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PILOT DESCRIPTION AND ASSESSMENT

Sierra de las Nieves aquifer (Spain)

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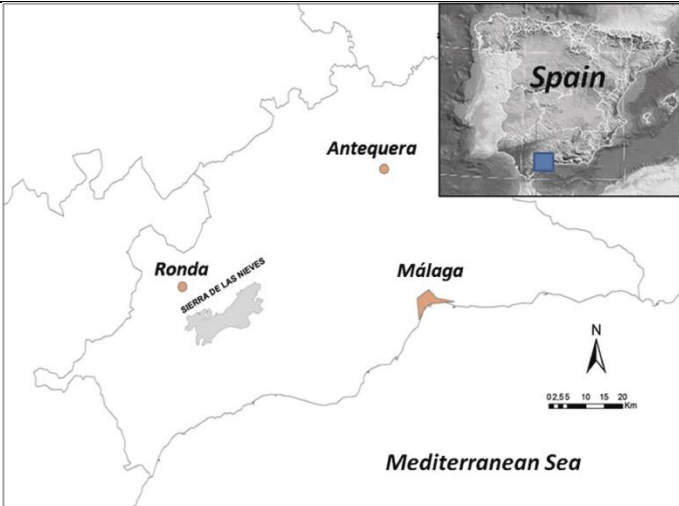
LIST OF ABBREVIATIONS & ACRONYMS

SN	Sierra de las Nieves
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1 EXECUTIVE SUMMARY

Pilot name	SIERRA DE LAS NIEVES AQUIFER	 Modified from Pardo-Igúzquiza et al., 2015
Country	Spain	
EU-region	Mediterranean region	
Area (km ²)	110	
Aquifer geology and type classification	karstic	
Primary water usage	Nature	
Main climate change issues	The SN high relief karst aquifer is located inside the Natural Park and UNESCO Biosphere Reserve with the same name. This zone is a terrain of great relevance by its geological, geomorphological, hydrogeological and ecological value. It is under near natural hydrological conditions, being the climatic characterized by relatively high rainfall and moderate temperatures. The aquifer contains important water resources and the three main karst springs are the starting points of three important regional rivers: Río Grande, Río Verde and Río Genal. The SN aquifer is located in a Mediterranean high elevation region where the latest studies on climate change forecast important increases in temperature and decreases in precipitation. These changes can provoke important perturbations on the hydrological and hydrogeological cycle in the future which will cause important impacts on the environmental values of the SN aquifer.	
Models and methods used	Generation of local future climate change scenarios following the method proposed in the framework of this project (Collados-Lara et al., 2018) and analysis and discussion of the impact that the changes suggested by the temperature and precipitation future projections can have in the aquifer using recharge models.	
Key stakeholders	Natural Park of SN, UNESCO Biosphere Reserve of SN, Environmental Conservation Groups, visitors of the park	
Contact person	Aj Collados-Lara, E. Pardo -Igurquiza, L. Baena, D. Pulido. IGME (Spain), aj.collados@igme.es.; e. pardo@igme.es; d.pulido@igme.es; l.baena@igme.es;	



The SN aquifer is located in the Mediterranean region of EU, inside the province of Málaga (south Spain). The karst aquifer has an extension of around 110 km². It is a high-relief karst aquifer, which is located in the natural park and UNESCO biosphere reserve of the same name, is an area of great interest due to its geological, geomorphological (both at the surface and underground), hydrogeological and ecological value. The aquifer is not influenced by pumping and is considered to be a natural laboratory for karst research because of how well developed the main karst characteristics are at both the surface (karst depressions and karst springs) and underground (with a large network of caves). The hydrological cycle is sustained by relatively high precipitation (annual mean precipitation of approximately 1000 mm) and moderate temperatures (annual mean temperature of approximately 16 °C). However, these climate parameters are susceptible to significant disruption due to climate change. Note that the mediterranean area, where is located the SN aquifer, is very vulnerable to climate change.

In the SN aquifer we generated local future climate change scenarios of precipitation and temperature and analysed the impact that these changes can have in the aquifer using recharge models. Different climate models have been corrected using several techniques based on two hypotheses, bias correction and delta change approaches. We have focus on the future assessment for the horizon 2071-2100 under the most pessimistic emission scenario (RCP 8.5) contemplated within the last published IPCC report (AR5, 2014). It is expected that there will be, on average, a 27% reduction in precipitation and a 19% increase in temperature. This is a dangerous combination that will dramatically decrease recharge. The mean reductions of recharge vary from 34 % to 63 % for the bias correction approach depending on the RCM considered. In the case of delta change approach the mean reduction vary from 41 % to 59 %. These dramatic decreases expected in recharge will require new strategies for adapting to and mitigating climate change.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts on Europe's hydrological systems including groundwater bodies, which is expected to intensify in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. To enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments, the GSOs, in the framework of GeoERA, has established the project "Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC". By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The specific TACTIC activities focus on the following research questions:

- What are the challenges related to groundwater- surface water interaction under future climate projections (TACTIC WP3).
- Estimation of renewable resources (groundwater recharge) and the assessment of their vulnerability to future climate variations (TACTIC WP4).
- Study the impact of overexploitation of the groundwater resources and the risks of saline intrusion under current and future climates (TACTIC WP5).
- Analyse the effectiveness of selected adaptation strategies to mitigate the impacts of climate change (TACTIC WP6).

This report describes the work undertaken by the Spanish Geological Survey (IGME) as a part of TACTIC WP4 to assess impacts of climate change on groundwater recharge at the Sierra de las Nieves (SN) karst aquifer (south Spain). WP4 is divided into seven tasks that cover the following activities: Review of tools and methods and identification of data requirements (Task 4.1), identification of principal aquifers and their characteristics aided by satellite data (Task 4.2), recharge estimation and its evolution under climate change scenarios in the principal aquifers (Task 4.3), analysis of long-term piezometric time series to evaluate aquifer vulnerability to climate change (Task 4.4), assessment of subsidence in aquifer systems using



DInSAR satellite data (Task 4.5), development of a satellite based net precipitation and recharge map at the pan-European scale (Task 4.6), and tool descriptions and guidelines (Task 4.7).

The work presented here is related to Task 4.1 and 4.3 and aims is to analyze the sensitivity of the potential impacts of climate change on precipitation, temperature, and recharge to different regional climate models (RCMs) and conceptual approaches to generate local scenarios. We used the bias correction and delta change approaches to generate future local scenarios of precipitation and temperature for the lumped area of the Sierra de las Nieves karst aquifer. The time series were generated by using nine RCMs nested to different global climate models (GCMs). These projections were used to assess the impacts of CC on recharge by using a recharge model for diffuse recharge and by employing the changes of precipitation for concentrated recharge.

3 PILOT AREA

The SN is a high relief karst aquifer, which is located in the Natural Park and UNESCO Biosphere Reserve with the same name. This place has great relevance by its geological, geomorphological (both at the surface and underground), hydrogeological and ecological values. The botanical variety inside the Park is impressive (around 1500 types of plants, 19 of them exclusive of the Ronda area. The main protagonist is the pinsapo, a Mediterranean fir which is a botanical relic with the last specimenes in these mountains. The Natural Park ecosystem is very dependent of the availability of water which can be reduced in the future due to climate change impacts. Different ensemble and downscaling techniques will be employed to define potential future global change scenarios for the study area based on the data coming from simulations with different Regional Circulation Models (RCMs). For this pilot area we intent to assess future potential impacts of global change scenarios in aquifer recharge.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The SN aquifer is located in the Mediterranean region of EU, inside the province of Málaga (south Spain) (see Fig.1). The karst aquifer has an extension of around 110 km². The aquifer operates in natural regime and it is considered a natural laboratory for karst research due to the spectacular development of the main karst characteristics as karst depressions, karst springs or caves.

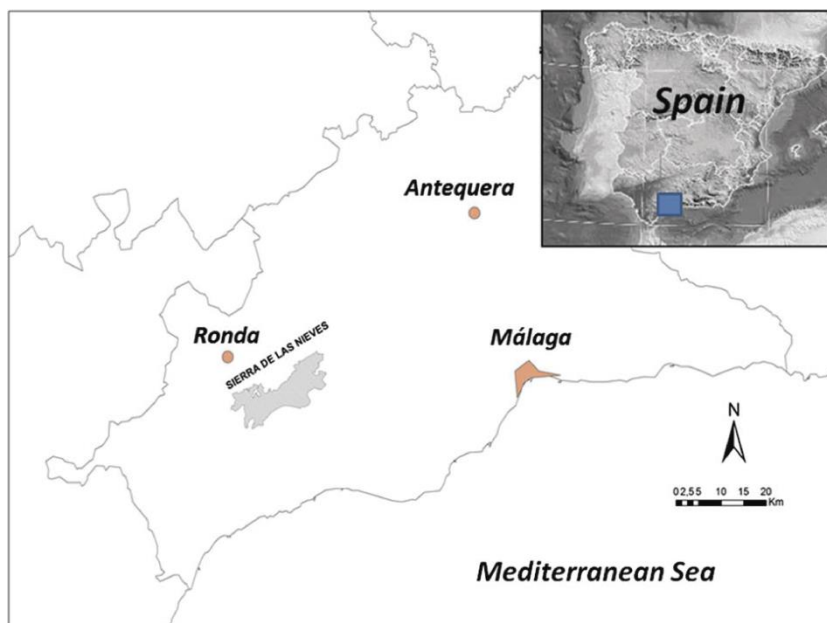


Fig. 1. Location of the pilot area (Modified from Pardo-Igúzquiza et al., 2015)



3.1.2 Geology/Aquifer type

The aquifer is formed mainly by a succession of carbonate rocks: Triassic marbles and dolostones, Jurassic limestones and a Tertiary carbonatic breccia (Fig. 2). The Mesozoic sequence is folded by a NE-SW trending overturned syncline plunging towards the NW (Liñán-Baena, 2005). The carbonatic breccia unconformably overlies the Mesozoic succession but is also deformed by the fold. In this sequence of rocks there is a important Mediterranean high relief karst which forms the aquifer. The conceptual model of the karstified massif can be defined by the existence of two main tectonic blocks: the Nava block in the west and the Torrecilla block in the east. The Torrecilla block has been uplifted (around 500 m) with respect to the Nava block with the Turquillas fault zone separating the two blocks (Fig. 2). In geomorphic terms, the Nava block is the zone of karst depressions and the Torrecilla block is the zone of super-caves.

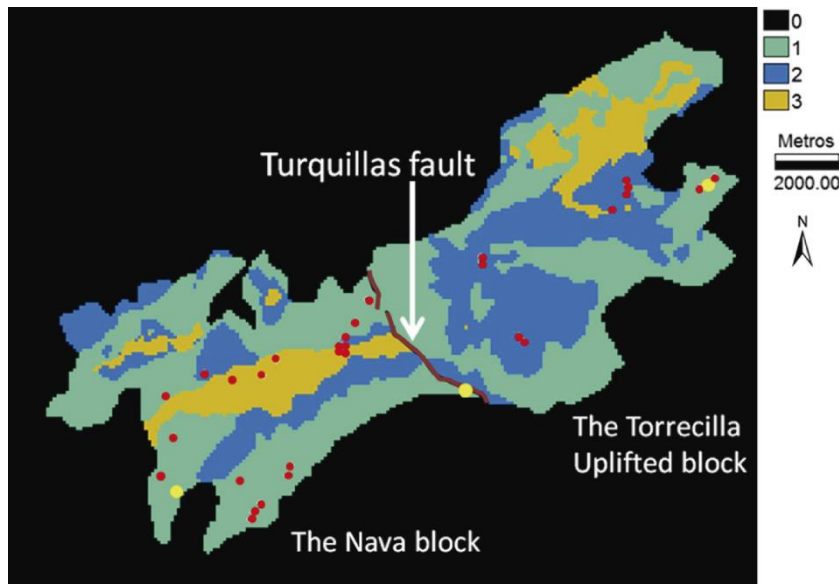


Fig. 2. Geological map of the SN aquifer with the main lithologies: dolostone (1) limestone (2) carbonatic breccia (3). Sampling locations for rock matrix porosity measurement are marked with red dots. Yellow dots show the three main karst springs that discharge the aquifer: Genal, Verde and Grande springs, W–E respectively. (From Pardo-Igúzquiza et al., 2015).

3.1.3 Topography and soil types

The SN aquifer is located in a high elevation zone where the elevation varies from 400 to 1900 m.a.s.l. (see Fig. 3) and the terrain is very rugged. The soils in the aquifer surface are mainly Lithosols, Chromic Luvisols and Rendisins with Calcium Cambisols but other kind of soils can be found around the aquifer (see Fig. 4).



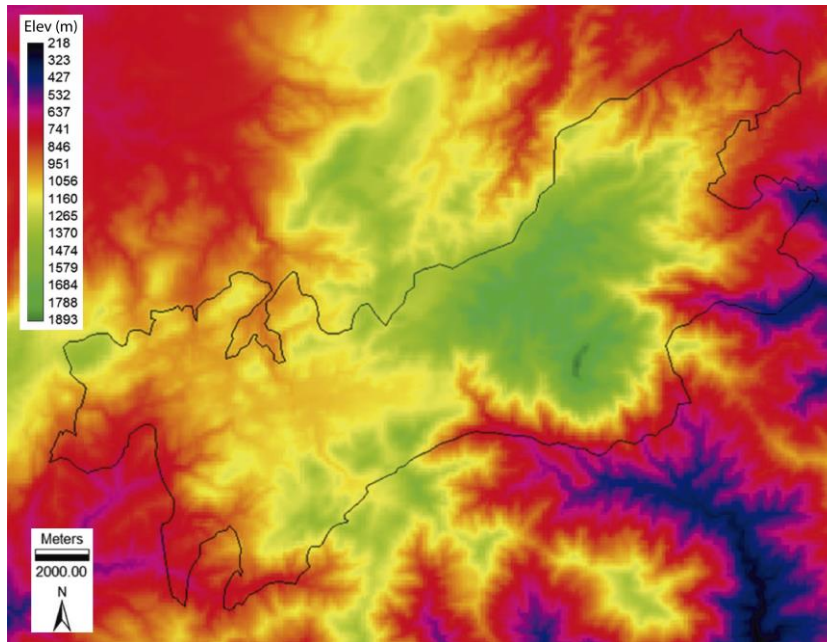


Fig. 3. Topography (Digital Elevation Model map) of the SN aquifer (modified from Pardo-Igúzquiza et al., 2015).

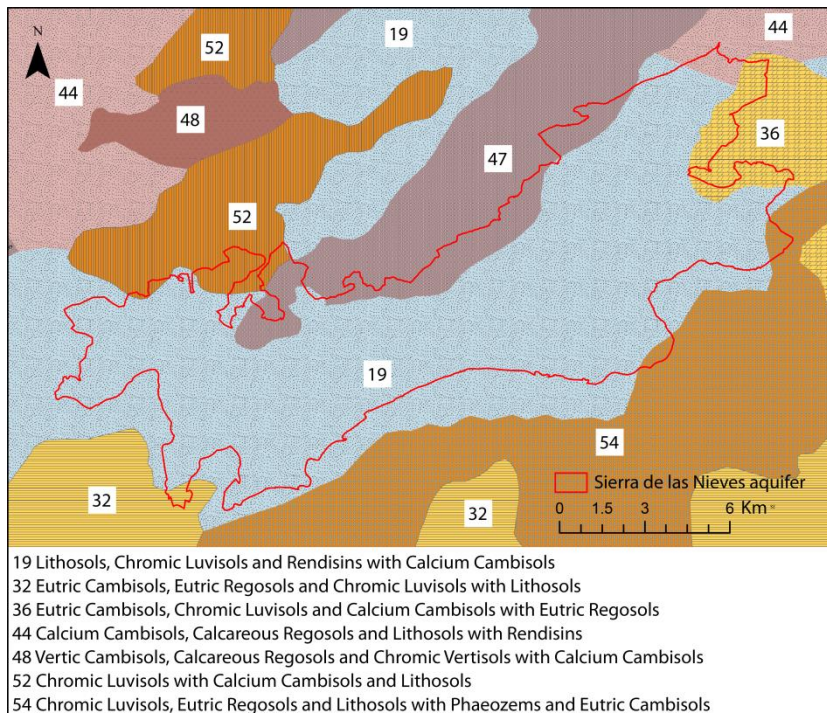


Fig. 4. Soil map of the SN aquifer (Elaborated with data from the Map of Soils of Andalusia at scale 1: 400000 (REDIAM)).

3.1.4 Surface water bodies

The SN Mountain is essential for the water availability in many rivers of the region. In particular, the SN aquifer water contributes to the headwaters of some rivers. The river system related to the SN aquifer is showed in Fig. 5. The aquifer has a great importance for the rivers Grande, Verde and Genal because its springs are associated directly to the SN aquifer.

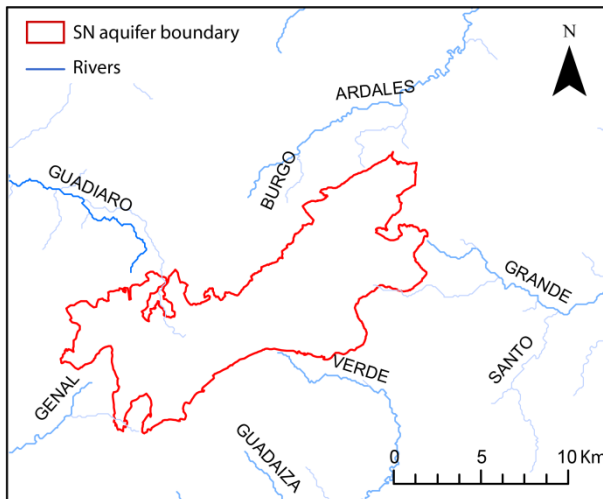


Fig. 5. River system in the SN aquifer region.

3.1.5 Hydraulic head distribution

The piezometric levels in the SN karstic aquifer are monitored in four points (see location in Fig. 6). The three springs of the rivers (Grande, Verde and Genal) and a pothole that reaches water-saturated siphons which is deepest pothole in south Spain, with a vertical variation of minus 1100 m relative to the land surface. The estimated hydraulic head obtained from these data is showed in Fig. 6.

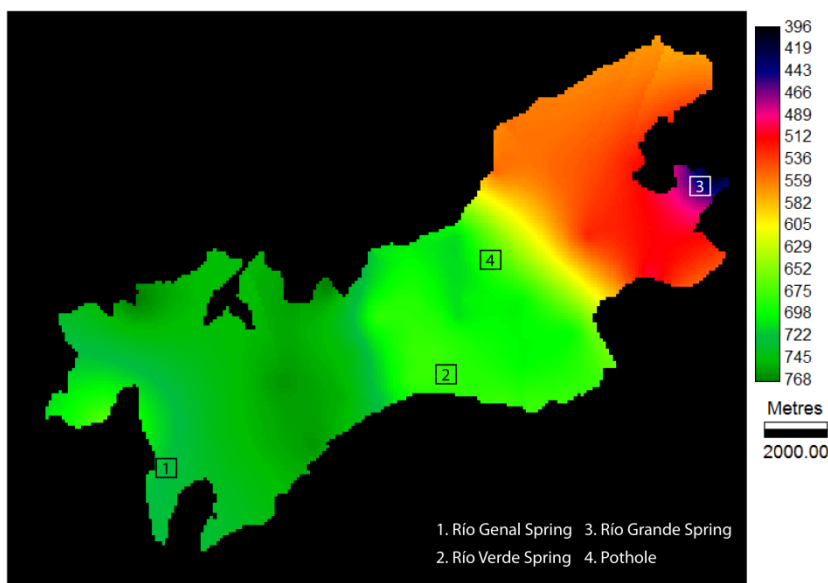


Fig. 6. Estimated hydraulic head map and monitoring points for the SN aquifer (from the research project CGL2015-CGL2015-71510-R from the Ministerio de Economía y Competitividad of Spain).

3.1.6 Climate

The whole Natural Park of SN is located within the zone of Mediterranean climate. Nevertheless, the presence of three essential factors as latitude, influence of the Mediterranean Sea and Atlantic Ocean and the strong variation of elevation provoke many variations in the climate, particularly with respect to the temperatures during the whole year and the abundance of the rainfall. The E-W alignment of the mountains favours the entry of precipitation fronts from the Atlantic Ocean that discharge in the SN due to the high elevation. Most of the rainfall concentrated between November to January. The coldest months are December and January while the hottest months are July and August. The annual mean temperature and precipitation for the period 1971-2000 in the SN aquifer are respectively 15.6 °C and 993 mm/year. The mean values of temperature and precipitation for the different months are showed in Fig. 7.

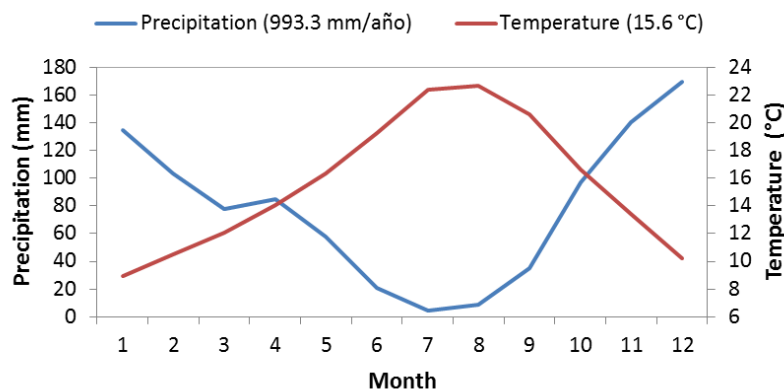


Fig. 7. Mean temperature and precipitation for the SN aquifer in the period 1971-2000 (from Collados-Lara et al., 2017; Data from Spain02 v4 project (Herrera et al., 2016)).

3.1.7 Land use

The SN aquifer is located inside a protected area (Natural Park and UNESCO Biosphere Reserve) where the human influence in the land uses is limited. The main land uses in the aquifer surface are dense trees formations, scrub and grassland formations with trees and open areas with shrubbery or scarce vegetation (see Fig. 8).

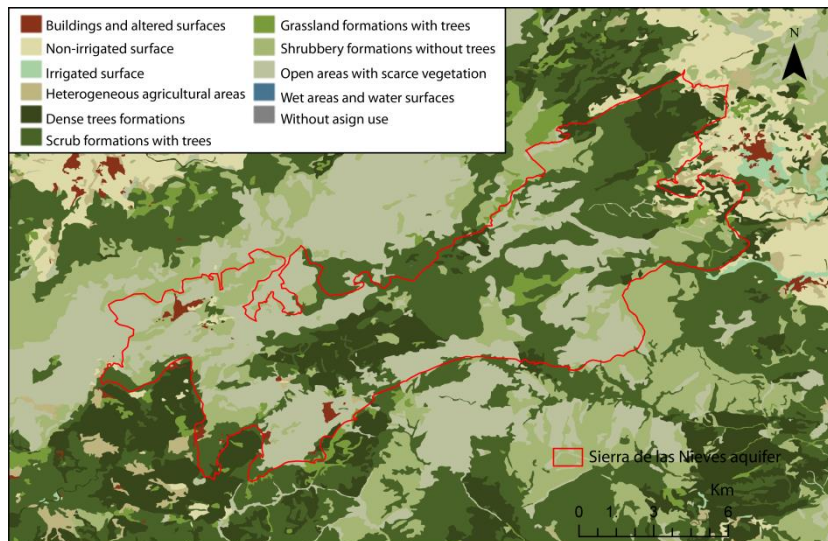


Fig. 8. Land use of the SN aquifer (Elaborated with data from the land use and vegetation cover map of Andalusia in 2007 at a scale of 1:25000 (REDIAM)).

3.1.8 Abstractions/irrigation

As commented previously, the SN aquifer is located in a Natural Park and UNESCO Biosphere Reserve where there is no pumping. The main outputs of the aquifer are the natural discharges to the springs thus the main water usage of the aquifer is the maintenance of natural ecosystems.

3.1.9 Flow balance components

The aquifer which operates in natural regime has as main input the precipitation recharge and the main outputs are the discharges to the springs (Rio Grande, Rio Verde and Rio Genal). Table 1 shows the water balance in the SN aquifer for the hydrological years 1995-1996, 1996-1997 and 1997-1998.

Table 1. Global water balance for the SN karst aquifer for three hydrological years. 1 hm³ is 1 Million Cubic Meters (MCM) (modified from Pardo-Igúzquiza et al., 2012)

	Year 1995-1996	Year 1996-1997	Year 1997-1998
Discharged volume Rio Grande spring (hm ³)	73	55	50
Discharged volume Rio Verde spring (hm ³)	30	24	21
Discharged volume Rio Genal spring (hm ³)	24	17	16
Total discharged volume of the three springs (hm ³)	127	96	87
Discharged volume of other springs (hm ³)	21	16	14
Total discharged volume of all springs (hm ³)	148	112	101
Total volume of rainfall (hm ³)	175	167	148
Annual rainfall (mm)	1710	1638	1452
Modelled recharge volume (hm ³)	146	112	111
Recharge as % of rainfall (%)	66	52	58

3.2 Climate change challenge

In accordance with the EEA map the main expected issues due to climate change in this case study are those described in Fig. 9 for the Mediterranean regions. Existing national estimates show also a significant reduction (around a 19% for the RCP8.5 emission scenario in the horizon 2071-2100) of the aquifer recharge in the area (see Pulido-Velazquez et al., 2017).

The main challenge is to find adaptation measures to reduce the impacts of future climate change scenarios in the aquifer recharge in order to maintain a good status in the Natural Park of SN to conserve the geological, geomorphological, hydrogeological and ecological values of the zone.

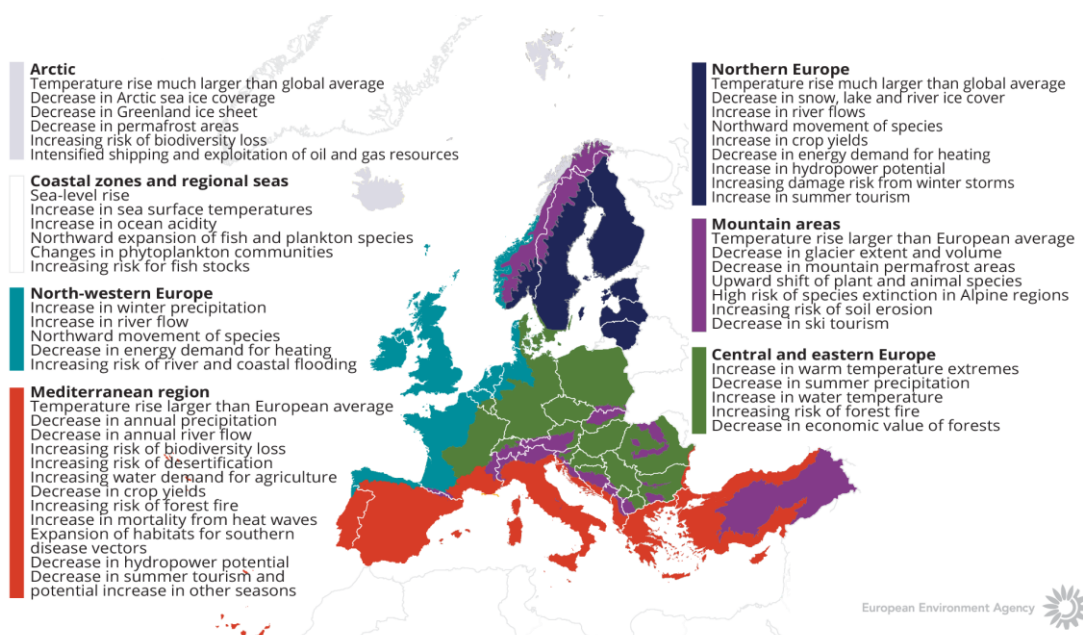


Fig. 9. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

The assessment of climate change impacts on recharge in SN aquifer is performed using climate change scenarios generated by using the GROUNDSD tool (Collados-Lara et al., 2020) and the R package qmap (Gudmundsson et al., 2012). To quantify the changes in recharge, the concentrated and diffuse recharge within the karst aquifers has been taken into account.

4.1 Methodology and climate data

4.1.1 Climate data

The historical precipitation and temperature data have been taken from the project Spain02 v4 (Herrera et al. 2016) for the period 1971–2000. Periods of 30 years are frequently employed in climate change impact studies. The Spain02 project provides an estimation of precipitation and temperature obtained using the original data from the Agencia Estatal de Meteorología (State Meteorological Agency—AEMET). The spatial resolution of the data is around 12.5 km and the spatial support is the same than the Euro-CORDEX project, from which the different RCMs were obtained. We used nine RCMs (see Table 2) nested to different GCMs under the most pessimistic scenario of the AR5 of the IPCC, the RCP 8.5, for the period 2071-2100.

Table 2. RCMs and GCMs considered.

RCM \ GCM	CNRM-CM5	EC-EARTH	MPI-ESM-LR	IPSL-CM5A-MR
CCLM4-8-17	X	X	X	
RCA4	X	X	X	
HIRHAM5		X		
RACMO22E		X		
WRF331F				X

4.1.2 Generation of local climate scenarios

For the SN aquifer pilot area two tools were explored. The GROUNDSD tool (Collados-Lara et al., 2020) allows to generate local potential scenarios climatic variables. The tool uses two approaches under different statistical correction techniques (first moment correction, first and second moment correction, and regression) to generate individual local projections and ensembles of them. The qmap tool (Gudmundsson et al., 2012) includes several empirical adjustments of variables originating from climate model simulations using quantile mapping. For both tools, the correction techniques can be used under two approaches, bias correction and delta change. The first applies a transformation function to the control simulation series to force some of its statistics or quantile distribution to get closer to the historical ones. This transformation function is also applied to the future simulation series to obtain the corrected future scenarios. It assumes that the bias between the statistics of historical data and the control simulation will remain invariant in the future. On the other hand, the delta change approach assumes that the relative changes between future simulation and control simulation from regional climate models are accurate and applies these changes to the historical series to obtain the corrected future series.



4.1.3 Recharge model

Recharge in most karst aquifers can be divided into concentrated and diffuse recharge. Concentrated recharge enters the aquifer along preferential flow paths related to underground karst conduits connected to potholes, sinkholes and the epikarst at the surface. Variation in this part of the recharge is due solely to precipitation and thus any modifications to it simply equal the modification in precipitation:

$$\Delta CR = \Delta P. \quad (1)$$

On the other hand, diffuse recharge must go through a soil-epikarst layer and represents a balance between precipitation and actual evapotranspiration which can be written as:

$$R = C(P - AET), \quad (2)$$

where P is precipitation, AET is actual evapotranspiration and C is a coefficient of infiltration that is considered to be constant during the historic and future periods. AET has been calculated at yearly scale by the empirical method proposed by Turc (1954):

$$AET = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}. \quad (3)$$

Where the factor L is expressed as:

$$L = 300 + 25T + 0.05T^3, \quad (4)$$

where T is the mean annual temperature.

Historical annual recharge is provided by:

$$R_h = C_h(P_h - AET_h), \quad (5)$$

Future recharge is provided by:

$$R_f = C_f(P_f - AET_f), \quad (6)$$

where equation (5) is equal to equation (6) but with the subscript f denoting final or projected values.

The variation in diffuse recharge (ΔDR) is provided by:

$$\Delta DR = \frac{R_f - R_h}{R_h}. \quad (7)$$

Thus, taking into account the previous equations, one has:

$$\Delta DR = \frac{C_f(P_f - AET_f) - C_h(P_h - AET_h)}{C_h(P_h - AET_h)}. \quad (8)$$

Taking into account the hypothesis that the recharge coefficient C does not vary over time, so $C_f = C_h$, finally:

$$\Delta DR = \frac{(P_f - AET_f)}{(P_h - AET_h)} - 1. \quad (9)$$

4.2 Tool(s) / Model set-up /calibration

4.2.1 Generation of local climate scenarios

We used the historical information and regional climate models (see section 4.1.1) to generate local scenarios for the SN aquifer (Fig. 10). In the case of temperature we used a first and second moment correction (GROUNDS tool) and in the case of precipitation an empirical quantile mapping (qmap tool). Both techniques were applied under the bias correction and delta changes approaches. We obtained nine projections (from nine RCMs) for each approach.



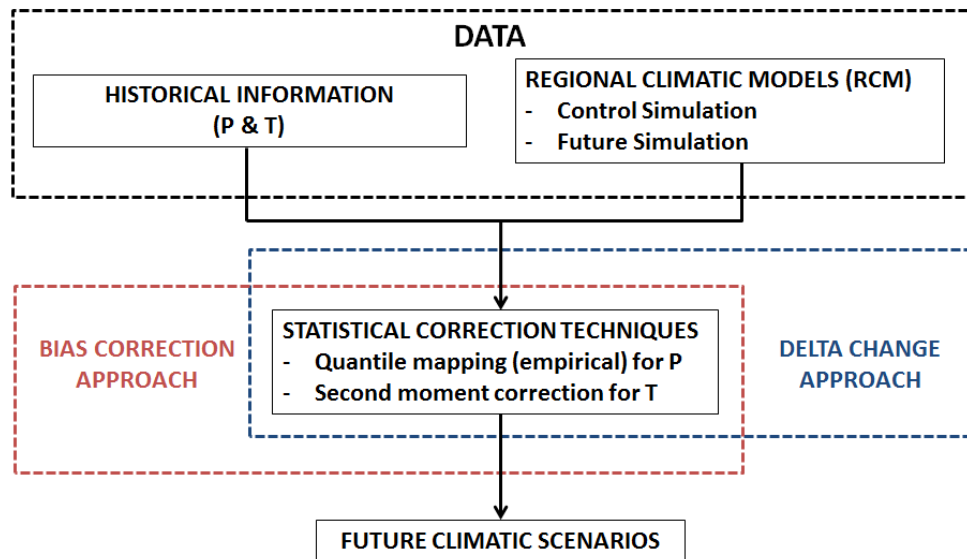


Fig. 10. Flowchart of the methodology used to generate potential future local climate scenarios in SN aquifer (from Pardo-Igúzquiza et al., 2019).

4.2.2 Recharge model

The historical and future climatic variables were used to calculate the changes in concentrated and diffuse recharge by using Equations 1 and 9 respectively (see Fig. 11). The final variation in recharge is a weighted average between the percentage of concentrated and diffuse recharge that takes place in the particular aquifer:

$$\Delta R = \alpha \Delta DR + (1 - \alpha) \Delta CR, \quad (10)$$

where ΔR is the variation in recharge, α is the ratio of diffuse recharge, ΔDR is the variation in diffuse recharge, $(1 - \alpha)$ is the ratio of concentrated recharge and ΔCR is the variation in concentrated recharge.

In the SN karst aquifer α is 0.7. The 30% of the recharge is concentrated and the remaining 70% is diffuse (Pardo-Igúzquiza et al. 2012). It has been assumed that this ratio will remain constant over time.

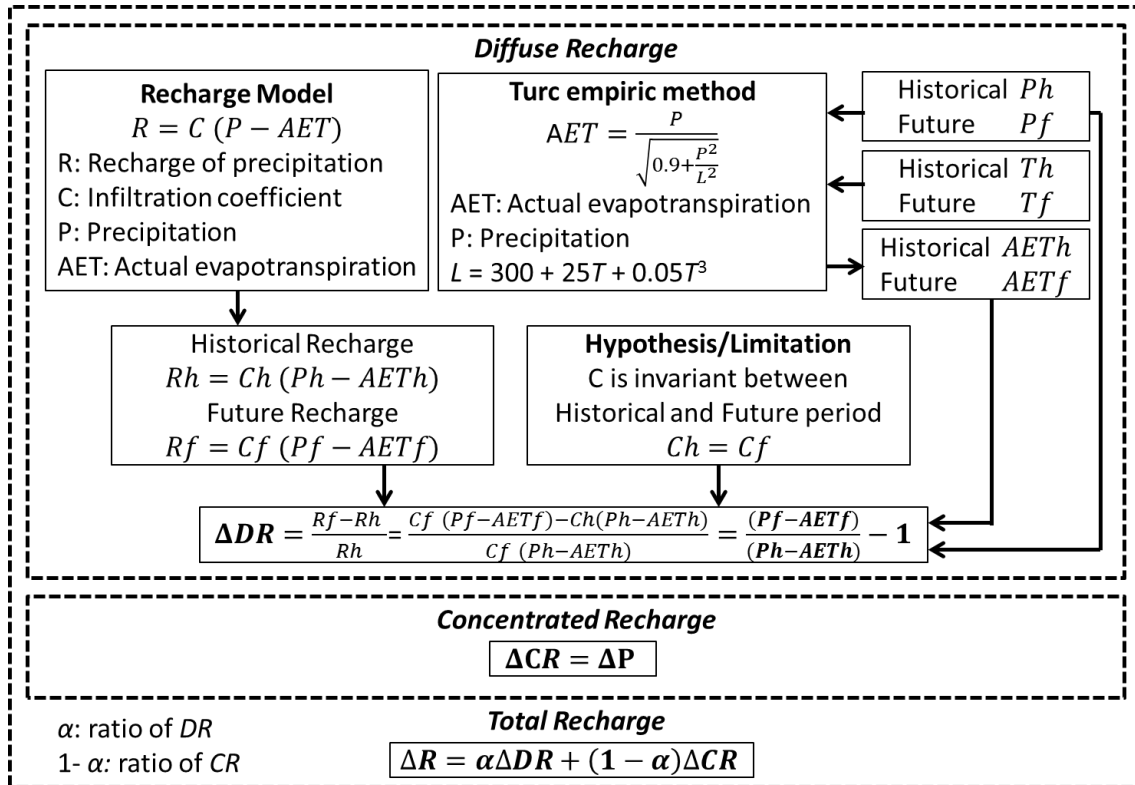


Fig. 11. Flowchart for assessing future changes in aquifer recharge (from Pardo-Igúzquiza et al., 2019).

4.3 Uncertainty

In this study the dominating source of uncertainty is related to RCMs. In general, there is a large degree of uncertainty in climate change impacts assessments. There are different climate models (both RCMs and GCMs) that can be used to make future climate projections. Every climate model includes its own model for the atmosphere, the ocean, the Earth's surface, and ice sheets as well, as different parameterizations of the physical processes that must be considered within each of these models. The correction approaches are another source of uncertainty but its importance in climate change impacts assessments is lower (Collados-Lara et al., 2018).

In this study we considered different RCMs (nine) and two correction approaches to take into account uncertainty. Note that the impacts on recharge was assessed by considering 18 future projections. It allows us to calculate mean changes and the ranges of variability of these changes.

5 RESULTS AND CONCLUSIONS

5.1 Impacts of climate change on precipitation and temperature

The statistics for the future time series generated using the bias correction and delta change approaches are shown in Figs. 12 and 13 respectively. The mean reduction in precipitation is 27.2% and the mean increase in temperature is 19.4%. However, the time series are different depending on the RCM used. Each RCM predicts different future climate changes. The correction technique used also has an influence on these time series. With the first and second moment approach (used for temperature), the same mean values are obtained for the mean and standard deviation in both correction approaches (bias correction and delta change). Note that the monthly time series generated are different for the two approaches. However, the quantile mapping technique generates times series with different mean and standard deviations with the two correction approaches in the case of precipitation. The differences range from 1.3 to 6.7%, which is also not that large. These values increase when sensitivity is measured with respect to the RCM used; in this case, the maximum differences are 0.68% for temperature and 21.0% and 18.2% for precipitation using the bias correction and delta change approaches, respectively. This implies that uncertainty related to the correction approach is low compared to the uncertainty associated to the RCMs.

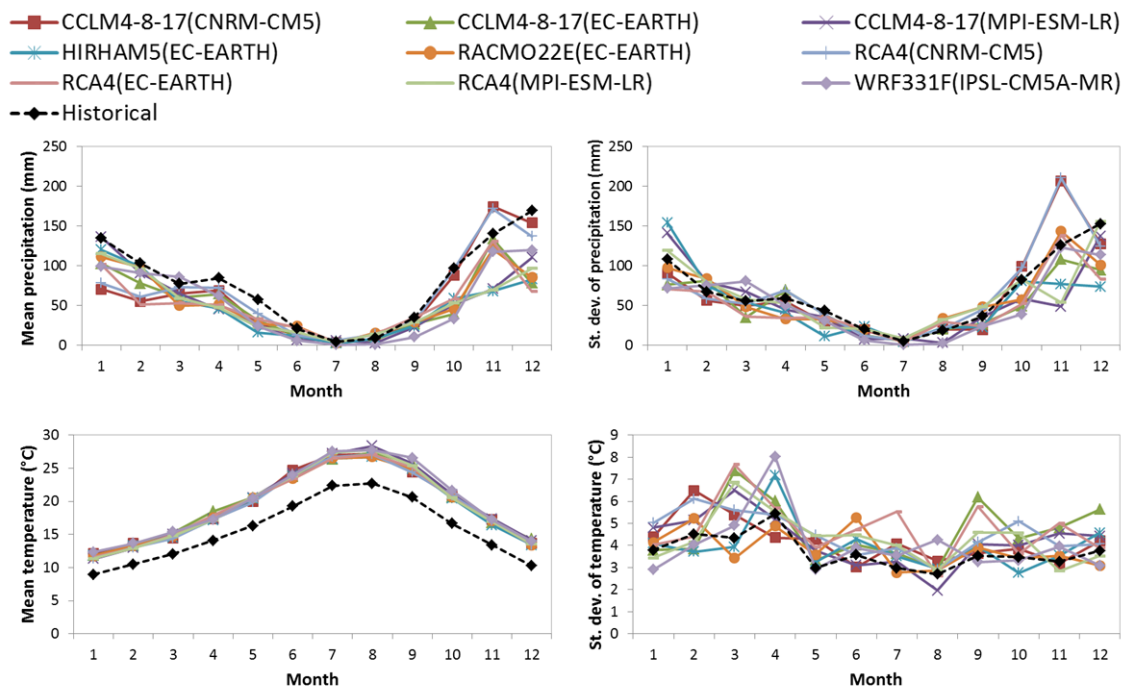


Fig. 12. Mean and standard deviation of the historical and generated future precipitation and temperature time series (bias correction approach) (from Pardo-Igúzquiza et al., 2019).



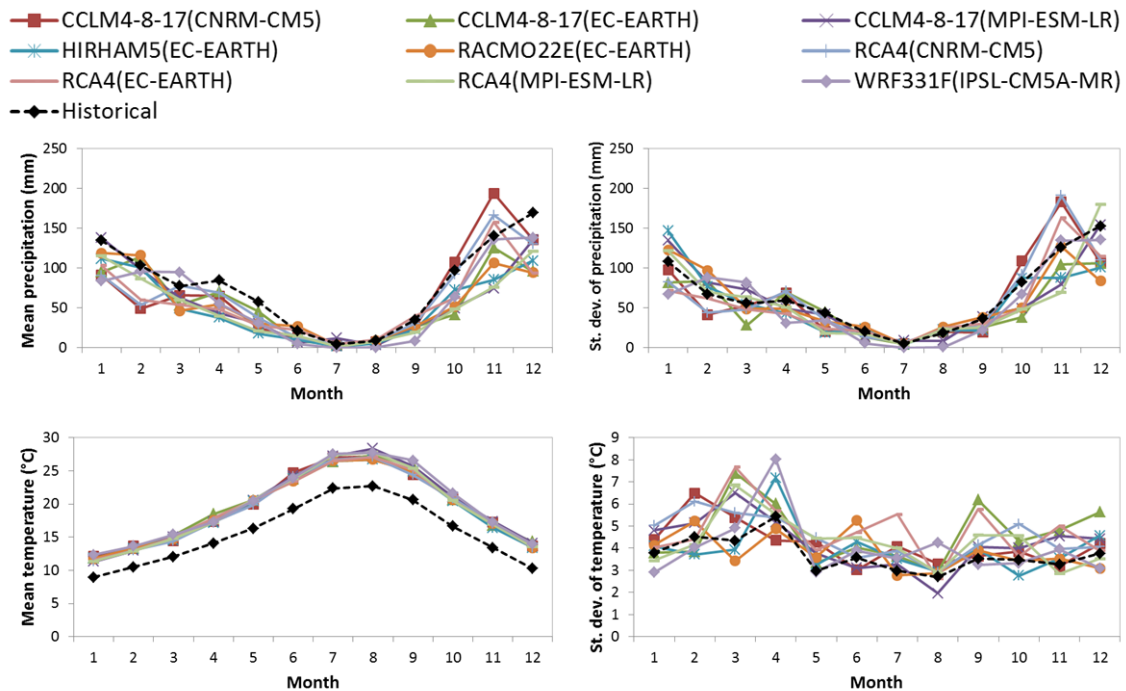


Fig. 13. Mean and standard deviation of the historical and generated future precipitation and temperature time series (delta change approach) (from Pardo-Igúzquiza et al., 2019).

5.1 Impacts of climate change on recharge

The changes of the climatic variables were used to propagate the impacts of climate change to recharge. Table 3 shows the relative changes in precipitation, temperature, and recharge forecasted for the period 2071–2100 as compared to the historical period 1971–2000. The mean reductions of recharge vary from 34 % to 63 % for the bias correction approach depending on the RCM considered. In the case of delta change approach the mean reduction vary from 41 % to 59 %. These dramatic decreases expected in recharge will require new strategies for adapting to and mitigating climate change. Park managers should take the results as a warning sign, and the issue of climate change should be included on their agenda.

Table 3. Relative change (in percentage) of future precipitation (P) and temperature (T) for the bias correction and delta change approaches and the different RCMs employed. The relative change in diffuse recharge (DR) and total recharge (R) has also been calculated (from Pardo-Igúzquiza et al., 2019).

RCM (GCM)	Bias correction				Delta change			
	ΔP (%)	ΔT (%)	ΔDR (%)	ΔR (%)	ΔP (%)	ΔT (%)	ΔDR (%)	ΔR (%)
CCLM4-8-17(CNRM-CM5)	-18.84	19.36	-48.51	-39.61	-16.17	19.36	-51.96	-41.22
CCLM4-8-17(EC-EARTH)	-31.74	19.52	-70.89	-59.15	-26.33	19.52	-66.18	-54.23
CCLM4-8-17(MPI-ESM-LR)	-31.88	19.60	-69.28	-58.06	-26.93	19.60	-62.28	-51.68
HIRHAM5(EC-EARTH)	-36.22	19.13	-74.37	-62.93	-33.08	19.13	-68.65	-57.98
RACMO22E(EC-EARTH)	-29.06	19.20	-69.17	-57.14	-26.50	19.20	-63.68	-52.53
RCA4(CNRM-CM5)	-15.18	19.12	-42.04	-33.98	-17.09	19.12	-53.06	-42.27
RCA4(EC-EARTH)	-33.24	19.26	-72.49	-60.72	-26.54	19.26	-65.39	-53.74



RCA4(MPI-ESM-LR)	-33.04	19.35	-70.43	-59.21	-34.32	19.35	-70.02	-59.31
WRF331F(IPSL-CM5A-MR)	-30.14	19.81	-68.82	-57.22	-23.63	19.81	-64.34	-52.13

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