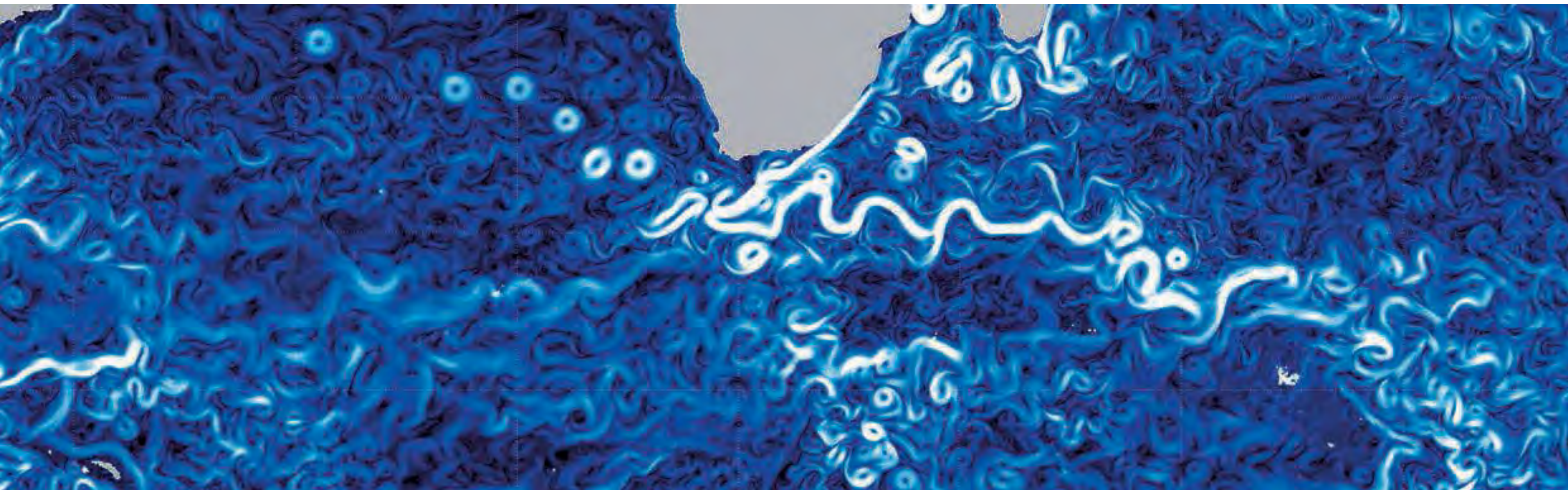
Chapter 4

Using climate models to understand the climate machine



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Mercator Ocean Model, a chart of surface currents. The Agulhas Current that flows along the east coast of Africa retroflects when it meets the cold Benguela Current and the Antarctic Circumpolar Current.

Understanding of the functioning of the earth's climate and environment system requires first the use of statistical tools applied to the analysis of observed data and secondly diagnostic approaches using certain concepts or theories and more broadly by using modelling tools that represent the complexity of the processes and physical mechanisms involved in the earth system. These modelling tools are very elaborate but still contain strong bias and uncertainties. Validation work using suitable observations is required. This work is essential for the subsequent evaluation of the confidence and uncertainty level of the climate forecasts provided by these models.

What is a climate model?

Climate models represent the functioning of the physical processes of the land-atmosphere system. They reproduce the movements of the atmosphere and the oceans, energy exchanges with the surface, the hydrological cycle and interactions between the climate and biogeochemical cycles. They function using the digital solving of the equations of atmosphere and ocean physics and are based on the division of a continuous environment into a large number of small volumes (discrete meshes) to be

Box 8

Ocean modelling, an essential component of climate models

The ocean component is very important in climate models. The ocean models developed by IRD are thus incorporated in the work of the IPCC. The models are also useful for forecasting—a kind of oceanic weather bulletin— and for understanding the mechanisms that govern variations of the seas. Applied at the local level, they make it possible to monitor changes of the environment.

IRD researchers contribute to the development of ocean modelling in the tropics. The models were first developed for global seas to represent the physical (temperature, salinity, currents) and biogeochemical characteristics (quantity of plankton, nutrient salts, dissolved oxygen) at the surface and at a depth. The global scale makes it possible to show the contrasts between ocean basins in upper latitudes, in the tropics, close to coastlines and in the centre of tropical oceans. The advantage of global models is that their capacity to reproduce the dynamics of seas and biogeochemical cycles under very different oceanic conditions (strong contrasts in temperature, light and nutrients) can be tested. The results of modelling are then compared with observations, especially by satellites, and *in situ* databases.

Global models …

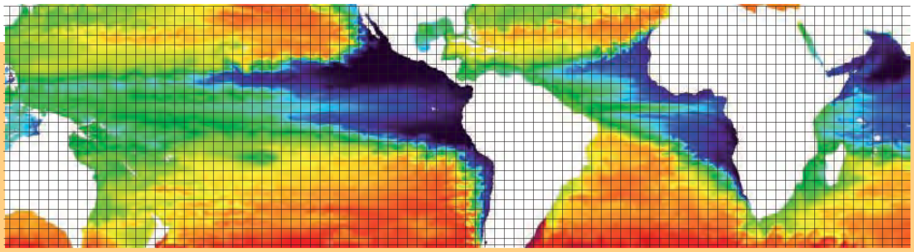
The ocean component is very important in climate models as the seas store heat and react at much longer time scales (from a few years to several hundreds of years) than the atmosphere. The NEMO (physical component) and PISCES (biogeochemical component) models, much of which were developed by the LOCEAN unit, run in two climate models used by the IPCC. The PISCES model can also represent the **carbon cycle** and measure the carbon dioxide pump effect played by oceans at the world scale. These models are also used for operational oceanography aimed at providing public or private users with a realistic picture of the oceans today and short-term forecasts (about a month), opening the way to a kind of ‘ocean bulletin’.

… at kilometre scale

The results of global models are also used to initiate regional models such as the ROMS model developed mainly by LEGOS units and the Laboratoire de Physique des Océans (LPO) that is used to study dynamics and biogeochemical cycles at much closer spatial scales. These regional models have a limited field of application by definition

able to link together the variables in each mesh and to quantify energy transfers and biogeochemical processes. The modelling of continental areas addresses transfers of water and energy and the amount of movement with the atmosphere, together with the continental hydrological cycle. The parameters of processes smaller than a **mesh**—sub-mesh processes: clouds, whirlwinds, waves, surface runoff, etc.—are drawn from field observations or result from the use of more detailed modelling of one process in particular.

(a few hundred kilometres) and their mesh size (up to 1 km) is much smaller than that of global models. Their representation of physical phenomena at a fine scale means that these models are capable of explicit calculation of the mass, heat and nutrient salt flows associated with ocean structures—such as whirlpools for example—whose characteristic size is around 10 kilometres. At these small scales physical mechanisms play a fundamental role in biogeochemistry, especially for the supply of nutrient salts and plankton production in surface water, as for example in the **upwelling** systems off the coasts of Peru, West and South Africa and India where there are very rich marine ecosystems with a great abundance of fish. These regional modelling tools can thus respond to a variety of problems that have a strong impact on populations in the south (resource management for fisheries, disoxygenation of the sea and the accumulation of pollutants in the trophic chain).



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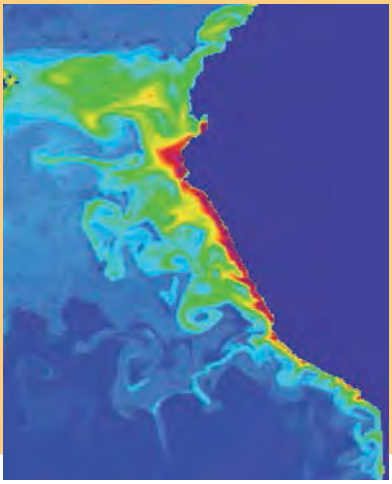
Dissolved oxygen concentration at a depth of 150 m simulated by the Nemo-Pisces global model at 1/4° resolution.
The minimum oxygen zones are in blackish blue ($O_2 < 150$ micromoles/litre) in the eastern Pacific, Atlantic and Indian tropical oceans.
The fine grid of the model is represented roughly by a 4° square grid (each square covers 16 x 16 grid points).



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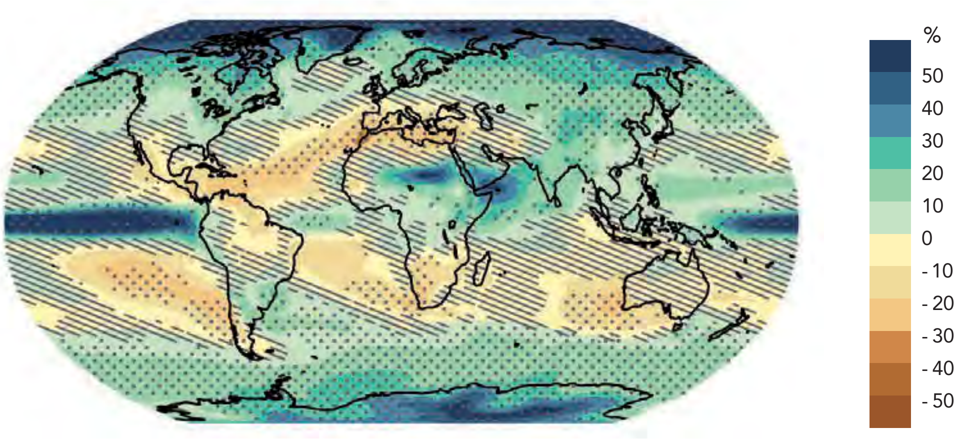
Surface chlorophyll as shown by the regional ROMS-PISCES model off the coast of Peru.
The high chlorophyll concentrations indicate abundant phytoplankton, mainly diatoms.

Since the 1970s, when climate modelling began to develop significantly, these models have been improved regularly, providing a better description of the complexity of processes. In parallel, the horizontal and vertical resolution of the mesh of the models have increased progressively to atmospheric volume dimensions of 200 km x 200 km x 1 km and ocean dimensions ranging from a few kilometres to several hundred kilometres with a depth of 1 m to 500 m. These tools thus enable progress in our understanding of the functioning of the climate system and forecasts of future changes.

Evaluating modelling tools

In spite of the continuous efforts made to improve climate models and in spite of their sophistication, they are less reliable as a whole in the tropics and subtropics than in the other parts of the world. In particular, the different models are not in agreement as regards precipitation forecasts for the tropics in 2100 (Fig. 9). The differences from one model to another are related to uncertainties with regard to certain retroaction mechanisms involving, among other things, clouds, atmospheric convection and continent-atmosphere-ocean interactions. One of the main sources of uncertainty is in the 'sub-mesh' parameterisation of these processes. This often leads to empirical adjustments.

Figure 9.
The evolution of average precipitations during the periods 1986-2005 and 2081-2100 (in percent) in the most pessimistic IPCC emissions scenario (RCP 8.5).
The models display greater uncertainty in the tropics.
Source: IPCC, 2013.



Grey points: zones in which the climate models display at least 90% agreement on the change feature: drier or more humid.
Hatched areas: zones of uncertainty.

Observed data are thus essential in tropical regions in order to improve the representation of these processes. For example, measurements of the isotopic composition of rain and water vapour make it possible to observe certain processes such as atmospheric convection and thus detect defects in convection parameters in the models. Indeed, water isotope composition is sensitive to many atmospheric and hydrological processes (origin, transport, mixing, phase change, etc.) and is thus a good way of diagnosing physical processes in climate models. These measurements have been developed in recent years by IRD research teams in Niger, Bolivia and now in Réunion in regions where forecasts of changes in precipitation remain very uncertain.

Box 9

Comparing the results of models with a view to improving them

The ALMIP project that has been running since 2007 is the first international experiment on the comparison of continental surface models dedicated to West Africa.
The results show very great variability from one model to another.

In climate modelling, models of continental land represent and calculate exchanges of mass (water, carbon, etc.) and energy (radiation, heat, etc.) between the atmosphere and the various surface, soil and subsoil compartments. This type of model is based on equations in fluid mechanics and thermodynamics. Different surface models have been developed around the world, all of which differ a little according to the experiments conducted by researchers in their study regions or their working hypotheses.

Comparisons of models are digital experiments consisting of feeding the same sets of data ('forcings') into the various models.
The results are then compared and also set against reference data such as observations when the latter exist.
The aim is not that of choosing 'the best model' but rather benefiting from their diversity by identifying the strengths and weaknesses of the different modelling principles used and enabling improvements.

Inter-model variability dominates the other sources of variability

The ALMIP project that has been running since 2007 within the framework of the AMMA programme is the first international experiment of this type devoted to West Africa.
The first project phase was dedicated to the regional scale and confirmed the very great variability from one model to another and the very strong impact of uncertainties concerning forcing data—especially precipitation—drawn from satellite imagery. The second project phase (ALMIP2) started in 2013 and is based on high resolution data from the AMMA-CATCH observatory and AMMA project measurements.
The results show that the simulations remain very marked by the constituent principles of each model and that inter-model variability outweighs the other sources of variability.

Incomplete representation of hydrological processes

The models are in relative agreement with regard to representation of the energy balance.
However, biases are observed in some components of the water balance (runoff and the dynamics of underground water) related to the seasonal cycle and quantities of water. These biases are attributed mainly to the incomplete representation of hydrological processes and to the sometimes inappropriate values of the parameters used in the equations (soil texture and depth, hydrodynamic properties, etc.).
Corrections to reduce these biases have since been envisaged.

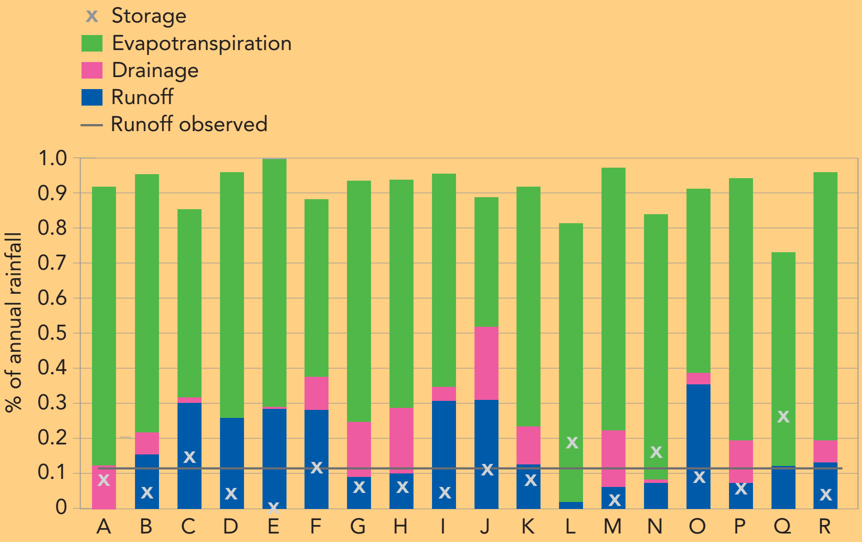


Figure 10.
Terms of the hydrological balance of the upper Ouémé basin simulated by 18 surface models (A to R), showing very different responses from one model to another.
ALMIP aims mainly at using the field observations available to understand the reasons for these differences, evaluating the most realistic simulations and seeking ways of improving simulations.
Source: IRD/C. PEUGEOT *et al.*, forthcoming

Box 10

The paradox of the Indian summer monsoon

Projections of the Indian monsoon presented in the last IPCC report are currently being hit by the observations available. Detailed work on observations and simulation of the Indian monsoon carried out by IRD in collaboration with the Indian Institute of Tropical Meteorology provides some explanations for this.

Some 75% to 90% of the annual rainfall in South-East Asia occurs during the summer monsoon (from June to September).

There is a risk that the phenomenon may be deeply disturbed by global climate change.

Models and observations suggest that global warming takes place with fairly constant relative humidity, that is to say with a substantial increase in the water vapour in the atmosphere (proportional to the increase in temperature). In other words, there is a risk that the precipitations and the hydrological cycle associated with the monsoon may be modified. As this warming is more marked on land than at sea, the land-sea thermal contrast (a fundamental ingredient of the monsoon system) will certainly be different as well in the future, with consequences for the monsoon that are difficult to forecast.

Observations contradict projections

Most of the projections in the fifth IPCC report indicate an increase in precipitation in the Indian sub-continent. The frequency and intensity of extreme rain events are also likely to increase in Southern Asia. The credibility of these projections for the Indian monsoon is currently not in agreement with the observations available.

Indeed, Indian monsoon precipitations have displayed a downward trend since 1950.

A problem of scale

The work at IRD goes towards providing an explanation. The projections of monsoon rains in the climate scenarios result from a 'positive' thermodynamic contribution and a 'negative' dynamic contribution. Given the rough spatial resolution of the models used, the positive effect—linked with the transport of water vapour at the surface—is dominant and accounts for the increase in rainfall.

However, the researchers consider that the negative dynamic contribution resulting from anthropic change is strongly under-estimated because the spatial resolution of the models is not high enough for satisfactory simulation of the convection processes and the monsoon system itself.

Finally, digital experiments addressing this suggest that the decrease in monsoon precipitation should be seen in relation to regional factors such as the substantial warming of the Indian Ocean, the role of aerosols and changes in land use that modify the surface **albedo**.

The models used for the projections simulate these factors poorly or only take them into account partially.

Monsoon rain at Udaipur, India.

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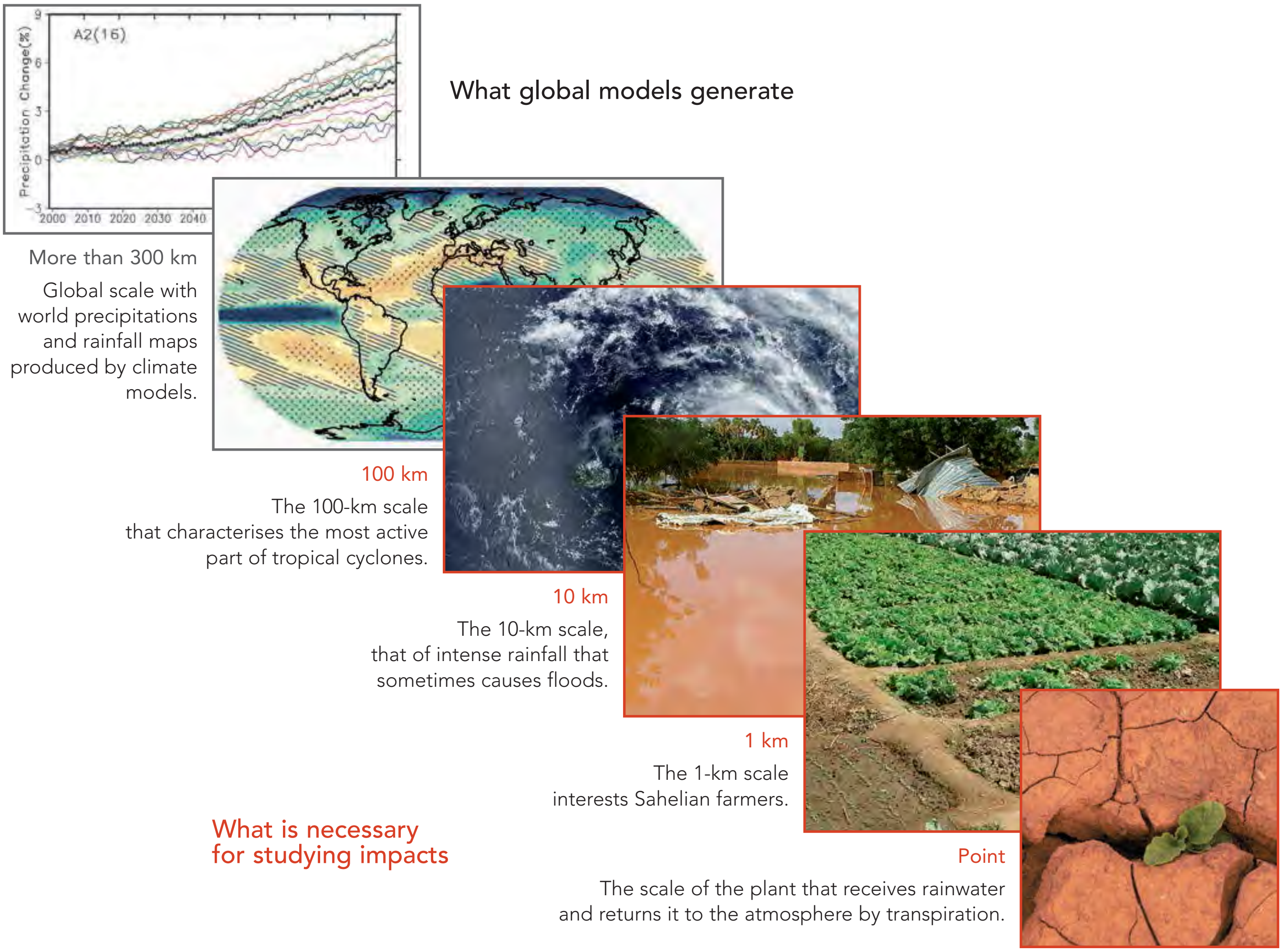

What global models generate

More than 300 km

Global scale with world precipitations and rainfall maps produced by climate models.

100 km

The 100-km scale that characterises the most active part of tropical cyclones.

10 km

The 10-km scale, that of intense rainfall that sometimes causes floods.

1 km

The 1-km scale interests Sahelian farmers.

What is necessary for studying impacts

Point

The scale of the plant that receives rainwater and returns it to the atmosphere by transpiration.

Figure 11.
Illustration of downscaling in climate change and its impacts.
Source: IRD/B. Sultan

Regionalise atmospheric models to reduce uncertainties?

It has been seen that the mathematical and physical equations used in climate modelling are rendered as discrete volume meshes. This approach is not fine enough and means that simulation of the behaviour of the atmosphere and oceans, where there are strong interactions at all scales of space and time, is not sufficiently accurate. This results in marked uncertainties in the simulated evolution of atmosphere and climate. To reduce these uncertainties, 'sub-mesh' parametering is aimed at describing the processes that take pace within the meshes of the model and their effects at mesh scale. But in spite of all the efforts made to quantify these processes, the parameters are often still based on empirical adjustments and only partially respond to the reduction of uncertainties. Finally, it must not be forgotten that the atmosphere remains a very unstable fluid and that an initially weak disturbance can gain amplitude and lead at a larger scale to contrasted meteorological situations (the 'butterfly effect'). Thus 'ensembles' of simulations should be formed in which the initial state is disturbed slightly to obtain a range of possible changes of the atmosphere and the climate.

Box 11

High resolution observations to re-establish the variability of rain in the Sahel

> Scientists used the dense pluviographic network of the AMMA-CATCH observation service in Niger to improve hydrological models whose spatial resolutions were too low for simulation of runoff in Sahel hydrological systems.

The West African monsoon is one of the three major monsoon systems that play a key role in the climate of the earth. Its intensity displays strong inter-annual and decadal variability whose causes are mainly unknown.
The AMMA-CATCH (*Analyse multidisciplinaire de la mousson africaine - couplage de l'atmosphère tropicale et du cycle hydrologique*) observation service makes possible long-term monitoring of the dynamics of vegetation and the water cycle and their interactions with the climate in West Africa.
It is based on facilities set up at three sites along the Sudan-Sahel bioclimatic gradient, in Benin, Niger and Mali respectively.

Underestimation can exceed 50%

Scientists used the dense AMMA-CATCH observation service in particular to assess the uncertainty of hydrological models resulting from the use of spatial resolution that was too low for simulation of runoff in Sahel hydrological systems.

Water balances in the Sahel are directly linked with the interaction between rainstorms and the soil surfaces that governs runoff.
Modelling the hydrological cycle thus requires representation of the spatial heterogeneity of the properties of soil surfaces and then supplying the surface models by rainfall forcings at scales that show the intrinsic variability of rainy periods. These spatial scales are of the order of a few kilometres in the Sahel. With resolution of 25 km (the resolution of satellite rainfall data), hydrological models may underestimate runoff by as much as 15%.
At a resolution of 100 km (typical of climate models), underestimation may reach more than 50%.

These scale effects justify the use of so-called 'disaggregation' methods that use large-scale climate simulations (of the order of 300 to 50 km) to work down to fine scales of the order of 10 km.

In order to overcome this stumbling block, regionalisation is based on climate models operating in a limited spatial field (a 'region') with higher spatial resolution (a grid point every 10 to 50 km). This approach conserves the local complexity of the physical processes involved. It does not necessarily correct the bias of global models as the regional models are faced with the same limits of 'sub-mesh' parametering. These uncertainties raise a major problem for quantifying the local impacts of climate change on resources (for example water resources or agricultural yields at field level) because of the possible propagation and amplification of the large scale towards the local scale. Particularly as the models of impacts (e.g. hydrological or agricultural) also have biases and uncertainties.

It was possible to develop disaggregation methods thanks to the high resolution observations made by the AMMA-CATCH team. They make it possible to re-establish the full variability of rainfall when the original resolution of the data—whether from classic ground measurements with low spatial density or given by climate models—is not sufficient for modelling the hydrological cycle.

An MIT radar used in an experimental set-up at the AMMA-CATCH observatory in the outskirts of Niamey, Niger. Several meteorological radars have been used during these research programmes to study the dynamics of the squall lines causing intense, very variable precipitation events that are a feature of the Sahelian climate.

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