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State of the art on global circulation models to resist the problem of climate change

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ABSTRACT

This article presents a State of the Art on Global Circulation Models to resist the problem of Climate Change. The relevance of this study lies in the understanding of downscaling, which is a process that involves the transformation of data to a finer spatial resolution. This paper will look at the classification of climate models into two main types, Global Circulation Models (GCMs) that cover the entire Planet and Regional Climate Models (RCMs) that cover a limited climate region. The information provided by GCMs usually has a resolution of between 100 and 200 km of grid, which is suitable for supporting decision-making on an international scale. The study is exploratory in scope and uses a state-of-the-art methodology, which is documentary and interpretative critical in nature, working with eight representative works. The results of the study indicate that in most cases, in which a Statistical Downscaling Model (SDSM) technique has not been fully studied, to obtain detailed information on changes in parameters associated with quality in the construction of local temperature and precipitation projections.

1. INTRODUCTION

The importance of applied mathematical research lies in the impact of other disciplines on the needs of human knowledge, either by directly applying well-developed results (theorems,

algorithms, etc.) or by constructing mathematical models (at least in part) as an answer to the problems posed.

For Herrera, (2022)

> Knowing about exact sciences such as Mathematics while being pleasant is important to interact with clarity, efficiency, and intelligence in a world full of numbers, formulas, and equations, where this science is related to others to respond to many situations in the real world and the need for mathematical knowledge grows more and more as well as its application. (p. 38)

Research is an activity aimed at acquiring new knowledge and applying it to the solution of social or scientific problems. That is why it is important, as far as mathematics is concerned, to carry out state-of-the-art Global Circulation Models to resist the problem of Climate Change, taking into consideration the different characteristics of each country and region, although, for this type of model, there are no disadvantages of ideological or cultural barriers. The work of mathematicians in this field is developed both theoretically and applied. The importance of this type of work is influenced by the human knowledge needs of other disciplines, as well as by problems arising from its context.

In Nicaragua, efforts are also being made to develop mathematical research. Universities are pioneers in these types of scientific work. There are few theses on the behavior of a heuristic model of a 2° to 0.5° scaling technique (Statistical Downscaling Model, SDSM) to obtain detailed information on changes in certain parameters, and local projections of temperature and precipitation were constructed, finding only foreign studies, and projections made by the Ministry of Environment and Natural Resources (MARENA).

For this reason, in this article, a state-of-the-art the art is made, since as Molina Montoya (2005) indicates:

> The origin of the state-of-the-art art dates back to the 1980s when studies were conducted mainly in the area of social sciences in Latin America, which sought to compile the available information on a given topic, to find policies and alternatives of action for social development; From this arose the state of the art associated to recognize research in the Latin American region. (p. 74)

Yes, although the origin of the state of the art is in the social sciences, its usefulness has been so great that it is widely used in studies, of a scientific nature, to know the scope of the subject to be addressed, models, methodologies, new systems that are being applied worldwide and that can be adapted to the reality that we want to study. For this reason, Urbina and Morel, (2017) take the following definition:

> The State of the Art/State of the Art refers to the ultimate state of knowledge about research and development (R+D), that is, it is the limit of knowledge generated on a topic or problem

> of scientific and/or technological research, establishing how far it has advanced, what is the frontier in a given time and space. (p.3)

Also, it is necessary to know What is a mathematical model?, in this regard Herrera Castrillo (2023) states:

> A mathematical model is based on a theory in the sense that it is a model of that theory. This means that it is a system that ignores the basic principles of this theory (called axioms). In other words, a mathematical model is an "object" that is used as an example to represent it or, in some cases, a special instance separate from the embodiment (interpretation) of this theory. Using this typical sense, the various numerical sets (natural, rational, real...) are good examples of abstract structures without content, which are either constructed or not. (p. 37)

1.1. Historical review of climatological models

For the past few decades, numerical models have been the only method capable of predicting climate change. This is due to the delay between the cause of the change and its consequences (whether natural causes or related to human activities, especially greenhouse gas emissions and land-use change that includes the indiscriminate exploitation of natural resources). For this reason, it is important to describe the development of models, the numerical techniques they use, the physical principles that give them their predictive power, how they are used, and how they can contribute to the definition of policy measures.

The first climate models, in the 1960s, were simple models of the Earth's energy balance: 40 or 50 years later, a representation of atmospheric dynamics (originally defined by meteorological applications), a representation of ocean dynamics and biogeochemistry, sea ice, hydrology, and vegetation cover in continental regions, chemistry, and air quality, were added. Great water cycle, carbon.

It is important to consider that Slingo, (2017)

> Climate science has a long and distinct history. In 1686, Edmund Halley published his landmark description of tropical winds in the journal Philosophical Transactions of the Royal Society: An Historical Account of the Trade Winds, and Monsoons, Observable in the Seas between and near the Tropics, with an Attempt to Assign the Physical Cause of the Said Wind. with an attempt to determine the physical cause of such winds]. Halley wondered why the winds invariably blew from the east and argued that they must be caused by the daily passage of the Sun, due to which the Sun warms the atmosphere, causing the air to rise and thus drawing air from the east after the passage of the Sun.

Likewise, Le Treut and Nuñez, (2017) indicate:

> The situation has changed over the last 10 or 20 years because the first symptoms of climate change can be measured. This evolution means that it is no longer possible to talk about climate

> change without taking into account its link with other environmental needs (preservation of biodiversity) and with socio-economic issues. This leads to a new evolution of the models in several directions. (p. 1)

1.2. Land Use Change

Land use change, including the indiscriminate exploitation of natural resources, is one of the human causes that has a direct impact on global warming.

Human activity has led to the transformation of vast areas of forests, wetlands, and other natural ecosystems into agricultural, urban, or industrial land. This conversion of natural ecosystems has multiple negative impacts on the global climate.

First, deforestation and forest degradation release large amounts of carbon dioxide (CO2) stored in trees and soil. CO2 is one of the main greenhouse gases contributing to global warming.

In addition, the destruction of forests and other natural ecosystems reduces the ability of vegetation to absorb CO2 from the atmosphere through photosynthesis. This leads to an increase in the concentration of CO2 in the atmosphere, intensifying the greenhouse effect and contributing to global warming.

Some studies that have been carried out in this regard are:

Orellana Salas and Lalvay Portilla carried out a study entitled "Use and importance of natural resources and their impact on tourism development. Case of Canton Chilla, El Oro, Ecuador" Tourism growth in a place is closely linked to the use of natural resources by the inhabitants and the importance that these resources have for their quality of life and subsistence. This article analyzes the use and importance of natural resources and their impact on tourism development in the canton of Chilla, in the province of El Oro, Ecuador. The methodology used was direct observation and surveys of the economically active population. The results revealed the most used and important natural resources for the community. It is suggested to promote its conservation to improve the quality of life of the inhabitants and achieve sustainable tourism in the area. Since local tourism is a source of economic income for the population, it is essential to carry it out taking into account the vulnerability of ecosystems and respecting and caring for the natural environment. The canton of Chilla receives a large influx of tourists every year, so it is necessary to raise awareness among the population about the importance of taking care of and properly managing the natural resources they have. (2018)

2. II. MATERIAL AND METHODS

2.1. Type and sources of research

The type of research is "documentary of a critical interpretative nature" where the compilation of bibliographic information is of utmost importance. Its exploratory scope, with a qualitative emphasis, since the aim is to learn about a new or little-studied phenomenon (Hernández Sampieri, et al., 2014, p. 97). The source from which the information is obtained is mainly available in relevant articles that refer to Global Circulation Models to resist the problem of Climate Change.

> State-of-the-art is a modality of documentary research that allows the study of accumulated knowledge (written in texts) within a specific area. (Molina, 2005, p. 73)
>
> As documentary research, the state of the art is guided by several principles that give rigor to its development, as follows: i) Purpose. It represents the commitment to establish prior research objectives; (ii) Coherence. It is to have internal unity in terms of phases, activities, and data; (iii) Fidelity. It alludes to an endorsement in terms of collection and transcription; (iv) Integration. It involves articulation and global evaluation of the process and iv) Understanding. It translates into the favoring of theoretical construction on the object of study, cited by Barbosa Chacón et al., 2013, p. 90).

The development of this study is based on bibliographic research, a process focused on the search, compilation, analysis, critique, and interpretation of data, that is, those obtained and documented by other researchers in bibliographic sources: printed, audiovisual, or electronic.

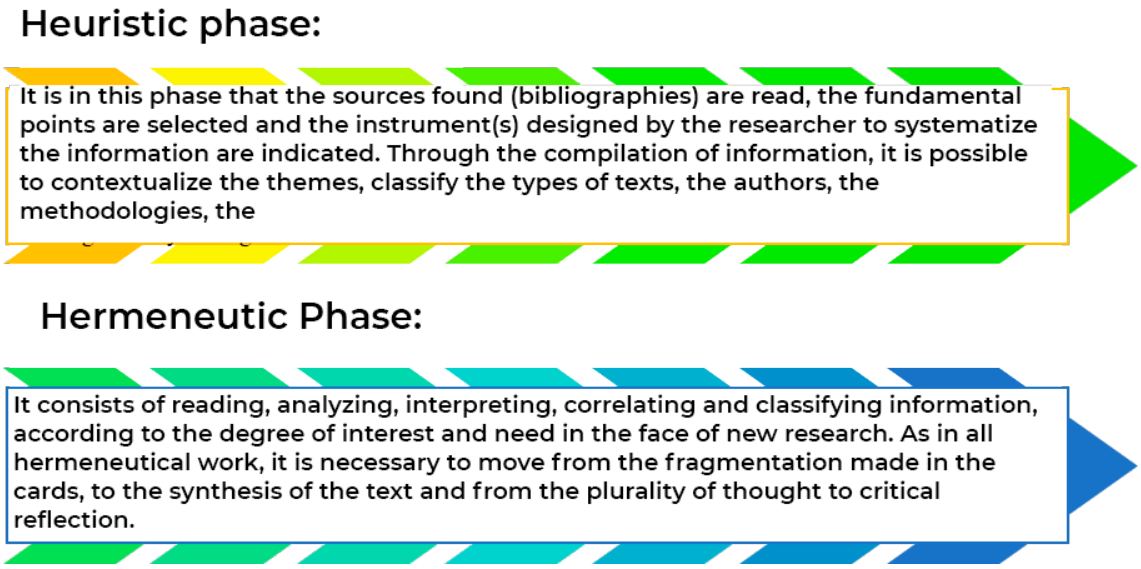
The hermeneutical historical approach to the state of the art is a way of rigorously reconstructing the developments of others and thereby providing diverse interpretations that transform and contribute to the phenomenon studied. For Bolaños Mejía et al., (2021) this study is framed in the constructivist approach, because "the literature review is a preliminary activity in search of a flexible frame of reference, which in most cases becomes a continuous activity during the course of the research" (p. 16)

For the elaboration of the state of the art, some of the stages and guidelines proposed by (Barbosa Chacón, et al., 2013) were used, addressing it in two major moments: Heuristic and Hermeneutic, respectively, according to the needs of the research.

The heuristic phase, of preparatory order, represents the procedure of searching for and compiling sources of information according to their nature and characteristics; it is the approach to the object of study, through the delimitation and definition of particular search strategies (Rojas Rojas, 2007; Hoyos, 2000; Bucheli and Cordoba, n.d.; Lopera and Adarve, 2008; Castañeda, 2004, cited by Barbosa Chacón et al., 2013, pp. 90-91).

Figure 1

Heuristic and Hermeneutic Phase



Note. Adapted from (Bolaños Mejía et al, 2021, pp. 17-18)

2.2. Methodological steps

To carry out the study, then, the five methodological steps shown in Figure 2 have been followed.

Figure 2

The purposes of the state-of-the-art

Note. Extracted from (Gómez Vargas, et al., 2015, p. 433).

They are described as follows:

1. To investigate, to make a general tracing of some Global Circulation Models to resist the problem of Climate Change, depending on the historical-cultural link with models used in Nicaragua, or by the regional or global impact they have.
2. Identify and select the most representative Global Circulation Models by region
3. Classify and systematize official documentary information.
4. Analyze the information.
5. Approach to the state of the art.

2.3. Criteria for the analysis of results

For the analysis of results, the existence of Global Circulation Models to resist the problem of Climate Change is identified, mainly the Statistical Downscaling Model, SDSM.

3. RESULTS

In the search for research carried out on the problem posed in this study, a tour was made on the topic raised "Behavior of a heuristic model of a Statistical Downscaling Model (SDSM) to obtain detailed information on changes in certain parameters and local projections of temperature and precipitation were constructed."

To situate the problematic area, a bibliographic review of the literature corresponding to the research topic was carried out, which consisted of digital texts in the period from 2000 to 2023. The sources consulted include textbooks, journal articles, conferences, master's and doctoral theses. Several studies were located that address some aspects related to the subject under investigation, carried out in different countries such as Costa Rica, Ecuador, Spain, Panama, and Peru, among others.

The research works carried out and that are related to the object of study in this research work can be mentioned the following:

1. Amador and Alfaro, (2007), authors of the paper: Dynamic and Statistical Methods of Scale Reduction: Applications to Climate, Climate Variability and Climate Change, at the National University, Heredia, Costa Rica. The objective of this project is to develop products for the analysis and applications of improved

daily, monthly, and seasonal precipitation data in a mesh system in support of climate monitoring, climate prediction, and applied research.

Broadly speaking, two approaches have been used to address this shortcoming: dynamic scaling methods and statistical scaling methods. Both techniques show similar levels of skill under the same climatic conditions when estimating surface atmospheric variables. In the present work, the basic elements of the climate system and the possible causes of the observed changes in the physical system are discussed. The main concepts associated with the elements that define the climate system, the definition of climate in a region, some aspects of climate variability associated with the average state of the atmosphere, and the generalities of the problem of global climate change with emphasis on the regional aspect of it are also presented in summary form. It also presents the methodological schemes of the downscaling process, a discussion of its advantages and limitations, as well as some applications to the weather and regional climate.

Statistical scaling techniques use the outputs of the MACGA and allow the construction of climate scenarios for individual sites or regions with a resolution at different time scales such as daily, monthly, and seasonal, using statistical or relationship information derived from historical time series.

Among the most widely used statistical methods are multivariate analysis techniques, several of which have been used by researchers from the Center for Geophysical Research of the University of Costa Rica (CIGEFI-UCR) for the study of different surface fields over Central America, such as precipitation and surface air temperature, which are supposed to be related to phenomena of a larger or global scale such as ENSO (El São Paulo). Niño-Southern Oscillation).

2. Amador and Alfaro, (2009) developed the study: Methods of Downscaling: Applications to Weather, Climate, Climate Variability and Climate Change,

Atmospheric-Oceanic Coupled General Circulation Models show good ability to simulate the evolution of global-scale circulations. However, this benefit is not very useful for the study of local impacts because the spatial resolution of these models is above the scale of the local impacts to be analyzed. It is important to take this into account when studying the impacts of climate on human activities, biodiversity, marine-coastal environments, and reefs in tropical regions, for example. There are two approaches to dealing with this difference in scale and information: dynamic and statistical downscaling methods. In this paper, the basic elements of the climate

system and the possible causes of the atmospheric changes observed in this system are discussed.

The collection and organization of most of the databases used in climate change-related studies and applications in the region is the responsibility of the National Meteorological or Hydrological Services, as well as other national or regional institutions responsible for providing public services to various sectors of society. In addition, some developed countries have also implemented more regional databases through their national entities or institutions.

3. Ribalaygua, et al., (2010) conducted a study entitled: Verification and Validation of a Statistical Downscaling Methodology for Nicaragua. Taking as motivation:

✓ Adapt the regionalization methodology of the Foundation for Climate Research (FIC) to the Nicaragua region. Selection of predictors appropriate to the study region.

✓ Verification and validation of the methodology in Nicaragua.

✓ The first study of its kind in Nicaragua.

The regionalization methodology developed by the FIC is a regionalization technique based on statistical techniques that attempts to establish empirical relationships between fields of low-resolution variables from the CGM (predictors) and high-resolution variables (predictors) at the surface (temperature and precipitation). The FIC methodology consists of a two-step analog method.

The success of a regionalization methodology lies not only in how good the methodology is at simulating the local climate but also in the fact that a good choice of predictors is an added value to it. For this reason, it is always necessary to work with the predictors that best suit the study region and the variable to be simulated.

The adaptation of the methodology to each study area and the selection of the most appropriate predictors are fundamental aspects of obtaining the best results. Using wind fields instead of geopotential fields not only allows us to capture the synoptic situations that affect Nicaragua, but also the phenomena that generate forced convection. The errors associated with the verification process do not depend on geographic distribution, either for temperature or precipitation. A possible relationship between the error and the altitude of meteorological stations has been observed in the case of temperature, but due to the limited number of observatories available for the study, it is not possible to draw a definitive conclusion.

4. García Herrera, et al., (2010) conducted a study under the theme: Future Scenarios of Temperature and Rainfall Under the Effect of Climate Change in the Agricultural Region of Los Llanos, Durango, Mexico.

This study is aimed at generating a representation of the future climate, temperature, and rainfall, in its average conditions; through the projection to the years 2020, 2050, and 2080, to integrate these projections into a climate threat index in the Agricultural Region of Los Llanos, Durango. A region that includes 5 municipalities: Cuencamé, Guadalupe Victoria, Panuco de Coronado, Peñón Blanco, and Santa Clara. Climatological stations with the most information were selected, with homogeneity and consistency in the data. The scenarios were made using the Spatial Downscaling Statistical Model (SDSM), which is one of the most useful spatial downscaling schemes in terms of generating climate change scenarios based on statistical regression procedures. Files and scenarios were generated for each meteorological variable of each station using a series of procedures with the SDSM. The results regarding the maximum temperature indicated that the months of July and August are the ones with the most considerable rate of increase in the three scenarios.

For the minimum temperature, the most considerable increases occurred in the months of April, June, and July, and as for rainfall, the month of June is the one that tends to present a considerable increase, followed by the month of September. The precipitation variable was the one that presented the most heterogeneity in the stations considered in this study. This work is the basis for conducting studies to assess the impacts of climate change in the study area. Keywords: Climate change, downscaling

5. Camargo-Bravo and García-Cueto, (2012) wrote an article entitled: Evaluation of two Models of Scale Reduction in the Generation of Climate Change Scenarios in the Mexicali Valley in Mexico. Two scale-down models were evaluated in the generation of climate change scenarios in the Mexicali Valley in Mexico. The techniques compared are a Stochastic Weather Generator (LARS-WG) and a dynamic-statistical method (SDSM). Each technique was evaluated for its ability to reproduce some statistical characteristics of the observed climate in the period 1961-1990.

Climate change scenarios of temperature and precipitation were developed for the time horizons 2020 and 2050. LARS WG and SDSM are simple techniques that showed different abilities in simulating statistical moments of the observed climate, both being more efficient at simulating temperature than precipitation. For one of

the scenarios considered, differences of 0.1°C and 0.2°C were found for maximum and minimum temperature and from 40.4% to 76.7% for precipitation.

6. Gualán, Sánchez, et al., (2014) conducted a study under the title: Simplification of the complex process of downscaling global climate models through the SDW web application.

Of the dynamic downscaling techniques, based on the resolution of regional climate models, and statistics, which look for statistical relationships between synoptic climate variables and surface observations, the latter have shown a better representation of climate variables in mountain areas, such as the Andes. However, to consider the uncertainties of future climate scenarios between GCM models, greenhouse gas emission scenarios, and downscaling techniques, there is a need to develop a versatile tool that is a fundamental part of a decision support system.

For the development of SDW, the following specifications were defined as guides to build a quality, useful, and efficient application:

- Create a simple and functional graphical interface;
- Provide mechanisms to facilitate the integration of artificial intelligence computational tools; and
- Design a generic flow for the management of statistical downscaling tools.

SDW groups its functionality into two modules or subsystems. The extraction, load and transform module, ECT, allows you to store data from reanalysis files, GCMs, and observations in a relational repository. The Model Generation and Downscaling module, GMD, allows you to execute the different stages necessary for the execution of statistical downscaling techniques. For the design, a layered architecture was defined, which presents a web portal for the user. As one of the guidelines for the development of the system, the creation of a generic process flow that allows the models to be used in a unified way was defined. This allows and facilitates the integration of new models in the future, a feature that adds versatility and usefulness to this tool, which would form a fundamental part of a decision support system for adaptation to climate change.

7. Duarte, et al., (2018) conducted the study: Hydrological Evaluation of the CSD (Chaotic Statistical Downscaling) Downscaling Technique in the Bogotá River Basin.

The MPI-ESM-MR of the Max Planck Institute was used as a global climate model under the first historical realization (1850-2005) and with the RCP8.5 scenario (2006-2100) in its first realization at the daily level for a total of 91676 data-based on the report of Angarita, (2014), in which it is concluded that this model adequately reflects most of the local weather patterns for the study region. In total, two cells of the model were used with an average value of 5.13 mm, an average standard deviation of 6.12 mm, and an average maximum value of 45.82 mm. For local data, 47 stations selected from the IDEAM (Institute of Hydrology, Meteorology and Environmental Studies) were used.

The hydrological model applied in the Bogotá River basin corresponds to the one developed by Sugawara in 1967, also known as the tank model. For this 4-tank model, precipitation is placed in the upper tank, and evaporation is individually subtracted from each tank as the water in the upper tank runs out.

8. Ferrando, (2019) carried out a study entitled: Advances in research in Spain on the use of modeling in the teaching and learning of mathematics. This contribution aims to show an overview of research focused on the use of modeling.

Research related to modeling is broad and diverse, ranging from theoretical work to research focused on the design and analysis of resources based on the use of modeling. In the advances made in Spain in recent years, the research carried out ranges from early childhood education to teacher training, including compulsory and university education. Given the heterogeneity of the themes and approaches, it is not easy to categorize the works in a univocal way, nor to unify the theoretical perspectives used. This contribution aims to show, in an accessible way, an overview of the advances made and their impact on research in the field of modeling at an international level.

4. CONCLUSIONS

There are very few works referring to the subject to be embroidered at a global level, in the case of Nicaragua, it will be the first work referring to applied mathematics since the existing ones are environmental works, which superficially take the statistical part, while this research delves into it.

For the design of the heuristic algorithms used in the Downscaling process, it is essential to know mathematical programming, especially in the field of software.

In this sense, it is necessary to have programming skills to implement the algorithms efficiently and effectively. This involves understanding the underlying mathematical concepts,

as well as being proficient in using programming languages and specific tools for software development.

In addition, it is important to note that the design of heuristic algorithms for downscaling involves considering aspects such as optimization, mathematical modeling, and data management. Therefore, it is necessary to have a solid knowledge of these areas, as well as an in-depth understanding of the fundamentals of programming and mathematical programming.

In summary, the design of heuristic algorithms for the Downscaling process requires a combination of skills in mathematical programming and software, which allows the development of efficient and accurate solutions for the analysis and projection of climate data at smaller scales.

Several software can be used for the design of heuristic algorithms in the Downscaling process and mathematical programming in general. Some popular options are:

1. MATLAB: MATLAB is a software widely used in the scientific and engineering fields. It offers a wide range of tools and functions for numerical analysis, mathematical programming, and the implementation of heuristic algorithms.
2. A: R is a programming language and software environment designed specifically for statistical analysis and data manipulation. It has numerous libraries and packages that allow you to implement heuristic algorithms and perform advanced analysis.
3. Python: Python is a general-purpose programming language that has become very popular in the field of data science. It has libraries such as NumPy, SciPy, and Pandas, which provide extensive capabilities for numerical analysis and mathematical programming.
4. GAMS: GAMS (General Algebraic Modeling System) is a modeling language and environment for mathematical programming and optimization. It is particularly suitable for solving linear, non-linear, and mixed optimization problems.
5. CPLEX: CPLEX is a mathematical optimization library developed by IBM. It provides a wide range of algorithms and techniques to solve mathematical programming problems efficiently.

Glossary of technical or specialized terms

Acronyms	Meaning	Acronyms	Meaning
CGM, or GCM	Global Circulation Models	MCR, or RCM	Regional Climate Models
SDSM	Statistical Downscaling Model Downscaling Statistical Model	MARENA	Ministry of Environment and Natural Resources
MACGA	Coupled MACG models	km	Kilometer
LARS-WG	Stochastic Weather Generator	MCG	Predictors
CIGEFI-UCR	Center for Geophysical Research of the University of Costa Rica	ENOS	El Niño-Southern Oscillation
FIC	Foundation for Climate Research	ECT	Extraction, loading, and transformation module,
MPI-ESM-MR	Climate series obtained with an RCP scenario from the Max Planck Institute	CSD	Chaotic Statistical Downscaling
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies	CPR	Representative Concentration Pathway

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