WACMOS-MED initiative

A Mediterranean water cycle analysis

Victor Pellet & Filipe Aires, *LERMA, Observatoire de Paris,*
Gabriel Jorda, University of the Balearic Islands (UIB), Majorque
Wouter Dorigo, Department of Geodesy and Geoinformation, TUWIEN
Jan Polcher & Fuxing wang, Laboratoire de Météorologie Dynamique (LMD), Paris
Luca Brocca, Stefania Camica, Research Institute of Geo-Hydrological Protection (IRPI), Perugia

WACMOS-MED project

ESA WACMOS Water Cycle Multi-mission Observation S*trat*egy for the Mediterranean (WACMOS-MED)

⇒ Assess the **feasibility of characterizing the water cycle at global and basin scales using Earth Observation (EO)**, promote the use of EO products within the hydrological and climate communities

- Objectives:
  - Investigate the water cycle budget closure from EO
  - Develop integration techniques with hydrological constraints
  - Provide a water cycle EO-based multi-components dataset over the Med. region

WACMOS-MED project

ESA WACMOS Water Cycle Multi-mission Observation *Strat*egy for the Mediterranean (WACMOS-MED)

⇒ Assess the **feasibility of characterizing the water cycle at global and basin scales using Earth Observation (EO)**, promote the use of EO products within the hydrological and climate communities

- Focus on Mediterranean, with various case studies:
  - **Climate analysis** -> Explore the links between oceanic-atmospheric circulation patterns and Mediterranean climate variability
  - **River discharge assimilation** -> Assimilate GRDC discharge data for realistic Mediterranean freshwater estimate
  - **Ocean circulation** -> Assess the impact of systematic error in Mediterranean freshwater input on the ocean circulation
  - **River discharges forecasting** -> Using EO-based precipitation estimate for discharge forecasting

Outline

Integration of EO for the water cycle budget closure:

- EO datasets & materials
- Water cycle budget closure assessment
- Integration techniques
- Results

Case studies:

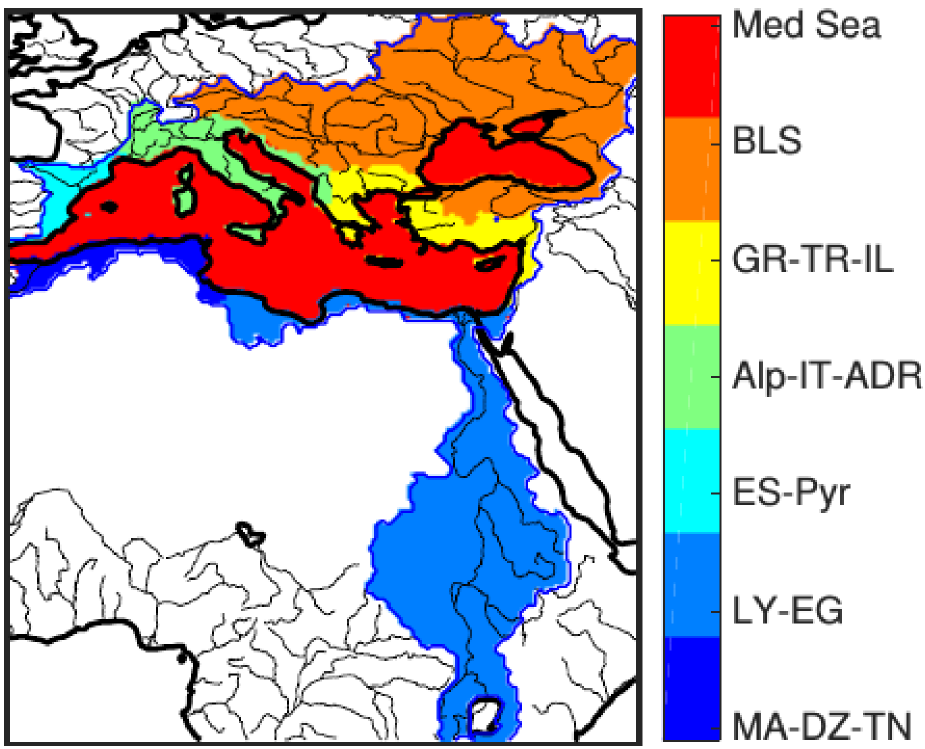
- Climate analysis
- Rivers discharge assimilation
- Ocean circulation
- River discharges forecasting

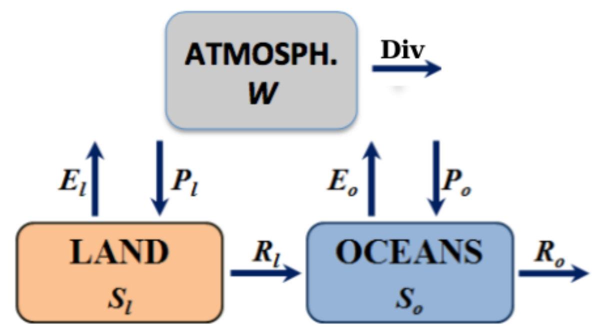
Integration of the EO datasets for the water cycle budget closure

Victor Pellet & Filipe Aires

Closure experiment

Assess the feasibility of characterizing the water cycle using EO data





3 equations:

$$\frac{\partial S_l}{\partial t} = P_l - E_l - R_l \quad (LAND)$$

$$\frac{\partial S_o}{\partial t} = P_o - E_o + R_l - R_o (OCEAN)$$

$$\frac{\partial W_{l/o}}{\partial t} = E_{l/o} - P_{l/o} - div(Q_{l/o}) \quad (ATMOSPHERE)$$

- 6 continental sub-basins
- 1 sea (Black + Med. Seas)

At sub-basin & basin scales

Closure experiment

Assess the feasibility of characterizing the water cycle using EO data

26 datasets; common period : 2004-2009

Precipitation
GPCP
CMORPH
TMPA
PERSIANN
ERA-I Precipitation
EOBS Precipitation
FLUXnet precipitation

Evap. / Land
GLEAM
MOD16
NTSG
ERA-I evapotranspiration
FLUXnet evapotranspiration

Evap. / Sea
OAflux
Seaflux
ERA-I Evaporation

Water storage
CSR
GFZ
GRGS (land only)
JPL
MSC-JPL

Water vapour
Globalvapor
ERA-I Wator vapor

River Disc.
CEFREM
ORCHIDEE

Div Q
ERA-I Moisture divergence

Gibraltar
IMEDEA- netflow

Simple Weighting (SW):

Seasonal bias correction ➔ for systematic errors

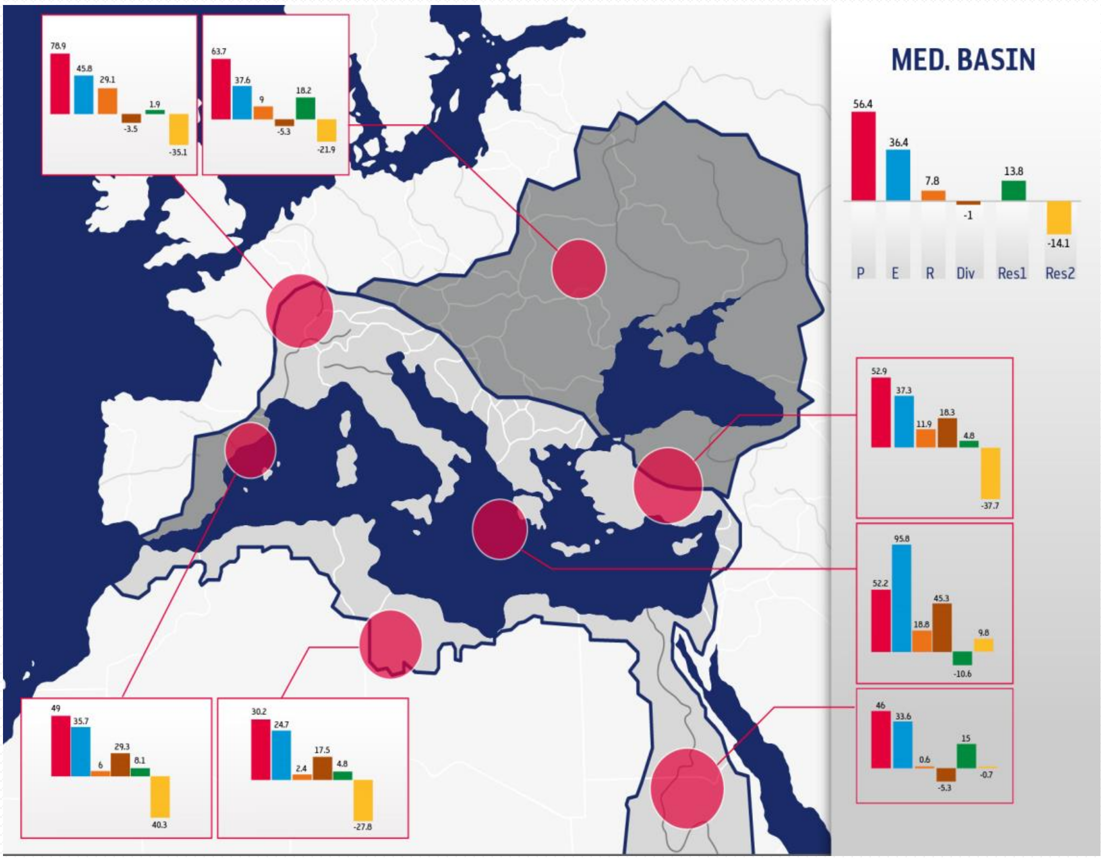
- Large systematic discrepancies exist between EO datasets for same variable
- A reference season is first chosen and the EO datasets are bias-corrected towards it

Statistical integration methods ➔ for random (Gaussian) errors

- Weighted average of the datasets
- Computes the optimal linear estimator for each components based on all the available datasets

Water cycle budget residuals

First WC description in annual fluxes at sub-basin scale, using SW solution



$$\boxed{Res1_l} = \hat{P}_l - \hat{E}_l - \hat{R}_l - \frac{\delta \hat{S}_l}{\delta t}$$

$$\boxed{Res1_o} = \hat{P}_o - \hat{E}_o + \hat{R}_l^* - \hat{R}_o - \frac{\delta \hat{S}_o}{\delta t}$$

$$\boxed{Res2_{l/o}} = \widehat{E_{l/o}} - \widehat{P_{l/o}} - div(\hat{Q}_{l/o}) - \frac{\delta \hat{W}_{l/o}}{\delta t}$$

Annual mean fluxes

P: Precipitation

E: Evapo(transpi)ration

R: Discharge

Div: Divergence (moist.)

Res1: Surface residual

Res2: Atmospheric residual

Budget residuals are still significant **There is a need for an integration technique**

Analyzing the Mediterranean water cycle via satellite data integration, Pellet et al. 2017, in review

Integration methodology: SW+PF

State vector of the water cycle SW solution:

$$\begin{cases} X_l=[P_l\ E_l\ R_l\ \Delta S_l\ \Delta \mathbf{W}_l\ \mathbf{Div}_l]^t \\ \textbf{over land} \\ \mathbf{X}_o=[\mathbf{P}_o\ \mathbf{E}_o\ \Delta\mathbf{S}_o\ \mathbf{Gib}]^t \textbf{ over sea} \\ \mathbf{X}_{lo}=[\mathbf{X}_l\ \mathbf{X}_o] \textbf{ for both} \end{cases}$$

With *a priori* error covariance matrix Bo

Closure equations:
At sub- and basin scale

$$\begin{cases} \hat{P}_l - \hat{E}_l - \hat{R}_l - \dfrac{\delta \hat{S}_l}{\delta t} \\ \hat{P}_o - \hat{E}_o + \hat{R}_l^* - \hat{R}_o - \dfrac{\delta \hat{S}_o}{\delta t} \\ \hat{E_{l/o}} - \hat{P_{l/o}} - div(\hat{Q}_{l/o}) - \dfrac{\delta \hat{W}_{l/o}}{\delta t} \end{cases} \Rightarrow$$

$$G_{lo} \cdot X_{lo} = \mathbf{r},\ \mathbf{r} \sim \mathcal{N}(\mathbf{0}, \Sigma)$$
with $\sqrt{\Sigma}$**=2 mm/month**

Closure with a 2mm/month relaxation

Constrained solution PF (Post-Filtering):

$$\boxed{\begin{aligned} X_{loc} &= (I - K_{PF} G_{lo} \Sigma^{-1} G_{lo}^t) \cdot X_{lo} \\ K_{PF} &= (B_{lo}^{-1} + G_{lo} \Sigma^{-1} G_{lo}^t)^{-1} \end{aligned}}$$

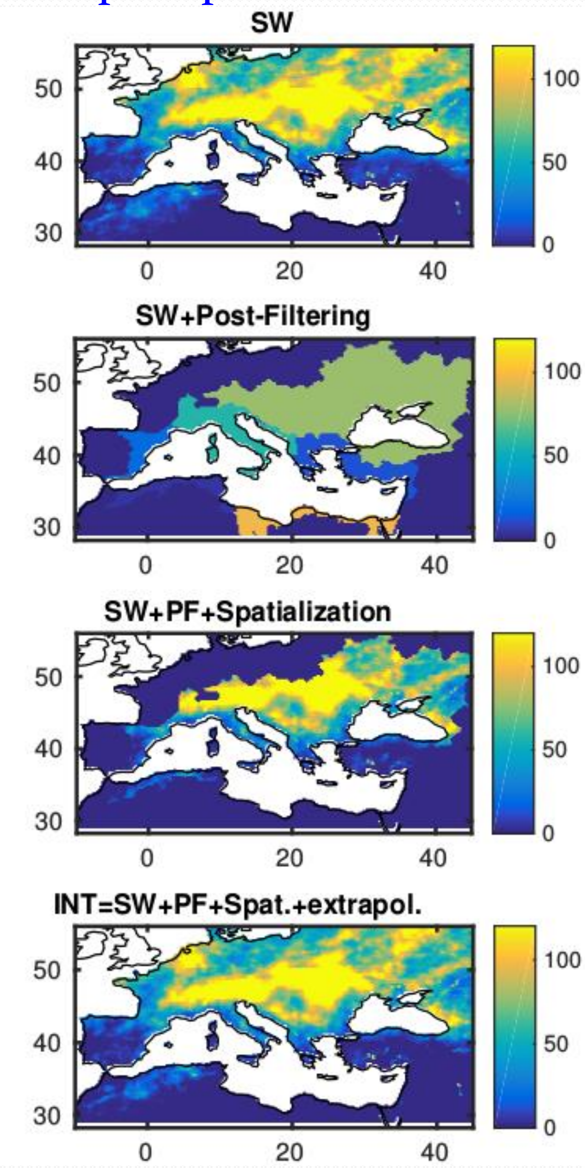
At sub- and basin scales
=> Time series only

Related publications:

- Combining Datasets of Satellite-Retrieved Products. Part I: Methodology and Water Budget Closure, JH,2014 →Methodology
- … Part II: Evaluation on the Mississippi basin and closure correction model, JGR, 2014 →Application and evaluation
- A new global method of satellite dataset merging and quality characterization constrained by the terrestrial water cycle budget RSE, 2017 →Global scale, with surface characterization

The INTegration spatial extension

For precipitation:



SW

Merge of satellite product

Do not close the WB

Spatial dataset

$$P_{SW} = \frac{1}{p-1}\sum_{i=1}^{p}\frac{\sum_{k\neq i}(\sigma_k)^2}{\sum_k(\sigma_k)^2}P_i.$$

SW+PF

Constrained product

Close the WB at sub-basin scale

Time series only

$$X_{PF} = (I - K_{PF}\cdot G_{lo}\sum{}^{-1}G_{lo}^{t})\cdot X_{SW},$$

$$\beta^{(i)}(m) = P_{PF}^{(i)}(m)/P_{SW}^{(i)}(m)$$

A correcting factor α for month (m),

for each pixel (j), in sub-basin (i)

$$\alpha(j,m) = \beta^{(i)}(m)$$

α is then interpolated between two sub-basin corrections $\beta^{(i1)}(m)$ and $\beta^{(i2)}(m)$

INT

α is then extrapolated outside the sub-basins

Close the water budget

Spatial dataset

$$P_{INT}^{(i)}(m) = \iint_{j\in A_l^{(i)}} P_{SW}(j,m)\dot{\alpha}(j,m) = \beta^{(i)}(m)\cdot P_{SW}^{(i)}(m)$$

Results

Annual mean fluxes in mm/day

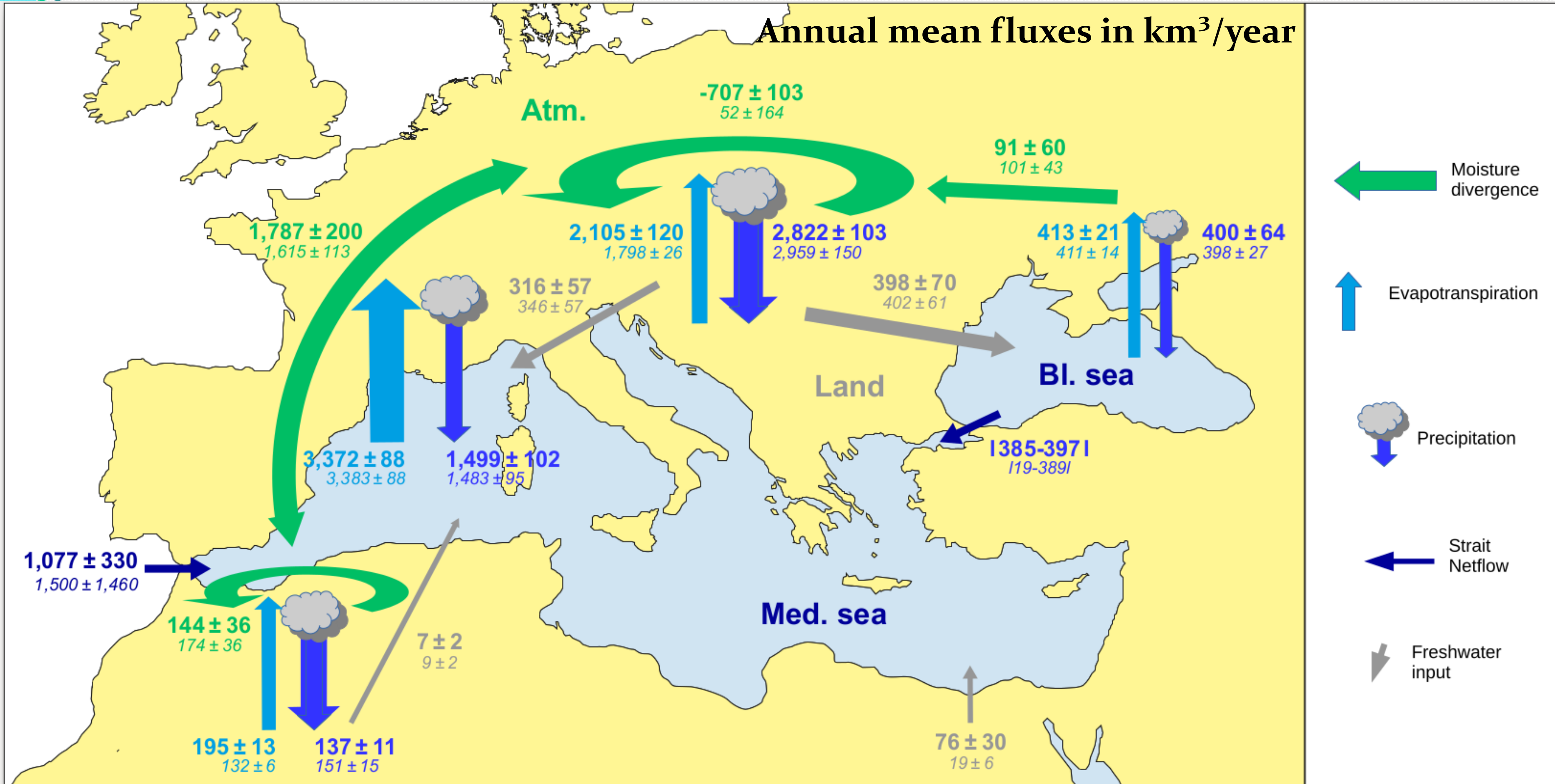
References		E	P	E-P	R	Bos	Gib	Div
Sanchez-Gomez et al. (2011)	HIRHAM	3.8±0.1	1.2±0.2	2.6±0.2	0.3±0.1	0.3±0.1	2.0±0.3	-
1957-2002	mean	3.4(±0.5)	1.2(±0.2)	2.2(±0.5)	0.3(±0.1)	0.2(±0.1)	1.5(±0.4)	-
	CRCM	3.3±0.2	1.7±0.2	1.6±0.2	0.2±0.1	0.3±0.1	1.2±0.4	-
Mariotti et al. (2002)	NCEP	3.0	1.2	1.9	0.3	0.2	1.3	1.8
1979-1993	ERA	2.6	0.9	1.7	0.3	0.2	1.0	1.4
Rodell et al. (2015)	orginal	3.8±0.4	1.6±0.2	2.1±0.5	-	-	-	2.4±0.4
2000-2010	optimized	3.9±0.3	1.6±0.2	2.2±0.5	-	-	-	2.3±0.3
Jordà et al. (2017)	prescribed	-	-	2.4±0.6	0.5±0.03	0.3±0.06	1.6±0.5	-
2005-2010								
Current study	SW	3.5±0.1	1.6±0.1	2.0±0.1	0.4±0.06	0.0±1.6	1.6±1.2	1.7±0.1
2004-2009	INT	3.5±0.1	1.6±0.1	2.0±0.1	0.4±0.04	0.4±0.1	1.1±0.3	1.9±0.1
	CAL	3.4±0.1	1.6±0.1	2.0±0.1	0.4±0.04	0.3±0.1	1.1±0.3	1.9±0.1

WC budget is improved

Fluxes are optimized

Results are in the range of Regional Climate Models

Results



- Bosporus netflow is also estimated and the Freshwater contribution of the BLS to the Med is better estimated
- Marginal contribution of the African coast to the Med. WC
- Mediterranean sea as a heat and moist reservoir
- The Nile discharge is re-evaluated

Summary

- Difficult to close water cycle budget over the Mediterranean (land and sea) with current satellite observations

- It is possible to integrate the multiple EO datasets using our methodology (SW+PF+INT), to reduce uncertainties.

- We obtain a multi-component dataset, with better WC budget closure, and limited changes of the original EO datasets.

- Two EO-based multi-components databases describing the WC are proposed to the scientific community:
  - INT (2004-2009), our reference since all observations are available
  - CAL (1980-2012), a temporal extrapolation of INT using a satellite calibration
- Indivually calibrated products are also available under request

- **Perspectives**
  - EO uncertainty characterization using the INT product as a reference
  - CAL used for rivers discharge forecasting (Case study 4)
  - Use of assimilated river discharge (Case study 1)

Case studies

River discharge assimilation

Fuxing wang & Jan Polcher

Estimation of freshwater into Mediterranean Sea: Assimilating observations in a model

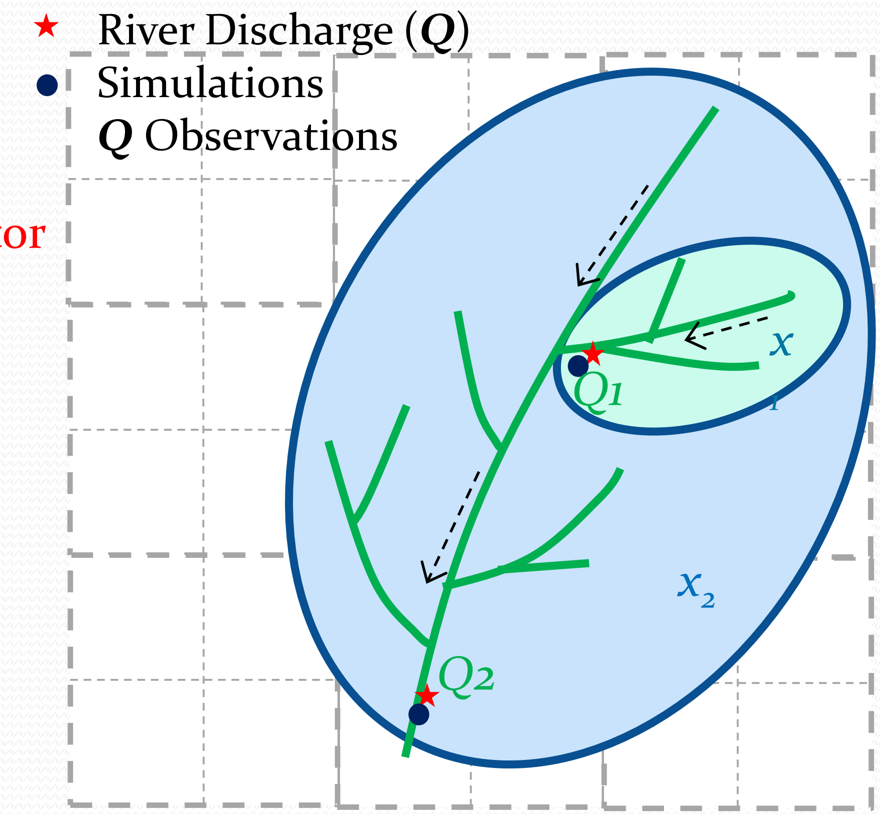
$$\frac{dW}{dt} = P - E - \boldsymbol{x} \cdot (R + D)$$

$$Q = f(R, D)$$

Correction factor

Observations available

Conceptional variable

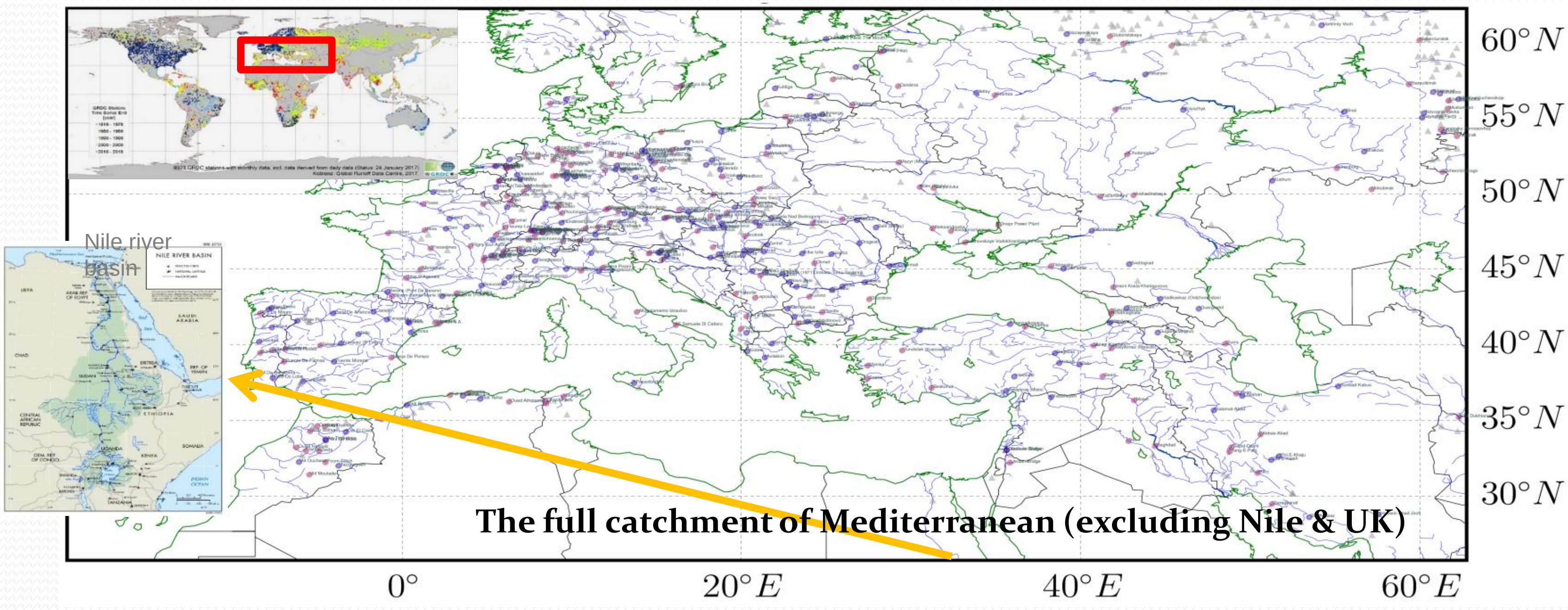


- $\frac{dW}{dt} \approx 0$, *P* & *E* errors end up in ***R***unoff + ***D***rainage
- Bias in *Q* → correct model ***R*** & ***D*** (by *x*)
- Apply each *x* to its upstream basin
- *N* of *x* depends on *N* of stations
- Improve ***Q*** simulation → Q_{corr} high temporal/spatial resolution; available when observations missing (climatology)

Wang F., J. Polcher, P. Peylin, and V. Bastrikov (2017). Assimilation of river discharge in a land surface model to improve estimates of the continental water cycles. *Hydrology and Earth System Sciences*. Under review

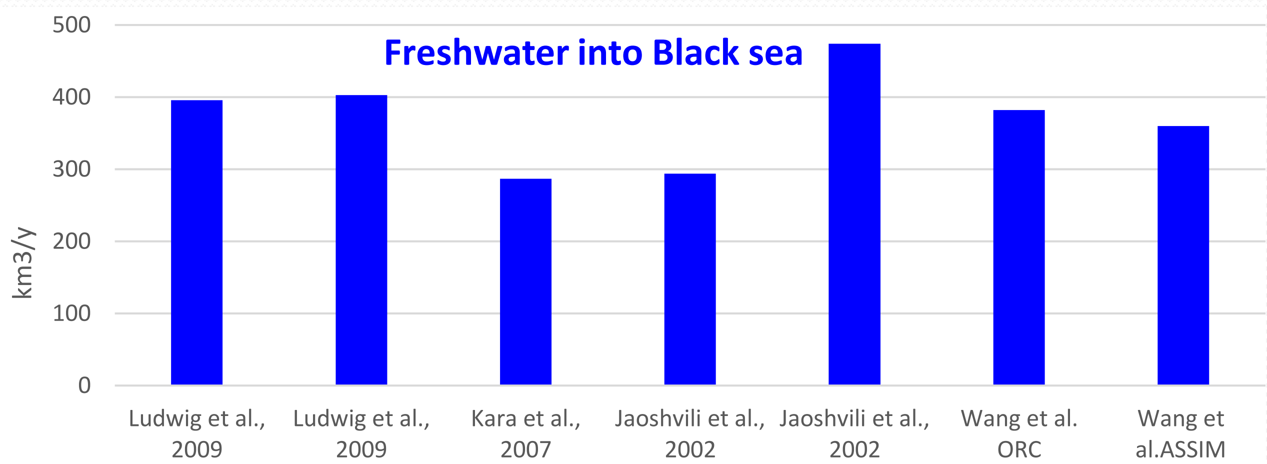
Datasets and study region

- **ORCHIDEE forcing data:** WFDEI with precipitation corrected by GPCC, 0.5°
- **River discharge observations:** Global Runoff Data Centre (GRDC).
  - ✓ UK and Nile river basin are excluded to accelerate the assimilation.
  - ✓ GRDC selection creteria: the difference of upstream area and distance between GRDC and ORCHIDEE model subbasin < 10% and < 25 km.
  - ✓ **338**/792 GRDC observation stations can be used (19.7ºW-62.7ºE, 25ºN-62ºN)
- **Previous freshwater datasets:** CEFREM, Low (Ludwig et al., 2009) and High Resolution



Fresh water (km^3/y) into the Black sea and the Mediterranean sea (with Nile)

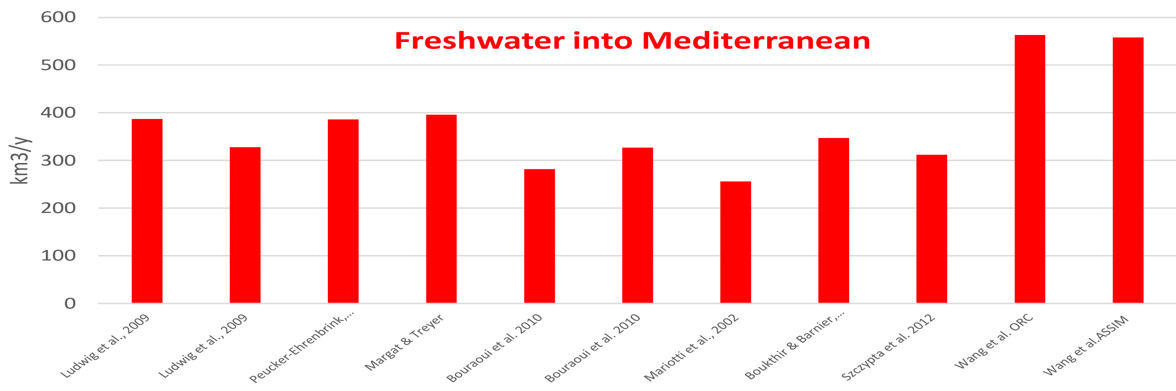
Source	Discharge	Method	Period
Ludwig et al., 2009	**396 (1960-1969), 403 (1991-2000)**	**GRDC + water balance**	**1960-1969, 1991-2000**
Kara et al., 2007	287	Model + observations	1952-1984
Jaoshvili et al., 2002	294 to 474	Literature review	Various periods
Wang, Polcher, et al. (2017)	**382 (ORCHIDEE); 360 (Assimilated)**		**1980-1997 to 2013**



Black sea: the assimilated value and previous studies are very close to each other.

Fresh water (km^3/y) into the Black sea and the Mediterranean sea (with Nile)

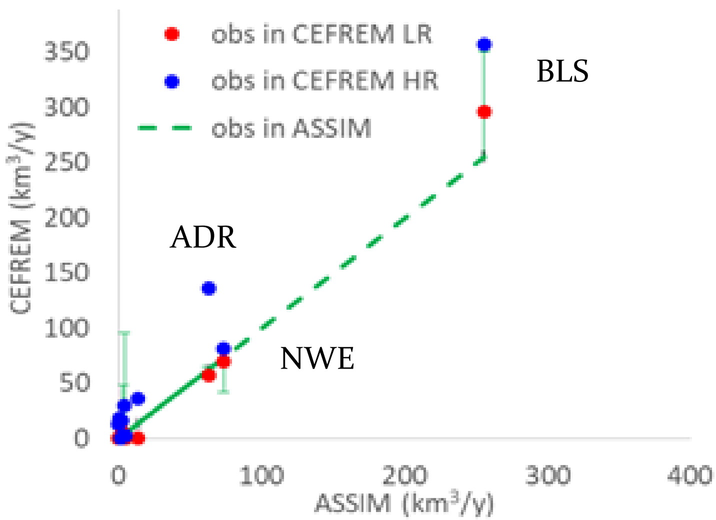
Source	Discharge	Method	Period
Ludwig et al., 2009 (CEFREM LR)	**387 (1960-1969), 328 (1991-2000)**	**GRDC + water balance**	**1960-1969, 1991-2000**
Peucker-Ehrenbrink, 2009	386	Land2Sea data	--
Margat & Treyer	396		
Bouraoui et al. 2010 (JGR)	282-327	model	1980-2000
Mariotti et al., 2002 (JC) Struglia et al. 2004 (JC)	256, <=328	GRDC,MED-HYCOS	>10 years
Boukthir & Barnier, 2000 (JMS)	347	UNESCO	different periods
Szczypta et al. 2012 (HESS)	312	GRDC	1991-2000
Wang, Polcher, et al. (2017)	**563 (ORCHIDEE); 558 (Assimilated)**		**1980-1997 to 2013**



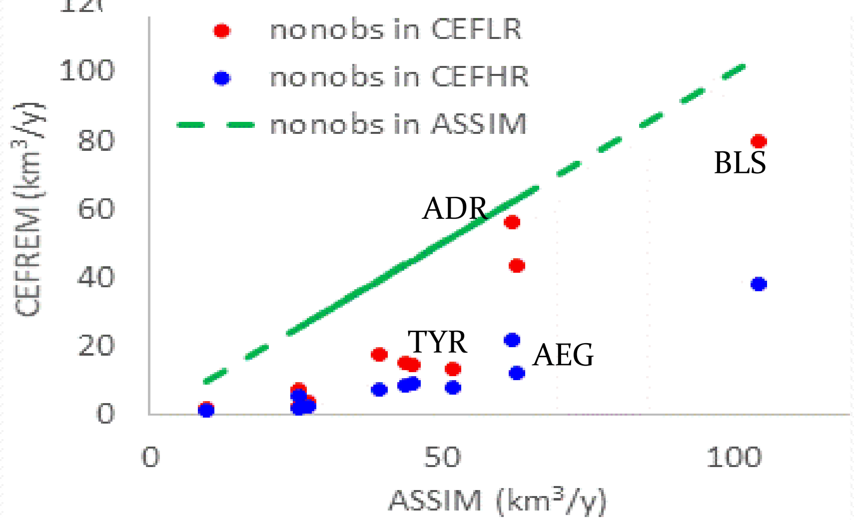
- Mediterranean: Assim. >> others (e.g., 170-230 km^3/y higher than Ludwig et al., 2009). **Why ???**

Separating total discharge coastal points with and without observations

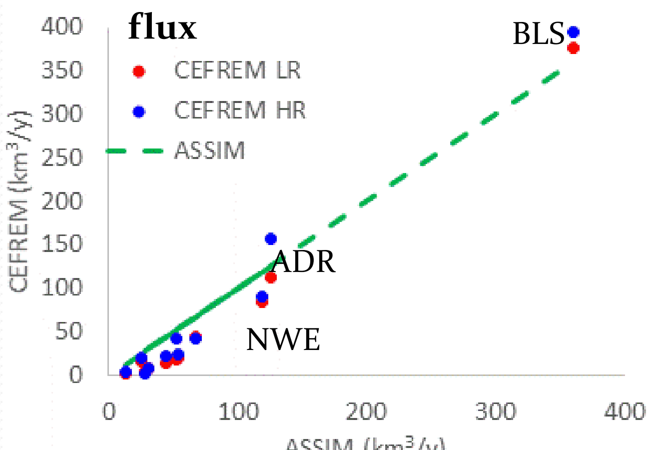
CEFREM vs ASSIM: coastal points with observations



CEFREM vs ASSIM: coastal points without observations



CEFREM vs ASSIM: Total flux



- **Discharge on coastal points with observations:**

  ASSIM ≈ CEFREM (LR) < CEFREM (HR)

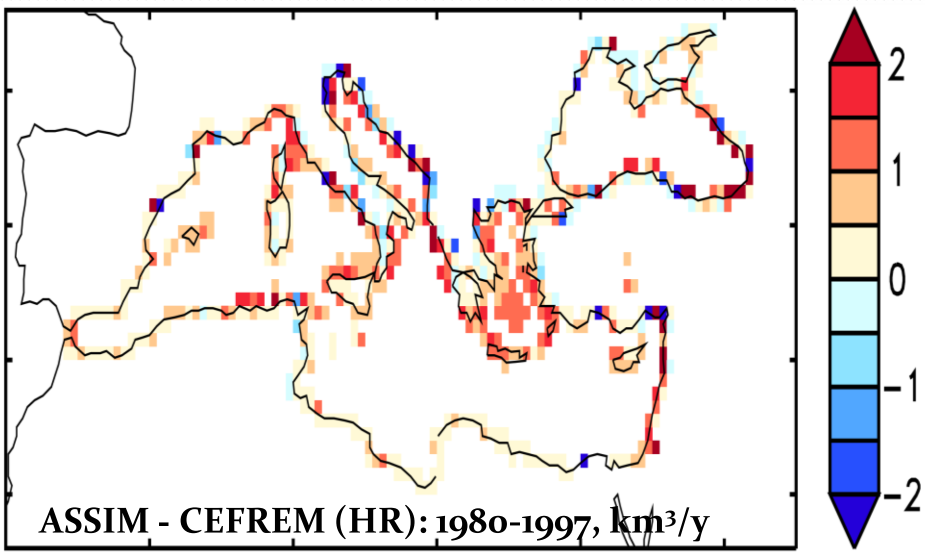
- **Non-observed coastal points:**

  ASSIM > CEFREM (LR) > CEFREM (HR)

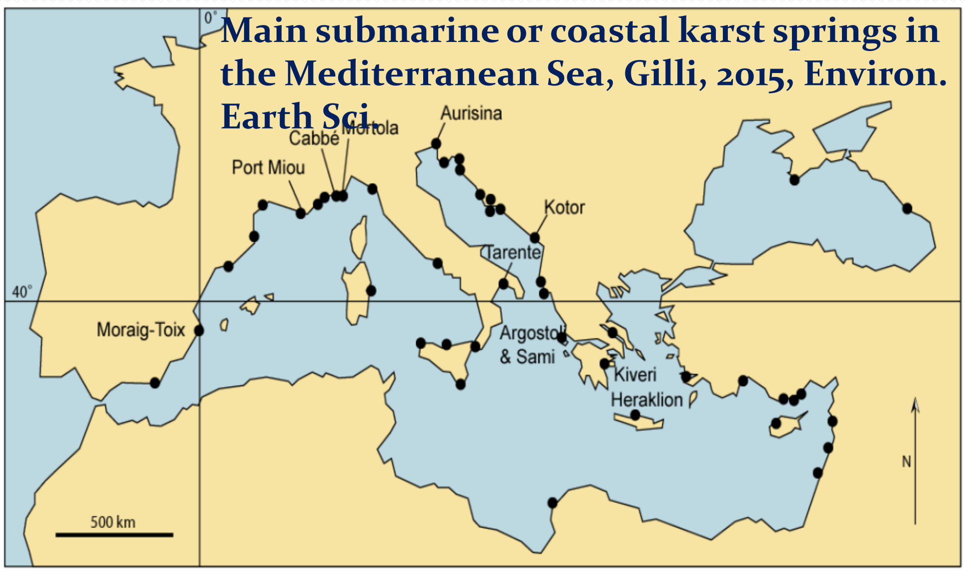
- **Total discharge (= obs + non-obs):**

  ASSIM > CEFREM (LR HR) (by nonobs. discharges ?)

Possible sources of excess freshwater flows into the Mediterranean



ASSIM - CEFREM (HR): 1980-1997, km³/y



Main submarine or coastal karst springs in the Mediterranean Sea, Gilli, 2015, Environ. Earth Sci.

The largest differences are in regions with complex coastlines: Agean, Balkan and Italy.

Some explanations are:

- Small un-gauged rivers.
- Submarine groundwater discharge (SGD) and kastic systems

Some extimates of SGD to the Mediterranean sea:

- 52 km^3/y by UNESCO (2004),
- 68 km^3/y by Zektser et al. (2007),
- 300-4800 km^3/y (fresh +saline), Rodellas et al. (2015)

SGD of Black sea: 16 km^3/y Schubert et al. (2017)

Why SGD is important ?

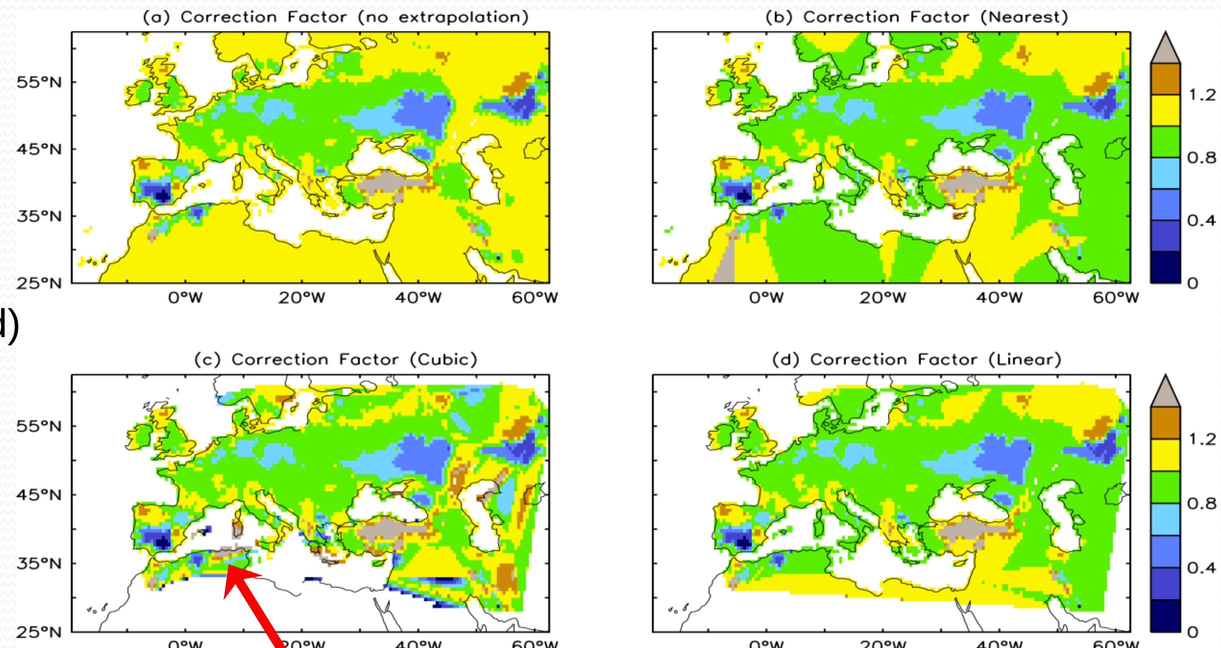
- strategic freshwater resources
- important source of nutrients

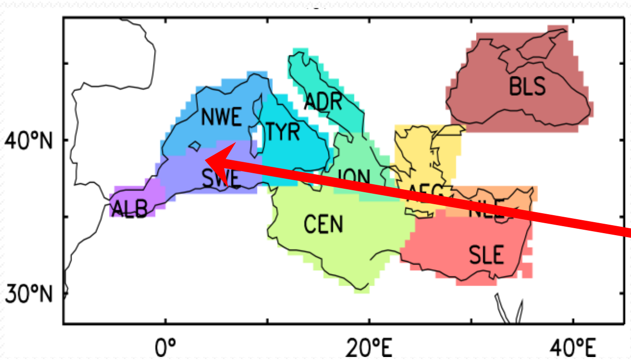
Uncertainty linked to the extrapolation methods for the correction factor

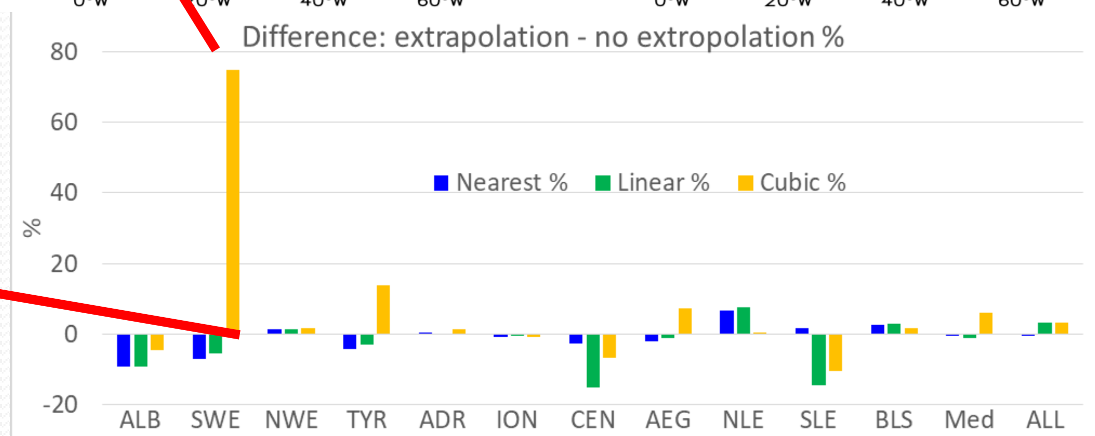
The method used here hinges on the extrapolation of the correction factor **from gauged to un-gauged basins.**

- Close pattern (most)
- Linear ≈ Nearest (they are used)
- Cubic different (e.g., SWE)

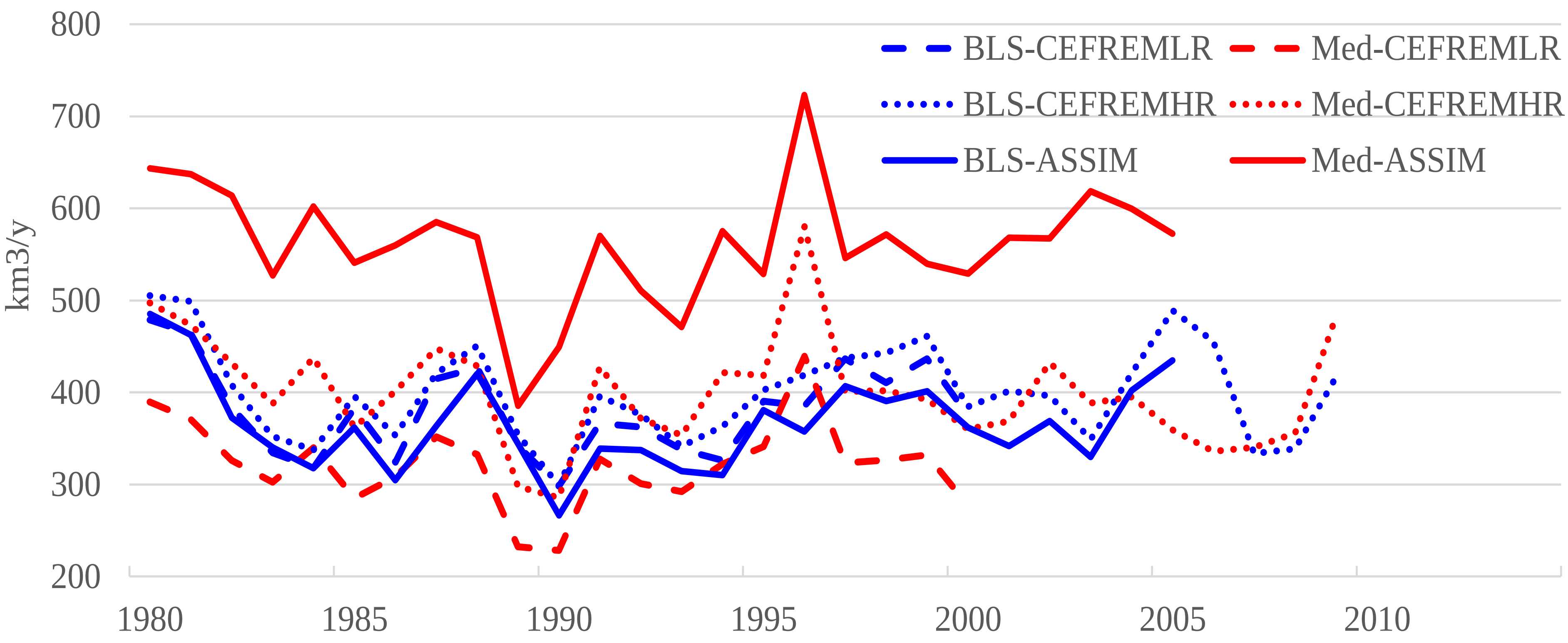
Conclusion: the extrapolation accounts for at most 5% of the total discharge.







Evolution of the discharge into the Mediterranean and the Black sea



- Trend of assimilated values: period dependent; No significant trend over 1980-2005.

Case studies

Ocean circulation

Gabriel Jorda

See presentation on Thursday at 12.40

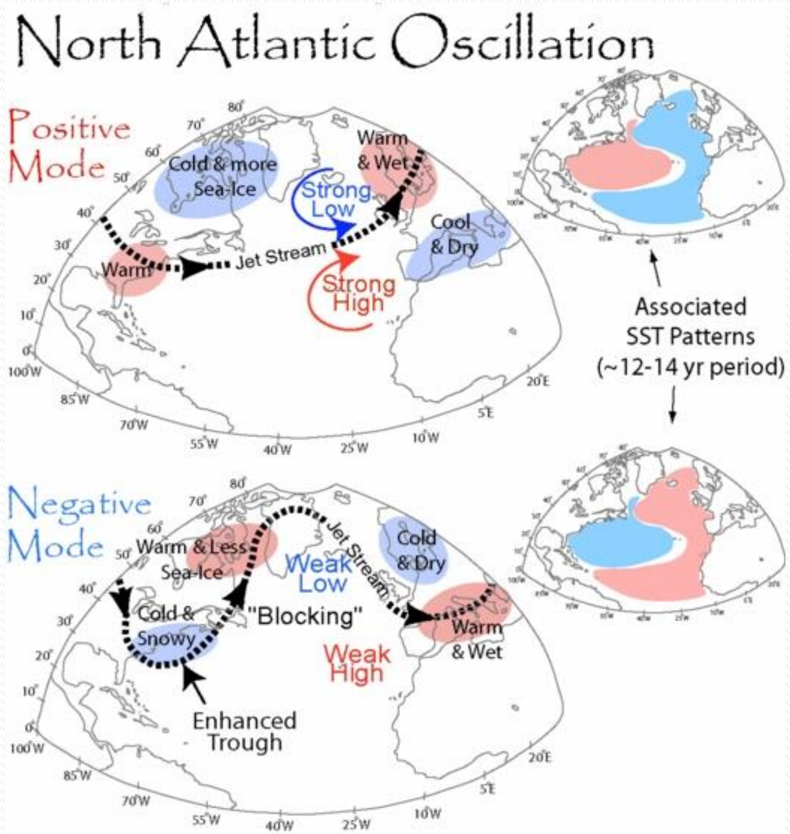
Case studies

Climate analysis

Wouter Dorigo

Climate variability

- **State-of-the-art:** Climate variability and, hence, hydrology in the Mediterranean region is strongly controlled by coupled oceanic-atmospheric circulation patterns but links are still unclear
- **Goal**: Empirically assess the relationships between climate modes and Mediterranean hydrology
- **Data**: Precipitation and evaporation from the integrated dataset (Task 5), and climate oscillation indices of 17 major global climate modes (NAO, ENSO, etc.)
- **Methods**: Machine Lasso Regression machine learning
  - Can deal with many input data
  - Disentangles correlations between input data

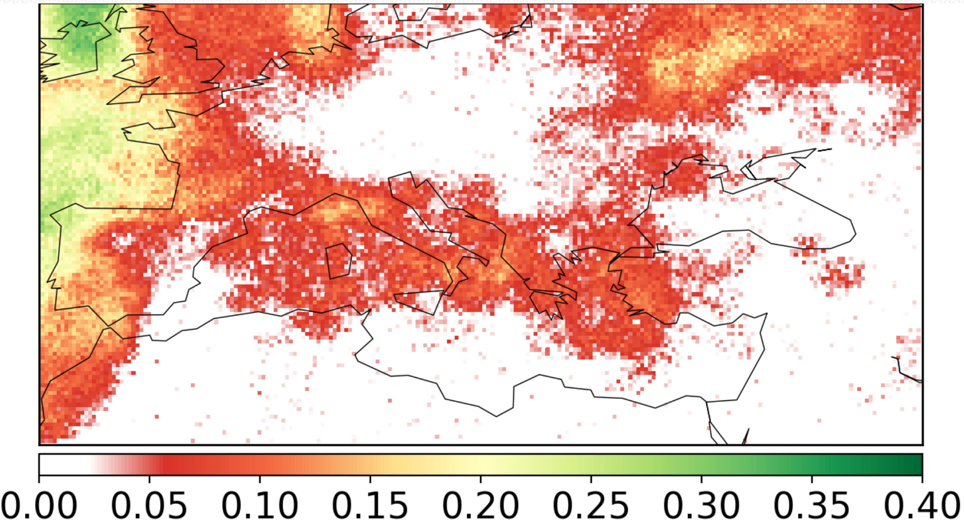


Schematic impact of NAO on European weather

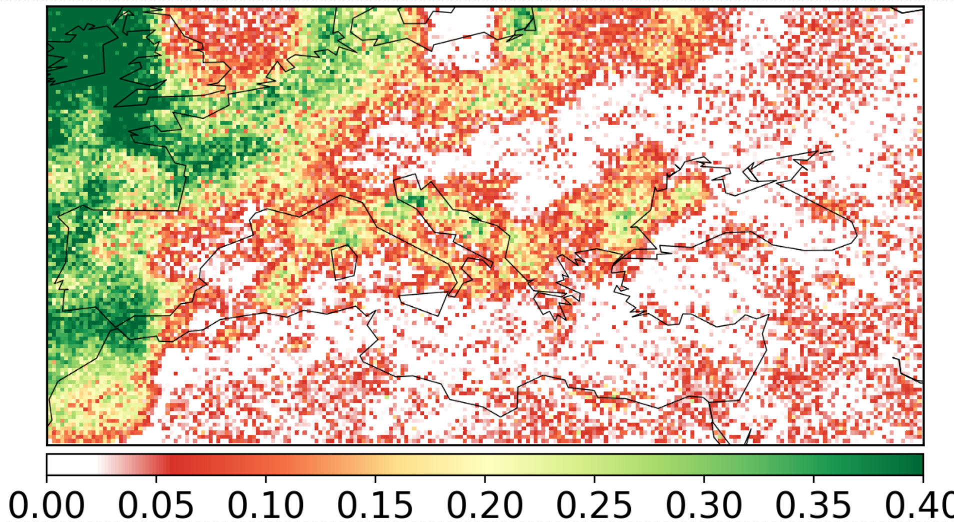
Climate variability

- Variance (R^2) of precipitation anomalies in P_CAL explained by LASSO regression using 17 climate modes as input

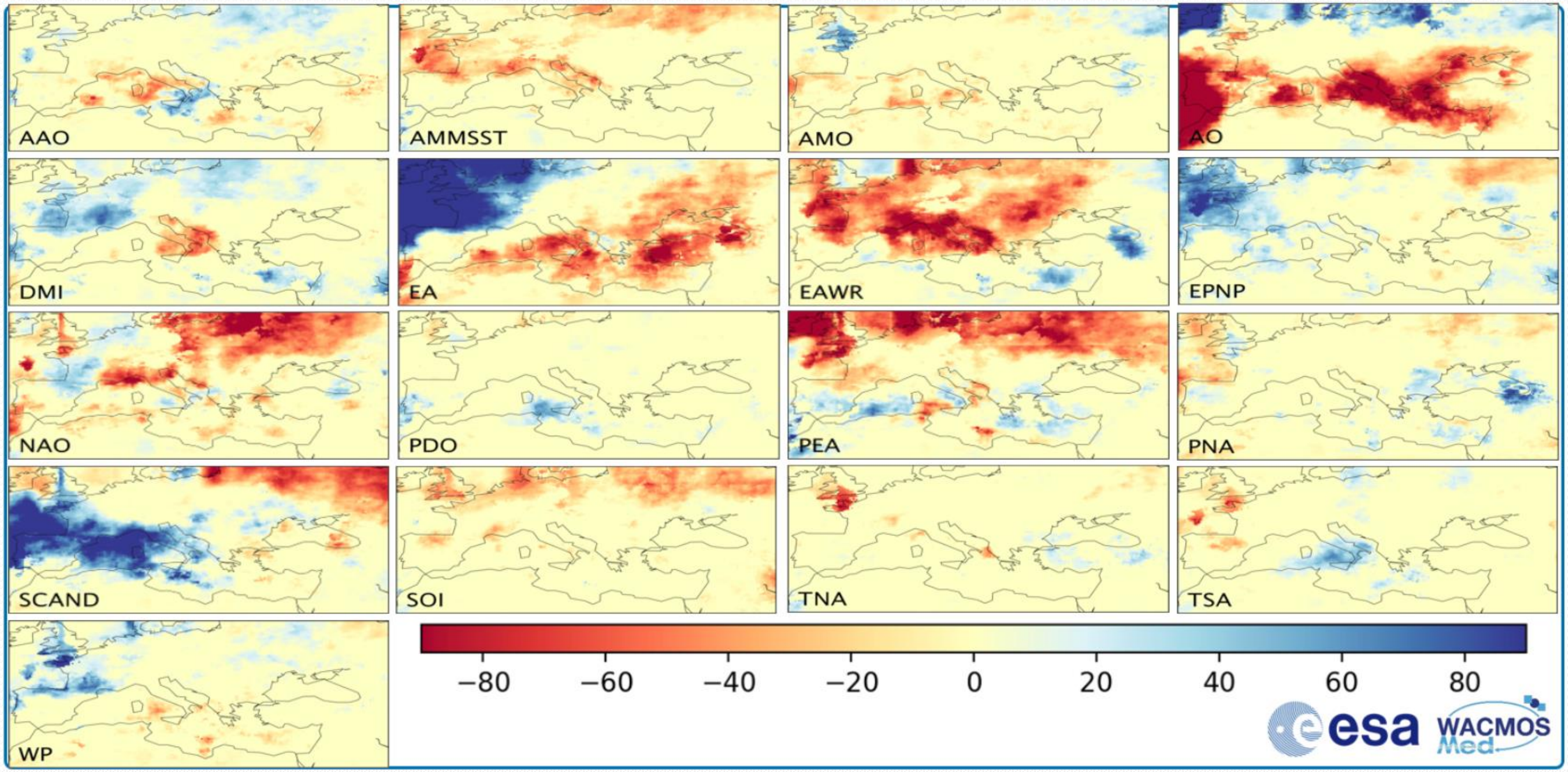
For a model trained and applied to all data



For a model trained and applied using only winter (DJF) data



Relative importance of individual climate modes derived from LASSO



Case studies

River discharges forecasting

Stefania Camica & Luca Brocca

River discharge forecasting

Open questions:

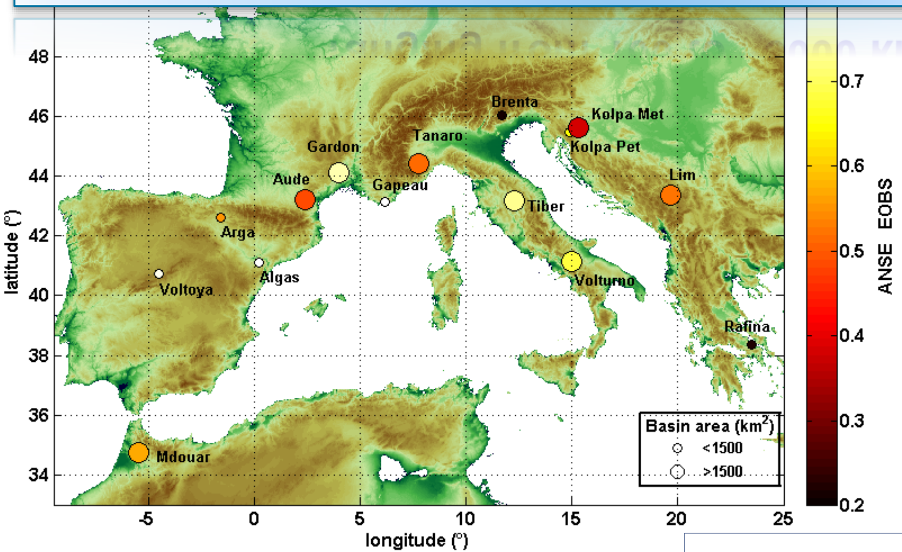
How useful are satellite rainfall products for hydrological modelling?

Which benefits can be obtained from

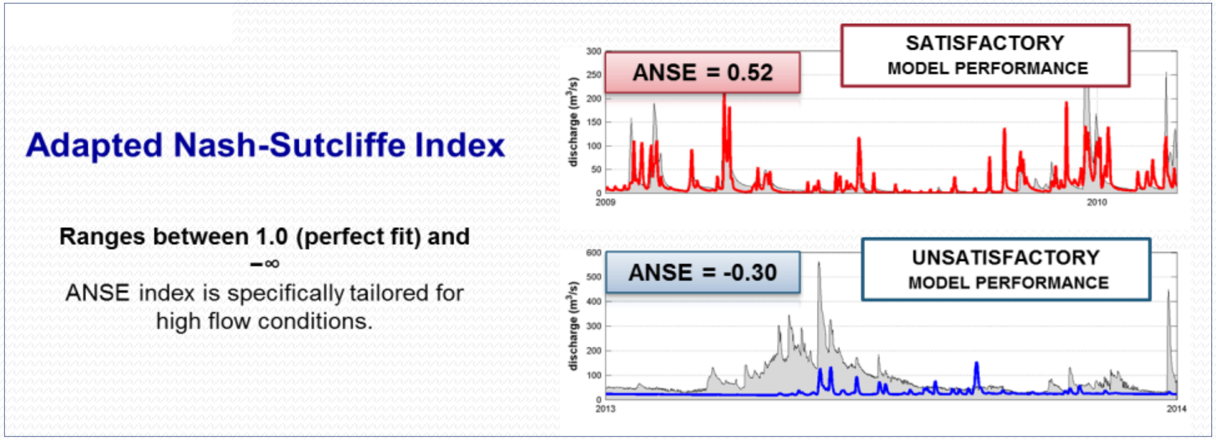
- The integration of satellite products?
- The assimilation of satellite soil moisture products?

River discharge forecasting

15 basins over the Mediterranean area with catchment area ranging from 100 to ~5000 km^2



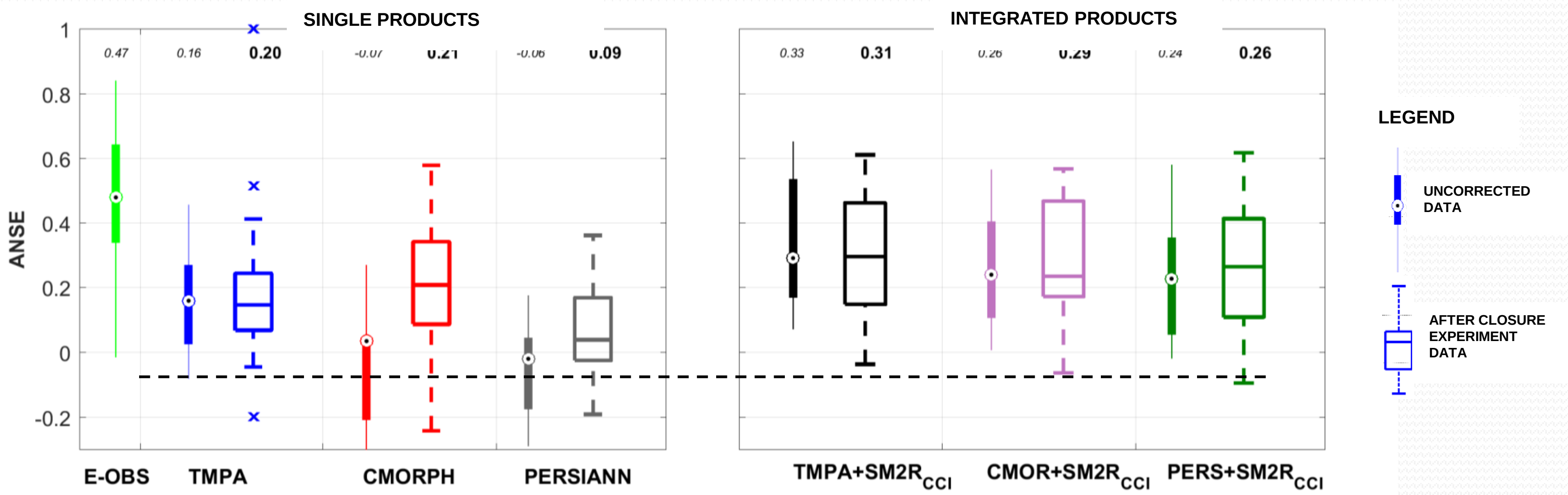
Metric for hydrological modelling capability: ANSE



River discharge forecasting

Performances of satellite precipitation dataset raw (or integrated with SM2R) with/without the correction from the integration process, in the estimation of river discharges

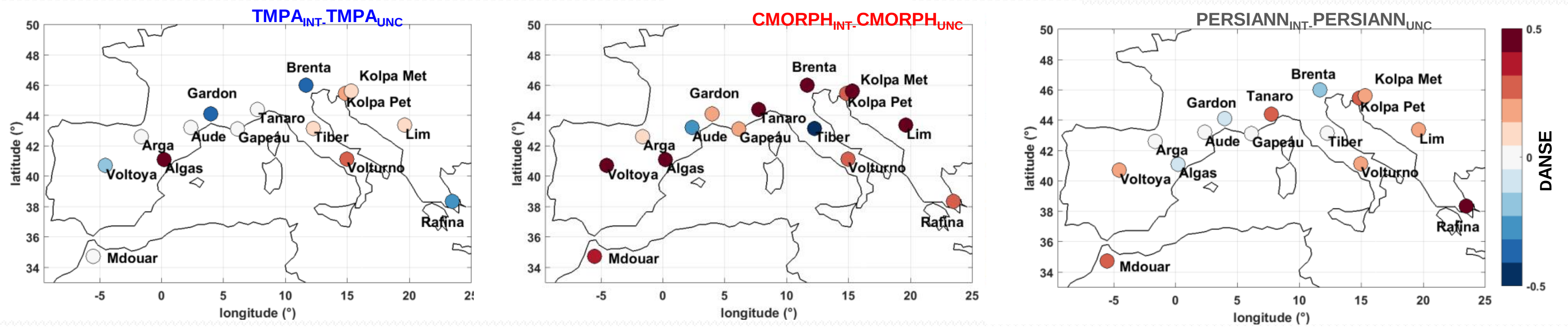
MEAN VALUES OVER THE STUDY AREA



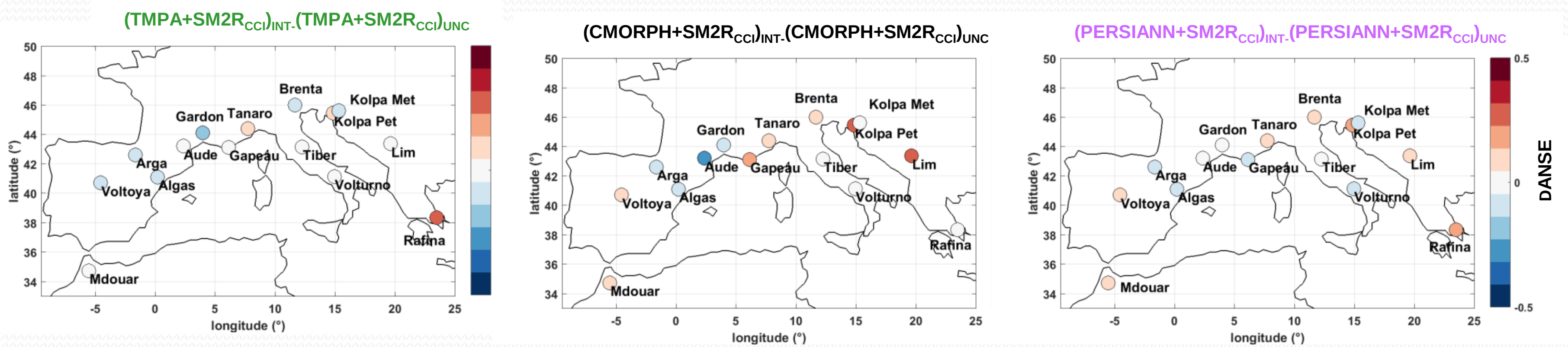
River discharge forecasting

<u>Difference</u> between the ANSE value obtained by using <u>uncorrected</u> rainfall products to force the hydrological modelling and the ANSE value obtained by using the <u>corrected</u> rainfall products is shown

SINGLE PRODUCTS



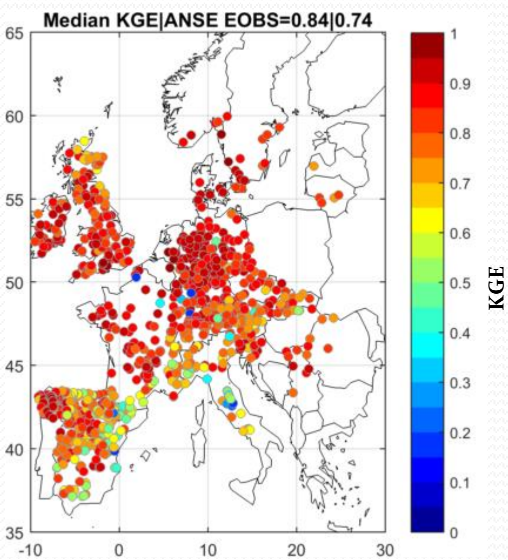
INTEGRATED PRODUCTS



River discharge forecasting

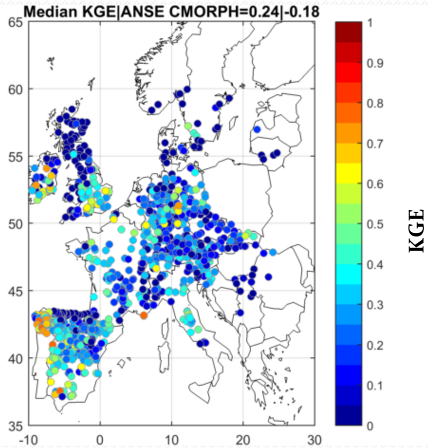
Enlarging the evaluation to many more basins

Many basins over the Mediterranean Europe

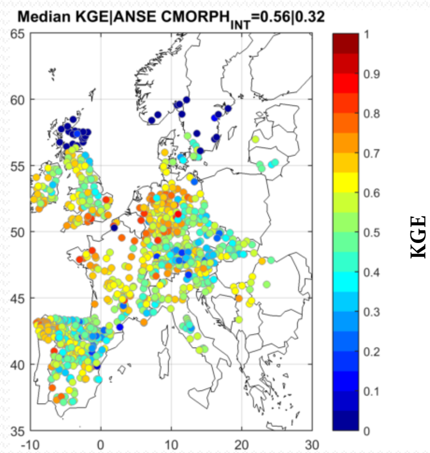


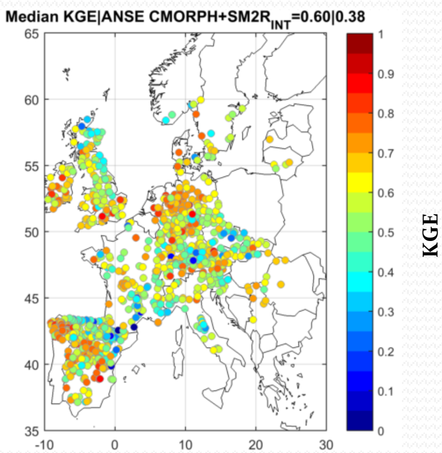
975 basins throughout Europe with catchment area ranging from 200 to ~ 60000 km^2

BEFORE THE CLOSURE EXPERIMENT



AFTER THE CLOSURE EXPERIMENT





Thank you

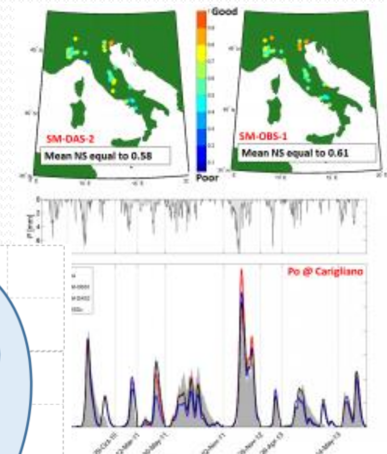
Water Cycle Multi-mission Observation Strategy for the Mediterranean. An ESA-HYMEX initiative

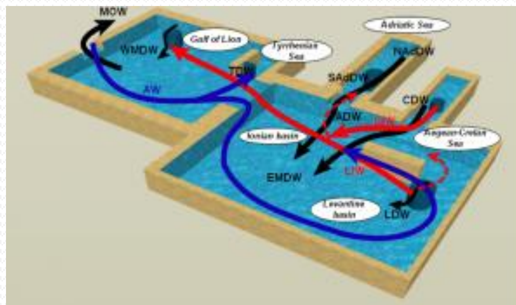
Thank you

Water Cycle Multi-mission Observation Strategy for the Mediterranean. An ESA-HYMEX initiative

Victor Pellet, Filipe Aires, Wouter Dorigo, Jan Polcher, Fuxing wang, Luca Brocca, Gabriel Jorda, *et al.*

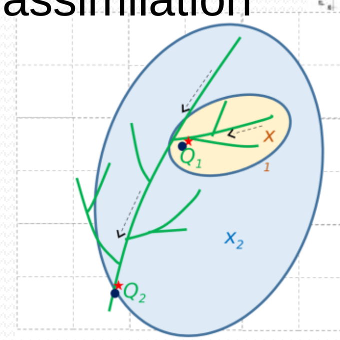
River discharge forecast



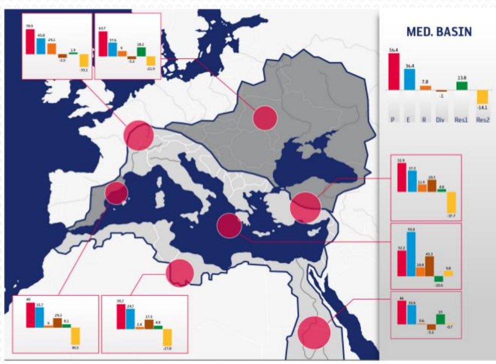


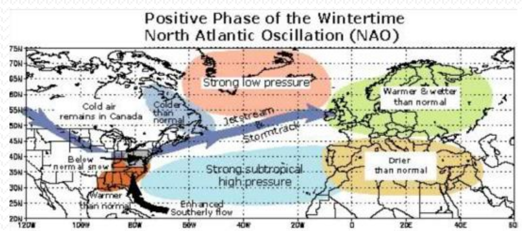
Ocean circulation

River assimilation



Water cycle closure





Climate Analysis

Estellus · Observatoire de Paris · LERMA · TU Wien · GEO — Vienna University of Technology, Department for Geodesy and Geoinformation, Research Groups Photogrammetry & Remote Sensing · LMD · irpi · IMEDEA · CSIC · Universitat de les Illes Balears

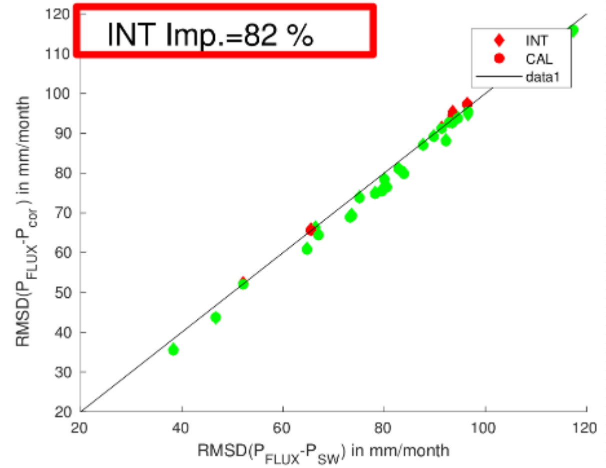
Extra slide: INT Validation

RMS of WB residual

	Climatic sub-basins										LAND		OCEAN	
	MA-DZ-TN		ES-Pyr		Alp-IT-ADR		GR-TR-IL		BLS					
	surf	atm	surf	atm	surf	atm	surf	atm	surf	atm	surf	atm	surf	atm
ERA. I	34.3	15.3	37.8	18.1	31.2	13.7	30.6	12.0	18.0	8.0	13.6	13.8	86.7	6.2
Sel. Opt.	25.1	36.0	27.5	43.5	28.5	37.7	25.8	39.7	25.4	27.3	19.8	15.1	75.2	24.7
SW	18.2	31.8	17.5	40.7	21.5	38.3	17.6	35.6	25.1	26.5	16.6	16.6	74.3	15.7
SW+PF	4.43 75%	3.27 89%	4.56 73%	4.35 89%	5.10 76%	3.70 90%	4.81 72%	3.48 90%	4.65 81%	3.99 84%	3.41 79%	2.98 88%	4.44 94%	2.92 81%
INT	5.37 70%	6.33 80%	5.51 68%	7.21 82%	8.32 61%	7.69 79%	6.81 61%	8.88 75%	5.43 78%	4.14 84%	3.55 78%	5.27 80%	4.44 94%	2.91 81 %

% shows improvement compared to SW

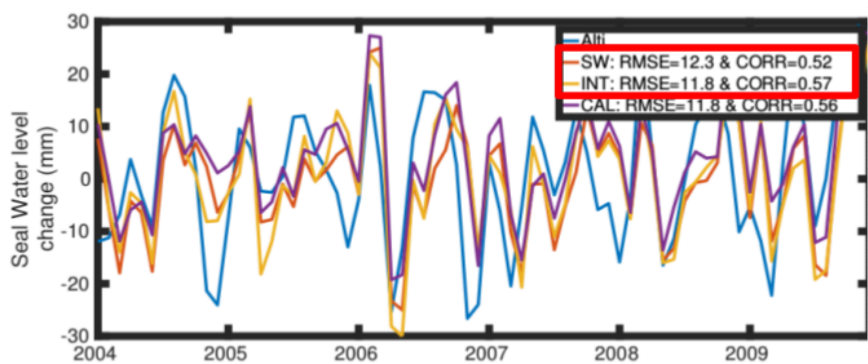
Precipitation validation on Fluxnet



Stat. on Precip.→ EOBS

		Climatic sub-basins					Continental
		MA-DZ-TN	ES-Pyr	Alp-IT-ADR	GR-TR-IL	BLS	
Correlation	SW	0.81	0.88	0.87	0.87	0.79	0.78
	SW+PF	0.84	0.90	0.88	0.87	0.81	-
	INT	0.84	0.89	0.88	0.87	0.81	0.80
	CAL	0.81	0.88	0.87	0.87	0.79	0.79
RMSE	SW	14.01	16.69	21.78	23.04	20.56	15.68
	SW+PF	13.60 2%	14.10 15%	22.42 -3%	21.98 4%	16.64 19%	- -
	INT	13.59 2%	14.35 14%	21.88 -1%	21.83 5%	16.84 18 %	12.93 17%

Stat. on Water storage change→ Altimetry



- Better WB closure
- Precip closer to gauge
- Water Sea Level Change closer to alti.