From EarthCARE to PMM: Expanding the Frontier of Doppler Radar Observations from Clouds to Precipitation

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  - mission overview
  - example of observation
- PMM
  - mission overview
  - mission purpose, scientific objectives
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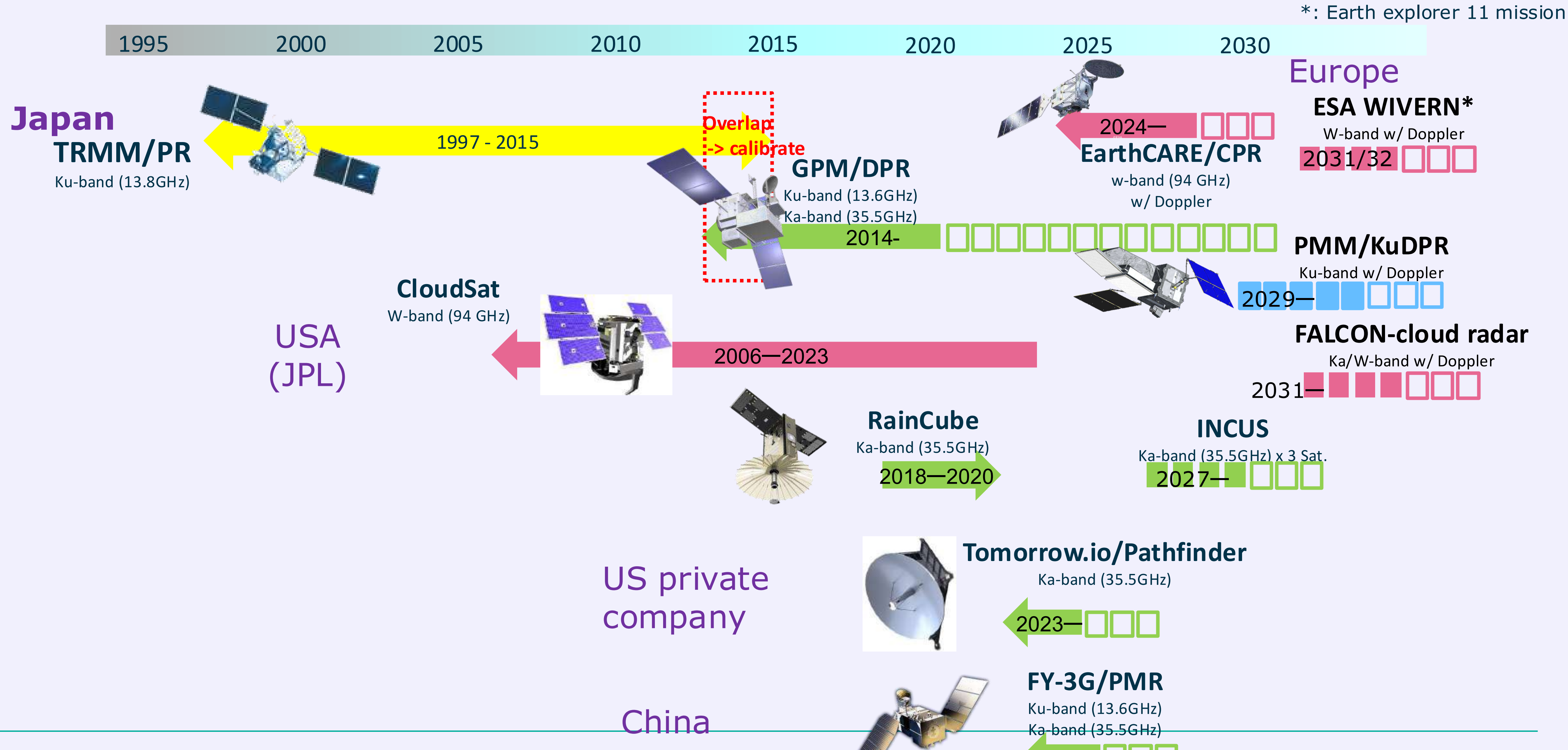
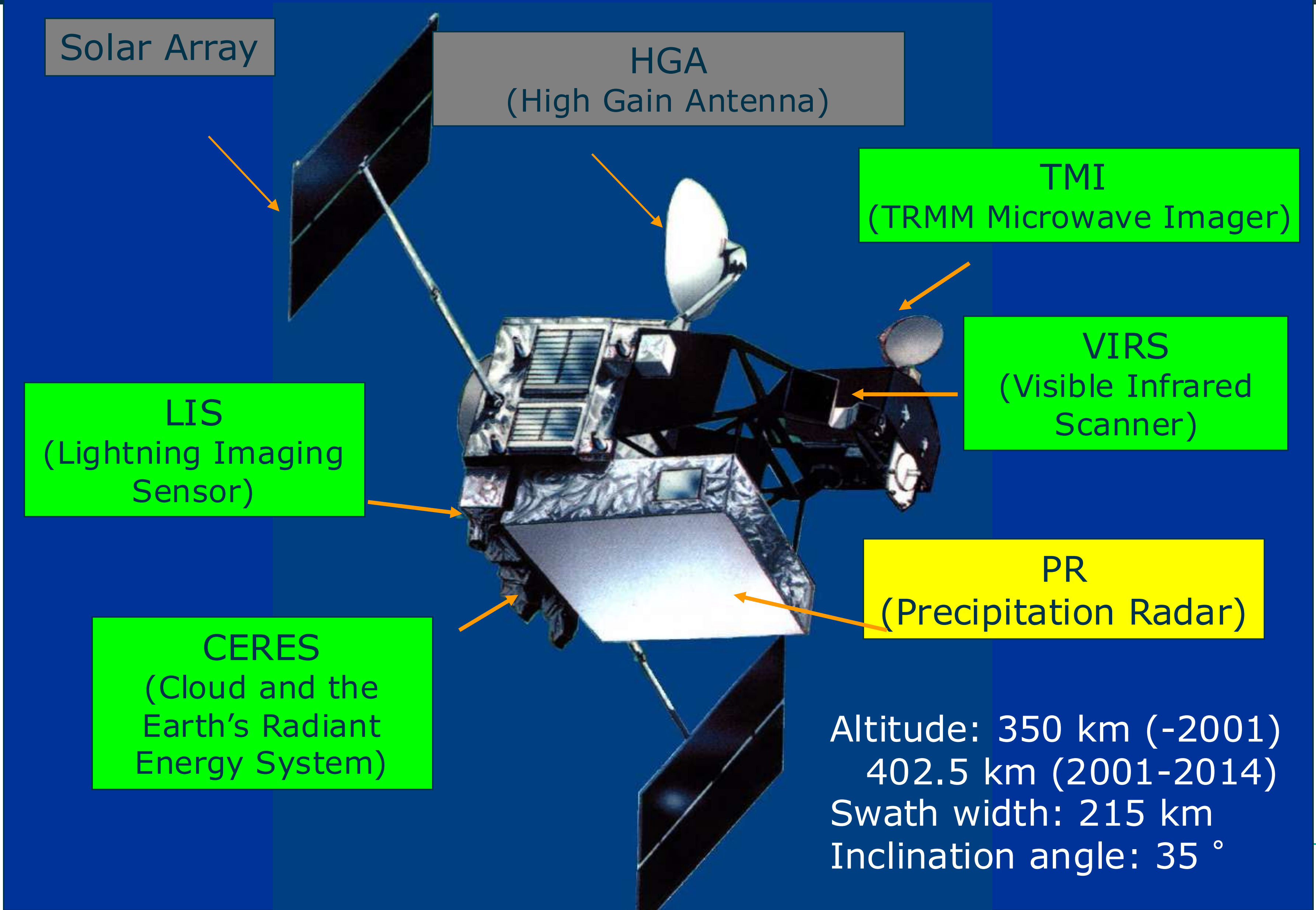
- Summary

Spaceborne Cloud/Precipitation Radar Missions



TRRM & GPM

Tropical Rainfall Measuring Mission (TRMM)



Altitude: 350 km (-2001)
402.5 km (2001-2014)
Swath width: 215 km
Inclination angle: 35 °

Launch: Nov. 1997

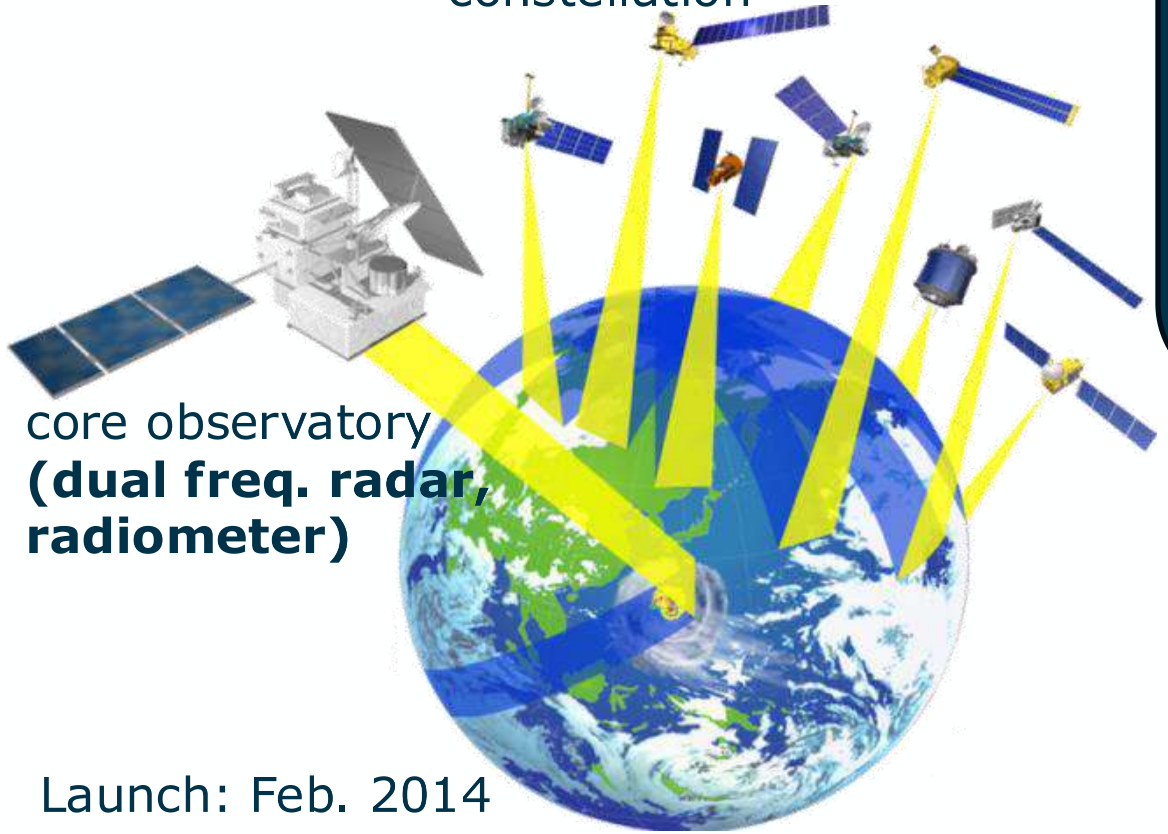
Science target:
Quantitative measurement of tropical rainfall, which drives the global atmospheric circulation.

Achievements:
- Quantitative estimation of **global surface rainfall**
- **3D rainfall** in global basis
- Characterization of **extreme precipitation**
- Estimation of **latent heating profiles**
- Global pattern of **diurnal cycle**
- Global reference for meteorological radars

Global Precipitation Measurement (GPM)

Expanded TRMM concept to combined radar and multi-satellite radiometer observations for frequent global precipitation estimation and expanded the partnership of JAXA, NASA with International partners

radiometer satellite constellation



core observatory **(dual freq. radar, radiometer)**

Launch: Feb. 2014

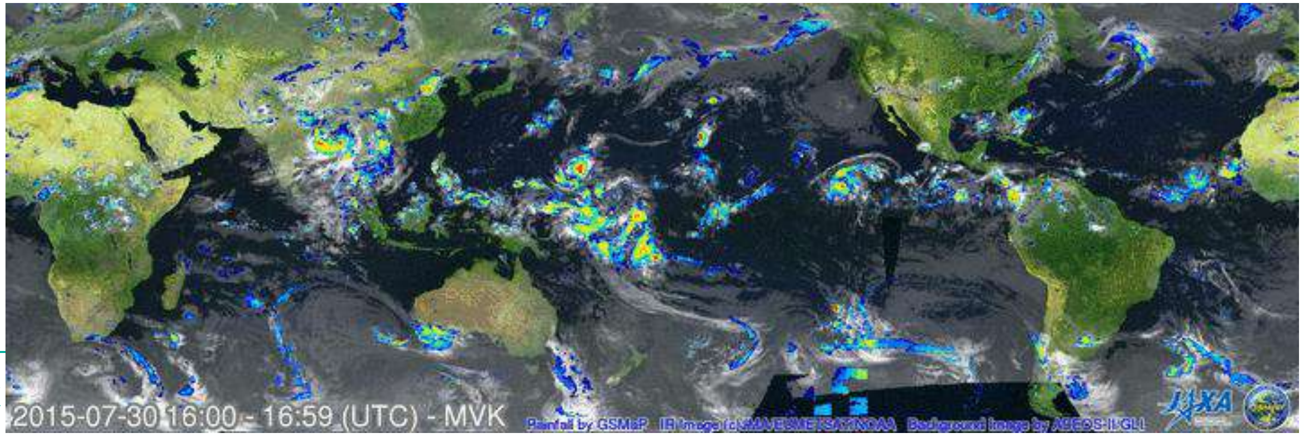
Scientific Achievements

- Better estimation of global surface precipitation by DPR.
- Characterization of precipitation (conv/strat., solid precip.)
- Global distribution of extreme precipitation events.

Societal Applications

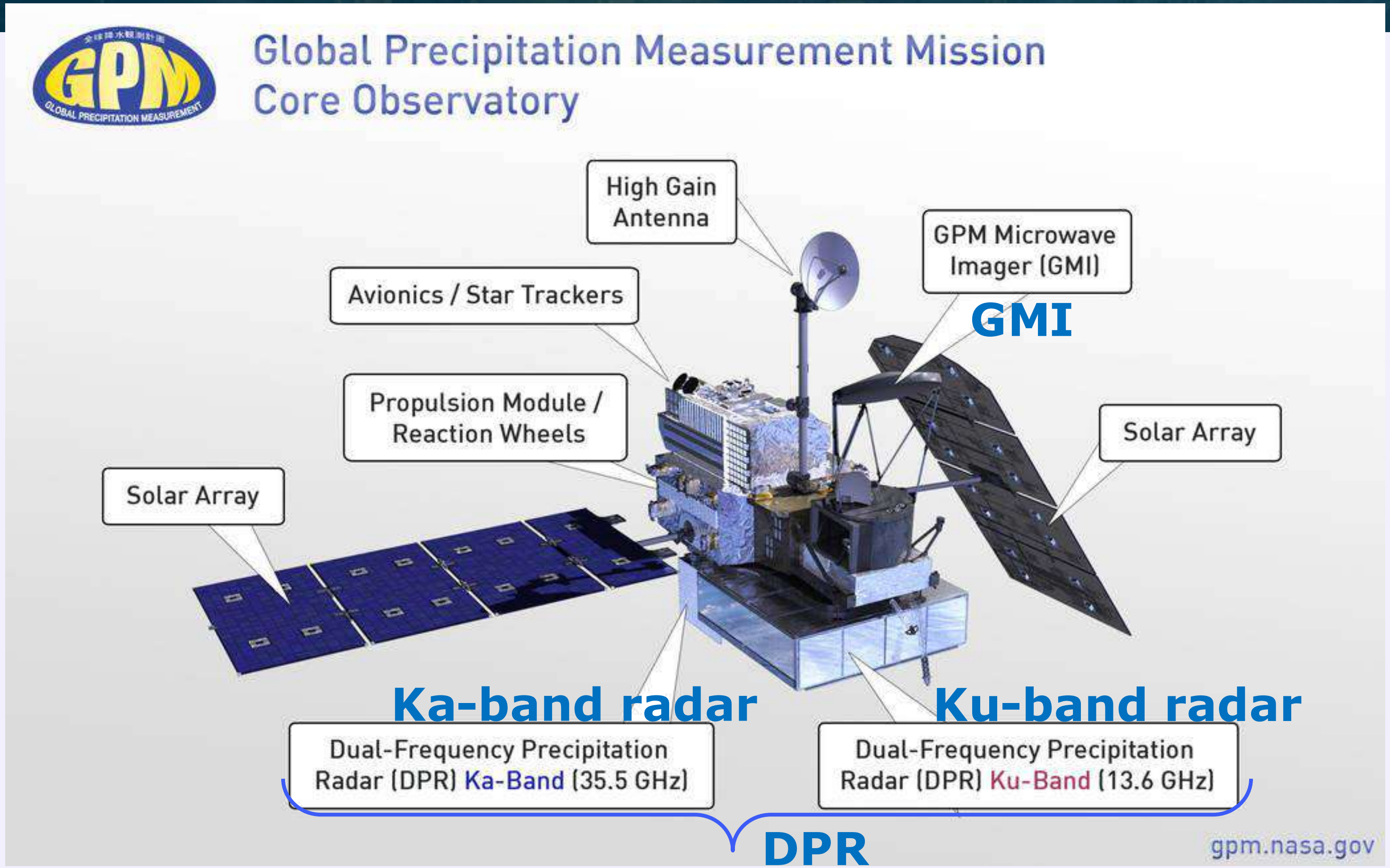
- Application for numerical weather forecasting
- Development of global precipitation map (e.g. GSMaP) and apply it for flood forecasting.

GSMaP: Hourly global precipitation map (©JAXA)



GPM core observatory

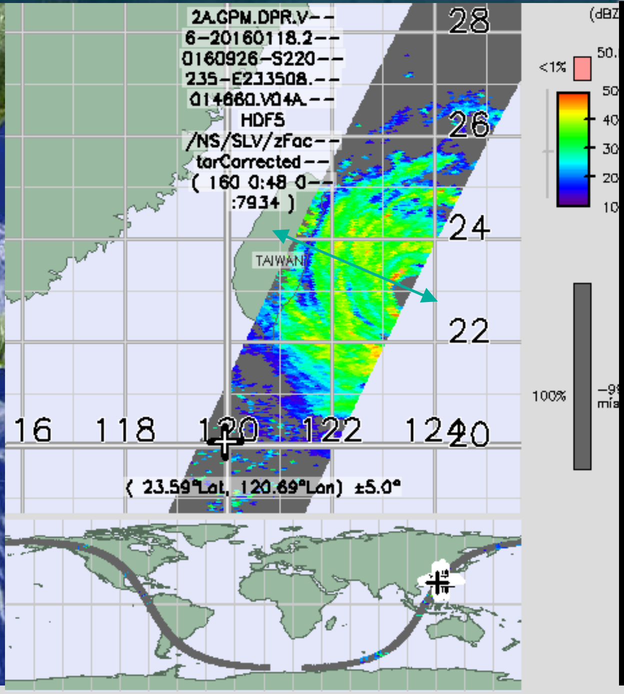
Launched Feb. 24, 2014

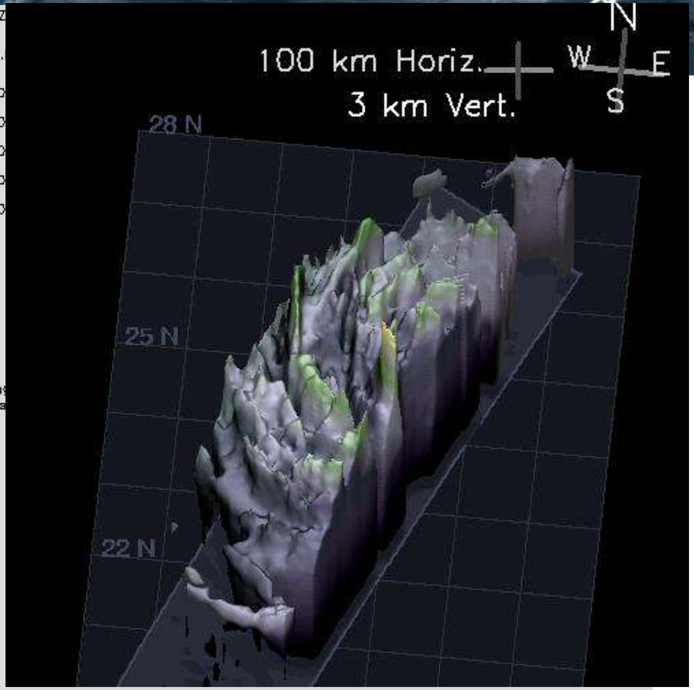


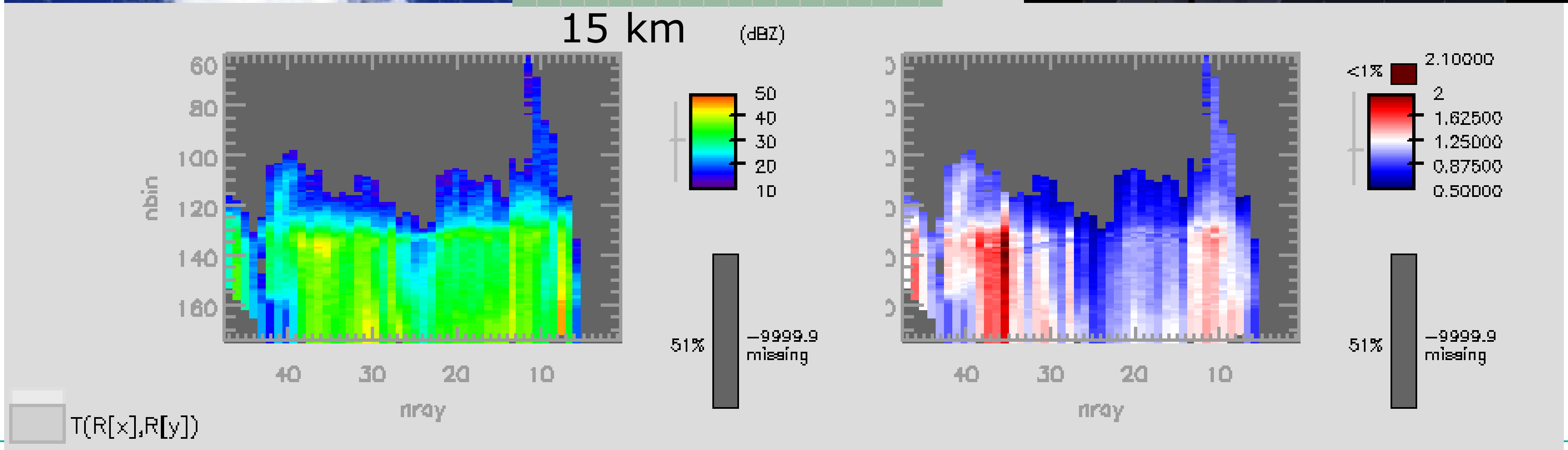
- Sensors: Dual frequency precipitation radar (**DPR**) and GPM Microwave Imager (**GMI**)
- Satellite altitude: 407 km (－Nov. 2023) , 442 km (Nov. 2023–)
- Swath width of DPR: 245 km
- Inclination angle: 65 degrees, covering tropics to mid-latitudes

JAXA 3D Rainfall Watch (https://www.eorc.jaxa.jp/GPM/3DRAIN/index_j.html)

GPM/DPR observation (Sep. 26, 2016, Typhoon)



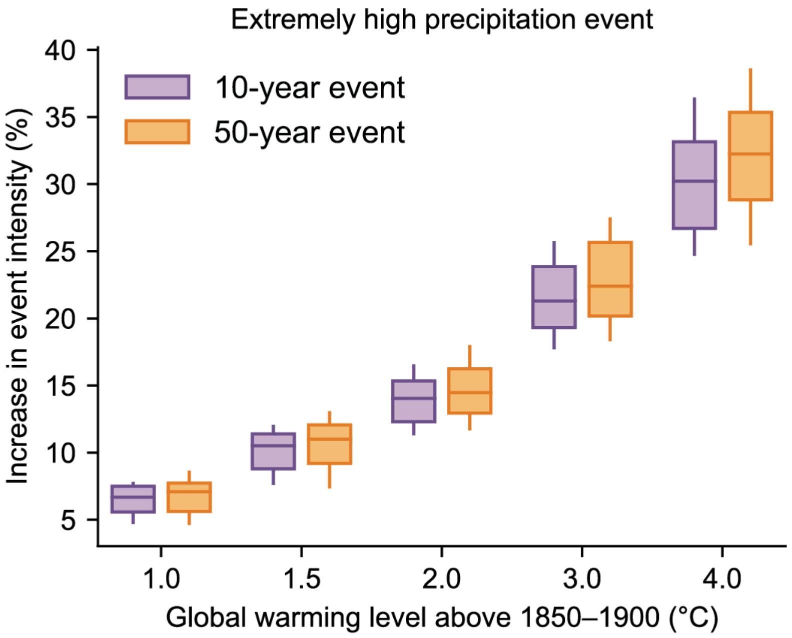




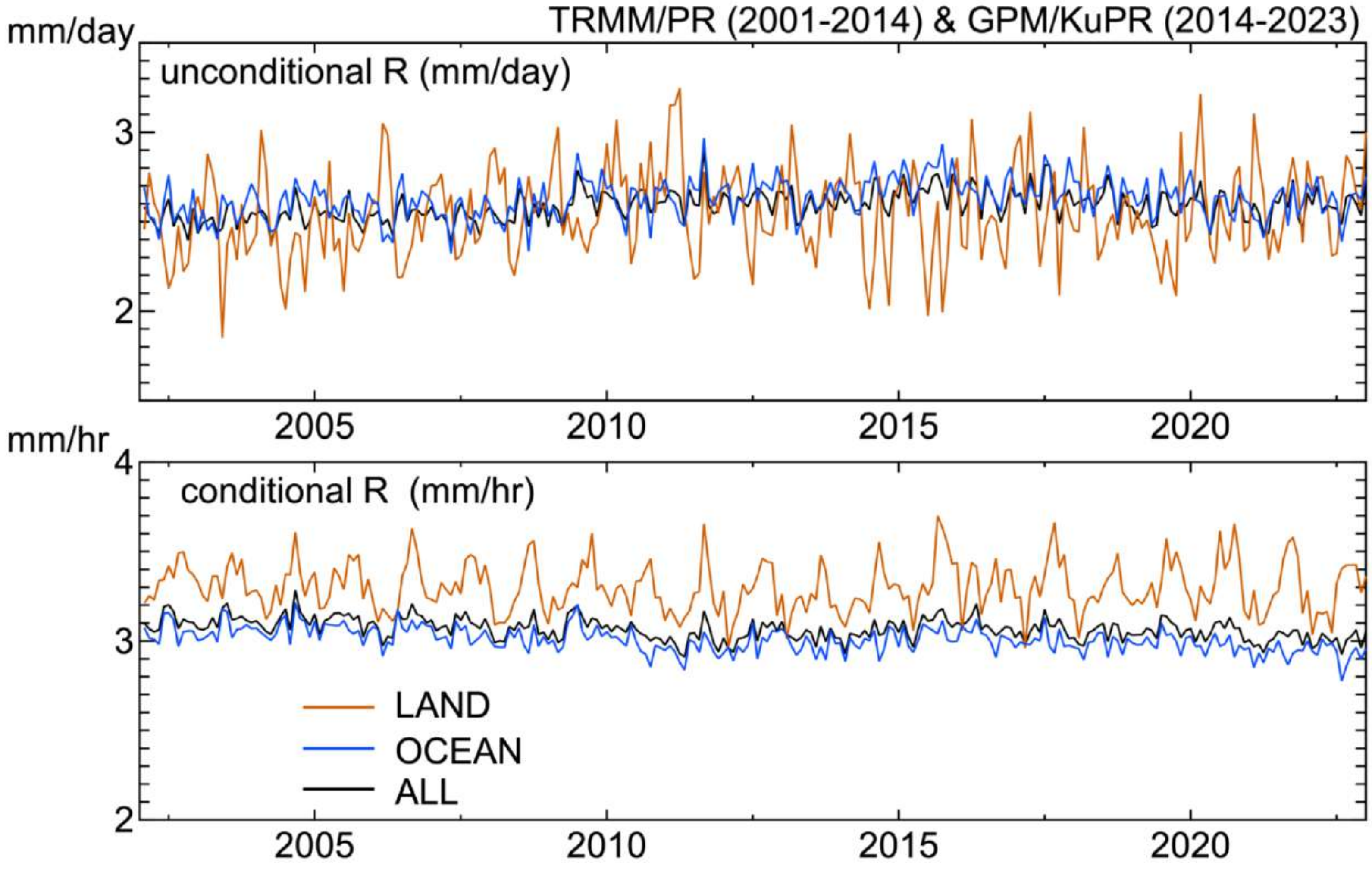
Radar reflectivity factor (dBZ) Mass weighted mean diameter (mm)

precipitation record by TRMM and GPM

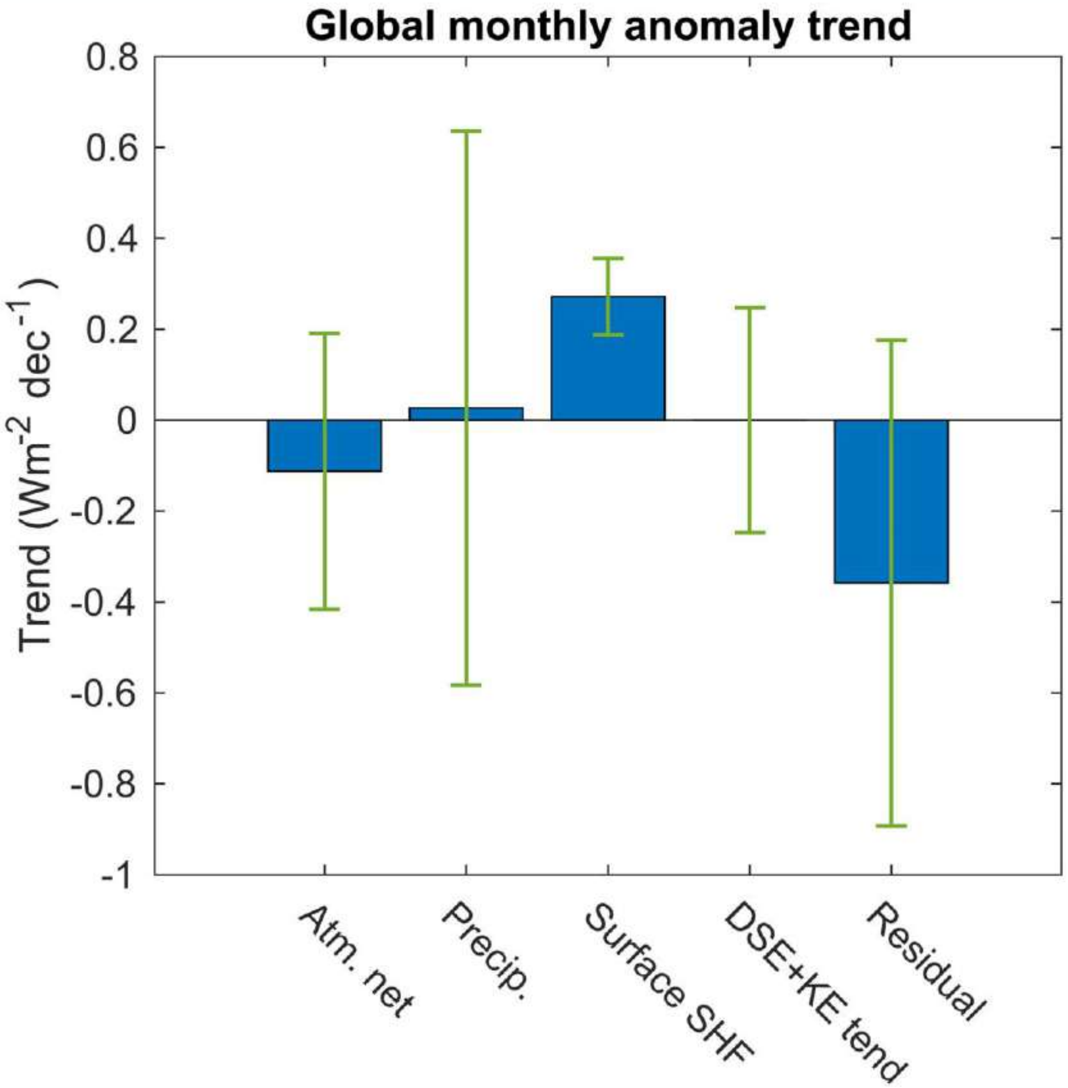
No significant increasing/decreasing trend, both for unconditional and conditional rainfall. This may be inconsistent with the IPCC AR6 report.



IPCC AR6



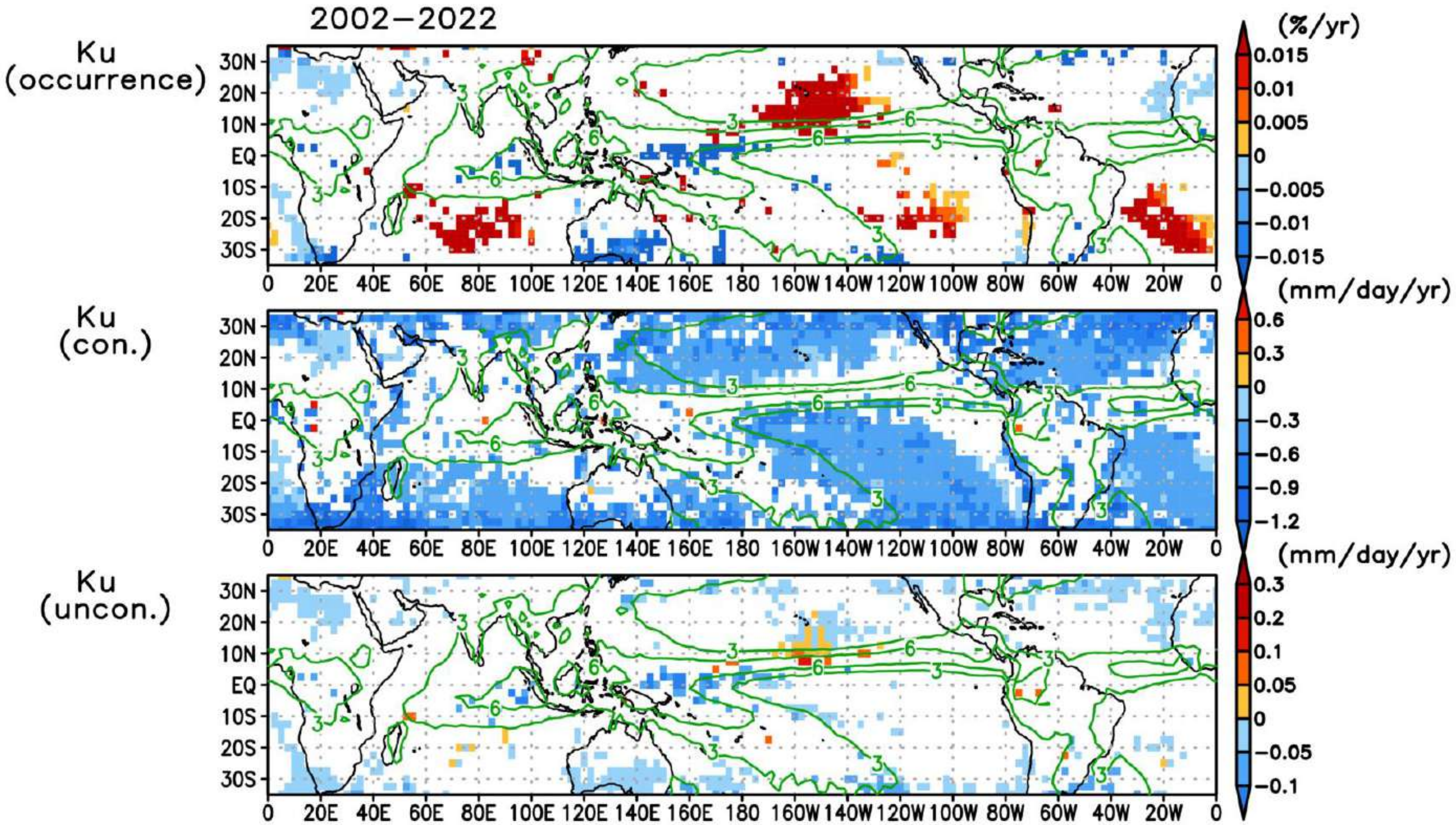
possible answer



Kato et al. 2025

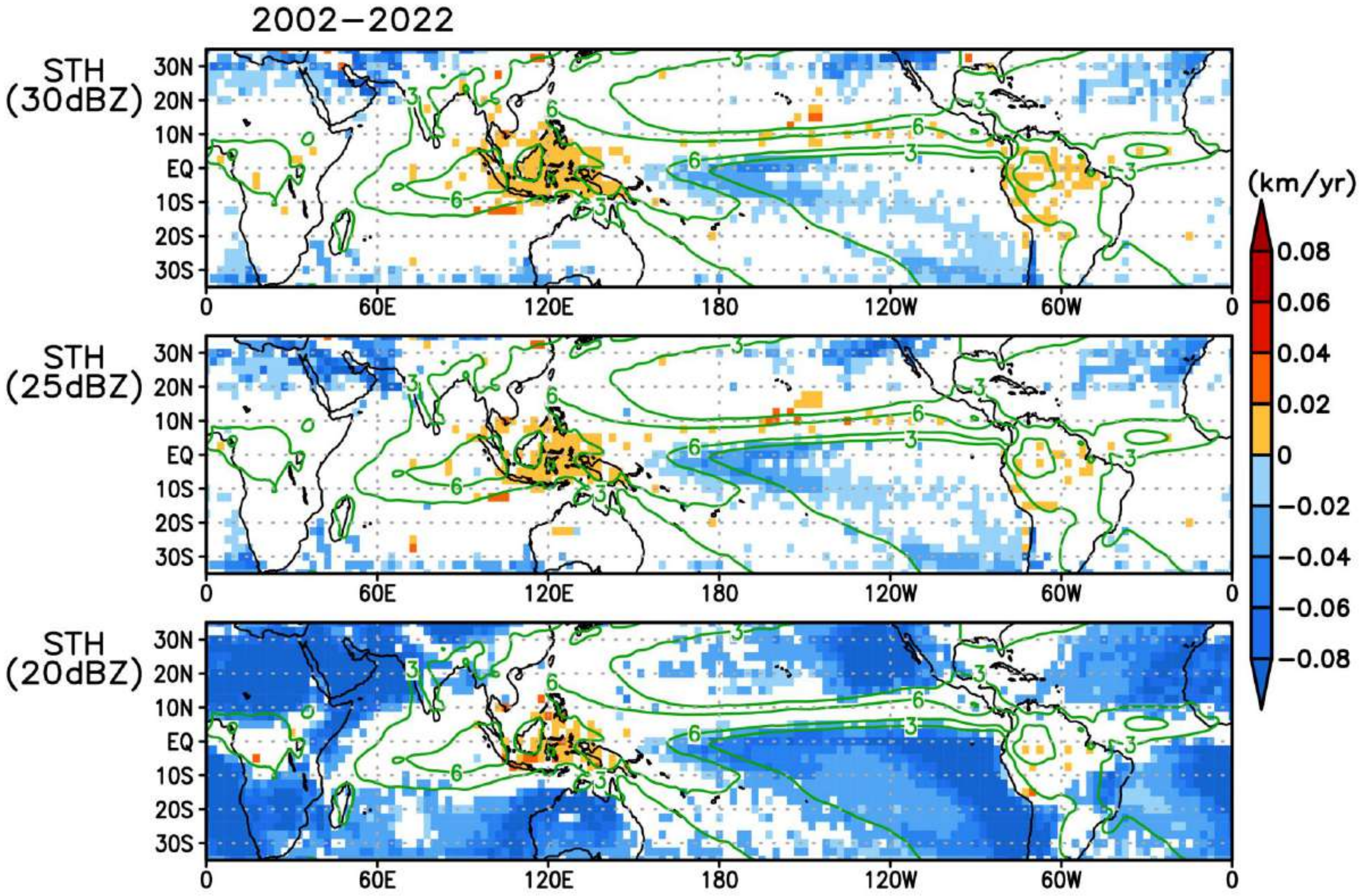
- Kato et al. (2025) analyzed radiative flux trends using CERES and GPCP data and showed that the **near-neutral trend in precipitation** can be explained by a balance between **increased shortwave heating associated with rising water vapor and longwave cooling**.

precipitation trend from precipitation radar
(displays only significant trend area)



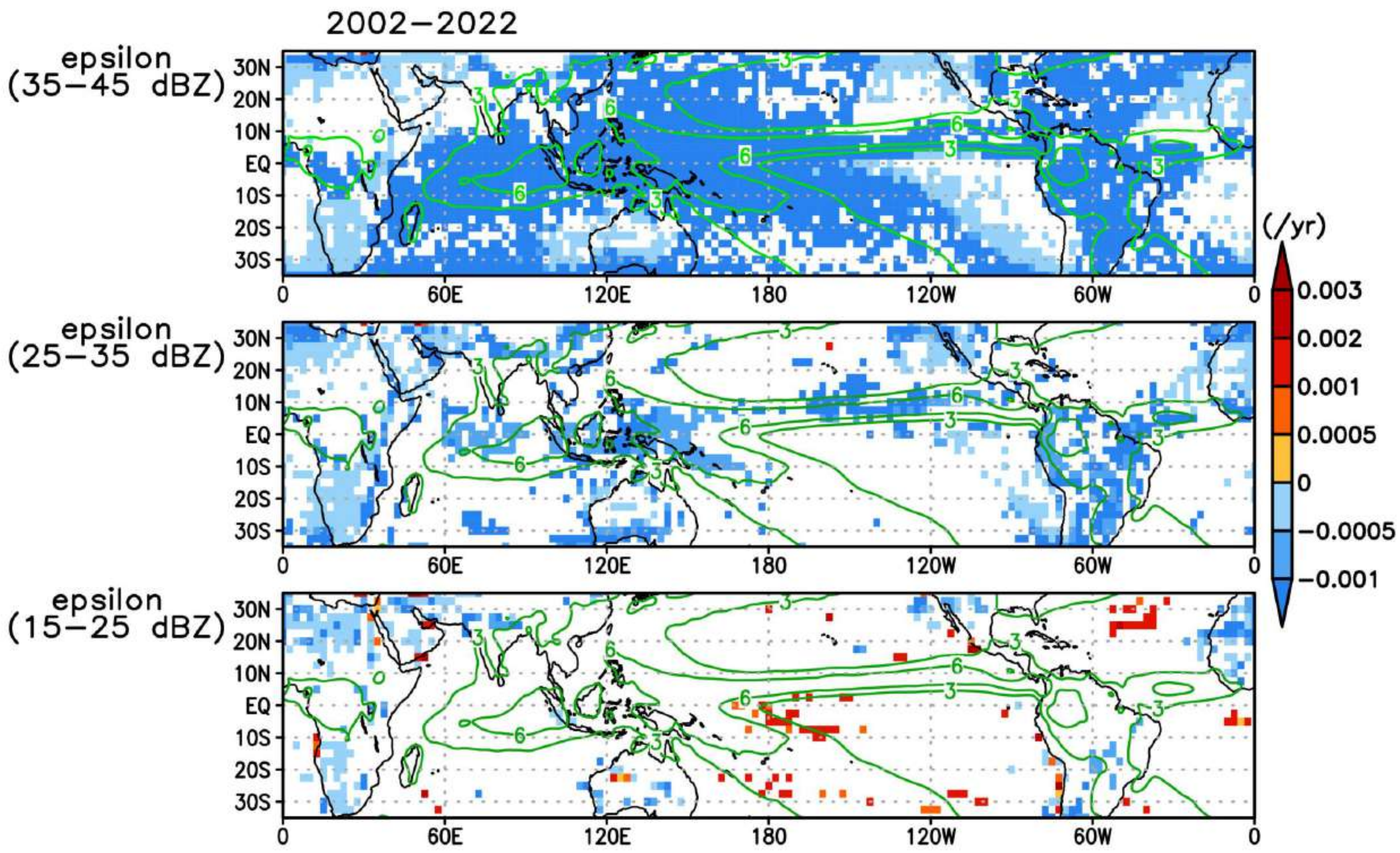
- significance level of 5 % by Mann-Kendall test
- **conditional rain rate** decreases except for tropical region (e.g. ITCZ)
- **unconditional rain rate** shows almost neutral trend except for around **ITCZ**

Storm top height trend
(displays only significant trend area)



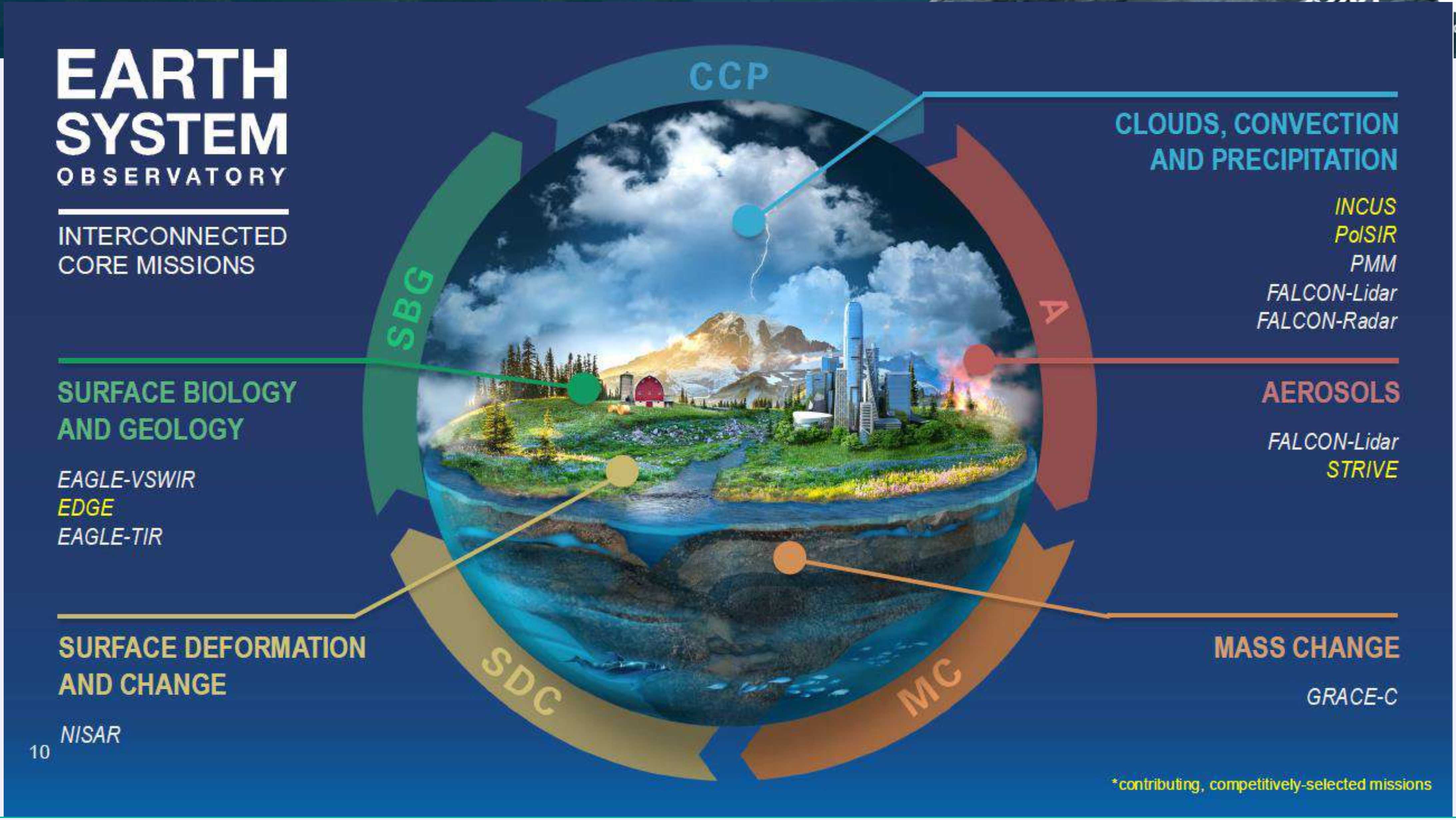
- storm top height decreases most of the region
- increasing trend over maritime continent
- no significant change over ITCZ, SPCZ, Indian Ocean, etc.
- storm top height with higher threshold shows similar pattern with precipitation trend
  - increase in precipitation corresponds to the increase in storm top height

Drop size distribution trend
(displays only significant trend area)



- epsilon: adjustment parameter for k-Z relationship
  - **smaller epsilon: larger drop**
  - **larger epsilon: smaller drop**
- 25-35 dBZ & 35-45 dBZ
  - epsilon decreases almost all region indicating the **increasing trend of drop size**.
- 15-25 dBZ
  - No clear trend for high precipitation region.

Precipitation Measuring Mission (PMM)



(from Dr. St. Germain’s (NASA) presentation)

Earth Science Flight Program

Fleet for the Atmosphere Linking Commercial Observations with NASA

FALCON

PMM (JAXA/GSFC)
Precipitation profiles

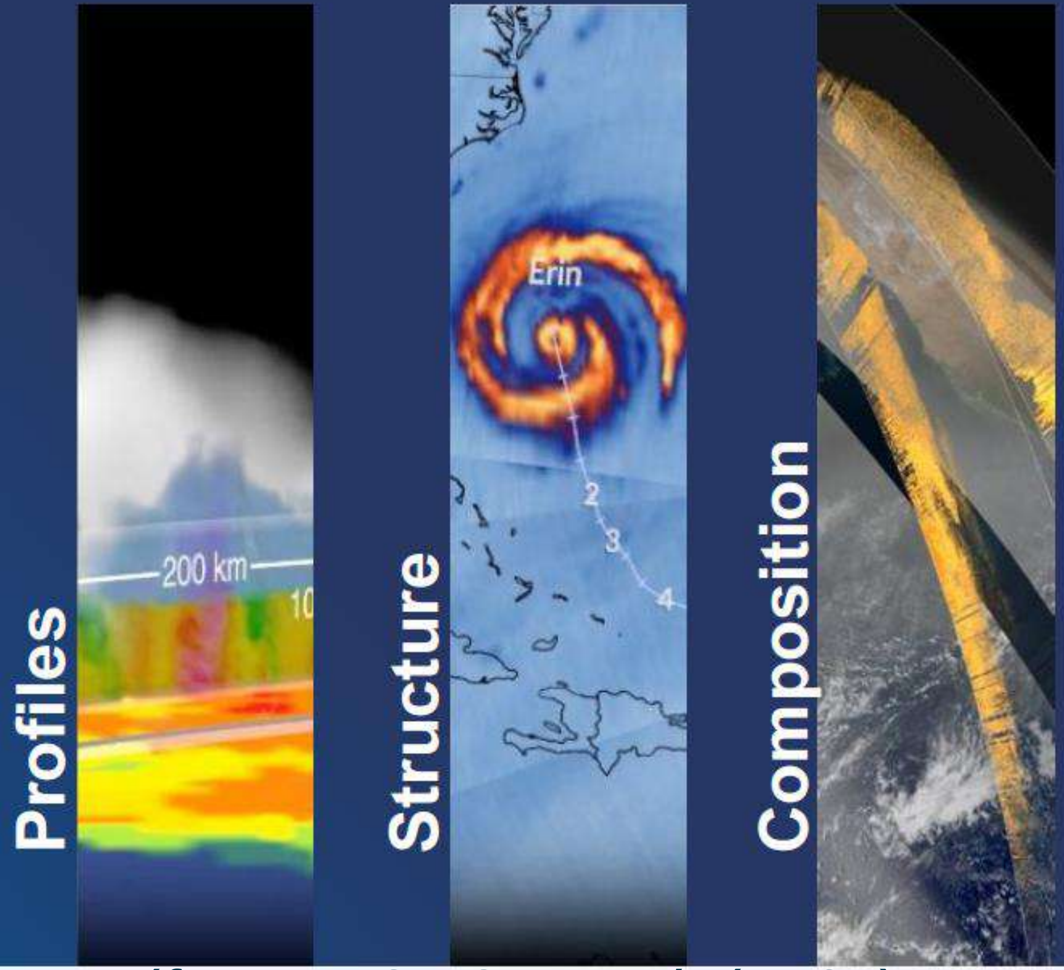
FALCON-Lidar (GSFC/LaRC)
Atmospheric structure and composition measurements

FALCON-Radar (JPL)
Cloud profiles to improve understanding of severe weather drivers.

FALCON-Radiometry (Commercial)
RFI Released this week for contribution options

Joining the FALCON fleet

- INCUS (CSU/JPL)
- PolSIR (Vanderbilt/GSFC)
- STRIVE (UW/GSFC)



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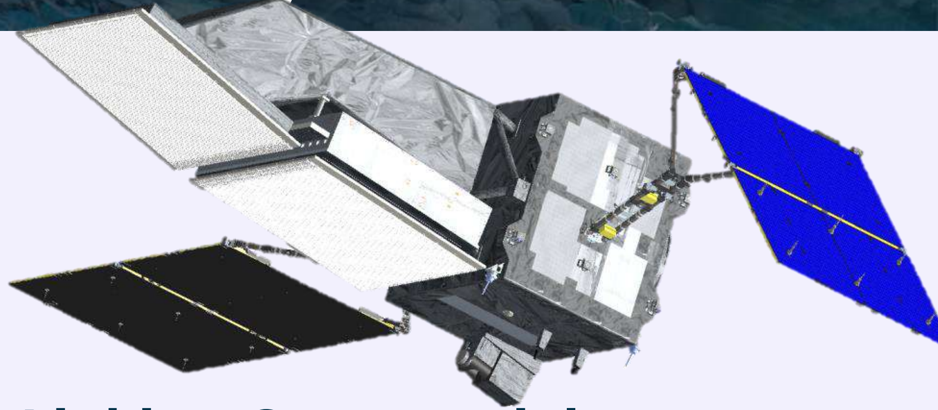
(from Dr. St. Germain’s (NASA) presentation)

PMM（Precipitation Measuring Mission）

- Evolution processes of precipitation system
- Cloud-precipitation interactions
- Improvement of global precipitation map



Joining to NASA’s FALCON (Fleet for the Atmosphere Linking Commercial Observations with NASA)

- **PMM satellite is under development by JAXA**

Launch: 2029-2030 (by NASA)

KuDPR: **Ku-band Doppler precipitation radar (JAXA)**

- **Doppler** radar: **nadir** direction (**DPCA**: displaced phase center antenna)
- **scanning** radar (similar to GPM/KuPR) for **long-term precipitation record**
- currently it is in critical design phase

C^2OMODO (CNES): 89 GHz, 183 GHz and 325 GHz radiometer (expected to be tandem flight with C^2OMODO satellite).

Scientific objectives of PMM

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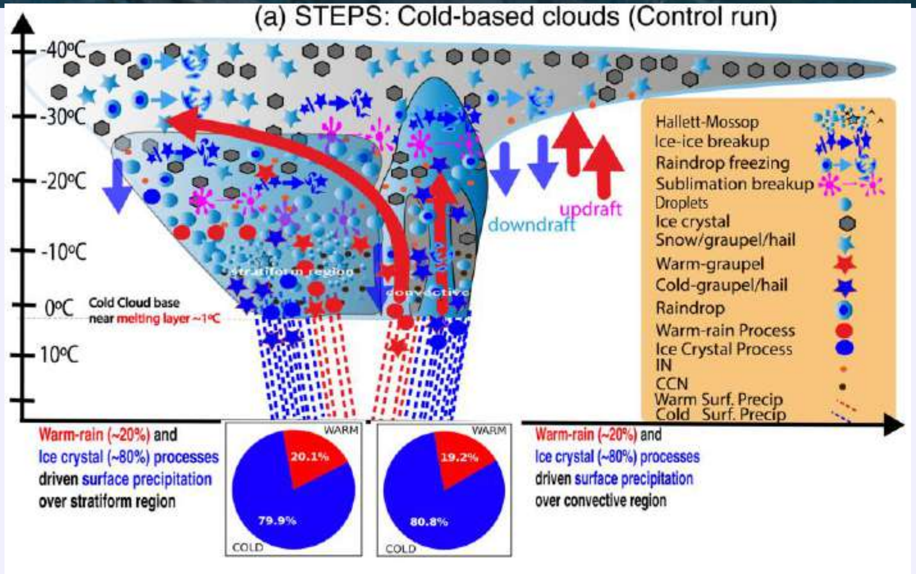
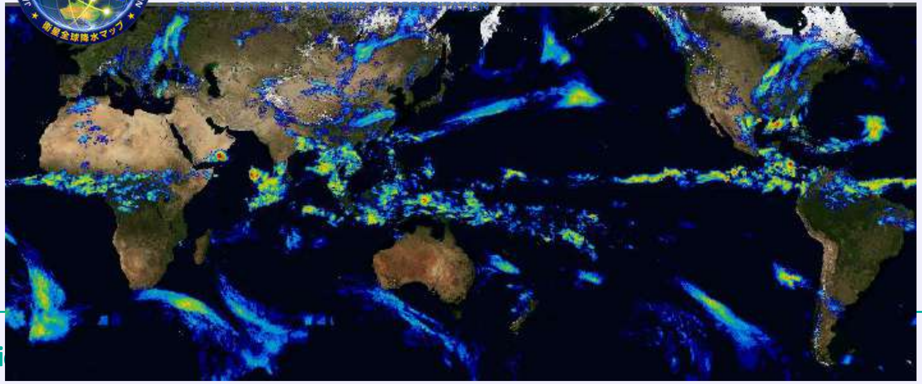
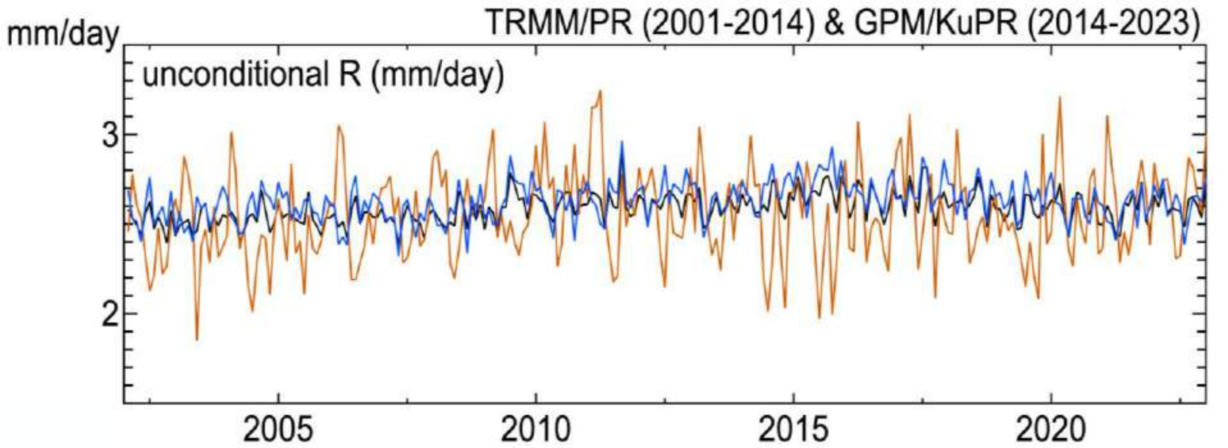
- **Convective Dynamics**
  - Updraft structure of deep convections and tropical cyclones
- **Cloud–Precipitation Processes**
  - Understand the global precipitation system incl. microphysical processes
  - Improvement of GSMaP
- **Climate Response of Precipitation**
  - long-term trend of precipitation



(Gupta et al., 2023)

GSMaP





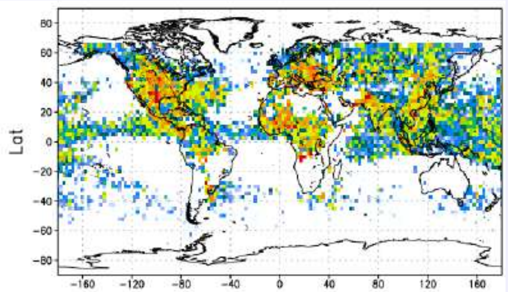
The transformation of satellite observation by Doppler velocity measurements

TRMM & GPM

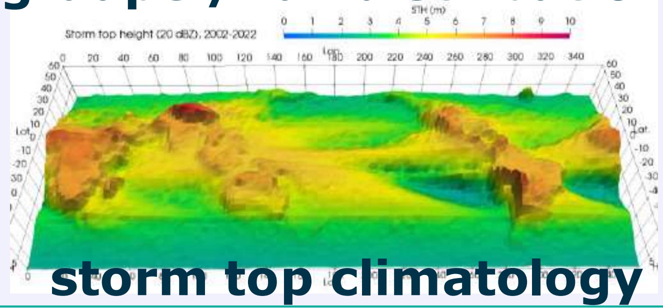
Deal the Earth as static system

Try to understand the characteristics of each parameters

- Precipitation characteristics
- Cloud physical quantities



graupel/hail distribution

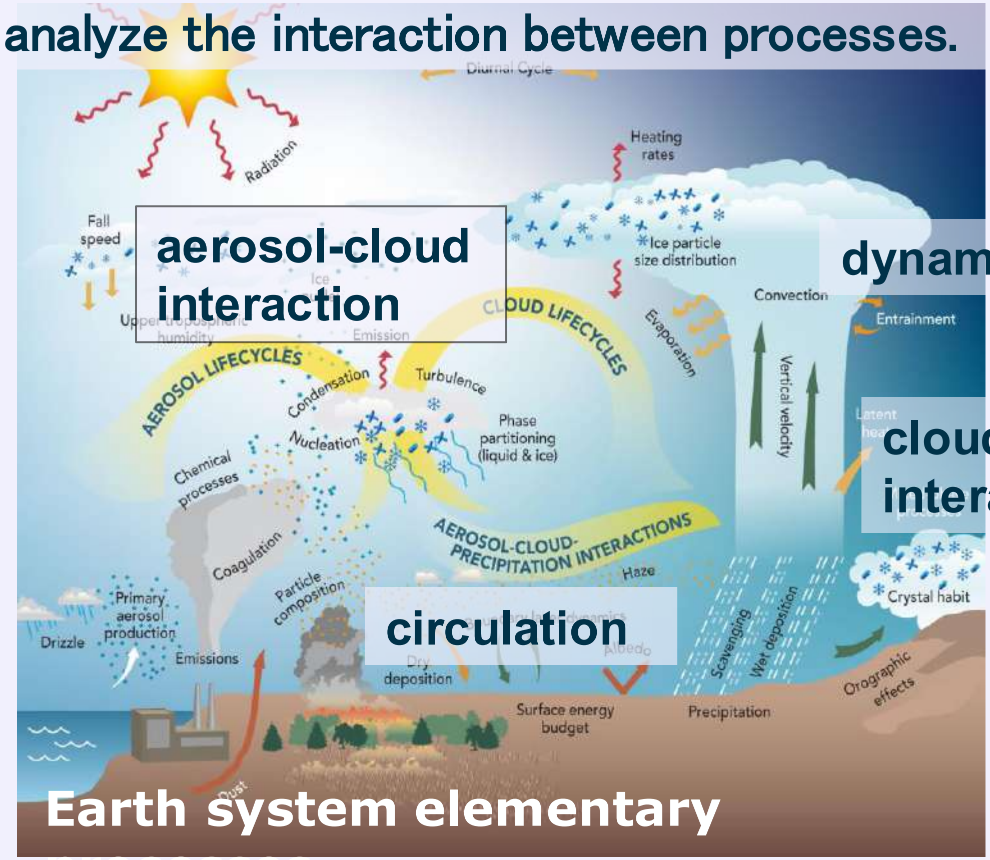


storm top climatology

EarthCARE & PMM

Deal the Earth as dynamic system

Kinematic information (Doppler velocity) allows to analyze the interaction between processes.



(NOAA)

PMM Ku-band Doppler radar (KuDPR)

The Ku-band Doppler Precipitation Radar (KuDPR) will be two-antenna system that adopts Displaced Phase Center Antenna (DPCA) approach (Durden et al. 2007, 2023, Tanelli et al. 2016, Nakamura and Furukawa 2023).

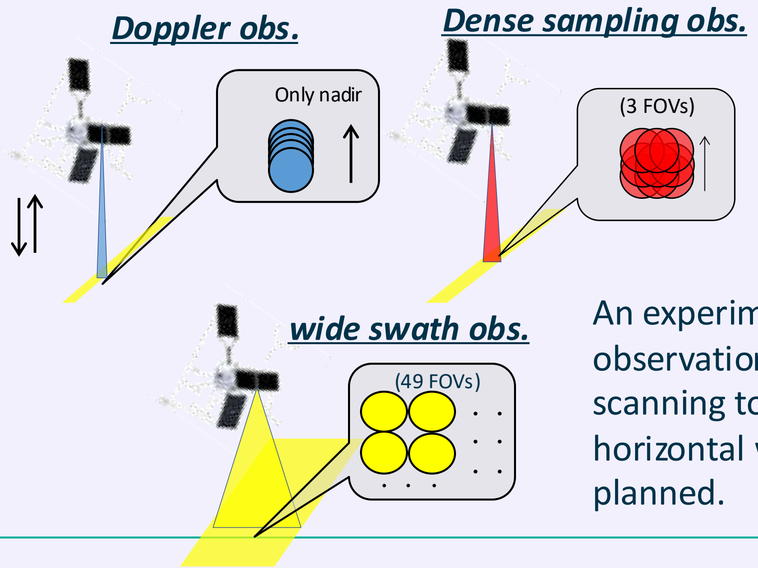
→ The DPCA approach can lead to **more accurate Doppler measurement.**

Major characteristics

Frequency	13.6 GHz
Observation modes	・**Doppler obs. (at-nadir)** ・**Dense sampling (near-nadir)** ・Wide swath obs. (similar to GPM)
footprint size	5 km
swath width	250 km (wide swath)

Ku-band Doppler Precipitation Radar (KuDPR)

(a design life of 5 years)

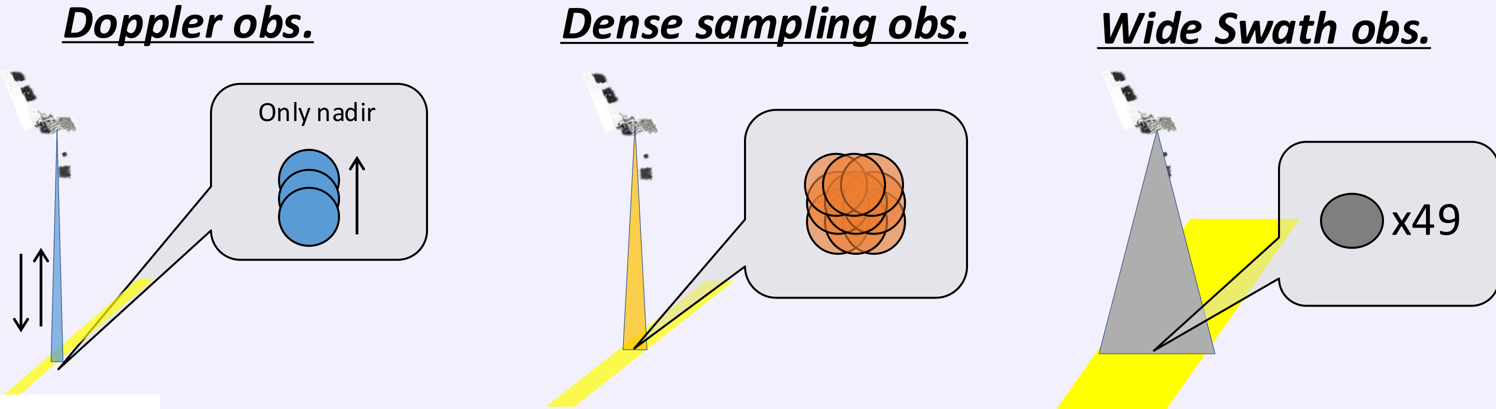


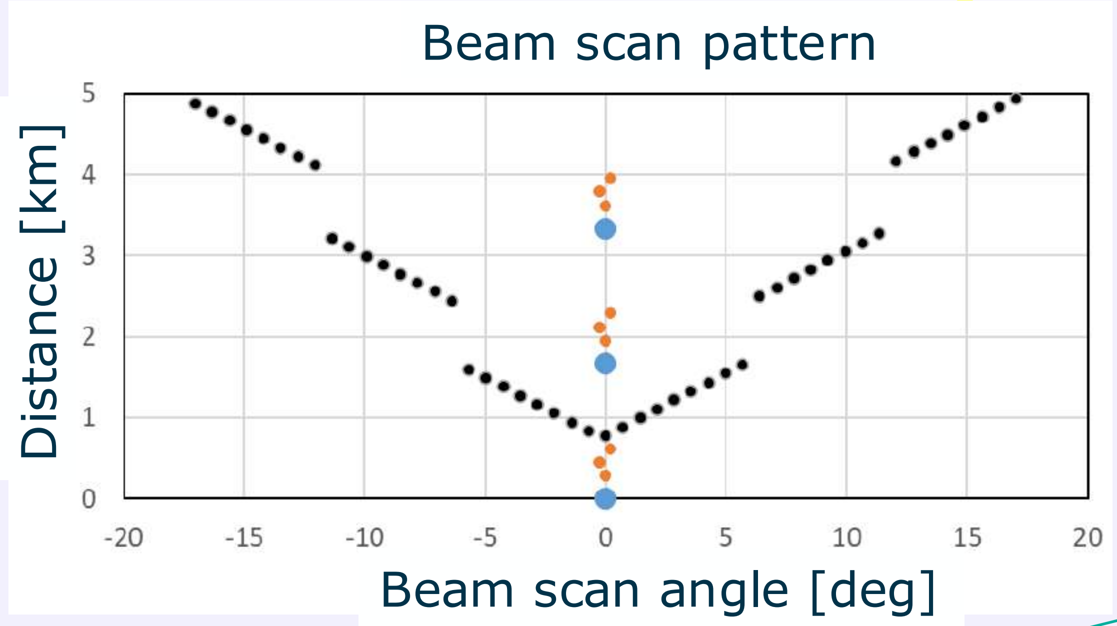
An experimental observation of doppler beam scanning to measure horizontal winds is also planned.

Basic concept of KuDPR L2 Precip.Doppler algorithm

Three modes in one scan cycle

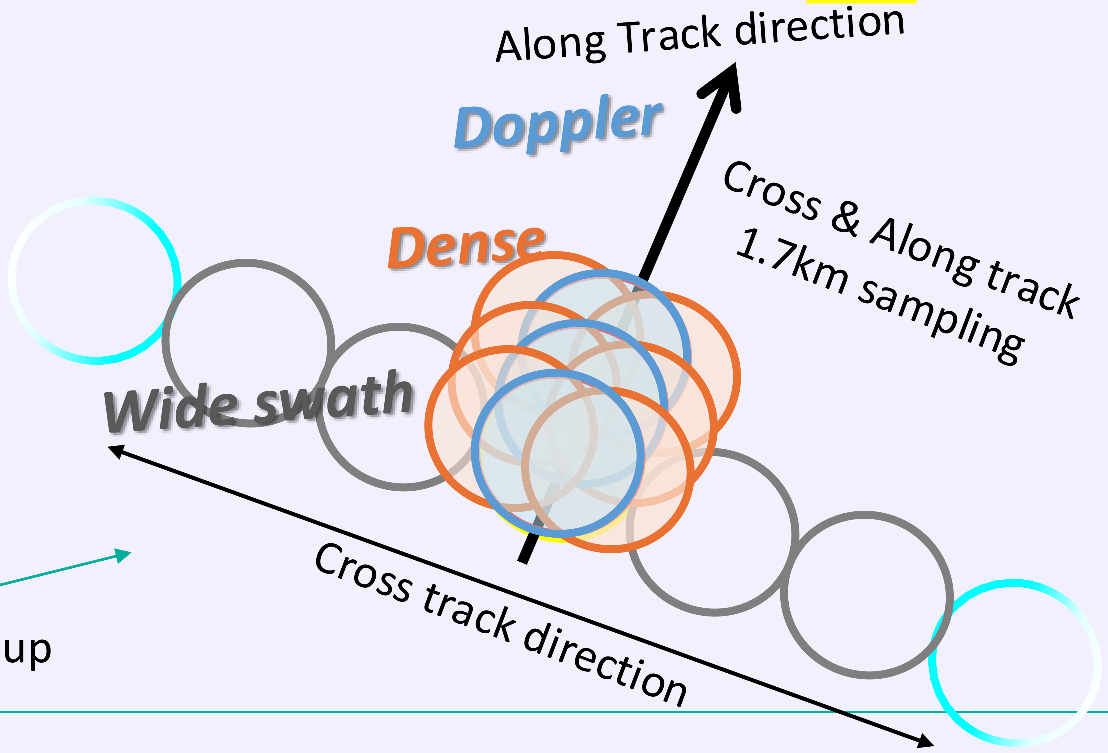
- Doppler obs. (DP) nadir
- Dense obs. (DS) near nadir
- Wide swath obs. (WS) 250 km swath width





Plotted on the geographic map

Close up



Predicted performance for KuDPR

Antenna Size	Along-Track	m	2.1 × 2		
	Cross-Track	m	2.1		
Measurement Mode		-	DPCA Doppler	Dense	Normal
Doppler Measurement Accuracy (assuming perfect bias correction, with uniform precipitation)		m/s	0.89 @S/N=6.13dB (Z=16dBZ)		
Spatial Resolution @Nadir & 430km	Along-Track	km	5.3	5.3	5.3
	Cross-Track	km	5.3	5.3	5.3
Spatial Sampling @430km	Along-Track	km	1.66	1.66	5.0
	Cross-Track	km	No Scan	1.76	5.3
Range Resolution		m	500	500	250
Range Sampling		m	250	250	125
Swath @430km		km	No Scan	8.8	270
Observation Height	< +- 13.49deg	km	17	20	20
	≥ +- 13.49deg	km	N/A	N/A	18
Transmit Pulse Width		μs	3.2	3.2	1.6
Zs	@Nadir	dBZ	7.17	7.16	14.73

Standard Products (KuDPR) (1)

Level	Product (representative variable)	Major geophysical variables	Sensor	Unit	Swath	Sampling		Resolution		Required accuracy (success criteria)
						Spatial	Vertical	Spatial	Vertical	
L1	Received echo power	Received echo power	KuDPR	Orbital	9km /255km	1x1km/ 5x5km	250m/ 125m	5x5km	500m/ 250m	In external calibration experiments, the calculated value of transmitted/received power and the actual measured value shall agree within ±1 dB.
L1	Doppler velocity (primary correction)	Doppler velocity (primary correction), Pulse Pair Covariance, Spectrum Width	KuDPR	Orbital	5km	1x5km	250m	5x5km	500m	Evaluated by Doppler velocity (final correction)
L2	Precipitation rate	Radar reflectivity factor, Surface backscatter(σ_0), Precip rate profile, DSD, Precip type, Non-uniform parameter etc.	KuDPR	Orbital	9km /255km	1x1km/ 5x5km	250m/ 125m	5x5km	500m/ 250m	[Rainfall] ~ ±10% of surface rainfall [Snowfall] 90% or more quantitative detection of snowfall (D) near the surface at nadir and observable by the satellite $D = 100 \times \sum_{j=1}^{M} Sd_j / \sum_{i=1}^{N} S_i$ where, S indicates snowfall rate [mm] observed by a high-sensitivity sensor located at nadir of the satellite and near the surface where the satellite can observe. Sd indicates snowfall rate[mm] observed by the high-sensitivity sensor detected by KuDPR.
L2	Doppler velocity (final correction)	Doppler velocity (final correction), Vertical Air velocity etc.	KuDPR	Orbital	5km	1x5km	250m	5x5km	500m	Doppler measurement accuracy of about 2 m/s or less just below the satellite
L2	Spectral Latent Heating (SLH)	Latent heating profile, type, etc.	KuDPR	Orbital	255km	5 x 5km	250m	5x5km	250m	Achieve either a zonal mean difference in equivalent precipitation, which is the vertical accumlation of precipitation and latent heat heating from KuDPR, of less than ±20% or less than 0.5 mm/day in each latitudinal band.
L2	Long-term dataset	Long-termK dataset of precipitation and SLH consistent with PMM/KuDPR	TRMM/PR, GPM/DPR	Orbital	255km	5x5km	125m	5x5km	250m	Evaluated by KuDPR

Standard Products (KuDPR) (2)

Level	Product	Major geophysical variables	Sensor	Observation range	Time resolution	Grid resolution		Required accuracy (success criteria)
						spatial	Vertical	
L3	Precipitation and Doppler velocity	Statistics of Precip rate profile, phase, DSD etc	KuDPR	Global	Daily /monthly	0.05° x0.05°	1 or 5 layer(s)	Evaluated in L2
		Statistics of Doppler velocity						
	Spectral latent heating	Statistics of SLH		Global	Monthly	0.5° x0.5°	80 layers	Evaluated in L2
	Long-term data record	Long-term precipitation dataset consistent with KuDPR	TRMM/PR, GPM/DPR*1	Global	Daily /monthly	0.05° x0.05°	1 or 5 layer(s)	Evaluated in L2
		Long-term SLH dataset consistent with KuDPR		Global	Monthly	0.5° x0.5°	80 layers	Evaluated in L2
	Global Satellite Mapping of Precipitation (GSMaP)	Mean surface precipitation rate, observation pixel counts, precipitating pixel counts, phase infomation	KuDPR, Multi-passive microwave radiometers (PoR)	Global	Hourly /monthly	0.1° x0.1°	N/A	GSMaP daily rainfall ~ ±40%

Basic concept of KuDPR L2 algorithm

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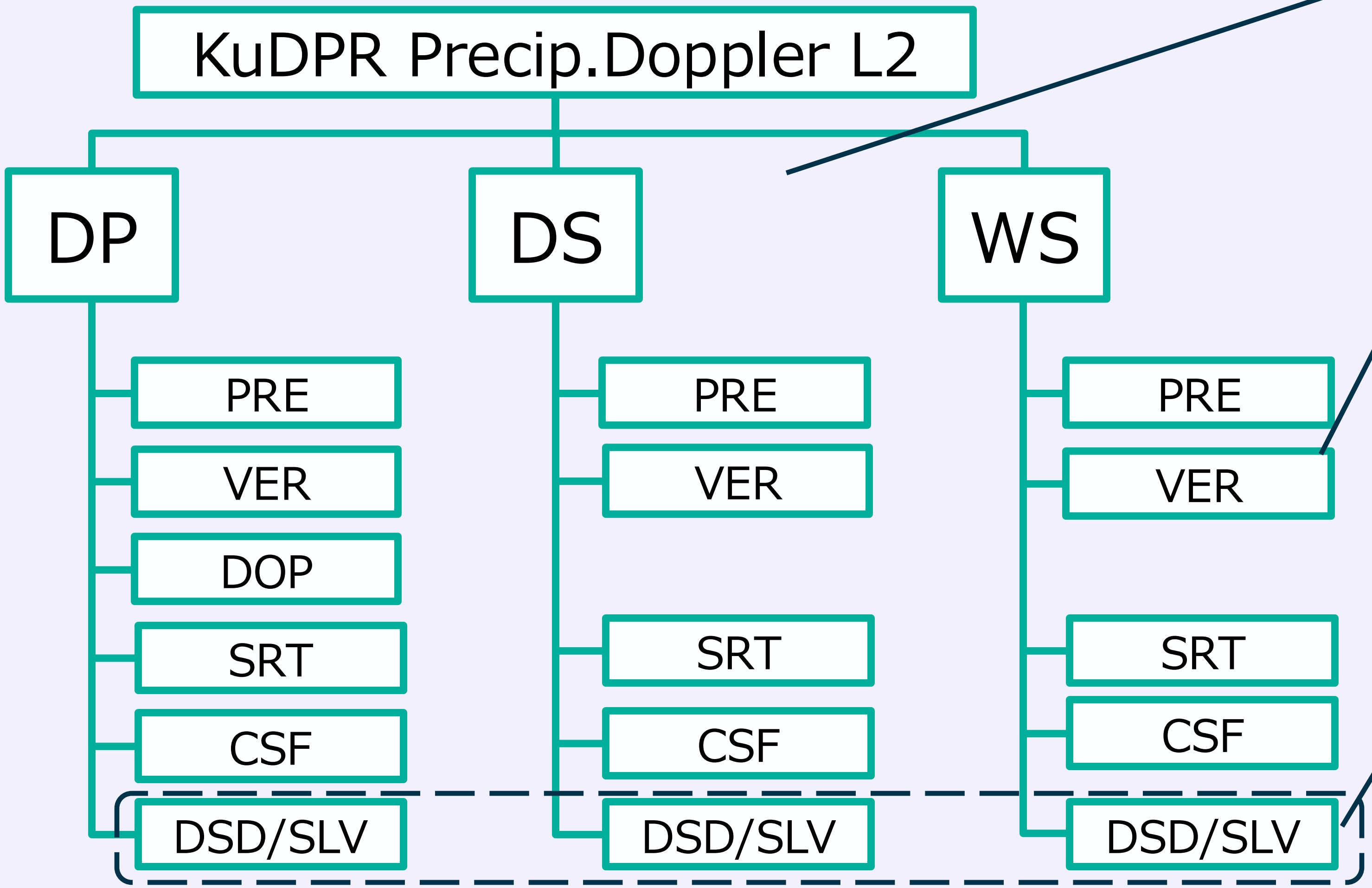
Structure of product



Output for DP, DS, and WS respectively.

PRE, VER···etc.
Variables are stored under each module, following the same style as GPM Ku and Ka.

Each outputs from DP, DS, and WS need to be consistent with one another.

Summary

PMM（Precipitation Measuring Mission）

PMM will be the second Doppler radar mission (or first Doppler precipitation radar mission) collaborating with NASA's FALCON (Fleet for the Atmosphere Linking Commercial Observations with NASA) program

- DPCA technique for better Doppler accuracy
- Launch: 2029-2030

PMM will focus on the Convection Dynamics and cloud-precipitation processes as well as the global precipitation record and improvement of global precipitation estimation

- more than 30 years of data since TRMM satellite

Future direction of precipitation missions

Radar technology

Conventional Radar
(Z only)

Doppler Radar
(Z and Doppler velocity)
ΔT observation (tandem satellites)

Science

Use of precipitation profile, latent heat profile, and surface rain map (e.g. GSMaP)
- extreme rainfall
- diurnal cycle

Researches combined dynamics and cloud physics
- Evolution processes of precip. system
- aerosol-cloud-precip. interaction

Satellite development (H/W, S/W)

Agency-driven (e.g. JAXA)

Agency-private collaboration

Thank you for your attention

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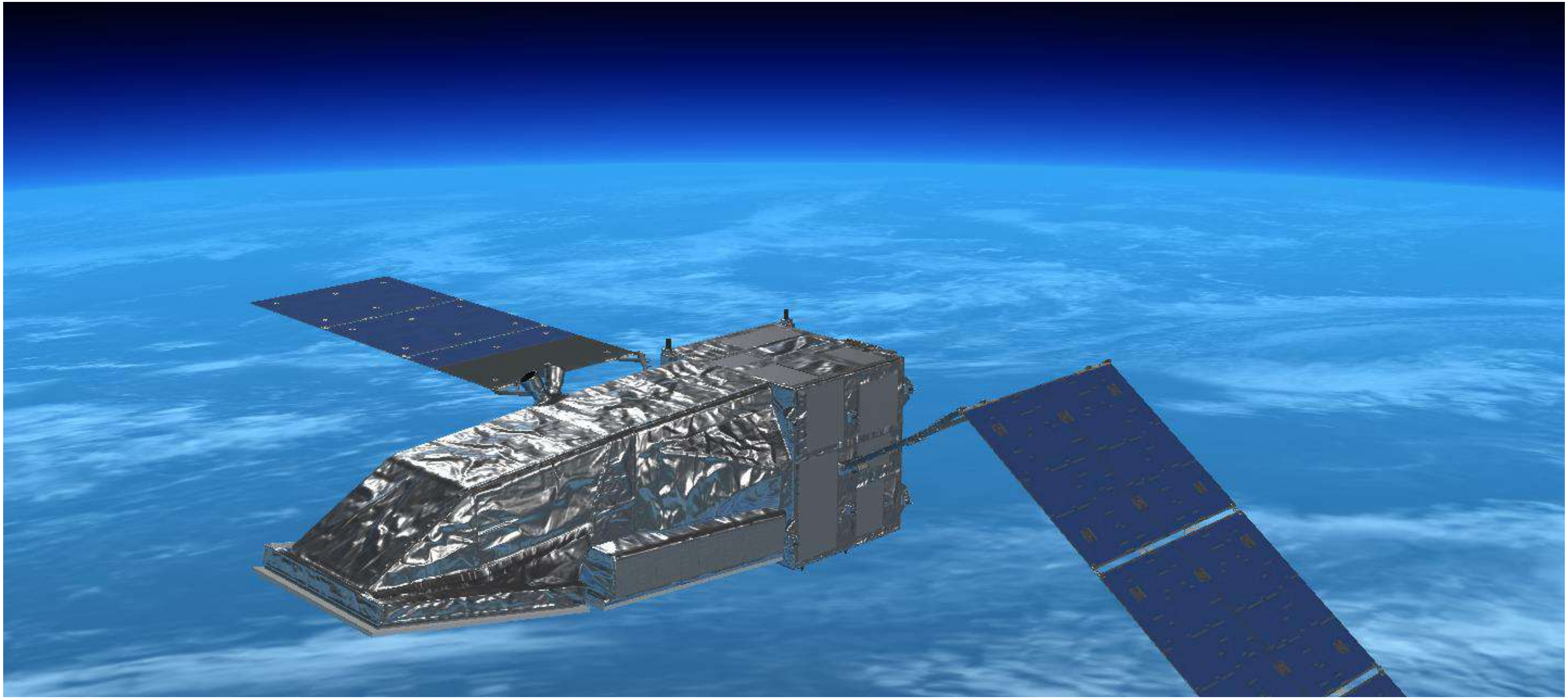

Scientific questions during PMM era

Key Science Questions for PMM

1. **Convective Dynamics**
   How do **vertical air motions in deep convection** regulate precipitation formation and intensity?

2. **Cloud–Precipitation Processes**
   What processes control the **formation and evolution of precipitation particles**?

3. **Climate Response of Precipitation**
   How do **precipitation systems** and **the global water cycle** respond to **global warming**

4. **Extreme Precipitation Mechanisms**
   What physical processes control the **occurrence and intensity of extreme rainfall events** that lead to disasters?

Details in the Key Scientific Questions

1. Convective Dynamics
How do vertical air motions in deep convection regulate precipitation formation and intensity?
- What is the relationship between **updraft intensity and hydrometeor growth**?
- How do **updrafts and downdrafts influence precipitation efficiency**?
- How does **vertical mass flux vary across different climatic regimes**?

2. Cloud–Precipitation Processes
What processes control the formation and evolution of precipitation particles?
- How do **cloud hydrometeors transition into precipitation particles**?
- What microphysical processes (**e.g., collision–coalescence, aggregation, and riming**) control precipitation growth?
- How do these processes differ between **convective and stratiform precipitation systems globally**?

3. Climate Response of Precipitation
How do precipitation systems and the global water cycle respond to global warming?
- How do **convective intensity and precipitation efficiency** change in a warmer climate?
- How do **observed precipitation changes compare with climate model projections**?
- How do **regional precipitation patterns change across the globe**?

4. Extreme Precipitation Mechanisms
What physical processes control the occurrence and intensity of extreme rainfall events that lead to disasters?
- What **dynamical and microphysical factors** determine the **intensity of extreme rainfall**?
- How do **atmospheric conditions** influence the **development of heavy rainfall systems**?
- How can **global satellite observations** improve understanding of **processes leading to heavy rainfall disasters**?

Contribution of Spaceborne Doppler Radar to the Key Scientific Questions (1)

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1. **Convective Dynamics in the Global Water Cycle**

   Science question : How do vertical air motions in deep convection regulate precipitation formation and intensity?

   - **Contribution of Doppler radar**
     - **Direct measurement** of vertical Doppler velocity
     - Estimation of **updraft and downdraft structures**
     - Retrieval of **convective mass flux**
     - **Global statistics** of **vertical velocity in precipitation systems**
   - **Scientific impact**
     - Quantify the relationship between **updraft** intensity and **precipitation formation**
     - Improve representation of **convection in global circulation models**

2. **Cloud–Precipitation Processes**

   Science question : What processes control the formation and evolution of precipitation particles?

   - **Contribution of Doppler radar**
     - Retrieval of **particle fall velocity**
     - Estimation of **hydrometeor type**
     - Inference of **microphysical processes** (e.g., aggregation, riming)
   - **Scientific impact**
     - Link **microphysics and dynamics**
     - Understand **precipitation particle growth mechanisms globally**

Contribution of Spaceborne Doppler Radar to the Key Scientific Questions (2)

3. **Climate Response of Precipitation**
   Science question : How do precipitation systems and the global water cycle respond to global warming?
   - **Contribution of Doppler radar**
     - Long-term observation of **global precipitation structure**
     - Statistics of **convective intensity and vertical motion**
     - Observation of **latent heating profiles**
   - **Scientific impact**
     - Detect **changes in precipitation dynamics**
     - Provide constraints for **climate models**

4. **Extreme Precipitation and Hydrological Hazards**
   Science question : What physical processes control the occurrence and intensity of extreme rainfall events that lead to disasters?
   - **Contribution of Doppler radar**
     - Observation of **vertical structure of intense storms**
     - Detection of **strong updrafts associated with heavy rainfall**
     - Identification of **microphysical signatures of extreme precipitation**
   - **Scientific impact**
     - Improve understanding of **heavy rainfall mechanisms**
     - Support **global monitoring of extreme precipitation**

Contribution of PMM for disaster mitigation

- Improvement of weather forecasting
  - PMM will help the better understanding of precipitation and will improve **the precipitation prediction** that helps disaster mitigation
- Improvement of global precipitation information
  - Improve the accuracy of **global precipitation maps (e.g. GSMaP)** based on the better understanding of precipitation mechanism (dynamics and microphysics)