Institut de Recherche pour le Développement FRANCE

Espace DEV
OBSERVATION SPATIALE, MODÈLES & SCIENCE IMPLIQUÉE

Hydrological impacts of climate change: linking climate and hydrological models

Yves Tramblay

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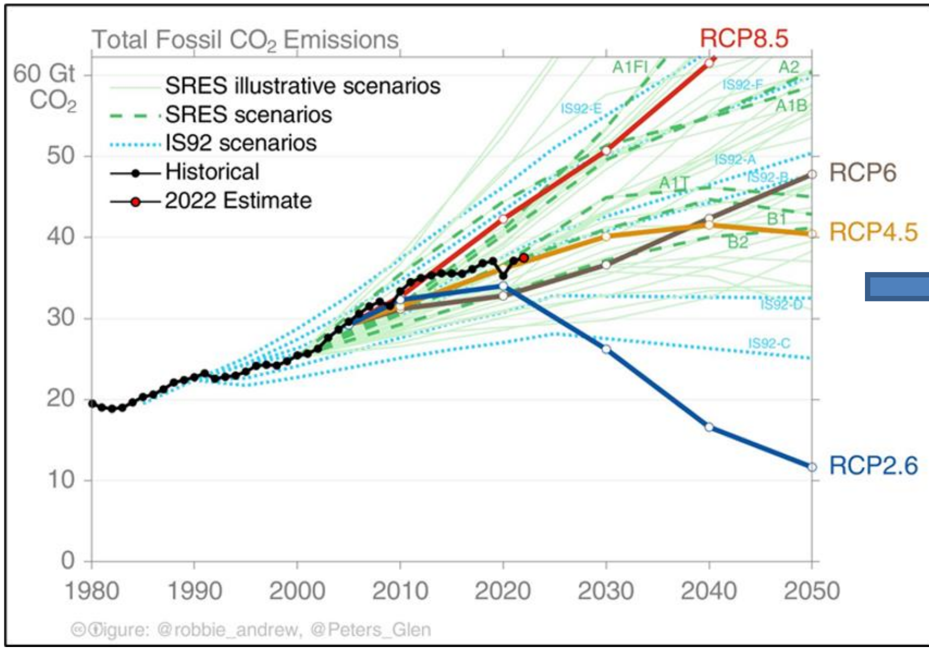
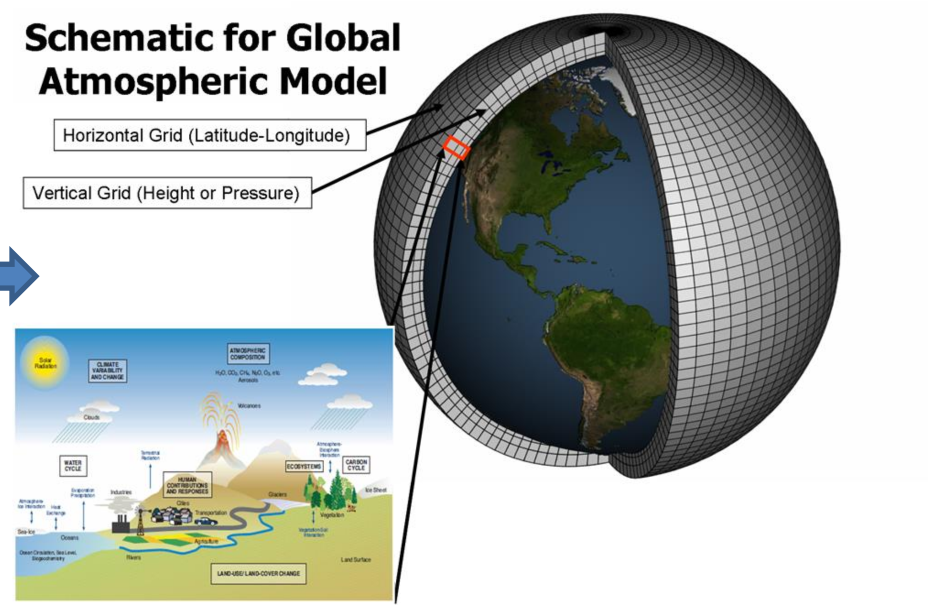
How to model climate change?

Emission scénarios



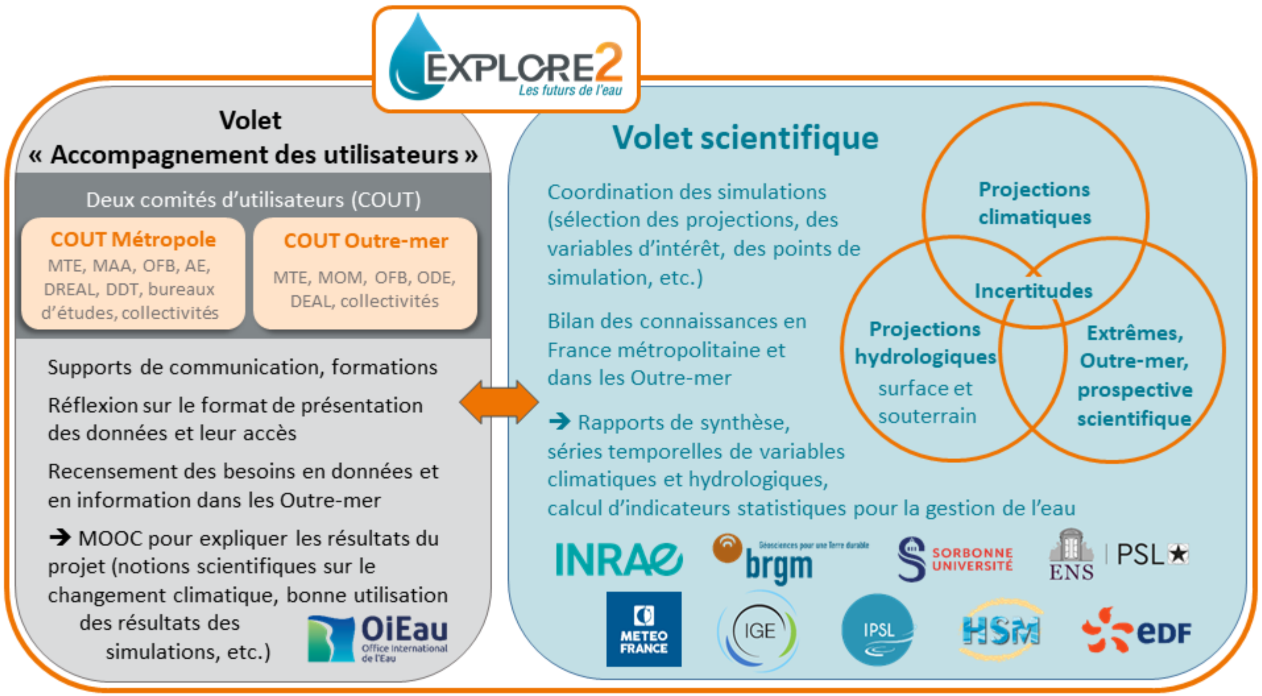
Climate model



Climate scenarios are based on greenhouse gas emission scenarios.

Climate models are based on physical equations and incorporate more and more elements: atmosphere, oceans, vegetation, aerosols, cities... and are constantly being improved.

A large project to assess climate change impacts on hydrology (2021-2024)

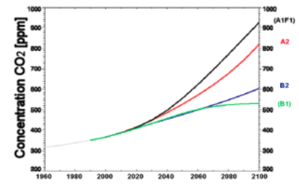


Co-financements : MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE — OFB

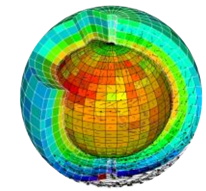
Assistance à maitrise d'ouvrage : ACTeon

Modelling chain

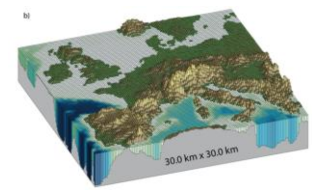
Emission scenarios



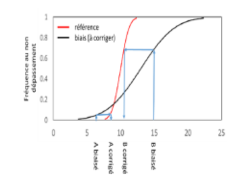
Global Circulation Model (GCM)



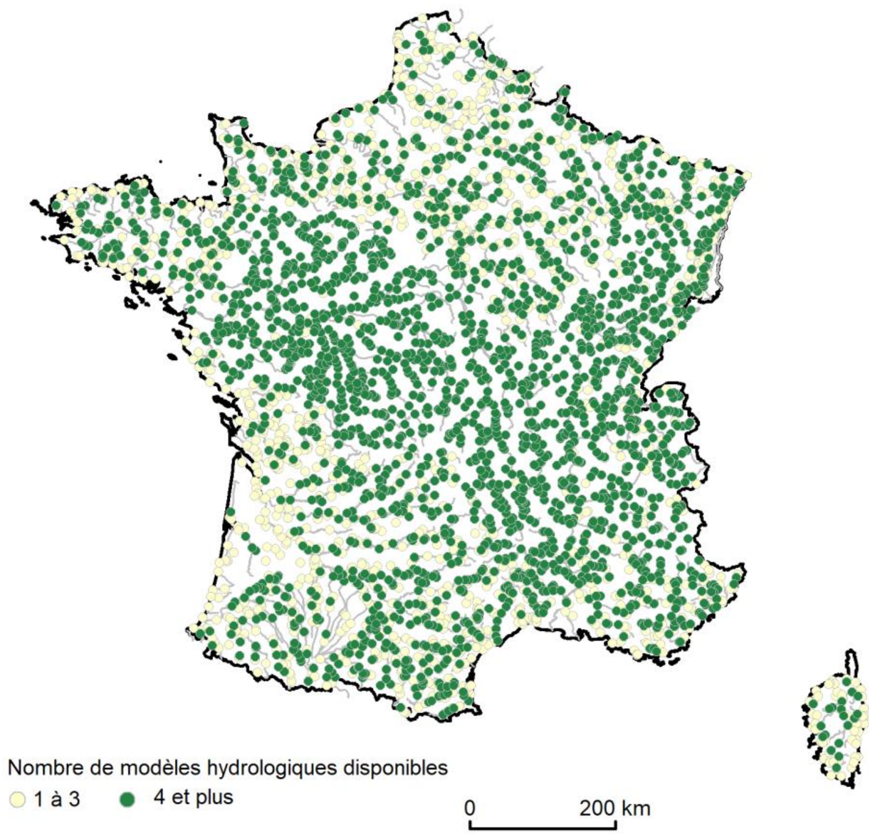
Regional Climate Model (RCM)



Bias correction methods



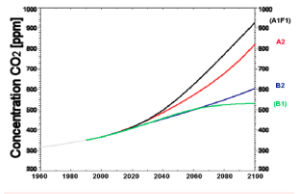
Hydrological models



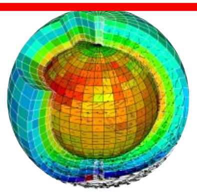
Hydrologic projections

Modelling chain

Emission scenarios



Global Circulation Model (GCM)



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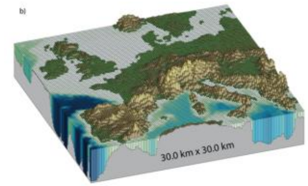
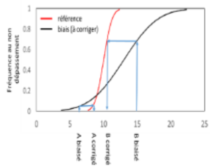
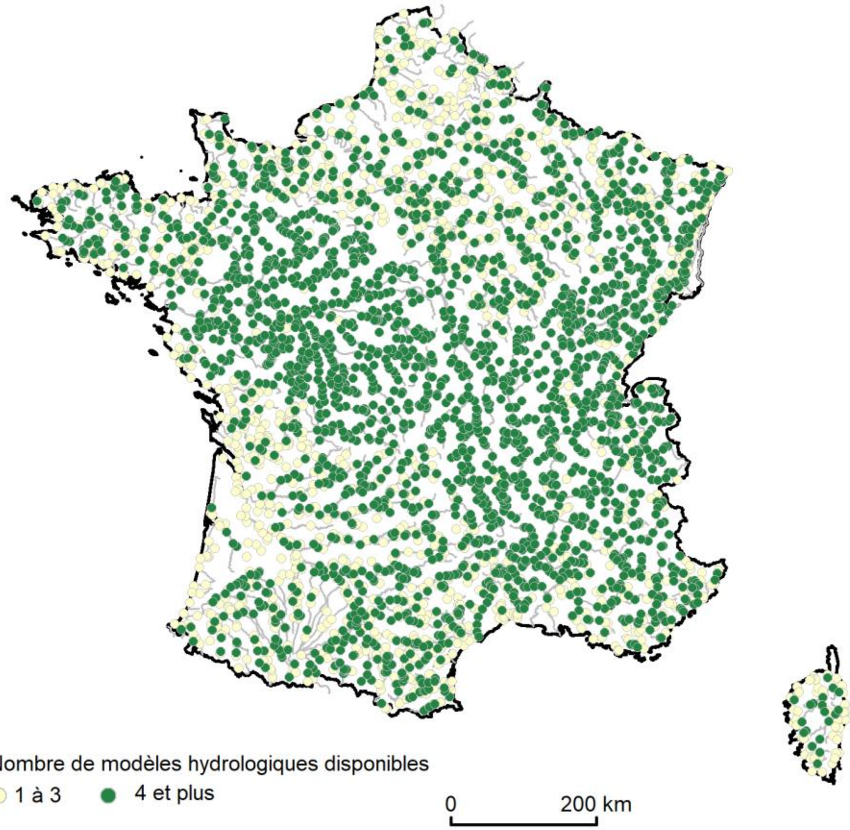


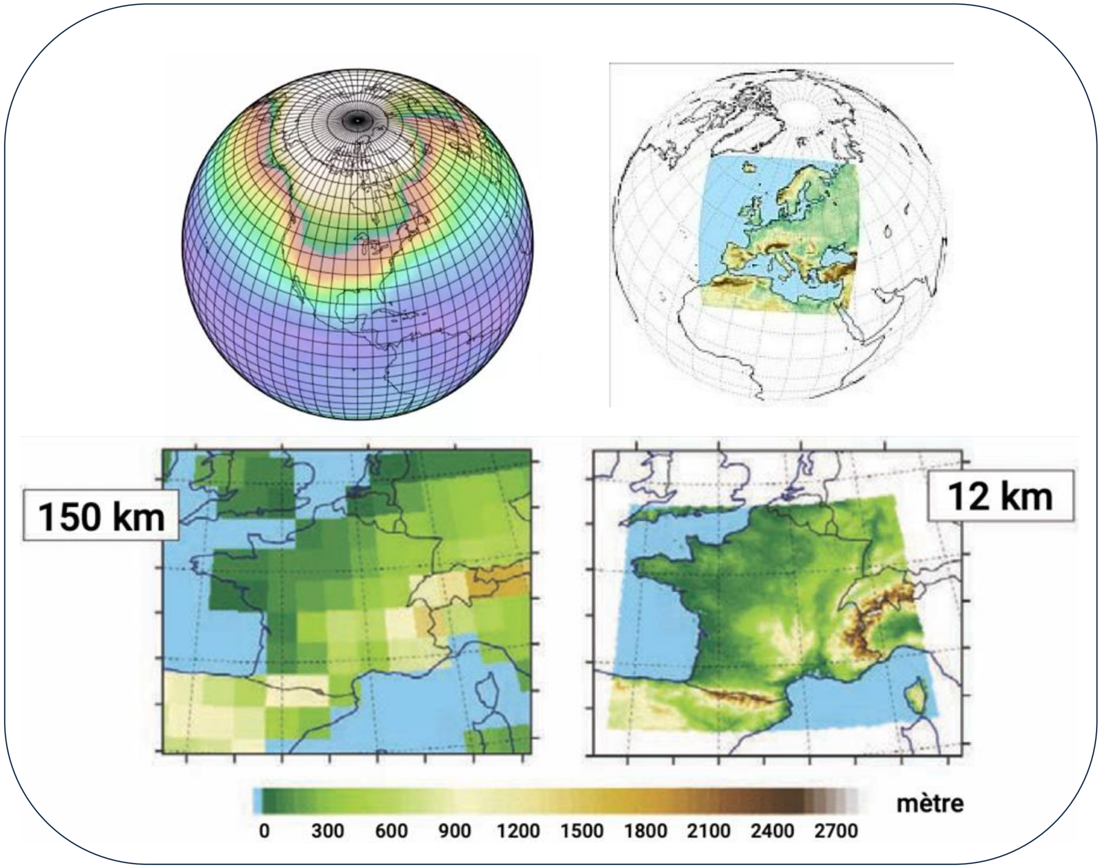
Bias correction methods

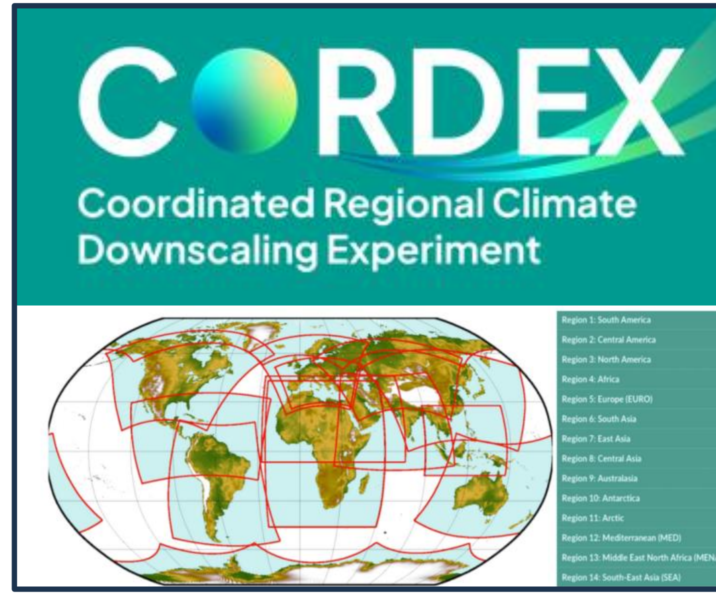


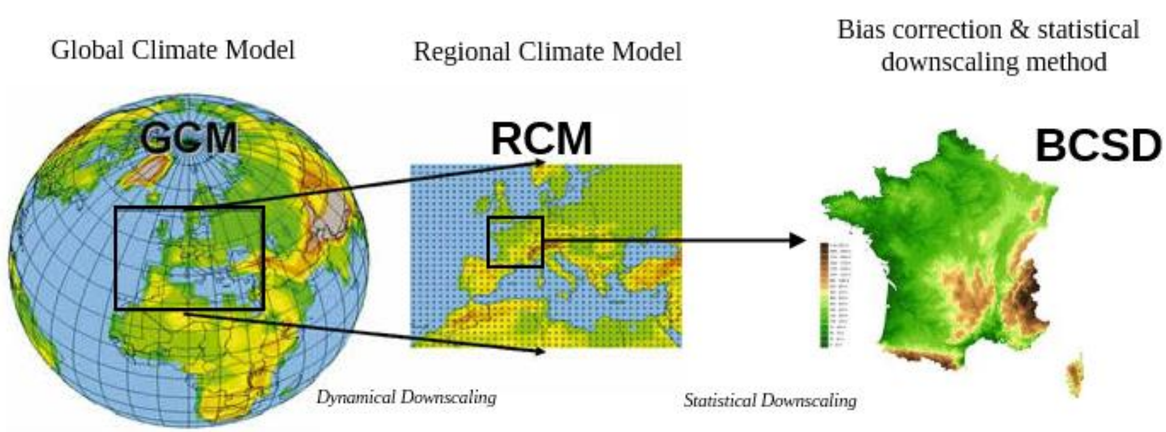
Hydrological models



Hydrologic projections

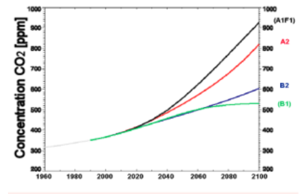

150 km
12 km
0
300
600
900
1200
1500
1800
2100
2400
2700
mètre


CORDEX
Coordinated Regional Climate
Downscaling Experiment
Region 1: South America
Region 2: Central America
Region 3: North America
Region 4: Africa
Region 5: Europe (EURO)
Region 6: South Asia
Region 7: East Asia
Region 8: Central Asia
Region 9: Australasia
Region 10: Antarctica
Region 11: Arctic
Region 12: Mediterranean (MED)
Region 13: Middle East North Africa (MENA)
Region 14: South-East Asia (SEA)

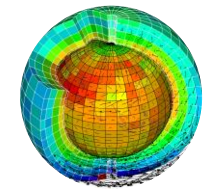

Global Climate Model
Regional Climate Model
Bias correction & statistical
downscaling method
GCM
RCM
BCSD
Dynamical Downscaling
Statistical Downscaling

Modelling chain

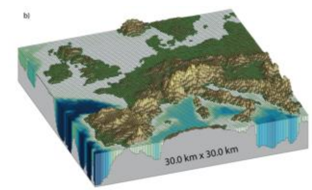
Emission scenarios



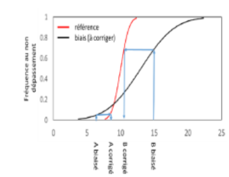
Global
Circulation Model
(GCM)



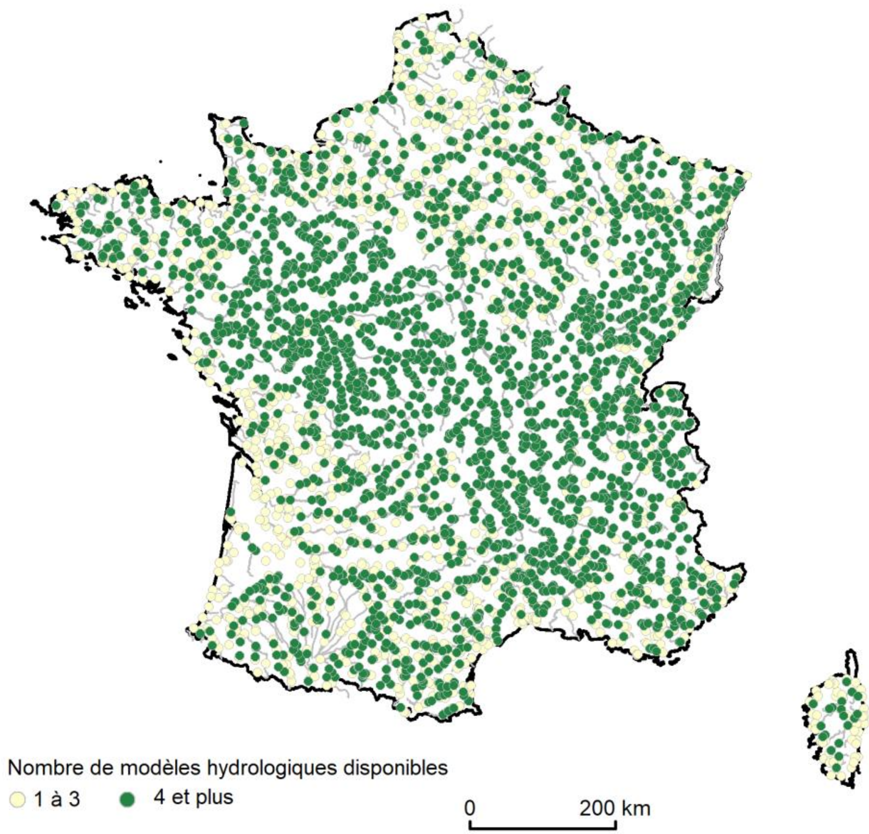
Regional Climate
Model (RCM)



Bias correction methods

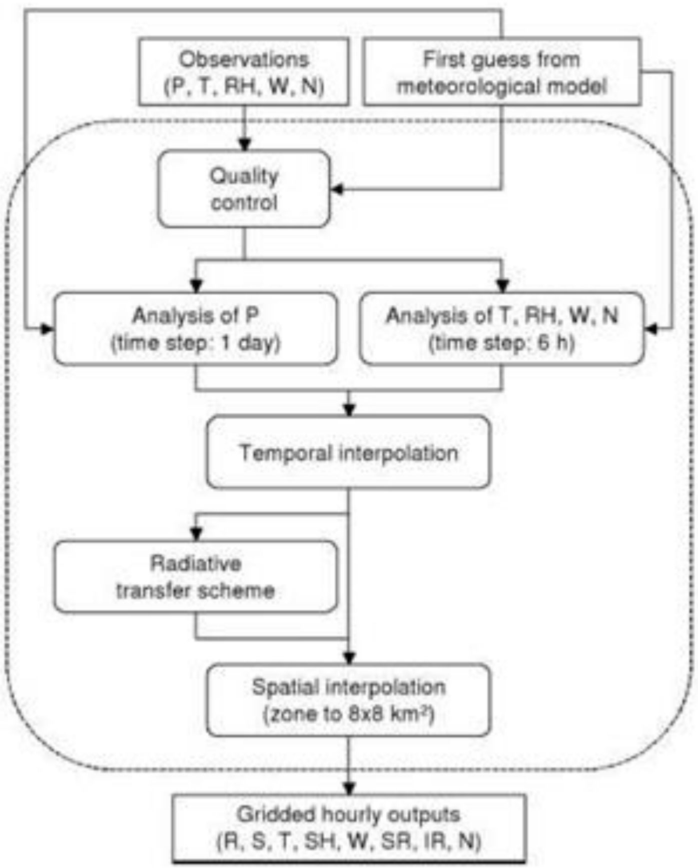


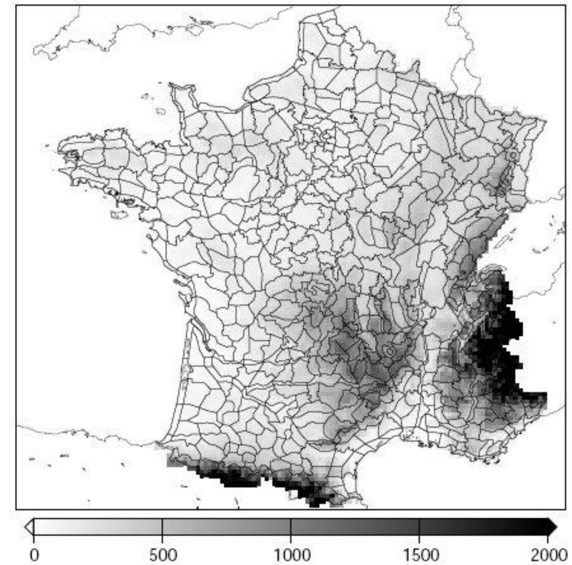
Hydrological models

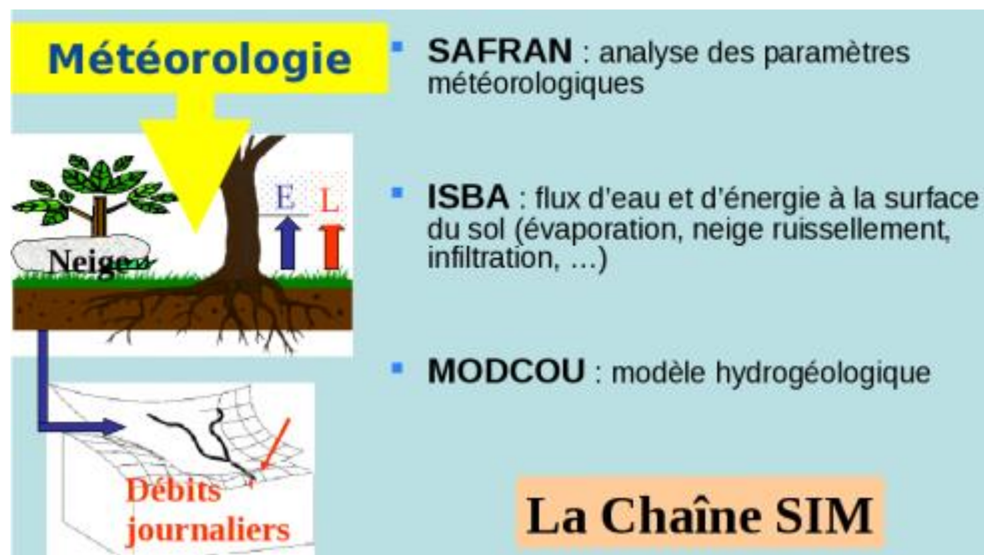


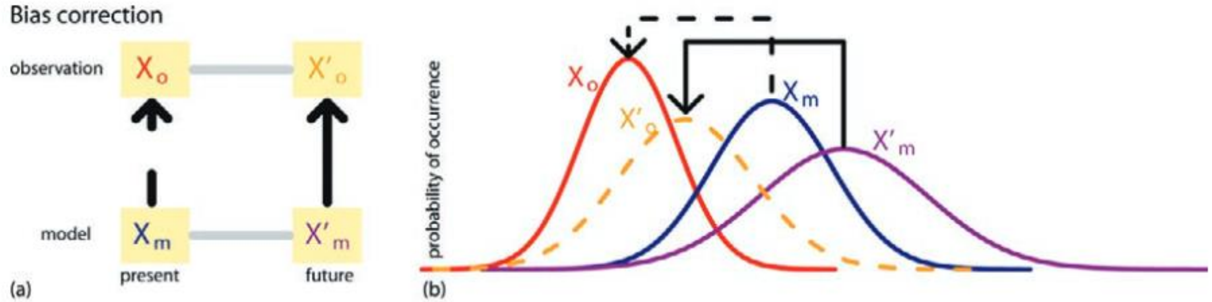
Hydrologic projections

The Safran-ISBA-Modcou (SIM) reanalysis 1958-present

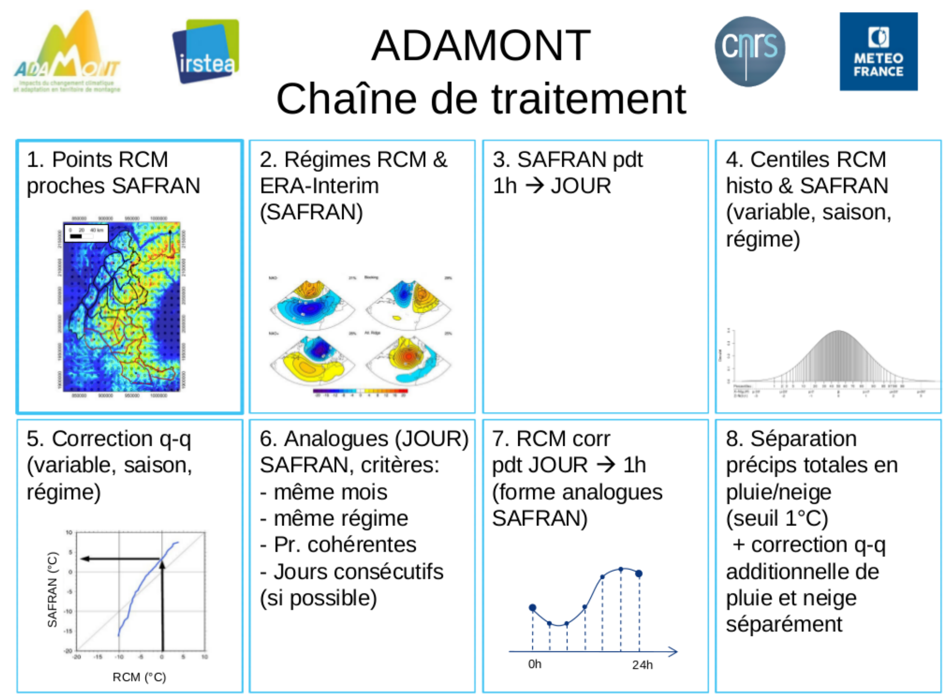








1. Bias-correction based on a quantile-mapping approach
2. Disaggregation from daily to hourly time steps
3. Correction based on weather analogs (weather types)
4. Using the SIM reanalysis as reference

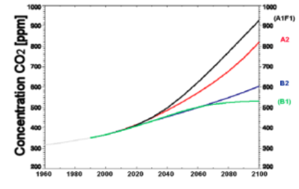


Verfaillie, D., Déqué, M., Morin, S., and Lafaysse, M. 2017 : The method ADAMONT v1.0 for statistical adjustment of climate projections applicable to energy balance land surface models, Geosci. Model Dev., 10, 4257-4283, [https://doi.org/10.5194/gmd-10-4257-2017].

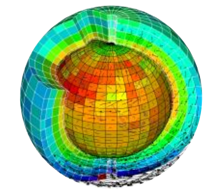
Déqué M. et al., 2007 : Frequency of precipitation and temperature extremes over France in an anthropogenic scenario : model results and statistical correction according to observed values. Global and Planetary Change. 57 : 16-26.

Modelling chain

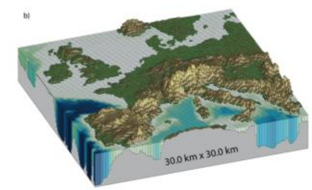
Emission scenarios



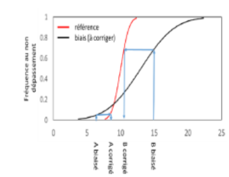
Global Circulation Model (GCM)



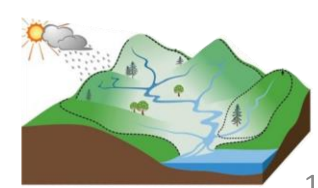
Regional Climate Model (RCM)

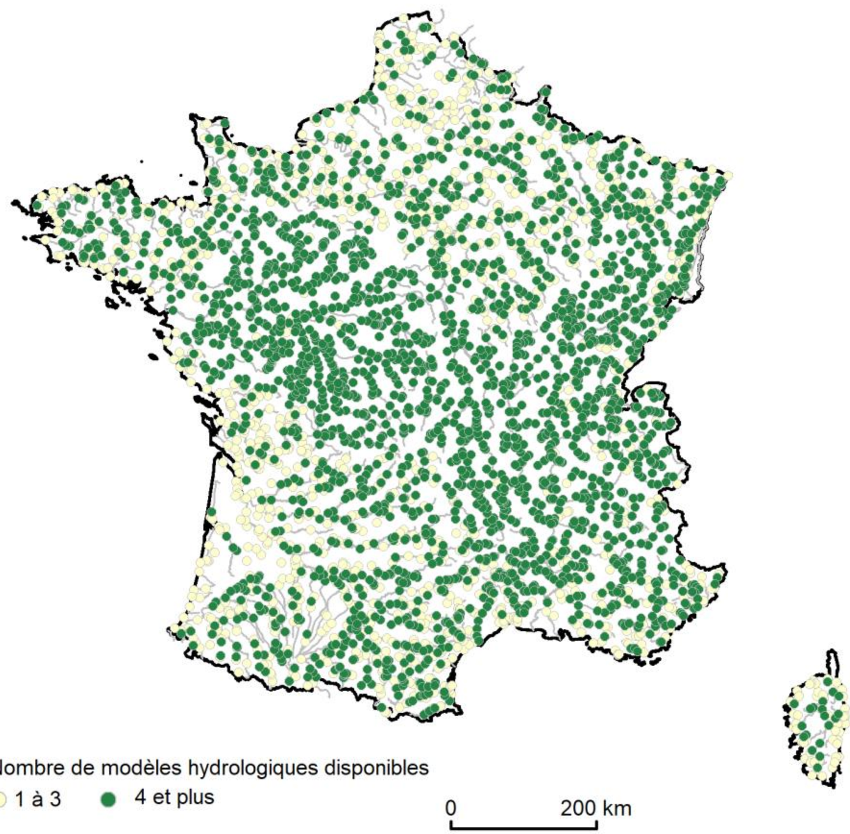


Bias correction methods



Hydrological models





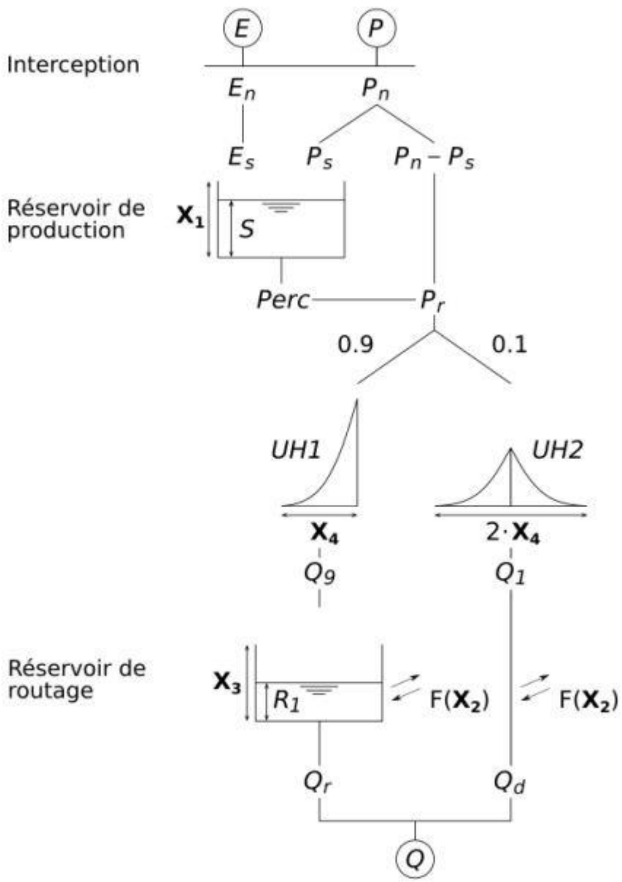
Hydrologic projections

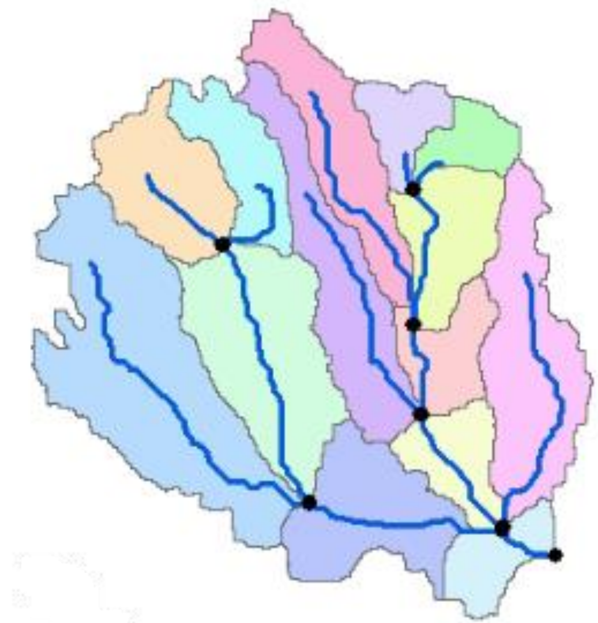
Model	Spatial discretisation	Spatial domain	Nb of Q points	Type	Parameter optimisation	Bias correction method
GR4J	Lumped			Conceptual	Yes, needed	
GRSD	Semi-distributed	France	3712	Conceptual	Yes	ADAMONT CDF-t
SMASH	Semi-distributed	France	3821	Conceptual	Yes	ADAMONT CDF-t
EROS	Lumped	Bretagne	60	Conceptual	Yes	ADAMONT CDF-t
	Semi-distributed	Loire River basin	327		yes	
MORDOR-SD	Lumped with altitude bands	France	611	Conceptual	Yes	ADAMONT CDF-t
MORDOR-TS	Semi-distributed with altitude bands	Upper Loire River basin	535	Conceptual	Yes	ADAMONT CDF-t
J2000	Semi-distributed (HRU)	Loire and Rhône River basins	1291	Process-oriented	No	ADAMONT CDF-t
ORCHIDEE	Distributed (regular grid cells)	France	3587	Physically-based Resolving energy balance	No	ADAMONT
SIM2	Distributed (regular grid cells)	France	649	Physically-based Resolving energy balance	No	ADAMONT
CTRIP	Distributed (regular grid cells)	France	2024	Physically-based Resolving energy balance	No	ADAMONT

Sauquet et al., soumis, HESSD

GRSD

- Simulation of Q only, from P and ETP
- Process: water balance + routing + volume correction
- Empirical to conceptual representation
- Optimization of 4 parameters to fit observed discharge
- Lumped/global: one model/parameter set per BV
- No vegetation, no topography, no anthropogenic pressures

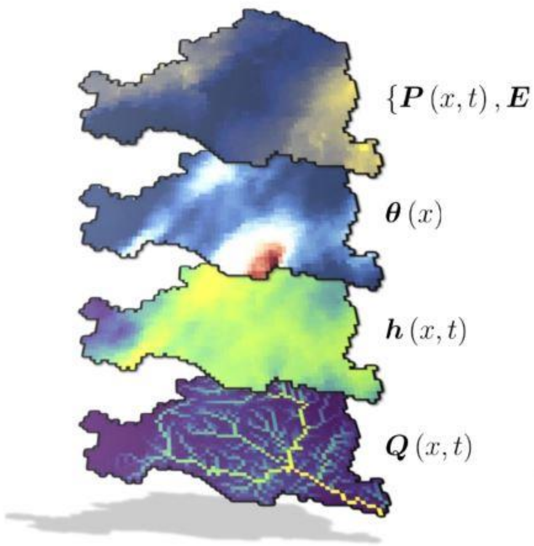


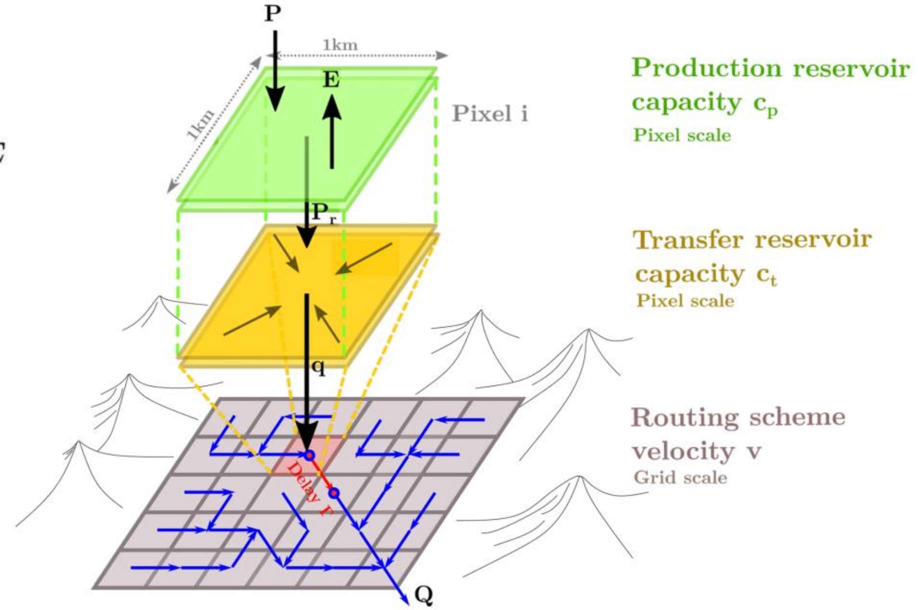


Lobligeois, F., Andréassian, V., Perrin, C., Tabary, P., and Loumagne, C.: When does higher spatial resolution rainfall information improve streamflow simulation? An evaluation using 3620 flood events, Hydrol. Earth Syst. Sci., 18, 575–594, https://doi.org/10.5194/hess-18-575-2014 , 2014

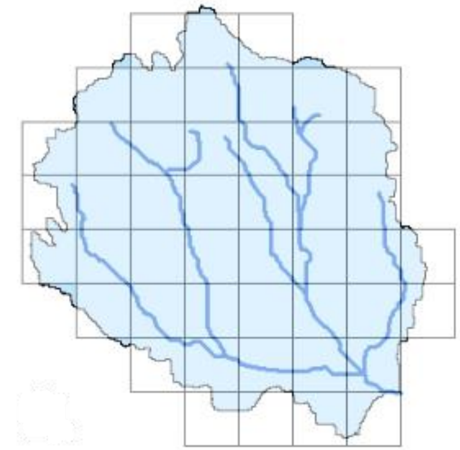
de Lavenne, A., Andréassian, V., Thirel, G., Ramos, M.-H., & Perrin, C. (2019). A regularization approach to improve the sequential calibration of a semidistributed hydrological model. Water Resources Research, 55, 8821–8839. https://doi.org/10.1029/2018WR024266

SMASH





- Same type of conceptual model as GR4J/GRSD
- Fully distributed with a routing scheme able to take into account channel characteristics

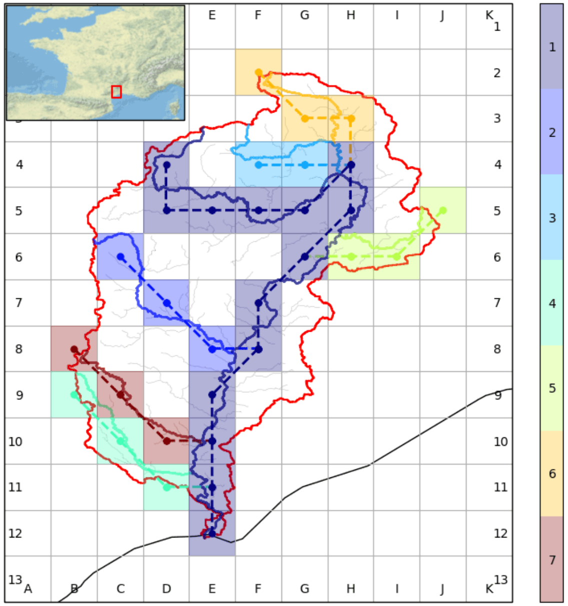


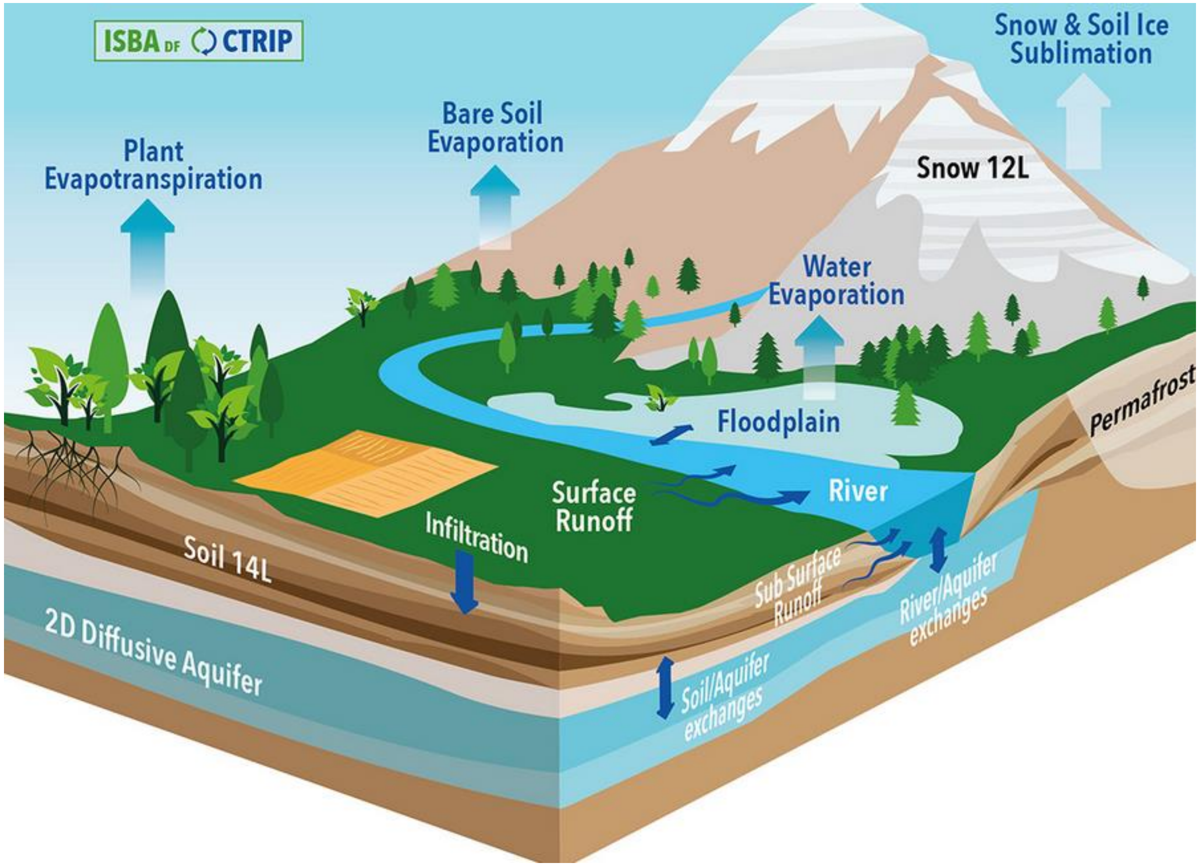
Huynh, N. N. T., Garambois, P.-A., Colleoni, F., & Javelle, P. (2023). Signatures-and-sensitivity-based multi-criteria variational calibration for distributed hydrological modeling applied to Mediterranean floods. Journal of Hydrology, 625, 129992. https://doi.org/10.1016/j.jhydrol.2023.129992

Jay-Allemand, M., Demargne, J., Garambois, P.-A., Javelle, P., Gejadze, I., Colleoni, F., Organde, D., Arnaud, P., and Fouchier, C.: Spatially distributed calibration of a hydrological model with variational optimization constrained by physiographic maps for flash flood forecasting in France, Proc. IAHS, 385, 281–290, https://doi.org/10.5194/piahs-385-281-2024 , 2024.

ISBA-CTRIP

Land-surface scheme of the CNRM global climate model

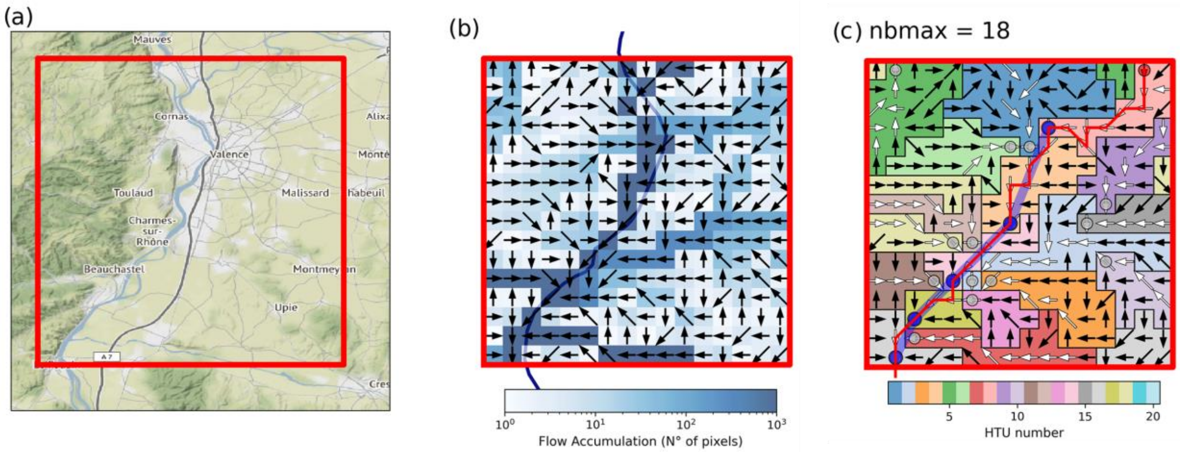


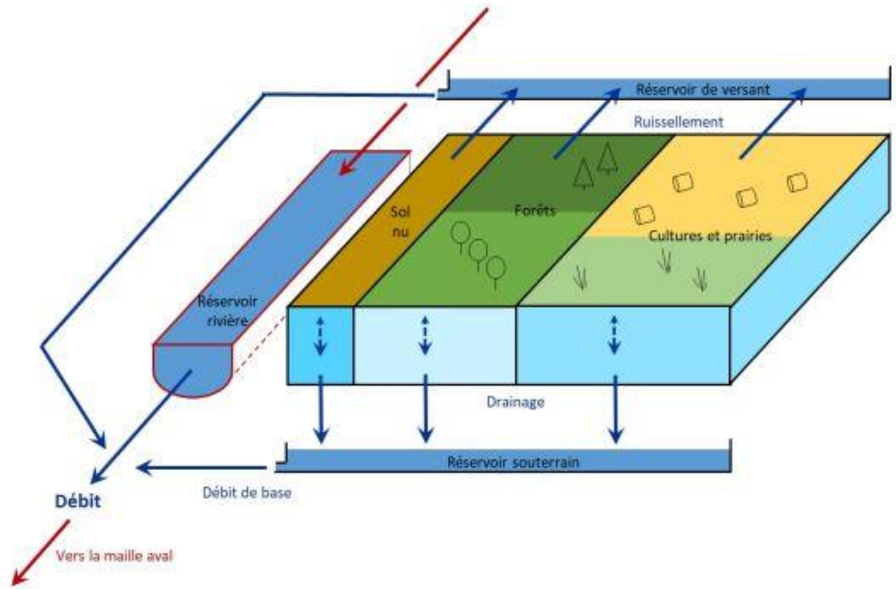


Decharme, B., Delire, C., Minvielle, M., Colin, J., Vergnes, J.-P., Alias, A., et al. (2019). Recent changes in the ISBA-CTRIP land surface system for use in the CNRM-CM6 climate model and in global off-line hydrological applications. *Journal of Advances in Modeling Earth Systems*, 11, 1207–1252. https://doi.org/10.1029/2018MS001545

ORCHIDEE

Land-surface scheme of the IPSL global climate model





Cheruy, F., Ducharne, A., Hourdin, F., Musat, I., Vignon, É., Gastineau, G., et al. (2020). Improved near-surface continental climate in IPSL-CM6A-LR by combined evolutions of atmospheric and land surface physics. *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002005. https://doi.org/10.1029/2019MS002005

Polcher, J., Schrapffer, A., Dupont, E., Rinchiuso, L., Zhou, X., Boucher, O., Mouche, E., Ottlé, C., and Servonnat, J.: Hydrological modelling on atmospheric grids: using graphs of sub-grid elements to transport energy and water, Geosci. Model Dev., 16, 2583–2606, https://doi.org/10.5194/gmd-16-2583-2023 , 2023.

METHODOLOGY

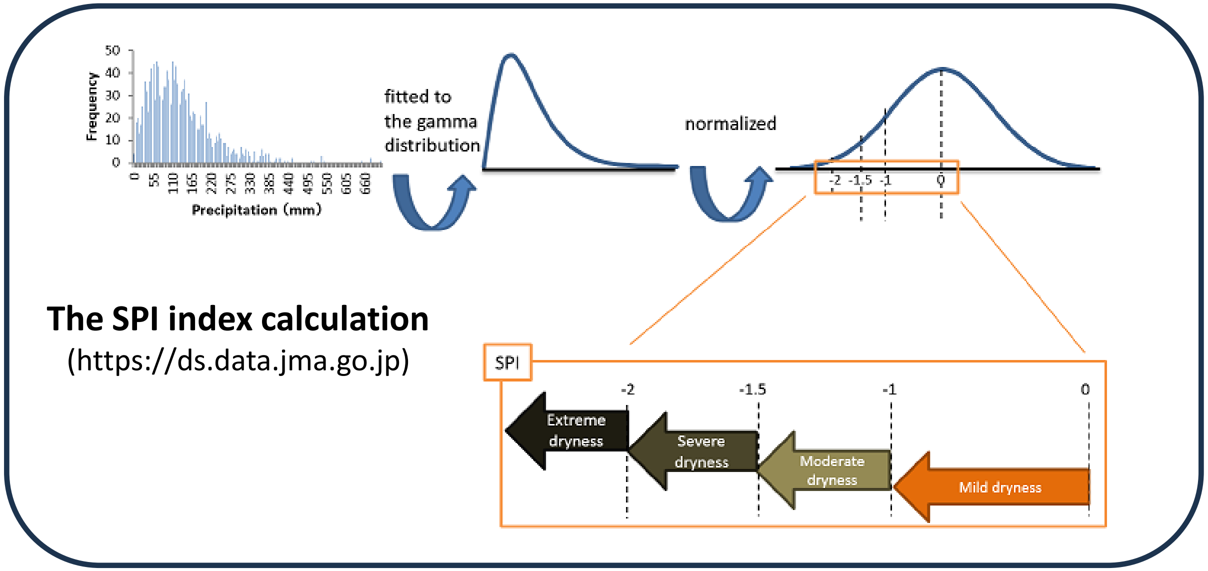
- **2 scenarios (RCP45 and RCP8.5), 2 future periods (2041-2070, 2071-2100, compared to 1975-2005) for an ensemble of 17 bias-corrected Euro-CORDEX simulations**
- **4 Hydrological models : GRSD, SMASH, ISBA-CTRIP, ORCHIDEE**
- **Return level of extreme events :**
  - Annual maximum rainfall with a 20-year return period (PJXA20)
  - Annual maximum river discharge with a 20-year return period (QJXA20)
  - Annual minimum monthly river discharge with a 5-year return period (QMNA5)

1. Computation with a Generalized Extreme Value distribution fitted to the data (L-Moments)
2. Estimation of the significance of the changes in quantiles with a parametric bootstrap
3. Estimation of the agreement between models using a Multi-Model Index of Agreement for each basin *u*:

$$\mathrm{MIA}_u = \frac{1}{n}\left(\sum\nolimits_{n=1}^{n} i_m\right)$$

For a given model m, $i_m = 1$ for significant positive trends, $i_m = -1$ for significant negative trends, $i_m = 0$ in case of no significant trends, and n is the number of climat simulations. The index is equal to 1 (− 1) if all model projects an increasing (decreasing) trend.

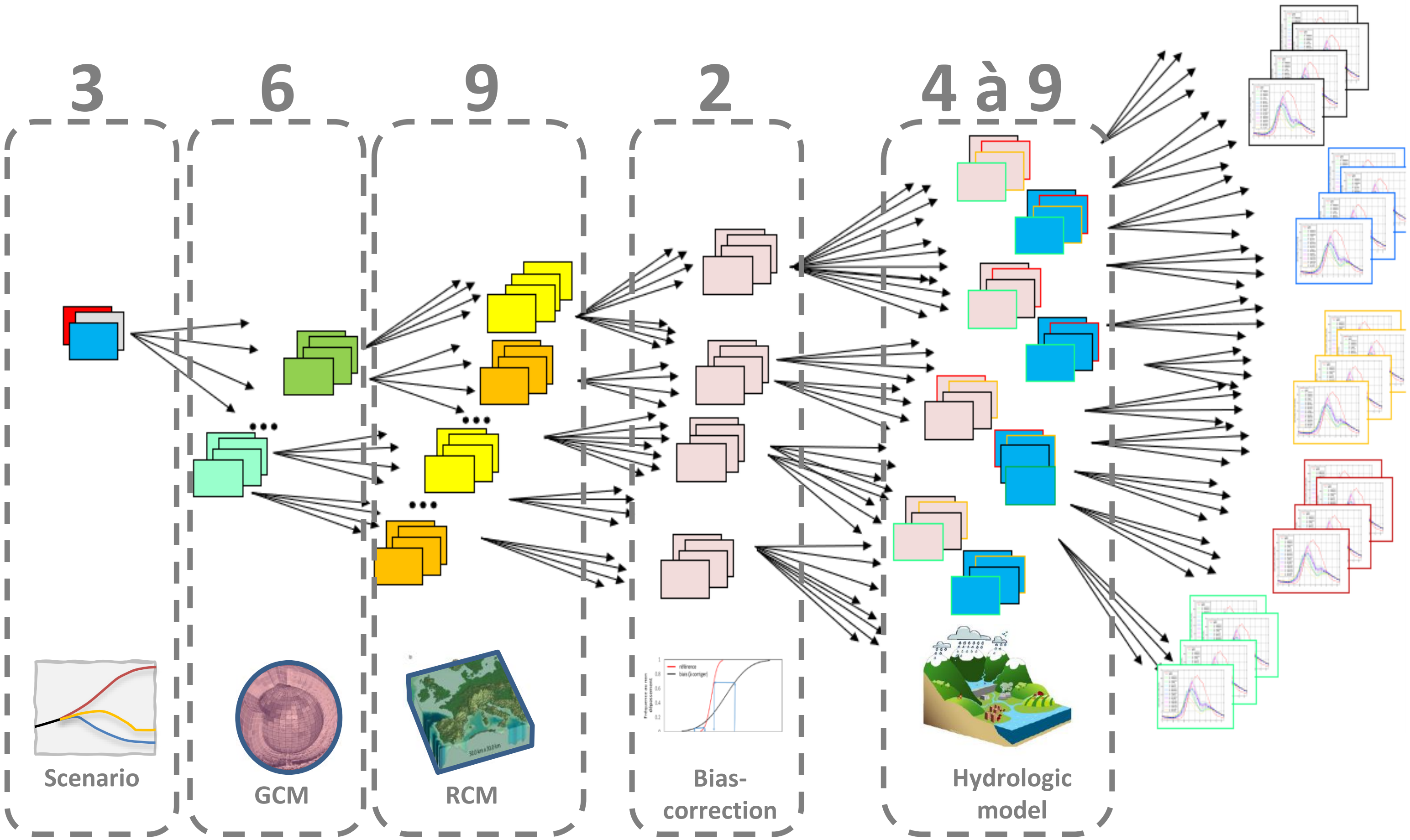
Methodology for Droughts



The SPI index calculation
(https://ds.data.jma.go.jp)

- **Computation of the Standardized Precipitation index (SPI) for meteorological droughts and the Standardized Soil Moisture Index (SSWI) for agricultural droughts (with soil moisture from the ISBA land surface model)**
- **Comparison of the frequency of 10-year return level droughts (-1.28) between historical and future time periods, for winter (DJF) and summer (JJA).**
- **Computation of the fraction of France each year from 1976 to 2100 experiencing severe droughts**

UNCERTAINTY CASCADE



THREE UNCERTAINTY SOURCES

- **Emission scenarios**

> The different RCP/SSP scenarios, different choices of future

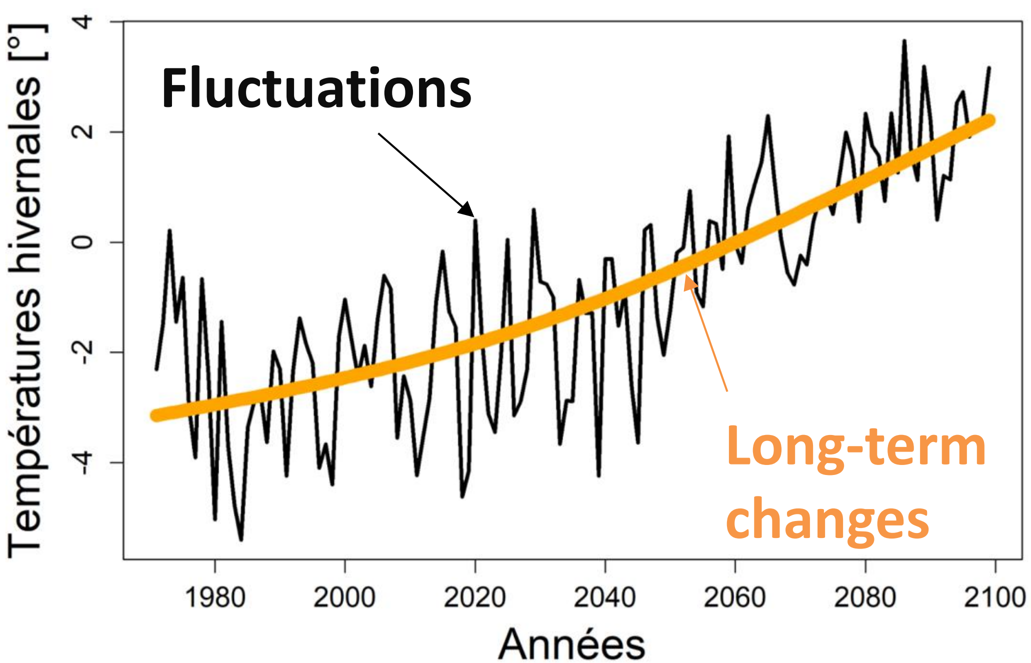
- **Modelling uncertainties**

> Scientific and technical uncertainties, imperfect models

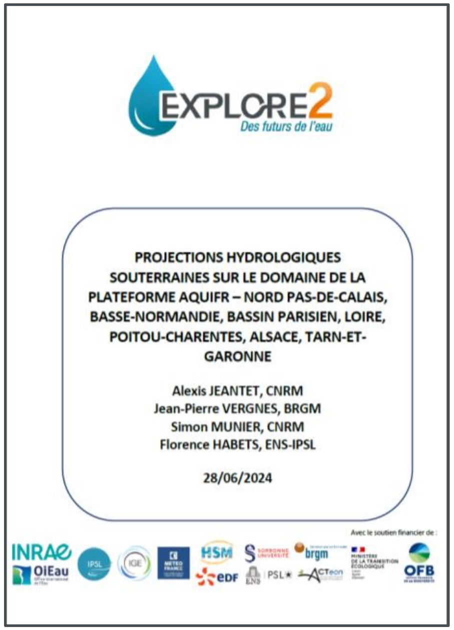
- **Internal climate variability**

> Unpredictable, adds random noise to profound changes

> **It must be distinguished from long-term trends resulting from climate change**



All the outputs of the Explore2 projet are 100% open data

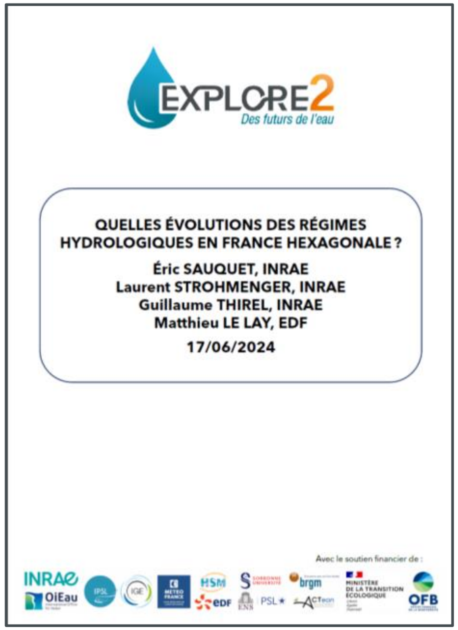

EXPLORE2
Des futurs de l'eau

PROJECTIONS HYDROLOGIQUES SOUTERRAINES SUR LE DOMAINE DE LA PLATEFORME AQUIFR – NORD PAS-DE-CALAIS, BASSE-NORMANDIE, BASSIN PARISIEN, LOIRE, POITOU-CHARENTES, ALSACE, TARN-ET-GARONNE

Alexis JEANTET, CNRM
Jean-Pierre VERGNES, BRGM
Simon MUNIER, CNRM
Florence HABETS, ENS-IPSL

28/06/2024

Avec le soutien financier de :


EXPLORE2
Des futurs de l'eau

QUELLES ÉVOLUTIONS DES RÉGIMES HYDROLOGIQUES EN FRANCE HEXAGONALE ?

Éric SAUQUET, INRAE
Laurent STROHMENGER, INRAE
Guillaume THIREL, INRAE
Matthieu LE LAY, EDF

17/06/2024

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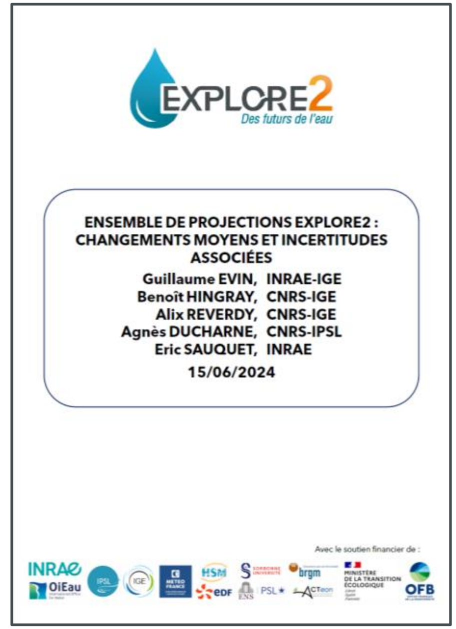
EXPLORE2
Des futurs de l'eau

ENSEMBLE DE PROJECTIONS EXPLORE2 : CHANGEMENTS MOYENS ET INCERTITUDES ASSOCIÉES

Guillaume EVIN, INRAE-IGE
Benoît HINGRAY, CNRS-IGE
Alix REVERDY, CNRS-IGE
Agnès DUCHARNE, CNRS-IPSL
Eric SAUQUET, INRAE

15/06/2024

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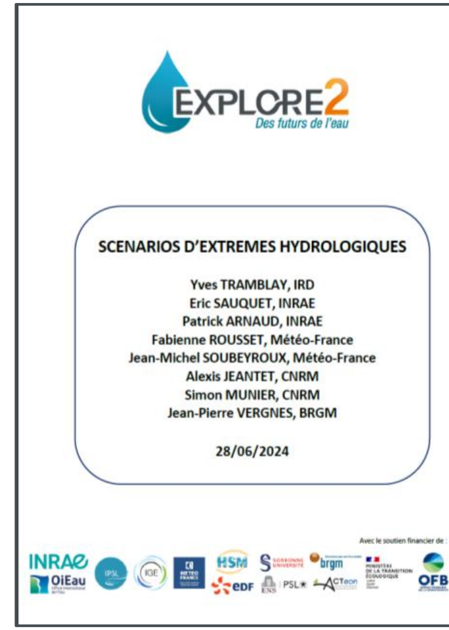

EXPLORE2
Des futurs de l'eau

SCENARIOS D'EXTREMES HYDROLOGIQUES

Yves TRAMBLAY, IRD
Eric SAUQUET, INRAE
Patrick ARNAUD, INRAE
Fabienne ROUSSET, Météo-France
Jean-Michel SOUBEYROUX, Météo-France
Alexis JEANTET, CNRM
Simon MUNIER, CNRM
Jean-Pierre VERGNES, BRGM

28/06/2024

Avec le soutien financier de :

- **A central repository including the topical reports:**

https://entrepot.recherche.data.gouv.fr/dataverse/explore2

- **Data access:**

https://www.drias-climat.fr/ et https://www.drias-eau.fr/

- **User-friendly websites to display results:**

https://makaho.sk8.inrae.fr/ (past trends)

https://meandre.explore2.inrae.fr/ (future scenarios)

- **MOOC : https://e-learning.oieau.fr/enrol/index.php?id=3799**

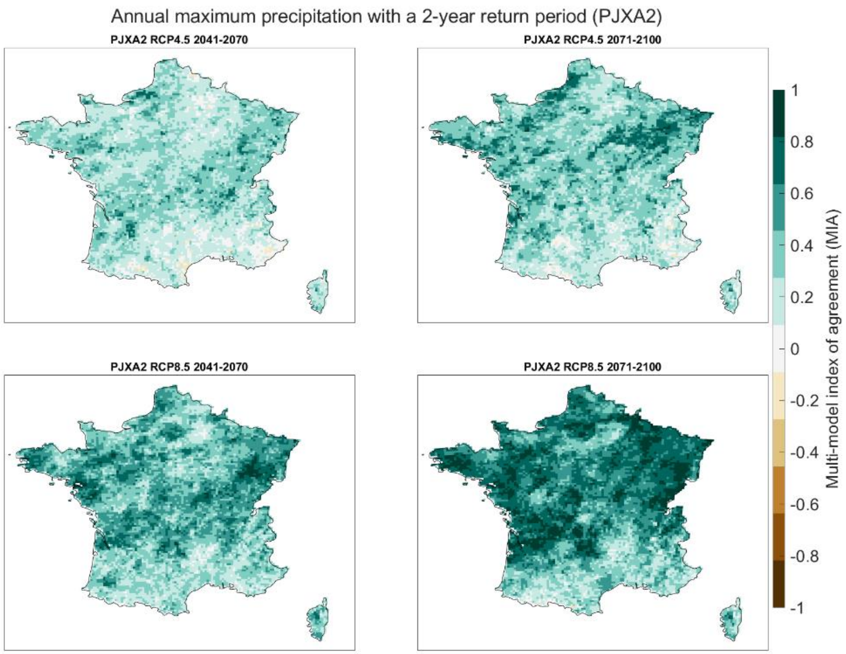
3- Climate change impacts on extreme rainfall and floods

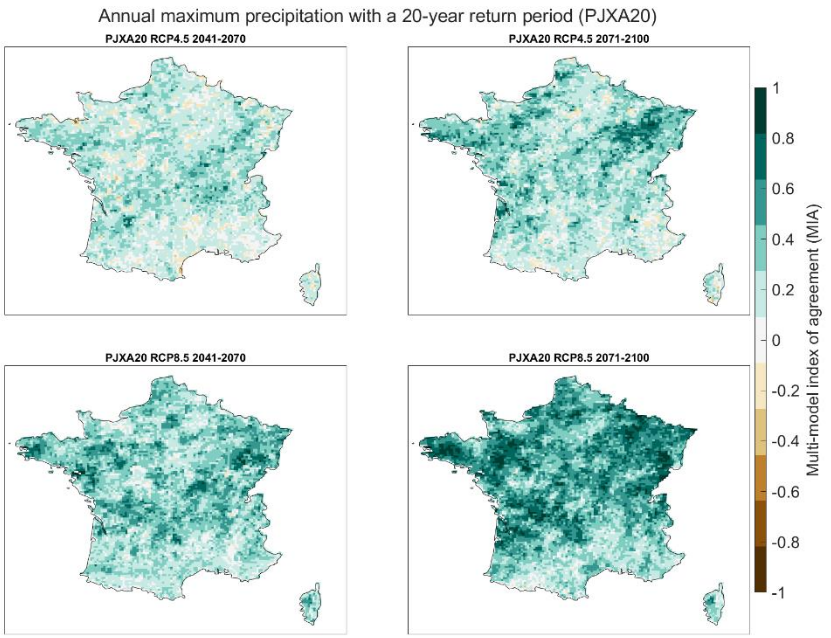
Derna, Libye, 11 sep. 2023

Valencia, Espagne, 29 oct. 2024

In France, 10 millions of building are exposed to flood risk (18 millions people)

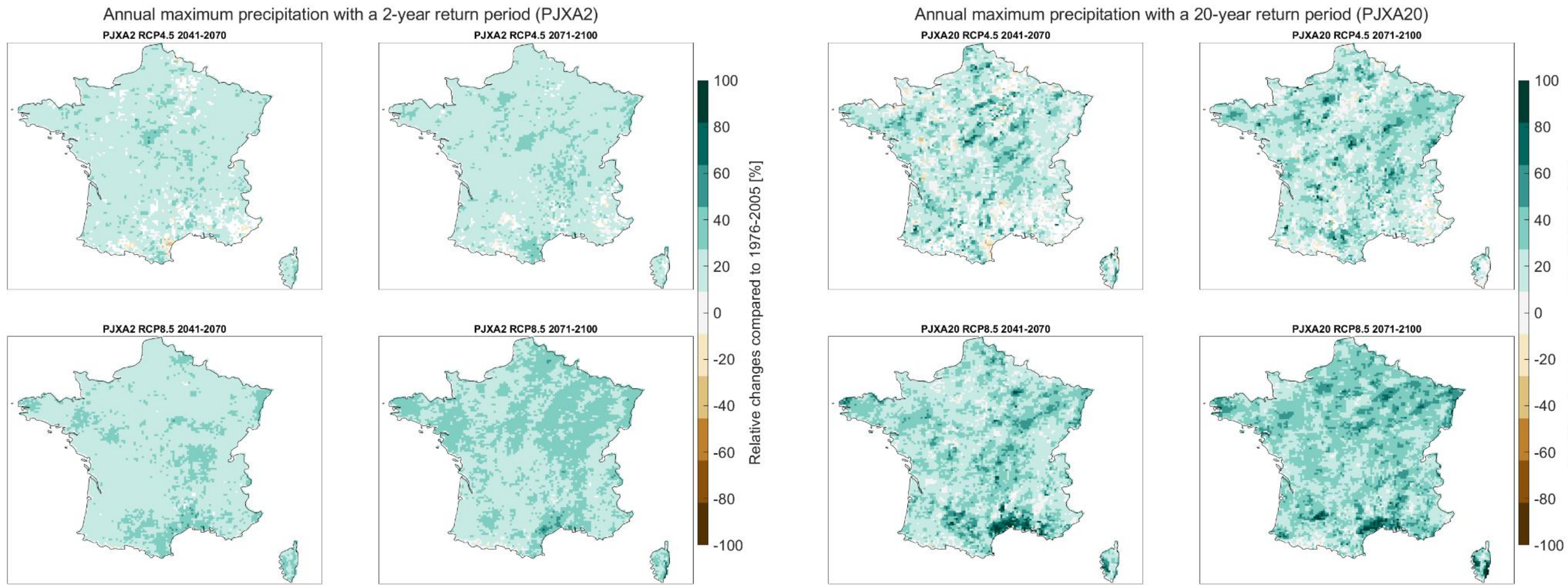
Projections of extreme rainfall
Agreement between the models





Strong convergence towards an increase, more important at the end of the centuty and 2-year return levels

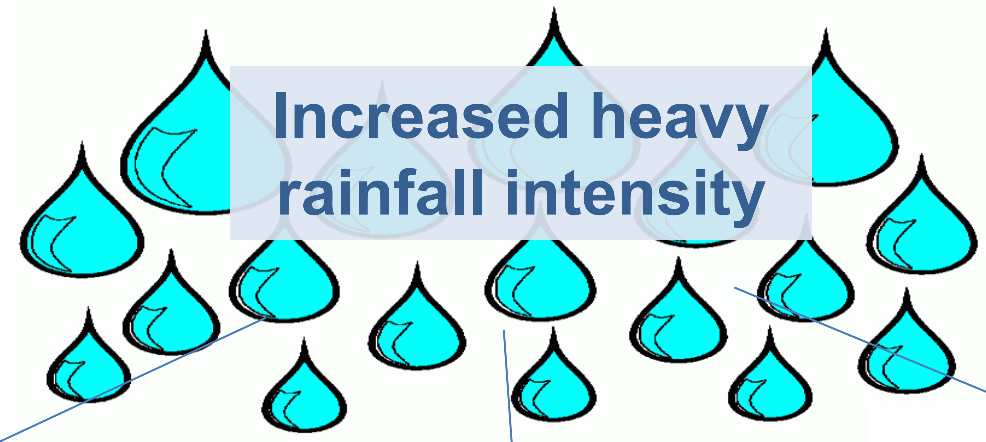
Projections of extreme rainfall
Changes in intensity



+20 / +30% on average in France

Strong signal in the Mediterranean for 20-year return levels

What is the impact on floods?



Increased heavy rainfall intensity

Impervious areas, urban

« Natural » soils

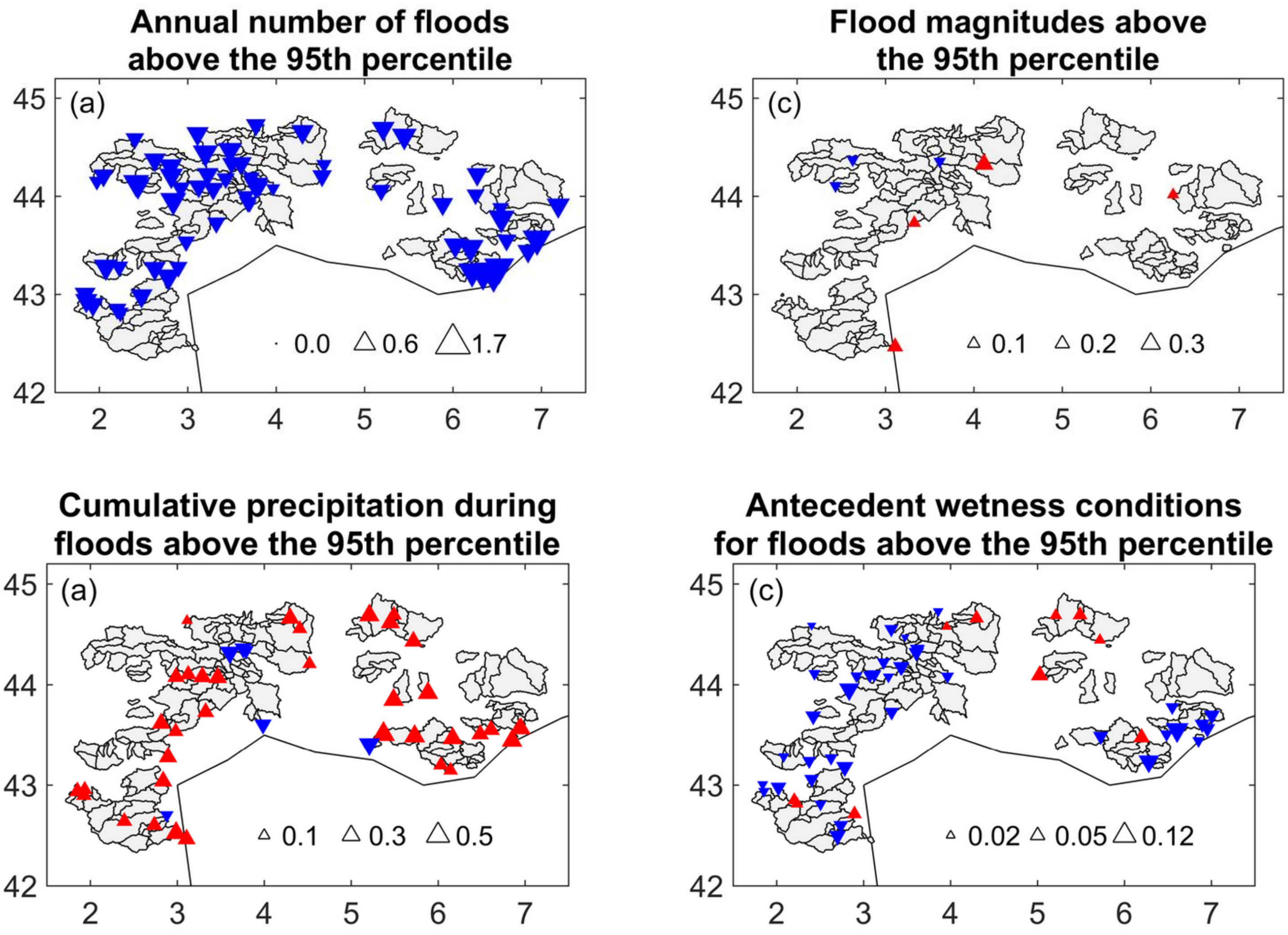
Cultivated soils

Increased surface runoff

Different hydrological responses

[Without flood mitigation structures!]

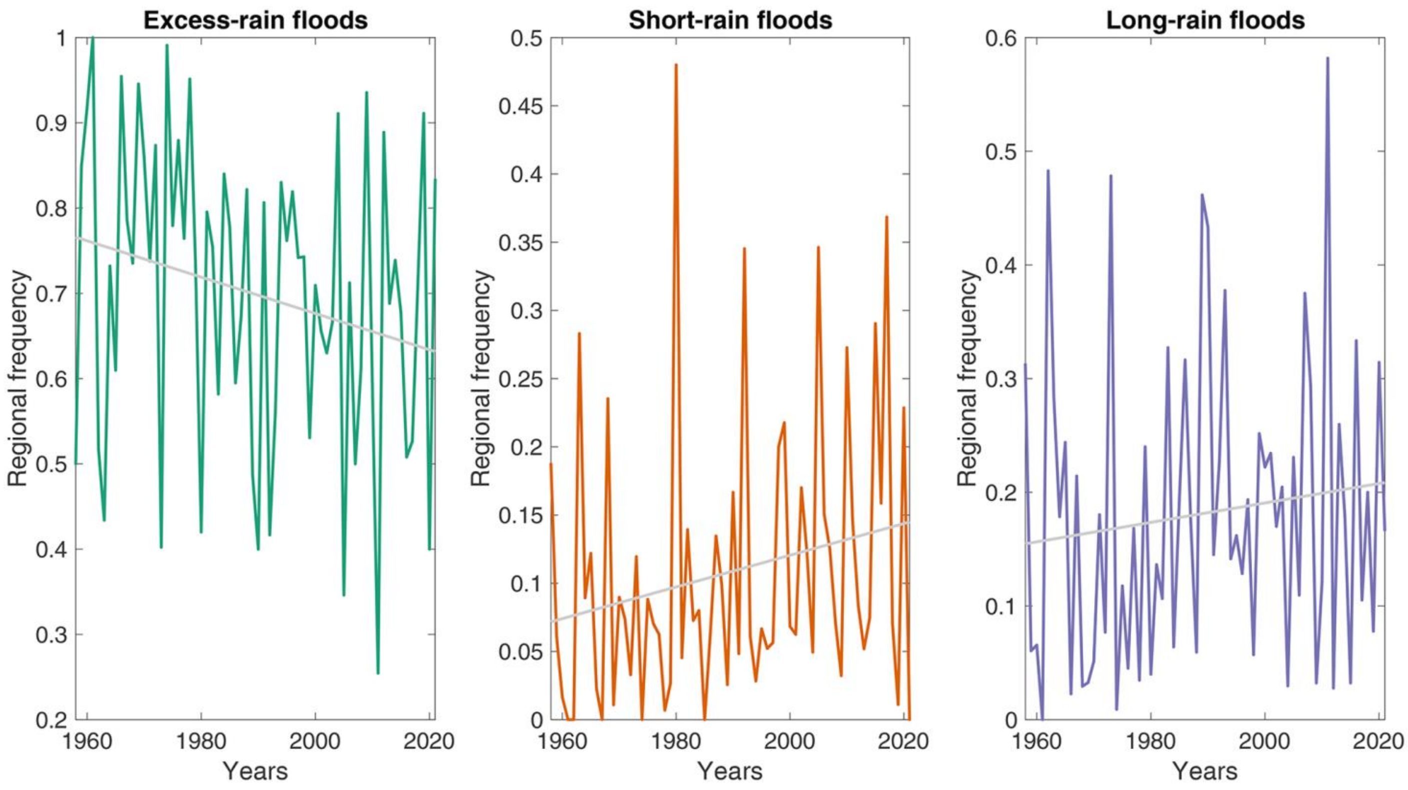
Historical trends in floods in Mediterranean basins



1. **Rainfall extremes are intensifying**
2. **Soil moisture before floods are decreasing**
3. **Flood frequency for frequent floods is decreasing, no clear signal for large floods**

Tramblay Y., Mimeau L., Neppel L., Vinet F., Sauquet E., 2019. Detection and attribution of flood trends in Mediterranean basins. Hydrology and Earth System Sciences, 23, 4419–4431, https://doi.org/10.5194/hess-23-4419-2019

Changes in floods characteristics in Mediterranean basins



Tramblay Y., Arnaud P., Artigue G., Lang M., Paquet E., Neppel L., Sauquet E., 2023. Changes in Mediterranean flood processes and seasonality, Hydrology and Earth System Sciences, 27, 2973–2987, https://doi.org/10.5194/hess-27-2973-2023

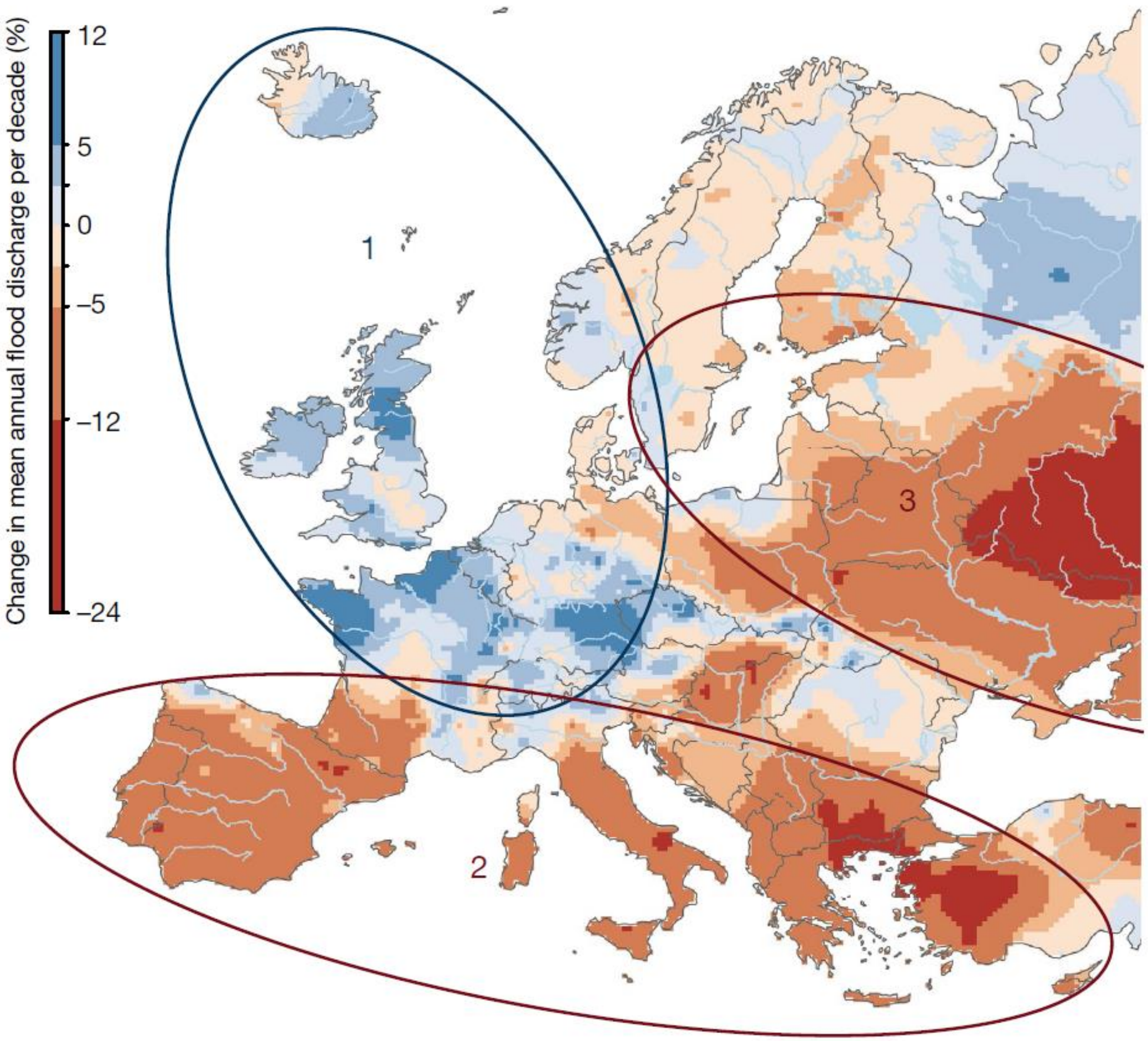
No uniform historical changes in floods

Historical trends in the Mediterranean show a decline in flooding, despite an increase in intense rainfall.

Factors influencing flood trends :

- Changes in soil moisture
- Changes in the rainfall mechanisms that cause flooding
- Changes in land use (urbanization..)
- Changes in agricultural practices
- Effects of compensatory measures (soil sealing, dams..)

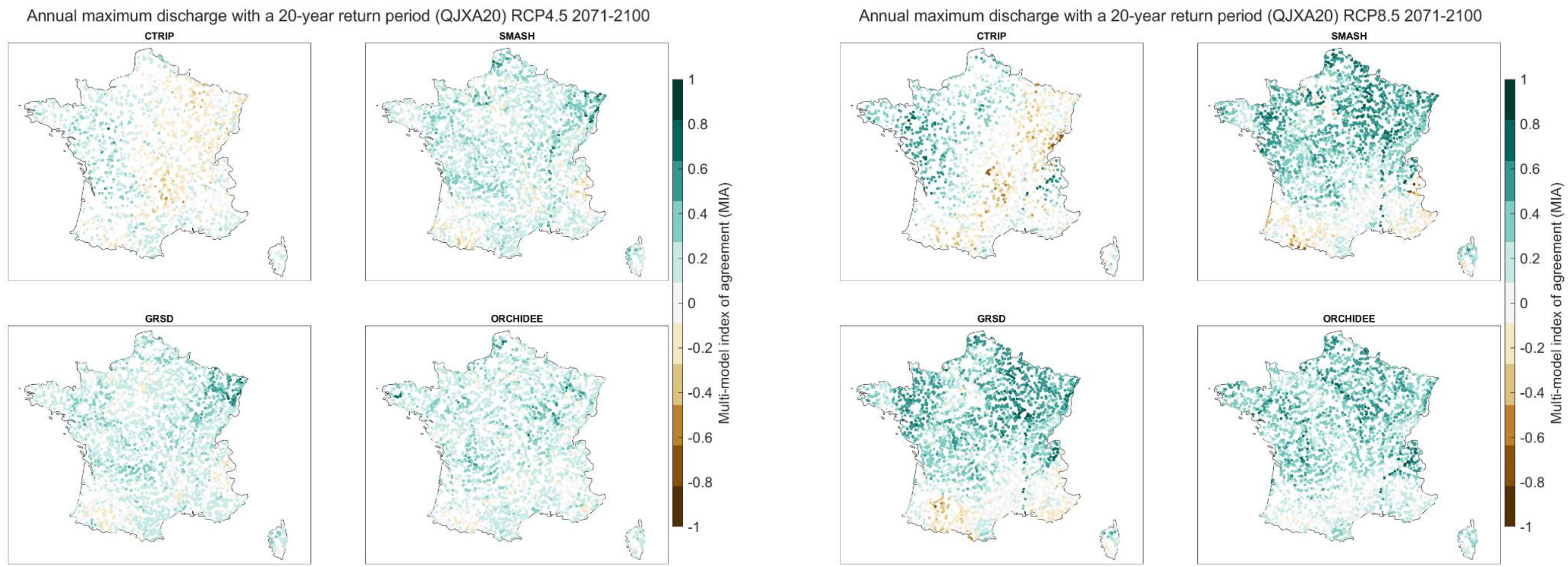
(subtitle: it's not easy!)



Observed regional trends of river flood discharges in Europe (1960–2010)

Blöschl et al 2019

Projections of floods
Agreement between the models

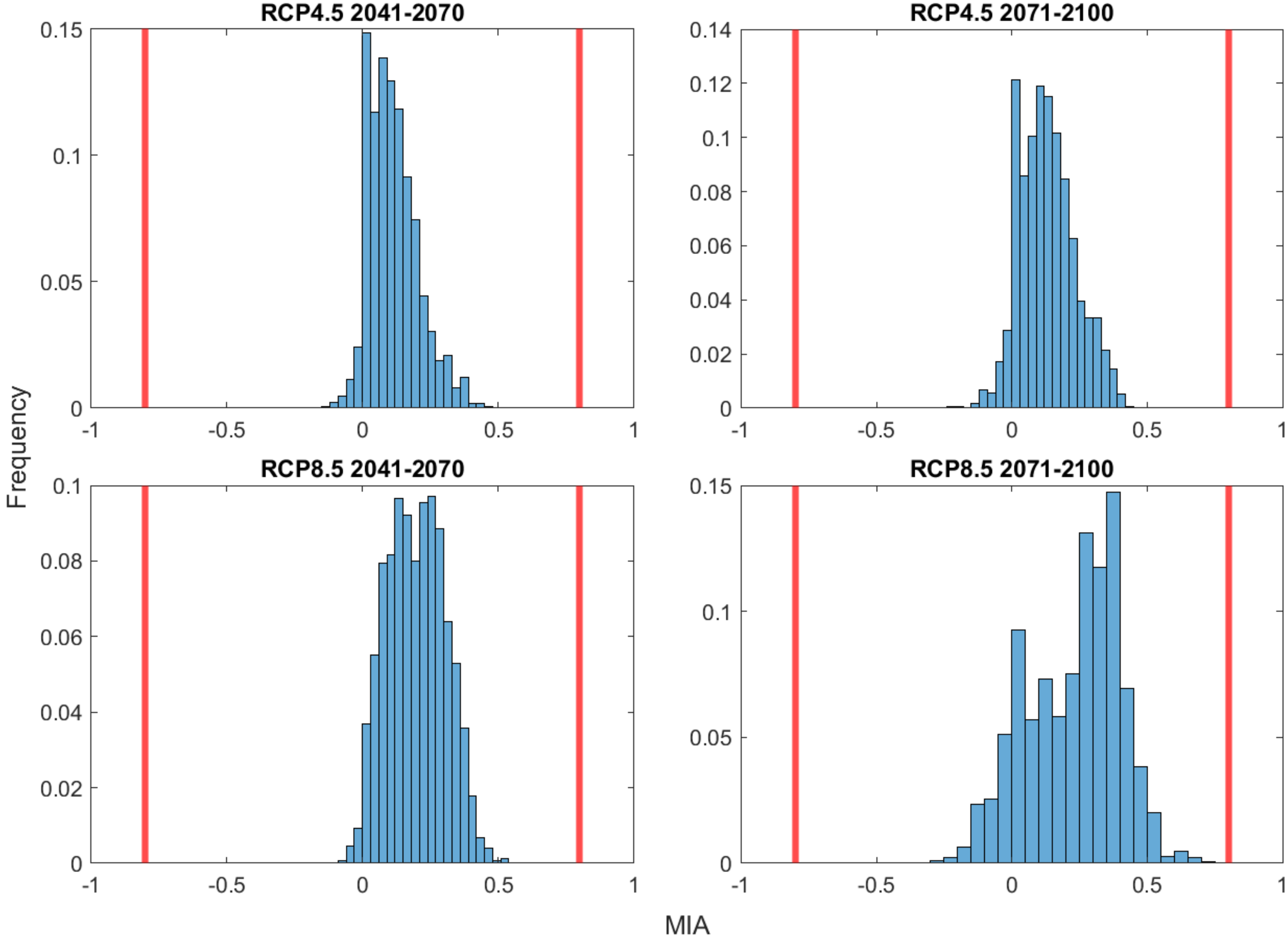


Very small convergence between the models = signal not robust

Different signals with different hydrological models

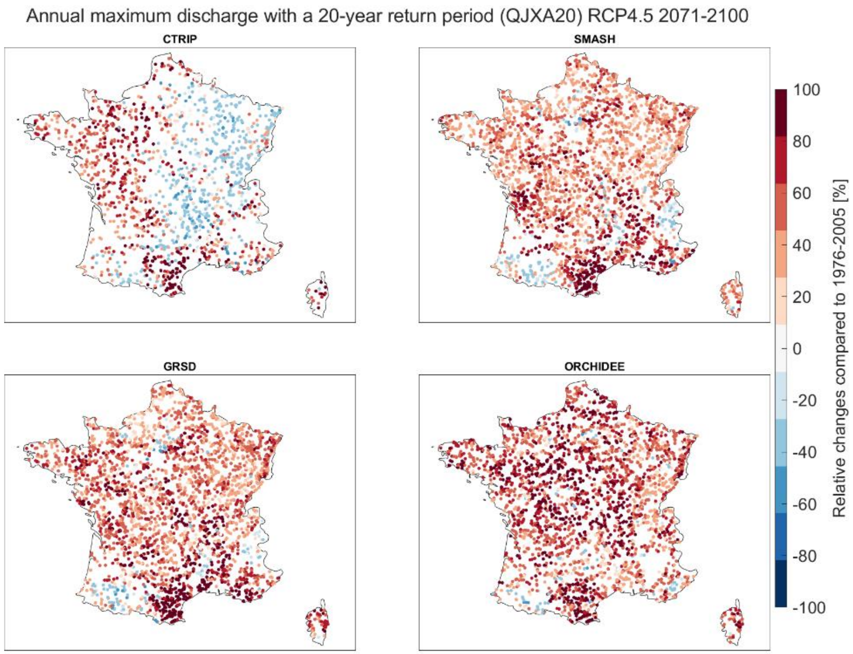
Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques

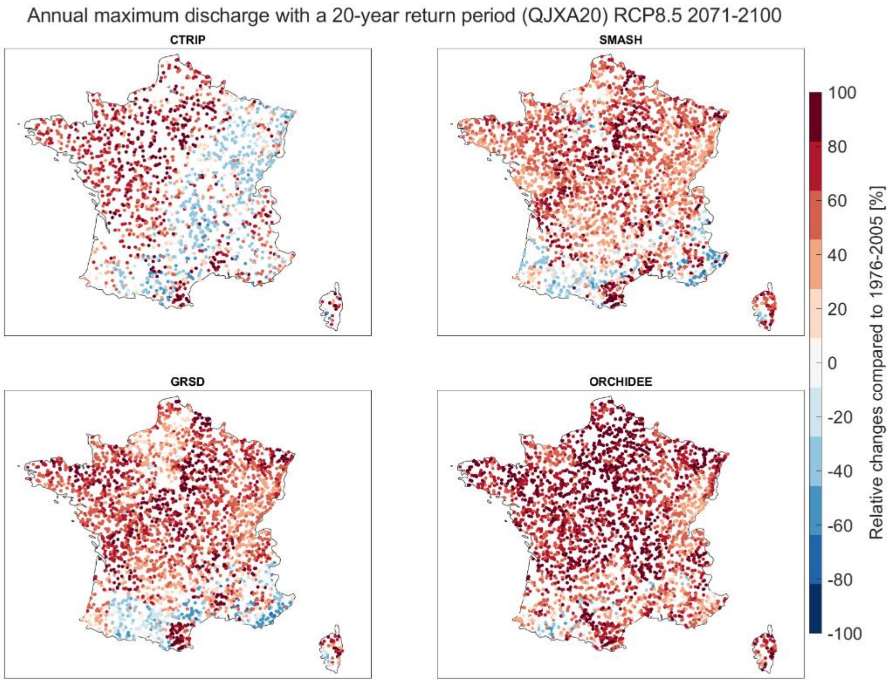
Multi-model index of agreement for floods (QJXA20)



Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques

Projections of floods
Relative changes





Misleading !

Averaging different simulations gives more weigth to outliers

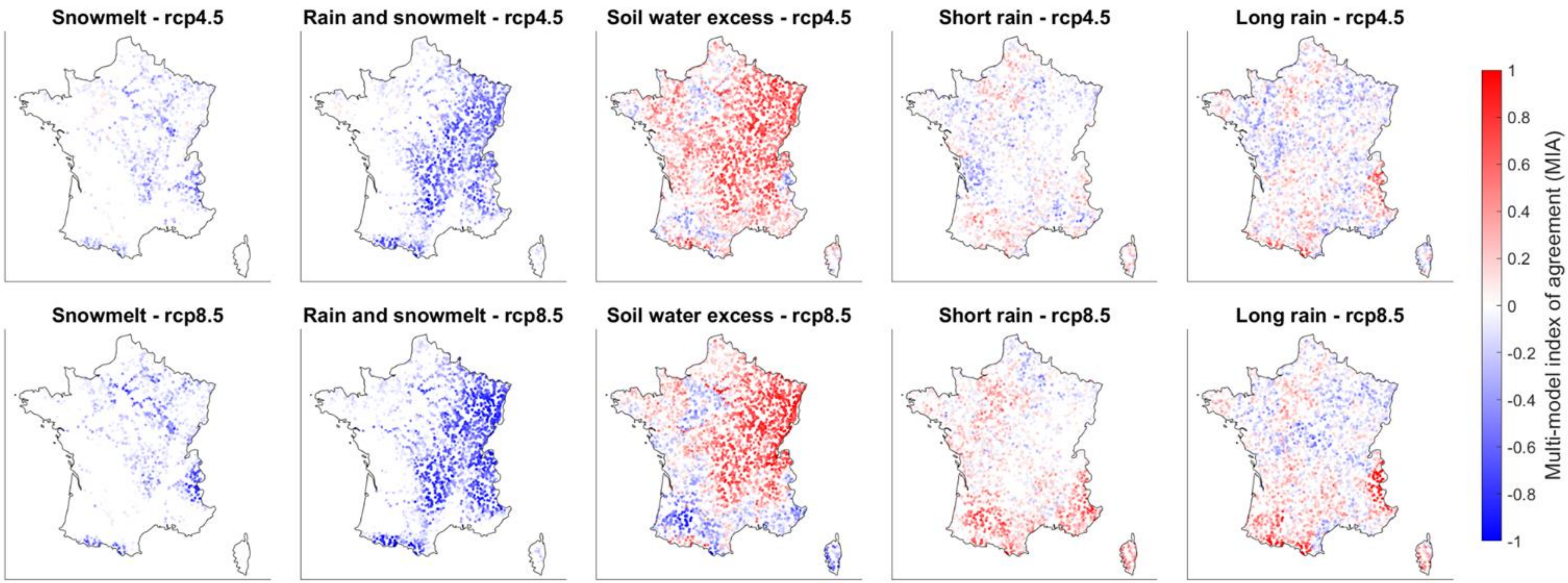
Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques

Future changes in flood types

Soil Water Excess *(ie. saturation excess floods)*

Short rain (*ie. short intense rainfall event on dry soils*)

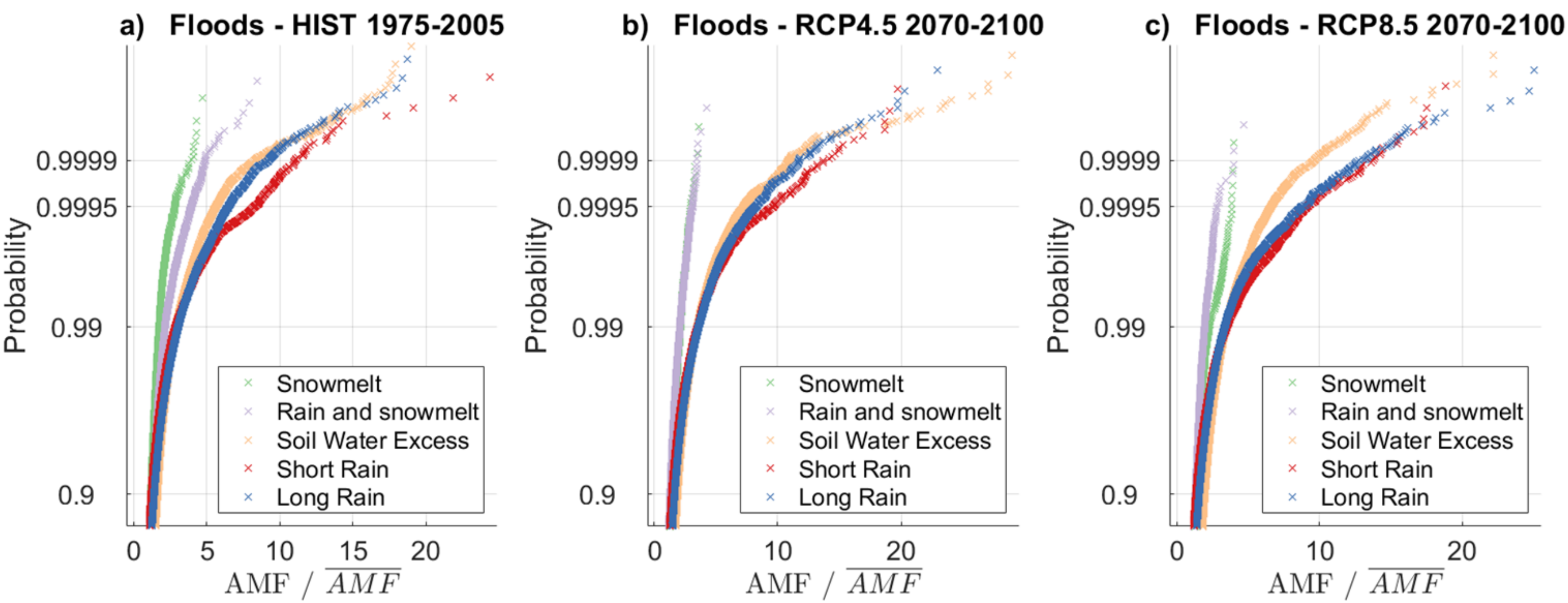
Long rain (*ie. long rainfall event on dry soils*)



- Sharp decline of snowmelt-related floods
- Increasing percentage of Soil Water Excess floods in the East/Center
- Increase of rainfall-induced floods on dry soils, mostly in the southern and mountainous regions

Tramblay, Y., Thirel, G., Strohmenger, L., Evin, G., Corre, L., Heraut, L., and Sauquet, E.: Evolution of flood generating processes under climate change in France, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-1635 , 2025.

Changes in the severity of floods depending on the generating process



Severity of floods: Short rain > Long rain > Soil Water Excess > Rain and Snowmelt > Snowmelt

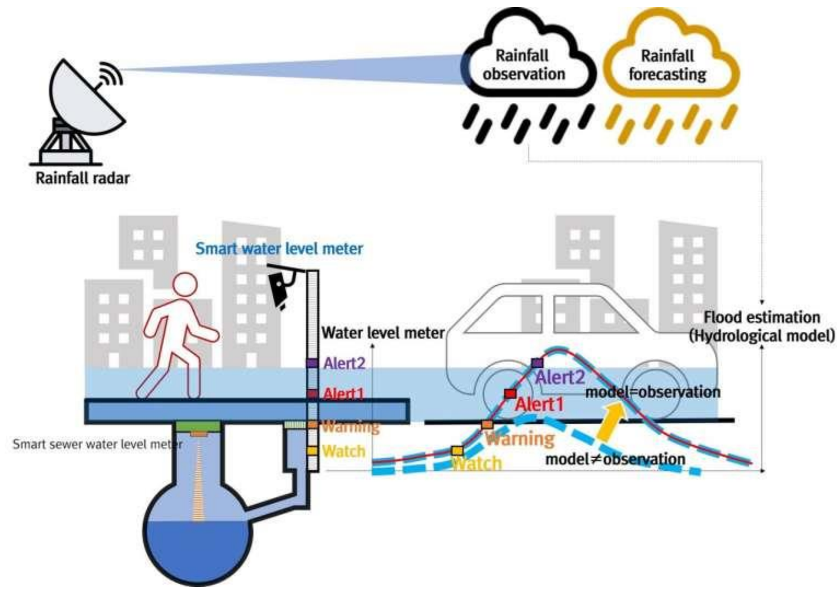
Not much change under RCP4.5, but with RCP8.5 increasing severity of the most extreme floods on dry soils (Short rain, Long rain)

Tramblay, Y., Thirel, G., Strohmenger, L., Evin, G., Corre, L., Heraut, L., and Sauquet, E.: Evolution of flood generating processes under climate change in France, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-1635 , 2025.

Reducing the impacts of floods

Dams

Real time monitoring and alert systems



Improve soil infiltration

Local protection measures

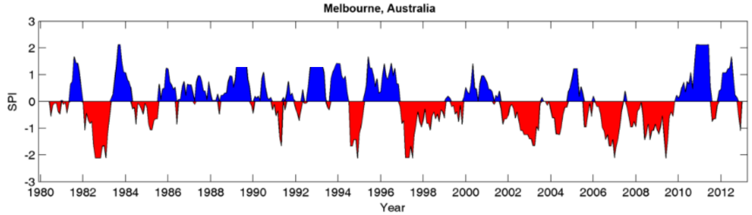
The cheapest solution: don't build in flood-prone areas

4- Climate change impacts on droughts




Droughts, some definitions

1. Drought = water deficit over a more or less long period
2. Drought ≠ aridity



Different types of drought:

1. Meteorological: precipitation, zero or below average
2. Agronomic: soil moisture deficit (water content available to plants)
3. Hydrological: low water table and aquifer levels (absence or low base flow)

Mechanisms of drought increase

Decrease in precipitation

+

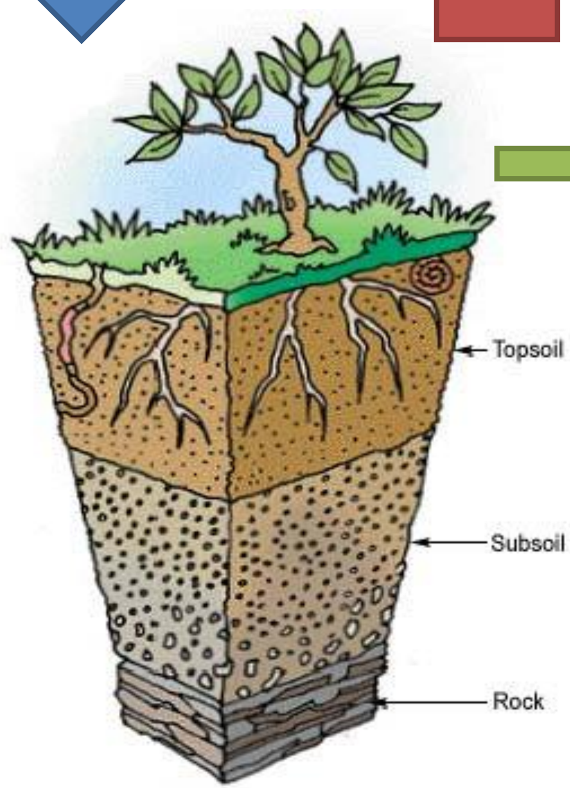
Increase in number of dry days

Rising temperatures

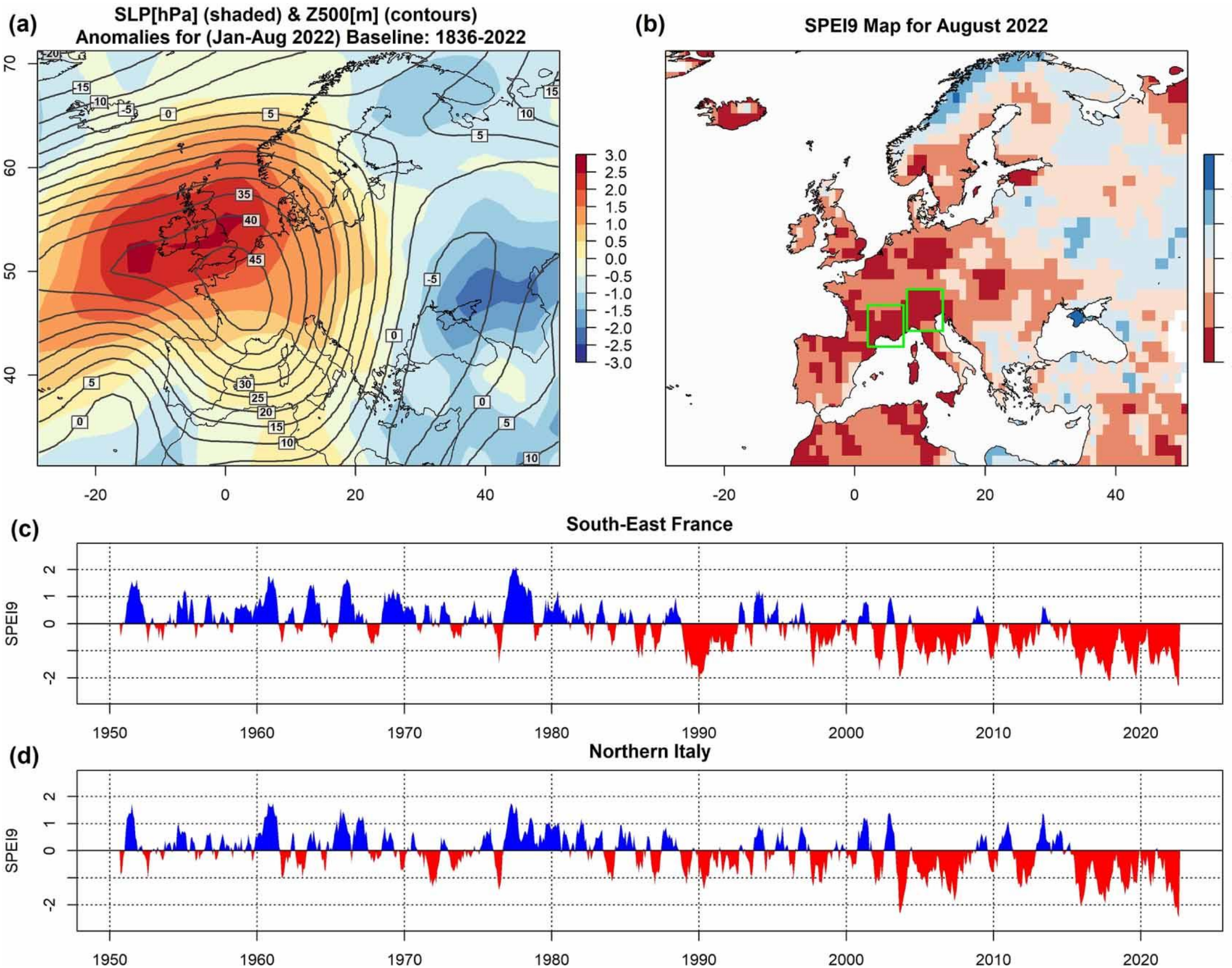
=>

Increased evapotranspiration

Plant adaptation, up to a certain limit?



Drought of 2022

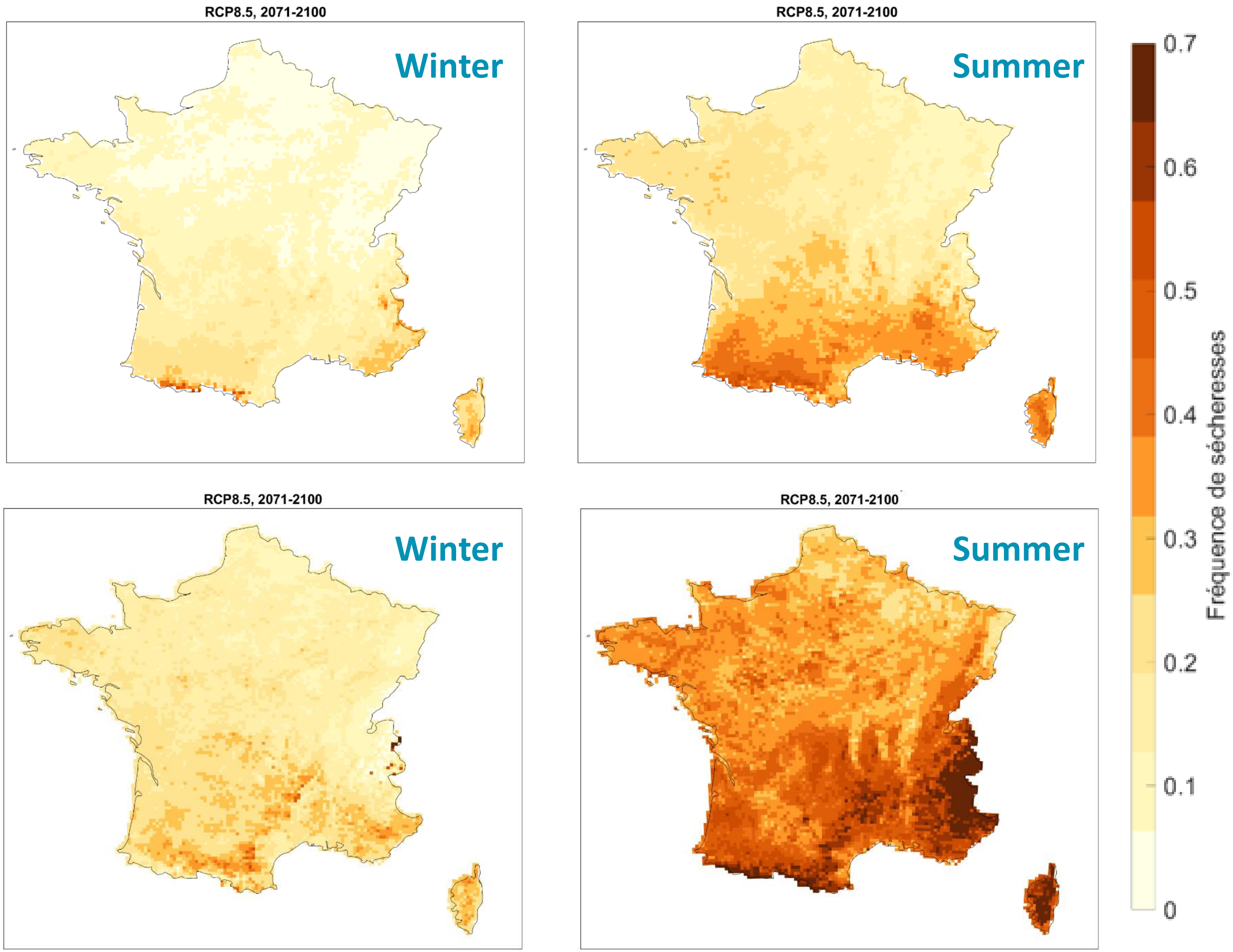


Faranda et al., 2023

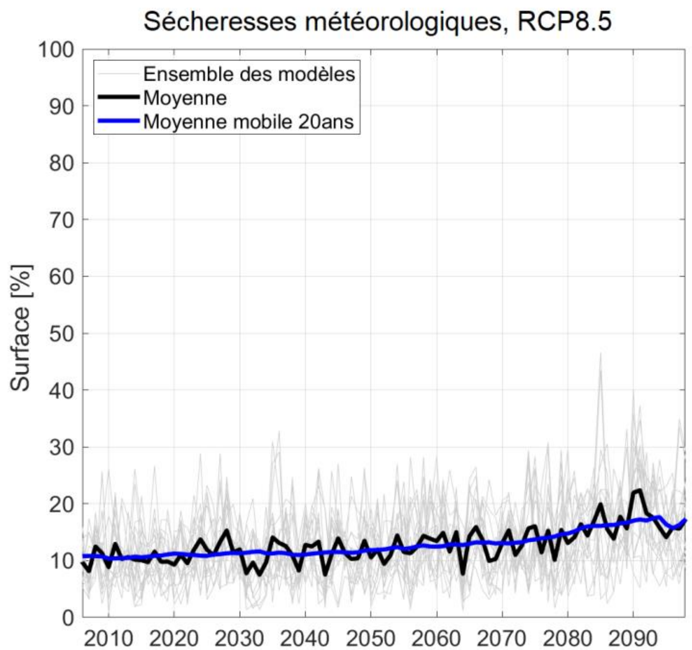
Projections of meteo and soil moisture droughts

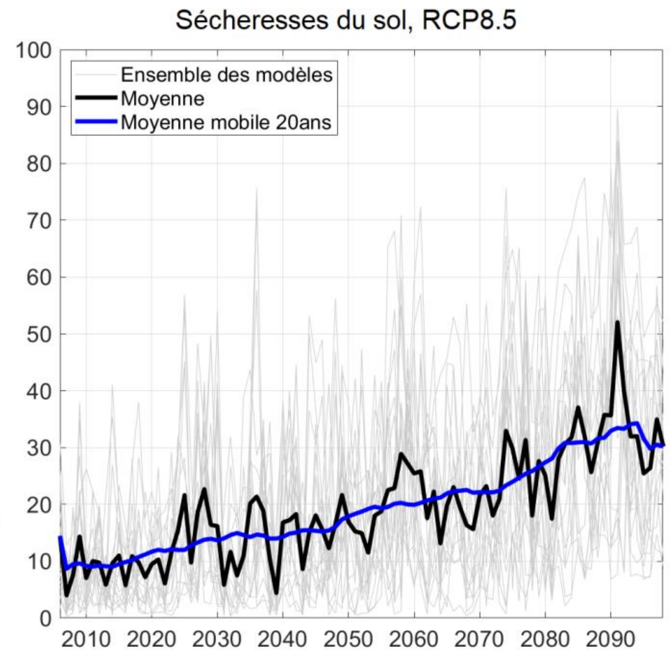
Meteo

Soil

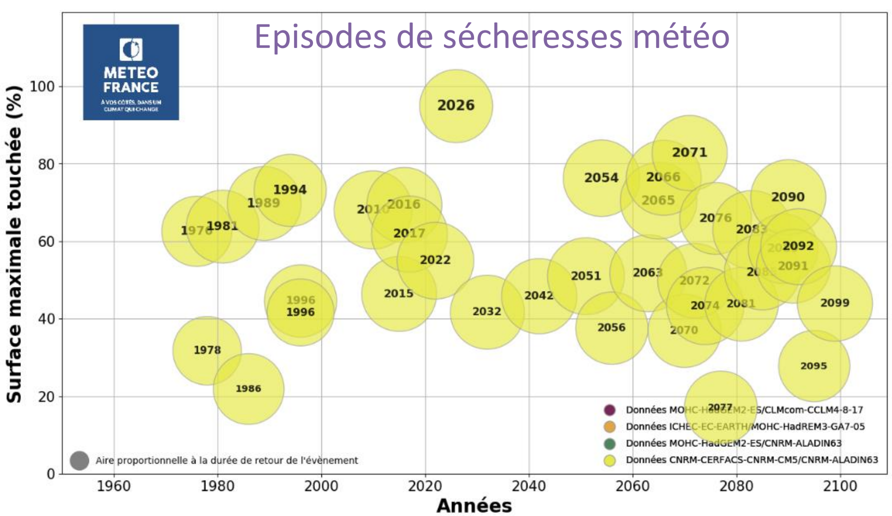


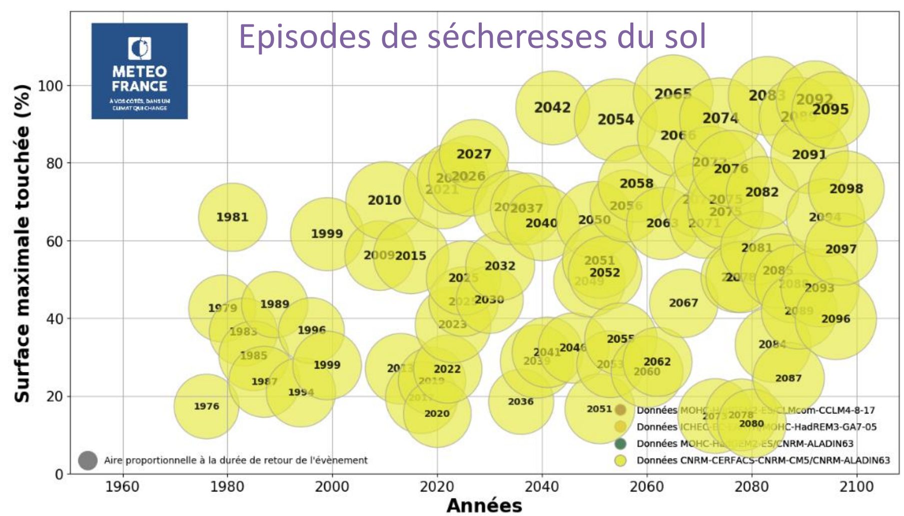
Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques



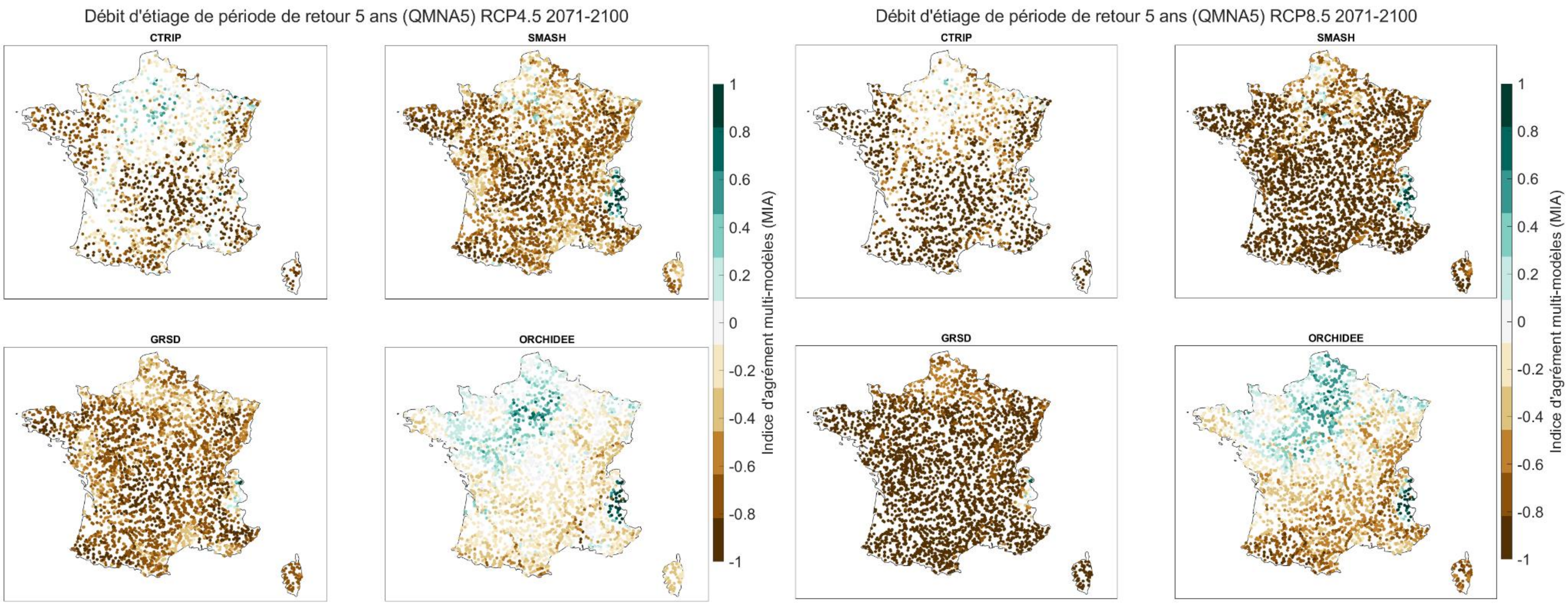


Evolution of the number of episodes (yellow storyline = small climate changes)





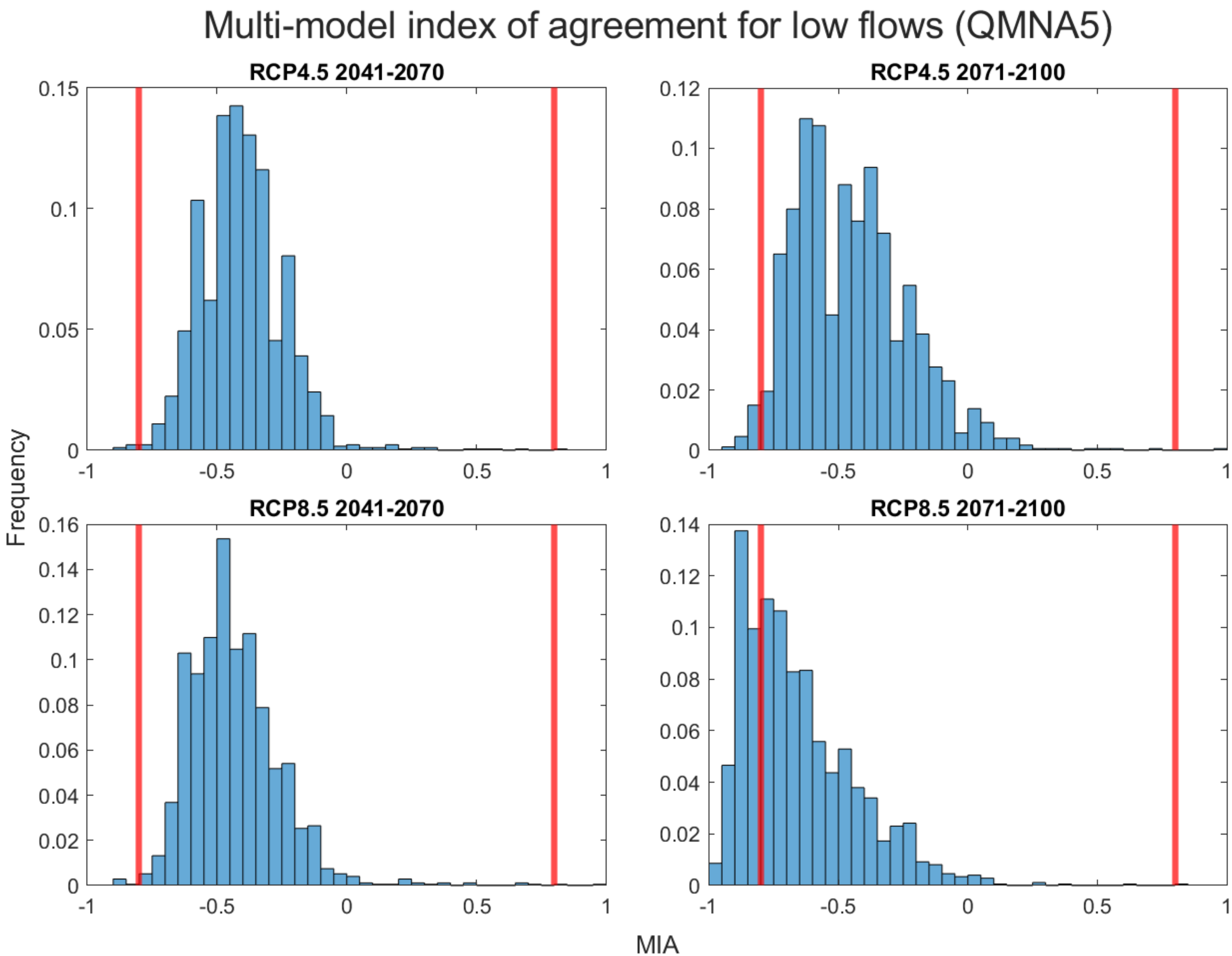
Projections of hydrological droughts
Agreement between the models



Good convergence towards an increase in hydrological drought severity

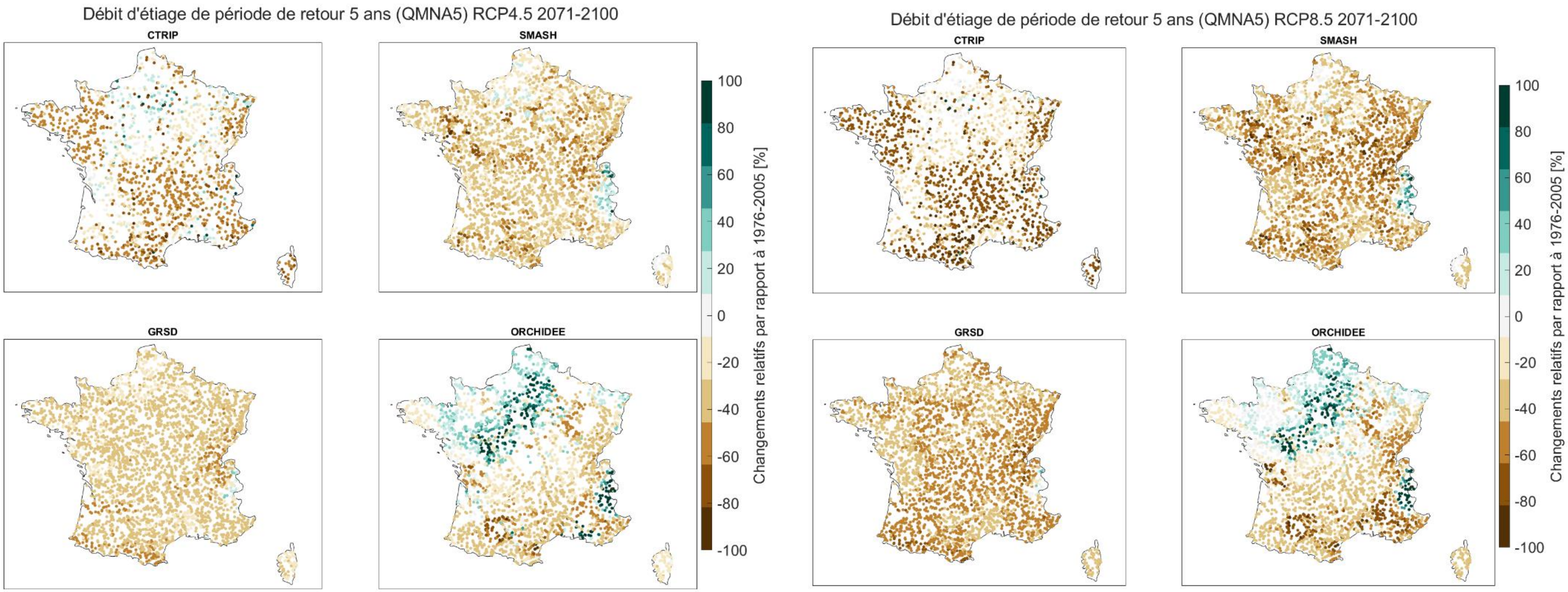
Different signals with different hydrological models

Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques



Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques

Projections of hydrological droughts
Relative changes



Relative changes up to -40 / -50%

Different signals with different hydrological models for some regions = uncertainties on the representation of low flow processes

Tramblay et al., 2024, rapport Explore2 sur les extrêmes hydrologiques

Which solutions ?

- Greater sobriety in water use
- Improving network efficiency
- Large-scale/small-scale infrastructures?

Observation: we're going to have less and less water.
Should we have more irrigation?

WATER

The paradox of irrigation efficiency

Higher efficiency rarely reduces water consumption

By **R. Q. Grafton[1,2], J. Williams[1], C. J. Perry[3], F. Molle[4], C. Ringler[5], P. Steduto[6], B. Udall[7], S. A. Wheeler[8], Y. Wang[9], D. Garrick[10], R. G. Allen[11]**

Reconciling higher freshwater demands with finite freshwater resources remains one of the great policy dilemmas. Given that crop irrigation constitutes 70% of global water extractions, which contributes up to 40% of globally available calories (*1*), governments often support increases in irrigation efficiency (IE), promoting advanced technologies to improve the "crop per drop." This provides private benefits to irrigators and is justified, in part, on the premise that increases in IE "save" water for reallocation to other sectors, including cities and the environment. Yet substantial scientific evidence (*2*) has long shown that increased IE rarely delivers the presumed public-good benefits of increased water availability. Decision-makers typically have not known or understood the importance of basin-scale water accounting or of the behavioral responses of irrigators to subsidies to increase IE. We show that to mitigate global water scarcity, increases in IE must be accompanied by robust water accounting and measurements, a cap on extractions, an assessment of uncertainties, the valuation of trade-offs, and a better understanding of the incentives and behavior of irrigators.

LOGIC AND LIMITS

Field IE is the ratio of the volume of all irrigation water beneficially used on a farmer's field [predominantly, evapotranspiration (ET) by crops and salt removal to maintain soil productivity] to the total volume of irrigation water applied (adjusted for changes in water stored for irrigation in the soil) (*2*). Annually, governments spend billions of dollars subsidizing advanced irrigation technologies, such as sprinklers or drip systems (*3*). Sometimes their goal is to increase IE on the understanding that this will allow water to be reallocated from irrigation to cities (*4*), industry, or the environment, while maintaining or even increasing agricultural production.

But water saved at a farm scale typically does not reduce water consumption at a watershed or basin scale. Increases in IE for field crops are rarely associated with increased water availability at a larger scale (*5*), and an increase in IE that reduces water extractions may have a negligible effect on water consumption. This paradox, that an increase in IE at a farm scale fails to increase the water availability at a watershed and basin scale, is explained by the fact that previously nonconsumed water "losses" at a farm scale (for ex-

PHOTO: GRANT FAINT/GETTY IMAGES

Published by AAAS

PNAS

Water conservation in irrigation can increase water use

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