IGS 2026 WORKSHOP
SANTIAGO DE CHILE
33°26' S 70°39' O

Recent Advances in Ground-based GNSS Atmospheric Monitoring

(Datasets, Methodologies, and Applications)

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RMIT UNIVERSITY

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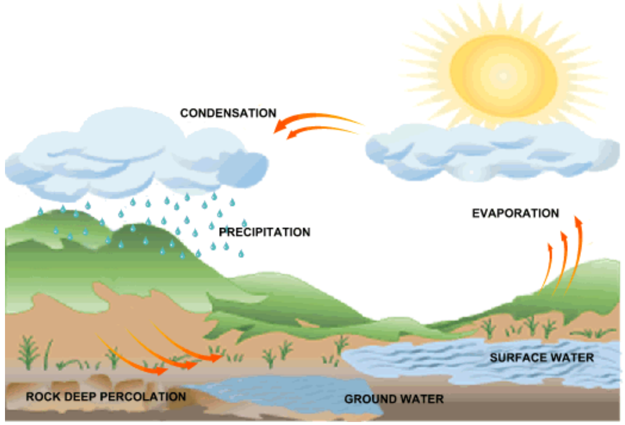
Outline

1. Background and motivation
2. Generation of ground-based GNSS atm. params.
3. Analysis of ground-based GNSS atm. params.
4. Applications of ground-based GNSS atm. params.
5. Summary and outlook

1. Background and Motivation

- **Weather and Climate Extremes pose risks on human society**
  - **1.5B** people already affected; **U$200M/d** economic losses;
  - **Detection and nowcasting – mitigate detrimental impacts.**

- **Water Vapor affects atm. dynamics, energy budgets, and water cycle**
  - Active natural greenhouse gas (**60-70%** of global warming);
  - **Continuous and accurate monitoring.**



- **Advanced Ground-based GNSS Atm. Monitoring**
  - High spatiotemporal resolution, accurate, and all-weather capability;
  - **Long-term data vs. NRT/RT data.**

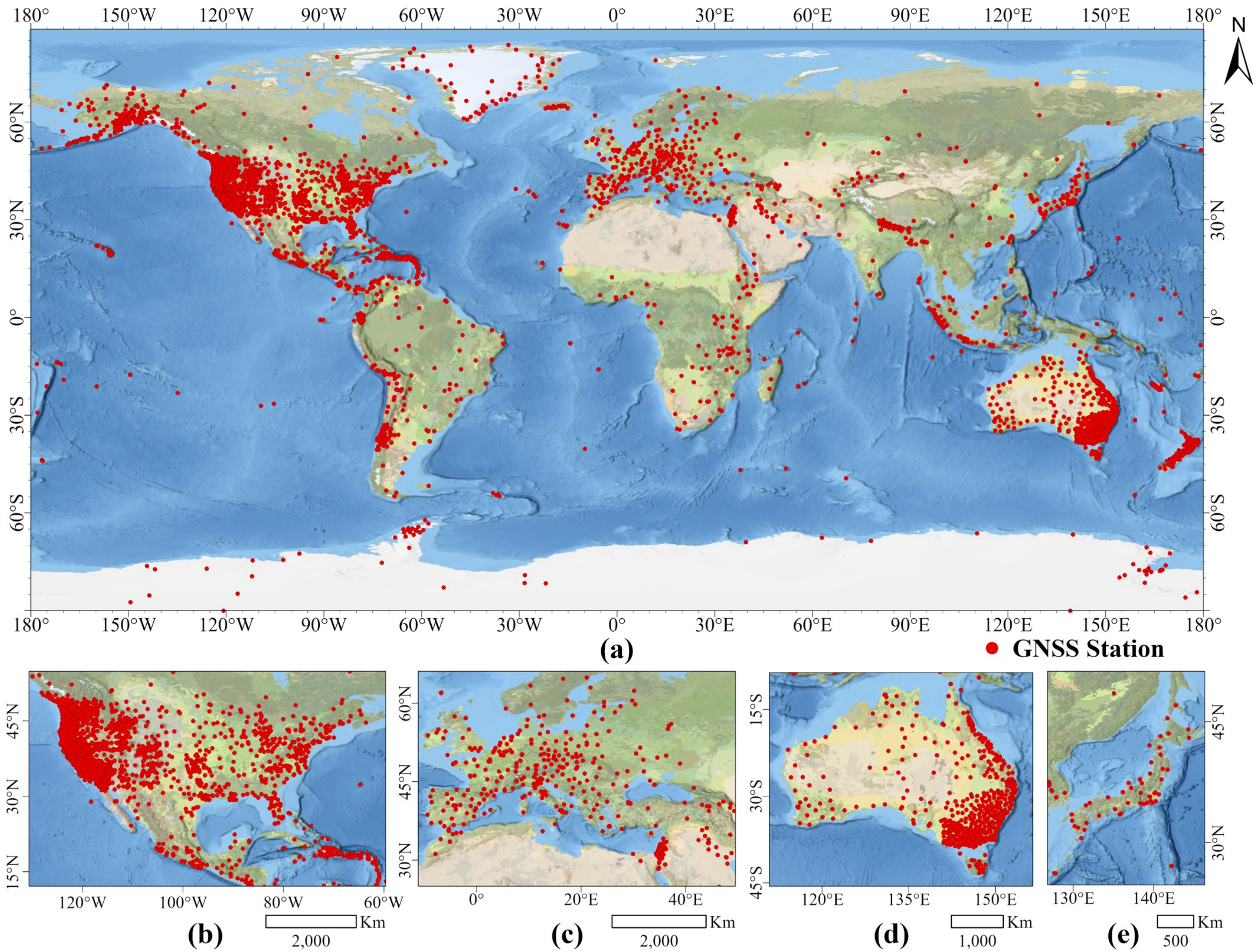
- **Proven value of ZTD & PWV in meteorological & climate science**

Generation

of ground-based GNSS atm. params.

2. Generation of GNSS atm. params.

(1) Long-term re-processed GNSS climate record (ZTD and PWV)



- ✓ **5085** stations
- ✓ up to **22 years** (2000-2021)
- ✓ **hourly** dataset
- ✓ subjected to **quality control**
- ✓ **Derivatives:**
  - Min & Max
  - Daily & Monthly mean
  - Climatological Standard Normals (Pentad, dekad, and monthly)

Wang, Li, Choy et al. *Earth System Science Data* (2025)

2. Generation of GNSS atm. params.

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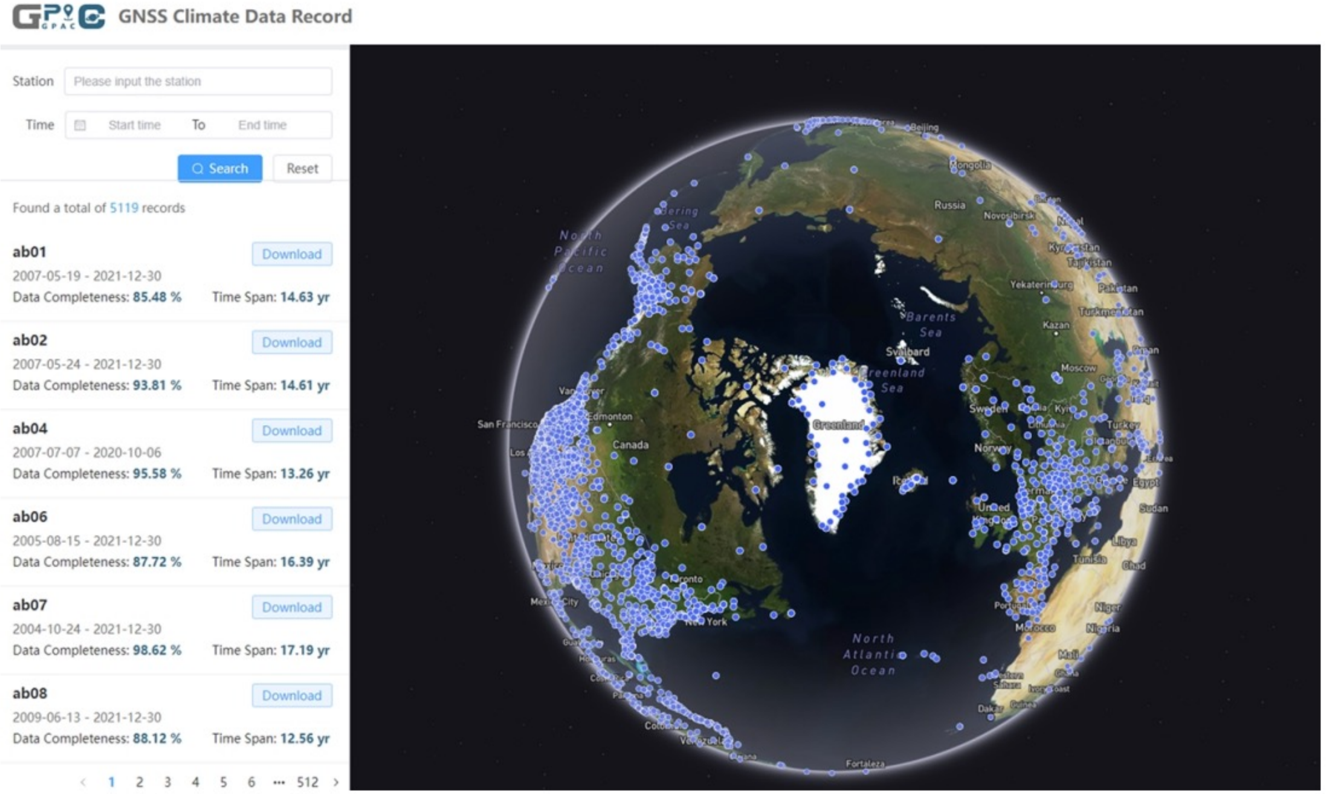

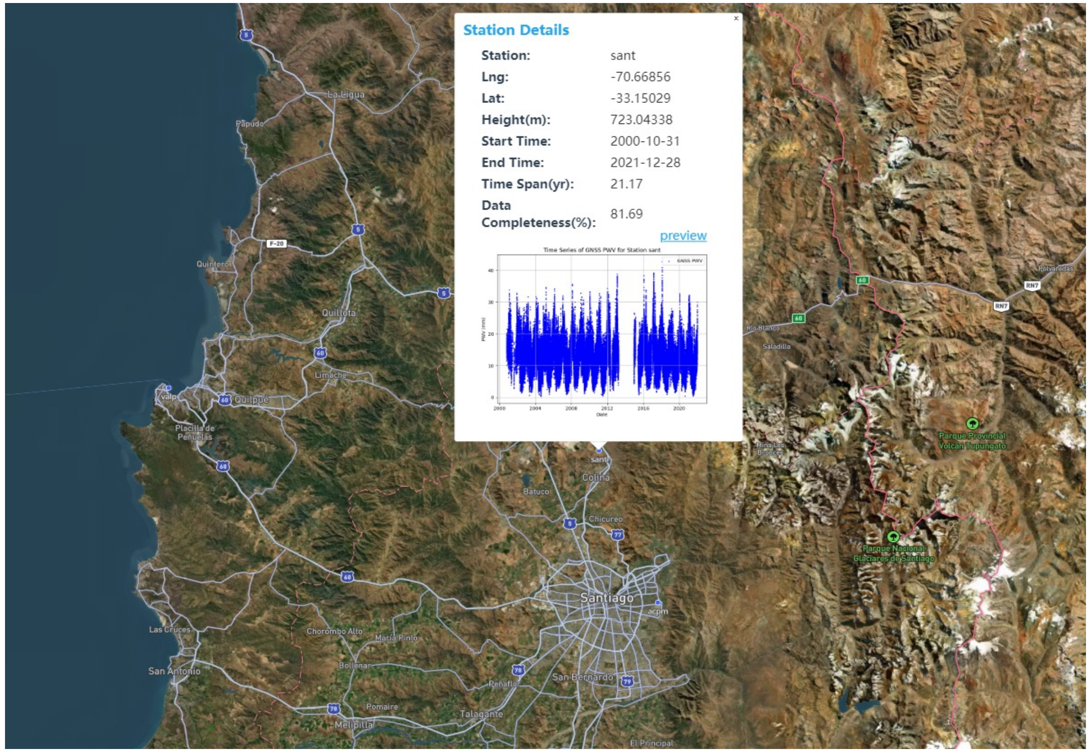

https://www.gnss.studio/Login

2. Generation of GNSS atm. params.

(2) Final products

- From 2022 to 2026, 4000+ stations, 5-min
- Delay: 3 Weeks (IGS Final products)

(3) Rapid products

- From 2022 to 2026, 4000+ stations, 5-min
- Delay: 1-3 days (IGS Rapid products)

(4) NRT products

- 500+ stations, 5-min
- Delay: less than 1 hour

(5) RT products (ZTD)

- 300-500 stations, 1-min
- Delay: without delay

Collaborating with industry and government stakeholders

Analysis

of ground-based GNSS atm. params.

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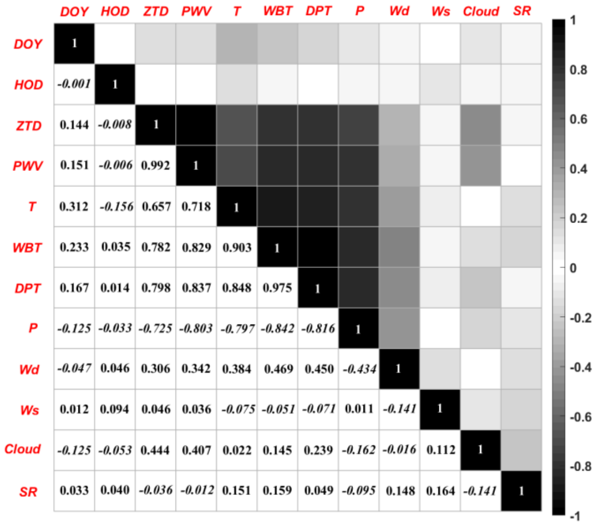
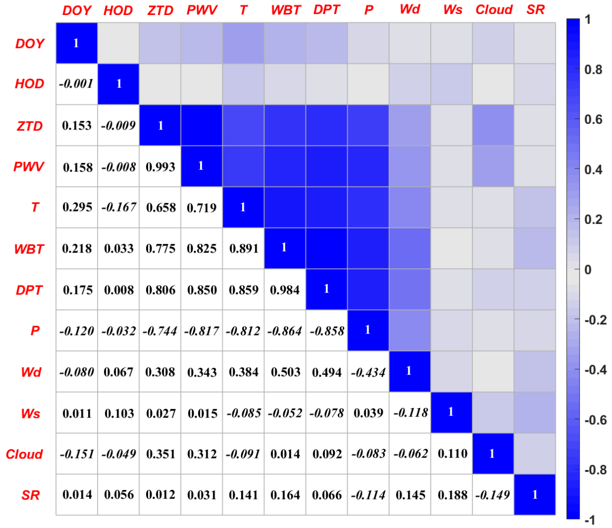
3. Analysis of GNSS atm. params.

3.1 Inter-relationship – statistical analysis



PCC results

- **Linear relationship**



SCC results

- **Monotonic relationship**

➢ **Higher correlations among ZTD, T, PWV, WBT, DPT, P**

- Calculation mechanism;
- Represented atm. states.

➢ **DOY/HOD vs. T**

- seasonal/diurnal cycles

➢ **Cloud vs. ZTD/PWV**

➢ **GNSS atm. params.**: ZTD and PWV.

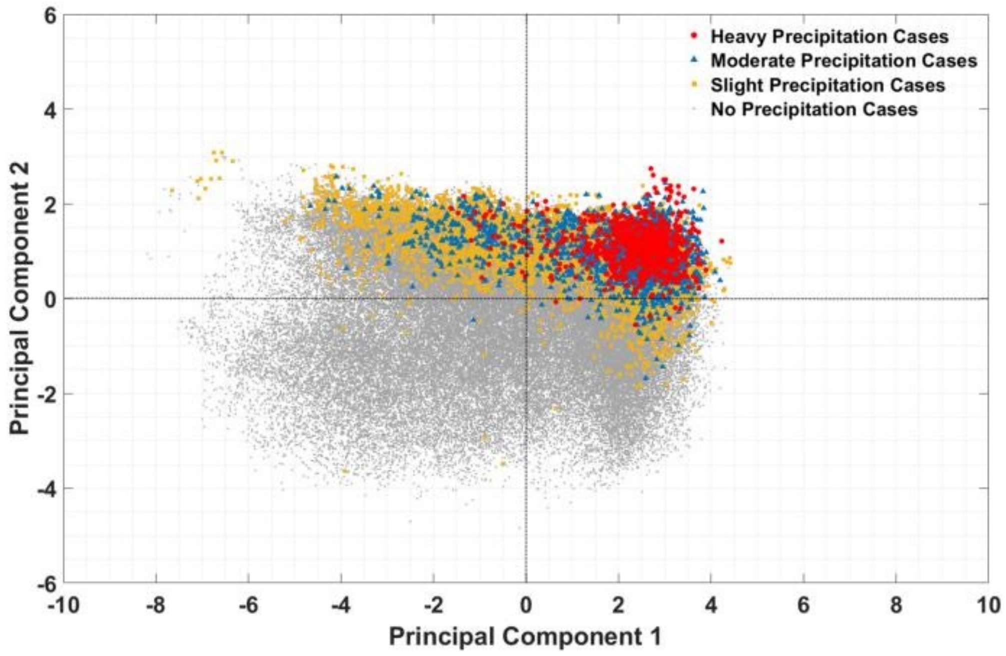
➢ **Met. params.**: dry-bulb temperature (T); wet-bulb temperature (WBT); dew point temperature (DPT); pressure (P); solar radiation (SR); cloud coverage (cloud); wind speed (W_s); wind direction (W_d).

➢ **Stat. params.**: day-of-year (DOY); hour-of-day (HOD).

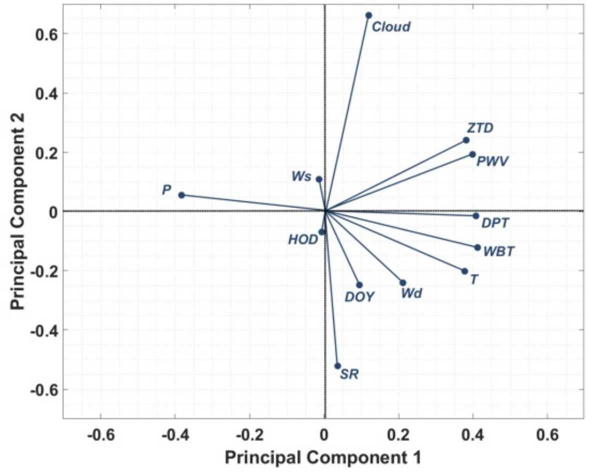
3. Analysis of GNSS atm. params.

3.2 Principal component analysis – statistical analysis

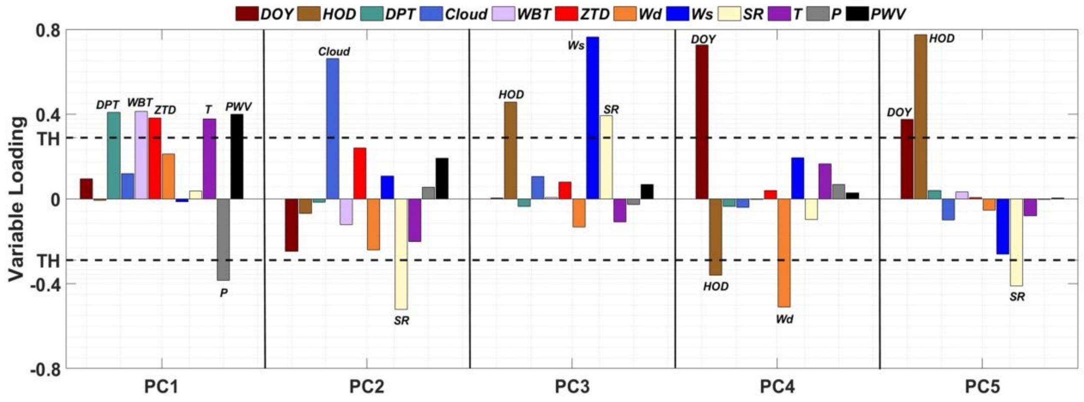
- FOUR scenarios (heavy, moderate, slight, and no)
- PWV, ZTD, and cloud coverage are key variables in heavy rainfall classification.



Dimension reduction for rainfall discrimination



Biplot representation of the variables



Variable loadings

3. Analysis of GNSS atm. params.

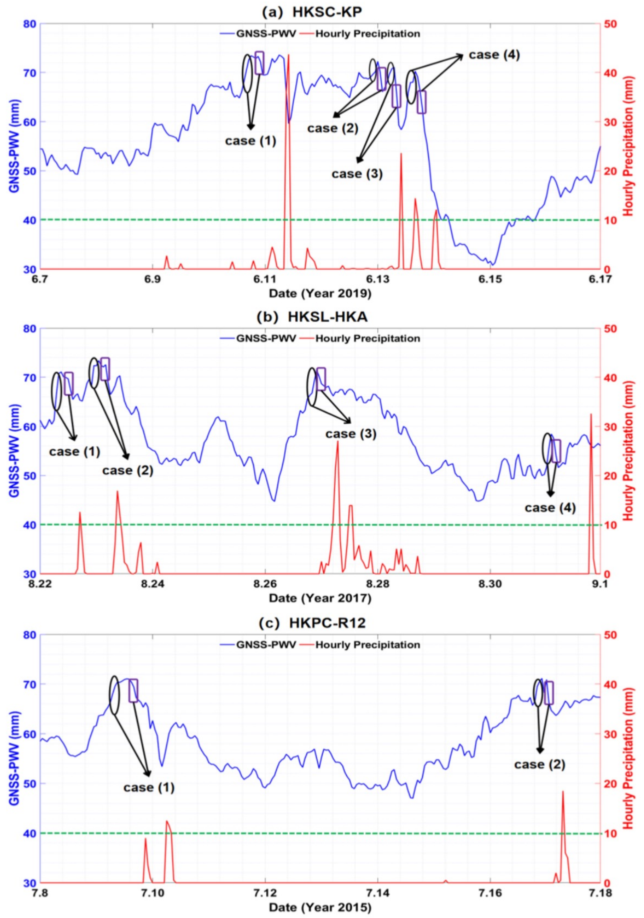
3. Analysis of GNSS atm. params.

3.3 PWV/ZTD variation before heavy rainfall – time series analysis

During the evolution of most heavy rainfall, PWV/ZTD typically <u>increase considerably</u> till reaching a larger value, then <u>decrease rapidly</u> before (and during) heavy rainfall.

Synoptic interpretation:

- Strong WV transport — **<u>Large increase</u>**;
- Convergence upward motion process, during which WV condenses into cloud droplets — **<u>Sharp decrease</u>**;
- Cloud droplets growth and fall as raindrops — **<u>Formation of heavy rainfall.</u>**



Comparison between hourly PWV and rainfall record

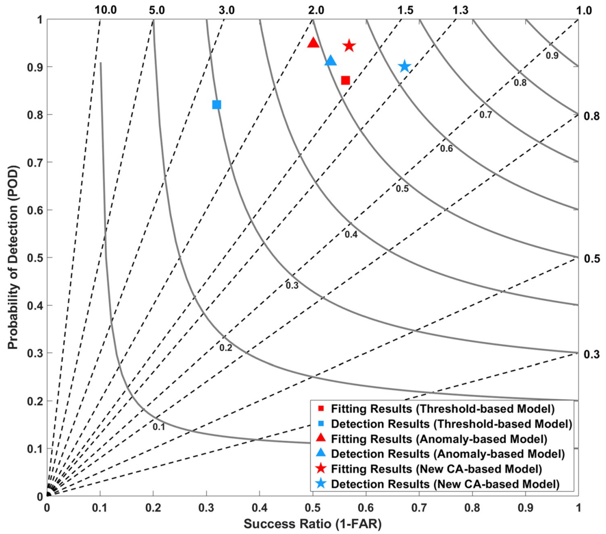
Applications

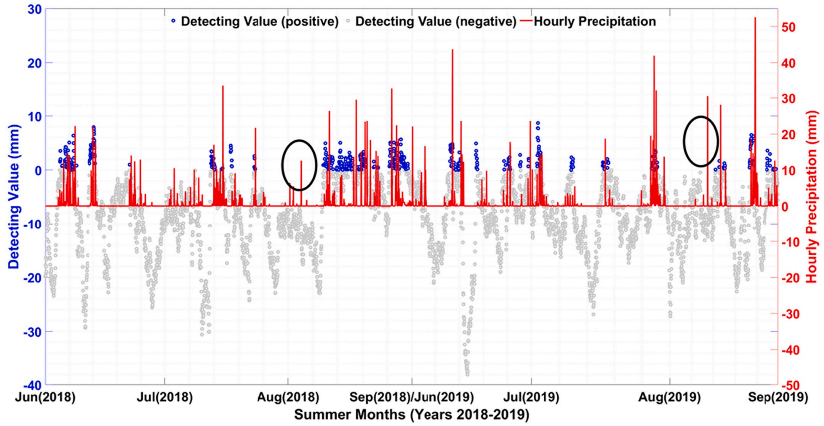
of ground-based GNSS atm. params.

4. Applications of GNSS atm. params.

4.1 Nowcasting of weather extremes – (1) Statistical model

- **Anomaly series** – deviations from a defined "normal" cycle;
- **Cumulative anomaly series** – long-term departure – filter out high-frequency "noises" in anomaly series;
- **Heavy rainfall reflects cumulative effects**, not just instantaneous features;
- TDR **> 97%;** FAR **< 23%;** Mean lead time **~3-4 hours**;
- *Provide quantitative insights into variable departures and anomalous variations;*
- ***How to define a reasonable "normal" cycle?***

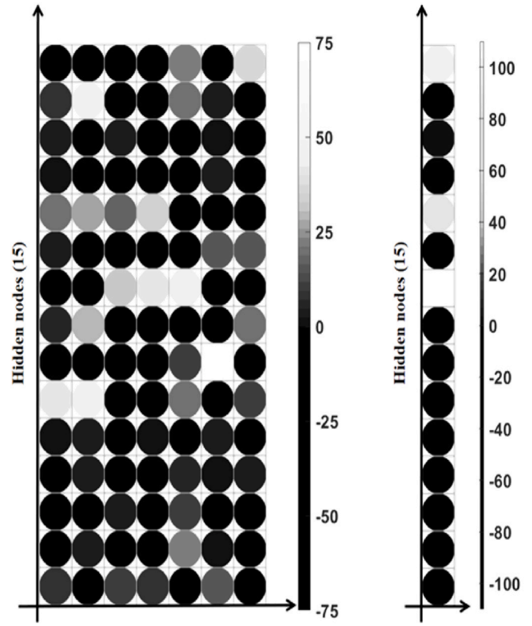




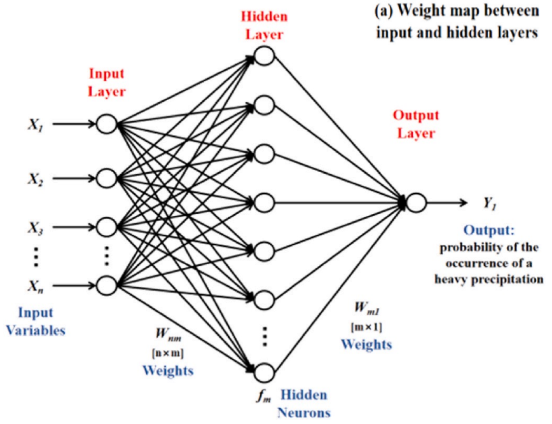
4. Applications of GNSS atm. params.

4.1 Nowcasting of weather extremes – (2) NN-based model

- **Input**: ZTD, PWV, T, P, RH, DOY, and HOD;
- **Output**: Probability of heavy rainfall occurrence;
- Weight pattern analysis – **PWV & T** are the most influential (contributing) variables;
- TDR **94.5%;** FAR **20.8%;** Mean lead time is **~3 hours;**
- *<u>Extract patterns from long-term series; self-learning, nonlinear mapping and fast convergence;</u>*
- ***<u>How to interpret internal mechanisms and physical process?</u>***



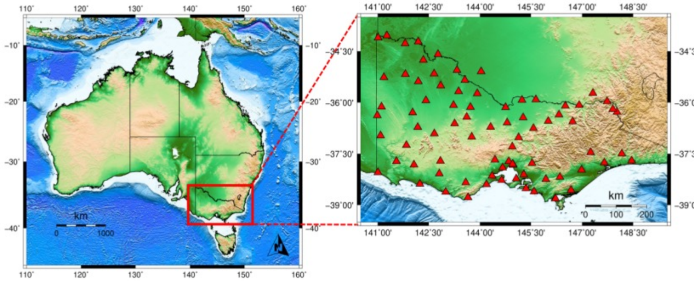
(a) Weight map between input and hidden layers
(b) Weight map between hidden and output layers



4. Applications of GNSS atm. params.

4.1 Nowcasting of weather extremes – (3) NWP model

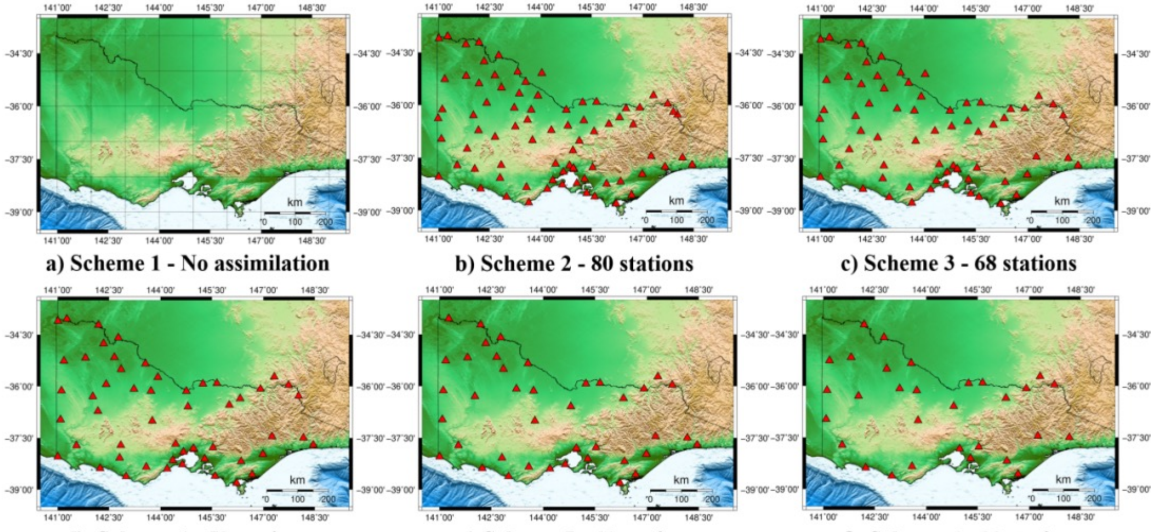
- **Motivations:**
  - Previous studies simply adopted all stations without optimisation;
  - Evaluate the adequacy of the existing infrastructure.



- **Determine optimal spatial resolution for assimilating GNSS atm. params.**

- **Data:** RMIT NRT ZTD platform (**80 stations**).
- **Methods:** Data thinning & Iterative 3DVAR.
- **Scenario:** Heavy rainfall and normal conditions.
- **Optimal resolution: ~46.4 km**.

Inform site deployment and network planning



a) Scheme 1 - No assimilation
b) Scheme 2 - 80 stations
c) Scheme 3 - 68 stations
d) Scheme 4 - 53 stations
e) Scheme 5 - 41 stations
f) Scheme 6 - 30 stations

4. Applications of GNSS atm. params.

4.2 Improve the quality of met. variables – PET

- **Motivations**:
  - **Thornthwaite (TH) model** (temperature-based): easy to operate, but limited accuracy;
  - **Penman-Monteith (PM) model** (physically-based): accurate, but complicated;
  - GNSS/met. params. show strong (linear) correlation with *PET difference* ($PET_{PM} - PET_{TH}$).
- **Propose a new method to calibrate TH-derived PET**
- **Investigate affecting factors,** including variable selection, seasonality, and site distribution;
- **Calibration Procedure**:
  1) Calculate PET differences ($PET_{PM}–PET_{TH}$);
  2) Calibrate TH-PET using GNSS/weather variables;
  3) Calculate new set of TH-PETs.

$$PET_{diff} = PET_P - PET_T,$$

$$PET_{cal} = a_1X_1 + a_2X_2 + a_3X_3 + \ldots + a_nX_n + b,$$

$$PET_{imp} = PET_T + PET_{cal},$$

4. Applications of GNSS atm. params.

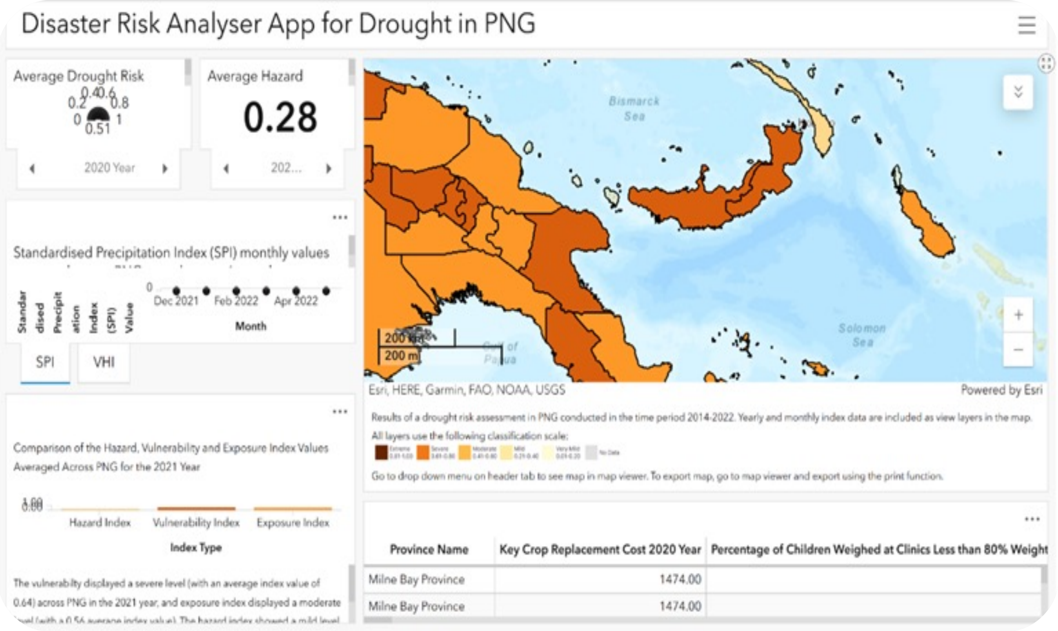
4.3 Detection of climate extremes – Flash drought

- **Flash Drought** – rapidly evolving drought with sudden onset, short duration, and high impact – How to **extend detection lead time**?

- **Evaporative Demand Drought Index (EDDI)** – a promising index for early warning and quantification of flash droughts – **limited precision**

- **Developed a method for improving the precision and temporal resolution of EDDI**, enabling effective flash drought detection

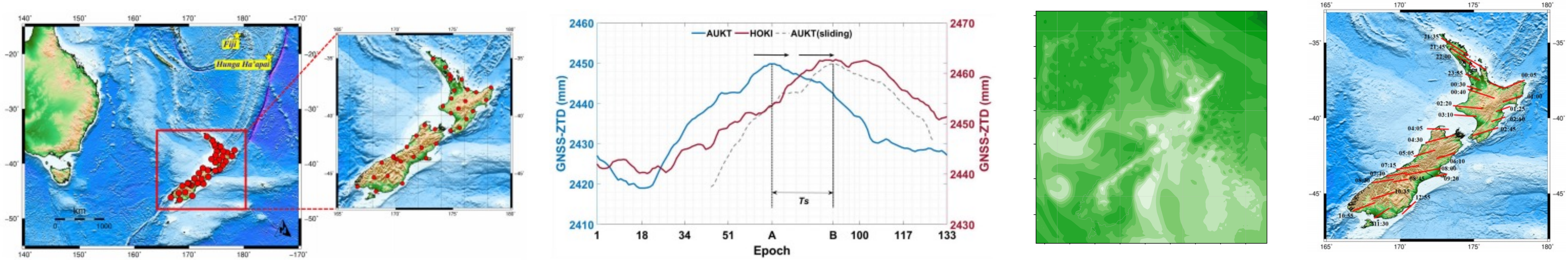
- TDR **87.1%**; FAR **16.7%**; lead time **~38 days**.



4. Applications of GNSS atm. params.

4.4 Monitoring of atm. circulation – WV migration

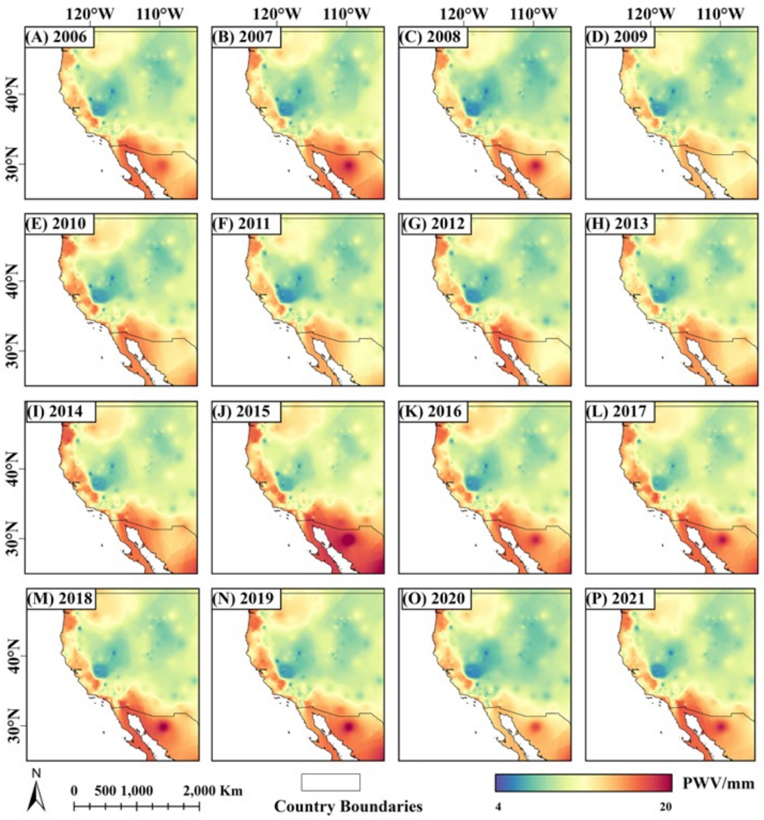
- **Data type**: **ZTD and its derivatives, gradients** from a dense network (5-min).
- **Basics**: **ZTD crests** obtained at different stations correspond to *different epochs*.
  ZTD and its derivatives — *speed*; **gradients** — *direction*.
- **Highlights**: **1) An improved method for monitoring WV migration is developed;**
  2) WV migration (speed and direction) is effectively monitored;
  3) To monitor atm. river and other types of WV migration.



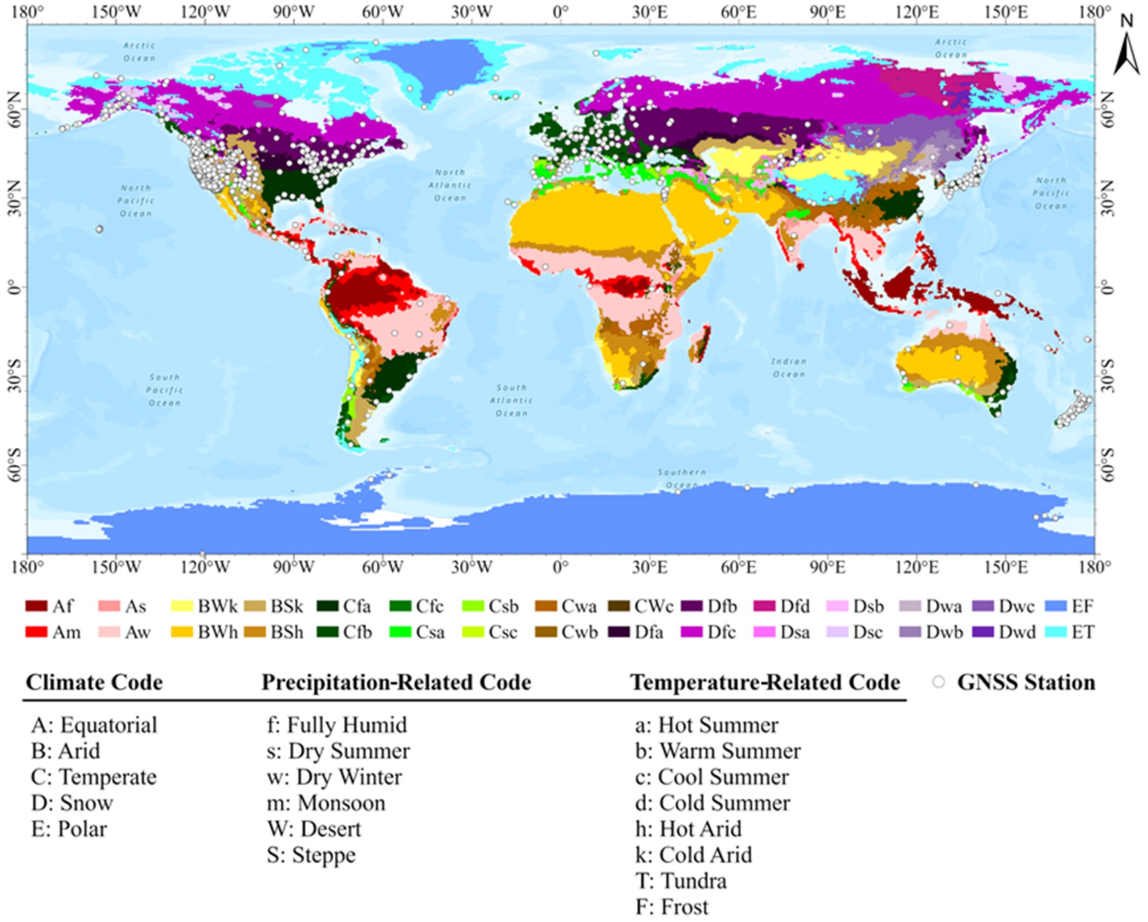
Affected by: *Hunga Tonga-Hunga Ha'apai Volcano Eruption* and *Tropical Cyclone Cody*

4. Applications of GNSS atm. params.

4.5 Other analyses



Southern California Wildfires 2025



Characterisation of PWV behaviours stratified by the Köppen-Geiger climate classification

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5. Summary and Outlook

5.1 What can we get from this

- ✓ Data generation and analysis
- ✓ Diverse applications of GNSS atm. params.

5.2 Where do we go from here

- ✓ NRT/RT GNSS data for weather nowcasting;
- ✓ AI-enhanced mining of long-term historical data;
- ✓ Enriching DA in the NWP community;
- ✓ Innovative applications for weather and climate resilience;
- ✓ Seeking interdisciplinary collaboration ….

Ground-based GNSS atmospheric monitoring for weather and climate resilience

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ABSTRACT

Amid the growing challenges of climate change impact and the fairly limited availability of observations of some Earth system parameters, this article highlights the potential of ground-based Global Navigation Satellite Systems (GNSS) atmospheric monitoring as a supplementary satellite observing technique to improve the monitoring and forecasting of weather and climate extremes. It spotlights current barriers and future opportunities, aiming to heighten public and institutional awareness of the research and application status and the prospective role of GNSS atmospheric monitoring for weather and climate resilience. The innovative uptake of diverse ground-based GNSS atmospheric parameters could support improved systems and policies for risk management and climate adaptation, thus empowering communities to better withstand hazardous weather and climate extremes.

Keywords: atmospheric monitoring, climate risks assessment, Global Navigation Satellite Systems, GNSS, precipitable water vapour, satellite Earth observation, severe weather events, weather parameters, zenith total delay.

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Thanks for your attention!

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