Funding: U.S. DOE RGMA Program

Pacific Northwest
NATIONAL LABORATORY

Diagnosing Mesoscale Convective Systems in DYAMOND Models: A Feature Tracking Intercomparison

Zhe Feng
Many contributions from coauthors

ECMWF Diagnostics Workshop
September 10, 2024

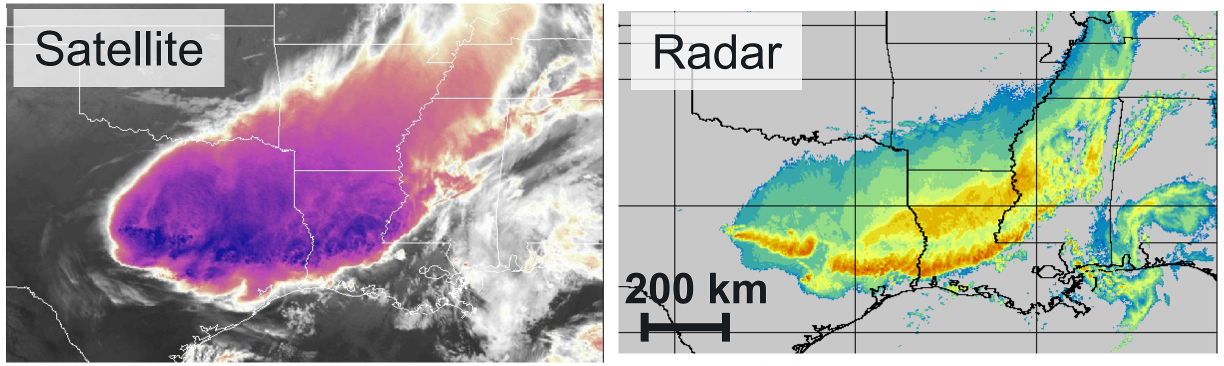
U.S. DEPARTMENT OF ENERGY   BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

WACCEM
WATER CYCLE AND CLIMATE EXTREMES MODELING

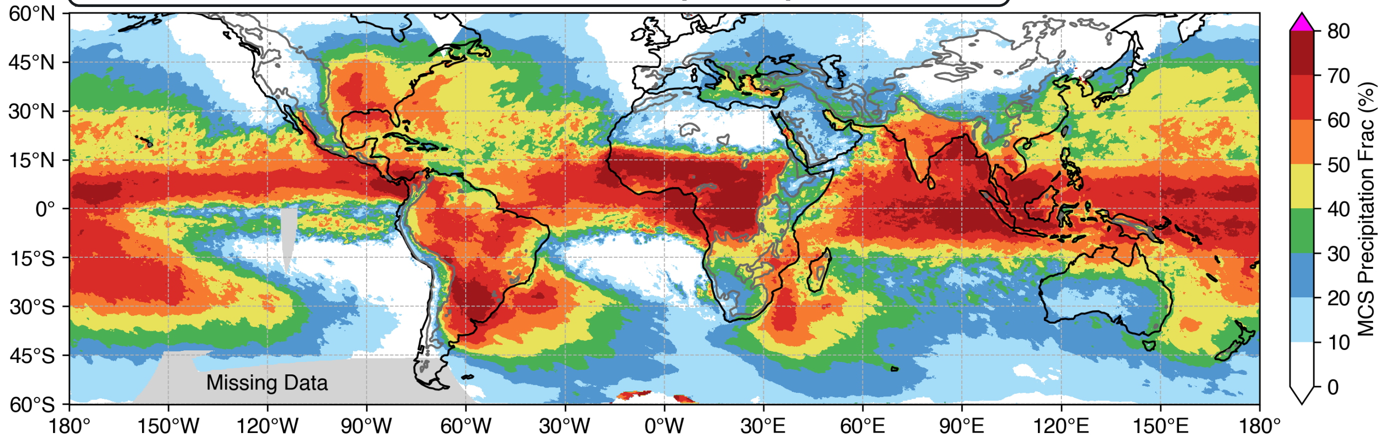
Motivation

- Mesoscale convective systems (MCS) produce most of the tropical **precipitation** (Nesbitt et al. 2006; Feng et al. 2021)
- MCS top-heavy heating profiles have profound impacts on **global circulation** (Schumacher et al. 2004; Barnes et al. 2015)
- MCS disproportionally contribute to **extreme precipitation** (Roca and T. Fiolleau 2020)
- Typical global models struggle to simulate MCS, convection-permitting (**km-scale**) models offer new opportunities to examine how MCSs and extreme precipitation may **change in future climate** (Prein et al. 2017; 2023)



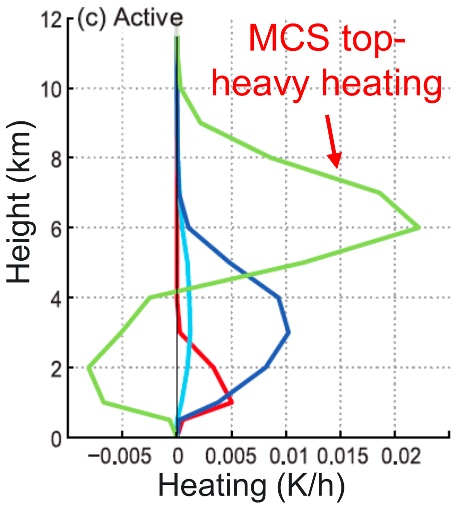
MCS example in the U.S.

MCS contribution to total precipitation



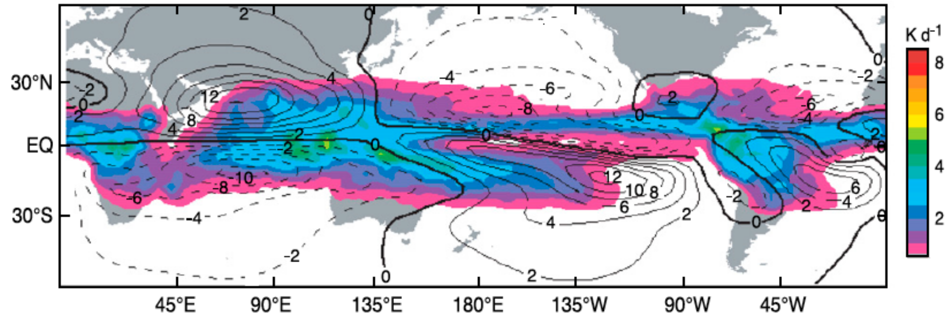
Feng et al. (2021) JGR

Latent heating profiles



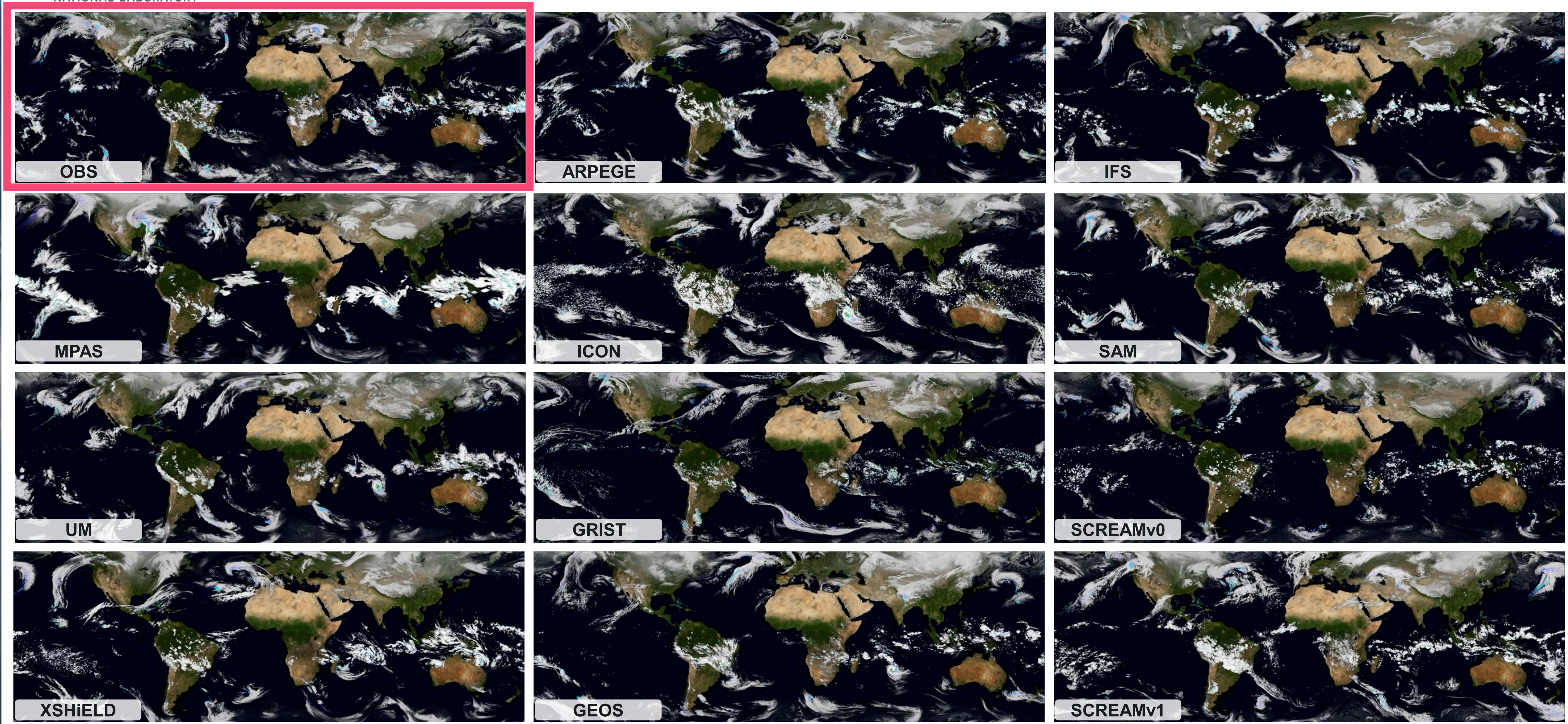
Barnes et al. (2015)

Impacts on global circulation



Schumacher et al. (2004)

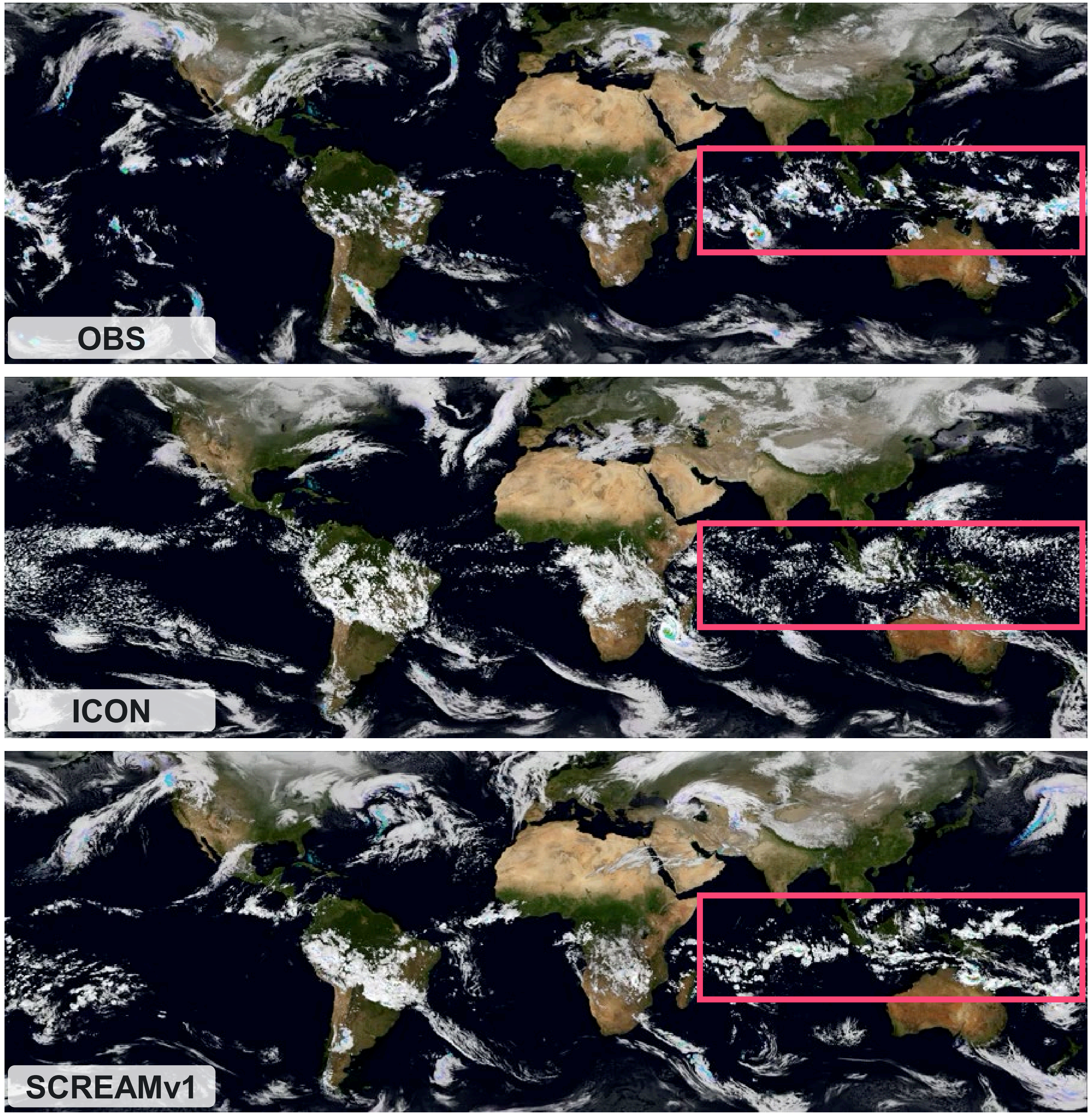
How close are DYAMOND models to reality?



MCSMIP (MCS tracking method intercomparison)

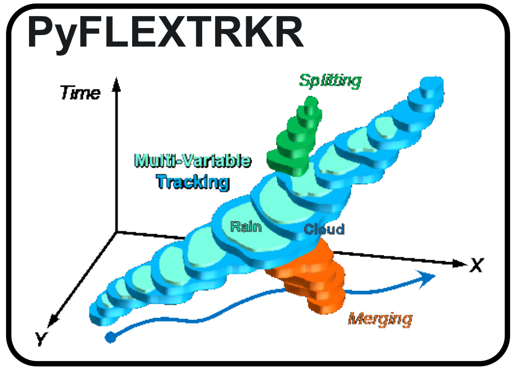
- Substantial **differences** in the simulated characteristics of deep convection & MCSs among models (**Feng et al. 2023 GRL**)

- **Science Questions**:
  - How sensitive are the DYAMOND simulated MCS characteristics to different tracker formulations?
  - What km-scale model biases are robust among trackers and how do the biases relate to environmental moisture?



MCSMIP Approach

- **Tracking intercomparison methods:**
  - Use common-resolution OBS and DYAMOND data (~10 km, hourly)
  - Follow the same MCS definition:
    - **Cold cloud shield** > 40,000 km^2, duration ≥ 4 h
    - **Precipitation** volume > 20,000 km^2 mm h^{-1}, contains > 10 mm h^{-1} for ≥ 4 h
  - 10+ international participating groups currently
    - **8 trackers** submitted tracking results



Feng et al. (2023) GMD

TOOCAN

TAMS

MOAAP (Multi-Object Analysis of Atmospheric Phenomena)

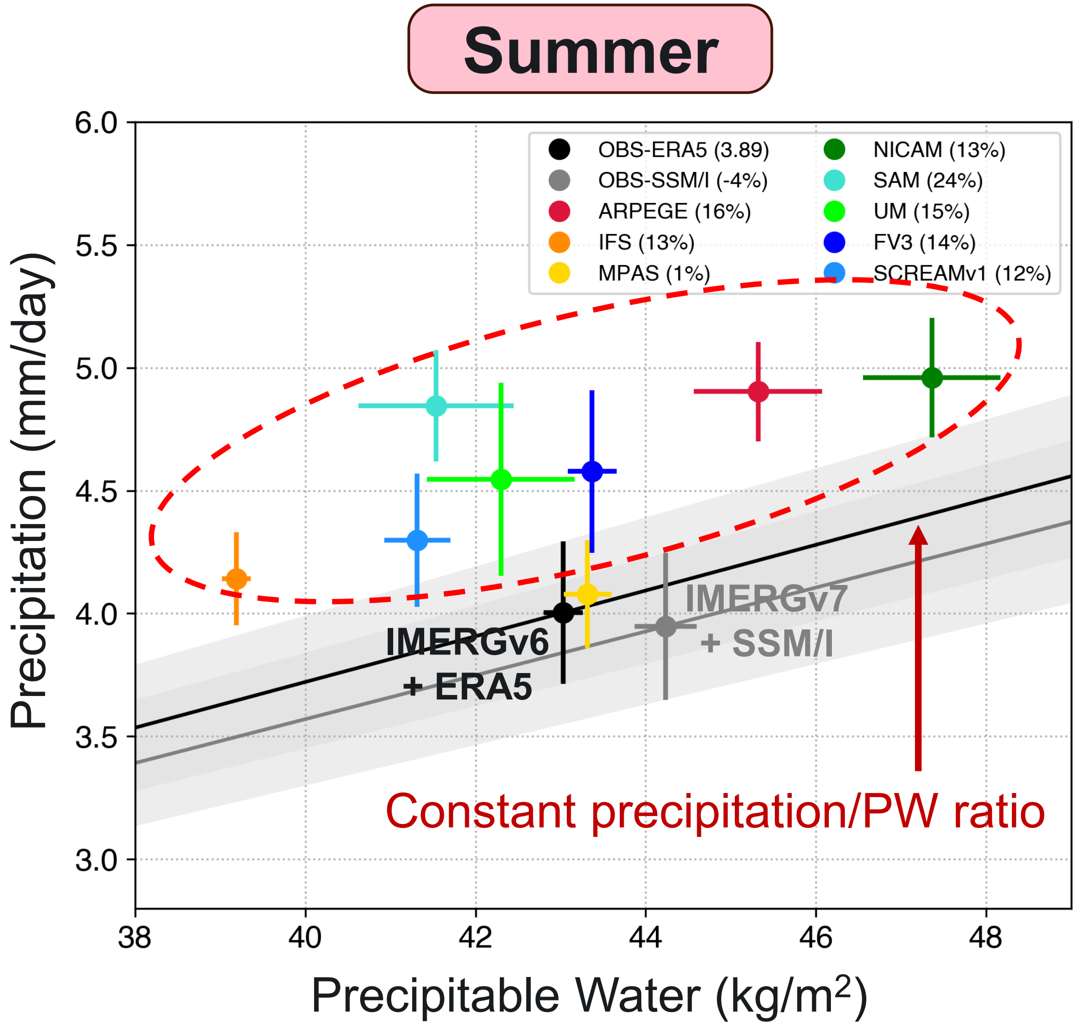
tobac (Tracking and Object-based Analysis of Clouds)

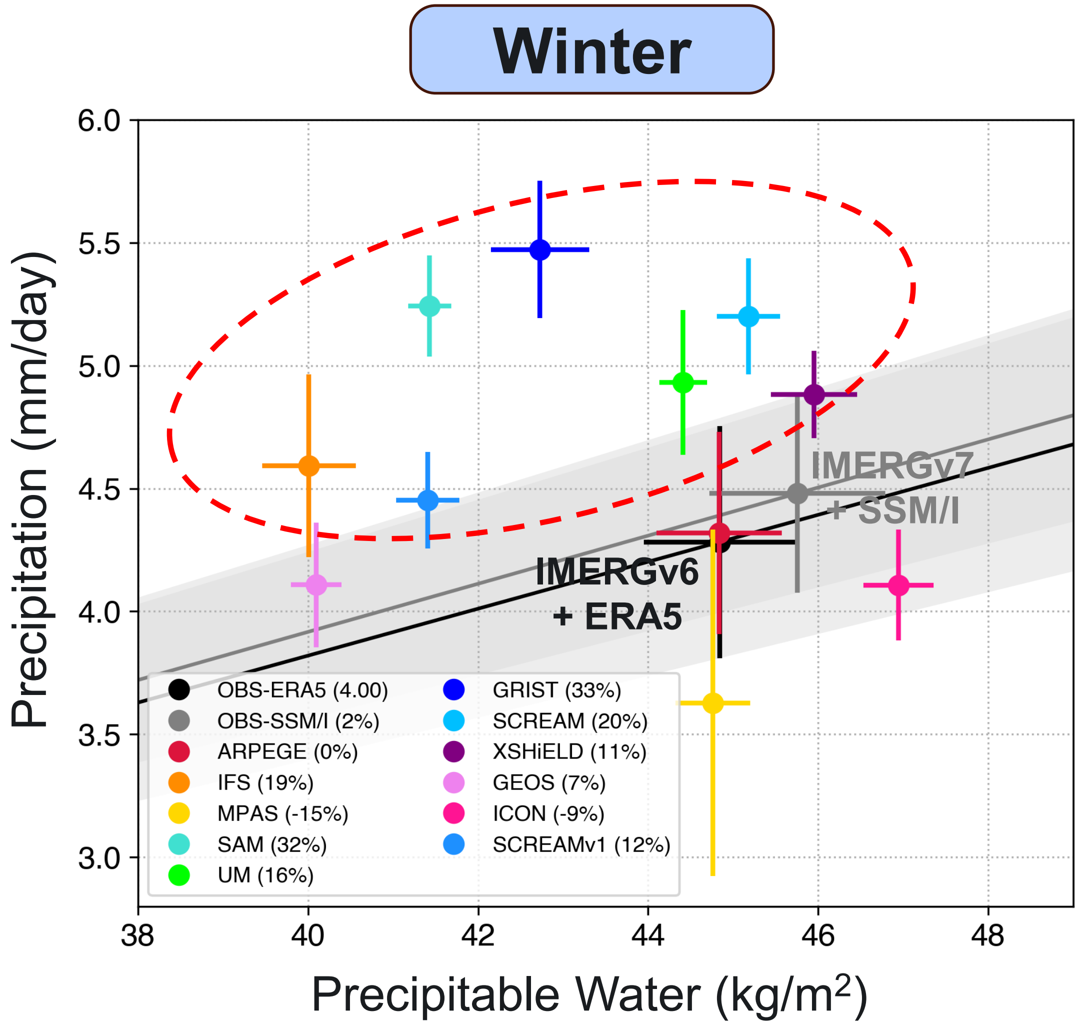
simpleTrack (Threshold-based object tracking algorithm)

DL (Deep-Learning + Tempest Extreme)

KFyAO (Kalman Filter and Area Overlapping)

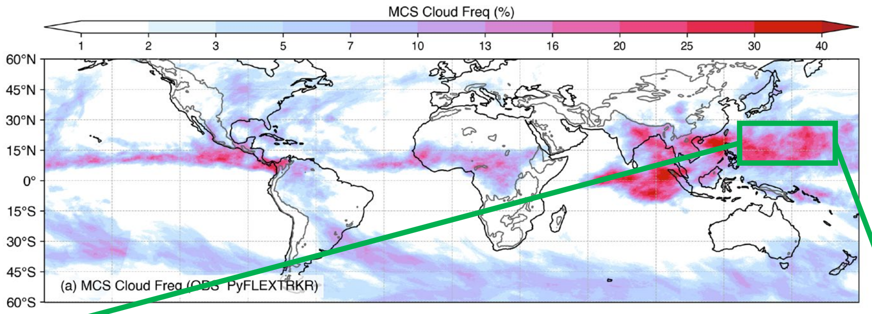
Models overestimate sensitivity of tropical oceanic precipitation to moisture

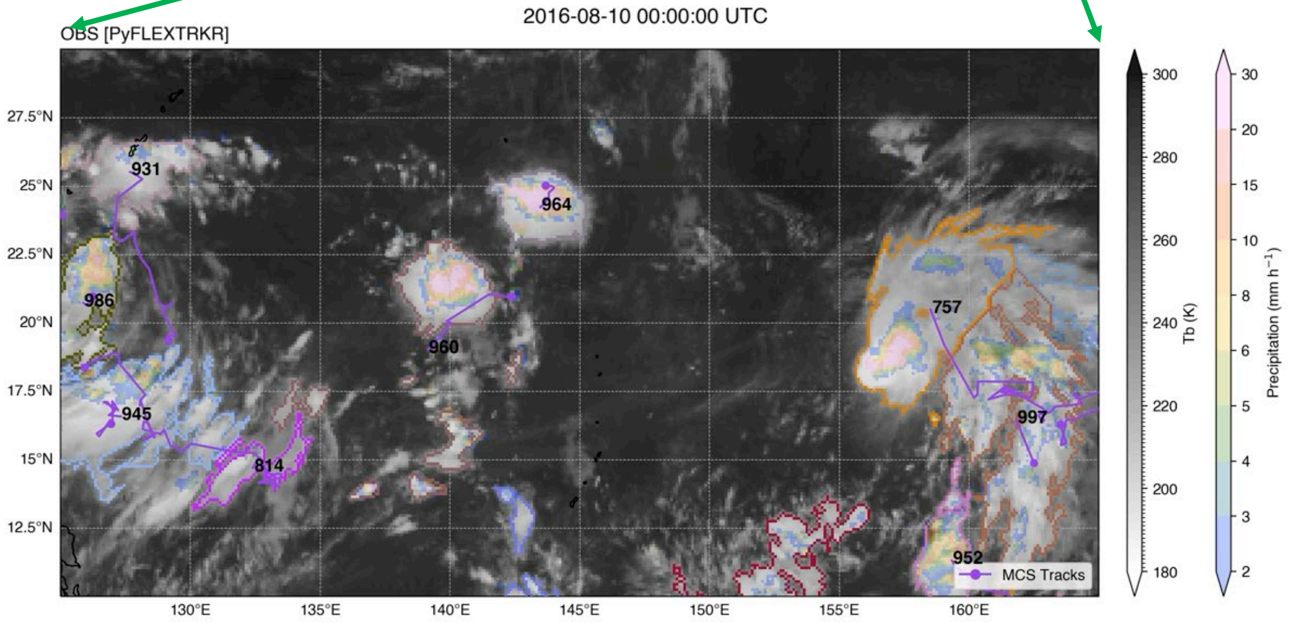




- Both phases have large inter-model spread in **PW** and **precipitation**
- Most models overestimate **precipitation/PW ratio** by up to **33%**, suggesting models may have higher sensitivity to moisture than OBS

MCS Tracking Examples

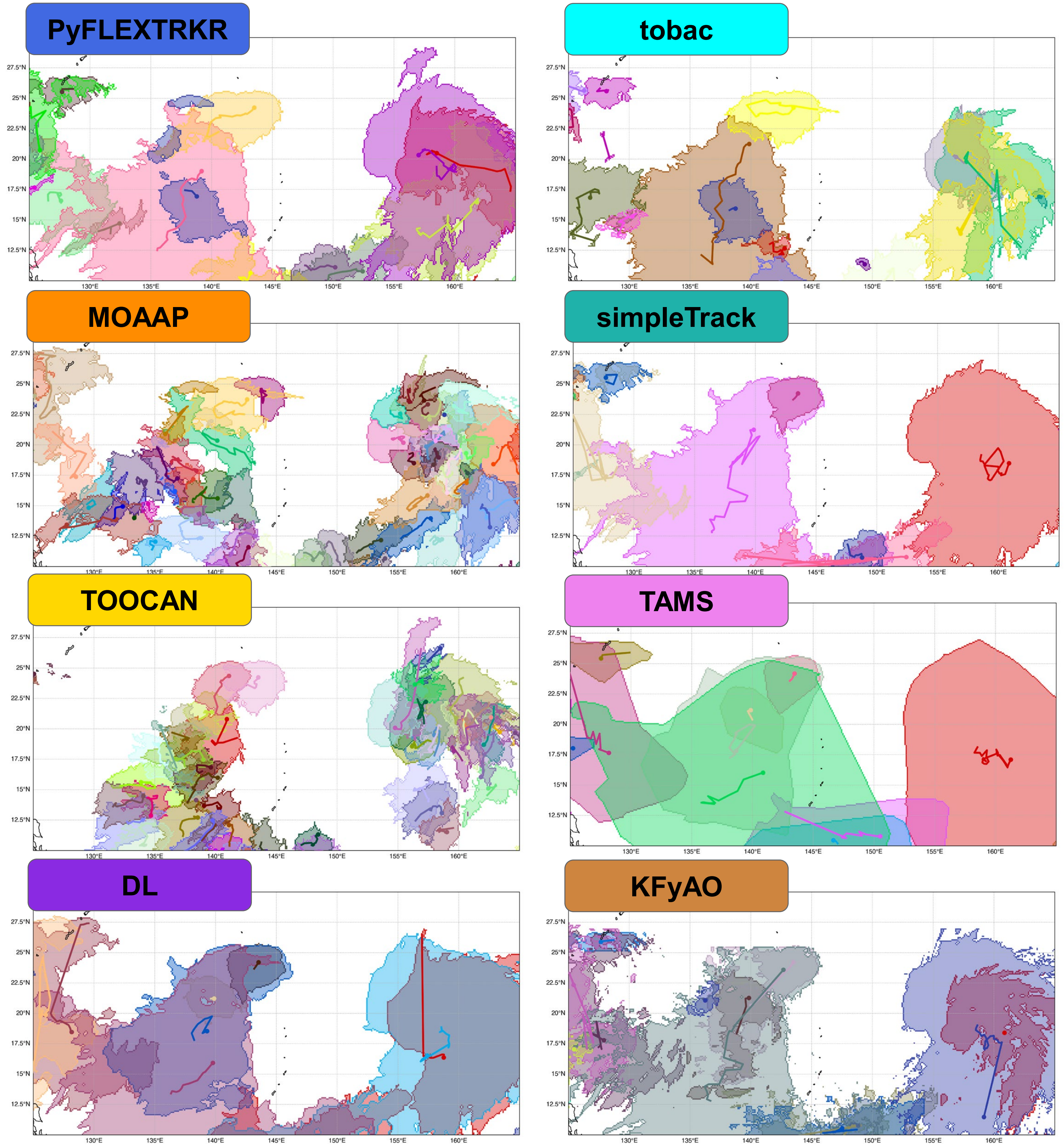




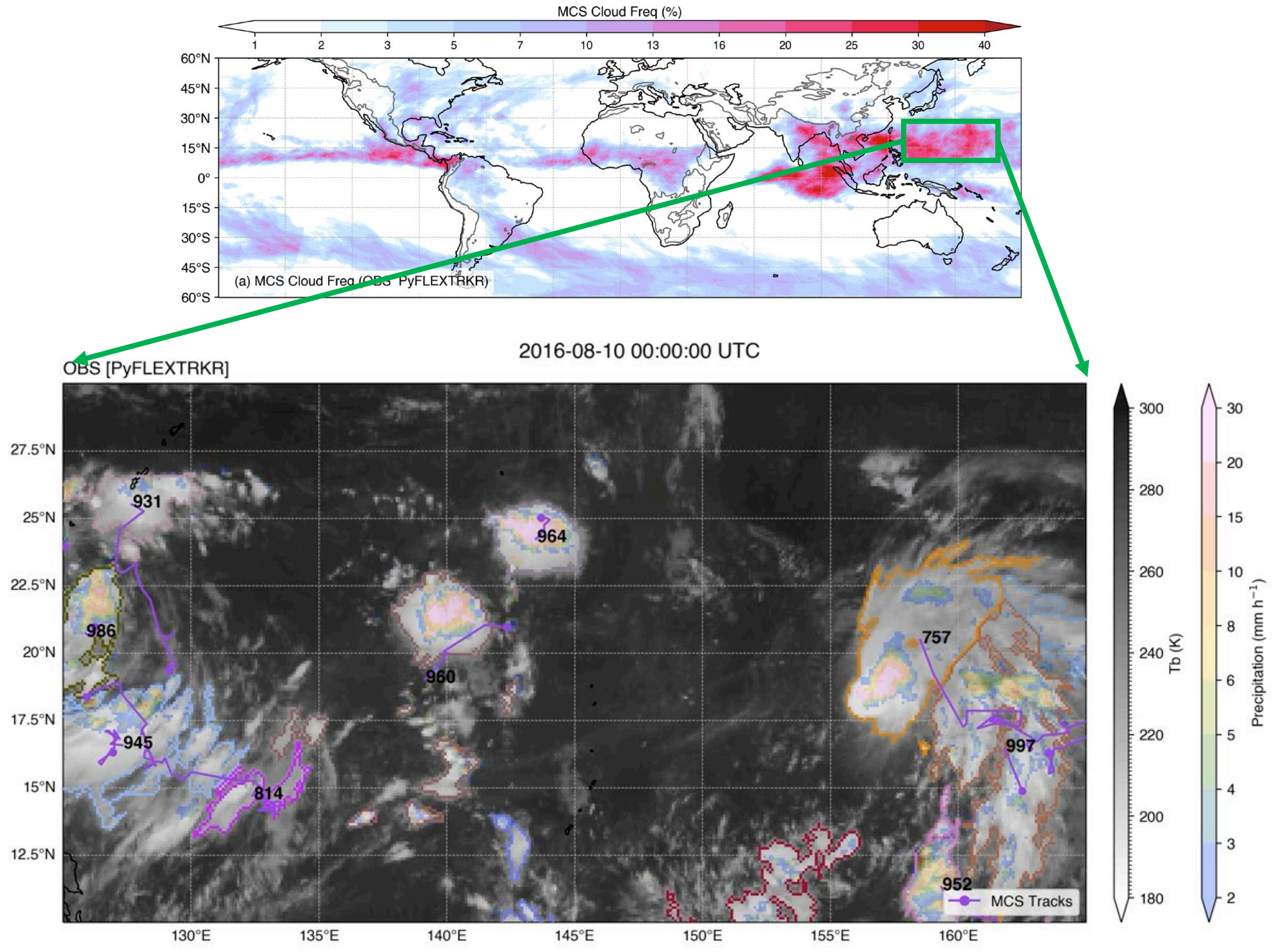
5-day animation (8/10 00Z – 08/15 00Z)

- **Number of MCS** may not be a good metrics to compare due to tracker formulation differences

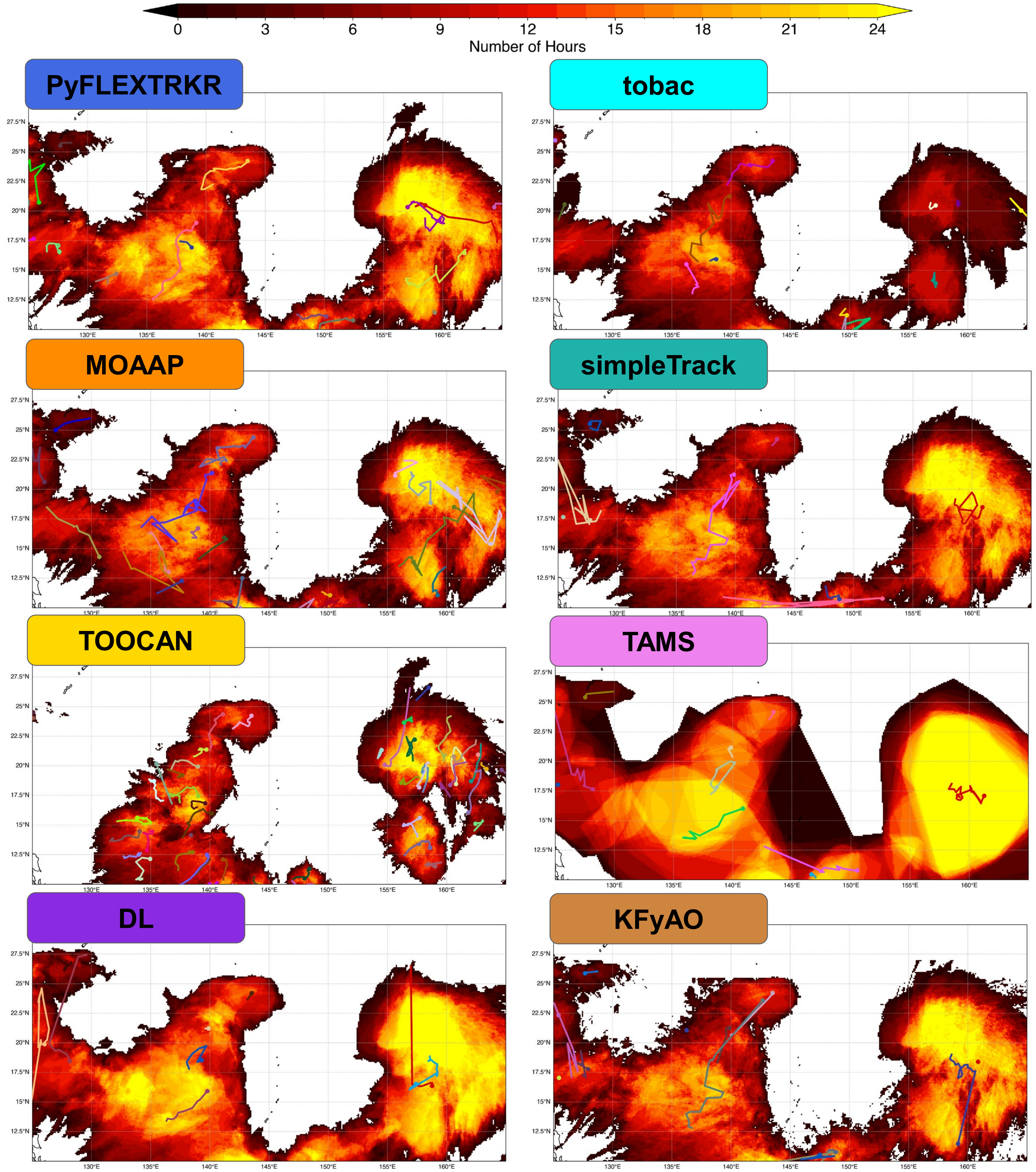
Color patches: MCS masks



MCS Tracking Examples

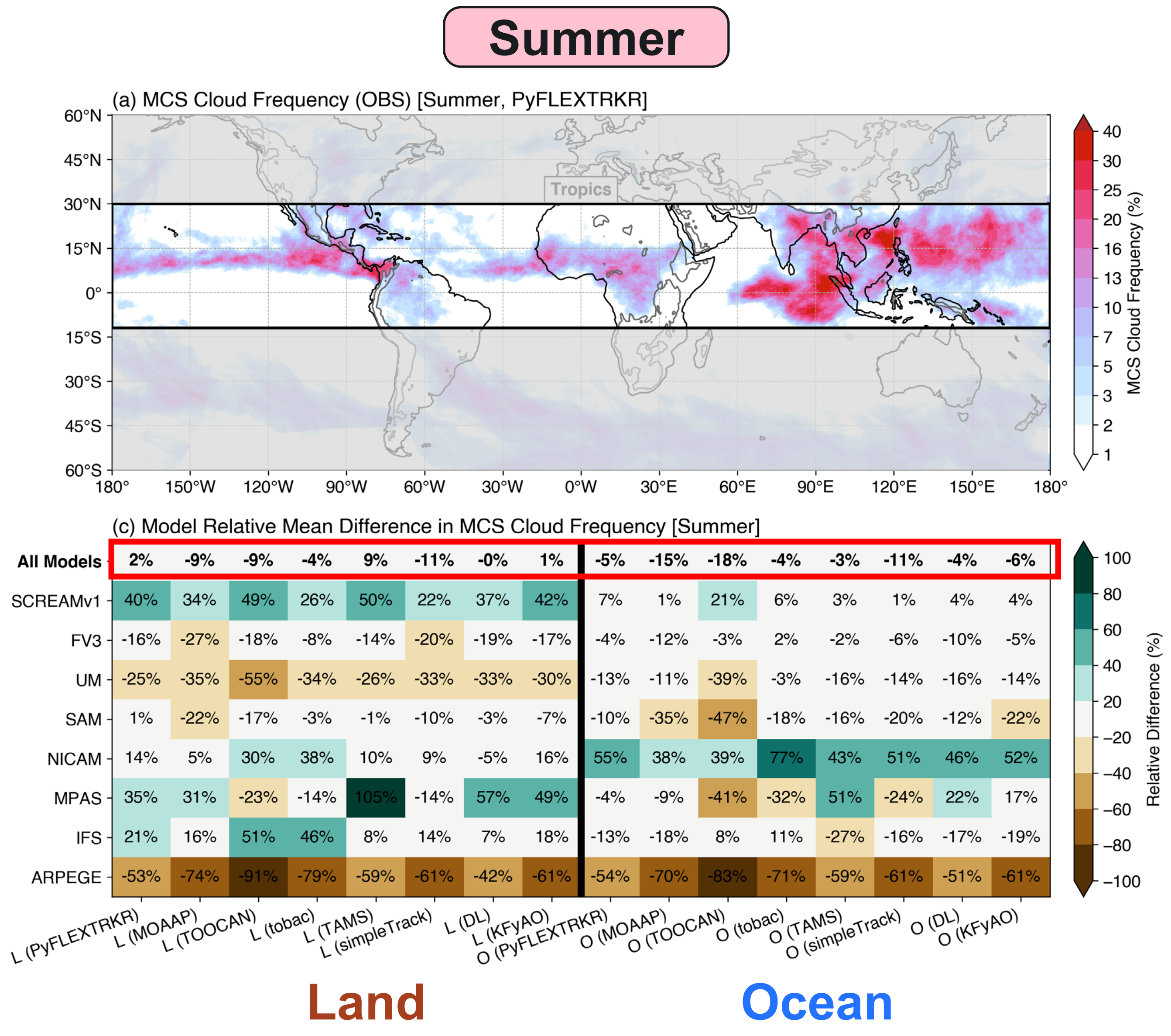


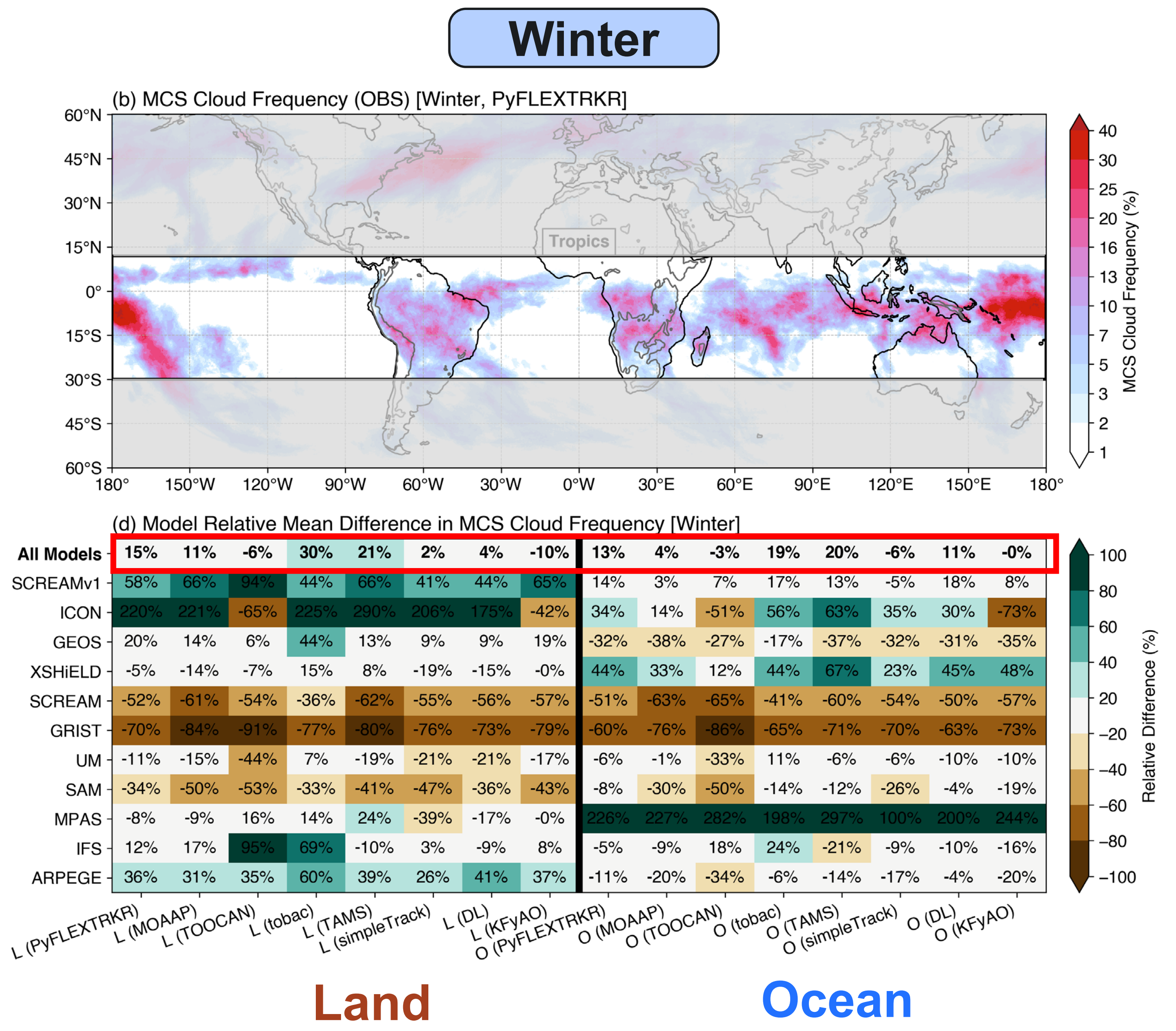
5-day animation (8/10 00Z – 08/15 00Z)



- **Frequency of MCS** is more amiable to tracker formulation differences

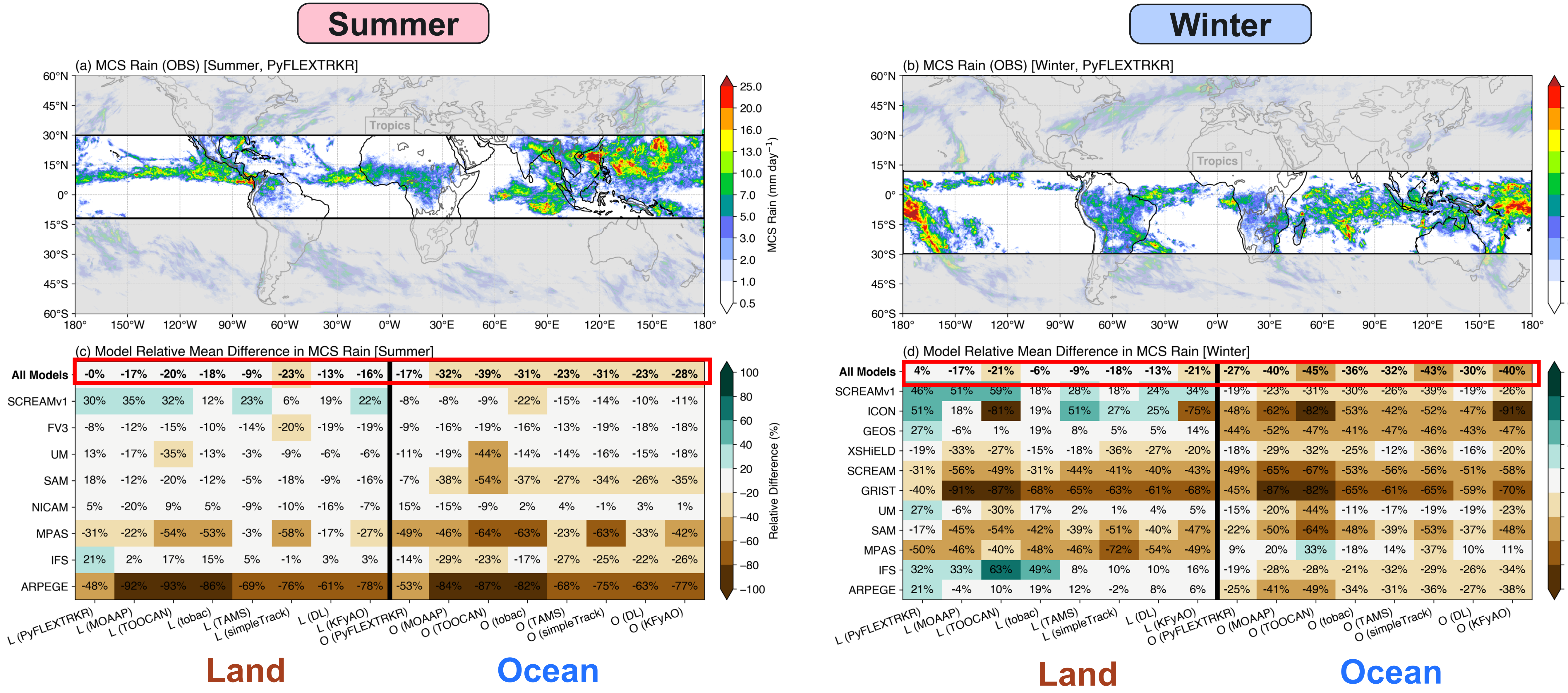
Model MCS cloud frequency variability is large





- Models are generally skillful in simulating MCS frequency, though intermodal variability is large (up to 3x)

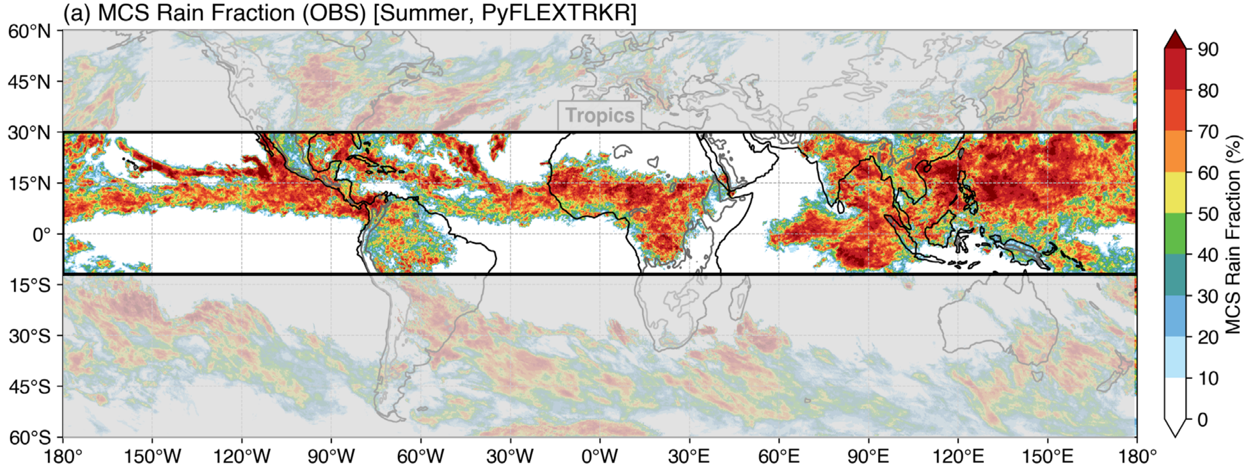
Models underestimate MCS precipitation amount



- Models generally underestimate MCS **precipitation** over **tropical ocean** by **32%**
- Biases over **tropical land** are slightly **smaller 14%**

Models underestimate MCS contribution to total precipitation

Summer



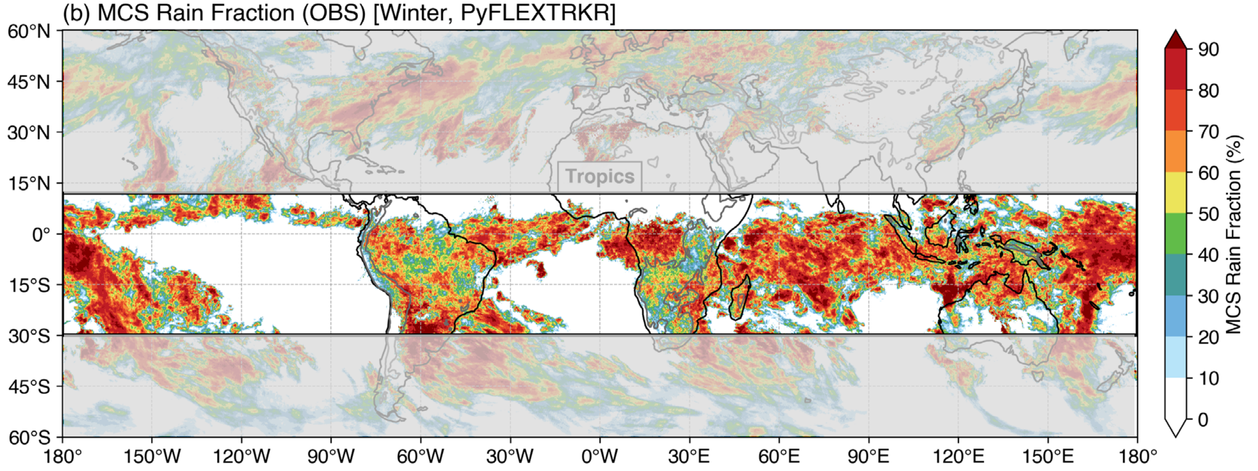
(c) Model Relative Mean Difference in MCS Rain Fraction [Summer]

	L (PyFLEXTRKR)	L (MOAAP)	L (TOOCAN)	L (tobac)	L (TAMS)	L (simpleTrack)	L (DL)	L (KFyAO)	O (PyFLEXTRKR)	O (MOAAP)	O (TOOCAN)	O (tobac)	O (TAMS)	O (simpleTrack)	O (DL)	O (KFyAO)
All Models	**-12%**	**-13%**	**-11%**	**-12%**	**-15%**	**-20%**	**-17%**	**-15%**	**-18%**	**-20%**	**-18%**	**-16%**	**-21%**	**-23%**	**-21%**	**-20%**
SCREAMv1	-3%	-0%	-1%	-6%	-5%	-11%	-7%	-5%	-9%	-6%	-5%	-11%	-13%	-11%	-10%	-9%
FV3	-9%	-7%	-7%	-6%	-11%	-14%	-14%	-12%	-13%	-13%	-11%	-11%	-15%	-17%	-18%	-16%
UM	-10%	-15%	-17%	-12%	-15%	-17%	-17%	-14%	-14%	-14%	-19%	-10%	-16%	-16%	-16%	-16%
SAM	-5%	-12%	-12%	-11%	-14%	-18%	-16%	-16%	-15%	-24%	-24%	-20%	-26%	-27%	-25%	-26%
NICAM	2%	-8%	2%	1%	-5%	-6%	-10%	-4%	-5%	-16%	-10%	-8%	-11%	-12%	-12%	-11%
MPAS	-21%	-10%	-18%	-19%	-5%	-31%	-13%	-15%	-33%	-23%	-25%	-26%	-16%	-38%	-22%	-24%
IFS	-7%	-10%	-5%	-6%	-12%	-14%	-14%	-11%	-10%	-15%	-9%	-7%	-19%	-16%	-16%	-15%
ARPEGE	-37%	-35%	-30%	-30%	-41%	-43%	-41%	-38%	-40%	-43%	-35%	-35%	-48%	-47%	-46%	-45%

Relative Difference (%): 50, 40, 30, 20, 10, −10, −20, −30, −40, −50

Land **Ocean**

Winter



(d) Model Relative Mean Difference in MCS Rain Fraction [Winter]

	L (PyFLEXTRKR)	L (MOAAP)	L (TOOCAN)	L (tobac)	L (TAMS)	L (simpleTrack)	L (DL)	L (KFyAO)	O (PyFLEXTRKR)	O (MOAAP)	O (TOOCAN)	O (tobac)	O (TAMS)	O (simpleTrack)	O (DL)	O (KFyAO)
All Models	**-8%**	**-12%**	**-9%**	**-6%**	**-14%**	**-17%**	**-17%**	**-16%**	**-22%**	**-22%**	**-19%**	**-16%**	**-24%**	**-28%**	**-23%**	**-26%**
SCREAMv1	1%	2%	3%	-5%	-6%	-9%	-8%	-3%	-14%	-13%	-13%	-13%	-18%	-25%	-14%	-16%
ICON	3%	-7%	-22%	-5%	3%	-6%	-8%	-37%	-31%	-30%	-32%	-20%	-26%	-30%	-29%	-52%
GEOS	-11%	-15%	-9%	-7%	-18%	-18%	-19%	-13%	-28%	-25%	-18%	-15%	-29%	-26%	-25%	-26%
XSHiELD	-12%	-13%	-7%	-5%	-11%	-19%	-16%	-10%	-19%	-19%	-16%	-13%	-15%	-26%	-17%	-18%
SCREAM	-23%	-23%	-14%	-11%	-28%	-25%	-27%	-23%	-39%	-36%	-29%	-24%	-42%	-38%	-39%	-38%
GRIST	-25%	-33%	-22%	-20%	-37%	-34%	-37%	-32%	-38%	-45%	-34%	-28%	-46%	-44%	-43%	-44%
UM	-7%	-13%	-13%	-5%	-16%	-16%	-16%	-13%	-17%	-15%	-20%	-9%	-18%	-17%	-19%	-19%
SAM	-16%	-19%	-15%	-14%	-26%	-30%	-28%	-25%	-25%	-29%	-28%	-22%	-33%	-37%	-31%	-33%
MPAS	-4%	0%	3%	-1%	0%	-25%	-9%	-3%	17%	19%	21%	-2%	21%	-16%	18%	16%
IFS	-2%	-1%	5%	3%	-11%	-10%	-11%	-7%	-17%	-17%	-13%	-11%	-25%	-21%	-20%	-23%
ARPEGE	-1%	-8%	-2%	-1%	-5%	-10%	-6%	-6%	-17%	-21%	-20%	-14%	-21%	-22%	-18%	-22%

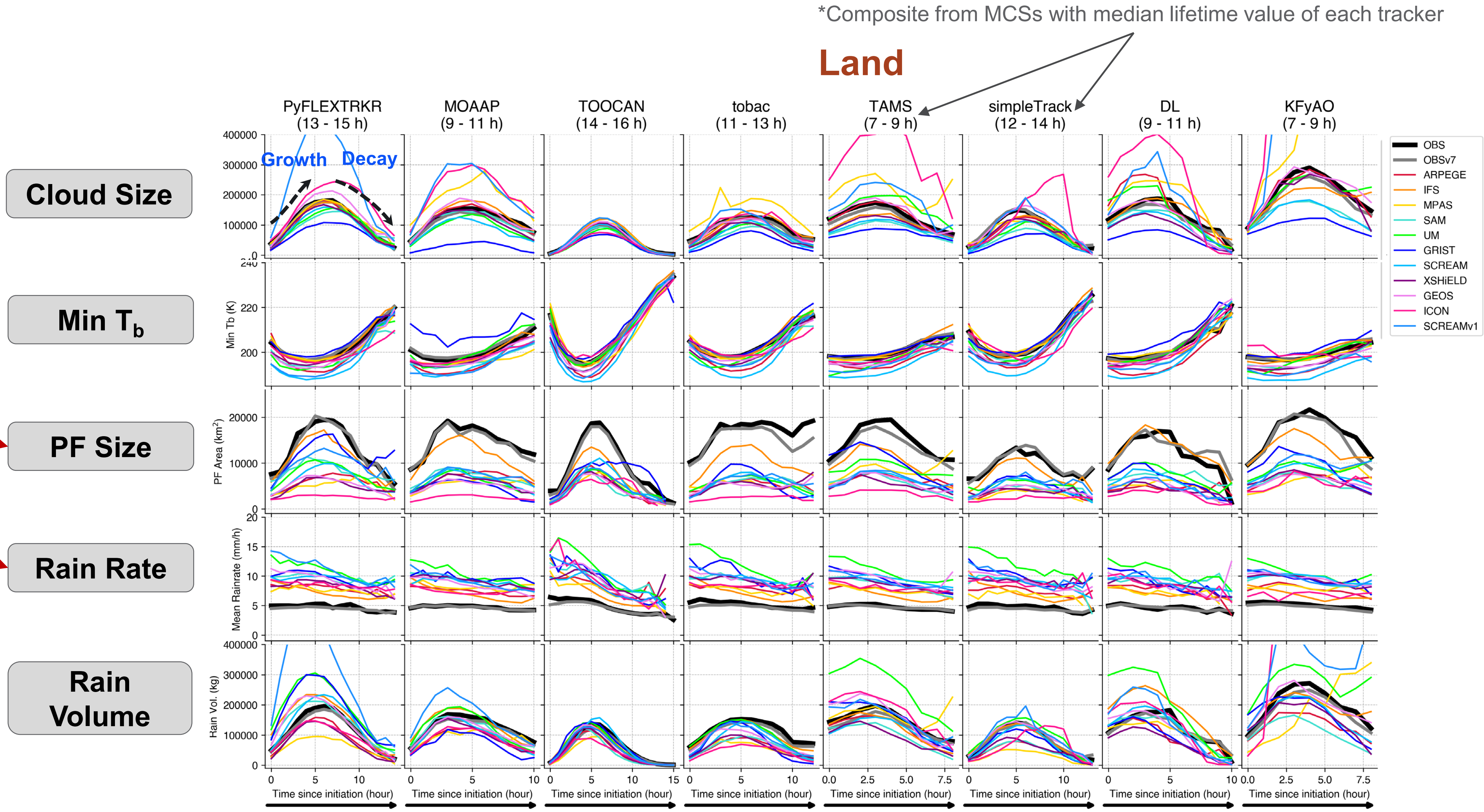
Relative Difference (%): 50, 40, 30, 20, 10, −10, −20, −30, −40, −50

Land **Ocean**

- Models underestimate MCS **contribution to total precipitation** over **tropical ocean** by **21%**
- Biases over **tropical land** are slightly **smaller** **13%**

Biases in MCS precipitation characteristics are more consistent among trackers than clouds

- Models generally capture cloud shield evolution, though the magnitudes differ among the trackers
- Almost all models underestimate PF area and overestimate PF mean rain rate throughout the lifecycle, compensating the errors → more comparable **rain volume**



*Exclude tracks with max CCS area during first & last 10% of their lifetime (split or merge)

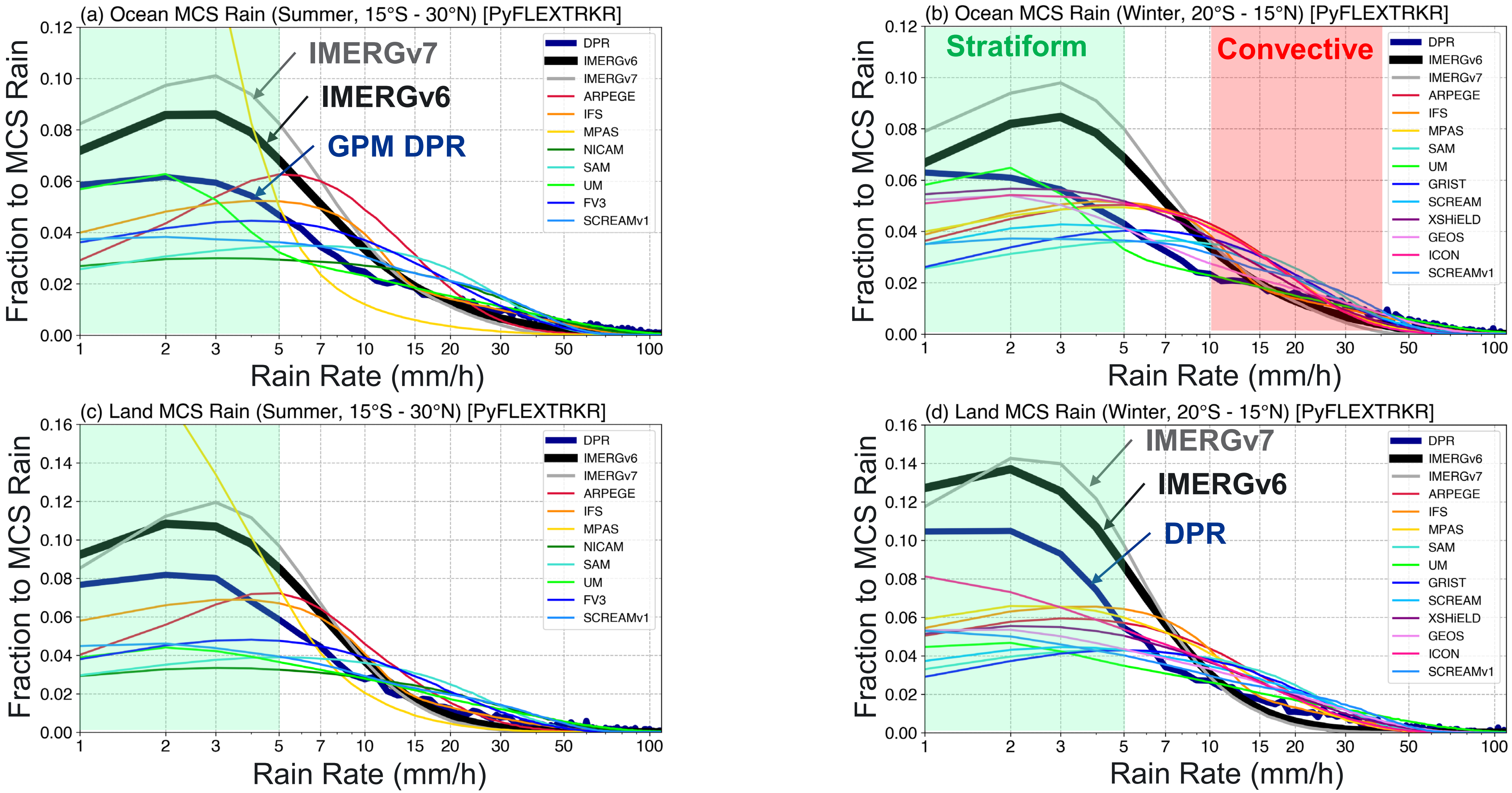
Models underestimate stratiform rain contribution to MCS precipitation

Summer

Winter

Ocean

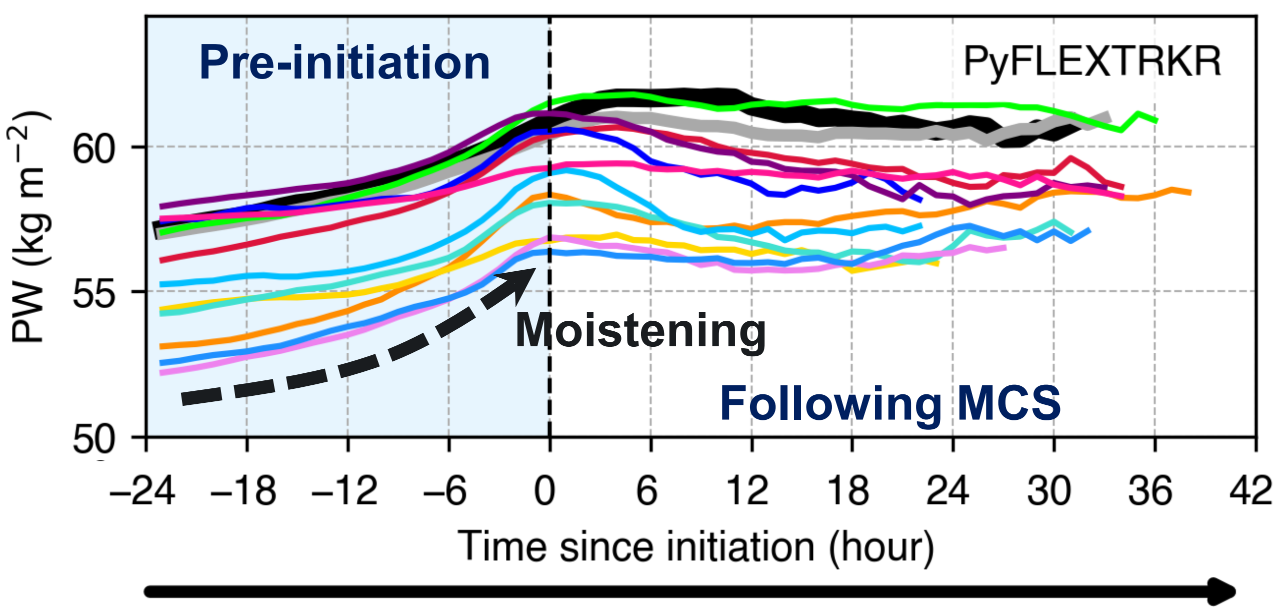
Land



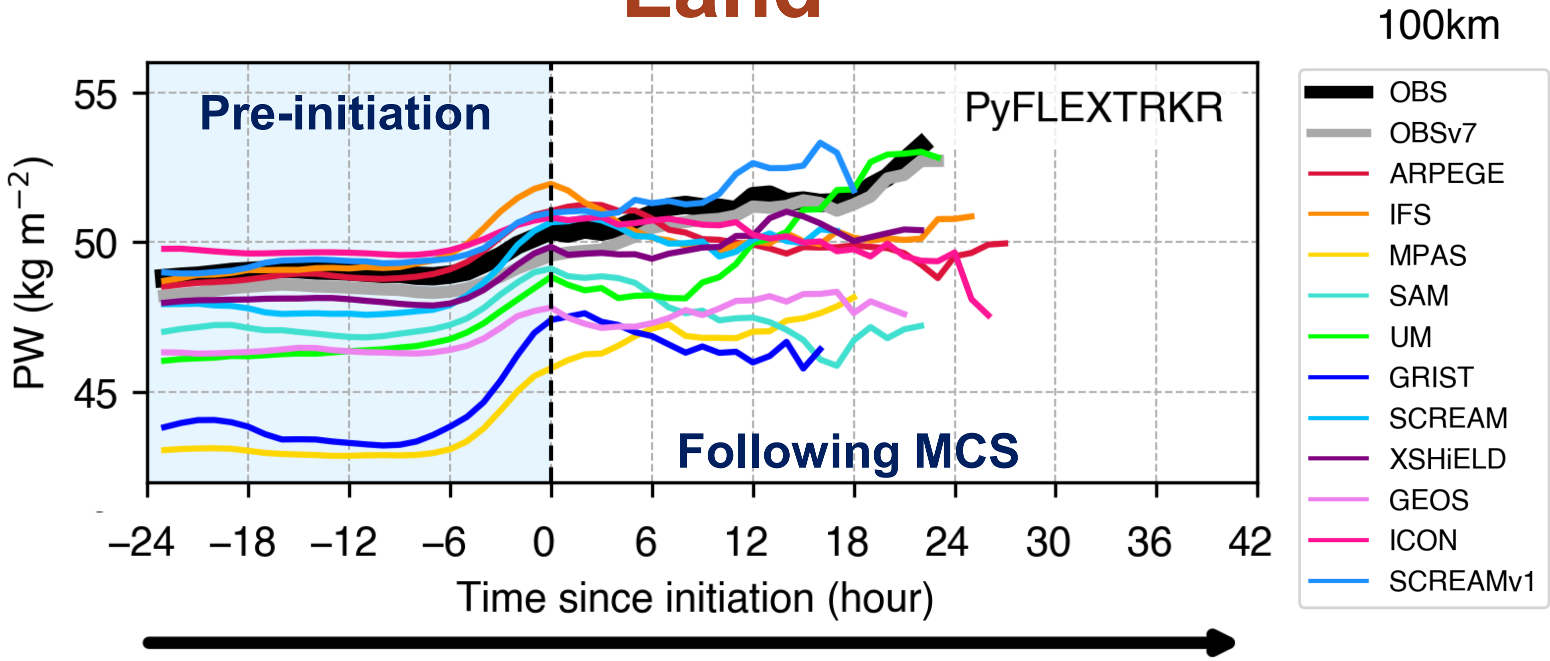
- Most models underestimate stratiform rain (< 5 mm/h) **contribution** to MCS rainfall compared to both IMERG & **DPR**, vice versa for convective rain **contribution** (> 10 mm/h)
- Biases are larger over land than ocean. Implications on **diabatic heating profiles** & **upscale effects**.

Models capture PW evolution with MCS lifecycle

Ocean



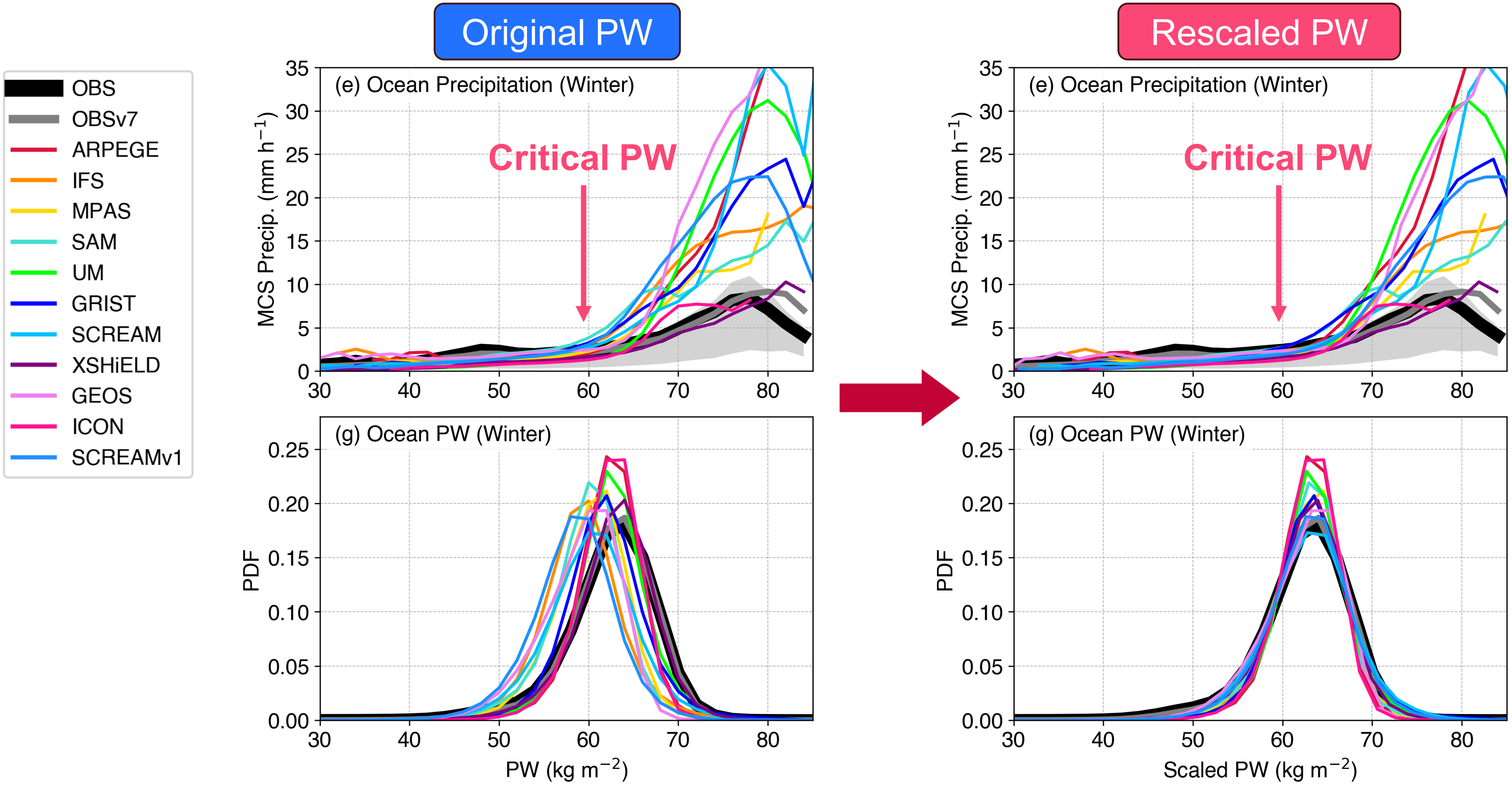
Land



*PWV: averaged within 100 km radius center at MCS tracks

- **Ocean**: models generally **capture steady increase in PW** prior to MCS initiation, and **plateau/decay after initiation**, despite difference in PW magnitude
- **Land**: **rapid increase** occur **~6 h before initiation**, possibly associated with the diurnal cycle
- Results are **consistent** across all **trackers** and **seasons**

Models overestimate sensitivity of MCS precipitation intensity to moisture



- Most models show **higher** MCS precipitation intensity sensitivity to PW than ERA5
- After rescaling PW, some biases at high PW remain, but precipitation pick-up near critical PW compares better

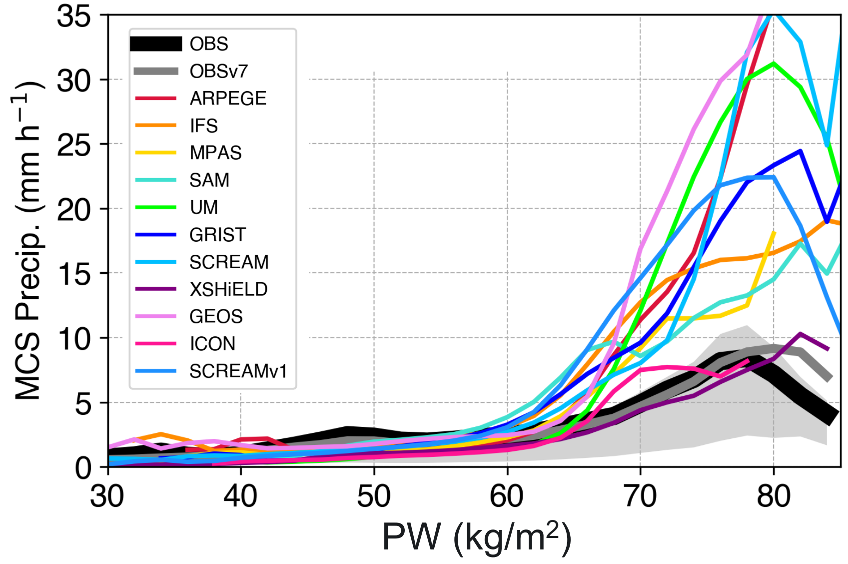
Summary

[Preprint](#)

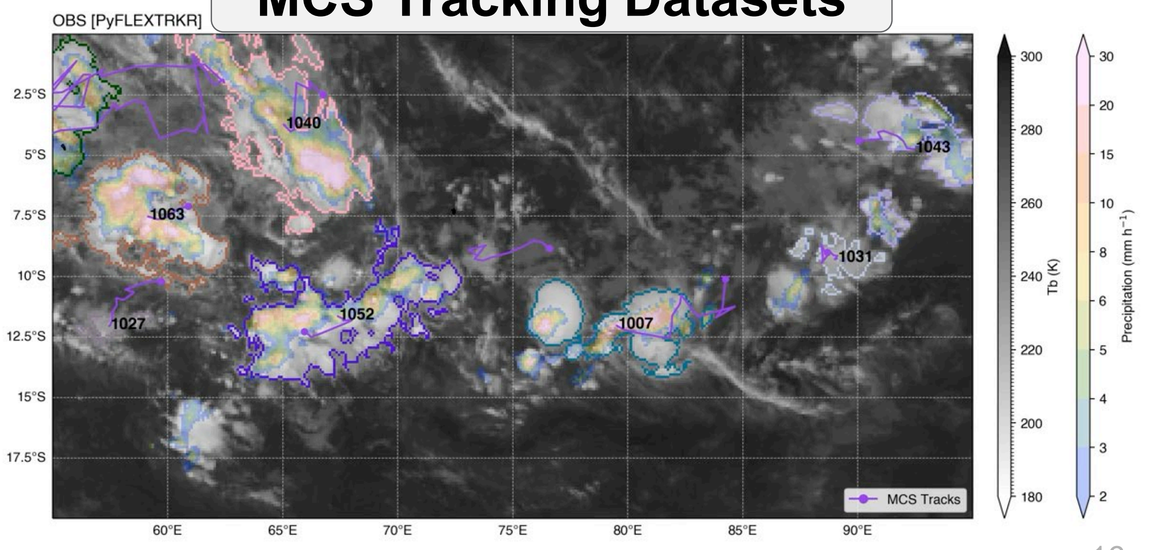
- DYAMOND models generally underestimate MCS rainfall amount and their contribution to total rainfall
- MCS **cloud shield** evolution is better simulated than MCS **precipitation**
- Many models overestimate observed MCS precipitation sensitivity to PW
- **MCSMIP in the future**
  - All data are open to the community
  - Diagnostics codes are on GitHub
  - Many MCS tracking codes are open-sourced (e.g., PyFLEXTRKR)

Contact: Zhe Feng (zhe.feng@pnnl.gov)

MCS Rainfall Sensitivity to PW



MCS Tracking Datasets

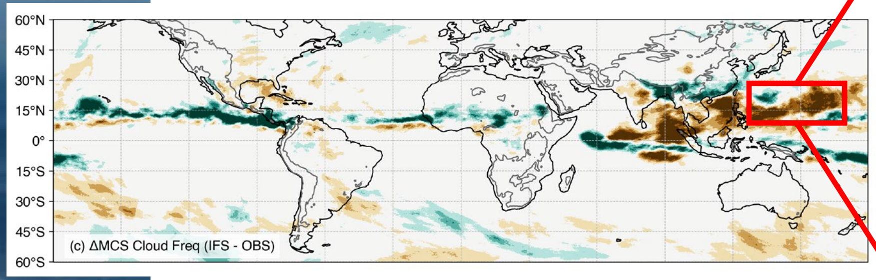


Thank you

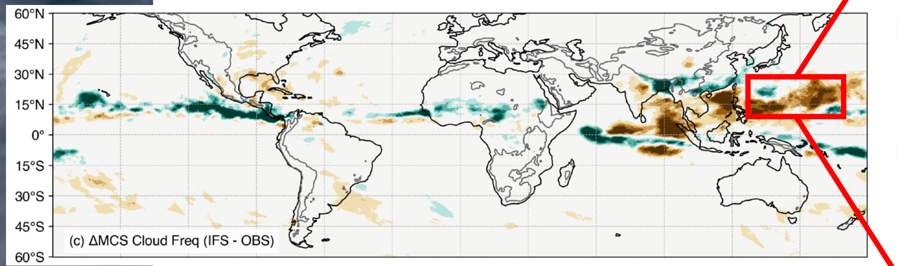
Contact: Zhe Feng (zhe.feng@pnnl.gov)

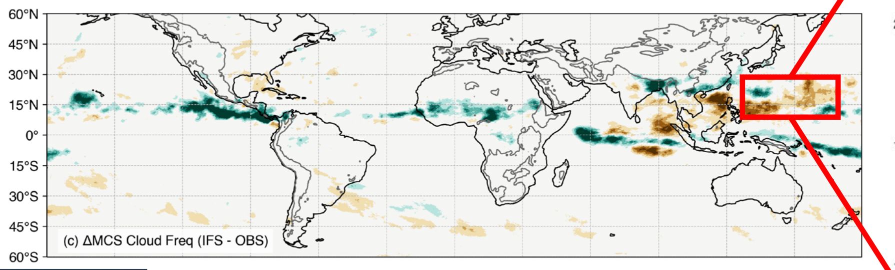
PNNL is operated by Battelle for the U.S. Department of Energy

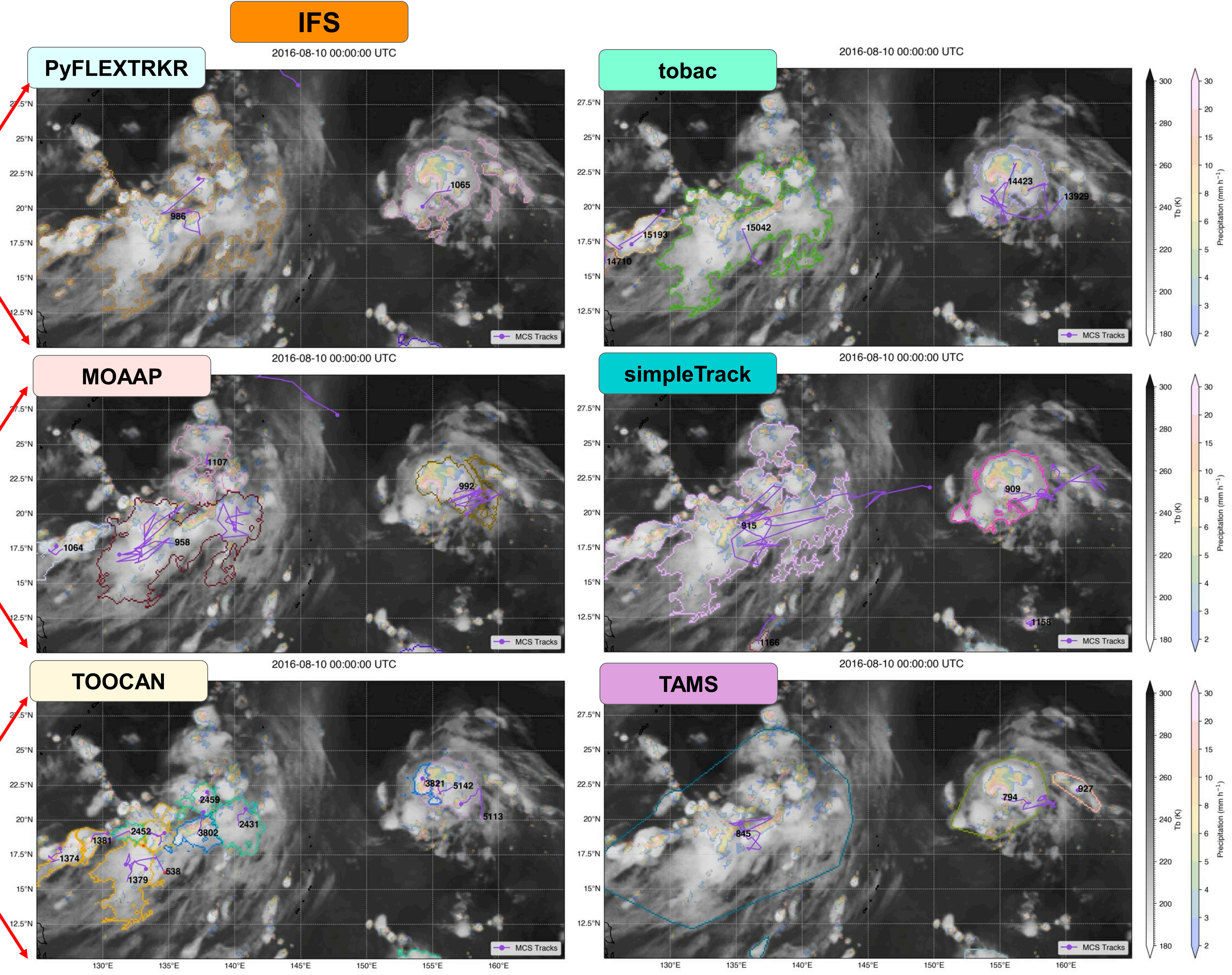
Summer (W. Pacific)



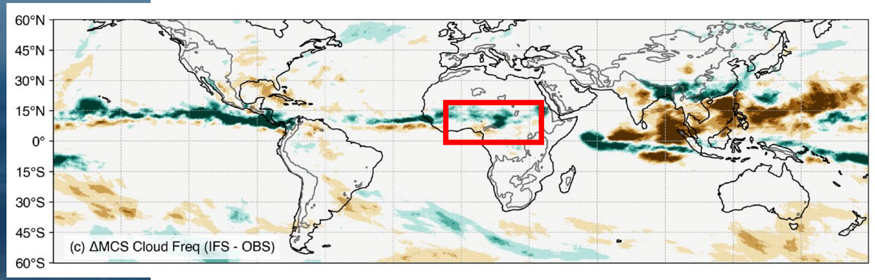
- MCS cloud frequency differences



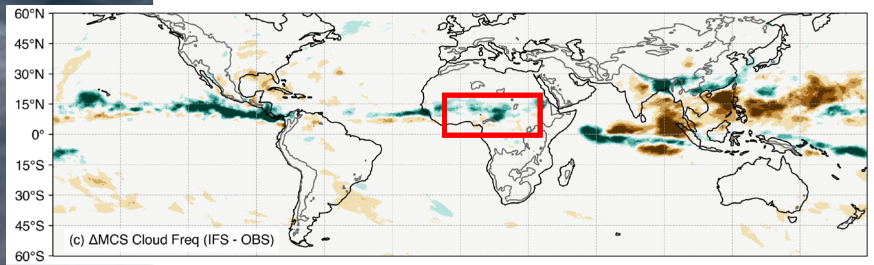


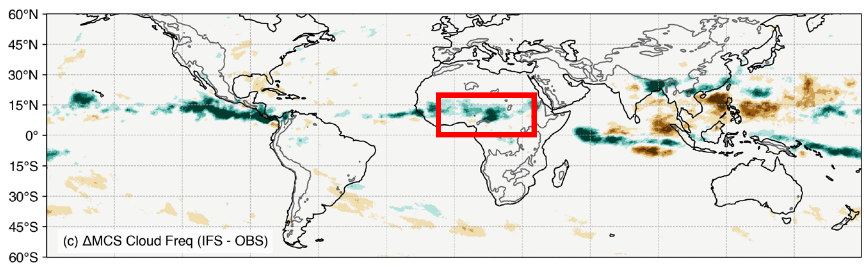


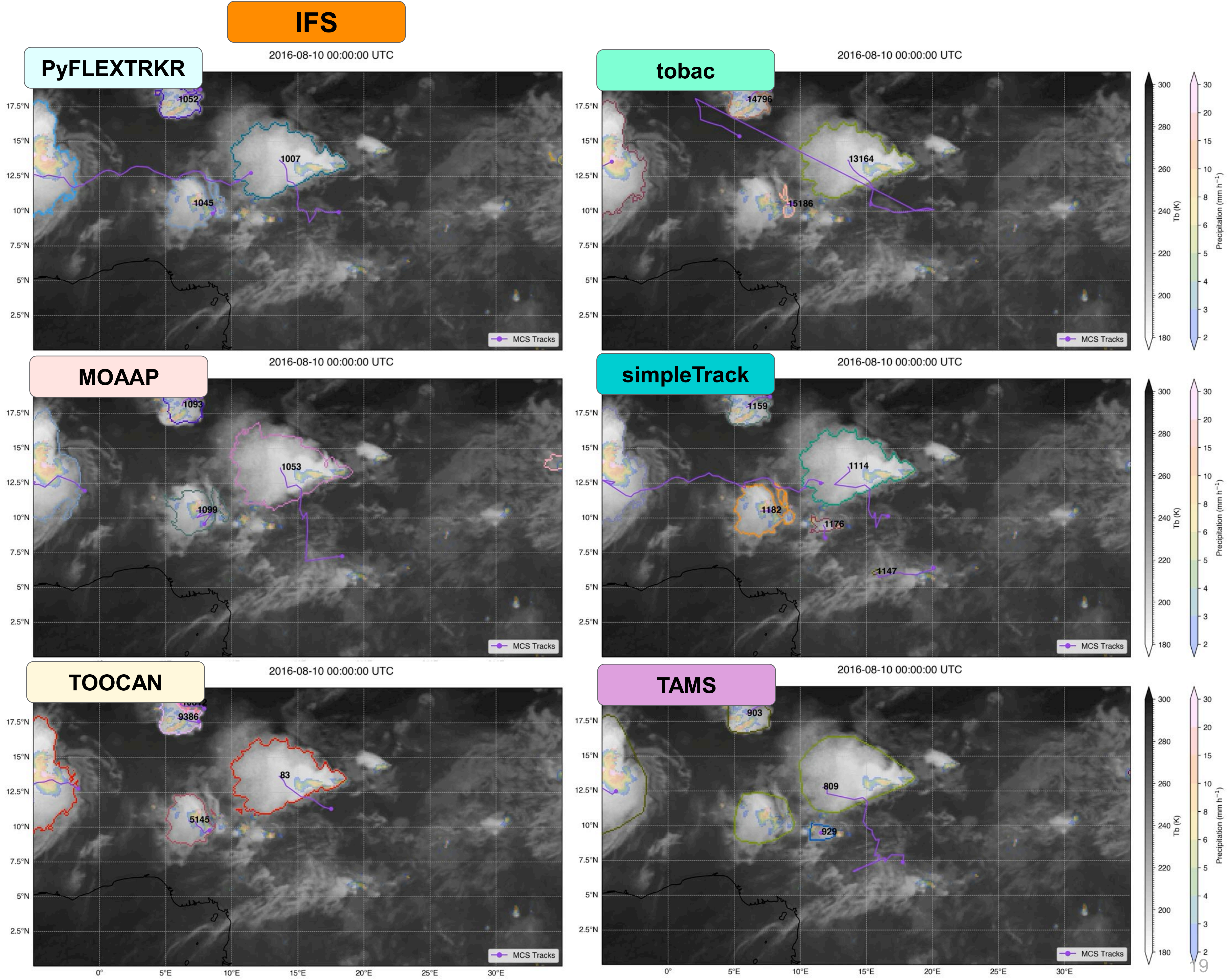
Summer (Africa)



- MCS cloud frequency differences

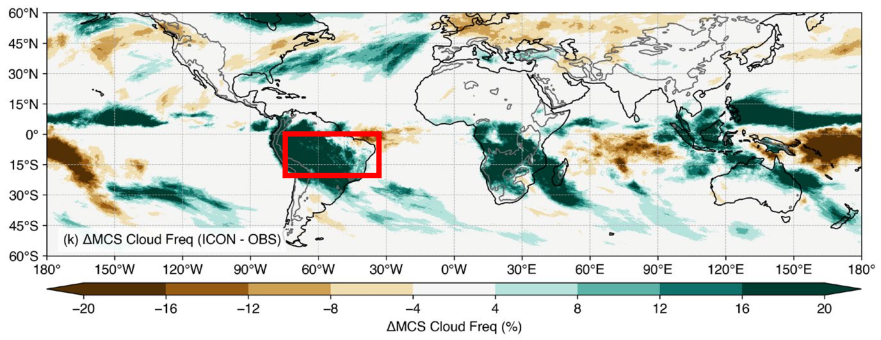




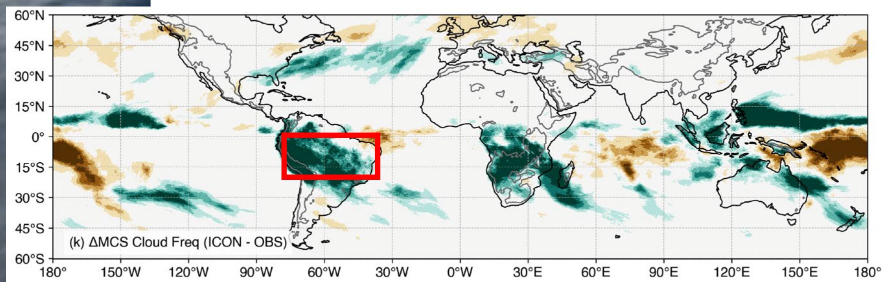


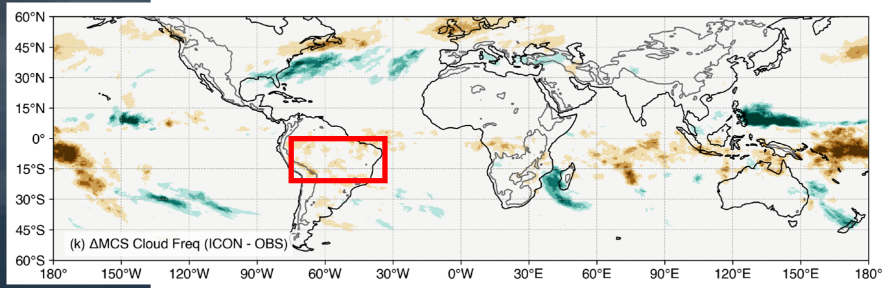
Winter (Amazon)

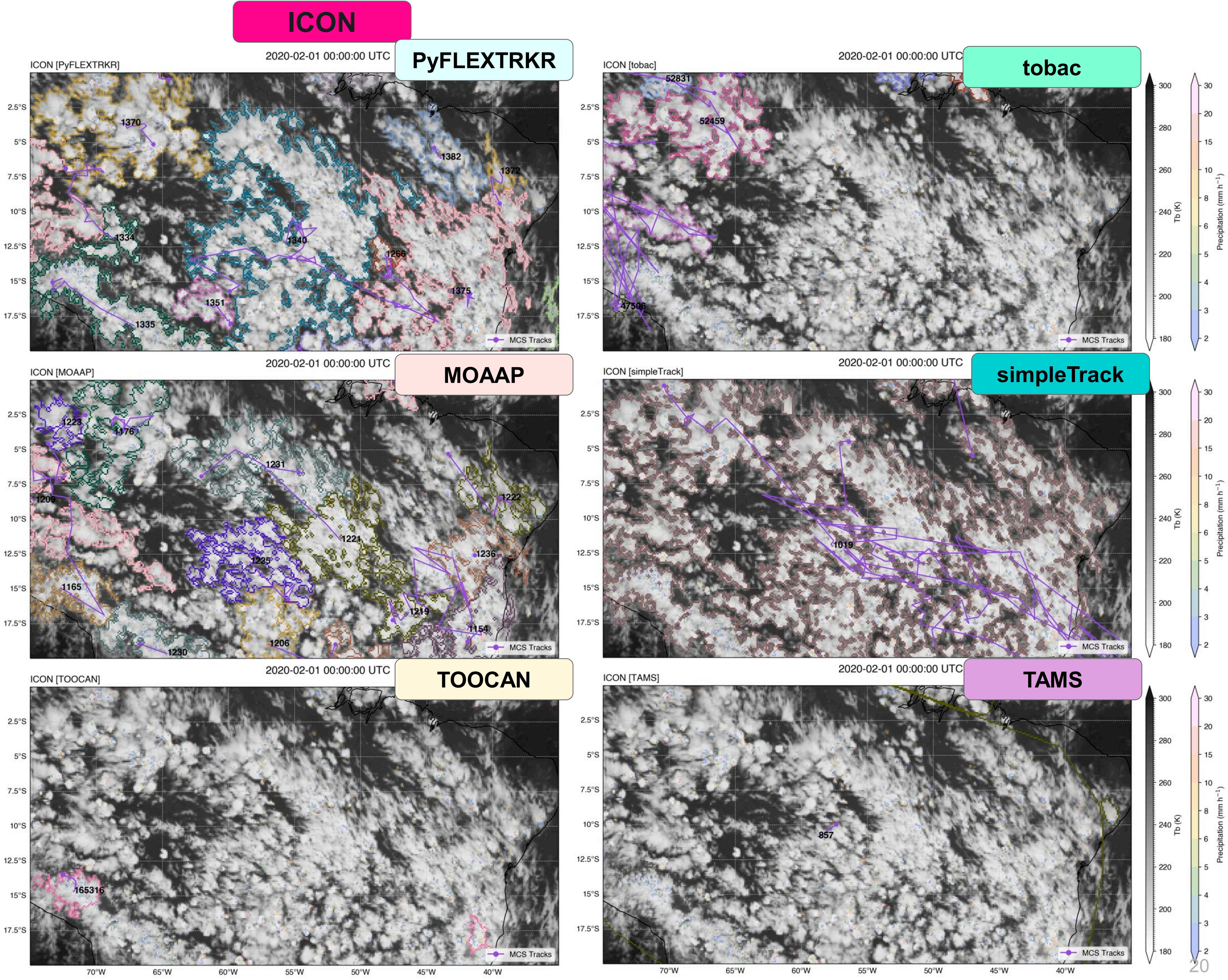
Pacific Northwest NATIONAL LABORATORY



- MCS cloud frequency differences







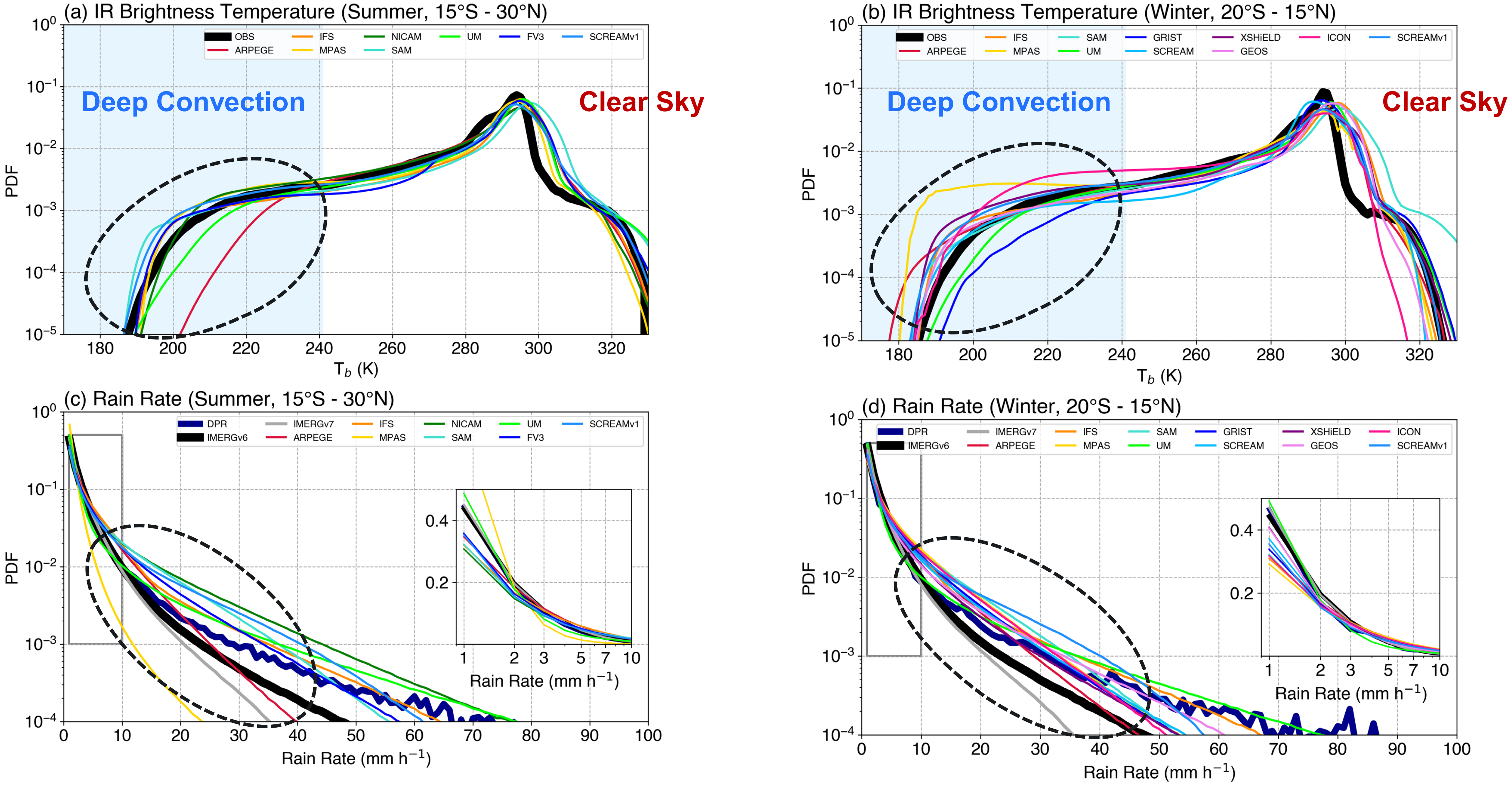
Spread in T_b & rain rate affects MCS tracking

Pacific Northwest NATIONAL LABORATORY

Summer | **Winter**

Infrared T_b

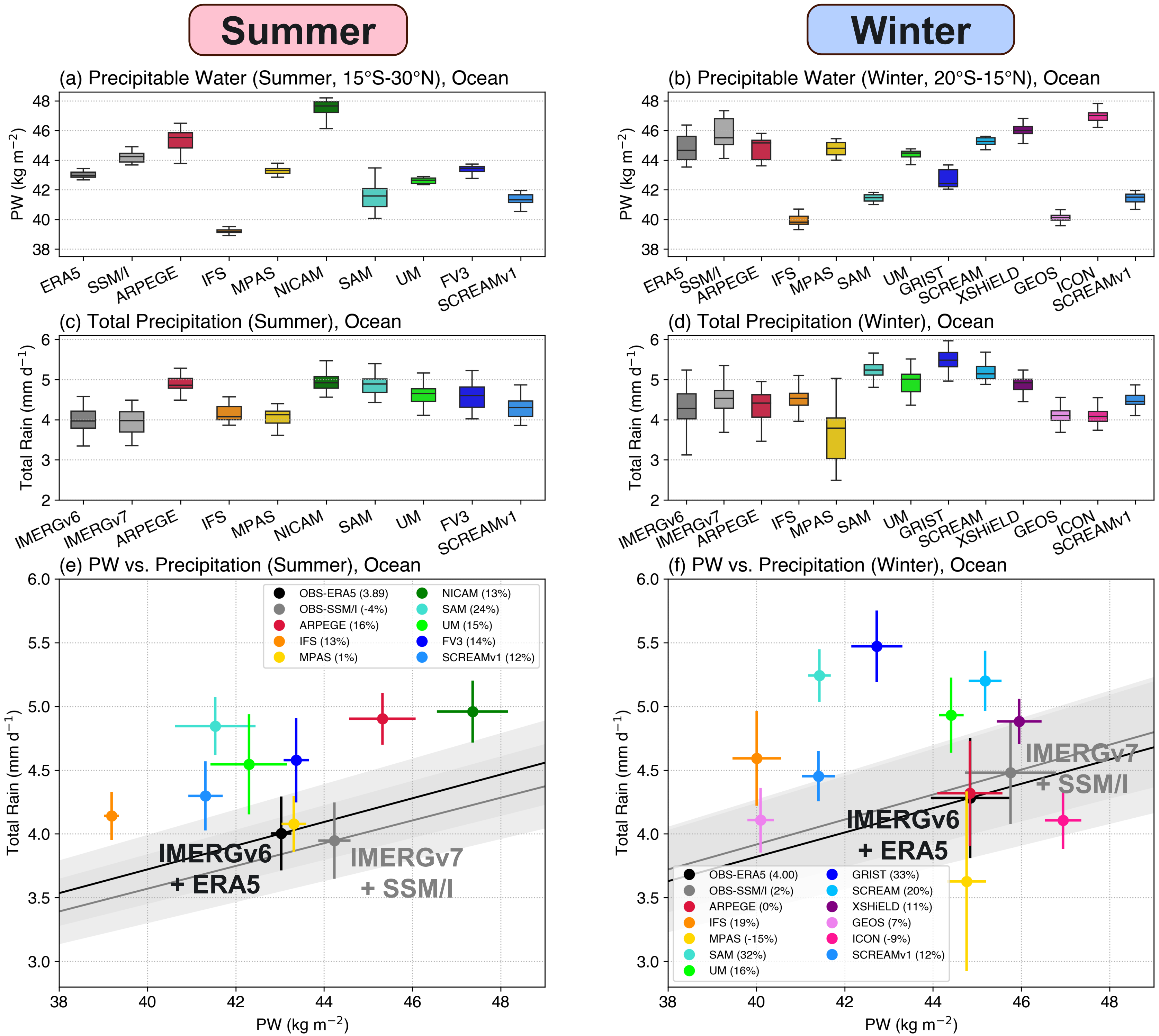
Rain Rate



- **Spread in low T_b** will cause differences in tracking of deep convective systems and MCSs
- **Spread in precipitation** intensity also affects MCS identification

Spread in tropical mean PWV & precipitation

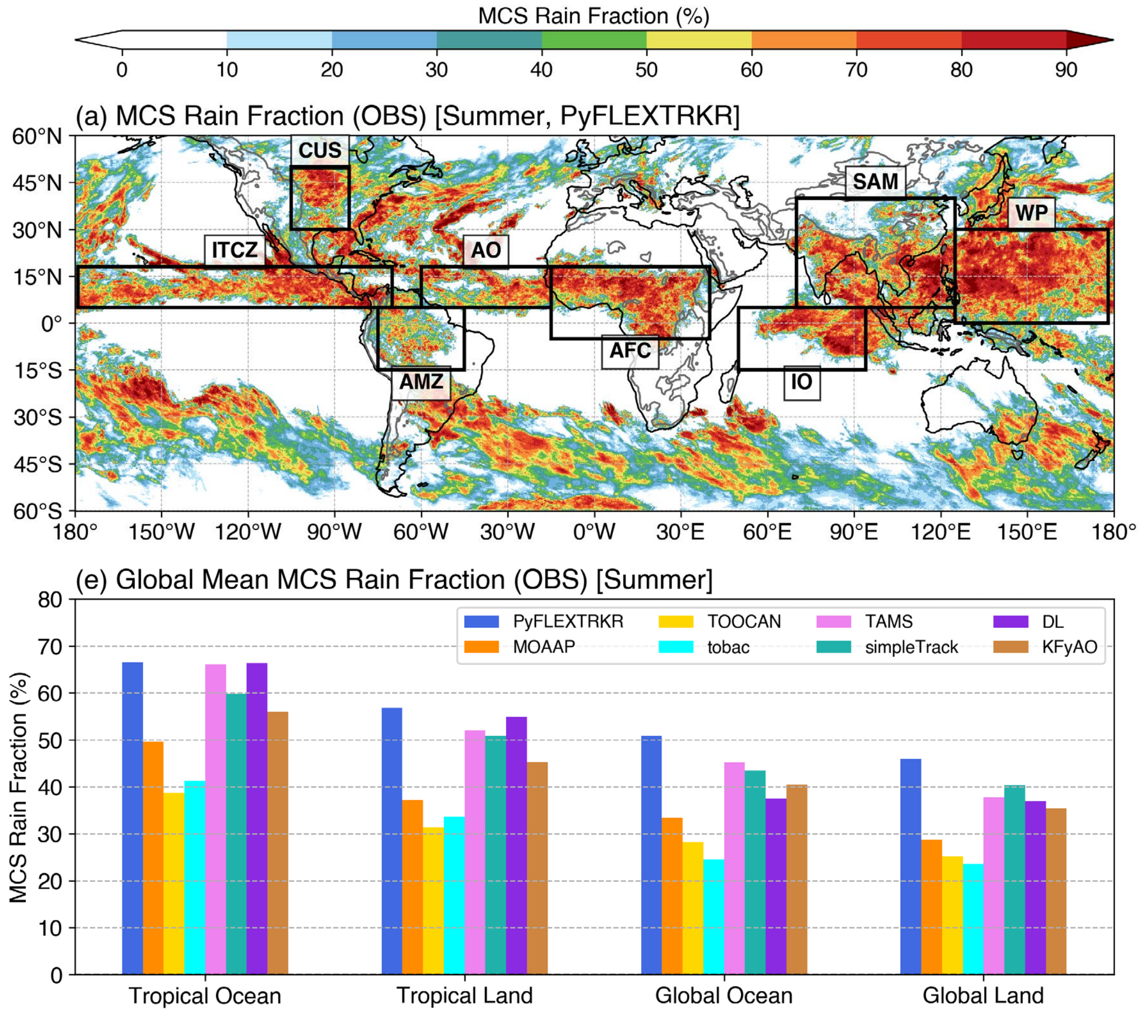
- Both phases have large inter-model spread in **PWV** and **precipitation**
- Most models overestimate **precipitation/PWV ratio** by **up to 33%**, suggesting models may have higher sensitivity to moisture than OBS
- **OBSv7 PWV** is from **SSM/I** (HOAPS4.0 product) 0.5° x 0.5°, 6-hourly, averaged to daily



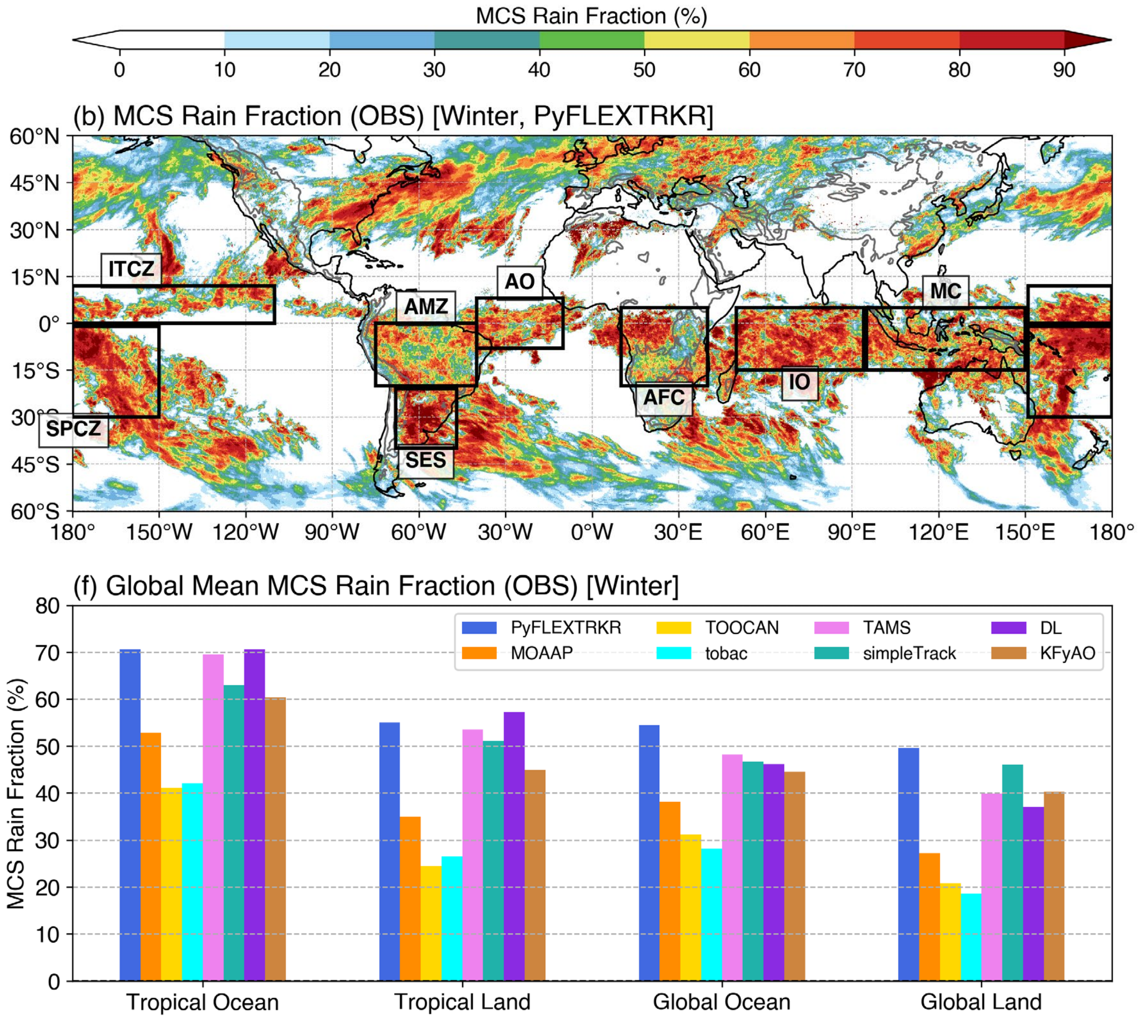
Tropical Ocean

Tracker variation on observed MCS contribution to total rainfall is large

Summer



Winter



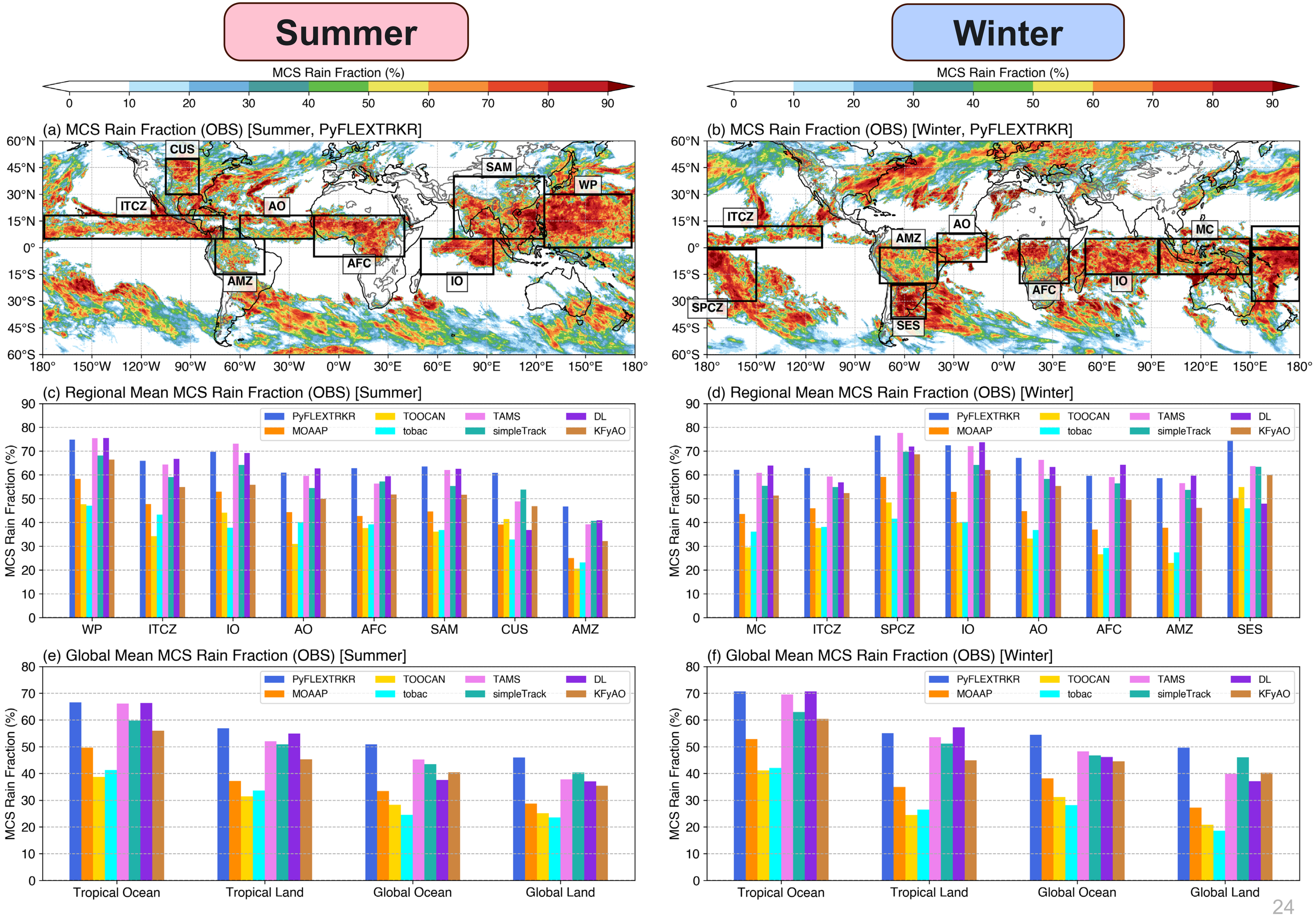
Tropics Global

Tropics Global

- Tracker differences are large (up to a factor of 2)
- **Consistent discrepancies** among trackers across different geographic **regions** and **seasons**

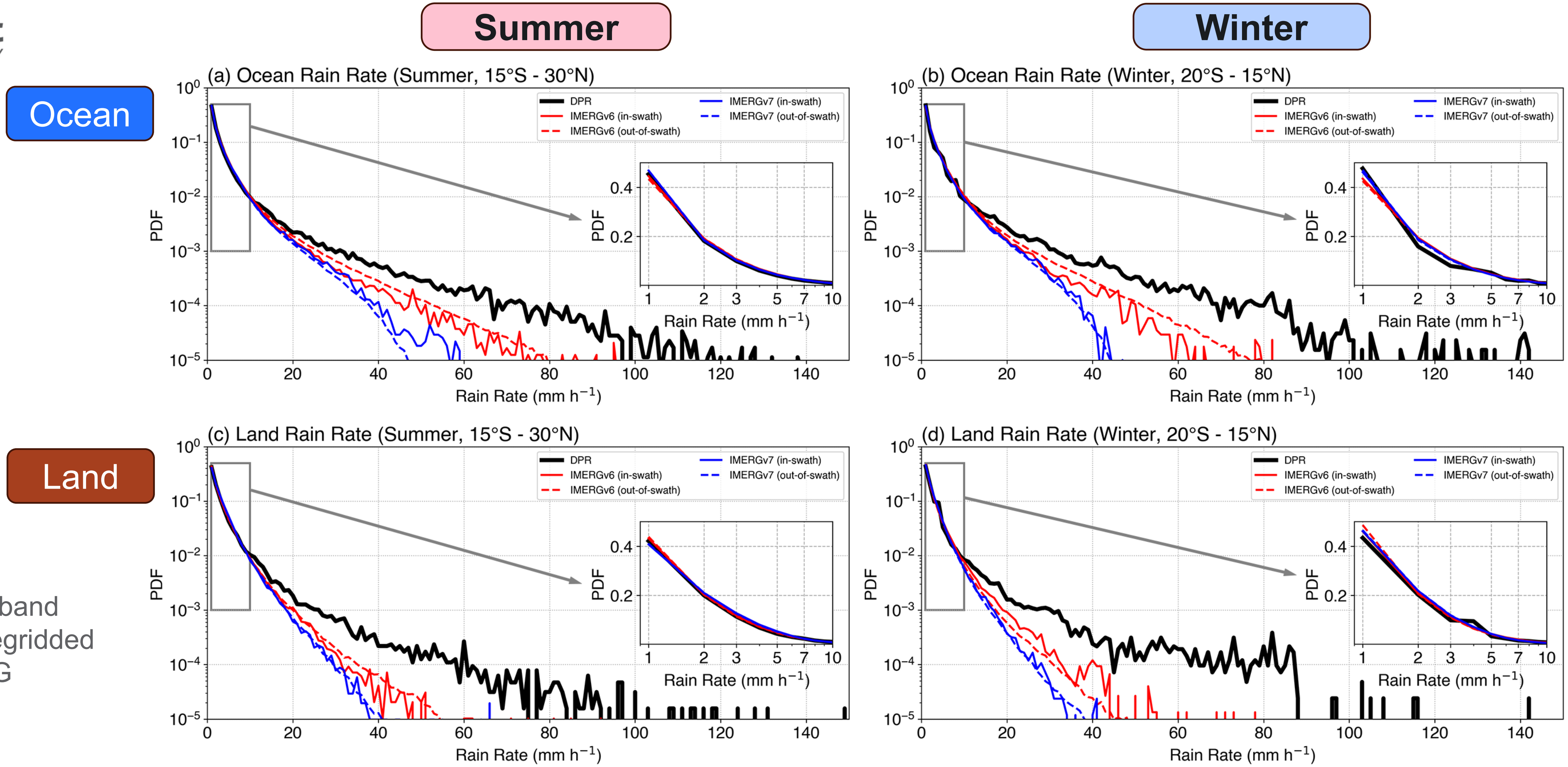
Tracker variation on observed MCS contribution to total rainfall is large

- Tracker differences are large (up to a factor of 2)
- Consistent discrepancies among trackers across different geographic regions and seasons



Supplementary

IMERG v6 rain rate agrees better with DPR



*GPM DPR Ku-band rain rates are regridded to match IMERG

- IMERG v6 underestimates very heavy rain rates (> 30 mm/h) over land more than over ocean, but biases are smaller than v7

Tropical MCS Diurnal Cycle (Land)

Summer | **Winter**

PyFLEXTRKR

MOAAP

TOOCAN

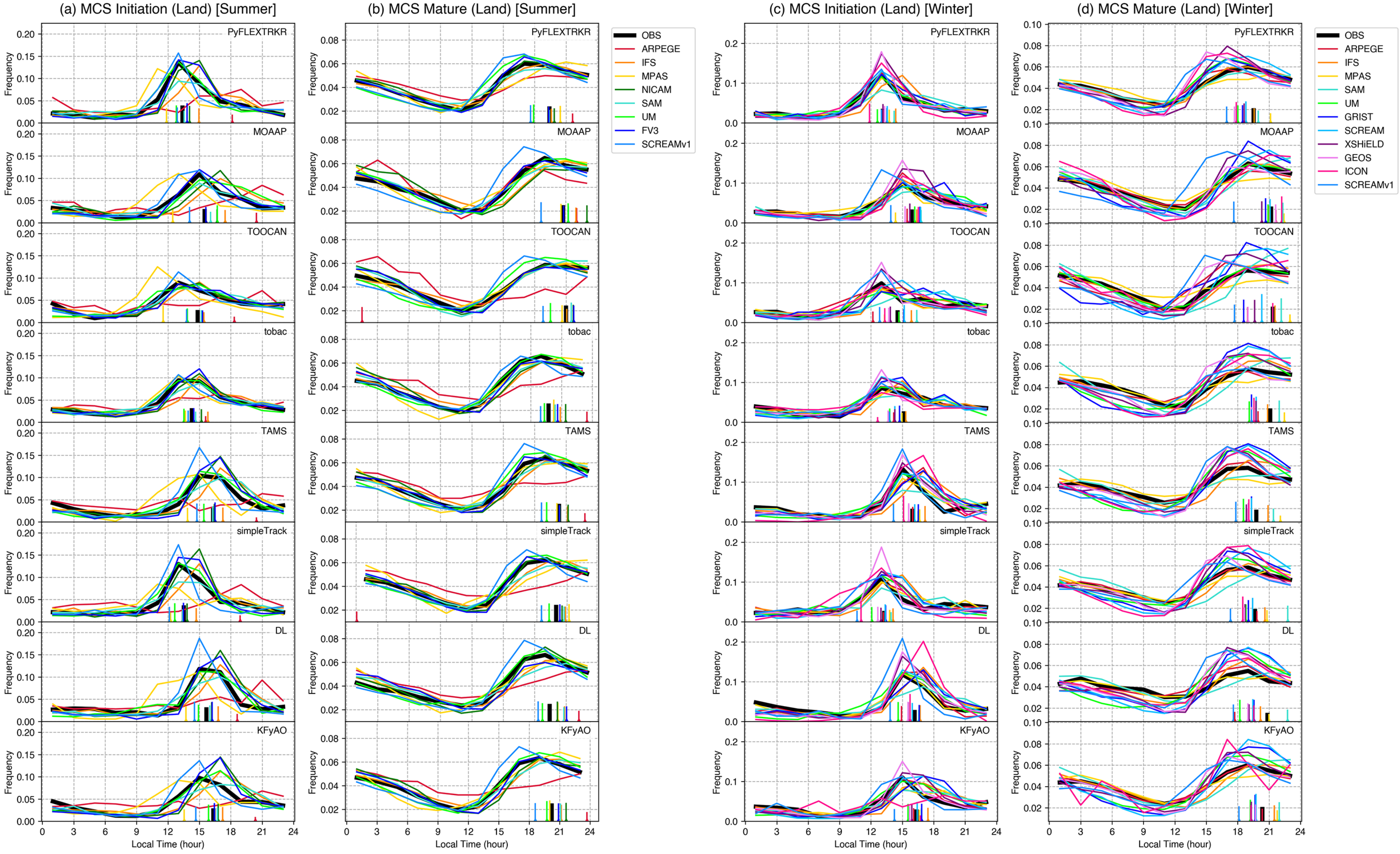
tobac

TAMS

simpleTrack

DL

KFyAO



Tropical MCS Diurnal Cycle (Ocean)

Supplementary

Pacific Northwest NATIONAL LABORATORY

Summer

Winter

PyFLEXTRKR

MOAAP

TOOCAN

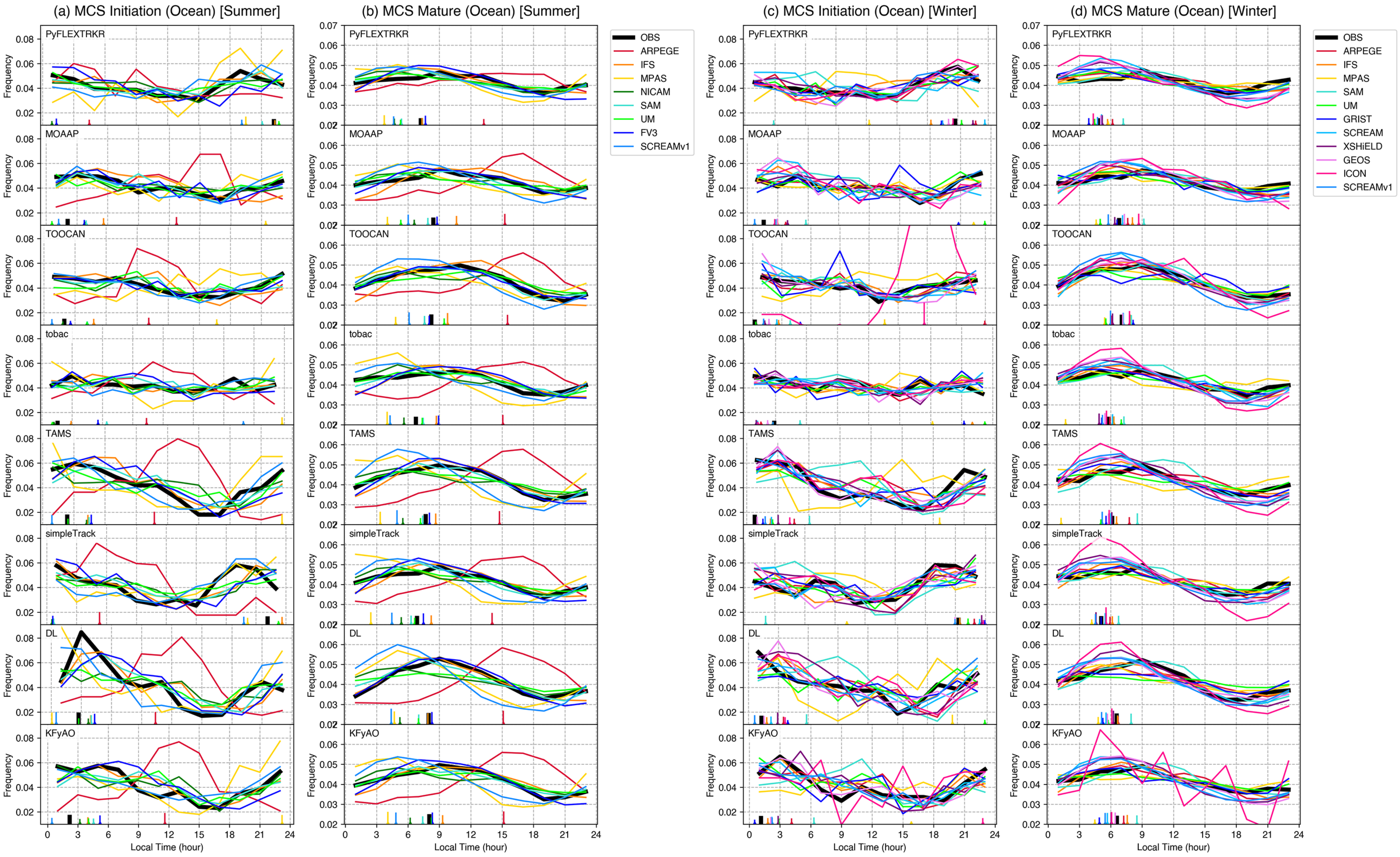
tobac

TAMS

simpleTrack

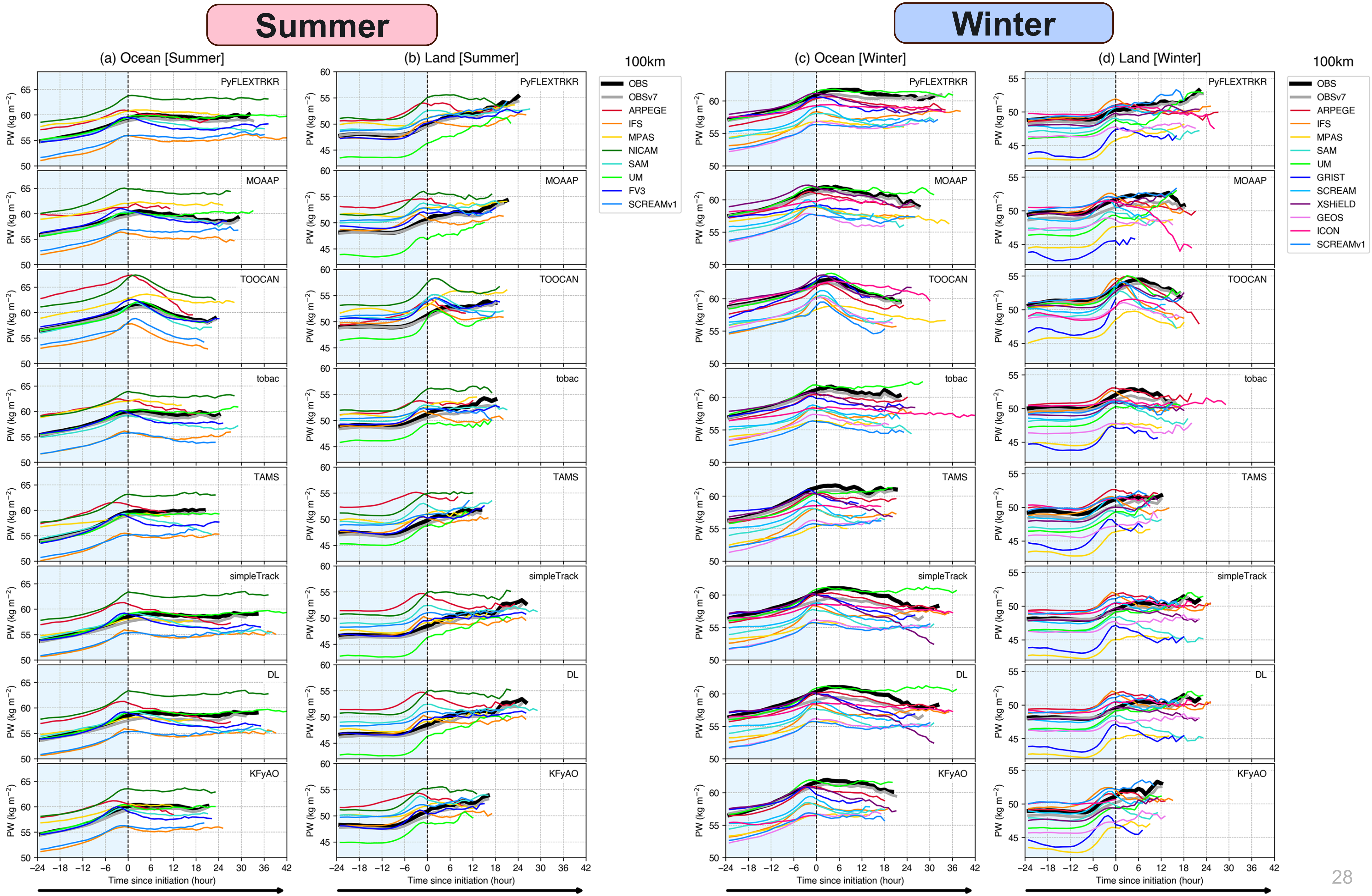
DL

KFyAO



Models capture PWV evolution with MCS lifecycle

- **Ocean**: models generally **capture steady increase in PWV** prior to MCS initiation, and **plateau/decay after initiation**, despite difference in PWV magnitude
- **Land**: **rapid increase** occur **~6 h before initiation**, possibly associated with the diurnal cycle

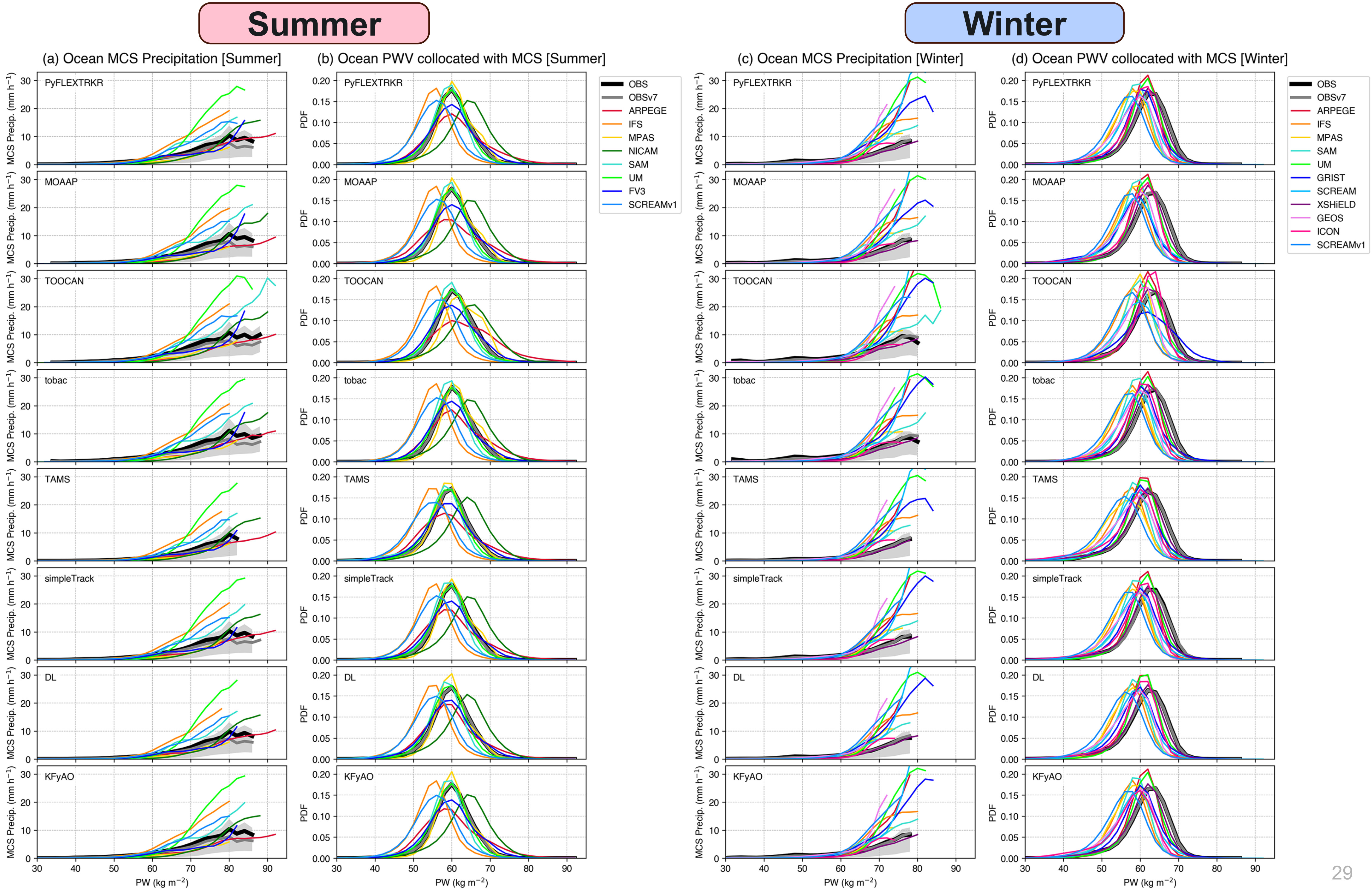


*PWV: averaged within 100 km radius center at MCS tracks

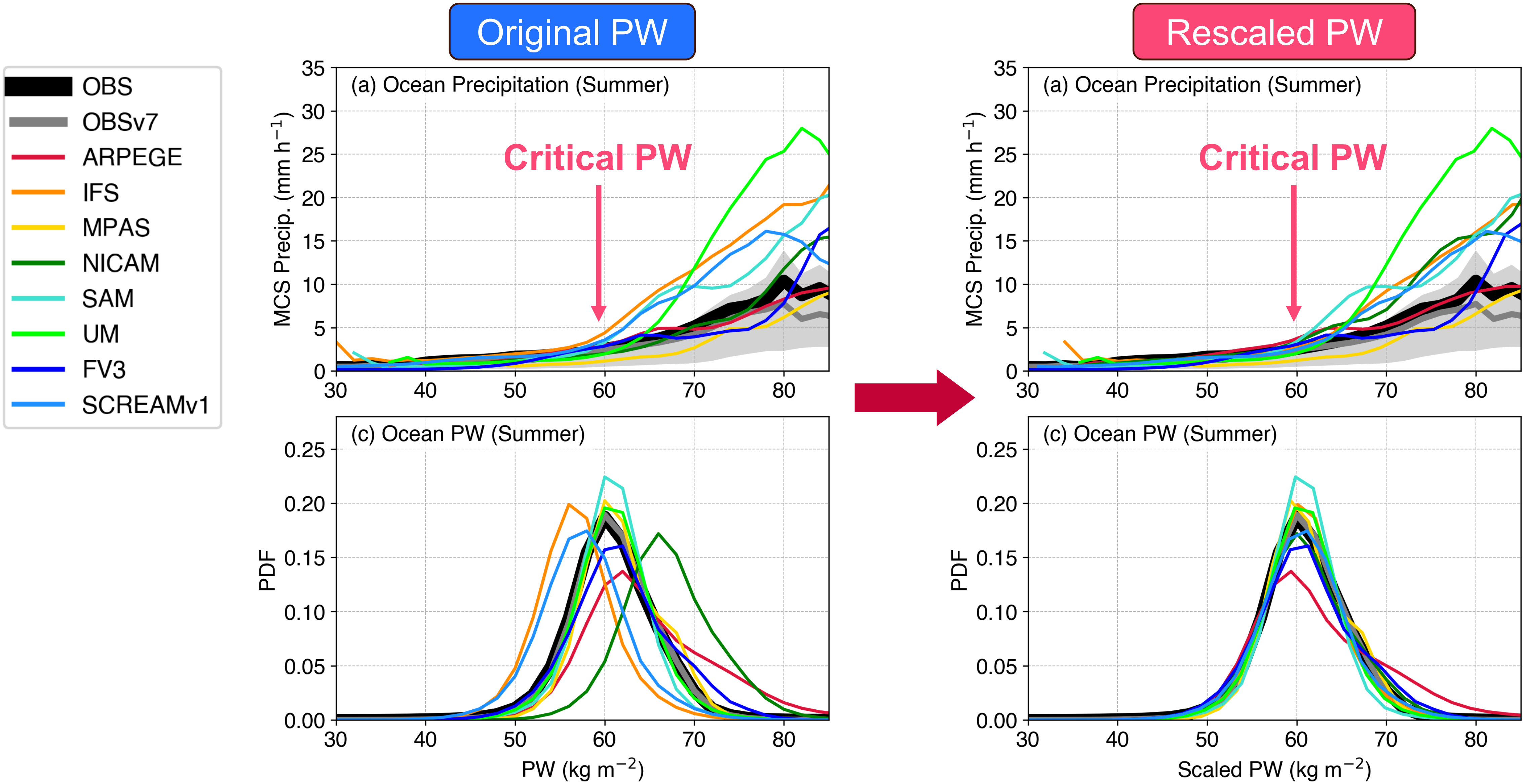
MCS precipitation vs. PWV

- **Summer:** most simulated MCS precipitation have slightly lower sensitivity to PWV than ERA5
  - IFS, UM, SAM have lower tropics-mean PWV than ERA5
- **Winter:** most models have stronger MCS precipitation at high PWV values (> 60 kg m^{-2}) than OBS
- Results are **robust** across all trackers

*Collocated Tropical PWV & MCS precipitation regridded to 0.25°



Models overestimate sensitivity of MCS precipitation intensity to moisture



- Most models show **higher** MCS precipitation intensity sensitivity to PW than ERA5
- After rescaling PW, some biases at high PW remain, but precipitation pick-up near critical PW compares better

Pacific Northwest
NATIONAL LABORATORY

Funding: U.S. DOE RGMA Program

PyFLEXTRKR Capabilities

Zhe Feng
Many contributions from coauthors

U.S. DEPARTMENT OF ENERGY
BATTELLE
PNNL is operated by Battelle for the U.S. Department of Energy

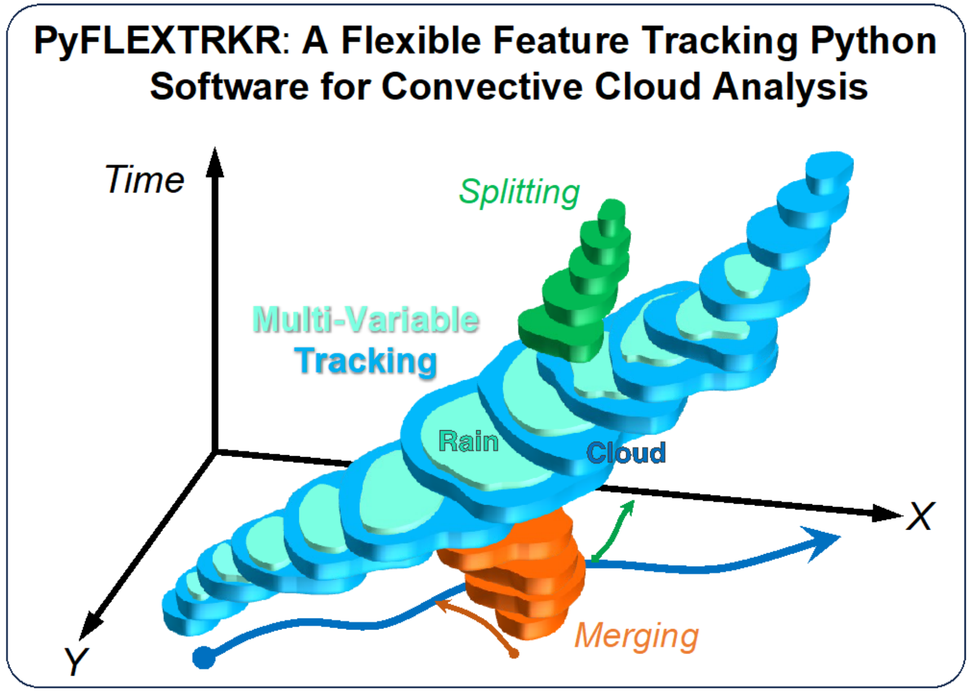
WACCEM
WATER CYCLE AND CLIMATE EXTREMES MODELING

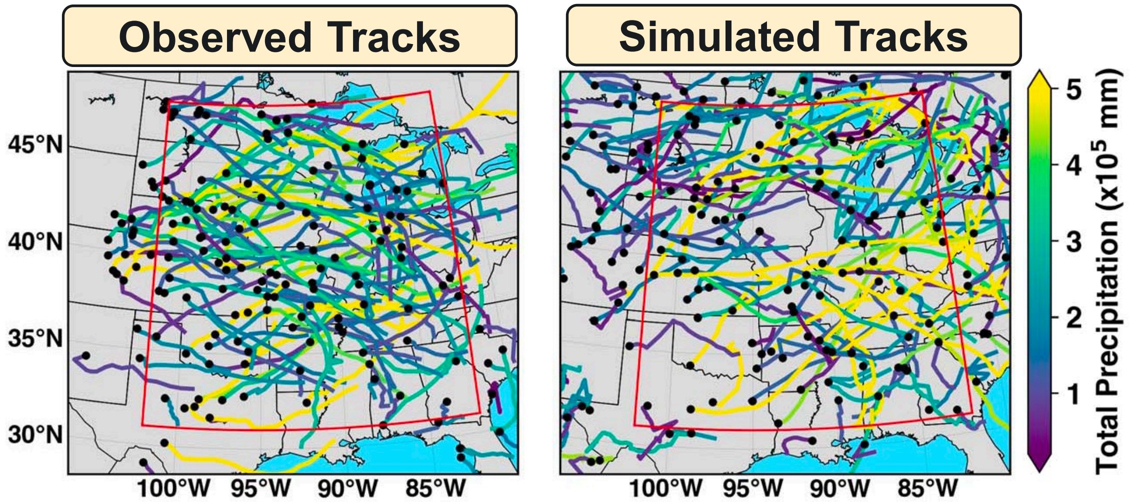
PyFLEXTRKR Overview

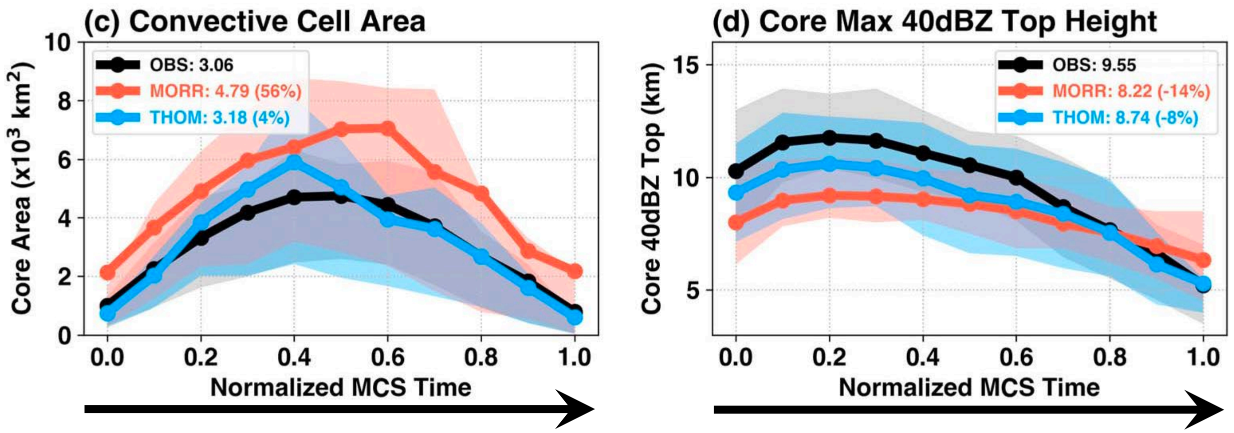
- PyFLEXTRKR is an open-source Python framework to **track 2D atmospheric objects**
- Specialized capability to track convective systems in **high-resolution datasets**
  - Works with multiple variables
  - Multi-object identification algorithms
  - Treats merging/splitting
  - Optimized for large datasets with scalable parallelization
  - Visualization, statistical analysis notebooks
- It facilitates **advanced model evaluations** by extracting most relevant storm statistics

Available on GitHub

Feng et al. (2023), GMD



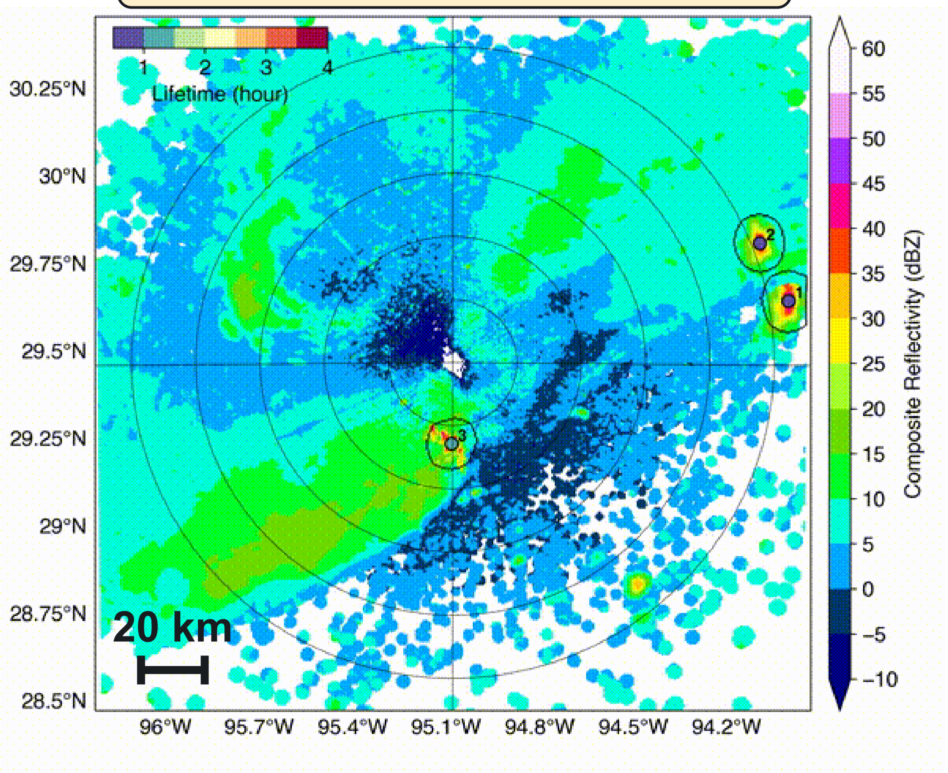




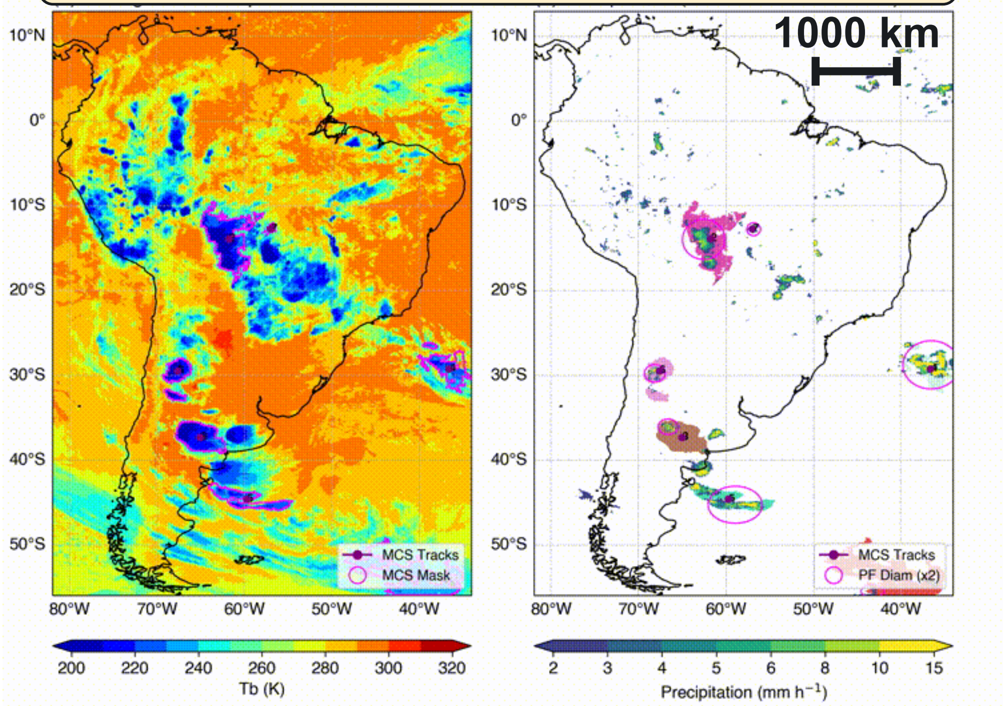
Current Capabilities

- Tracking **convective cells** using radar reflectivity data [Feng et al. (2022) *MWR*]
- Tracking **MCSs** using satellite (T_b) data, or model outgoing longwave radiation (OLR) data, with optional collocated precipitation or 3D radar reflectivity data to identify robust MCSs [Feng et al. (2021) *JGR*]
- **General 2D feature tracking** using simple methods to define objects (easy to add new custom functions)
  - Threshold & connectivity
  - Local maxima & watershed

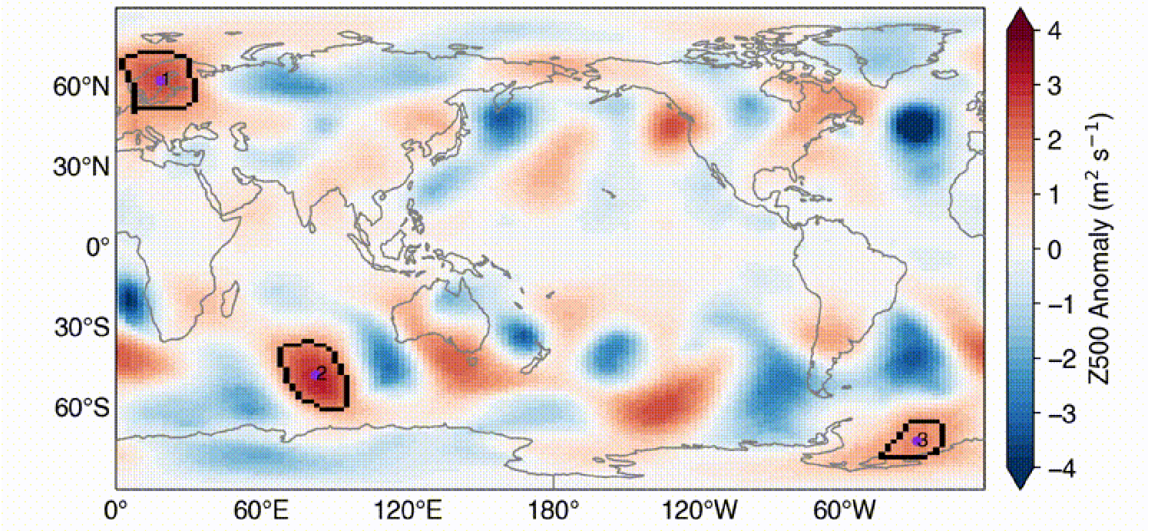
Convective Cell Tracking



MCS Tracking

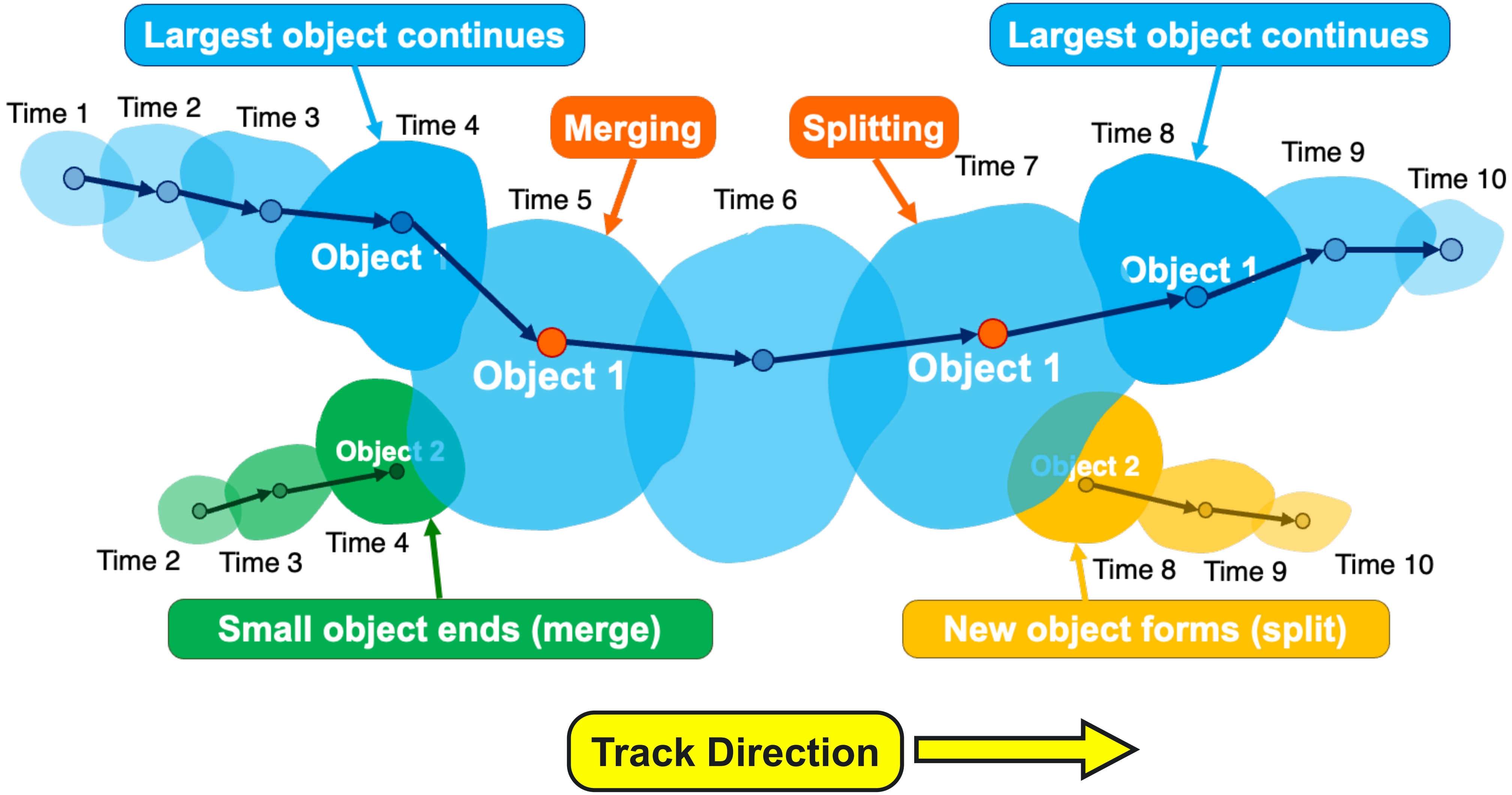


General Feature Tracking



Basic Tracking Methodology

- Objects with **area overlap** exceeding a **user-defined fraction** between two times are considered the same feature and tracked
- Treat **merging** and **splitting** explicitly

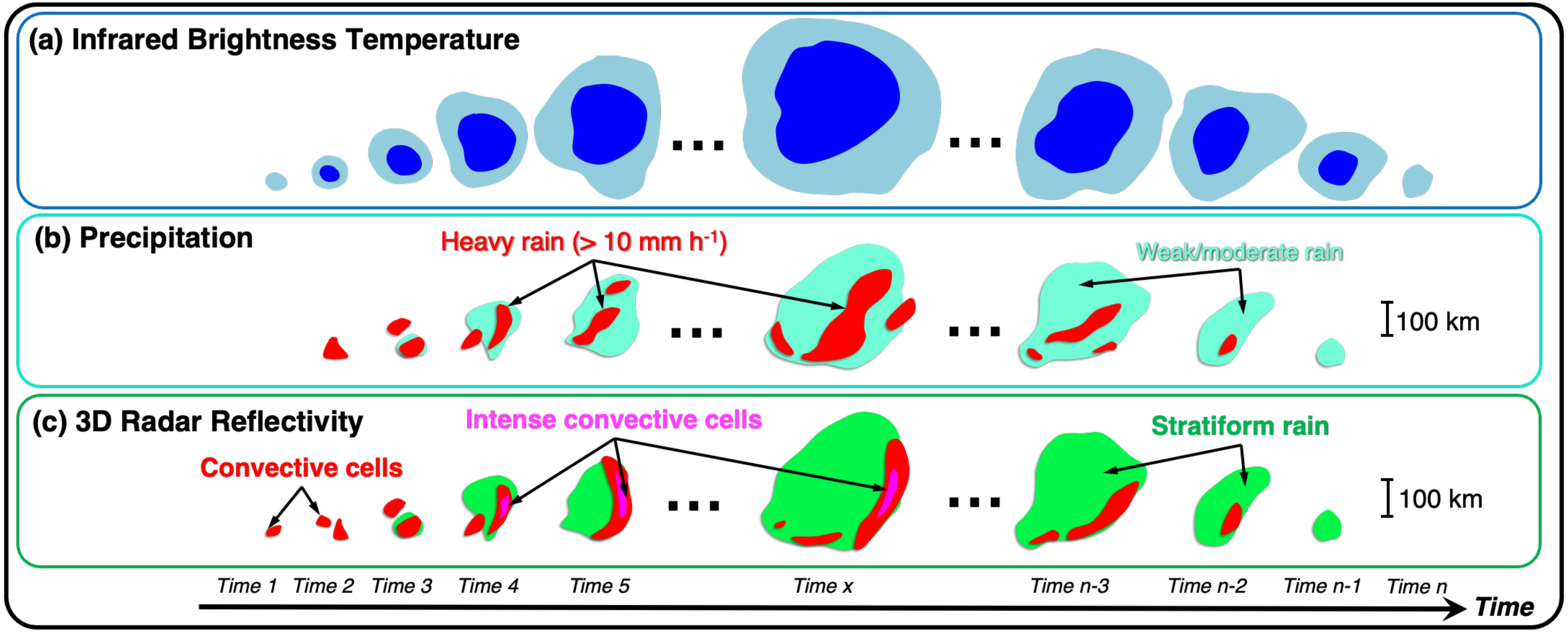


Multi-Variable MCS Tracking Algorithms

Required

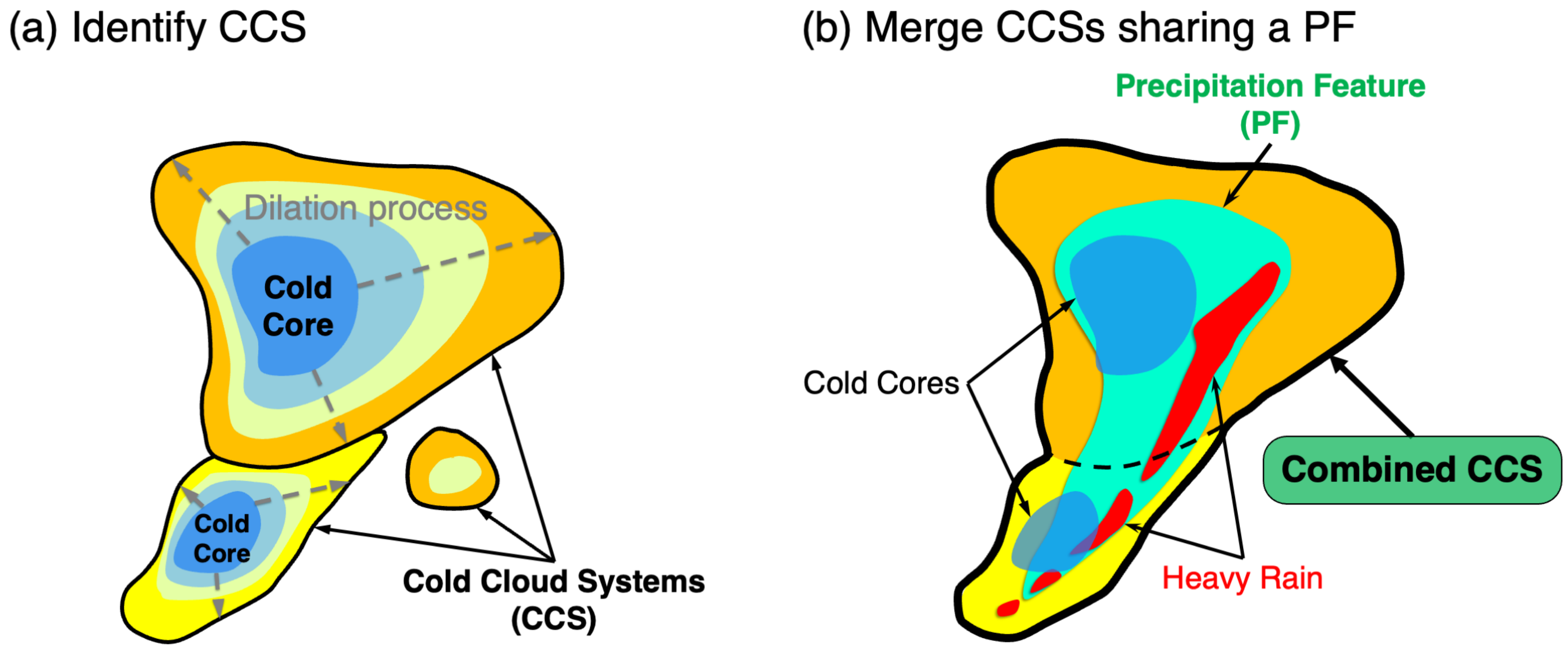
Optional

Optional



- IR T_b is required, surface precipitation, 3D radar reflectivity are optional but adds significant values
- Using **both** precipitation and 3D radar reflectivity is also supported (applicable to European radar network?)
- **SL3D** convective/stratiform/anvil classification algorithm (Starzec et al. 2017 MWR)

Cold Cloud System Identification



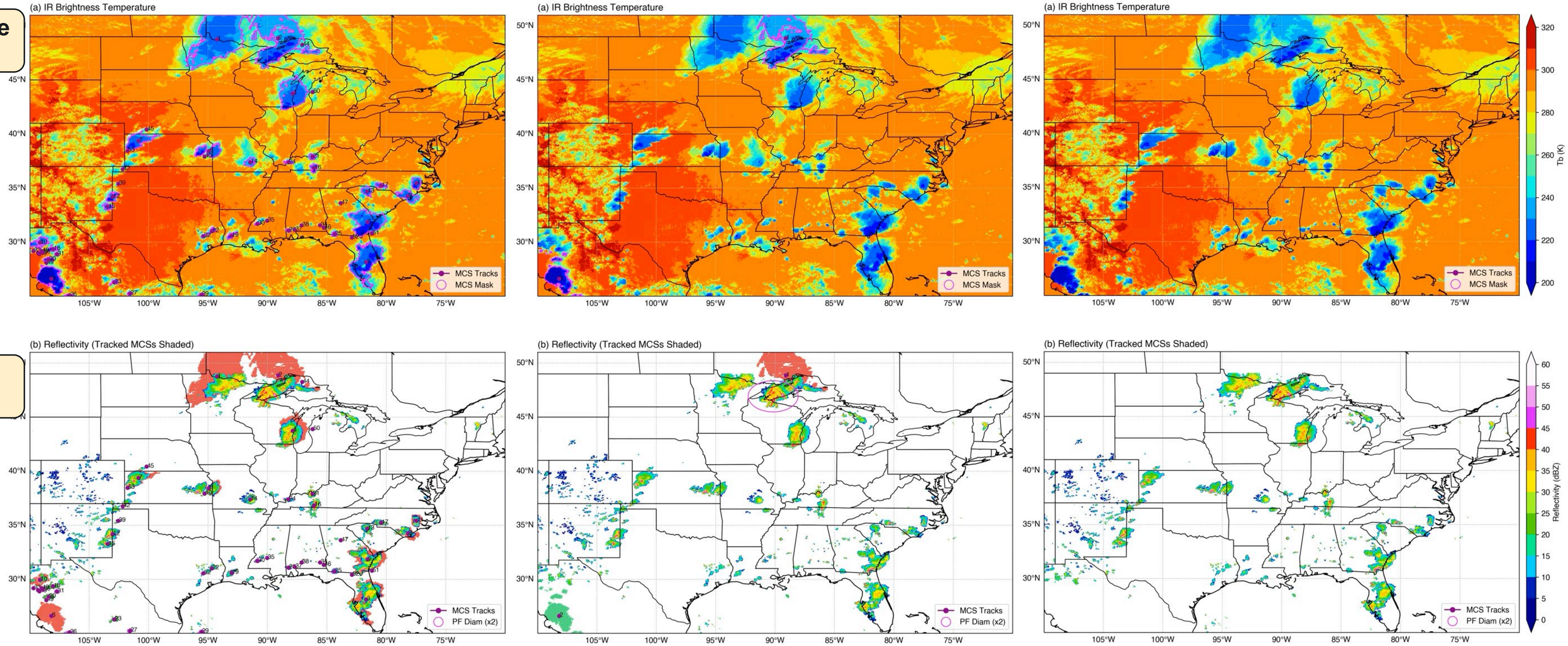
- Cold Cloud System (CCS) identification algorithm based in PyFLEXTRKR uses **detect and spread** approach with two T_b thresholds (user-defined)
  - **Cold core:** contiguous area (T_b < T_b-cold), optional smoothing can be applied to T_b
  - **Grow cold cores outwards** to reach T_b-warm thresholds
- Optional function to **merge CCSs** that **share the same Precipitation Feature (PF)**
  - PF can be defined by either precipitation or radar reflectivity (e.g., contiguous area with smoothed rain rate > 3 mm/h)

Multi-Variable MCS Identification

All Deep Convection Tracks | MCS Tracks (T_b-only) | MCS Tracks (T_b+Radar)

Satellite T_b

Radar Z_e



- Tracks **all deep convective clouds** using satellite T_b (model OLR)
- Retain **MCS candidates** based on **cloud shield size** and **duration**
- Identify **robust MCS** based on **radar signatures** of **convection** and **precipitation**