# Monitoring Tropical Moisture and Floods Using GNSS and GNSS Reflectometry

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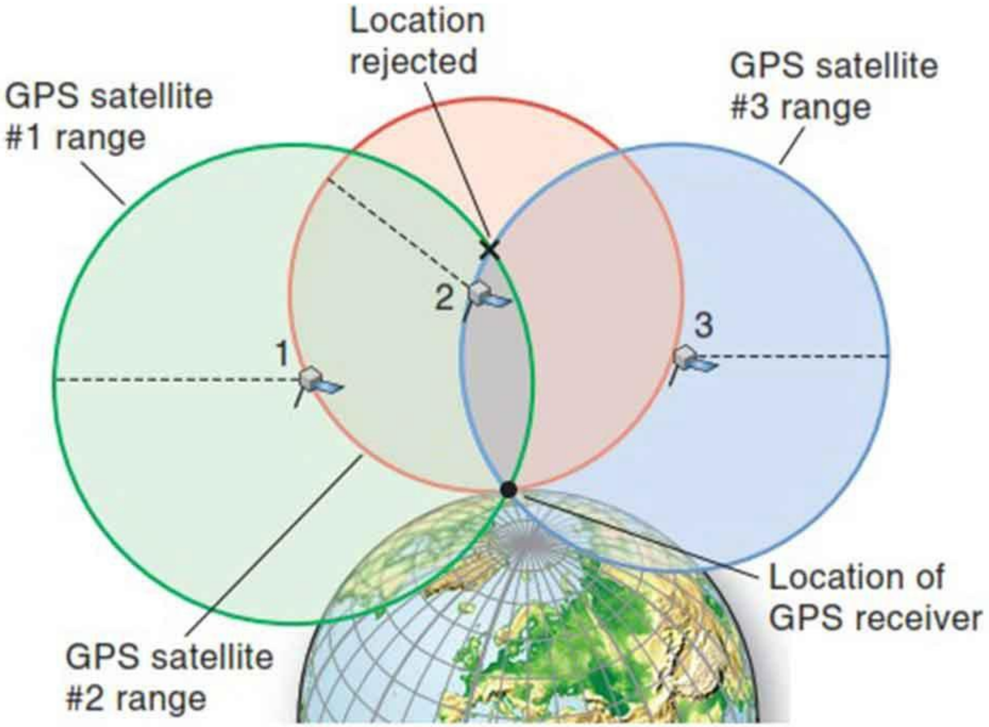
# Global navigation satellite system

Global navigation satellite system (GNSS) consists of:

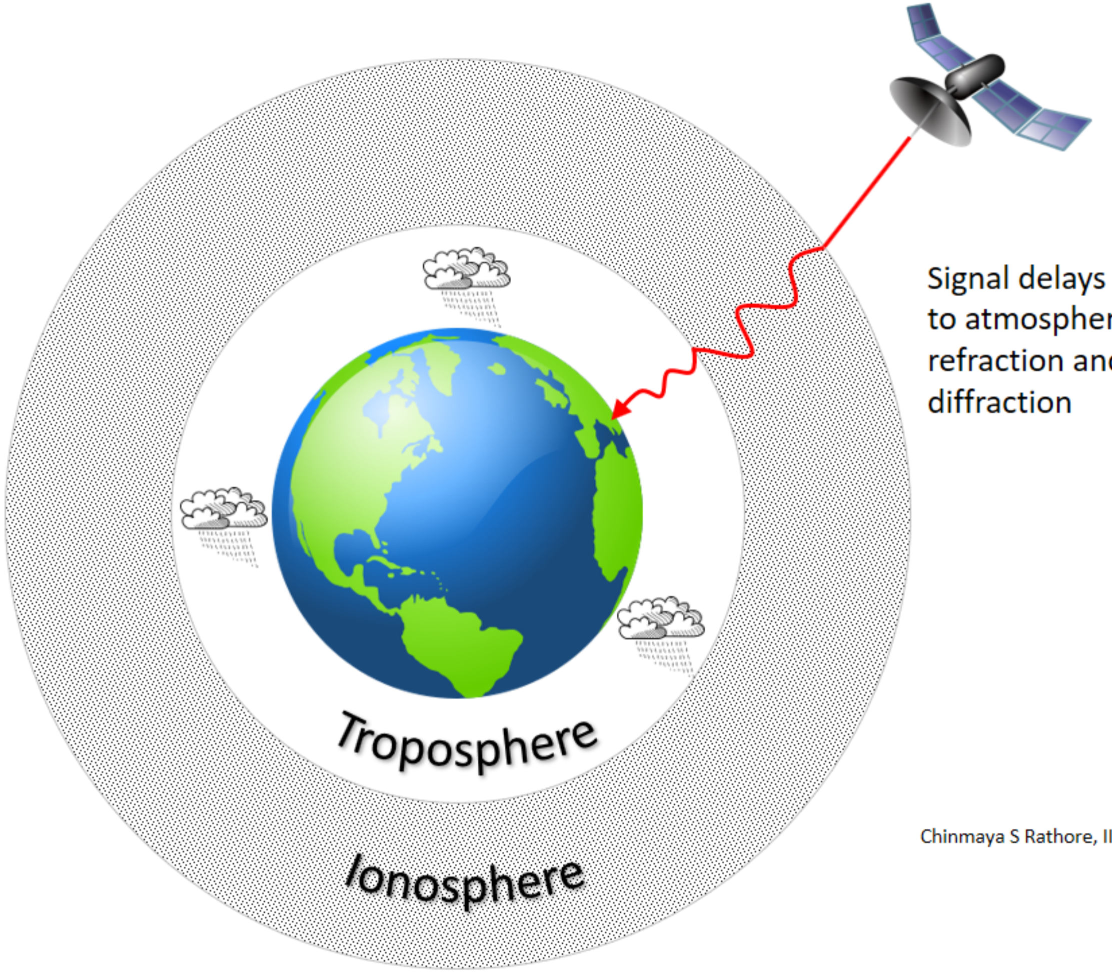
- Global Positioning System (GPS)
- Galileo
- GLONASS
- BeiDou

- (QZSS)
- (IRNSS)

In GNSS, the estimation of position and related parameters is based on the very precise time measurement of electromagnetic wave propagation.



# GNSS signal propagation in the atmosphere




Signal delays due to atmospheric refraction and diffraction

Chinmaya S Rathore, IIFM, CoG

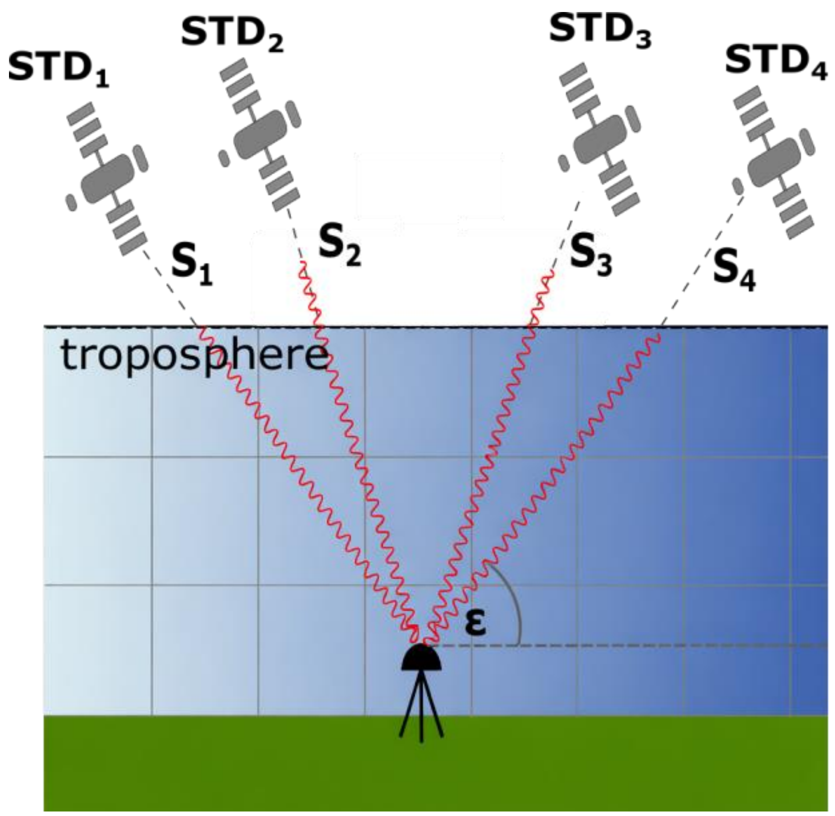
GNSS signals in the atmosphere

- ionospheric delay
- tropospheric delay
  - hydrostatic delay
  - wet delay

# Troposphere influence on the GNSS signal propagation

Tropospheric delay for each satellite-receiver path can be described as:

$$STD = SHD + SWD$$




$\boldsymbol{STD}$ (slant tropospheric delay) – total delay caused by the troposphere along the satellite-receiver path.

$\boldsymbol{SHD}$ (slant hydrostatic delay) – delay caused by the hydrostatic part of the atmosphere which value depends on pressure and temperature.

$\boldsymbol{SWD}$ (slant wet delay) – delay caused by the wet part of the atmosphere which value depends on temperature and water content in the troposphere.

# Troposphere influence on the GNSS signal propagation

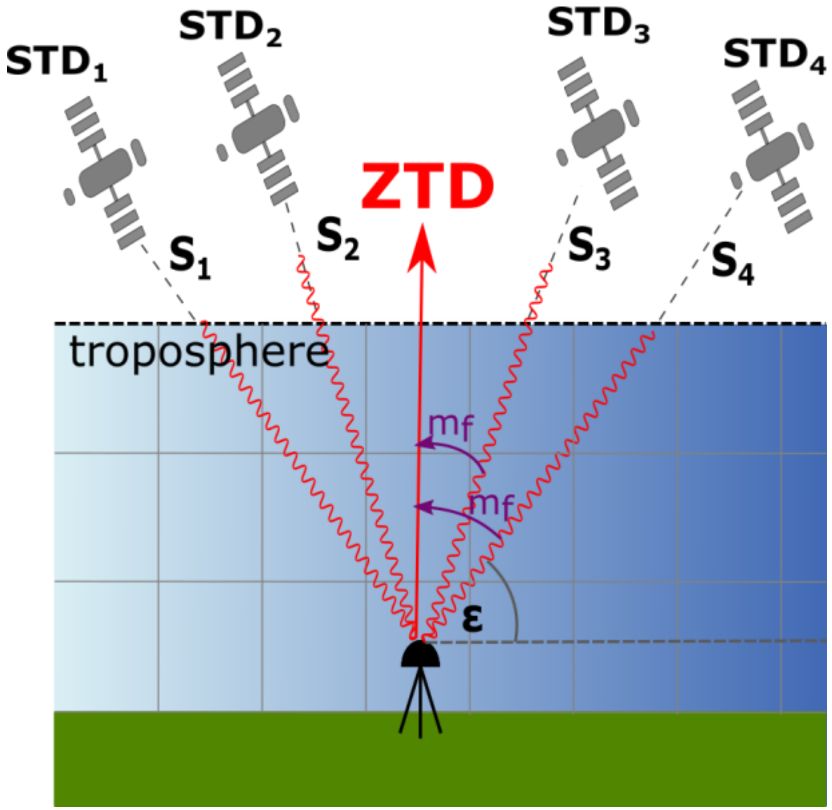
In practice, tropospheric delay is expressed in the zenith direction:

$$ZTD = \underbrace{mf_{hyd}(\varepsilon)^{-1} \cdot SHD}_{\substack{ZHD \\ \text{zenith hydrostatic} \\ \text{delay}}} + \underbrace{mf_{wet}(\varepsilon)^{-1} \cdot SWD}_{\substack{ZWD \\ \text{zenith wet} \\ \text{delay}}}$$

$mf(\varepsilon)$ is the mapping function dependent on the elevation angle (ε) of the satellite:

$$mf(\varepsilon) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{\sin(\varepsilon) + \frac{a}{\sin(\varepsilon) + \frac{b}{\sin(\varepsilon) + c}}}$$

where $a, b, c$ are coefficients separately determined for hydrostatic and wet delays.




GNSS ZTD reflects the spatially averaged, temporary state of the atmosphere

# GNSS meteorology - zenith tropospheric delay conversion to IWV

Zenith tropospheric delay:

direct outcome of GNSS observation peocessing

an approximate function of $e$

an approximate function of $ZTD, P, T$

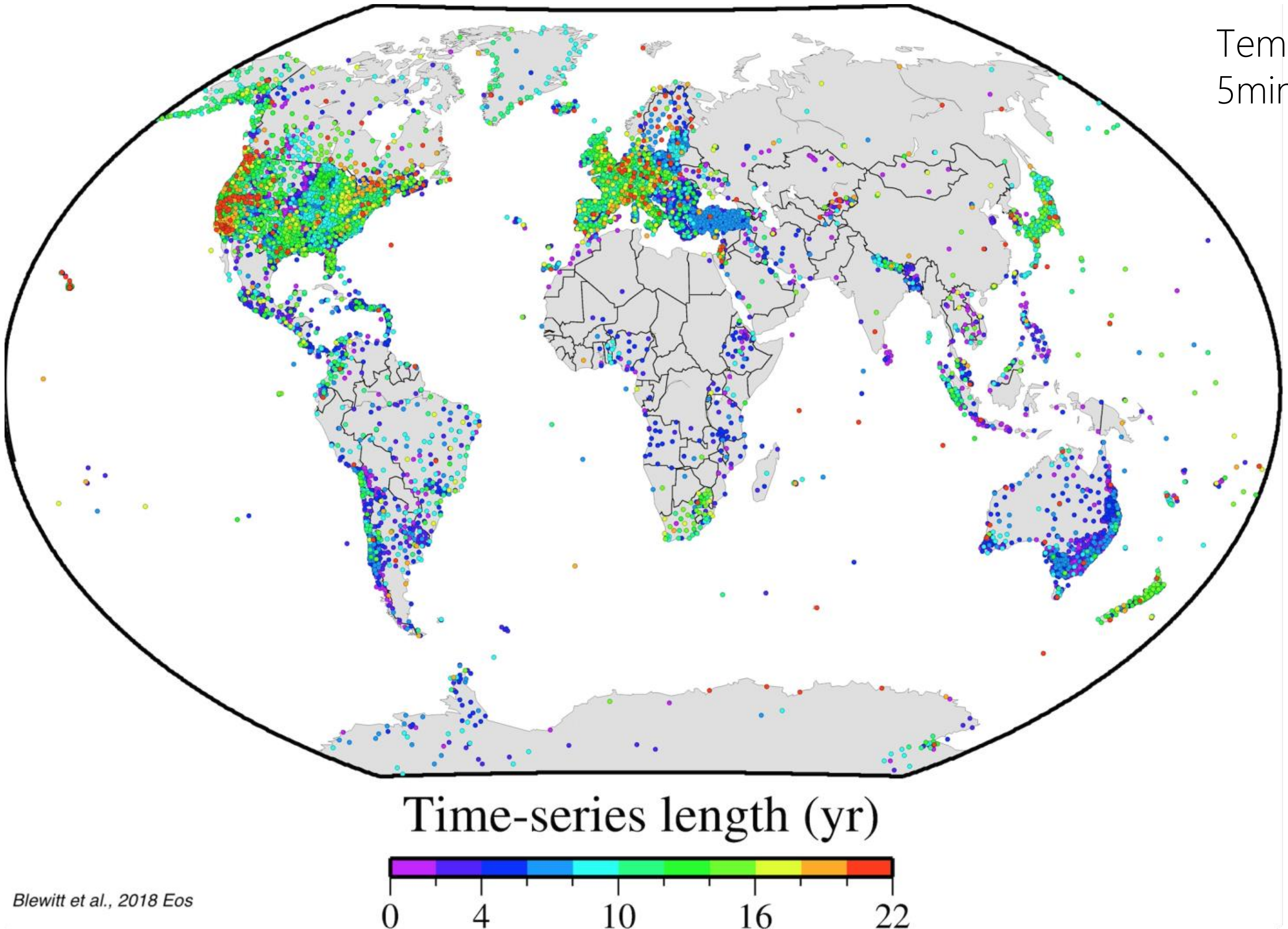
$$ZTD = ZHD + ZWD \quad \Rightarrow \quad IWV(ZWD, P, T)$$

an approximate function of $P$

integrated water vapour (kg/m2) or
precipitable water vapour (mm)

# The GNSS meteorology

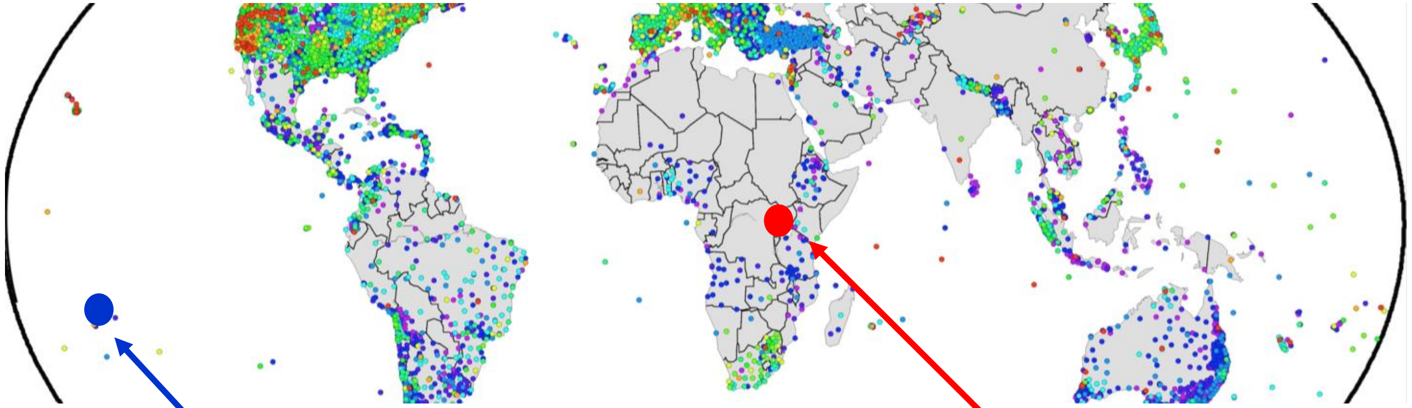
GNSS-delivered PWV/IWV reflects moisture content in the atmosphere and can be obtained with various temporal resolution, while the spatial resolution is determined with numer of stations.



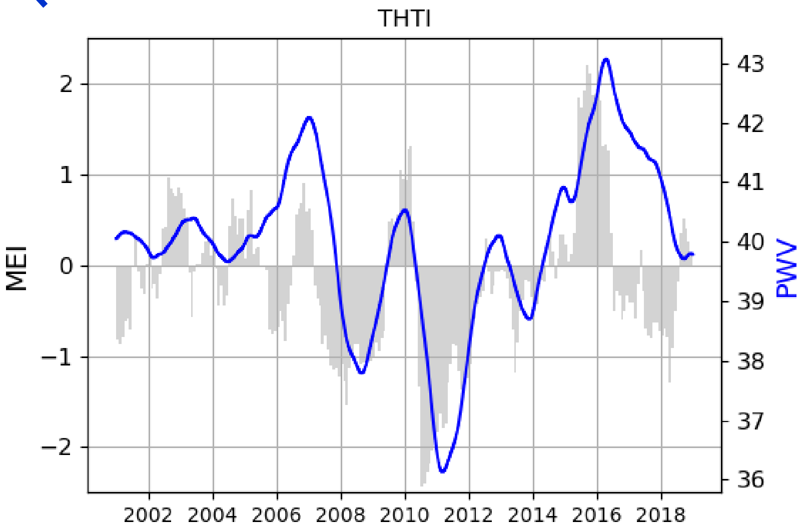

Blewitt et al., 2018 Eos

Temporal resolution typically from 5min to 1 hour

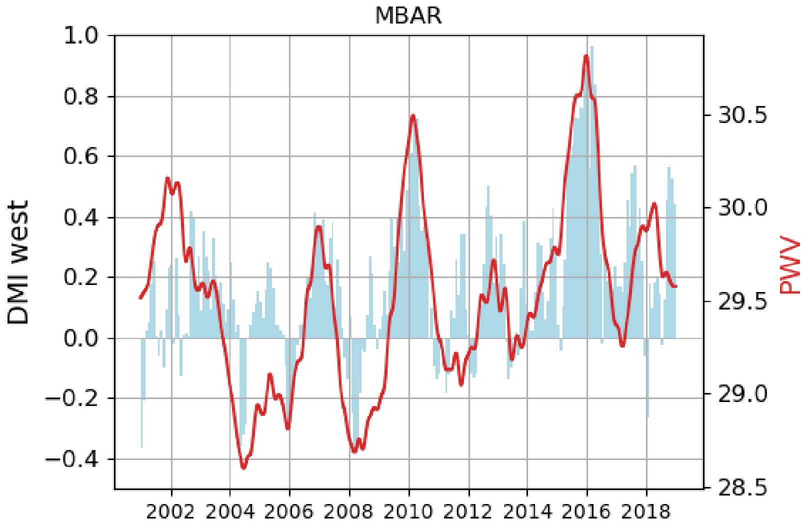
# Tropical moisture: long-term variability



- ENSO (MEI index)

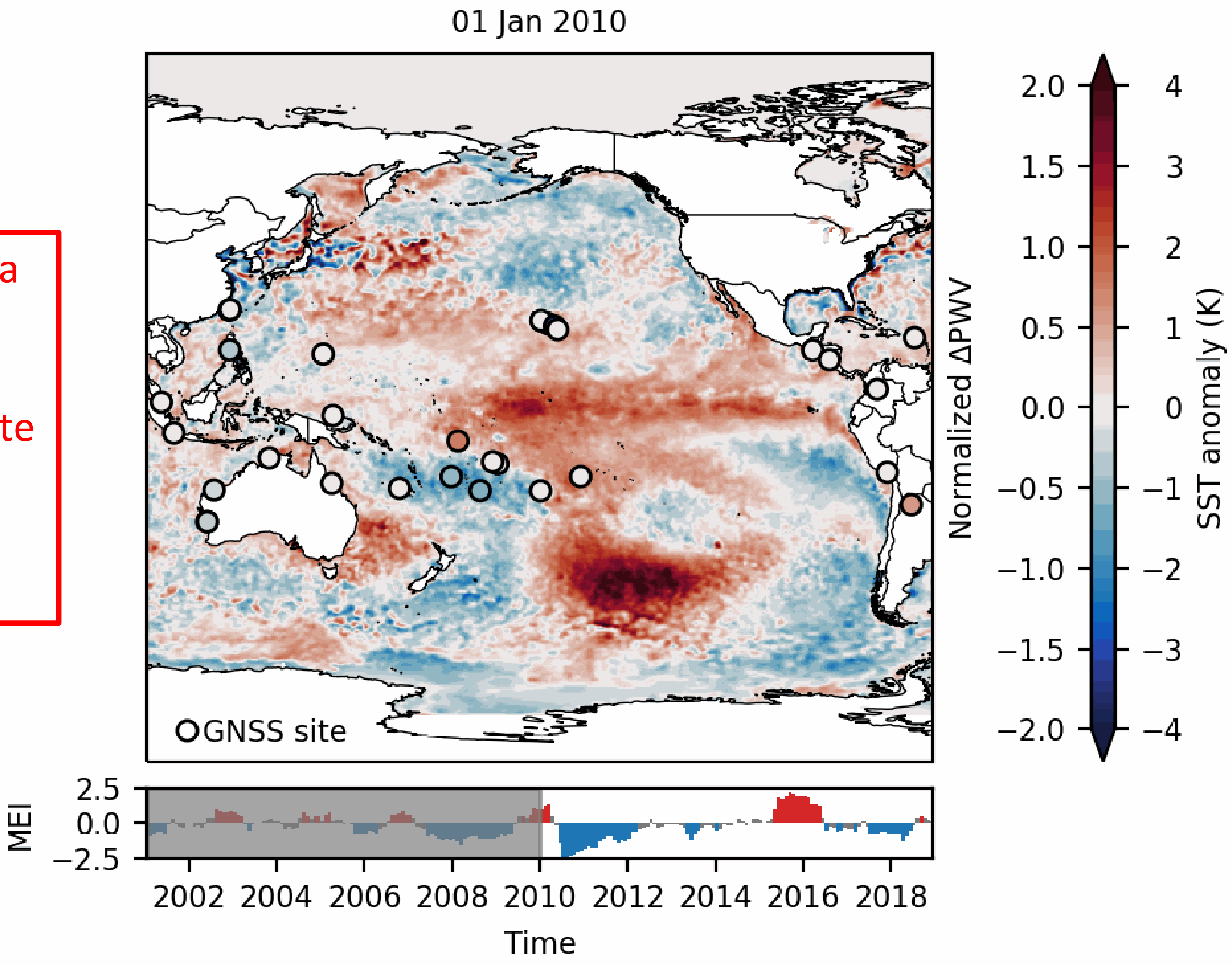



- Indian Ocean Dipole (DMI index)

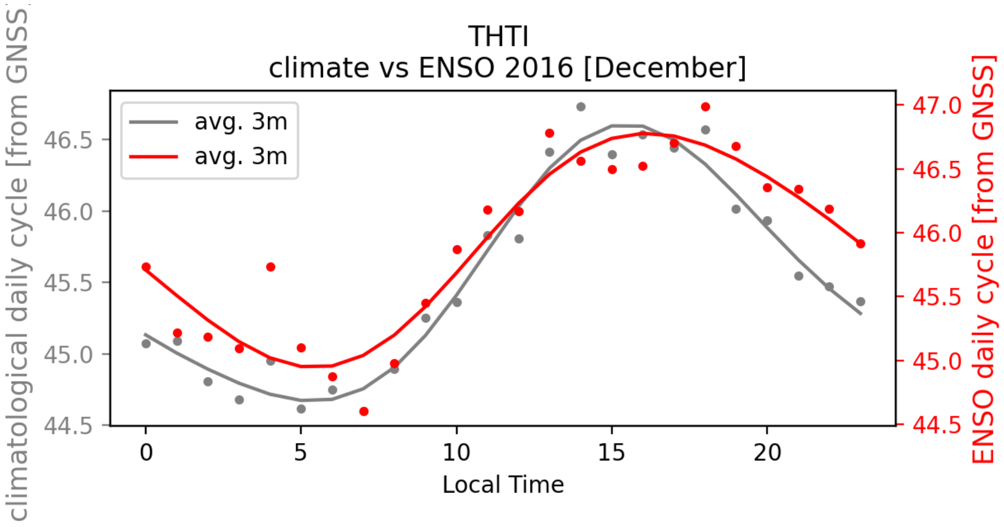


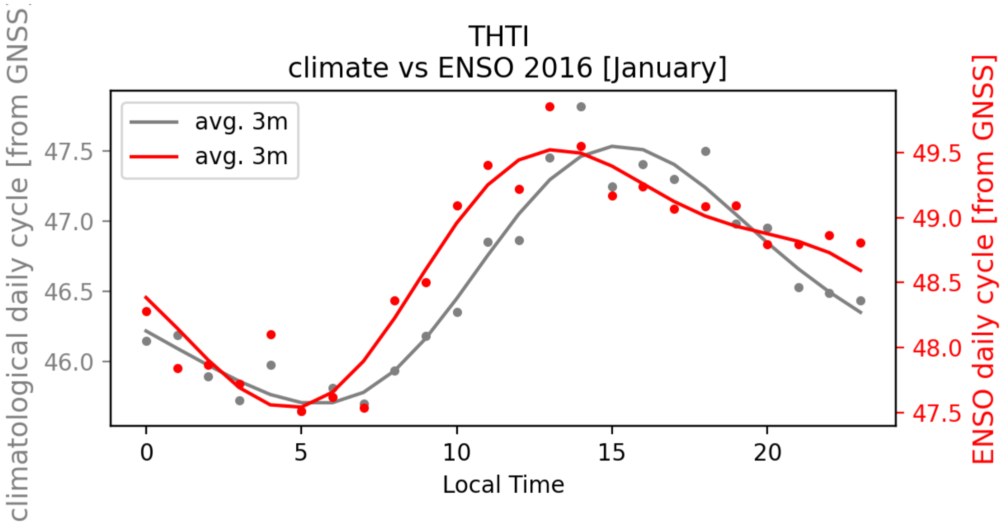
# Tropical moisture: long-term variability

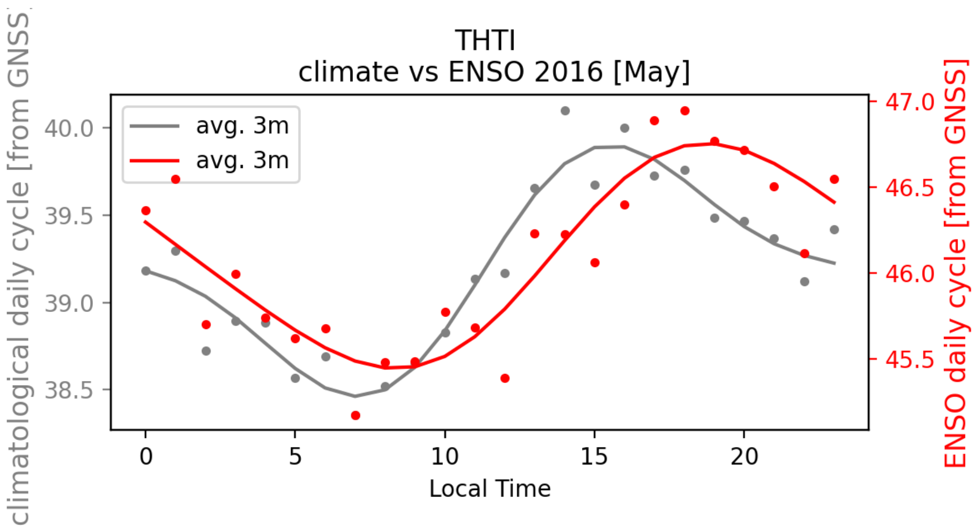
GNSS systems can be deployed as a permanent network and operated continuously without the need for dedicated field campaigns or on-site personnel, while simultaneously providing information at multiple temporal scales



# Tropical moisture: long-term variability impact on diurnal time scale



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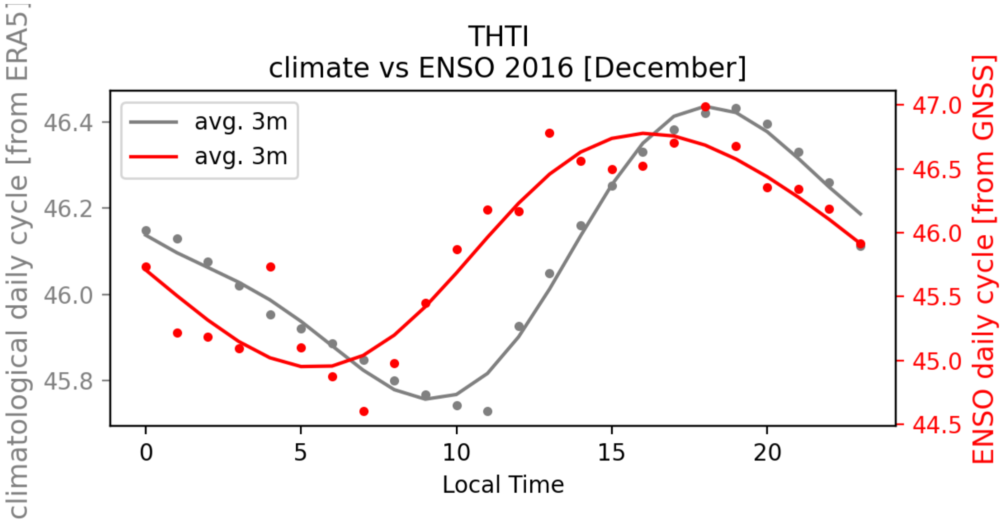
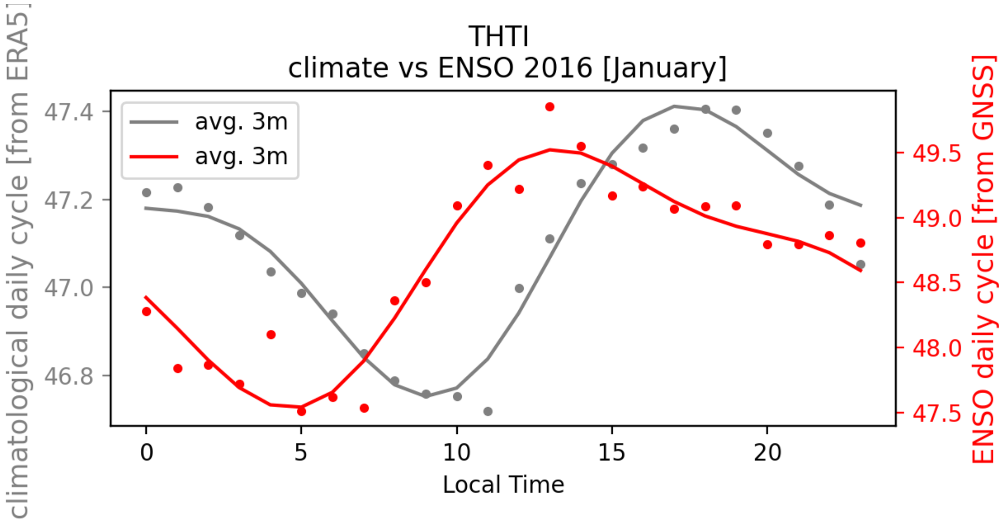
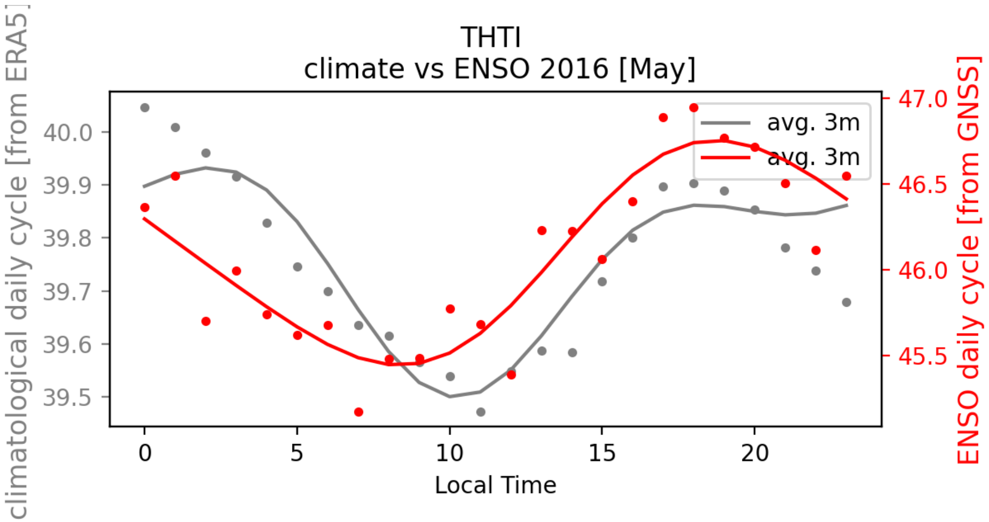
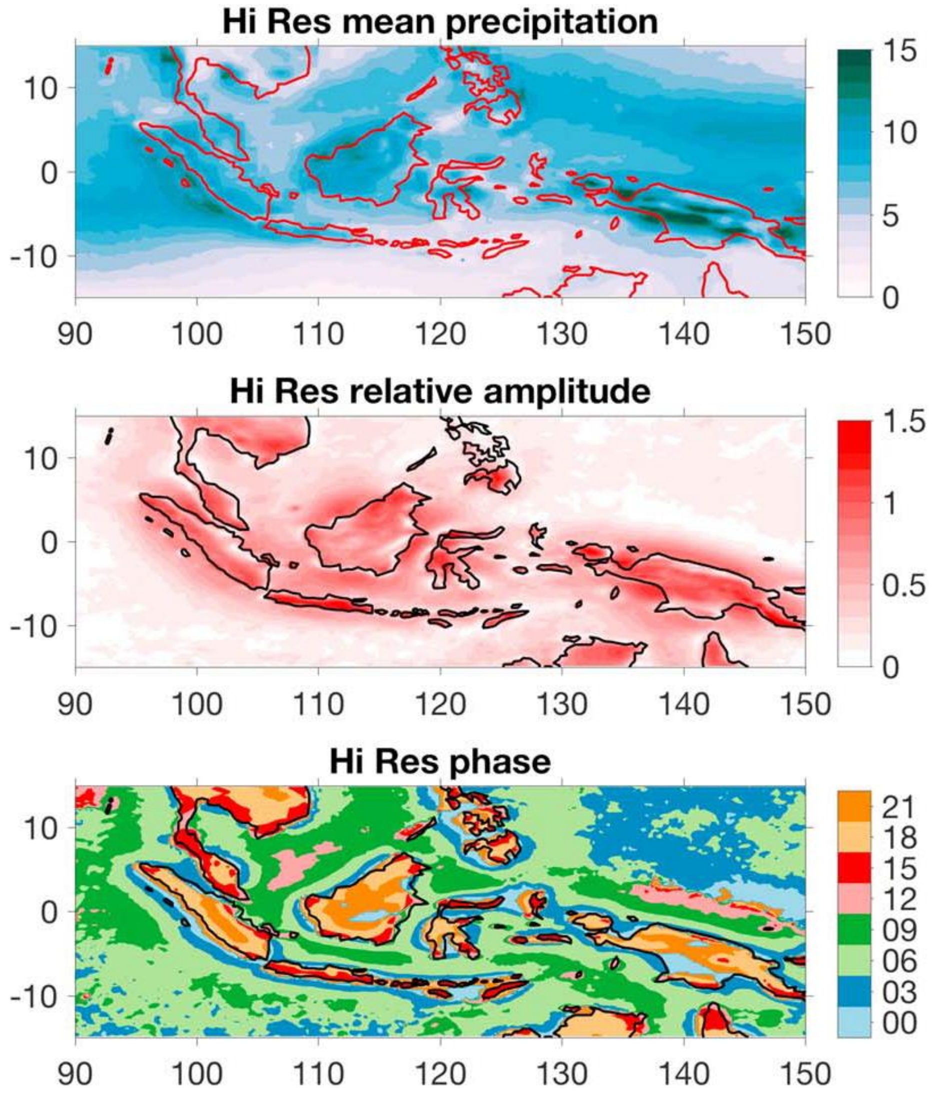


# Tropical moisture: diurnal variability

- The diurnal cycle is the primary mode of convective variability in the tropical environment.
- Monitoring and understanding its diurnal features are important for a better understanding of weather variability in the tropics and global energy transport.
- Insufficient diurnal and spatial sampling of in situ observations
- Bulk properties (clouds, precipitation) well sampled by satellites, but not moisture.
- <u>Can GNSS fill the gap and advance understanding of coupling between moisture variability and precipitation on a diurnal time scale within the global tropics?</u>




Baranowski et al.2019

# Tropical moisture: diurnal variability

### Precipitation

The Tropical Rainfall Measurement Mission gridded dataset (TRMM 3B42 v7)

- 0.25 ˚spatial resolution
- 3-hour temporal resolution
- 01.2001 – 12.2018 time span (full 18 years)

### Cloud Top Temperature (Tb)

Global, merged infrared gridded, multi-satellite product (Level 3) dataset

- 4 km spatial resolution
- 30-min temporal resolution
- 01.2001 – 12.2018 time span (full 18-years)

### Integrated moisture (PWV)

Reprocessed observations from 42 Integrantional GNSS Servise (IGS) stations,

- Scattered across global tropics
- 1- hour temporal resolution
- 01.2001 – 12.2018 (at least 16-year long observations)

Climate Dynamics (2024) 62:1965–1982
https://doi.org/10.1007/s00382-023-07005-0

OBSERVATIONAL RESEARCH

**Diurnal variability of atmospheric water vapour, precipitation and cloud top temperature across the global tropics derived from satellite observations and GNSS technique**

Zofia Baldysz[1] · Grzegorz Nykiel[1,2] · Dariusz B. Baranowski[3] · Beata Latos[3] · Mariusz Figurski[1]

# Tropical moisture: diurnal variability

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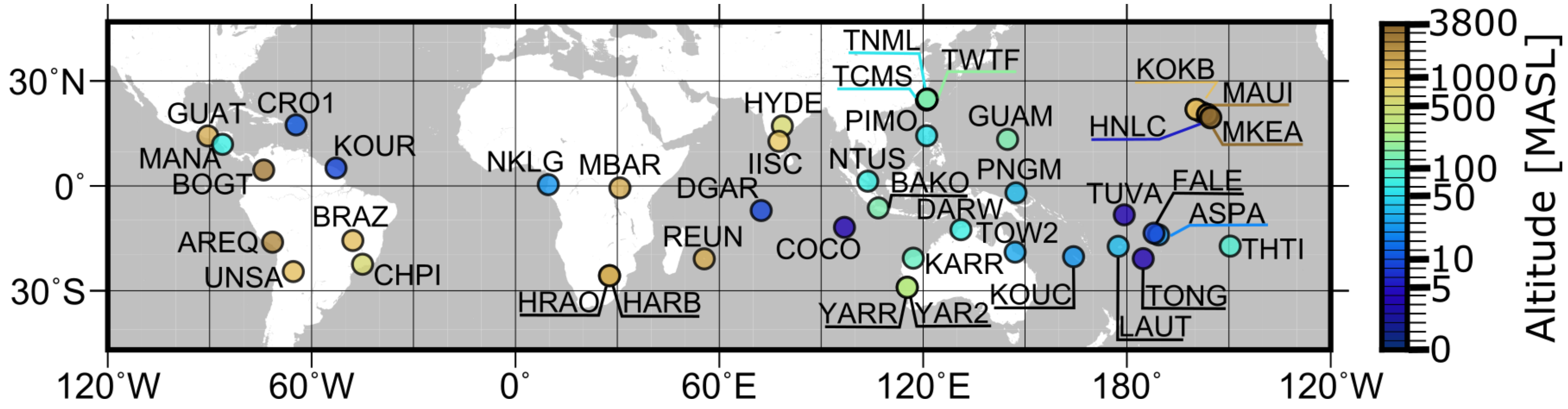
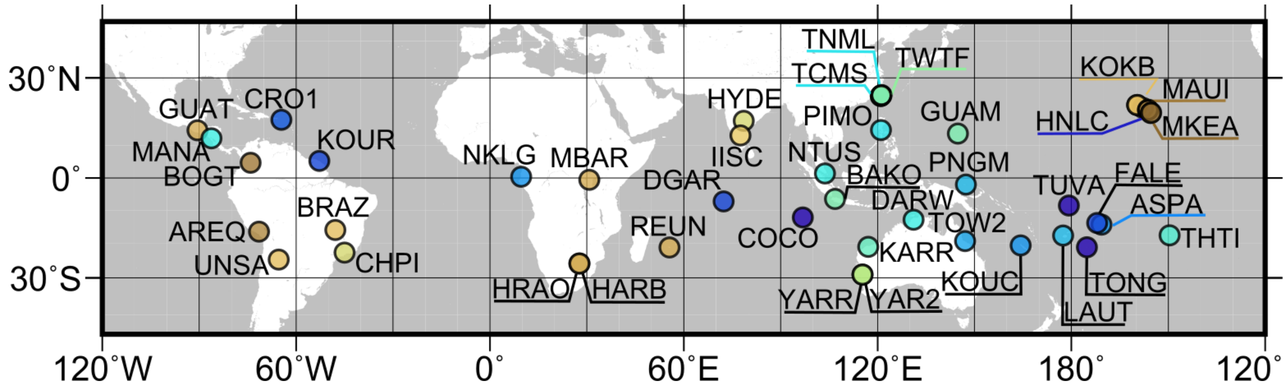
⇩ interpolated to GNSS site locations ⇩ ⇩

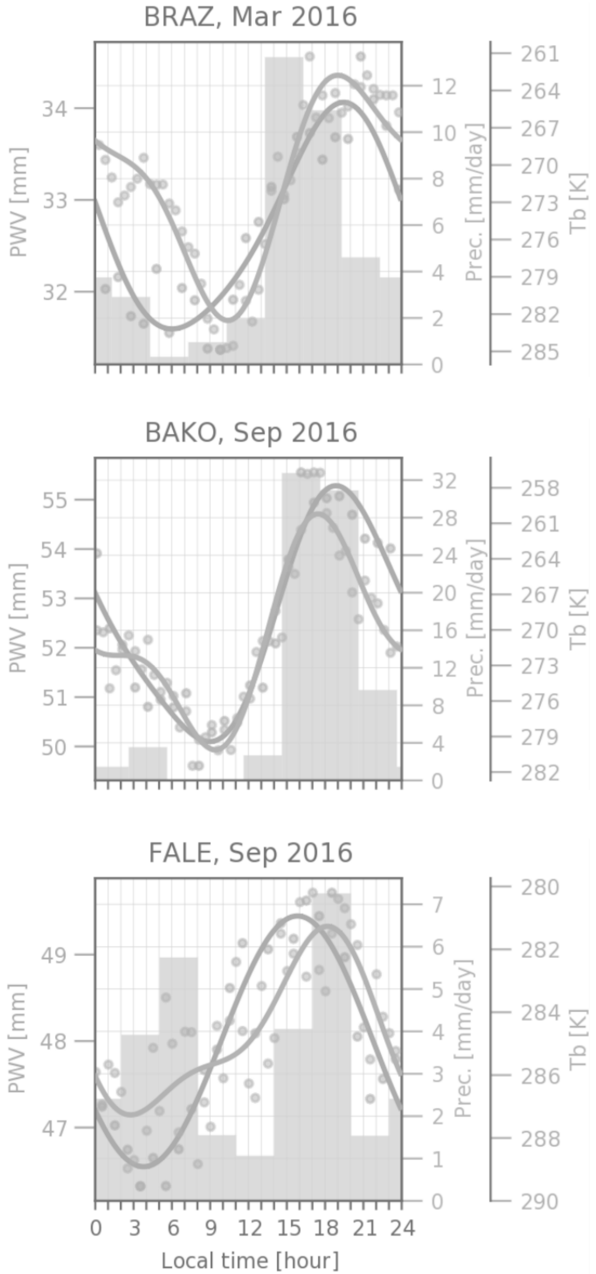


# Tropical moisture: diurnal variability

Diurnal cycle decomposition:

- Including daily mean, diurnal and semi-diurnal harmonics
- conducted independently for each variable at all locations to investigate variability in a range of tropical climates
- calculated as a monthly composite, a multi-year annual average and a multi-year seasonal average for each of the four seasons

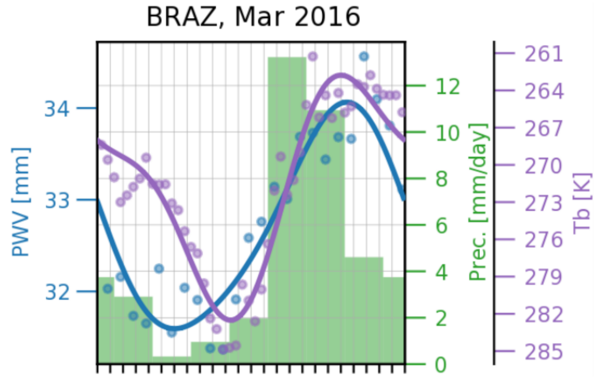


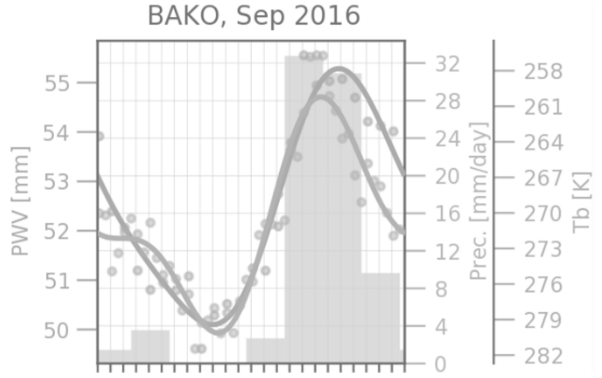



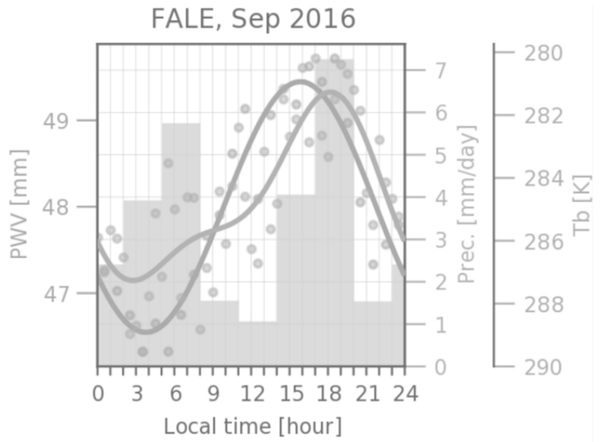
# Tropical moisture: diurnal variability

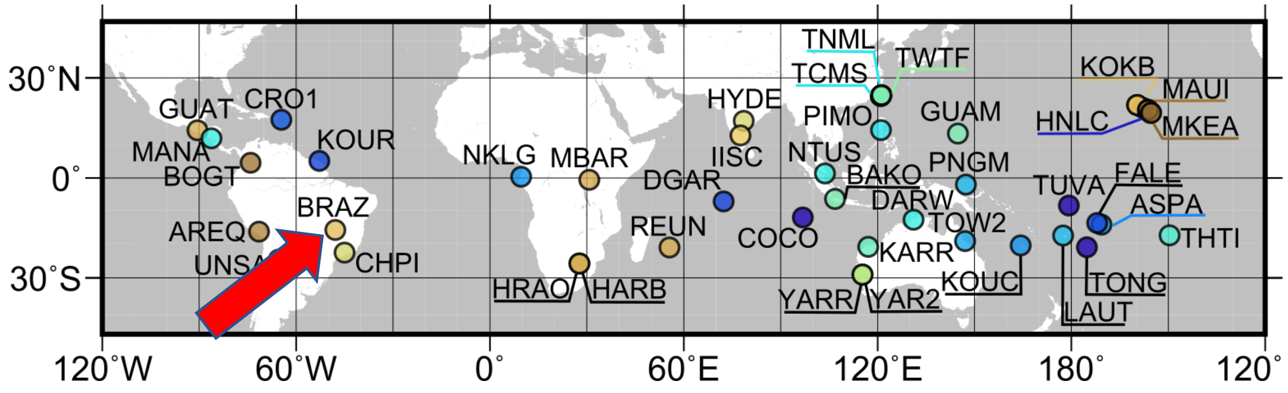
Land-locked stations

- Clear variability of PWV, prec and TB
- PWV single maximum in local afternoon during enhanced precipitation
- Daily variation in PWV is small compared to the average
- Precipitation and Tb maximum in local afternoon



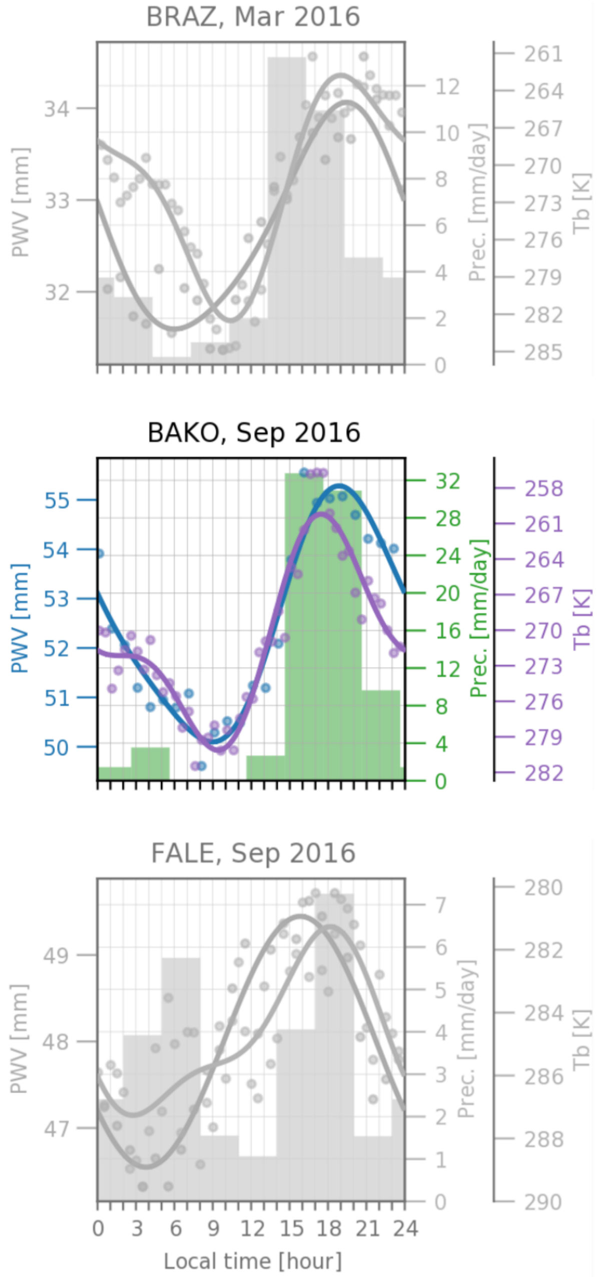



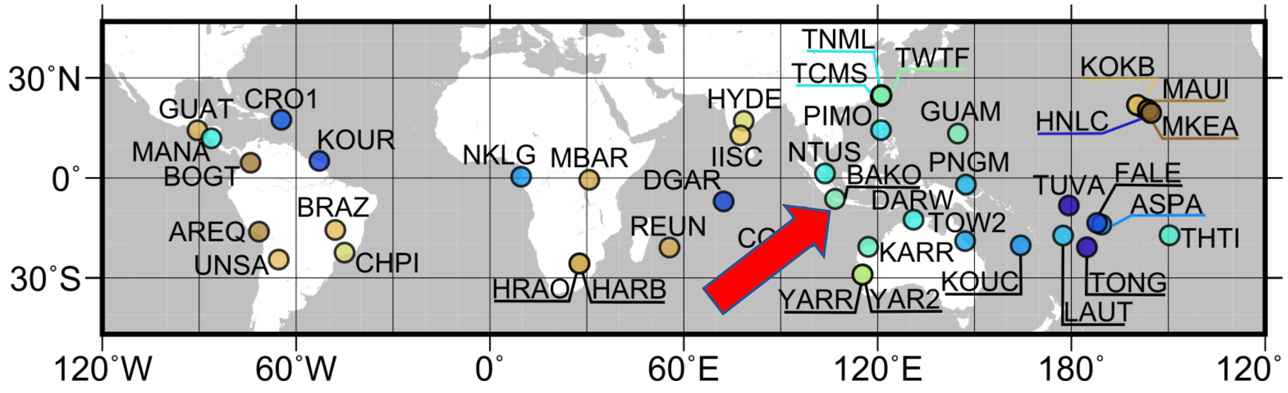



# Tropical moisture: diurnal variability

Coastal stations:

- PWV consistent with Tb and precipitation
- Single PWV maximum in local afternoon
- Higher mean PWV compared to land-locked examples

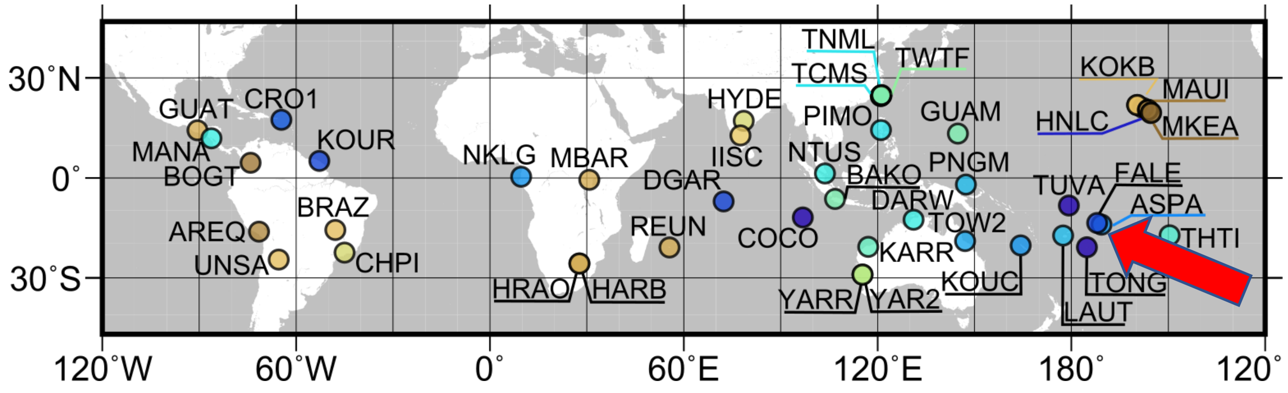


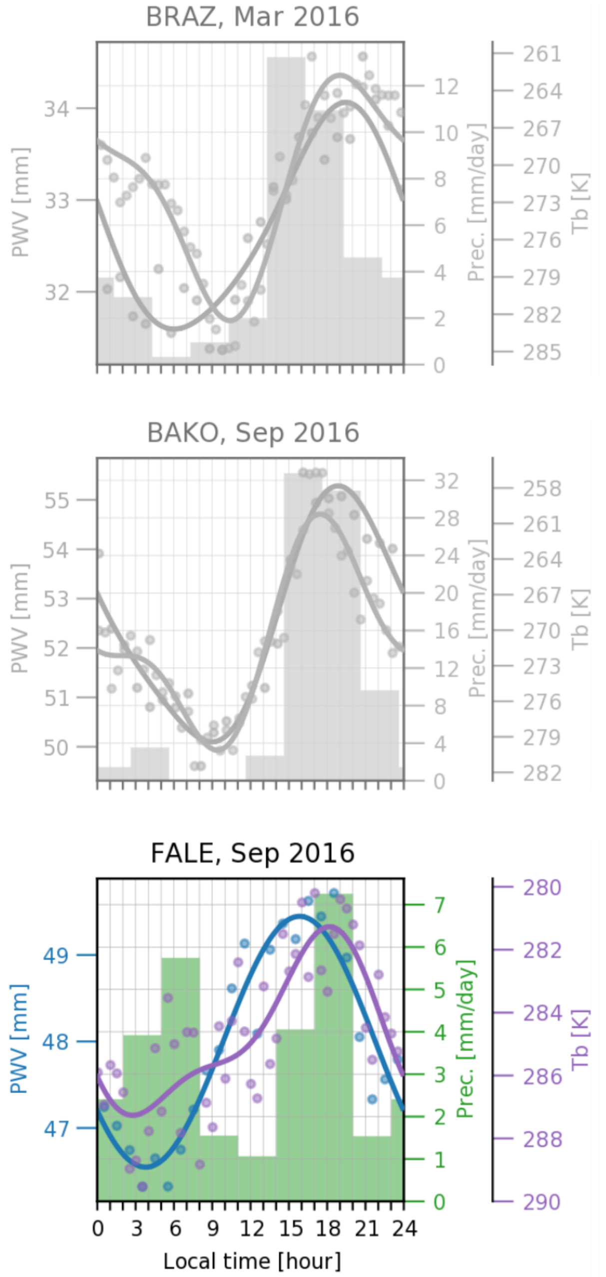



# Tropical moisture: diurnal variability

Small islands stations:

- Single PWV maximum in local afternoon
- Secondary, early-morning precipitation peak, associated with a larger than usual variability in cloud top temperature averages (dots) and PWV minimum
- Tb points are scattered during the morning minimum, indicating substantial variability in cloud populations

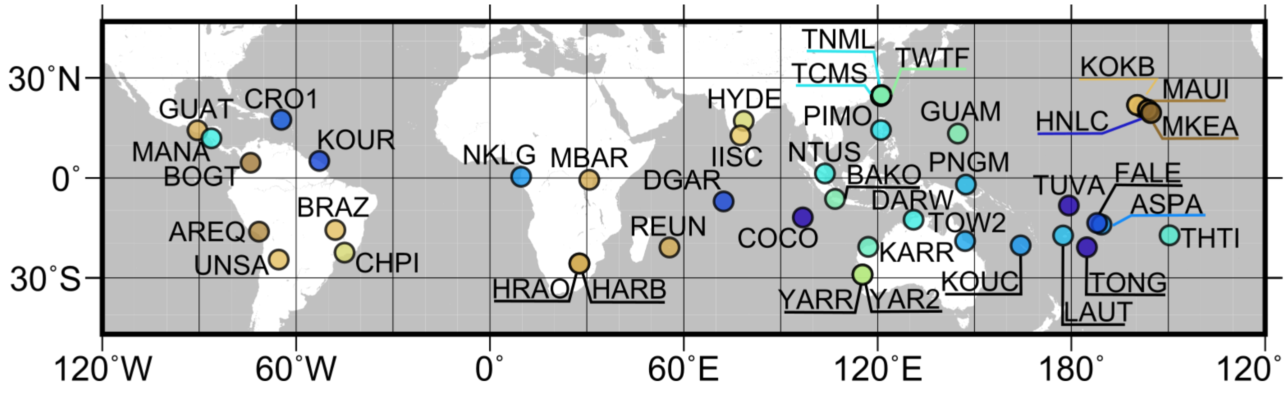


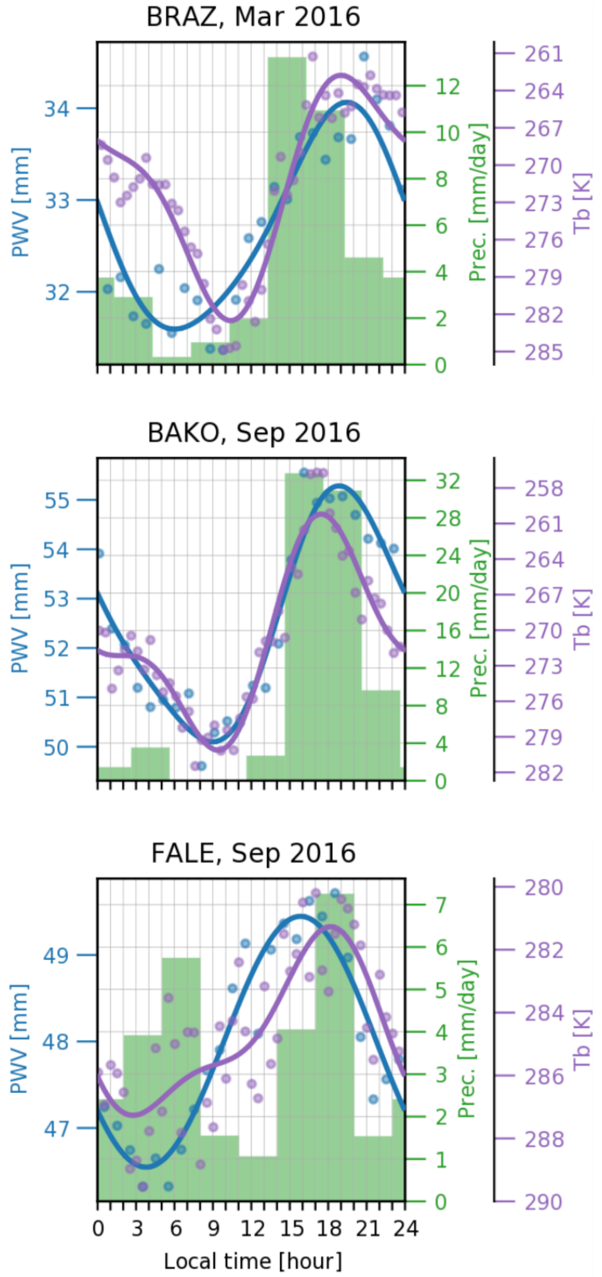



# Tropical moisture: diurnal variability

GNSS enables to follow diurnal variability in atmospheric integrated moisture

There appears to be difference in diurnal evolution of coupled thermodynamics between land-locked, coastal and small island stations



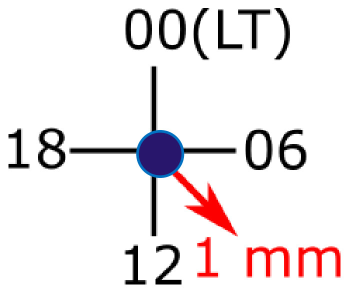



# Tropical moisture: diurnal variability

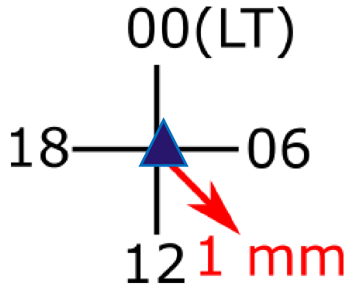
PWV

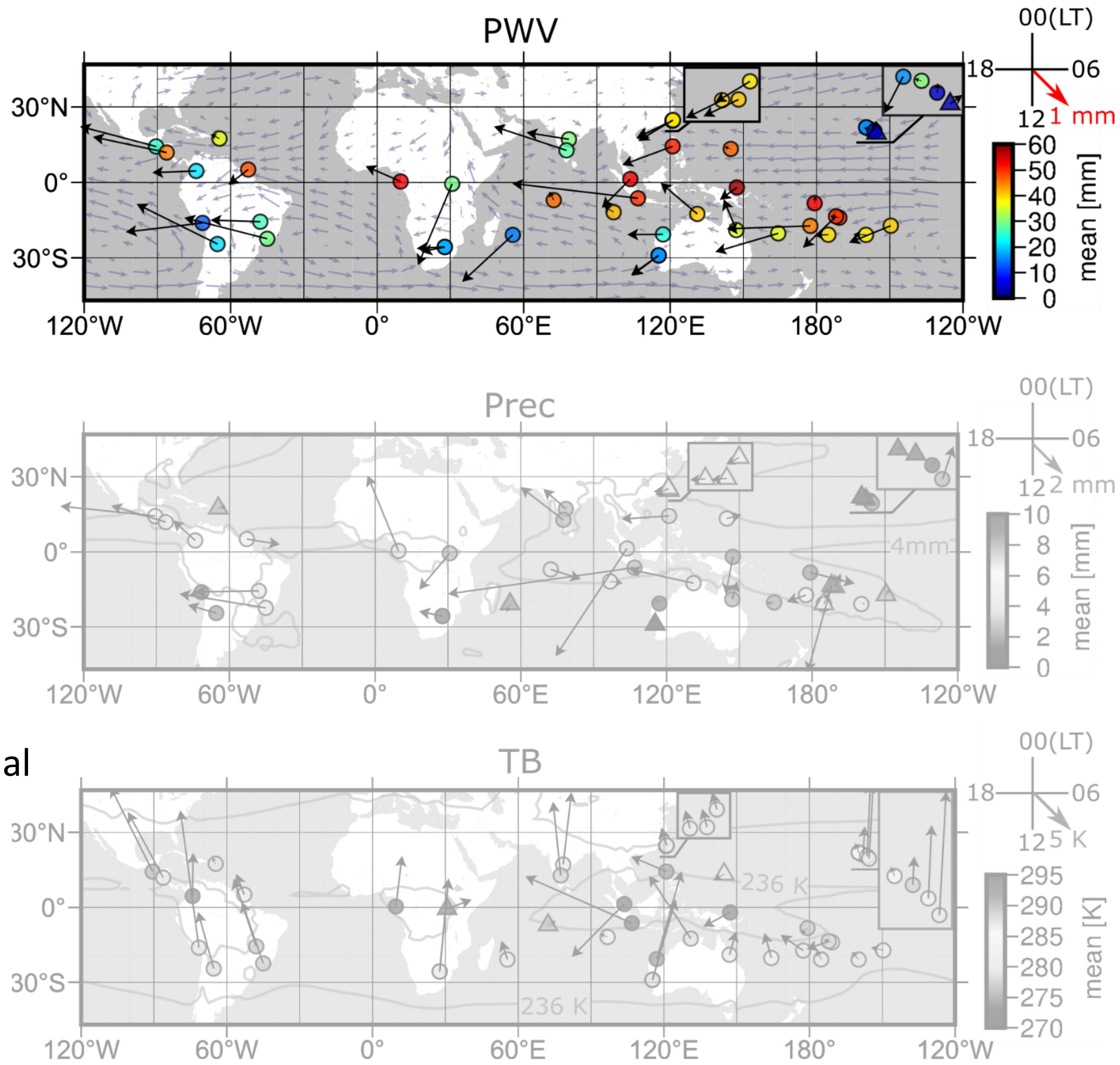
- GNSS allows us to identify visible differences between analysed stations
- Daily mean PWV ranges from 3.64 to 57.52 mm – determined by station location and altitude
- Continental and large island stations show larger diurnal amplitude of PWV than small islands
- Amplitudes of diurnal PWV variations are small compared to daily mean values (0.13 - 2.47)

distinct diurnal




distinct semi-diurnal

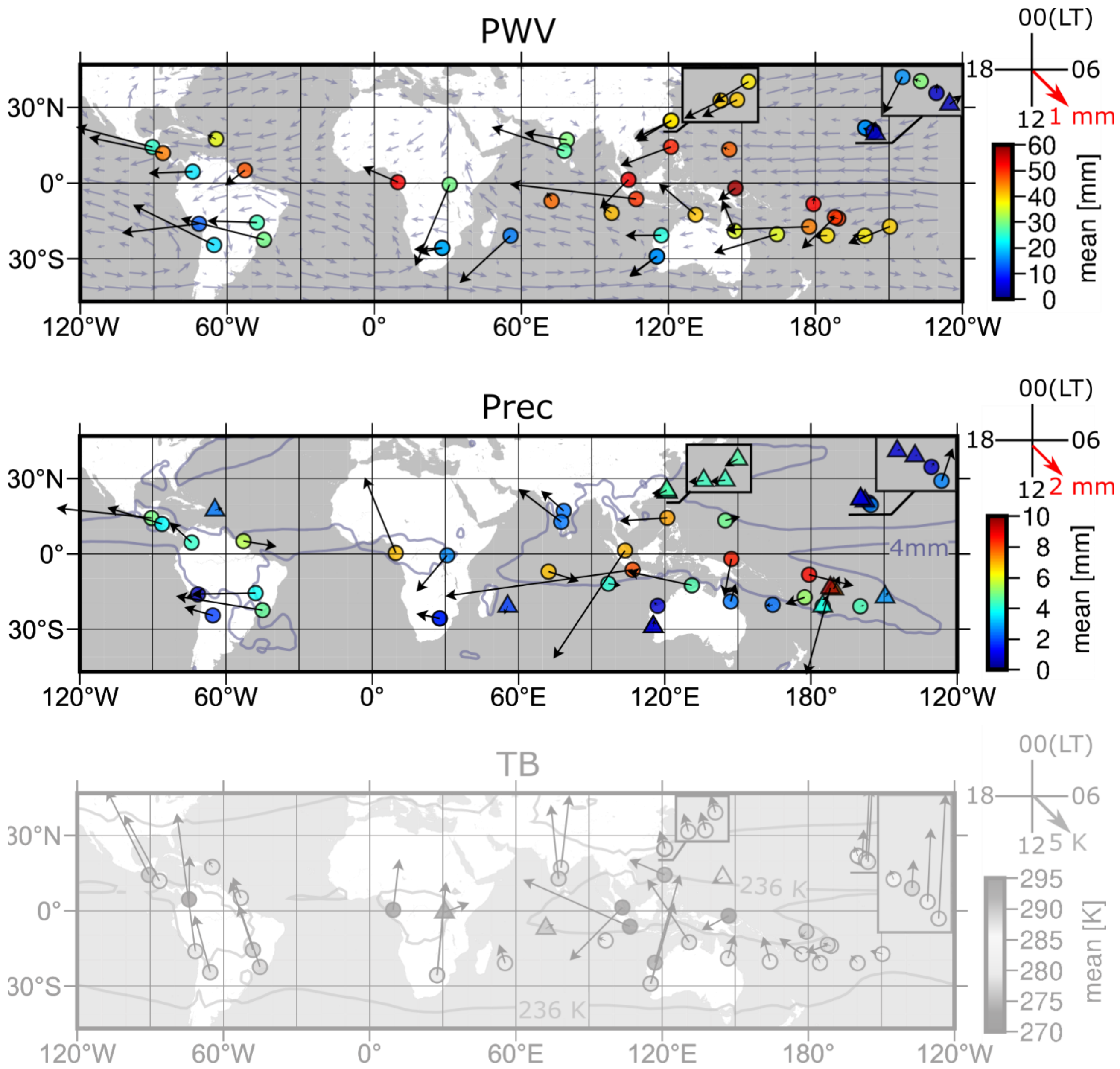


# Tropical moisture: diurnal variability

Precipitation

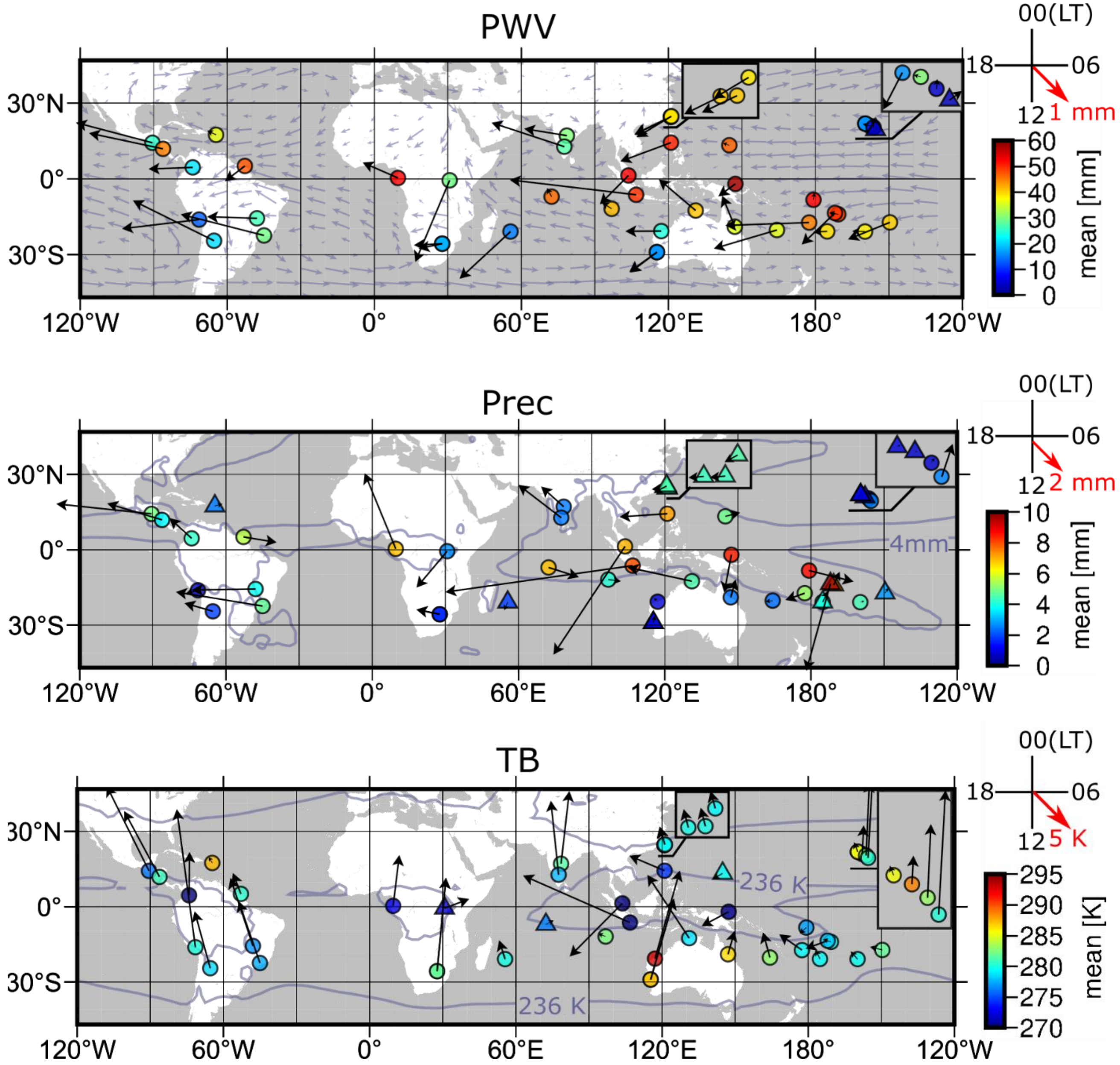
- High PWV values are associated with high precipitation rates (e.g. BAKO), and low PWV values correspond to small precipitation values (e.g. AREQ)
- diurnal amplitude is high over continental and large island stations, where precipitation peaks in the local afternoon
- 30% of stations are characterized by a semi-diurnal precipitation amplitude exceeding a diurnal one.
- The semi-diurnal cycle is the primarily subdiurnal mode at small islands that show an overall small diurnal variation.



# Tropical moisture: diurnal variability

Cloud top temperature (TB)

- the evolution is dominated by diurnal cycle
- substantially larger diurnal variation over continental and large islands than small islands
- shift in the phase towards later hours in comparison with diurnal peak in either PWV or precipitation



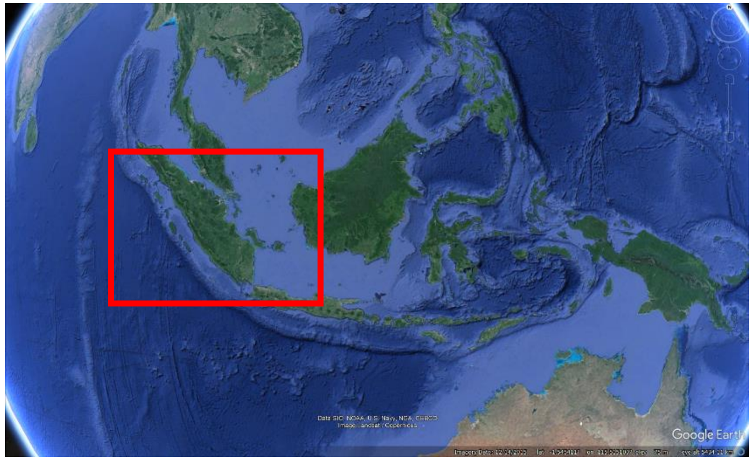

PWV has a mono-modal distribution on a diurnal time scale

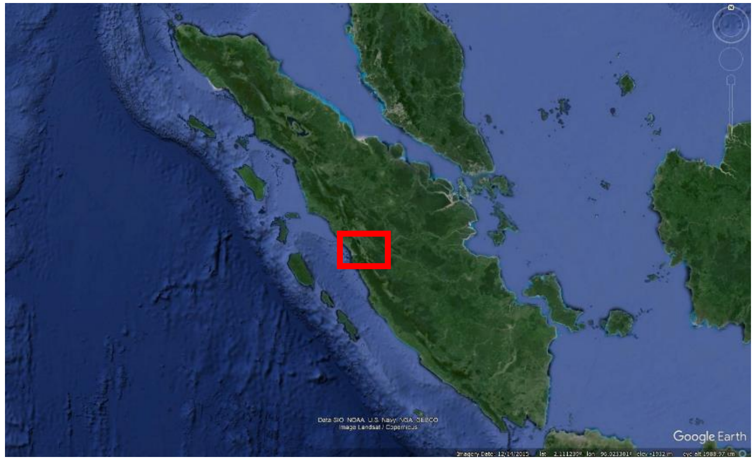
PWV diurnal variability is smallcompared  to average

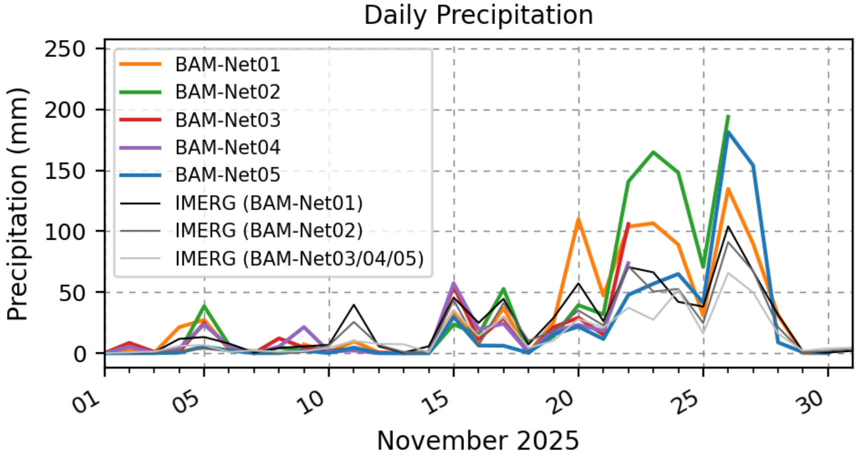
Precipitation has double peak on small Island

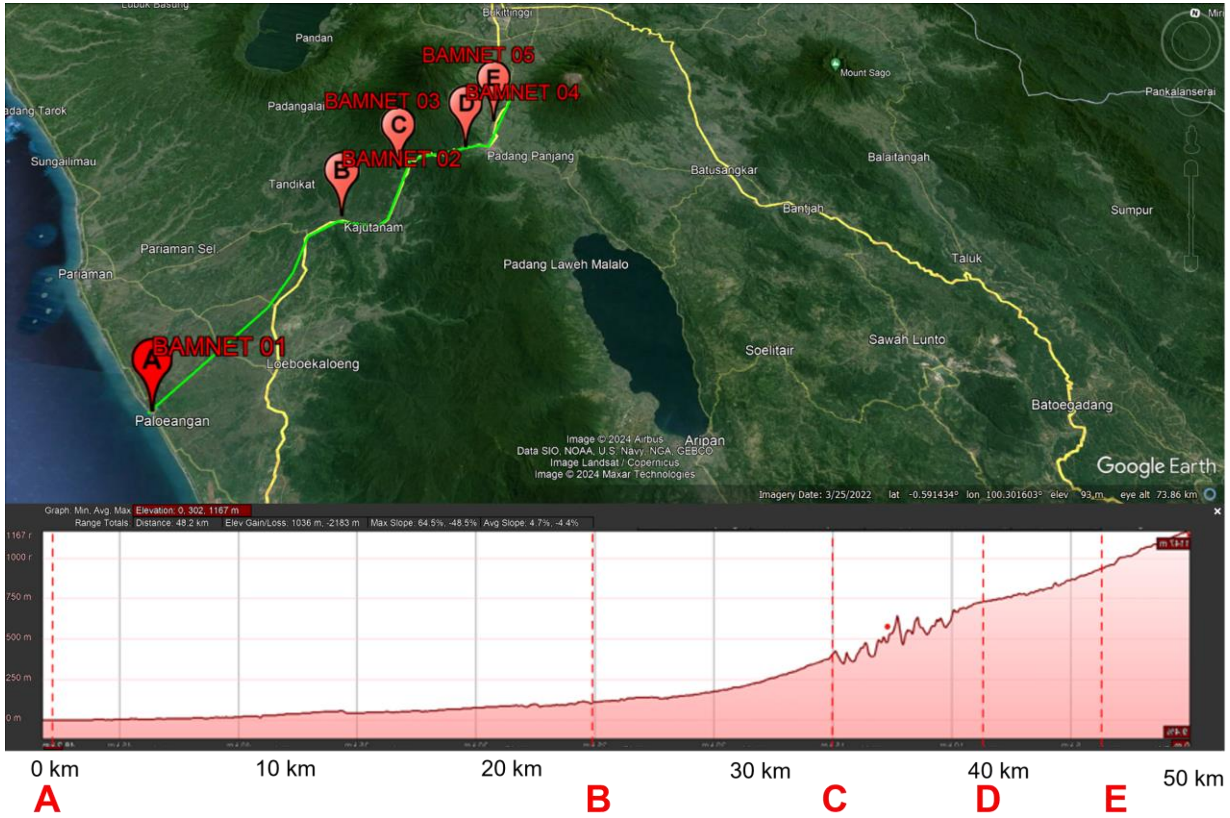
Clouds peak is shifted towards later hours

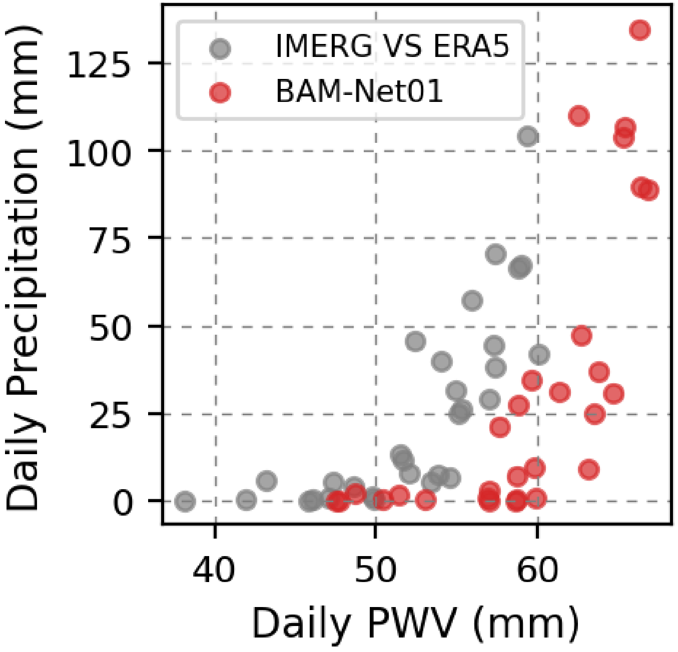
# Tropical moisture: diurnal and subdiurnal variability



# The GNSS meteorology in tropical moisture variability – summary

- GNSS has ability to deliver integrated moisture data with an accurracy comparable to RS, and even 30 year observations
- GNSS IWV observations offer temporal resolution adequate for studying both interannual and diurnal variability, while their spatial resolution allows the analysis of the spatial variability of these processes
- We were able to study a diurnal evolution of integrated moisture and found out that it is characterized by a mono-modal distribution, unlike e.g. the precipitation

But GNSS has also another advantages that were used in our studies

# The GNSS Reflectometry

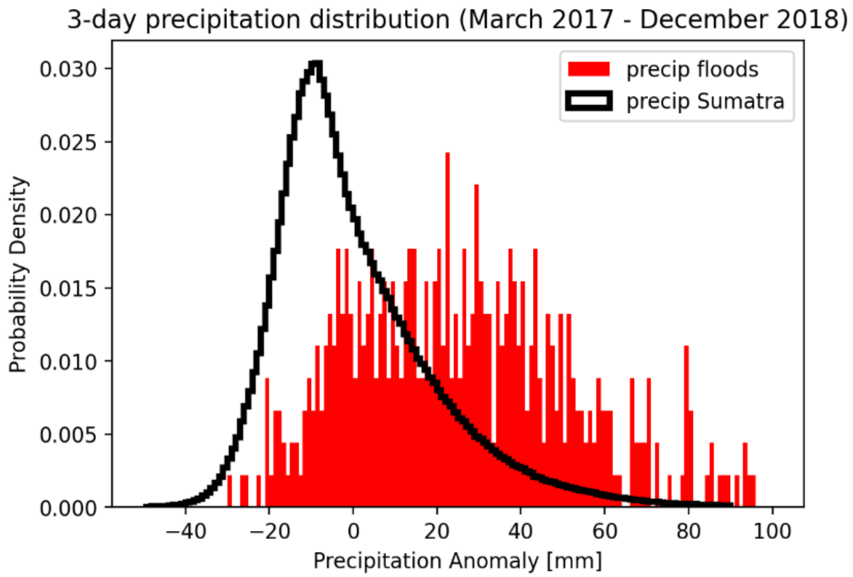
There is an improvement in understanding of tropical dynamics which translates to better model representation and improved forecast skill of an extreme precipitation.

VOLUME 154 MONTHLY WEATHER REVIEW MARCH 2026

**The Role of Equatorial Waves in Triggering Precipitation Extremes in the Maritime Continent**

BEATA LATOS,[a] SAMANTHA FERRETT,[b,c] THIERRY LEFORT,[d] ADRIAN J. MATTHEWS,[e] SANDRO W. LUBIS,[f] NATASHA V. SENIOR,[c] PHILIPPE PEYRILLÉ,[g] HANH NGUYEN,[h] MATTHEW C. WHEELER,[h] JEONG-YIK DIONG,[i] DARIUSZ B. BARANOWSKI,[j] MARIA K. FLATAU, PIOTR J. FLATAU,[k] IDA PRAMUWARDANI,[l] FADHLIL R. MUHAMMAD,[m,n] DONALDI S. PERMANA,[l] MUHAMAD R. FERDIANSYAH,[l] AGIE WANDALA,[l] KIKI,[l] IDHAN ABUBAKAR,[l] TITO PRADITYA,[l] EDDY HERMAWAN,[o] AND JACEK PISKOZUB[a]

While relationship between precipitation and floods may appear obvious, it is not.



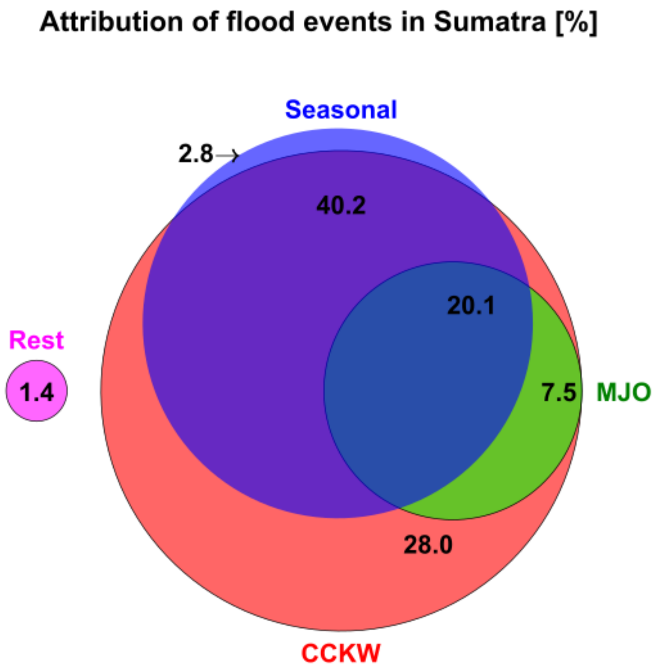

**The key limitation in understanding a proper link between precipitation and floods occurrence is a robust, coherent and long-term flood data.**

# The GNSS Reflectometry

Methods for flood data access:

SUBJECTIVE DATA SOURCES

- Goverment reports/database – require human-based observation and subsequent reporting it
- Crowd sourced:
  - newspapers  - but the highest attention to large events
  - social networks - but the highest attention to large events




Baranowski et al.2021

OBJECTIVE DATA SOURCES

- Satellite
  - optical (e.g. VIIRS/LANDSAT) – but cloud cover/dense vegetation
  - active radars (e.g. Sentinel-1/PALSAR) – but revisit time
  - microwave radiometers (e.g. SWAMPSv3/GIEMS-2) – but spatial resolution
- In situ observations – irregular observational network

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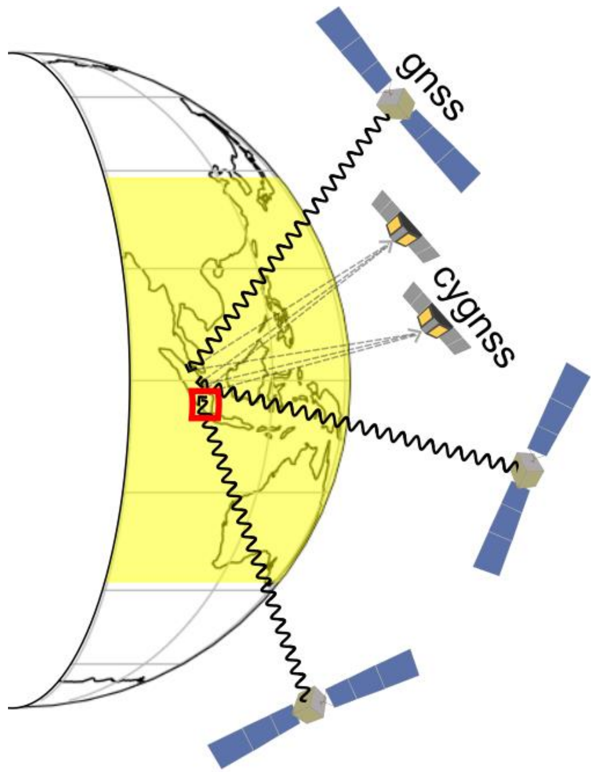
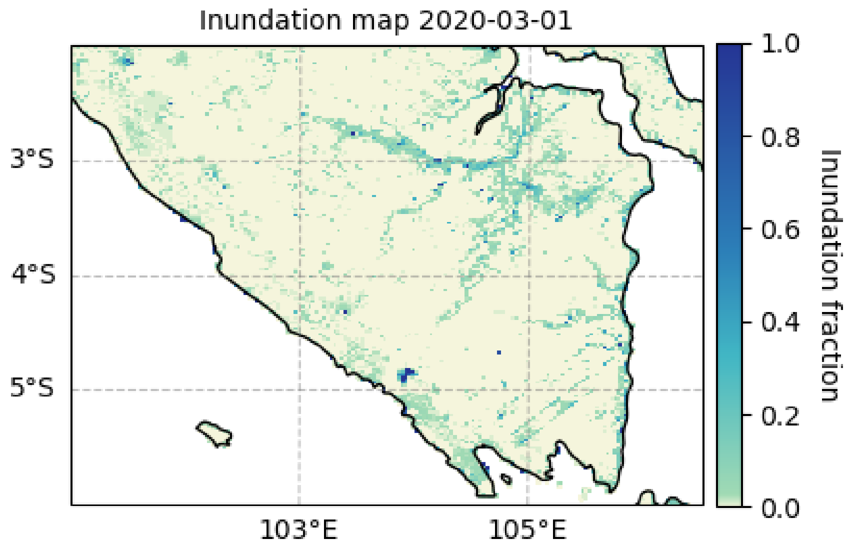
Alternative:
GNSS-Reflectometry




**CYGNSS deliver information about surface properties based on characteristic of reflected GNSS signal**

# The GNSS Reflectometry – Cyclone GNSS (CYGNSS) dataset





Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL118111

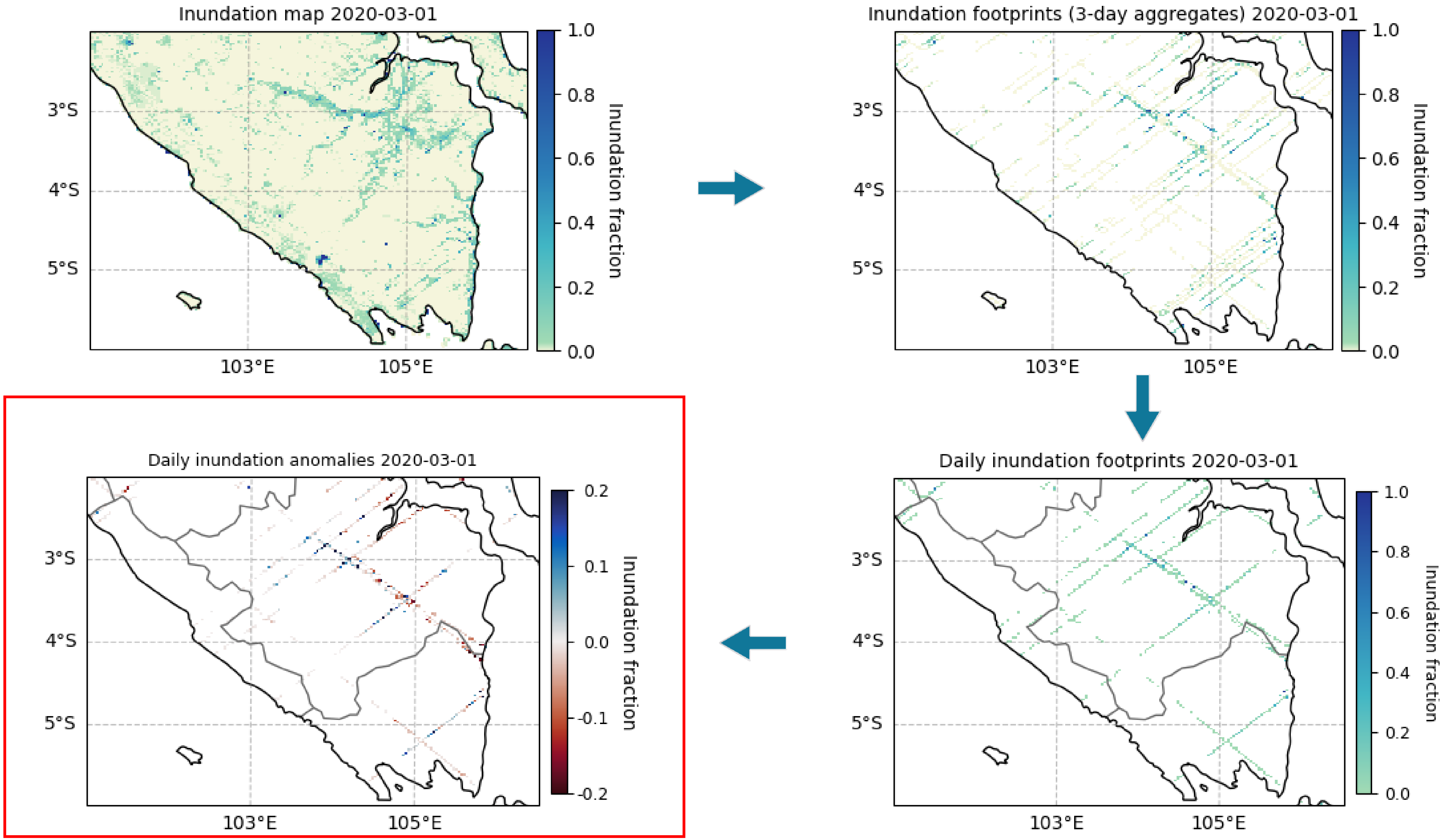

**Key Points:**

- Lack of reliable long-term records of small and regional floods across global tropics hinders understanding their dynamics and forecasting

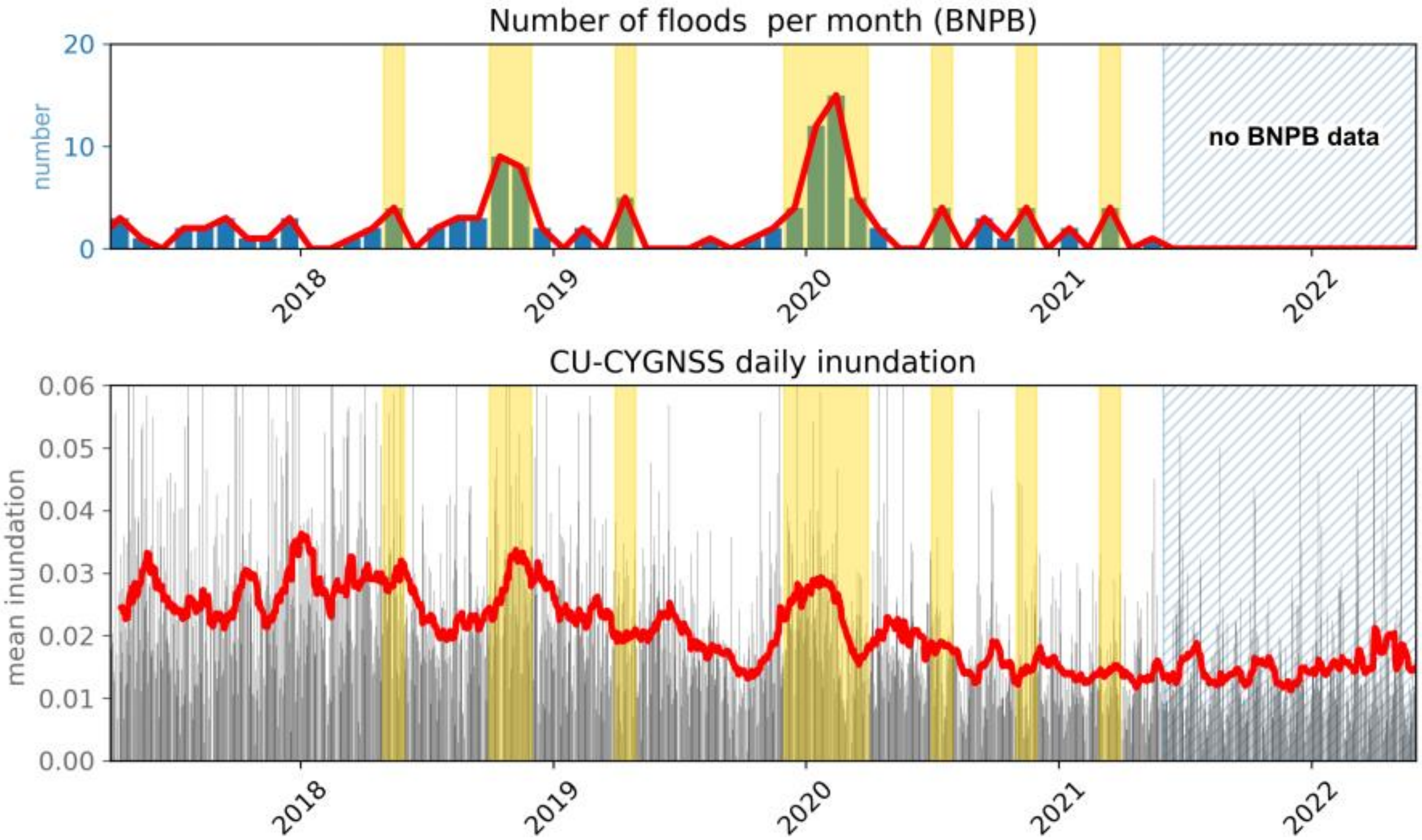
## Detecting Localized Floods in Tropical Regions With CYGNSS SmallSat Constellation: A Proof of Concept From the Maritime Continent


**Zofia Baldysz[1], Dariusz B. Baranowski[1], Piotr J. Flatau[2], Maria K. Flatau[1], and Clara Chew[3]**

# The GNSS Reflectometry



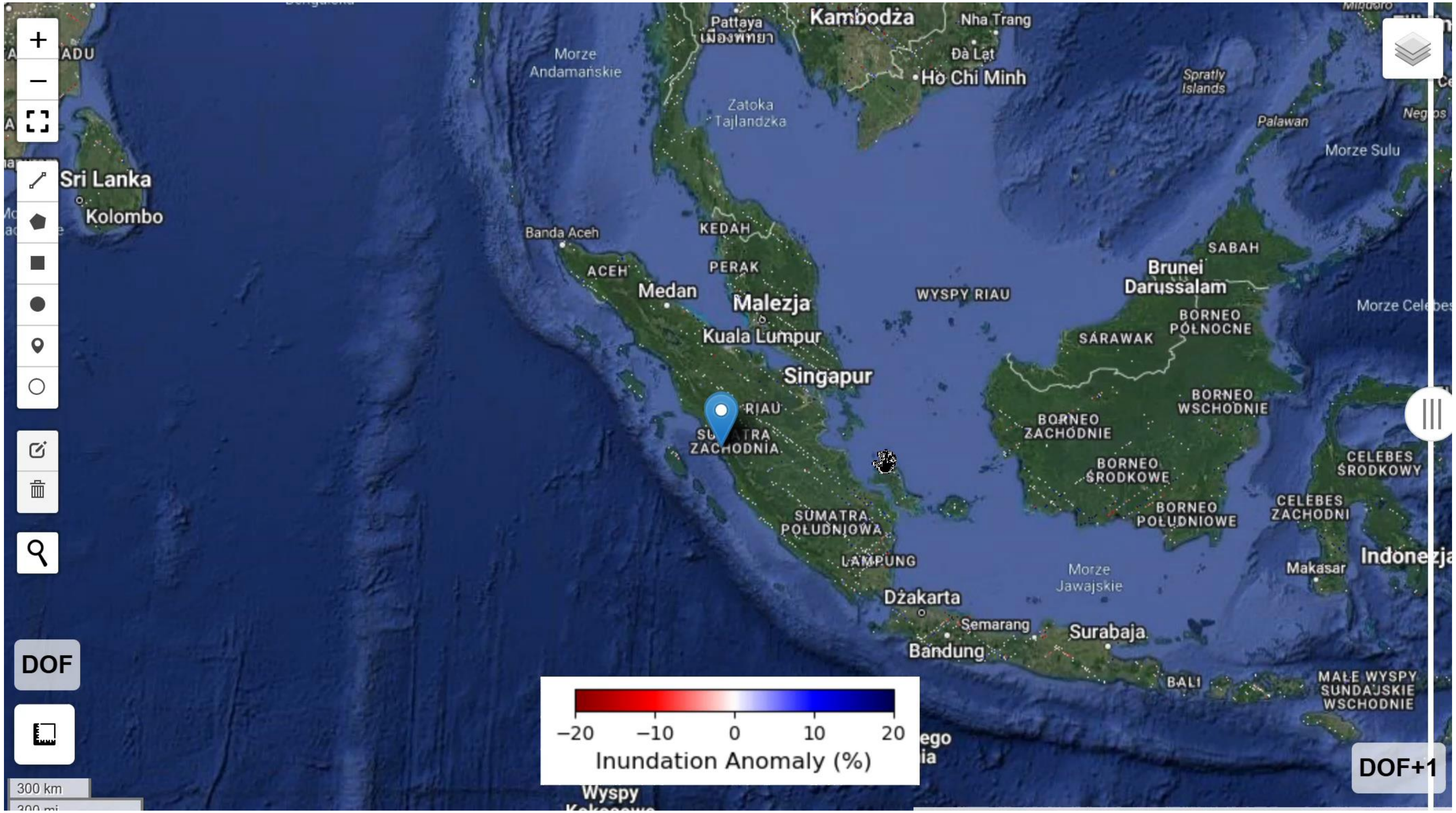
# CYGNSS for floods objective identification



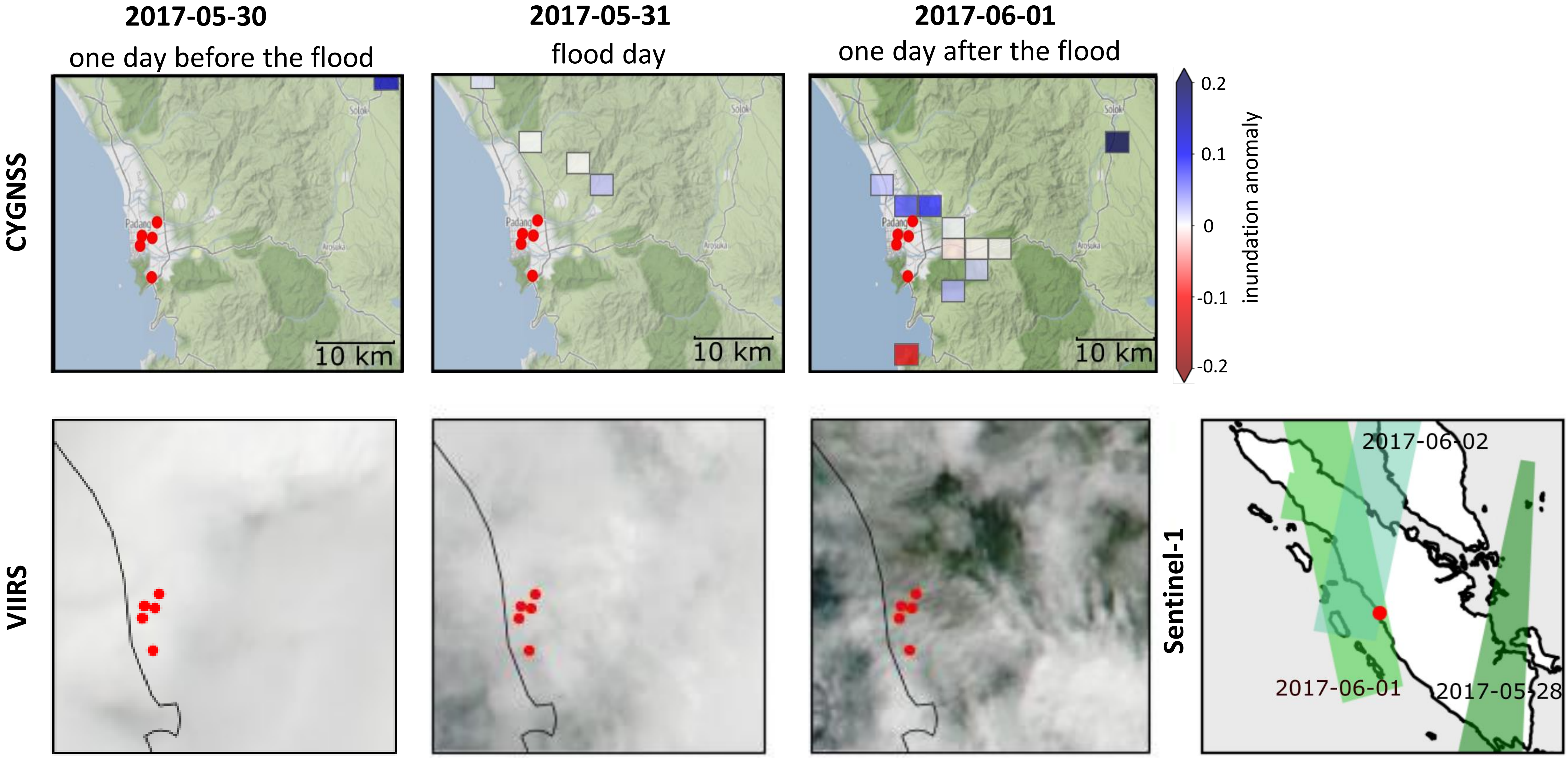
# CYGNSS small-scale floods identification

Case study:
Flood in Padang
(31.05.2017)

- CYGNSS can capture CCKW inducted flood
- CYGNSS can detect submerged areas under city-scale



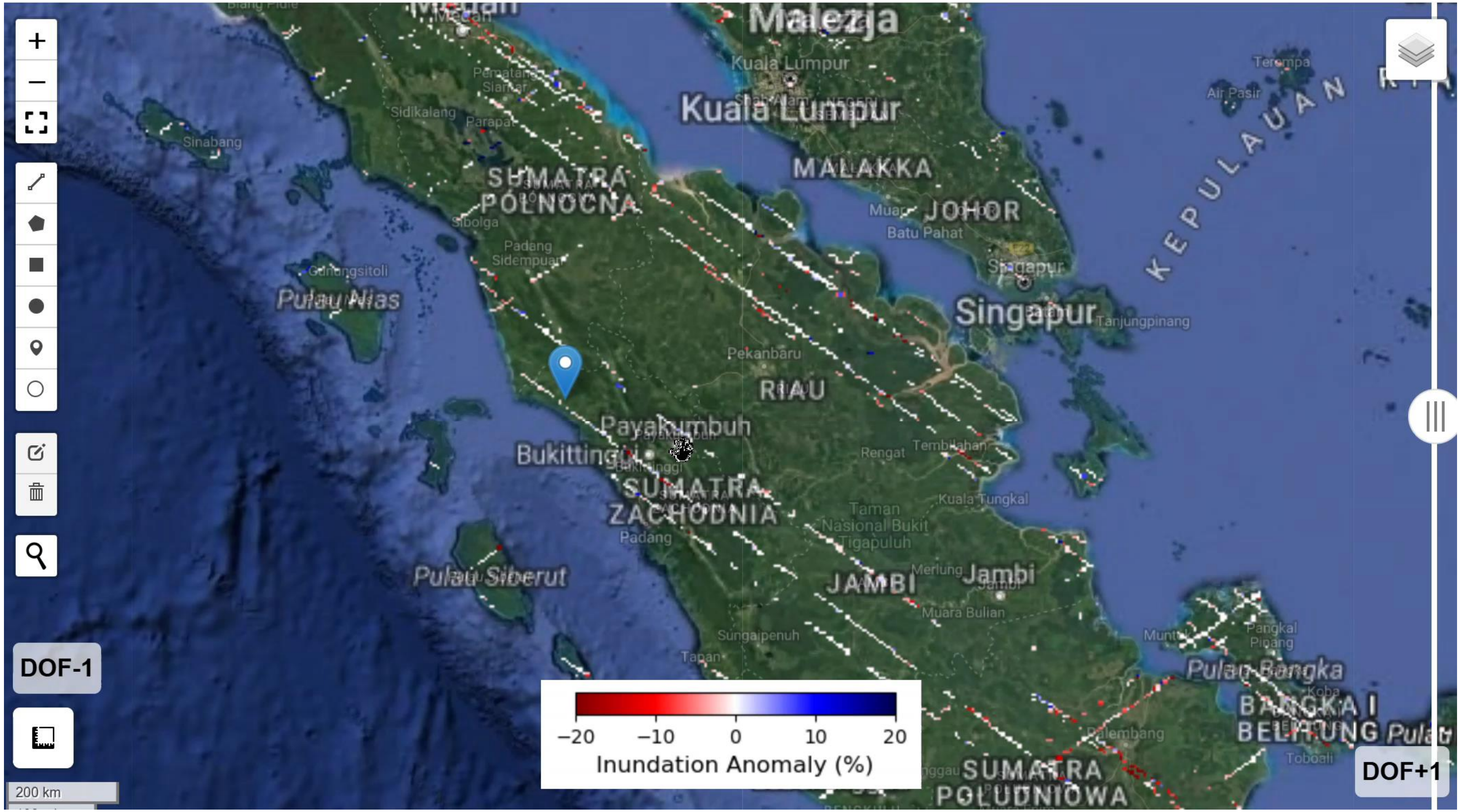
# CYGNSS small-scale floods identification



# CYGNSS small-scale floods identification

Case study:
Flood in Pasaman Barat
(20.08.2019)

- CYGNSS can detect floods in areas with a lower likelihood of being reported, such as less urbanized regions.
- CYGNSS data from a similar trajectory can illustrate day-to-day evolution and reveal flood dynamics.



# CYGNSS – case study summary

- CYGNSS “captured” the events from the flood databases.
- The CYGNSS anomalies appear to be more positive near the flood locations.
- The number of CYGNSS positive anomalies increases one day after the flood.

Is it possible to identify CYGNSS signal characteristics that would allow the detection of previously unknown flood events?

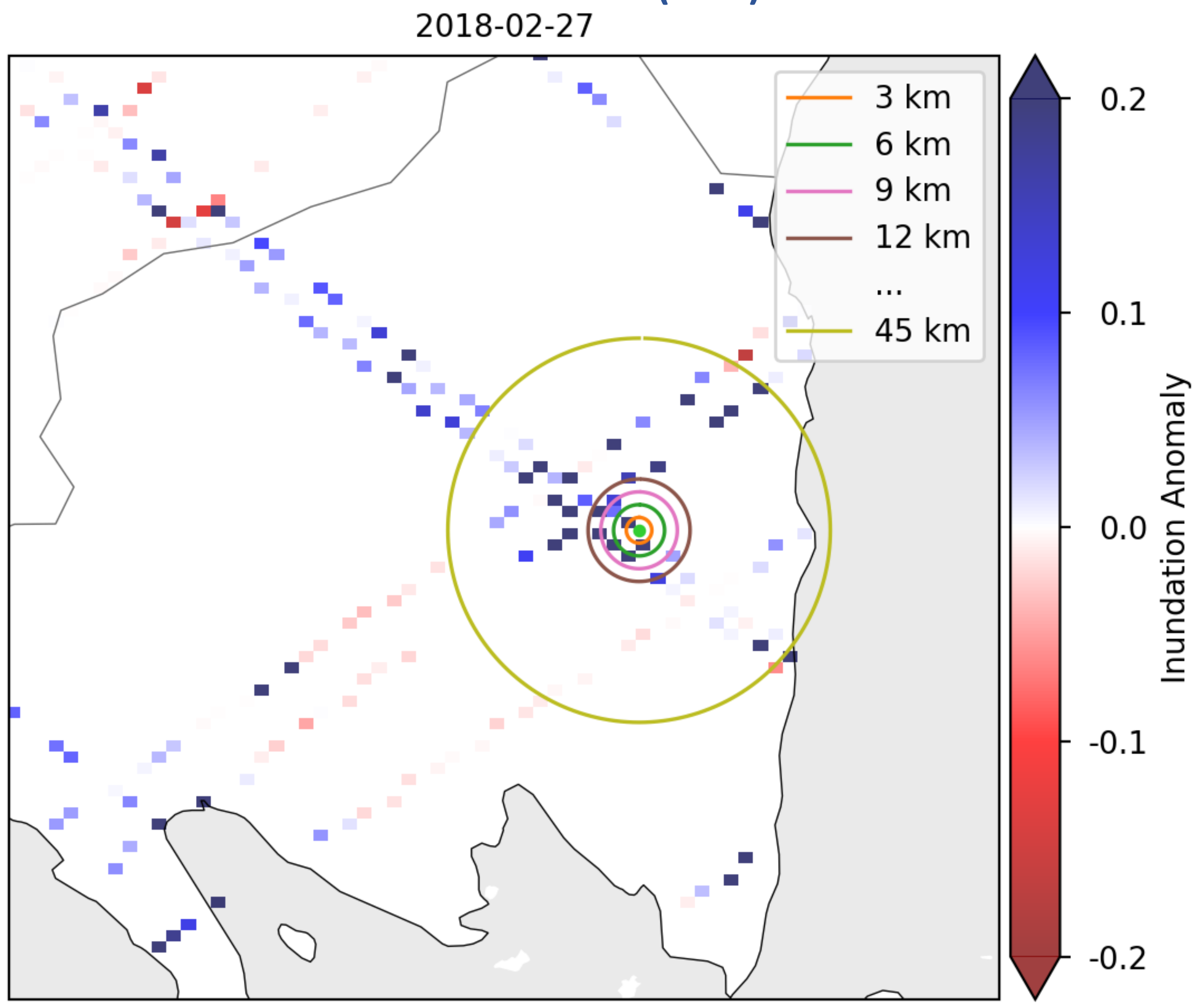
The characteristics of CYGNSS anomalies were analysed as a function of distance from the flood and time relative to the flood.

# CYGNSS – etablishing a threshold for flood detection

- We analyzed 555 reliable flood records from a newspaper database.

- We considered CYGNSS data at various distances from the flood location.

## DAY OF THE FLOOD (DOF)



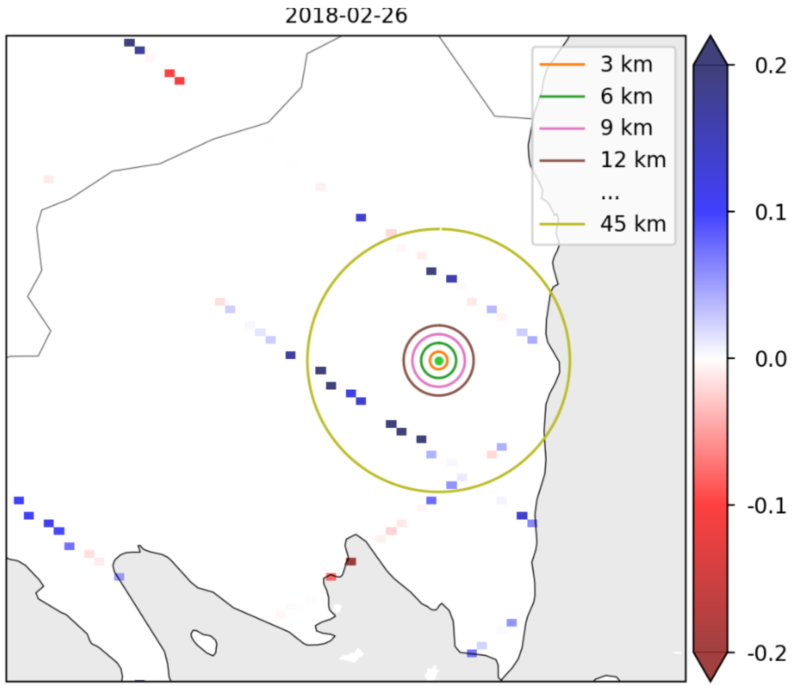
# CYGNSS – etablishing a threshold for flood detection

- We analyzed 555 reliable flood records from a newspaper database.
- We considered CYGNSS data at various distances from the flood location.
- We examined CYGNSS inundation anomalies on the day before the flood, the day of the flood, and the day after.
- We aggregated detected CYGNSS anomalies by day (before, during and after the flood) and distance across all identified cases.

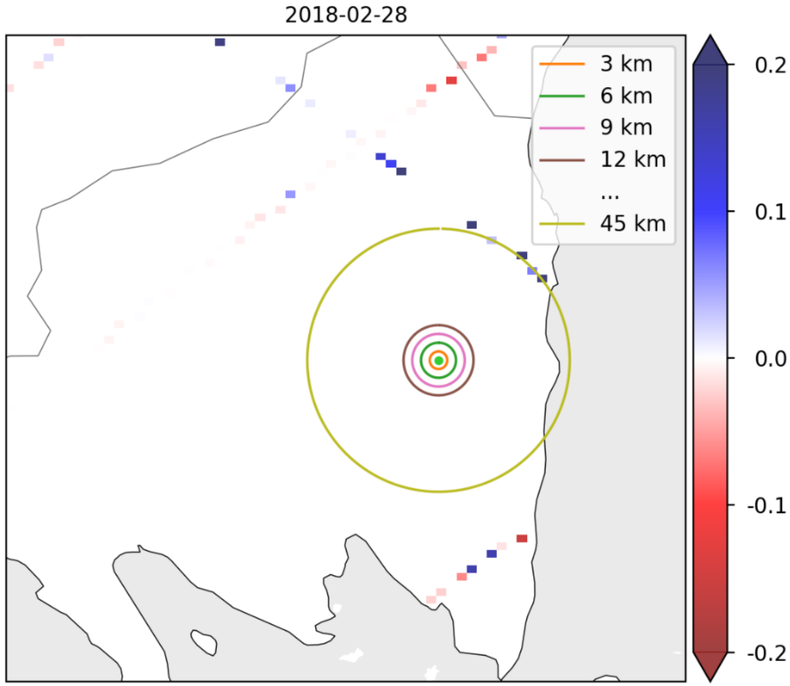
DAY OF THE FLOOD (DOF)




DAY BEFORE THE FLOOD (DOF -1)

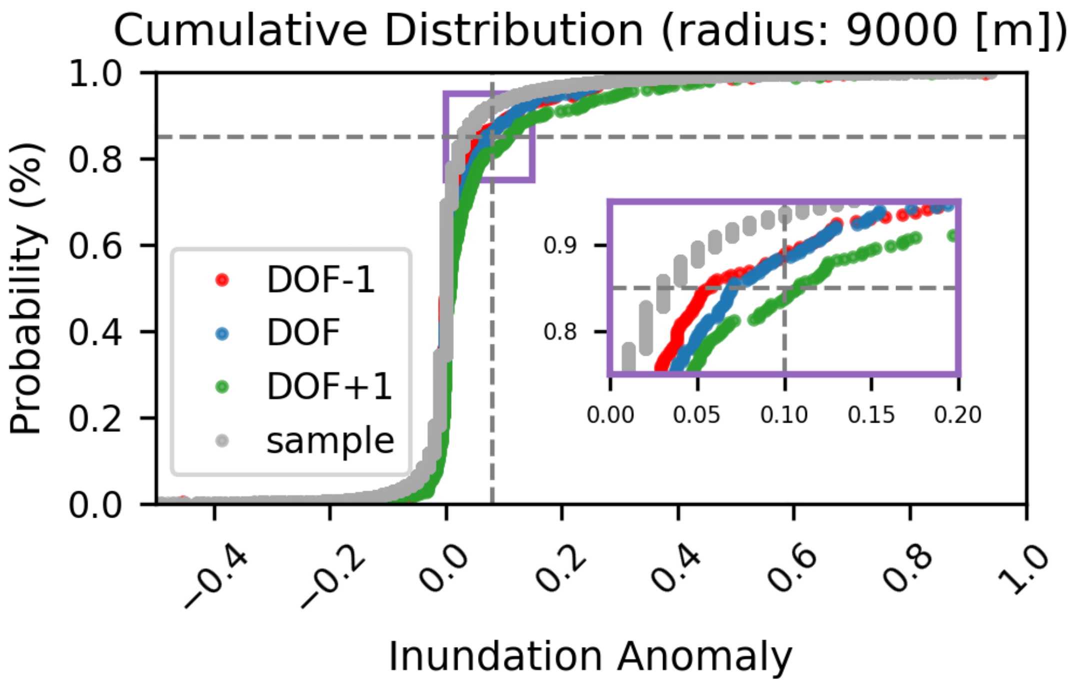



DAY AFTER THE FLOOD (DOF +1)



# CYGNSS – etablishing a threshold for flood detection

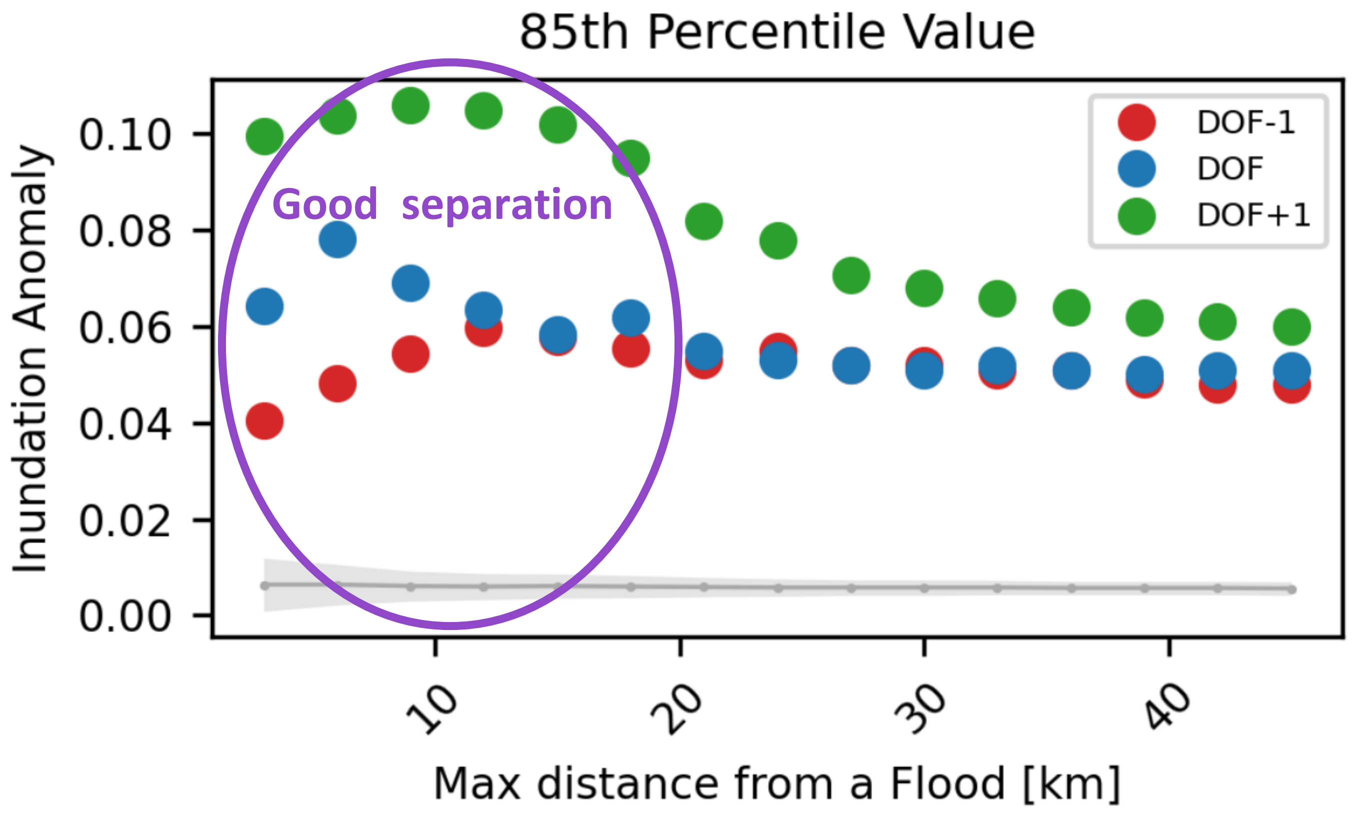
Cumulative distribution of aggregated CYGNSS anomalies and identification of the interval characterized by the greatest separation between data from before and immediately after the flood.




**Anomaly value 0.1:**
- **Good separation between distributions**
- **85th percentile for DOF+1**
- **93th percentile for random sample**

# CYGNSS – etablishing a threshold for flood detection

Cumulative distribution of aggregated CYGNSS anomalies and identification of the interval characterized by the greatest separation between data from before and immediately after the flood.



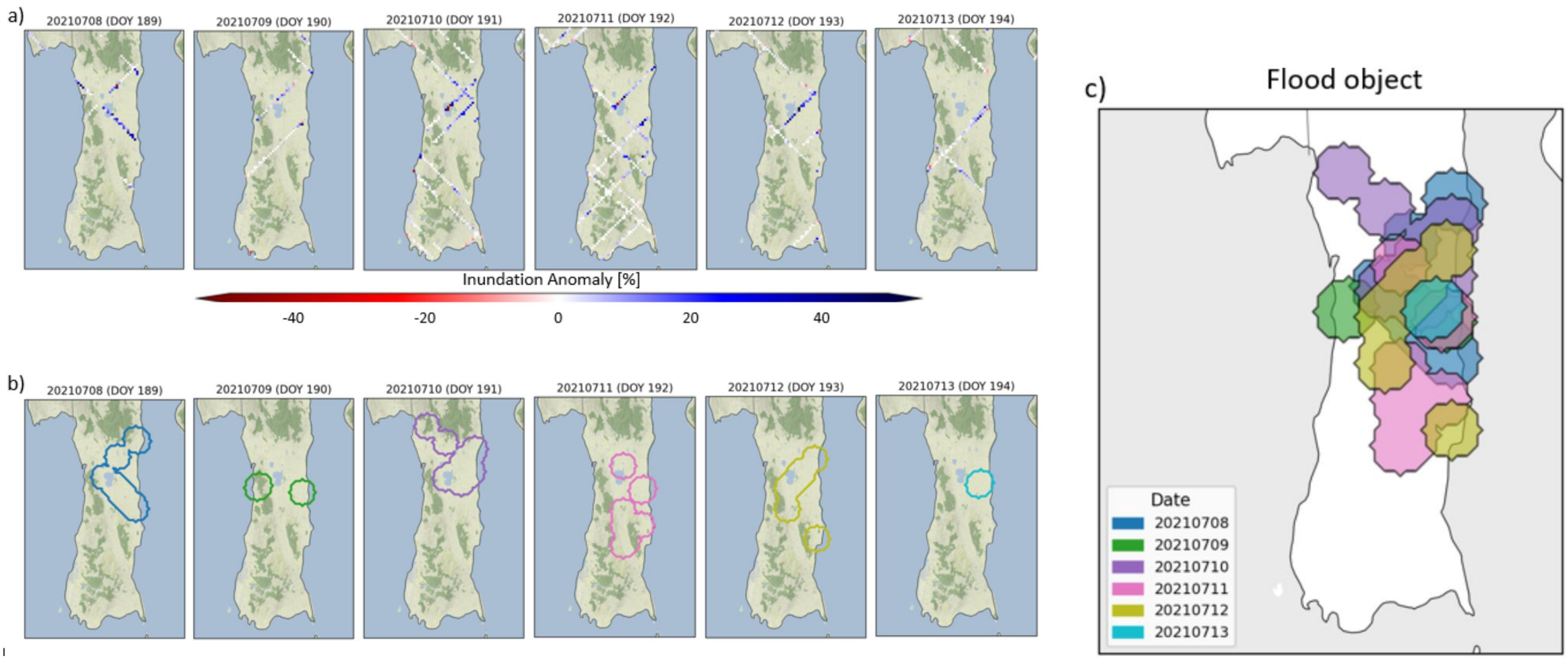

**Distances between 9 and 18 km around the flood represent a fair compromise between data availability and characteristic differences, allowing for flood evolution monitoring**

# CYGNSS – automatic flood detection

What we do:

- calculate anomaly distribution for given region
- take the value of 93th percentile of this distribution
- ekstrapolate such values for 18 km distance

→ Automatic detection in space and time of abnormally high inundation area (possible floods)



# What do we get by using GNSS?

- Using existing infrastructure, while new stations can be cost effective.
- Very high temporal resolution (even every 15 seconds) and long time series (multi-scale processes)
- Can augument automatic weather station data
- GNSS-R provides characteristic of Surface properties (e.g. soil moisture, wind speed or floods) with relatively high spatial and high temporal resolution.
- Satellite-based GNSS-Rr is sensitive to even small-scale and short-lived floods and canprovide robust andlong-termmonitoring of floods events.
- There is a growing numer of GNSS-R missions, including governmental and private sector (HydroGNSS, FireSat).

# Thank you for your attention!

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# Tropical moisture: long-term variability