Guide to the Science of Climate Change in the 21st Century

Chapter 17
Climate Models

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https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

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Chapter 17.0 Climate Models

17.1 Introduction

The importance of climate modelling is recognized. Climate models are used to predict future climate and should not be confused with very different models that are used to forecast weather (See Chapter 3.) Two researchers, Syukuro Manabe and Klause Hasselmann, shared one-half the Nobel Prize in Physics 2021 "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming", https://www.nobelprize.org/prizes/physics/2021/summary/, https://www.nobelprize.org/prizes/physics/ and https://www.nature.com/articles/d41586-021-02703-3?utm_source=Nature+Briefing&utm_campaign=38fd982e90-briefing-dy-20211008&utm_medium=email&utm_term=0_c9dfd39373-38fd982e90-46124954. Their work was performed in the 1960s and 1970s.

An article published by the newsletter CarbonBrief titled Timeline: The history of climate modelling, January 16, 2018, https://www.carbonbrief.org/timeline-history-climate-modelling, provides details of the beginning and evolution of climate modelling from first concepts published in 1938 to present.

CarbonBrief also published an article January 15, 2018 titled Q&A: How do climate models work? https://www.carbonbrief.org/qa-how-do-climate-models-work/ . This article is very useful as it provides a thorough and very readable introduction the development, verification and use of climate models.

Climate models are providing the ability to assess the potential impacts of climate change and guide adaptation and mitigation efforts. A NASA report, by Alan Buis, January 9, 2020, titled 'Study Confirms Climate Models are Getting Future Warming Projections Right' emphasizes this conclusion https://climate.nasa.gov/news/2943/study-confirms-climate-models-are-getting-future-warming-projections-right/.

Computer models are the only approach to synthesizing the science of climate change as discussed in previous chapters in order to generate actionable projections of climate change. The models and the computers that run them have been under development for more than thirty years and have provided input to the First Assessment Report on Climate Change prepared by the Intergovernmental Panel on Climate Change in 1990 (See https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf .) Considerable progress has been made since then as reported in the Fifth Assessment Report in 2013 (See https://www.ipcc.ch/report/ar5/wg1/ .)

The Sixth Assessment Reports published in 2021 use the latest versions which satisfactorily performed in the Computer Model Intercomparison Project Phase Six or CIMP6 (https://pcmdi.llnl.gov/CMIP6/) that is overseen by the World Climate Research Program, WCRP, (https://www.wcrp-climate.org/) Working Group on Coupled Modeling, WGCM, (https://www.wcrp-climate.org/wgcm-overview).

The mission of the World Climate Research Programme, WCRP: "The World Climate Research Program coordinates and facilitates international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being."

The World Climate Research Programme (https://www.wcrp-climate.org/about-wcrp/wcrp-overview) supports research that "provides the climate science that underpins the United Nations Framework Convention on climate change (https://unfccc.int/), including national commitments under the Paris Agreement of 2015, and contributes to the knowledge that supports the 2030 Agenda for Sustainable Development (https://sdgs.un.org/2030agenda), the Sendai Framework for Disaster Risk Reduction (https://www.undrr.org/implementing-sendai-framework/what-sendai-framework), and multilateral environmental conventions".

There are many intense ongoing efforts to improve climate models as the science is better understood and more and higher quality data is being collected to support the science. With improved science comes growing complexity, the need for better computational methods, need for improved data management and strategies to use the ever more powerful computers.

Climate models are used as part of Integrated Assessment Models to develop potential greenhouse gas emission scenarios as described in Chapters 18 and 21 and help to develop policy guidelines to realize these and any other scenarios of interest. (See Section 17.12.)

The limitations of climate models are discussed in an article by David Stainforth, The Guardian, Oct 2, 2023m titled 'The big idea: can we predict the climate of the future?', https://www.theguardian.com/books/2023/oct/02/the-big-idea-can-we-predict-the-climate-of-the-future?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-10-03&utm_campaign=Daily+Briefing+03+10+2023 . He states; 'There's no doubt that the latest climate models are outstanding achievements of computer-based science, but they aren't equivalent to reality. They don't represent all the stunning complexity of Earth's many interlocking systems. They might be useful tools for research, but they're not perfect representations of the real world.

So, if our models can't give us reliable, detailed climate predictions, what do we do? How do we know how high to build those flood defences? The answer is twofold. First, we have to relax and accept that we have incomplete information. Instead of trying to make our responses just right for the climate of the future we should seek out resilient and flexible solutions, remedies that will be robust in a wide range of possible climate outcomes. Flood defences could, for example, be designed to enable them to be easily extended if that becomes necessary.

Second, we need to use models better. They can't provide precise predictions, but they can tell us what climate change might look like in a world that's different, but nevertheless similar, to our own. Well-designed experiments could use them to get information about the scope of effects different responses could have. Give me £1bn for modelling and I wouldn't be able tell you what's going to happen, but I would get a better grasp of the uncertainties and the range of plausible futures. Knowledge of this range would help us design climate-resilient infrastructure and usefully set the context for debates. If all we knew was that a particular policy would increase the intensity of UK heatwaves by 2 to 4C, while another would increase them by 3 to 10C, then even though the uncertainties are large, the information is still a useful basis for making decisions.'

17.2 Climate models

The utility of the climate models is more than just their ability to forecast. They:

1. Advance the understanding of complex systems,
2. Guide future research – theoretical and physical,
3. Guide development of data collection systems, and
4. Improve interpretation of data.

Climate models are always improving. There are several organizations around the world which have developed their own models using their own approach. They each have advantages and disadvantages but tend to be complimentary. Most of the climate models are used.

The objectives of all models are to determine how natural and man-made forcings might influence temperature and precipitation.

Some of the steps in the development and use of computer models include:

1. System identification. Identify all of the elements that might affect the behavior of the system. (Energy budget, carbon cycle, hydrological cycle, atmosphere circulation, ocean current, biosphere and anything else that is relevant.)
2. Collection and development of relevant science.
3. Collection and identification of data requirements for input to model and required to calibrate and test models.
4. Develop computer programs.
5. Calibrate model and modify model as required. (May also require additional data.)
6. Test model against different data sets.
7. Use model:

1. With ‘real’ data.
2. With generated data that reflects ‘chaos’ or statistical characteristics of real data.

Figure 17.1 provides guidance on the type of information that is required to run the climate models. Satellites are meeting this need.

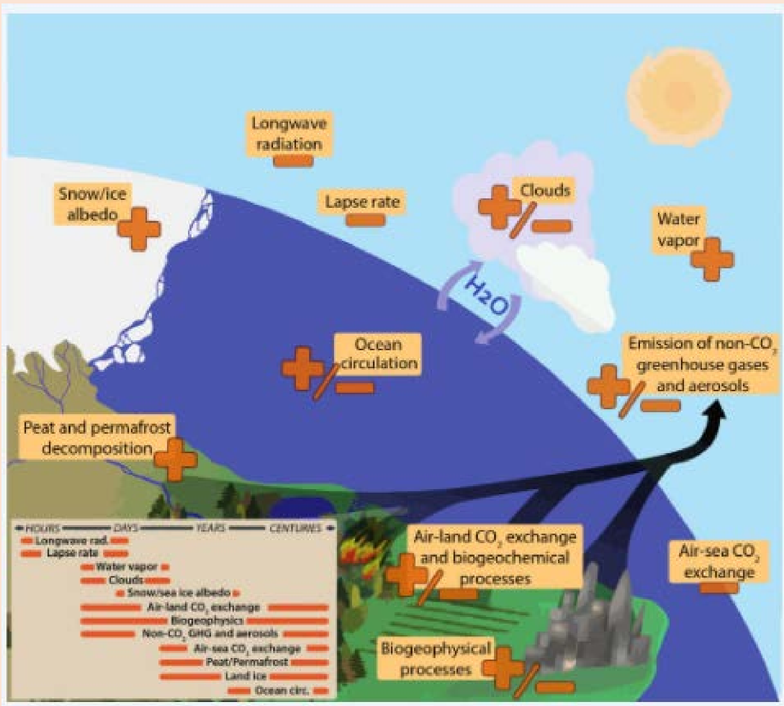
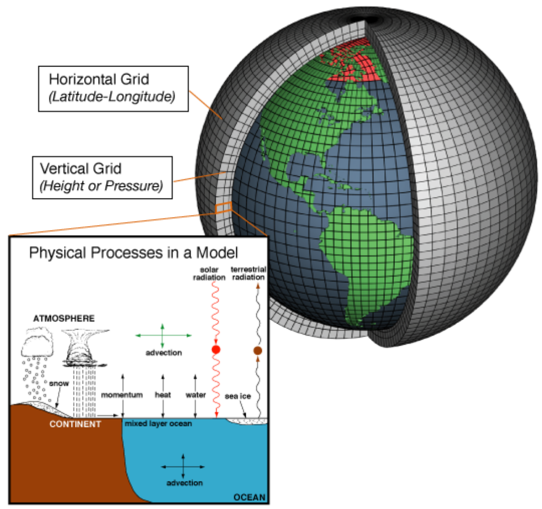


Figure 17.1 Subsystems included in climate models.
https://www.ipcc.ch/report/ar5/wg1/

Figures 17.2 and 17.3 illustrate how the surface of the Earth is divided into a grid and how the grid is extended into the atmosphere and ocean to produce a 3-D model of the type that would be used in atmosphere-land surface-ocean and sea ice models used in IPCC Assessment Report 5.

Figure 17.4 shows how the amount of detail in climate models has increased in recent years, largely because of the calculation power provided by newer supercomputers. In the 1990s, high-resolution *global climate models* operated on the T42 resolution scheme (upper left). At this resolution, temperature, moisture, and other features were tracked in grid boxes that each spanned about 200 by 300 kilometers at midlatitudes. In the modelling that led up to the 2007 IPCC Working Group I report, the NCAR-based Community Climate System Model (CCSM) routinely operated at T85 resolution (upper right), with midlatitude grid points of about 100 by 150 km (60 x 90 miles).   The finest grid, T340, is now routinely used by climate models.

Figure 17.5 show how the surface grids extend vertically in the ocean. It is apparent that decreasing horizontal and vertical dimensions by fifty per cent would increase the number of computational elements by a factor of eight and the computational power would need to increase by at least this amount.



This image shows the concept used in climate models. Each of the thousands of 3-dimensional grid cells can be represented by mathematical equations that describe the materials in it and the way energy moves through it. The advanced equations are based on the fundamental laws of physics, fluid motion, and chemistry. To "run" a model, scientists specify the climate forcing (for instance, setting variables to represent the amount of greenhouse gases in the atmosphere) and have powerful computers solve the equations in each cell. Results from each grid cell are passed to neighboring cells, and the equations are solved again. Repeating the process through many time steps represents the passage of time. Image source: NOAA.

Figure 17.2   Modelling concept used in atmosphere-ocean general circulation climate models, AOGCM's and earth system models, ESM's.
https://www.climate.gov/maps-data/primer/climate-models
https://soccom.princeton.edu/content/what-earth-system-model-esm

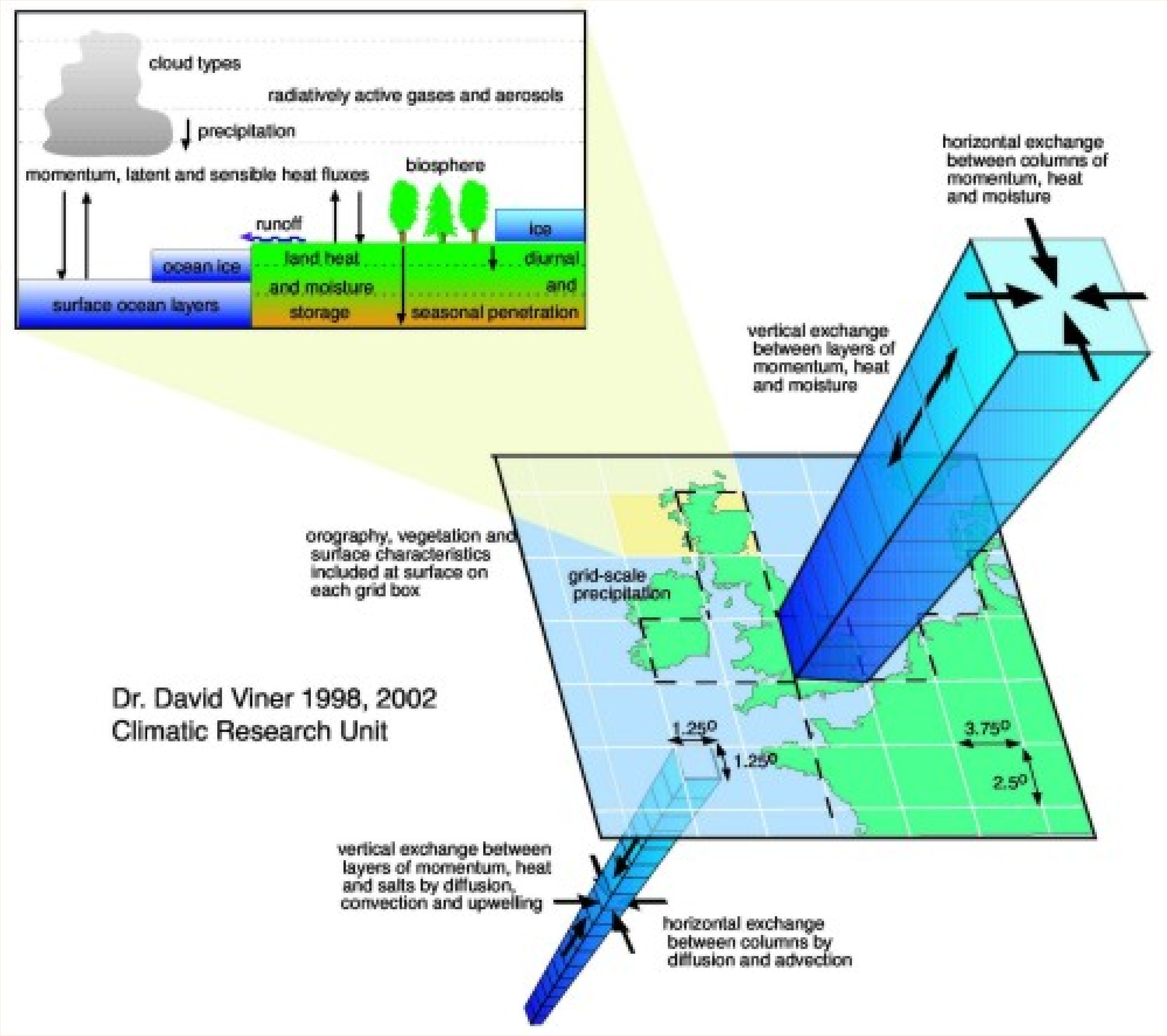
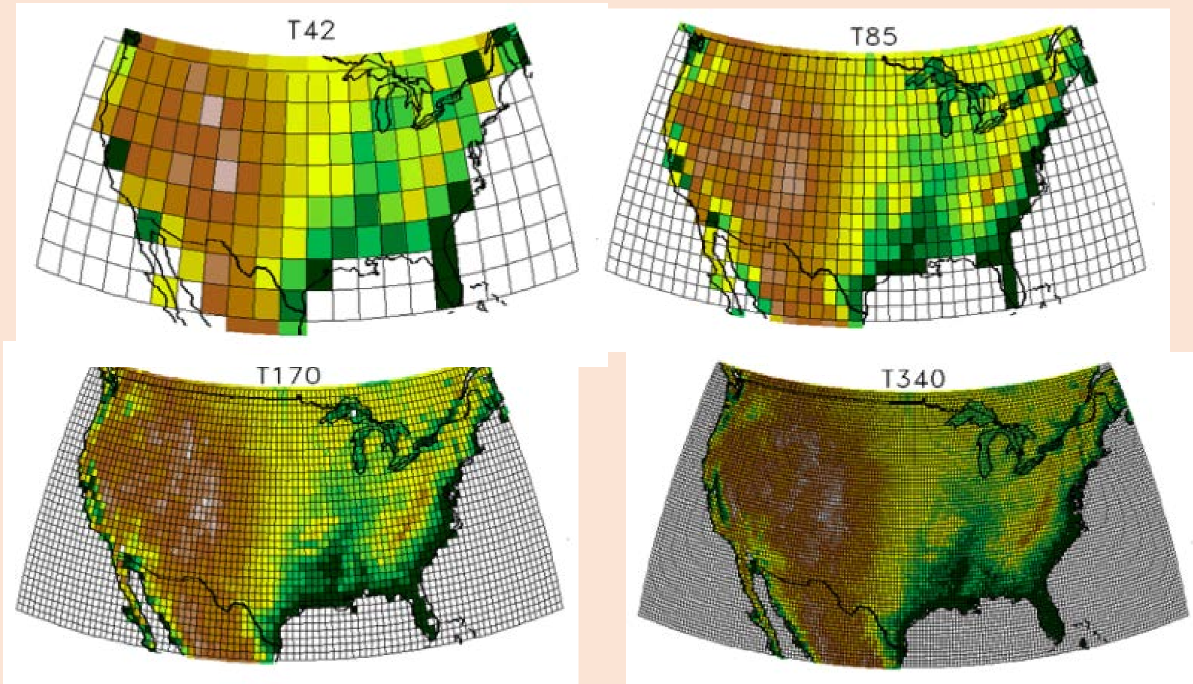


Figure 17.3 Concept used in climate models showing vertical column extending into the oceans.



Resolution:

1. T42 – 200 x 300 km
2. T85 – 100 x 150 km
3. T170 and T340 – regional models much finer resolution – interpolation techniques.
4. Today – 87.5 km x 87.5 km and 30 km x 30 km

Figure 17.4 Comparison of grids used in climate models since they were first being developed for use in IPCC Assessment Report 1 to Assessment Report 5.
https://scied.ucar.edu/longcontent/climate-modeling
https://eo.ucar.edu/staff/rrussell/climate/modeling/climate_model_resolution.html

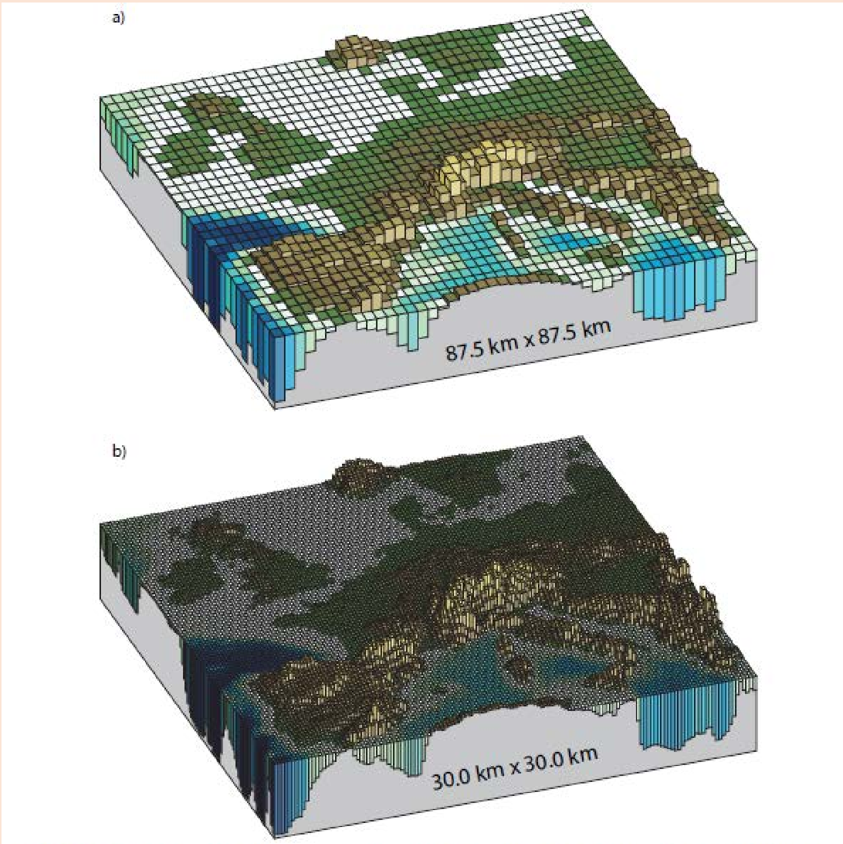


Figure 1.14 | Horizontal resolutions considered in today's higher resolution models and in the very high resolution models now being tested: (a) Illustration of the European topography at a resolution of 87.5 × 87.5 km; (b) same as (a) but for a resolution of 30.0 × 30.0 km.

Figure 17.5 Computational elements used in climate models.
https://www.ipcc.ch/report/ar5/wg1/

Figure 17.6 illustrates how climate models have increased in complexity since the 1970's. The most complete climate models used in AR5 include:

- Atmosphere
- Land surface
- Ocean and sea ice
- Aerosols
- Carbon cycle
- Dynamic vegetation (consider how the vegetation changes with climate)
- Atmospheric chemistry, and
- Land ice.

Climate models used in AR6 are even more complex. The objective is to accurately represent the energy budget, carbon cycle, hydrological cycle, atmospheric circulation, ocean water circulation, and any relevant biochemical reactions and dynamic physical phenomena (such as deforestation due to wildfires, melting permafrost and others).

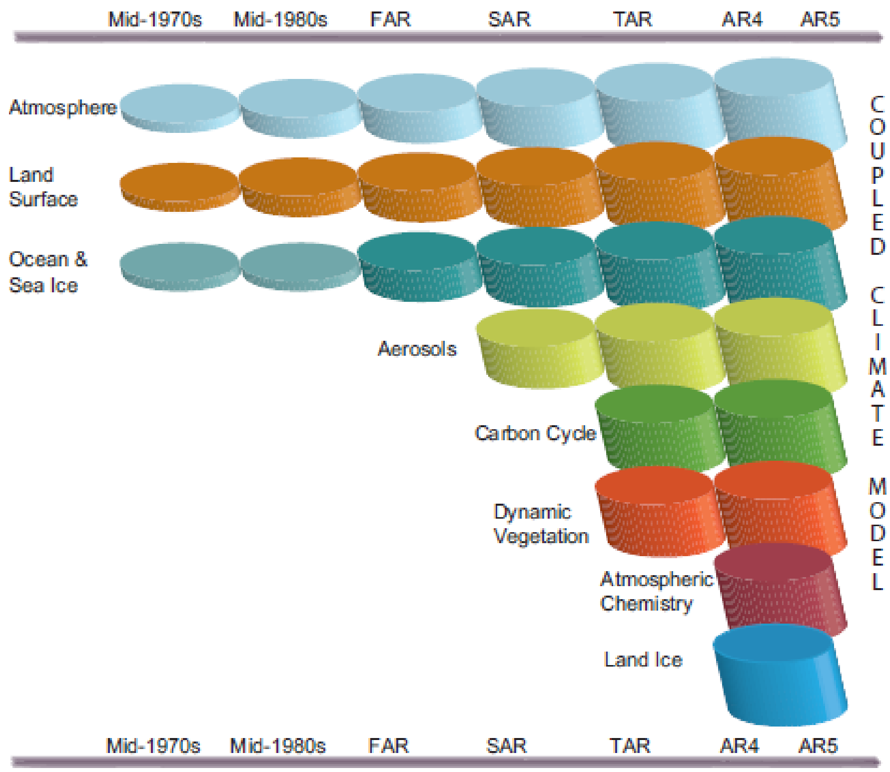


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard.

Figure 17.6 Increase in climate model complexity since the 1970's.
https://www.ipcc.ch/report/ar5/wg1/

17.3 Data available for climate models

Most of the data needs required by climate models is obtained by satellites. Land, sea and airborne instrumentation provide data that is used for calibrating (also known as ground truthing) satellite scanners and to obtain data that can't as yet be obtained by satellites such as ocean bottom morphology, biology and chemistry. An example of the extent of satellite acquired information, by NASA alone, is illustrated in Figure 17.7. NASA has an extensive fleet of space-based platforms as shown in Figure 14.11. There are many more satellites and space-based platforms operated by other agencies in the United States and many more operated by several agencies around the world (European Union, Japan, Canada, China and others). Most of this information is shared on a cost-recovery basis.   Satellite technology has become sufficiently affordable that the private sector is providing data acquisition services and competing with or complimenting government agencies.

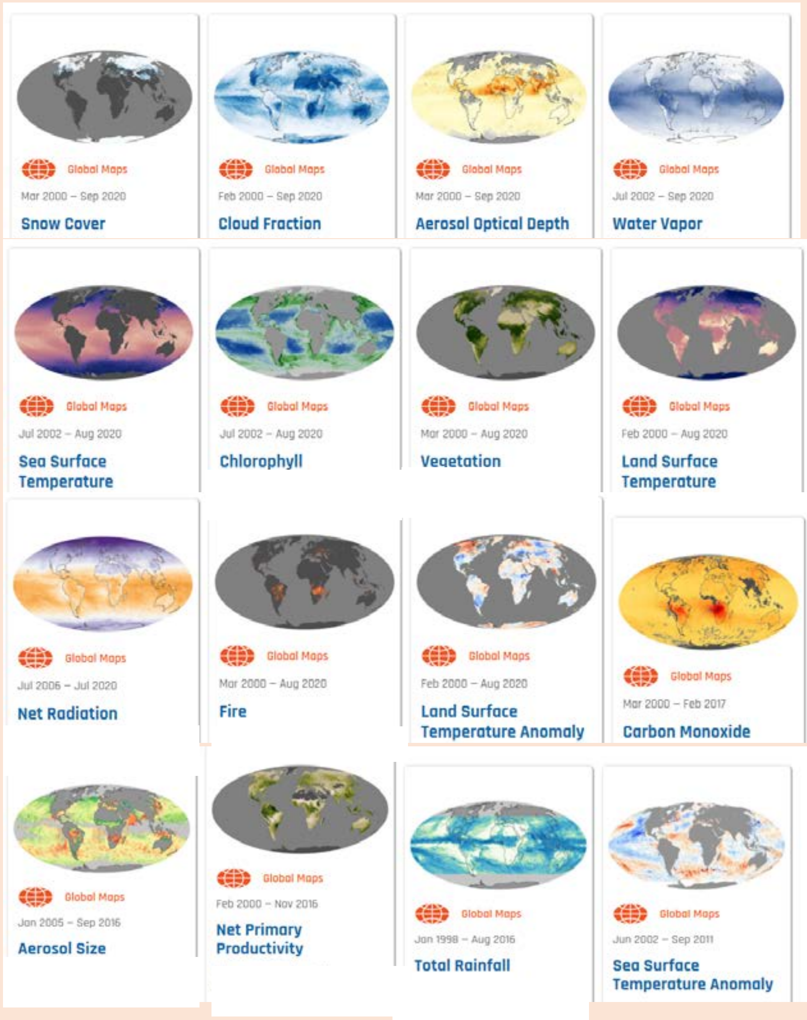


Figure 17.7 NASA Earth Observatory global maps. https://earthobservatory.nasa.gov/global-maps?utm_campaign=nav20&utm_source=topnav&utm_medium=globalmaps

Another good example of the data acquisition utility of satellites is their ability to supply data that can be used to accurately map global vegetation including ocean plankton. Figure 17.8 shows a map of global vegetative biomass capable of converting CO_2 to plant tissue. Figure 17.9 shows ocean chlorophyl concentrations. Figure 17.10 shows land use including vegetative cover (available for fifty years).

This information is being enhanced with additional space-based platforms that are capable of mapping ice cover, Figure 17.11, space weather, Figure 17.12 and the Global Ecosystem

Dynamics Investigation instrument (GEDI) that is mounted on the International Space Station. GEDI produces the first high resolution laser ranging observations of the 3D structure of the Earth. It makes precise measurements of forest canopy height, canopy vertical structure, and surface elevation. GEDI radically improves our ability to characterize important carbon and water cycling processes, biodiversity, and habitat.

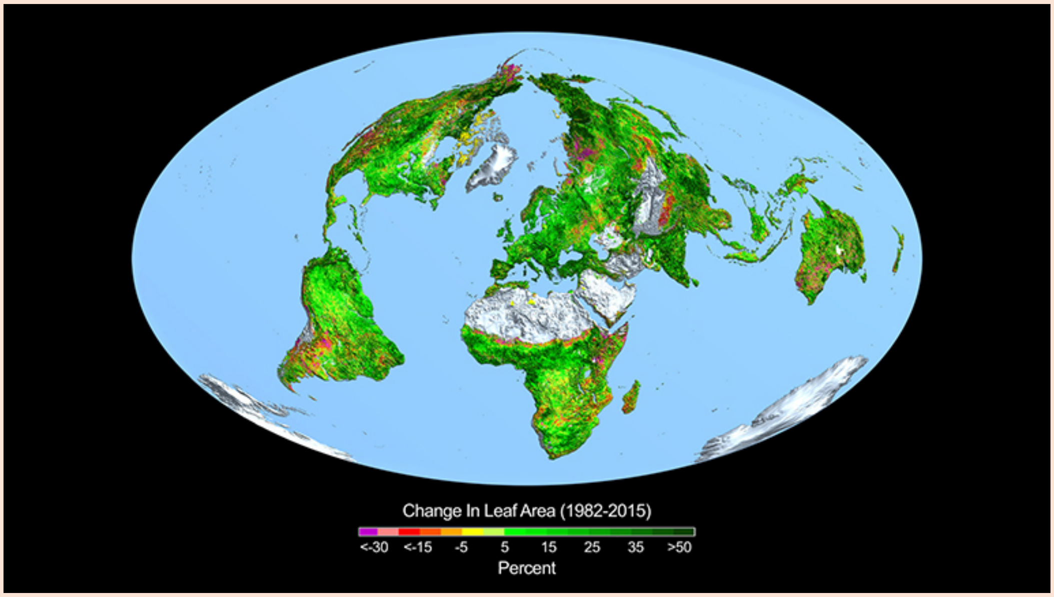


Figure 17.8 Assessment of global vegetative biomass capable of converting CO_2 to plant tissue using satellite carbon dioxide data. https://climate.nasa.gov/news/2436/co2-is-making-earth-greenerfor-now/

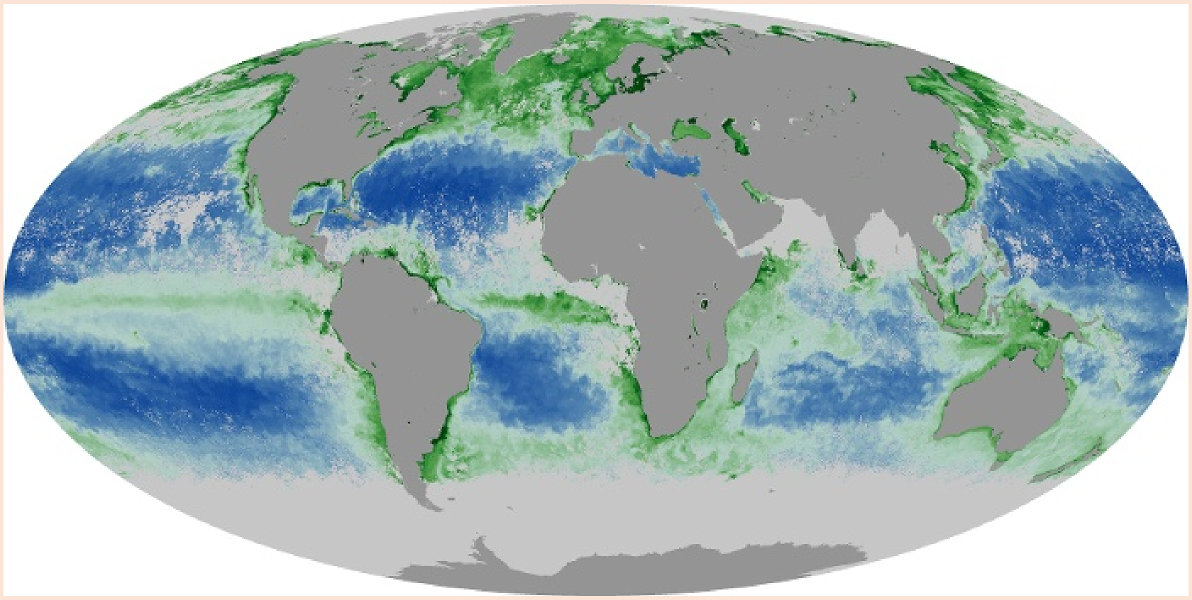


Figure 17.9 Ocean chlorophyl concentrations. https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA

Figure 17.10 Land use including vegetation and type of vegetative cover. https://earthobservatory.nasa.gov/features/LandCover/land_cover_3.php

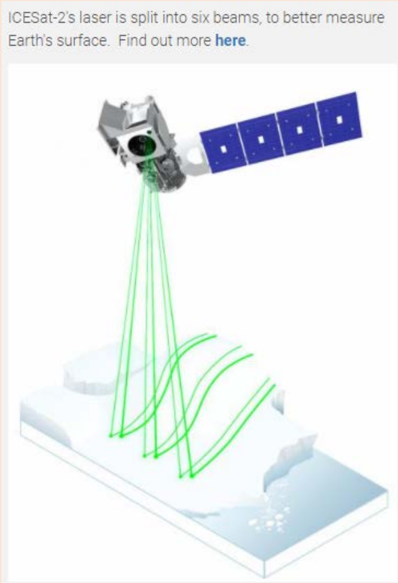


Figure 17.11 Ice thickness. https://icesat-2.gsfc.nasa.gov/

Figure 17.12 Space weather satellite.
https://www.spaceweatherlive.com/en/news/view/399/20191209-welcome-goes-16.html

GEDI's data on surface structure are also of immense value for weather forecasting, forest management, glacier and snowpack monitoring, and the generation of more accurate digital elevation models. GEDI provides the missing piece – 3D structure – in NASA's observational assets which enables us to better understand how the Earth behaves as a system, and guides the actions we can take to sustain critical resources.

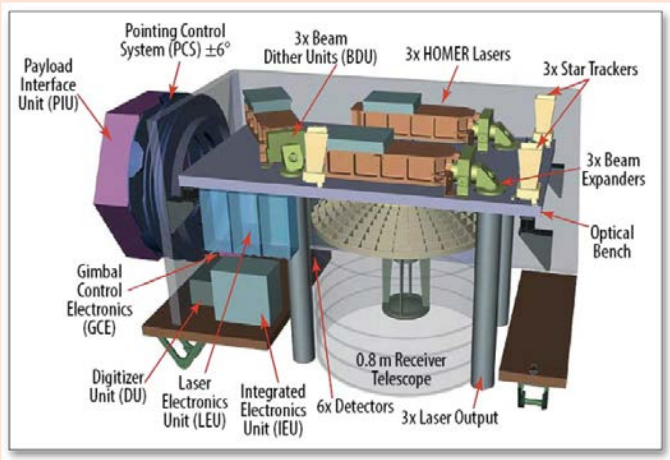


Figure 17.13 GEDI instrument showing lasers, optical paths, detectors and digitizers. https://gedi.umd.edu/instrument/instrument-overview/

THE INTERNATIONAL SPACE STATION [TOP] AND THE JAPANESE EXPERIMENT MODULE – EXPOSED FACILITY [BOTTOM] WHERE GEDI, HIGHLIGHTED IN GOLD, IS INSTALLED.

Figure 17.14 GEDI, shown in gold, as mounted on the International Space Station.

17.4 Climate models

There are basically three classes of models:

1. General circulation (atmosphere - ocean) models, AOGCM's or GCM's used in AR4, AR5 and AR6.
2. AR5 and AR6 also use Earth System Models or ESMs that include various biochemical cycles, (carbon, sulphur, ozone).
3. Regional climate change (circulation) models or RCM's. High resolution regional climate models were known as convection permitting models or CPM's.

A very good description is provided by IPCC fifth assessment report, AR5, Chapter 9, Working Group 1 (scientific basis). Each of these model classes are important on their own, require different resources to run and meet different modelling needs.

17.4.1 Atmosphere-ocean general circulation models (AOGCM)

Atmosphere-ocean general circulation models (AOGCM) combine atmospheric general circulation models (AGCM) discussed in Chapter 7 and ocean general circulation models (OGCM) discussed in Chapter 8. Sub-models to consider other hydrological elements such as sea ice, evapotranspiration discussed in Chapter 6 and other elements of the energy budget (such as GHG emissions, clouds, etc.) discussed in Chapter 4 to provide full climate models. See Figures 17.2 and 17.3.

17.4.2 Earth System Models (ESM)

An Earth System Model (ESM) is a coupled climate model that also models the movement of carbon (and other substances) through the earth system. They are the current state-of-the-art models. They may expand on AOGCMs to include the carbon cycle, aerosols, methane cycle and permafrost, global vegetation and wildfires, effects of land use, chemistry-climate interactions, land ice sheets, penetration of solar radiation into the ocean (phytoplankton) and more. Figure 17.15 illustrates the relationship between AOGCMs and ESMs. These models challenge computational resources. This issue is partly resolved using Earth System Models of Intermediate Complexity (EMICs) which reduce computational demands by using lower resolution, coarser computational grid.

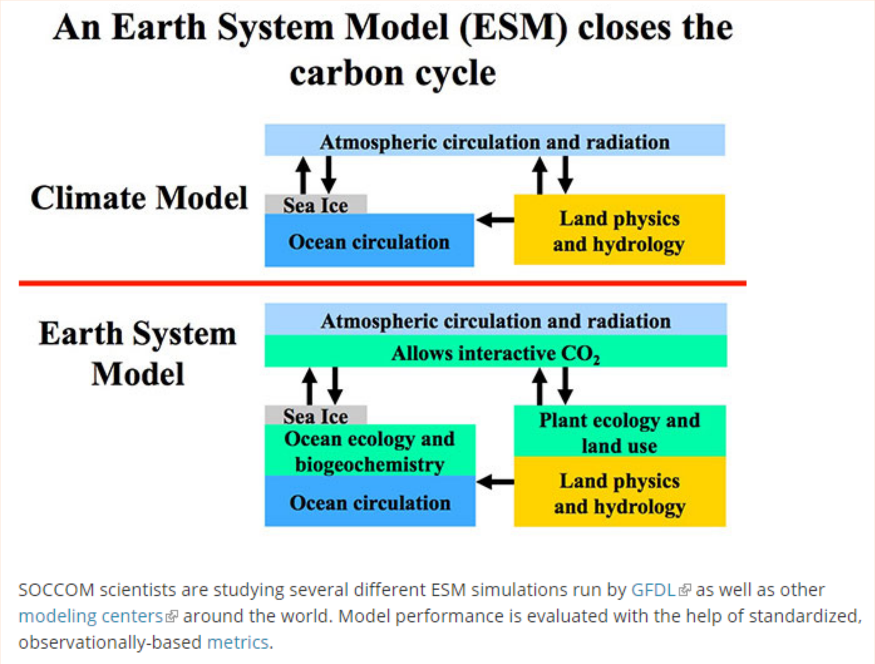


Figure 17.15 Comparison between a climate model and an earth system model
https://soccom.princeton.edu/content/what-earth-system-model-esm

17.4.3 Regional climate models

Regional climate models (RCMs) are limited-area models. These models are used to downscale the global model simulations for a particular geographical region of interest to provide more detailed information (higher resolution) on climate variation throughout the region. The global model simulations provide the boundary conditions for the RCMs.

For example, an RCM might want to use more detailed topographic information to be able to consider the effects of mountains. T340 may be considered too coarse a resolution (30km by 30km grid) and an RCM might try to take this down to 5km by 5km or less to provide a better idea as to how climate varies at the local level.

High resolution regional models (https://www.carbonbrief.org/guest-post-how-high-resolution-climate-models-will-help-europe-plan-for-extreme-weather?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210413&utm_medium=email&utm_source=Revue%20Daily and https://link.springer.com/article/10.1007/s00382-021-05708-w) that use horizontal grid spacing of approximately 3 km are considered to produce improved estimates of mean precipitation, precipitation intensity and frequency and heavy precipitation on daily and hourly timescales (convective storms). These models are known as convection permitting models or

CPM's. A discussion on what is actually being modelled is reported in https://www.carbonbrief.org/guest-post-why-climate-change-could-mean-heavier-bouts-of-summer-rain-in-the-uk .

17.4.4 Emulator models

Emulator models are simple climate models. They are calibrated against Earth System Models (ESMs) or observations and used to perform investigations that might require several hundreds of simulations which would be impractical to perform using ESMs. Emulator models may consider parameters which ESMs do not or consider circumstances where there is insufficient information to use an ESM. Emulator models are used in IPCC WG1 AR6.

A thorough description of emulator models and their use is available in a CarbonBrief 28 September 2021 Guest post: The role 'emulator' models play in climate change projections https://www.carbonbrief.org/guest-post-the-role-emulator-models-play-in-climate-change-projections?utm_campaign=Feed%3A%20carbonbrief%20%28The%20Carbon%20Brief%29&utm_content=20210929&utm_medium=feed&utm_source=feedburner .
The paper, 'Evaluating climate emulation: fundamental impulse testing of simple climate models' by Schwarber, A. K. et al. Earth System Dynamics, 13 Nov 2019 provides an example of how emulator models may be evaluated and therefore how they might be used, https://esd.copernicus.org/articles/10/729/2019/ .

17.4.5 Ensemble modeling

Ensemble modeling is discussed in Section 2.3.4 by Vijay Kotu, Bala Deshpande PhD, in Predictive Analytics and Data Mining, Science Direct 2015, https://www.sciencedirect.com/topics/computer-science/ensemble-modeling . It is described as follows: "Ensemble modeling is a process where multiple diverse models are created to predict an outcome, either by using many different modeling algorithms or using different training data sets. The ensemble model then aggregates the prediction of each base model and results in one final prediction for the unseen data. The motivation for using ensemble models is to reduce the generalization error of the prediction. As long as the base models are diverse and *independent*, the prediction error of the model decreases when the ensemble approach is used. The approach seeks the wisdom of crowds in making a prediction. Even though the ensemble model has multiple base models within the model, it acts and performs as a single model."

Ensemble modeling as it relates to modeling of climate change is described in the Climate Information web site, https://climateinformation.org/data-production-and-tailoring/why-use-a-model-ensemble/ , as follows: "A method that is usually used in studies of climate scenarios is ensembles; where several climate models are used together. The use of ensembles enables estimations of the certainty of results. The spread can be significant, partly because models describe climatological processes in different ways. It's in the nature of the problem that it is difficult to estimate the future climatic response, since this is what the models are supposed to study. The correct answer will not show until the future occurs. This is the advantage of model ensembles. If the same response is seen in several models the result is considered to be certain. If the responses are different in different models the result is considered to be less certain." See Section 21.4.7 for more information, https://climateinformation.org/ .

The Government of Canada web site, https://climatedata.ca/resource/multi-model-ensembles/ provides a very clear example of how ensemble modeling is used. Also see Climate Data Canada web site, https://climatedata.ca/ (Section 21.4.8) to see how ensemble modeling is used.

The IPCC, https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch10s10-5-4-1.html, describes the multi-model ensemble approach 'The use of ensembles of AOGCMs developed at different modelling centres has become established in climate prediction/ projection on both seasonal-to-interannual and centennial time scales. To the extent that simulation errors in different AOGCMs are independent, the mean of the ensemble can be expected to outperform individual ensemble members, thus providing an improved 'best estimate' forecast.' Modelling results reported by the IPCC are the product of ensemble modelling. See Figure 17.19. The shaded areas represent the range of values produced by the models used in the ensemble. The solid line represents the ensemble median (the range of models that fall within the 10^{th} and 90^{th} percentiles).

An advanced description of how ensemble modeling is used may be found in the paper titled 'Large ensemble climate model simulations: introduction, overview, and future prospects for utilising multiple types of large ensemble' by Maher, N., Milinski, S. and Ludwig, R. in the journal Earth System Dynamics 2021 https://esd.copernicus.org/articles/12/401/2021/.

17.5 CMIP5 Coupled model intercomparison project AR5

The IPCC reports evaluations of several climate models developed and supported by organizations around the world that were used to assess impacts of future climate change. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf . The models used in AR5, CMIP5, are listed in Table 17.1. The models used in AR4, CMIP3, are listed in Table 17.2. This table shows the features of each model and the resolution with which each feature is considered. Further details may be found in https://pcmdi.llnl.gov/index.html .

Table 17.3 lists and describes several EMICs which were also compared. The results of these comparisons are detailed in the report. As one might expect the various models demonstrated different strengths and weaknesses.   This information is relevant when selecting a model or models for a particular study.

Table 9.1 | Main features of the Atmosphere–Ocean General Circulation Models (AOGCMs) and Earth System Models (ESMs) participating in Coupled Model Intercomparison Project Phase 5 (CMIP5), and a comparison with Coupled Model Intercomparison Project Phase 3 (CMIP3), including components and resolution of the atmosphere and the ocean models. Detailed CMIP5 model description can be found in Table 9.A.1 (* refers to Table 9.A.1 for more details). Official CMIP model names are used. HT stands for High-Top atmosphere, which has a fully resolved stratosphere with a model top above the stratopause. AMIP stands for models with atmosphere and land surface only, using observed sea surface temperature and sea ice extent. A component is coloured when it includes at least a physically based prognostic equation and at least a two-way coupling with another component, allowing climate feedbacks. For aerosols, lighter shading means 'semi-interactive' and darker shading means 'fully interactive'. The resolution of the land surface usually follows that of the atmosphere, and the resolution of the sea ice follows that of the ocean. In moving from CMIP3 to CMIP5, note the increased complexity and resolution as well as the absence of artificial flux correction (FC) used in some CMIP3 models.

			AOGCM					ESM			
	Model name		Atmos	Land Surface	Ocean	Sea-Ice	FC	Aerosol	Atmos Chem	Land Carbon	Ocean BGC
CMIP5	ACCESS1.0, ACCESS1.3	Australia									
	BCC-CSM1.1, BCC-CSM1.1(m)	China									
	BNU-ESM	China									
	CanCM4	Canada									
	CanESM2										
	CCSM4	USA									
	CESM1 (BGC)										
	CESM1 (WACCM)		HT								
	CESM1 (FASTCHEM)										
	CESM1 (CAM5)										
	CESM1 (CAM5.1-FV2)	USA									
	CMCC-CM, CMCC-CMS	Italy	HT								
	CMCC-CESM		HT								
	CNRM-CM5	France									
	CSIRO-Mk3.6.0	Australia									
	EC-EARTH	Europe									
	FGOALS-g2	China									
	FGOALS-s2										
	FIO-ESM v1.0	China									
	GFDL-ESM2M, GFDL-ESM2G	USA									
	GFDL-CM2.1										
	GFDL-CM3		HT								
	GISS-E2-R, GISS-E2-H	USA	HT					p2,p3*	p2, p3*		
	GISS-E2-R-CC, GISS-E2-H-CC		HT					p2,p3*	p2, p3*		
	HadGEM2-ES	UK									
	HadGEM2-CC		HT								
	HadCM3										
	HadGEM2-AO	Korea									
	INM-CM4	Russia									
	IPSL-CM5A-LR / -CM5A-MR / -CM5B-LR	France	HT								
	MIROC4h, MIROC5	Japan	HT								
	MIROC-ESM		HT								
	MIROC-ESM-CHEM		HT								
	MPI-ESM-LR / -ESM-MR / -ESM-P	Germany	HT								
	MRI-ESM1	Japan	HT								
	MRI-CGCM3		HT								
	NCEP-CFSv2	USA									
	NorESM1-M	Norway									
	NorESM1-ME										
AMIP	GFDL-HIRAM C180 / -HIRAM C360	USA									
	MRI-AGCM3.2S / -AGCM3.2H	Japan									

Table 17.1   Comparison of AOGMs and ESMs, CMIP5. https://pcmdi.llnl.gov/index.html and https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf

CMIP3

BCC-CM1	China					FC				
BCCR-BCM2.0	Norway									
CCSM3	USA									
CGCM3.1(T47)	Canada					FC				
CGCM3.1(T63)						FC				
CNRM-CM3	France									
CSIRO-MK3.0, CSIRO-MK3.5	Australia									
ECHAM5/MPI-OM	Germany									
ECHO-G	D/Korea					FC				
FGOALS-g1.0	China									
GFDL-CM2.0	USA									
GFDL-CM2.1										
GISS-AOM	USA									
GISS-EH										
GISS-ER										
INGV-ECHAM4	Italy									
INM-CM3.0	Russia					FC				
IPSL-CM4	France									
MIROC3.2(hires)	Japan	HT								
MIROC3.2(medres)										
MRI-CGCM2.3.2	Japan					FC				
NCAR-PCM	USA									
UKMO-HadCM3	UK									
UKMO-HadGEM1										

Increasing complexity

Increasing resolution Atmosphere / Ocean (total number of horizonal grid points) 8000 30000 52000 12000 50000 110000

Table 17.2 Comparison of AOGMs and ESMs, CMIP3. https://pcmdi.llnl.gov/index.html and https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf

Table 9.2 | Main features of the EMICs assessed in the AR5, including components and complexity of the models. Model complexity for four components is indicated by colour shading. Further detailed descriptions of the models are contained in Table 9.A.2.

Model name		Atmos	Ocean	Land Surface	Sea Ice	Coupling	Biosphere	Ice Sheets	Sediment & Weathering
Bern3D	Switzerland								
CLIMBER2	Germany								
CLIMBER3	Germany								
DCESS	Denmark								
FAMOUS	UK								
GENIE	UK								
IAP RAS CM	Russia								
IGSM2	USA								
LOVECLIM1.2	Netherlands								
MESMO	USA								
MIROC-lite	Japan								
MIROC-lite-LCM	Japan								
SPEEDO	Netherlands								
UMD	USA								
Uvic	Canada								

Increasing Complexity (light to dark)					
EMBM	2-Box	NST/NSM			None
SD	Q-flux ML	LST/NSM			BO
QG	FG	LST/BSM			BO,BT
PE	PE	LST/CSM			BO,BT,BV

Table 17.3 Comparison of earth system models of intermediate complexity, EMICs. https://pcmdi.llnl.gov/index.html and

https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf
17.6 CMIP5 model predictions of surface temperature change compared to observed

The only data set that is available with which to evaluate model predictions is the temperature data between 1850 to present, the instrumental period. Several comparisons are made.

Both CMIP3 and CMIP5 models were compared to observed global temperature as shown in Figure 17.16 (a), (b) and (c). The observed global temperature set used for comparison is an average of three data sets shown in the small graph in the upper left corner of Figure 17.16 (b) similar to that shown in Figure 14.1. When both anthropogenic forcing and natural forcings were used, Figure 17.16 (a), model results compare reasonably to observed temperature. When only natural forcings were used, Figure 17.16 (b) model results did not match observed temperature. When only anthropogenic forcings were used, Figure 17.16 (c), model results did not match observed temperature. Clearly, both anthropogenic and natural forcings must be considered for models to predict observed global temperature which they do quite well.

Figure 17.17 shows a comparison of model predictions using natural forcings only and using both natural and anthropogenic forcings to observed temperature on each of the continents and oceans. The agreement between model predictions and observed temperatures is very good when both natural and anthropogenic forcings are used.

Figure 17.18 shows a comparison of model predictions using natural forcings only and using both natural and anthropogenic forcings to observed global ocean, land, and land and ocean temperature. The agreement between model predictions and observed temperatures is very good when both natural and anthropogenic forcings are used. A similar comparison was made on prediction of ocean heat content which again demonstrated very good agreement between model predictions and observed when both natural and anthropogenic forcings are used.

Chapter 10 of AR5 provides an extensive discussion on detection and attribution of a wide variety of climate features of interest and the confidence that climate models can be used to assess them. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

The results shown in Figures 17.16, 17.17 and 17.18 provide considerable confidence, at the intuitive level, that the climate models used by IPCC are predicting PAST changes well enough to be used for PREDICATION PURPOSES.

1. Impacts (possible/probable).
2. Adaptation (if desired).
3. Mitigation (if desired).

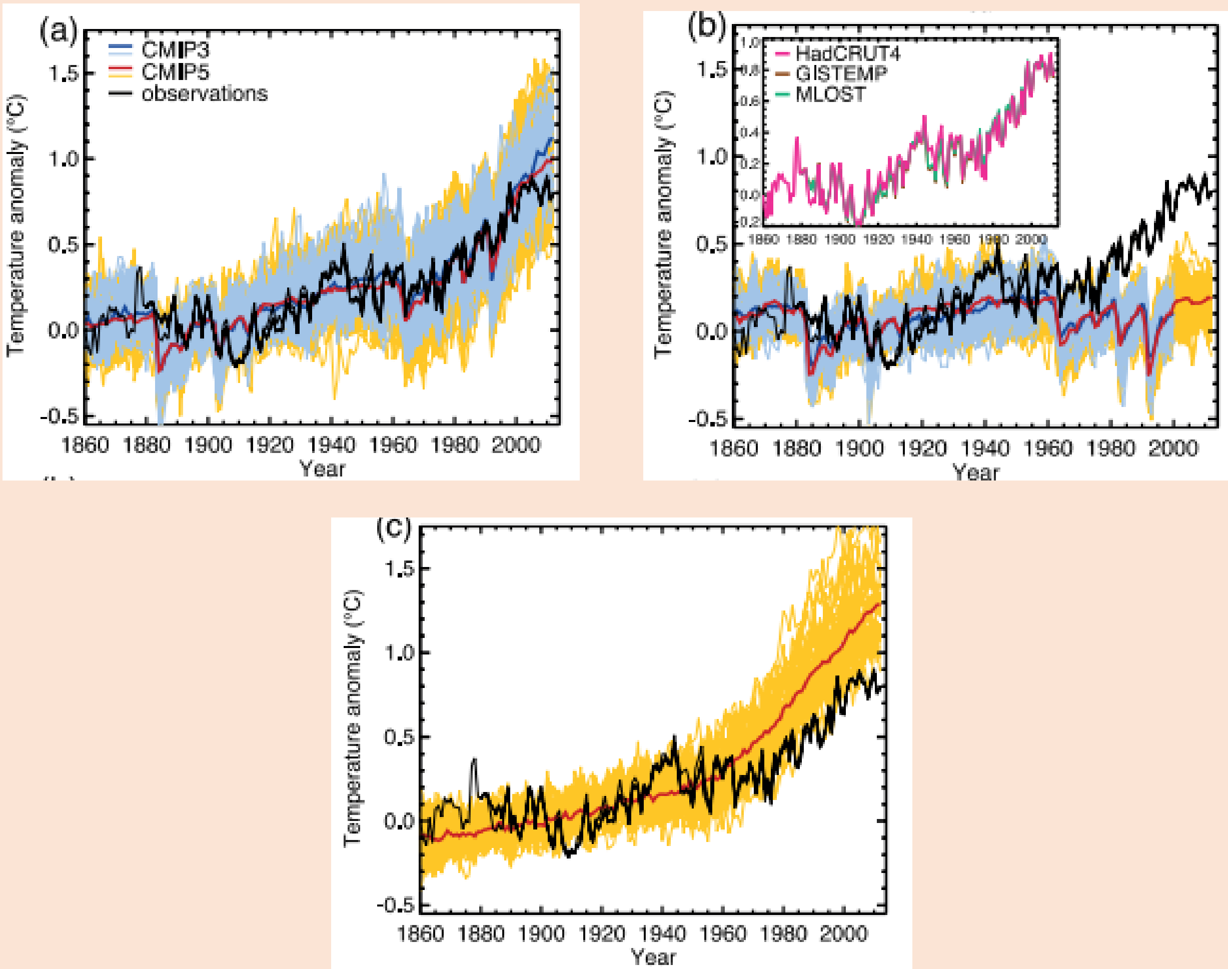


Figure 17.16 Estimates of global mean surface temperature (GMST) using averages of CMIP3(blue) and CMIP5(yellow) models using (a) both anthropogenic and natural forcings; (b) only natural forcings; and (c) only anthropogenic forcings compared to observed temperatures from 1850 to present. The red line is an average of CMIP5 predictions. CMIP3 models were not available for (c).
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

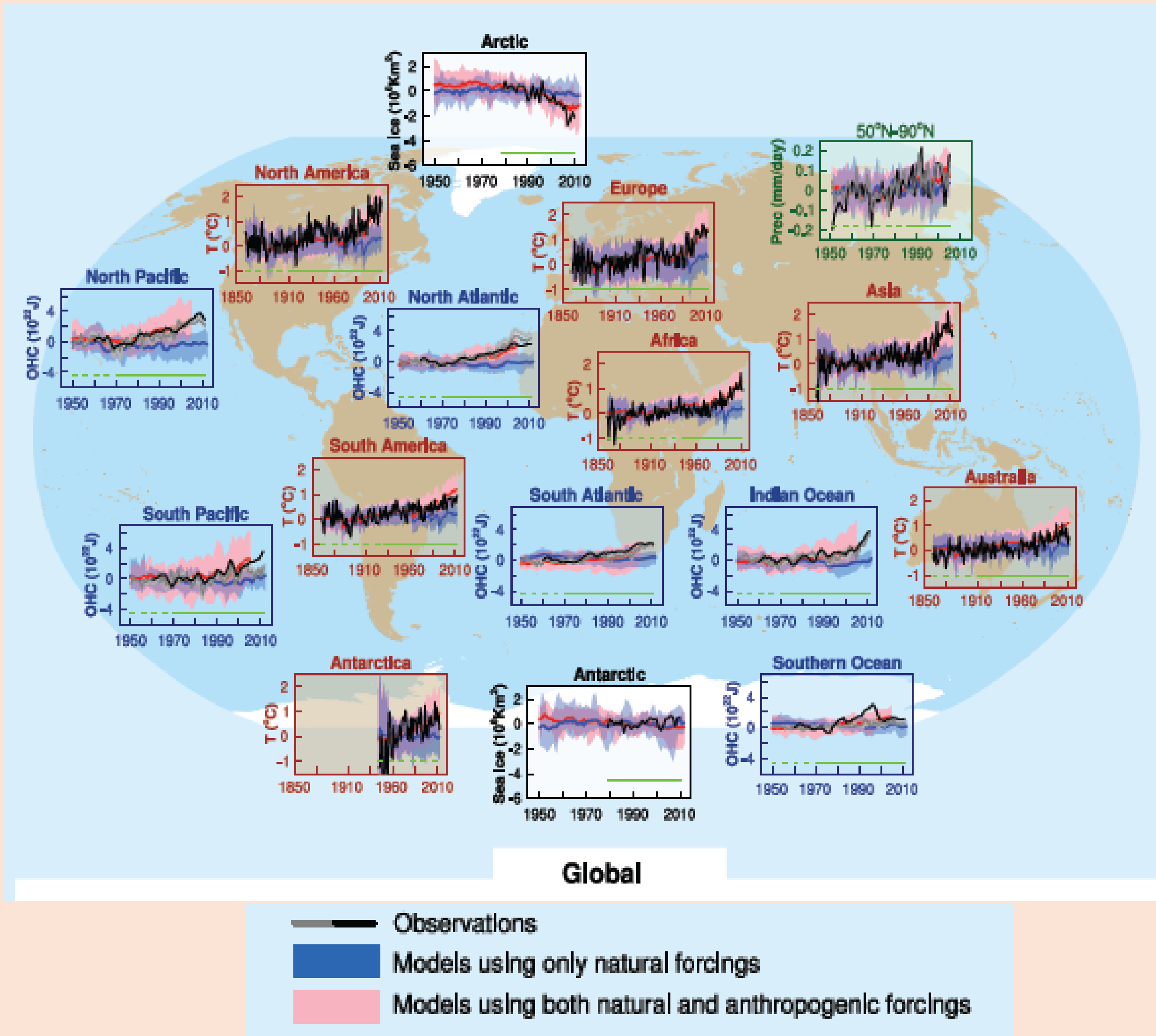


Figure 17.17 Comparison of model predictions to observed temperature on each of the continents.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

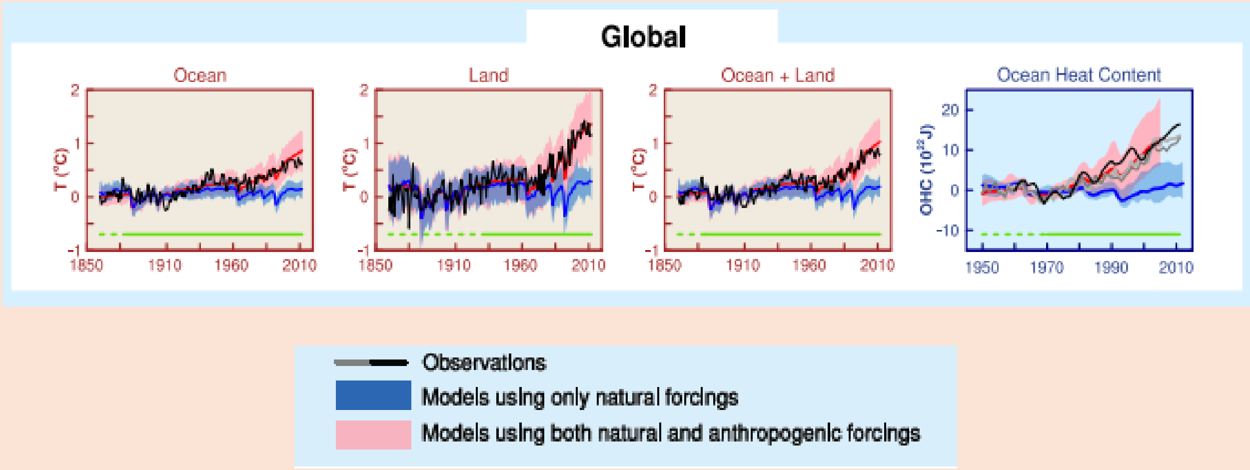


Figure 17.18 Comparison of CMIP5 model results when performed with only natural forcings and using both natural and anthropogenic forcings to observed global temperature of the ocean, land, ocean and land and ocean heat content.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

17.7 CMIP6 Coupled model intercomparison project AR6

The CMIP6 project addresses what the World Climate Research Programme calls the 'Grand Challenges' https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview. They are:

"The Grand Challenges:

- are both highly specific and highly focused, identifying a specific barrier preventing progress in a critical area of climate science;
- enable the development of targeted research efforts with the likelihood of significant progress over 5-10 years, even if their ultimate success is uncertain;
- enable the implementation of effective and measurable performance metrics;
- are transformative - a Grand Challenge should bring the best minds to the table (voluntarily), building and strengthening communities of collaborative innovators, perhaps also extending beyond "in-house expertise";
- capture the public's imagination - teams of renowned scientists working to solve pressing challenges; and
- offer compelling storylines to capture the interest of media and the public."

Several current Grand Challenges are listed.

The major observation and modelling developments and their implications in AR6 WG1, Climate Change: The Physical Science Basis may be found in Chapter 1, Section 1.5 of the report. The significant developments include:

- Expansions in observational capacity, atmosphere, land and hydrological cycle, ocean, cryosphere and biosphere.
- Improved paleo climate reconstruction over past 2000 years.
- Reanalyses of data sets.
- Higher resolution used in advanced earth system models.
- Use of 23 CMIP6-endorsed MIPs (see https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-cmip6-endorsed-mips) are used to investigate how models respond to specific forcings, their potential systematic biases, their variability, and their responses to detailed future scenarios such as the Shared Socioeconomic Pathways (SSPs).

The homepage for CMIP6, https://pcmdi.llnl.gov/CMIP6/, provides a thorough description of the CMIP6 project. This is complemented by an overview of the experimental design and organization in the excellent presentation prepared by the CMIP Panel in 2018 https://www.wcrp-climate.org/images/modelling/WGCM/CMIP/CMIP6FinalDesign_GMD_180329.pdf. Another very good description of the World Climate Research Programme's Coupled Model Intercomparison Project may be found in https://www.wcrp-climate.org/wgcm-cmip (It includes a video presentation titled, A Short Introduction to Climate Models – CMIP).

Another very useful description of the CMIP6 project may be found in the paper published in the newsletter, Carbon Brief, titled CMIP6: the next generation of climate models explained, https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained.

It has been observed that despite the numerous refinements of the CMIP6 models the results are remarkably similar to that produced by the CMIP5 models. This is gratifying in that it suggests a convergence to a very good model/ synthesis of climate science.

17.8 CMIP6 model predictions of surface temperature change compared to observed

The validity of AR6 simulations (CMIP6 models) is discussed in Chapter 21, Section 21.3.1. The results agree very well with observed data from 1850 to 2020 as shown in Figure 17.19 when both human (anthropogenic) and natural forcings are considered.

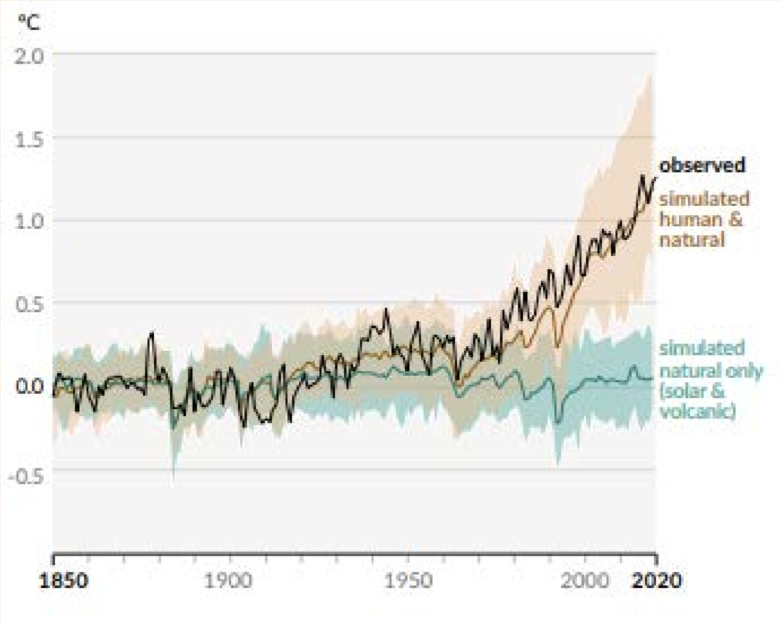


Figure 17.19 Change in global surface temperature (annual average) as observed and simulated using human and natural and only natural factors (both 1850-2020) °C https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

17.9 CORDEX regional climate model

CORDEX stands for Coordinated Regional Climate Downscaling Experiment https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1052-modelling-cmip6-cordex. It is one of the 23 CMIP6-Endorsed MIPs. It is described by WCRP as follows:

"The Coordinated Regional Downscaling Experiment (CORDEX) is a CMIP6 diagnostic MIP requesting specific CMIP6 output for regional climate downscaling. CORDEX builds on a foundation of previous downscaling intercomparison projects to provide a common framework for downscaling activities around the world. The CORDEX Regional Challenges provide a focus for downscaling research and a basis for making use of CMIP6 global output to produce downscaled projected changes in regional climates, and assess sources of uncertainties in the projections."

The horizontal resolutions of CMIP6 models range from 100 to 300 km. Regional models significantly reduce the resolution to where local effects become apparent. A discussion of regional climate models (RCMs) may be found in the American Geophysical Union, JGR Atmospheres Volume 124, Issue 11 16 June 2019 titled 'Thirty years of regional climate modeling: Where are we and where are going next?' by Filippo Georgi, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD030094.

The CORDEX regional model has a horizontal resolution of 12.5 km. The boundary conditions for the region chosen are taken from the CMIP6 model. This allows for much greater refinement of model predictions. (The importance of model horizontal resolution on simulated precipitation in Europe – from global to regional models is discussed, https://wcd.copernicus.org/preprints/wcd-2020-31/wcd-2020-31-manuscript-version3.pdf.)

Output from CORDEX simulations is reported.

Note that other regional models may use smaller horizontal resolution.

17.10 CMIP6 models and CORDEX model results

CMIP6 and CORDEX model results are discussed in Chapter 21 which introduces the Interactive Atlas in Section 21.4.5 IPCC WG1 Interactive Atlas https://interactive-atlas.ipcc.ch/ .

17.11 Confidence, agreement and likelihood terminology - assessment of model predictions

Predictions using climate models, of any type, are assessed using qualitative descriptors.
Table 17.4 lists the meaning of confidence terms.
Table 17.5 provides guidance as to how to use confidence terms.
Table 17.6 lists the meaning likelihood terms used in old IPCC reports.
Table 17.7 summary of IPCC usage of calibrated language.

Confidence Terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Table 17.4 Confidence terminology used in IPCC reports.
https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

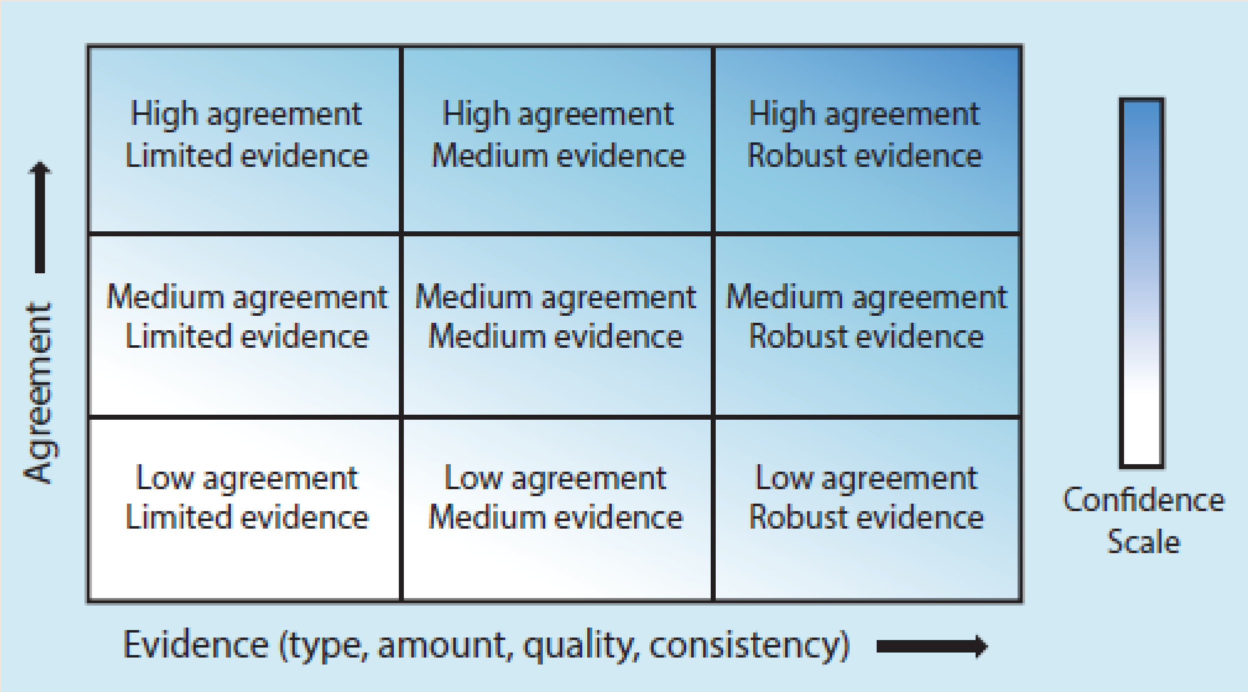


Table 17.5 Agreement-evidence scale used in IPCC reports to aid in use of confidence descriptors.
https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

Likelihood Terminology	Likelihood of the occurrence/ outcome
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

Table 17.6 Likelihood terminology used in IPCC reports.
https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

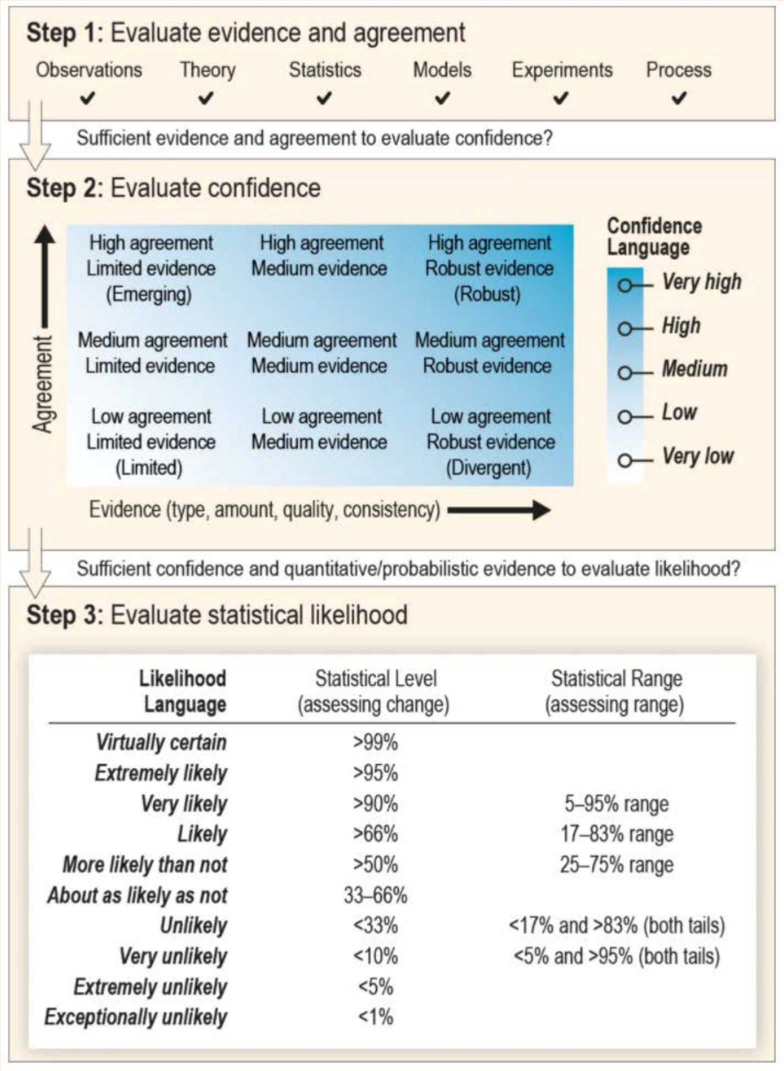


Table 17.7 Method for IPCC usage of calibrated language.

17.12 Integrated assessment models, IAMs

The IPCC studies use what are known as Integrated Assessment Models, (IAMs) to consider all aspects of human life (social, economic, governance, land-use and more) to develop scenarios or pathways used in the modelling studies discussed in Chapters 18 and 21. The IAM approach is described in detail in paper titled 'Integrated assessment climate policy models have proven useful, with caveats', https://www.pnas.org/doi/10.1073/pnas.2101899118 and a Carbon Brief Explainer, Q&A: How integrated assessment models are used to study climate change, https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change .

It is important to note that IAMs are not climate models. Climate models are one of several different models that are used in IAMs. The primary use of IAMs is to develop policy to provide a guide for the management of human activities that impact GHG emissions and global warming. The guidance provided is typically global in nature but is useful on regional scales and political jurisdictions.

A recent paper published in the journal Nature titled 'Determinants of emissions pathways in the coupled climate-social system', https://www.nature.com/articles/s41586-022-04423-8 and in an article by the lead author in a Carbon Brief Guest Post: How to model society's response to climate change https://www.carbonbrief.org/guest-post-how-to-model-societys-response-to-climate-change?utm_campaign=Daily%20Briefing&utm_content=20220228&utm_medium=email&utm_source=Revue%20newsletter , describes how models similar in nature to IAMs that also include societal feedback can predict what policies are required to limit climate impacts.

Another useful overview of IAM may be found in the Wikipedia article, https://en.wikipedia.org/wiki/Integrated_assessment_modelling.

17.13 Earth Virtualization Engines (EVE)

Copernicus Publications, Earth Systems Science Data in a preprint, 19 Sep 2023 states; 'Earth Virtualization Engines are proposed as international federation of centers of excellence to empower all people to respond to the immense and urgent challenges posed by climate change.', https://essd.copernicus.org/preprints/essd-2023-376/ and discussed in The Berlin Summit July 2023 where the intention was to 'draft a blueprint for an international climate science and service center', https://www.gewex.org/event/the-berlin-summit/ and https://eve4climate.org/ .

17.14 Summary comment

Today's models of climate change:

- Help explain the history of Earth's climate including recent impacts. (What happened and why?)
- Predict the future climate impact of natural processes and human activities which allows guidance for
    - Identifying needs to adapt to impacts of changing climate conditions.
    - Opportunities to avoid or minimize unwanted impacts.

17.15 Information support

Key web sites:

1. Timeline: The history of climate modelling, CarbonBrief January 16, 2018. https://www.carbonbrief.org/timeline-history-climate-modelling.

2. Nobel Prize for Physics 2021. https://www.nobelprize.org/prizes/physics/2021/summary/, https://www.nobelprize.org/prizes/physics/ and https://www.nature.com/articles/d41586-021-02703-3?utm_source=Nature+Briefing&utm_campaign=38fd982e90-briefing-dy-20211008&utm_medium=email&utm_term=0_c9dfd39373-38fd982e90-46124954.

3. Climate models. https://www.climate.gov/maps-data/primer/climate-models

4. Q&A: How do climate models work? CarbonBrief January 15, 2018. https://www.carbonbrief.org/qa-how-do-climate-models-work/

5. Early climate modelers got global warming right. https://news.berkeley.edu/2019/12/04/early-climate-modelers-got-global-warming-right-new-report-finds/

6. Evaluating the performance of past climate model projections. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019GL085378

7. Study confirms climate models are getting future warming projections right. https://climate.nasa.gov/news/2943/study-confirms-climate-models-are-getting-future-warming-projections-right/.

8. Coupled Model Intercomparison Project Phase 6, Homepage. https://pcmdi.llnl.gov/CMIP6/.

9. World Climate Research Program, WCRP, https://www.wcrp-climate.org/.

10. World Climate Research Programme, WCRP, overview https://www.wcrp-climate.org/about-wcrp/wcrp-overview.

11. United Nations Framework Convention on climate change https://unfccc.int/.

12. United Nations 2030 Agenda for Sustainable Development https://sdgs.un.org/2030agenda.

13. United Nations Sendai Framework for Disaster Risk Reduction https://www.undrr.org/implementing-sendai-framework/what-sendai-framework.

14. Working Group on Coupled Modeling, WGCM, https://www.wcrp-climate.org/wgcm-overview.

15. Global maps, NASA, Earth observatory. https://earthobservatory.nasa.gov/global-maps/MYD28M

16. Climate model diagnosis and intercomparison. https://pcmdi.llnl.gov/index.html

17. Evaluation of climate models. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf

18. Detection and attribution of climate change: global to regional. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

19. Climate modelling. https://scied.ucar.edu/longcontent/climate-modeling

20. Resolution of climate models. https://eo.ucar.edu/staff/rrussell/climate/modeling/climate_model_resolution.html

21. Use of models in detection and attribution of climate change. https://www.geos.ed.ac.uk/~ghegerl/assets/WIRES.pdf

22. Climate change, the IPCC scientific assessment. https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf

13. NASA Global precipitation measurement mission, GPM. https://www.nasa.gov/mission_pages/GPM/overview/index.html

14. NASA CO2 is making Earth greener for now. https://climate.nasa.gov/news/2436/co2-is-making-earth-greenerfor-now/

15. NASA explore Earth. https://www.nasa.gov/topics/earth/index.html

16. IPCC Chapter 1. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

17. Earth system model. https://soccom.princeton.edu/content/what-earth-system-model-esm

18. General circulation model. https://en.wikipedia.org/wiki/General_circulation_model

19. Earth systems models of intermediate complexity. https://en.wikipedia.org/wiki/Earth_systems_model_of_intermediate_complexity

20. Atmosphere-ocean general circulation models (AOGCMs). https://www.narccap.ucar.edu/about/aogcms.html

21. Evaluation of climate models. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf

22. Guide for treatment of uncertainties, IPCC. https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

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24. High resolution regional climate models review, Carbon Brief. https://www.carbonbrief.org/guest-post-how-high-resolution-climate-models-will-help-europe-plan-for-extreme-weather?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210413&utm_medium=email&utm_source=Revue%20Daily.

25. Development of high-resolution regional climate models – convection permitting models, Met Office, UK, Carbon Brief. https://www.carbonbrief.org/guest-post-why-climate-change-could-mean-heavier-bouts-of-summer-rain-in-the-uk.

26. WCRP Grand Challenges, https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview.

27. Change in global surface temperature (annual average) as observed and simulated using human and natural and only natural factors (both 1850-2020) °C https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

28. CMIP6 – Coupled Model Intercomparison Project Phase 6, Program for Climate Model Diagnosis & Intercomparison, https://pcmdi.llnl.gov/CMIP6/.

29. CMIP6-Endorsed MIPs https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-cmip6-endorsed-mips.

30. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization, PowerPoint presentation, The World Climate Research Program's Coupled Model Intercomparison Project, March 2018, https://www.wcrp-climate.org/images/modelling/WGCM/CMIP/CMIP6FinalDesign_GMD_180329.pdf.

31. World Climate Research Programme, WCRP Coupled Model Intercomparison Project (CMIP), https://www.wcrp-climate.org/wgcm-cmip.

32. CMIP6: the next generation of climate models explained by Zeke Hausfather in Carbon Brief 02.12.2019. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained.

33. The importance of model horizontal resolution on simulated precipitation in Europe – from global to regional models, Strandberg, G. and Lind, Peter, Copernicus preprint, https://wcd.copernicus.org/preprints/wcd-2020-31/wcd-2020-31-manuscript-version3.pdf.

34. IPCC WG1 Interactive Atlas https://interactive-atlas.ipcc.ch/.

35. Timeline: The history of climate modelling. CarbonBrief January 16, 2018. https://www.carbonbrief.org/timeline-history-climate-modelling.

36. Guest post: The role 'emulator' models play in climate change projections, CarbonBrief 28 September 2021. https://www.carbonbrief.org/guest-post-the-role-emulator-models-play-in-climate-change-projections?utm_campaign=Feed%3A%20carbonbrief%20%28The%20Carbon%20Brief%29&utm_content=20210929&utm_medium=feed&utm_source=feedburner.

37. Thirty years of regional climate modeling: Where are we and where are we going next? by Filippo Georgi, AGU JGR Atmospheres Volume 124, Issue 11, 16 June 2019. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD030094.

38. Evaluating climate emulation: fundamental impulse testing of simple climate models by Schwarber, A. K. et al. Earth System Dynamics, 13 Nov 2019. https://esd.copernicus.org/articles/10/729/2019/.

39. Ensemble modeling is discussed in Section 2.3.4 by Vijay Kotu, Bala Deshpande PhD, in Predictive Analytics and Data Mining, Science Direct 2015 https://www.sciencedirect.com/topics/computer-science/ensemble-modeling.

40. Ensemble modeling description, Climate Canada. https://climatedata.ca/resource/multi-model-ensembles/.

41. Application of ensemble modeling, Climate Data for a Resilient Canada https://climatedata.ca/ and the report, Canada in a Changing Climate, https://changingclimate.ca/.

42. Ensemble modeling as it relates to modeling of climate change is described in the Climate Information web site, https://climateinformation.org/data-production-and-tailoring/why-use-a-model-ensemble/.

43. Large ensemble climate model simulations: introduction, overview, and future prospects for utilising multiple type of large ensemble by Maher, N., Milinski, S. and Ludwig, R. in the journal Earth System Dynamics 2021, https://esd.copernicus.org/articles/12/401/2021/.

44. Ensemble models as used by the IPCC https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch10s10-5-4-1.html.

45. Integrated assessment climate policy models have proven useful, with caveats by Gaythri Vaidyanathan in Proceedings of the National Academy of Sciences (PNAS) February 24, 2021 118(9) e2101899118. https://www.pnas.org/doi/10.1073/pnas.2101899118

46. Integrated assessment models, Q&A Carbon Brief 02.10.2018 https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.

47. Determinants of emissions pathways in the coupled climate-social system by Moore, Frances C., Lacasse, Katherine, Shin, Yoon Ah, Gross, Louis J. and Beckage, Brian, published on line February 16, 2022 and March 3, 2022, in journal Nature Vol 603, 103-111 (2022). https://www.nature.com/articles/s41586-022-04423-8.

48. Carbon Brief Guest Post: How to model society's response to climate change February 25, 2022 https://www.carbonbrief.org/guest-post-how-to-model-societys-response-to-climate-change?utm_campaign=Daily%20Briefing&utm_content=20220228&utm_medium=email&utm_source=Revue%20newsletter.

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