ICTP Summer school on Climate Modelling

5 to 9 June 2023

University of Dschang, Dschang, Cameroon

INTRODUCTION
TO
CLIMATE MODELLING

By

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OUTLINE

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> Objectives of climate modelling

> General information on climate modelling

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CONTEXT

The issues of ***climate change*** and ***climate variability*** are the ***most concerns*** of scientists and decision-makers around the world.

Why?

- Because of their immediate and lasting repercussions on the natural environment and on human beings.
- As the water cycle is one of the major components of the climate, the implications of these changes on rainfall patterns and on other atmospheric parameters are significant.

OBJECTIVES

The ***main objectives of climate modeling***

- Understanding the climate and its components,
- Be able to model it with mathematical equations
- Follow its evolution in time and space

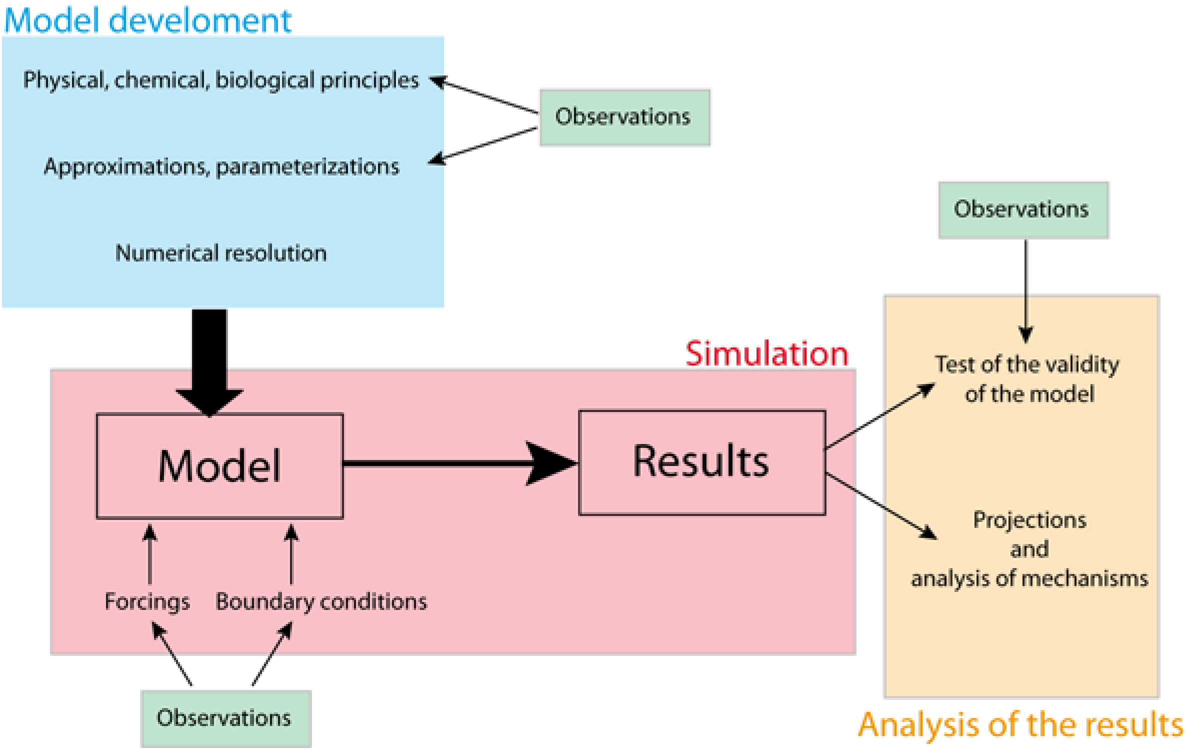
GENERAL INFORMATION ON CLIMATE MODELLING

BASICS DEFINITIONS

- Climate is the **average course or condition of the weather at a place and over a period of years (e.g., Precipitation, temperature, wind, ….).** [https://www.merriam-webster.com/dictionary/climate]
- A climate model is a set of programs that simulate climate parameters based on equations describing the physico-chemical processes in the atmosphere and soil-vegetation-atmosphere interactions.

BASICS DEFINITIONS

In general terms, ***a climate model could be defined as a mathematical representation of the climate system based on physical, biological and chemical principles***



The ***equations derived from these laws are so complex*** that they must be solved numerically. ***As a consequence, climate models provide a solution which is discrete in space and time***, meaning that the results obtained represent averages over regions, whose size depends on model resolution, and for specific times.

Components of the climate system

The climate system is the highly complex system consisting of five major components:

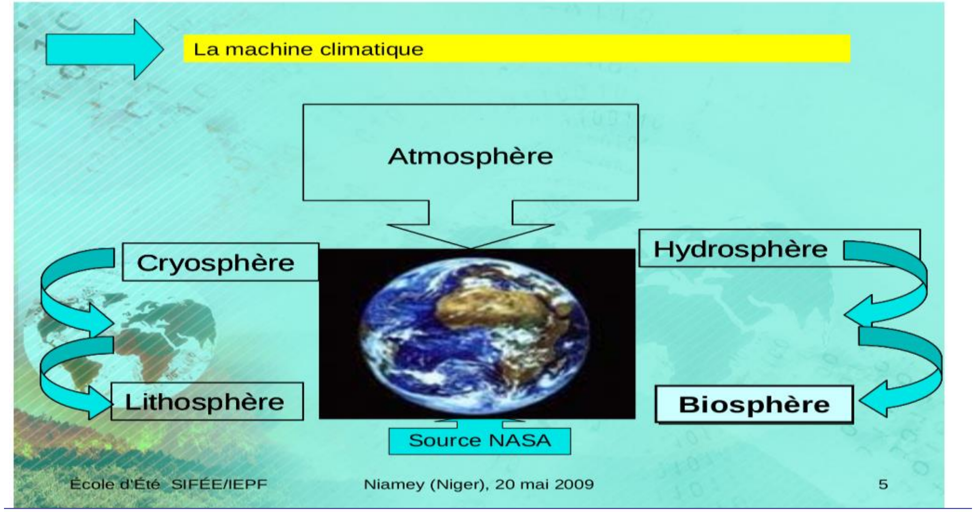
1-The atmosphere: the gaseous envelope surrounding the Earth.

2-The Hydrosphere: comprising liquid surface and subterranean water, such as oceans, seas, rivers, lakes, underground water, etc.

3-The Biosphere (terrestrial and marine): the part of the Earth system comprising all ecosystems and living organisms… including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

4-The Cryosphere: all regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers and ice sheets, and frozen ground (which includes permafrost).

5-The Lithosphere: the upper layer of the solid Earth, both continental and oceanic, which comprises all crustal rocks and the cold, mainly elastic part of the uppermost mantle.



La machine climatique

Atmosphère

Cryosphère

Hydrosphère

Lithosphère

Biosphère

Source NASA

École d'Été SIFÉE/IEPF

Niamey (Niger), 20 mai 2009

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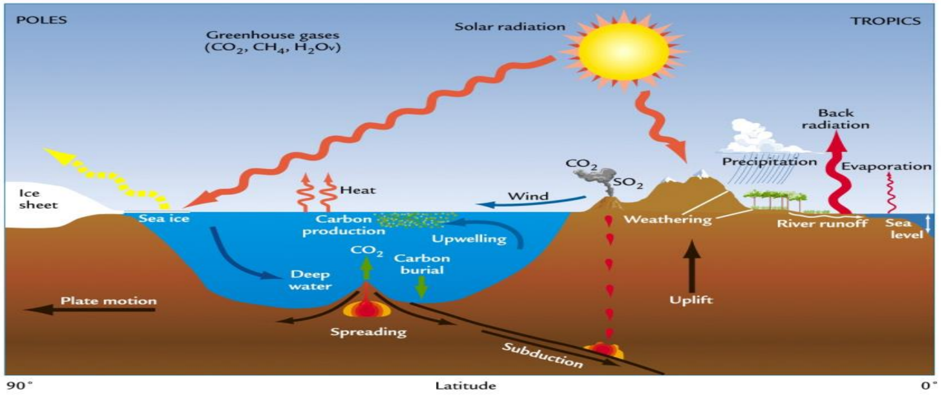


Basic types of climate model

There are five basic types of climate model

1. The Energy Balance Models (EBMs)

2. The Radiative-Convective (RC) or Single-Column models (SCMs)

3. The “Dimensionally Constrained” models

4. The Global Circulation Models (GCMs)

5. The Earth System Models (ESMs)

Basic types of climate model

1. Energy Balance Models (EBMs)

Zero- or one-dimensional models predicting the surface (strictly the sea-level) temperature as a function of the energy balance of the Earth.

Simplified relationships are used to calculate the terms contributing to the energy balance in each latitude zone in the one-dimensional case.

More details on EBMs can be found in the following links:

http://dimacs.rutgers.edu/archive/MPE/Energy/DIMACS-EBM.pdf

https://www.uib.no/sites/w3.uib.no/files/attachments/ebm.pdf

Basic types of climate model

2. Radiative-Convective (RC) or Single-Column models (SCMs)

Focus on processes in the vertical column. There are:

****RC models compute the (usually global average) temperature profile by explicit modelling of radiation and convection processes, which together determine the *lapse rate.***

****SCMs are single columns 'extracted' from a three-dimensional model and include all the processes that would be modelled in the three-dimensional version but without any of the horizontal energy transfers.***

More information on RC models and SCMs can be found in the following links:

https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/RG016i004p00465

https://ramanathan.ucsd.edu/wp-content/uploads/sites/460/2017/10/pr15.pdf

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017MS001189

https://www.arm.gov/publications/proceedings/conf04/extended_abs/randall_da.pdf

Basic types of climate model

3. Dimensionally constrained models

Include the following:

-> ***Statistical-Dynamical (SD) models***, deal explicitly with surface processes and dynamics in a zonal average (average around latitude circles) framework and have a vertically resolved atmosphere.

[https://www.scirp.org/html/6-2360209_54579.htm;

https://www.tandfonline.com/doi/pdf/10.3402/tellusa.v34i3.10806]

-> ***Earth-System Models of Intermediate Complexity (EMICs)*** extend SD models to include interactive chemistry, especially the cycling of carbon between ocean, atmosphere and land.

[https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-8-3.html ;

https://www.researchgate.net/publication/225534764_Earth_system_models_of_intermediate_complexity_Closing_the_gap_in_the_spectrum_of_climate_system_models]

-> ***Integrated Assessment Models (IAMs)*** couple the climate system to models of economic activity to more fully assess the impact of particular policy choices affective emissions.

[https://sedac.ciesin.columbia.edu/mva/iamcc.tg/mva-questions.html ;

https://www.nber.org/reporter/2017number3/integrated-assessment-models-climate-change]

Basic types of climate model

4. Global Circulation Models (GCMs)

The ***three-dimensional nature of the atmosphere and ocean*** is incorporated.

->These models can exists as fully ***coupled ocean-atmosphere models*** or, for testing and evaluation, as ***independent ocean or atmospheric circulation models***.

->These models ***attempt to simulate as many processes as possible*** and ***produce a three-dimensional picture of the time evolution*** of the state of the whole climate system.

->***Vertical resolution is much finer than horizontal resolution*** but, even so, the number of layers is usually much less than the number of columns.

The Global/General Circulation Models

(GCMs)

The Global Circulation Models (GCMs)

1. Generality

The objectives

The aim objectives of the GCM are:

>Calculation of the full three-dimensional character of the atmosphere and ocean.

>Simulate the fluid flow and its effects on other components of the climate system, instead of parameterizing the flow.

The Global Circulation Models (GCMs)

2. Equations governing the motion of fluids

a- Conservation of momentum,

- $$\frac{d\vec{V}}{dt} = \vec{g} - \frac{1}{\rho}\,\overrightarrow{\mathrm{grad}}\,p - 2\,\vec{\Omega} \wedge \vec{V} + \mathrm{Ff}$$

b- Conservation of mass

- $$\mathrm{Div}\,\vec{V} + \frac{1}{\rho}\frac{d\rho}{dt} = 0$$

c- Conservation of energy

- $\mathrm{dU(T)} = \delta\mathrm{U} + \delta\mathrm{Q}$ (Travail + Chaleur)

d- Equation of state, linking thermodynamic properties of the fluid

- $p = \rho \mathrm{RT}$

e- Equations for the formation of clouds, sea ice, etc.

- $\frac{dq}{dt}$ = *Evaporation* - Précipitation

$\vec{\mathrm{V}}$(u, v, w) = vecteur vitesse

P : pression

ρ: densité

U : énergie interne

T : température

q : concentration en vapeur d’eau

These physical laws are expressed in terms of differential equations.

The Global Circulation Models (GCMs)

2. Equations governing the motion of fluids (...)

These physical laws are expressed in terms of differential equations.

Example: Conservation of momentum

$$\left|\begin{array}{l}
\dfrac{du}{dt}-\dfrac{uvtg(\phi)}{r}+\dfrac{uw}{r}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial x}-2\Omega\cos(\phi)w+2\Omega\sin(\phi)v+F_{rx}\\
\dfrac{dv}{dt}+\dfrac{u^2tg(\phi)}{r}+\dfrac{vw}{r}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial y}-2\Omega\sin(\phi)u+F_{ry}\\
\dfrac{dw}{dt}-\dfrac{u^2+v^2}{r}=-g-\dfrac{1}{\rho}\dfrac{\partial P}{\partial z}+2\Omega\cos(\phi)u+F_{rz}
\end{array}\right.$$

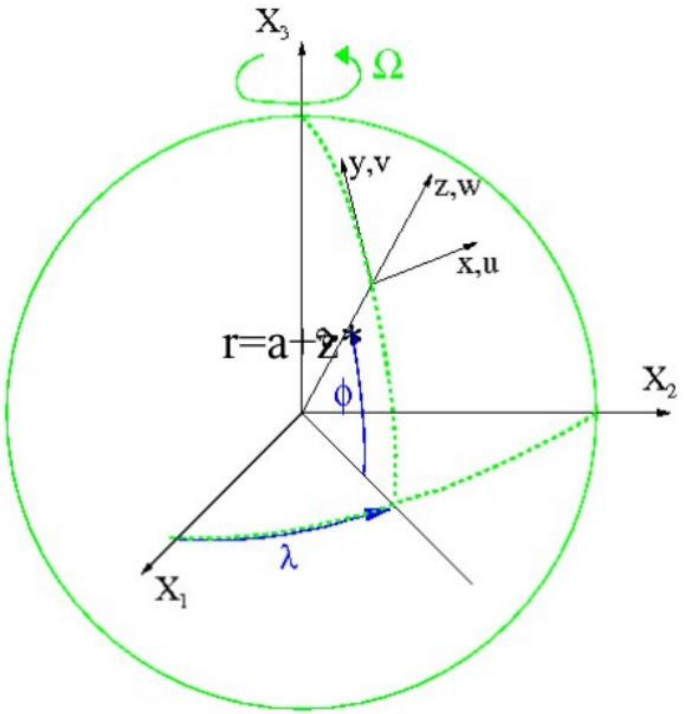
courbure

gravité

Force de pression

Coriolis

frottements



The Global Circulation Models (GCMs)

3. Solving Model Equations

To account for the ***"large-scale" evolutions of the atmosphere*** described by ***fluid mechanics***, the atmosphere is represented in a meshed form that can be represented as ***a giant Rubik's cube*** with intersections ***every 10 to 20 km horizontally*** for a regular grid and over ***70 levels vertically*** as shown in the figure below.

The discretized equations are then solved numerically by timestepping,

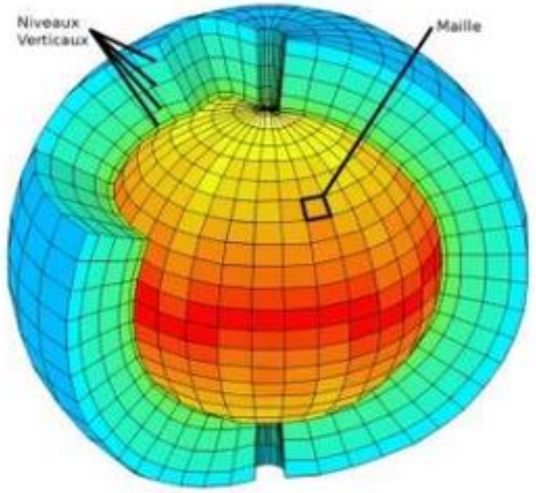


Fig. 1. Représentation schématique du maillage de l'atmosphère: à chaque maille, est associée une valeur de chaque grandeur physique nécessaire pour décrire l'atmosphère (source: Météo-France).

The Global Circulation Models (GCMs)

4. Input data of the models

The main inputs for a climate model are external factors, so called “***forcings***”, that change the amount of the ***sun’s energy absorbed by the Earth*** or ***trapped in the atmosphere***.

Examples of these ***forcings*** are ***the sun’s varying radiation output***, variable atmospheric concentrations of ***greenhouse gasses*** (e.g. CO2, methane, N2O) or ***aerosols*** (particles emitted e.g. by fossil fuel burning and volcanic eruptions influencing sunlight and cloud formation).

These factors are ***incorporated*** into the ***climate model*** as best estimates of past conditions or as part of ***future socio-economic*** and ***emission scenarios***.

The Global Circulation Models (GCMs)

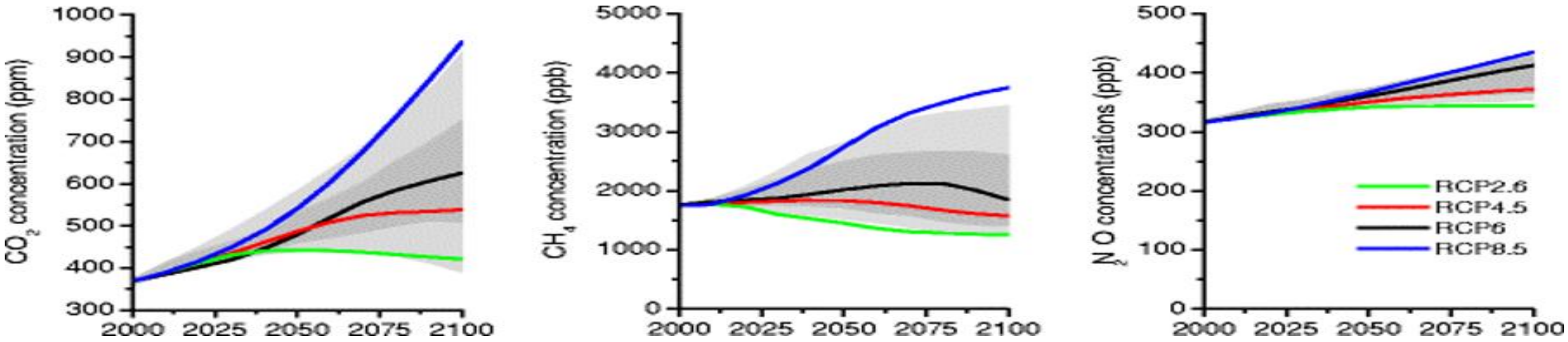
4. Input data of the models (...)

4.1 Past forcing

Past forcings can be estimated by reconstructing ancient greenhouse gas concentrations (e.g. by analyzing air trapped in ice cores), climate gas and particle emissions during past volcanic eruptions or changes in the Earth’s orbit (i.e. cyclical variations in solar radiation reaching the Earth due to Milankovitch cycles).

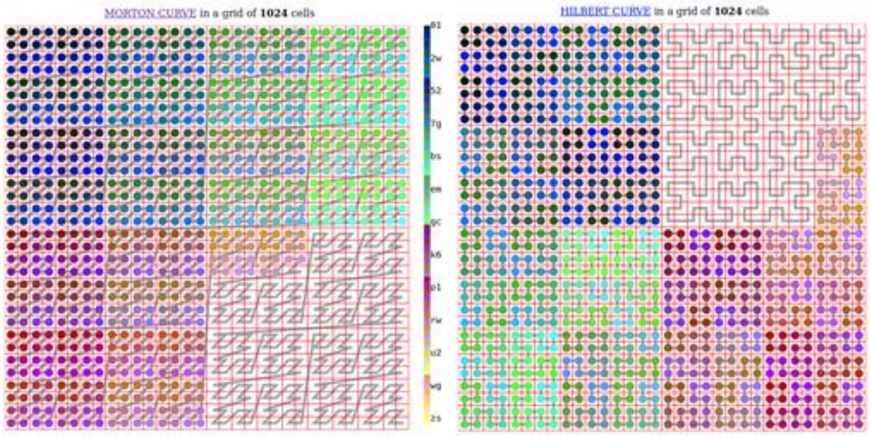
4.2 Future forcing

Concerning future forcings, different scenarios of future developments in technology, energy and land use provide potential pathways, so called “Representative Concentration Pathways” (RCPs), for atmospheric greenhouse gas concentrations (Fig.).



The Global Circulation Models (GCMs)

5. Climate Model Resolution and time step



5.1 Resolution of the model

Climate models separate Earth’s surface into a ***three-dimensional grid of cells***.

The results of processes modeled in each cell are passed to neighboring cells to model the exchange of matter and energy over time. **Grid cell size** defines the **resolution of the model.**

The ***smaller the size of the grid cells, the higher the level of detail in the model***. More detailed models have more grid cells, so they need more computing power.

5.2 Time step of the model

Climate models also include the ***element of time***, called a ***time step***. Time steps can be in ***minutes***, ***hours***, ***days***, or ***years***. Like grid cell size, ***the smaller the time step, the more detailed the results will be***.

However, this higher temporal resolution requires additional computing power.

The Global Circulation Models (GCMs)

6. Model parameterization

Scientists do not have a limitless supply of computing power at their disposal, and so it is necessary for models ***to divide up the Earth into grid cells*** to make the calculations ***more manageable***.

This means that at every step of the model through time, it ***calculates the average climate of each grid cell***.

However, ***there are many processes in the climate system*** and on the ***Earth's surface that occur on scales within a single cell***.

*****For example, ***the height of the land surface will be averaged across a whole grid cell*** in a model, meaning it potentially overlooks the detail of any physical features such as mountains and valleys.

Similarly, ***clouds can form and dissipate at scales*** that are ***much smaller than a grid cell***.

The Global Circulation Models (GCMs)

6. Model parameterization

To solve this problem, these variables are "***parameterised***", meaning their values are defined in the computer code rather than being calculated by the model itself.

The graphic shows some of the processes that are typically parameterized in models.

Parameterizations may also be used as a ***simplification*** where a ***climate process isn't well understood***.

Note: Parameterizations are one of the main sources of uncertainty in climate models.

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The Global Circulation Models (GCMs)

6. Model parameterization

In many cases, ***it is not possible to narrow down parameterized variables into a single value***, so the ***model needs to include an estimation***.

Scientists ***run tests with the model*** to ***find*** the ***value*** – or ***range of values*** – that ***allows the model to give the best representation of the climate***.

This complex process is known variously as ***model "tuning"*** or ***"calibration"***.

While it is a necessary part of climate modeling, it is not a process that is specific to it.

Notice
If all parameters were 100% certain, then ***this calibration would not be necessary.***
But ***scientists' knowledge of the climate is not perfect***, because the ***evidence*** they have ***from observations*** is ***incomplete***.
Therefore, they need to ***test their parameter values in order to give sensible model output for key variables***.

The Global Circulation Models (GCMs)

6. Model parameterization

As most global models will contain parameterization schemes, virtually all modelling centres undertake model tuning of some kind. A survey in 2014 found that, in most cases, modellers tune their models to ensure that the long-term average state of the climate is accrate – including factors such as absolute temperatures, sea ice concentrations, surface albedo and sea ice extent.

The ***factor most often tuned*** for – in 70% of cases – is the r***adiation balance at the top of the atmosphere***. This process involved adjusting parameterisations particularly of ***clouds – microphysics***, ***convection*** and ***cloud fraction*** – but also ***snow***, ***sea ice albedo*** and ***vegetation***.

This tuning does not involve simply "fitting" historical observations. Rather, if a reasonable choice of parameters leads to model results that differ dramatically from observed climatology, modellers may decide to use a different one. Similarly, if updates to a model leads to a wide divergence from observations, modellers may look for bugs or other factors that explain the difference.

The Global Circulation Models (GCMs)

7. Output data of the models

The main outputs for a climate model are normally :

***temperatures** and **humidity** of different atmospheric layers from the surface to the upper stratosphere.

*Climate models also produce estimates of ***ocean temperatures***, ***salinity*** and ***pH*** from the surface to the seafloor as well as ***snowfall***, ***rainfall***, ***snow cover*** and the extent of ***glaciers***, ***ice sheets*** and ***sea ice***.

*They also give information about ***wind*** speed, strength and direction, as well as climate features, such as the ***jet stream*** and ***ocean currents***.

"***Climate sensitivity***" can also be modelled (i.e. the warming expected when the concentration of carbon dioxide in the atmosphere reaches twice the amount it was in preindustrial times).

The Global Circulation Models (GCMs)

8. Climate model validation

Scientists test, or “***validate***”, their ***models*** by ***comparing them against real-world observations***. This might include, for ***example***, ***comparing the model projections against actual global surface temperatures over the past century***.

Climate models can be tested against past changes in the Earth’s climate. These comparisons with the past are called “***hindcasts***”.

Scientists do not “tell” their models how the climate has changed in the past – they do not feed in historical temperature readings, for example. Instead, they feed in information on past climate forcings and the models generate a “hindcast” of historical conditions. This can be a useful way to validate models.

Climate model hindcasts of different climate factors including temperature (across the surface, oceans and atmosphere), rain and snow, hurricane formation, sea ice extent and many other climate variables have been used to show that models are able to accurately simulate the Earth’s climate.

There are hindcasts for the historical temperature record (1850-present), over the past 2,000 years using various climate proxies, and even over the past 20,000 years.

The Global Circulation Models (GCMs)

8. Climate model validation (...)

Climate models are also compared against the average state of the climate, known as the "***climatology***".

For ***example***, researchers check to see ***if the average temperature of the Earth in winter*** and ***summer is similar in the models and reality***.
They also compare sea ice extent between models and observations, and may choose to use models that do a better job of representing the current amount of sea ice when trying to project future changes.

Experiments where many different models are run with the same greenhouse gas concentrations and other "***forcings***", as in ***model intercomparison projects***, provide a way to look at similarities and differences between models.

For many parts of the climate system, the average of all models can be more accurate than most individual models. ***Researchers have found that forecasts can show better skill, higher reliability and consistency when several independent models are combined***.

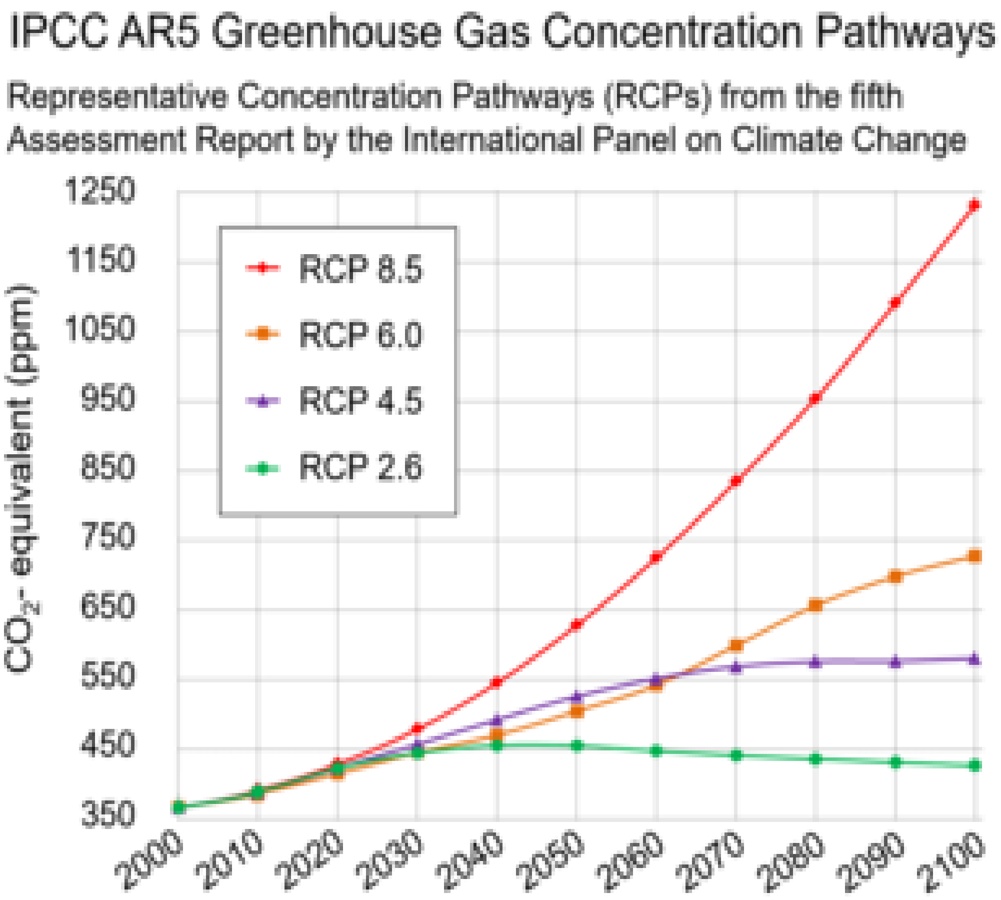
One way ***to check if models are reliable is to compare projected future changes against how things turn out in the real world***. This can be hard to do with long-term projections, however, because it would take a long time to assess how well current models perform.

The Global Circulation Models (GCMs)

9. Future greenhouse gas emission scenario

The IPCC’s fifth assessment report focused on ***four future warming scenarios***, known as ***the Representative Concentration Pathway (RCP) scenarios***. These look at how the climate might change ***from present through to 2100 and beyond***.

Many things that drive future emissions, such as population and economic growth, are difficult to predict. Therefore, ***these scenarios span a wide range of futures, from a business-as-usual world where little or no mitigation actions are taken (RCP6.0 and RCP8.5) to a world in which aggressive mitigation generally limits warming to no more than 2C (RCP2.6)***. You can read more about the different RCPs here.



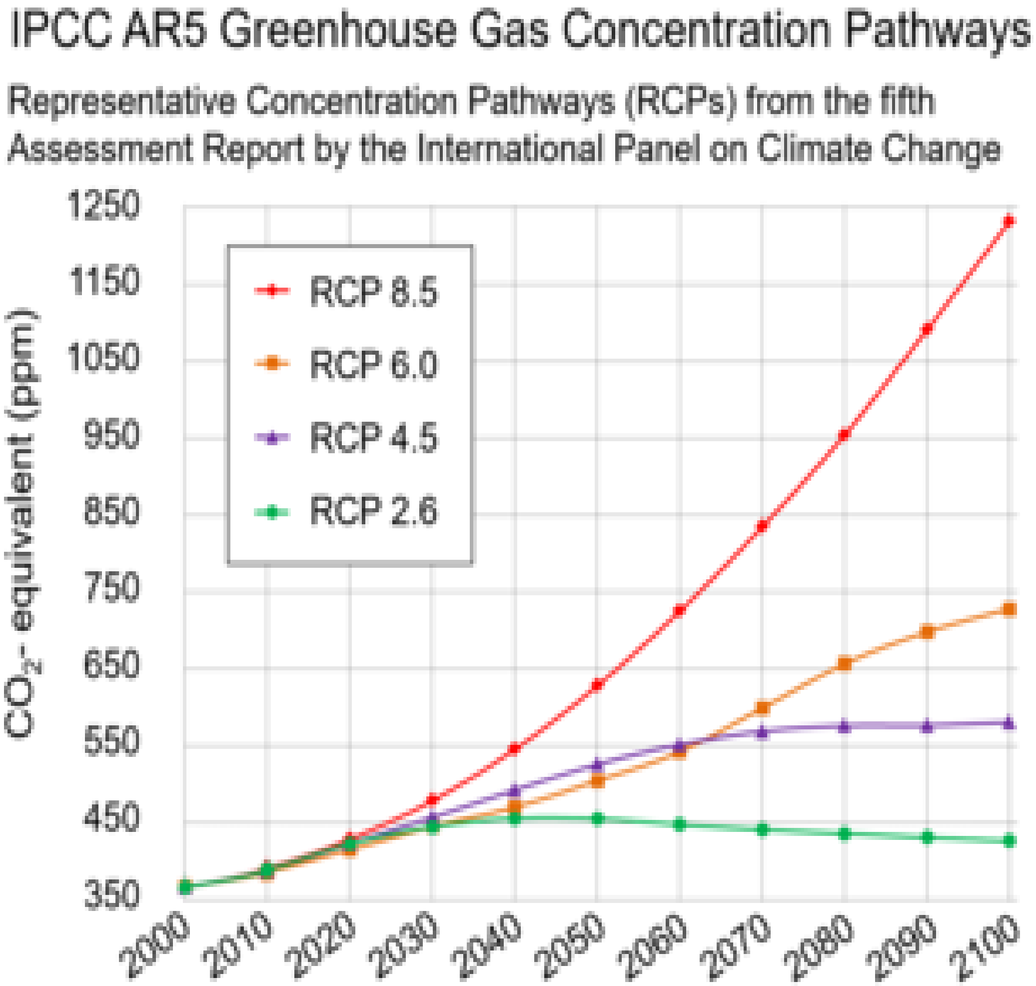
The Global Circulation Models (GCMs)

9. Future greenhouse gas emission scenario (...)

These ***RCP scenarios*** specify ***different amounts of radiative forcings***.

Models use those ***forcings to examine how the Earth's system will change*** under each of the different pathways.

The ***upcoming CMIP6*** exercise, associated with the ***IPCC sixth assessment report***, had the aim to ***add four new RCP scenarios to fill in the gaps*** around the four already in use, ***including a scenario that meets the 1.5°C temperature limit***.



The Global Circulation Models (GCMs)

9. Future greenhouse gas emission scenario (...)

New scenarios called ***Shared Socioeconomic Pathway (SSP) Experiments*** were created.

The ***SSP*** scenario experiments can be understood in terms of two pathways, a Shared Socioeconomic Pathway (***SSP***) and a Representative Concentration Pathway (***RCP***). The two pathways are represented by the three digits that make up the experiment's name.

>The first digit represents the ***SSP*** storyline for the socio-economic mitigation and adaptation challenges that the experiment represents (see Figure).

>The second and third digits represent the ***RCP*** climate forcing that the experiment follows.

For example, experiment ssp245 follows ***SSP2***, a storyline with intermediate mitigation and adaptation challenges, and RCP4.5 which leads to a radiative forcing of 4.5 Wm^{-2} by the year 2100.

***Figure**: The socioeconomic "Challenge Space" to be spanned by the CMIP6 SSP experiments (O'Neil et al. 2014).*

The Global Circulation Models (GCMs)

10. Some climate model limitations

Climate models are not a perfect representation of the Earth's climate.
>As ***the climate is inherently chaotic***, it is ***impossible to simulate with 100% accuracy***, yet models do a pretty good job at getting the climate right.

>***The accuracy of projections made by models is also dependent on the quality of the forecasts that go into them***.
For example, ***scientists do not know if greenhouse gas emissions will fall***, and ***so make estimates based on different scenarios of future socio-economic development***. This adds another layer of uncertainty to climate projections.

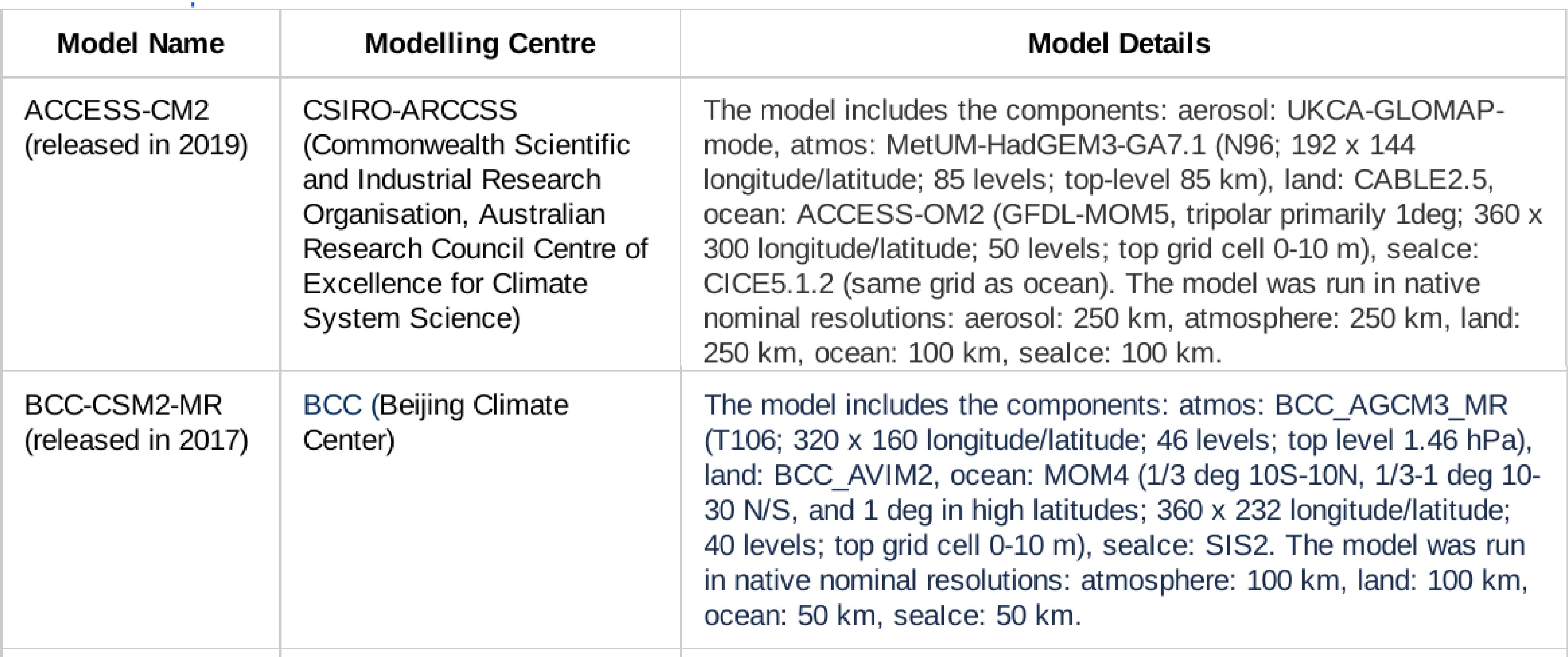
>Similarly, ***there are aspects of the future that would be so rare in Earth's history that they're extremely difficult to make projections for***.
One example is that ice sheets could destabilize as they melt, accelerating expected global sea level rise.

Yet, ***despite models becoming increasingly complex and sophisticated***, ***there are still aspects of the climate system that they struggle to capture as well as scientists would like***.

The Global Circulation Models (GCMs)

11. Some GCMs

The CMIP6 MODELS:

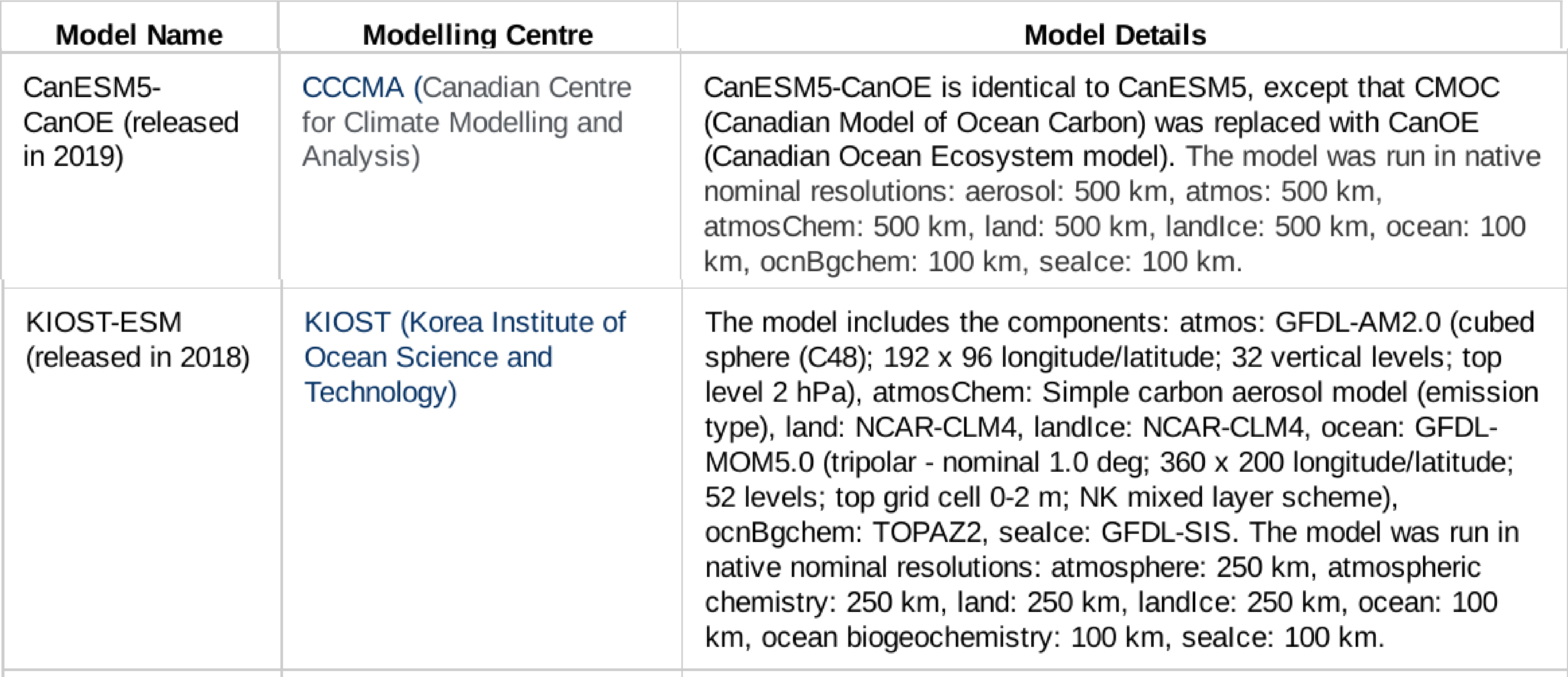


Model Name	Modelling Centre	Model Details
ACCESS-CM2 (released in 2019)	CSIRO-ARCCSS (Commonwealth Scientific and Industrial Research Organisation, Australian Research Council Centre of Excellence for Climate System Science)	The model includes the components: aerosol: UKCA-GLOMAP-mode, atmos: MetUM-HadGEM3-GA7.1 (N96; 192 x 144 longitude/latitude; 85 levels; top-level 85 km), land: CABLE2.5, ocean: ACCESS-OM2 (GFDL-MOM5, tripolar primarily 1deg; 360 x 300 longitude/latitude; 50 levels; top grid cell 0-10 m), seaIce: CICE5.1.2 (same grid as ocean). The model was run in native nominal resolutions: aerosol: 250 km, atmosphere: 250 km, land: 250 km, ocean: 100 km, seaIce: 100 km.
BCC-CSM2-MR (released in 2017)	BCC (Beijing Climate Center)	The model includes the components: atmos: BCC_AGCM3_MR (T106; 320 x 160 longitude/latitude; 46 levels; top level 1.46 hPa), land: BCC_AVIM2, ocean: MOM4 (1/3 deg 10S-10N, 1/3-1 deg 10-30 N/S, and 1 deg in high latitudes; 360 x 232 longitude/latitude; 40 levels; top grid cell 0-10 m), seaIce: SIS2. The model was run in native nominal resolutions: atmosphere: 100 km, land: 100 km, ocean: 50 km, seaIce: 50 km.

The Global Circulation Models (GCMs)

11. Some GCMs

The CMIP6 MODELS:

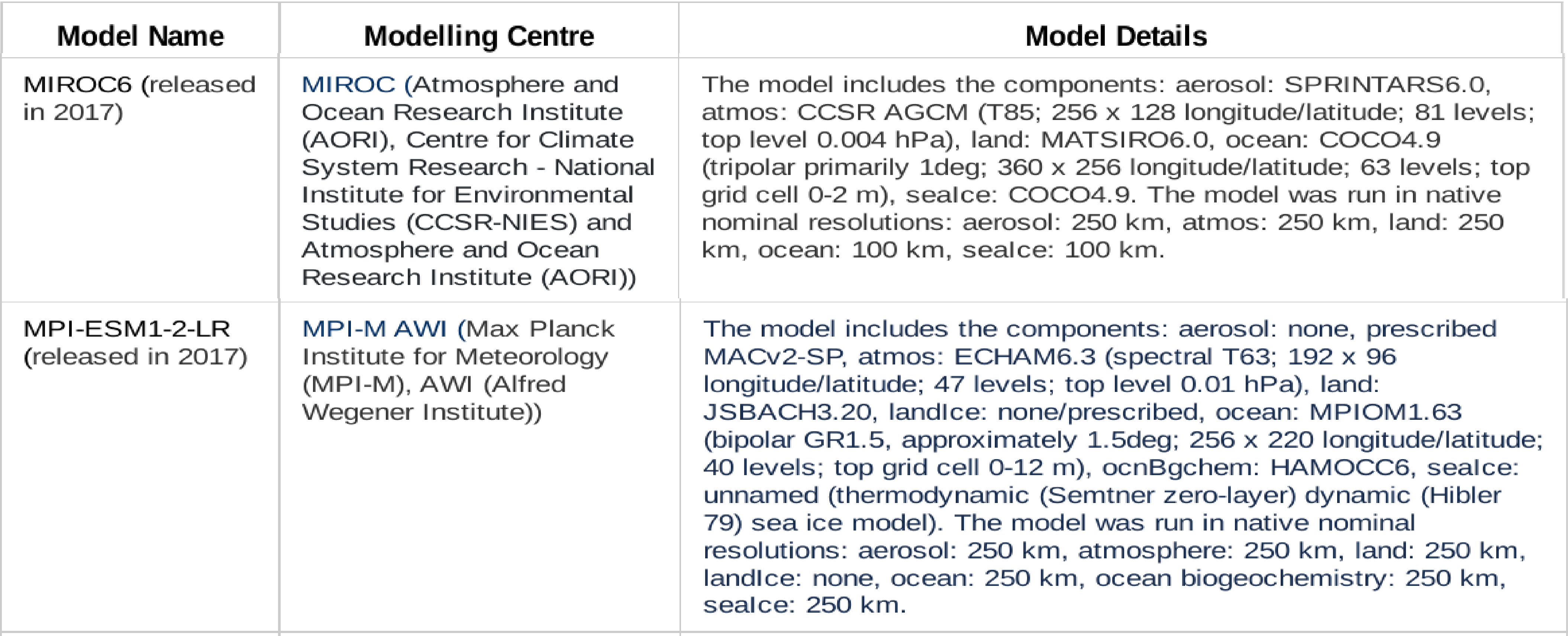


Model Name	Modelling Centre	Model Details
CanESM5-CanOE (released in 2019)	CCCMA (Canadian Centre for Climate Modelling and Analysis)	CanESM5-CanOE is identical to CanESM5, except that CMOC (Canadian Model of Ocean Carbon) was replaced with CanOE (Canadian Ocean Ecosystem model). The model was run in native nominal resolutions: aerosol: 500 km, atmos: 500 km, atmosChem: 500 km, land: 500 km, landIce: 500 km, ocean: 100 km, ocnBgchem: 100 km, seaIce: 100 km.
KIOST-ESM (released in 2018)	KIOST (Korea Institute of Ocean Science and Technology)	The model includes the components: atmos: GFDL-AM2.0 (cubed sphere (C48); 192 x 96 longitude/latitude; 32 vertical levels; top level 2 hPa), atmosChem: Simple carbon aerosol model (emission type), land: NCAR-CLM4, landIce: NCAR-CLM4, ocean: GFDL-MOM5.0 (tripolar - nominal 1.0 deg; 360 x 200 longitude/latitude; 52 levels; top grid cell 0-2 m; NK mixed layer scheme), ocnBgchem: TOPAZ2, seaIce: GFDL-SIS. The model was run in native nominal resolutions: atmosphere: 250 km, atmospheric chemistry: 250 km, land: 250 km, landIce: 250 km, ocean: 100 km, ocean biogeochemistry: 100 km, seaIce: 100 km.

The Global Circulation Models (GCMs)

11. Some GCMs

The CMIP6 MODELS:

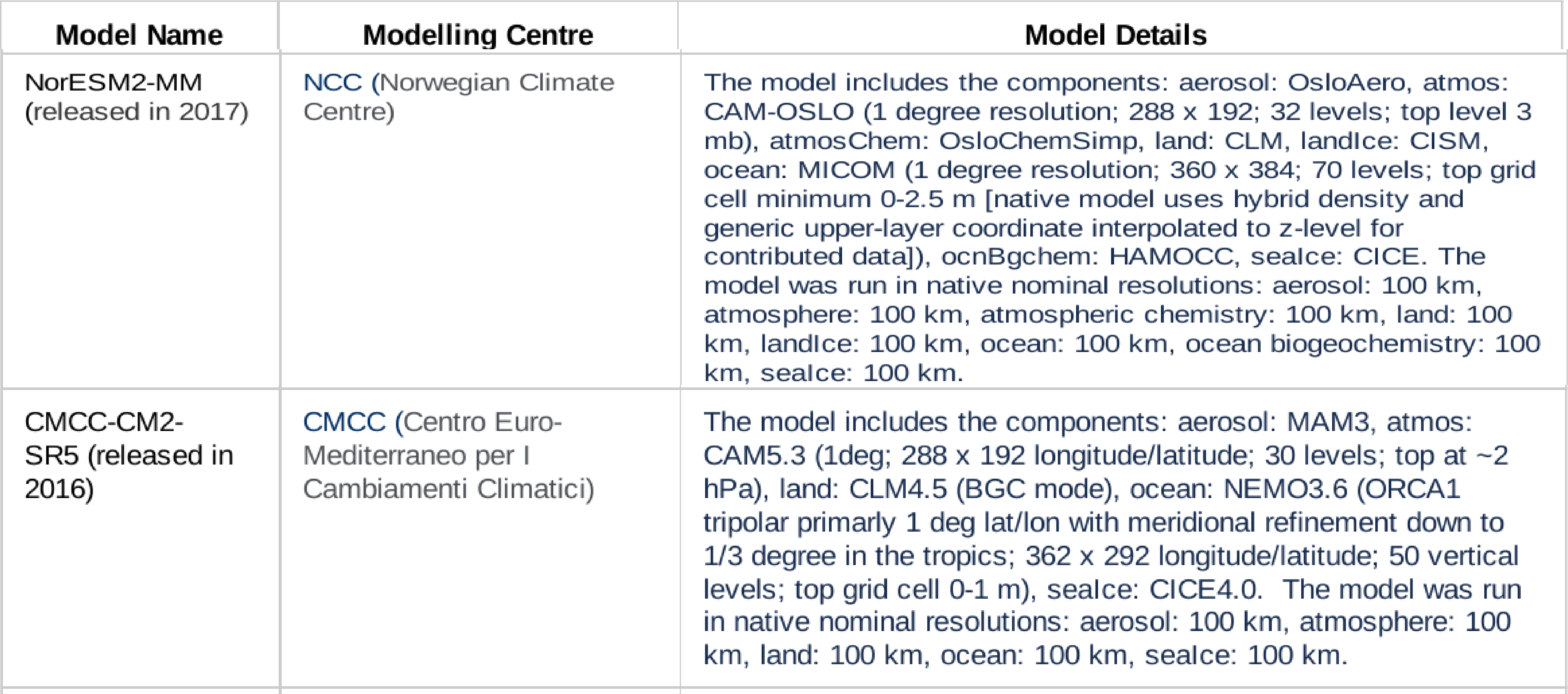


Model Name	Modelling Centre	Model Details
MIROC6 (released in 2017)	MIROC (Atmosphere and Ocean Research Institute (AORI), Centre for Climate System Research - National Institute for Environmental Studies (CCSR-NIES) and Atmosphere and Ocean Research Institute (AORI))	The model includes the components: aerosol: SPRINTARS6.0, atmos: CCSR AGCM (T85; 256 x 128 longitude/latitude; 81 levels; top level 0.004 hPa), land: MATSIRO6.0, ocean: COCO4.9 (tripolar primarily 1deg; 360 x 256 longitude/latitude; 63 levels; top grid cell 0-2 m), seaIce: COCO4.9. The model was run in native nominal resolutions: aerosol: 250 km, atmos: 250 km, land: 250 km, ocean: 100 km, seaIce: 100 km.
MPI-ESM1-2-LR (released in 2017)	MPI-M AWI (Max Planck Institute for Meteorology (MPI-M), AWI (Alfred Wegener Institute))	The model includes the components: aerosol: none, prescribed MACv2-SP, atmos: ECHAM6.3 (spectral T63; 192 x 96 longitude/latitude; 47 levels; top level 0.01 hPa), land: JSBACH3.20, landIce: none/prescribed, ocean: MPIOM1.63 (bipolar GR1.5, approximately 1.5deg; 256 x 220 longitude/latitude; 40 levels; top grid cell 0-12 m), ocnBgchem: HAMOCC6, seaIce: unnamed (thermodynamic (Semtner zero-layer) dynamic (Hibler 79) sea ice model). The model was run in native nominal resolutions: aerosol: 250 km, atmosphere: 250 km, land: 250 km, landIce: none, ocean: 250 km, ocean biogeochemistry: 250 km, seaIce: 250 km.

The Global Circulation Models (GCMs)

11. Some GCMs

The CMIP6 MODELS:



Model Name	Modelling Centre	Model Details
NorESM2-MM (released in 2017)	NCC (Norwegian Climate Centre)	The model includes the components: aerosol: OsloAero, atmos: CAM-OSLO (1 degree resolution; 288 x 192; 32 levels; top level 3 mb), atmosChem: OsloChemSimp, land: CLM, landIce: CISM, ocean: MICOM (1 degree resolution; 360 x 384; 70 levels; top grid cell minimum 0-2.5 m [native model uses hybrid density and generic upper-layer coordinate interpolated to z-level for contributed data]), ocnBgchem: HAMOCC, seaIce: CICE. The model was run in native nominal resolutions: aerosol: 100 km, atmosphere: 100 km, atmospheric chemistry: 100 km, land: 100 km, landIce: 100 km, ocean: 100 km, ocean biogeochemistry: 100 km, seaIce: 100 km.
CMCC-CM2-SR5 (released in 2016)	CMCC (Centro Euro-Mediterraneo per I Cambiamenti Climatici)	The model includes the components: aerosol: MAM3, atmos: CAM5.3 (1deg; 288 x 192 longitude/latitude; 30 levels; top at ~2 hPa), land: CLM4.5 (BGC mode), ocean: NEMO3.6 (ORCA1 tripolar primarly 1 deg lat/lon with meridional refinement down to 1/3 degree in the tropics; 362 x 292 longitude/latitude; 50 vertical levels; top grid cell 0-1 m), seaIce: CICE4.0. The model was run in native nominal resolutions: aerosol: 100 km, atmosphere: 100 km, land: 100 km, ocean: 100 km, seaIce: 100 km.

The Regional Climate Model (RCM)
to solve
some limitations
of the
General Climate Model (GCM)

Regional Climate Models (RCM)

1. Vacuum of GCMs

→ In some situations, the ***spatial resolution of global climate model (GCM) outputs is too coarse*** for ***informing regional or local adaptation***.

→ In addition, ***GCMs may not be able to adequately represent the climate of a specific region*** with ***a varied and complex climate***.

As solution

In these cases, ***it is necessary to transform GCM simulations into finer resolution climate simulations***. This leads to the conception of the ***Regional Climate Models (RCMs)***.

Regional Climate Models (RCMs)

2. Definition and types of RCMs

2.1 Definition

A ***regional climate model*** (Abbreviated ***RCM***) is a ***numerical climate prediction model forced by specified lateral and ocean conditions from a general circulation model*** (GCM) or ***observation-based dataset*** (reanalysis) that simulates atmospheric and land surface processes, while ***accounting for high-resolution topographical***.

This ***process is called downscaling***.

2.2 Types of RCMs

There exist ***dynamical*** and ***statistical downscaled model.***

Dynamically and statistically downscaled model data can be used to develop climate projections.

Regional Climate Models (RCMs)

2. Definition and types of RCMs (...)

2.2 Types of RCMs

2.2.1 Dynamical downscaling

This method, also known as ***regional climate modelling*** (RCM) ***simulates local climate using output from a GCM*** as ***input to a high-resolution climate model***. Examples include ***CSIRO's*** Conformal Cubic Atmospheric Model (***CCAM***) and the ***ICTP RCM*** (RegCM4).

2.2.2 Statistical downscaling

This method ***also simulates local climate using output from a GCM as input*** but ***through a statistical model***.

This is usually a ***two-step process:***
>First, an ***empirical relationship between local climate variables*** such as rainfall and large-scale predictors such as the mean sea-level pressure ***is developed***.

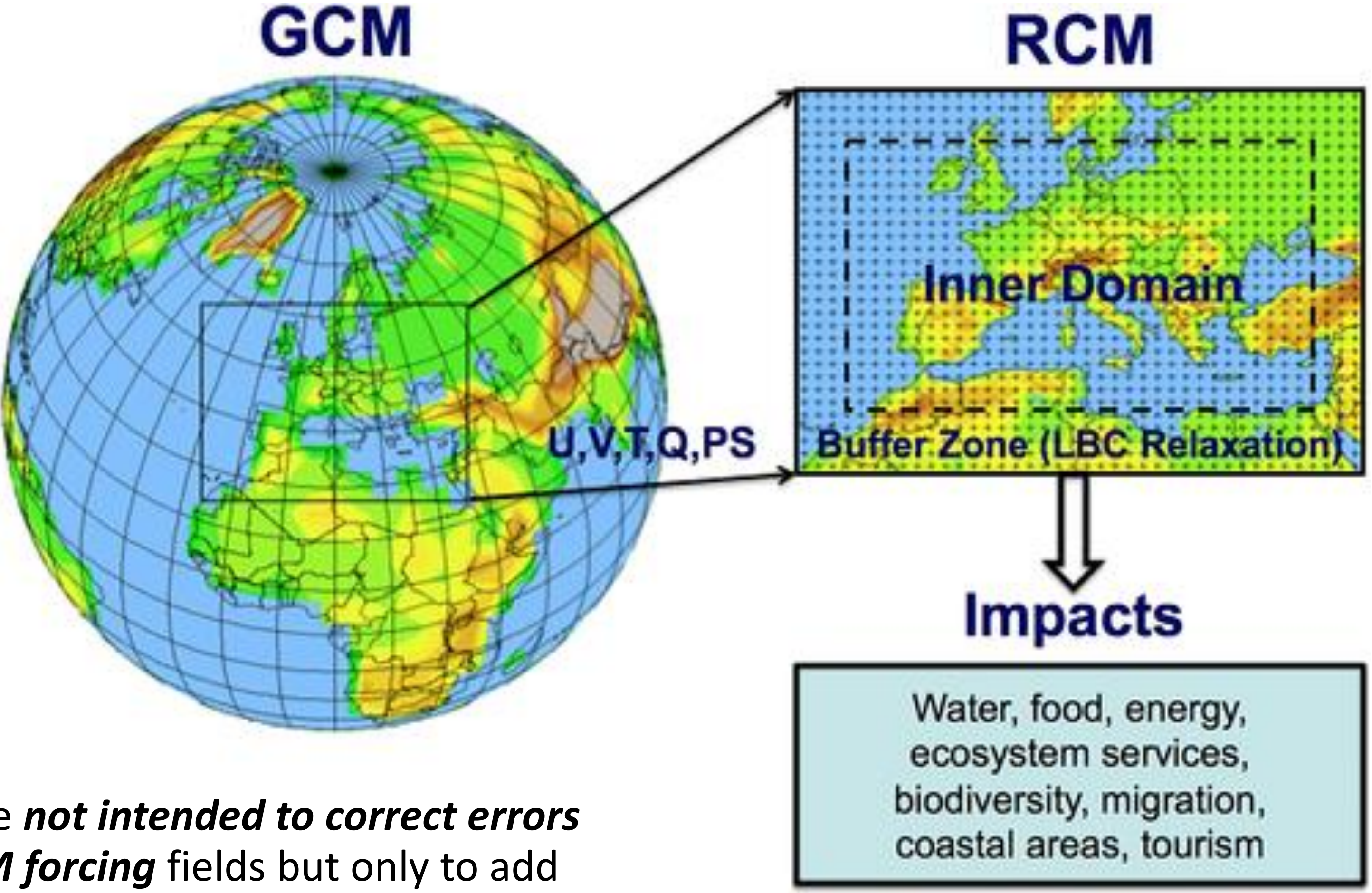
>The ***relationship is then applied to GCM simulation data to simulate local climate variables***.
Examples include the Generalised Linear Modelling for Daily Climate Series (GLIMCLIM) and the nonhomogeneous hidden Markov model (NHMM).

Regional Climate Models (RCM)

2. Definition and types of RCMs (...)

2.3 Illustration of downscaling

The downscaling technique is usually referred to as ***one-way nesting*** because ***information flows from the GCM*** large-scale driving conditions ***to the RCM.***



in general the ***nested RCMs*** are ***not intended to correct errors present in the large-scale GCM forcing*** fields but only to add realistic sub-GCM grid-scale detail.

Regional Climate Models (RCM)

3. Model Initialization and Spin-Up

3.1 Model Initialization

In order ***to start a model run***, ***certain variables need to be specified***: like ***domains***, ***grids***, and ***bathymetry***;
Now ***there are starting values used for the variables that the model is actually going to predict***. These include temperature, salinity, density, sea level, and velocity.

Driving Global Climate Models and Regional Climate Models

Regional Climate Model ***(RCM) simulations needs lateral boundary conditions from*** Global Climate Models ***(GCMs)*** that ***provide reliable climate information*** on ***global***, ***continental*** and ***large regional scales covering what could be a vastly differing landscape*** (from very mountainous to flat coastal plains for example) with greatly varying potential for floods, droughts or other extreme events.

Regional Climate Models (RCM)

3. Model Initialization and Spin-Up (...)

3.2 Spin-up

Definition
It is the ***time taken for a RCM to reach a state of statistical equilibrium under the applied forcing***.
Note: In spin-ups of several decades, deep watermass properties away from strong currents or deepwater formation sites will not evolve far from the initial state.

Climatology
One way to initialize models is by using ***climatological values of temperature and salinity*** from databases and ***assuming the velocity field is zero at the start***.

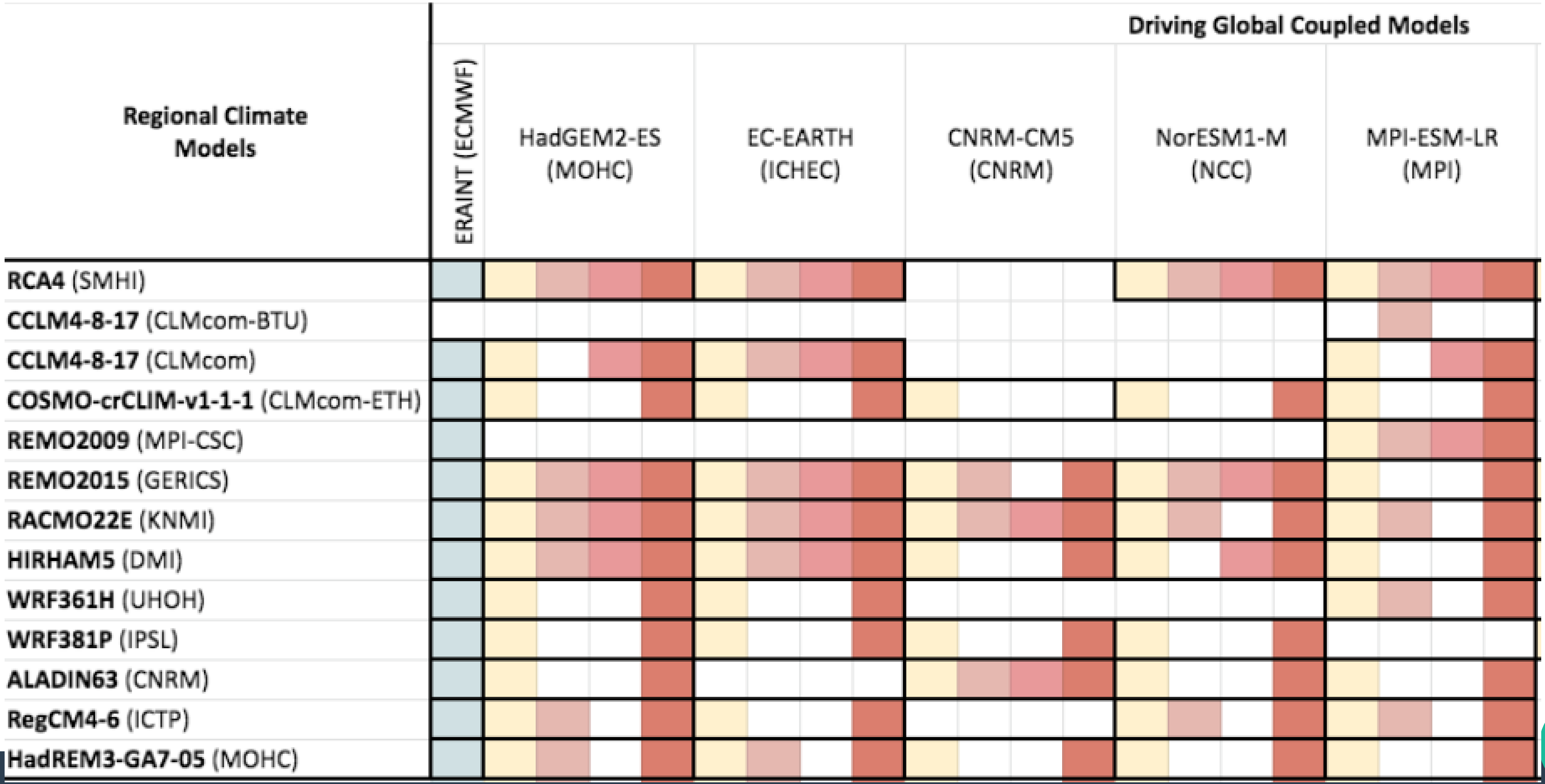
The model physics will spin up a velocity field in balance with the density field, even in the absence of forcing.

As forcing is applied, the velocity field will respond to it initially with transient flows that may not be realistic for an ocean that undergoes continuous, albeit always changing, forcing. For this reason, the results from the beginning of ocean circulation model runs are usually not used.

Regional Climate Models (RCM)

Examples of some RCMs

Numerous ***RCMs*** are today available from laboratories worldwide.
e.g. : The models of the Coordinated Regional Climate Downscaling Experiment (***EURO***-CORDEX):

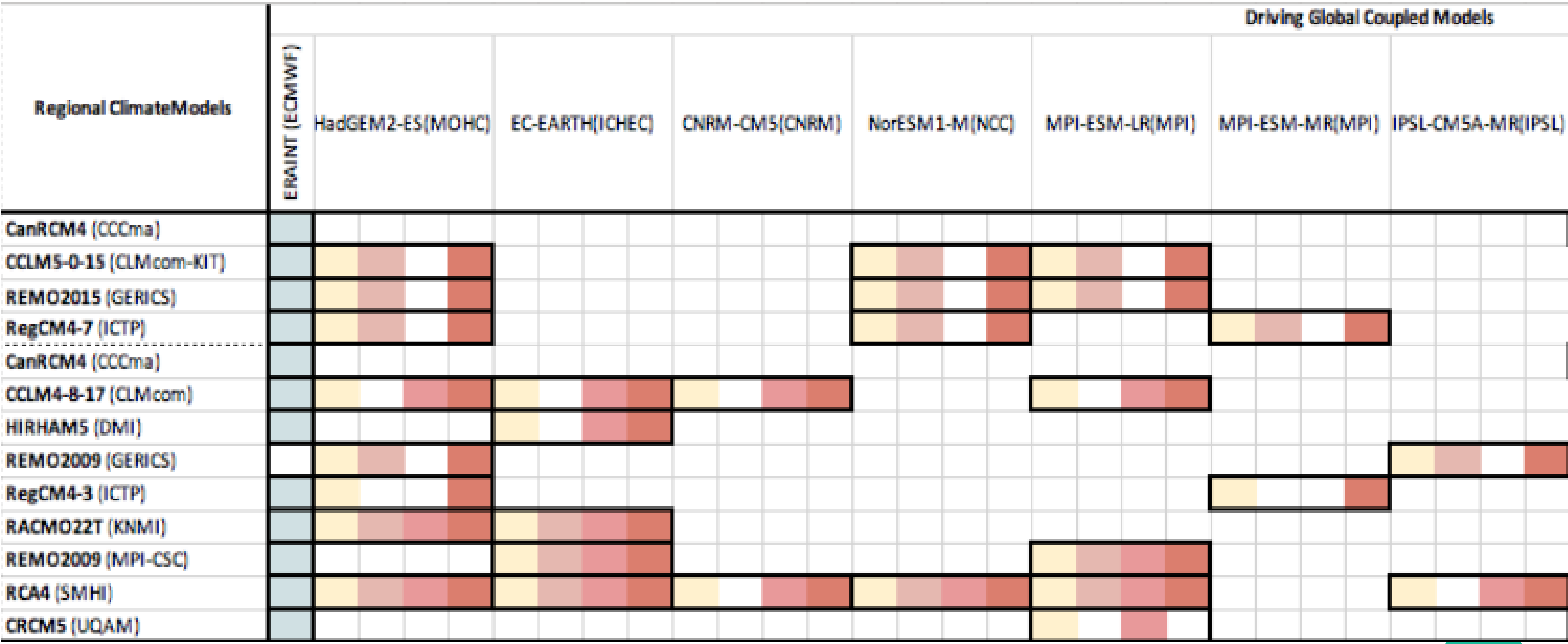


	Driving Global Coupled Models																				
Regional Climate Models	ERAINT (ECMWF)	HadGEM2-ES (MOHC)				EC-EARTH (ICHEC)				CNRM-CM5 (CNRM)				NorESM1-M (NCC)				MPI-ESM-LR (MPI)			
RCA4 (SMHI)	■	■	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■
CCLM4-8-17 (CLMcom-BTU)																			■		
CCLM4-8-17 (CLMcom)	■	■		■	■	■	■	■	■									■		■	■
COSMO-crCLIM-v1-1-1 (CLMcom-ETH)	■	■			■	■			■	■				■			■	■			■
REMO2009 (MPI-CSC)	■																	■	■	■	■
REMO2015 (GERICS)	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■			■
RACMO22E (KNMI)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■		■
HIRHAM5 (DMI)	■	■	■	■	■	■	■	■	■	■			■	■		■	■	■			■
WRF361H (UHOH)	■	■			■	■			■									■	■		■
WRF381P (IPSL)	■	■			■	■			■	■			■	■			■				
ALADIN63 (CNRM)	■	■			■					■	■	■	■	■			■	■			■
RegCM4-6 (ICTP)	■	■	■		■	■			■					■	■		■	■	■		■
HadREM3-GA7-05 (MOHC)	■	■	■		■	■	■		■	■			■	■			■	■			■

Regional Climate Models (RCM)

Examples of some RCMs (...)

Numerous RCMs are today available from laboratories worldwide.
e.g. : The models of the Coordinated Regional Climate Downscaling Experiment (***AFR***-CORDEX):



Regional ClimateModels	ERAINT (ECMWF)	Driving Global Coupled Models						
		HadGEM2-ES(MOHC)	EC-EARTH(ICHEC)	CNRM-CM5(CNRM)	NorESM1-M(NCC)	MPI-ESM-LR(MPI)	MPI-ESM-MR(MPI)	IPSL-CM5A-MR(IPSL)
CanRCM4 (CCCma)	🟦							
CCLM5-0-15 (CLMcom-KIT)	🟦	🟨▨⬜🟥			🟨▨⬜🟥	🟨▨⬜🟥		
REMO2015 (GERICS)	🟦	🟨▨⬜🟥			🟨▨⬜🟥	🟨▨⬜🟥		
RegCM4-7 (ICTP)	🟦	🟨▨⬜🟥			🟨▨⬜🟥		🟨▨⬜🟥	
CanRCM4 (CCCma)	🟦							
CCLM4-8-17 (CLMcom)	🟦	🟨⬜▩🟥	🟨⬜▩🟥	🟨⬜▩🟥		🟨⬜▩🟥		
HIRHAM5 (DMI)	🟦		🟨⬜▩🟥					
REMO2009 (GERICS)	⬜	🟨▨⬜🟥						🟨▨⬜🟥
RegCM4-3 (ICTP)	🟦	🟨⬜⬜🟥					🟨⬜⬜🟥	
RACMO22T (KNMI)	🟦	🟨▨▩🟥	🟨▨▩🟥					
REMO2009 (MPI-CSC)	🟦		🟨▨▩🟥			🟨▨▩🟥		
RCA4 (SMHI)	🟦	🟨▨▩🟥	🟨▨▩🟥	🟨⬜▩🟥	🟨▨▩🟥	🟨▨▩🟥		🟨⬜▩🟥
CRCM5 (UQAM)	🟦					🟨⬜▩⬜		

Conclusion

>***The process of developing a climate model is a long-term task,*** which does not end once a model has been published. ***Most modeling centres will be updating and improving their models*** on a continuous cycle, with a development process where scientists spend a few years building the next version of their models.

>***The Process Evaluation Groups are essentially taskforces which look after certain aspects of the model***. They ***monitor the biases*** in their area as the model develops, and ***test new methods to reduce these biases***. These groups meet regularly to discuss their area, and often contain members from the academic community as well as Met Office scientists.

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