Ground-based GNSS for climate research: review and perspectives

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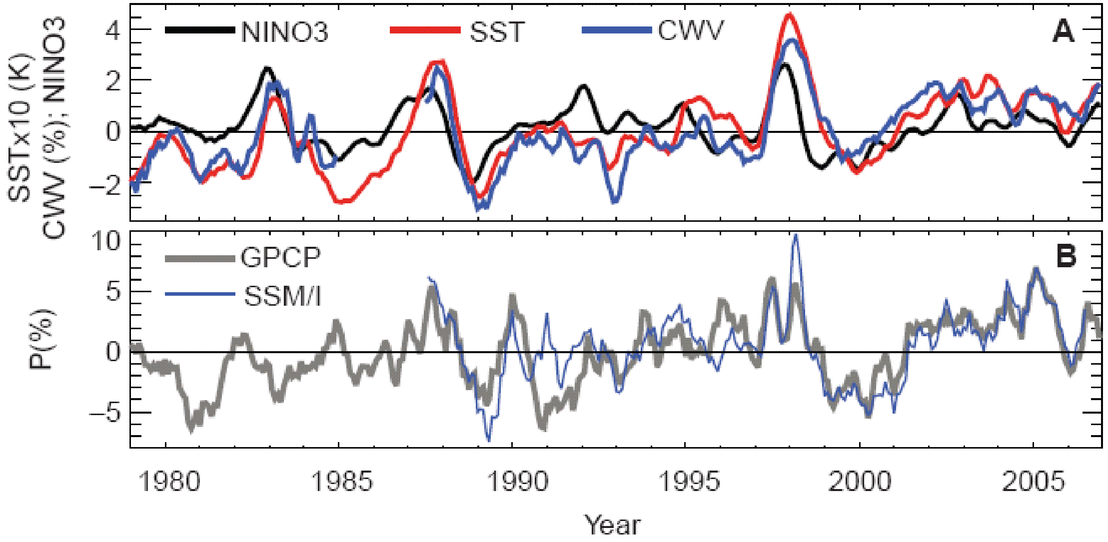
Outline

- 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 ≈ 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



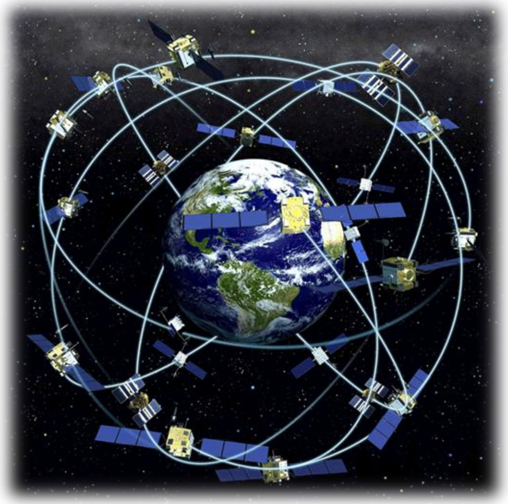
— ENSO (oceanic) index
— sea surface temperature
— water vapour amount
— precipitation

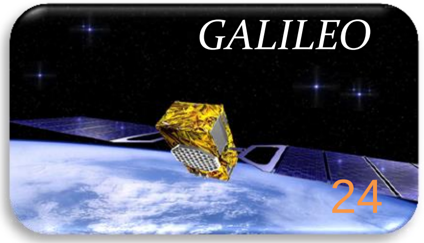
Source: Allan and Soden, Science, 2008

Global Navigation Satellite Systems (GNSS)

System Design

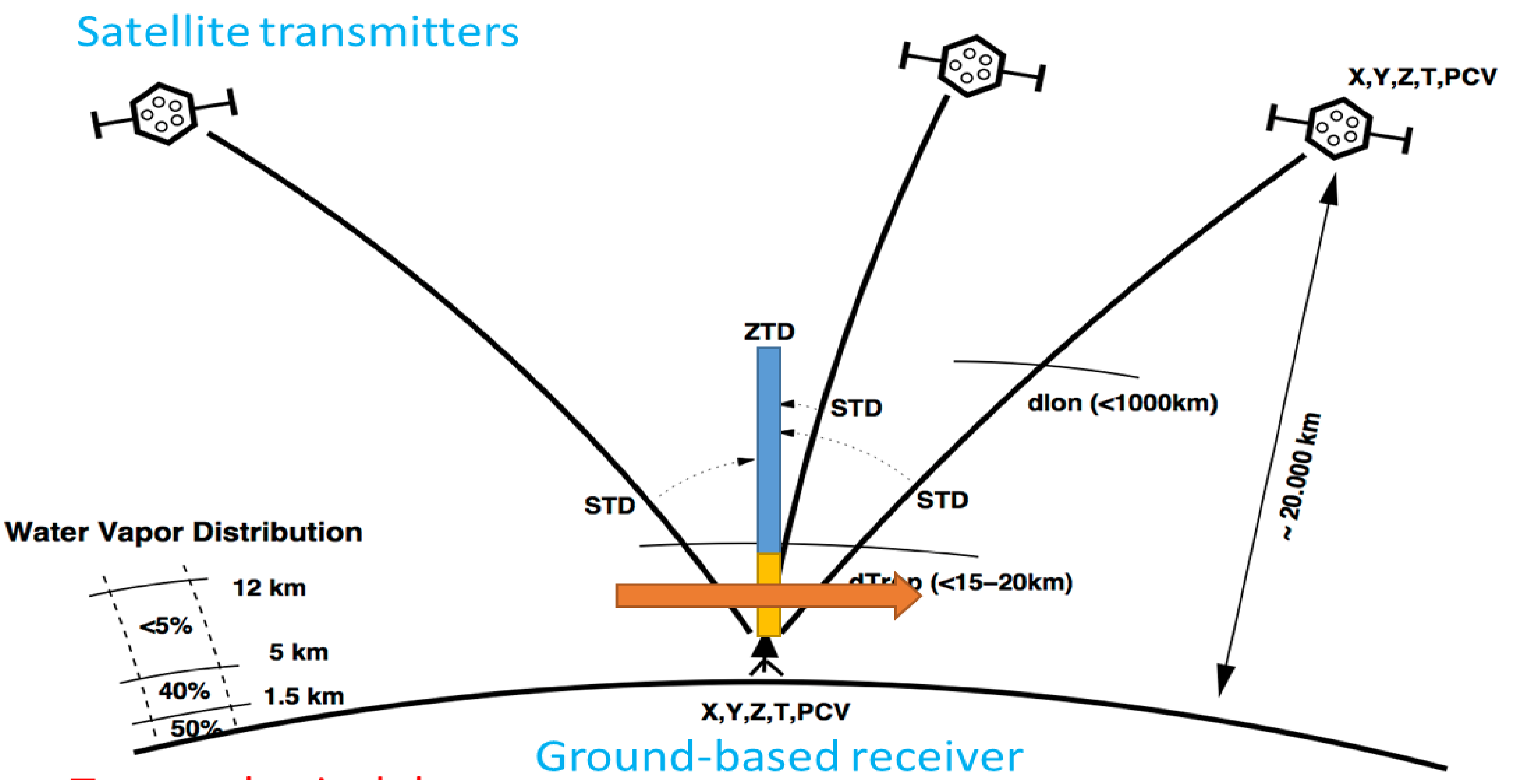
- constellation of satellites (altitude ~20000km)
- emitting radio-frequency signals (carriers + codes)
- recorded by ground-based receivers/antennas on Earth
- measurements = propagation time of the signal





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 Observations

GNSS Data Processing

ZTD

IWV or PW(V)

Integrated Water vapour
Precipitable Water Vapour

Conversion to ECV

GNSS Phase Equation:

Tropospheric delay

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

Zenith Hydrostatic/Dry Delay, Zenith Wet Delay, Horizontal Gradients

$$d_{tropo}(\alpha, e) \equiv ZHD \times m_h(e) + ZWD \times m_w(e) + [G_N \cos\alpha + G_E \sin\alpha] \times m_G(e)$$

$$ZTD = ZHD + ZWD$$

Zenith Total Delay

$$ZWD = ZTD - ZHD$$

$$IWV = \kappa(T_m)\, ZWD$$

Saastamoinen Equation

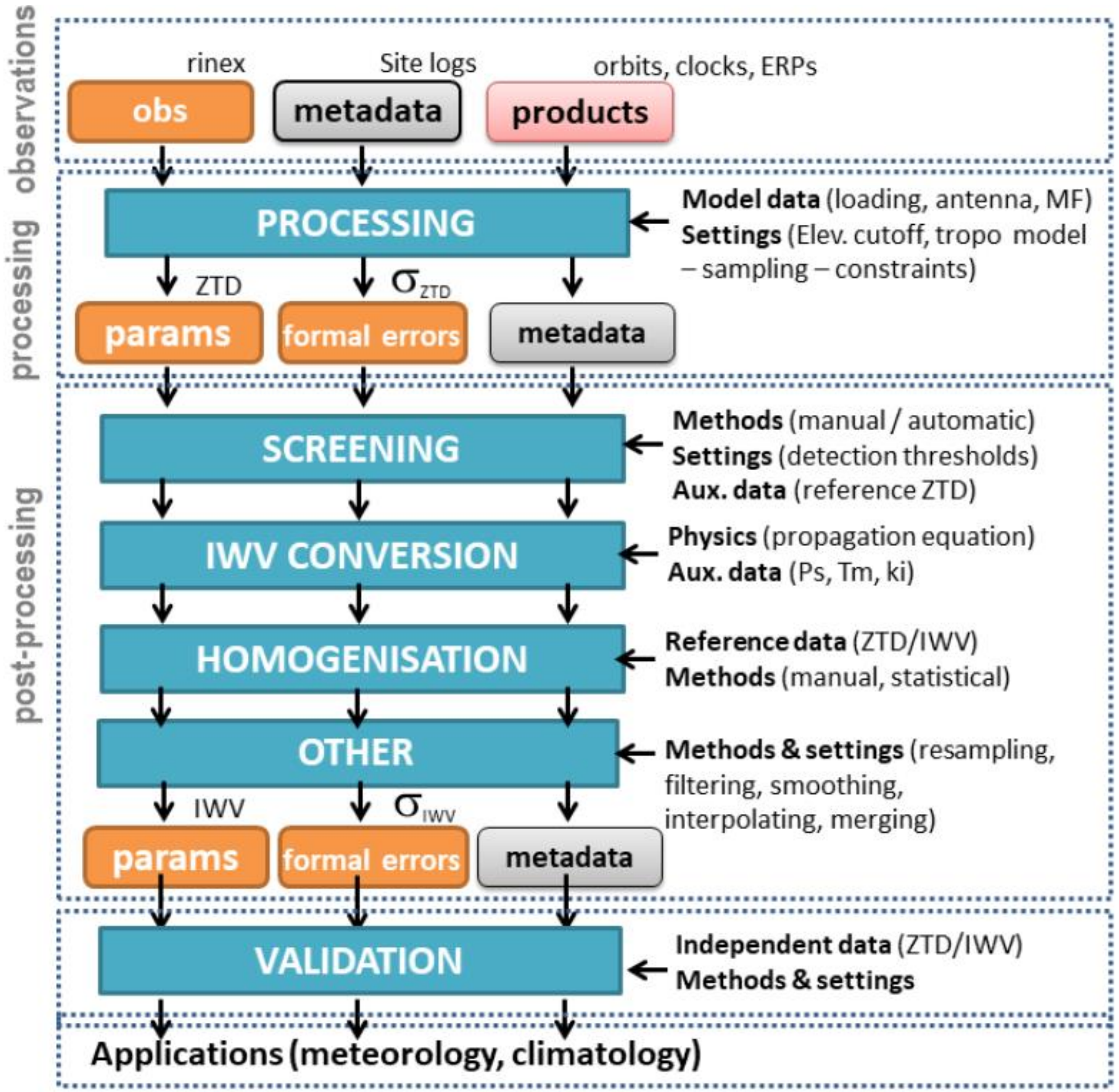
$$ZHD \approx 2{,}3 \left[\frac{mm}{hPa}\right] * P_s\ [hPa]$$

meteo data P_s

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

meteo data T_s and estimated T_m

Ground-based GNSS : From Data to Product



Obs & Products
(station obs & info, satellite products & info, ERPs...)

Processing
(estimation of station coordinates, ZTD...)

Screening
(detection & removal of outliers)

Conversion
(ZTD = total delay to IWV = integrated water vapour)

Homogenisation
(detection of breaks and correction of offsets)

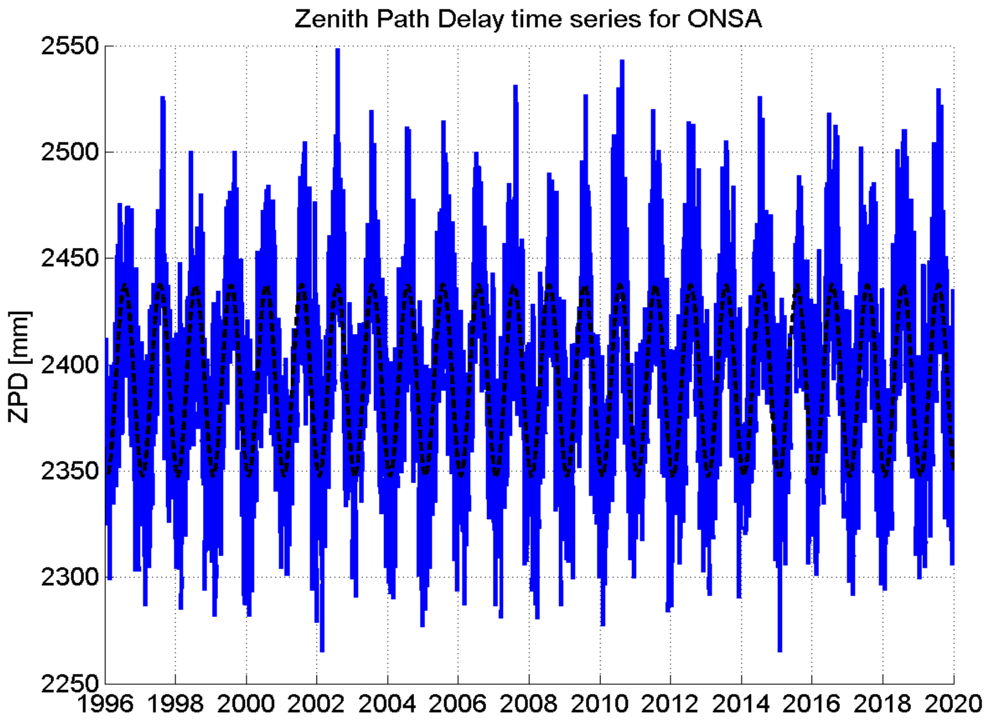
Validation
(detection of biases, excess noise, trends spurious signals...)

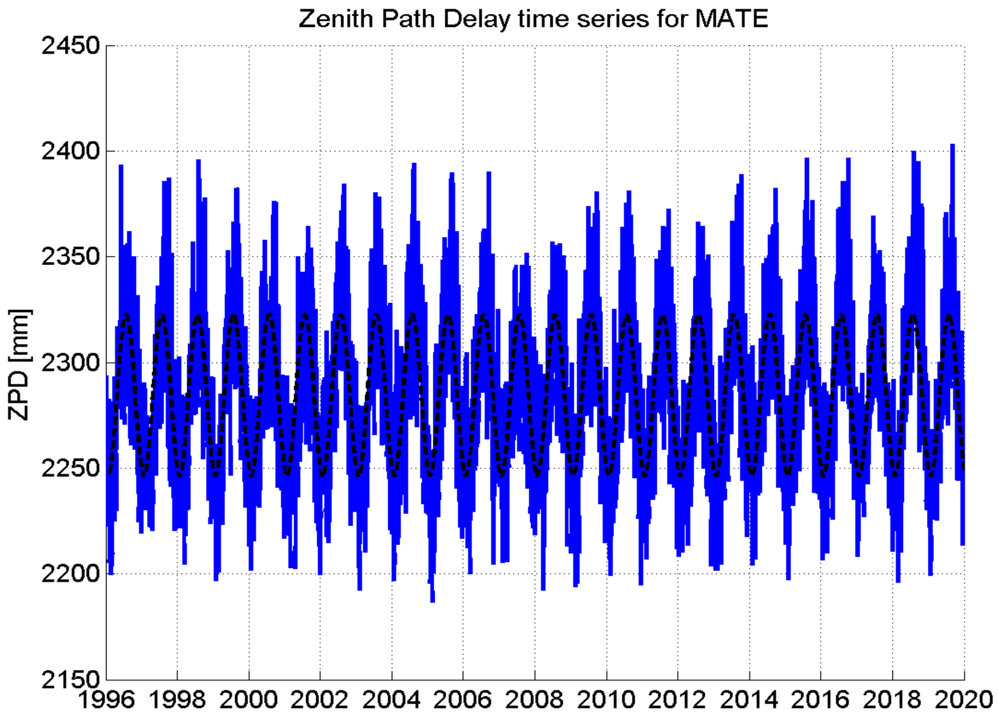
2

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!)

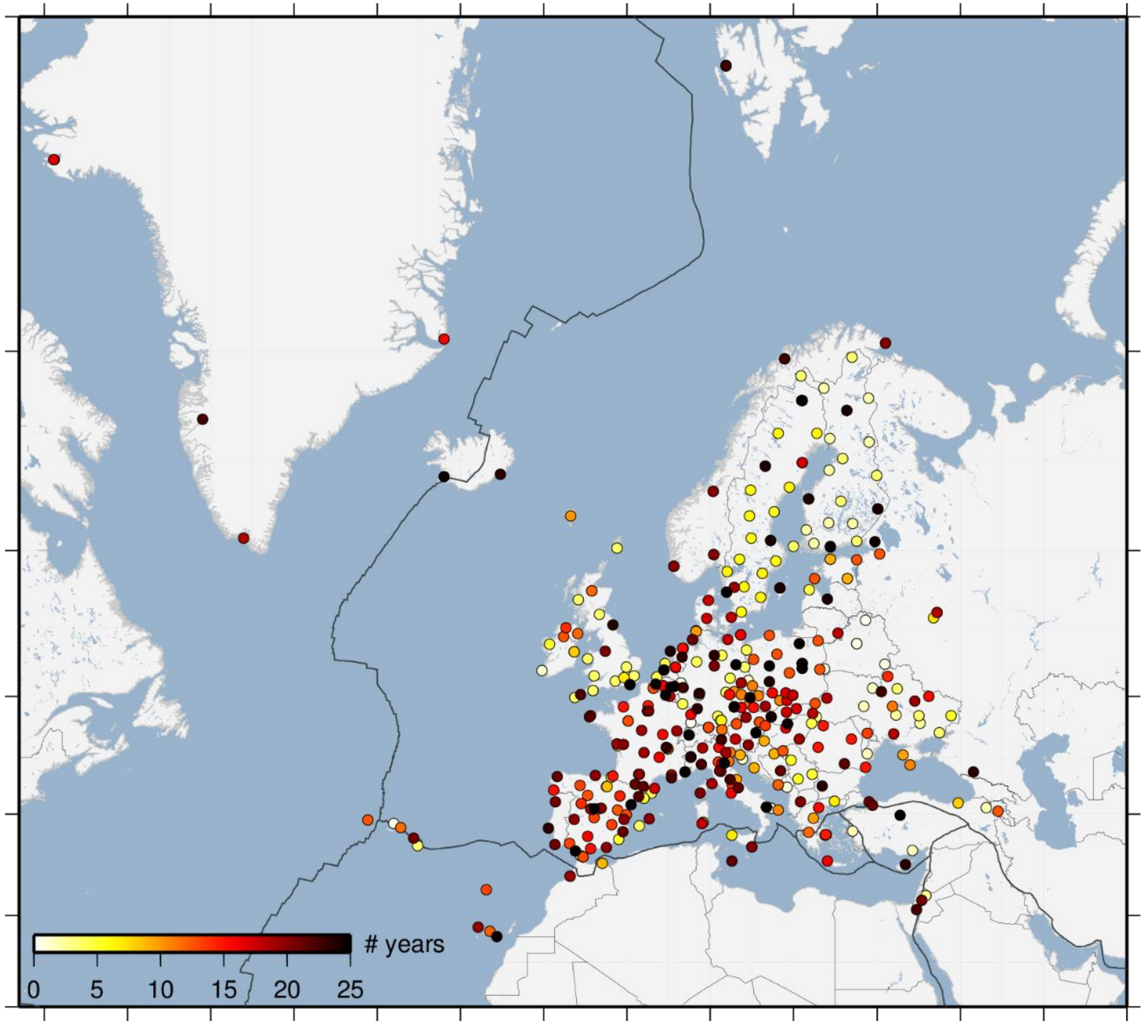


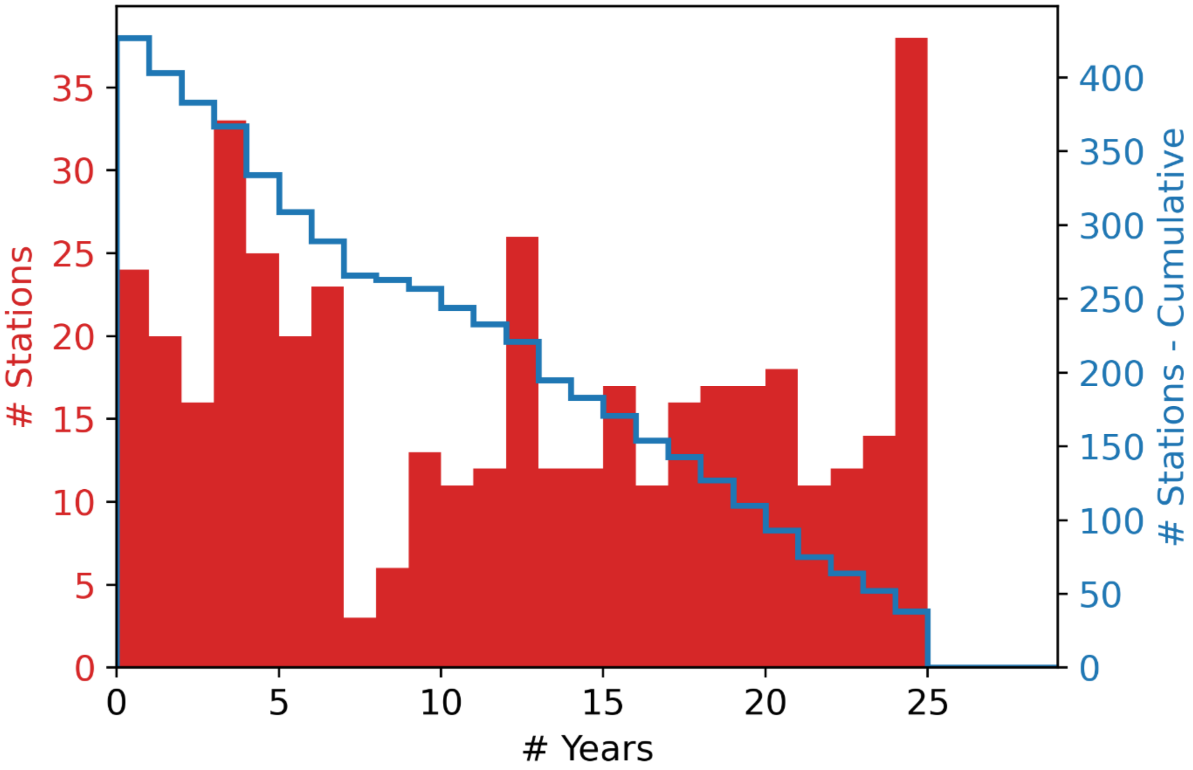


Source: http://www.epncb.oma.be/_productsservices/troposphere/

GNSS for Climate: Requirements

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

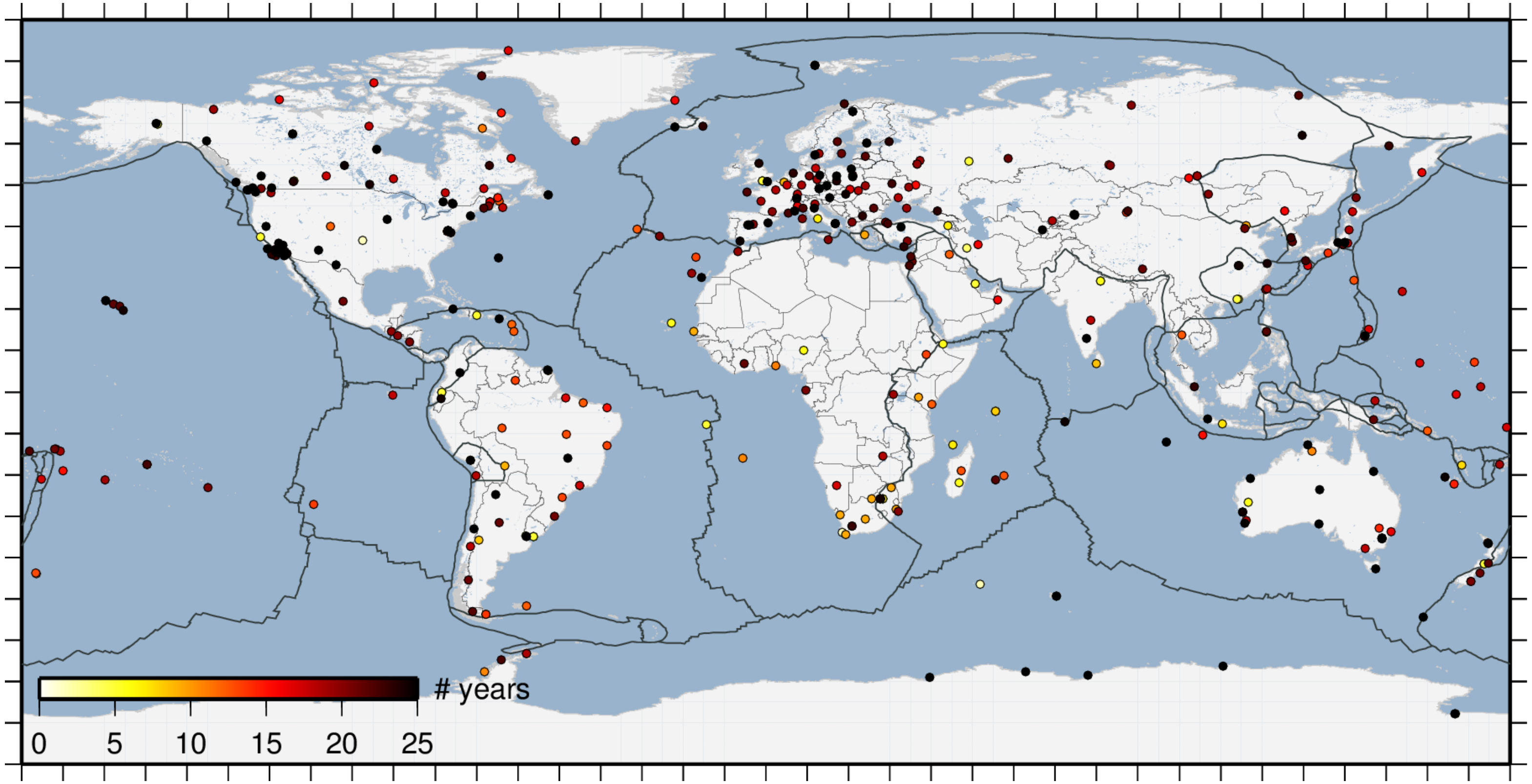


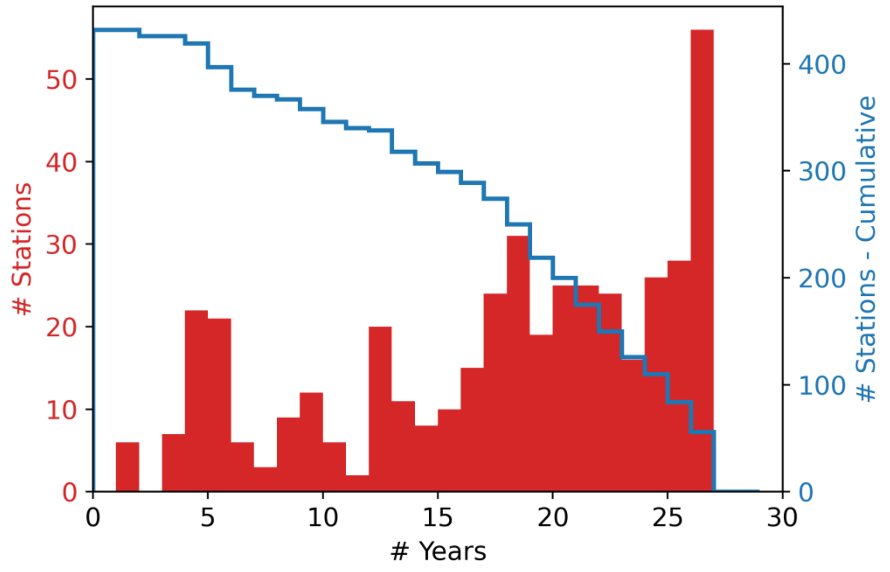


Source: © Juliette Legrand, ROB, 2021

GNSS for Climate: Requirements

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





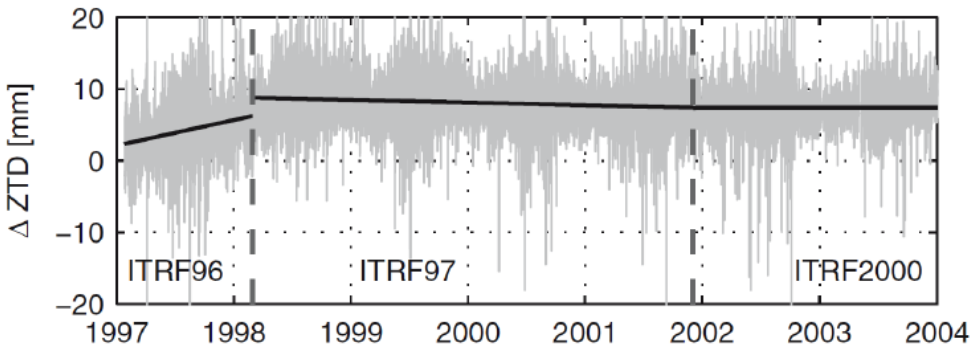
Source: © Juliette Legrand, ROB, 2021

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).

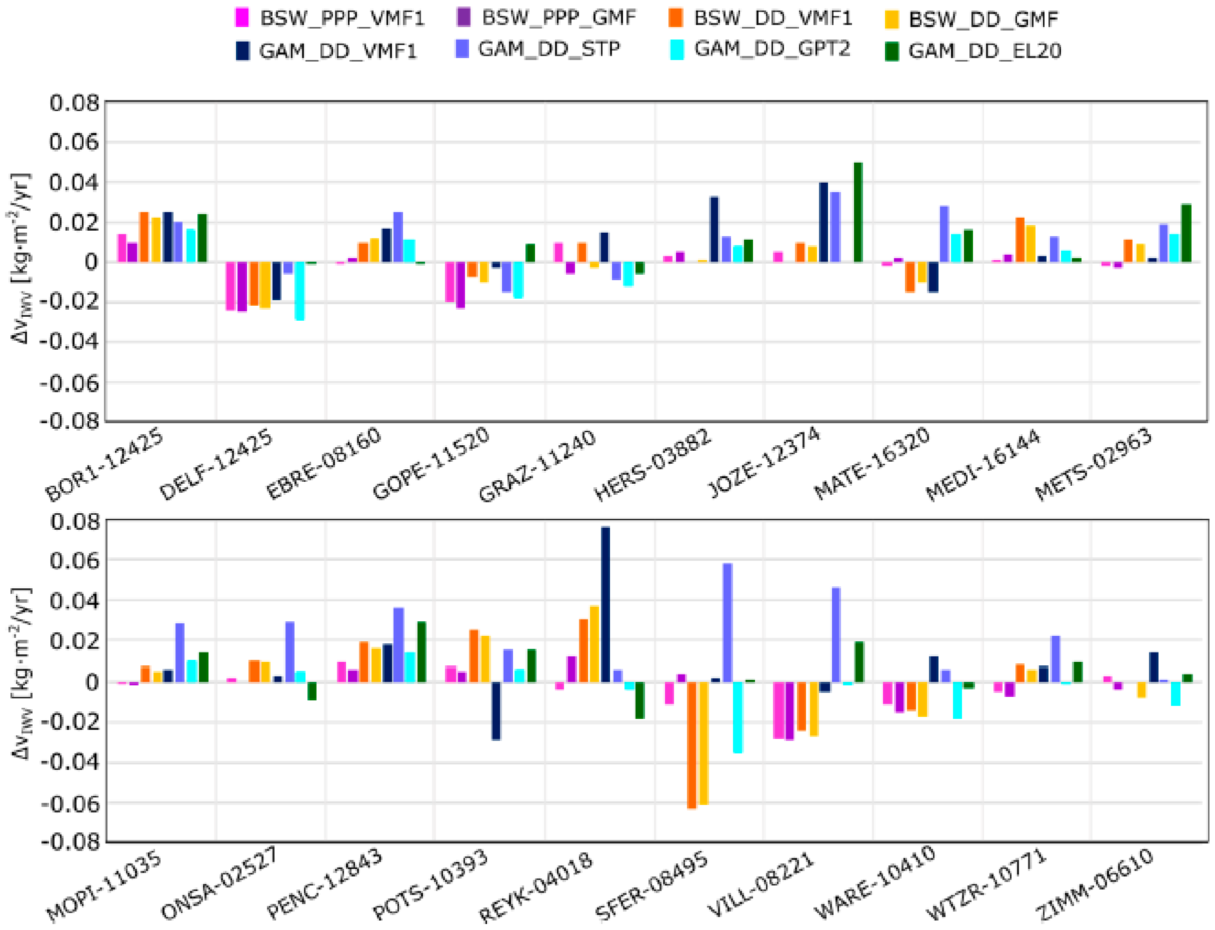
Source: Steigenberger et al. J. Geod. ,2007

- 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

Δv_{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)

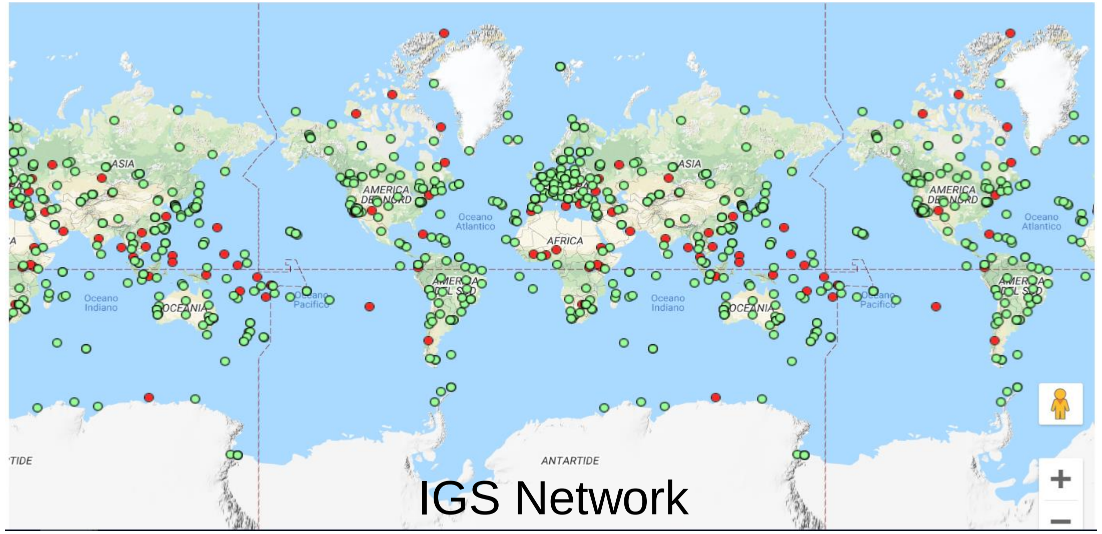
- highest consistency for PPP solutions: DD method may introduce to the troposphere solutions errors that affect the proper investigation of long term changes.

Source: Baldysz et al., Remote Sensing, 2019

GNSS for Climate: Requirements

- ➢ homogeneity of the time series processing

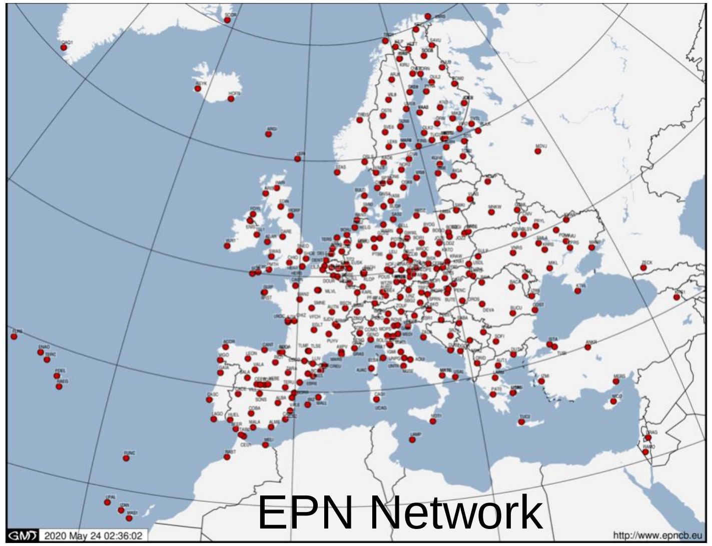
- International Reprocessing Activities
  - ➢ EPN-Repro2 (1996-2014),
  - ➢ IGS-Repro3 (ongoing 1994-2020)
  - ➢ EPN-Repro3 (to be planned 1996-2020)



- Regional / National Reprocessing Initiatives

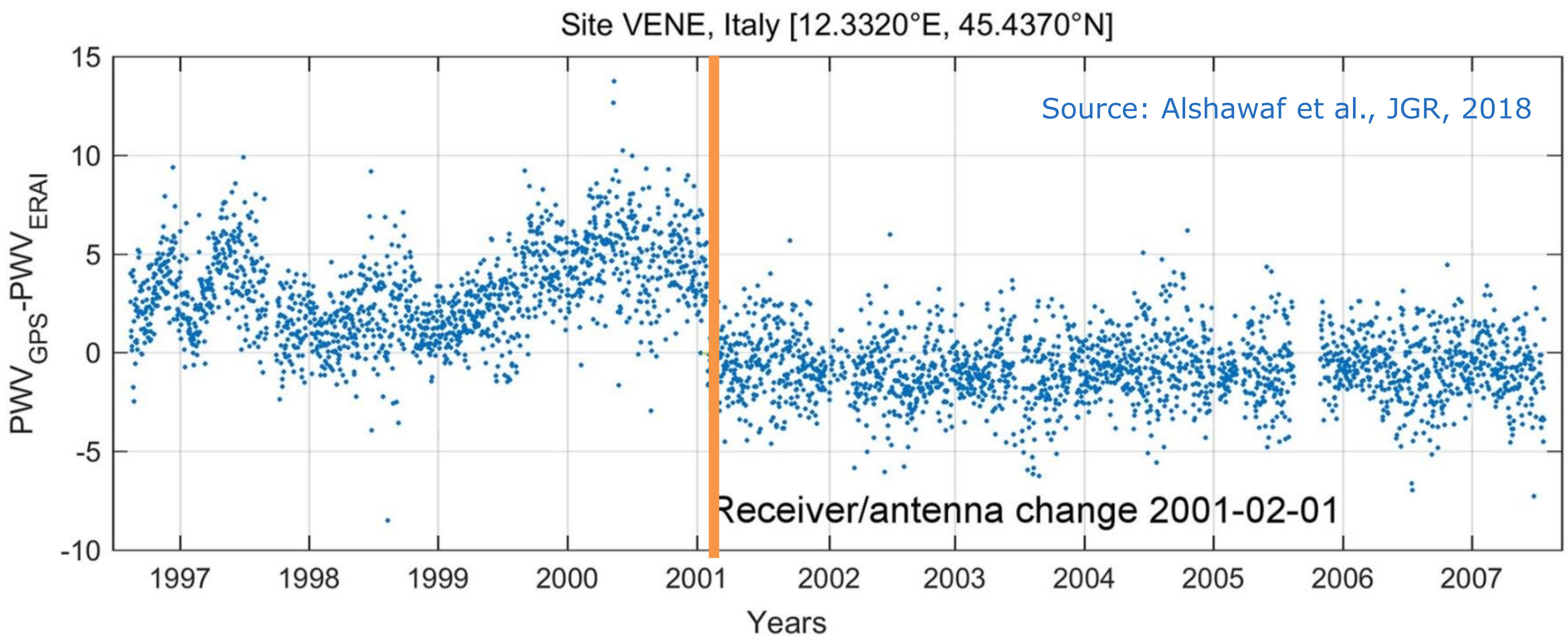
- Some are updated regularly

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



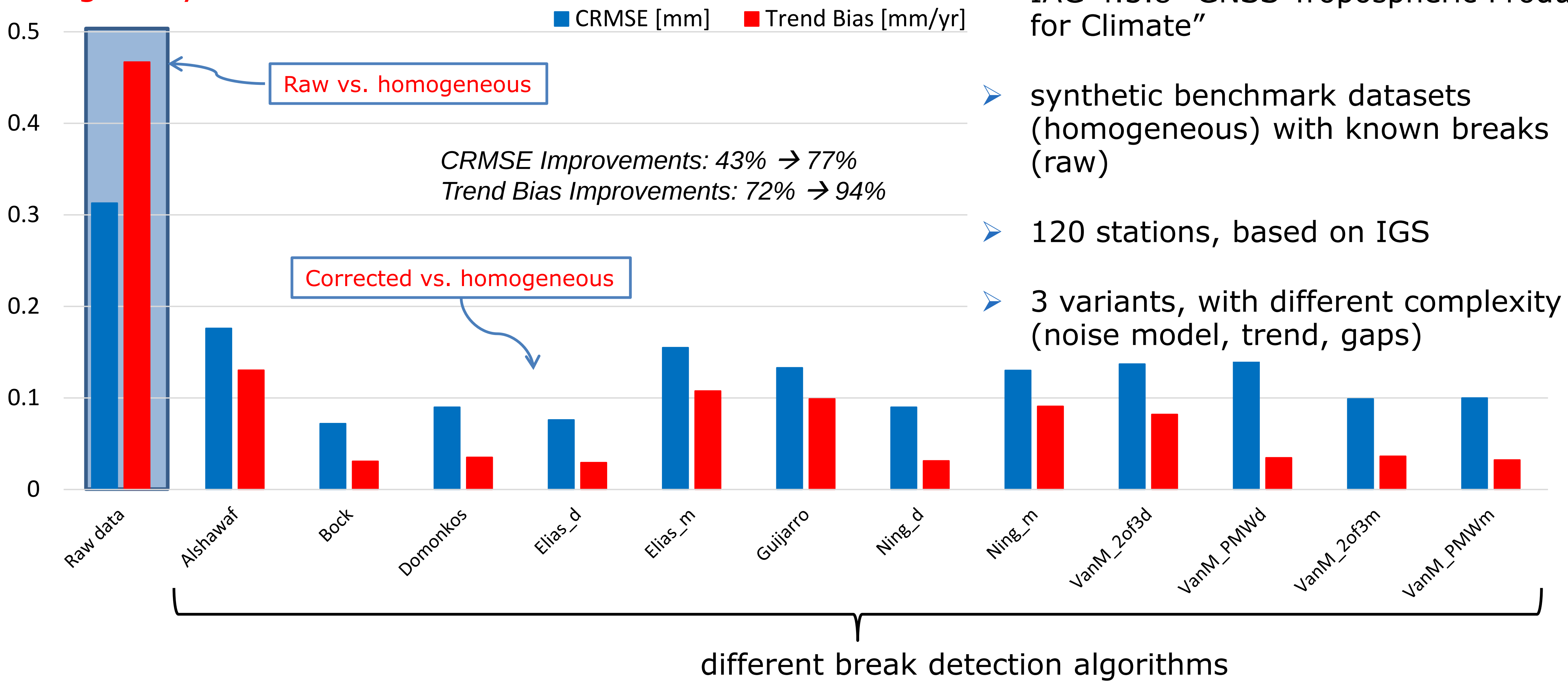
GNSS for Climate: Requirements

- 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
spatial coverage	± 400 active IGS stations	± 1500 IGRA sites	global	global	oceans
spatial resolution	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
temporal resolution	every 5 min	on average twice/day	GOME/SCIAMACHY: max. once/day, GOME-2: max. twice/day	maximum twice/day	twice/day
temporal coverage	1995 - now	1950s - now	1996 - now	2002 - now	1987 - now
all weather?	yes	yes	only if (almost) cloud-free	only if (almost) cloud-free	yes (except heavy rain)
all direction?	yes	vertical profile	nadir	nadir/limb	nadir/limb
precision	< 2 mm or kg/m²	≈ 5% (≈ 15% for very dry conditions)	≈ 15% for clear sky	≈ 5%	< 2 mm or kg/m²

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

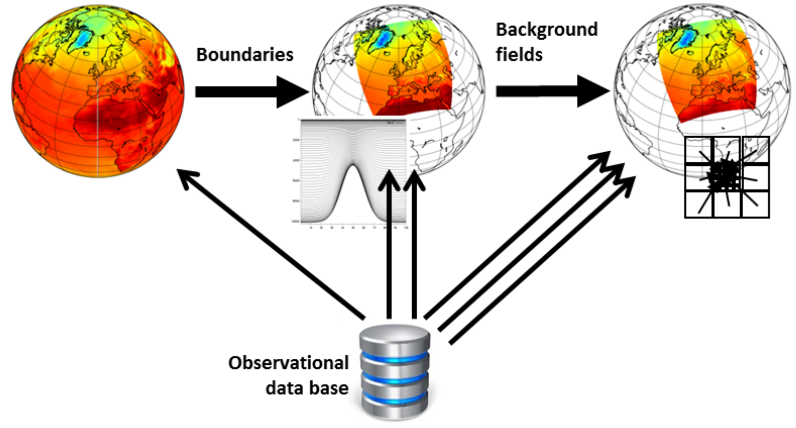
GNSS for Climate: Applications

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.

Global Reanalysis ➔ Regional Reanalysis ➔ Surface Reanalysis

ERA40/ERA-Interim UERRA-HARMONIE MESCAN-SURFEX



white list of 96 EPN stations

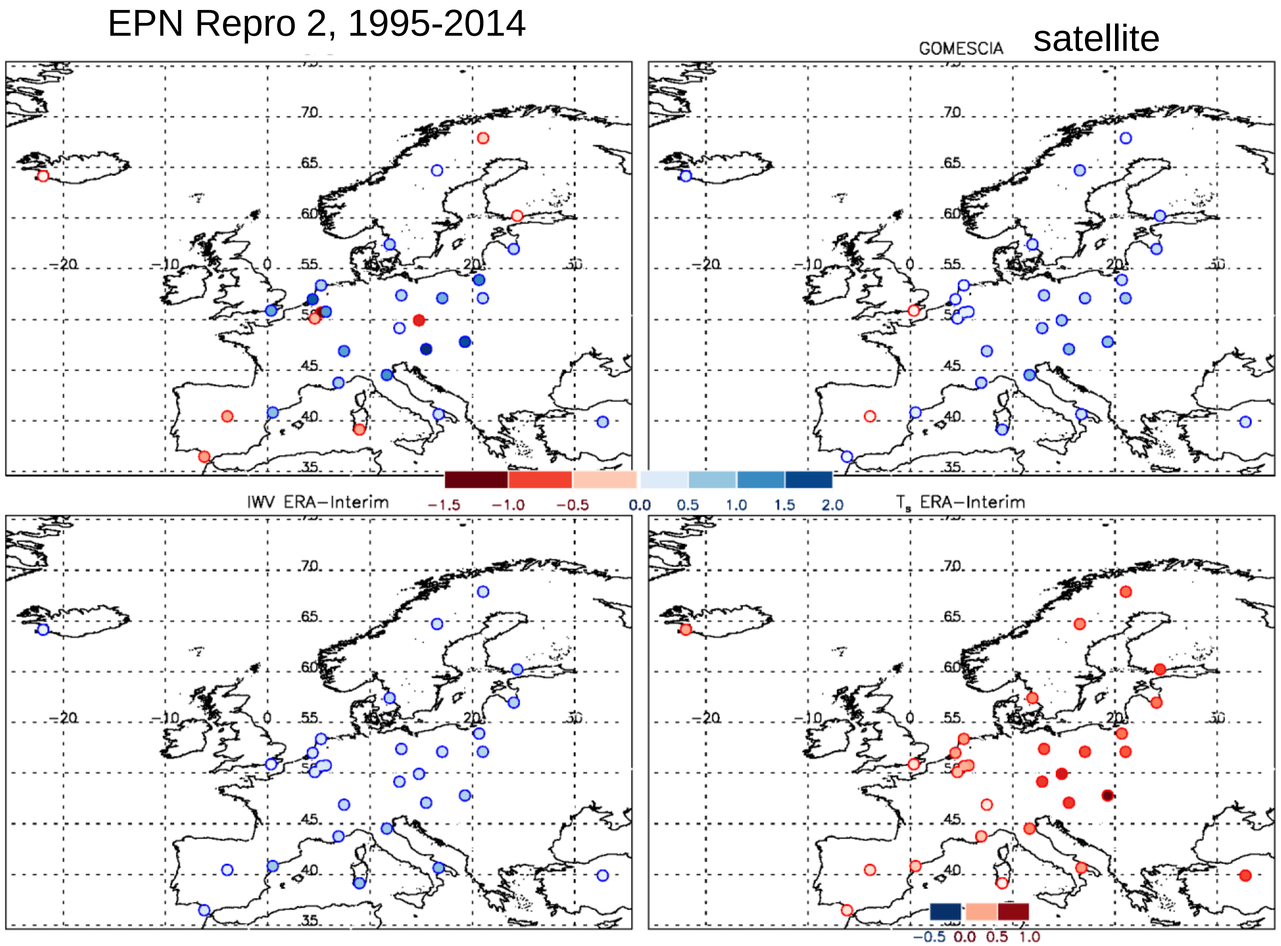
Additional Requirement

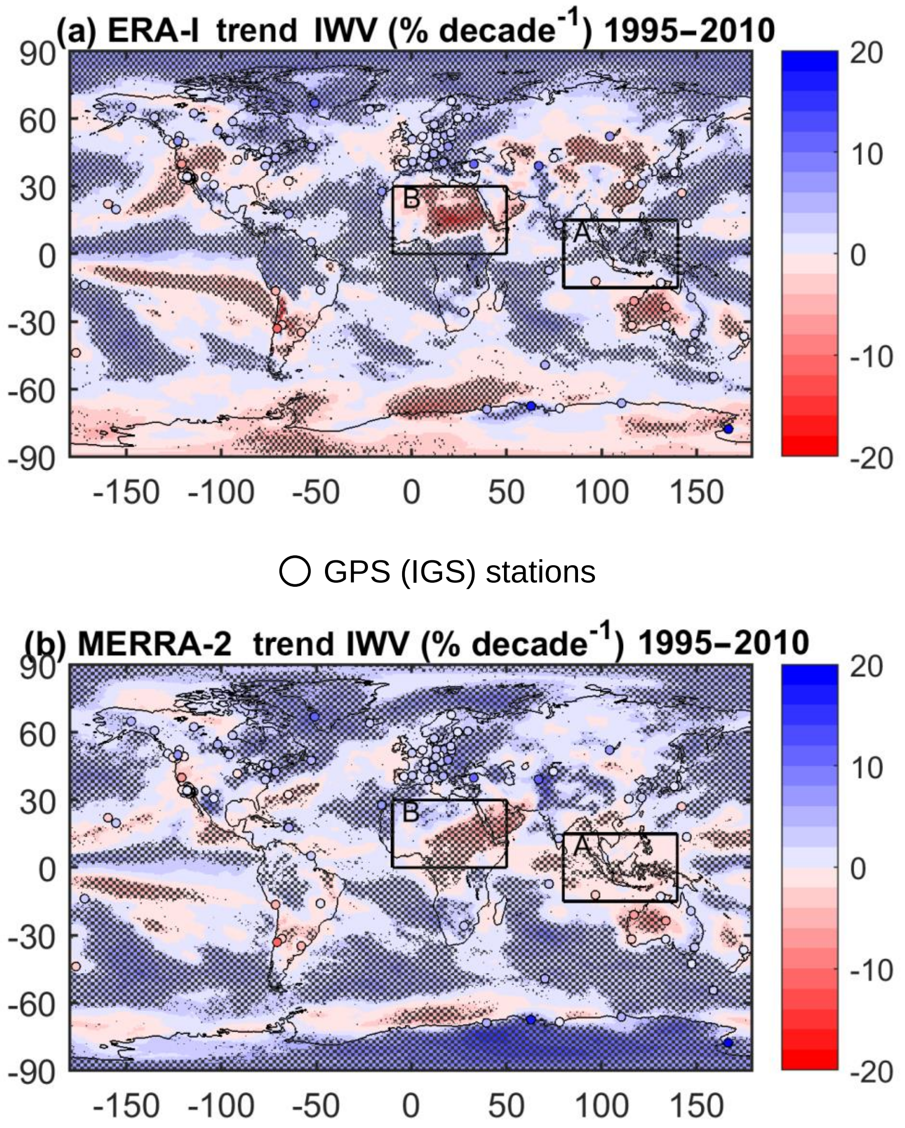
- data continuity

GNSS for Climate: Applications

IWV time variability

- calculation of IWV trends

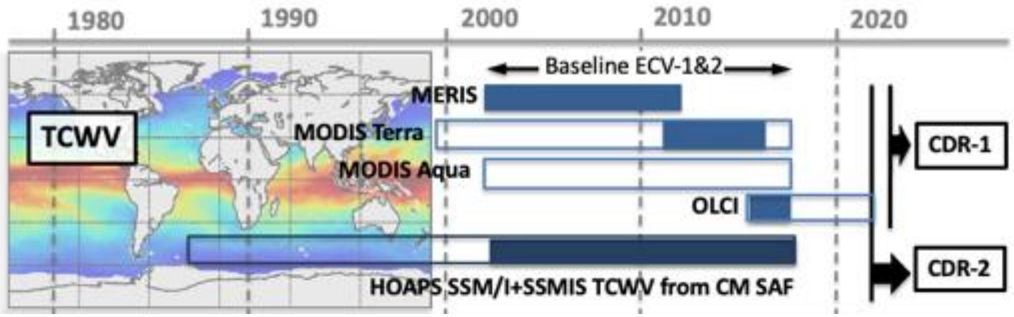




Source: Parracho et al., ACP, 2018

GNSS for climate: Applications

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

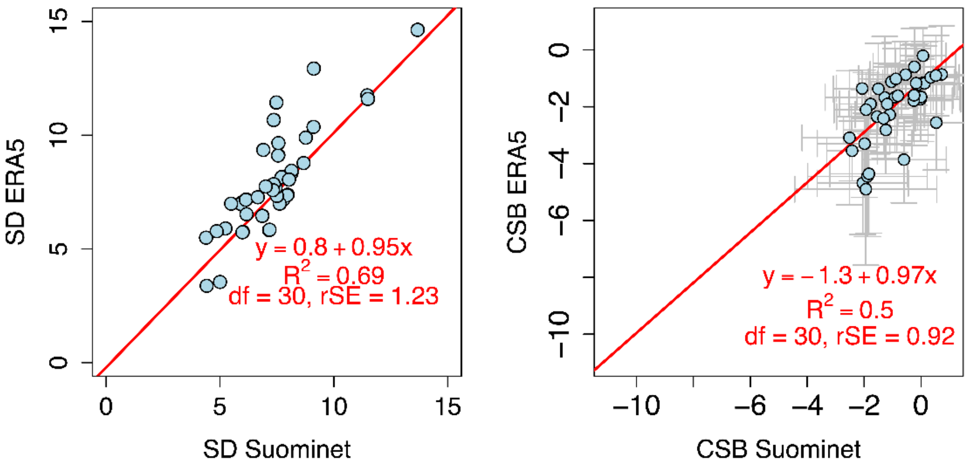


remote sensing MDPI

Article

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

Stelios Mertikas [1], Panagiotis Partsinevelos [2,*], Achilleas Tripolitsiotis [3], Costas Kokolakis [3], George Petrakis [2] and Xenophon Frantzis [1]



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

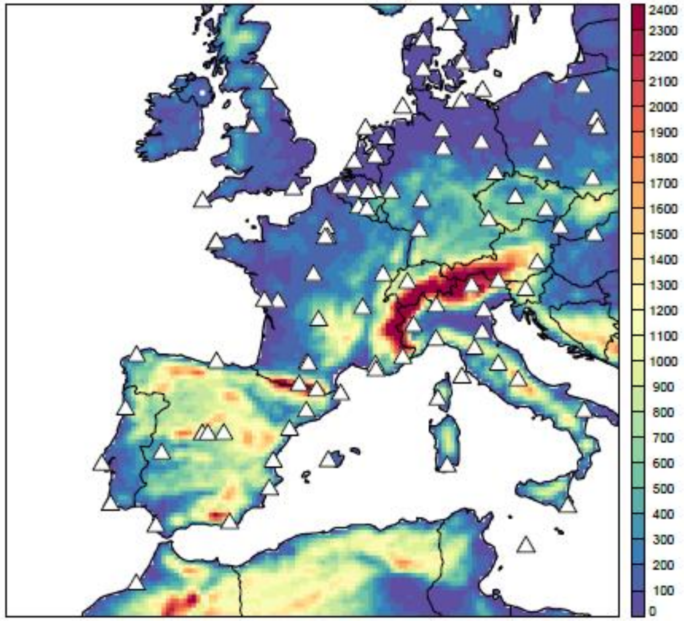
- all-weather device, also under clouds

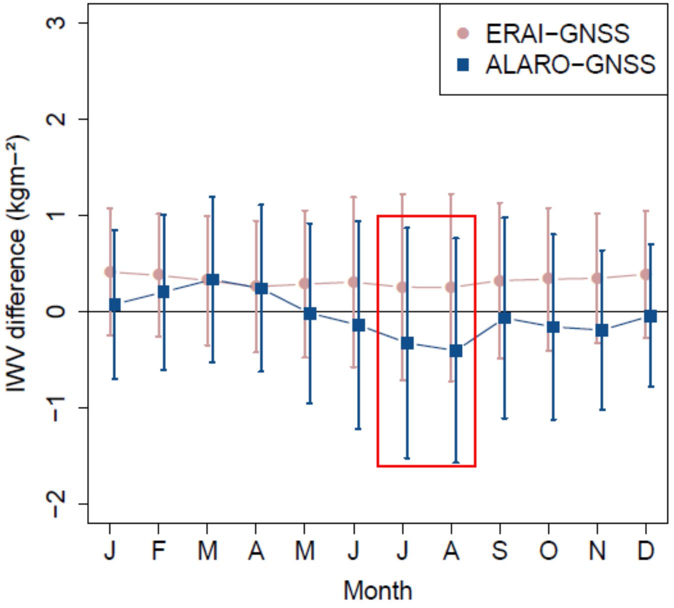
GNSS for climate: Applications

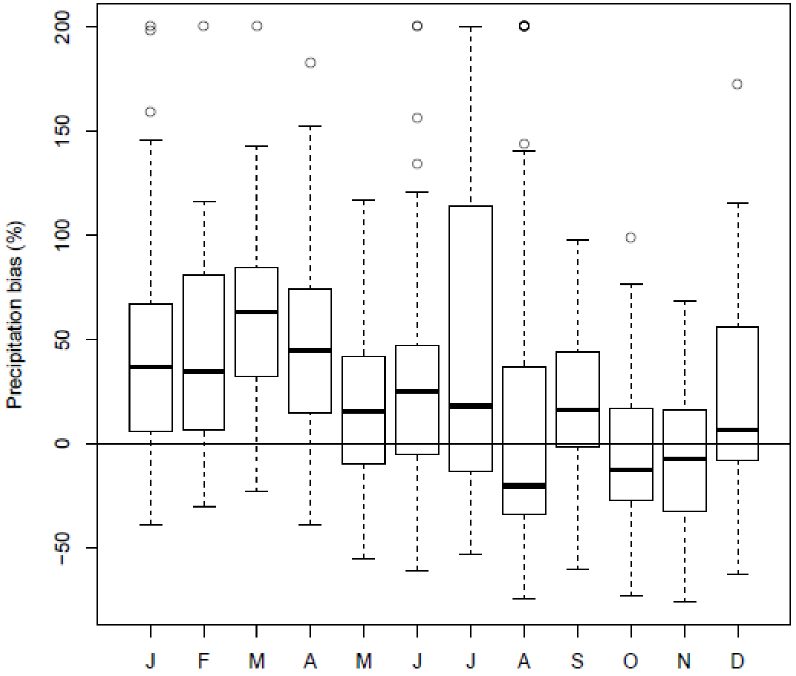
- assessment of climate model water vapour fields

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

ALARO Domain - Model







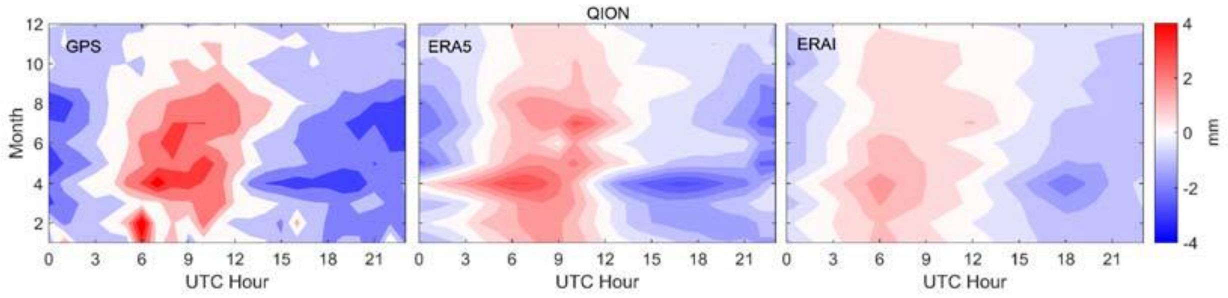
- seasonal variation in ALARO-GNSS IWV differences

- similar seasonal variation in ALARO precipitation biases

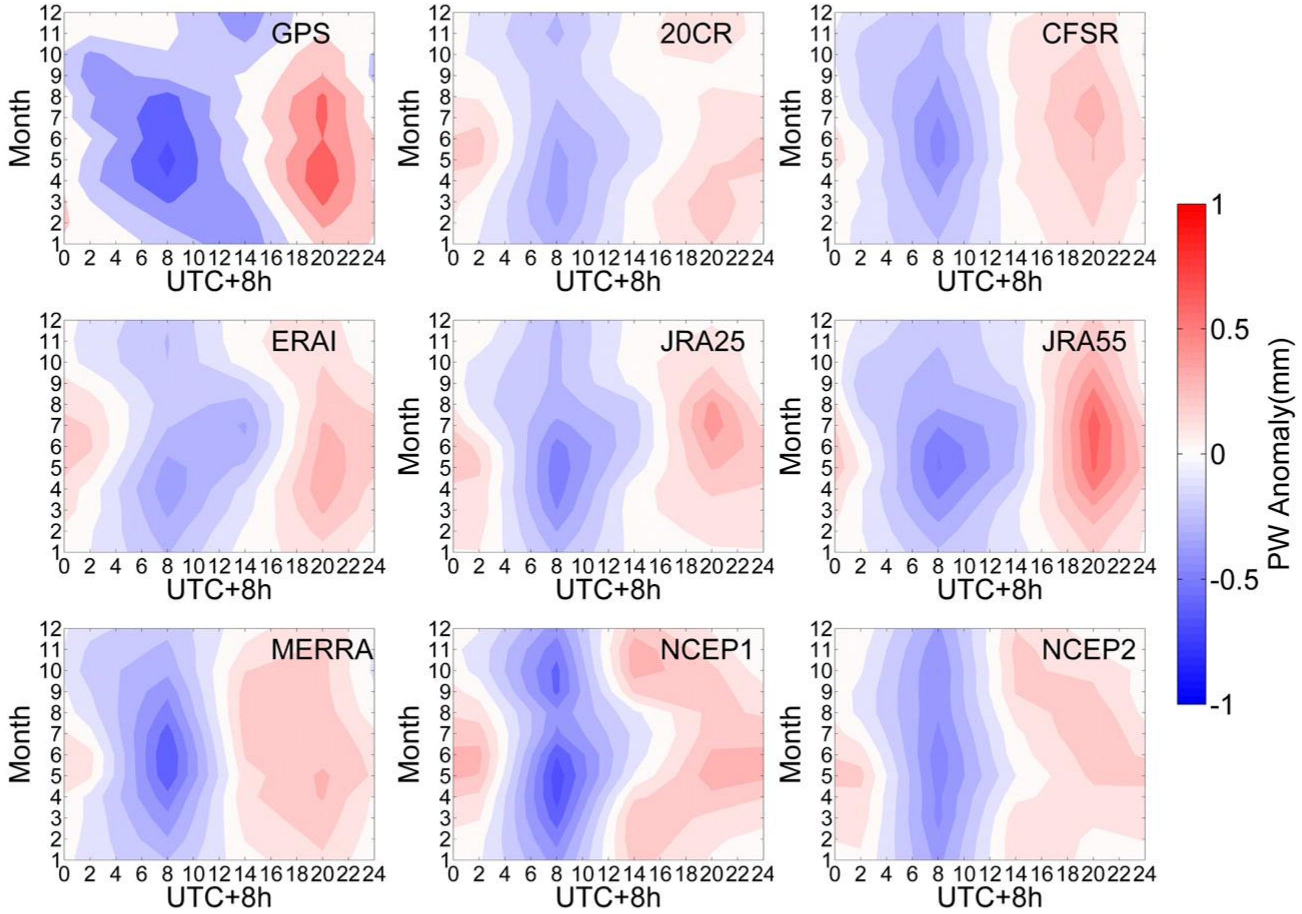
Source: Berckmans et al., ACPD, 2018.

GNSS for Climate: Applications

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



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



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

Additional Requirement

- High temporal resolution

GNSS for Climate: Conclusions and Outlook

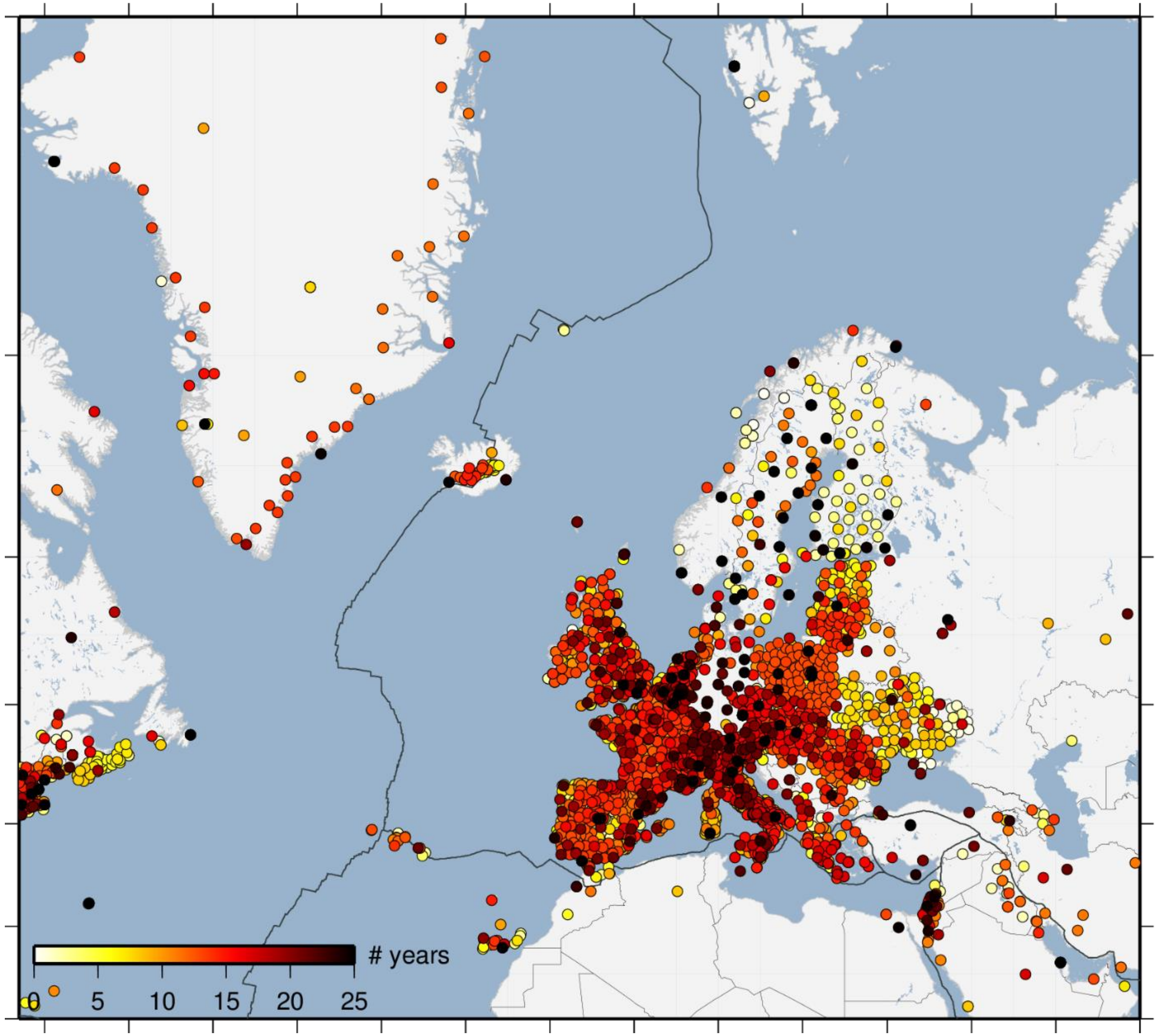
- Ground-based GNSS can provide climate communities a high-frequency, all-weather, long-term, homogeneously processed, homogeneous, global or denser regional, independent datasets of ZTD, IWV, gradients (?) to
  - assimilate in their climate models
  - validate the datasets climate models ingest during assimilation (cloud bias of satellite retrievals)
  - assess the model water vapour output (integrated water vapour, humidity, precipitation) spatially and temporally (long-term, diurnal cycle)
  - ???

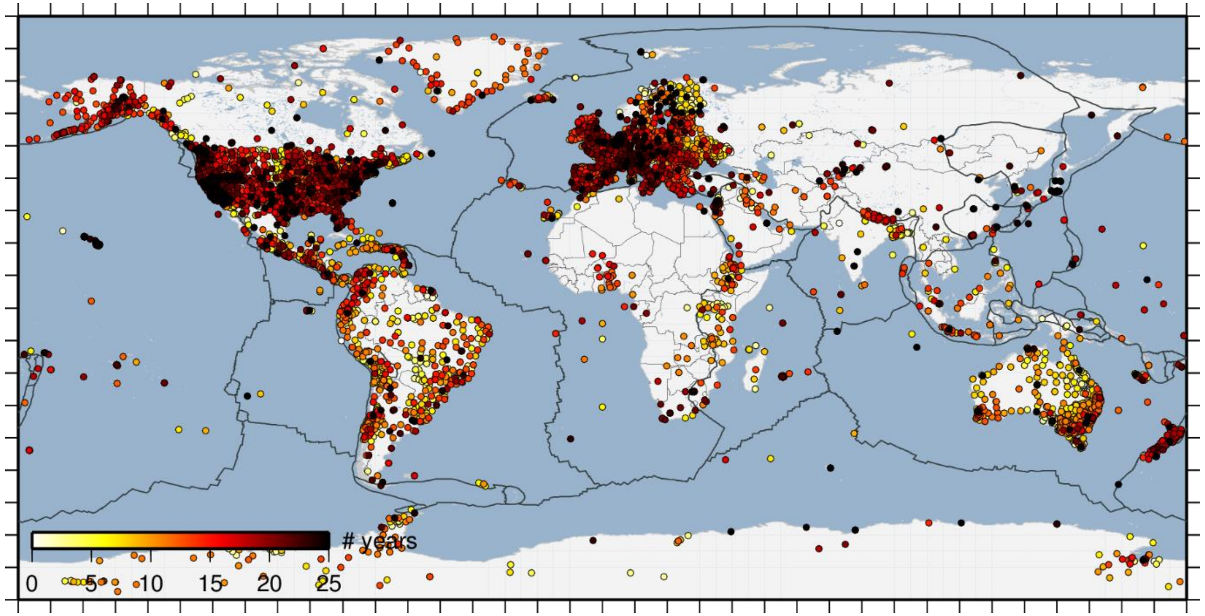
- We are open to your input and are ready to get organized to serve better the climate community needs (Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) Joint Working Group C.2 Quality control methods for climate applications of geodetic tropospheric parameters)

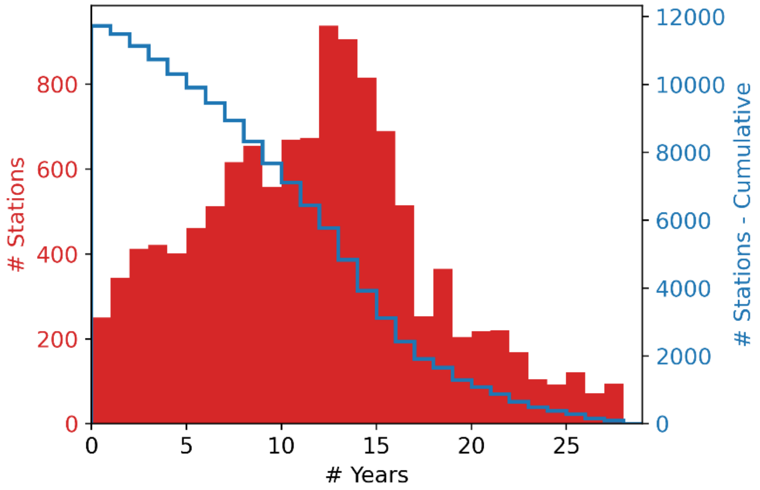
- Remote Sensing special issue ""Climate Modelling and Monitoring Using GNSS"
  https://www.mdpi.com/journal/remotesensing/special_issues/Global_Climate_GNSS

GNSS for Climate: Conclusions and Outlook

Potential Contribution to Climate





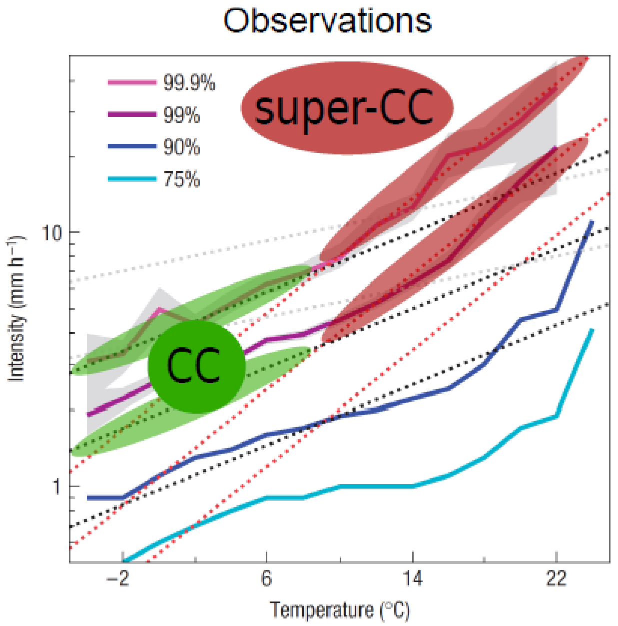


Source: © J. Legrand, ROB, 2021

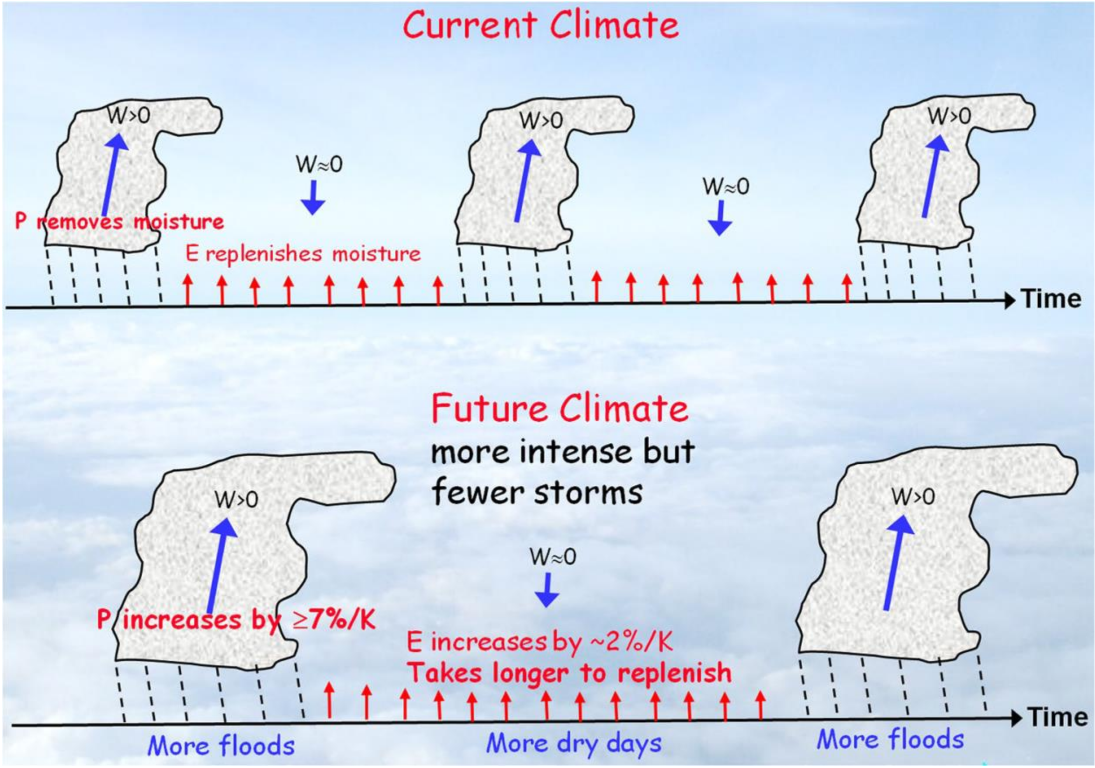
GNSS for Climate: Conclusions and Outlook

Super-CC and Climate Change

- Integrated Water Vapour is "intermediate" between surface temperature (Claussius-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

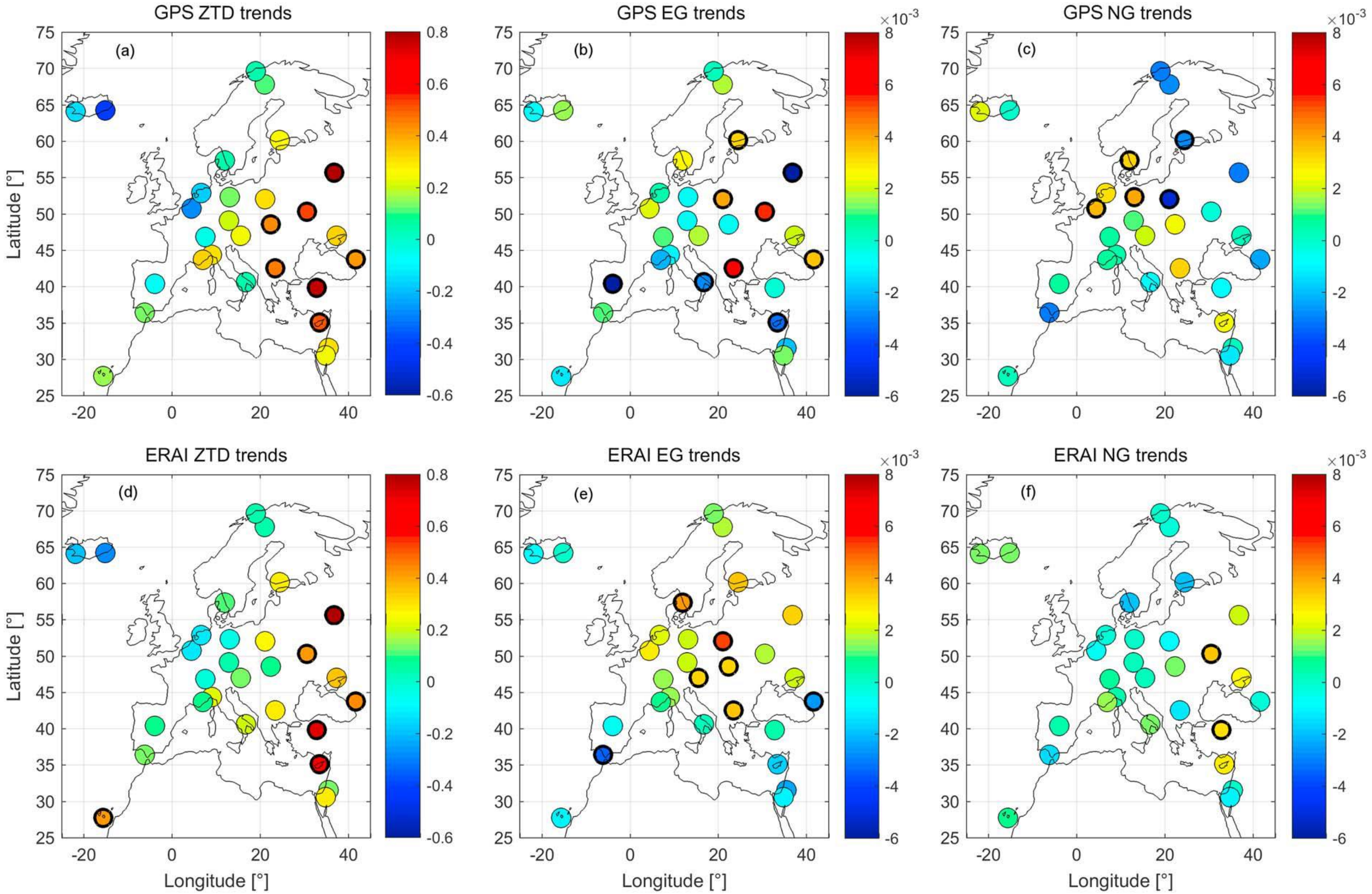


Source: Dai et al., Clim. Dyn., 2020

GNSS for Climate: Conclusions and Outlook

Horizontal gradients?

- ➢ trends in EW and NS gradients
- ➢ added value?



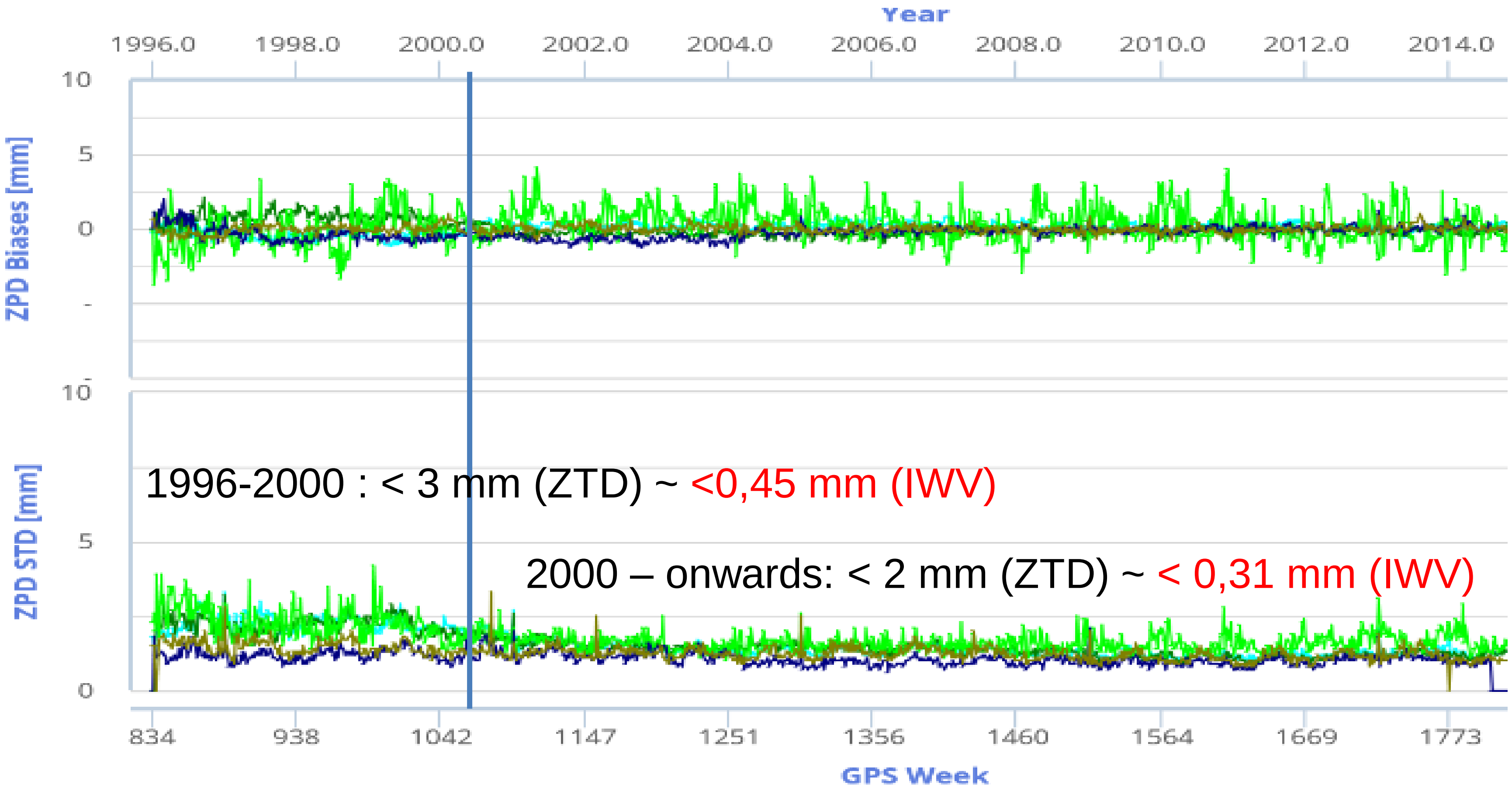
ZTD, EW, and NS gradient trends (mm/yr) from GPS and ERAI

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)



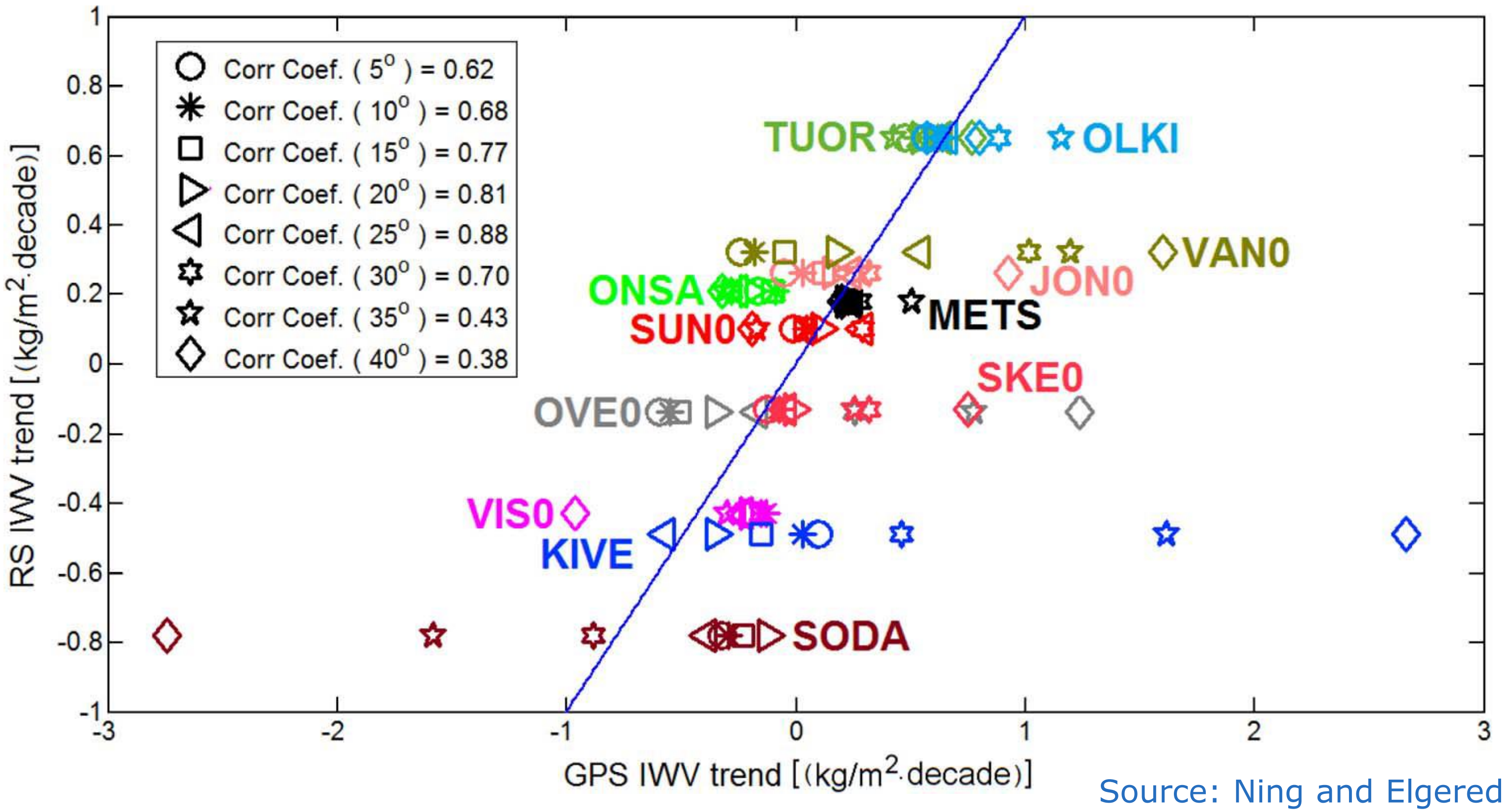
EPN Network

Source: Pacione, R., Araszkiewicz, 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)*



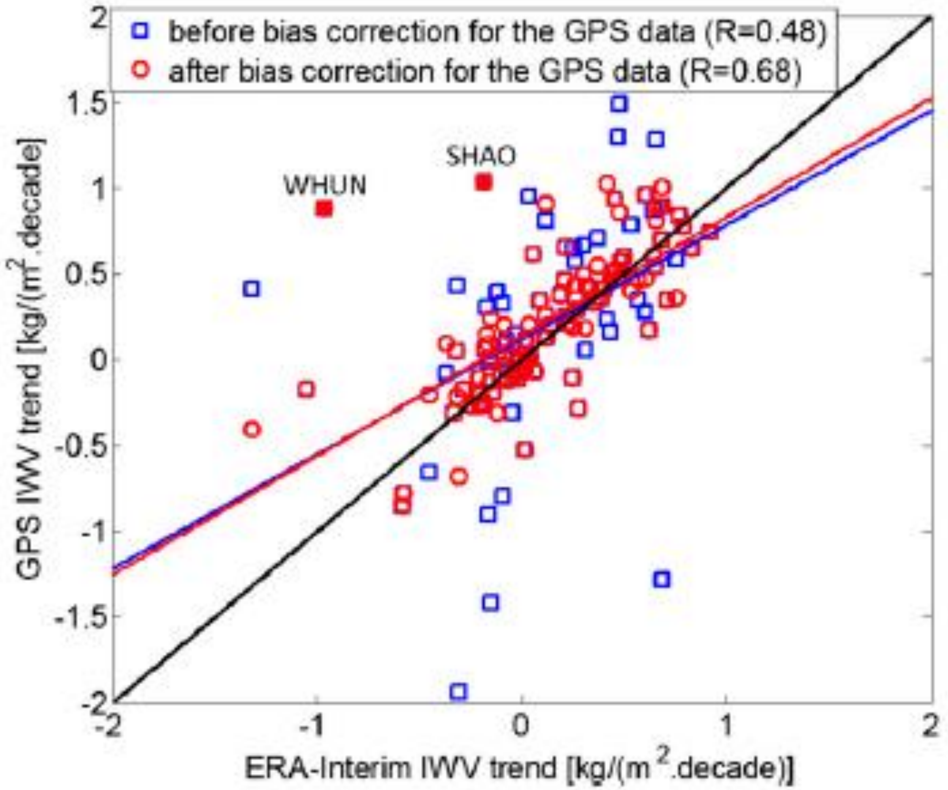
- For example, the chosen elevation cutoff angle has an impact on the IWV which is site dependent.
- If this dependence varies with time it will also affect the estimated trends.
- For these sites, the highest correlation is obtained for an elevation cutoff angle = 25°

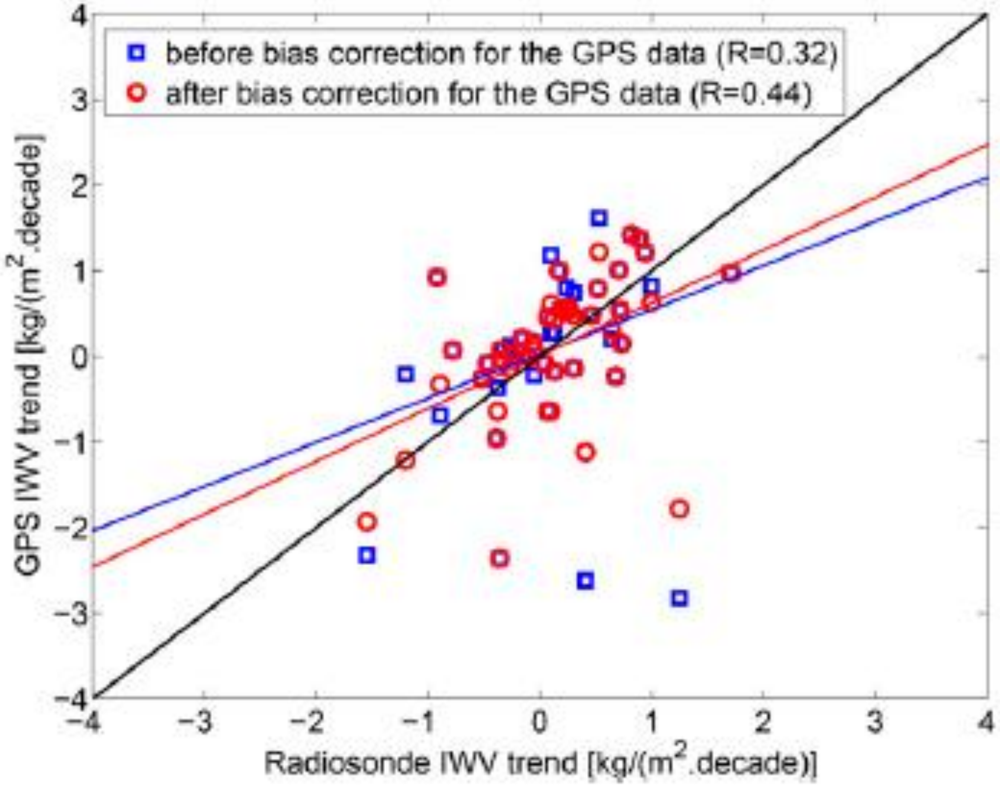
Source: Ning and Elgered, IEEE JSTARS, 2012

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 an RS stations