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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

Computer simulation models of global climate exist. They are providing the ability to assess the potential impacts of climate change and guide adaptation and mitigation efforts. A recent NASA report, by Alan Buis, January 9, 2020, titled 'Study Confirms Climate Models are Getting Future Warming Projections Right' emphasizes this conclusion.

Computer models are the only approach to synthesizing the science of climate change as discussed in previous chapters to generate actionable projections. 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 Report is in final stages of preparation.

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.

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.

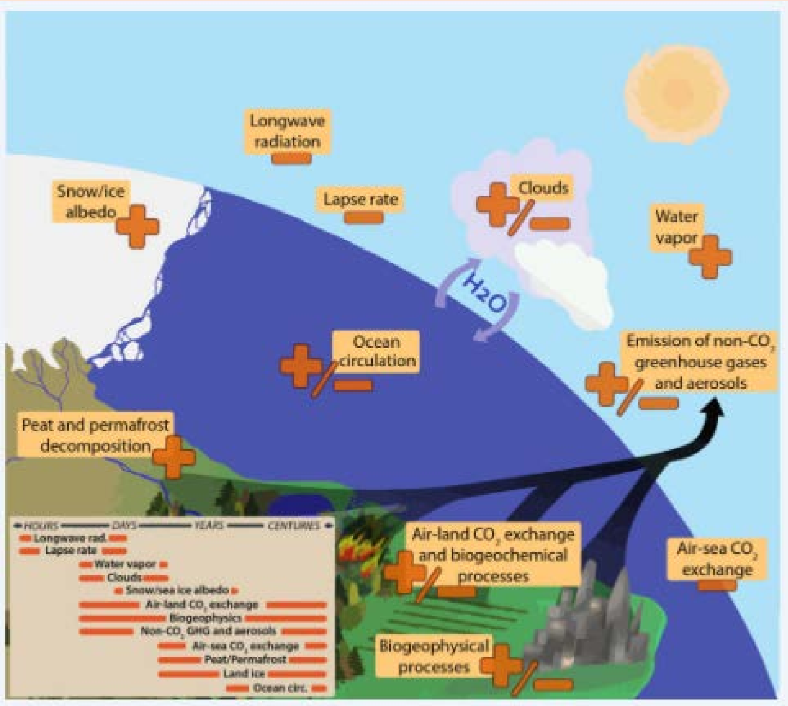
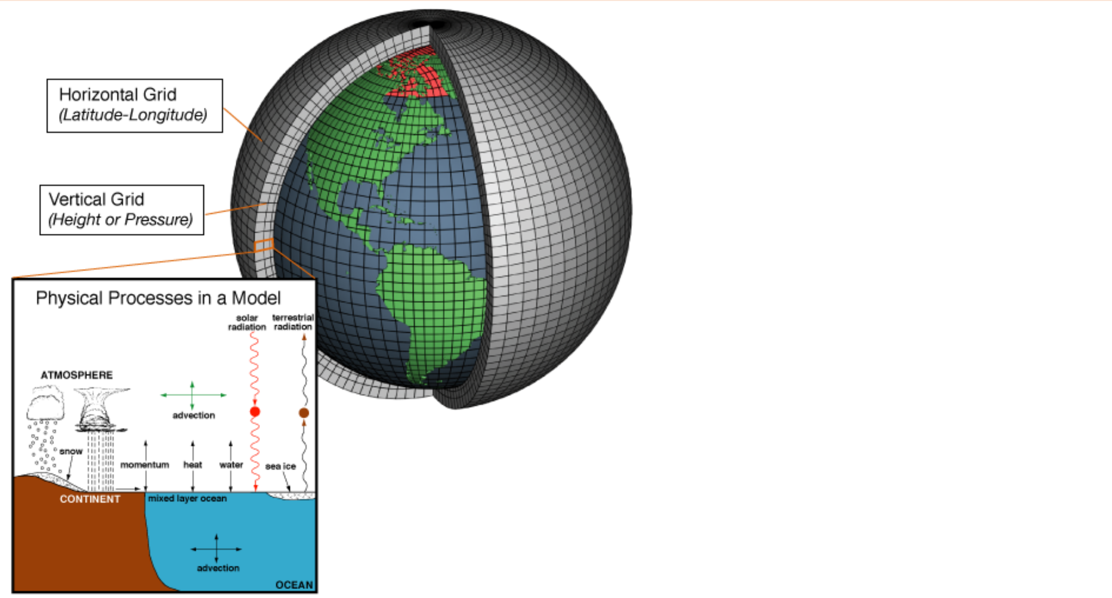


Figure 17.1 Subsystems included in climate models.
https://www.ipcc.ch/report/ar5/wg1/

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

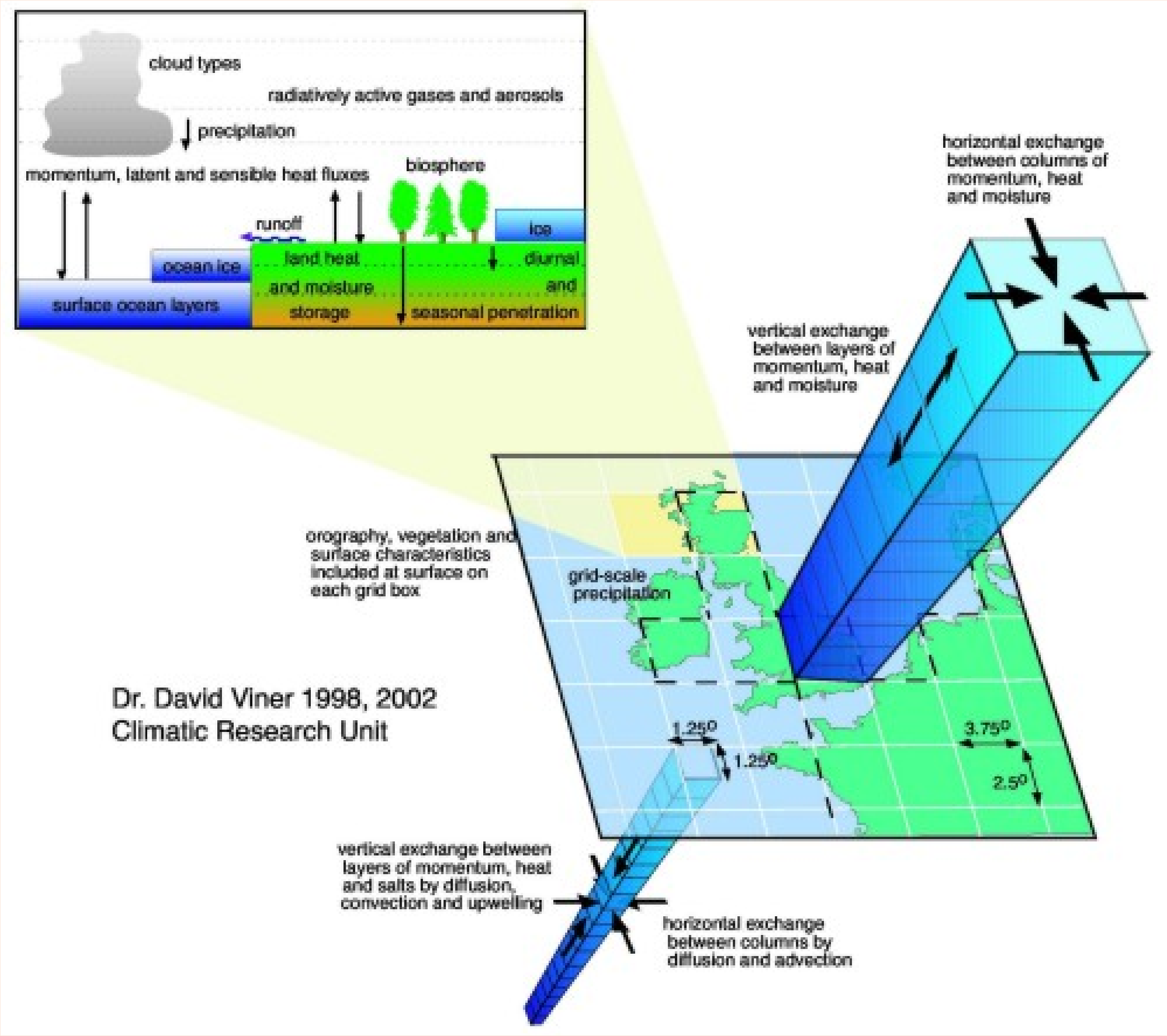
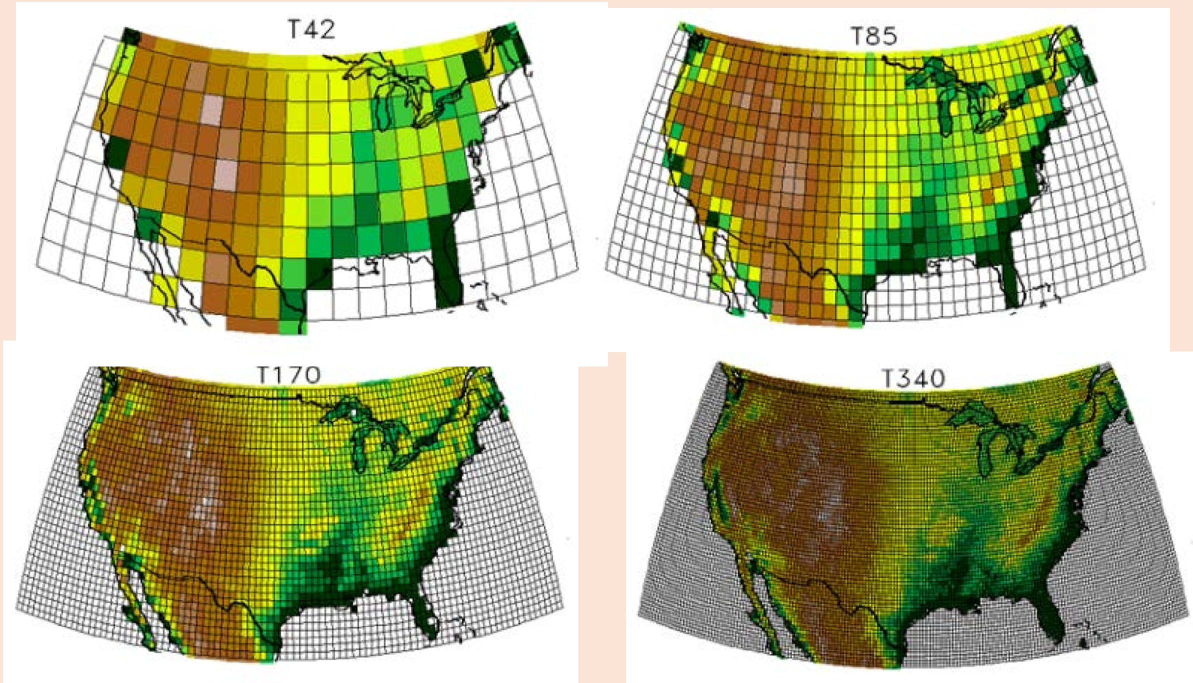


Figure 17.3 Concept used in climate models showing vertical column extending into the oceans.



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

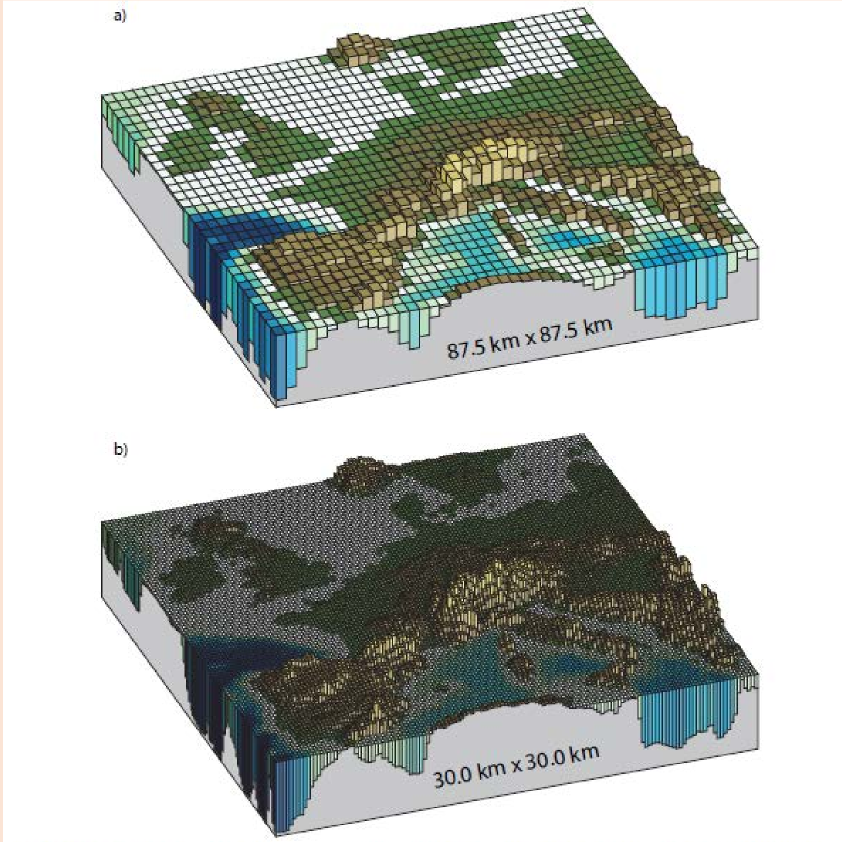


Figure 1.14 | Horizontal resolutions considered in today's higher resolution models and in the very high resolution models now being tested: (a) Illustration of the European topography at a resolution of 87.5 × 87.5 km; (b) same as (a) but for a resolution of 30.0 × 30.0 km.

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

Figure 17.7 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.

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).

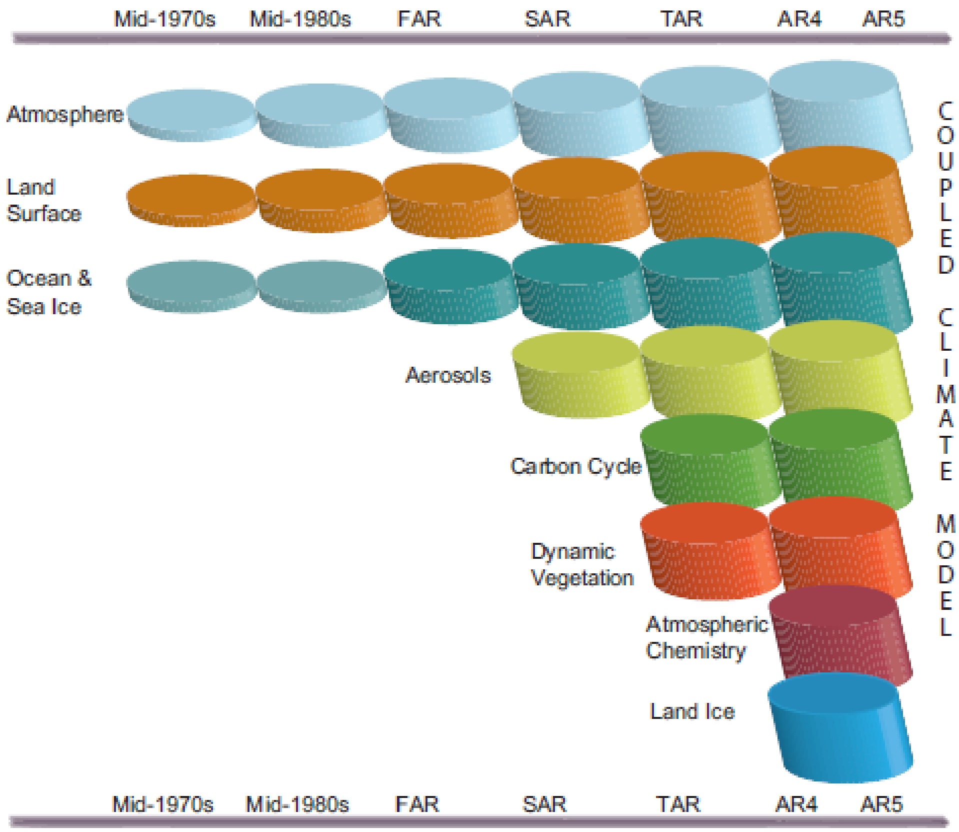


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has 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 14.12. 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.

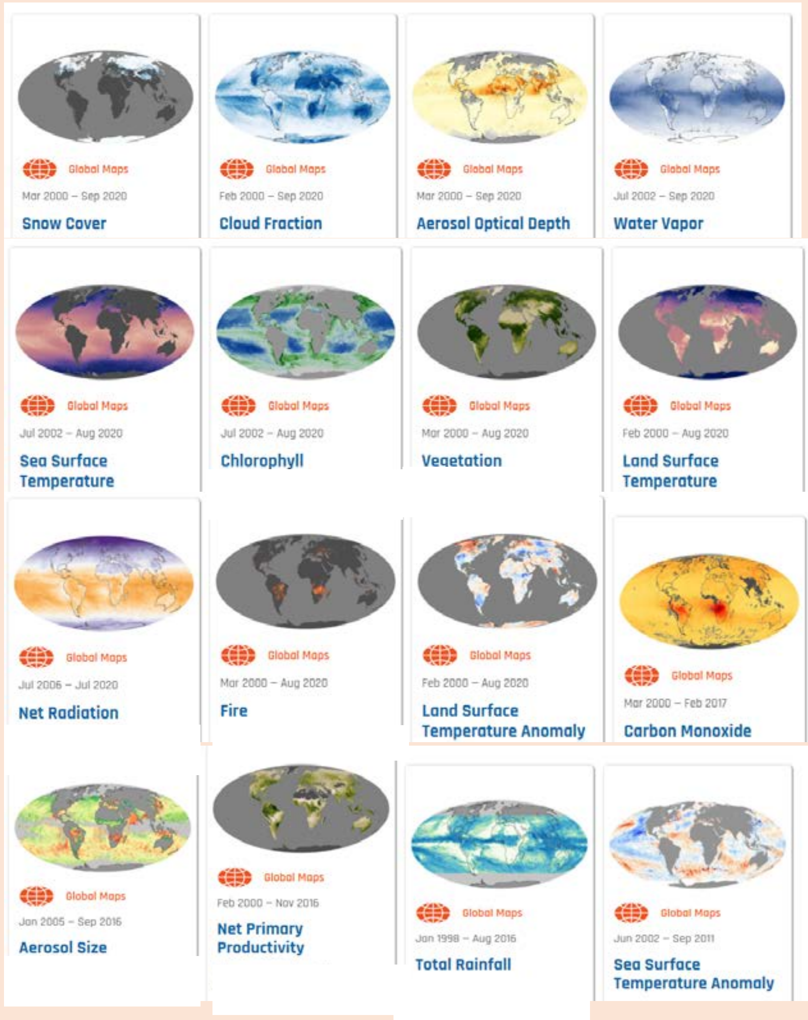


Figure 17.7 NASA Earth Observatory global maps. https://earthobservatory.nasa.gov/global-maps?utm_campaign=nav20&utm_source=topnav&utm_medium=globalmaps

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 17.9 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.

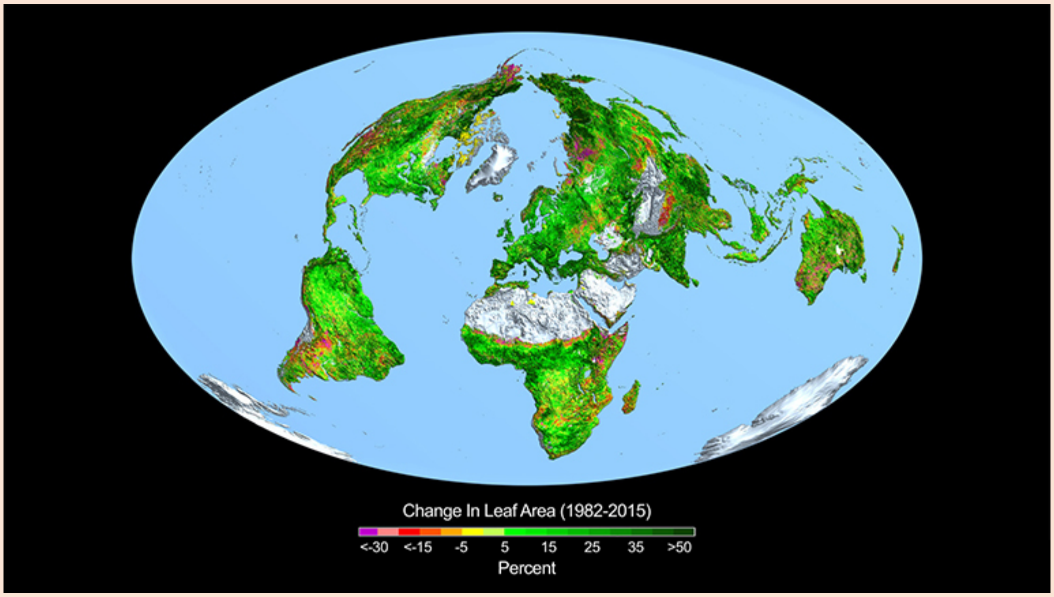


Figure 17.8 Assessment of global vegetative biomass capable of converting CO_2 to plant tissue using satellite carbon dioxide data. https://climate.nasa.gov/news/2436/co2-is-making-earth-greenerfor-now/

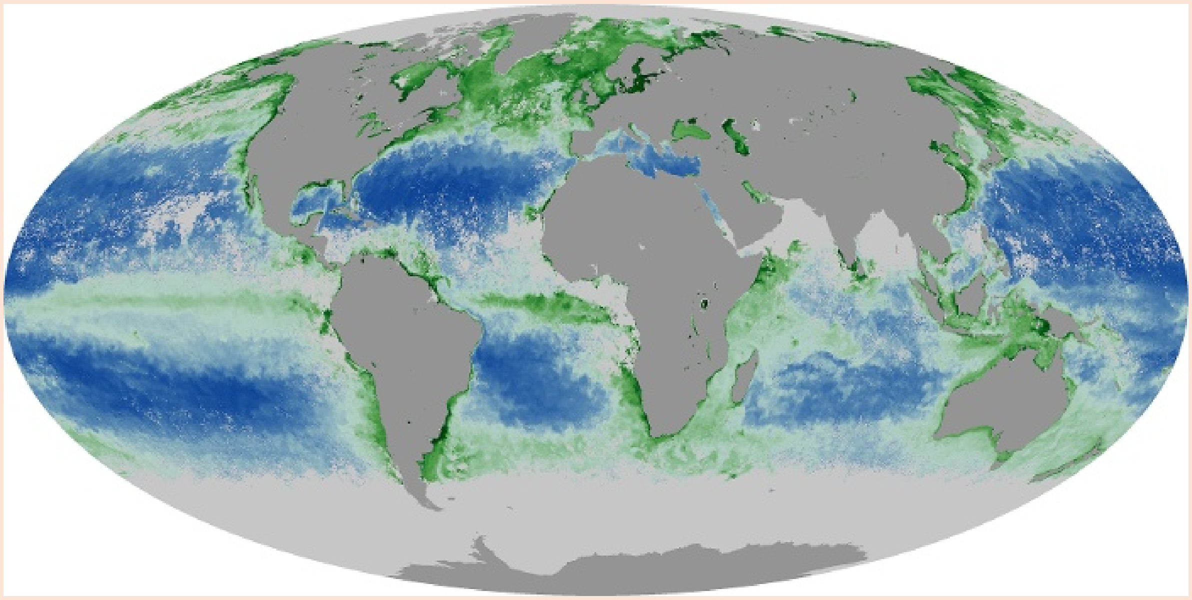


Figure 17.9 Ocean chlorophyl concentrations. https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA

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

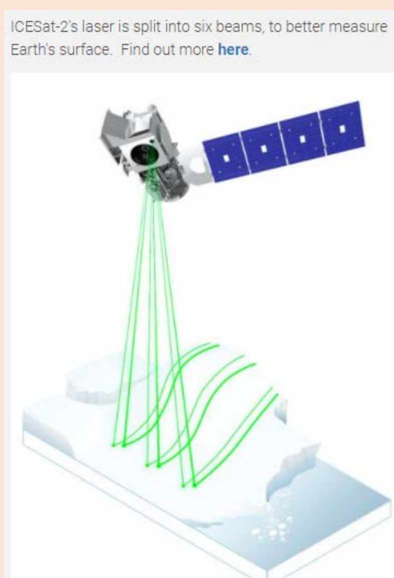


Figure 17.11 Ice thickness. https://icesat-2.gsfc.nasa.gov/

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.

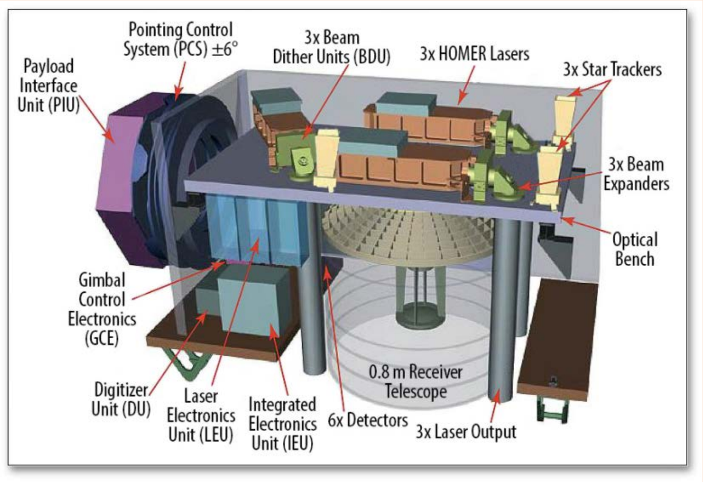


Figure 17.13 GEDI instrument showing lasers, optical paths, detectors and digitizers.
https://gedi.umd.edu/instrument/instrument-overview/

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 and also AR5.
2. AR5 also uses Earth System Models or ESMs that include various biochemical cycles, (carbon, sulphur, ozone).
3. Regional climate change (circulation) models or RCM'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.

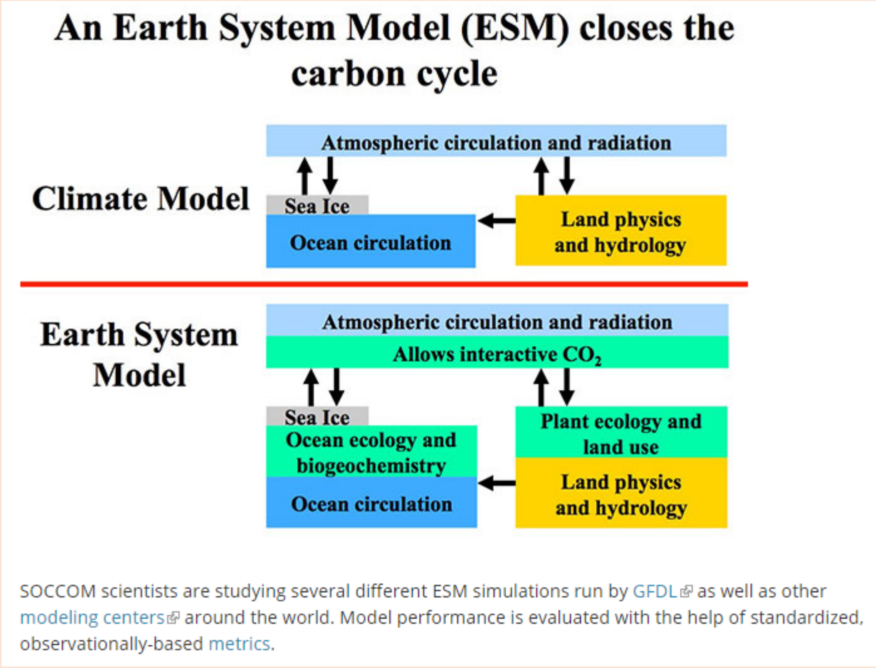


Figure 17.15 Comparison between a climate model and an earth system model
https://soccom.princeton.edu/content/what-earth-system-model-esm

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.

17.4.4 Coupled model intercomparison project, CMIP5
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 .

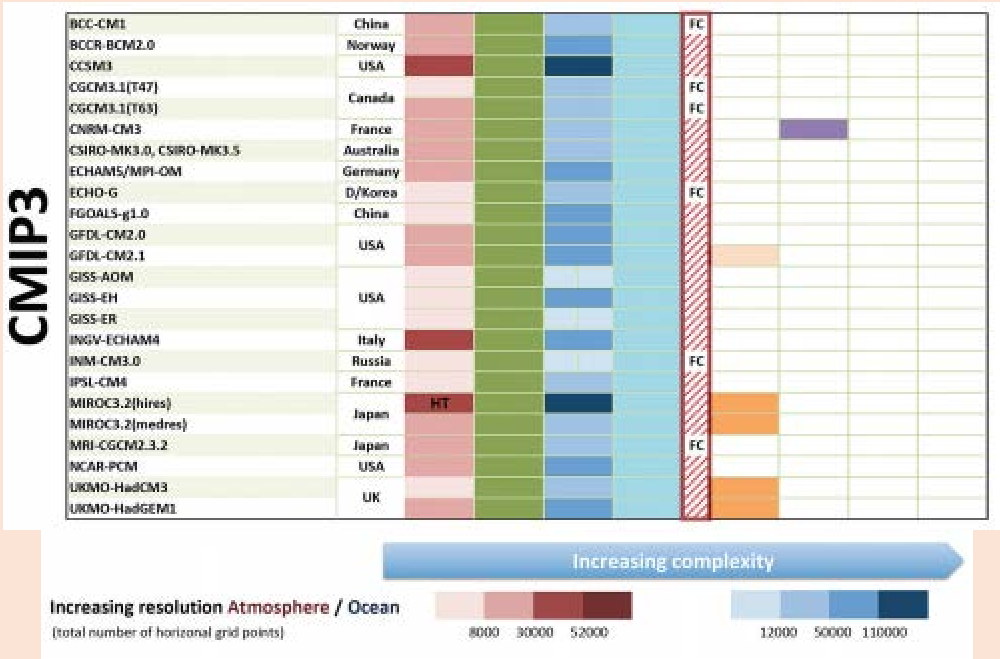
Table 17.3 lists and describes several EMICs which were also compared.
The results of these comparisons are detailed in the report.

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										
	CESM1 (BGC)										
	CESM1 (WACCM)	USA	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		

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

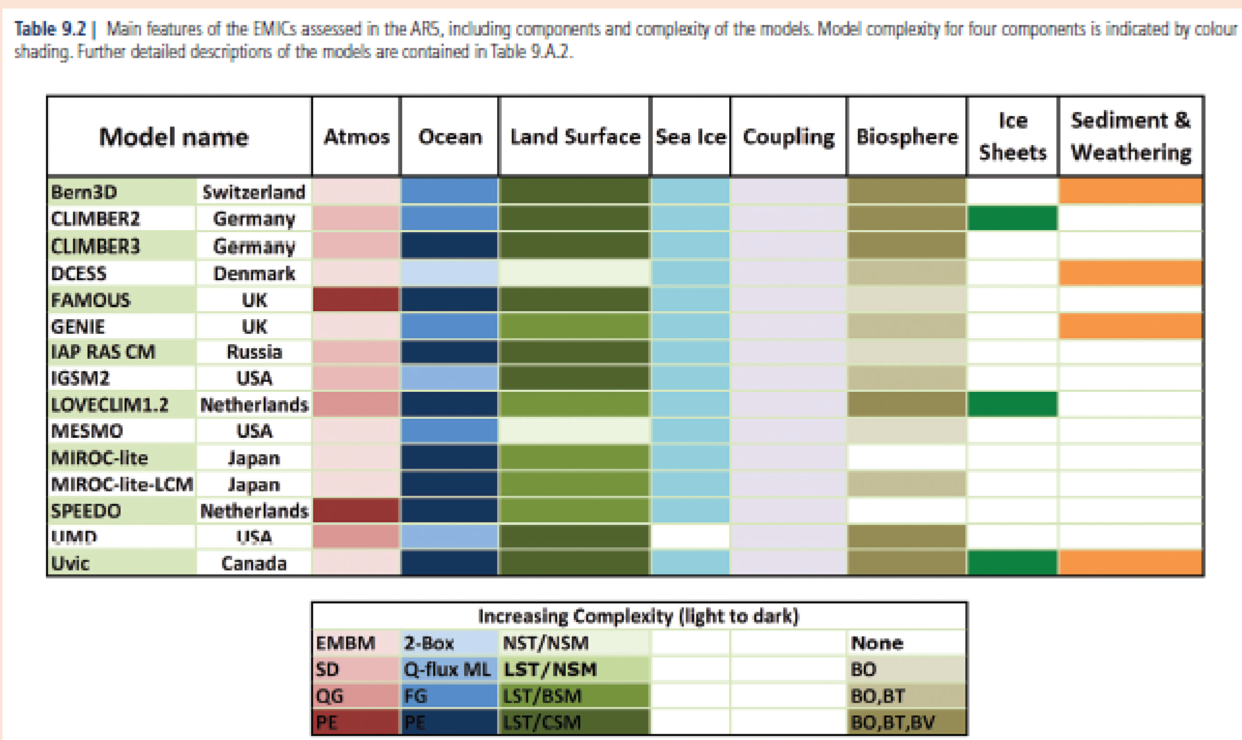


Table 9.2 | Main features of the EMICs assessed in the AR5, including components and complexity of the models. Model complexity for four components is indicated by colour shading. Further detailed descriptions of the models are contained in Table 9.A.2.

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 EMICs. https://pcmdi.llnl.gov/index.html and https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf

17.5 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).

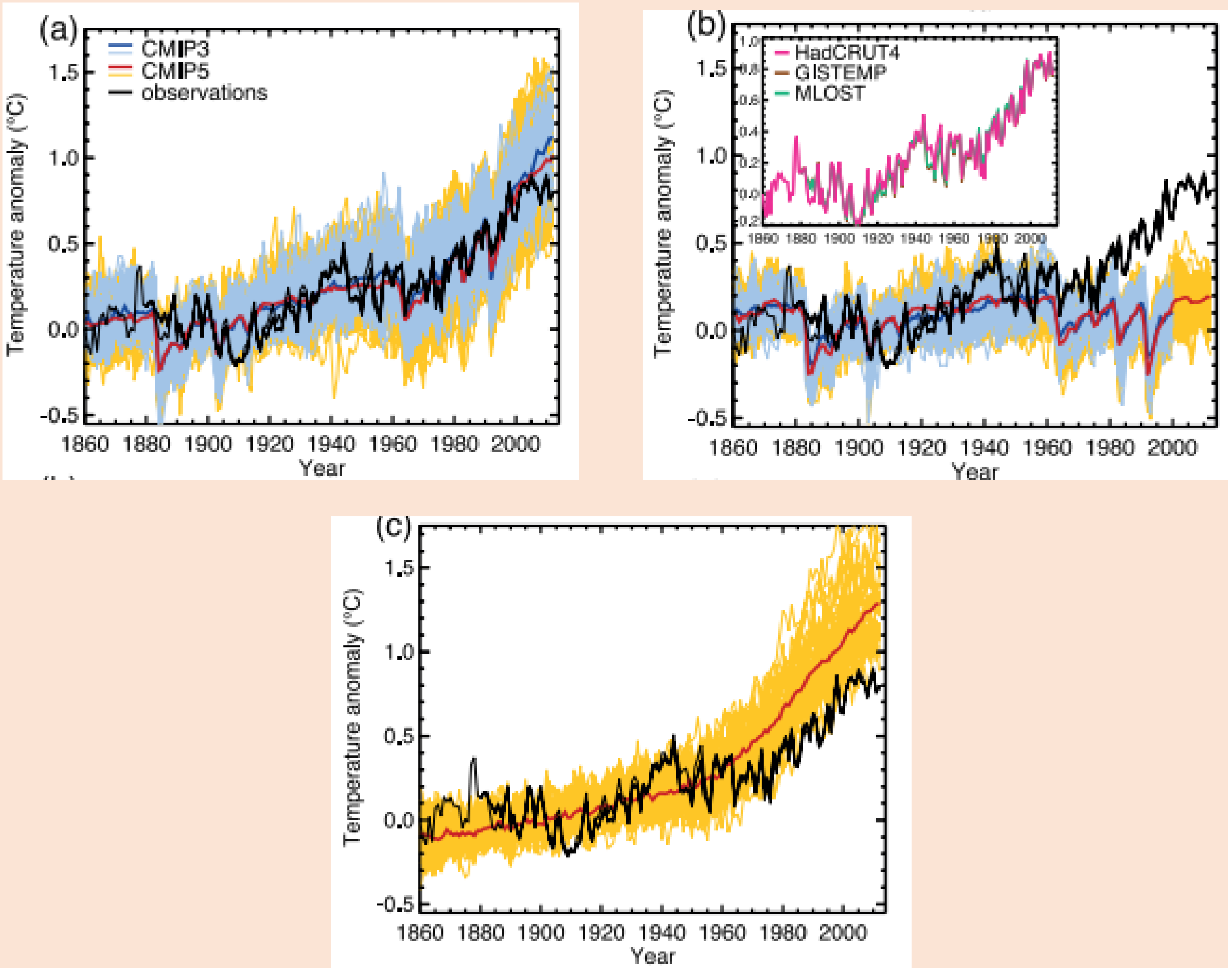


Figure 17.16 Estimates of global mean surface temperature (GMST) using averages of CMIP3(blue) and CMIP5(yellow) models using (a) both anthropogenic and natural forcings; (b) only natural forcings; and (c) only anthropogenic forcings compared to observed temperatures from 1850 to present. The red line 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

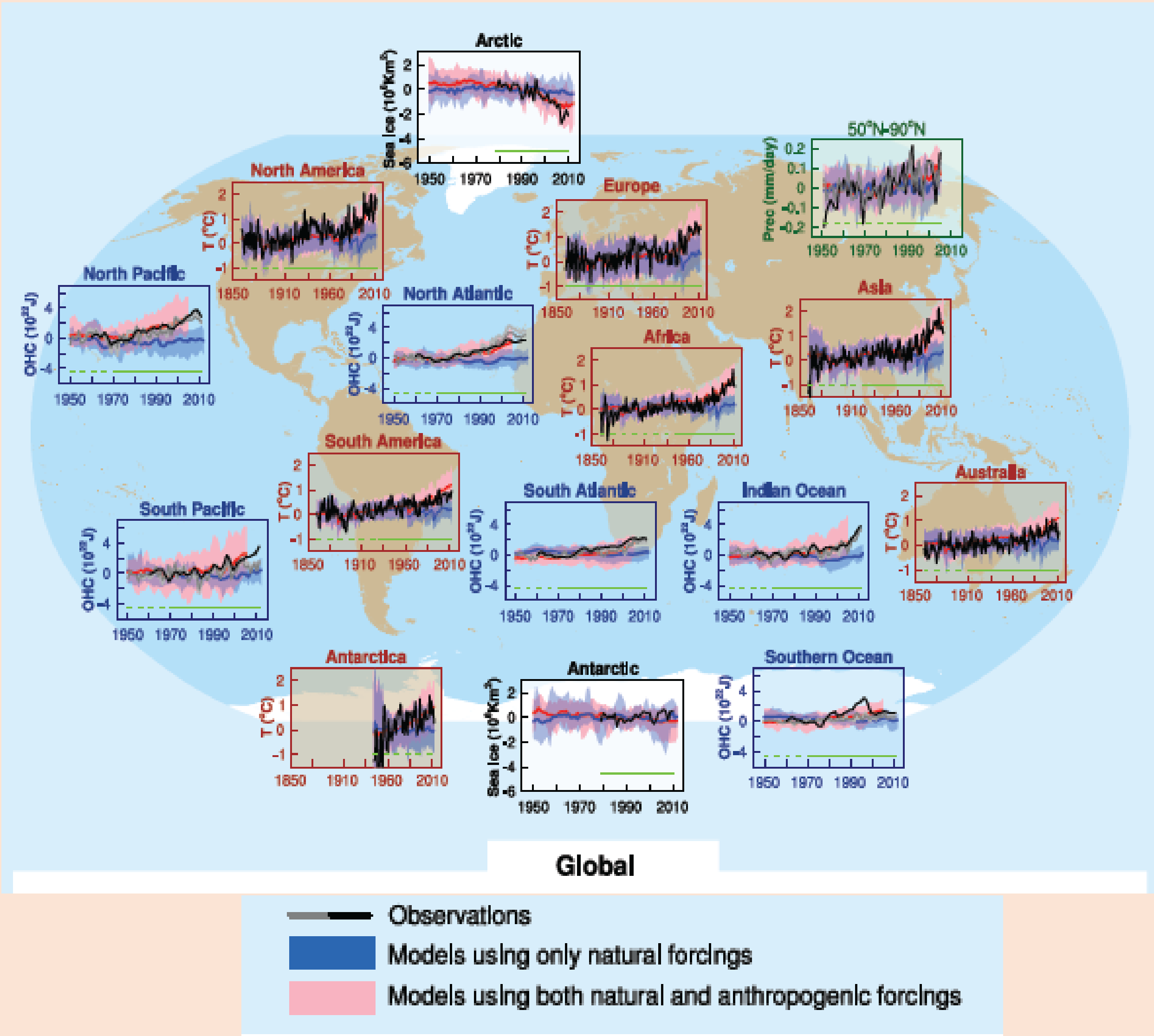


Figure 17.17 Comparison of model predictions to observed temperature on each of the continents.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

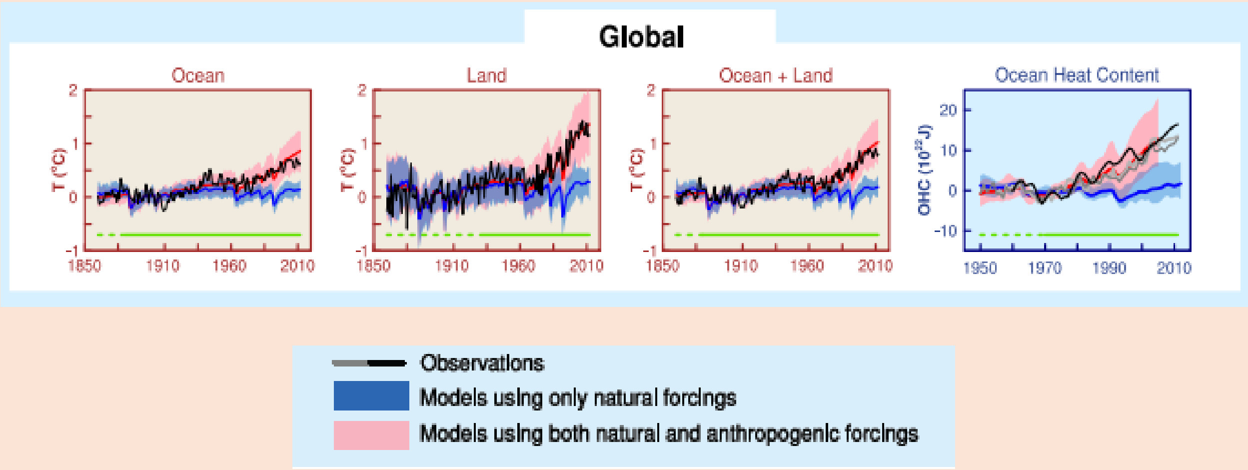


Figure 17.18 Comparison of model results when performed with only natural forcings and using both natural and anthropogenic forcings to observed global temperature of the ocean, land, ocean and land and ocean heat content.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

17.6 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

Agreement ↑	Evidence (type, amount, quality, consistency) →		
	High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
	Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
	Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Confidence Scale

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

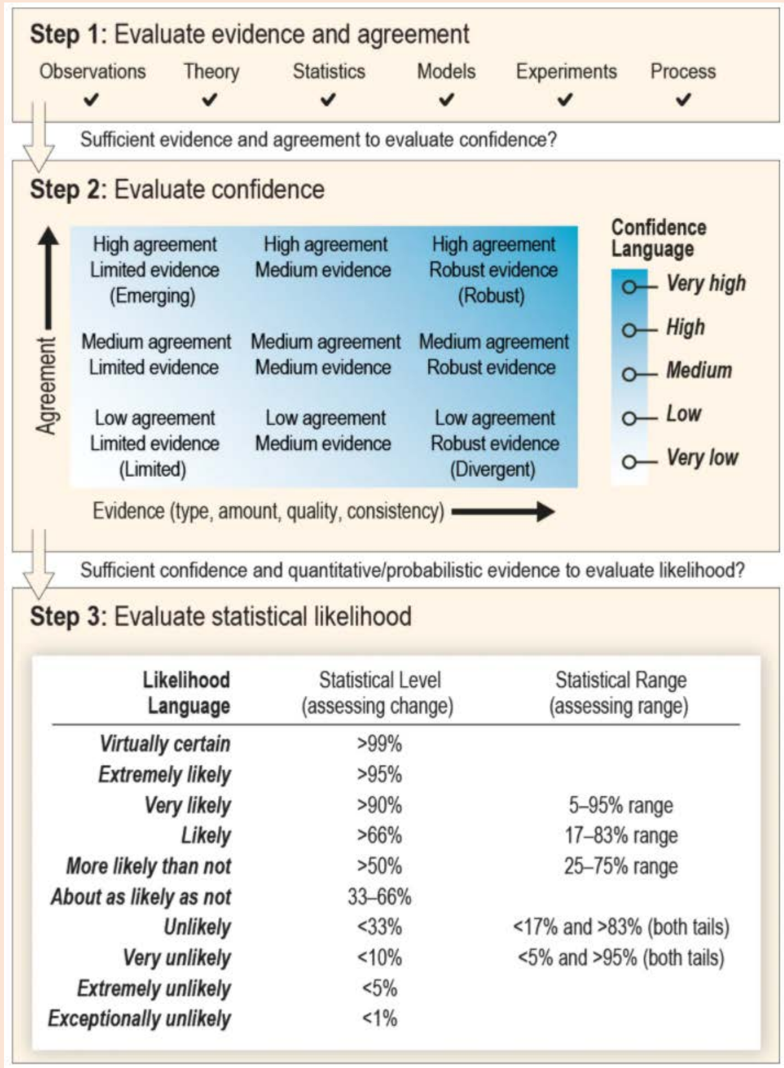


Table 17.7 Method for IPCC usage of calibrated language.

17.7 Information support

Key web sites:

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

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

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

4. 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/

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

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

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

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

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

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

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

12. 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