

# Ground-based GNSS for climate research: review and perspectives

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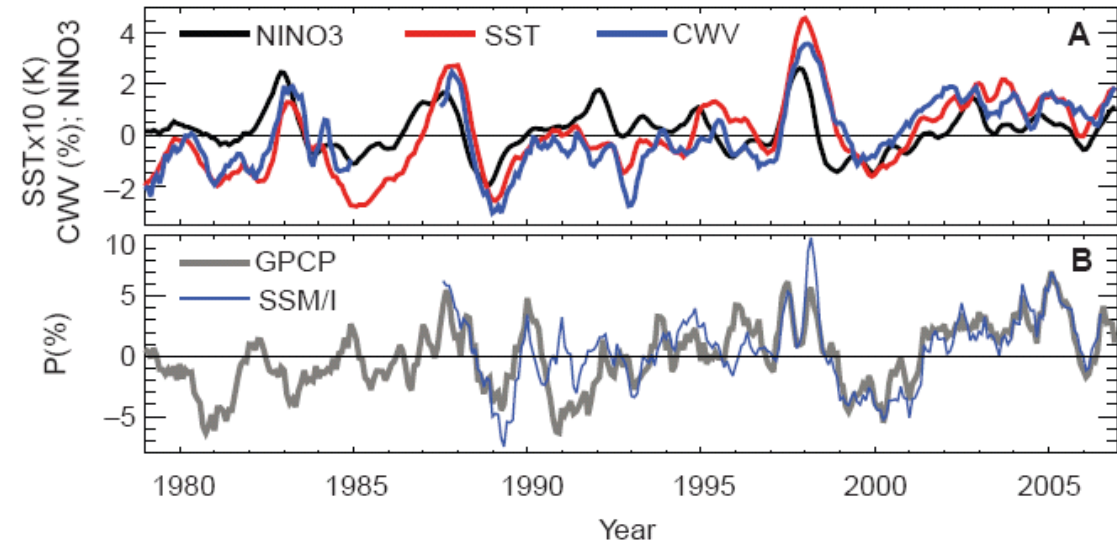
# Outline

- Introduction
- From ground-based GNSS to water vapour
- GNSS for climate: requirements
- GNSS for climate: advantages
- GNSS for climate: applications
- Conclusions and Outlook

# Water Vapour and Climate

- important **greenhouse gas** (but amount not controlled by emissions)
- amount controlled by air **temperature** through Clausius-Clapeyron:  $d \ln IWV/dT \approx 7\% K^{-1}$   
→ positive feedback mechanism
- key role in the atmospheric **hydrological cycle** by allowing winds to move water around Earth and by providing the water source for the formation of clouds and precipitation (Trenberth et al., 2003)
- key component in the **global energy cycle** through surface evaporation and atmospheric latent heating (Trenberth et al. 2009)

## Temporal correlation



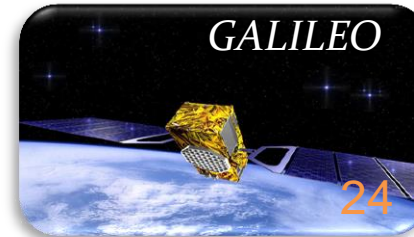
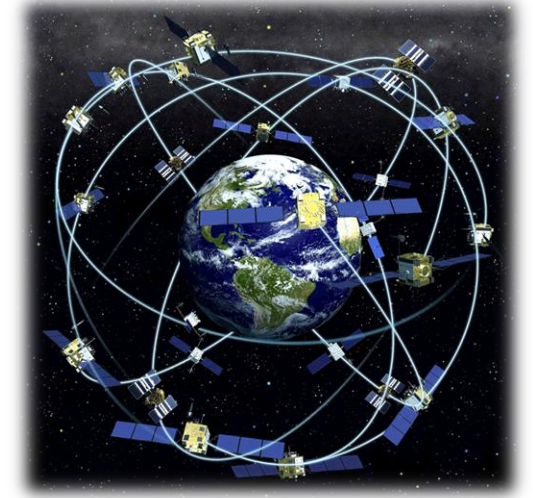
- ENSO (oceanic) index
- **sea surface temperature**
- **water vapour amount**
- precipitation

Source: Allan and Soden, Science, 2008

# Global Navigation Satellite Systems (GNSS)

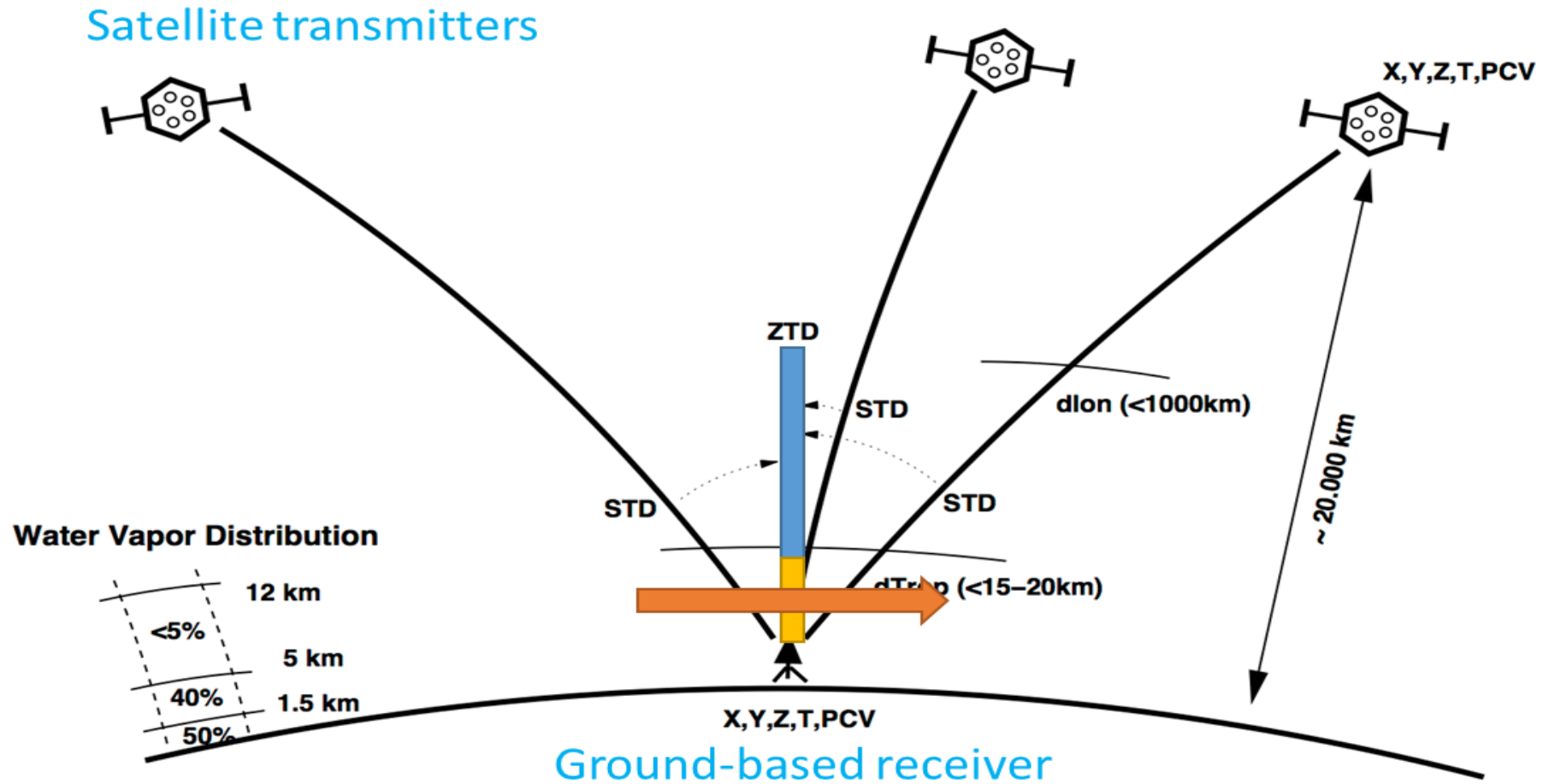
## System Design

- constellation of satellites (altitude  $\sim 20000\text{km}$ )
- emitting radio-frequency signals (carriers + codes)
- recorded by ground-based receivers/antennas on Earth
- measurements = propagation time of the signal



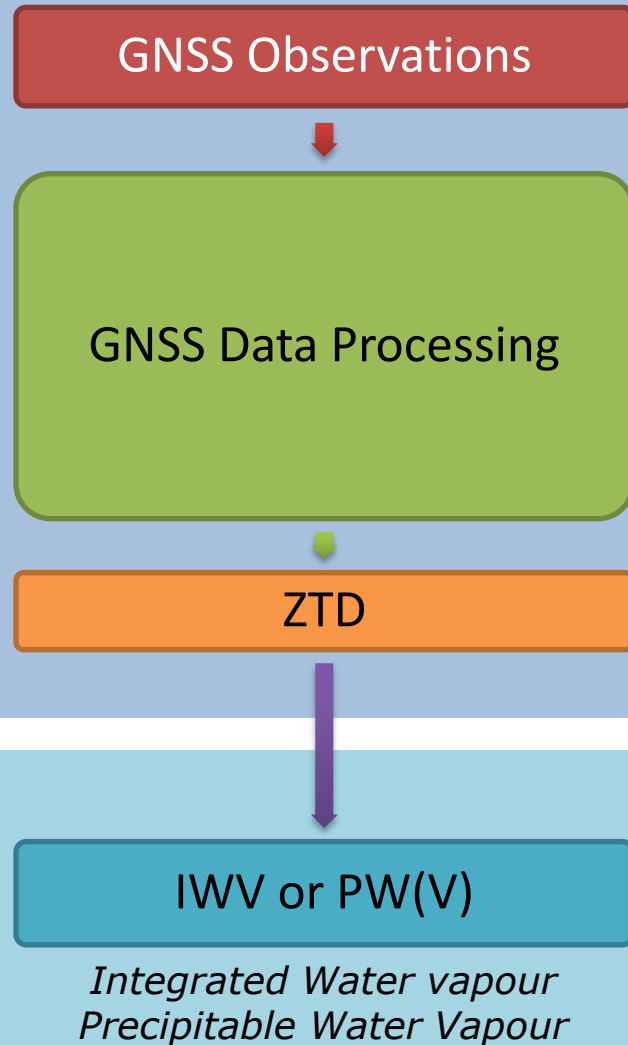
# Ground-Based GNSS and Neutral Atmosphere

Noise for Geodesy, Signal for Meteorology/Climate



# From Ground-based GNSS Observations to Integrated Water Vapour

IWV recognized as an **Essential Climate Variable** by WMO Global Climate Observing System (**GCOS**)



GNSS Phase Equation:

$$L_{rec}^{sat} = \rho_{rec}^{sat} + c \cdot (\delta t_{rec} - \delta t^{sat}) + \lambda \cdot N_{rec}^{sat} - d_{iono} + \boxed{d_{tropo}} + \varepsilon_{\phi}$$

*Tropospheric delay*

$$d_{tropo}(\alpha, e) \equiv \underbrace{\boxed{ZHD} \times m_h(e)}_{\text{Zenith Hydrostatic/Dry Delay}} + \underbrace{\boxed{ZWD} \times m_w(e)}_{\text{Zenith Wet Delay}} + \underbrace{[\boxed{G_N} \cos \alpha + \boxed{G_E} \sin \alpha]}_{\text{Horizontal Gradients}} \times m_G(e)$$

$$\boxed{ZTD} = ZHD + ZWD$$

*Zenith Total Delay*

$$ZWD = \boxed{ZTD} - \boxed{ZHD}$$

*Saastamoinen Equation*

$$\boxed{ZHD} \approx 2,3 \left[ \frac{mm}{hPa} \right] * P_s [hPa]$$

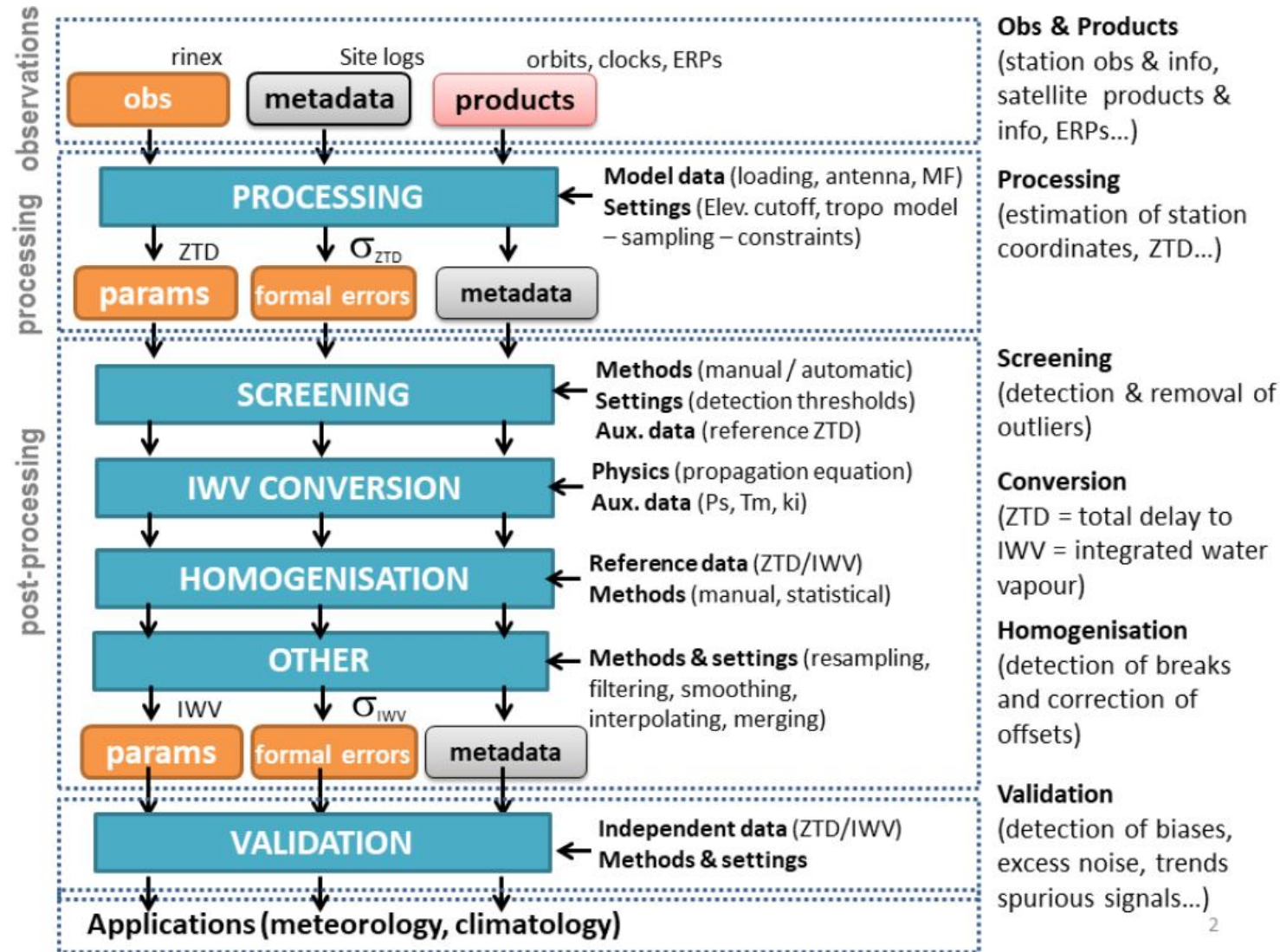
*meteo data  $P_s$*

$$IWV = \boxed{\kappa(T_m)} ZWD$$

$$\boxed{\kappa(T_m)} \approx 155 \left[ \frac{kg}{m^3} \right]$$

*meteo data  $T_s$  and estimated  $T_m$*

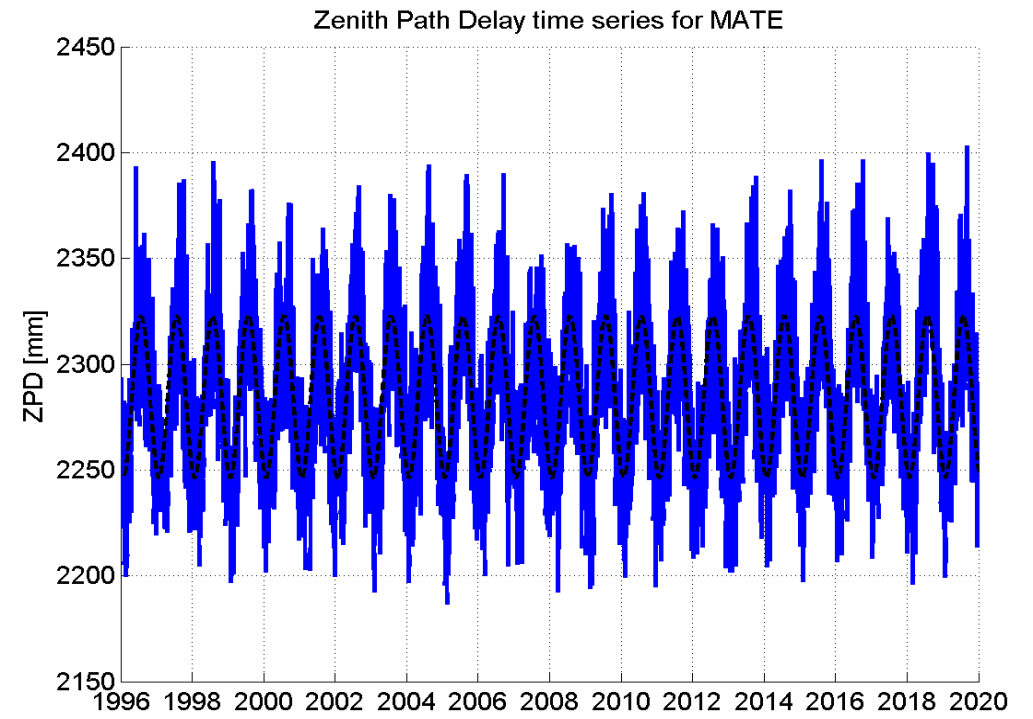
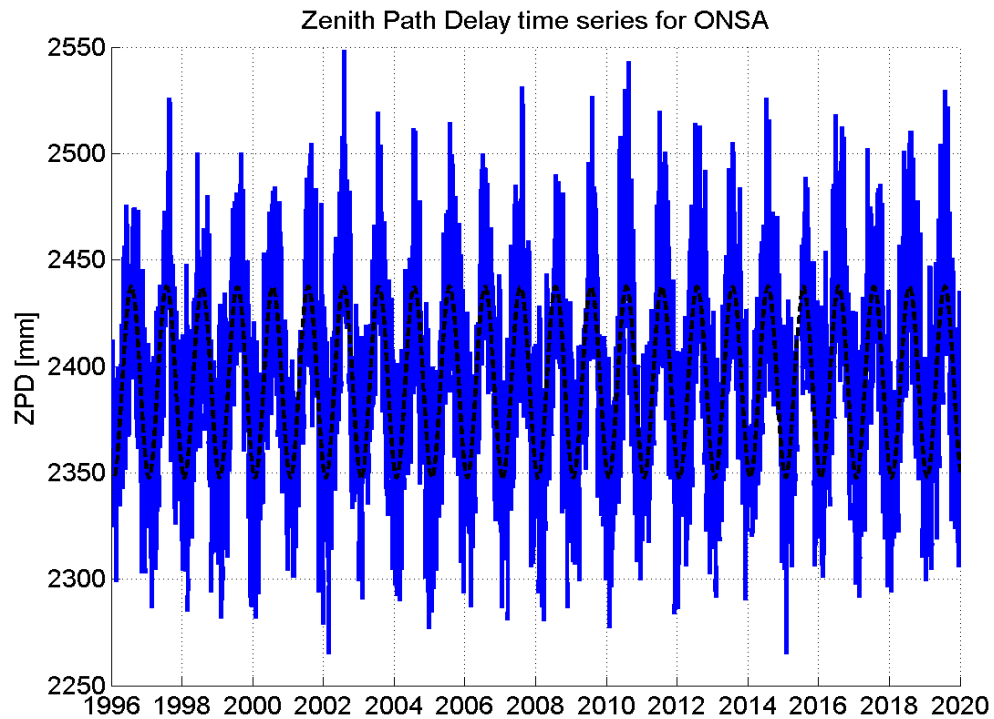
# Ground-based GNSS : From Data to Product



Source: Jones et al., Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate, COST Action ES1206 Final Action Dissemination Report, 2019

# GNSS for Climate: Requirements

- global **coverage**/dense regional coverage
- **long-term** time series (first IGS stations installed in 1994 → almost 30 years!)

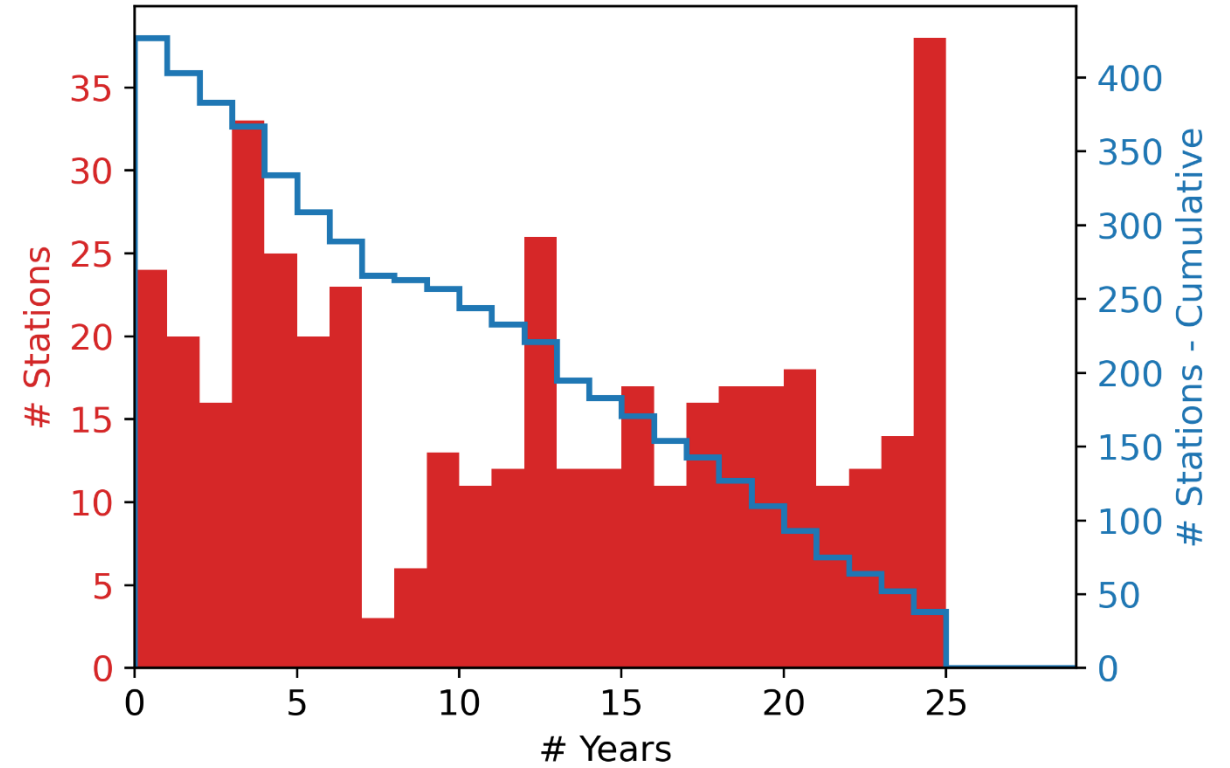
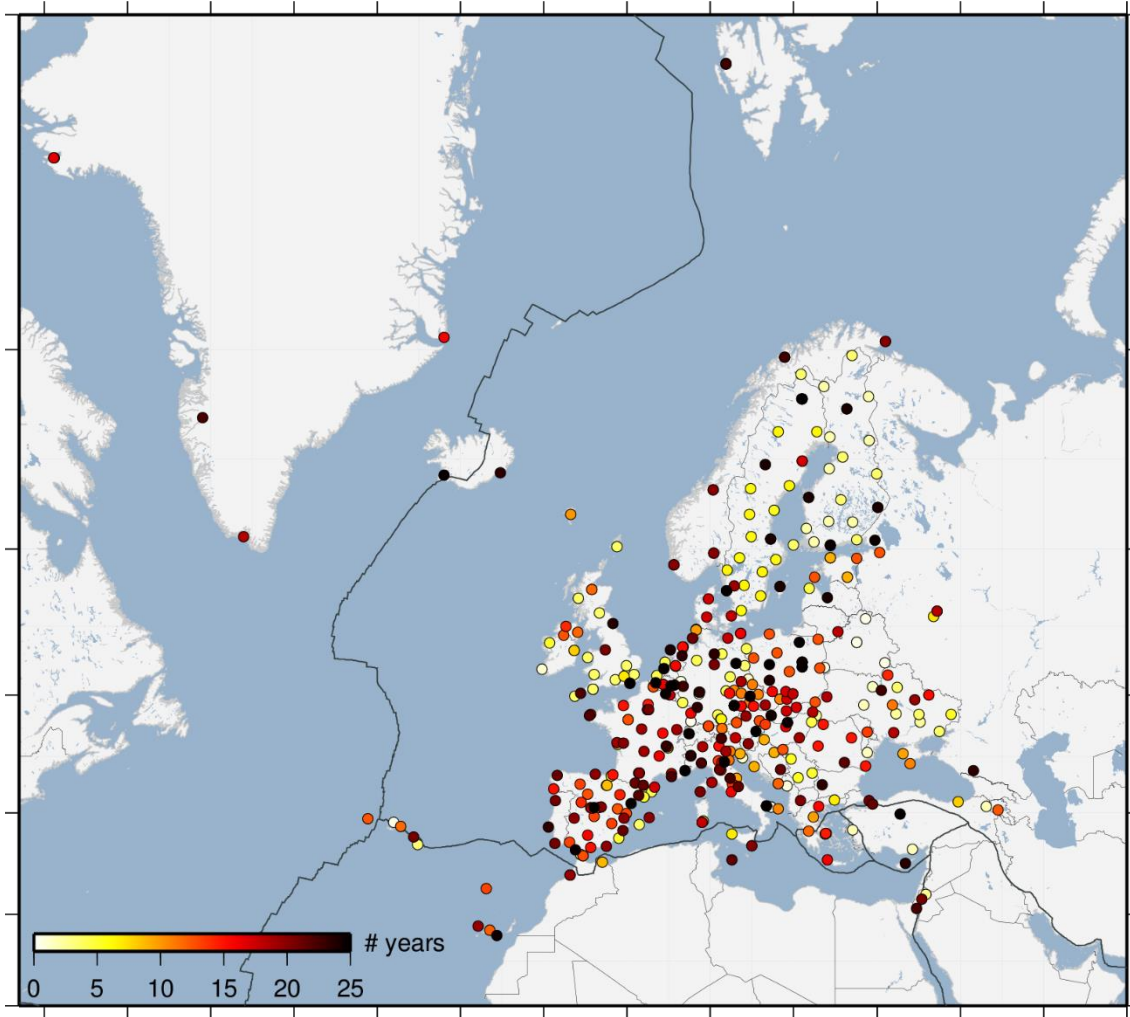


Source: [http://www.epncb.oma.be/\\_productsservices/troposphere/](http://www.epncb.oma.be/_productsservices/troposphere/)



# GNSS for Climate: Requirements

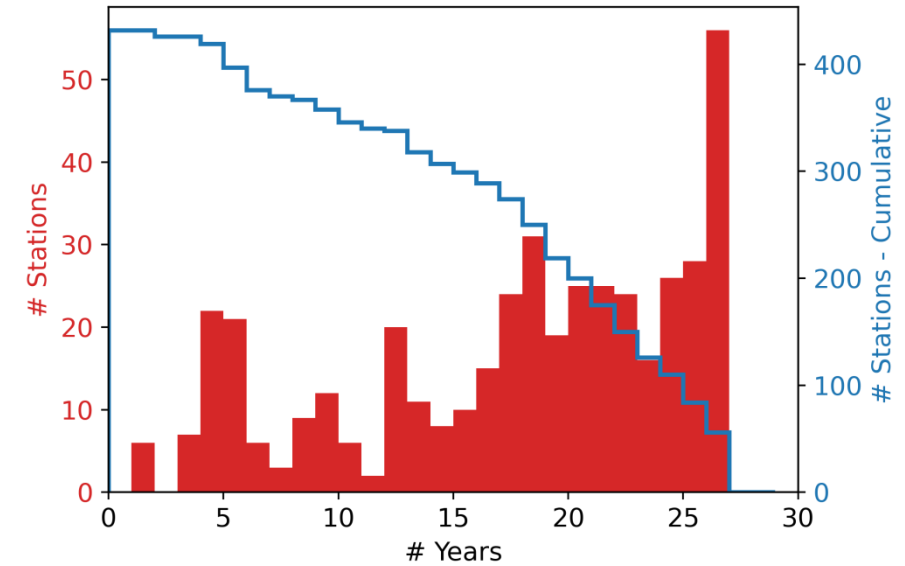
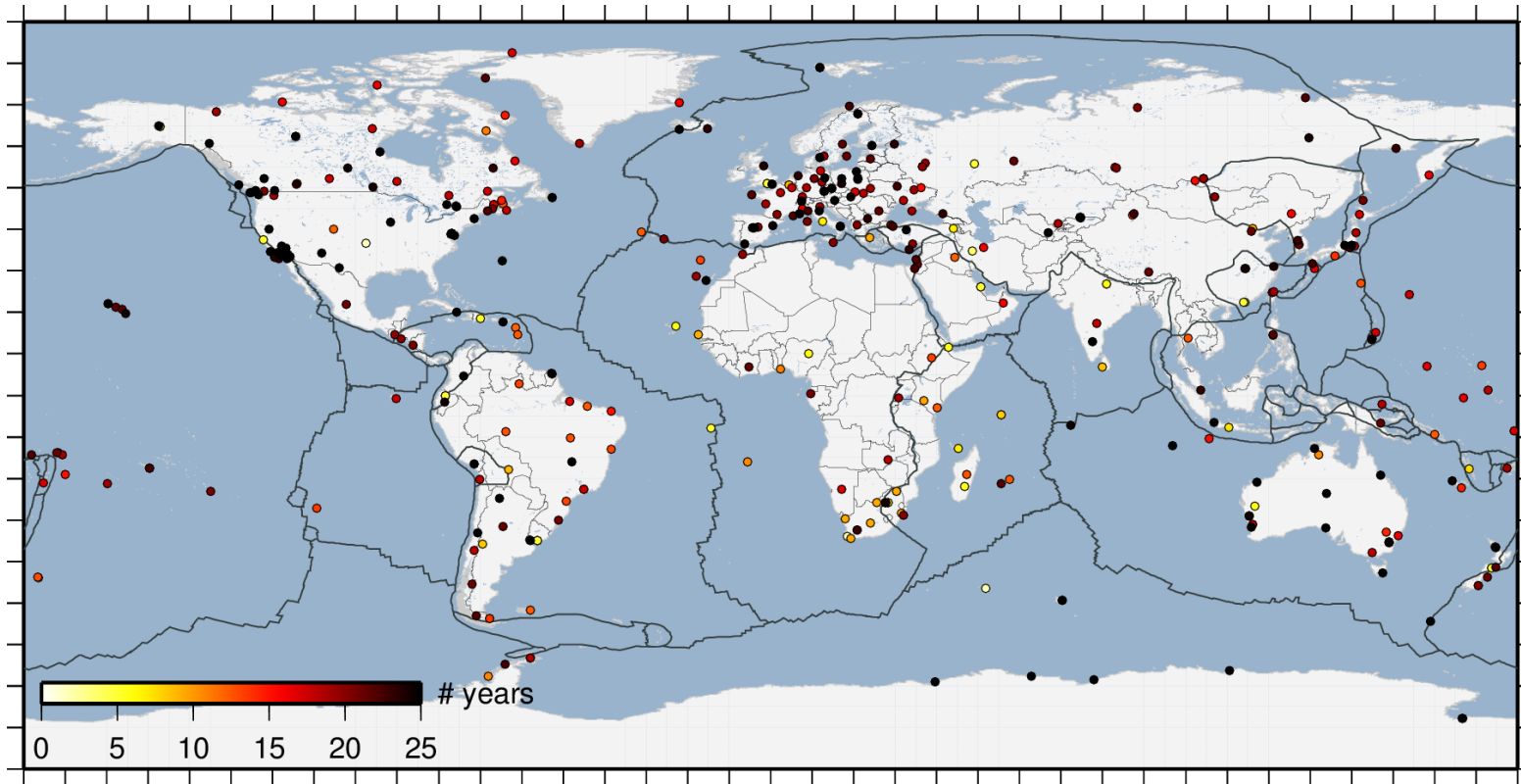
## Length of the Observation Period – Europe – EUREF Permanent Network (EPN)



Source: © Juliette Legrand, ROB, 2021

# GNSS for Climate: Requirements

## Length of the Observation Period – World-Wide – International GNSS Service (IGS) Network



Source: © Juliette Legrand, ROB, 2021

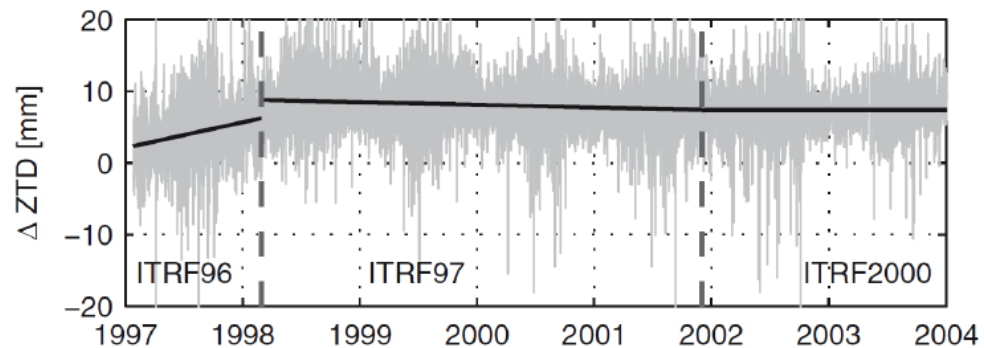
# GNSS for Climate: Requirements

➤ **homogeneity** of the time series

1. different GNSS **processing** software, different processing methodologies, and different variants for each modelling step

→ need to find the best processing options for climate (according to specific application)

+ reprocessing with the fixed processing options all the historical GNSS data



Differences between IGS and reprocessed zenith total delay (2-hourly) for Algonquin Park (ALGO).

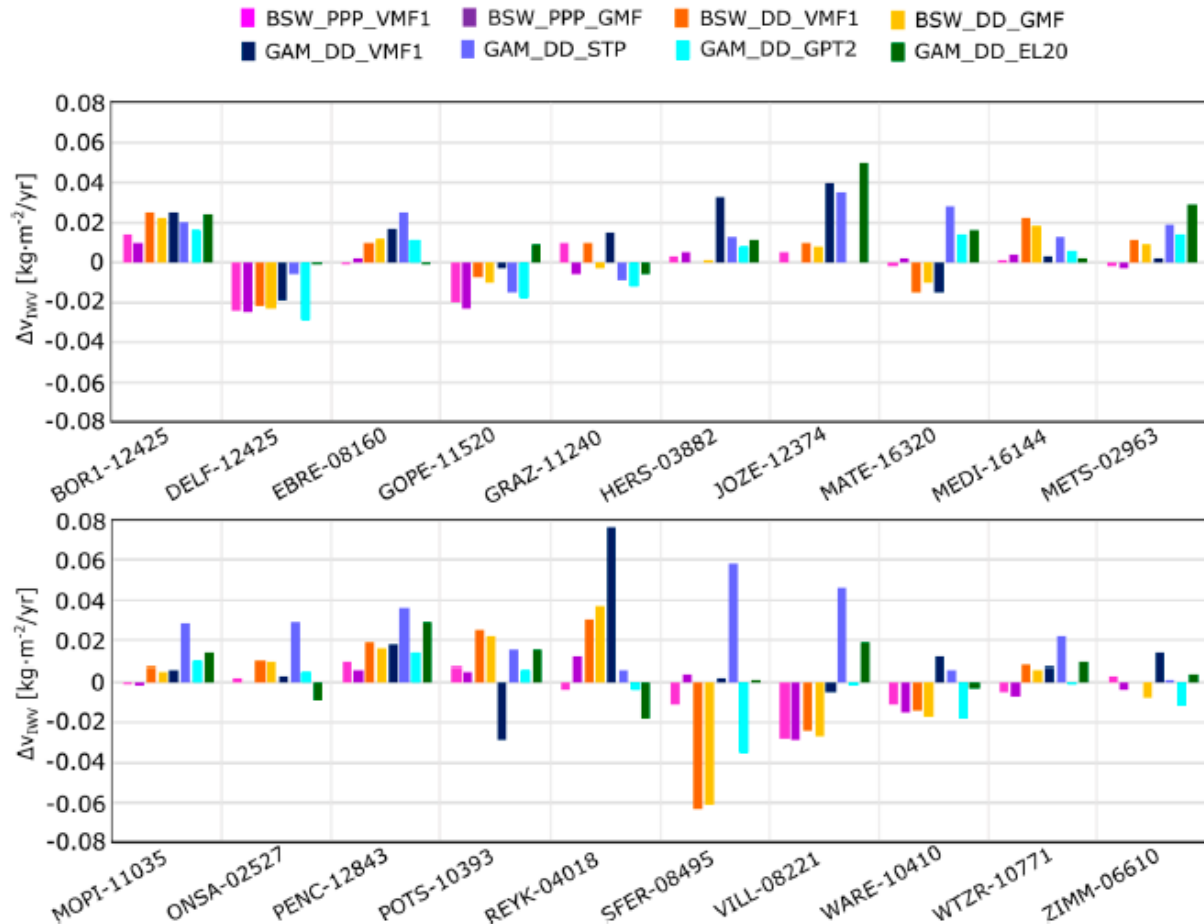
Source: Steigenberger et al. J. Geod. ,2007

- A **reprocessed** time series does not contain any inhomogeneities due to the processing itself (e.g. no change in the reference system, no change in the modelling...)

# GNSS for Climate: Requirements

- **homogeneity** of the time series **processing**

$\Delta v_{Iwv}$  (GNSS-RS) : differences between IWV trends in GNSS and radiosondes



- different softwares, methods (PPP/DD), a priori ZHD models, tropospheric mapping functions
- trend differences between solutions (0.015-0.121 mm/yr) larger than trend estimation errors (0.006-0.008 mm/yr)
- highest consistency for PPP solutions: DD method may introduce to the troposphere solutions errors that affect the proper investigation of long term changes.

Source: Baldysz et al., Remote Sensing, 2019

# GNSS for Climate: Requirements

➤ **homogeneity** of the time series **processing**

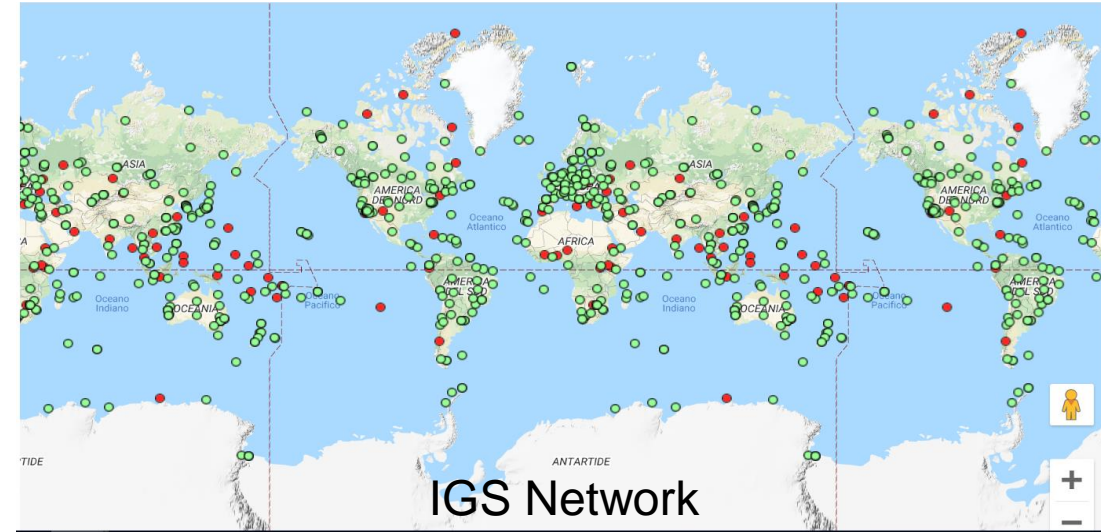
- International Reprocessing Activities

- EPN-Repro2 (1996-2014),
- IGS-Repro3 (ongoing 1994-2020)
- EPN-Repro3 (to be planned 1996-2020)

- Regional / National Reprocessing Initiatives

- Some are updated regularly

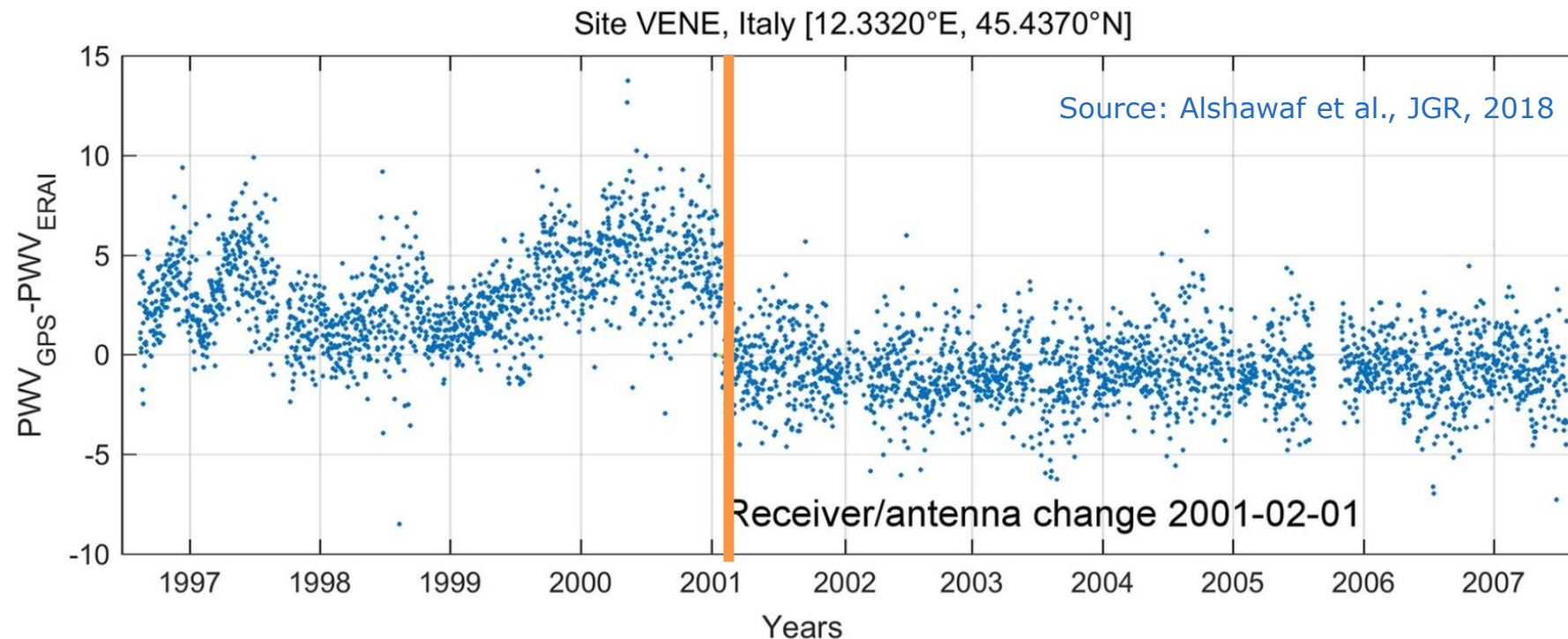
- GRUAN processing: [see talk S06C04 "GNSS-based Precipitable Water Vapor: Certification for the Global Climate Observing System"](#)



# GNSS for Climate: Requirements

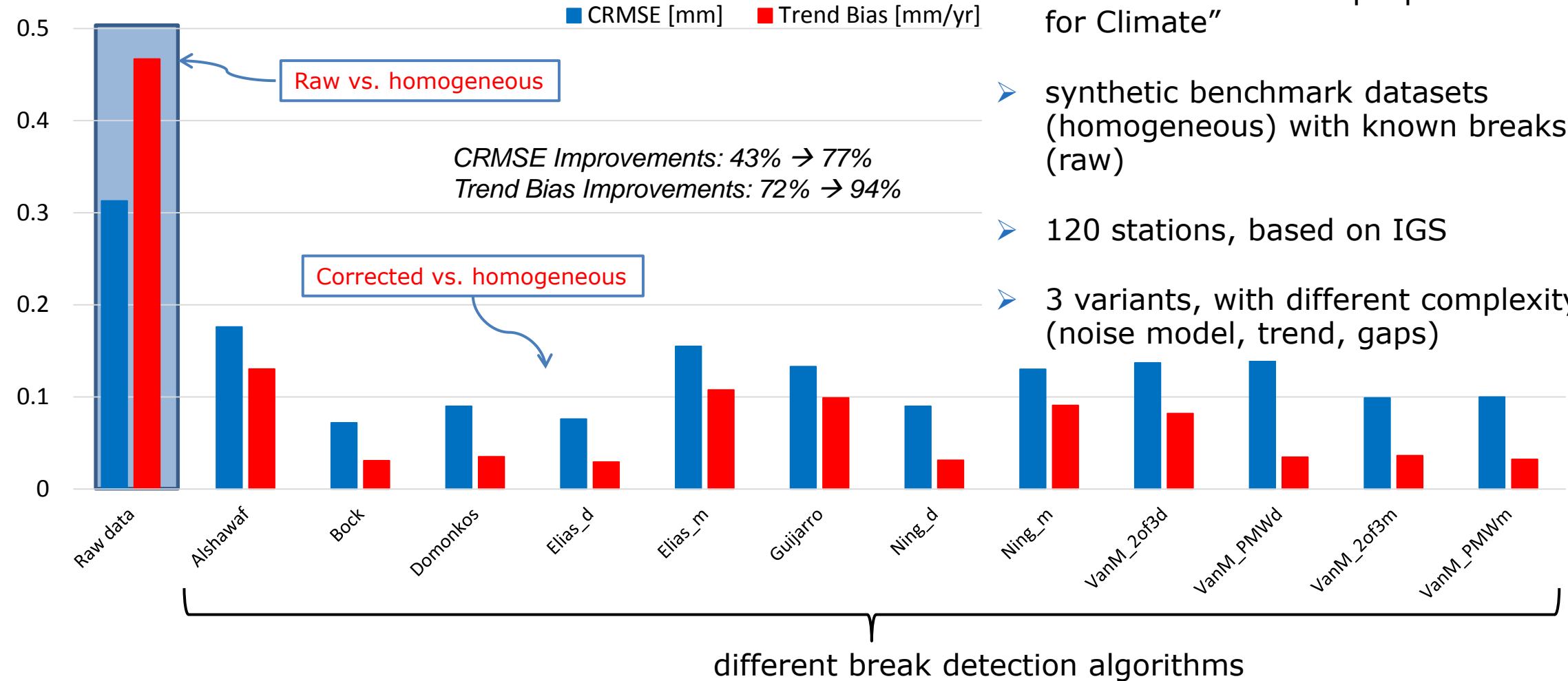
➤ **homogeneity** of the time series

1. reprocessing with the fixed processing options all the historical GNSS data
2. undocumented or mismodelled **instrumental changes**, **environmental** effects (tree cuts): breaks in the time series (metadata! correction!), see talk S06C05 "Tracking inhomogeneities in long reprocessed GNSS data sets for climate monitoring"



# GNSS for Climate: Requirements

## ➤ homogeneity of the time series



- dedicated activity in GNSS4SWEC and IAG 4.3.8 "GNSS Tropospheric Products for Climate"
- synthetic benchmark datasets (homogeneous) with known breaks (raw)
- 120 stations, based on IGS
- 3 variants, with different complexity (noise model, trend, gaps)

Source: Van Malderen et al., Earth and Space Science, 2020

# IWV Retrieval Techniques

	GPS	RS	GOMESCIA	AIRS	SSM/I & SSMIS
<b>spatial coverage</b>	± 400 active IGS stations	± 1500 IGRA sites	global	global	oceans
<b>spatial resolution</b>	cone, average radius 25 km	point, horizontal displacement depending on the wind	GOME: 40 x 320 km, SCIAMACHY: 30 x 60 km, GOME-2: 40 x 80 km	ellipsoidal, with major axis varying from 13.5 to 31.5 km	±40 km
<b>temporal resolution</b>	every 5 min	on average twice/day	GOME/SCIAMACHY: max. once/day, GOME-2: max. twice/day	maximum twice/day	twice/day
<b>temporal coverage</b>	1995 - now	1950s - now	1996 - now	2002 - now	1987 - now
<b>all weather?</b>	yes	yes	only if (almost) cloud-free	only if (almost) cloud-free	yes (except heavy rain)
<b>all direction?</b>	yes	vertical profile	nadir	nadir/limb	nadir/limb
<b>precision</b>	< 2 mm or kg/m <sup>2</sup>	≈ 5% (≈ 15% for very dry conditions)	≈ 15% for clear sky	≈ 5%	< 2 mm or kg/m <sup>2</sup>

Adapted from Van Malderen et al., *Atmos. Meas. Tech.*, 2014



# GNSS for Climate: Advantages

- long-term, homogeneous, precise → long-term variability of IWV all around the world
- all-weather device → validate implementation of cloud feedback mechanism in climate models, validation of clear-sky satellite retrievals of IWV (assimilated in Numerical Weather Prediction models)
- high temporal resolution → diurnal variation of IWV
- dense regional networks of GNSS stations → validate convective-permitting regional climate models

# GNSS for Climate: Applications

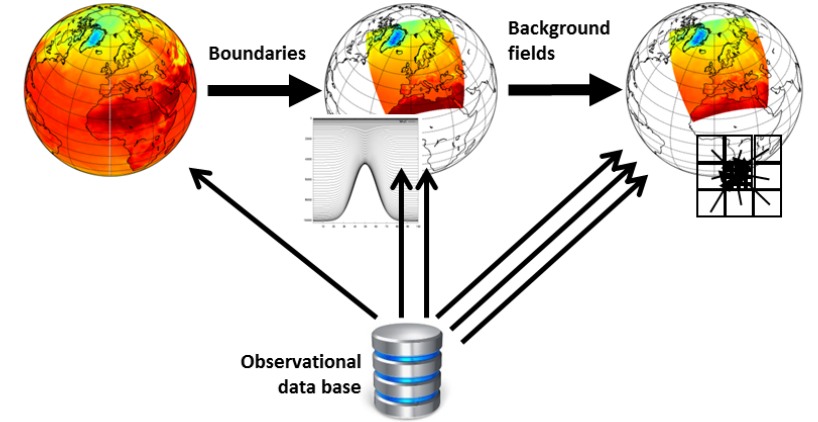
## Data Assimilation in European Regional Reanalysis

- **data assimilation** in European Regional Reanalysis for Copernicus Climate Change Service: high-resolution reanalysis from the early 1980s up to today
- **EPN-Repro2 + operational** GNSS ZTD observations planned to be used in the HARMONIE-ALADIN modelling system
- white list of stations, stations selected on data availability
- variational bias correction
- 4-week data assimilation trial shows reasonable and positive impact.

### Additional Requirement

- **data continuity**

Global Reanalysis → Regional Reanalysis → Surface Reanalysis  
ERA40/ERA-Interim      UERRA-HARMONIE      MESCAN-SURFEX



white list of 96 EPN stations

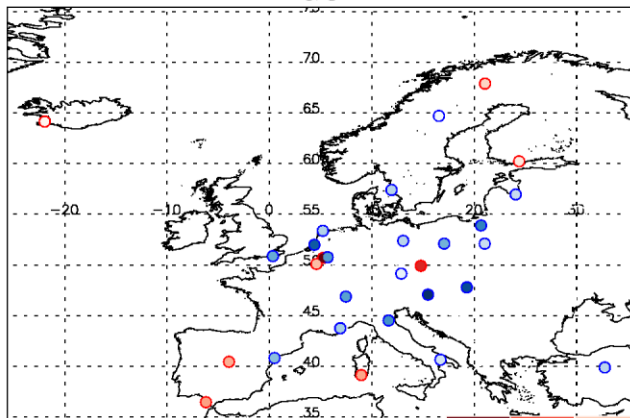


# GNSS for Climate: Applications

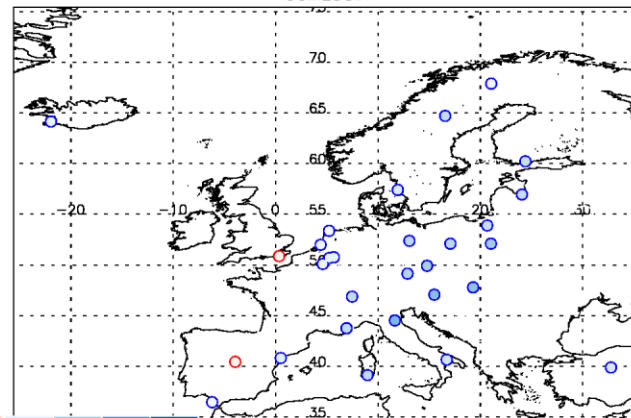
## IWV time variability

- calculation of IWV trends

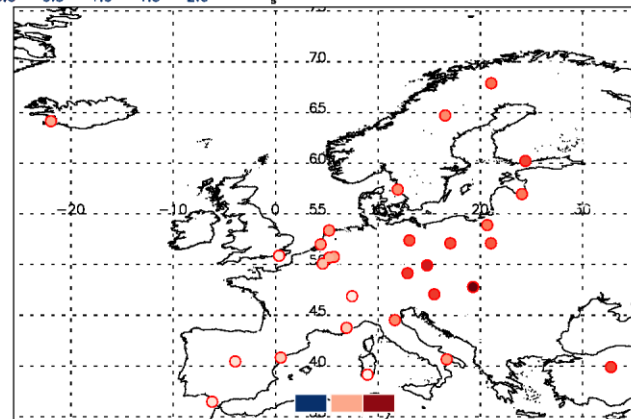
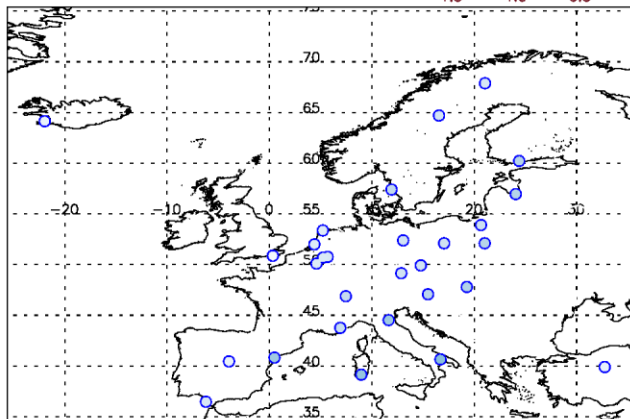
EPN Repro 2, 1995-2014



GOMESCIA satellite

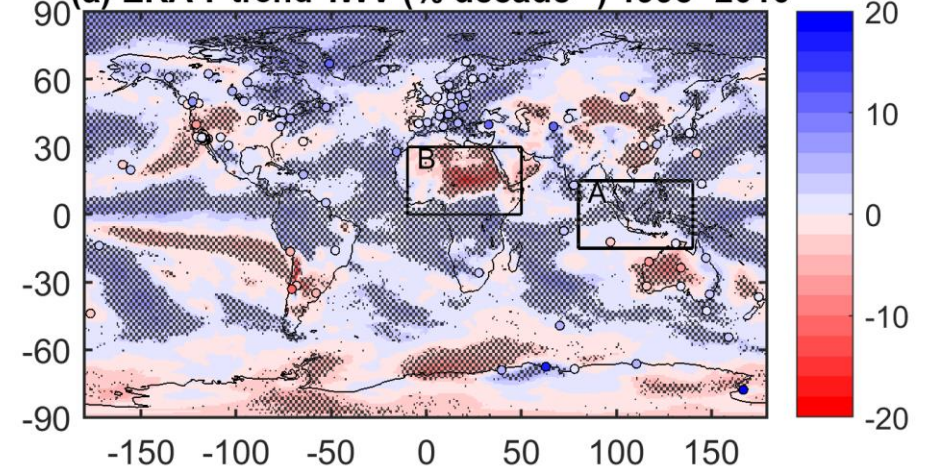


IWV ERA-Interim -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 T<sub>e</sub> ERA-Interim



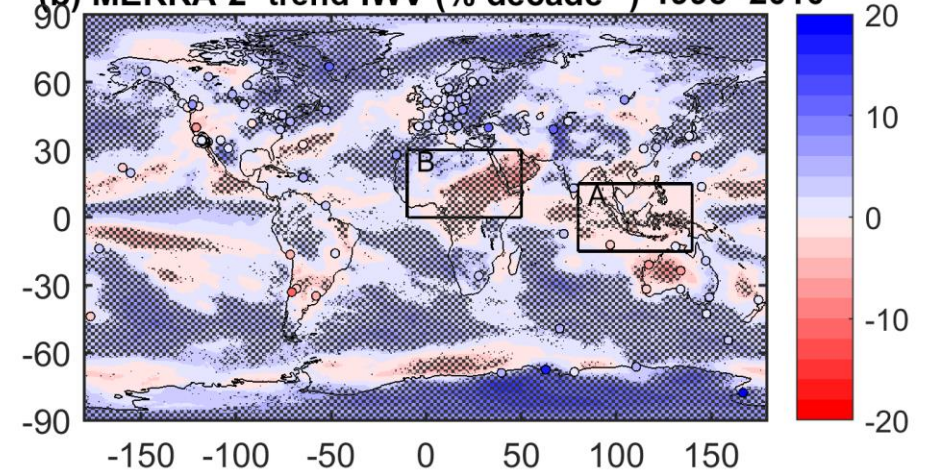
-0.5 0.0 0.5 1.0

(a) ERA-I trend IWV (% decade<sup>-1</sup>) 1995-2010



○ GPS (IGS) stations

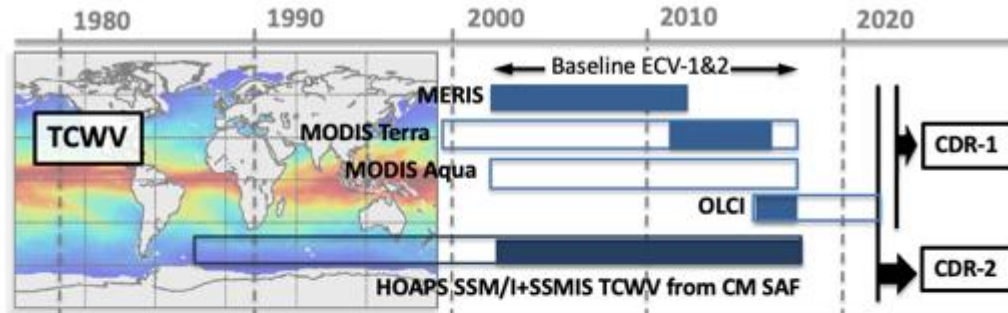
(b) MERRA-2 trend IWV (% decade<sup>-1</sup>) 1995-2010



Source: Parracho et al., ACP, 2018

# GNSS for climate: Applications

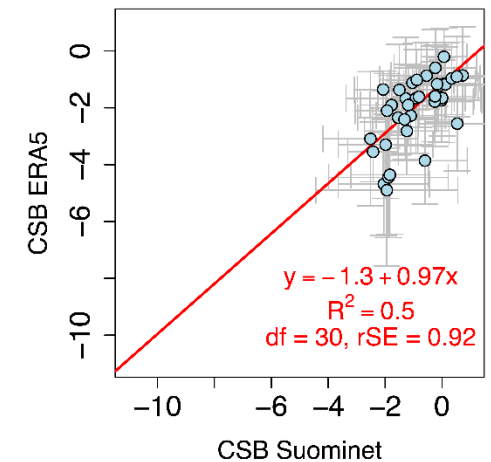
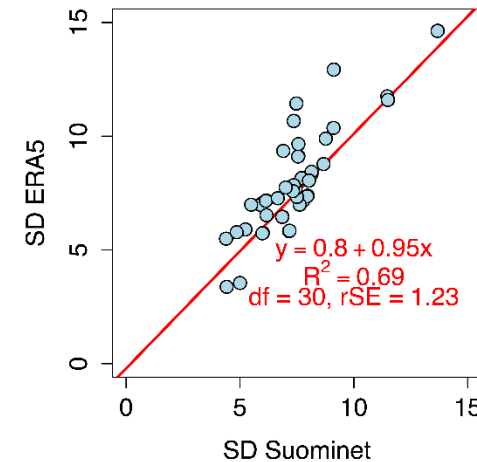
- validation of satellite data records of IWV e.g. ESA-Climate Change Initiative (Copernicus Climate Change Service + EUMETSAT CM-SAF)



Article

## Validation of Sentinel-3 OLCI Integrated Water Vapor Products Using Regional GNSS Measurements in Crete, Greece

Stelios Mertikas<sup>1</sup>, Panagiotis Partinevelos<sup>2,\*</sup>, Achilleas Tripolitsiotis<sup>3</sup>, Costas Kokolakis<sup>3</sup>, George Petrakis<sup>2</sup> and Xenophon Frantzis<sup>1</sup>



Validation of the clear-sky bias (CSB) assessment: standard deviation (SD) and CSB calculated from ERA5 IWV data records against GNSS (SuomiNet) IWV data records using the MERIS cloud mask for the time period 2005-2011

source: [Water Vapour CCI Climate Assessment Report, Nov. 2020](#)

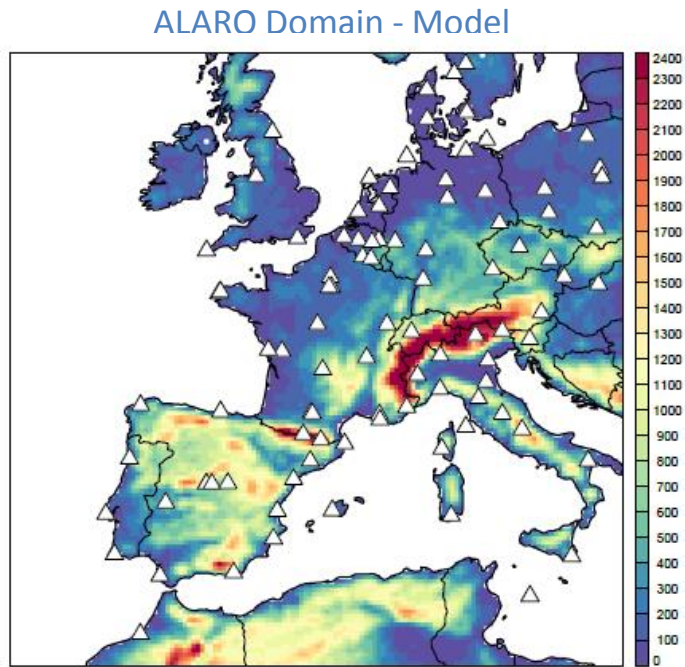
## Additional Requirement

- all-weather device, also under clouds

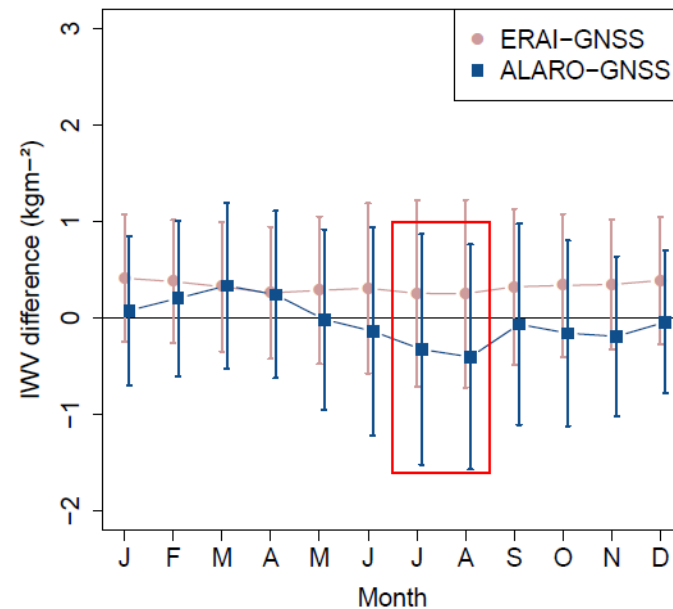
# GNSS for climate: Applications

## ➤ assessment of climate model water vapour fields

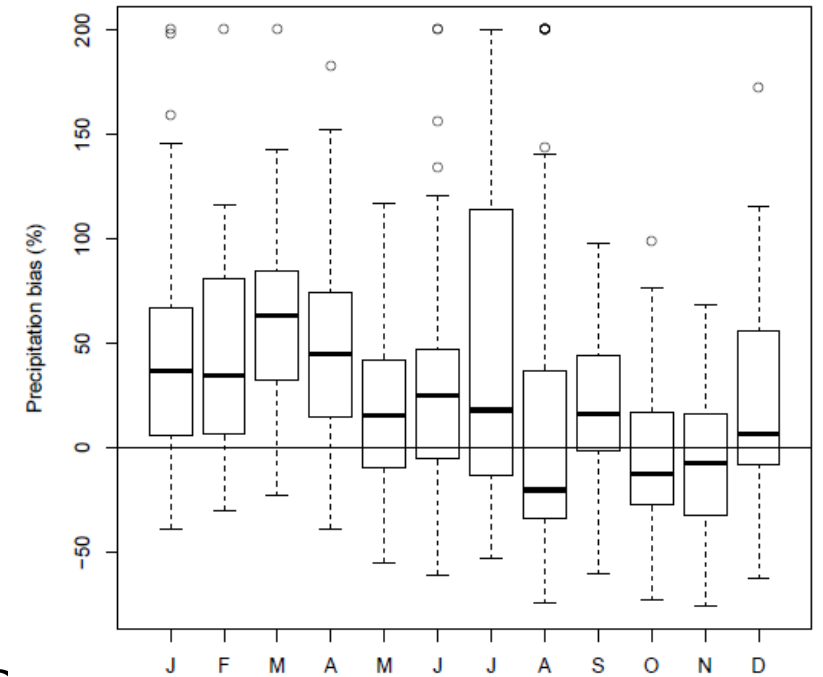
GNSS-based (EPN repro2 + IGS repro 1) validation of the IWV in ALARO-0 coupled to SURFEXv5 for the 19-yr period 1996-2014 over western Europe



Source: Berckmans et al., ACPD, 2018.



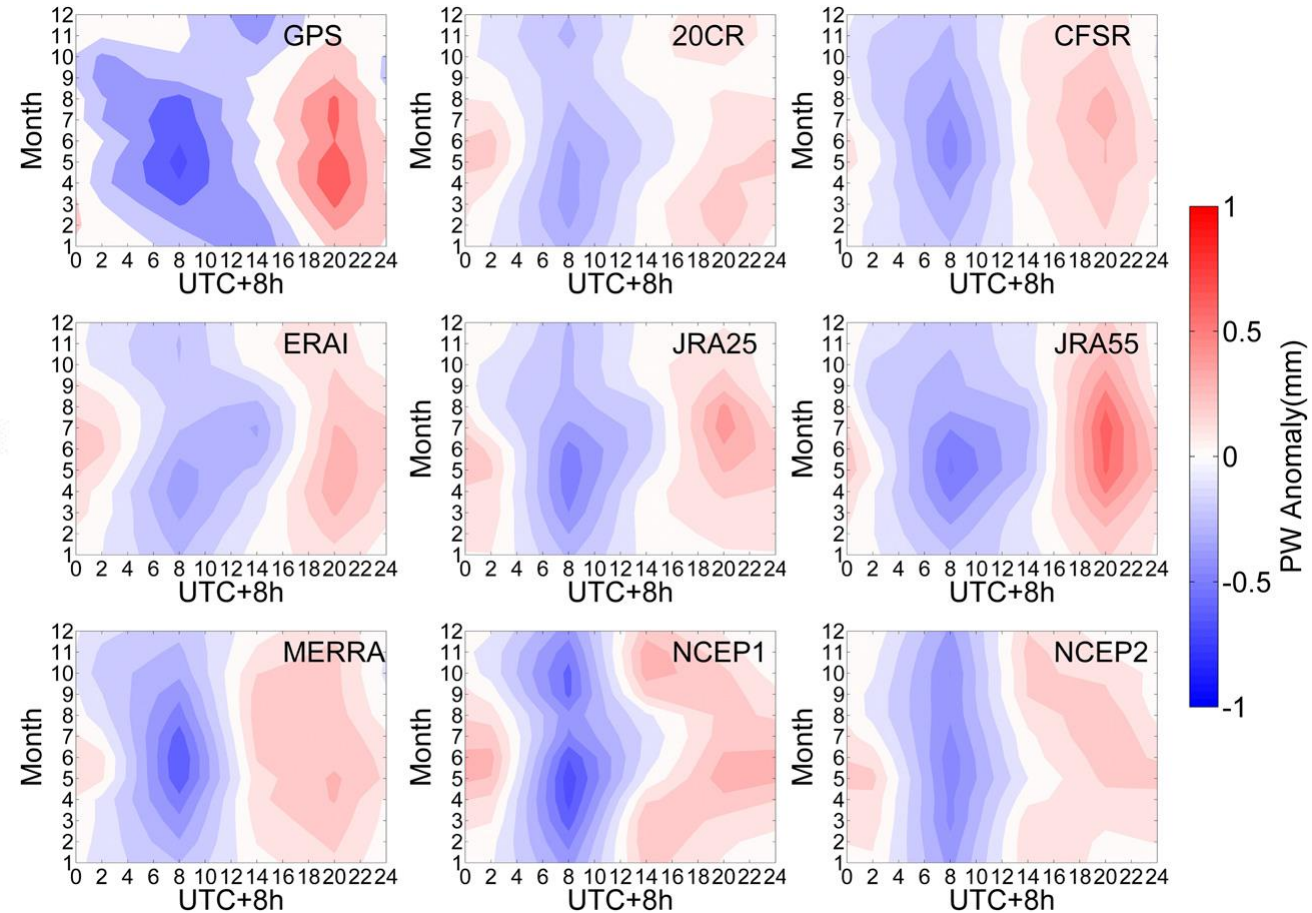
➤ seasonal variation in ALARO-GNSS IWV differences



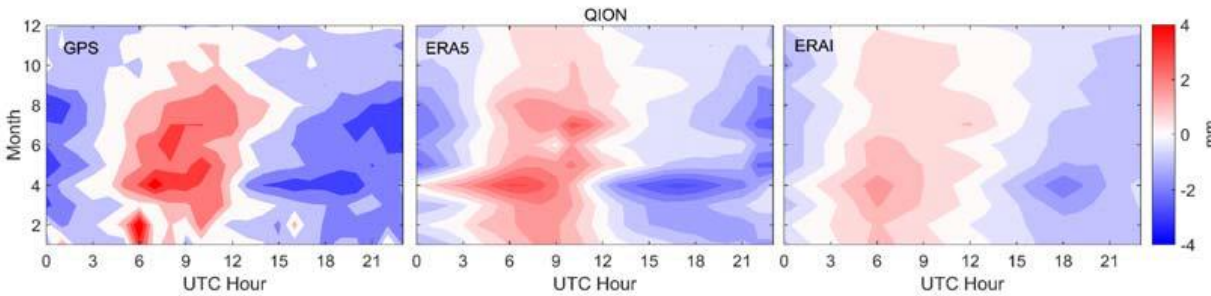
➤ similar seasonal variation in ALARO precipitation biases

# GNSS for Climate: Applications

- validation of the diurnal cycle in IWV in climate models (or common climate reanalyses)



seasonal variation of PW diurnal anomalies derived from GPS and reanalysis products over China  
Source: Zhang et al., J. Climate, 2018



seasonal variation of PW diurnal anomalies at QION (China) derived from GPS, ERA5, and ERAI  
Source: Yang et al., Adv. in Comp. Sci. Res., 2019

## Additional Requirement

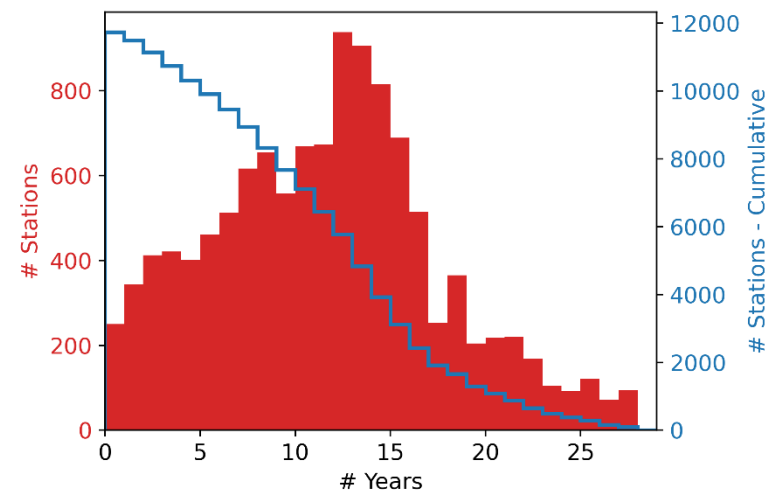
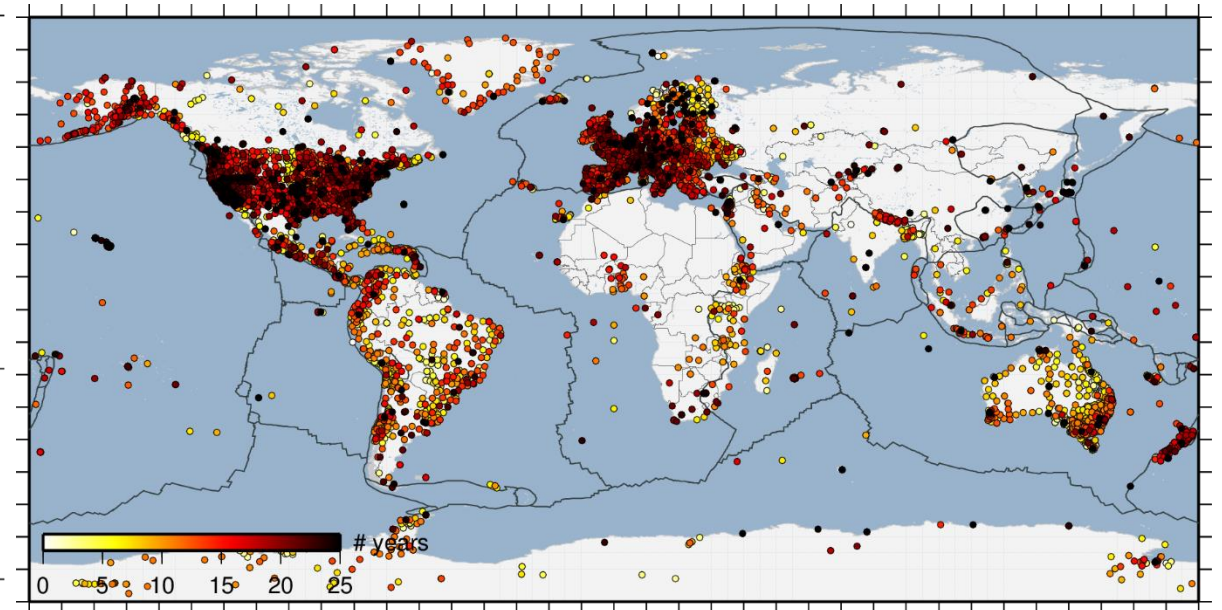
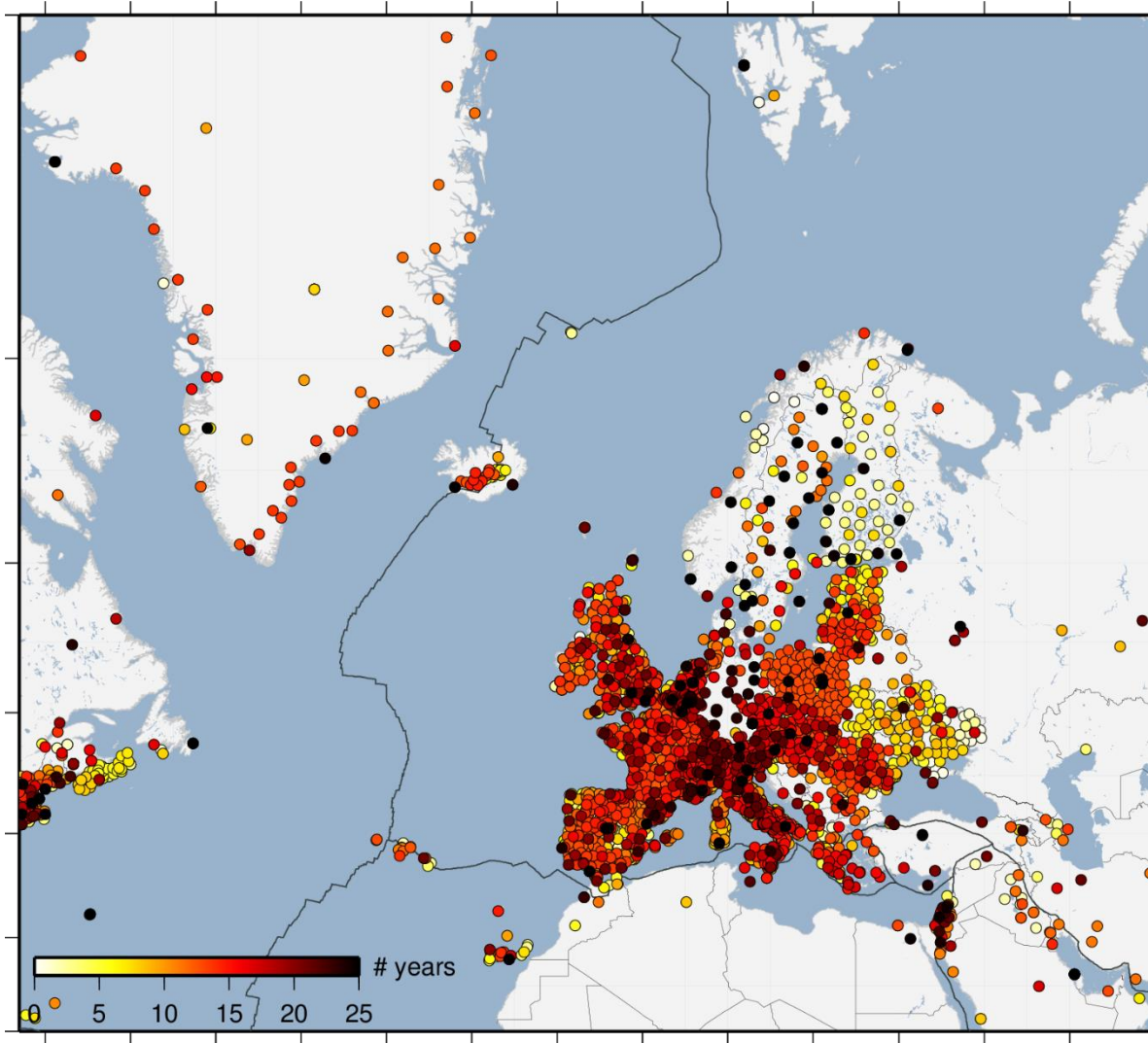
- High temporal resolution

# GNSS for Climate: Conclusions and Outlook

- Ground-based GNSS can provide climate communities a high-frequency, all-weather, long-term, homogeneously processed, homogeneous, global or denser regional, independent datasets of ZTD, IWV, gradients (?) to
  - assimilate in their climate models
  - validate the datasets climate models ingest during assimilation (cloud bias of satellite retrievals)
  - assess the model water vapour output (integrated water vapour, humidity, precipitation) spatially and temporally (long-term, diurnal cycle)
  - ???
- We are open to your input and are ready to get organized to serve better the climate community needs (Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) Joint Working Group C.2 Quality control methods for climate applications of geodetic tropospheric parameters)
- Remote Sensing special issue "'Climate Modelling and Monitoring Using GNSS"  
[https://www.mdpi.com/journal/remotesensing/special\\_issues/Global\\_Climate\\_GNSS](https://www.mdpi.com/journal/remotesensing/special_issues/Global_Climate_GNSS)

# GNSS for Climate: Conclusions and Outlook

## Potential Contribution to Climate



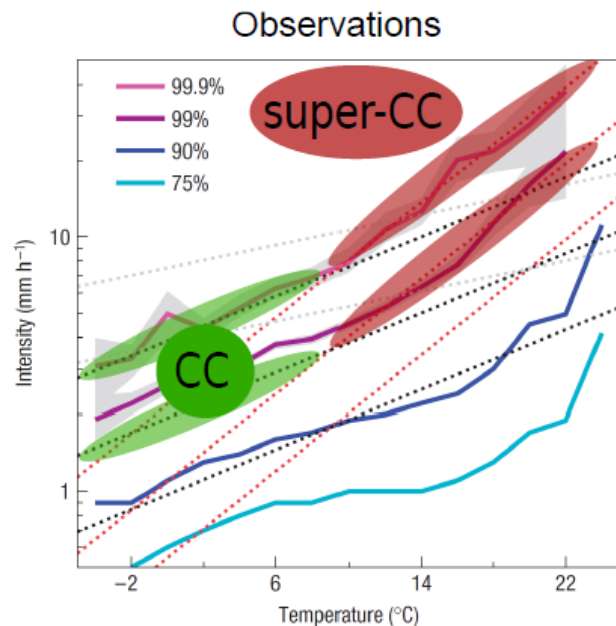
Source: © J. Legrand, ROB, 2021



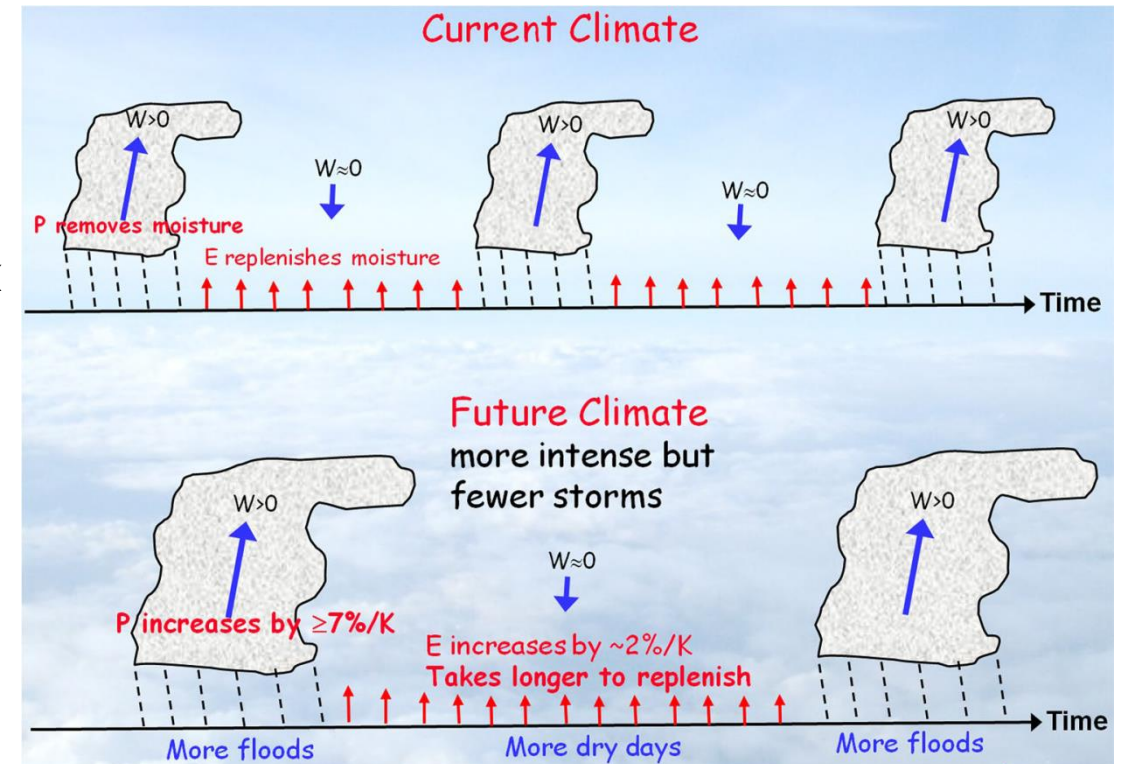
# GNSS for Climate: Conclusions and Outlook

## Super-CC and Climate Change

- Integrated Water Vapour is “intermediate” between surface temperature (Clausius-Clapeyron) and precipitation
- use of GNSS IWV for validation of more complex (regional) climate models (high resolution, convection permitting models)



Source: Lenderink & Van Meijgaard, Nat. Geosc., 2008

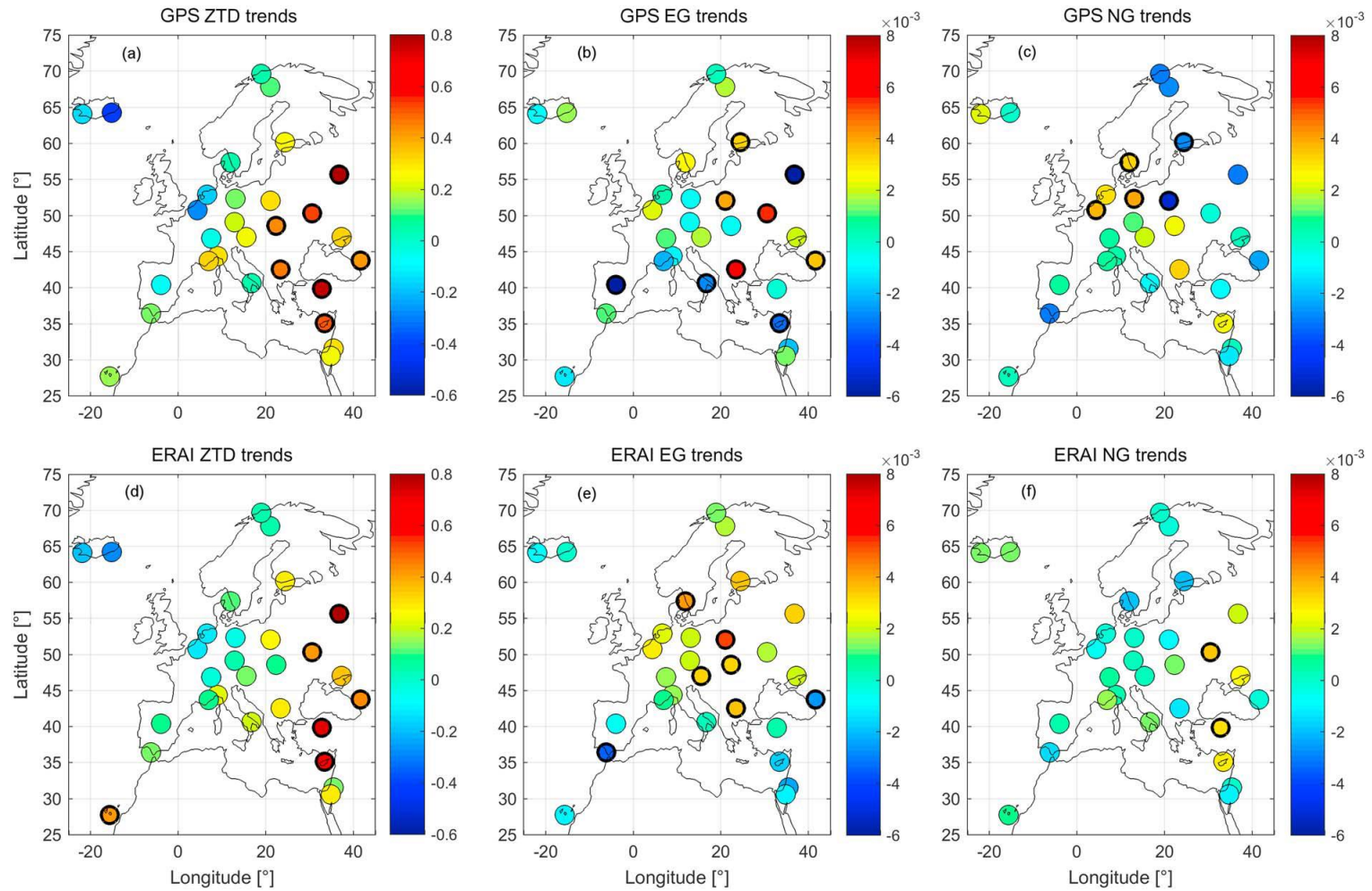


Source: Dai et al., Clim. Dyn., 2020

# GNSS for Climate: Conclusions and Outlook

## Horizontal gradients?

- trends in EW and NS gradients
- added value?



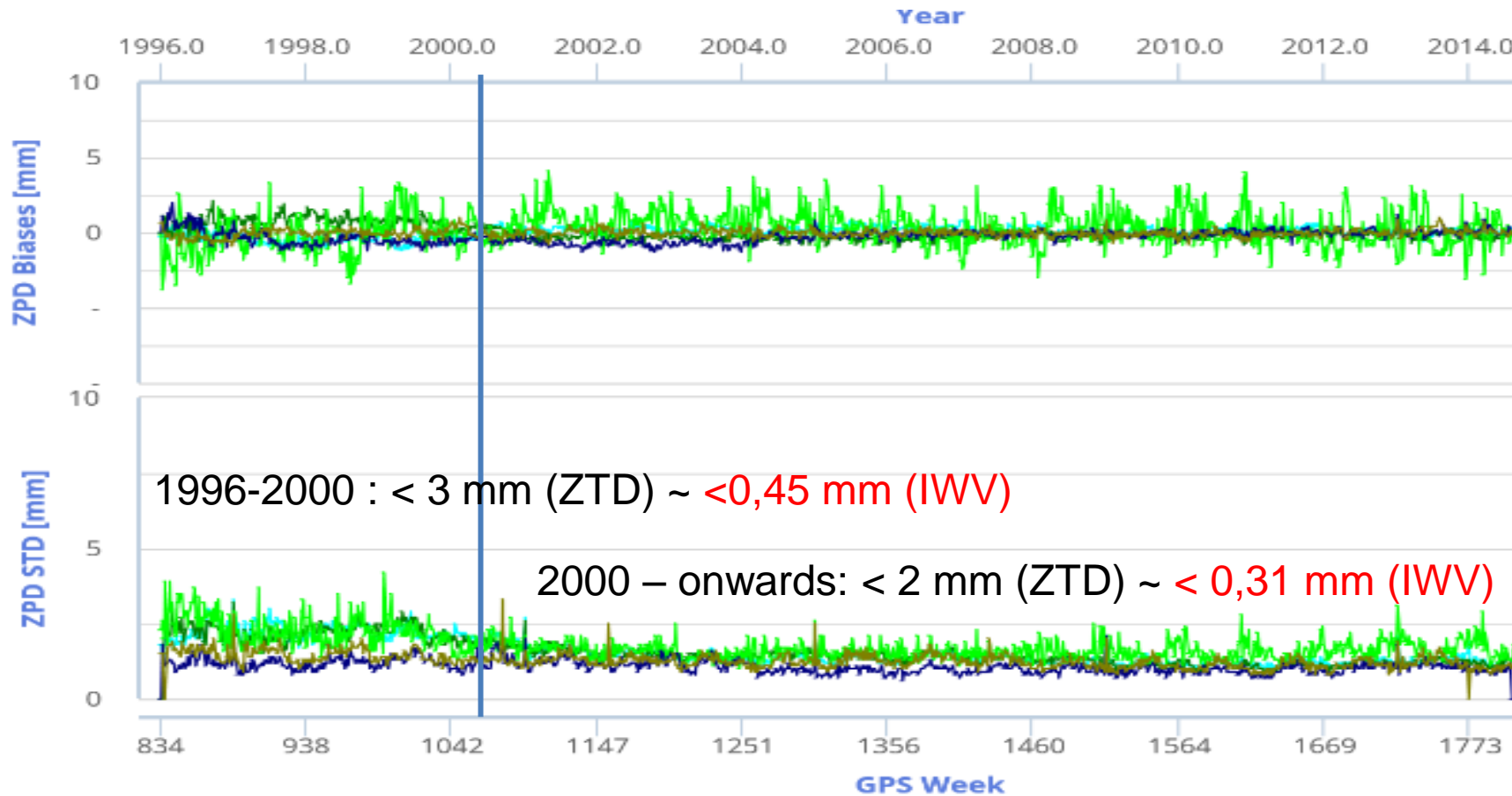
ZTD, EW, and NS gradient trends (mm/yr) from GPS and ERAI

Source: Alshawaf et al., JGR, 2018

Extra slides

# Ground-based GNSS : Reprocessed Datasets

Example of agreement of reprocessed dataset with different software packages (Bernese, Gamit, Gipsy)



**EPN Network**

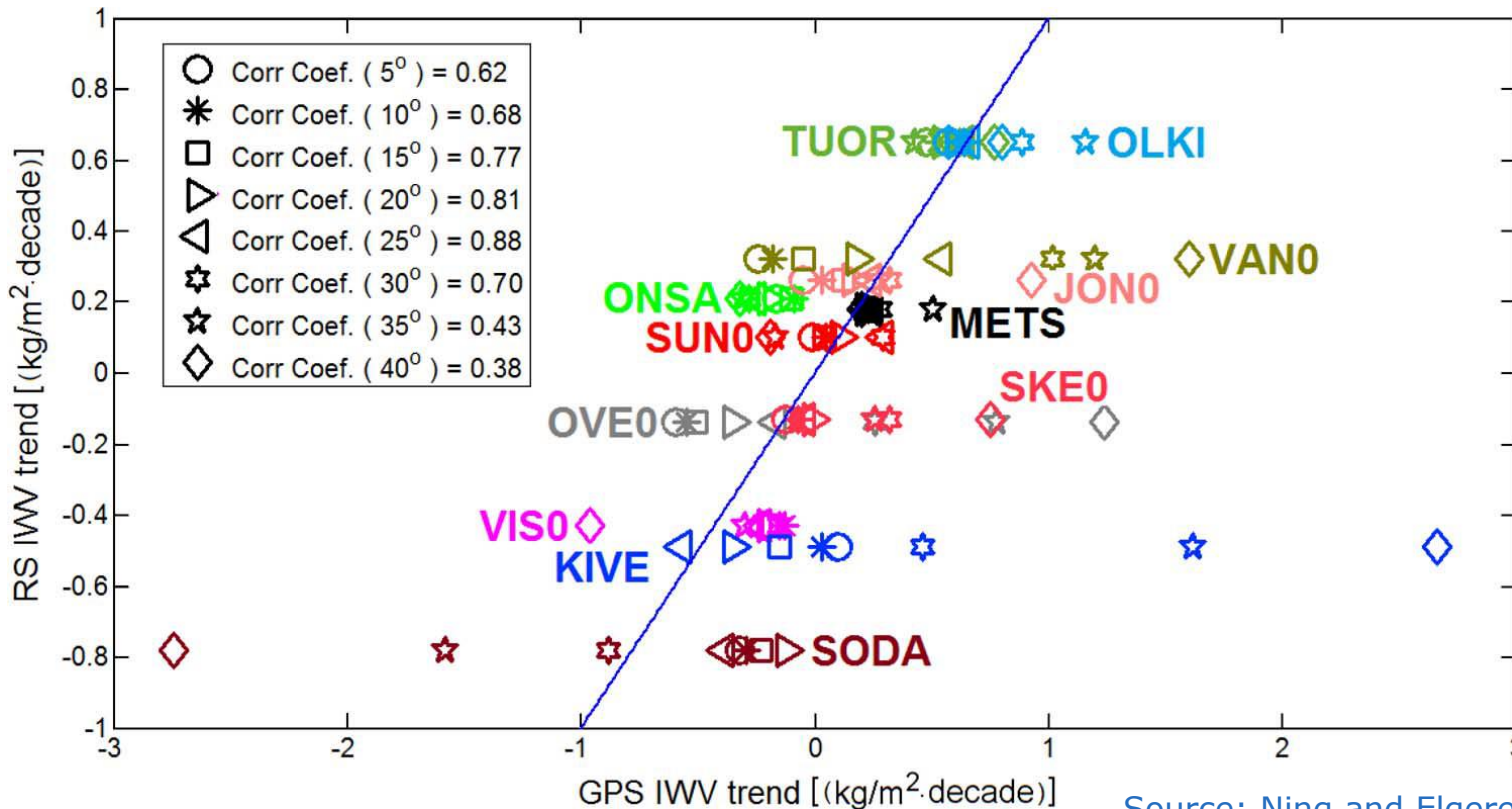


Source: Pacione, R., Araszkiwicz, A., Brockmann, E., and Dousa, J.: EPN-Repro2: A reference GNSS tropospheric data set over Europe, Atmos. Meas. Tech., 10, 1689–1705, <https://doi.org/10.5194/amt-10-1689-2017>, 2017

# GNSS for Climate: Requirements

- **homogeneity** of the time series **processing**

**linear IWV trends based on radiosonde vs. GPS** (based on 14 years of data from 12 sites in Sweden and Finland)



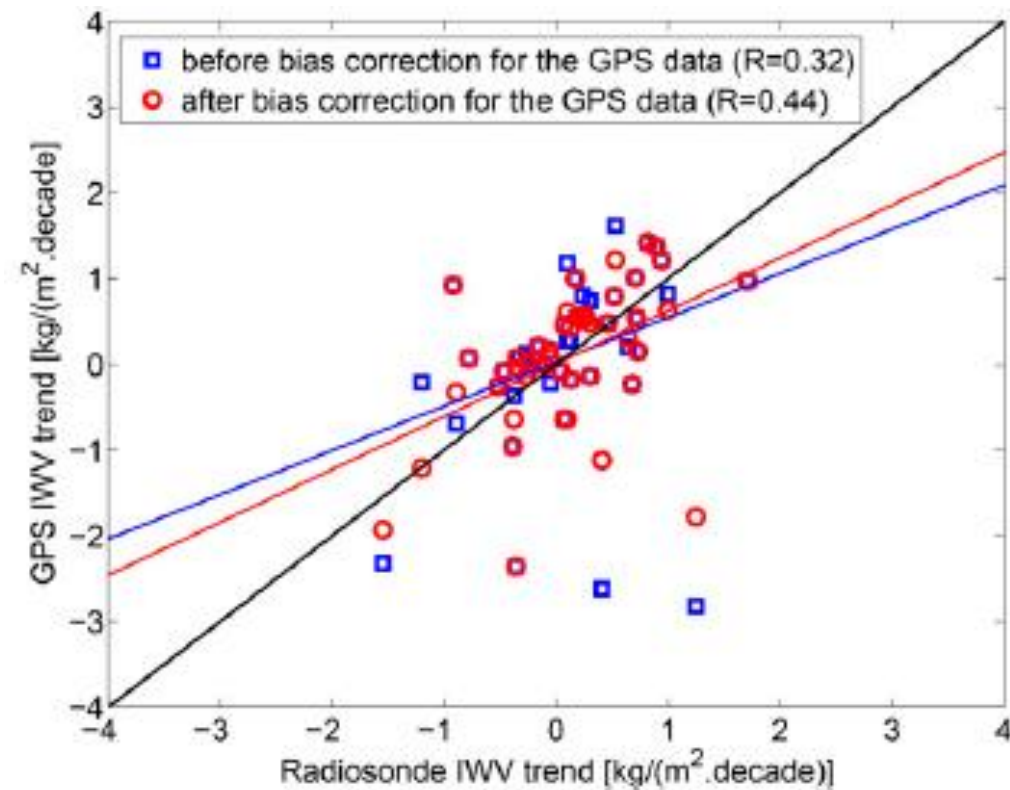
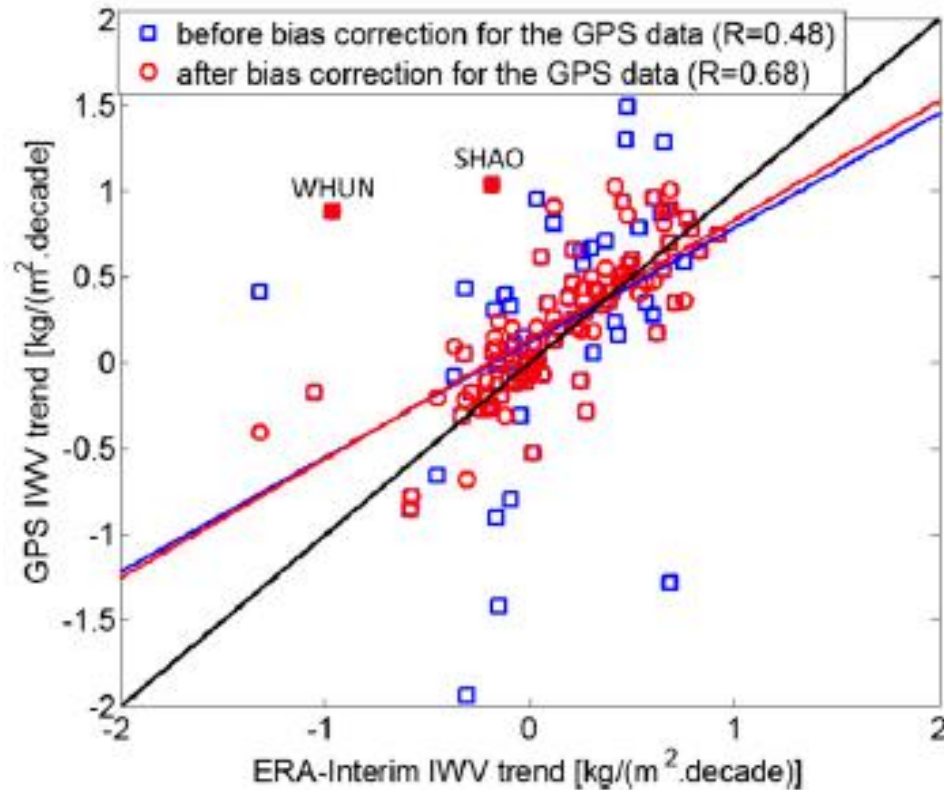
Source: Ning and Elgered, IEEE JSTARS, 2012

- For example, the chosen elevation **cutoff angle** has an impact on the IWV which is site dependent.
- If this dependence varies with time it will also affect the estimated trends.
- For these sites, the highest correlation is obtained for an elevation cutoff angle = 25°

# GNSS for Climate: Requirements

Source: Ning et al., J. Clim, 2016

- **homogeneity** of the time series



- after correcting for biases detected with PMTred in GPS-ERA-interim IWVs: better consistency between trends
- also better consistency between IWV trends at co-located GPS and RS stations