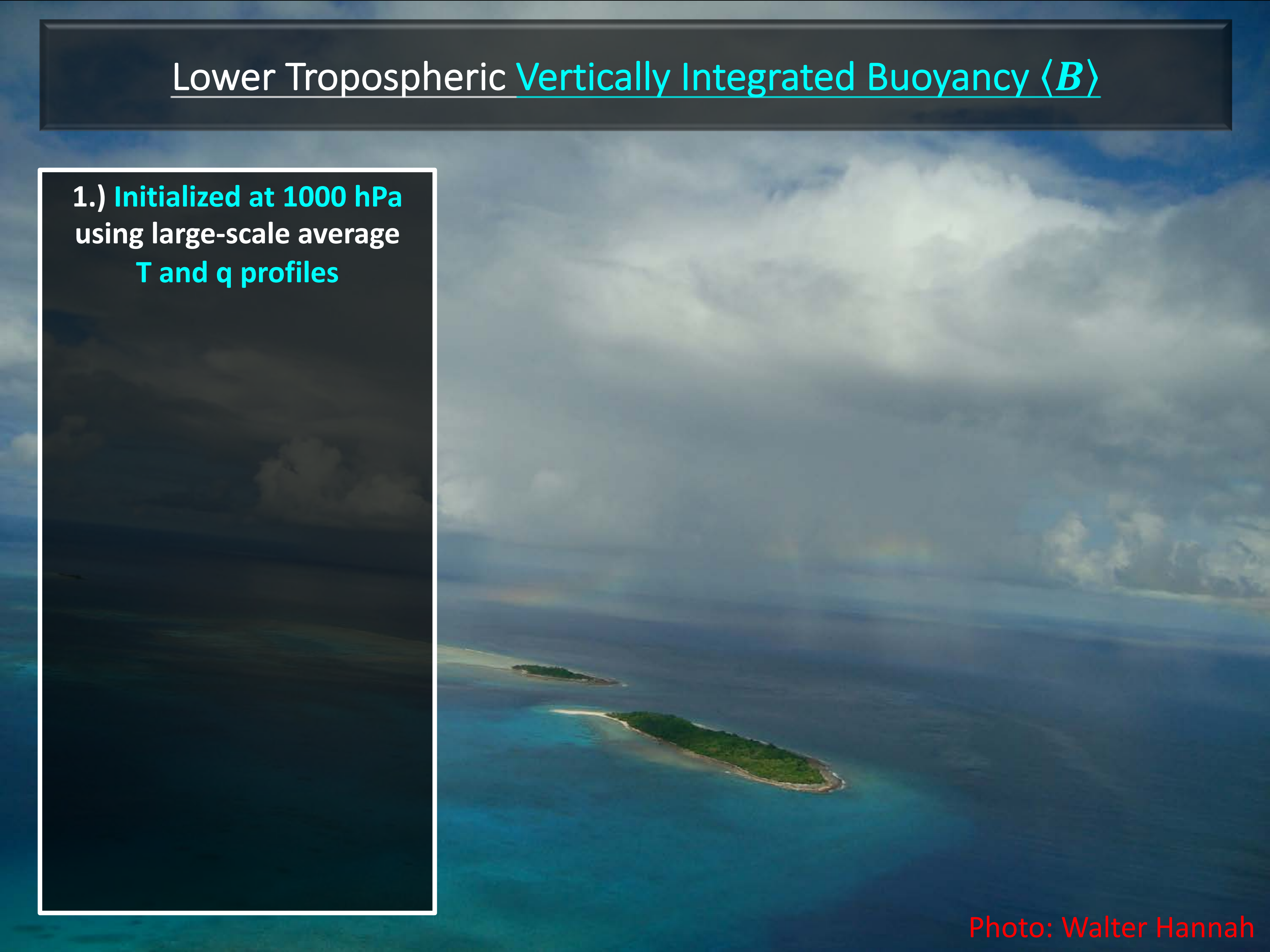


Photo: Walter Hannah

Lower Tropospheric Vertically Integrated Buoyancy $\langle B \rangle$

1.) **Initialized at 1000 hPa** using large-scale average **T and q profiles**

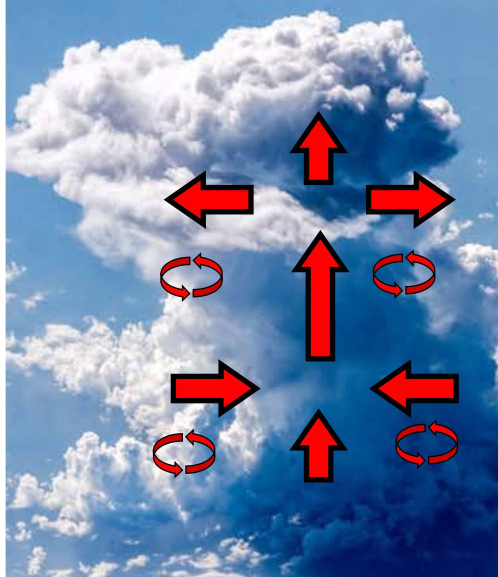
2.) **Entrains** environmental air with **large-scale average** thermodynamic properties

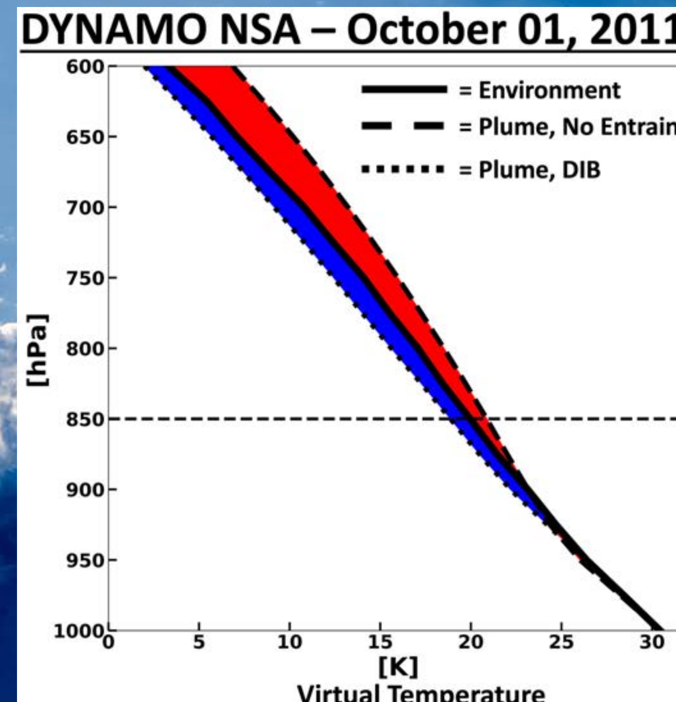
3.) **"Deep Inflow B" entrainment** profile with peak vertical velocity at 450 hPa.

4.) Conserves ice-liquid water potential temperature, liquid water exceeding 1 g Kg^{-1} rained out

5.) Outputs **T_v profiles**

$$\langle \mathbf{B} \rangle_{\mathbf{DIB}} = \int_{1000\,\mathrm{hPa}}^{600\,\mathrm{hPa}} = R_d \left(T_{v,p} - T_{v,e}\right) d \ln p$$





Lower Tropospheric Vertically Integrated Buoyancy $\langle B \rangle$

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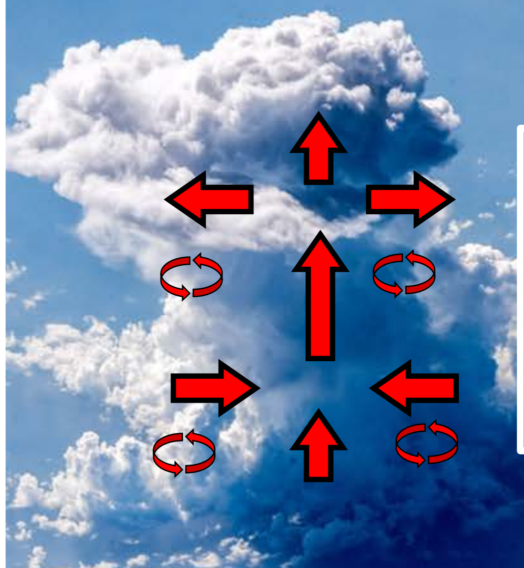
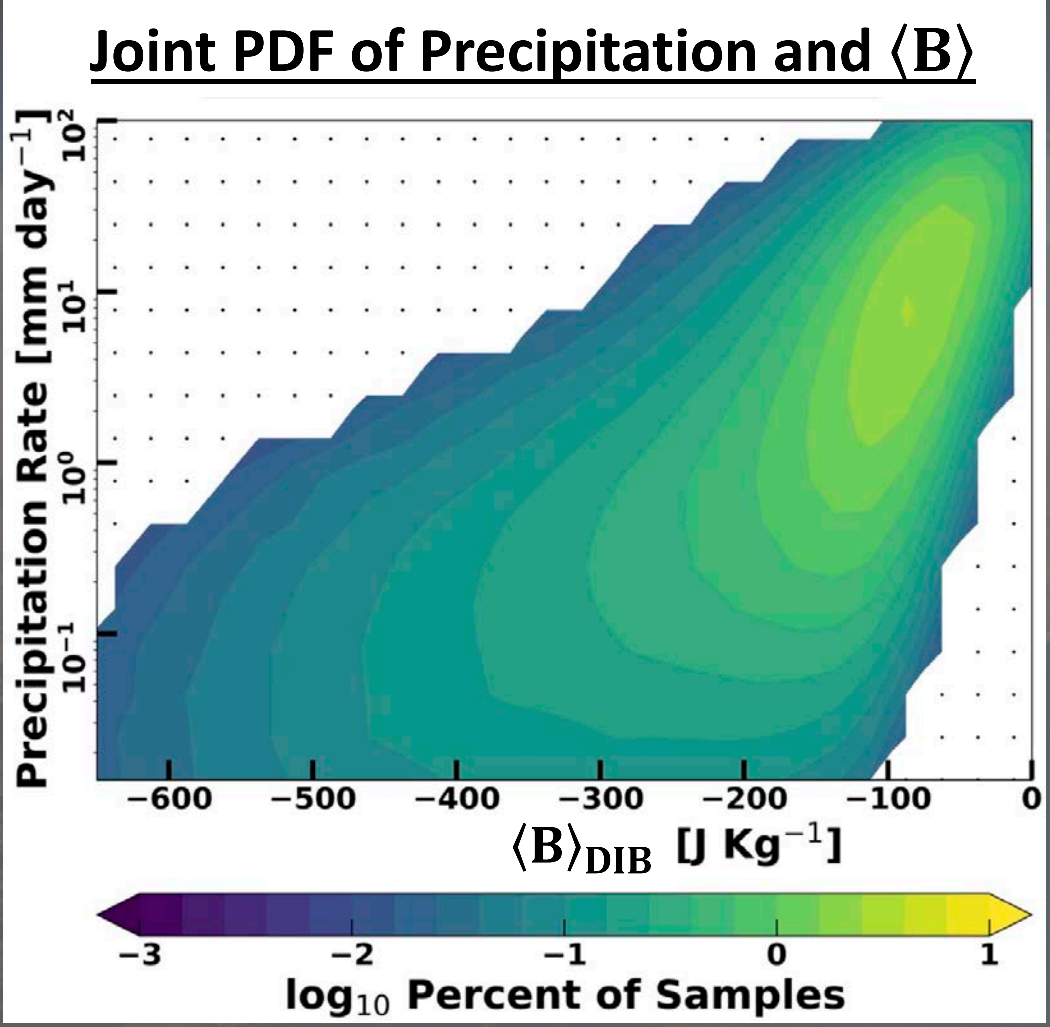


$\langle \mathbf{B} \rangle$

Coarse estimate of ability of large-scale environment to support deep convection

Identifying Convective Discharge-Recharge Cycles



Single mode

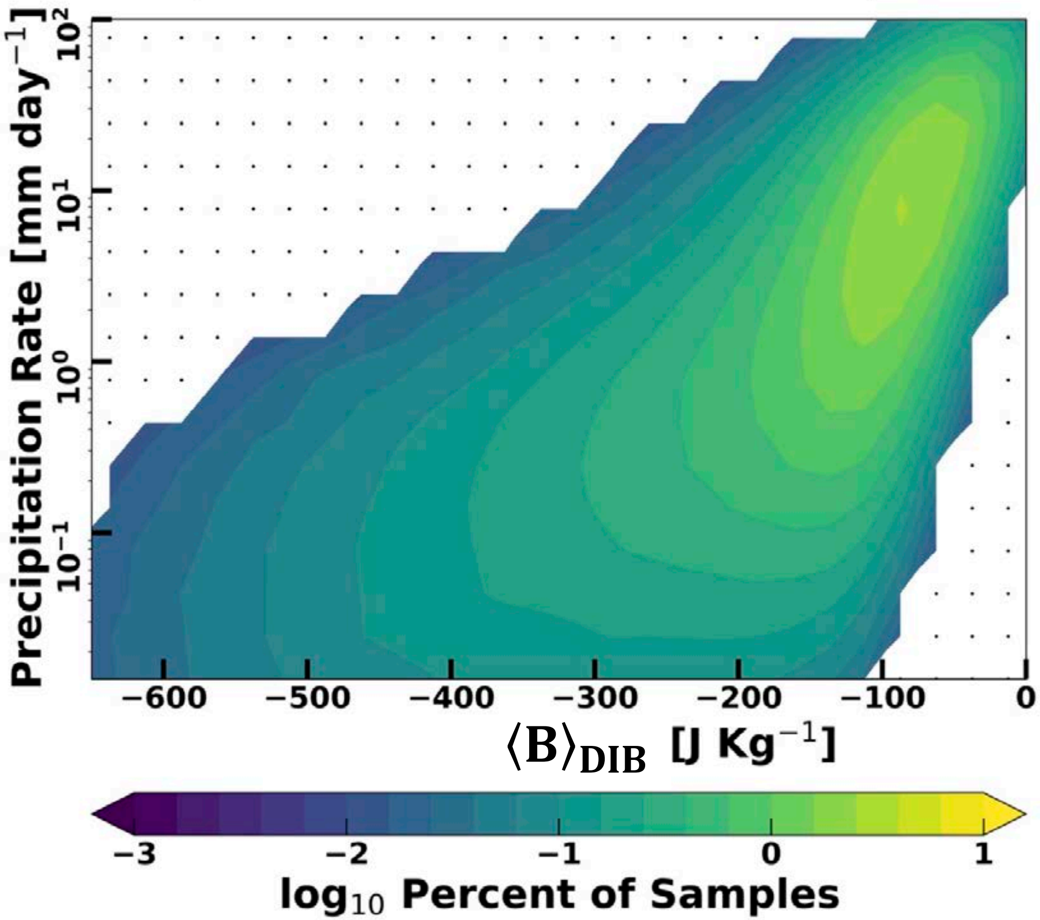
Precipitation rate generally increases with increasing ⟨B⟩

but…

Wide range of precipitation rates for fixed/given ⟨B⟩ value

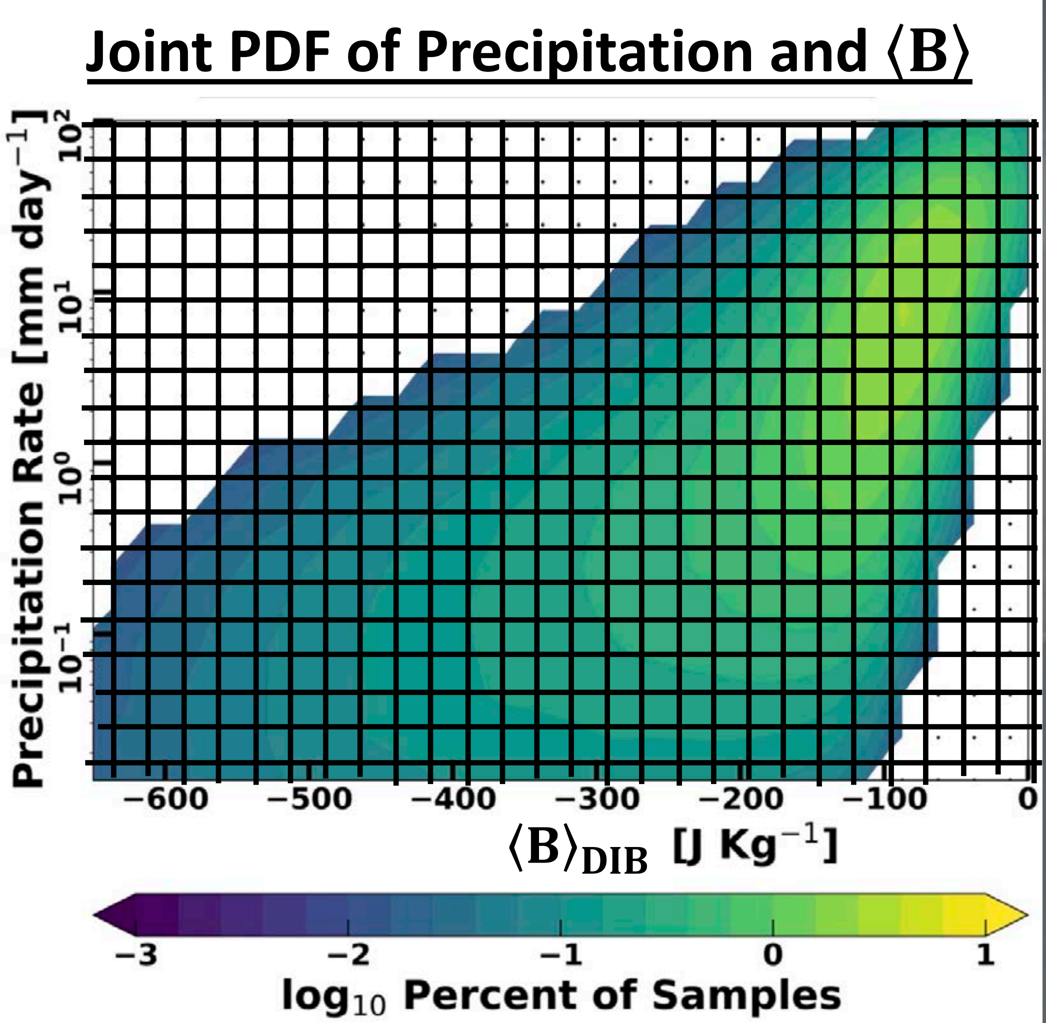
Identifying Convective Discharge-Recharge Cycles

Joint PDF of Precipitation and ⟨B⟩



How do precipitation and ⟨B⟩ co-evolve in time?

Identifying Convective Discharge-Recharge Cycles



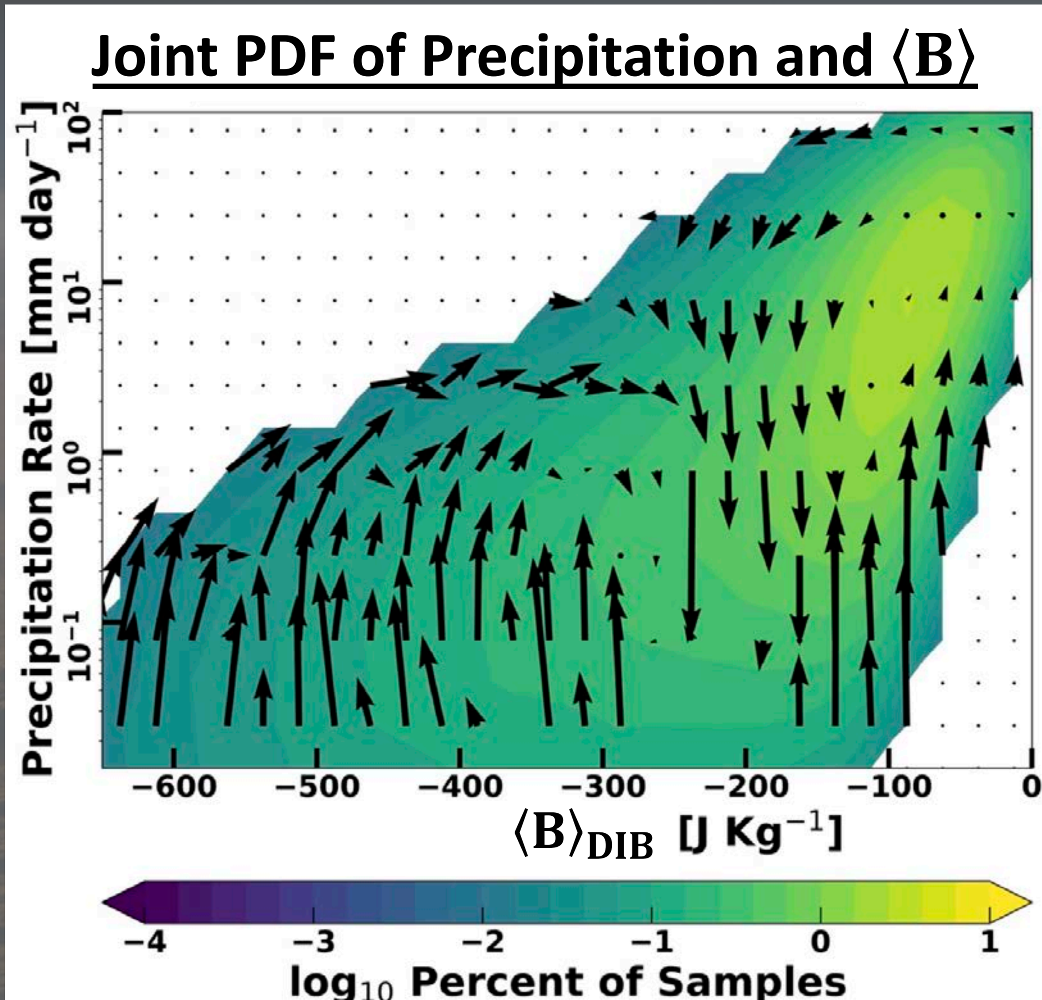
Methodology

1.) separate data into bins of precipitation rate and $\langle B \rangle$

then examine

2.) bin-mean temporal tendency of precipitation and $\langle B \rangle$ in each bin

Identifying Convective Discharge-Recharge Cycles



Discharge-Recharge Cycle

Cyclical amplification/decay of convection coupled to cyclical increases/decreases in a relevant measure of convective instability

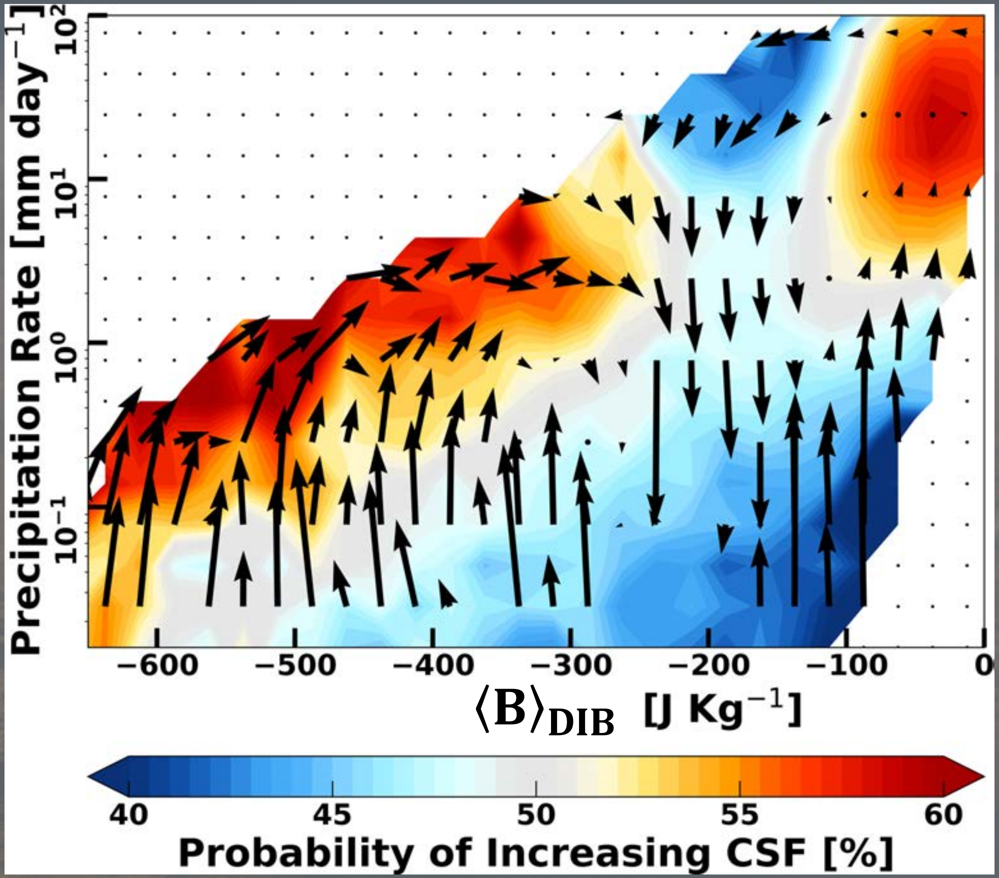
Estimated timescale ~10-40 days

Overlapping shallow and deep convective D-R cycles

Identifying Convective Discharge-Recharge Cycles

Discharge-Recharge Cycle

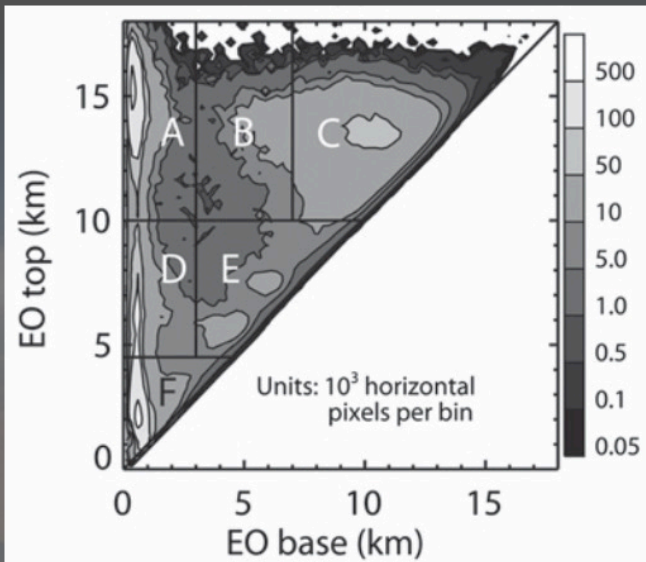
Cyclical amplification/decay of convection coupled to cyclical increases/decreases in a relevant measure of convective instability



Discharge-recharge cycles evident in probability of moistening

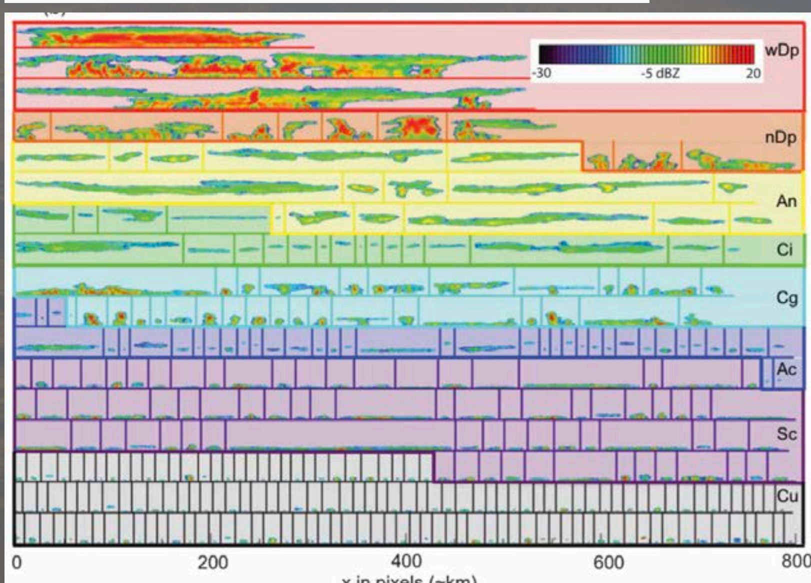
Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects



Cloud profiling radar (λ~mm) detects smaller cloud liquid and ice particles, but attenuates more rapidly than precipitation radar (λ~cm)

Echo Objects (EOs) = contiguous regions (> 3 pixels) of "cloud mask" (> 20)



Cloud Types determined by EO base, EO top, and EO width

Thin cirrus undetected, and some shallow clouds missed due to surface clutter

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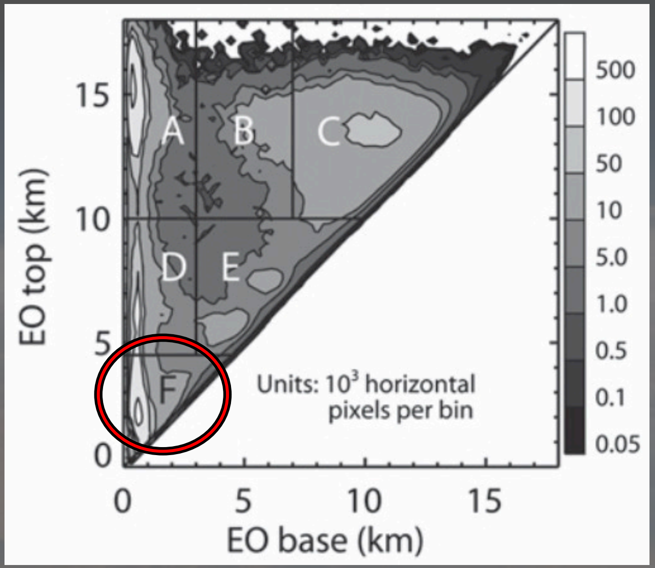
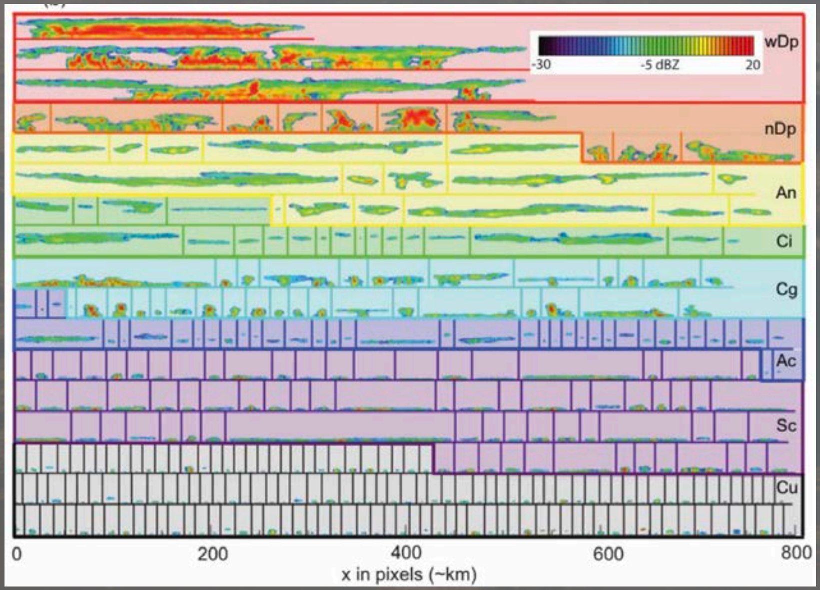


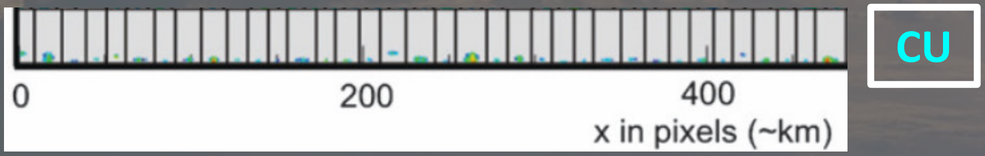


Cumulus (CU)

EO Base N/A

EO Top <= 4.5 km

EO Width <= ~10 km



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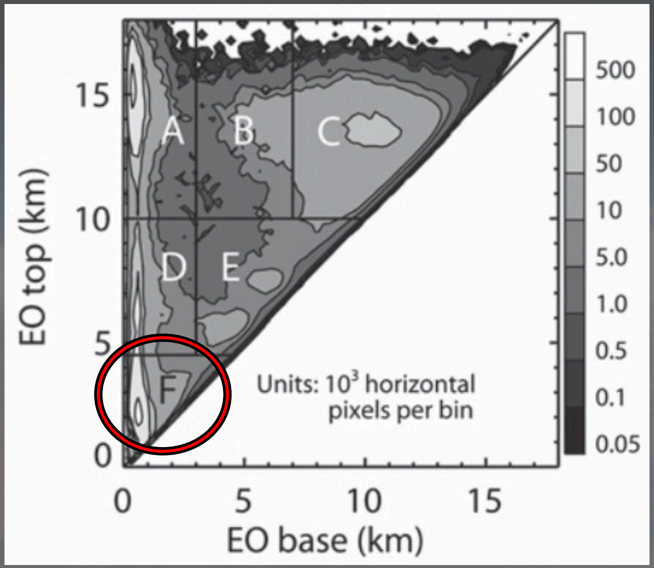
Riley et al. 2011 CloudSat Echo Objects

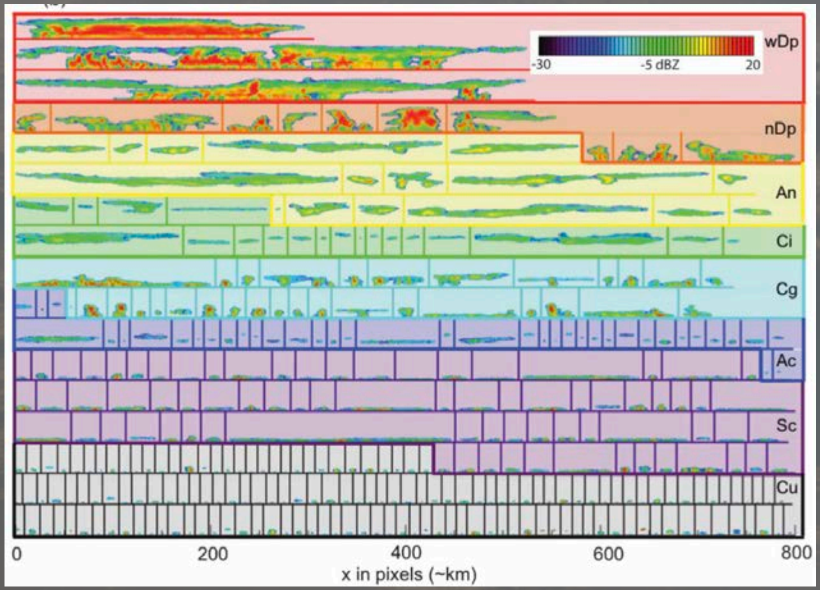


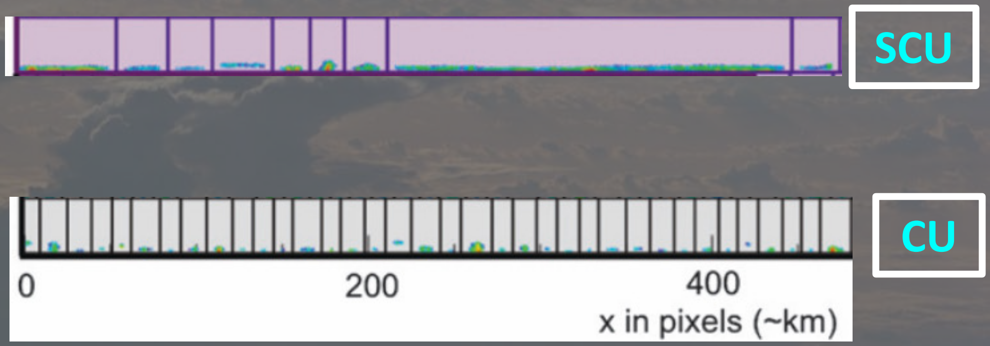
Strato Cumulus (SCU)

EO Base N/A

EO Top <= 4.5 km

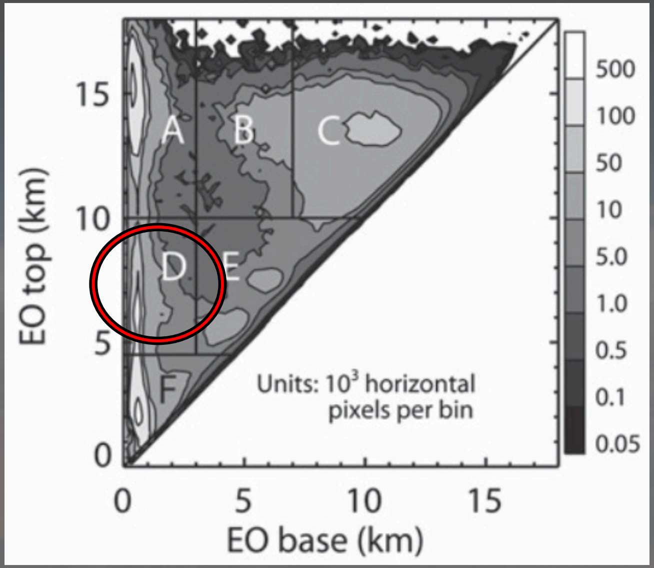
EO Width > ~10 km





Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects

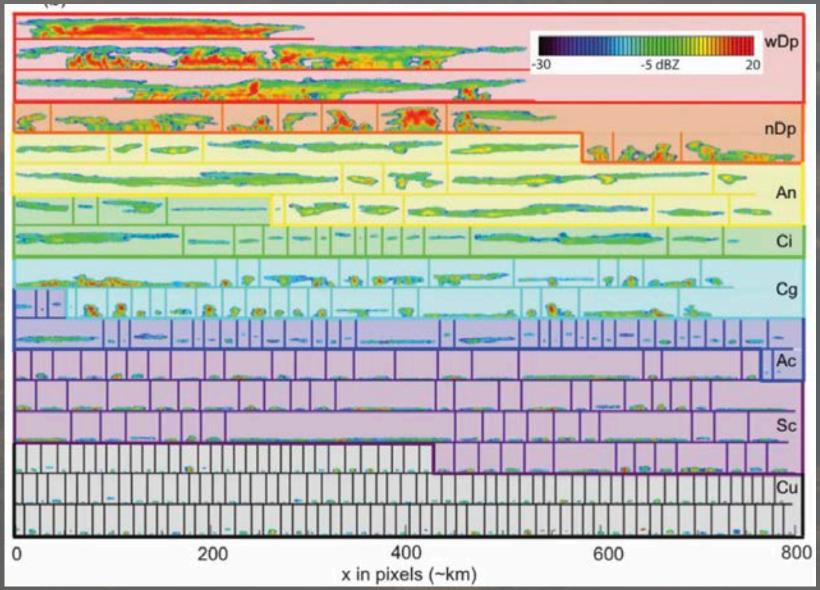


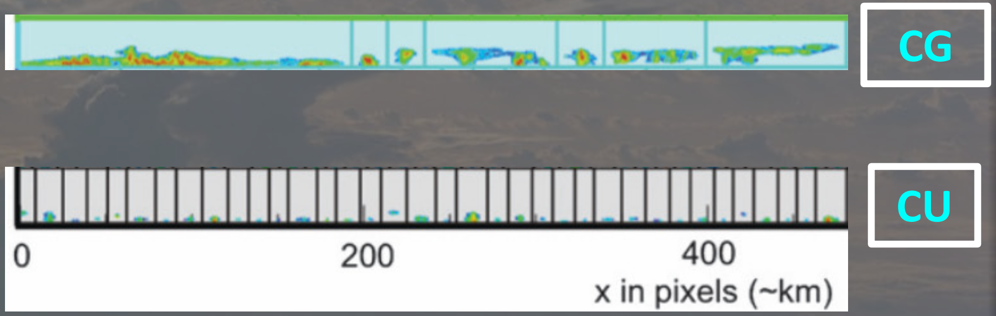
Congestus (CG)

EO Base < 3 km

EO Top >= 4.5 km, < 10 km

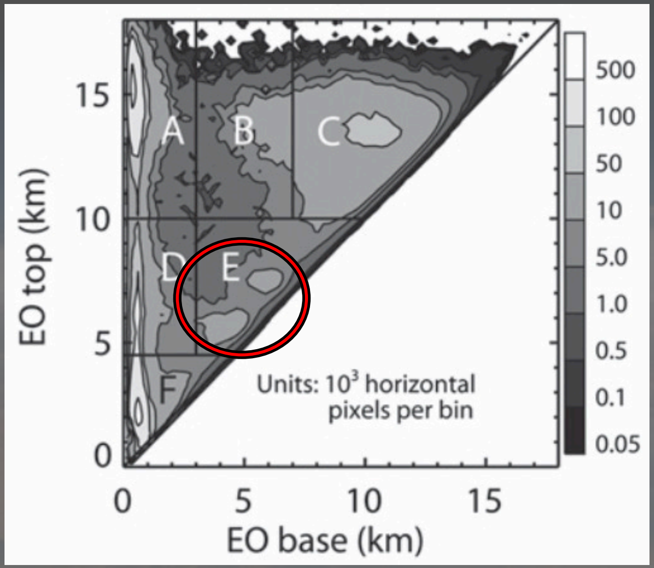
EO Width N/A





Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects

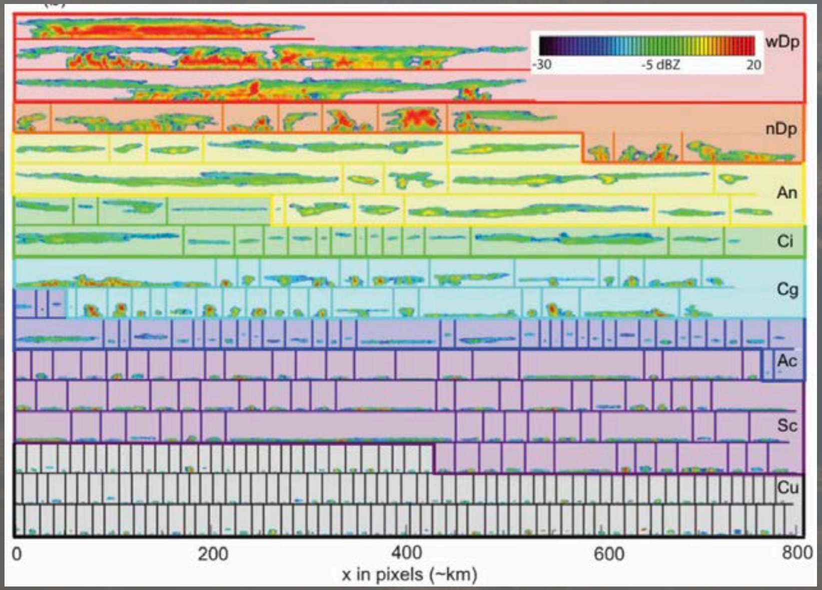


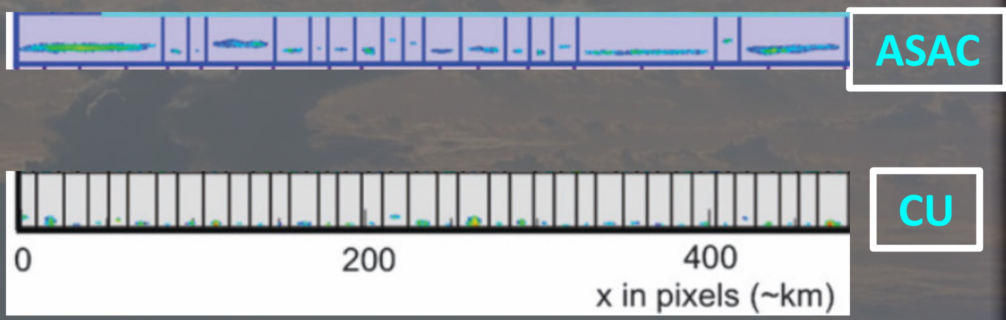
Alto Stratus & Alto Cumulus (ASAC)

EO Base >= 3 km

EO Top >= 4.5 km, < 10 km

EO Width N/A





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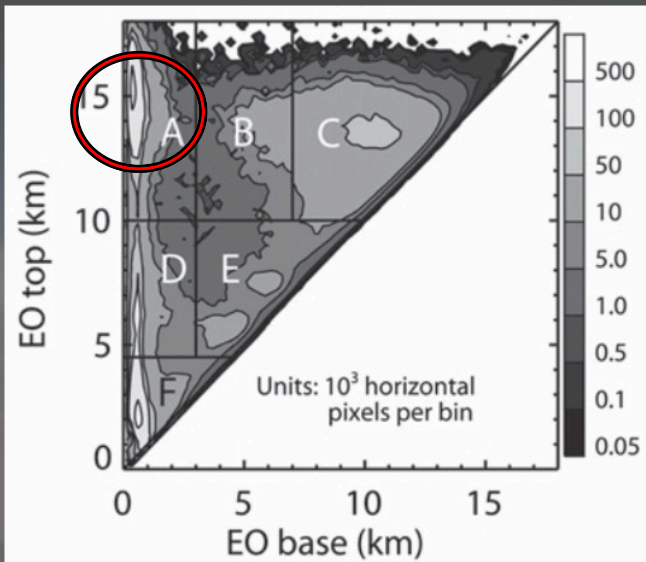
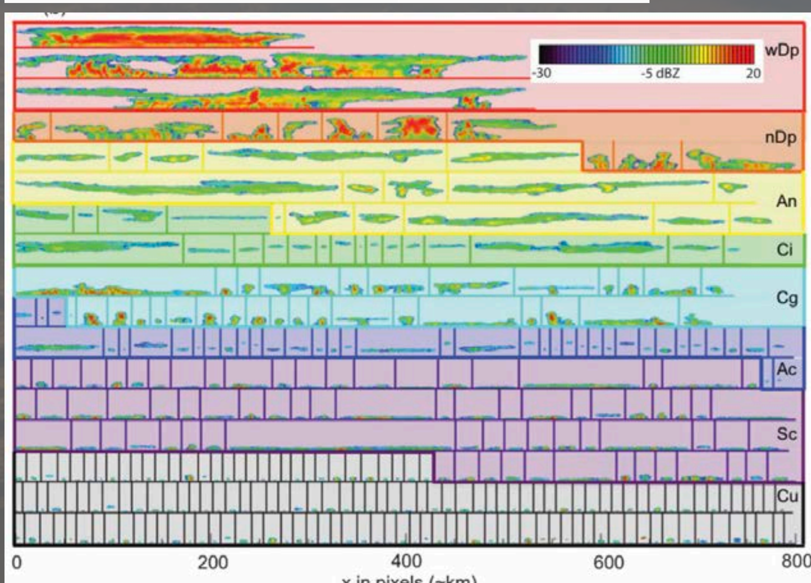


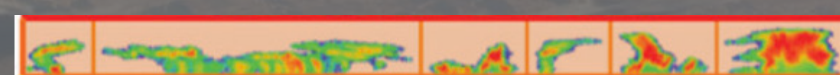


Narrow Deep Precipitation (NDP)

EO Base < 3 km

EO Top > 10 km

EO Width < 200 km

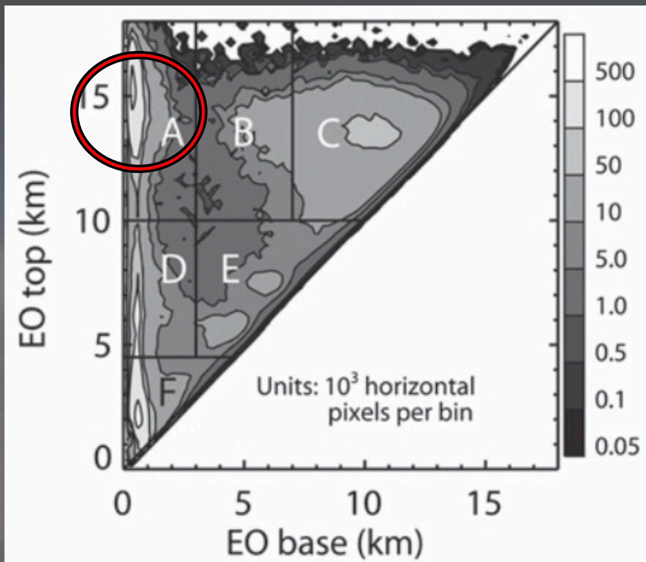


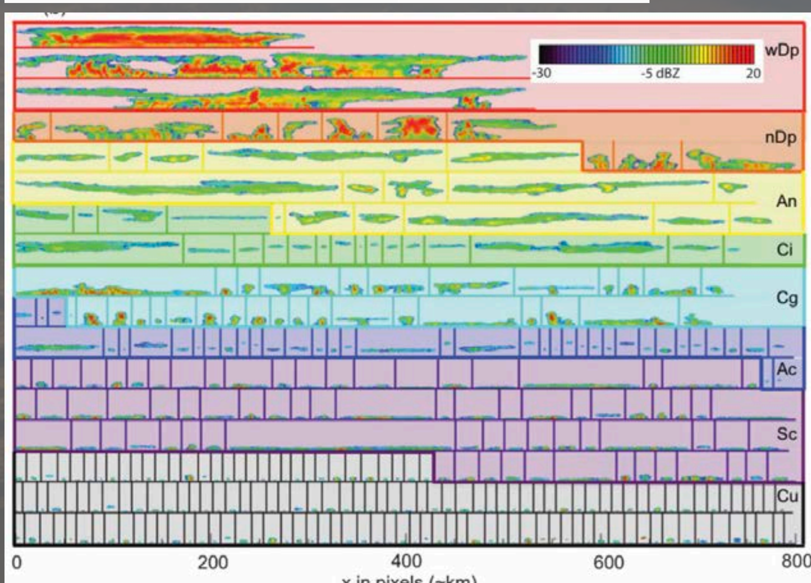
NDP

CU

Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects



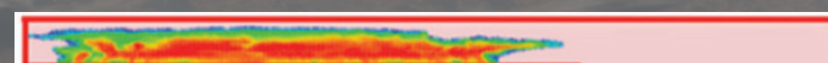


Wide Deep Precipitation (WDP)

EO Base < 3 km

EO Top > 10 km

EO Width >= 200 km

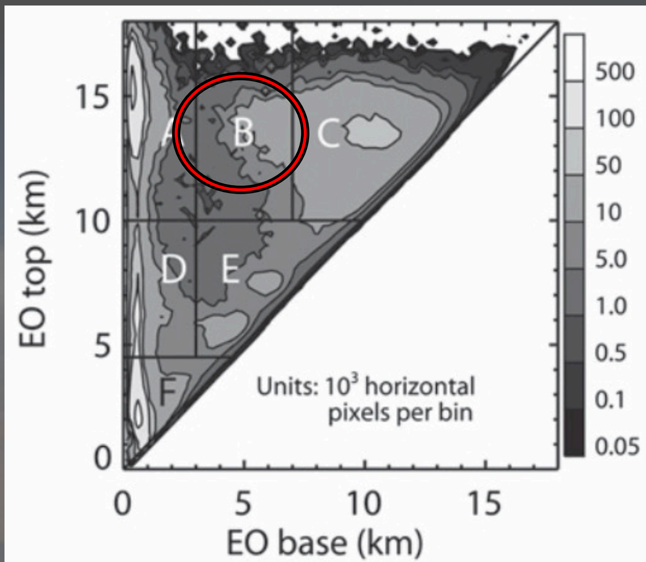


WDP

CU

Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects

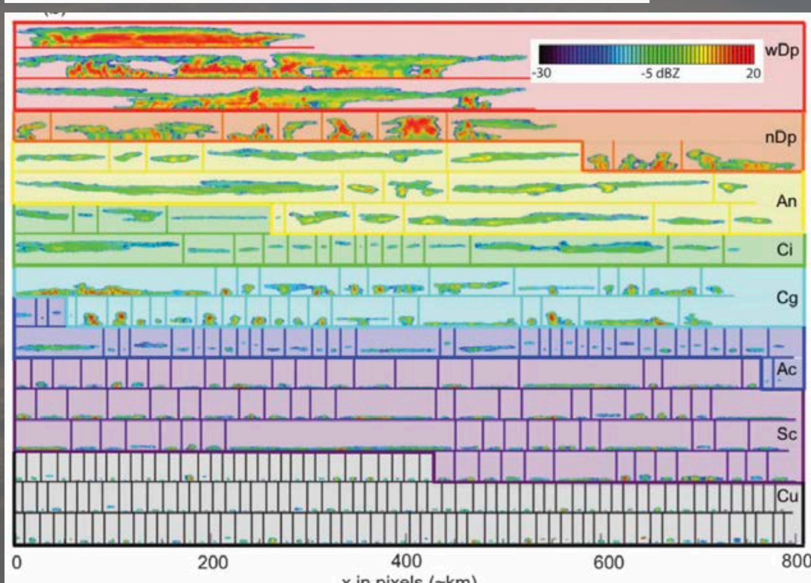


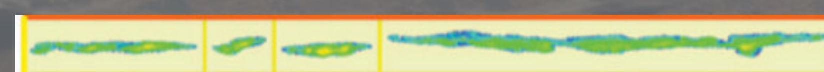
Detached Anvil (DAN)

EO Base > 3 km

EO Top > 10 km

EO Width N/A



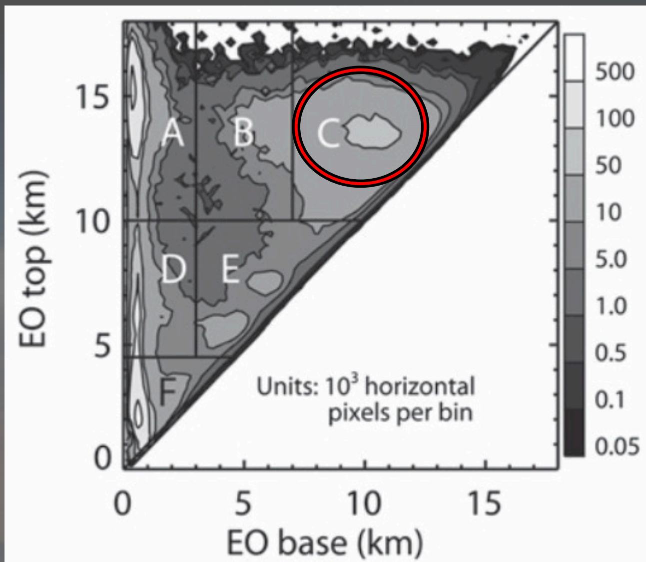


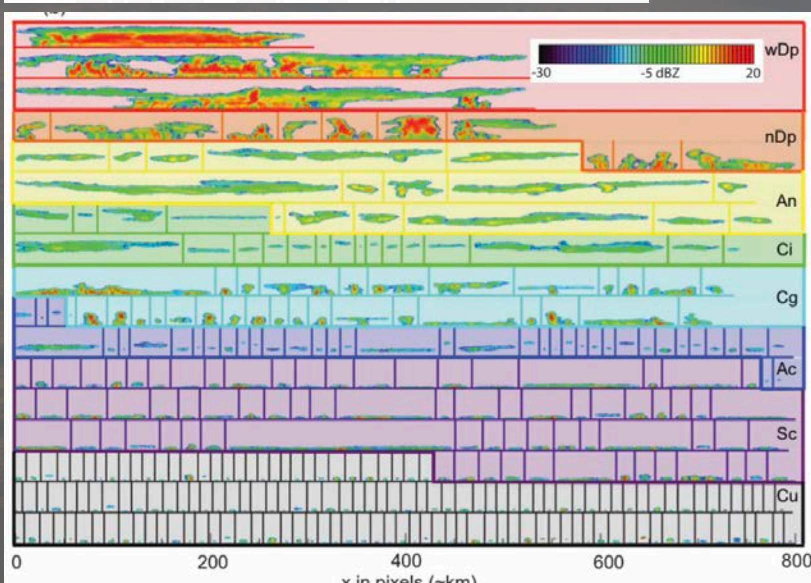
DAN

CU

Characterizing Clouds: Vertical and Horizontal Structure

Riley et al. 2011 CloudSat Echo Objects



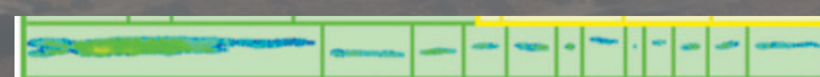


Cirrus (CI)

EO Base >= 7 km

EO Top > 10 km

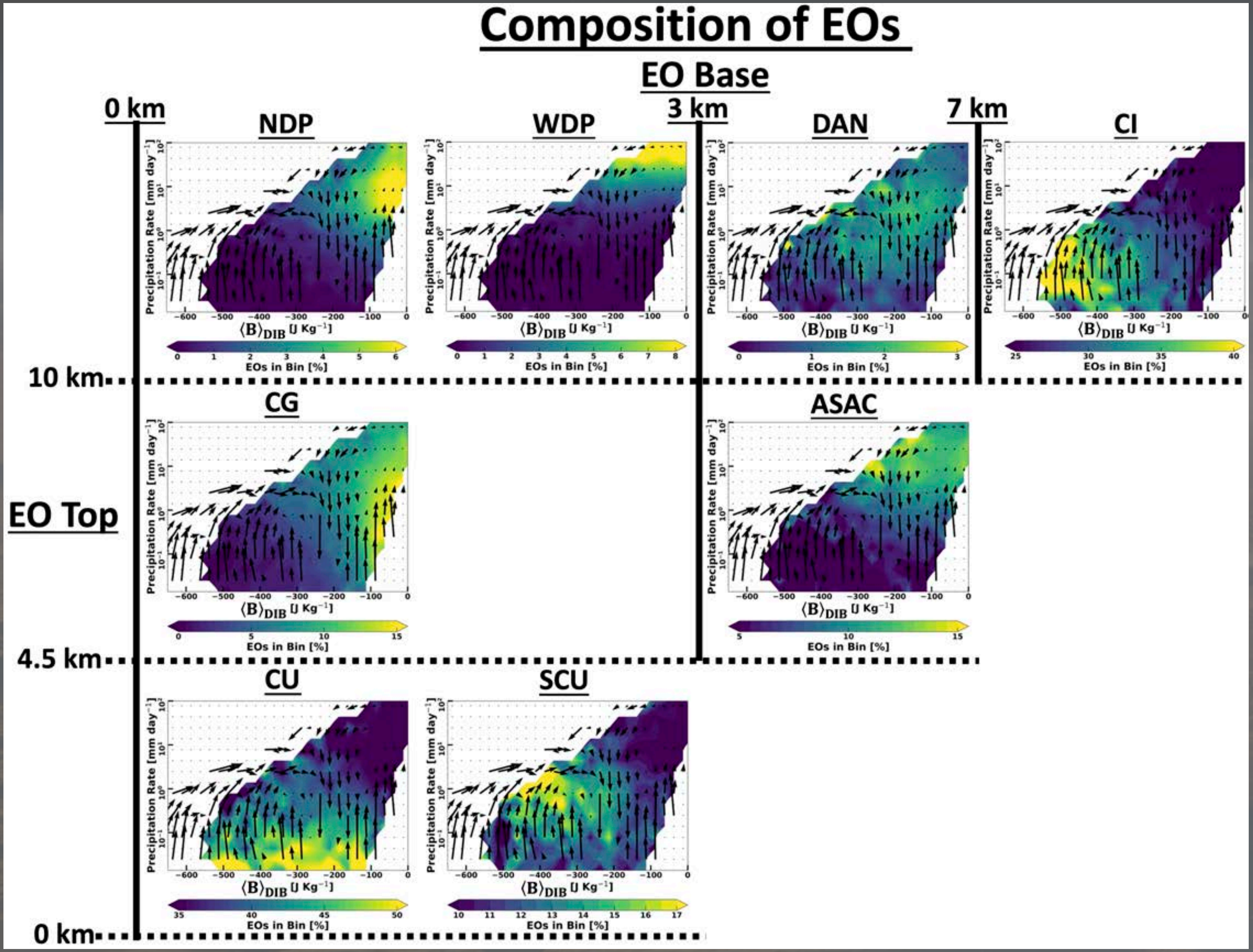
EO Width N/A



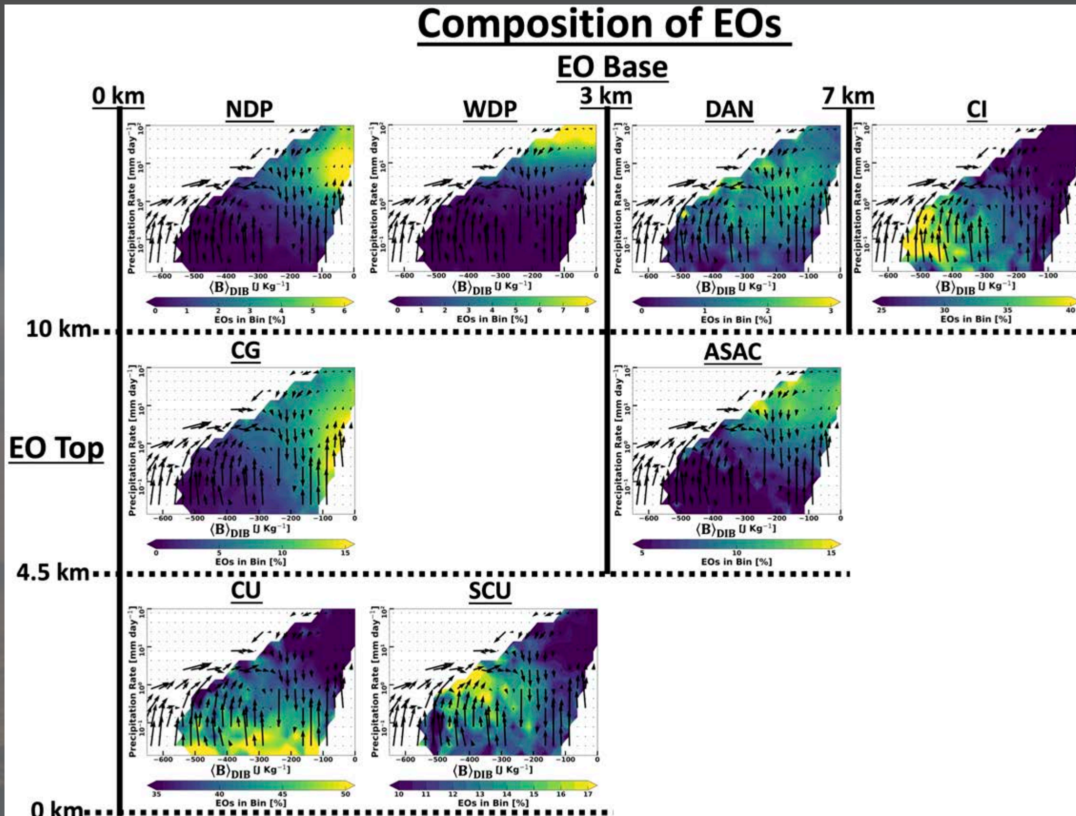
CI

CU

Characterizing Clouds: Vertical and Horizontal Structure



Characterizing Clouds: Shallow and Deep D-R Cycles



Deep Convective D-R Cycle

Shallow Cumulus

↓

Congestus

↓

Narrow Deep Precipitation

↓

MCS - Wide Deep Precipitation

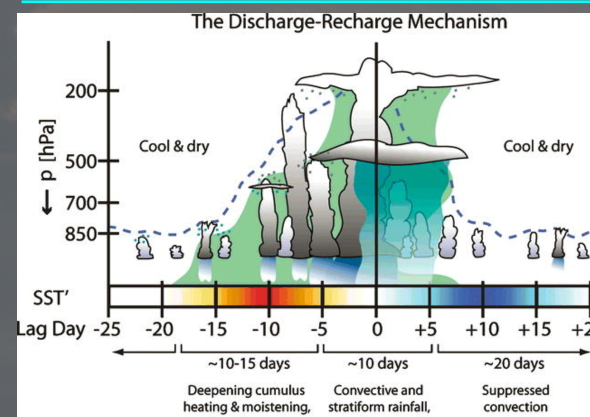
↓

Detached Anvil + Alto Stratus Alto Cumulus

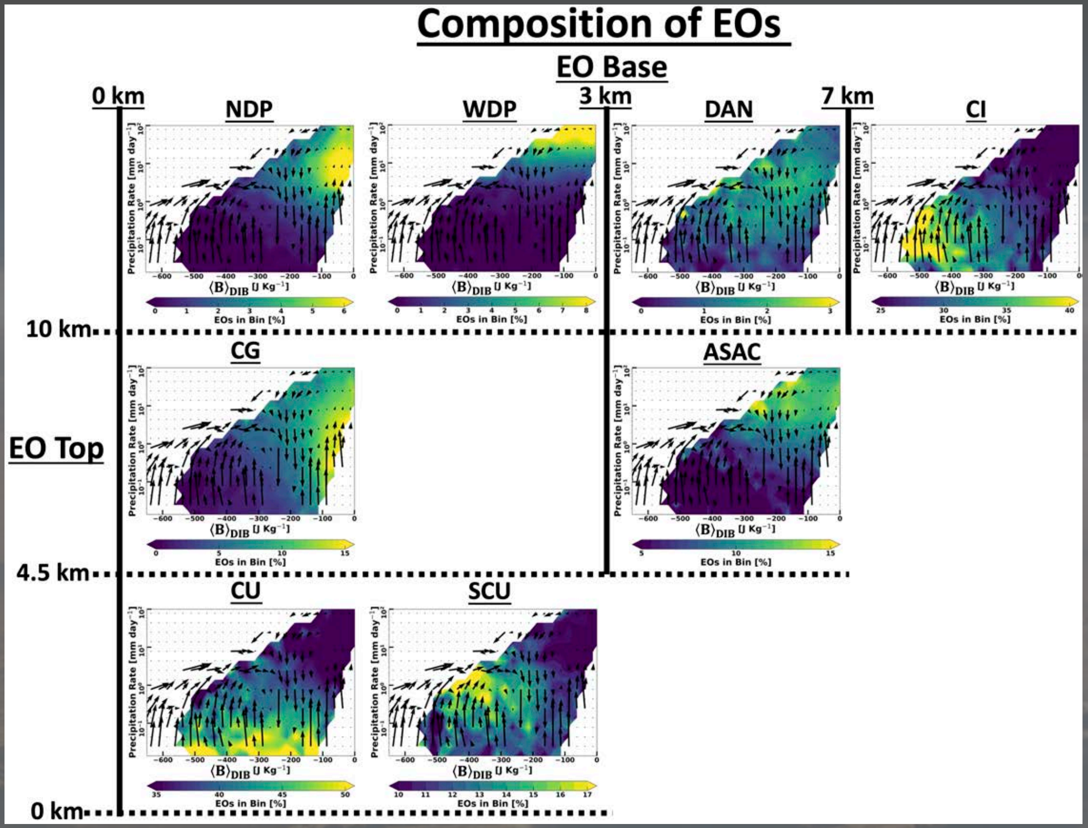
↓

Shallow Cumulus

Benedict and Randall 2007 - MJO



Characterizing Clouds: Shallow and Deep D-R Cycles

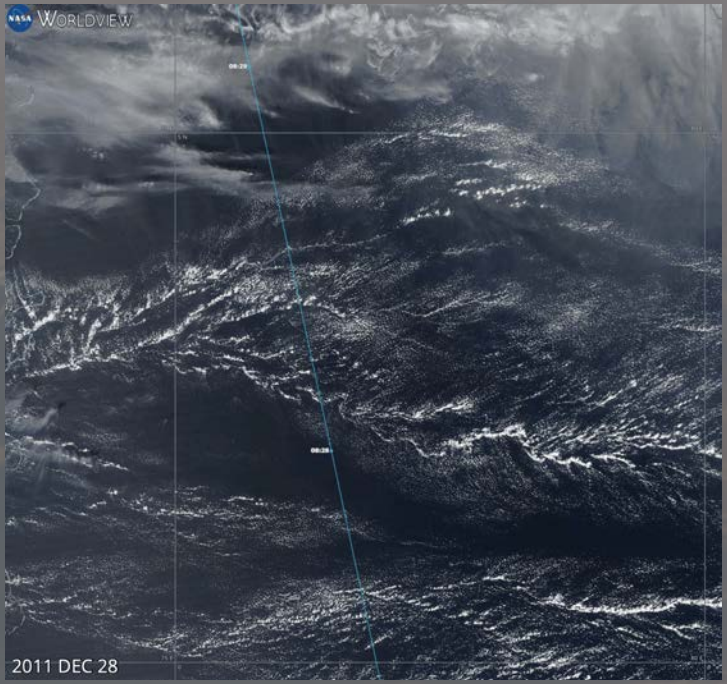


Shallow Convective D-R Cycle

Shallow Cumulus + Cirrus

Stratocumulus + Mixed

Shallow Cumulus + Cirrus



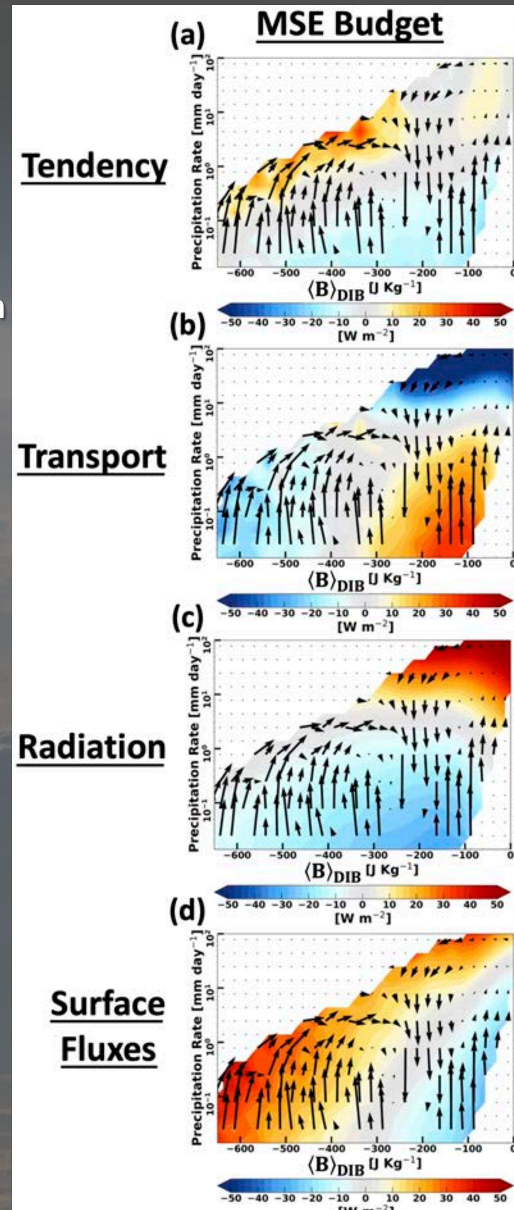
Ocean-Atmosphere Coupled Energy Budgets

Atmosphere MSE Budget

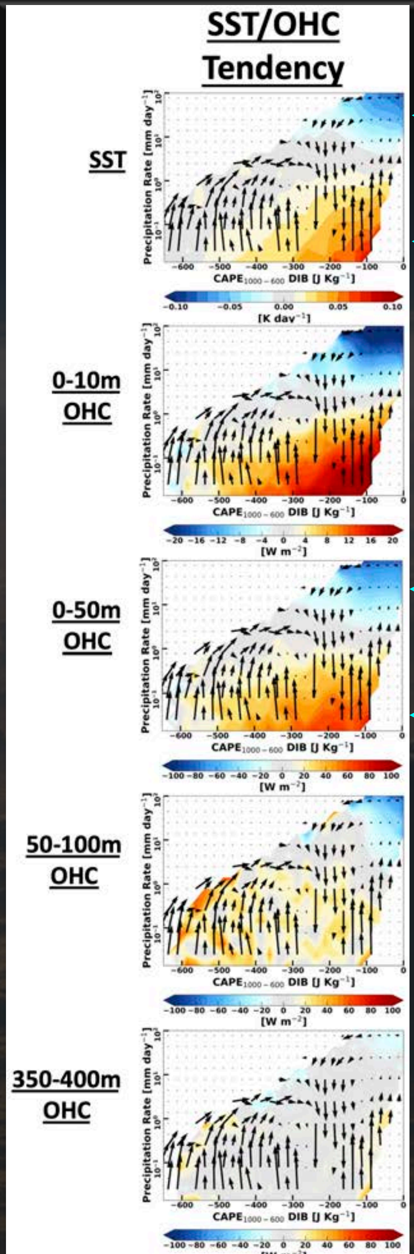
$$\left\langle \frac{\partial \bar{h}}{\partial t} \right\rangle = -\left\langle \bar{\mathbf{V}} \cdot \nabla \bar{h} \right\rangle - \left\langle \bar{\omega} \frac{\partial \bar{h}}{\partial p} \right\rangle + L_v E + H + \langle Q_r \rangle$$

Transport | Surface Fluxes | Radiation

Ocean acting as important energy source/sink



Ocean-Atmosphere Coupled Energy Budgets



SST cooling

SST warming

Upper ocean losing energy

Upper ocean gaining energy

Ocean-Atmosphere Coupled Energy Budgets

Atmosphere MSE Budget

$$\left\langle \frac{\partial \bar{h}}{\partial t}\right\rangle = -\left\langle \bar{\mathbf{V}}\cdot\nabla \bar{h}\right\rangle - \left\langle \bar{\omega}\frac{\partial \bar{h}}{\partial p}\right\rangle + L_v E + H + \langle Q_r\rangle$$

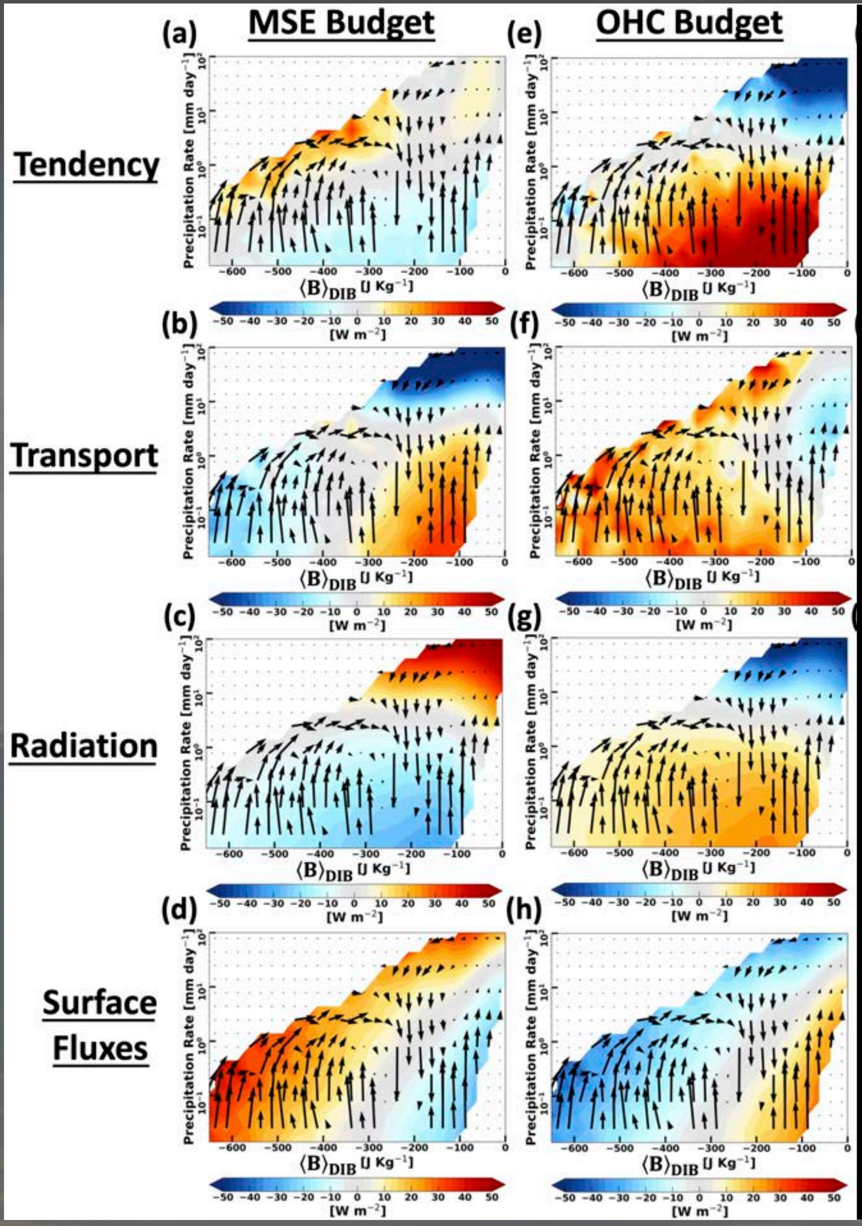
Transport | Surface Fluxes | Radiation

Ocean Heat Content Budget

Transport

$$\left\langle \frac{\partial \overline{OHC}}{\partial t}\right\rangle = -\left\langle \bar{\mathbf{V}}\cdot\nabla \overline{OHC}\right\rangle - \left\langle \bar{w}\frac{\partial \overline{OHC}}{\partial z}\right\rangle - A_h\nabla^2 OHC - \frac{A_z}{H}\frac{\partial \overline{OHC}}{\partial z} - L_v E - H - LW|_{surface} - SW|_{surface} + SW|_H$$

Surface Fluxes | Radiation



Ocean-Atmosphere Coupled Energy Budgets

Atmosphere MSE Budget

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Transport | Surface Fluxes | Radiation

+

Ocean Heat Content Budget

Transport

$$\left\langle \frac{\partial \overline{OHC}}{\partial t} \right\rangle = -\left\langle \bar{\mathbf{V}} \cdot \nabla \overline{OHC} \right\rangle - \left\langle \bar{w} \frac{\partial \overline{OHC}}{\partial z} \right\rangle - A_h \nabla^2 OHC - \frac{A_z}{H} \frac{\partial \overline{OHC}}{\partial z}$$
$$- L_v E - H - LW|_{surface} - SW|_{surface} + SW|_H$$

Surface Fluxes | Radiation

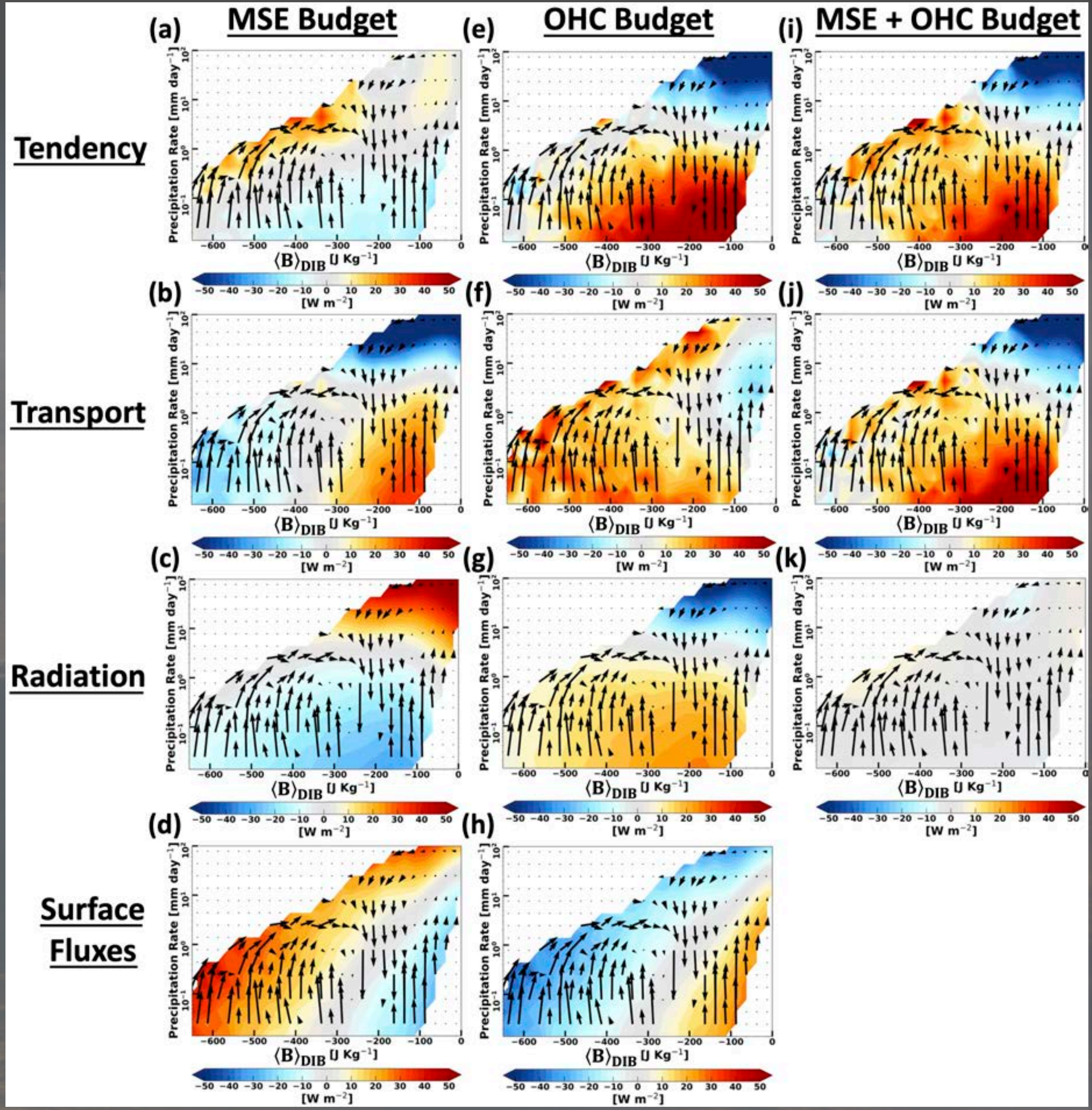
=

Ocean-Atmosphere Budget

Transport

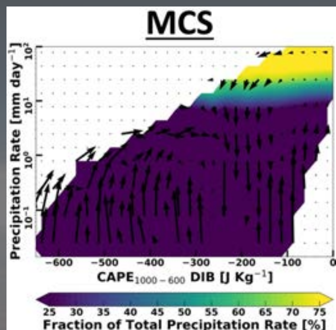
$$\left\langle \frac{\partial \bar{c}}{\partial t} \right\rangle = -\left\langle \bar{\mathbf{V}} \cdot \nabla \bar{h} \right\rangle - \left\langle \bar{\omega} \frac{\partial \bar{h}}{\partial p} \right\rangle - \left\langle \bar{\mathbf{V}} \cdot \nabla \overline{OHC} \right\rangle - \left\langle \bar{w} \frac{\partial \overline{OHC}}{\partial z} \right\rangle - A_h \nabla^2 OHC - \frac{A_z}{H} \frac{\partial \overline{OHC}}{\partial z}$$
$$- LW|_{100hPa} - SW|_{100hPa} + SW|_H$$

Radiation



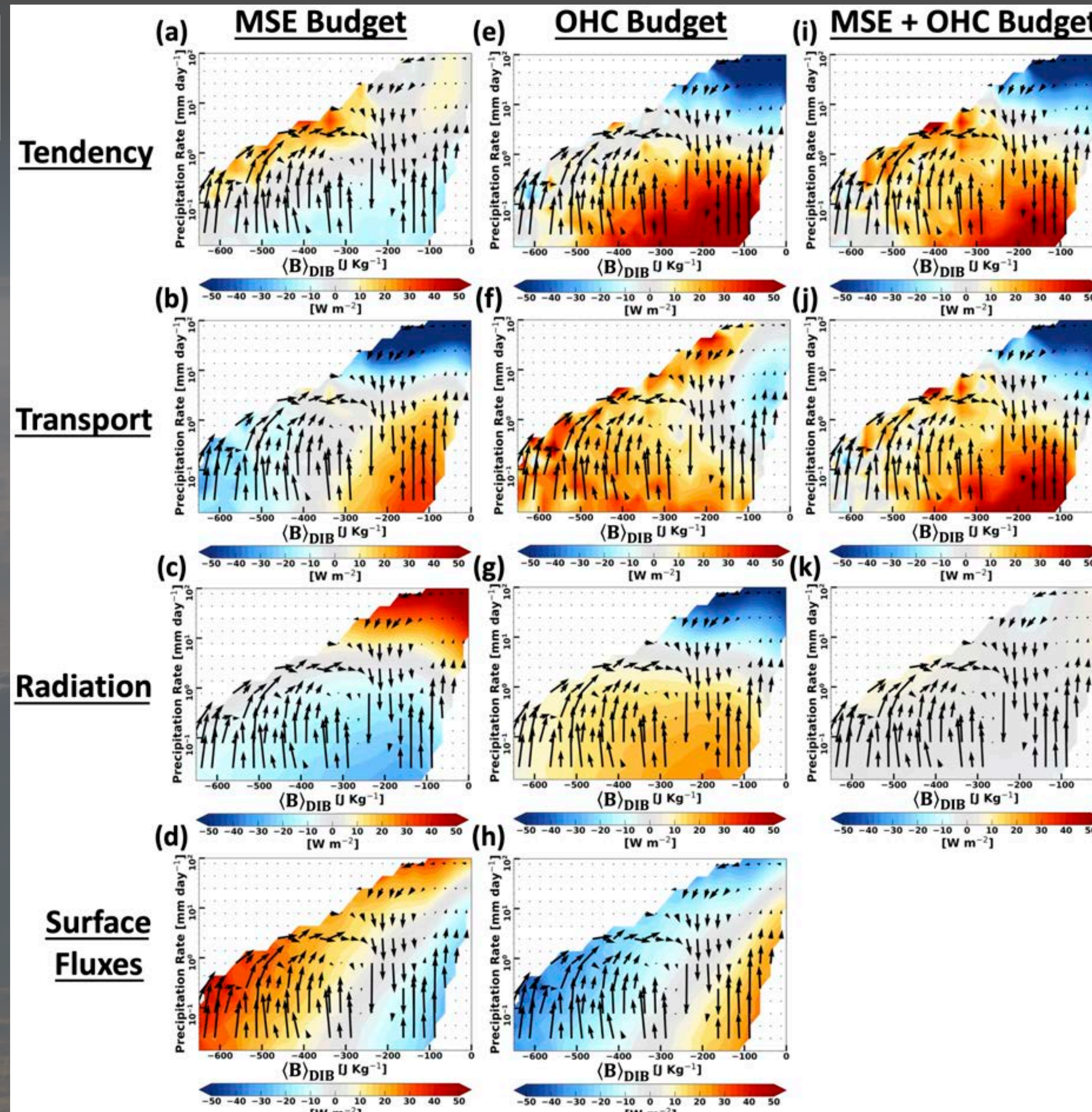
Ocean-Atmosphere Coupled Energy Budgets

How do MCSs impact ocean and atmosphere energy budgets?



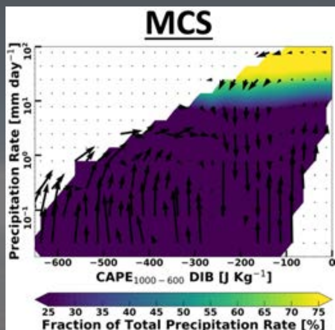
atmospheric export of MSE supported by reduced LW cooling and enhanced surface fluxes

upper ocean rapidly losing energy by reduced SW radiation and enhanced surface fluxes

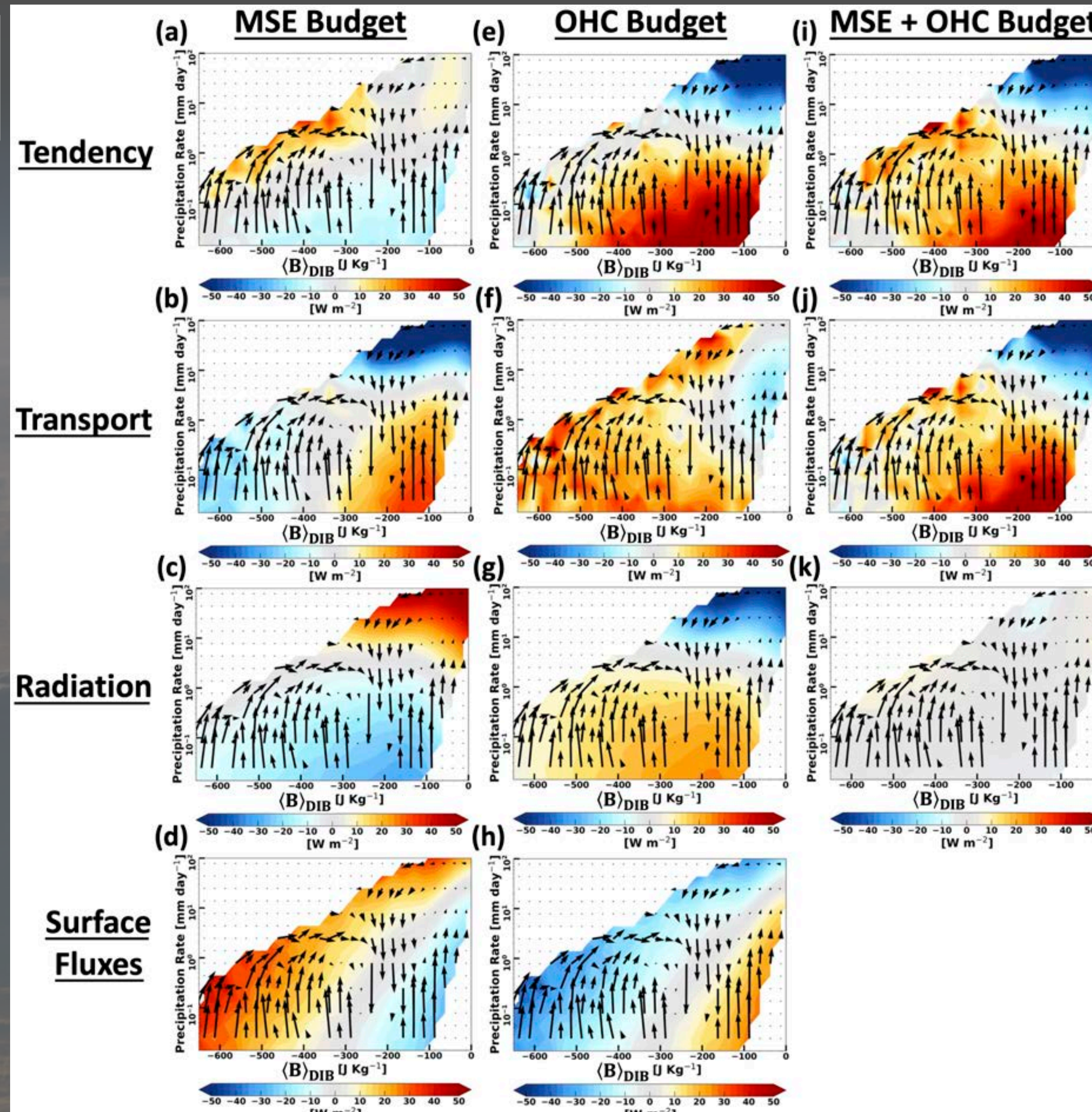


Ocean-Atmosphere Coupled Energy Budgets

How do **MCSs impact** ocean and atmosphere **energy budgets?**

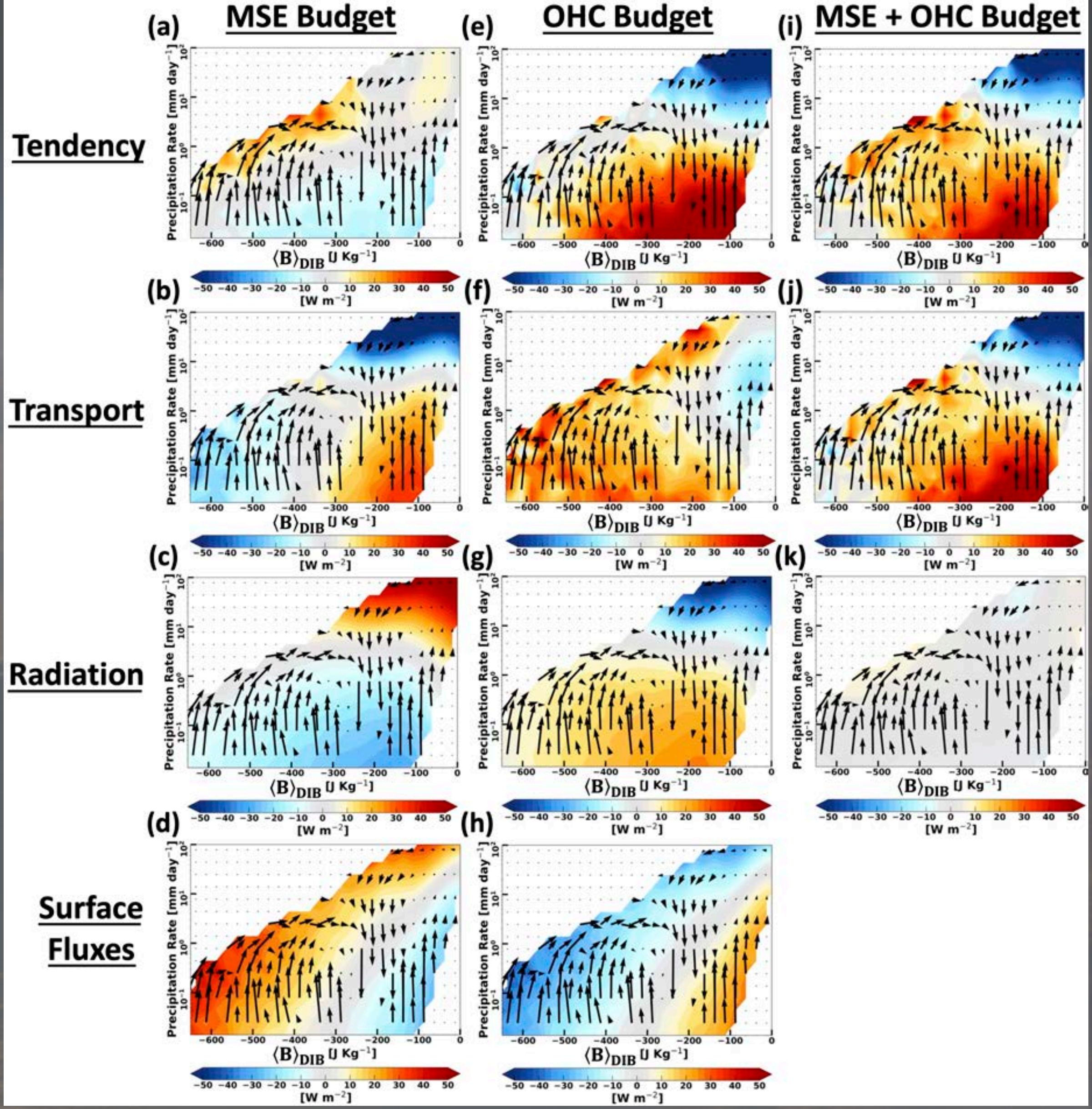


MCS are unique in their ability to rapidly **discharge** lower tropospheric convective instability and **OHC**



Ocean-Atmosphere Coupled Energy Budgets

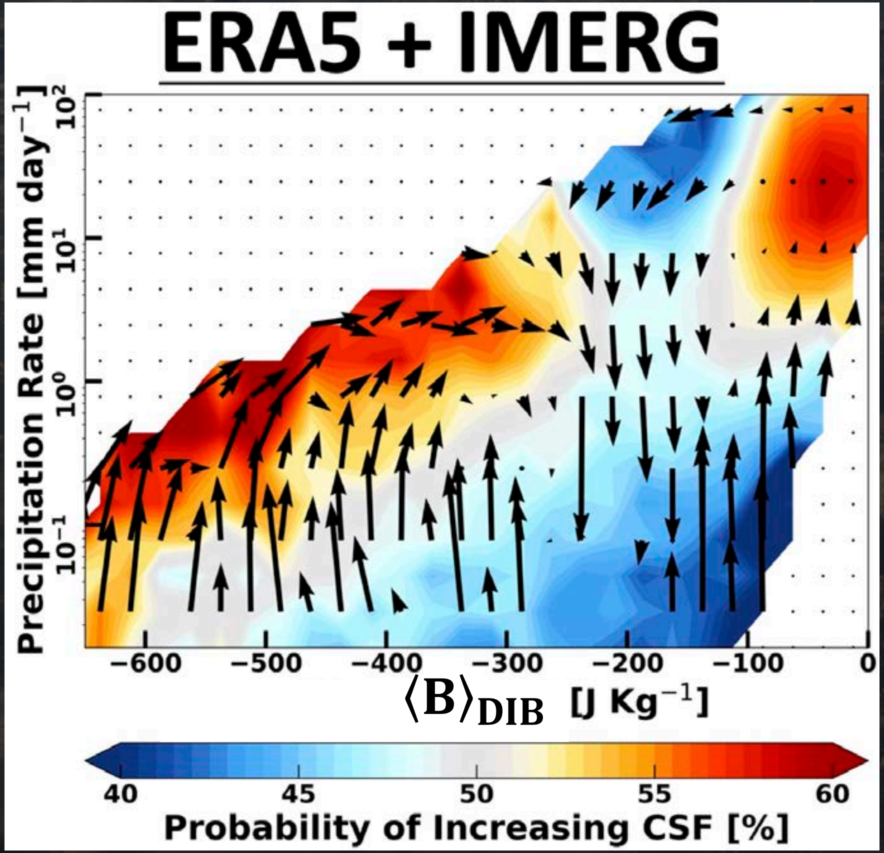
Variability in processes impacting MSE comparable in magnitude to, but more balanced than, variability in processes impacting OHC



Radiative feedbacks are similar to surface flux feedbacks, in that they re-distribute energy between the atmosphere + ocean, without changing the total quantity of MSE + OHC

Summary

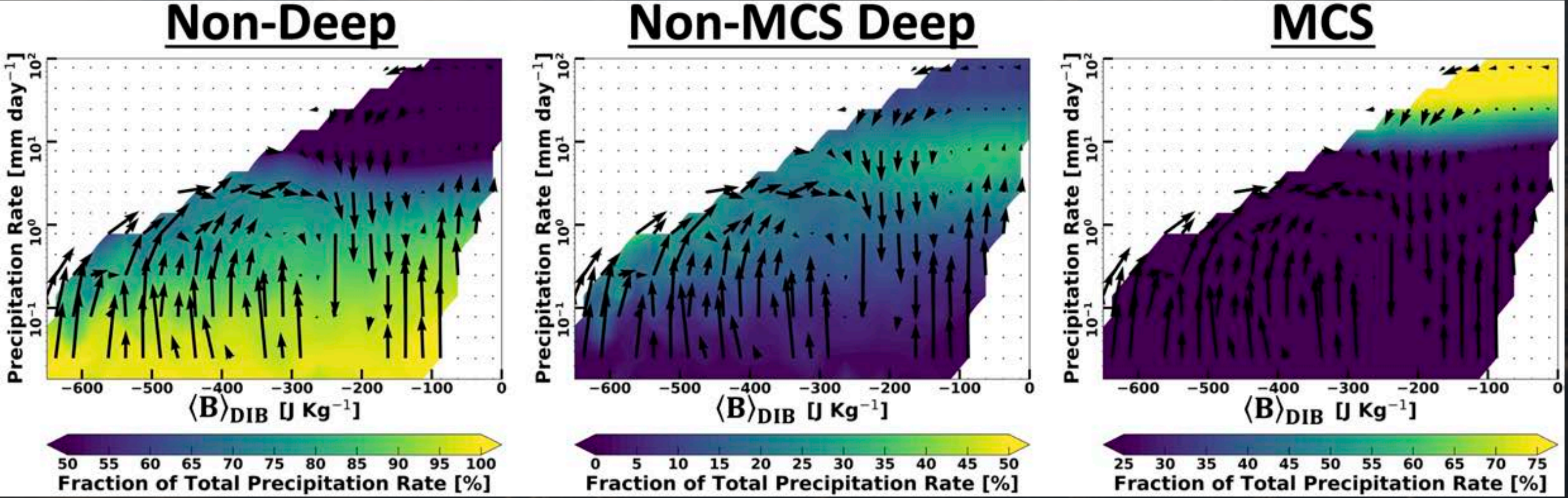
1.) Identified shallow convective and deep convective discharge-recharge cycles



Summary

1.) Identified shallow convective and deep convective discharge-recharge cycles

2.) Characterized structure and organization of clouds associated with D-R cycles



Summary

1.) Identified shallow convective and deep convective discharge-recharge cycles

2.) Characterized structure and organization of clouds associated with D-R cycles

3.) Combined ocean and atmosphere energy budgets to examine D-R cycles