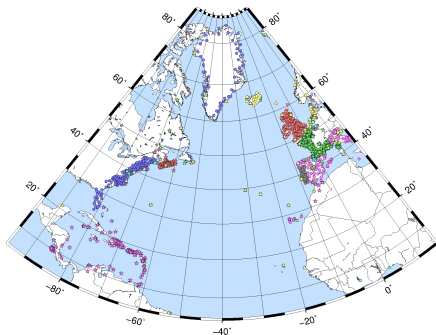




IWV retrieval from ground and shipborne GPS receivers during NAWDEX

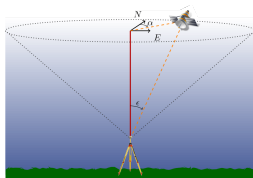
Pierre Bosser¹, Nicolas Laurain^{1,2} and
Olivier Bock³

¹ ENSTA Bretagne - Lab-STICC, Brest, France

² IGN - ENSG, Marne-La-Vallée, France

³ IGN - IPGP, Paris, France

Recap : GPS meteorology concept



Troposphere propagation delay :

$$\Delta L_{\text{tropo}}(\alpha, \epsilon) = \Delta L_h^z \cdot mf_h(\epsilon) + \Delta L_w^z \cdot mf_w(\epsilon) + m_\alpha(\epsilon)[\Gamma_{ns} \cos \alpha + \Gamma_{ew} \sin \alpha]$$

- $\Delta L_{\text{tropo}}(\alpha, \epsilon)$: troposphere delay for a given direction
- ΔL_h^z : Zenith Hydrostatic Delay (**ZHD**) retrieved from ground pressure measurements.
- ΔL_w^z : Zenith Wet Delay (**ZWD**) estimated during the processing.
- Γ_{ns}, Γ_{ew} : horizontal gradients
- mf_h, mf_w, m_α : mapping functions for delays and gradients.

ZWD is closely linked to IWV:

$$IWV = k(T_m) \times \Delta L_w^z$$

A short summary



- Retrieval of GPS IWV by the analysis of measurements from more than **1,200 GPS antenna** (sept. to nov. 2016).
- **Quality check** of GPS IWV using **intrinsic methods**.
- **Global assessment** of IWV from **ERA-I and ERA5 reanalysis** over the period using GPS IWV.
- Analysis of **GPS IWV and gradients** during two **high impact weather events** (related to Walpurga and Sanchez Cyclon / IOPs 5 and 9)
- Retrieval of **IWV from on-board GPS receiver** on the French **RV Atalante** during a cruise in the northern Atlantic Ocean in autumn 2016.
- **Evaluation of Atalante IWV** using ERA-I and ERA5 reanalysis, IWV from ground GPS antenna (CORS, *Continuously Operating Reference Stations*).

Outlines



- 1 Comparisons with ECMWF reanalysis
- 2 Focus on GPS retrievals during two high impact weather events
- 3 IWV from RV Atalante
- 4 Conclusion

Outlines



- 1 Comparisons with ECMWF reanalysis
- 2 Focus on GPS retrievals during two high impact weather events
- 3 IWV from RV Atalante
- 4 Conclusion

Methodology



ERA4 (6h x 0.75°) and ERA5 (1h x 0.25°) : P_{surf} and IWV
inter/extrapolated from grid at GPS antenna height:

- Horizontal: bilinear interpolation
- Vertical: extrapolation [Parracho et al., 2018; Steigenberger et al., 2011]

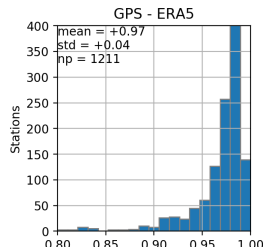
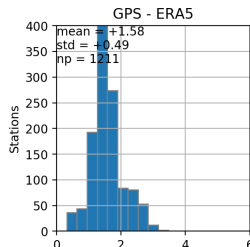
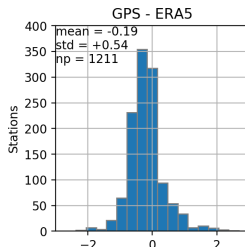
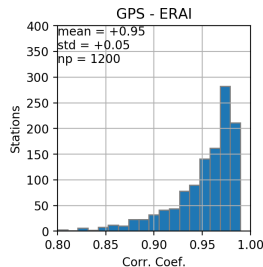
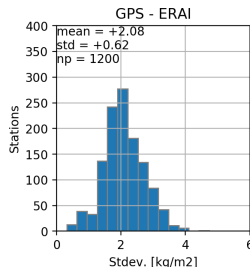
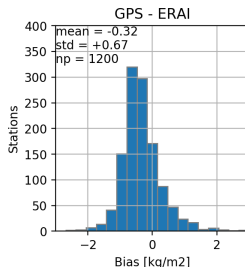
GPS IWV (5min):

- Use of ERA4/ERA5 surface pressure field extrapolated at GPS antenna height for ZHD computation.
- Converted from ZWD to IWV using T_m from TU Wien.

Global differences

ERA4 (↑) / ERA5 (↓)

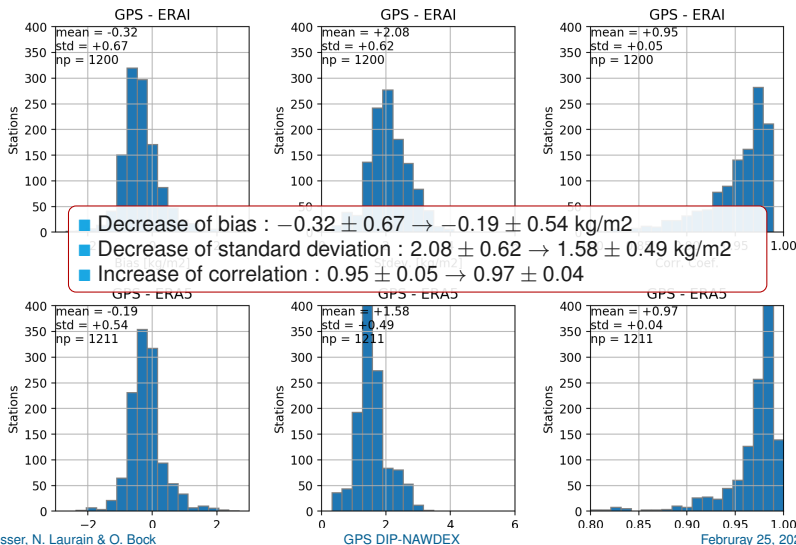
Bias (←) / Standard-deviation (→) / Correlation (→)



Global differences

ERA4I (↑) / ERA5 (↓)

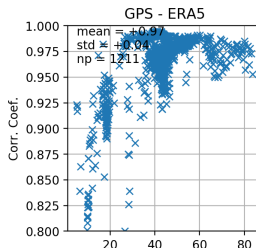
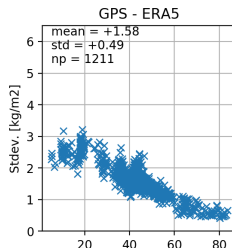
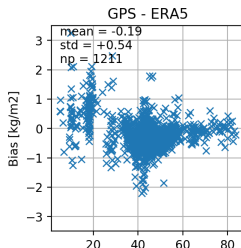
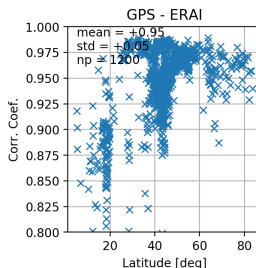
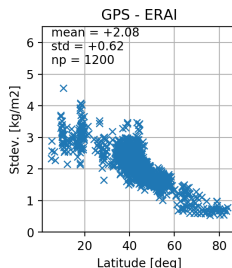
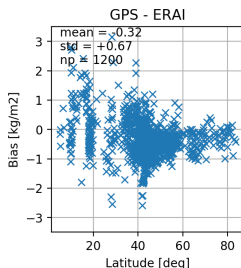
Bias (←) / Standard-deviation (−) / Correlation (→)



Spatial distribution of differences (latitude)

ERA4I (↑) / ERA5 (↓)

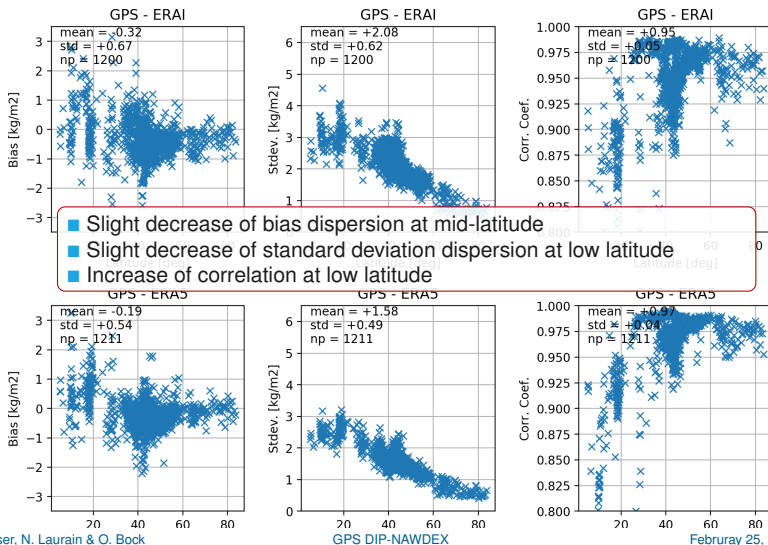
Bias (←) / Standard-deviation (→) / Correlation (→)



Spatial distribution of differences (latitude)

ERA4I (↑) / ERA5 (↓)

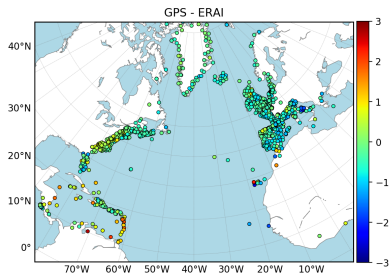
Bias (←) / Standard-deviation (→) / Correlation (→)



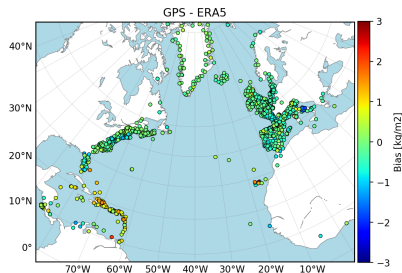
Spatial distribution of differences



Bias



ERAI

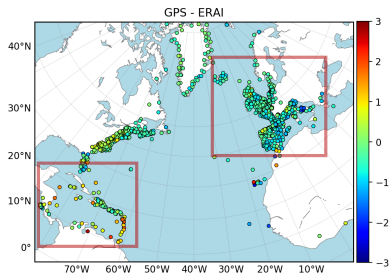


ERA5

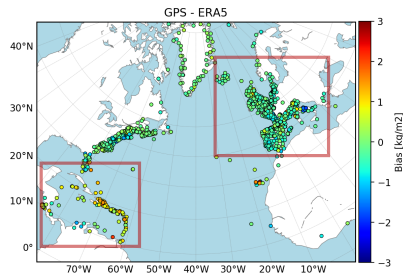
Spatial distribution of differences



Bias



ERAI



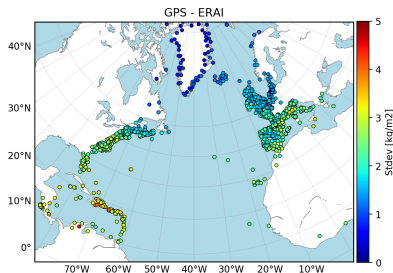
ERA5

Spatial consistency ; higher values in Caribbean region.
Decrease over Europe and Caribbean (slight) with ERA5.

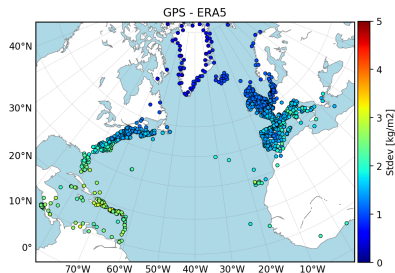
Spatial distribution of differences



Standard deviation



ERAI

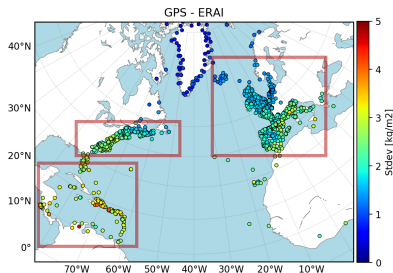


ERA5

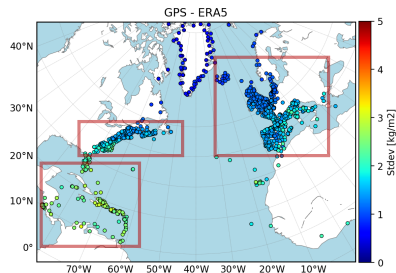
Spatial distribution of differences



Standard deviation



ERAI

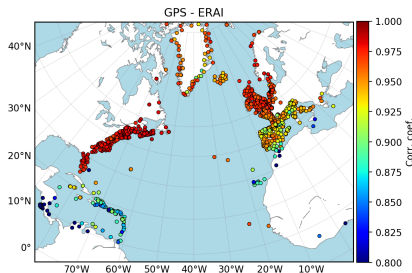


ERA5

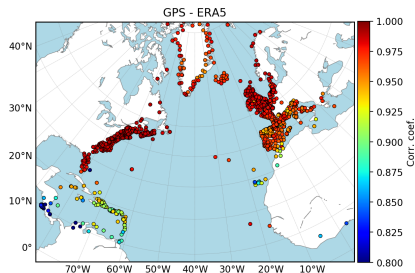
Spatial consistency ; higher values in Caribbean.
Decrease over Europe, US East Coast and Caribbean with ERA5.

Spatial distribution of differences

Correlation



ERAI

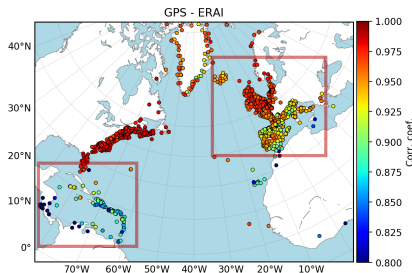


ERA5

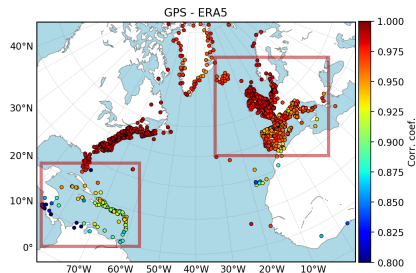
Spatial distribution of differences



Correlation



ERAI



ERA5

Lower correlation over Caribbean ; slight improvements with ERA5.
Significant increase over Europe with ERA5.

Outlines



- 1 Comparisons with ECMWF reanalysis
- 2 Focus on GPS retrievals during two high impact weather events
 - Walpurga Cyclon over UK and Norway (IOP5)
 - Cut-off Sanchez over Mediterranean Area (IOP9)
- 3 IWV from RV Atalante
- 4 Conclusion

Short description



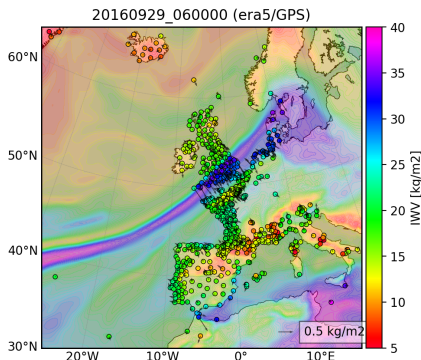
From [Schäfler et al., 2018]:

- Strong water vapor transport of extratropical cyclon Walpurga.
- Atmospheric river that extended to Norway
- HIW over Scandinavia

➡ Characterization of AR using GPS solution?

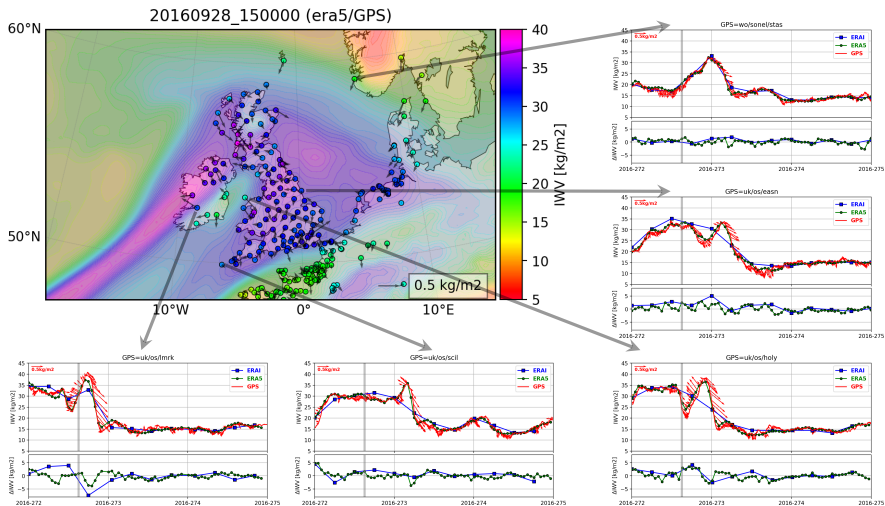
Use of:

- GPS IWV and IWV gradients (5 min)
- ERAI IWV & TP fields (6h / $0,75^\circ \times 0,75^\circ$)
- ERA5 IWV & TP fields (1h / $0,25^\circ \times 0,75^\circ$)



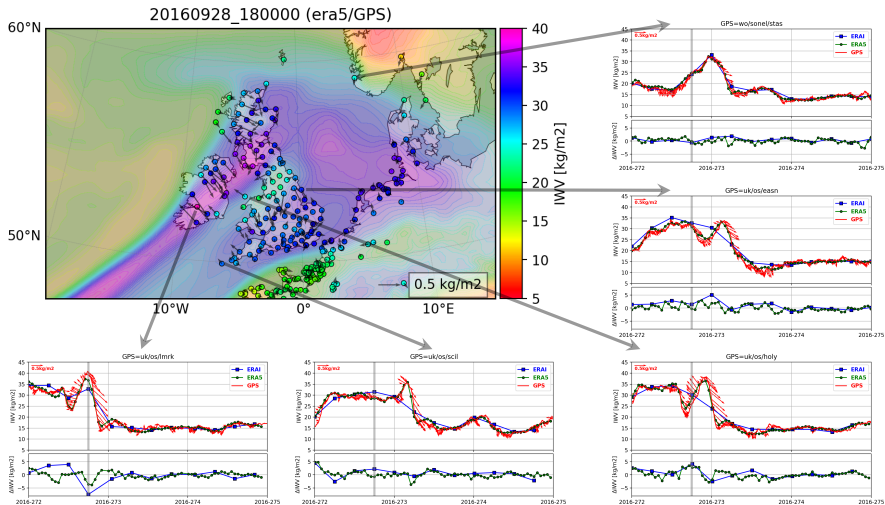
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



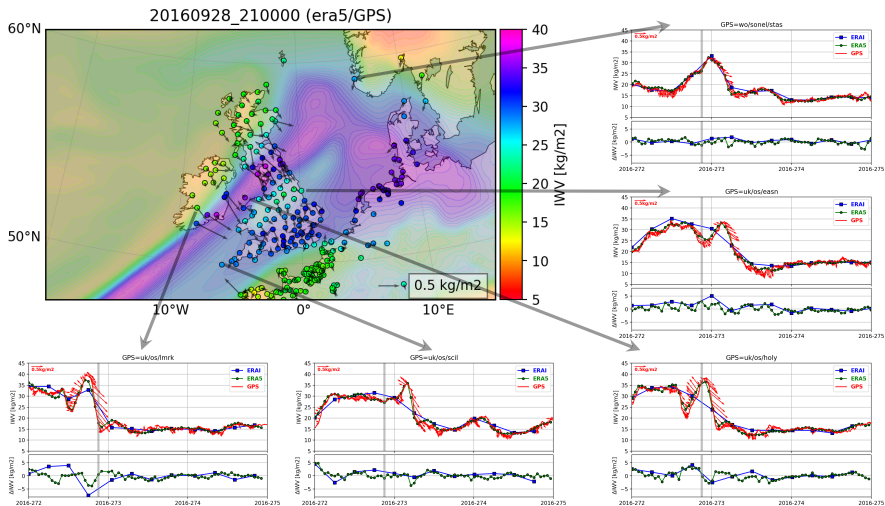
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



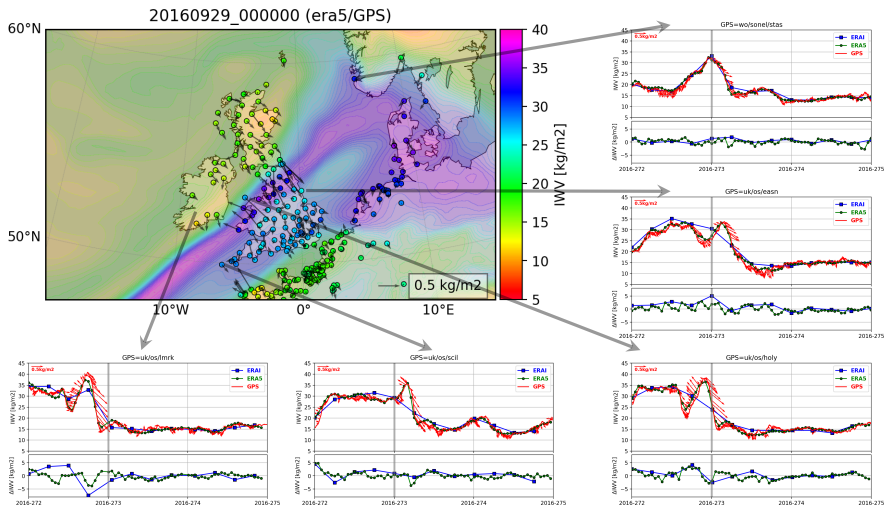
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



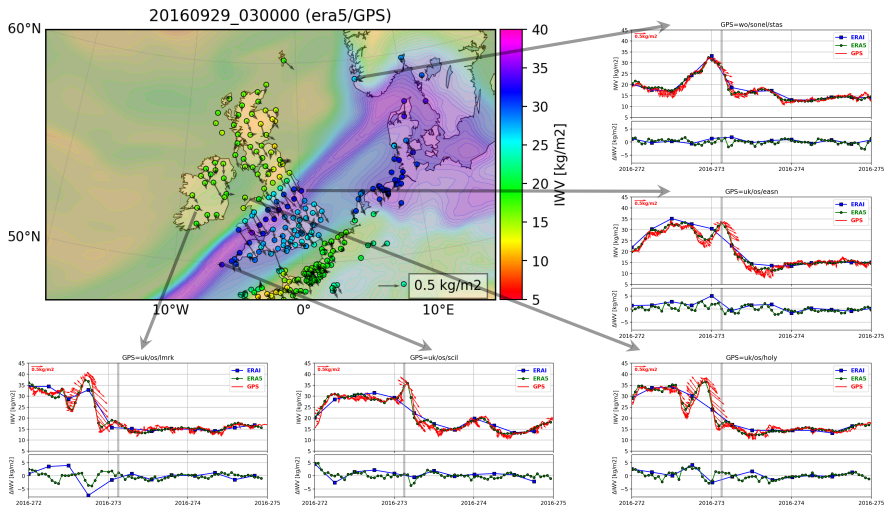
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



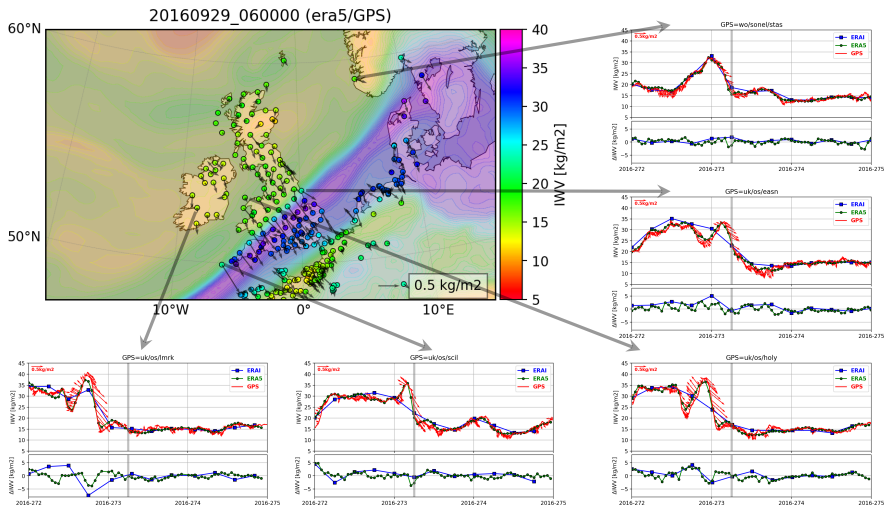
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



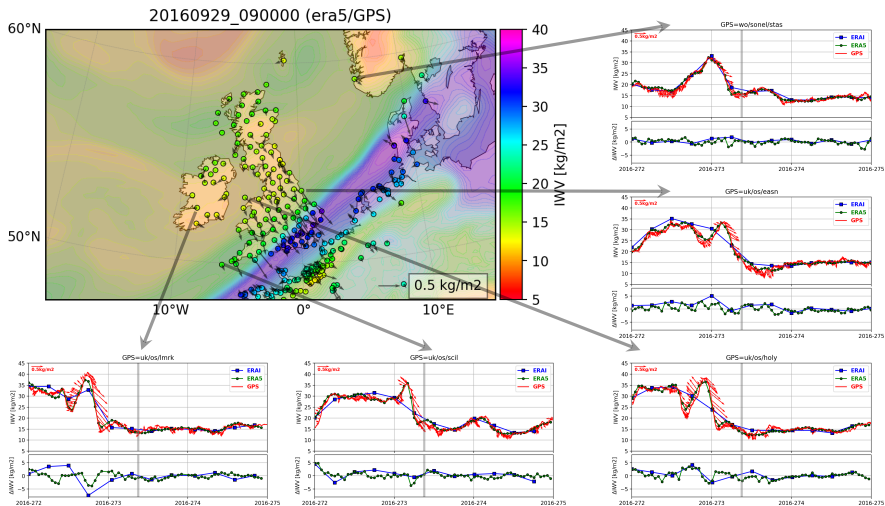
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



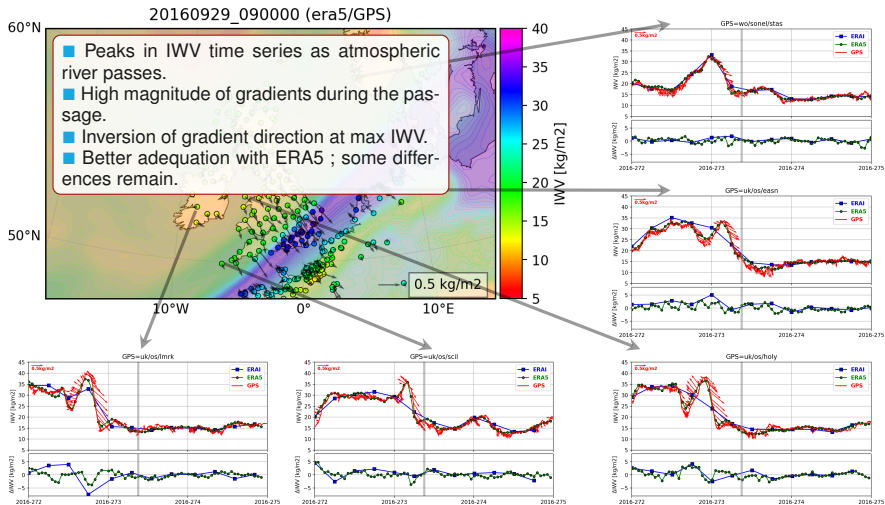
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



Short description



From [Schäfler et al., 2018]:

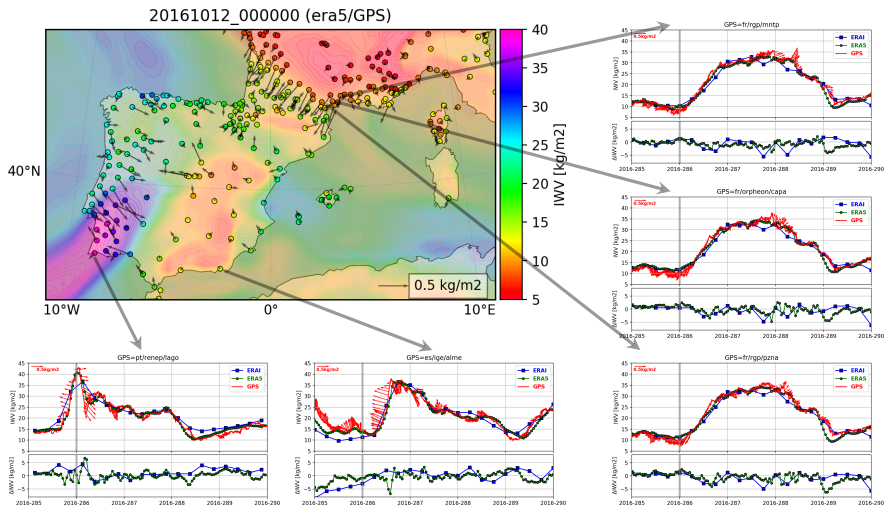
- Surface cyclone Sanchez formed in the middle of the Atlantic Ocean (35°W , 40°N) around 2016/10/08 18:00 UTC.
- Associated high-impact event over Southern France on 13-14 Oct 2016 (heavy precipitations and strong winds over France and Italy).

Use of:

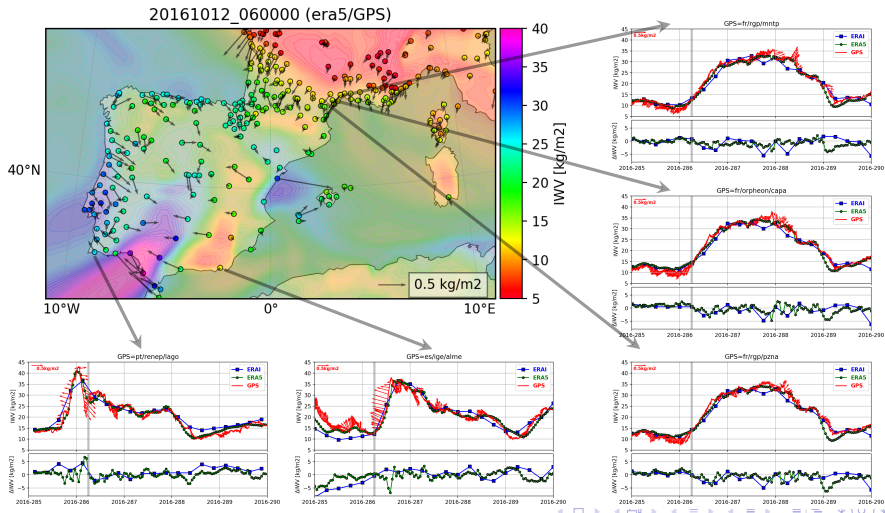
- GPS IWV and IWV gradients (5 min)
- ERAI IWV & Total precipitation fields ($6\text{h} / 0,75^{\circ} \times 0,75^{\circ}$)
- ERA5 IWV & Total precipitation fields ($1\text{h} / 0,25^{\circ} \times 0,75^{\circ}$)
- Total precipitation from NCDC /NOAA

IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)

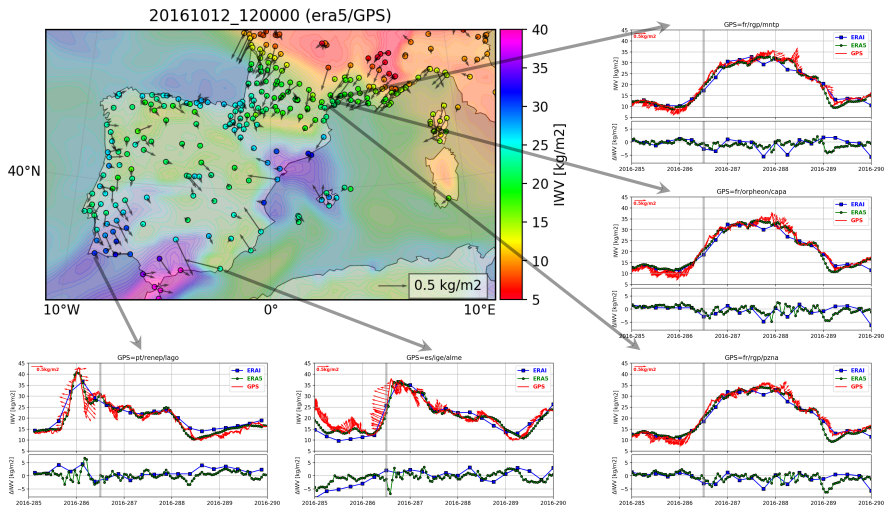


GPS IWV + gradient, ERAI, ERA5 (+colormap)



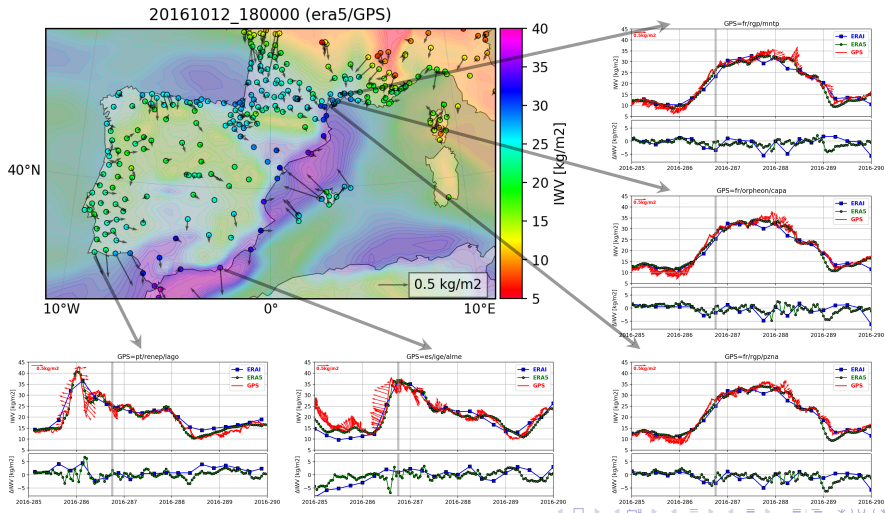
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



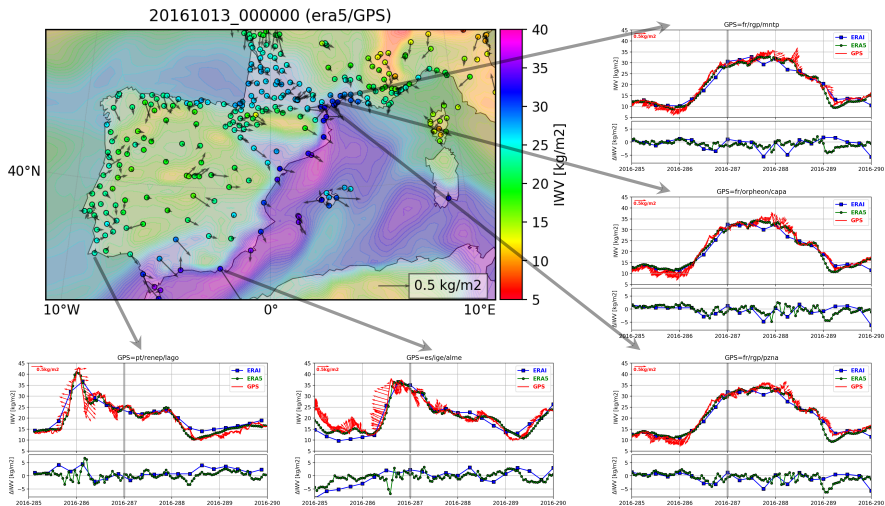
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)

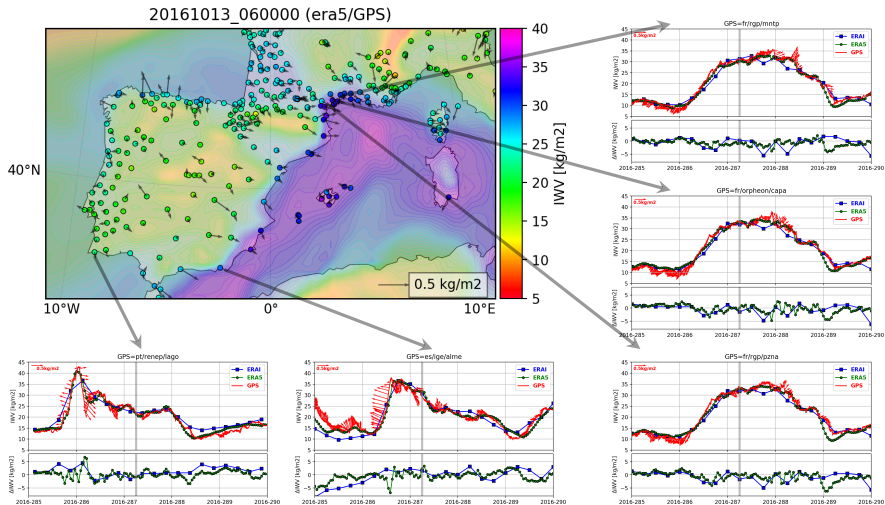


IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)

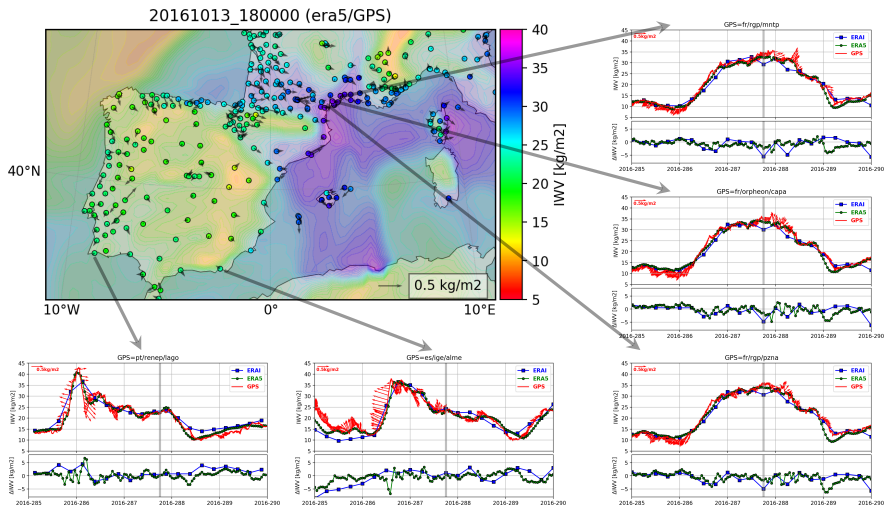


GPS IWV + gradient, ERAI, ERA5 (+colormap)



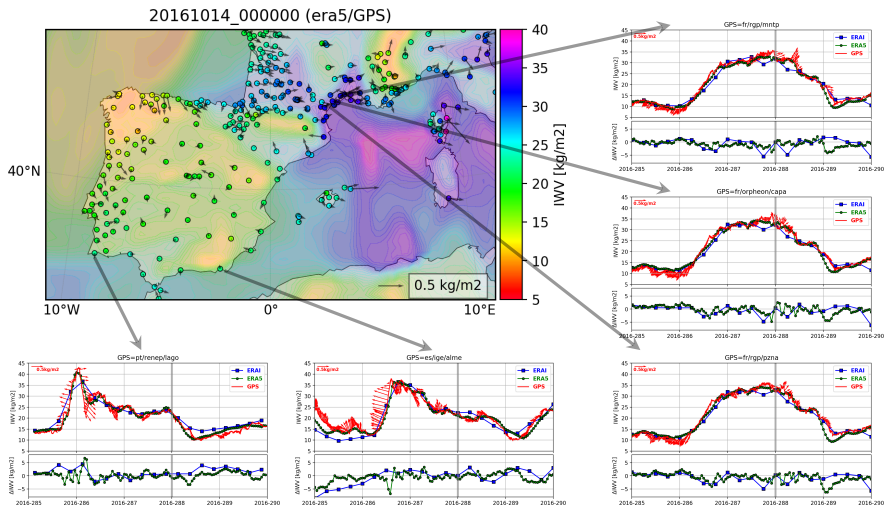


GPS IWV + gradient, ERAI, ERA5 (+colormap)



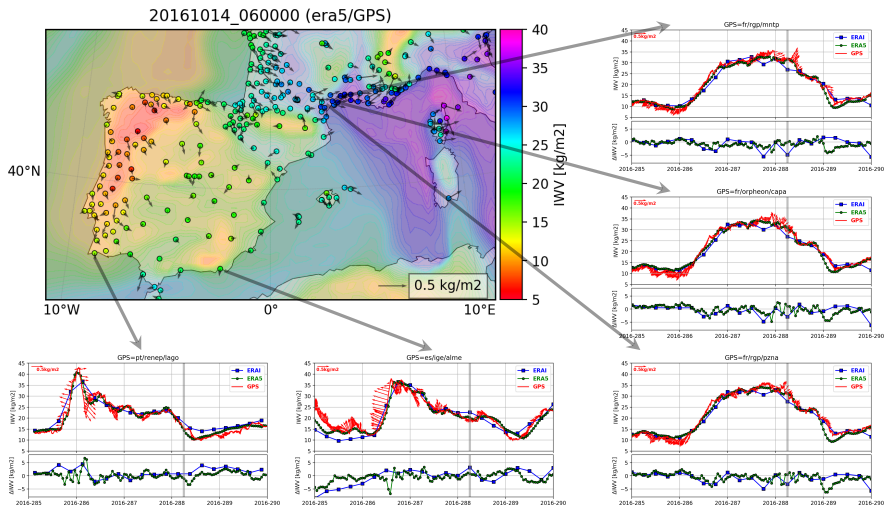
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



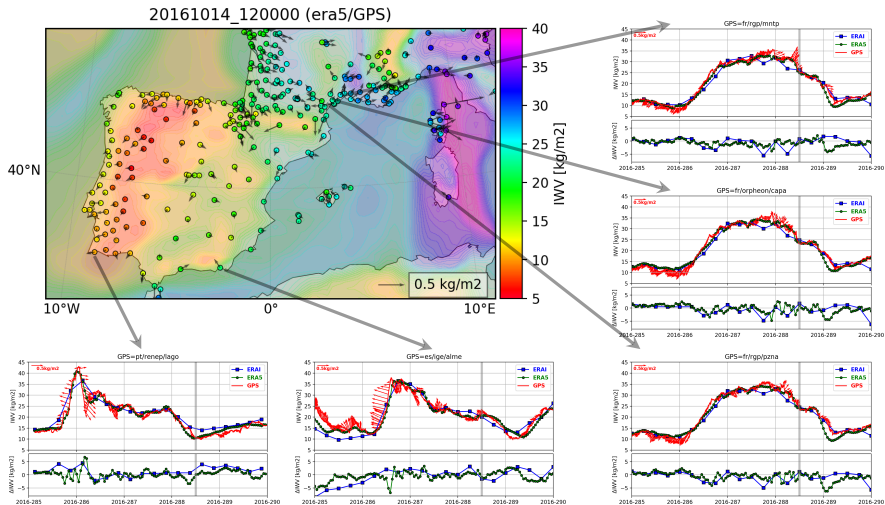
IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)



IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)

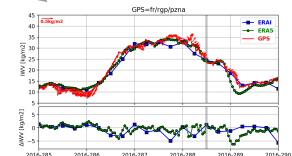
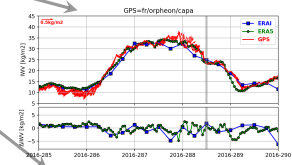
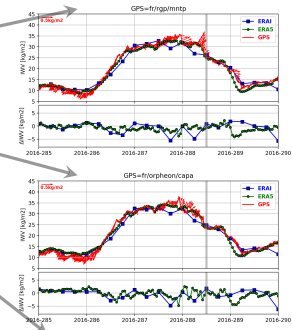
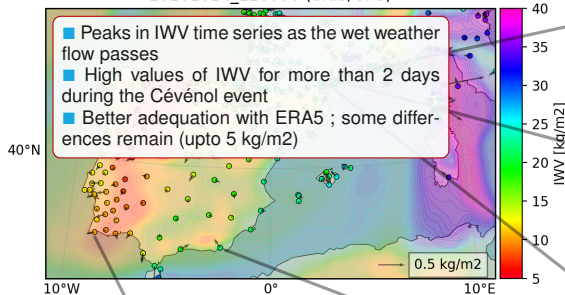


IWV space and time evolution

GPS IWV + gradient, ERAI, ERA5 (+colormap)

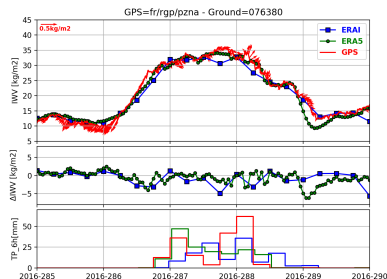
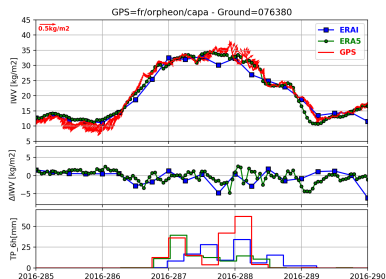


20161014_120000 (era5/GPS)



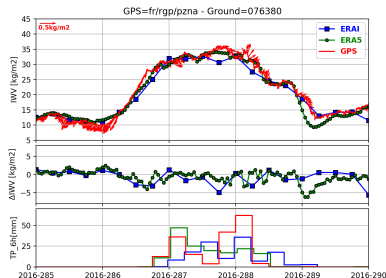
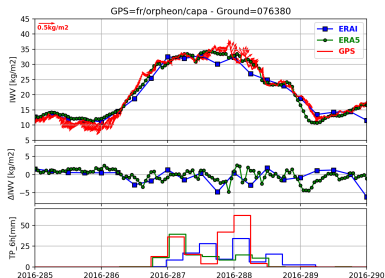
Rainfall

GPS IWV, ERAI, ERA5



Rainfall

GPS IWV, ERAI, ERA5



- High IWV values for more than 2 days
- High rainfall rates induce decrease of IWV

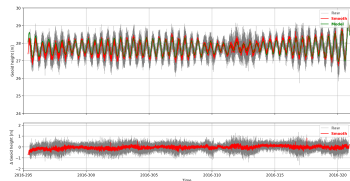
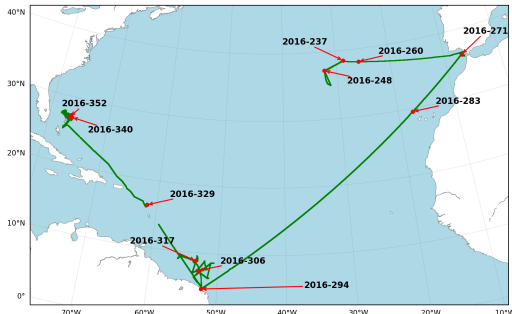
Outlines



- 1 Comparisons with ECMWF reanalysis
- 2 Focus on GPS retrievals during two high impact weather events
- 3 IWV from RV Atalante**
- 4 Conclusion

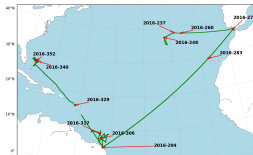
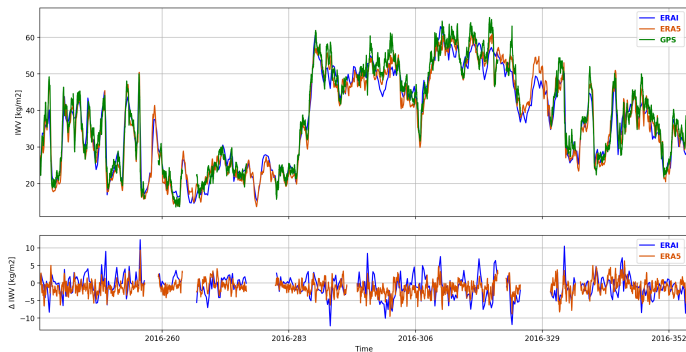
Overview

- GNSS data acquired during 120 days during cruises in the North Atlantic Ocean.
- Kinematic analysis and IWV extraction using ERA5 atmospheric pressure fields at MSL.



IWV comparisons wrt ECMWF reanalysis

GPS IWV, ERAI, ERA5



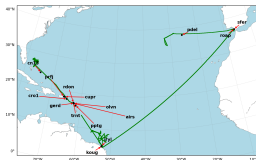
Differences [kg/m²] :

ERAI (392)	-0.98 ± 3.19	$-12.22 \rightleftharpoons 12.33$	$+0.969$
ERA5 (2349)	-1.31 ± 2.00	$-9.54 \rightleftharpoons 9.37$	$+0.988$

- Improvements considering ERA5 instead of ERAI
- Bias similar to that observed on CORS

IWV comparisons wrt CORS

GPS IWV, CORS



Deviations vary from station to station

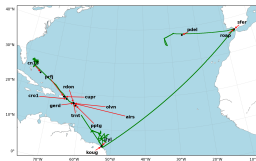
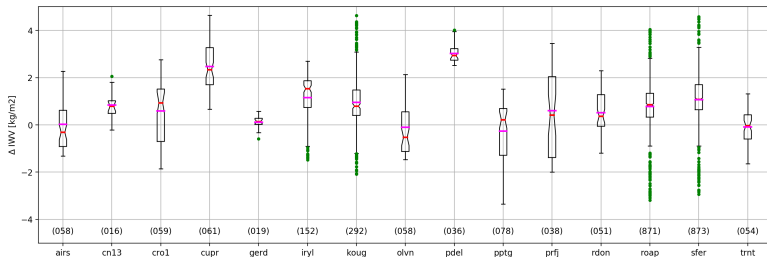
→ Significant bias for PDEL (Azores) and CUBR (Porto-Rico)

Mean differences [kg/m²] :

CORS (2716) -0.88 ± 1.22 $-3.35 \rightleftharpoons 4.64$

IWV comparisons wrt CORS

GPS IWV, CORS



Deviations vary from station to station

→ Significant bias for PDEL (Azores) and CUPR (Porto-Rico)

Mean differences [kg/m²] :

CORS (2716) -0.88 ± 1.22 $-3.35 \rightleftharpoons 4.64$

Outlines



- 1 Comparisons with ECMWF reanalysis
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- 4 Conclusion**

Summary



■ Improvements induced by ERA5 :

- Decrease of bias, standard deviation and increase of correlation ;
- Reduced latitude variability of deviations ;
- Improvements are notable in Europe and US East Coast ;
- Differences remain more significant in Caribbean (but reduced anyway)

■ Improvements are also highlighted on study cases.

■ **Characterization of atmospheric river** over UK by GPS IWV and gradients :

- IWV peak with fast variations
- Significant magnitude and inversion for gradients

■ **Promising results for GNSS** data acquired on sea by **RV Atalante**:

- Good agreement with ECMWF reanalysis, despite a remaining bias (already observed in this area considering CORS).
- Also good agreement with CORS
- ... But outside the Nawdex period / area

Further investigations



- Better extraction from ERA5, ERAI (use of profiles instead of surface data ? Better vertical extrapolation ?)
 - Rainfall data over Scandinavia during IOP5
 - Comparisons with humidity products from satellites in coastal area (MODIS)
 - Atalante :
 - GPS analysis methodology for IWV retrieval from on board receiver using Atalante data set.
 - Further investigation of current results (particularly, differences with some CORS as PDEL and CUBR)
 - Evaluation of gradients wrt CORS.
- (LEFE project "GEMMOC")

■ Publication...

Acknowledgments



ANR / DIP-NAWDEX (ANR-17-CE01-0010).

GPS data providers :

- DTU Space (Dk) [Khan et al., 2016 - Sci. Adv.].
- British Isles continuous GNSS Facility (Uk / Ir).
- NRCAN (Ca), IGE, RGAPA, (Es), RENAG, Orpheon, RGP (Fr), LMI (Is), Asi (It), DGPA (NI), NGS (Us), RENEP (Pt), UNAVCO, SONEL, IGS, EPN.

Atalante dataset :

- Cannat M., Sarradin Pierre-Marie (2016) MOMARSAT2016 cruise, RV L'Atalante, <https://doi.org/10.17600/16001200>
- (2016) TR_LHACAD cruise, RV L'Atalante,
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Precise Point Positioning



GPS processing using **PPP** strategy:

- **Absolute** and **post-processed** positioning using **GPS carrier phase measurements**.
- Use of **Gipsy-Oasis II 6.4** (JPL / NASA)
- Further details:
 - SRIF for filtering / estimation
 - PPP with fixed ambiguities
 - 30h session around midday
 - Use of IERS 2010 standard
 - One position per sessions
 - troposphere parameters modeled as random walk processes.

Troposphere modeling



Use of ECMWF-based data (VMFgrid):

- Values for ZHD
- A priori values for ZWD
- Mapping function, for hydrostatic and wet delays, horizontal gradients

Estimation as random walk process:

- ZWD, $5 \text{ mm} \cdot \text{h}^{-1/2}$
- Horizontal gradients, $0.5 \text{ mm} \cdot \text{h}^{-1/2}$
- 5 min resolution

Conversion into I WV for further comparisons

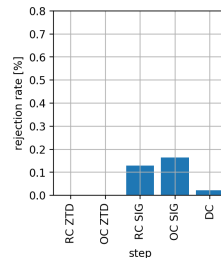
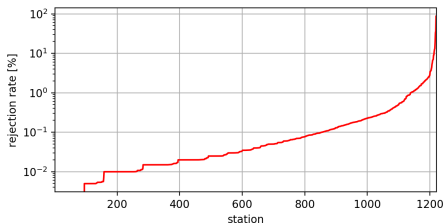
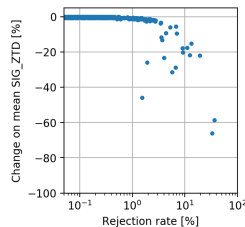
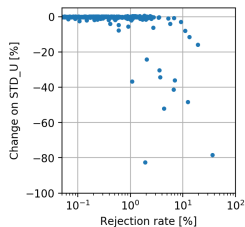
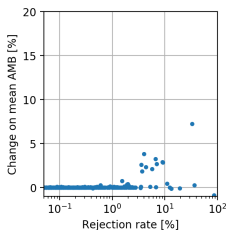
Troposphere solution



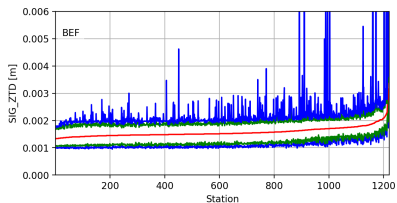
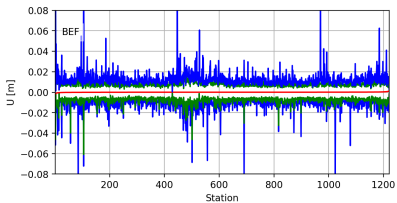
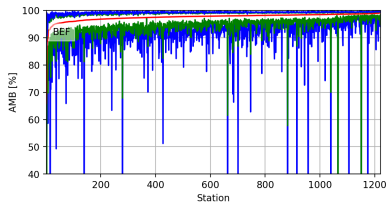
Screening of ZWD estimates using formal errors

- Rejection rate about 0.3%
- Validation of screening with the improvement of weighted outputs (positions, RMS, etc.)

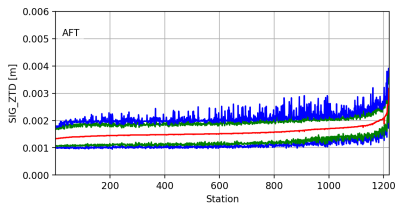
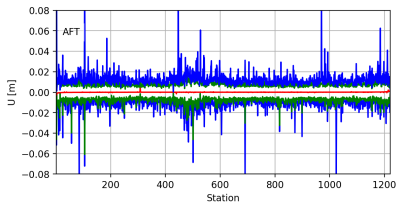
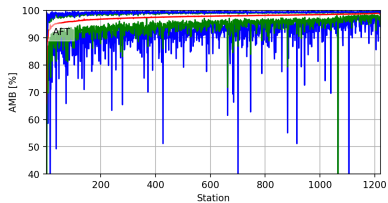
Screening



Screening



Screening

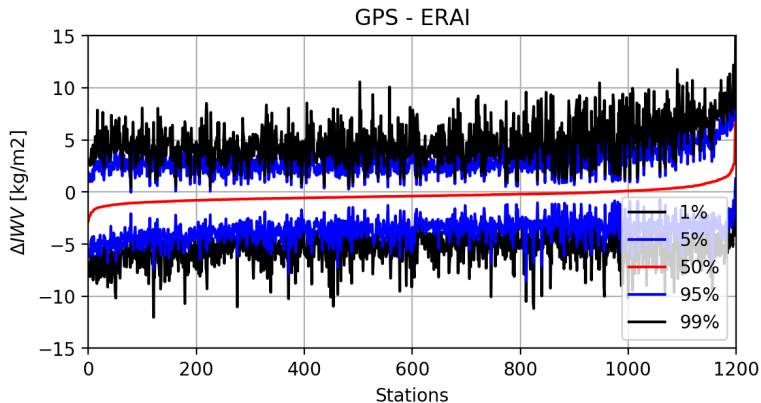


GPS - RS

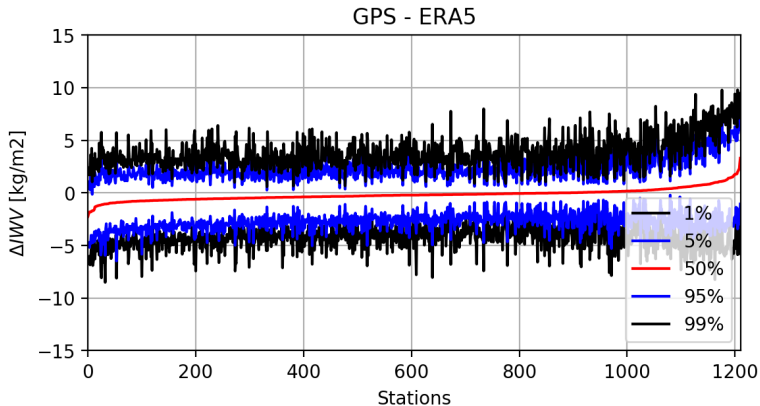
- Difficulties to manage RS from NAWDEX database
- Use of RS from UWYO database
- 45 collocations < 50 km (H) / 50 m (V).

	b [kg/m ²]	σ [kg/m ²]	ρ
GPS-RS	-0.58 ± 0.89	1.4 ± 0.63	0.979
GPS - ERAI	-0.54 ± 0.49	2.0 ± 0.75	0.947

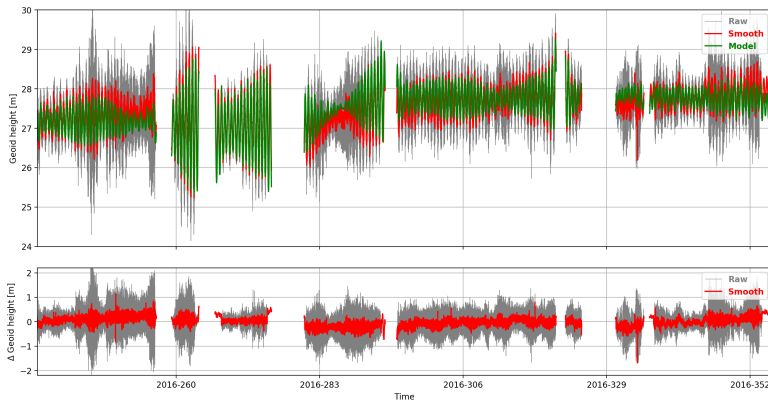
ERA5 / ERAI



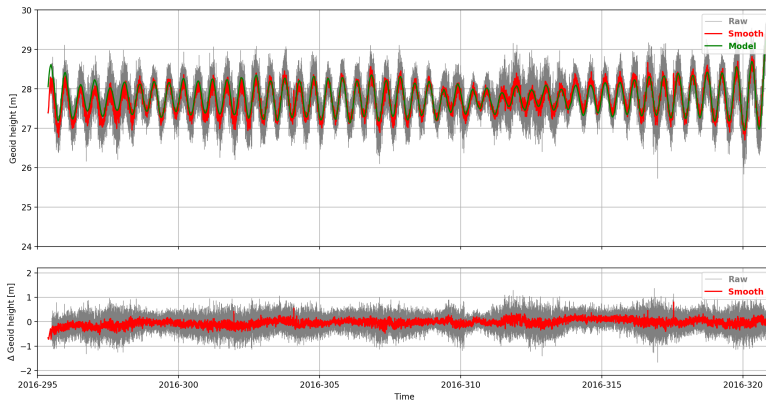
ERA1 / ERA5



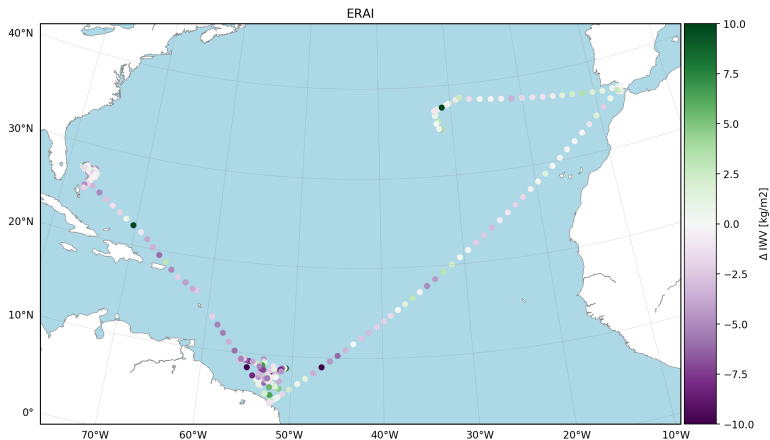
Atalante



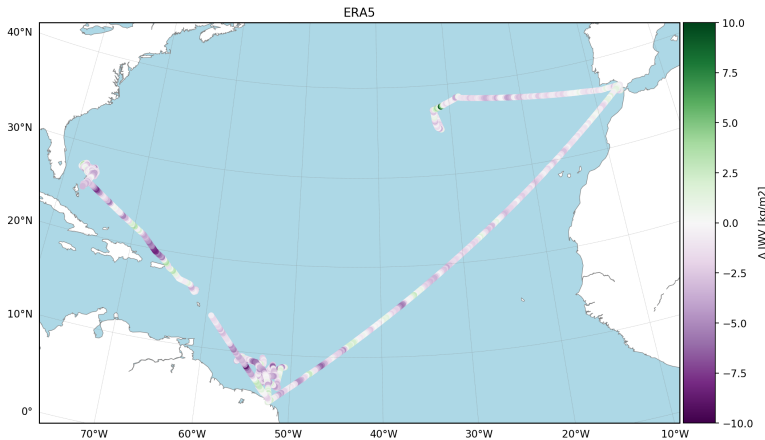
Atalante



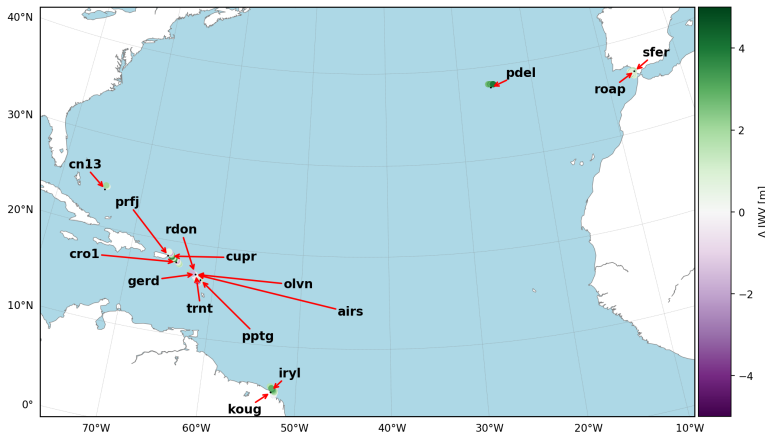
Atalante



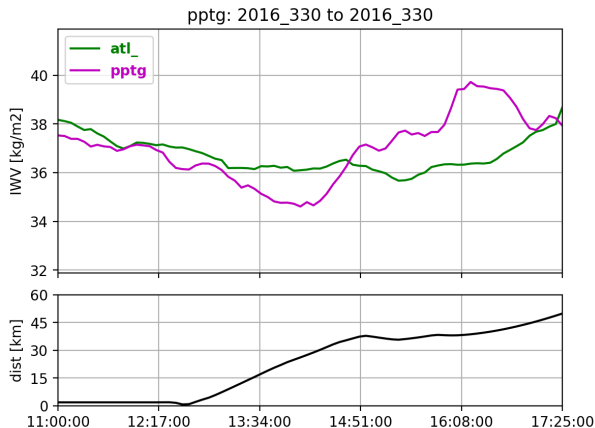
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