Copernicus Climate Change Service

FLAUDE PROJECT

Recommendations on C3S & CEMS data and products use for local flood risk management (WP3)

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Note
Formatted text in blue matchs to the update of C3S_D3.1_202012_Recommendations on C3S data_v1, 15/12/2020 report.

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Introduction – Scope of the document

The FlAude project aims to improve the resilience of the Aude region to flooding in a perspective of adaptation to climate change, by jointly enhancing the spatial images produced by CNES and the climate data made available by the Copernicus Climate Change Service (C3S).

WP3 is in charge of processing climate data for the characterization of flood risk and its evolution in a past and future perspective. With the objective of replicability on other territories in France and in Europe, the C3S data will be evaluated in relation to the reference data produced by Météo-France.

The Aude territory is affected by intense Mediterranean rainfall events that can bring several hundred millimeters in a few hours. These rains cause heavy runoff and flash flooding of rivers that can cause a few fatalities and huge damages.

Several climatic parameters have been identified to characterise these events:

- rainfall over daily or sub-daily time steps (1 to 6 hours)
- soil moisture characterising runoff
- River flows causing catastrophic floods

The selection of the best C3S data to describe these parameters was proposed by Météo-France and discussed with the C3S team during a meeting organised at the beginning of the project (10th July 2020).

For precipitation, these are data from the UERRA reanalysis at daily time step, the ERA5-Land reanalysis at daily and infra-daily time step, soil moisture data from these two products, as well as the EFAS product from the Copernicus Emergency Service (CEMS), which also provides flow rates.

The reference data for the evaluation of C3S products are the statistical reanalysis of precipitation PRESCILIA available daily, the COMEPHORE product fusion between radar data and rain gauges available hourly, and the observed flow rates provided by the DDTM of Aude.

Regarding future climate projections, an evaluation of the CORDEX data available on the Copernicus data store, in comparison with the DRIAS-2020 dataset, derived from CORDEX data and produced by Météo-France is carry out.

All these products are presented below.

1. Products description

a) Total precipitation

UERRA MESCAN SURFEX reanalysis

UERRA system (Uncertainties in Ensembles of Regional ReAnalysis - Bazile, E. and al. 2017) offers a complete deterministic reanalysis over Europe, using historical observations with a dynamical modeling. The following 3 systems make up the UERRA dataset.

UERRA-HARMONIE (11 km resolution), driven by the ERA40/ERA Interim reanalysis data, uses 3DVar data assimilation. MESCAN system using an optimal 2D interpolation algorithm for temperature, relative humidity precipitation and wind. SURFEX, which is the land surface platform, produces from the downscaled MESCAN fields, 30 surface parameters at a resolution of 5.5 km, for 14 soil levels.

Total daily precipitation is available on the Climate Data Store at 5.5km resolution. Concerning soil moisture parameter, CDS does not provide this parameter produced by UERRA MESCAN SURFEX system at 5.5 km resolution. We use instead volumetric soil moisture parameter supplied by UERRA-HARMONIE dataset at 11 km horizontal resolution and 3 soil levels.

ERA5-Land reanalysis

ERA projects are meteorological reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF). ERA5 is the latest version (formerly ERA15 from 1978 to 1994, ERA40 from 1957 to 2002, ERA Interim from 1979 to 2018) of ECMWF reanalysis and combines past observations of several variables, using 4DVar data assimilation at 31 km resolution. ERA5, with a large panel of hourly atmospheric, land and ocean variables, provides a complete description of the past climate and covers the entire globe.

ERA5-Land is the surface counterpart of ERA5, offering hourly analysis of surface parameters at a 9 km resolution covering the 1981-2020 period. Coupled with atmospheric reanalysis fields of ERA5, ERA5-Land (H-TESSEL land surface model) system does not directly use data assimilation.

Total precipitation (including convective and large-scale precipitation) and volumetric soil moisture at 4 soils layers (0 cm 7 cm 28 cm 100 cm 289 cm) available on climate data store are evaluated in this report.

PRESCILIA (PRÉcipitations Spatialisées Contraintes par une InitiaLisatIon Aurelhy)- Météo France product

The Prescilia method is based on a statistical approach aimed at producing daily rainfall fields over France over a very long depth (61 years: 1958-2018). These daily fields can then be aggregated at every weather step to form climatological products. This production seeks to make the most of the long series of daily observations in high spatial density available in climatological databases from 1960 onwards.

The first stage of the method consists in setting up an Aurelhy climatology by weather type based on a classification method using a canonical analysis linking local data and fields describing the general circulation (Lassegues, 2016): 6 classes of weather type have been selected to explain climate variability in France over two major seasons, winter and summer. A stationary climatology for each of the weather types is then calculated and the Aurelhy spatialization method makes it possible, based on relief predictors, to produce climatological fields on a 1 km grid for each of the 12 weather type classes.

A daily spatialization of precipitation is then carried out using the climatology of the weather type of the day (produced in the previous step) as a rough draft in the framework of a kriging method with external drift (Matheron, 1963). For each grid point, the model processes the rain/no rain occurrence forecast and the rainfall amount forecast separately. The specific treatment of rain/no rain occurrence eliminates the residual low rainfall inherent in most spatial analysis techniques. The quantitative treatment of rainfall is carried out after a log transformation, a technique known as trans-Gaussian kriging (Cressie, 1993). In the end, the spatial resolution of the fields produced is 1 km.

COMEPHORE – Météo France product (HOraiRE Best Estimate Precipitation Combination)

COMEPHORE is an hourly re-analysis of precipitation by merging radar and rain gauges, covering metropolitan France. The production has so far been carried out over the period 1997-2019. The method of elaboration takes into account two periods with differences in data processing

-> Years 1997 to 2006 : The several steps of data processing are

Treatments at each local radar; Fixed echoes and mask rate are estimated at annual time steps; Hourly totals are calculated; correcting faults inherent in the measurement radar: fixed echoes, masks, clear sky echoes, advection; a daily cumulation (6h-6h) is calculated from valid data and if applicable values obtained by kriging rain gauge data; A map of corrective factors is established by moving a disc with a radius of 30 km in which takes the median value of the radar/rain gauge ratios; The daily radar total is "calibrated" using the correction factor when it is available; Compositing / fusion with rain gauges; Hourly and daily data are supplemented with values obtained from kriging of rainfall data; The hourly and daily data are composed according to the distance to the radar; The daily reference cumulation is obtained by kriging with external drift of the rain gauge data by taking the composite of the daily cumulative rainfall calibrated as auxiliary field; 24 intermediate hourly water slats are established by kriging with external drift of rain gauge data, taking radar accumulations as auxiliary fields; Time interpolation (descending from daily time step to hourly time step); The breakdown of the daily reference cumulation over all the hours of the day is made using the intermediate water slats as weights.

-> Years 2007 and following : The several steps of data processing are

Radar treatments, Fusion with rain gauges : the daily reference accumulation is obtained by applying the ANTILOPE method based on the separation of stratiform and convective rainfall from water slides 5 minutes, hourly cumulation of stratiform and convective radar water levels, kriging with external drift of hourly rainfall data; The breakdown of the daily reference cumulative total over all hours of the day is as follows made using the intermediate water slats as weights.

Coordinated Regional Climate Downscaling Experiment - CORDEX dataset

The Copernicus data portal offers a set of climate simulations, from the CORDEX project (Coordinated Regional Climate Downscaling Experiment). CORDEX project is an international program between regional climate modeling centers, whose main objectives are :

- to better understand important regional and local climate phenomena, their variability and evolution through downscaling methods,
- to evaluate and improve regional climate downscaling models and techniques,
- produce a global regional climate projection dataset,
- improve communication and knowledge exchange with users of regional climate information.

The CORDEX datasets have been produced from 2009 to date and are considered the state of the art in regional climate modelling at the present time. They are the largest ensemble ever produced with this type of climate model and are reference in high-resolution description of future climate change in Europe.

Figure 1 : European domain (EURO-CORDEX) - CORDEX project

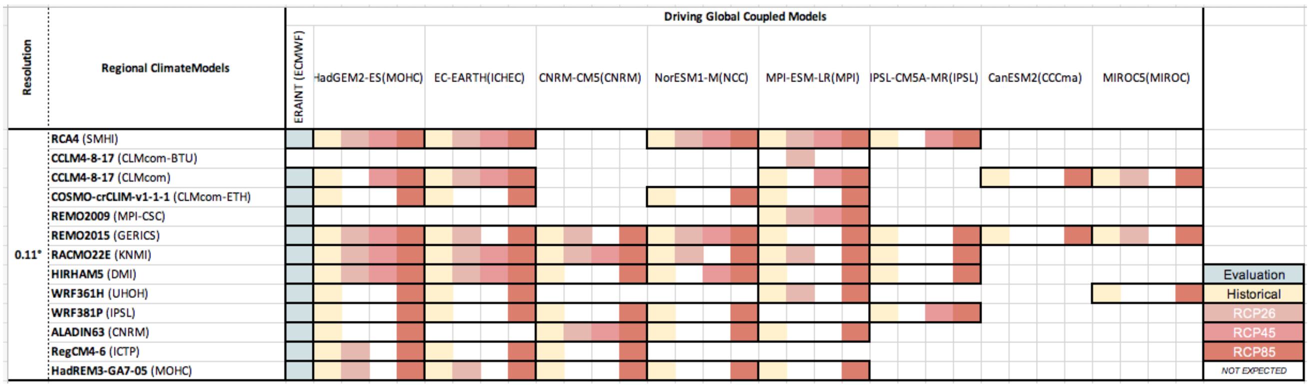


Figure 2 : RCMs, GCMs and Historical/RCP experiments available in Copernicus Climate Data Store

The Copernicus data portal proposes a set of combinations between Regional Climate Model (RCM), Global Climate Model (GCM) and radiative forcing scenarios, for the European domain at a spatial resolution of 0.11 degree or 12.5 km (called EUR-11 domain) summarized in the figure above.

For this domain, 13 RCMs available, coupled with 8 different GCMs for the 4 experiments:

- evaluation (CORDEX experiment driven by ECMWF ERA-Interim reanalysis for a past period, not analyzed in this project),
- historical (experiment which covers a period for which modern climate observations exist. Boundary conditions are provided by GCMs. These experiments, that follow the observed changes in climate forcing, show how the RCMs perform for the past climate when forced by GCMs and can be used as a reference period for comparison with scenario runs for the future. The period covered is typically 1950-2005),
- scenario : Representative Concentration Pathways (RCP) forcing scenarios. These scenarios are the RCP 2.6, 4.5 and 8.5 scenarios providing different pathways of the future climate forcing. The period covered is typically 2006-2100.

Climate data store of Copernicus offers 24 atmospheric variables, including total precipitation for downloading, at different temporal resolutions : 3h, 6h, monthly and seasonal.

Summary of C3S and Météo-France datasets - precipitation

Name	**Unit**	**Temporal coverage**	**Horizontal resolution**	**Parameter description**
Uerra Mescan Surfex reanalysis	kg m^{-2}	01/01/1961 to 31/12/2018 daily data	5.5km x 5.5km	Amount of water falling onto the ground/water surface. It includes all kinds of precipitation forms as convective precipitation, large scale precipitation, liquid and solid. It is an accumulated parameter over the 24 hours from 06:00 to 06:00 of the next day. Values are valid for a grid cell.
ERA5-Land reanalysis	m	01/01/1981 to 30/06/2020 hourly data	0.1° x 0.1° (approximately 9km x 9km)	Accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface. It is the sum of large-scale precipitation (that precipitation which is generated by large-scale

				weather patterns, such as troughs and cold fronts) and convective precipitation (generated by convection which occurs when air at lower levels in the atmosphere is warmer and less dense than the air above, so it rises). Precipitation variables do not include fog, dew or the precipitation that evaporates in the atmosphere before it lands at the surface of the Earth. This variable is accumulated from the beginning of the forecast time to the end of the forecast step. The units of precipitation are depth in meters. It is the depth the water would have if it were spread evenly over the grid box.
Prescilia	mm	01/01/1958 to 31/12/2018 daily data	1km x 1km	Amount of water falling onto the ground. It includes all kinds of precipitation forms as convective precipitation, large scale precipitation, liquid and solid. It is an accumulated parameter over the 24 hours from 06:00 to 06:00 of the next day. Values are valid for a grid cell.
Comephore	mm	01/01/1997 to 31/12/2019 hourly data	1km x 1km	Hourly amount of water falling onto the ground. It includes all kinds of precipitation forms as convective precipitation, large scale precipitation, liquid and solid. Values are valid for a grid cell.
CORDEX	kg m^{-2} s^{-1}	From 1951 to 2005 for historical experiments From 2006 to 2100 for RCP experiments	European domain (EUR-11) : 0.11° x 0.11° (approximately 12 km x 12 km)	Deposition of water to the Earth' s surface in the form of rain, snow, ice or hail. The precipitation flux is the mass of water per unit area and time. The data represents the mean over the aggregation period (3h, 6h, daily, monthly and seasonal)

b) Soil moisture

UERRA HARMONIE

See total precipitation for UERRA-MESCAN-SURFEX description above

ERA5-Land reanalysis

See total precipitation for ERA5-Land description above

SIM2 (Surfex - ISBA - Modcou)

The hydrometeorological model SIM2 consists of a meteorological analysis system (SAFRAN), a land surface model (ISBA) and a hydrogeological model (MODCOU). It simulates the flow of water and energy balance on the surface in France, as well as the evolution of the flow of rivers and the main water layers.

Soil water content from the SIM2 modelling chain (SAFRAN-ISBA-MODCOU version 2) is used to monitor the state of water resources in the soil. Within this chain, it comes from the ISBA-DF model, which has been validated in terms of temperature and soil water content, both punctually (Decharme et al. 2011) and spatially distributed (Decharme et al. 2013). This model has been used operationally since October 2016 within the SIM2 chain (Le Moigne et al. 2020, Besson et al. 2020).

The ISBA-DF model is used in the SIM2 chain at a regular resolution of 8 km. The modelling discretises the soil in 14 layers of variable thickness down to a depth of 10 m.

In addition, different types of vegetation are modelled at the scale of each grid cell, derived from the Ecoclimap2 classification.

CEMS-EFAS Copernicus Emergency Management Service - European Flood Awareness System

The European Flood Awareness System (EFAS), jointly developed by the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF), is a hydrological forecast and monitoring system independent of administrative and political boundaries in the greater European domain.

Historical data provided by the Climate Data Store consists in a set of gridded parameters, river discharge in the last 24 hours, daily snow depth equivalent and daily volumetric soil moisture, across all Europe at a 5 km resolution and covering the 01/1991 - 09/2020 period. Modelled time series are produced by the LISFLOOD (distributed water balance and flood simulation model) hydrological model, drived by a set of ground observations of temperature and precipitation. LISFLOOD model also uses static variables, such as upstream area and orography, and can be downloaded using CDS website.

Summary of C3S and Météo-France datasets - soil moisture

Name	**Unit**	**Temporal coverage**	**Horizontal resolution**	**Soil level**	**Parameter description**
Uerra Harmonie reanalysis	$m^3.m^{-3}$	01/01/1961 to 31/12/2018 daily data	11km x 11km	1 : NA 2 : NA 3 : NA level depths are grid dependent	Amount of water in a cubic meter soil valid for the cell grid at the corresponding soil level. The value is instantaneous meaning that it is valid for the last time step of the integration at the issued model time step. The vertical coordinates have no precise depth values. They are defined in terms of a time constant determining how quickly they adjust and restore
ERA5-Land reanalysis	$m^3.m^{-3}$	01/01/1981 to 30/06/2020	0.1° x 0.1° (approximately 9km x 9km)	1 : 0cm-7cm 2 : 7cm- 28cm	Volume of water in soil layer of the ECMWF Integrated Forecasting System.

		hourly data		3 : 28cm – 100cm 4 : 100cm – 289cm	
CEMS -EFAS 3.5 model	$m^3.m^{-3}$	01/01/1991 to 20/09/2020	5km x 5km	1 : 0cm -5cm constant for all grid cell 2 : 10cm (min) - 18cm (max) level depths are grid dependent 3 : 15cm (min) – 500cm (max) level depths are grid dependent	Amount of water in a cubic meter of soil valid for the cell grid at the corresponding soil layer. The value is instantaneous meaning that it is valid for the last time step of the integration at the issued model time step.
Safran Isba Modcou 2 reanalysis	$m^3.m^{-3}$	01/01/1958 to 31/07/2019 hourly data	8km x 8km	14 soil layers 0cm-1cm-4cm-10cm-20cm-40cm-60cm-80cm-100cm-150cm-200cm-300cm-500cm-800cm-1000cm	Amount of water in a cubic meter of soil valid for the cell grid at the corresponding soil layer

c) River discharge

CEMS-EFAS Copernicus Emergency Management Service - European Flood Awareness System

See CEMS-EFAS soil moisture description above

Hydrometric observations of Aude department

In the department of Aude, the State (SPC Méditerranée Ouest) permanently monitors the level of the Aude, Cesse, Orbieu and Berre rivers from 46 measuring stations, including 28 stations belonging to the flood forecasting network (Vigicrues). This monitoring concerns 7% to 10% of the total linear area of the basin's rivers.

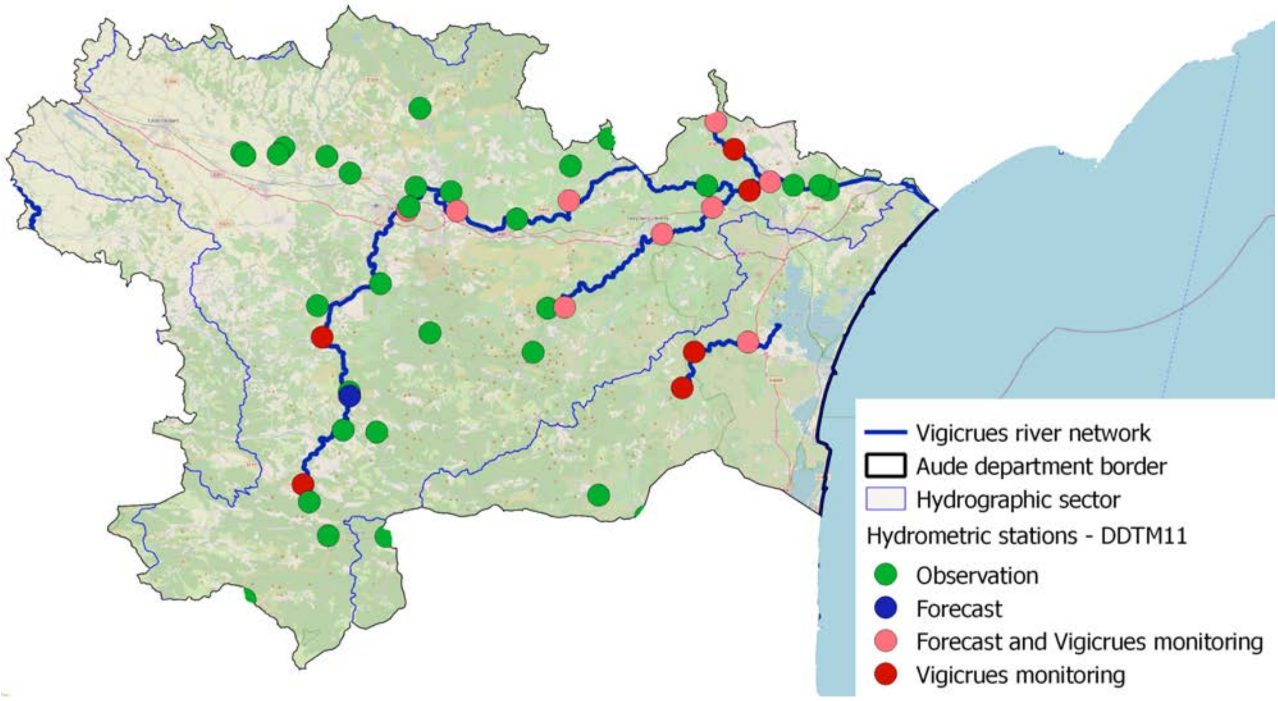


Figure 3 : Map of hydrometric stations (Observation, Forecast and Vigicrues monitoring) of Aude department

Summary of C3S and Météo-France datasets - river discharge

Name	Unit	Temporal coverage	Horizontal resolution	Parameter description
Observation of hydrometric stations of Aude department	$m^3.s^{-1}$	01/01/1920 to 31/12/2018 daily data	46 stations	Monthly and daily river discharge
CEMS -EFAS 3.5 model	$m^3.s^{-1}$	01/01/1991 to 20/09/2020 daily data	5km x 5km	Volume rate of water flow, including sediments, chemical and biological material, in the river channel averaged over a time step through a cross-section. The value is an average over each 24-hour time step.

2. Case study

a) Study Area

As described by Ribes et al 2018, "French Mediterranean areas experience a contrasted climate with dry, warm summers and fall and winter seasons punctuated by heavy rainfall over short durations—typically a few minutes to 1 day (Ducrocq et al. 2014). Compared to the rest of mainland

France, 10-year return values of maximum daily precipitation are two to four times larger near the Mediterranean, and daily rainfall exceeding one hundred millimeters within a day are common. These heavy precipitation events (HPEs) occur mainly in autumn under specific atmospheric circulation conditions (Nuissier et al. 2011), and have a broad impact on human society, as they are associated with flash floods and landslides that may cause widespread destruction and even fatalities (Llasat et al. 2013)."

For this purpose, we define a bounding box covering from 0° to 10° of longitude, and 41° to 46° of latitude, including all French Mediterranean regions. Mean of annual maximum 1-day precipitation (called RX1D indicator) over Aude department is evaluated at 72 mm. In the south-east part of the departement RX1D varies from 80 mm and 120 mm. In mountainous regions, as Cevennes (North of Gard, Hérault departments, Ardèche department) , RX1D reaches values varying from 150 mm to 250 mm.

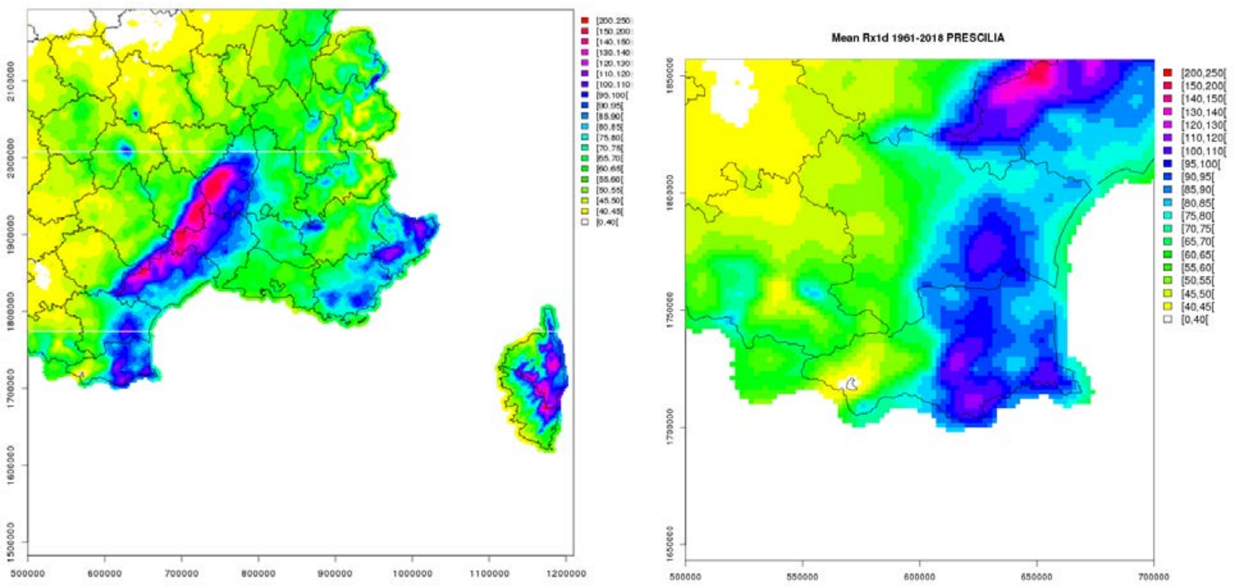


Figure 4 : Mean of annual maximum daily precipitation (RX1D) of Meteo France PRESCILIA dataset (kg.m-²) - 1958-2018 - Mediterranean Basin (left) and Aude department (right)

b) Characterization of flood events

Source : Extreme rainfall Meteo France database (http://pluiesextremes.meteo.fr/)

17 extreme rainfall events (daily precipitations greater than 200mm) over Aude department have been identified.
The 200 mm threshold in 24 hours generally corresponds to a return period of between 20 and 50 years in the east of the department, of the order of 100 years in Carcassonne (head of the department)

Date	Maximum daily value of precipitation (mm) in the department of Aude	Maximum two or three consecutive days values of precipitation
22/01/2020 (20 au 23)	100 mm (172 mm in the neighbouring department of the Oriental Pyrenees)	172 mm (378 mm the neighbouring department of the Oriental Pyrenees)
22/10/2019 (22 et 23/10/2019)	214 mm	244 mm
14/10/2018 (14 au 16/10/2018)	300 mm	327 mm
29/11/2014 (au 30/11/2014)	234 mm	293 mm
10/10/2010 (09 au 11/10/2010)	200 mm	277 mm
14/11/2005 (13 au 14/11/2005)	250 mm	300 mm
12/11/1999 (12 et 13/11/1999)	551 mm	620 mm
10/08/1997 (10 et 11/08/1997)	205 mm	219 mm
07/12/1996 (05 au 09/12/1996)	212 mm	351 mm
26/09/1992	292 mm	-
05/08/1989	240 mm	-
13/10/1986 (12 et 13/10/1986)	300 mm	405 mm
26/10/1985 (25 et 26/10/1985)	236 mm	246 mm
16/02/1982 (15 au 17/02/1982)	315 mm	340 mm
08/01/1979 (8 au 11/01/1979)	235 mm	256 mm
18/10/1977	203 mm	-
11/10/1970	215 mm	-

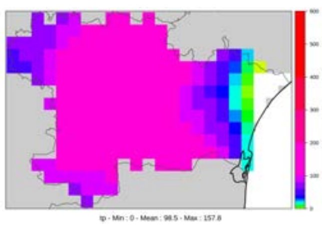
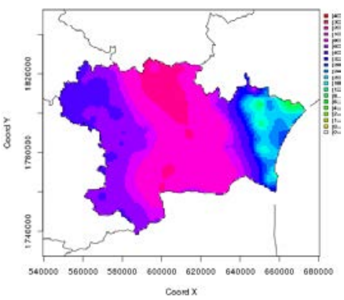
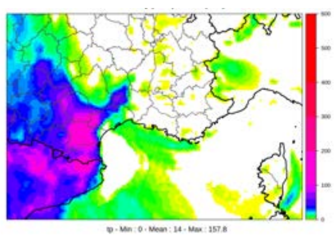
c) Flood event – 14-15 October 2018

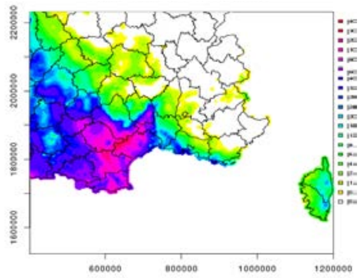
This event, the strongest of the last 10 years on the department of Aude, was at the origin of the collaboration of the CNES and the DDTM on the valorization of spatial images and thus of the FlAude project. It is the subject of numerous treatments within the framework of WP2 and close exchanges between these two WPs.

Description : During the night of 14th October 2018 a Mediterranean Heavy Precipitation Event occurred in the Aude Pyrénées-Orientale and Hérault departments and generating deadly floods in the Aude river catchment. Typical meteorological ingredients were involved : an upper-jet right-entrance region, and a warm and wet low-level jet feeding a convergence line.
The episode began on the evening of October 14th in Pyrénées-Orientales and Aude departments until on October 15th early morning. It then shifted eastward over Hérault department. The heaviest 12-hour rainfall, up to 150 mm from October 14-20h CUT to October 15 at 07h CUT, occurred in the center of Aude with strong hourly intensities.
12-hour cumulative precipitation reaches 295 mm at Trèbes, 212 mm at Arquettes-en-Val, 146 mm at Villardebelle, 139 mm at Carcassonne. During this period, the highest hourly intensities are observed in Lézignan (55 mm), Mouthoumet (53 mm), Villardebelle (52 mm), Arquettes-en-Val (46 mm).
Besides this extreme rainfall context, several factors have contributed to the catastrophic reactions of Aude river and its left bank tributaries (Trapel, Orbiel).

The rainfall convergence zone was exactly aligned with the valleys of the Rieu Sec river, a small tributary of Orbiel, and Trapel rivers. Also note the small size of this watershed (60 km² for Trapel river and 16 km long for Rieu Sec creek), related to the heavy rainfall. Secondly, 60 mm to 80 mm of rain was recorded during 8-9 October, which contributed to a significant soil moistening of this area.
Another important factor is that the duration of the intense rains (6 to 9 hours), which is of the order of magnitude of the concentration times of the basins concerned, led to a full mobilisation of the drainage capacities of these basins (Musy, 2005). Orbiel, Rieu Sec and Trapel flash flooding devastated localities of Aragon, Villegailhenc, Villemoustaussou, Villalier, Conques. At Villedubert hydrometric station, the water rose up to 6 meters in 4 hours. In Corbières massif, the water of Lauquet river rose up to 6 meters in 2 hours in Saint-Hillaire village. In Trèbes and Aude river, water rose up to 8 meters in 6 hours. Flooding of Orbieu Argent-Double Cesse rivers, tributaries of Aude river were less important in terms of damages.
(source http://pluiesextremes.meteo.fr/)

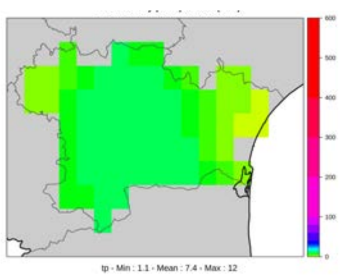
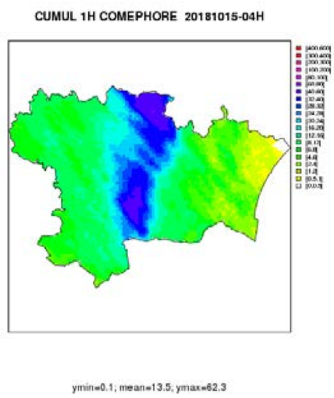
Evaluation of daily total precipitation : UERRA vs PRESCILIA

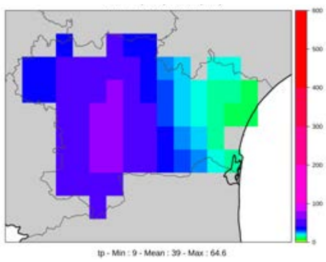
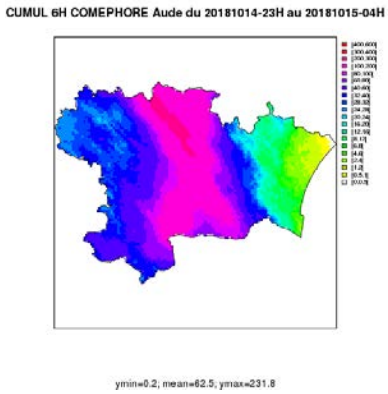
Total precipitation from 14 to 15/10/2018	UERRA	PRESCILIA	Comment
Aude department			The event is well represented by UERRA but the daily maximum is well over 200 mm in PRESCILIA while UERRA is around 160 mm
Medit region			The regional vision of the event shows the extension of the zone of heavy precipitation towards the neighbouring department

Evaluation of hourly total precipitation : ERALand vs COMEPHORE

The very intense rainfall accumulations in less than 6 hours were at the origin of the violence of the event.

Hourly total precipitation between 14 to 15/10/2018	ERA5Land	COMEPHORE	Comment
1h max			The max hourly rainfall is reached at 4h UTC with cumulations higher than 40 mm at 60 mm. On ERA5 Land, the max does not exceed 13 mm

6h max			In 6 hours, max observed between 200 and 250 mm. On ERA5 Land, 6-hour cumulative precipitation reaches 65 mm.

d) Flood event – 12-13 November 1999

The catastrophic floods of November 1999 were the most severe in the last 50 years and are used as a reference in many flood risk management documents.

Description : In November 1999, extreme flooding affected the southern part of France, including Aude, Pyrénées Orientales, Tarn and Hérault departments. Extreme rainfall event occurred between November 11 to November 14, generating dramatic flash flooding on Berre, Orbieu, Argent-Double watersheds.
Most of the rainfall is due to a single multicell V-shaped convective system. Analysis of this meteorological situation indicates that propitious conditions to the development of the convective system were gathered the 12 to 13th.

Maximum rainfall intensities were located around Lézignan-Corbières, and were close to 622 mm as daily precipitation. We notice on this rain gauge 192 mm of precipitation within a 2-hour period, at midnight on November 13. Overall, 200 mm of precipitation were observed over a wide area of 7000 km² covering 4 departments.

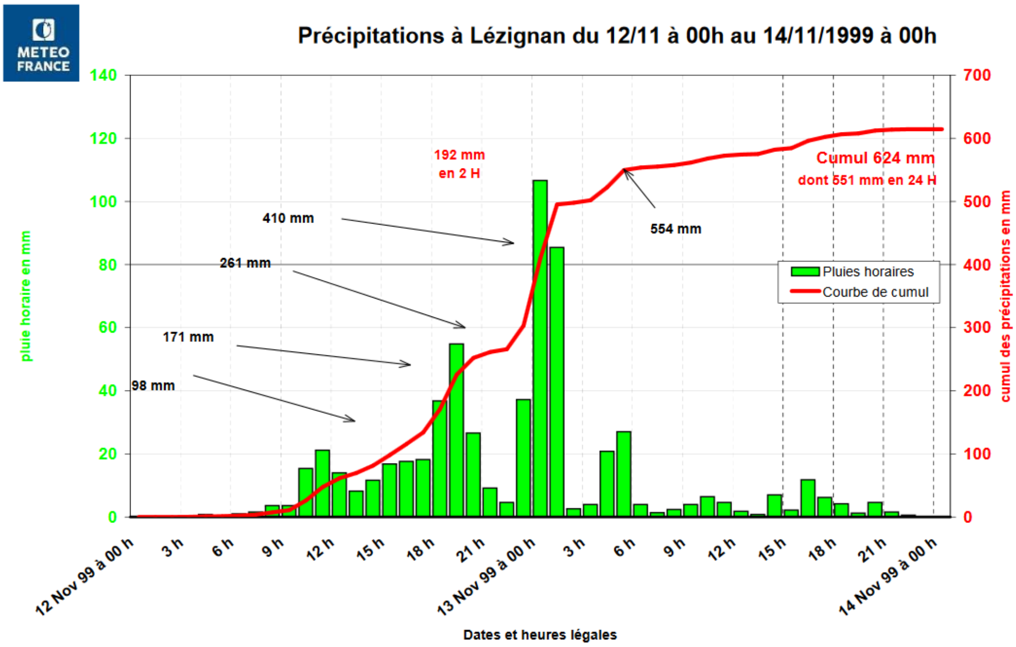
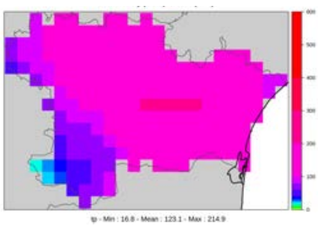
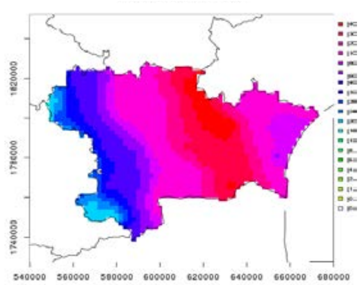
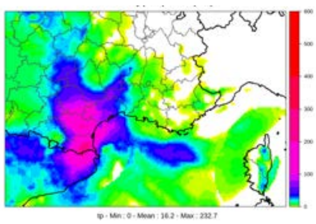
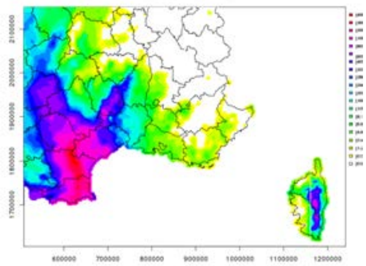


Figure 5 : Hourly precipitation observed in Lézignan-Corbières - 12/11 to 14/11 (source http://pluiesextremes.meteo.fr/)

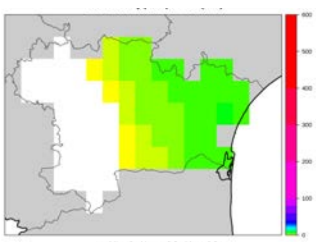
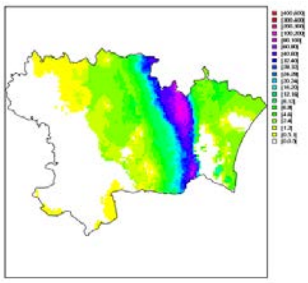
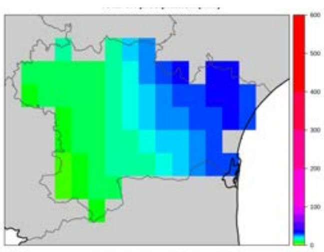
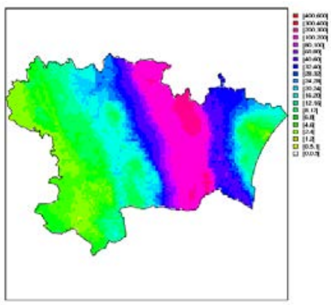
This extreme rainfall was coupled with a violent eastern storm blowing from off the French Riviera to the Gulf of Lion coast. The semaphores of Leucate (Aude) and Cap Béar (Pyrénées-Orientales) recorded, on the 12th and 13th, mean wind speed above 100 km/h. This strong swell near the coast was an aggravating phenomenon, disrupting the flow of rainwater to the sea. In Argent-Double river at la Redorte village, the water rose up to 3.50 m from 12/11 - 19h to 21h30. Same brutal surges were recorded on many small watersheds, as Orbieu (rose up of 4.70 m from 19h00 to 23h00), Clamoux, Verdouble rivers.
(source http://pluiesextremes.meteo.fr/)

Evaluation of daily total precipitation : UERRA vs PRESCILIA

Total precipitation from 12 to 13/11/1999	UERRA	PRESCILIA	Comment
Aude department			This major event is quite well treated by UERRA, at lower 2-day intensities : 215 mm in UERRA compared with 608 mm in PRESCILIA on November 12 1999
Medit region			

Evaluation of hourly total precipitation : ERALand vs COMEPHORE

The very intense rainfall accumulations in less than 6 hours were at the origin of the violence of the event.

Hourly total precipitation between 12 to 13/11/1999	ERA5Land	COMEPHORE	Comment
1h max			The max hourly rainfall is reached the 12/11 at 23h UTC with cumulations higher than 80 mm at 110 mm. On ERA5 Land, the max does not exceed 7 mm at the same time.
6h max			In 6 hours, max observed between 250 and 280 mm. On ERA5-Land, 6-hour precipitation does not exceed 35 mm.

3. Evaluation of C3S products - historical period

a) Developing hydro-meteorological indicator for characterization of flood event

We design a multi-dimensional climate indicator, incorporating 3 aspects of extreme rainfall and flooding event : qualification of the intensity (maximum 2-day precipitations in mm), estimation of the spatial extension (km²) and total precipitated volume on the area (m^3 or meter). This three dimensional indicator was previously developed for extreme heat waves (Ouzeau et al, 2016), (Soubeyroux et al, 2016), droughts (projet Extremoscope 2017) and storms (http://tempetes.meteofrance.fr/spip.php?article205).

The spatial extension is considered above a high threshold that can generate impacts in terms of flooding. The threshold chosen here is based on the average RX1D indicator over the study area.

b) Daily total precipitation evaluation : UERRA MESCAN SURFEX versus PRESCILIA

In UERRA, in the French Mediterranean area, spatial structures are globally respected : the maximums are observed first in the Cevennes region, the Eastern Pyrenees, the eastern part of Corsica. There is an overall under-estimation of heavy precipitation, more marked in mountainous areas (Pyrenees, Southern Alps) where the highest values are observed. The high spatial variability of precipitation on these regions, is poorly restituted. Mean of the maximum RX1D indicator on Aude department is 179 mm for PRESCILIA for 110 mm UERRA, partially explained by the difference in resolution of the datasets (5,5 km grid versus 1 km grid).

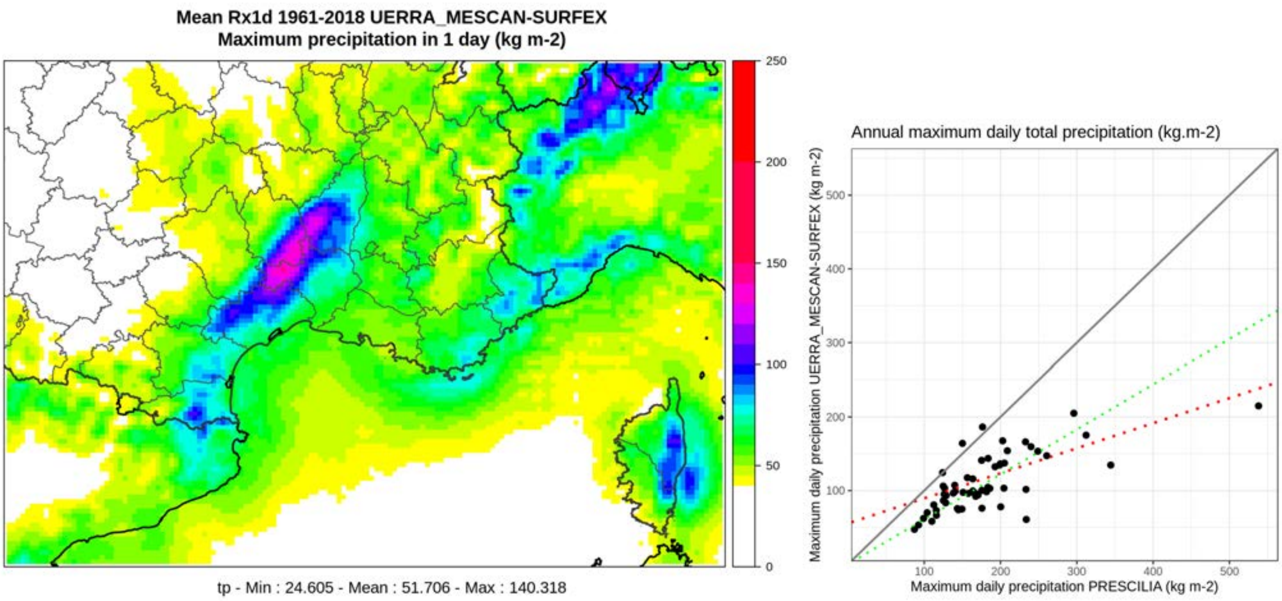


Figure 6 : Left : Mean of annual maximum daily precipitation (RX1D) of UERRA MESCAN SURFEX dataset (kg.m-²) 1961-2018

Right : Annual RX1D (kg.m-²) Aude department - PRESCILIA (x-axis) UERRA MESCAN SURFEX (y-axis) - 1961-2018

Daily PRESCILIA data are available from 1958 to 2018. From this database, we count the number of events whose cumulative precipitation within 2-day exceeds the threshold of 200 mm on at least one point of the domain. The intense events that can be observed straddling two consecutive climatological days (06h-06h). We identify 47 independent events from 1961/01/01 to 2018/12/31, and we compute for each sequence :

- maximum 2-day cumulative rainfall in mm,
- affected area by 200 mm threshold in km²,
- cumulative precipitation above 120 mm for all grid cells exceeding 120 mm within 2 days, in meters.

The graph below shows surface (x-axis in km²), 2-day intensity rainfall (y-axis, mm) and cumulative rainfall above 120 mm threshold (size of bubble) observed in the reference PRESCILIA dataset. The color of each bubble refers to the values observed in UERRA reanalysis. In order to take into account reduction of the maximum intensities and resolution loss in UERRA, we choose a detection threshold of 100 mm for UERRA, in accordance with RX1D plot trend.

9 events are reproduced by UERRA with a 2-day intensity greater than 200 mm : October 10, 1970, February 15, 1982, October 25, 1985, September 26, 1992, November 12, 1999, November 13, 2005, October 10, 2010, November 28, 2014 and October 14, 2018. These major events are quite well treated by UERRA, at lower 2-day intensities : for instance, 299 mm in UERRA compared with 608 mm in PRESCILIA on November 12 1999, 205 mm in UERRA compared with 296 mm in PRESCILIA on September 26 1992.

25 events are provided by UERRA with intensities between 120 mm and 200 mm, including flooding episodes of October 27, 2011, October 12, 1986. 3 events are associated with intensities between 100 mm and 120 mm. Using a 100 mm threshold, there is no matching in UERRA reanalysis for about 20% of events. These events are generally either associated with a surface lower than 500 km², or with an 2-day cumulative precipitation lower than 250 mm in PRESCILIA dataset.

These elements show the UERRA's capacity to identify and spatially represent the major extreme rainfall events in the Aude department, despite a rather strong underestimation of the maximum intensities, partly due to the 5.5 km resolution of the product (versus 1 km for Prescilia).
The detection performances logically decrease with the surface area of the events considered, especially under 1000 km².

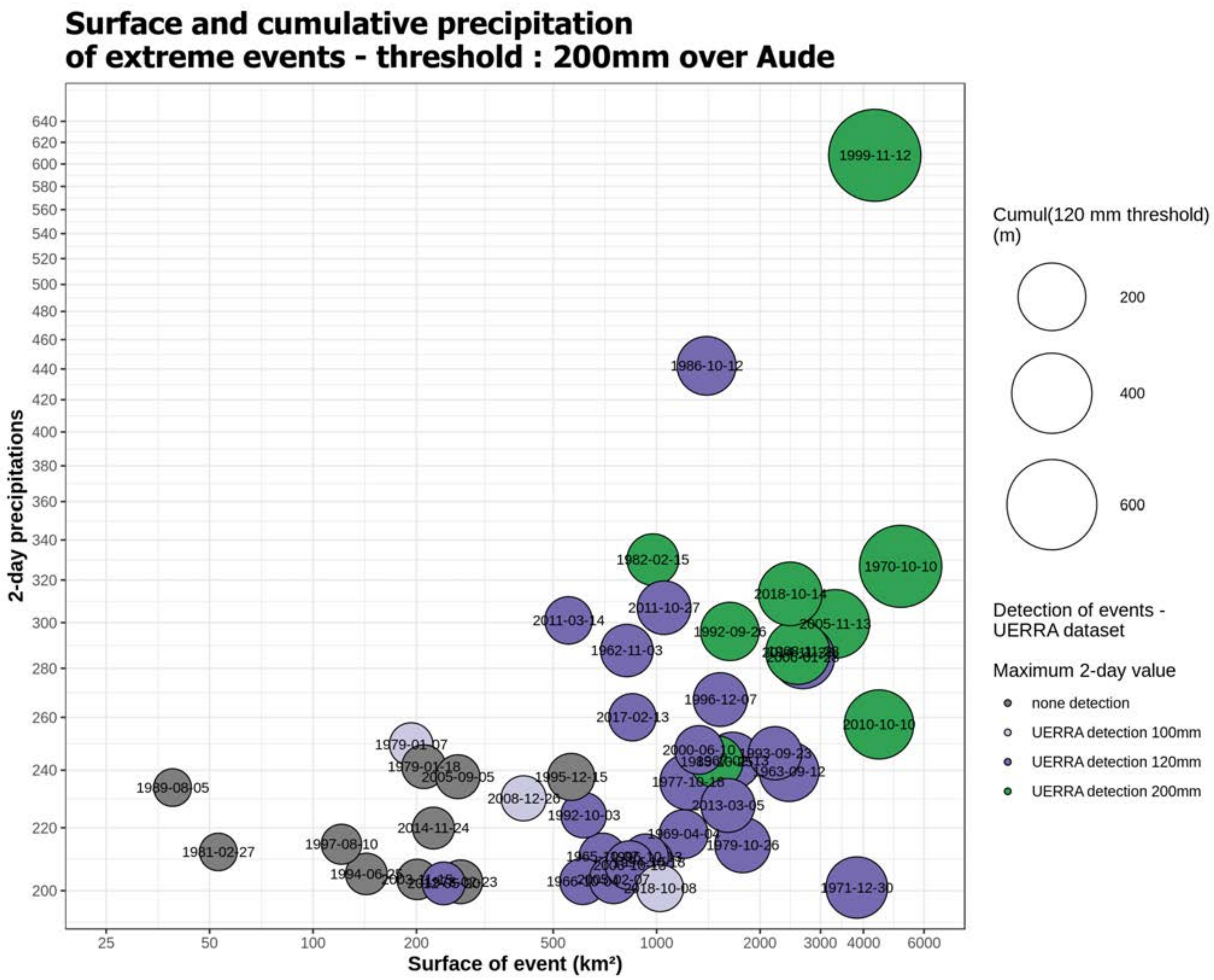


Figure 7 : Surface event (x-axis, km²), 2-day precipitation (y-axis, mm) and total volume over a threshold of 120mm (size of bubble, m), for PRESCILIA - Value of 2-day precipitation in UERRA dataset (mm)

The second graph below presents the same PRESCILIA data, as a function of the surface computed by UERRA (presented as a percentage in relation to the PRESCILIA value). The values are dispersed and range from 6% to 307% of the surface predicted by PRESCILIA.

13 events (including November 28, 2014, October 10, 2010 and November 13, 2005) are associated with surfaces correctly predicted by UERRA, ranging from 75% to 125% of the surface of PRESCILIA. Surfaces are underestimated (ratio below 50% between UERRA/PRESCILIA) for 5 events, including 2 events with ratio lower than 25%. On the contrary, there is a relatively large overestimate, greater than 175%, for 6 flooding events (including October 14, 2018).

The correct determination of the spatial extension of the event does not present a systematic bias but a great variability, requiring great care in the use of this parameter.

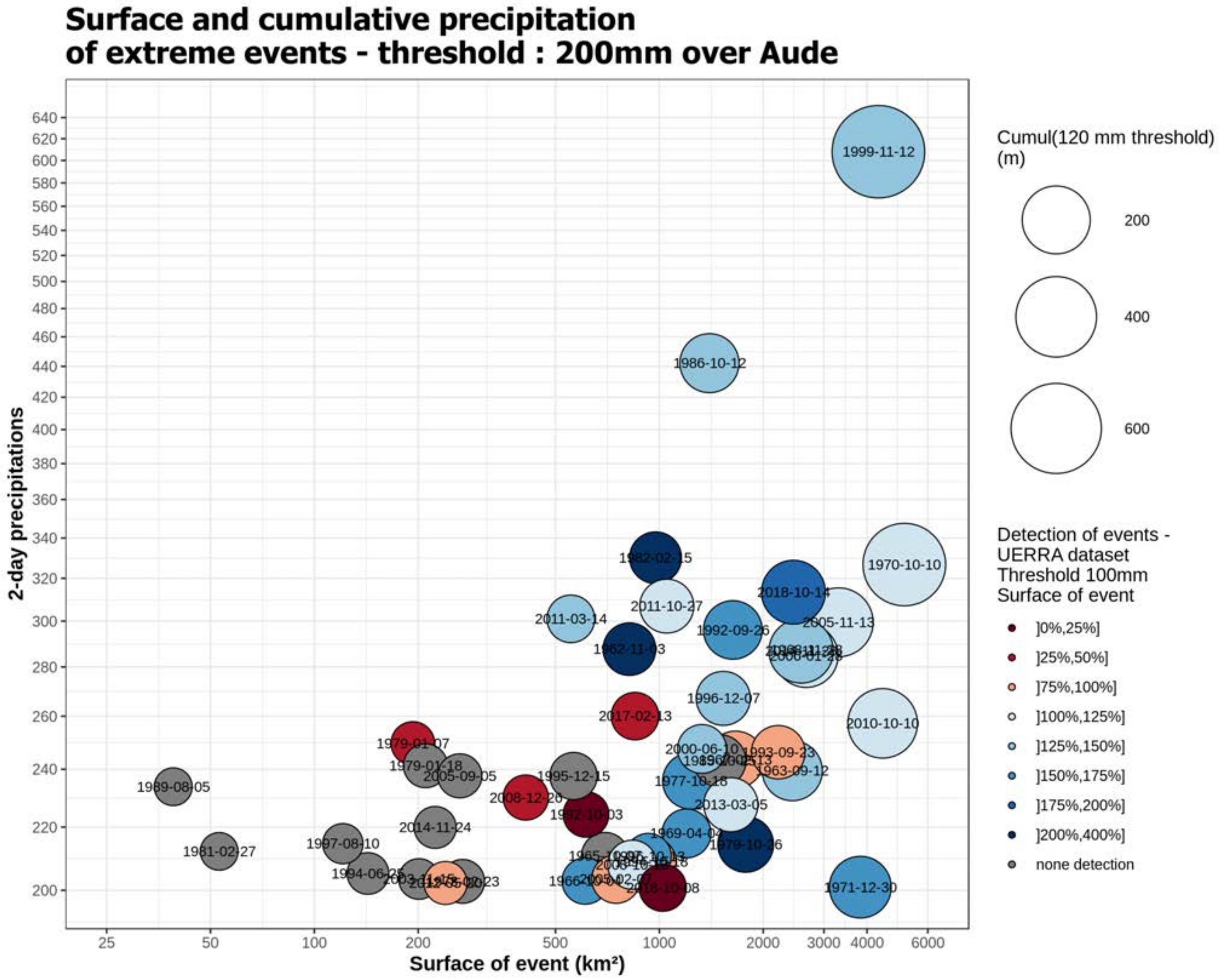


Figure 8 : Surface event (x-axis, km²), 2-day precipitation (y-axis, mm) and total volume over a threshold of 120mm (size of bubble, m), for PRESCILIA - Relative difference (%) in surface between UERRA and PRESCILIA datasets

According to 2-day precipitation trends, total cumulative precipitations are clearly underestimated. 12 events are correctly represented with a ratio ranging between 75% and 125%. Using a threshold of 100 mm, ratio is lower than 50% for 13 events.

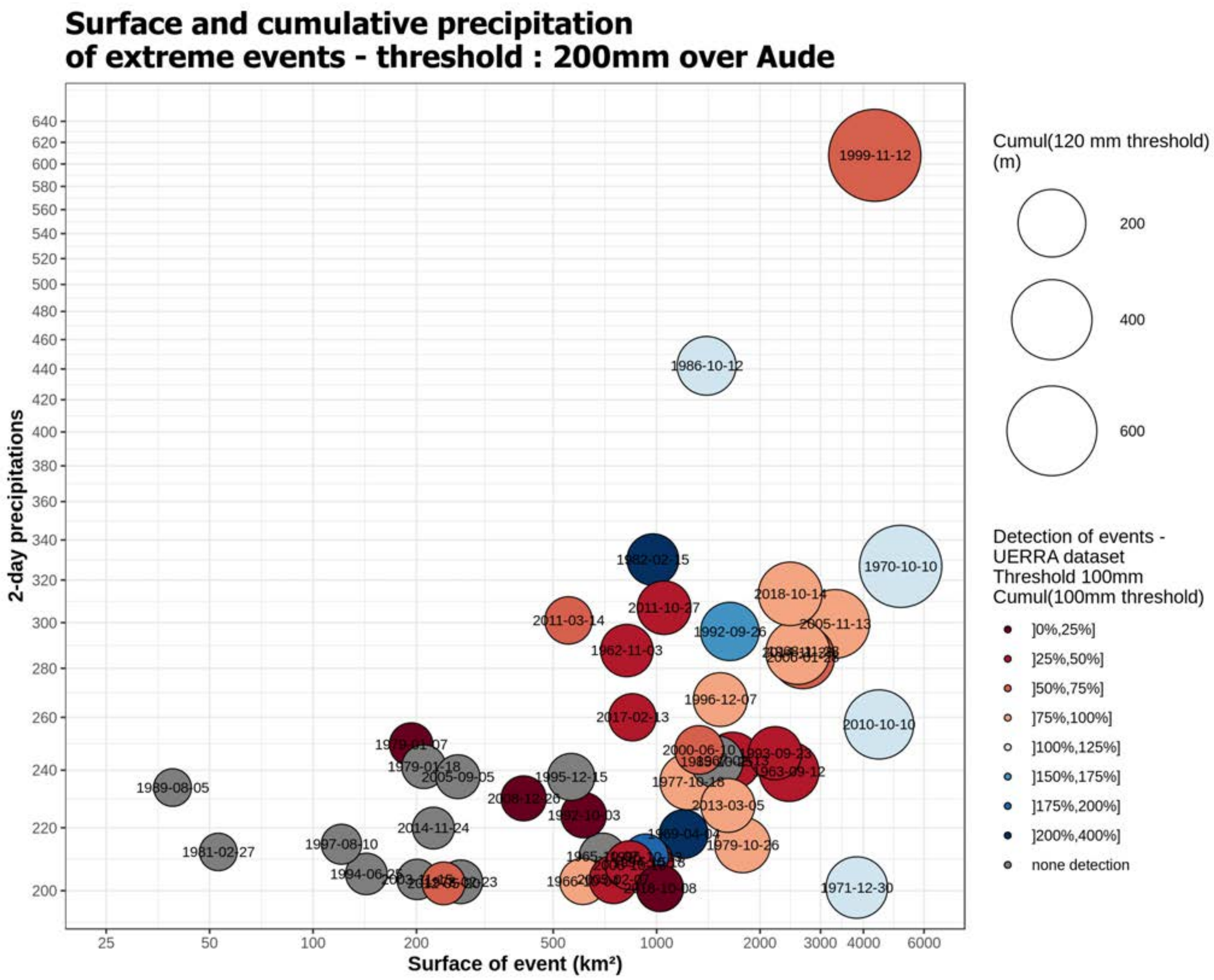


Figure 9 : Surface event (x-axis, km²), 2-day precipitation (y-axis, mm) and total volume over a threshold of 120 mm (size of bubble, m), for PRESCILIA - Relative difference (%) in total volume between UERRA and PRESCILIA datasets

c) Hourly total precipitation evaluation : ERA5-Land versus COMEPHORE

Mapping of RX1D indicator allows to quantify both spatial and intensity accuracies of ERA5-Land over the Mediterranean area. ERA5-Land roughly restituates the extent of rainfall over this zone. As expected, maximums of RX1D indicator are located on the Cevennes mountains. Intensity of extreme rainfall events are strongly underestimated on the whole area, particularly in the Pyrénées Orientales department, Southern Alps and Corsica, where maxima are particularly biased. Mean of 1997-2018 RX1D over Aude department is estimated at 73 mm for Comephore and 48 mm for ERA5-Land. Similarly, maximum of RX1D indicator over this area is 218 mm for Comephore and 75 mm for ERA5-Land.

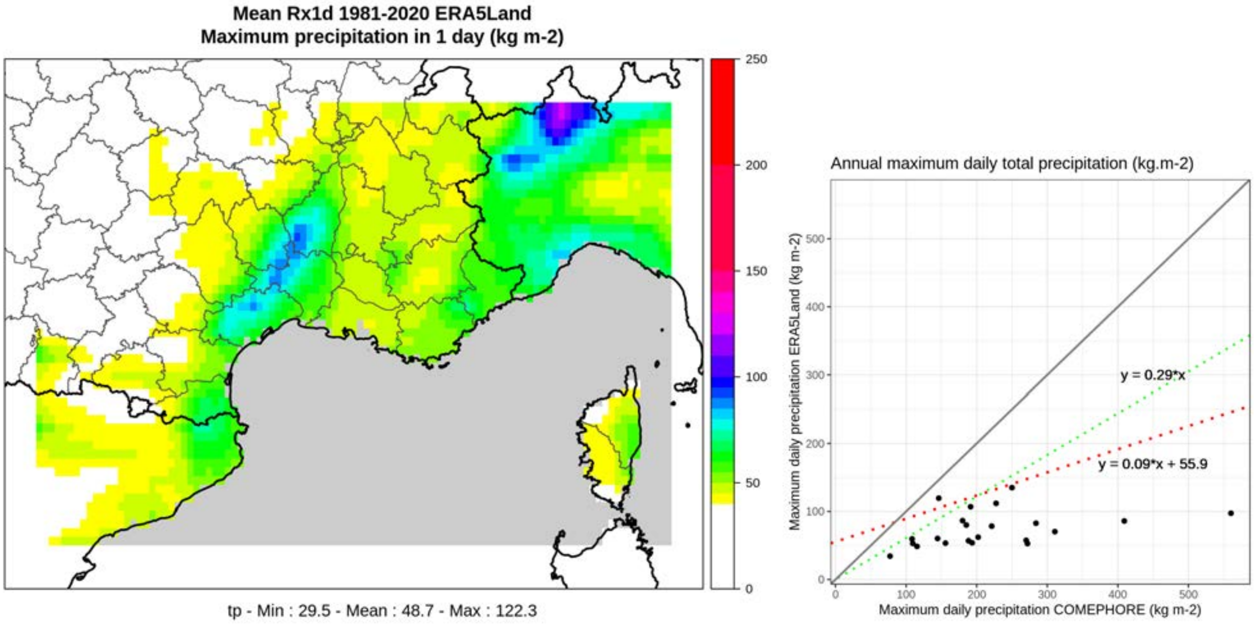


Figure 10 : Left : Mean of annual maximum daily precipitation of ERA5-Land dataset (kg.m-²) - 1981-2018

Right : Annual RX1D (kg.m-²) Aude department - COMEPHORE (x-axis) ERA-Land (y-axis) - 1997-2018

In order to compare COMEPHORE produced at high resolution (1 km resolution) and ERA5-Land (9 km resolution), COMEPHORE dataset is bilinearly interpolated on the ERA5-Land grid, allowing a more realistic comparison of these two datasets. From COMEPHORE regrided dataset (called COMEPHORE-0.1°), we select events with a daily maximum precipitation greater than 120 mm. 61 events are listed between 1997 and 2018, i.e. 1461 hourly data to be processed. In addition, setting a threshold of 0.1 mm, 3-hour cumulative rainfall (mm), surface (km²) and volume (10^2 m^3) are computed for both datasets.

Concerning 3-hour cumulative precipitation, correlation (R2 squared coefficient) is moderate, associated with a factor of about 0.2 between COMEPHORE-0.1° and ERA5-Land data. Associated volumes of precipitation are also clearly underestimated, with an average factor 0.5 between COMEPHORE-0.1° and ERA5-Land. Overall ERA5-Land overestimates surfaces of 3-hour cumulative precipitation during flooding events. 38% of the data present a correct surface evaluation with a relative error between -25% and 25%. 12% of the data have a relative error between +/-25% and +/-50%. The relative error is large, greater than 200%, for 19% of the 3-hour data processed. The NA category (8% of the data) includes cases where there is no precipitation, either in COMEPHORE-0.1° or in UERRA datasets.

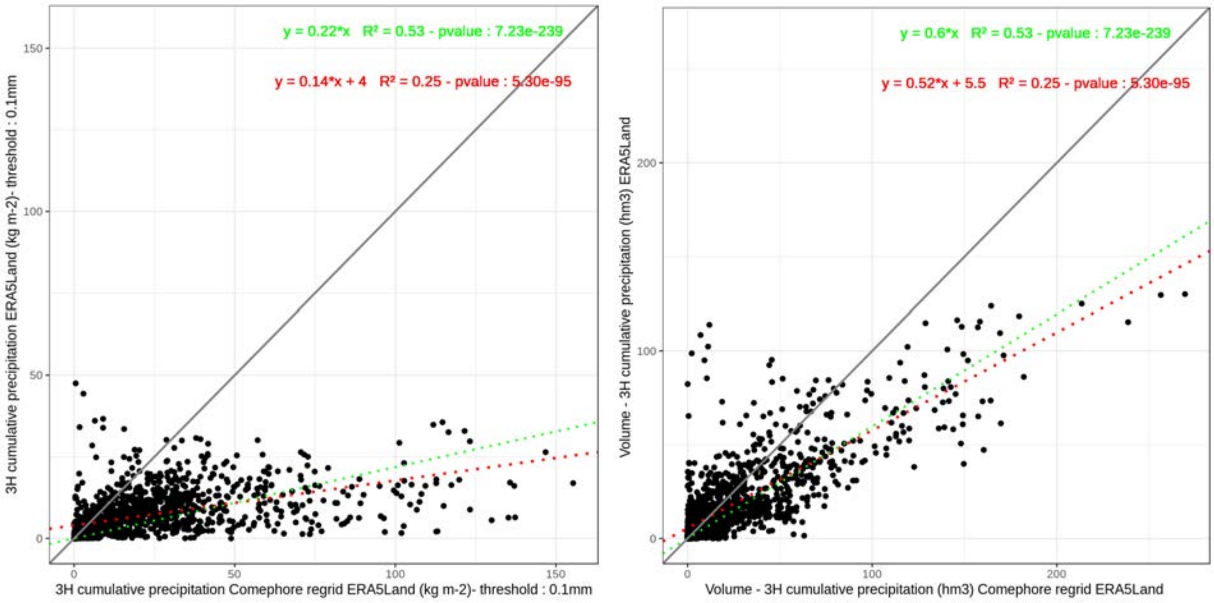


Figure 11 : Left : 3h cumulative precipitation (mm) COMEPHORE-0.1° (x-axis) and ERA5-Land (y-axis)

Right : Volume of 3-hour cumulative precipitation (10^2m^3) COMEPHORE-0.1° (x-axis) and ERA5-Land (y-axis)

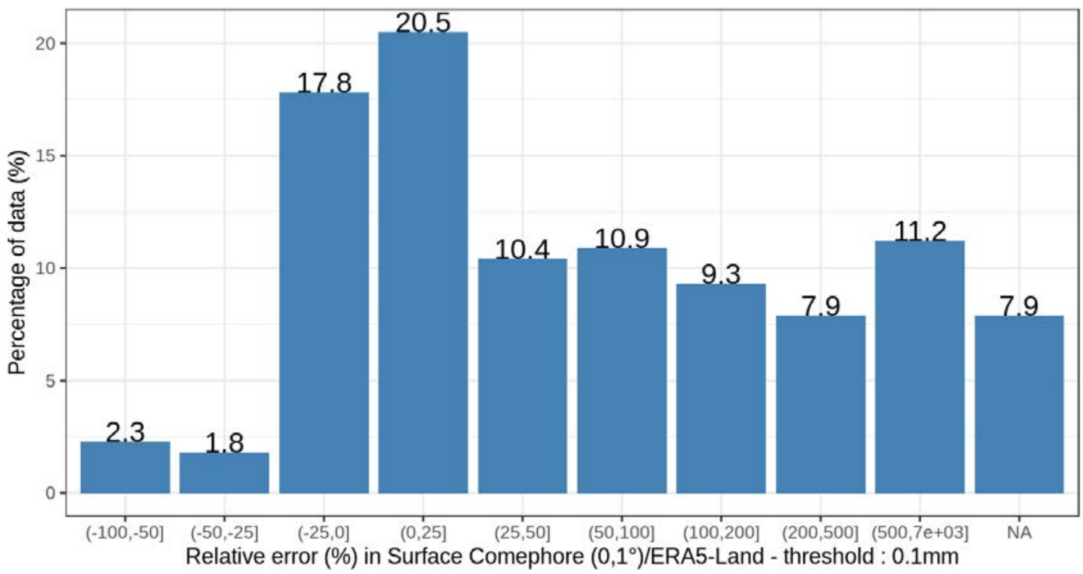


Figure 12 : Relative error in surface provided by ERA5-Land comparing with COMEPHORE-0.1° (x-axis)

d) Soil moisture evaluation: UERRA-HARMONIE, CEMS/EFAS and ERA5 Land versus SIM2

Three Copernicus productions have been evaluated: CEMS-EFAS, ERA5-Land and UERRA-HARMONIE products. Volumetric soil moisture from SIM2 Meteo France chain is used as reference for this comparison.

Soil Wetness Index (SWI) is frequently used to quantify the moisture condition at different depths in the soil taking in account different soil properties of each grid cell (raw soil moisture, wilting point and field capacity). Unfortunately, SWI is not directly available and can not be downloaded using the Copernicus climate data store. We used instead normalised volumetric soil moisture.

Four majors events on Aude departement are analysed : 12/11/1999, 10/10/2010, 28/11/2014 and 14/10/2018

a) For each dataset and each soil layer and grid point, a normalization of the soil moisture is carried out by the maximum observed soil moisture during the period. This normalisation overcomes the nature of the soil taken into account by the different models..

b) Convex hull for each flooding event is generated, based on 200 mm isohyetal line simulated by PRESCILIA Meteo France datasets.

c) A aggregate volumetric soil moisture ($m^3.m^{-3}$) is carried out over the convex hull, according to soil depths specific to each model and using the following terms :

<u>CEMS-EFAS vs SIM2</u>

For CEMS-EFAS, data are available for 3 soil layers. We focused analysis on the first layer (or surface layer), which is a 5 cm constant depth over the grid.

$$vsm\ (SIM2\ 0cm - 1cm) \times ep1 + vsm(SIM2\ 1cm - 4cm) \times ep2$$

$$\approx vsm\ (CEMS - EFAS\ 0cm - 5cm)$$

with $ep1 = 0.25,\ ep2 = 0.75\ weighting\ soil\ depth\ factors$

<u>ERA5-Land vs SIM2</u>

For ERA5-Land reanalysis, data are available for 4 soil layers and depth layers are not grid dependent. The lower boundary of the studied surface layer is 7 cm.

$$vsm\ (SIM2\ 0cm - 1cm) \times ep1 + vsm\ (SIM2\ 1cm - 4cm) \times ep2$$

$$+ vsm\ (SIM2\ 4cm - 10cm) \times ep3 \approx vsm\ (ERA5 - Land\ 0cm - 7cm)$$ with

$$ep1 = 0.10,\ ep2 = 0.30\ and\ ep3 = 0.60\ ,\ weighting\ soil\ depth\ factors$$

UERRA-HARMONIE vs SIM2

UERRA-HARMONIE soil model has 3 vertical levels, which are not are not related with a constant depth over the grid. The first layer representing the surface is used as below, comparing to SIM2 surface layer.

$$vsm\ (SIM2\ 0cm - 1cm) \approx vsm\ (UERRA - HARMONIE\ soil\ layer\ 1\ )$$

Taylor diagram provides a synthetic comparison between different datasets in terms of three statistics : correlation (Pearson coefficient), global error (centered root mean square error) and normalised standard deviation.

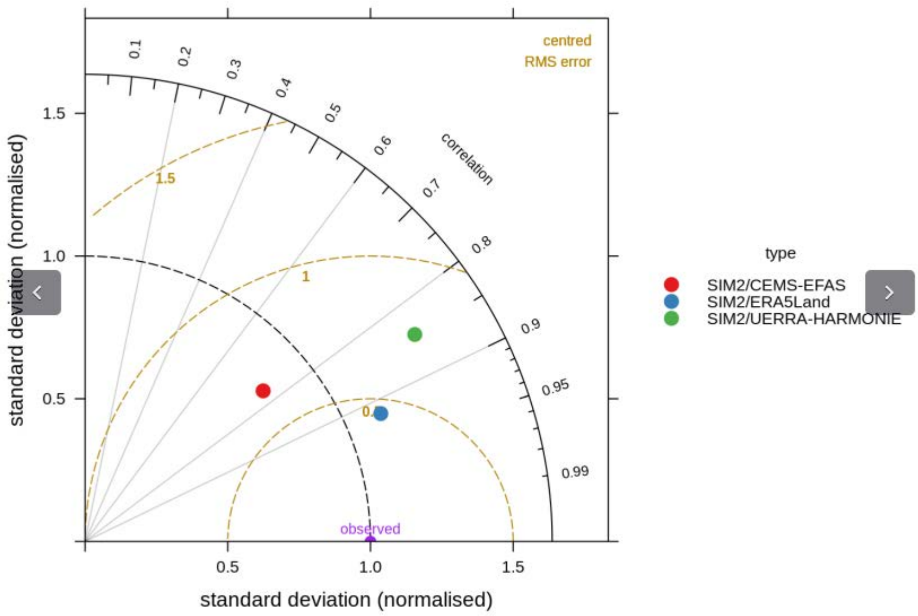


Figure 13 : Taylor Diagram throughout flooding events for CEMS-EFAS,ERA5-Land, UERRA-HARMONIE compared to SIM2 product

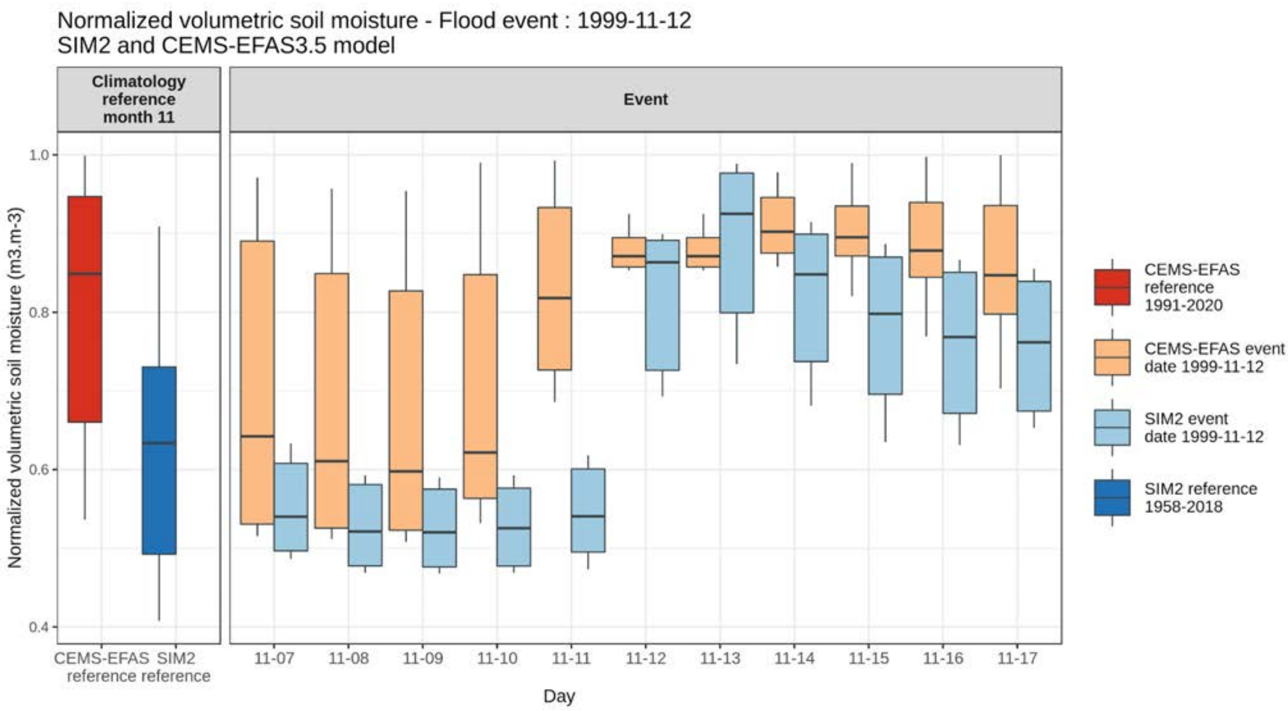
Set of data	Correlation coefficient	Normalised standard deviation	Centered RMS error
SIM2/EFAS	0.77	0.82	0.65
SIM2/ERA5-Land	0.92	1.13	0.45
SIM2/UERRA HARMONIE	0.85	1.36	0.74

Diagram Taylor (correlation coefficient, normalised standard deviation) scores

Pearson coefficient ranges from 0.77 (SIM2/EFAS) to 0.92 (SIM2/ERA5-Land) indicating a good agreement of trends. ERA5-Land reanalysis carries out the best performance in terms of correlation (R=0.92), dispersion (sd=1.13) and global error (centered rms=0.45).

Flood event 12/11/1999 : SIM2/CEMS-EFAS

Correlation between SIM2 and CEMS-EFAS is moderate. Median values are always higher with CEMS-EFAS along the flood event, also in climate November norms. CEMS-EFAS correctly set soil moisture gap on November 11 (median : 0.82 $m^3.m^{-3}$, maximum : 0.99 $m^3.m^{-3}$), one day before SIM2 platform (median : 0.86 $m^3.m^{-3}$, maximum : 0.90 $m^3.m^{-3}$). Maximum soil moisture of the flooding area predicting by CEMS-EFAS is around 1.00 $m^3.m^{-3}$, while SIM2 provides a decreasing of this parameter (0.90, 0.88 and 0.85 $m^3.m^{-3}$ on 15/11, 16/11, 17/11 respectively).

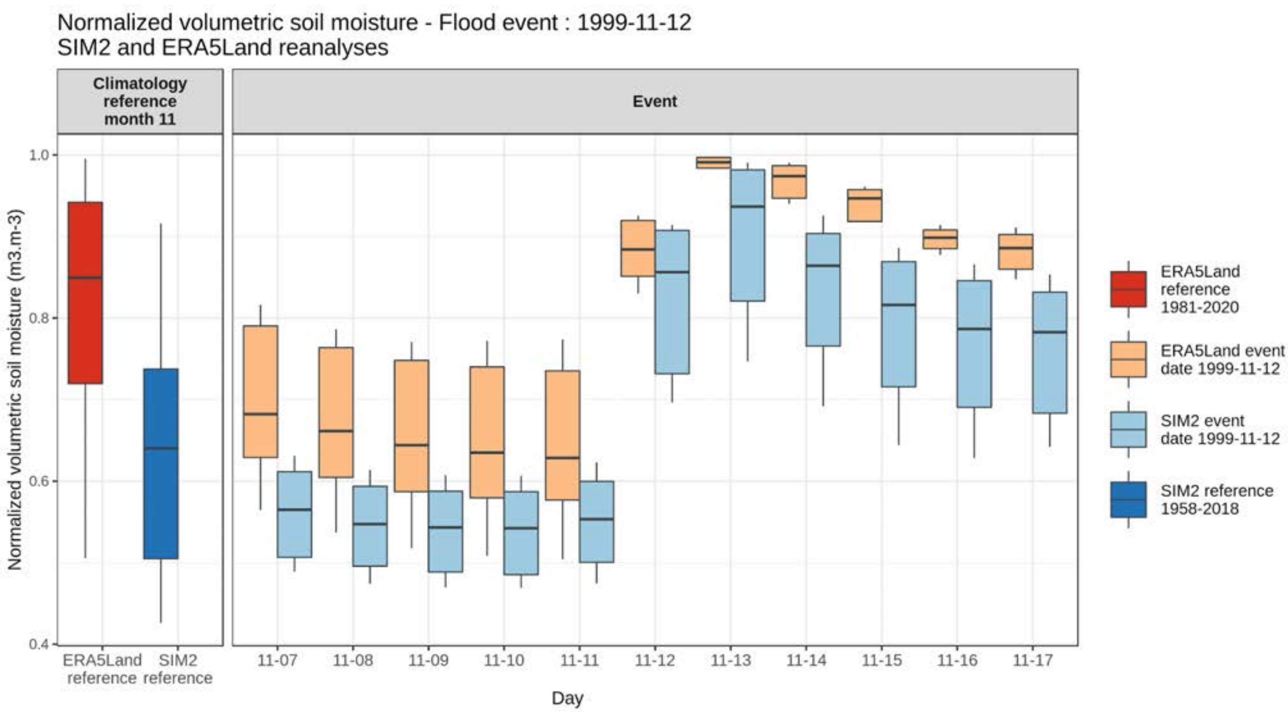


		11-07	11-08	11-09	11-10	11-11	11-12	11-13	11-14	11-15	11-16	11-17
Median	SIM2	0,54	0,52	0,52	0,53	0,54	0,86	0,93	0,85	0,80	0,77	0,76
	CEMS-EFAS	0,64	0,61	0,60	0,62	0,82	0,87	0,87	0,90	0,90	0,88	0,85
Maximum	SIM2	0,63	0,59	0,59	0,59	0,62	0,90	0,99	0,91	0,89	0,87	0,86
	CEMS-EFAS	0,97	0,96	0,95	0,99	0,99	0,92	0,92	0,98	0,99	1,00	1,00

Figure 14 : Boxplot of minimum, quantile 10, median, quantile 90, maximum of normalized volumetric soil moisture - SIM2 and CEMS-EFAS data - from 1999/11/07 to 1999/11/17

Flood event 12/11/1999 : SIM2/ERA5-Land

SIM2 and ERA5-Land soil moisture are closely correlated. Median value over the flooding area rises from 0.76 $m^3.m^{-3}$ on November 11 to 0.92 $m^3.m^{-3}$ November 12. This gap of soil moisture is well reproduced by ERA5-Land. On November 13, ERA5-Land displays a high soil moisture value, close to 1.00 $m^3.m^{-3}$, all over the area. Soil moisture gradually decreases, from 0.99 $m^3.m^{-3}$ on November 14 to 0.91 $m^3.m^{-3}$ on November 17, in agreement with SIM2 trend. Dispersion of ERA5-Land values over the area after flooding is low, values ranging between 0.85 $m^3.m^{-3}$ and 0.95 $m^3.m^{-3}$.

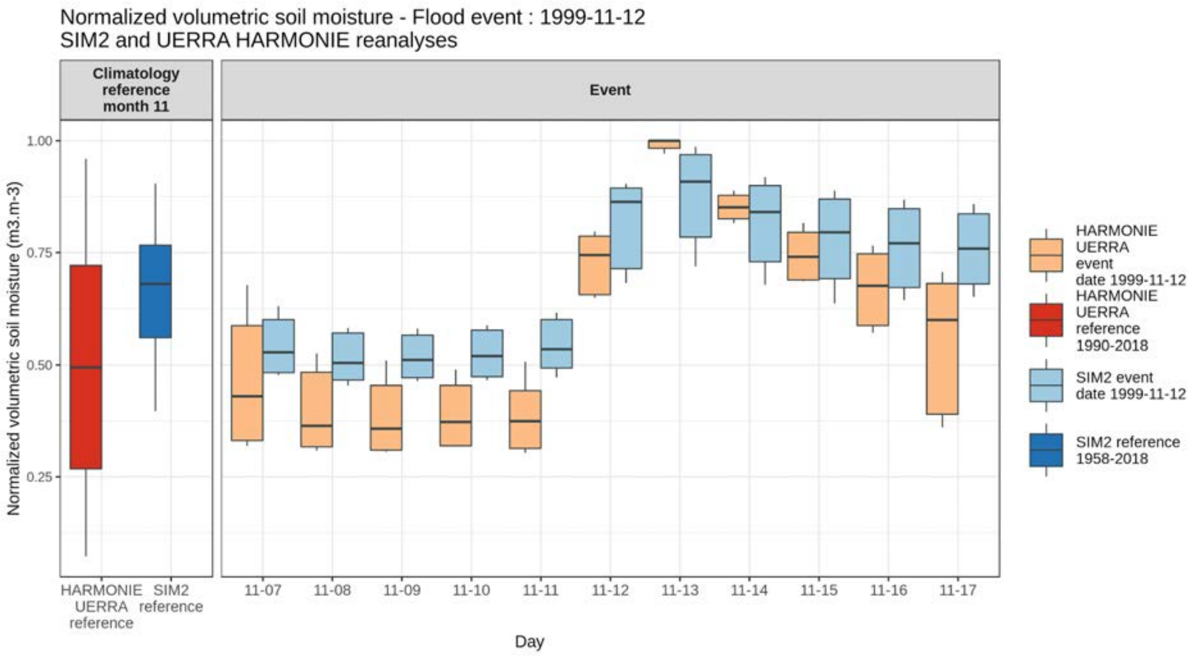


		11-07	11-08	11-09	11-10	11-11	11-12	11-13	11-14	11-15	11-16	11-17
Median	SIM2	0,56	0,55	0,54	0,54	0,55	0,86	0,94	0,87	0,82	0,79	0,78
	ERA5-Land	0,68	0,66	0,64	0,63	0,63	0,88	0,99	0,97	0,95	0,90	0,88
Maximum	SIM2	0,63	0,61	0,61	0,61	0,62	0,91	0,99	0,93	0,89	0,87	0,85
	ERA5-Land	0,81	0,78	0,76	0,76	0,76	0,92	1,00	0,99	0,96	0,91	0,91

Figure 15 : Boxplot of minimum, quantile 10, median, quantile 90, maximum of normalized volumetric soil moisture - SIM2 and ERA5-Land data - from 1999/11/07 to 1999/11/17

Flood event 12/11/1999 : SIM2/UERRA-HARMONIE

Such as ERA5-Land, UERRA-HARMONIE soil moisture follow SIM2 trends. UERRA-HARMONIE provides average values lower than SIM2, also in climatology norm of November. Median values are estimated to 0.37 $m^3.m^{-3}$ on 11/11, 0.74 $m^3.m^{-3}$ on 12/11 and 1.00 $m^3.m^{-3}$ on 13/11. Values gradually decrease after flooding event, from 0.85 $m^3.m^{-3}$ (14/11) to 0.60 $m^3.m^{-3}$ (17/11).



		11-07	11-08	11-09	11-10	11-11	11-12	11-13	11-14	11-15	11-16	11-17
Median	SIM2	0,53	0,50	0,51	0,52	0,54	0,86	0,91	0,84	0,80	0,77	0,76
	UERRA	0,43	0,36	0,36	0,37	0,37	0,74	1,00	0,85	0,74	0,68	0,60
Maximum	SIM2	0,63	0,58	0,58	0,59	0,62	0,90	0,99	0,92	0,89	0,87	0,86
	UERRA	0,68	0,53	0,51	0,49	0,51	0,80	1,00	0,89	0,82	0,77	0,71

Figure 16 : Boxplot of minimum, quantile 10, median, quantile 90, maximum of normalized volumetric soil moisture - SIM2 and UERRA HARMONIE data - from 1999/11/07 to 1999/11/17

d) River discharge evaluation

Introduction

The CEMS-EFAS product was evaluated using daily observations from hydrometric stations, managed and supplied by the Departmental Direction of Territories of Aude (DDT11). The evaluation focused on extreme precipitation events, identified by the PRESCILIA Meteo France dataset (28 extremes events between 1991 and 2020).

46 hydrometric stations in the department of Aude were identified in the initial dataset. A selection was made in order to consolidate this data, according to the following criteria :

a) For each identified event, a 5-days window around the event is selected. This allows to perform initial state of soil in the concerned flood area.
b) For assuring a good completeness of the dataset, all observed data with quality codes "Doubtful" and "Unknown strong" were excluded. Data coverage over the 11-day window is expected to be up to 70%.
c) Hydrometric network of Aude covers various geographic and hydrologic situations. Small streams (creeks) were eliminated from the analysis. Datasets review finally focus on 13 hydrometric stations on Aude (5), Fresquel (2), Orbiel (1), Orbieu (1), Cesse (1), Rebenty (1), Argent-Double (1), Rougeanne (1) rivers.
d) A grid cell of CEMS-EFAS model is assigned to each hydrometric station, according to a geographical criteria (nearest neighbor using euclidean distance).

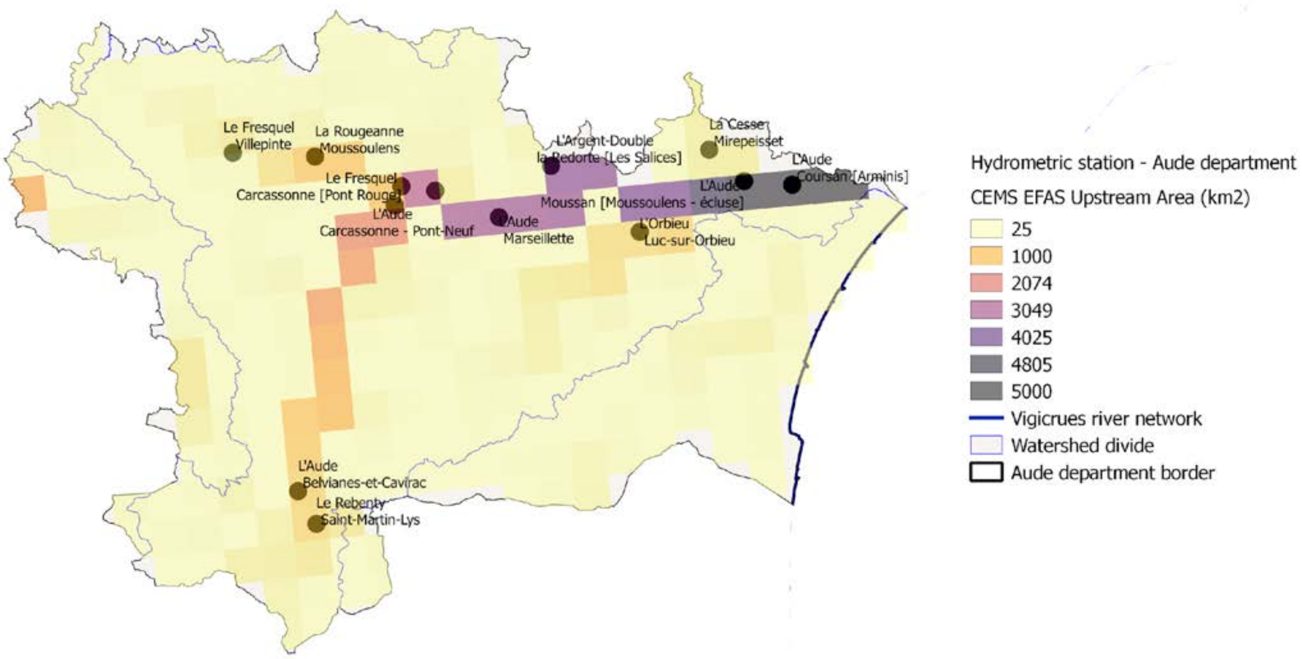


Figure 17 : Hydrometric stations of Aude department and Upstream area (km²) grid of CEMS-EFAS model

Scoring

Many specific scores for hydrological model evaluation are available (hydroGOF R package, Zambrano-Bigiarini M., 2020). 3 scores were selected in this analysis, in order to assess the ability of the CEMS-EFAS model to reproduce temporal variations during extreme flooding, and also to quantify global accuracy of this model.

1) King-Gupta Efficiency (KGE) developed by Gupta and al., 2009, is largely used in hydrological model evaluation and supplies a global score performance of the model, in terms of bias, correlation and variability.
Objective function of KGE is defined by :

$$KGE = 1 - \sqrt{(r - 1)^2 + (vr - 1)^2 + (\beta - 1)^2}$$

with :
rPearson correlation coefficient
$\beta = \frac{\mu_s}{\mu_o}$ratio of mean simulated and mean observed values
$vr = \frac{\sigma_s}{\sigma_o}$ratio of simulated and observed standard deviation

Kling-Gupta efficiency ranges from -Inf to 1. Essentially, the closer to 1, the more accurate the model is. 5 hydrometric stations note a very poor performance, associated with negative KGE metric and concerning tributary streams of Aude river (Argent-Double, Rougeanne, Rebenty and Fresquel rivers). Looking at the upstream area data raster provided by CEMS-EFAS, we can see for example that the station of Argent-Double at La Redorte village is located in a cell, associated with an upstream area of 3500 km². The Argent-Double is a small tributary of the Aude river (average flow of 1m^3/s), and can not be correctly restored by CEMS-EFAS platform, operating at a resolution of 5 km. Same bias is noticed for Fresquel river in Carcassonne hydrometric station and Rebenty river in Saint-Martin-Lys. 2 hydrometric stations provide a correct KGE score : Aude river in Belviannes-et-Cavirac (0.53) and Aude river in Moussan (0.63).

Station name	EFAS upstream area (km²)	KGE score
L'Argent-Double à la Redorte [Les Salices]	3500	-29,62
La Rougeanne à Moussoulens	850	-7,72
Le Rebenty à Saint-Martin-Lys	650	-5,62
Le Fresquel à Villepinte	375	-5,14
Le Fresquel à Carcassonne [Pont Rouge]	2800	-4,36
L'Orbieu à Luc-sur-Orbieu	575	-0,08
L'Aude à Coursan [Arminis]	4950	-0,02
L'Aude à Carcassonne - Pont-Neuf	900	0,35
La Cesse à Mirepeisset	300	0,44
L'Aude à Marseillette	3200	0,45
L'Orbiel à Bouilhonnac [Villedubert]	275	0,49
L'Aude à Belvianes-et-Cavirac	700	0,53

L'Aude à Moussan [Moussoulens - écluse]	4900	0,63

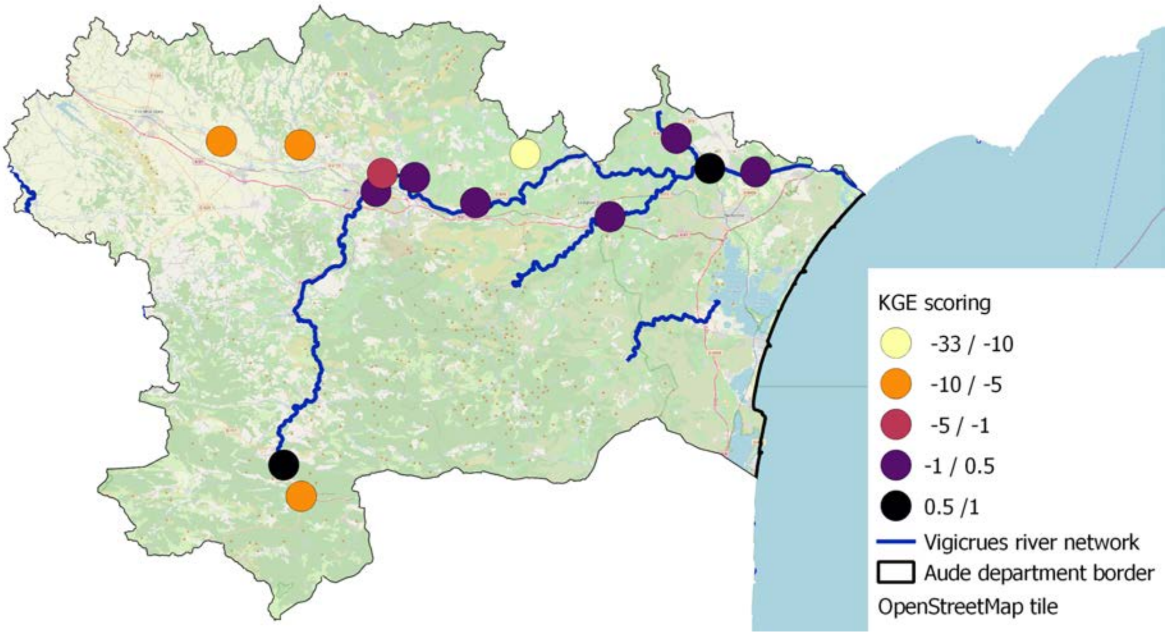


Figure 18 : KGE score – hydrometric stations of Aude department

2) The Pearson correlation coefficient (r) measures linear correlation between simulated and observed data. A value of r=1 is total positive linear correlation, r= −1 indicates a total negative linear correlation, while r=0 is no linear correlation. Pearson coefficient is also a component of KGE score. R coefficient ranges from 0.43 (Rougeanne at Moussoulens station) to 0.71 for Aude river in Coursan. R coefficient is roughly proportional with upstream area simulated by CEMS-EFAS platform. R correlation should be interpreted with caution : an intermediate or relative good R score may not reflect an exact agreement between model and observation. For instance, Argent-Double hydrometric station has a R score of 0.61. As seen previously, grid cells of CEMS-EFAS model related to this station may rather describe Aude river than Argent-Double river.

Station name	EFAS upstream area (km²)	r score
La Rougeanne à Moussoulens	850	0,43
Le Fresquel à Villepinte	375	0,44
La Cesse à Mirepeisset	300	0,48
L'Orbiel à Bouilhonnac [Villedubert]	275	0,52
Le Rebenty à Saint-Martin-Lys	650	0,53
L'Orbieu à Luc-sur-Orbieu	575	0,56
L'Aude à Belvianes-et-Cavirac	700	0,56
L'Aude à Carcassonne - Pont-Neuf	900	0,60
L'Argent-Double à la Redorte [Les Salices]	3500	0,61
Le Fresquel à Carcassonne [Pont Rouge]	2800	0,62
L'Aude à Marseillette	3200	0,64
L'Aude à Moussan [Moussoulens - écluse]	4900	0,65
L'Aude à Coursan [Arminis]	4950	0,71

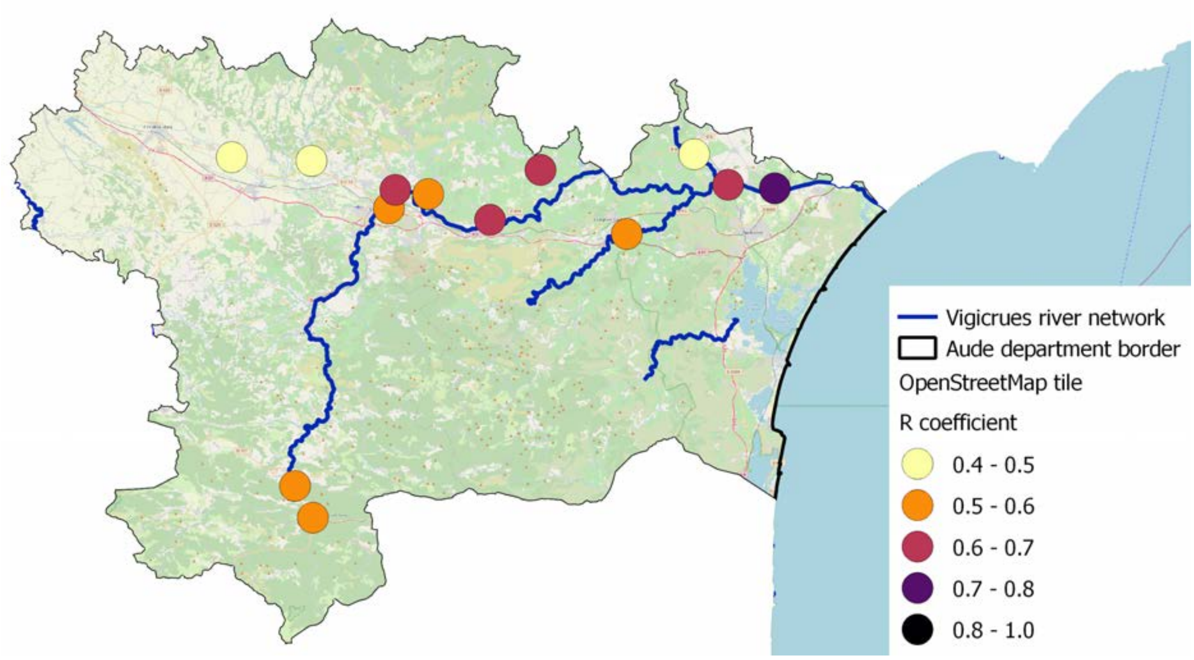


Figure 19 : Pearson correlation score – hydrometric stations of Aude department

3) Root mean square error (RMSE) is a measure of the systematic mean square error between simulated and observed values. We use normalised root mean square error (NRMSE in percent) which allows comparison over the 13 hydrometric stations. A null RMSE indicates a perfect match between model and observation.

$$NRMSE = 100\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(S_i - O_i\right)^2}}{sd}$$ with sd, standard deviation of observations

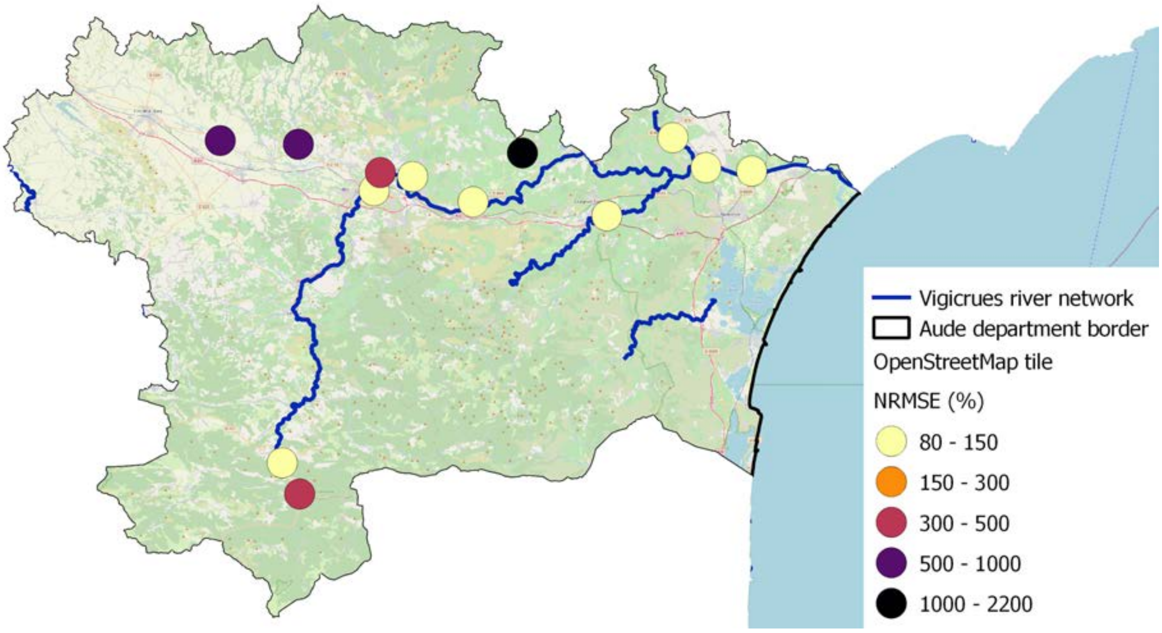


Figure 20 : NMRSE (%) – hydrometric stations of Aude department

NRMSE scores are slightly poor for all stations. 7 stations have an NRMSE between 80% and 100%. The corresponding stations are those with good or intermediate KGE scores, and in particular all the hydrometric stations of the Aude river. Concerning tributary streams of the Aude rivers (Argent-Double, Fresquel,Rebenty, Rougeanne rivers), the systematic errors made by CEMS-EFAS are large, estimated greater than 300%.

Station name	EFAS upstream area (km²)	NRMSE score (%)
L'Aude à Carcassonne - Pont-Neuf	900	81,3
L'Aude à Moussan [Moussoulens - écluse]	4900	82,1
L'Aude à Belvianes-et-Cavirac	700	87,1
L'Orbiel à Bouilhonnac [Villedubert]	275	90,9
L'Aude à Marseillette	3200	91,0
L'Orbieu à Luc-sur-Orbieu	575	91,8
La Cesse à Mirepeisset	300	92,8
L'Aude à Coursan [Arminis]	4950	137,2
Le Fresquel à Carcassonne [Pont Rouge]	2800	377,4
Le Rebenty à Saint-Martin-Lys	650	486,0
Le Fresquel à Villepinte	375	521,1
La Rougeanne à Moussoulens	850	747,4
L'Argent-Double à la Redorte [Les Salices]	3500	2031,7

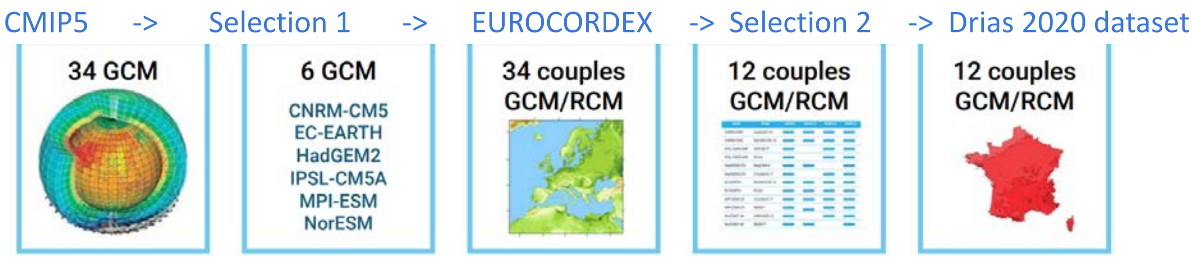
4. Evaluation of C3S products - future period

a) DRIAS-2020 dataset description

DRIAS-2020, French climate service aims to provide regionalized climate projections from Eurocordex simulations to better cover the expected variability of several meteorological variables in future climate over the Metropolis.
In order to optimize data processing (which requires significant computing resources), a selection of climate models was made from the sixty or so models proposed in the EUROCORDEX project. In DRIAS 2020 dataset, 8 to 12 simulations (RCM/GCM pairs from Cordex project) for each of the three scenarios RCP2.6, RCP4.5 and RCP8.5, have been selected according to different selection criteria :

- selection of 12 GCM/RCM pairs,
- availability of simulations for at least two emission scenarios,
- use of GCMs considered to be the most realistic for Europe to force RCMs,
- the consideration of a diversity of RCM,
- rejection the of GCM/RCM pairs affected by known errors,
- preferential selection of RCMs from French climate modeling centers,
- optimization of the dispersion of climate change signals over France by the selected couples,
- preferential selection of couples with coherent physics between GCM and RCM models

This set of simulations provides the best possible coverage of the range of future changes in temperature and precipitation over France, as well as the uncertainty associated with these changes.



GCM	RCM	HISTO	RCP2.6	RCP4.5	RCP8.5
CNRM-CM5	Aladin63 V2	▬	▬	▬	▬
CNRM-CM5	Racmo22E v2	▬	▬	▬	▬
IPSL-CM5A-MR	WRF381P	▬		▬	▬
IPSL-CM5A-MR	RCA4	▬		▬	▬
HadGEM2-ES	RegCM4-6	▬	▬		▬
HadGEM2-ES	CCLM4-8-17	▬		▬	▬
EC-EARTH	Racmo22E v2	▬	▬	▬	▬
EC-EARTH	RCA4	▬	▬	▬	▬
MPI-ESM-LR	CCLM4-8-17	▬	▬	▬	▬
MPI-ESM-LR	REMO*	▬	▬	▬	▬
NorESM1-M	HIRHAM5 v3	▬		▬	▬
NorESM1-M	REMO**	▬	▬		▬

** REMO 2009 ; ** REMO 2015*

Figure 21 : 12 RCM/GCM pairs used in DRIAS dataset. 30 regionalized simulations from CORDEX ensemble declined in 3 Representative Concentration Pathway - emission scenarios.

b) Bias correction method

In general, regional climate models cannot be used directly for local-scale impact studies because they are biased in relation to observations. It is essential to implement a correction method of climate models in order to be able to compare the results of the projections with the current or past climate and to be able to calculate a large number of climate indicators based in particular on absolute thresholds.

In DRIAS-2020 project, the ADAMONT method mapping (Verfaillie and al., 2017), has been adapted and used to correct bias. ADAMONT method is consolidation of the so-called "quantile-quantile" statistical adjustment method developed by Déqué M. and al. Main computing steps are as follows :

- Observational dataset, used as climate reference for quantile mapping is SAFRAN meteorological analysis (Durand and al 1993), which provides a set of atmospheric variables, such as temperature, precipitation, wind speed, solar radiation and humidity at a 8km resolution over France and hourly time steps. Reference period used is 1980 -2011.
- Quantile-quantile correction method is applied to CORDEX RCM (1976-2005) data at the daily time step by taking into account seasons and weather types. A linear interpolation is used for quantile values between the quantile values specifically computed (99th percentile values as well as 0.5th and 99.5th values). For RCM values greater than the 99.5 % quantile, a constant adjustment based on the value of this last quantile is applied in order to allow for new extremes (Verfaillie and al. 2017).
- Then, an hourly disaggregation of the corrected daily data is performed, using hourly SAFRAN data and searching analogues approach.
- Correction is performed for each grid point. Quantile-quantile historical correction is applied on future periods of the climate projections.

In addition, some climate models can largely overestimated extreme of precipitation or may have outlier values. For this purpose, a threshold, depending on the grid point, and based on 5 times of daily maximum of total precipitation of SAFRAN reanalysis is applied. The correction threshold is between 1000mm and 2000mm in the Mediterranean perimeter. Note that this number of outliers (less than 2000 grid points/day) is very low compared to the entire Drias 2020 dataset (more than 1,200,000 days of simulation on 9892 grid points). Thus, it can be considered that this thresholding does not affect the analysis of extreme precipitation values of the CORDEX data.

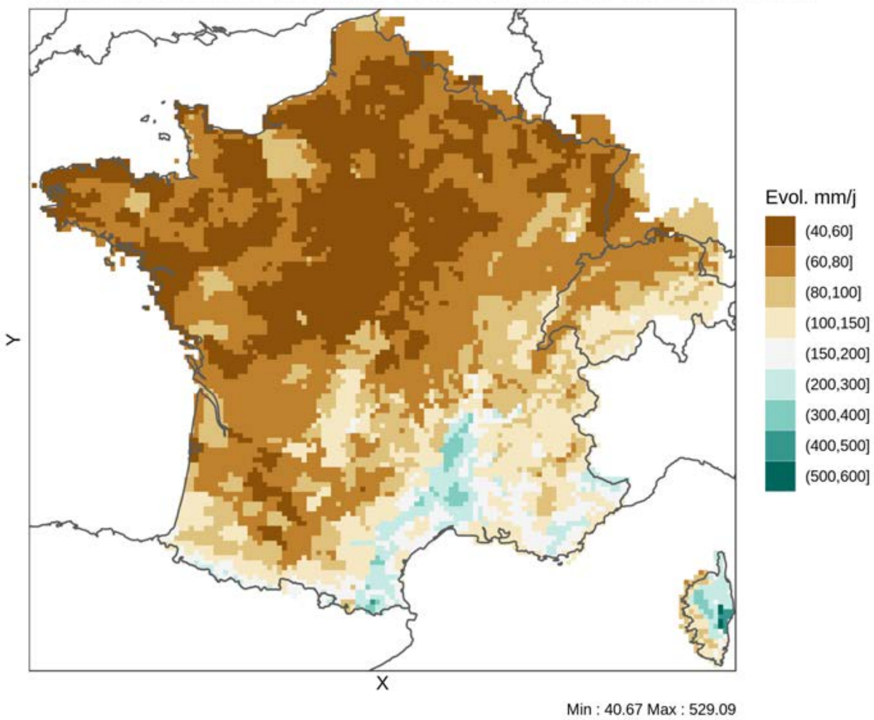


Figure 22 : Maximum of daily total precipitation between 1959 and 2015 – SAFRAN reanalysis

c) Impact of the bias correction method on CORDEX climate data

In this part, we evaluate the impact of Adamont method on the extremes of precipitation. Since the Adamont method may correct extremes of the distribution marginally, we analyze the impact of the Adamont method, using either raw CORDEX data or DRIAS 2020 data. This also allows testing the reproducibility of data analysis on other territories.

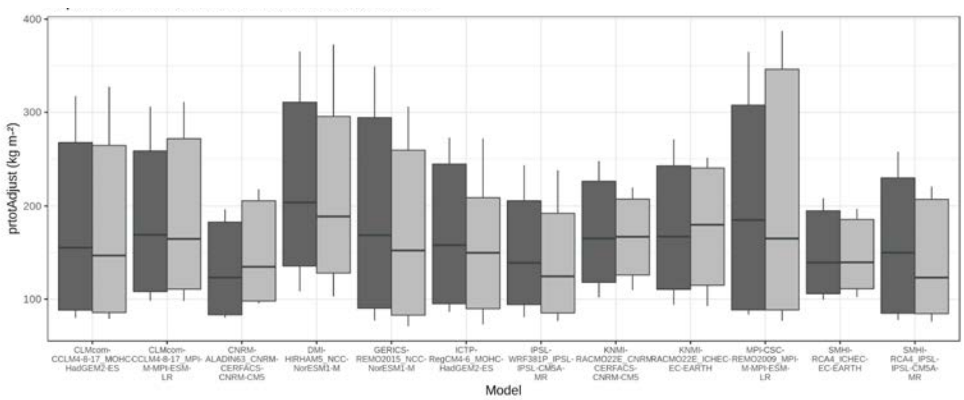
The relative bias of daily precipitation maxima between raw and corrected simulations is analyzed to quantify the impact of the quantile-quantile correction method. The study area is the Languedoc-Roussillon region, defined by 5 French departments : Eastern Pyrenees , Aude, Herault, Gard, Lozere administrative departments.

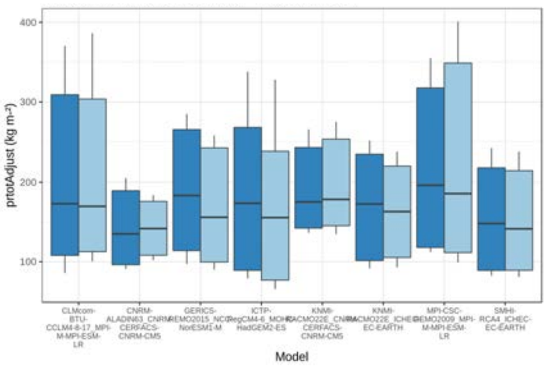
The following boxplots present the dispersion of the values of the mean annual precipitation maximum (rx1day), according to RCM/GCM pairs, and for 4 experiments : historical (1976-2005), RCP2.6, RCP4.5, RCP8.5 (mean over 2071-2100 period). Dispersion of values is apprehended by 5 statistics: 5th ,10th percentiles, median, 90th, 95th percentiles computed on the study area.

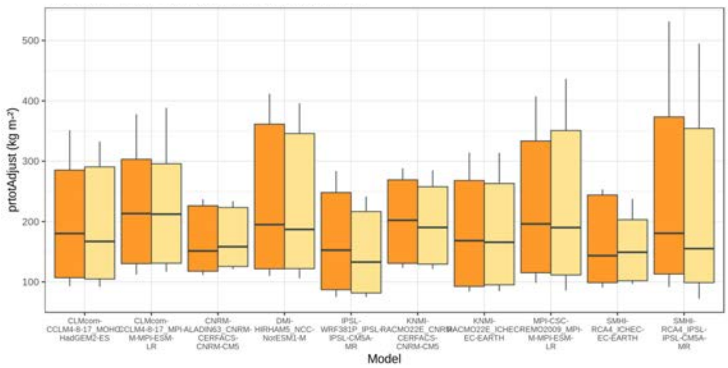
Regardless of experiment (historical or RCP emission scenario) or climate model, bias of annual maximum 1-day precipitation (rx1day indicator) between raw and corrected simulations is low over the grid. The following table summarizes the quantile values over the Languedoc-Roussillon area for the CNRM-ALADIN63/CNRM-CERFACS-CNRM-CM5 climate model.

		P5	P10	Median	P90	P95
Historique 1976-2005	raw	95	98	135	206	217
	corrected	80	83	123	183	196
RCP 2.6 2071-2100	raw	102	108	142	176	184
	corrected	91	96	135	189	205
RCP 4.5 2071-2100	raw	121	126	158	223	234
	corrected	111	118	151	226	237
RCP 8.5 2071-2100	raw	104	110	147	213	237
	corrected	87	94	142	198	212

Figure 23 : Value of 5th, 10th percentiles, median, 90th and 95th percentiles (kg.m-²) for raw and corrected Eurocordex data – Languedoc-Roussillon grid







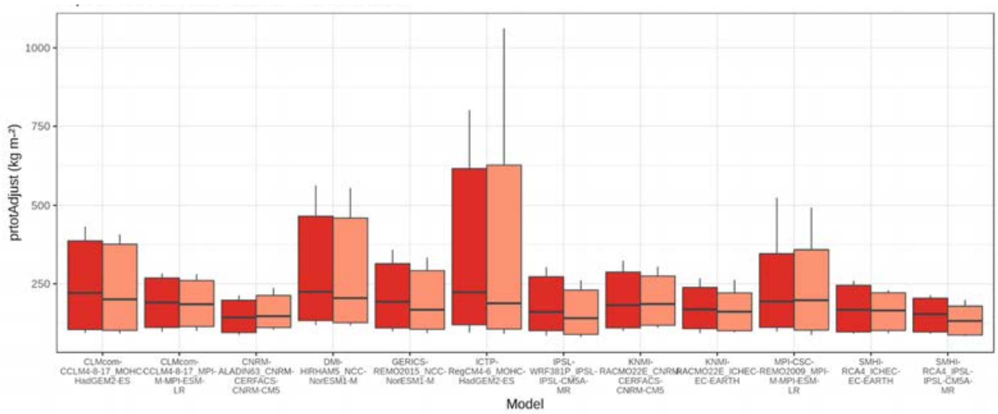


Figure 24 : Boxplots of 5th, 10th percentiles, median, 90th and 95th percentiles (kg.m-²) for raw (light color) and corrected Eurocordex data (dark color) – Languedoc-Roussillon grid - Historical (top), RCP2.6 (middle-left) and RCP4.5 (middle-right), RCP8.5 (bottom) experiments.

Relative bias between raw and corrected rx1day data were also mapped (see maps below for the CNRM-ALADIN63/CNRM-CERFACS-CNRM-CM5 model). The average relative biases are small over the area, in agreement with the boxplots. The average bias for this model is 13.4% for the historical experiment, 4.3%, 4.2% and 6.9% respectively for the RCP2.6, RCP4.5 and RCP8.5 scenarios for the 2071-2100 time horizon.

By contrast, relative bias may be relatively large on particular grid points. For instance, on these grid points, relative bias ranges from -43% to +99% for historical experiment. Concerning RCP scenarios, extreme relative bias ranges roughly from -40% to +60%.

This point should be considered with caution if analyses are to be reproduced using the raw Eurocordex data, directly downloaded from the Copernicus climate data store. It is also advisable to study the extreme precipitation statistics over a relatively large area, or to study beforehand the bias between raw and Adamont corrected Eurocordex model, if one wants to work on one/some particular grid points.

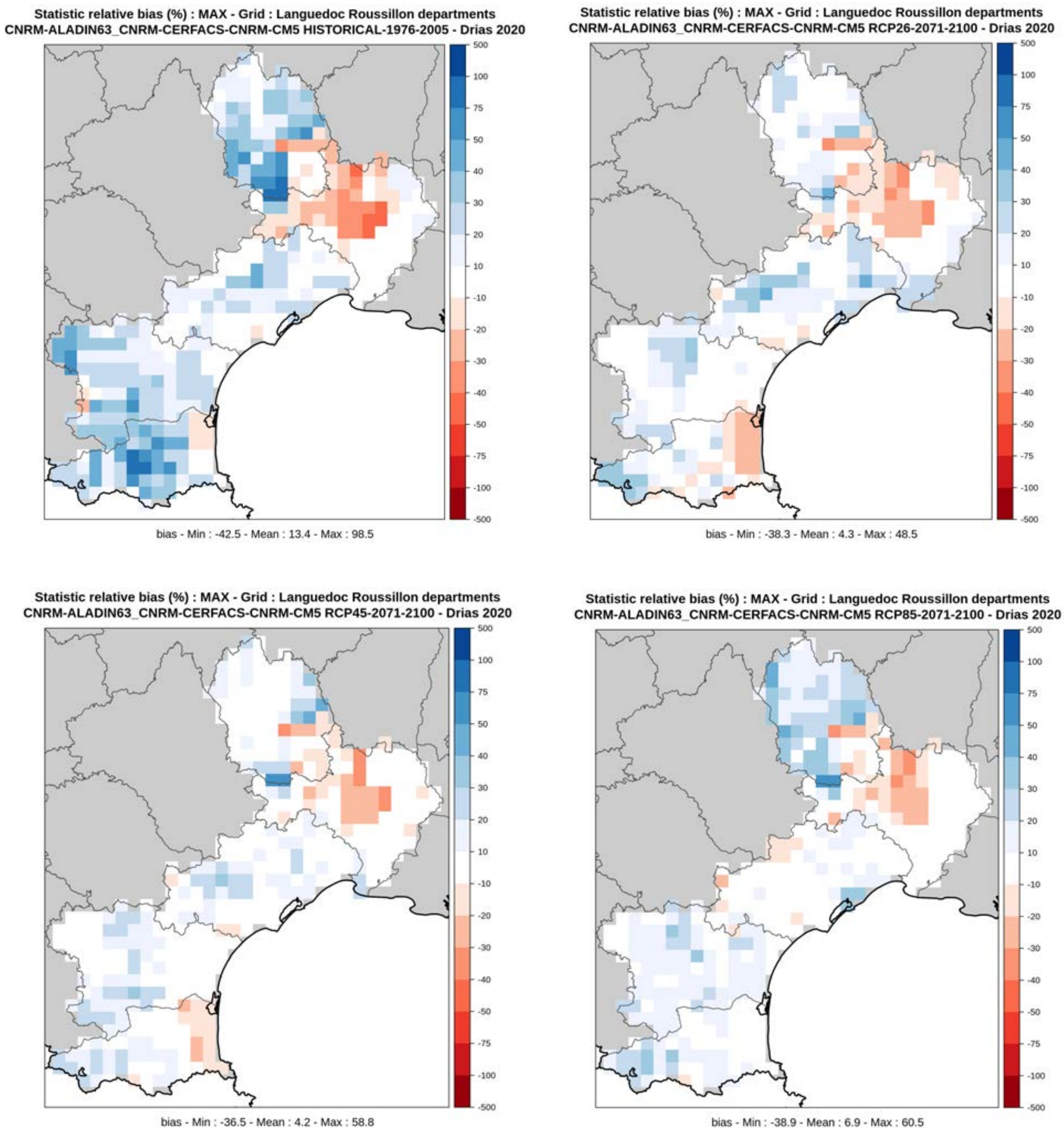


Figure 25 : Relative bias between raw and corrected rx1day (%) - Historical (1976-2005 mean – left top) and RCP2.6 (right top), RCP4.5 (left bottom) and RCP8.5 (right bottom) 2071-2100 mean – CNRM-ALADIN63/CNRM-CERFACS-CNRM-CM5 climate model

5. Caveats and conclusion

To conclude, the best C3S products for the analysis of extreme events have been identified and evaluated in terms of daily precipitation (UERRA) , sub-daily intensity (ERA5Land) , soil moisture (UERRA, ERA5Land, CEMS) and river discharges (CEMS), compared with Météo-France reference datasets and observations.

The UERRA product, which benefits from an assimilation of precipitation observations, shows good qualities for the restitution of the local climate with a reduced bias in terms of maximum daily precipitation versus PRESCILIA analysis (179 mm for PRESCILIA and 110 mm for UERRA), explainable by the differences in spatial resolution of these two products. The major events (like October 2018 and November 1999) are quite well treated by UERRA, despite lower 2-day intensities: for example 299 mm in UERRA compared with 608 mm in PRESCILIA on November 12 1999. The detection performances logically decrease with the surface area of the events considered.

The ERA5-Land products roughly restituate the extent of rainfall over this zone. Intensity of extreme rainfall events are strongly underestimated on the whole area, particularly in the mountainous regions where maxima are particularly biased. Concerning 3-hour cumulative precipitation, correlation is moderate between COMEPHORE-0.1° and ERA5-Land data. Associated volumes of precipitation are also clearly underestimated, with an average factor 0.5 between COMEPHORE-0.1° and ERA5-Land. Overall ERA5-Land overestimates surfaces of 3-hour cumulative precipitation during flooding events.

For soil moisture analysis, the three C3S products analyzed UERRA, ERA5Land, EFAS show good skills compared to SIM2 analysis: Pearson coefficient ranges from 0.77 (SIM2/EFAS) to 0.92 (SIM2/ERA5-Land) indicates a good agreement of trends. ERA5-Land reanalysis carries out the best performance in terms of correlation (R=0.92), dispersion (sd=1.13) and global error (centered rms=0.45).

In terms of river discharges, several scores have been calculated to evaluate CEMS-EFAS products versus observations. Results are roughly proportional with watershed sizes simulated by the products. Poor scores were found for watersheds of less than 1000 km².

Concerning the future climate dataset, a comparison is made between C3S CORDEX and DRIAS-2020 datasets. The DRIAS-2020 dataset derives directly from the CORDEX data, and on which 2 treatments were applied, outlier filtering and Adamont debiasing method. These treatments are advisable for study at a local level, and do not impact diagnoses made on large-scale precipitation extremes (especially for the study of relative thresholds). In fact, the CORDEX data can be used to evaluate precipitation extremes over other territories.

From a replicability perspective, our results are mainly representative of Mediterranean climate zones experiencing intense rainfall events within a few hours.

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