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

Brandon Wolding
U.S. CLIVAR Summit
July, 2025

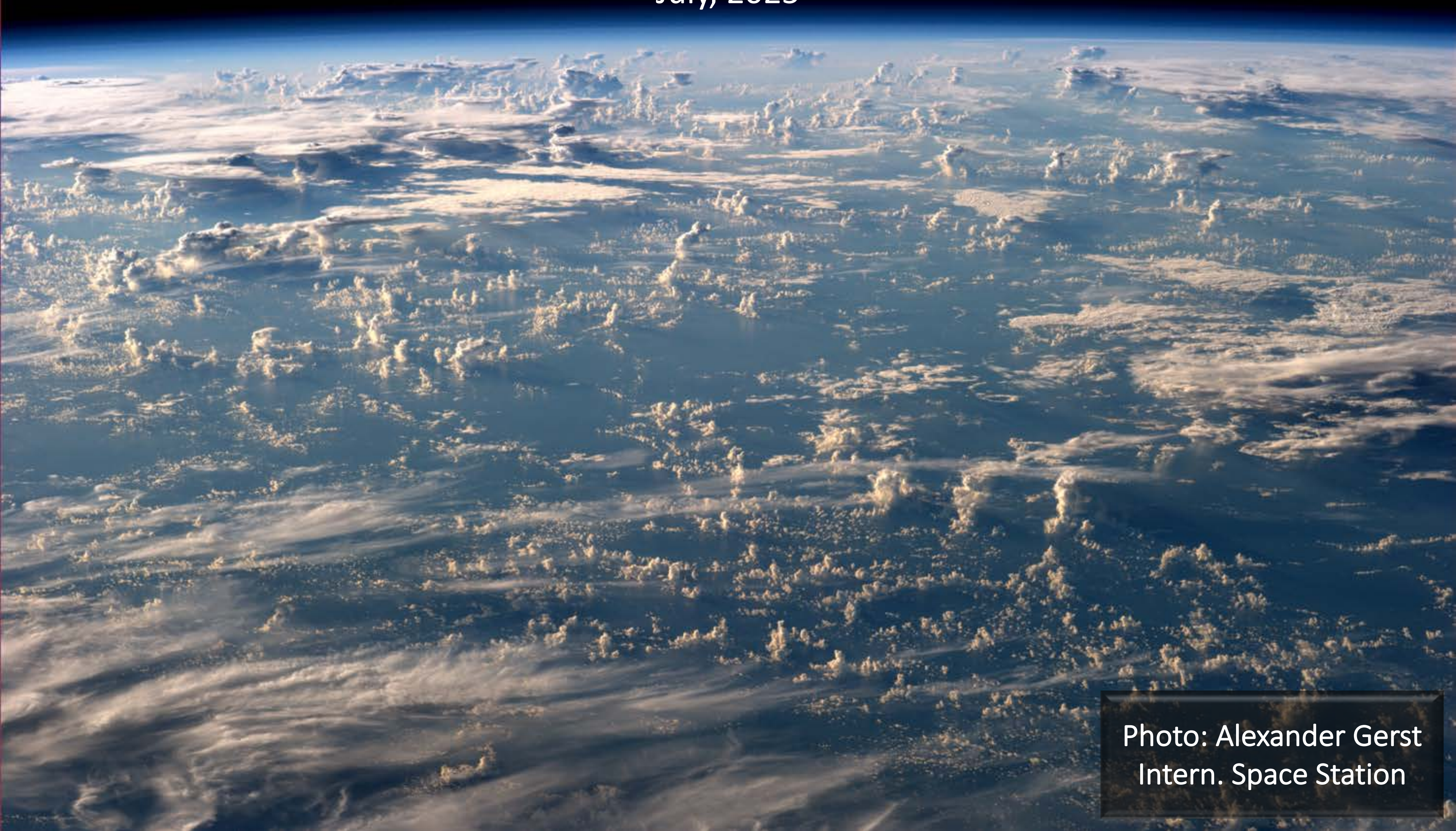

Photo: Alexander Gerst
Intern. Space Station

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Collaborators

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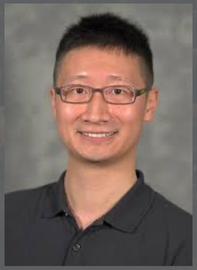
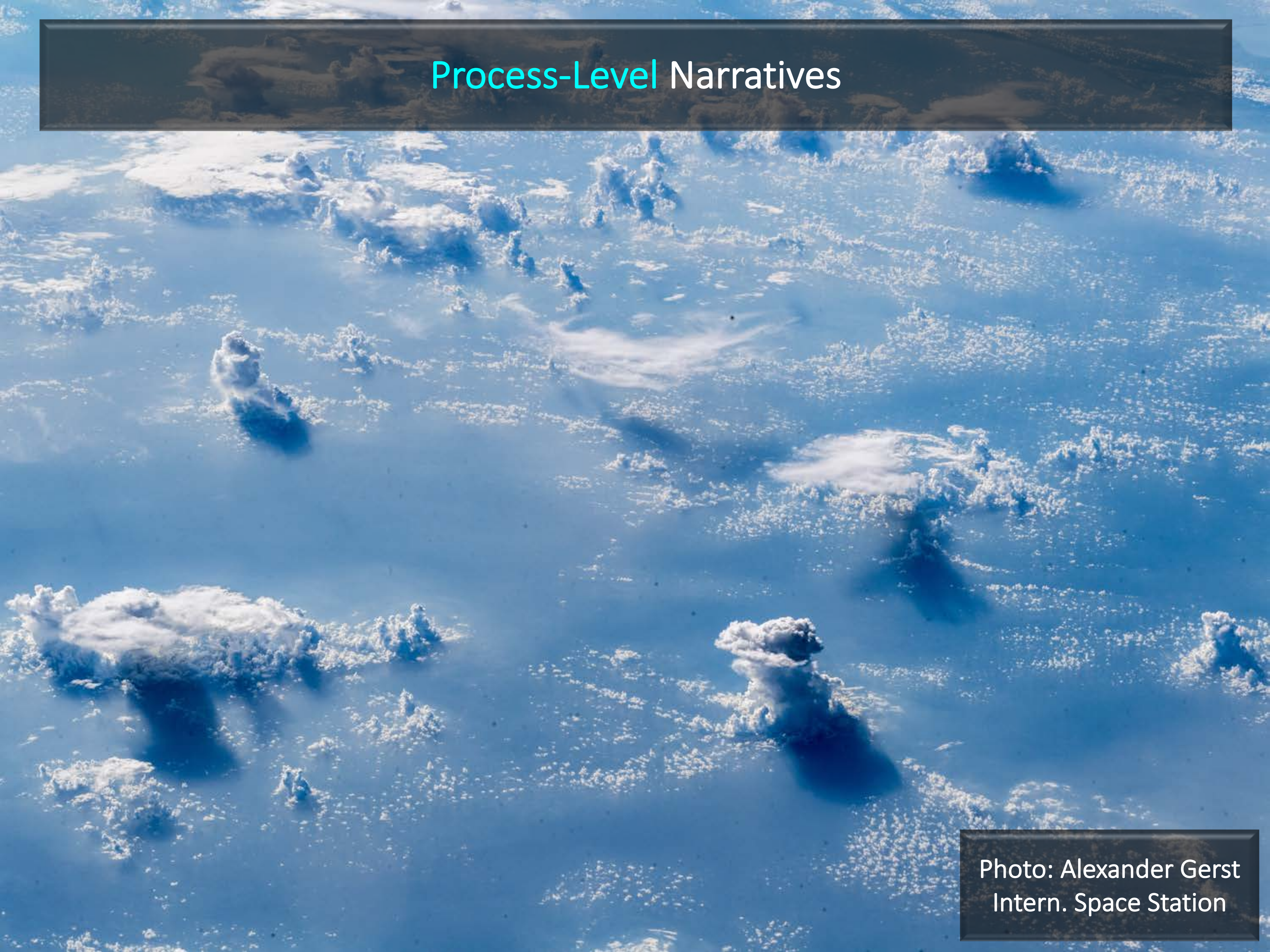


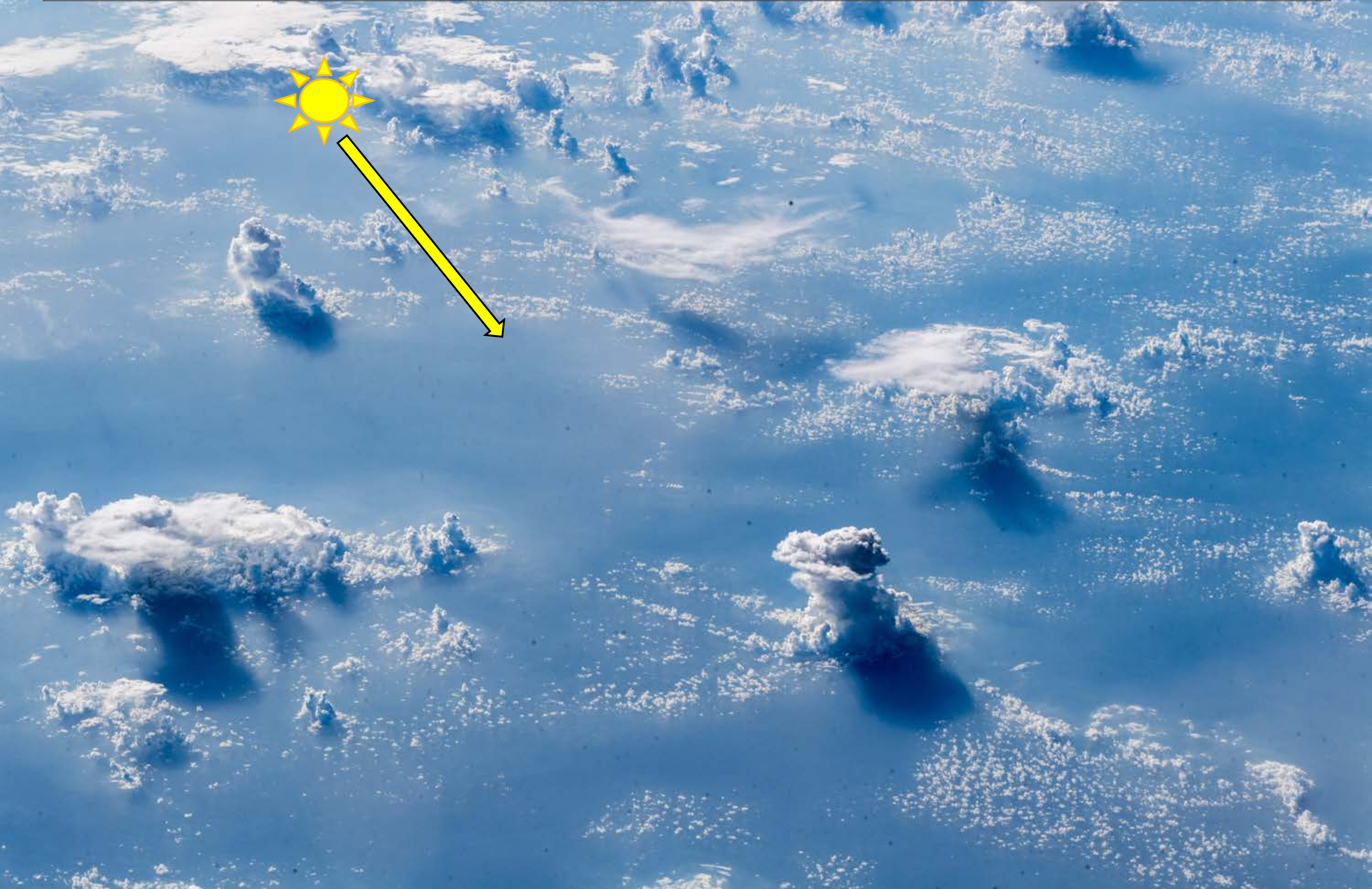
Isabel McCoy



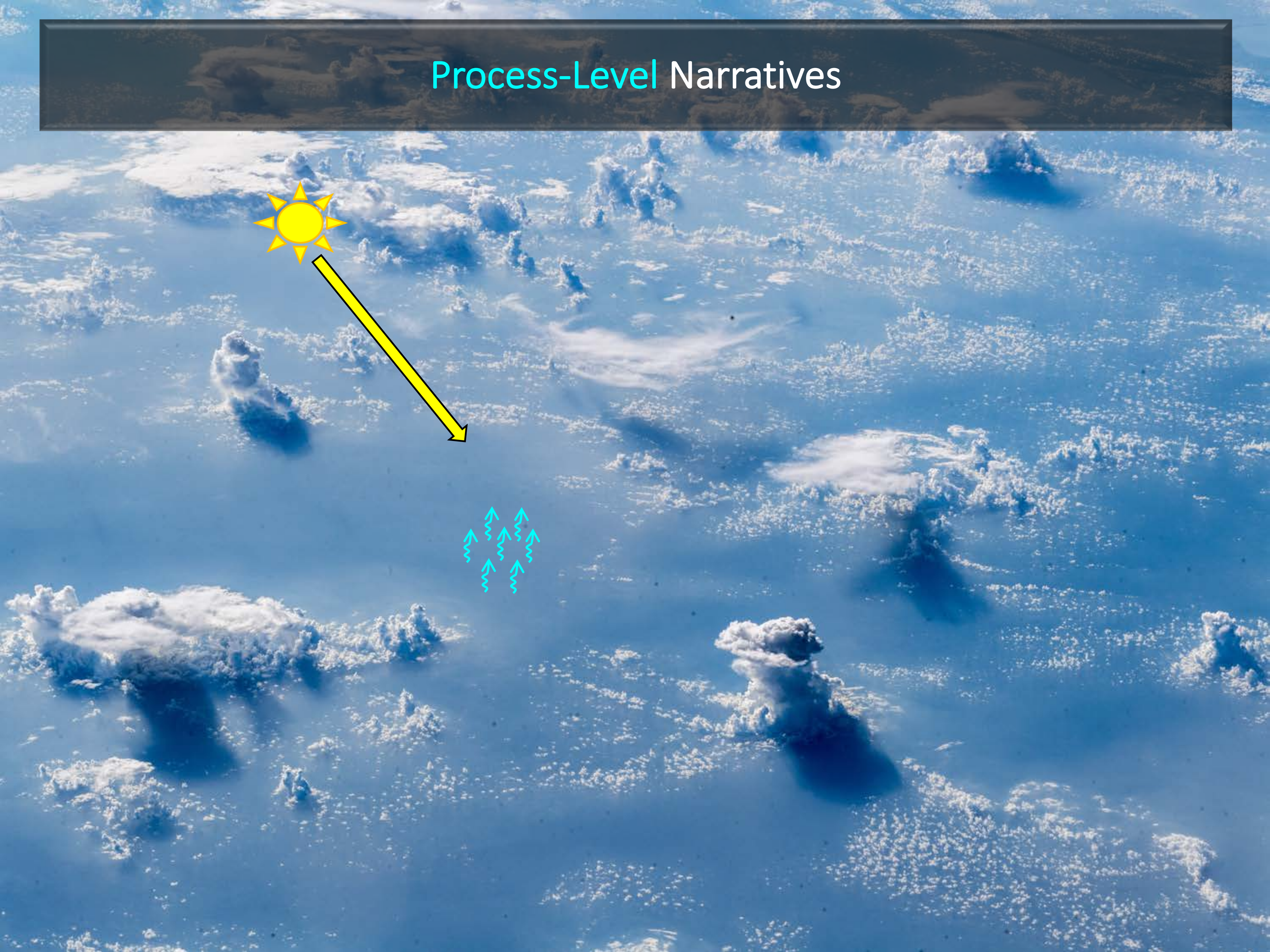
Process-Level Narratives

Photo: Alexander Gerst
Intern. Space Station

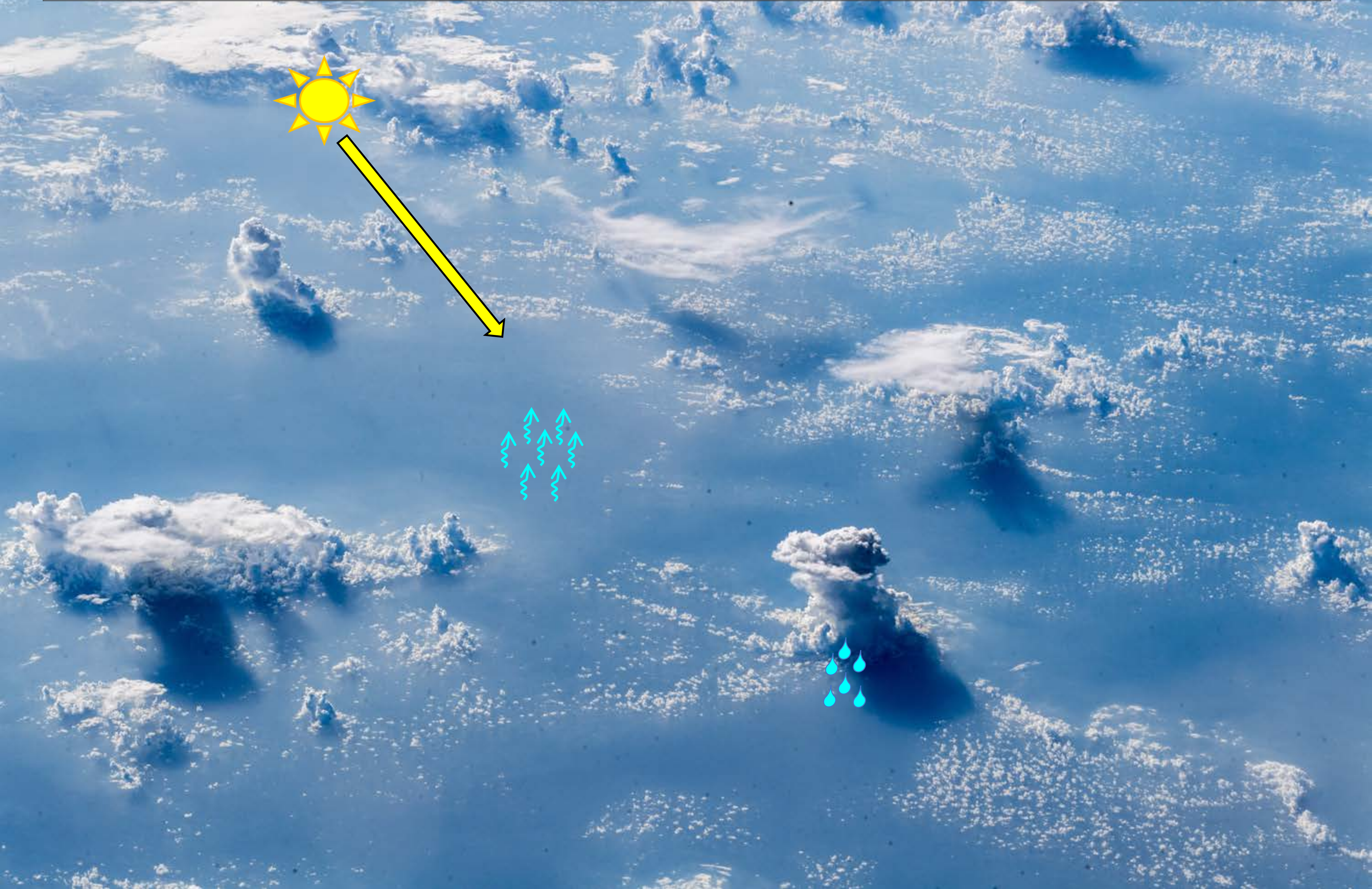
Process-Level Narratives



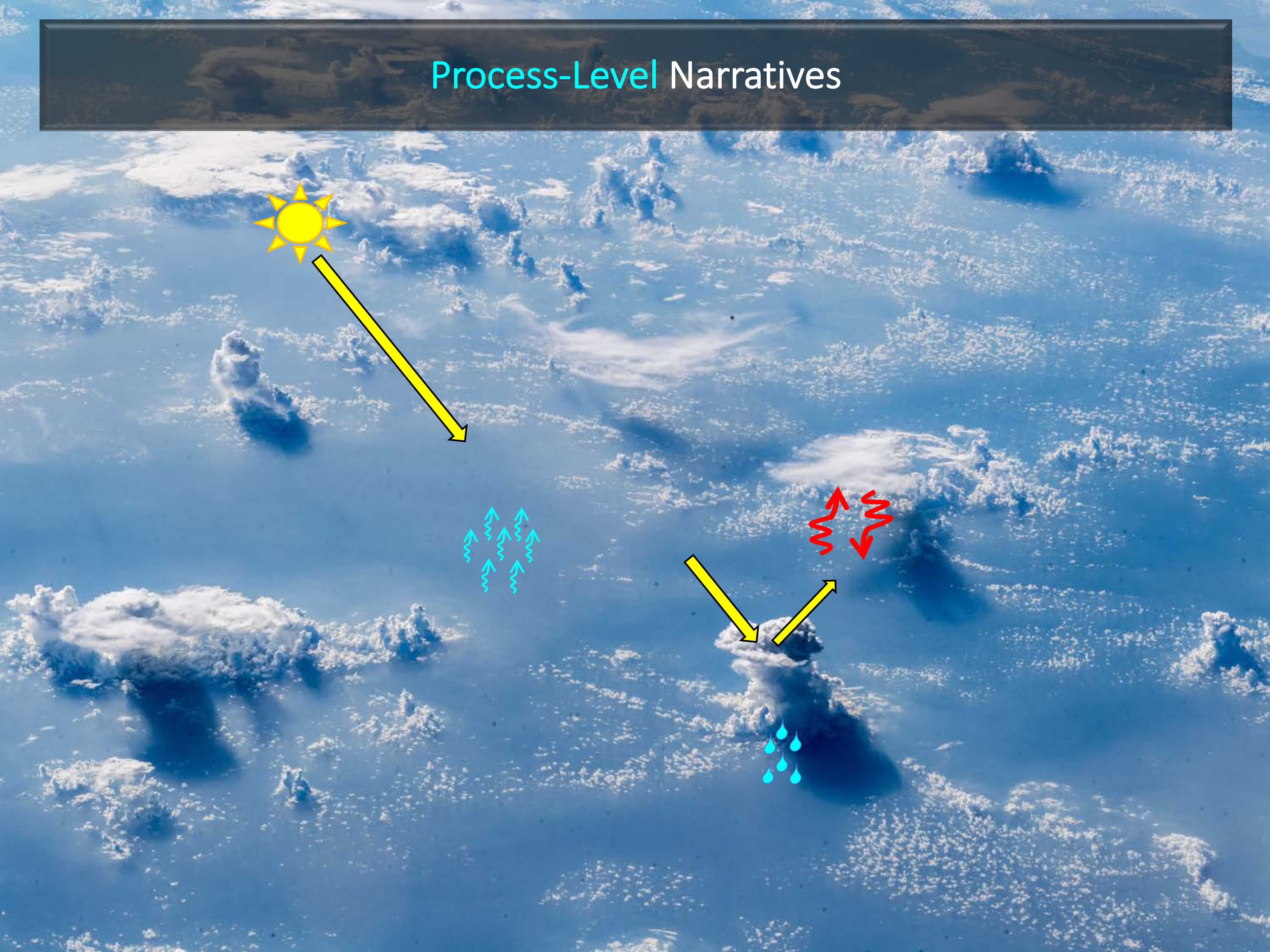
Process-Level Narratives



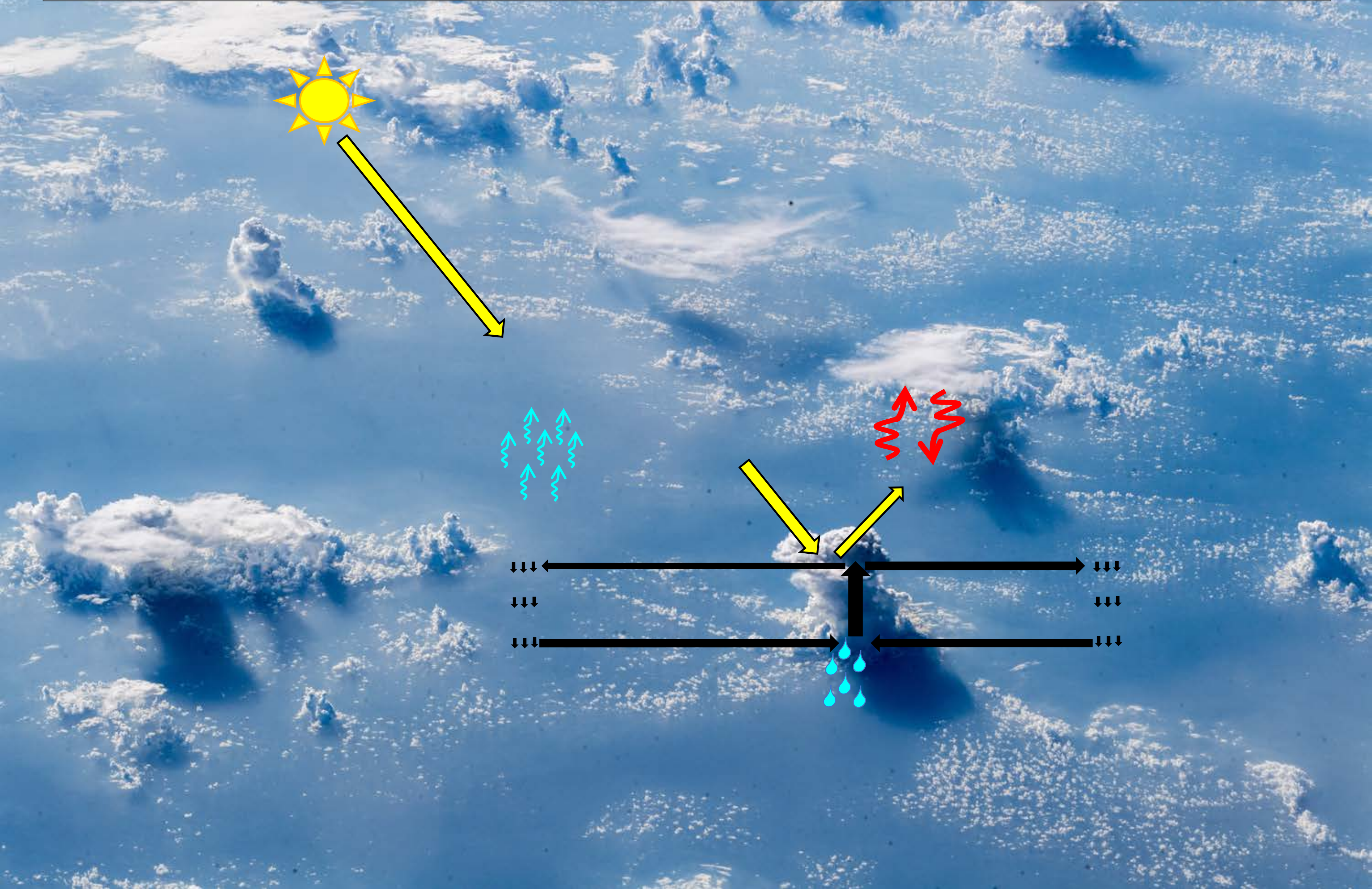
Process-Level Narratives



Process-Level Narratives

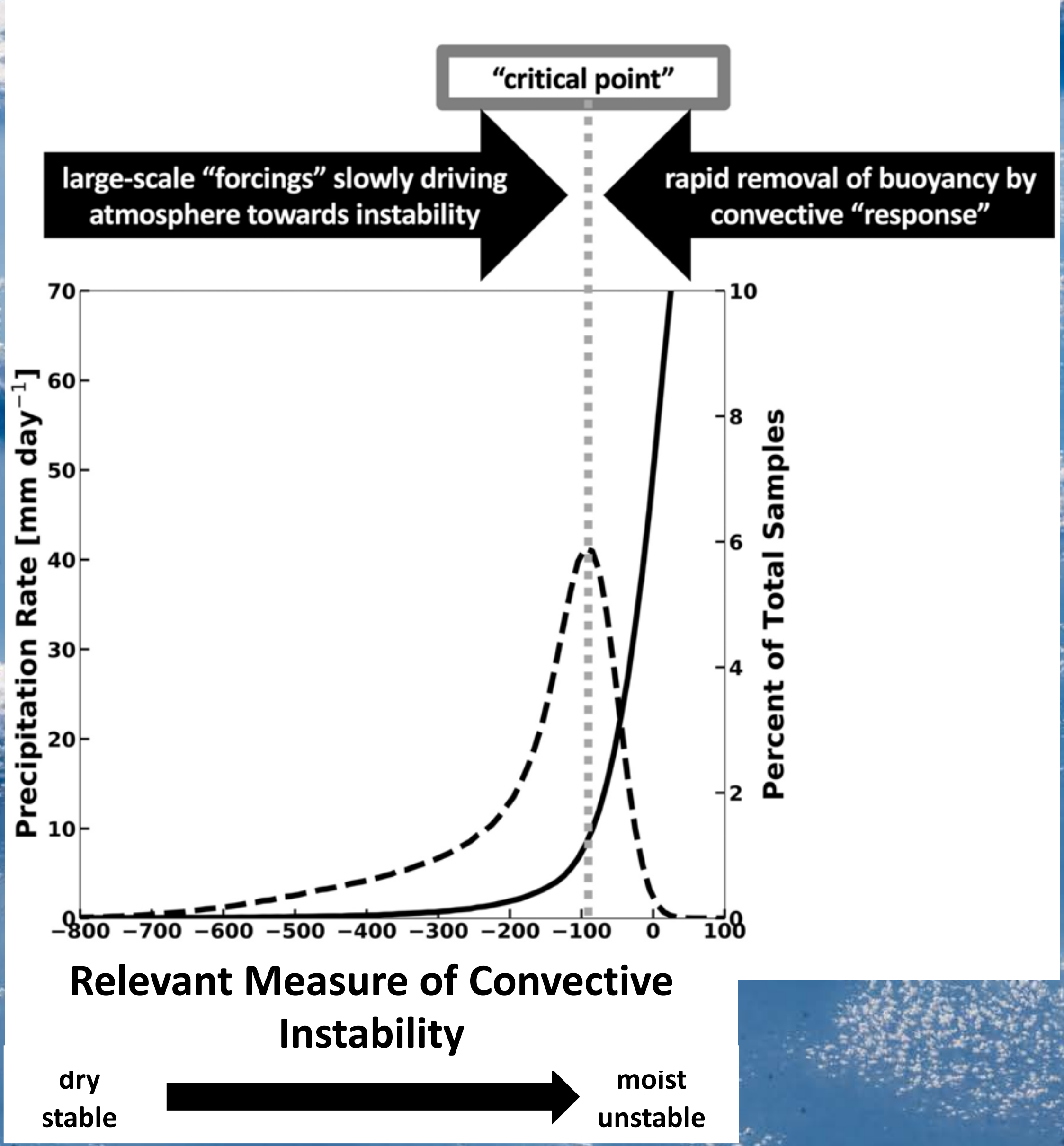


Process-Level Narratives



Large-Scale “Forcing” and Convective “Response”

Large-Scale “Forcing” and Convective “Response”



“critical point”

large-scale “forcings” slowly driving atmosphere towards instability

rapid removal of buoyancy by convective “response”

Relevant Measure of Convective Instability

dry
stable

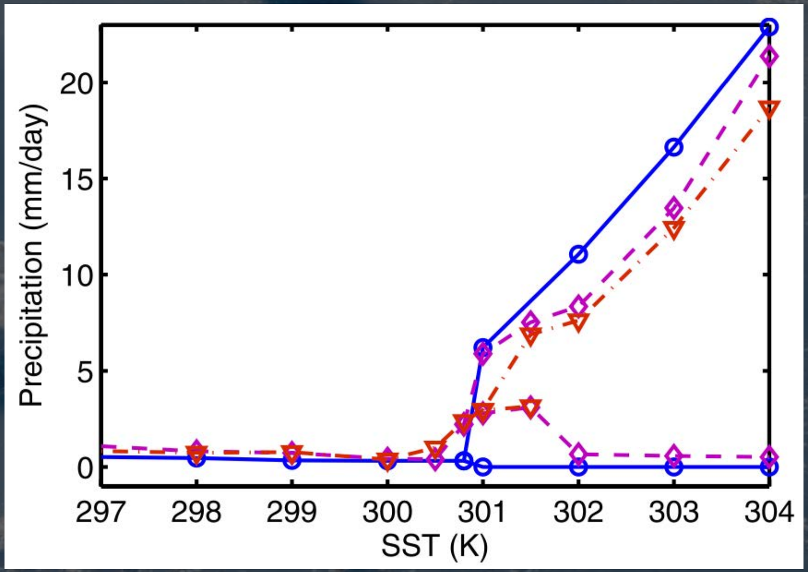
moist
unstable

Large-Scale “Forcings” Respond to Convection

Multiple Equilibria of Tropical Convection

Single column model:

- **Weak Temperature Gradients (WTG) approximation**
- **all use 301K RCE temperature profile**
- **initialized using different humidity profiles**



Sobel et al. 2007

Moist Initial Conditions

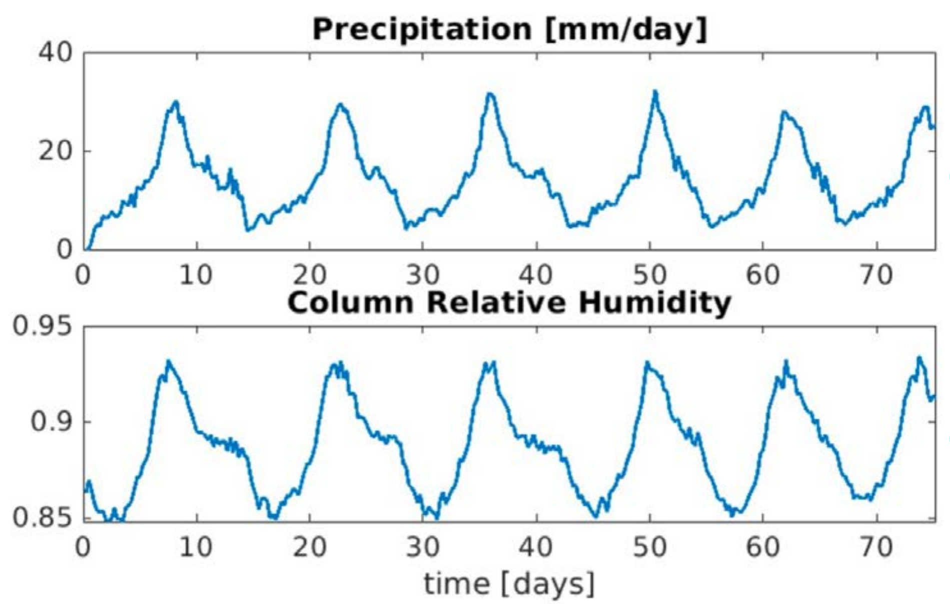
moist, precipitating equilibrium
convective heating > radiative cooling
large-scale ascent

Dry Initial Conditions

dry, non-precipitating equilibrium
convective heating < radiative cooling
large-scale subsidence

Oscillatory Equilibria and Tropical Convection

Small domain CRM (64 x 64 km) with WTG approximation



~10 mm day^{-1}

~90% RH

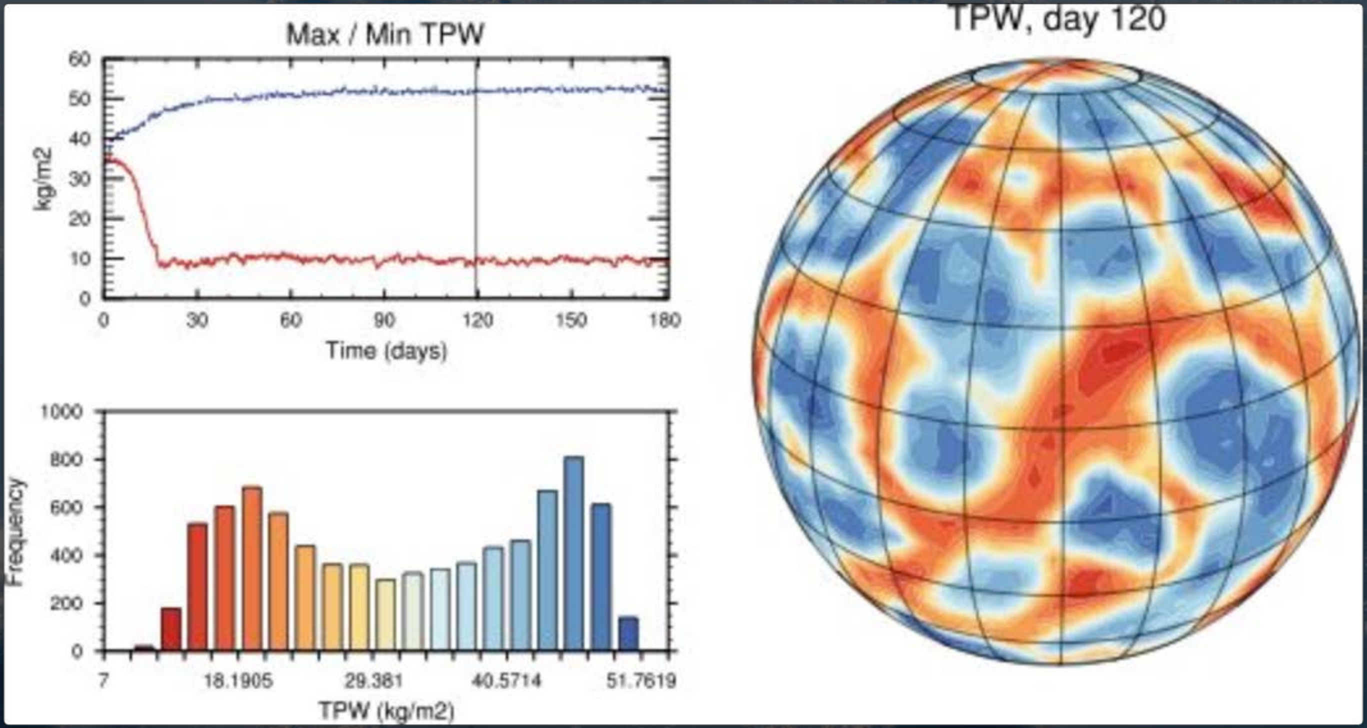
Bernardez and Back 2025

see also Nathanael Wong and Zhiming Kuang

oscillations around a moist, precipitating statistical quasi-equilibrium
“discharge-recharge cycles”

Convective Self-Aggregation

Global non-rotating aquaplanet with uniform boundary conditions



two distinct states of statistical quasi-equilibrium
bi-modal distribution of CWV
pulsing or oscillatory behavior around each mode
“discharge-recharge cycles”

Roadmap for Today’s Presentation

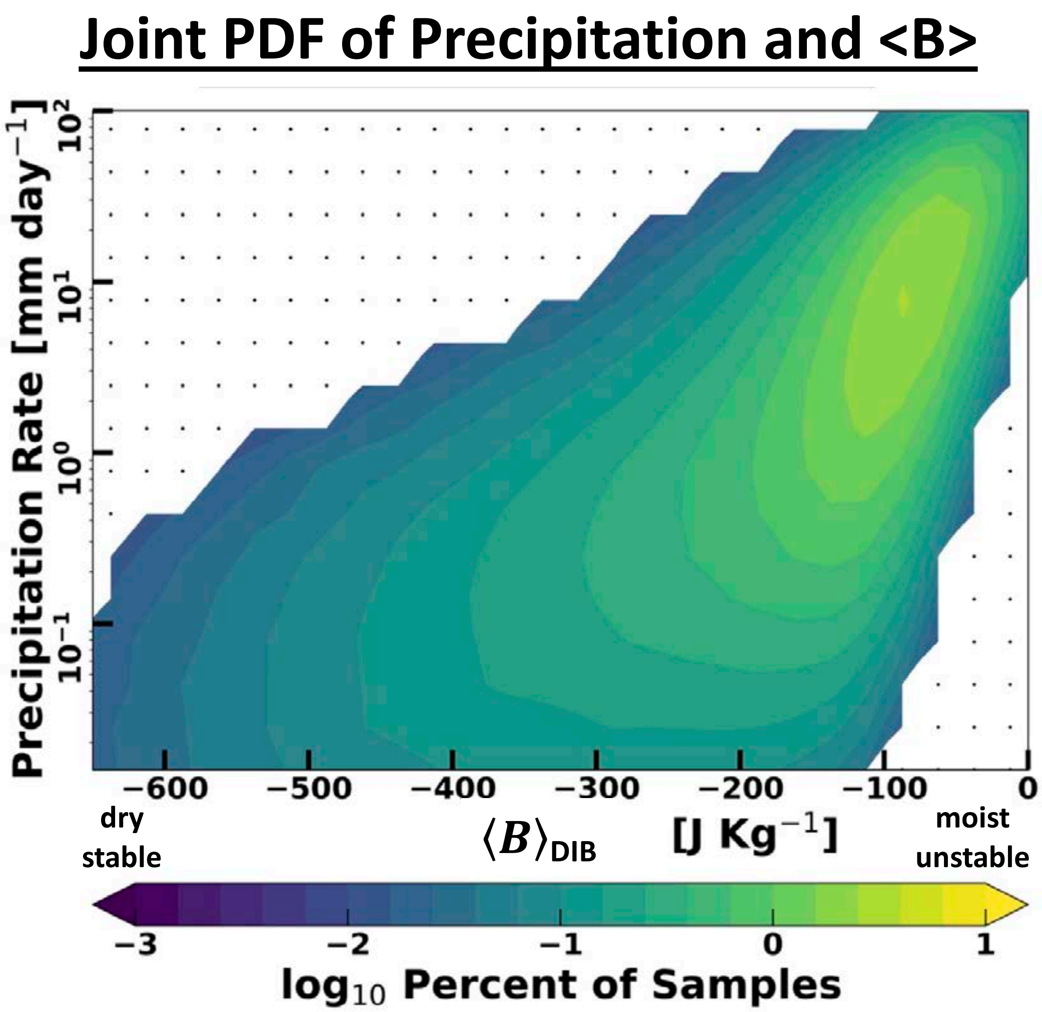
1.) Identify convective discharge-recharge cycles in observations

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

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

Tropical warm pool
Daily average 2.5°x 2.5°
ERA5 T and q
HYCOM SST and Θ
IMERG precipitation

Identifying Convective Discharge-Recharge Cycles



<B>

offline plume model prescribed “deep inflow” entrainment

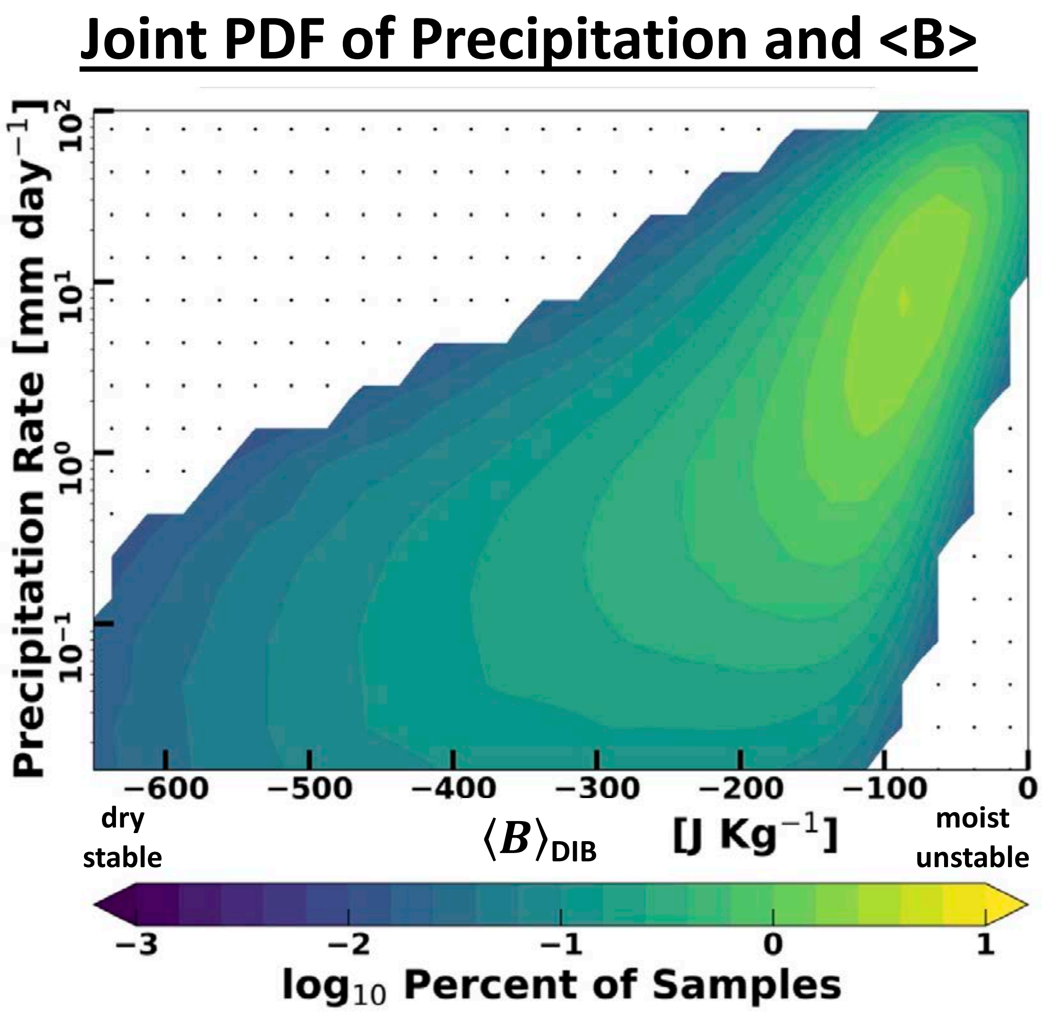
coarse large-scale measure of convective instability

Precipitation rate generally increases with increasing <B>

but…

Wide range of precipitation rates for fixed/given <B> value

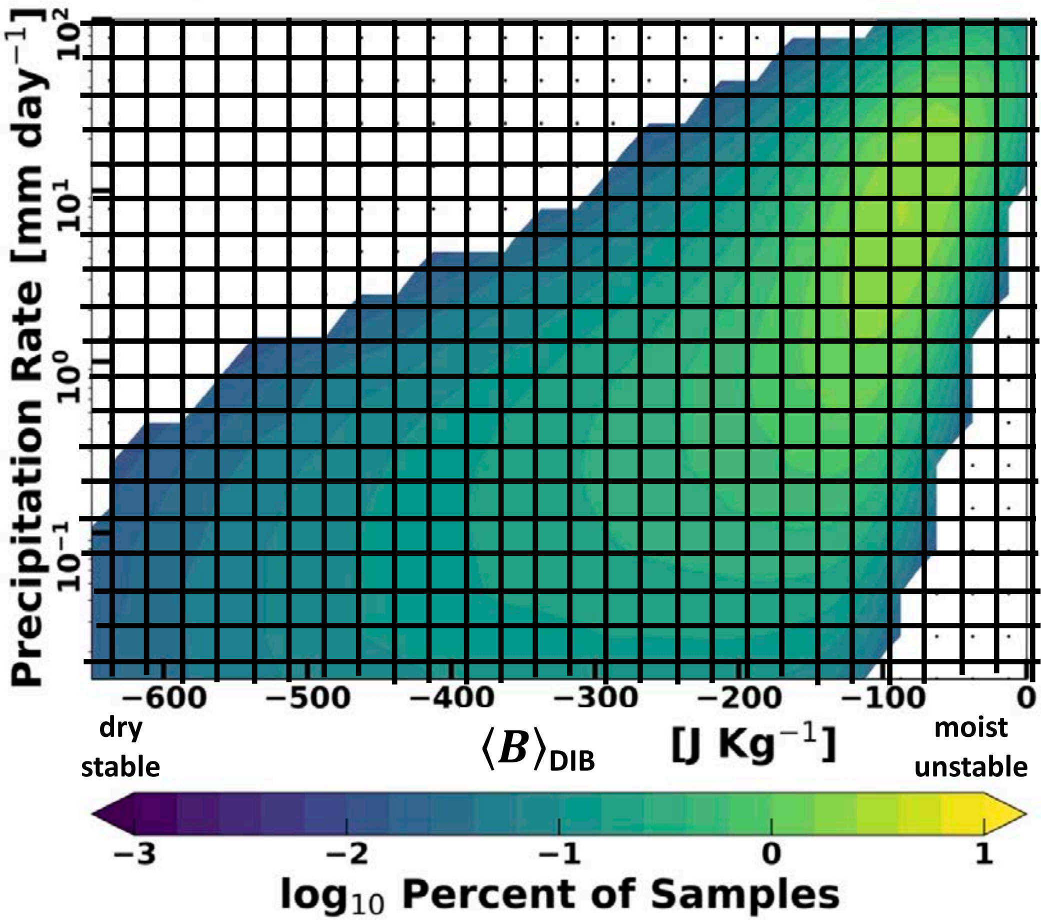
Identifying Convective Discharge-Recharge Cycles



How do precipitation and <B> co-evolve in time?

Identifying Convective Discharge-Recharge Cycles

Joint PDF of Precipitation and <B>



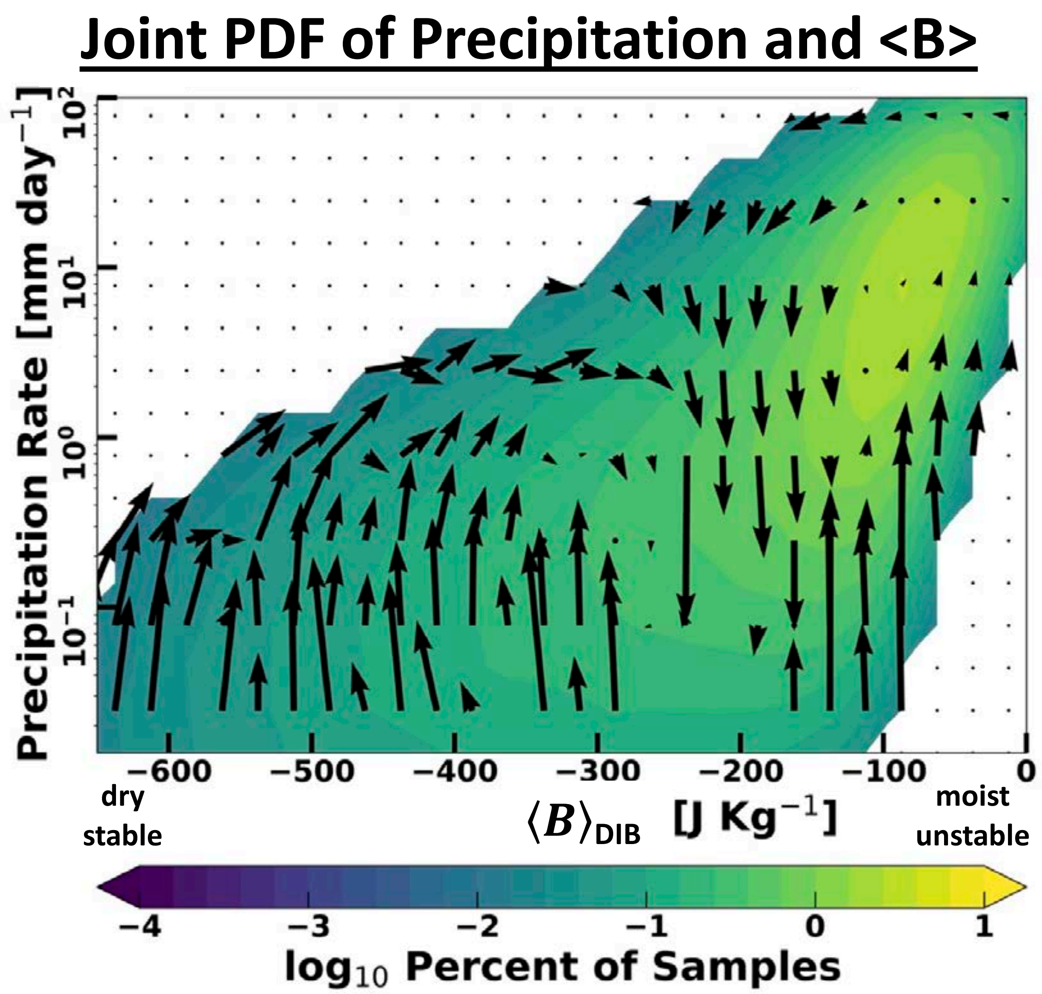
Methodology

1.) separate data into bins
of precipitation rate and <B>

then examine

2.) bin-mean temporal tendency of
precipitation and <B>
in each bin

Identifying Convective Discharge-Recharge Cycles



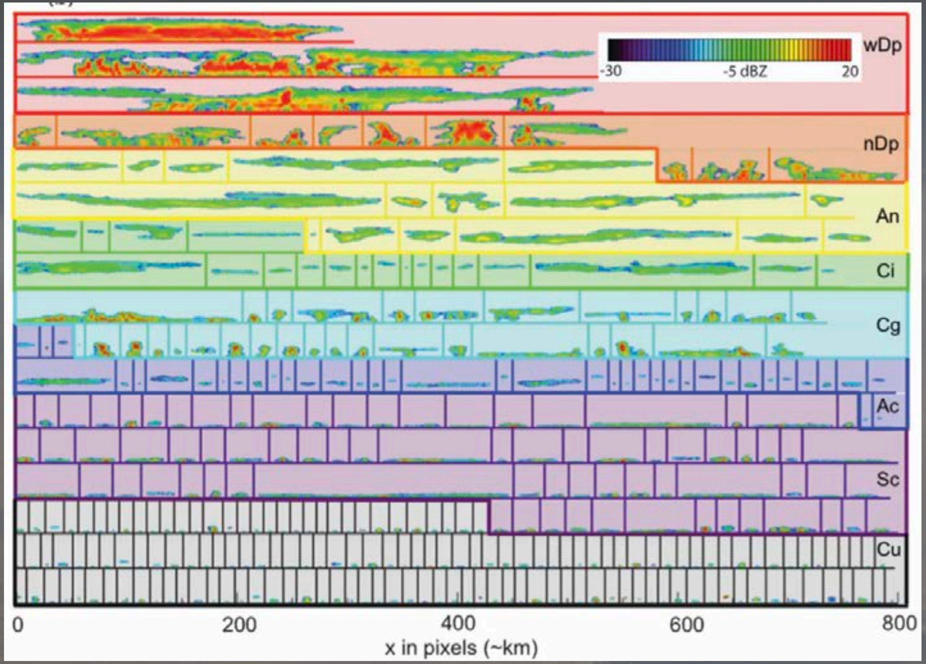
Discharge-Recharge Cycle

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

Overlapping shallow and deep convective D-R cycles

Characterizing Clouds: Vertical and Horizontal Structure

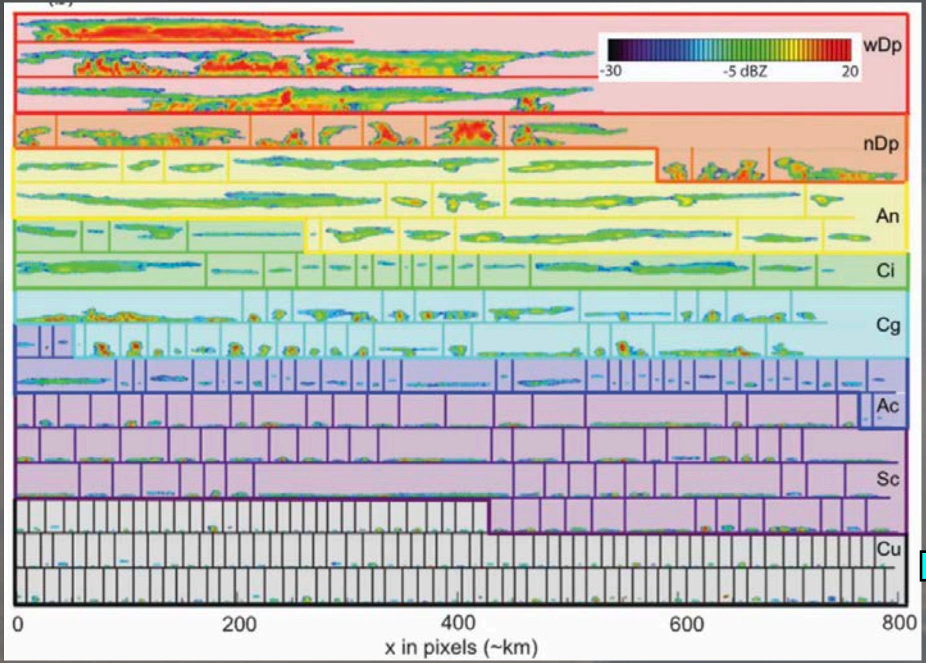
CloudSat Echo Objects



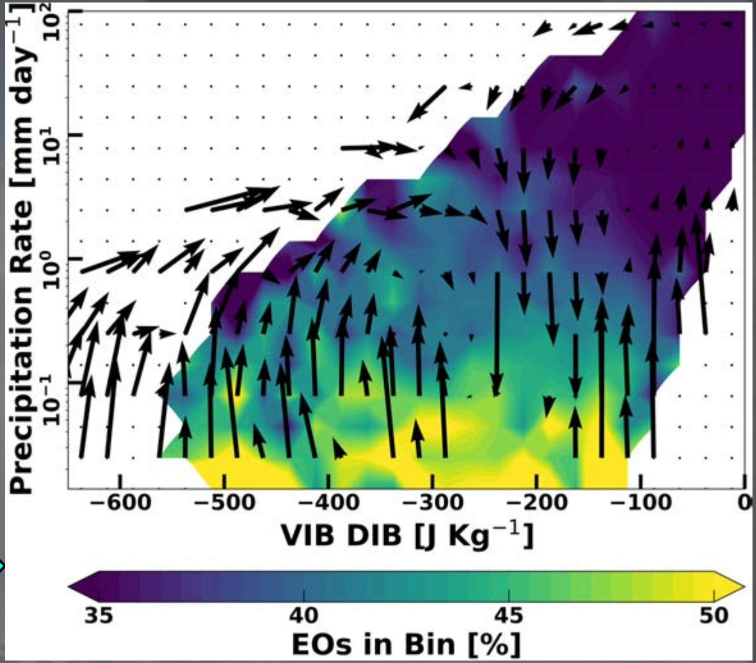
Cloud Types determined by EO base, EO top, and EO width

Characterizing Clouds: Vertical and Horizontal Structure

CloudSat Echo Objects



Shallow Cumulus

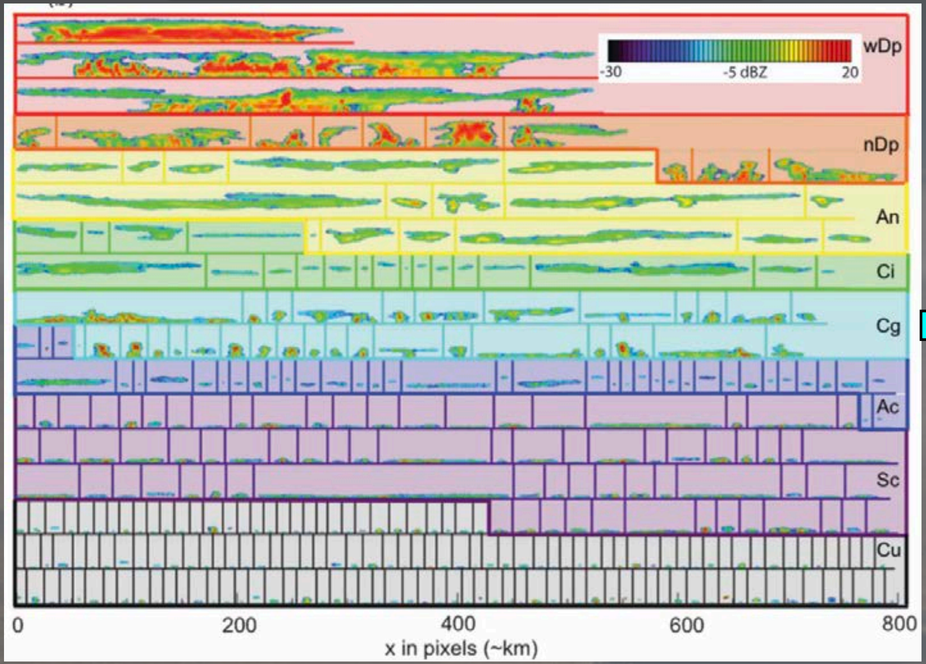


Deep Convective D-R Cycle

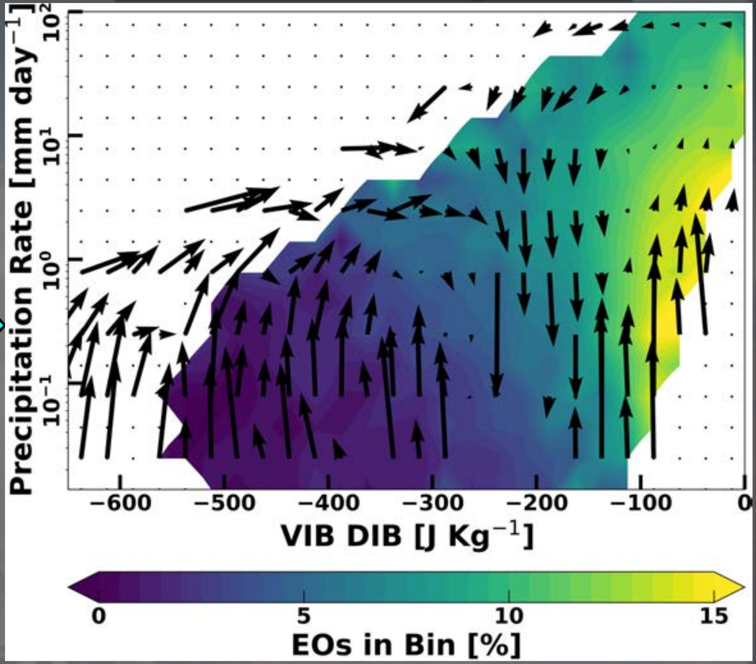
Shallow Cumulus

Characterizing Clouds: Vertical and Horizontal Structure

CloudSat Echo Objects



Cumulus Congestus

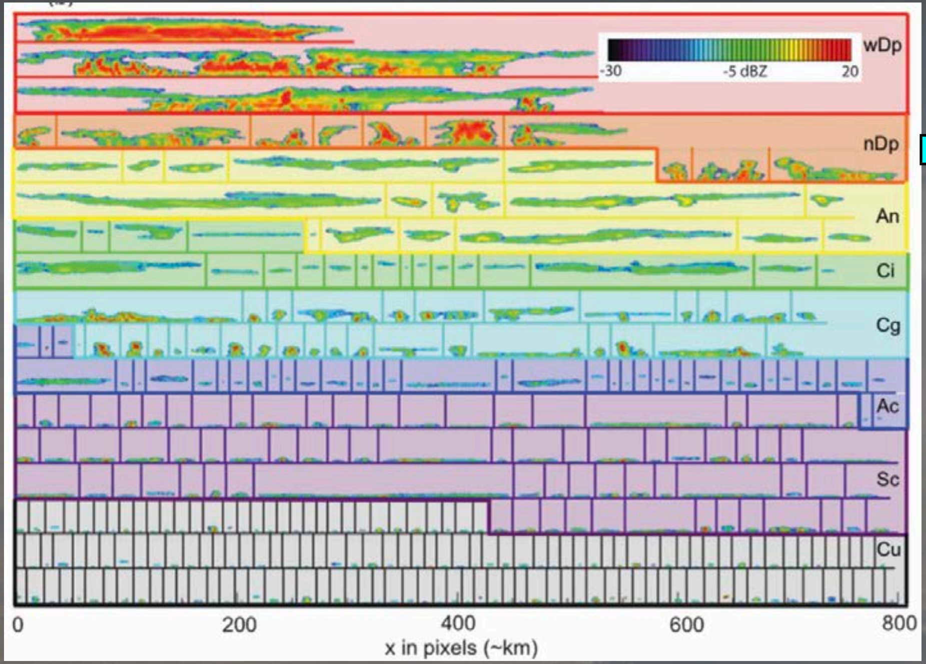


Deep Convective D-R Cycle

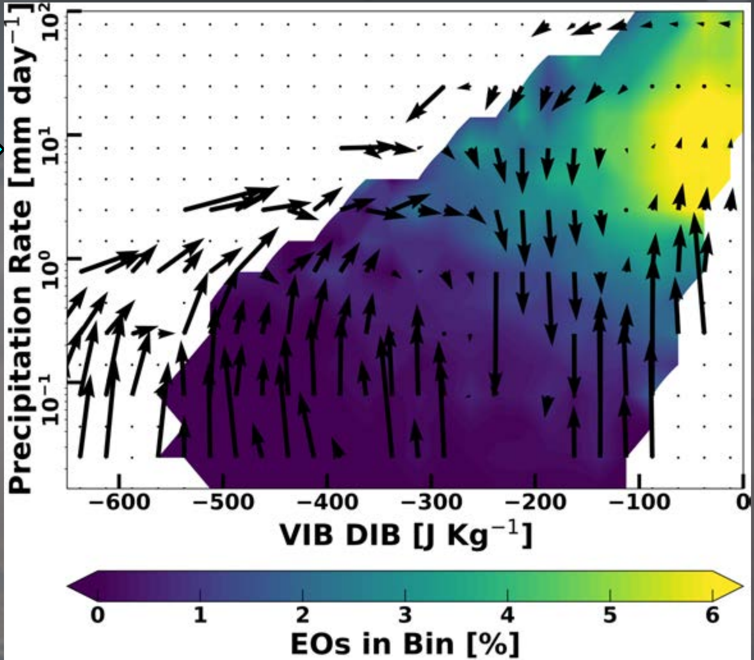
Shallow Cumulus → Cumulus Congestus

Characterizing Clouds: Vertical and Horizontal Structure

CloudSat Echo Objects



Narrow Deep Convection

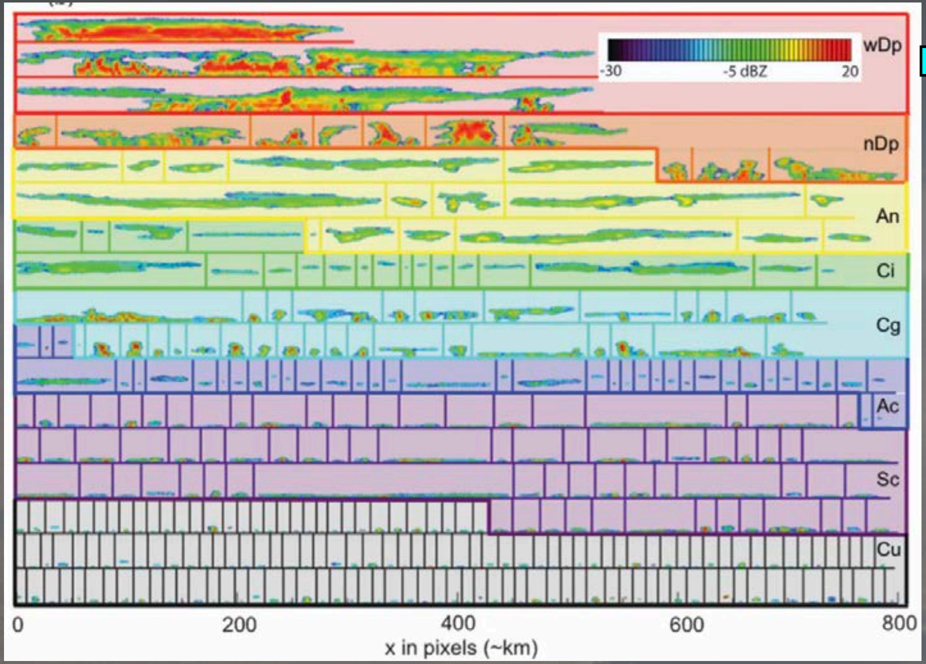


Deep Convective D-R Cycle

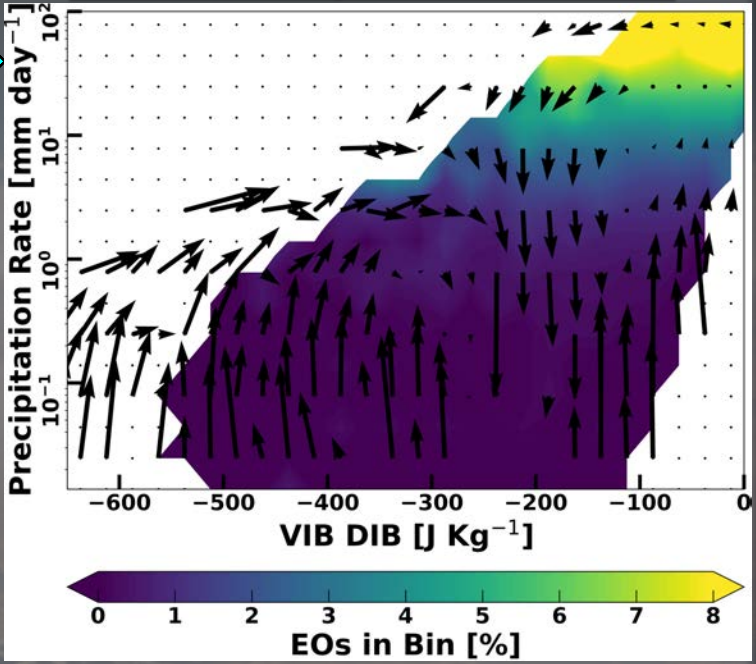
Shallow Cumulus → Cumulus Congestus → Narrow Deep Convection

Characterizing Clouds: Vertical and Horizontal Structure

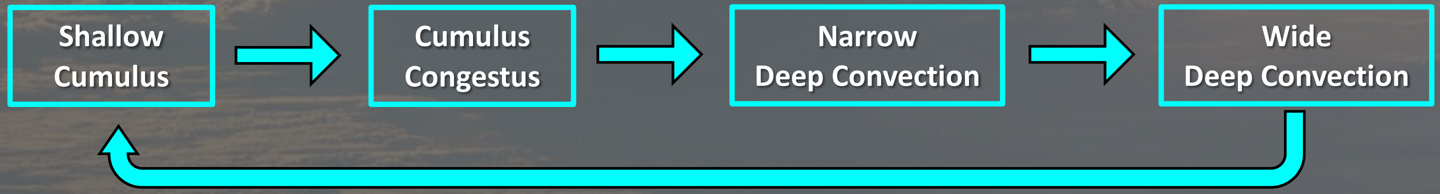
CloudSat Echo Objects



Wide Deep Convection



Deep Convective D-R Cycle

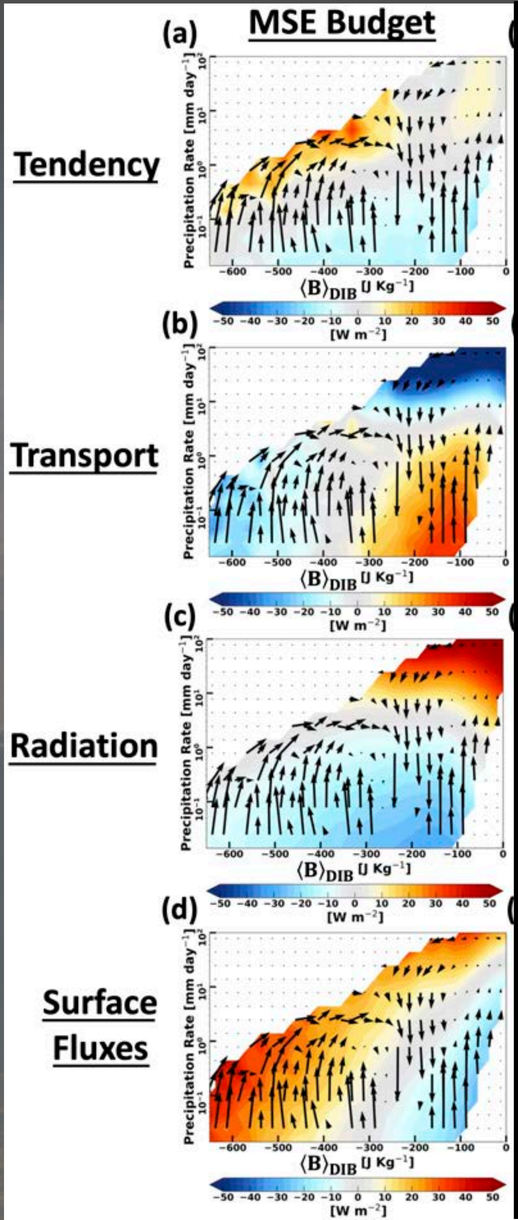


Shallow Cumulus → Cumulus Congestus → Narrow Deep Convection → Wide Deep Convection

Ocean-Atmosphere Coupled Energy Budgets

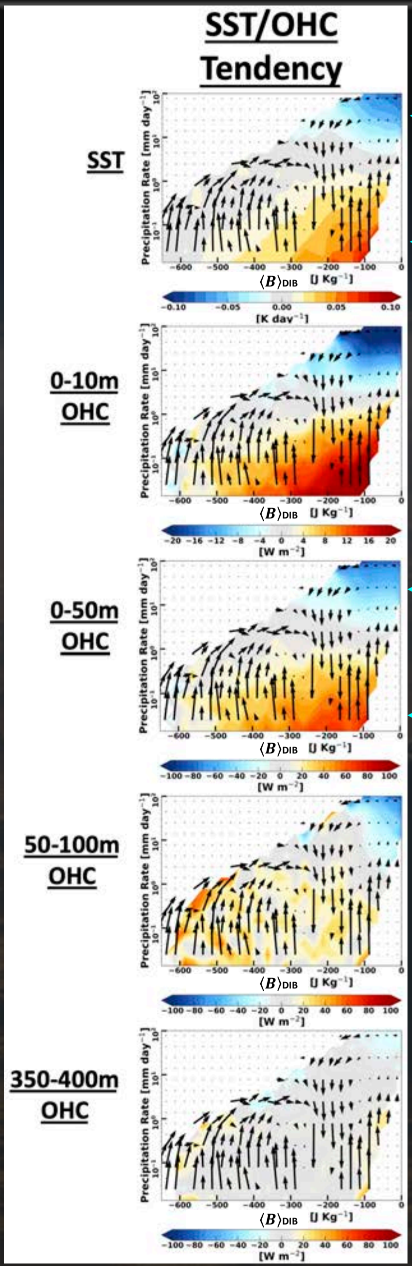
Atmosphere MSE Budget

$$\left\langle \frac{\partial \overline{h}}{\partial t} \right\rangle = \underbrace{-\left\langle \overline{\mathbf{V}} \cdot \nabla \overline{h} \right\rangle - \left\langle \overline{\omega} \frac{\partial \overline{h}}{\partial p} \right\rangle}_{\text{Transport}} \underbrace{+ \mathrm{L_v} E + H}_{\text{Surface Fluxes}} \underbrace{+ \langle Q_r \rangle}_{\text{Radiation}}$$



Ocean acting as important **energy source/sink** →

Ocean-Atmosphere Coupled Energy Budgets



SST cooling

SST warming

Upper ocean losing energy

Upper ocean gaining energy

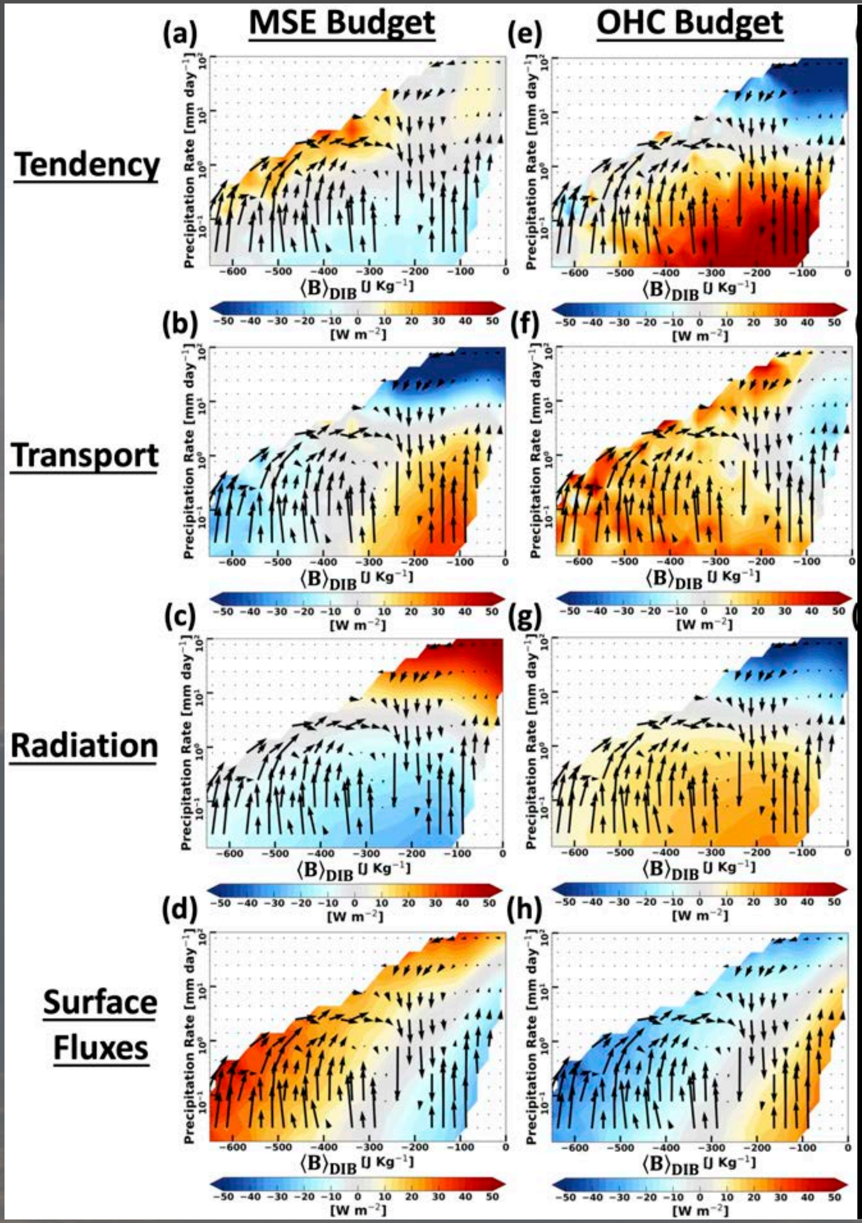
Ocean-Atmosphere Coupled Energy Budgets

Atmosphere MSE Budget

$$\left\langle \frac{\partial \overline{h}}{\partial t}\right\rangle = \underbrace{-\left\langle \overline{\mathbf{V}}\cdot\nabla\overline{h}\right\rangle - \left\langle \overline{\omega}\frac{\partial \overline{h}}{\partial p}\right\rangle}_{\text{Transport}} \underbrace{+\mathrm{L_v}E + H}_{\text{Surface Fluxes}} \underbrace{+\langle Q_r\rangle}_{\text{Radiation}}$$

Ocean Heat Content Budget

$$\left\langle \frac{\partial \overline{OHC}}{\partial t}\right\rangle = \overbrace{-\left\langle \overline{\mathbf{V}}\cdot\nabla\overline{OHC}\right\rangle - \left\langle \overline{w}\frac{\partial \overline{OHC}}{\partial z}\right\rangle - A_h\nabla^2 OHC - \frac{A_z}{H}\frac{\partial \overline{OHC}}{\partial z}}^{\text{Transport}} \underbrace{-\mathrm{L_v}E - H}_{\text{Surface Fluxes}} \underbrace{- LW|_{surface} - SW|_{surface} + SW|_H}_{\text{Radiation}}$$



Ocean-Atmosphere Coupled Energy Budgets

Atmosphere MSE Budget

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

Transport

Surface Fluxes

Radiation

\+

Ocean Heat Content Budget

Transport

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

Surface Fluxes

Radiation

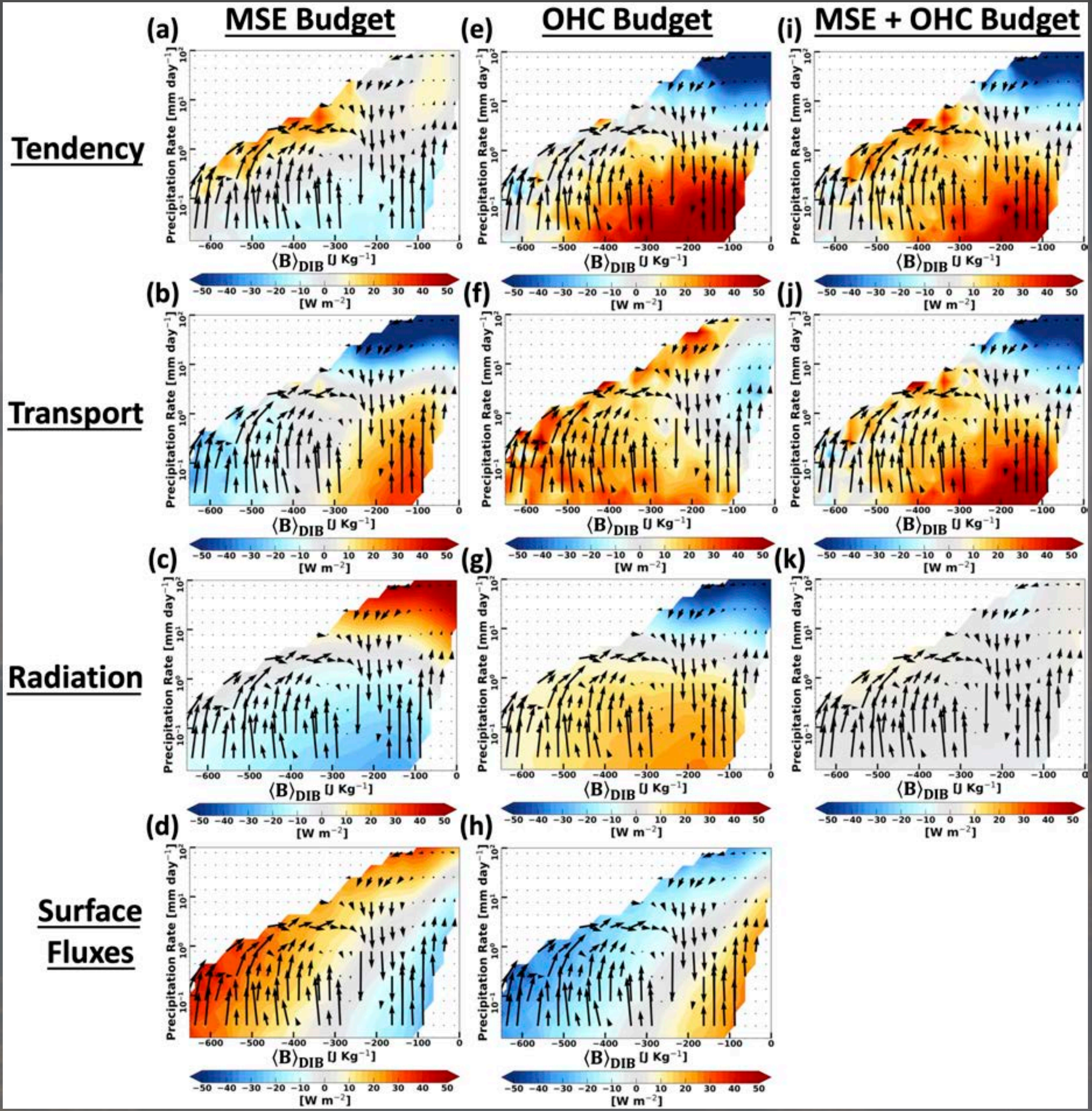
=

Ocean-Atmosphere Budget

Transport

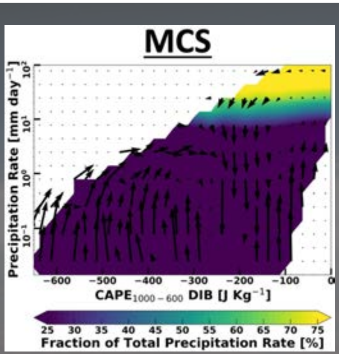
$$\left\langle \frac{\partial \bar{c}}{\partial t} \right\rangle = -\left\langle \overline{\mathbf{V}} \cdot \nabla \bar{h} \right\rangle - \left\langle \bar{\omega} \frac{\partial \bar{h}}{\partial p} \right\rangle - \left\langle \overline{\mathbf{V}} \cdot \nabla \overline{OHC} \right\rangle - \left\langle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

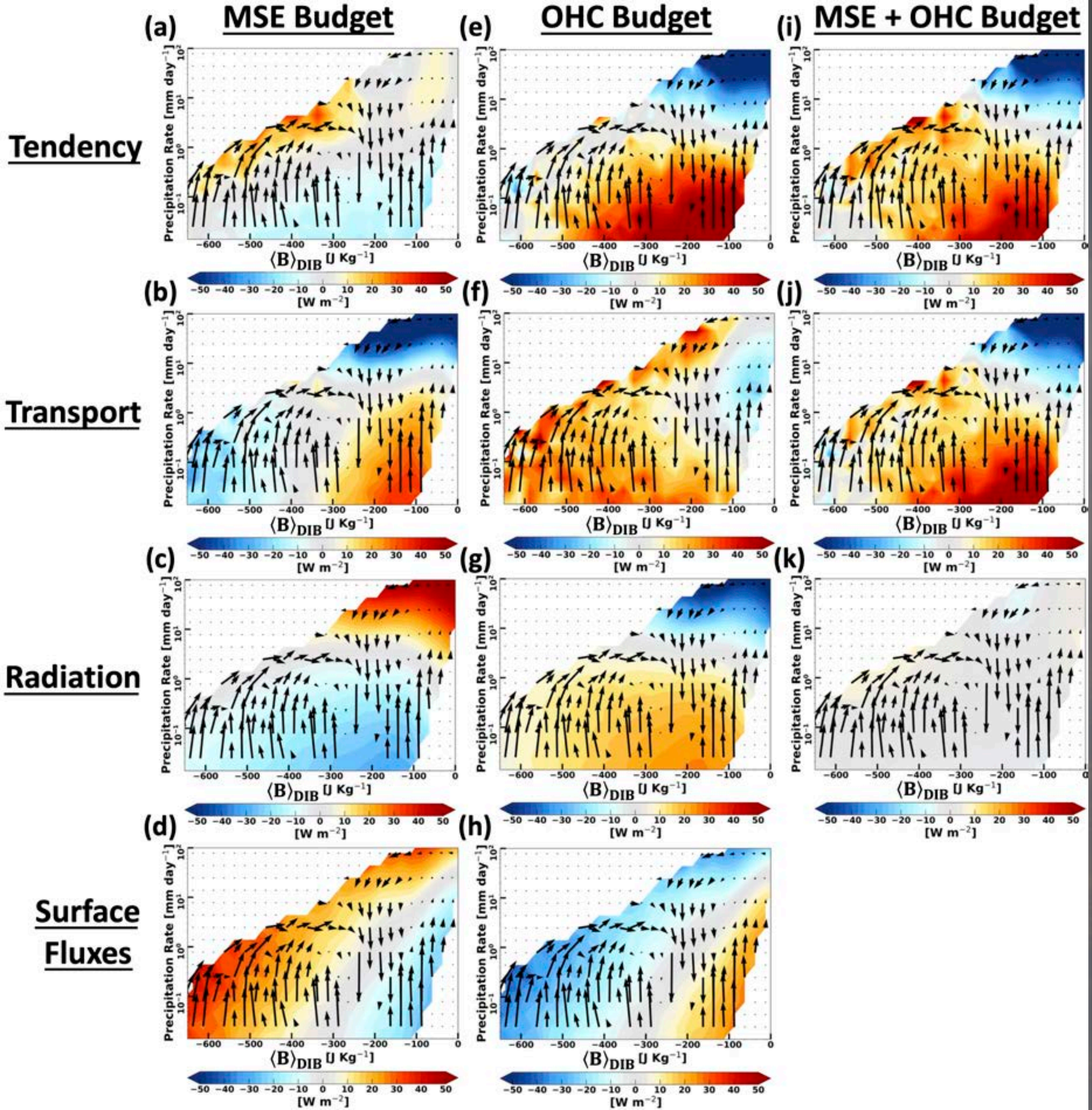
Radiation



Ocean-Atmosphere Coupled Energy Budgets

How do MCSs impact ocean and atmosphere energy budgets?



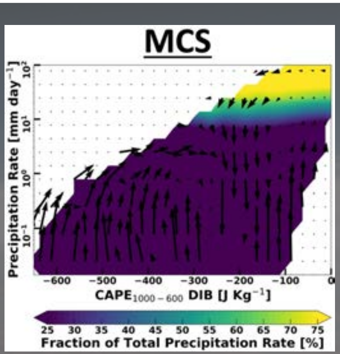


atmospheric export of MSE supported by reduced LW cooling and enhanced surface fluxes

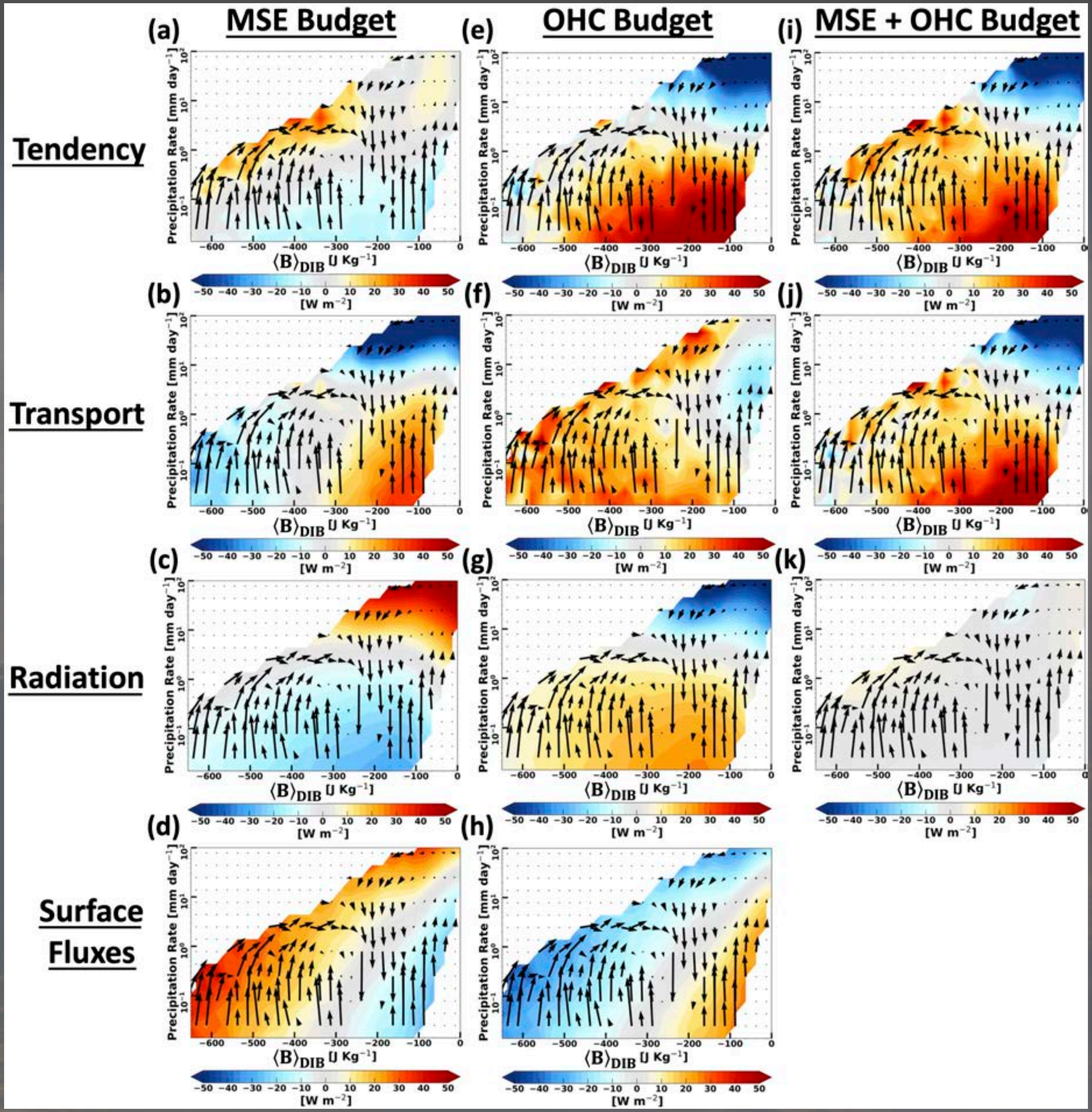
upper ocean rapidly losing energy by reduced SW radiation and enhanced surface fluxes

Ocean-Atmosphere Coupled Energy Budgets

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



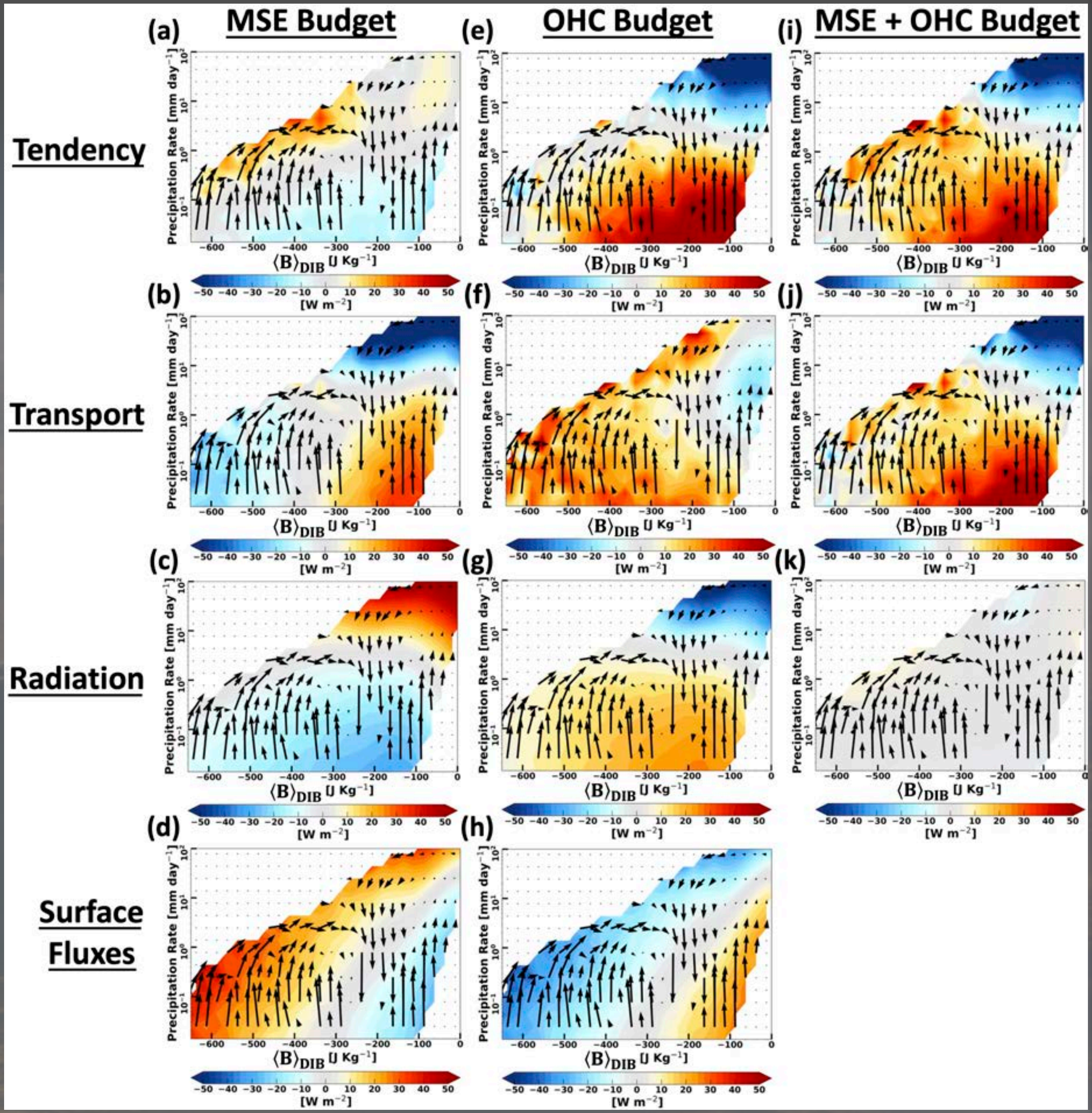
MCS are unique in their ability to rapidly **discharge OHC**



Ocean-Atmosphere Coupled Energy Budgets

Variability in ocean-atmosphere column energy **driven by transport processes**, realized as changes in OHC

Atmospheric transports poorly represented in models with parameterized and explicit convection



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

While D-R cycles emerge in idealized simulations with fixed surface boundary conditions, understanding the role of upper ocean variability is key to understanding the real world manifestation of D-R cycles

Ocean-atmosphere energy budgets useful tool for understanding D-R cycles and ocean-atmosphere coupled phenomena

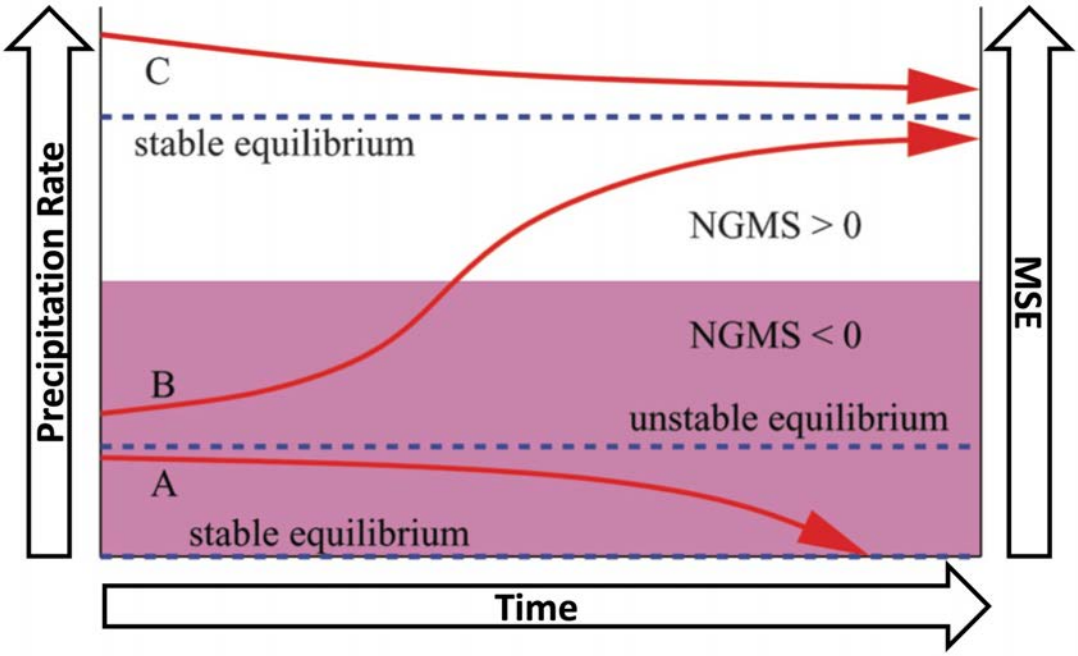
Budgets show atmospheric MSE transports closely tied to OHC variability

Models with both parameterized and resolved convection struggle to represent MSE transports, suggesting will struggle with OHC variability and coupling

Multiple Equilibria of Tropical Convection

In an idealized system where:

- **precipitation increases with humidity**
- **efficiency of moist static energy export increases with precipitation**

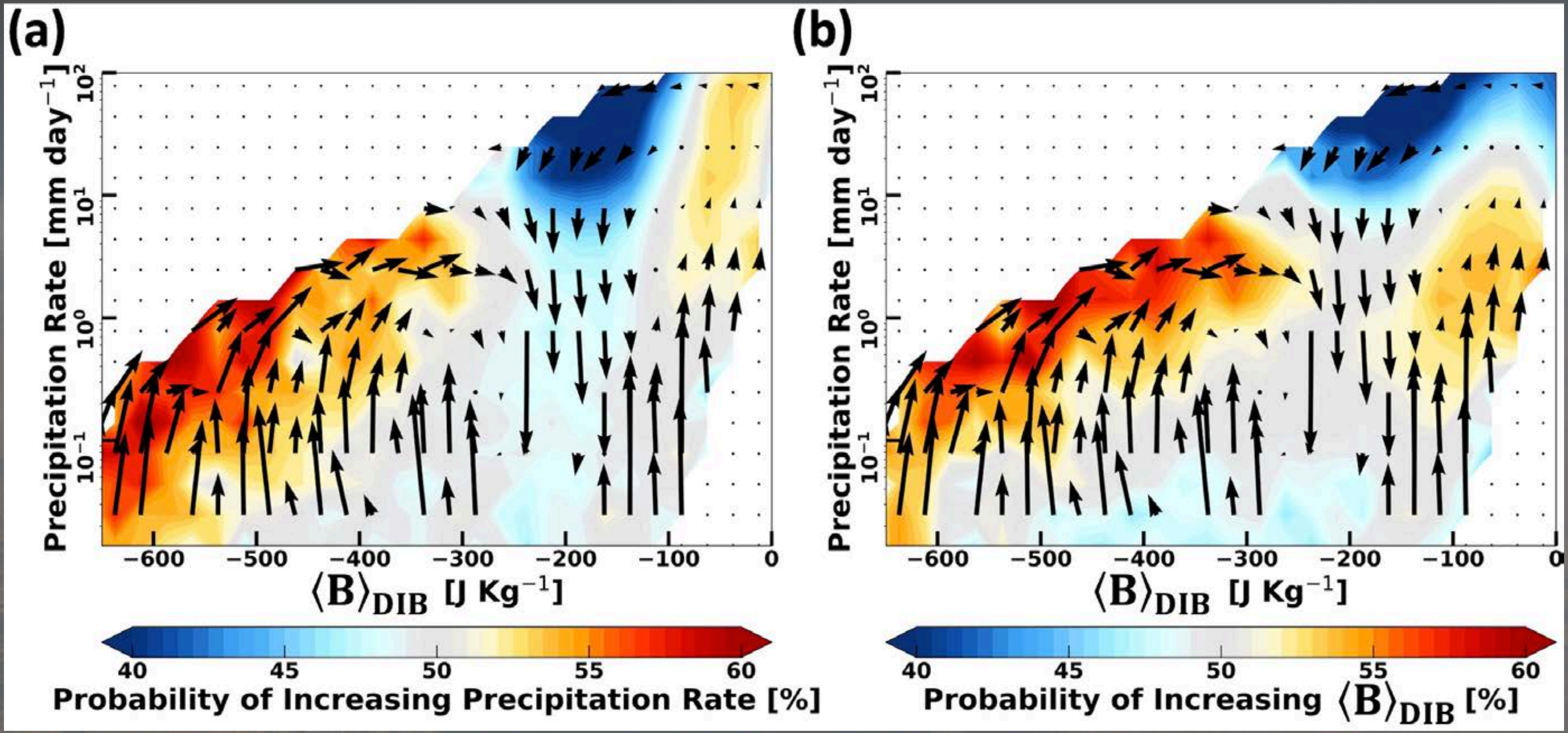


Adapted *Raymond et al. 2009*

moist, precipitating equilibrium

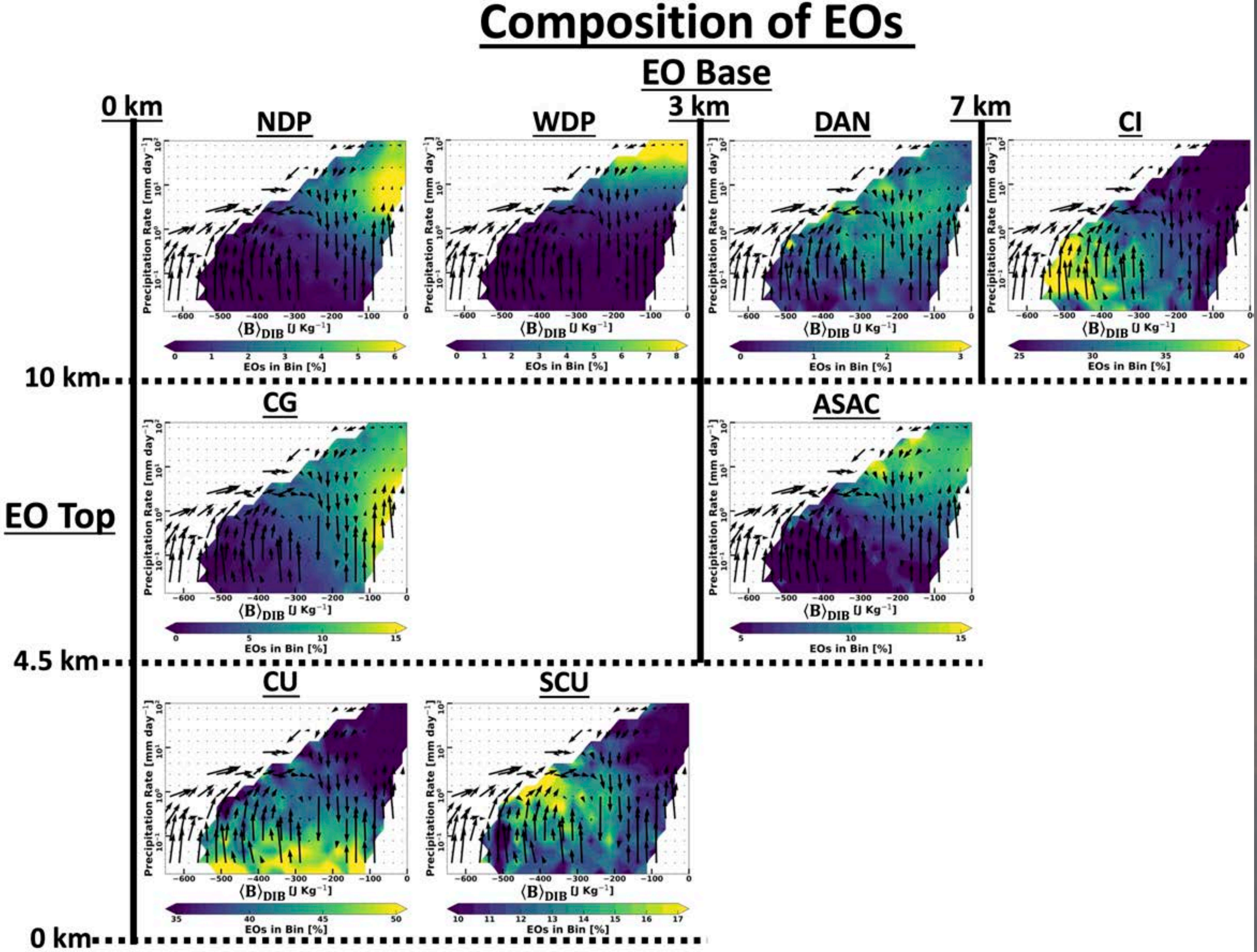
dry, non-precipitating equilibrium

Identifying Convective Discharge-Recharge Cycles



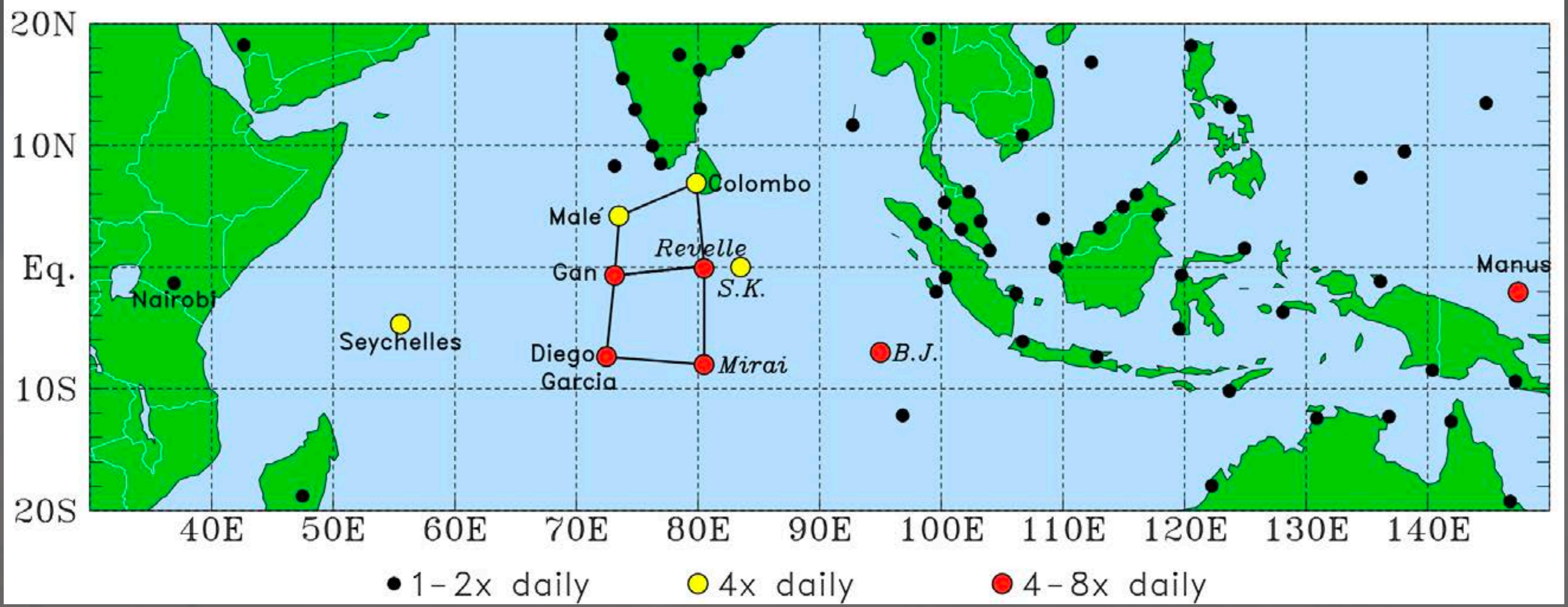
Discharge-recharge cycles are not highly deterministic!

Characterizing Clouds: Vertical and Horizontal Structure



Composition of EOs

Dynamics of the Madden-Julian Oscillation (DYNAMO)

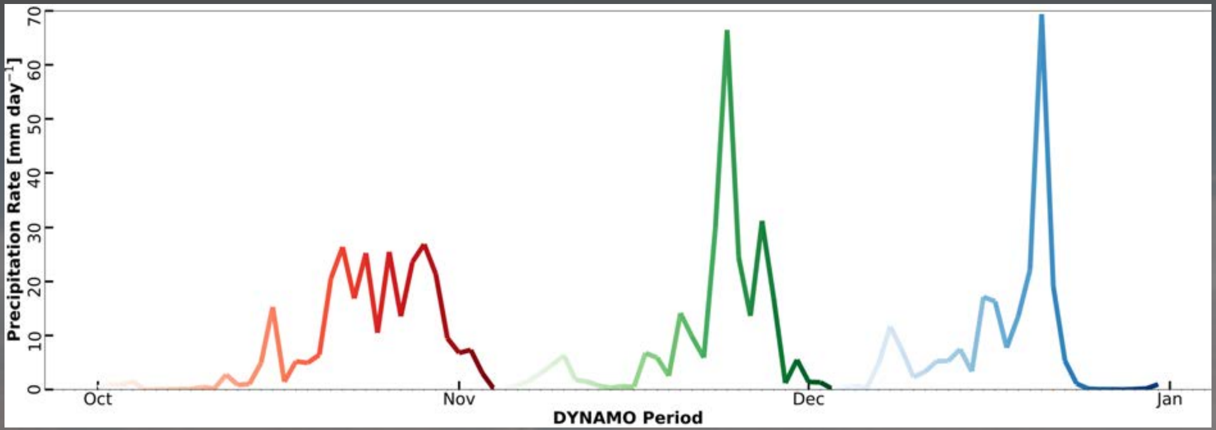


October 1st – December 31st 2011

Northern Sounding Array (NSA) quality controlled version 3B array-averaged variables from CSU

Dynamics of the Madden-Julian Oscillation (DYNAMO)

NSA Precipitation – Daily Mean

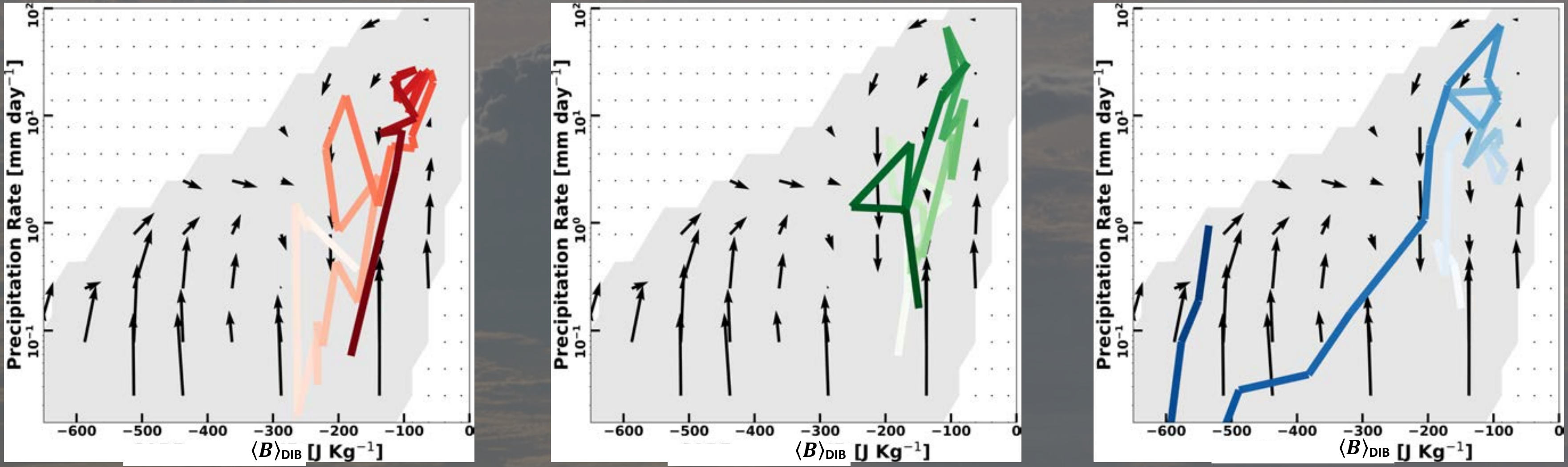


Three consecutive periods of enhanced convection, separated by periods of suppressed convection

Period 1

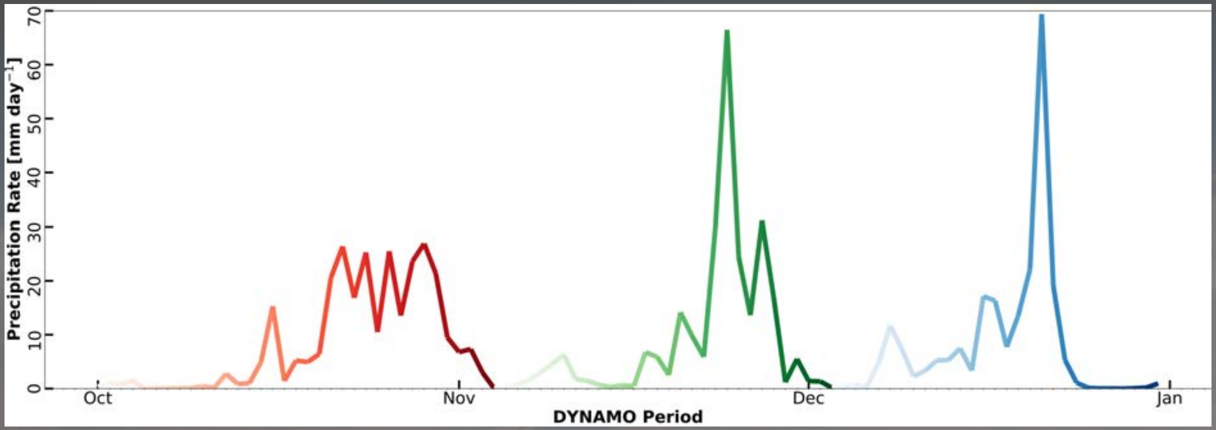
Period 2

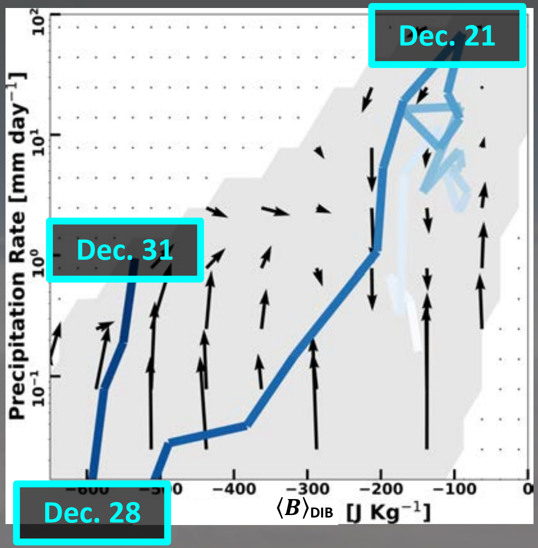
Period 3

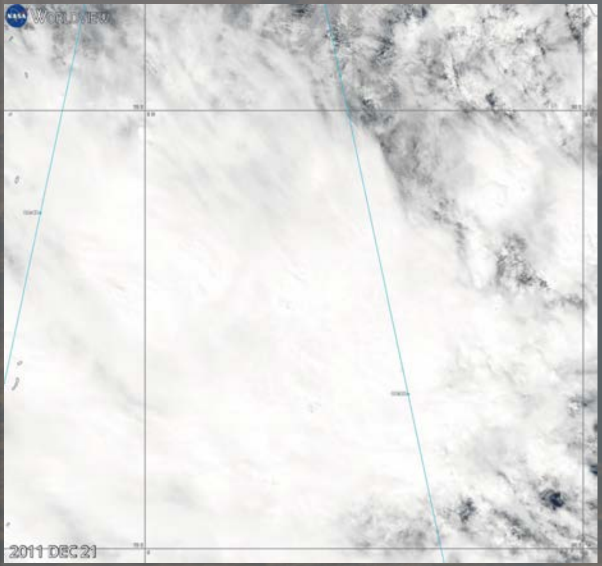


Dynamics of the Madden-Julian Oscillation (DYNAMO)

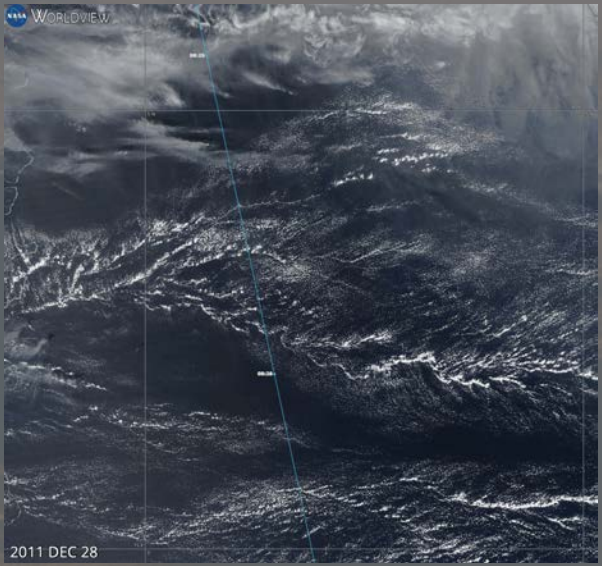
NSA Precipitation – Daily Mean



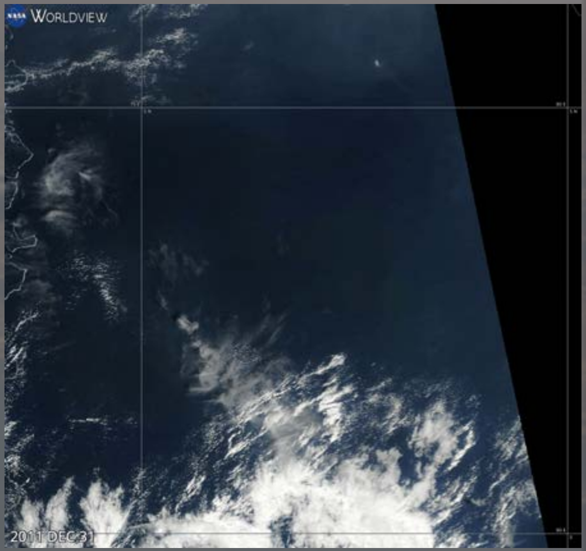




Dec. 21



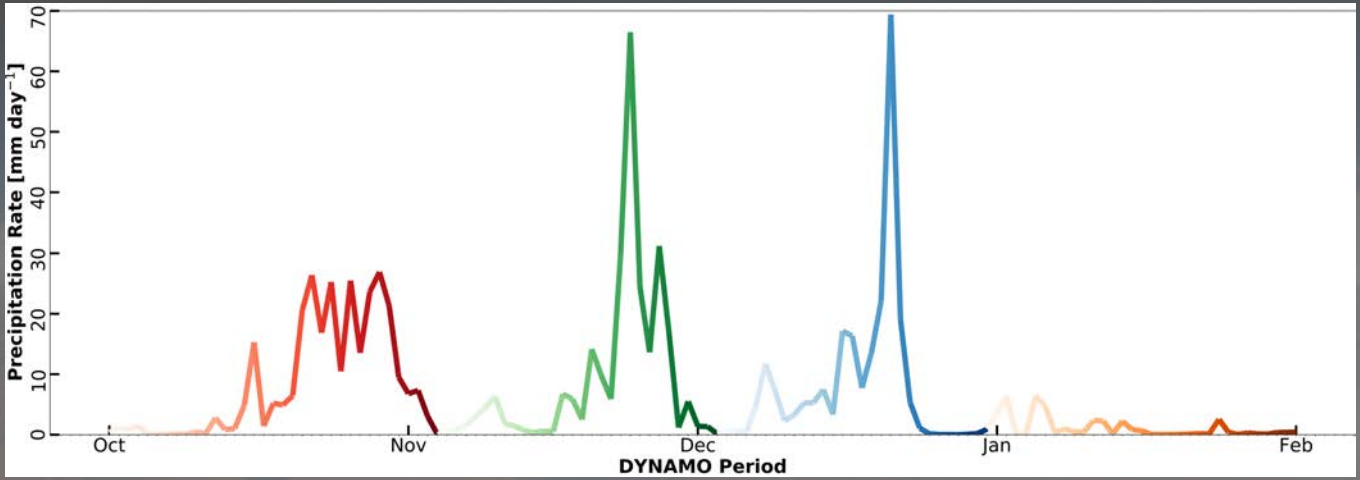
Dec. 28



Dec. 31

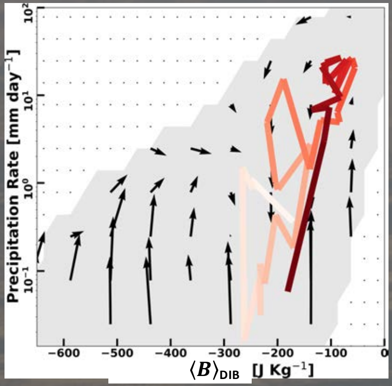
Dynamics of the Madden-Julian Oscillation (DYNAMO)

NSA Precipitation – Daily Mean

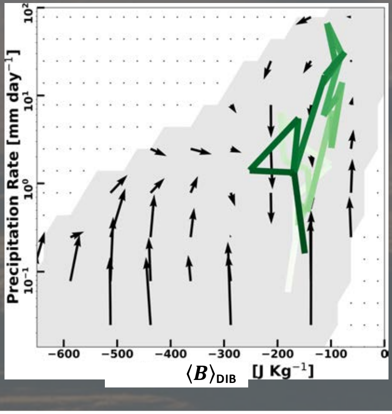


Third MJO followed by **extended period of suppressed conditions**

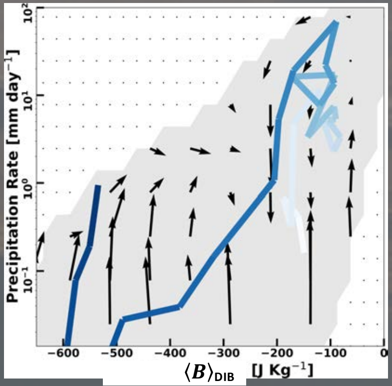
Period 1



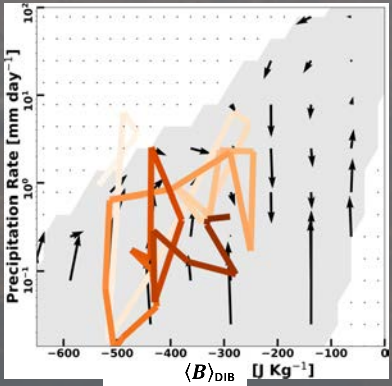
Period 2



Period 3



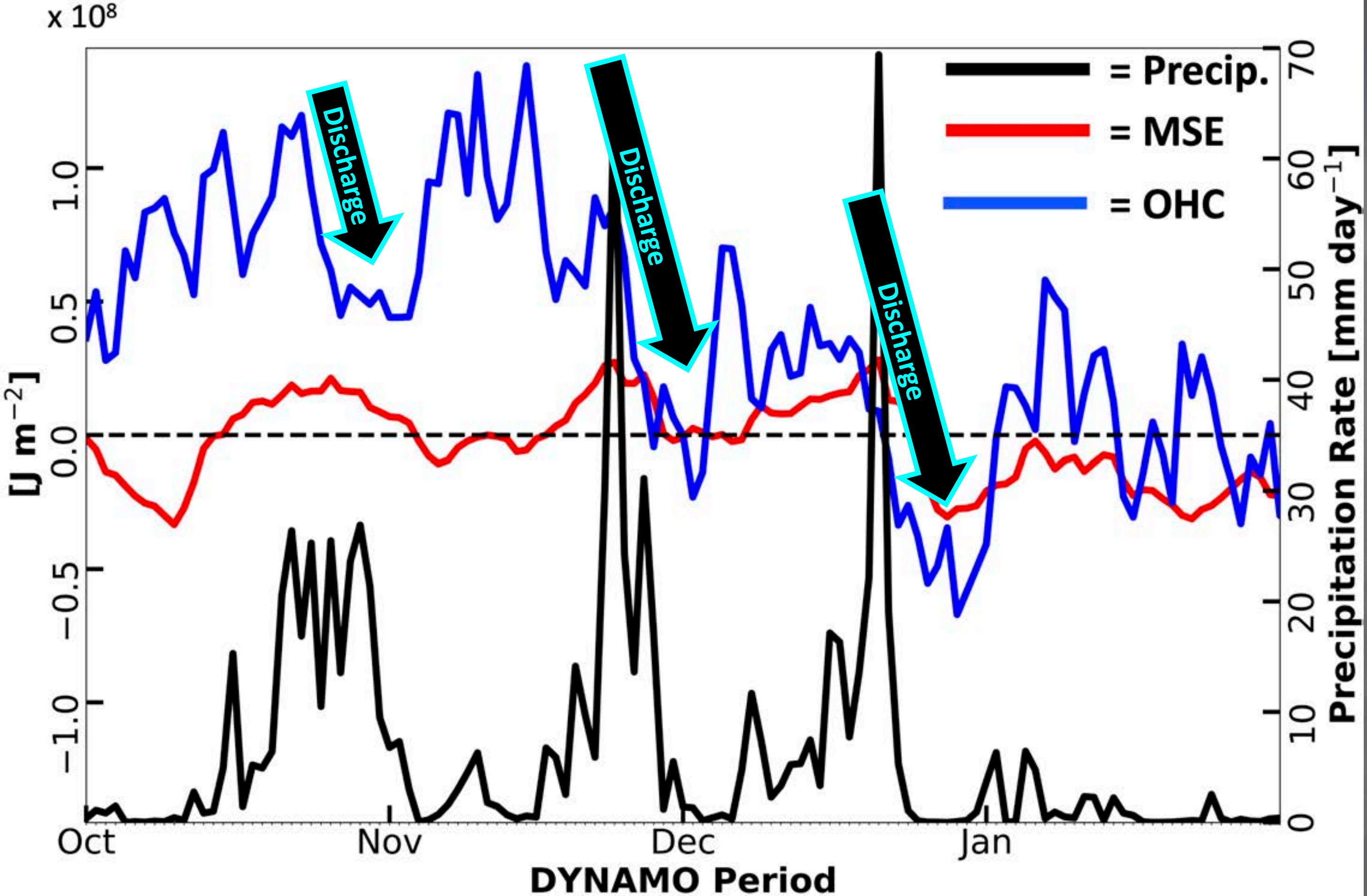
Period 4



Did significant “discharge” event contribute to transition to persistent shallow convective regime?

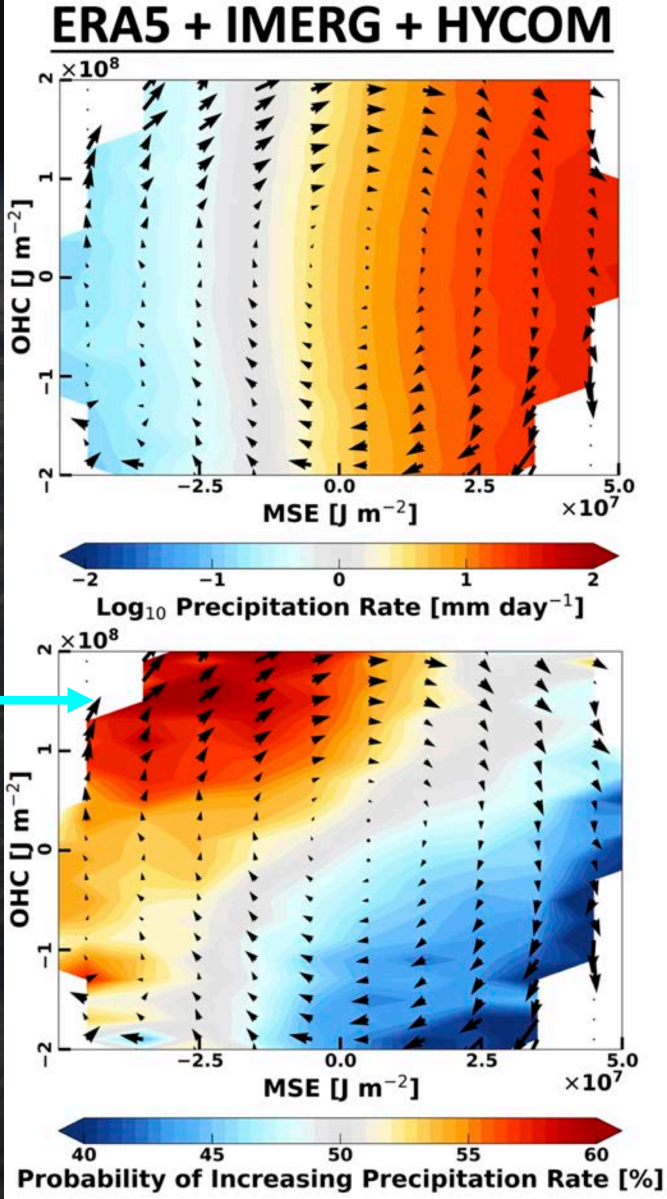
Dynamics of the Madden-Julian Oscillation (DYNAMO)

Repetitive "discharge" events change OHC surplus to OHC deficit



OHC limits ability to support consecutive/sustained periods of deep convection?

Potential Relevance



OHC has little value for diagnosing precipitation, but…

Large ocean-atmosphere imbalance

OHC has value for prognosing precipitation on day-to-day timescales