Cryosphere Models and Simulations

Yong Luo

Department of Earth System Science,
Tsinghua University

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Part Ⅰ

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**Department of Earth System Science,
Tsinghua University**

Contents

Climate System Model

Cryosphere Models

Shortly after the world's first computer, ENIAC, was created on February 15, 1946, John von Neumann and others proposed to the U.S. military to use computers for weather forecasting.

In 1950, under the leadership of John von Neumann, the Institute for Advanced Study in Princeton developed the world's first numerical weather forecasting model.

Since then, weather forecasting (climate system modeling) has remained one of the largest users of supercomputers.

- Simulating the working mechanisms of the Earth system on a global scale
- Revealing the overall evolutionary patterns of the Earth system
- Predicting future climate changes

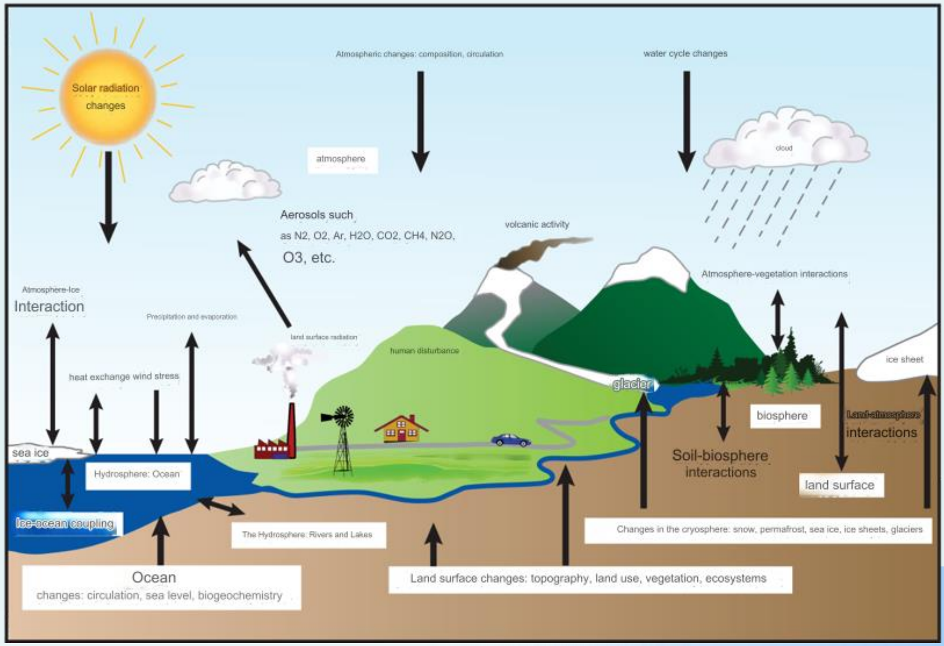
➢ "Digital" Experimental Method: Climate System Numerical Modeling

➢ The Only Scientific Tool: Climate Models

Climate System Models

Mathematical-physical model, built on the scientific understanding of dynamic, physical, chemical, and biological processes, provides a quantitative description of the state of each component of the climate system.

Numerical methods are used to solve these models, and high-performance computing enables the simulation and prediction of the nonlinear and complex behaviors and processes of the climate system.



The climate system and the interactions between its spheres

Three Stages of Earth System Model Development

Basic Stage: Physical Climate System Model

- Focuses primarily on Earth's fluid components, with the solid parts considering only land surface processes. The model describes only the dynamic and physical processes of the system.

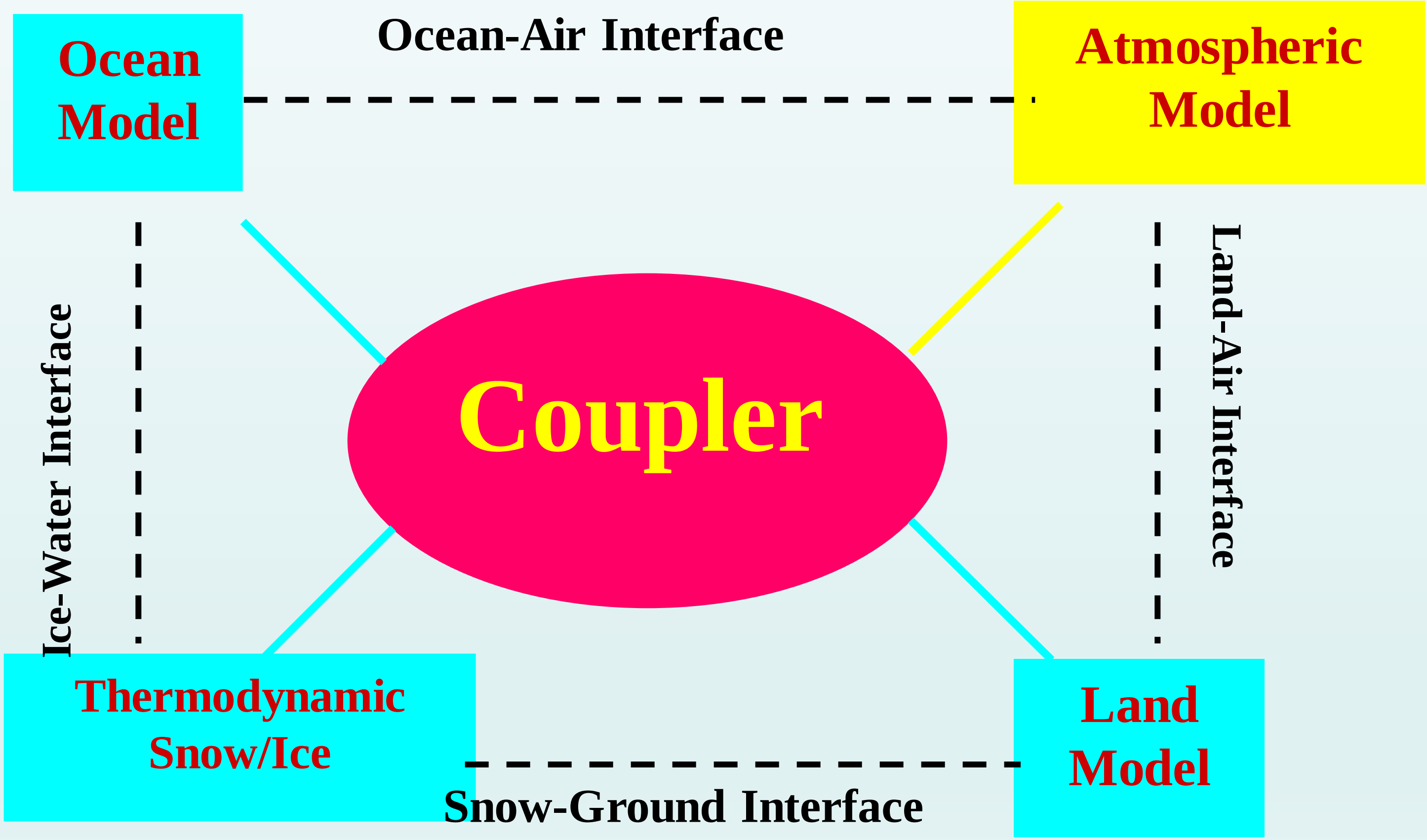
Intermediate Stage: (Earth) Climate System Model

- Builds on the physical climate system models by incorporating atmospheric chemical processes and Earth's biogeochemical processes (terrestrial and marine biology).

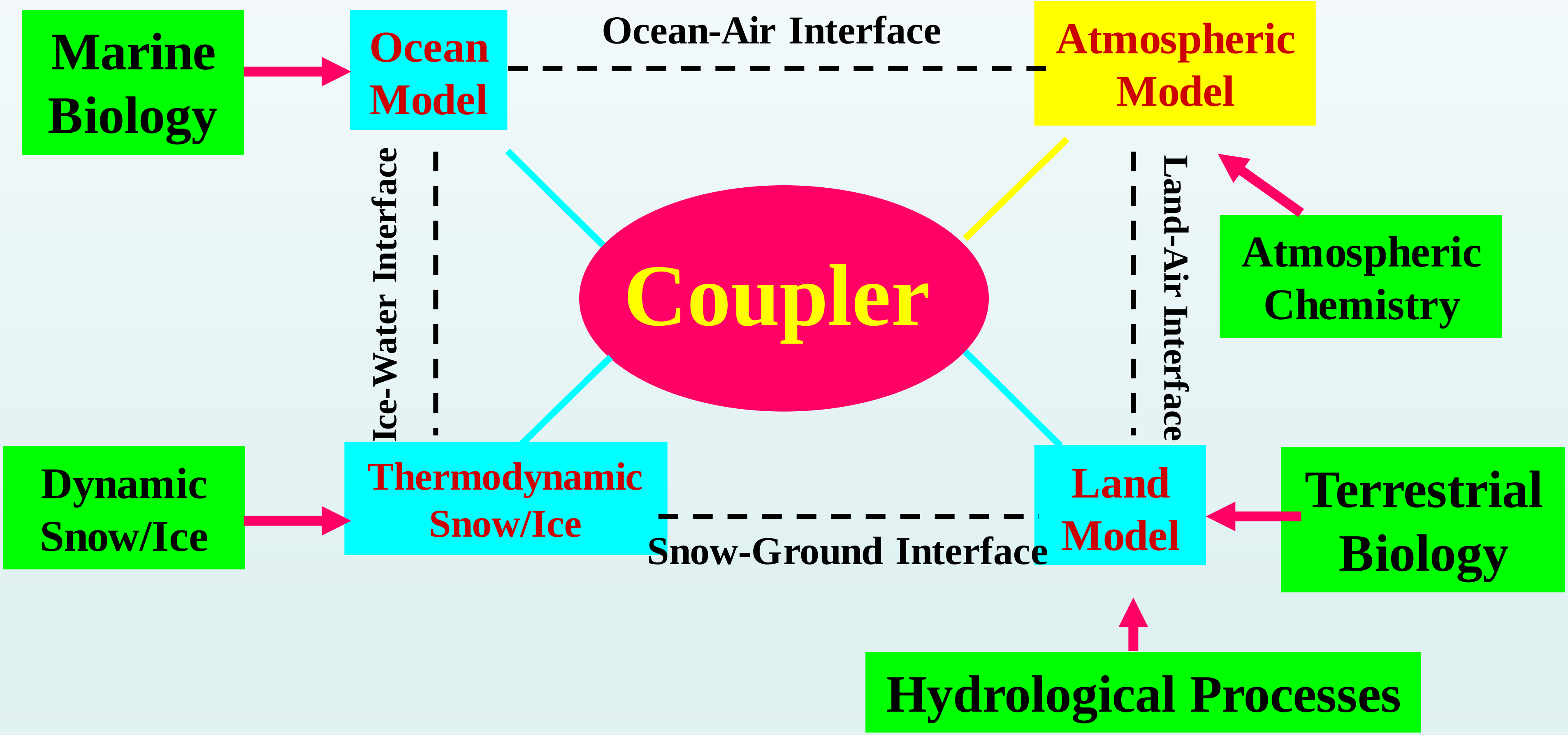
Mature Stage: Comprehensive Earth System Model

- Extends the Earth Climate System Models to include interactions with the solid Earth (e.g., tectonic plate movements and the resulting topographical changes, earthquakes, and volcanic eruptions) and space weather.

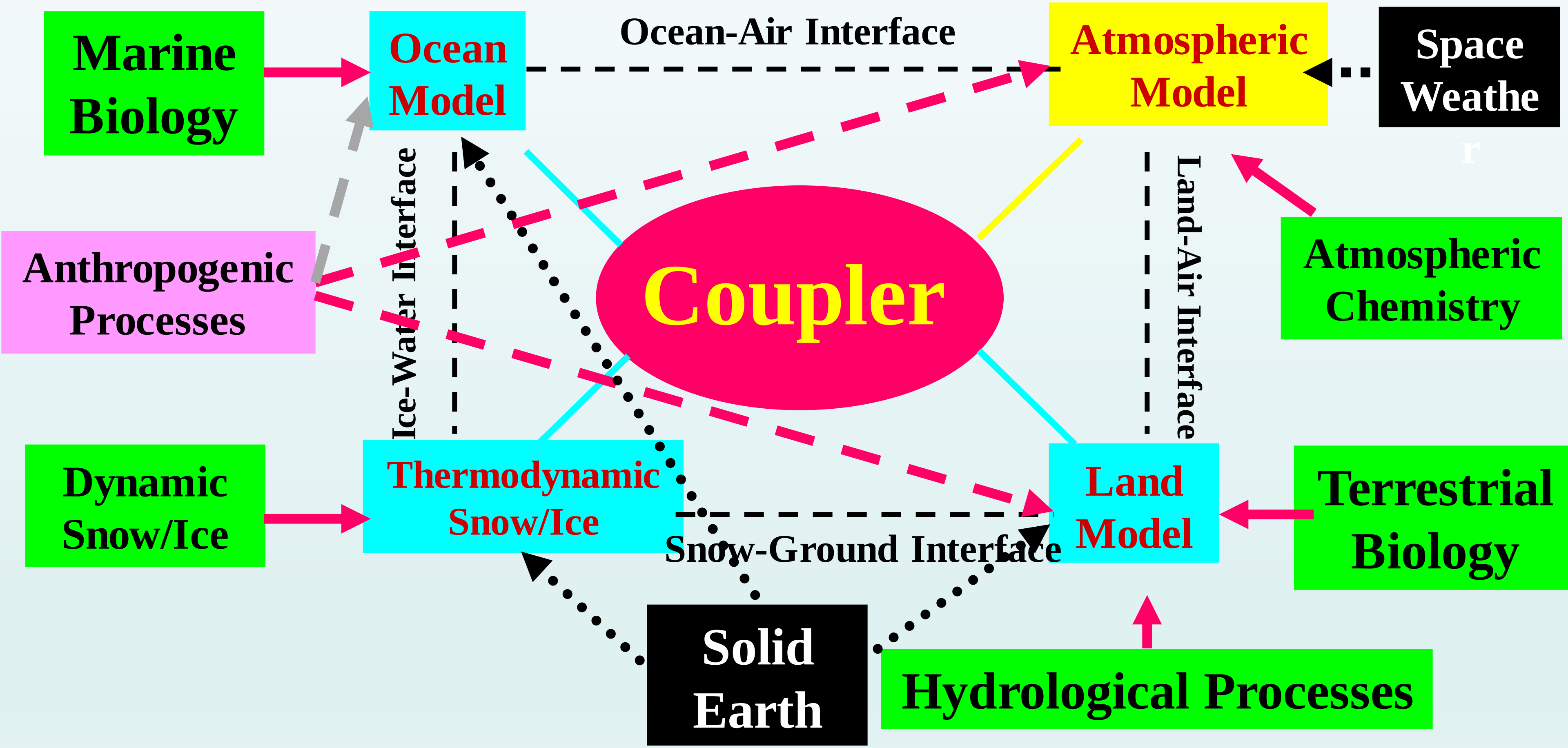
Physical Climate System Model



(Earth) Climate System Model

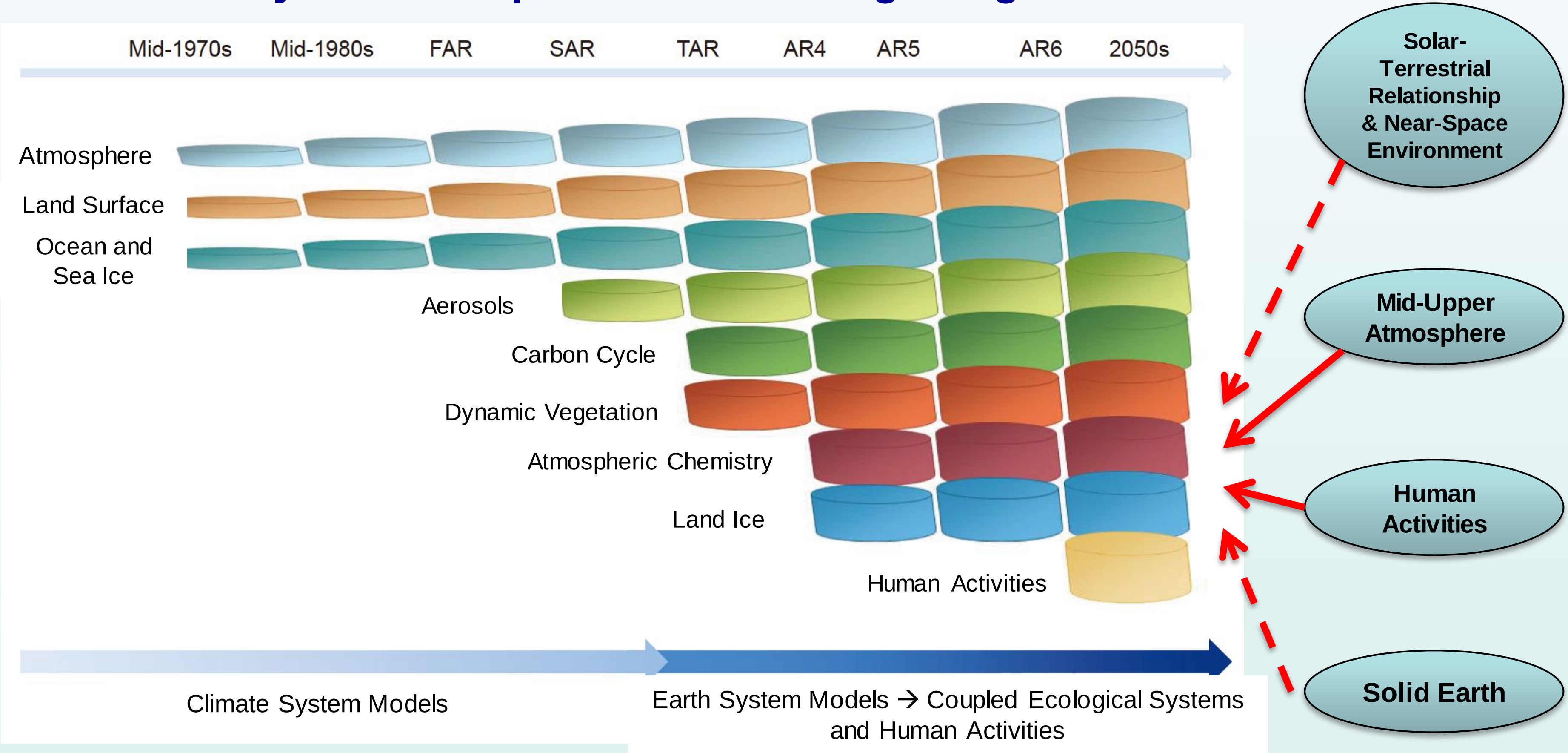


Earth Climate System Models



Development of Climate System Models

More Earth system components are being integrated



Mid-1970s

Mid-1980s

FAR

SAR

TAR

AR4

AR5

AR6

2050s

Atmosphere

Land Surface

Ocean and Sea Ice

Aerosols

Carbon Cycle

Dynamic Vegetation

Atmospheric Chemistry

Land Ice

Human Activities

Climate System Models

Earth System Models → Coupled Ecological Systems and Human Activities

Solar-Terrestrial Relationship & Near-Space Environment

Mid-Upper Atmosphere

Human Activities

Solid Earth

Zhou Tianjun, Zhang Wenxia, Chen Deliang, Zhang Xuebin, et al.: Interpretation of the 2021 Nobel Prize in Physics: From the Greenhouse Effect to Earth System Science. Science China, 2021, 52, doi: 10.1360/SSTe-2021-0338.

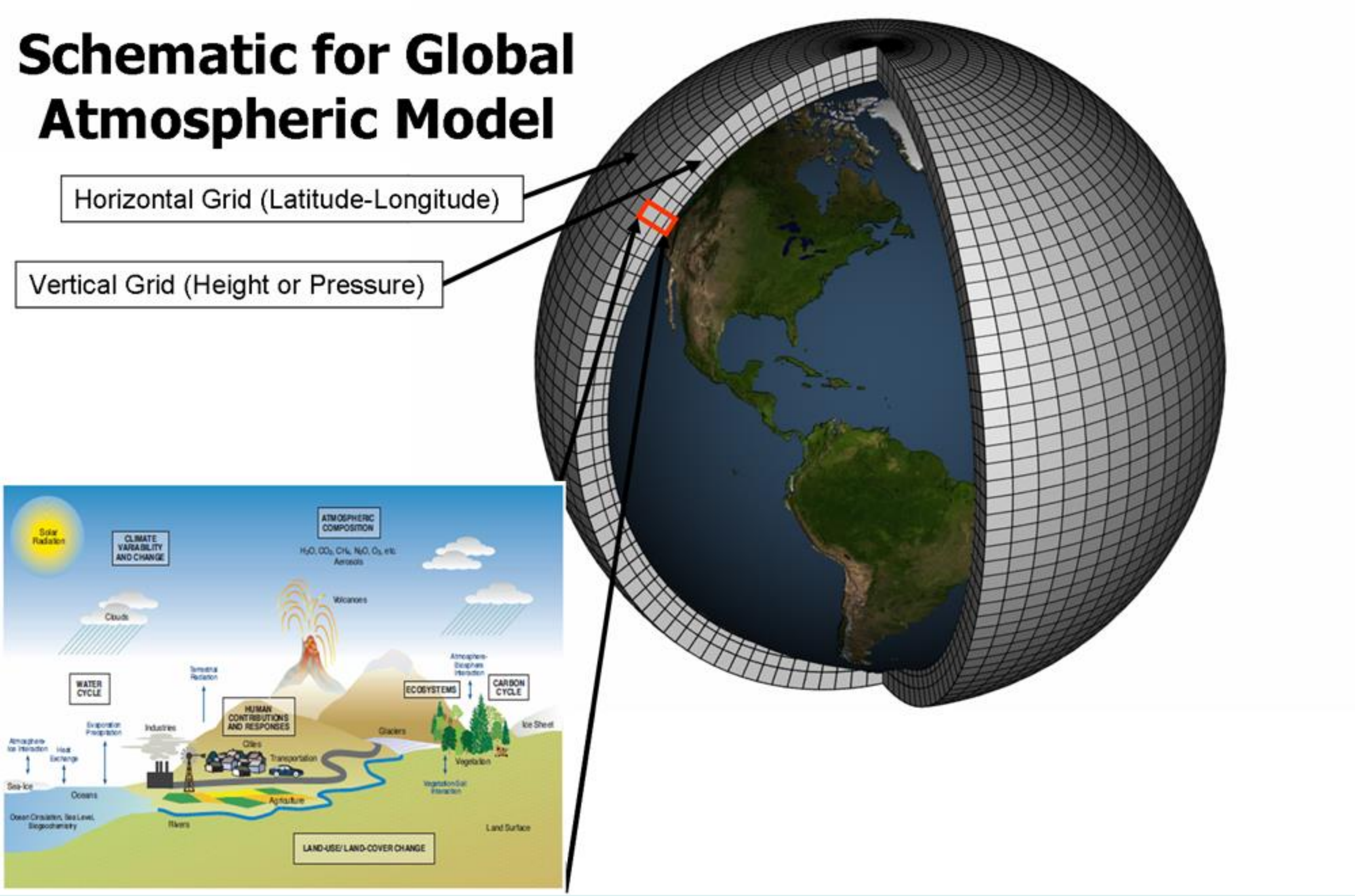
History of Atmospheric Model Development

- **Early 20th Century: Vilhelm Bjerknes proposed weather forecasting as a mathematical physical problem.**
- **1922: Lewis Fry Richardson attempted to produce weather forecast using numerical calculation methods.**
- **1950: Jule Charney and colleagues produced the world's first usable 500 hPa weather forecast map.**

$$
\begin{cases}
\dfrac{\mathrm{d}u}{\mathrm{d}t} - fv = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + F_x \\
\dfrac{\mathrm{d}v}{\mathrm{d}t} + fu = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial y} + F_y \\
\dfrac{\mathrm{d}w}{\mathrm{d}t} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial z} - g + F_z \\
\dfrac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\left(\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z}\right) = 0 \\
c_p \dfrac{\mathrm{d}T}{\mathrm{d}t} - \alpha \dfrac{\mathrm{d}p}{\mathrm{d}t} = Q \\
p = \rho RT
\end{cases}
$$

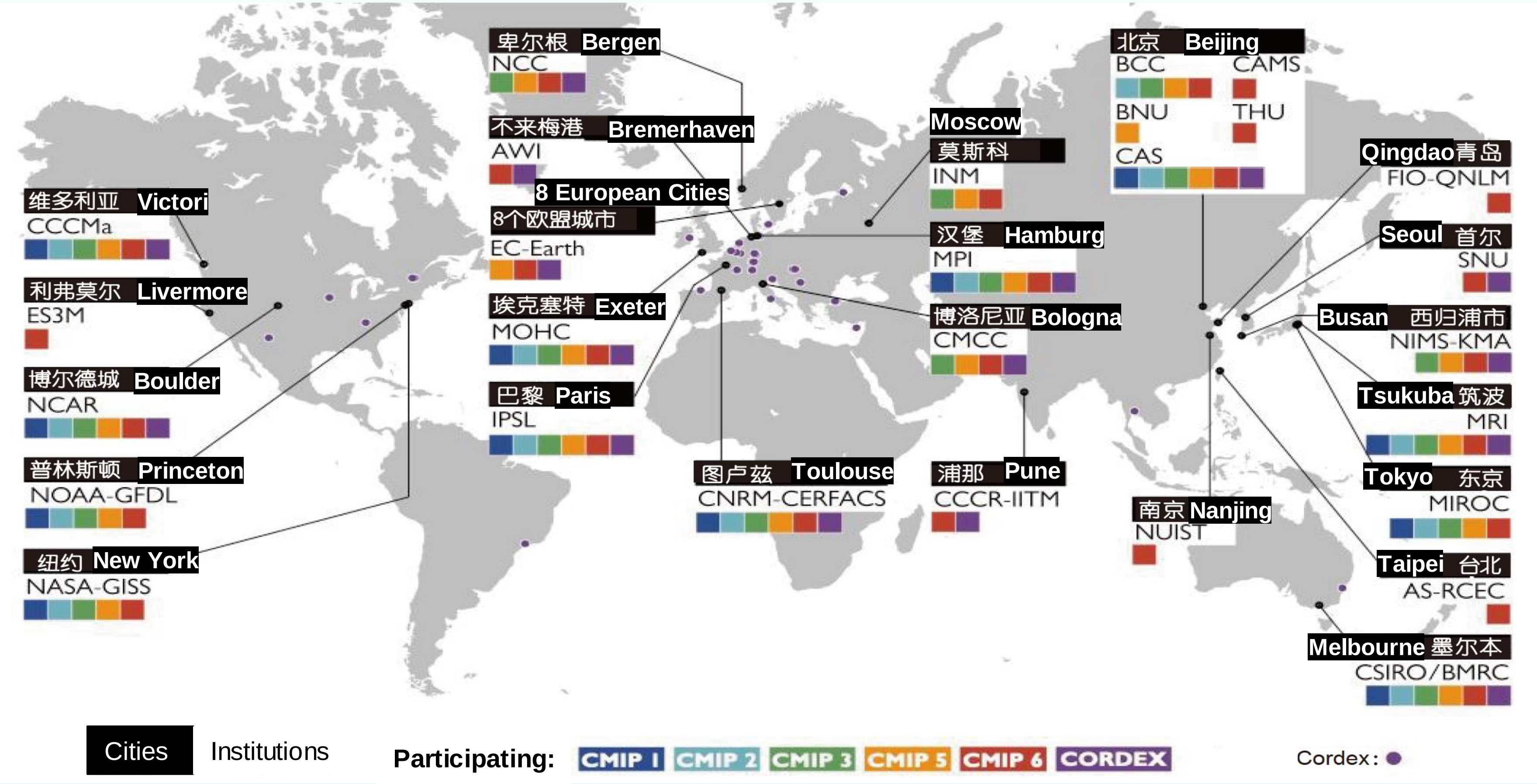
Navier-Stokes equations

Dynamic Core



(*Adapted from Wikipedia*)

IPCC AR6 utilized 112 model versions from 33 institutions worldwide



(*Adapted from IPCC AR6*)

Zhou Tianjun, Zhang Wenxia, Chen Deliang, Zhang Xuebin, et al.: Interpretation of the 2021 Nobel Prize in Physics: From the Greenhouse Effect to Earth System Science. Science China, 2021, 52, doi: 10.1360/SSTe-2021-0338.

Current Status of Earth System Model Development

Models and Resolutions in CMIP5

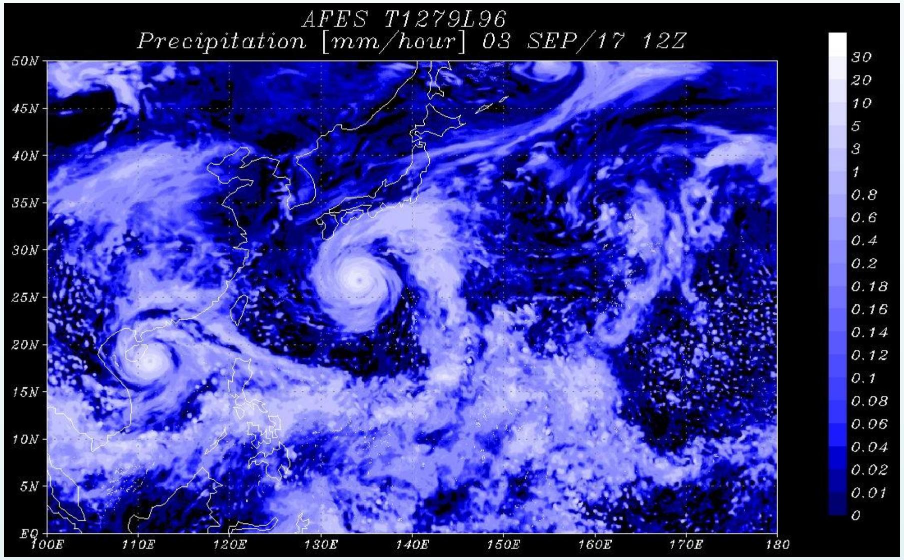
- 57 model versions from 23 institutions across 10 countries and the European Union.
- General improvement in horizontal resolution compared to CMIP3, with the highest resolution reaching 50 km and an average of 200 km.

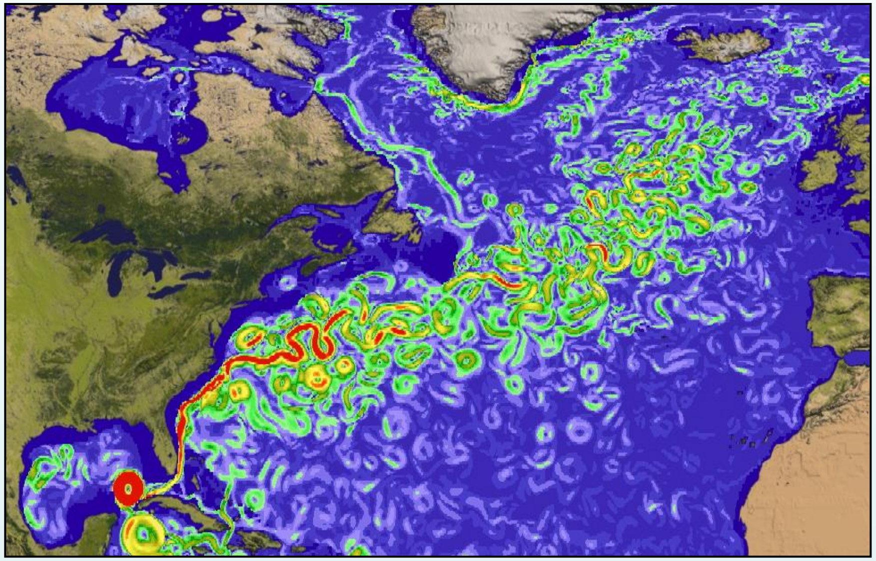
Model and Resolutions in CMIP6

- 112 model versions from 33 institutions, with resolutions generally reaching 50 km.
- Computational demands increased 200-fold and storage needs reached 10-50 PB, compared to CMIP5.
- China contributed 9 models from 7 institutions.

Future of Climate System Model Development

❑ Toward to "High Spatiotemporal Resolution"





● **Example:** Illustrating the relationship between computational load and model resolution:

- Global simulation at "100 km"
- Enhanced to "10 km”
- Further refined to "< 5 km"

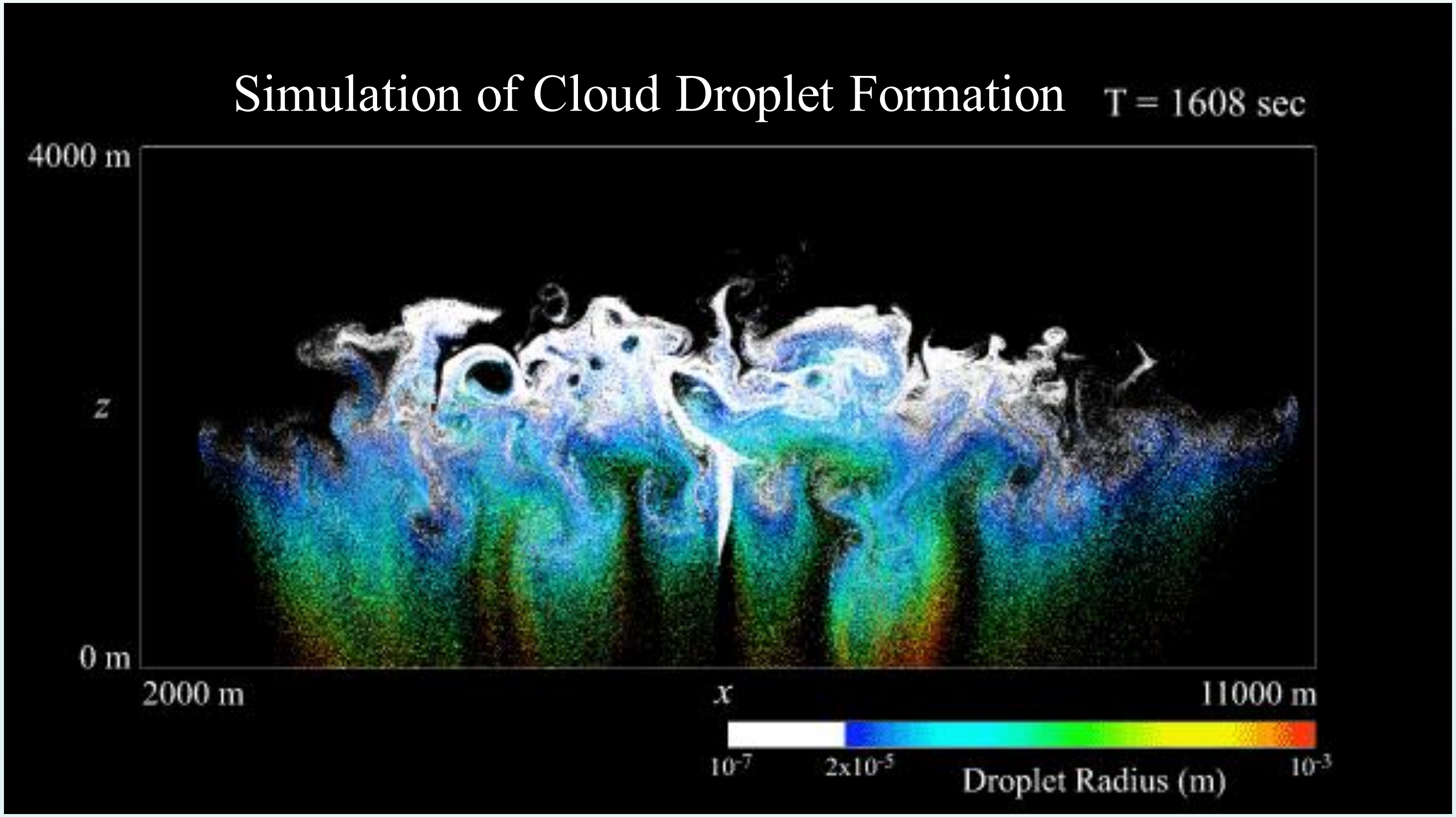
●Spatial scales in Earth sciences:

- Atmosphere: 1 km to 10,000 km
- Oceans: 100 m to 10,000 km
- Ecology: Few km to 1,000 km
- Water resources: Few km to 1,000 km
- Geological hazards: Tens of meters to tens of km
- Air pollution: Street to urban scale

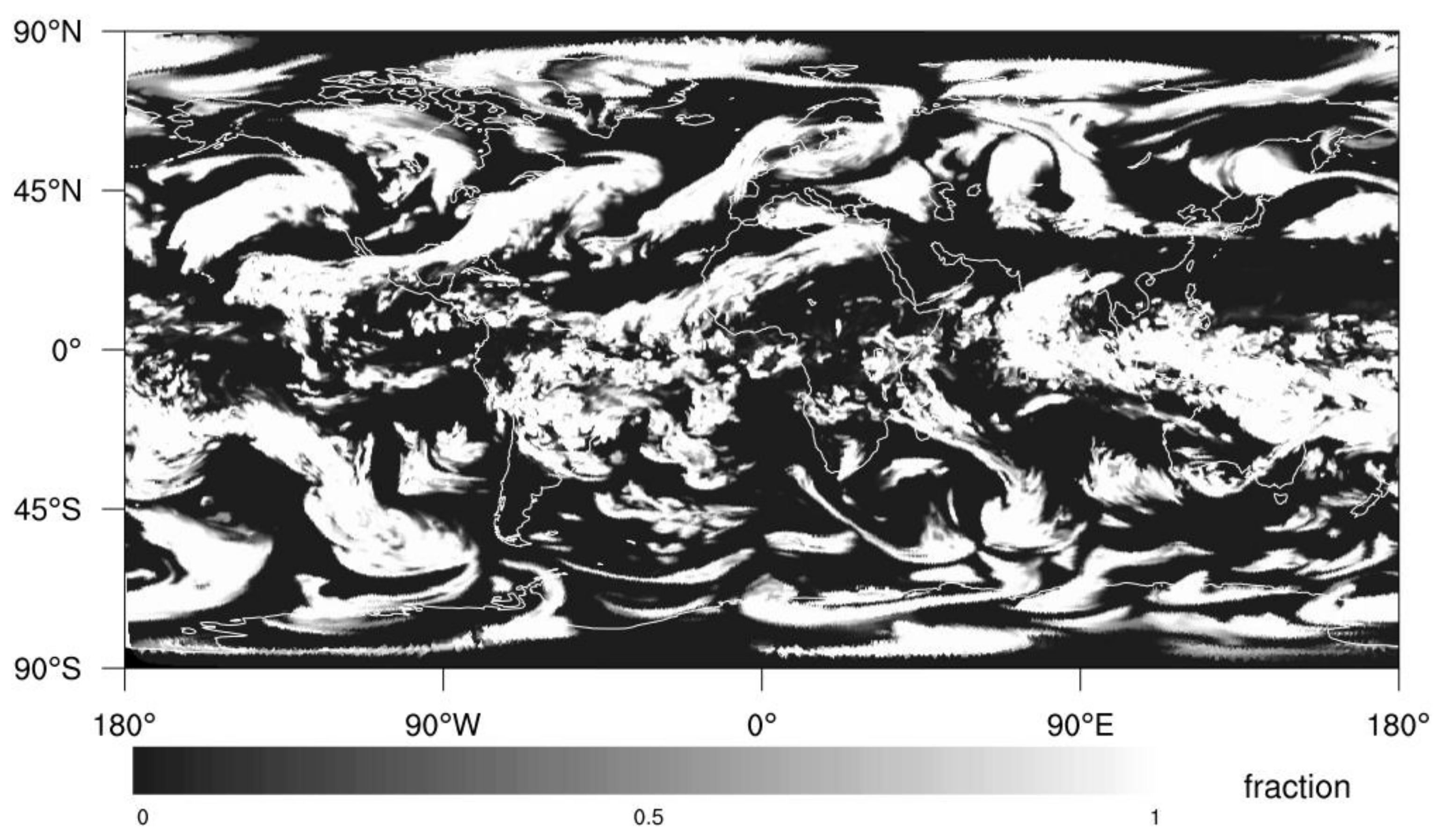
Future of Climate System Model Development

☐ **Incorporating more fine-scale processes**

E.g. : cloud-radiation interaction is one of the most critical parts



High Cloud Simulation in an Atmospheric Model with 25 km Horizontal Resolution



Climate System Model Code

Xu-Randall Cloud Fraction Diagnostic Formula

$$C_s = \mathrm{RH}^p[1 - \exp(-\alpha \bar{q}_l)]$$

- **Fortran code:**

```
!     Alternative calculation for critical RH for grid saturation
!     RHGRID=0.90+.08*((100.-DX)/95.)**.5, which is the meaning of RHGRID
!     PEXP: empirical parameter
!     RHUM: relative humidity
!     ** : an exponentiation operator in Fortran
CLDFRA(i, k, j)=(RHUM/RHGRID)**PEXP*(1.-EXP(ARG))
```

Climate Model Programs and their High Performance Computing are highly Complex

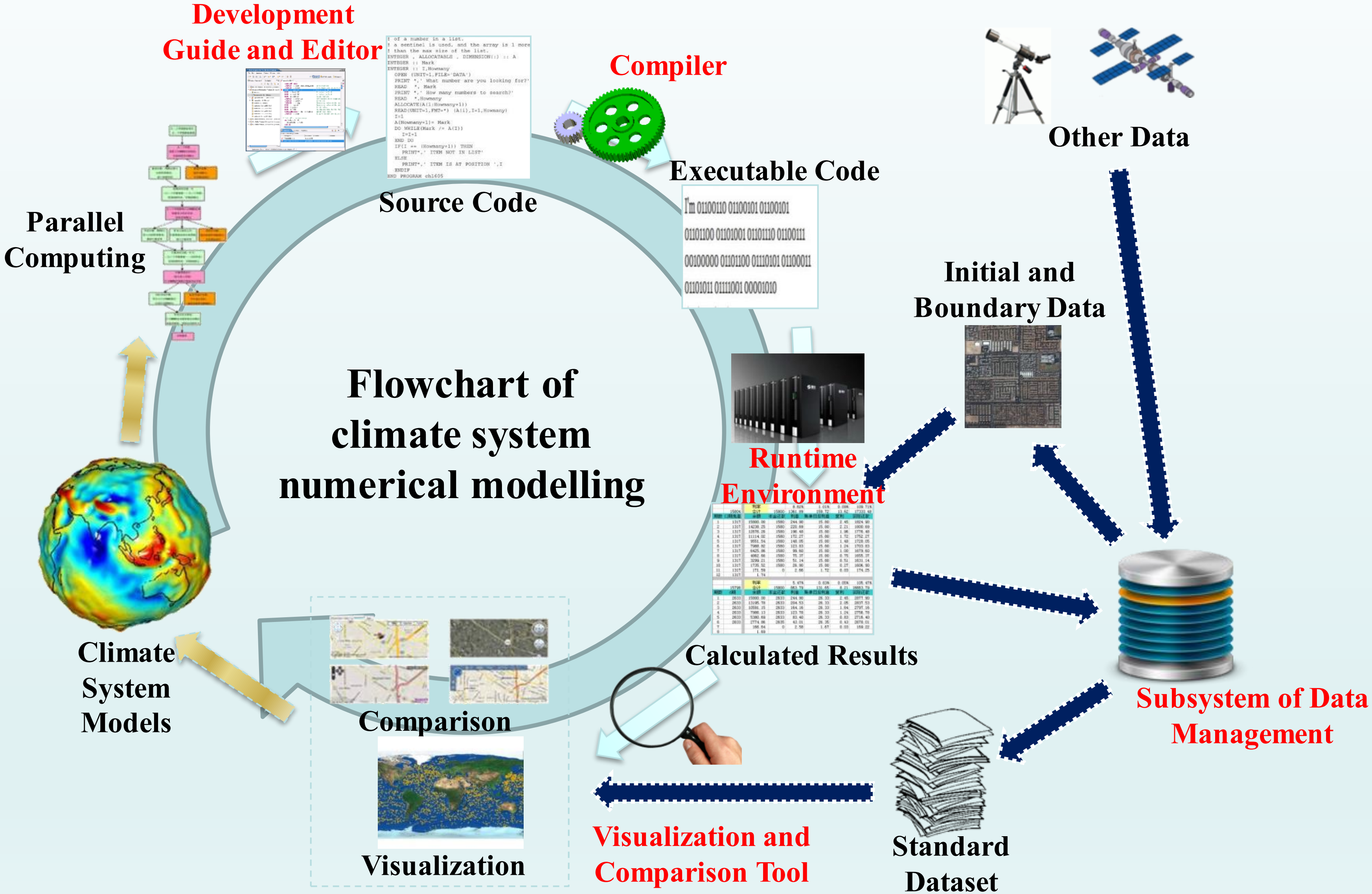
Complex program structure， massive codebase (e.g., 2.6 million lines)

Challenges in matching long-accumulated model programs (30 years) with high-performance computing architectures

These challenges involve all aspects of supercomputing’s hardware and software

- Application, Compilation, Parallel Processing, Runtime Environment, Operating System, Interconnect Communication, Management of Large Memory…

Flowchart of climate system numerical modelling



Development Guide and Editor

Source Code

```
! of a number in a list.
! a sentinel is used, and the array is 1 more
! than the max size of the list.
INTEGER , ALLOCATABLE , DIMENSION(:) :: A
INTEGER :: Mark
INTEGER :: I,Howmany
  OPEN (UNIT=1,FILE='DATA')
  PRINT *,' What number are you looking for?'
  READ  *, Mark
  PRINT *,' How many numbers to search?'
  READ  *,Howmany
  ALLOCATE(A(1:Howmany+1))
  READ(UNIT=1,FMT=*) (A(i),I=1,Howmany)
  I=1
  A(Howmany+1)= Mark
  DO WHILE(Mark /= A(I))
    I=I+1
  END DO
  IF(I == (Howmany+1)) THEN
    PRINT*,' ITEM NOT IN LIST'
  ELSE
    PRINT*,' ITEM IS AT POSITION ',I
  ENDIF
END PROGRAM ch1605
```

Compiler

Executable Code

```
I'm 01100110 01100101 01100101
01101100 01101001 01101110 01100111
00100000 01101100 01110101 01100011
01101011 01111001 00001010
```

Other Data

Initial and Boundary Data

Runtime Environment

Calculated Results

Subsystem of Data Management

Standard Dataset

Visualization and Comparison Tool

Comparison

Visualization

Climate System Models

Parallel Computing

Are Climate Models Reliable?

- **Developed from weather forecasting models, which have over 60 years of history and are now highly accurate for 1-2 week forecasts.**
- **Climate models have continuously improved in producing short-term climate predictions.**
- **Climate models mainly rely on external forcing and coupled system signals in climate system (e.g., ocean and land), as well as the radiative forcing change caused by slow changes in GHGs concentrations for long-term prediction, offering extended predictability.**
- **Climate models are the primary tool for projecting future climate change and its impacts, and the only method for quantitative projection.**

- **Climate models are built on a foundation of physical laws and mathematical equations that describe the Earth's system.** These laws and equations are well-proven and widely accepted in the fields of physics and computational mathematics. Additionally, comprehensive global observational data sets provide a standard for comparing model calculations with real-world conditions.

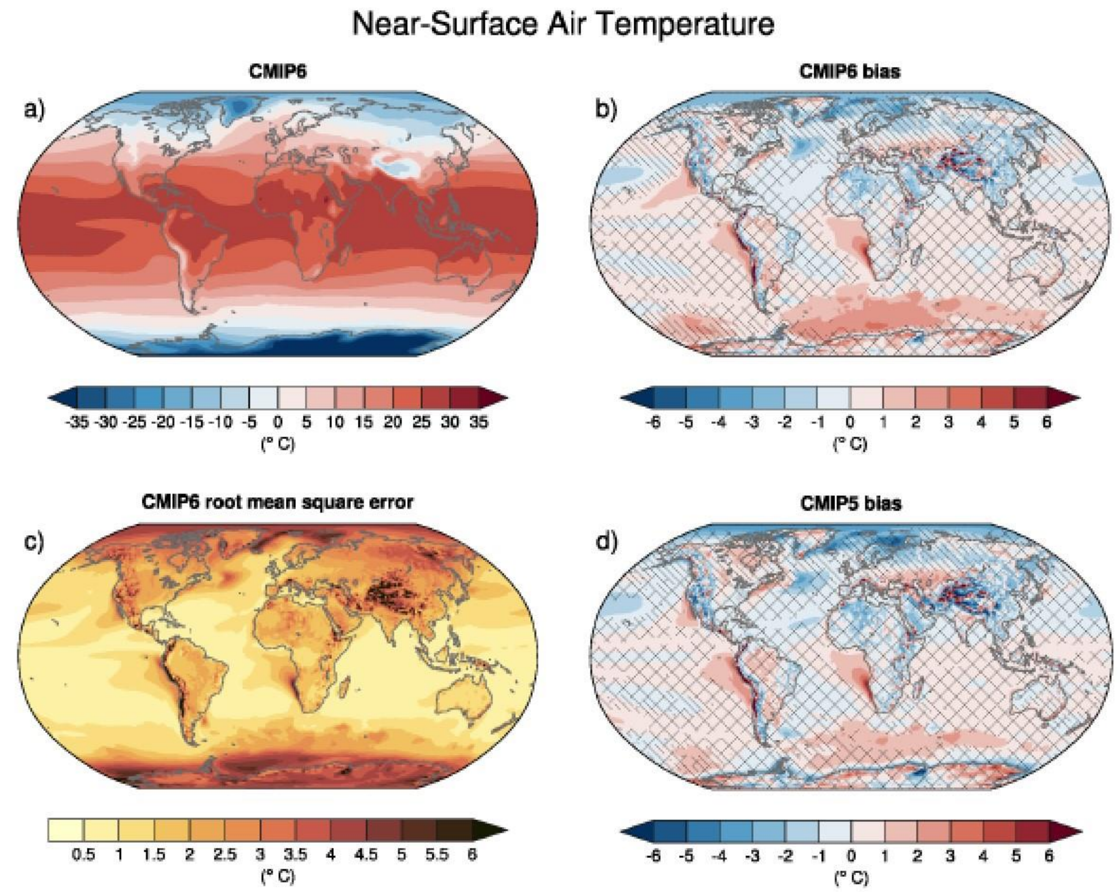
- **Climate models have the capability to simulate or reproduce modern climates.** Extensive comparisons and evaluations with atmospheric, oceanic, cryospheric, and land surface observations show that climate models have demonstrated significant and continuously improving skill in simulating many important mean climate features, as well as patterns and variability across different timescales.

- **Climate models have the capability to reproduce or replicate the characteristics of past climates (paleoclimate) and climate changes.** These models have been used to simulate ancient climates such as the mid-Holocene warm period (around 6,000 years ago) or the Last Glacial Maximum (around 21,000 years ago). They are able to simulate many features such as the ocean cooling values and their widespread distribution during the Last Glacial Maximum.

- **Climate models can also simulate many observational climate change characteristics after 1850,** such as global temperature changes over the past century and short-term (1-2 years) cooling effects causing by volcanic eruption (e.g., 1991 eruption of Mount Pinatubo).

Annual-mean surface (2 m) air temperature (℃) for the period 1995–2014.

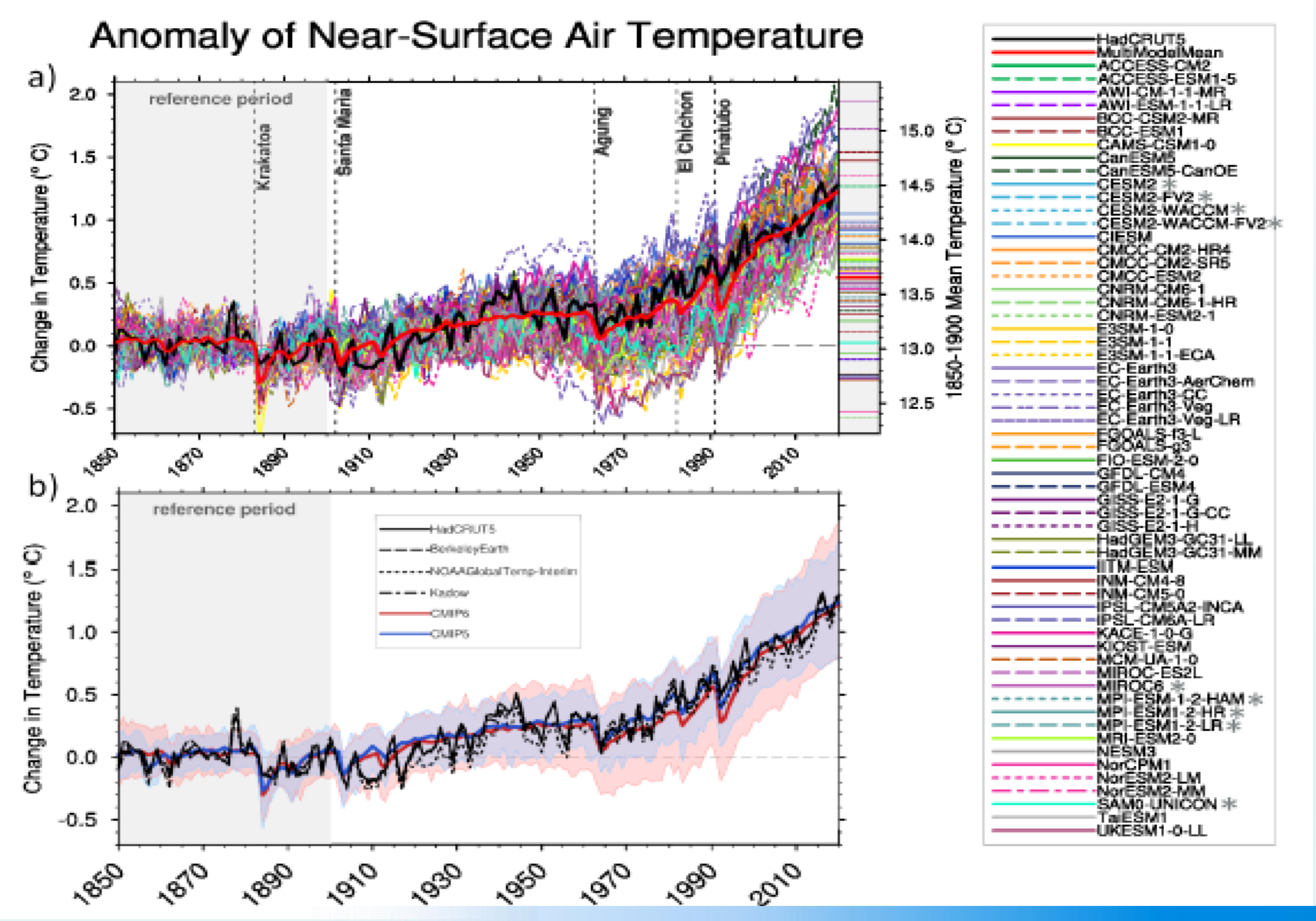
(a) Multi-model (ensemble) mean constructed with one realization of the CMIP6 historical experiment from each model. (b) Multi-model mean bias, defined as the difference between the CMIP6 multi-model mean and the climatology of the Fifth generation of ECMWF atmospheric reanalyses of the global climate (ERA5).



(c) Multi-model mean of the root mean square error calculated over all months separately and averaged with respect to the climatology from ERA5.

(d) Multi-model-mean bias as the difference between the CMIP6 multi-model mean and the climatology from ERA5.

Observed and simulated time series of anomalies in annual global mean near surface air temperature (GSAT)



Uncertainties in Climate System Models

The uncertainties in climate models arise from limitations in our scientific understanding of the physical, chemical, and biological processes within the climate system, as well as constraints related to spatial resolution and subgrid-scale process parameterization.

- ✓ Uncertainties in cloud physics parameterization;
- ✓ Uncertainty in the description of aerosol-cloud-radiation coupling processes;
- ✓ Uncertainties in describing the response and feedback processes of ecosystems to climate change;
- ✓ Uncertainties in the physical description of cryospheric processeses;
- ✓ …….

Contents

Climate System Models

Cryosphere Models

Composition of the Climate System

Cryosphere： Ice sheets、glaciers、snow cover、permafrost、sea ice、river/lake ice；

Plays a crucial role in the climate system through processes like albedo and the water cycle.

Five spheres

Atmosphere

Hydrosphere

Cryosphere

Biosphere

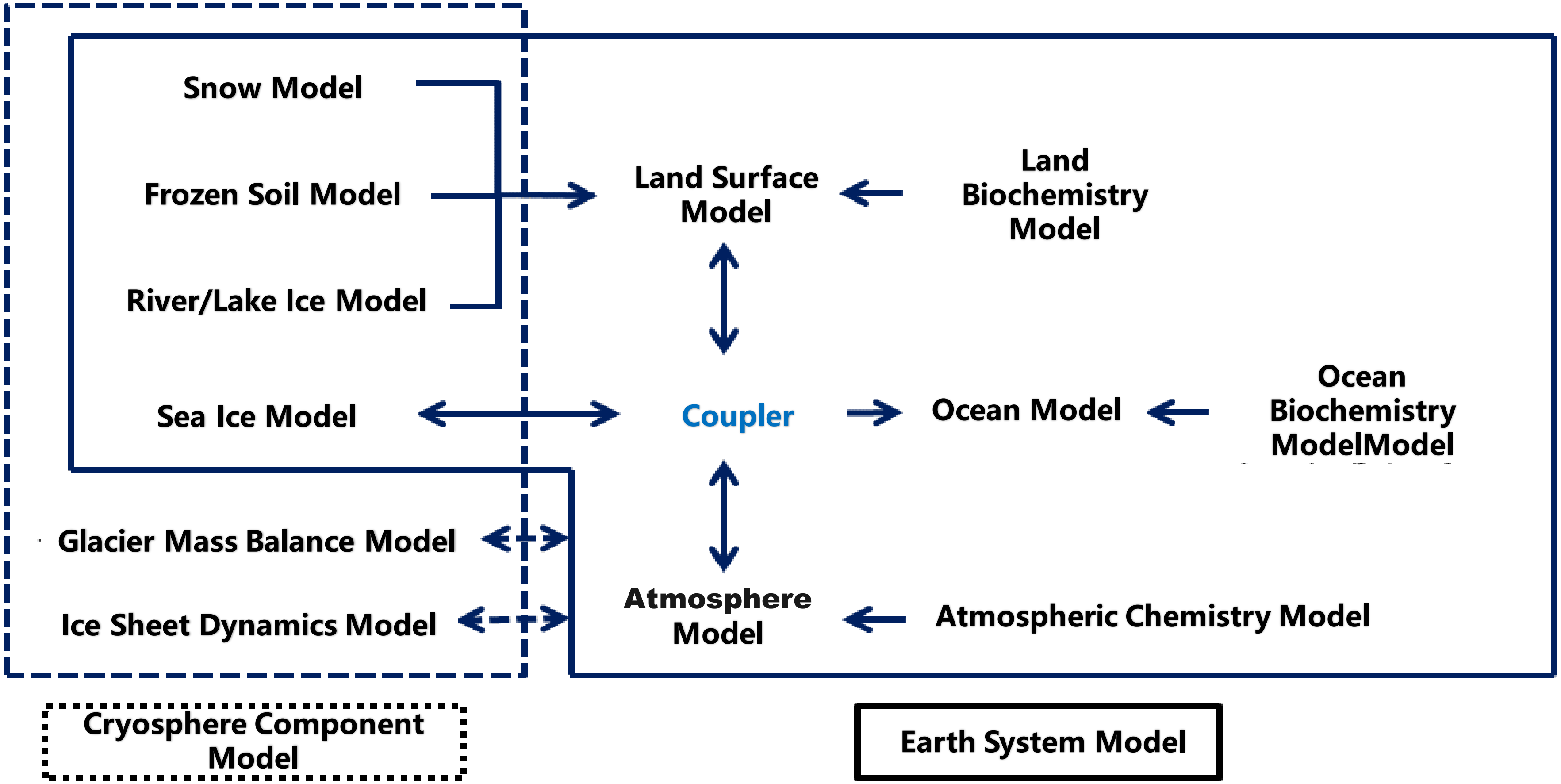
Lithosphere

Cryosphere Model

is a collective term for models of various cryospheric components, which are crucial parts of the climate system model. They play significant roles in studying cryospheric processes and the mechanisms of interaction between the cryosphere and other spheres. They are also the most important research methods and analytical tools for understanding past changes in the cryosphere and their causes, as well as for projecting future changes.

Cryosphere Model mainly includes mountain glacier models, ice sheet dynamics models, frozen soil models, snow models, sea ice models, and river/lake ice models.

In current Earth Climate System Models, the **sea ice models** have been implemented as an independent component model that is fully coupled with atmospheric models, ocean models, and terrestrial models. **Snow models**, **frozen soil models**, and **river/lake ice models** are generally integrated as important components within terrestrial models. **Glacier models** and **ice sheet models** have also developed and are achieving online coupling with Earth system models.



Snow Model

Frozen Soil Model

River/Lake Ice Model

Sea Ice Model

Glacier Mass Balance Model

Ice Sheet Dynamics Model

Land Surface Model

Land Biochemistry Model

Coupler

Ocean Model

Ocean Biochemistry ModelModel

Atmosphere Model

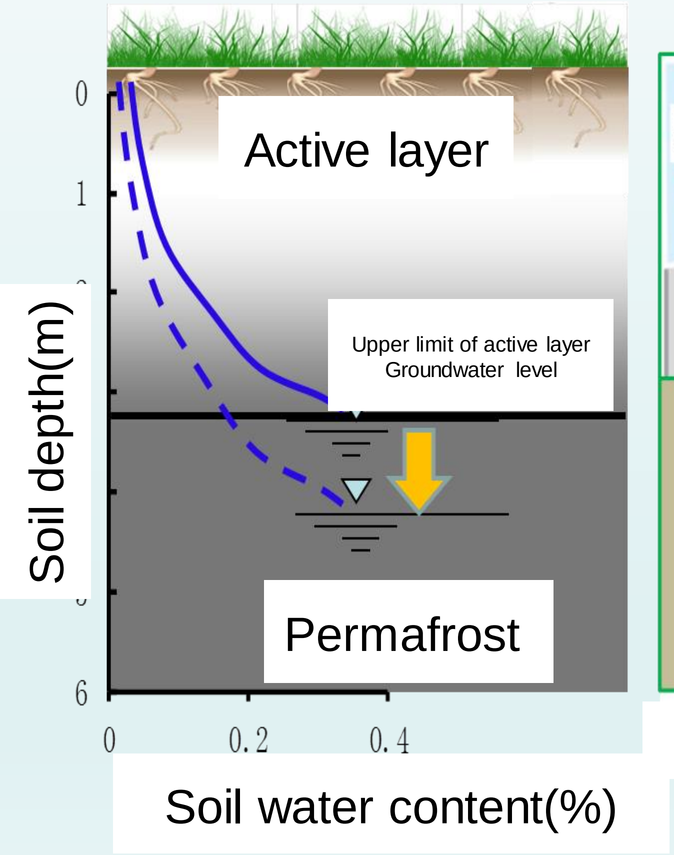
Atmospheric Chemistry Model

Cryosphere Component Model

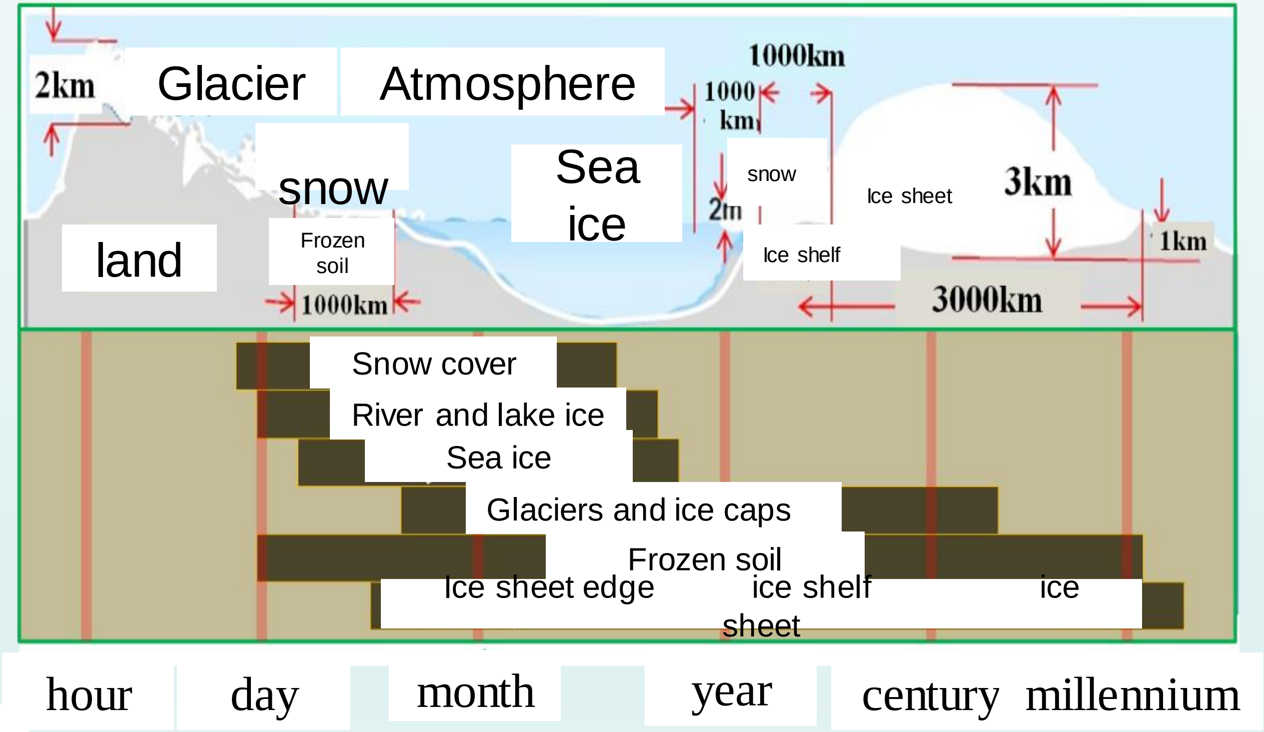
Earth System Model

Roles of Cryosphere Component Models in Earth System Models

Varying spatio-temporal scales and complex physical processes

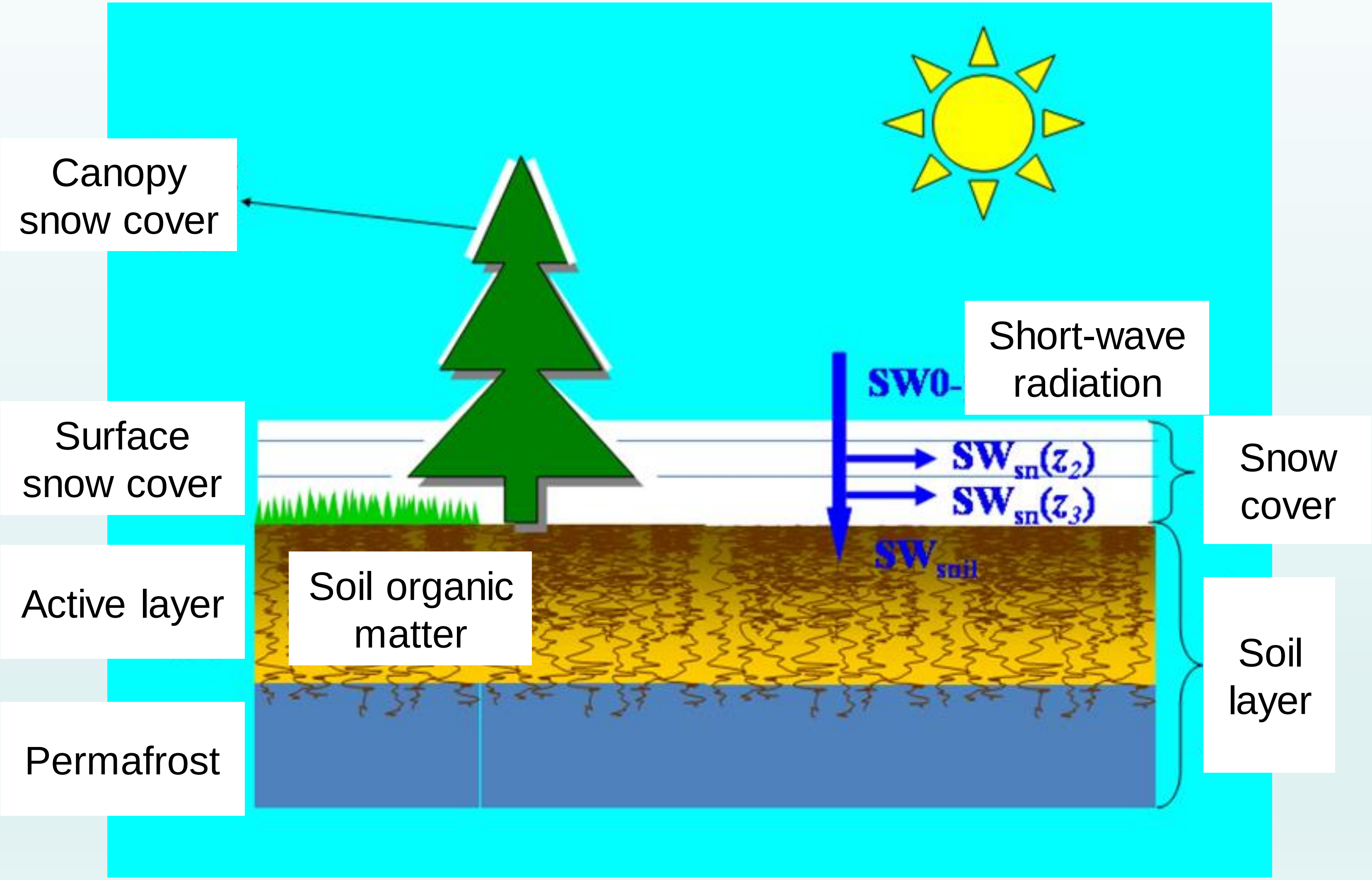


Spatial scale: a few meters – several thousand km



Time scale: Few hours - millennia

Snow Model



Canopy snow cover

Surface snow cover

Active layer

Soil organic matter

Permafrost

Short-wave radiation

Snow cover

Soil layer

Common Features of Cryospheric Models

Energy Balance of Land Snow Surface

Utilizing the principle of energy balance, observations and calculations of energy fluxes at the snow surface determine the heat required for snowmelt, thereby simulating snowmelt amounts. The energy balance model establishes the connection between snow and the atmosphere, describing the physical processes involved in snowmelt. The corresponding equation is as follows:

$$Q_M = R_n + H + LE + Q_G + Q_P$$

Q_M: Heat for snowmelt. Snow begins to melt when the surface temperature reaches 0℃. R_n: Net radiation at the snow surface. H and LE: Sensible and latent heat fluxes between the snow surface and the atmosphere. Q_G: Ground heat flux at the snow surface. Q_P: Heat released by precipitation. Typically, Q_G and Q_P are small and can be neglected.

Internal Heat Conduction in Ice and Snow

In a type of snow model, specific enthalpy (H) is used instead of temperature (T) as the prognostic variable. The energy equation is established by defining the specific enthalpy of liquid water at the melting point as zero. The governing equation is:

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial z}\left\{K\frac{\partial T}{\partial z} - R_s(z)\right\}$$

Where: K（$\mathrm{Wm^{-1}\ K^{-1}}$）is the effective thermal conductivity, accounting for thermal effect from vapor phase change and diffusion. Since snow is transparent to solar radiation, the internal solar radiation flux R_s（$\mathrm{Wm^{-2}}$）in snow follows Beer's law:

$$R_s(z) = R_s(0) \times (1-\alpha) \times exp(-\lambda z)$$

Where: α is the snow surface albedo and λ (1/m) is the extinction coefficient.

The relationship between specific enthalpy and temperature is

$$H = C_V \times (T - 273.16) - f_i \times L_{li} \times W \times \rho_l$$

Where: L_{li}(J/kg) is the latent heat of fusion for ice melting to water. ρ_l(kg/m^3) is the density of water (1000 kg/m^3). W is the snow water equivalent by volume. f_i is the mass fraction of dry ice in the total snow mass, ranging from 0 (melted state) to 1 (dry snow). C_v(Jm^{-3}K^{-1}) is the mean volumetric heat capacity, calculated from the mass fractions and specific heat of each phase.

This approach ensures that temperature variations within the snow, driven by liquid water transport at the melting point, do not induce additional energy flows. This simplifies the equations, streamlines programming, and reduces computational time.

Thermal Balance Equation at the Snow/Ice Base

- ✓ **The heat flux at the base of snow and ice is a critical component in numerical forecasting. Due to observational challenges and uncertainties in factors affecting the ice base, there is limited observational data.**

- ✓ **In snow/ice numerical models, this heat flux is typically handled in two ways: (1) assuming a constant value, or (2) using empirical formulas. Commonly used empirical methods include the eddy method, volume block method, and residual energy method.**

- ✓ **However, these empirical formulas heavily rely on observed temperature (ice base temperature and water temperature), and require region-specific empirical parameters. The lack of temperature observations and uncertainty in parameter values often make it difficult to accurately calculate the heat flux.**

Cryosphere Models and Simulations

Part Ⅱ

Yong Luo

Department of Earth System Science,
Tsinghua University

Contents

- **Attribution of Climate Change**
- **Emission Scenarios**
- **Climate Change Projections**
- **Cryosphere Change Projections**

Detection and Attribution

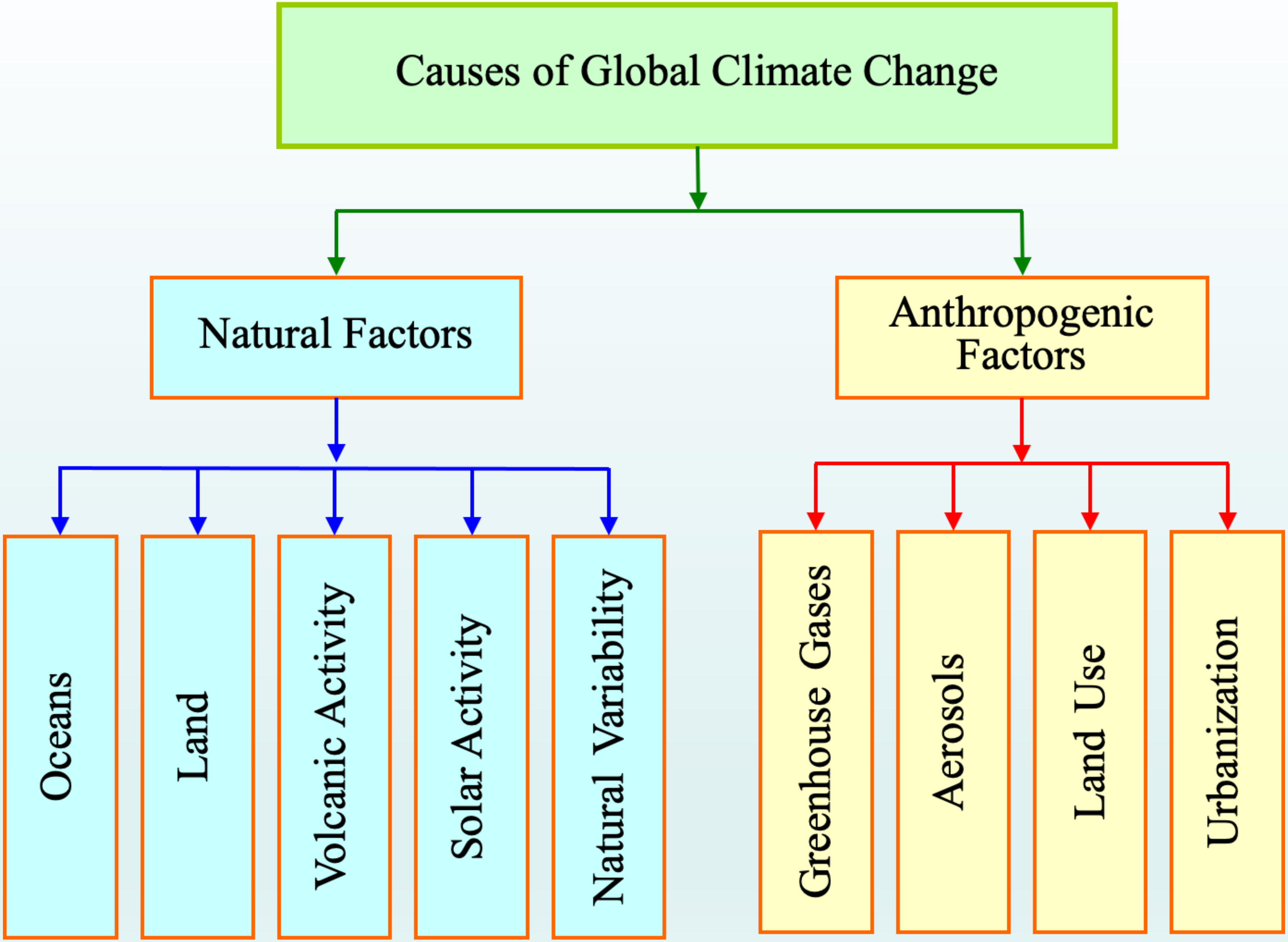
Detection：

The process of identifying whether a statistically significant change has occurred in the climate or a climate-affected system, without explaining the causes of the change.

Attribution：

The process of assessing the relative contributions of various factors to the observed change.

(IPCC WGI AR5, 2013; WGII AR5, 2014a)



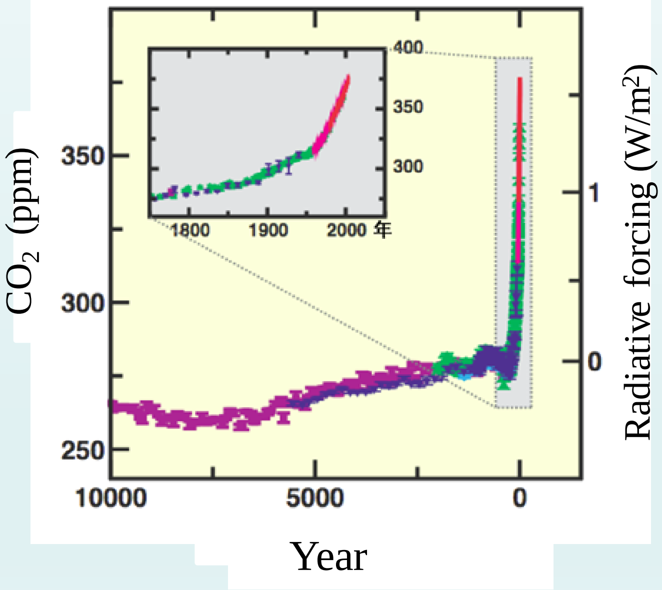
Causes of Global Climate Change

- Natural Factors
  - Oceans
  - Land
  - Volcanic Activity
  - Solar Activity
  - Natural Variability
- Anthropogenic Factors
  - Greenhouse Gases
  - Aerosols
  - Land Use
  - Urbanization

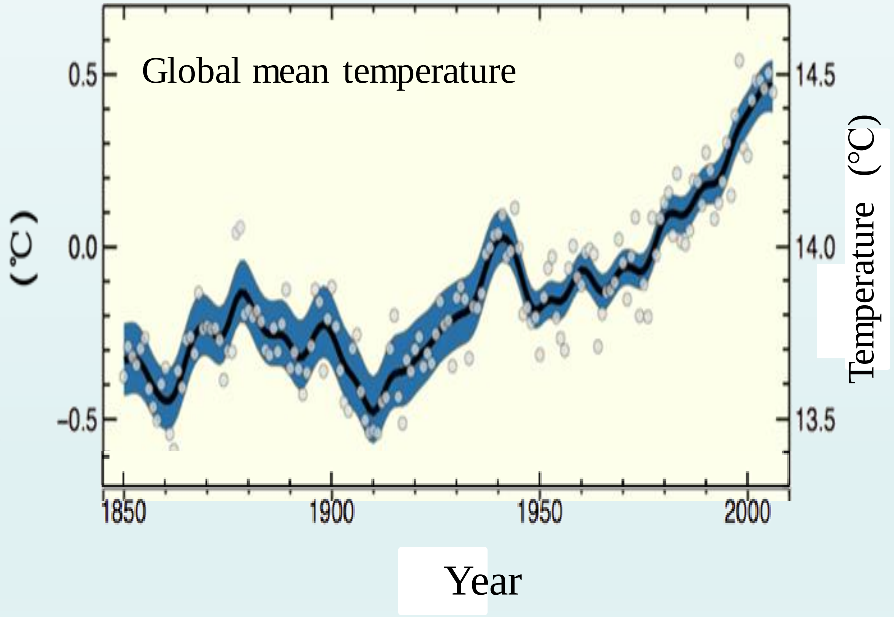
Global GHGs Concentration
VS
Surface Temperature

CO_2 approximately 410.5 ppm in 2019

From 1880 to 2019 global mean surface temperature has increased by 1.1℃



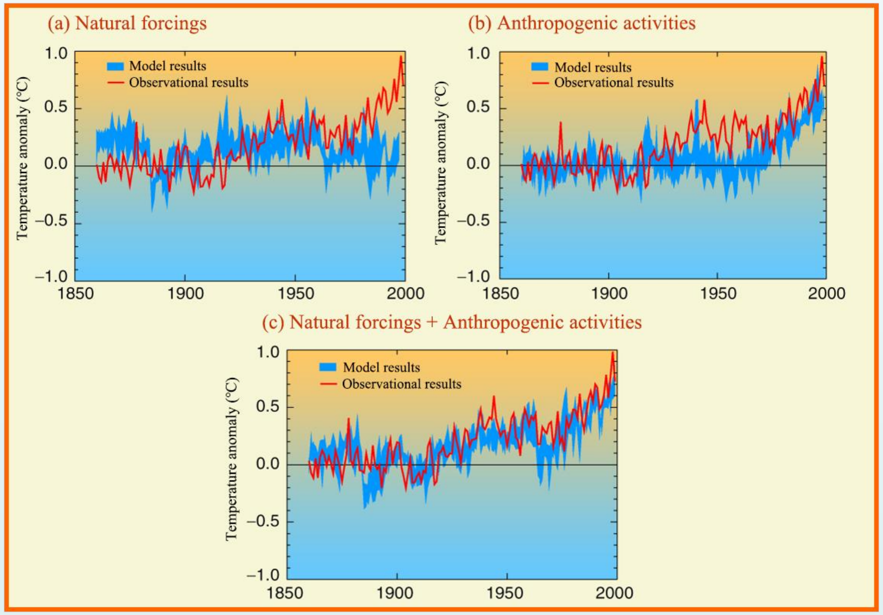
Enhanced Greenhouse Effect



Statistical relationship VS Cause-effect relationship?

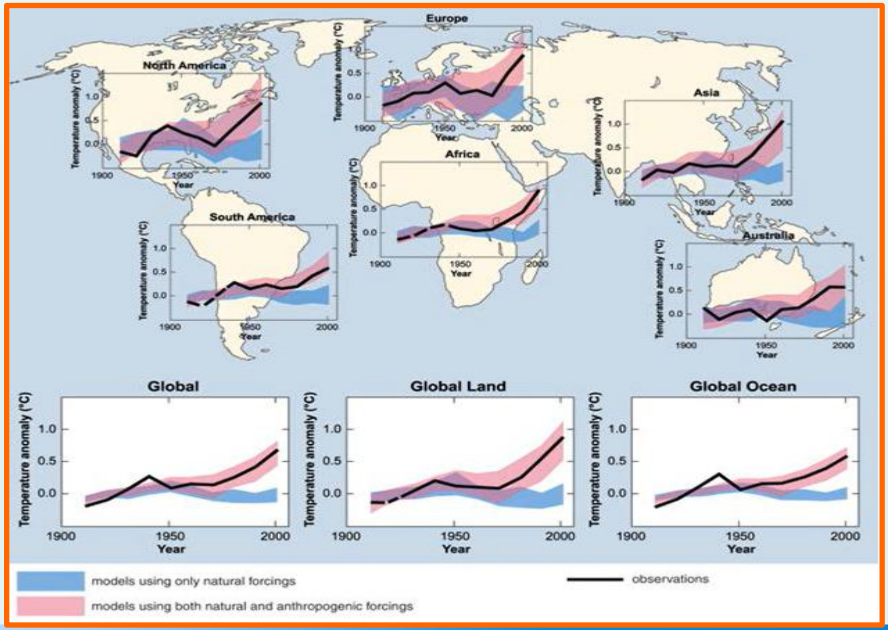
Human activities are very likely the main cause of climate change since the mid-20th century

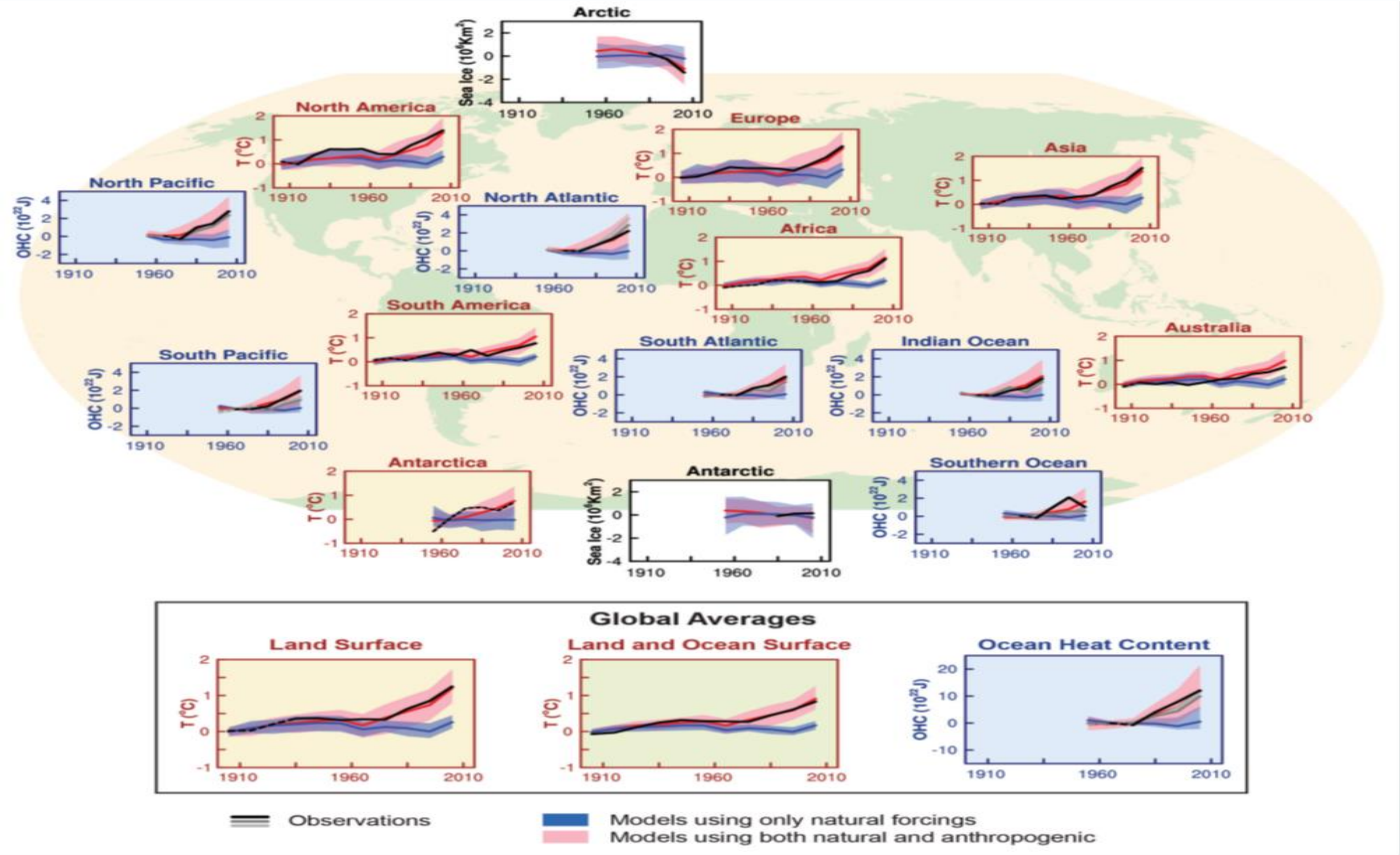
The observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed rise in anthropogenic greenhouse gas concentrations.



IPCC Third Assessment Report（2001）

IPCC Fourth Assessment Report（2007）





Comparison of observed and simulated climate changes based on three large-scale indicators from the atmosphere, cryosphere, and oceans: these indicators include land surface temperature (yellow shaded background), Arctic and Antarctic sea ice (white shaded background), and ocean heat absorption in major marine regions (blue shaded background). Global average changes are also provided. All time series are decade-averaged, with markers indicating the central year of each decade. In the temperature plots, observed values are shown with dashed lines if the spatial coverage of the detection area is less than 50%. In the ocean heat and sea ice plots, solid lines indicate better data coverage and higher quality, while dashed lines indicate data coverage that is sufficient but with higher uncertainty. Model results are presented as the multi-model mean and ensemble range from CMIP5, with shaded areas representing the 5-95% confidence intervals.[13]

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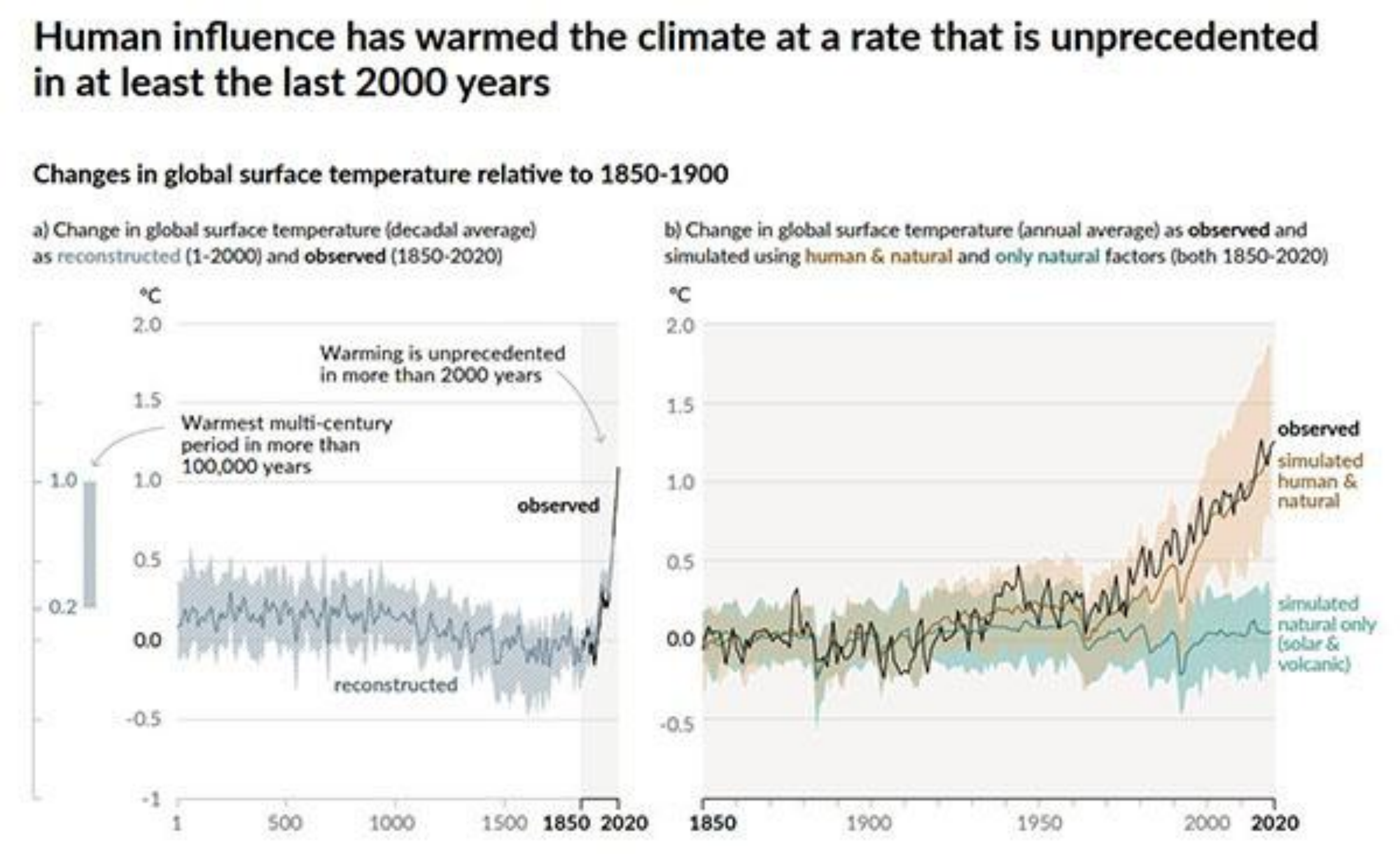
[13] For surface temperature, the blue shaded area represents simulations from 52 runs of 17 climate models using only natural forcing, while the red shaded area represents simulations from 147 runs of 44 climate models using both natural and anthropogenic forcings. In the ocean heat plots, simulations from 10 models with 10 runs and 13 models with 13 runs are used. For sea ice extent, subsets of models are considered that simulate the mean and seasonal cycle of sea ice extent within 20% of the observed 1981-2005 sea ice climatology (Arctic: red and blue shaded areas represent 24 runs from 11 models, Antarctic: red and blue shaded areas represent 21 runs from 6 models).

It is unequivocal that human influence has induced the widespread and rapid climate warming



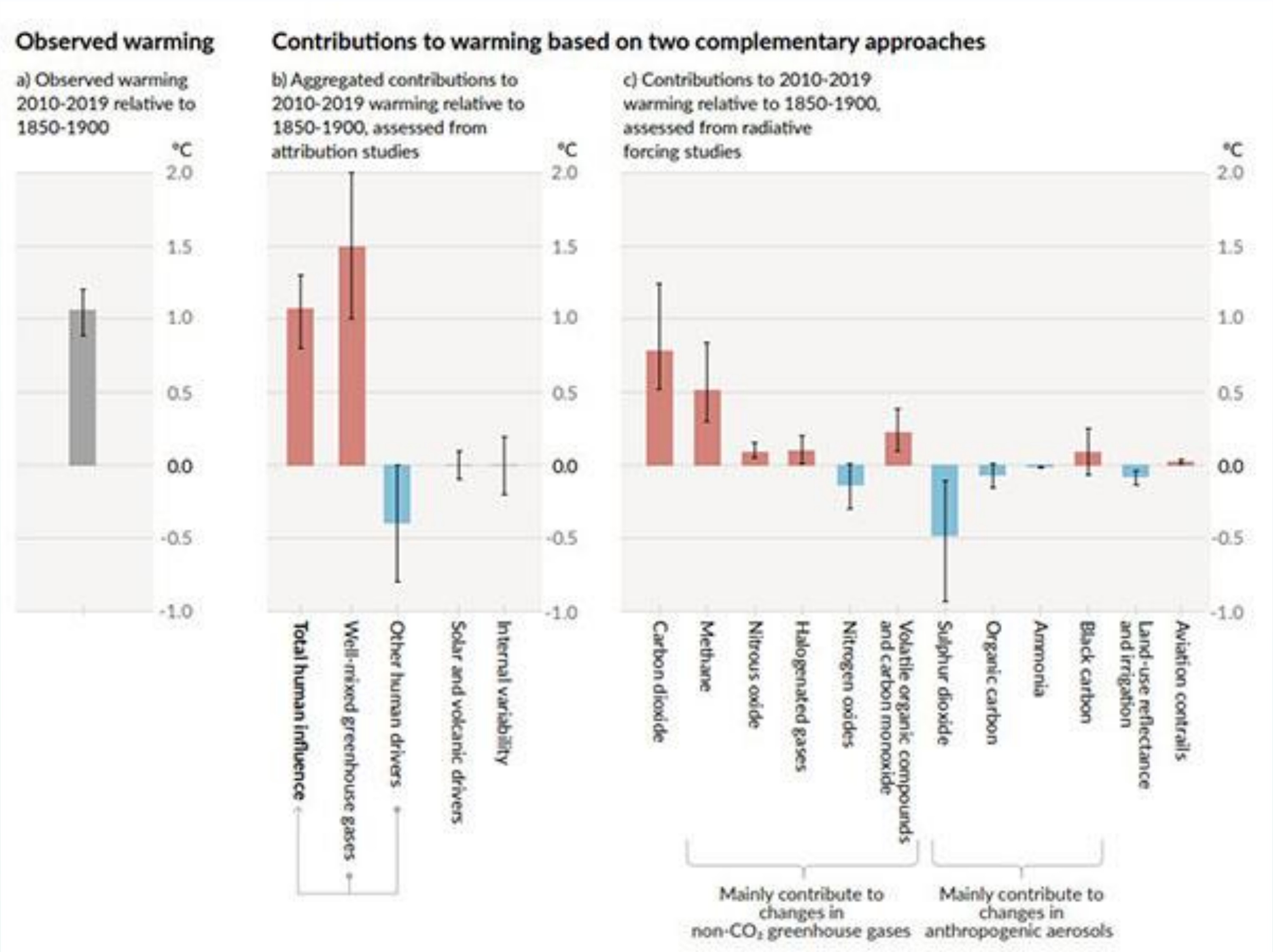
Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850-1900

a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and observed (1850-2020)

b) Change in global surface temperature (annual average) as observed and simulated using human & natural and only natural factors (both 1850-2020)

Compared with the average temperature before the industrial revolution (1850-1900), the average temperature of the earth has increased by 1.1℃, and the climate warming caused by human activities in the past 2000 years is unprecedented. The temperature change caused by the simulated natural variability (including solar activity and volcanic activity) is relatively stable and will not exceed 0.3℃, while the simulated human activity+natural variability is in good agreement with the observed average temperature change. This shows that the current global warming is mainly due to the emission of greenhouse gases caused by human activities: burning fossil fuels and land use.



All kinds of mixed greenhouse gases will increase in temperature by 1.5℃, while aerosol gases will decrease in temperature by 0.4℃. The overall effect of solar activity and volcanic activity is not obvious. Greenhouse gases are mainly carbon dioxide, methane and nitrogen oxides, among which carbon dioxide will increase by 0.8℃, methane will increase by 0.5℃, and other gases will have limited temperature increase. Aerosol as a whole will reduce the warming effect of greenhouse gases, among which sulfide has a cooling effect of 0.5℃, which almost offsets the warming effect of methane, while black carbon has a weak warming effect.

- ✓ **Human influence is very likely the main driver of the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (about 40% in September and about 10% in March).**

- ✓ **Human influence very likely contributed to the decrease in Northern Hemisphere spring snow cover since 1950. It is very likely that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only limited evidence, with medium agreement, of human influence on the Antarctic Ice Sheet mass loss.**

IPCCAR6 WGI， 2021

IPCC's conclusions about human contributions have strengthen over time!

FAR: Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface.

SAR: The observed warming trend is unlikely to be entirely natural in origin. There is a discernible human influence on global climate.

TAR: Most of observed warming over last 50 years likely (>66% chance) due to increases in greenhouse gas concentrations due to human activities.

AR4: Most of the global average warming over the past 50 years is very likely (>90% chance) due to anthropogenic GHG increases.

AR5: It is extremely likely (>95% chance) that more than half of the observed increase in global average surface temperature from 1951-2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together.

AR6: It is unequivocal that human influence has warmed atmosphere, ocean and land.

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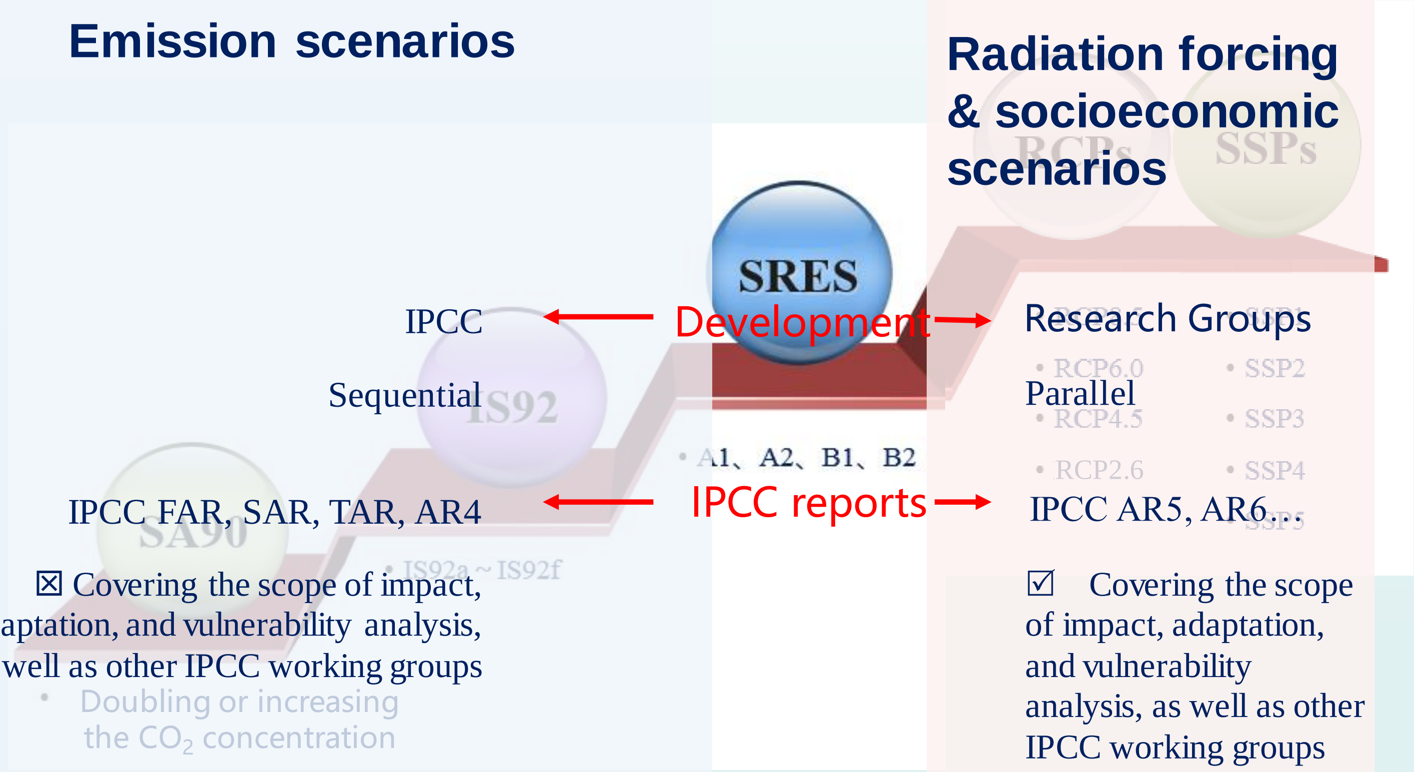
A climate projection is the simulated **response** of the climate system to a **scenario** of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using **climate models**. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized.

IPCC WGI AR5, 2013

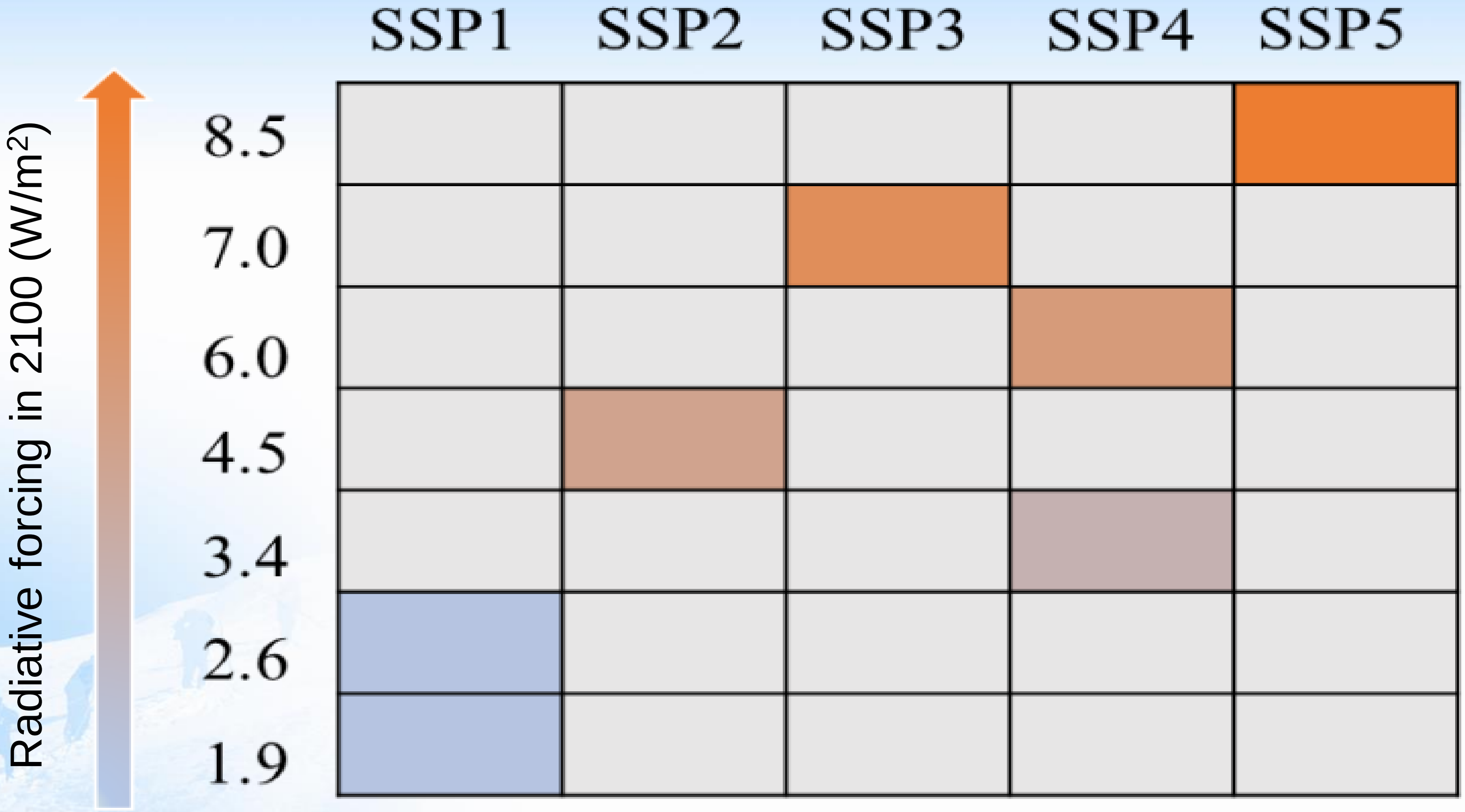
Development and Role of scenarios



Emission scenarios		**Radiation forcing & socioeconomic scenarios**
IPCC	← Development →	Research Groups
Sequential		Parallel
IPCC FAR, SAR, TAR, AR4	← IPCC reports →	IPCC AR5, AR6…
☒ Covering the scope of impact, adaptation, and vulnerability analysis, as well as other IPCC working groups		☑ Covering the scope of impact, adaptation, and vulnerability analysis, as well as other IPCC working groups

RCPs (Representative Concentration Pathways)

SSPs (Shared Socioeconomic Pathways)



Radiative forcing in 2100 (W/m^2)	SSP1	SSP2	SSP3	SSP4	SSP5
8.5					🟧
7.0			🟧		
6.0				🟧	
4.5		🟧			
3.4				🟪	
2.6	🟦				
1.9	🟦				

Shared Socio-economic Pathways

- Assessing the Relationship Between Different Socioeconomic Development Pathways and Climate Change Risks

- Facilitating Effective Dialogue with Decision-makers

➢ SSP1: Sustainability

SSP1 represents a world characterized by sustainable development and low climate change challenges. It features reduced resource intensity and fossil fuel dependence, rapid development in low-income countries, global and intra-economic equilibrium, technological advancement, and a strong emphasis on preventing environmental degradation. Notably, the rapid economic growth in low-income countries significantly reduces the population living below the poverty line.

➢ SSP2: Middle of the Road (Business As Usual, BAU)

SSP2 is the intermediate pathway, facing moderate climate change challenges. Its primary characteristics include: global development continuing along recent historical trends, moderate progress towards achieving development goals, some reduction in resource and energy intensity, and a gradual decrease in fossil fuel dependence.

➢ SSP3: Regional Rivalry

SSP3 depicts fragmented or inconsistent development, confronting high climate change challenges. It maps onto the A2 scenario, with key features including: a world divided into extremely poor countries, moderately wealthy nations, and affluent countries striving to maintain living standards for growing populations. There is a lack of coordination between these groups, resulting in pronounced regional differentiation.

➢ SSP4: Inequality

SSP4 describes an uneven development path, primarily focused on adaptation challenges. It envisions a world with high inequality both internationally and domestically.

➢ SSP5: Fossil-fueled Development

SSP5 is a conventional development scenario, primarily addressing mitigation challenges. This pathway emphasizes traditional economic growth-oriented approaches, resolving social and economic issues through the pursuit of self-interest.

Elmar Kriegler: SSP Narratives

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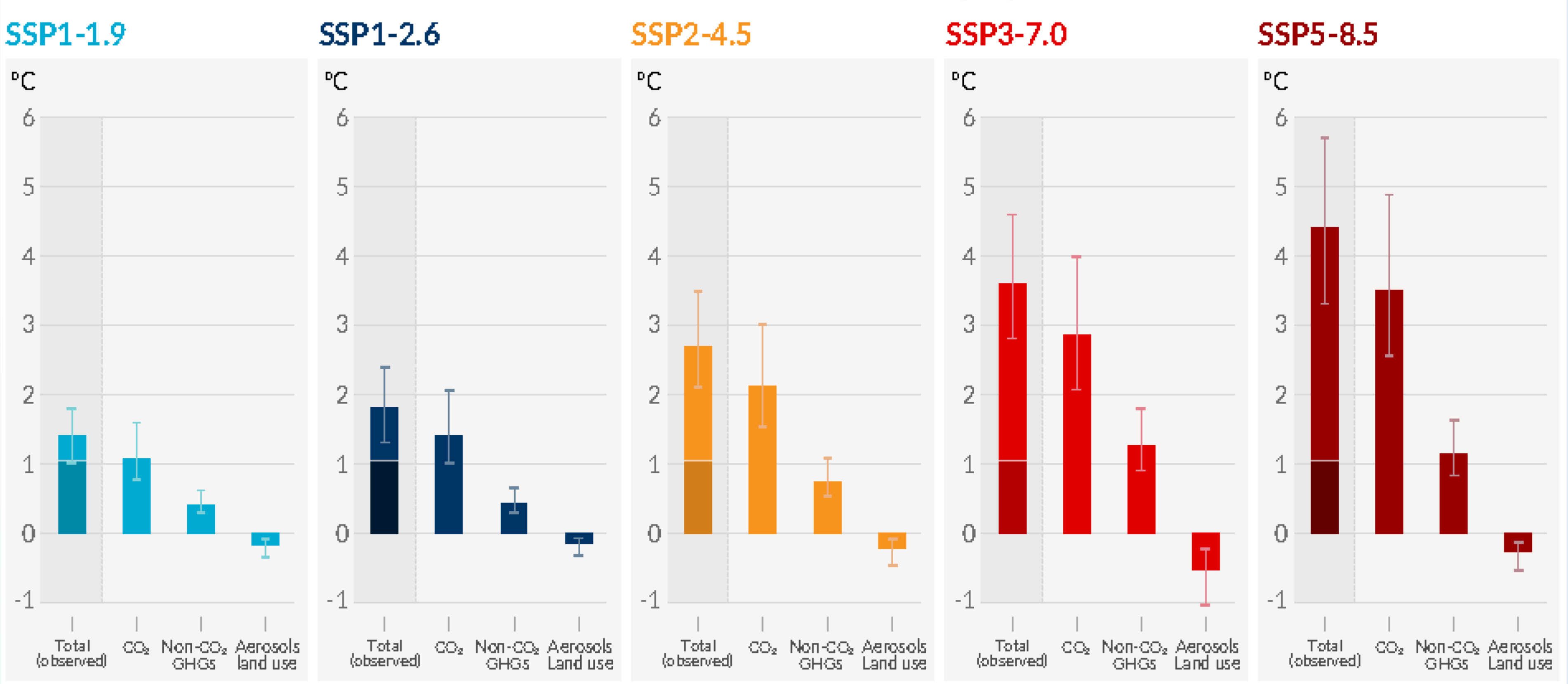
IPCC WGI AR5, 2013

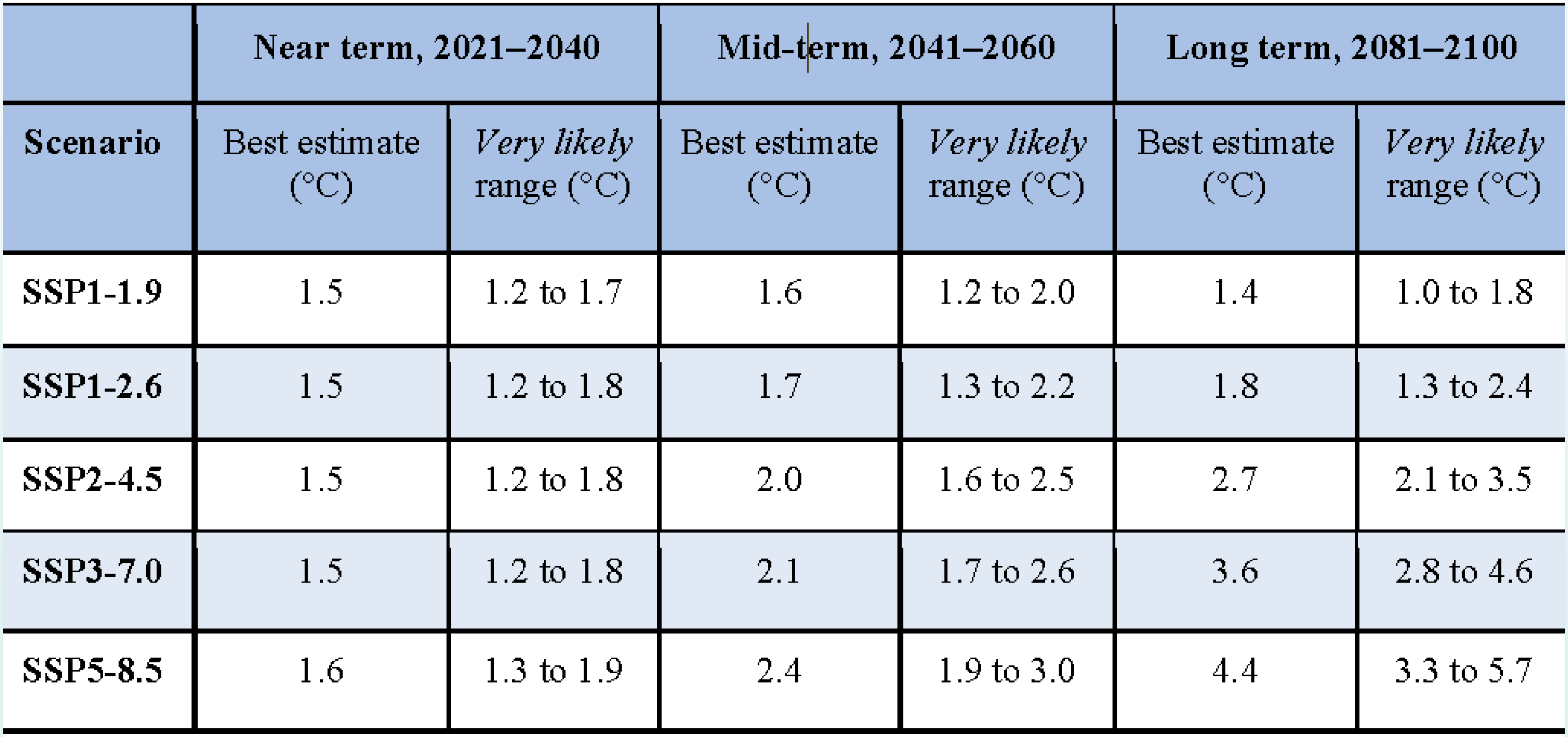
Different emissions contribute to the global surface temperature rise, and CO_2 emissions are dominant. Change of global surface temperature in 2081-2100 relative to 1850-1900 (℃)



Total warming (observed warming to date in darker shade), warming from CO_2, warming from non-CO_2 GHGs and cooling from changes in aerosols and land use

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*

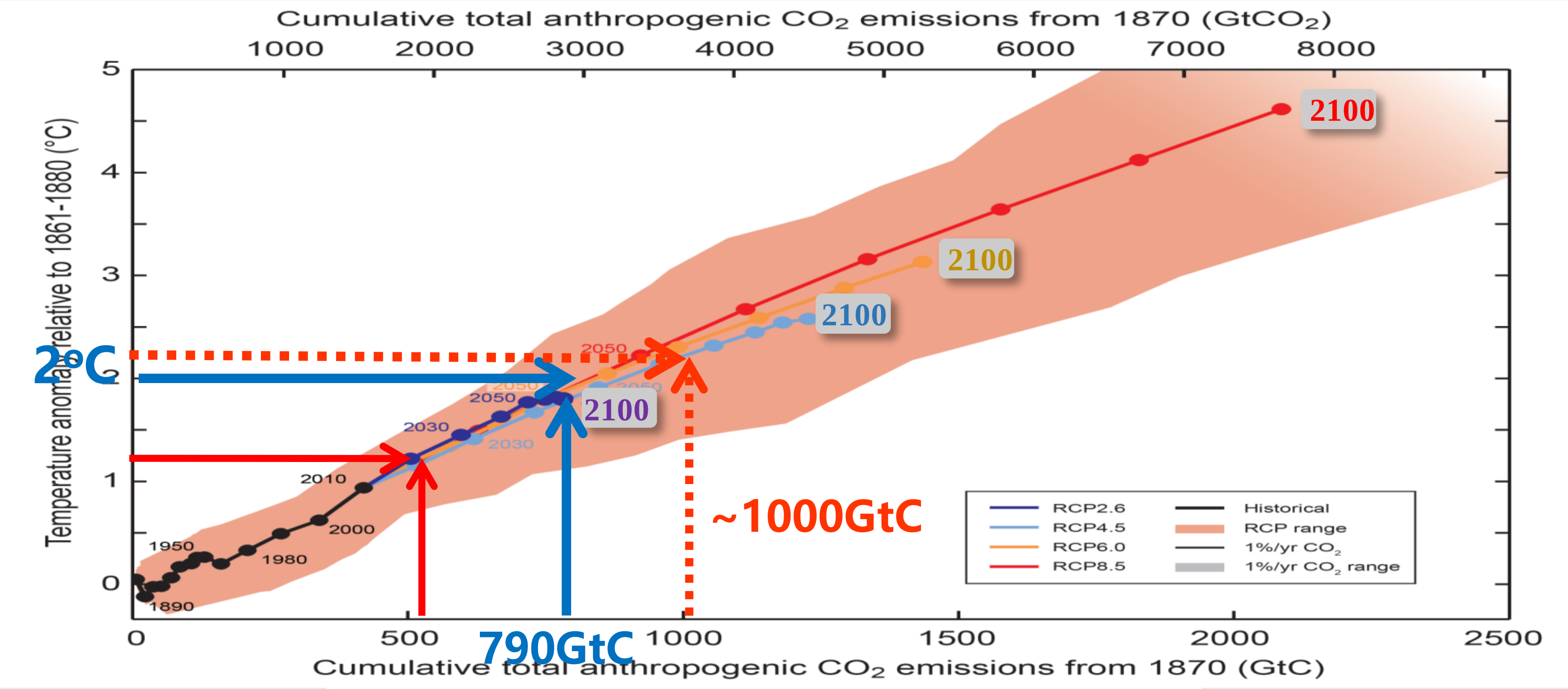
Global surface temperature change based on multi-evidence evaluation. Estimated change of global average surface temperature from 1850 to 1900 (℃)



	Near term, 2021–2040		**Mid-term, 2041–2060**		**Long term, 2081–2100**	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*

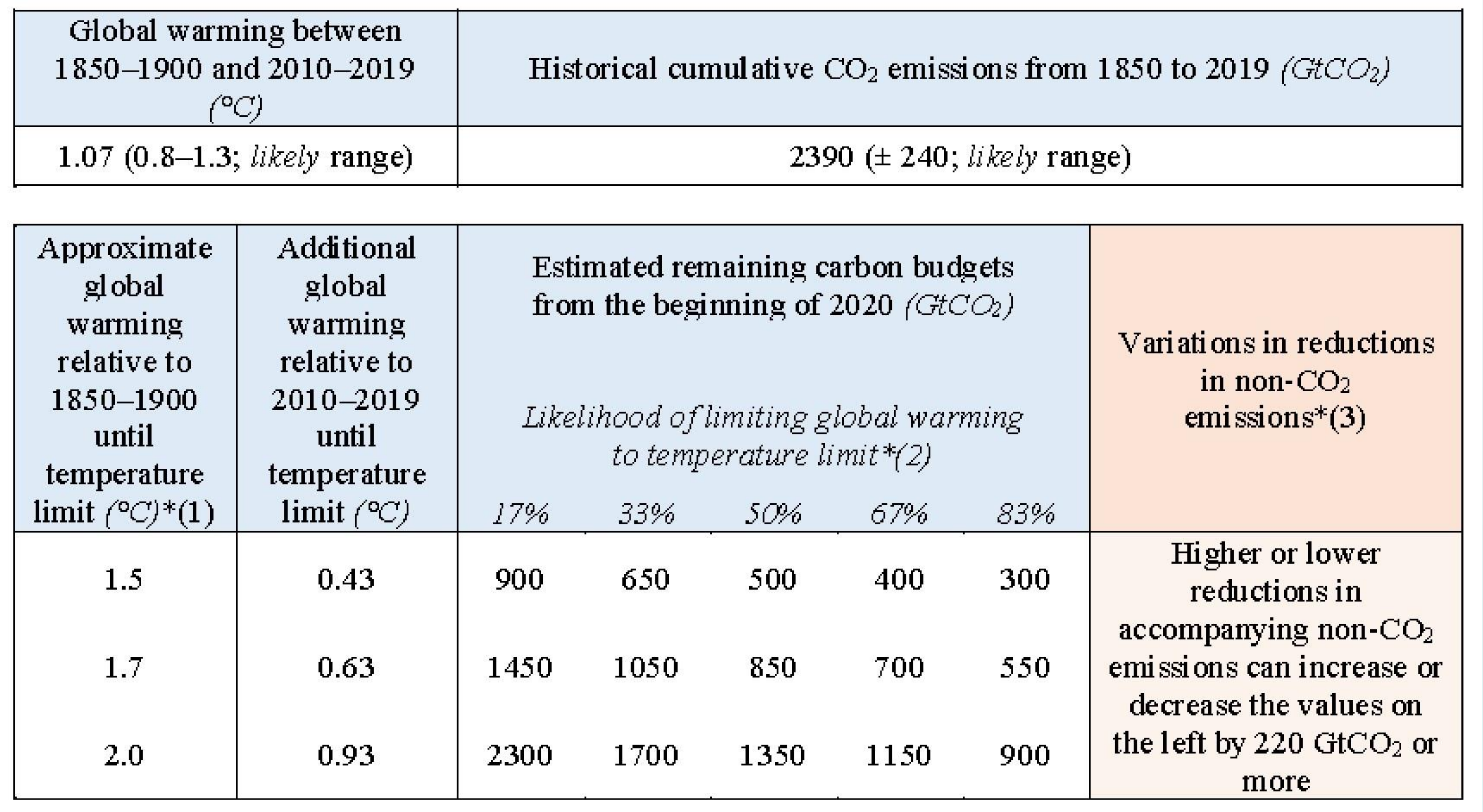
Relationship Between Temperature Rise and CO_2 Emissions



Cumulative anthropogenic CO2 emissions have already reached approximately 555 GtC. Under the moderate emission pathway <u>RCP4.5</u> scenario, global cumulative emissions are projected to reach 1000 GtC by 2050. This implies that from the present day until 2050, there remains only about 450 GtC of permissible emissions.

IPCC 2013, AR5,WG3

Estimates of historical CO$_2$ emissions and remaining carbon budgets



Global warming between 1850–1900 and 2010–2019 *(°C)*	Historical cumulative CO$_2$ emissions from 1850 to 2019 *(GtCO$_2$)*
1.07 (0.8–1.3; *likely* range)	2390 (± 240; *likely* range)

Approximate global warming relative to 1850–1900 until temperature limit (°C)*(1)	Additional global warming relative to 2010–2019 until temperature limit *(°C)*	Estimated remaining carbon budgets from the beginning of 2020 *(GtCO$_2$)*					Variations in reductions in non-CO$_2$ emissions*(3)
		Likelihood of limiting global warming to temperature limit*(2)					
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO$_2$ emissions can increase or decrease the values on the left by 220 GtCO$_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

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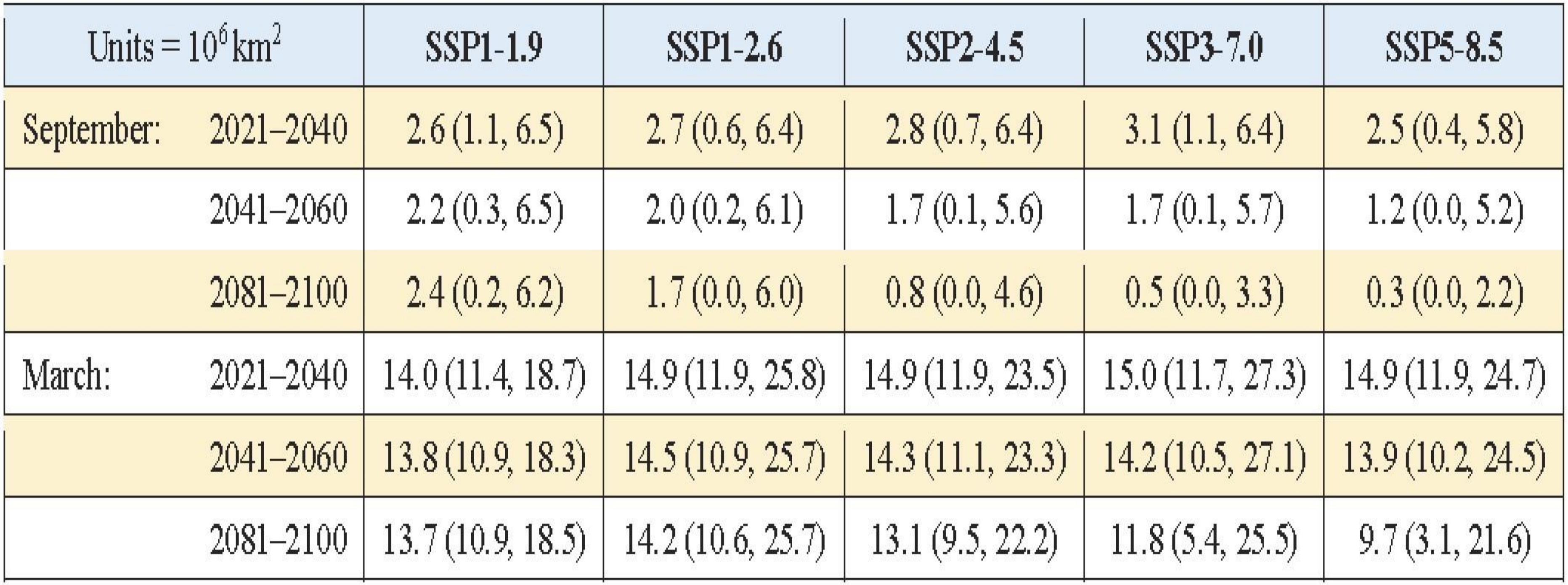
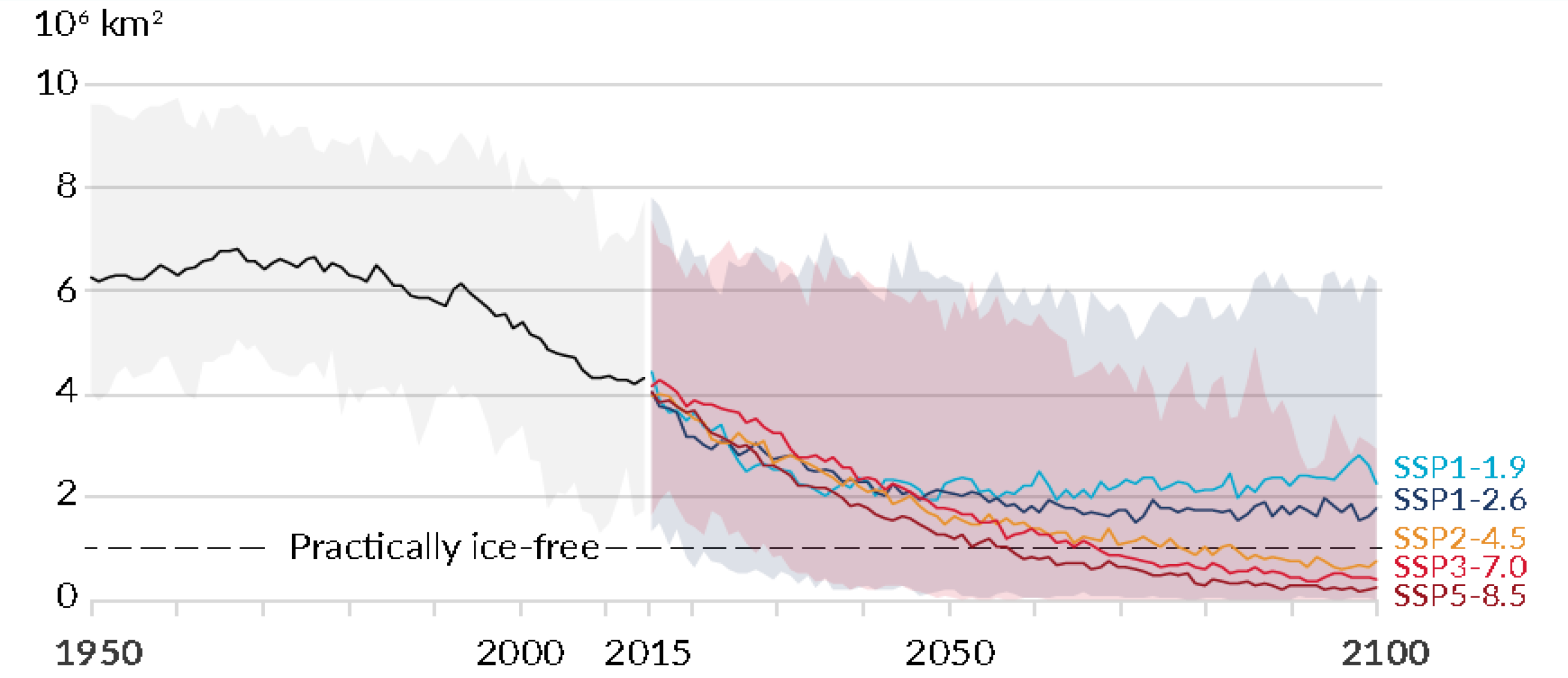
CMIP6 Arctic sea-ice area for selected months, time periods, and across five SSPs. Displayed are the multi-model averages across the individual models and, in parentheses, the 5–95% ranges.



Units = 10^6 km^2		SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
September:	2021–2040	2.6 (1.1, 6.5)	2.7 (0.6, 6.4)	2.8 (0.7, 6.4)	3.1 (1.1, 6.4)	2.5 (0.4, 5.8)
	2041–2060	2.2 (0.3, 6.5)	2.0 (0.2, 6.1)	1.7 (0.1, 5.6)	1.7 (0.1, 5.7)	1.2 (0.0, 5.2)
	2081–2100	2.4 (0.2, 6.2)	1.7 (0.0, 6.0)	0.8 (0.0, 4.6)	0.5 (0.0, 3.3)	0.3 (0.0, 2.2)
March:	2021–2040	14.0 (11.4, 18.7)	14.9 (11.9, 25.8)	14.9 (11.9, 23.5)	15.0 (11.7, 27.3)	14.9 (11.9, 24.7)
	2041–2060	13.8 (10.9, 18.3)	14.5 (10.9, 25.7)	14.3 (11.1, 23.3)	14.2 (10.5, 27.1)	13.9 (10.2, 24.5)
	2081–2100	13.7 (10.9, 18.5)	14.2 (10.6, 25.7)	13.1 (9.5, 22.2)	11.8 (5.4, 25.5)	9.7 (3.1, 21.6)

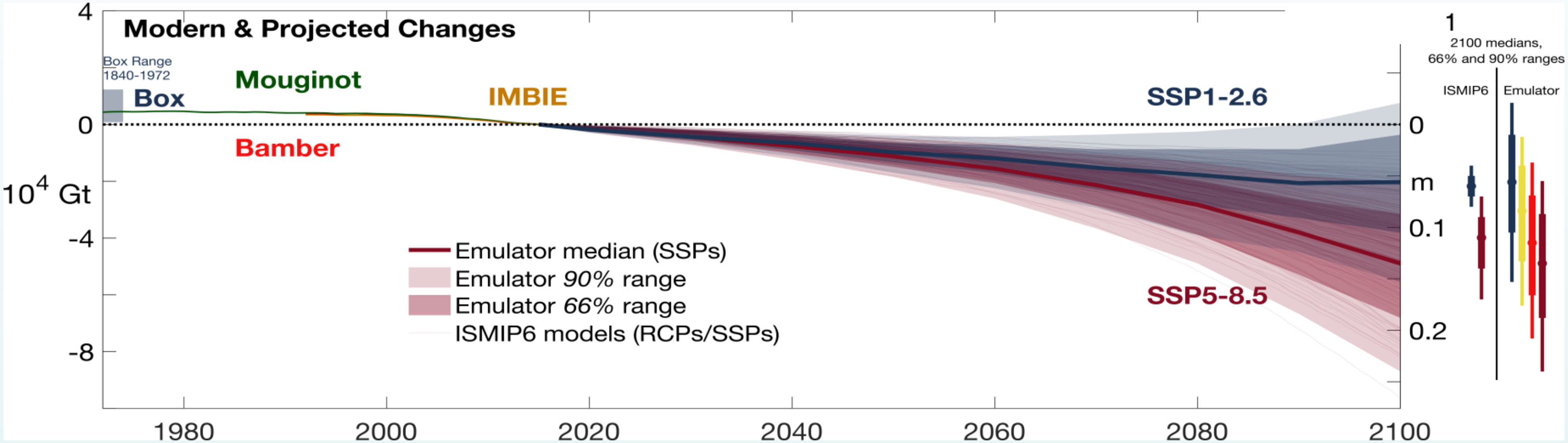
IPCC AR6 WGI, 2021

September Arctic sea ice area in 10^6 km^2 based on CMIP6 model simulations. Very likely ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under mid and high GHG emissions scenarios.



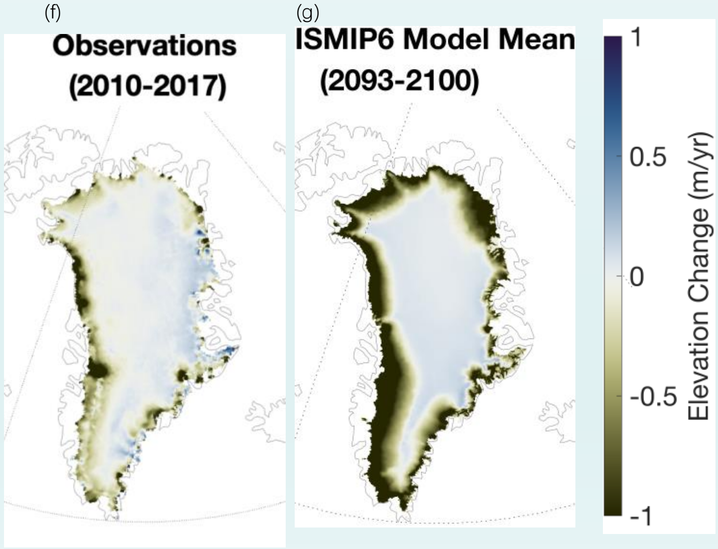
IPCC AR6 WGI, 2021

Greenland Ice Sheet Cumulative Mass Change & Equivalent Sea Level Contribution



(top) Cumulative mass loss (sea level equivalent) from the Greenland ice sheet since 1840, with satellite observations shown from 1972 and 1993, and projections from ISMIP6 by 2100 under RCP8.5/SSP5-8.5 and RCP2.6/SSP1-2.6 scenarios and likely range of the ISMIP6 emulation.

(right) Maps of mean elevation changes 2010-2017 derived from CryoSat 2 radar altimetry (Bamber et al., 2018b) and ISMIP6 model mean (2061-2100) projected changes (Goelzer et al., submitted)



(IPCC AR6, 2021)

Uncertainty in projecting cryospheric change

- Lack of Observational Data:
- Climate and Earth system models for cryospheric projections require comprehensive spatial and temporal observational data for calibration and evaluation. However, before the development of satellite observation technologies in the 1970s, systematic observational data for many cryospheric components were severely lacking. Even today, due to the remote and high-latitude locations of cryospheric regions, observational gaps remain significant for key variables such as ice thickness, coverage, accuracy, and precision. This makes it challenging to quantify global and regional trends and short-term variability in key cryospheric indicators..
- Insufficient understanding Cryospheric Processes and Mechanisms:
- This includes limited knowledge of processes such as glacier and ice sheet melt and the role of these processes in the broader climate system.

- **Enhancement Needed in Modeling Capabilities:** The simulation performance of climate and Earth system models still requires further improvement, especially in cryospheric component models. Current models lack completeness in representing all climate system elements, making it difficult to analyze key processes responsible for the rapid and dynamic changes in the Antarctic and Greenland ice sheets. Model resolution remains a limiting factor in studying regional climate change and its attribution, and uncertainties in simulating internal climate variability continue to constrain certain aspects of attribution research.
- **Uncertainty in Emissions Scenarios:** Assumptions about future greenhouse gas and aerosol emissions directly affect climate change projections. The main sources of uncertainty include CO_2 emissions from fossil fuel combustion, methods for calculating CH_4 and N_2O emissions from fixed and mobile sources, and the influence of policies, technological advancements, and new energy development on greenhouse gas emission estimates. Future emission inventories and scenarios also contribute to this uncertainty.

Yong Luo

Office：Room S-807, Meng Minwei Science &
Technology Building, Tsinghua University
TEL：+86-10-62788891
Email：yongluo@tsinghua.edu.cn
WeChat ID：JakeYLuo

Thank you !

Sea ice model

- ✓ **Sea ice is a crucial component of the climate system, primarily influencing polar, mid-to-high latitude, and global circulation and energy balance through albedo positive feedback, Salting out, and modulation of deep ocean convection.**

- ✓ **The radiative effects and positive feedback mechanisms of sea ice are key areas of concern, and a series of theoretical works on sea ice salinity and dynamics modeling were developed in the 1980s and earlier.**

- ✓ **Since the 1990s, with the development of coupled models incorporating the atmosphere, ocean, and land, sea ice has gradually appeared in coupled models either as a separate component or as a submodule within ocean models.**
- ✓ **The initial sea ice models only included simple thermodynamic processes of ice formation and melting, without considering dynamic factors such as horizontal advection and rheology.**
- ✓ **These simplified models are also commonly used in the testing of standalone ocean models.**

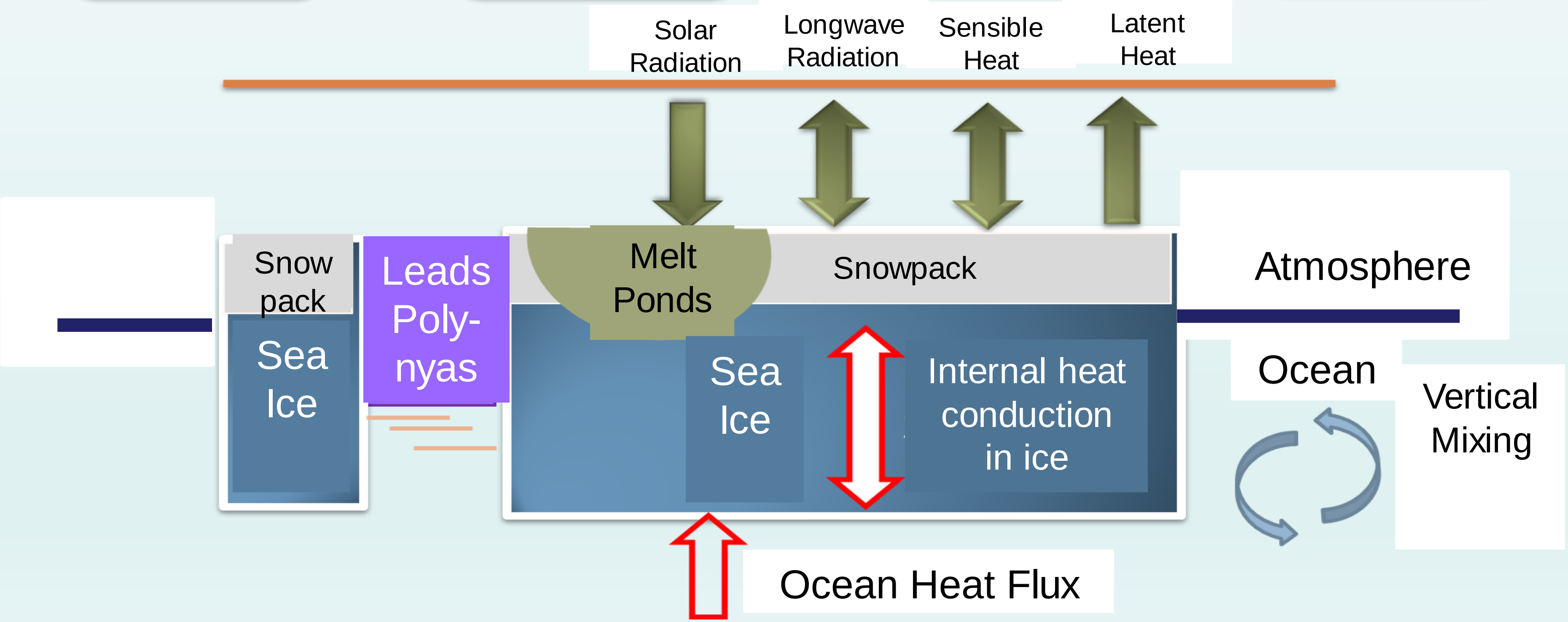
With the enhancement of computational power and advances in rheology and numerical algorithms, modern climate system models now include sea ice models with both thermodynamic and dynamic processes:

- ✓ The thermodynamic processes mainly include: Temperature (or enthalpy) simulation, salinity simulation, snow accumulation and melt pond processes, shortwave albedo schemes, shortwave penetration, and heat flux exchanges in the boundary layer.

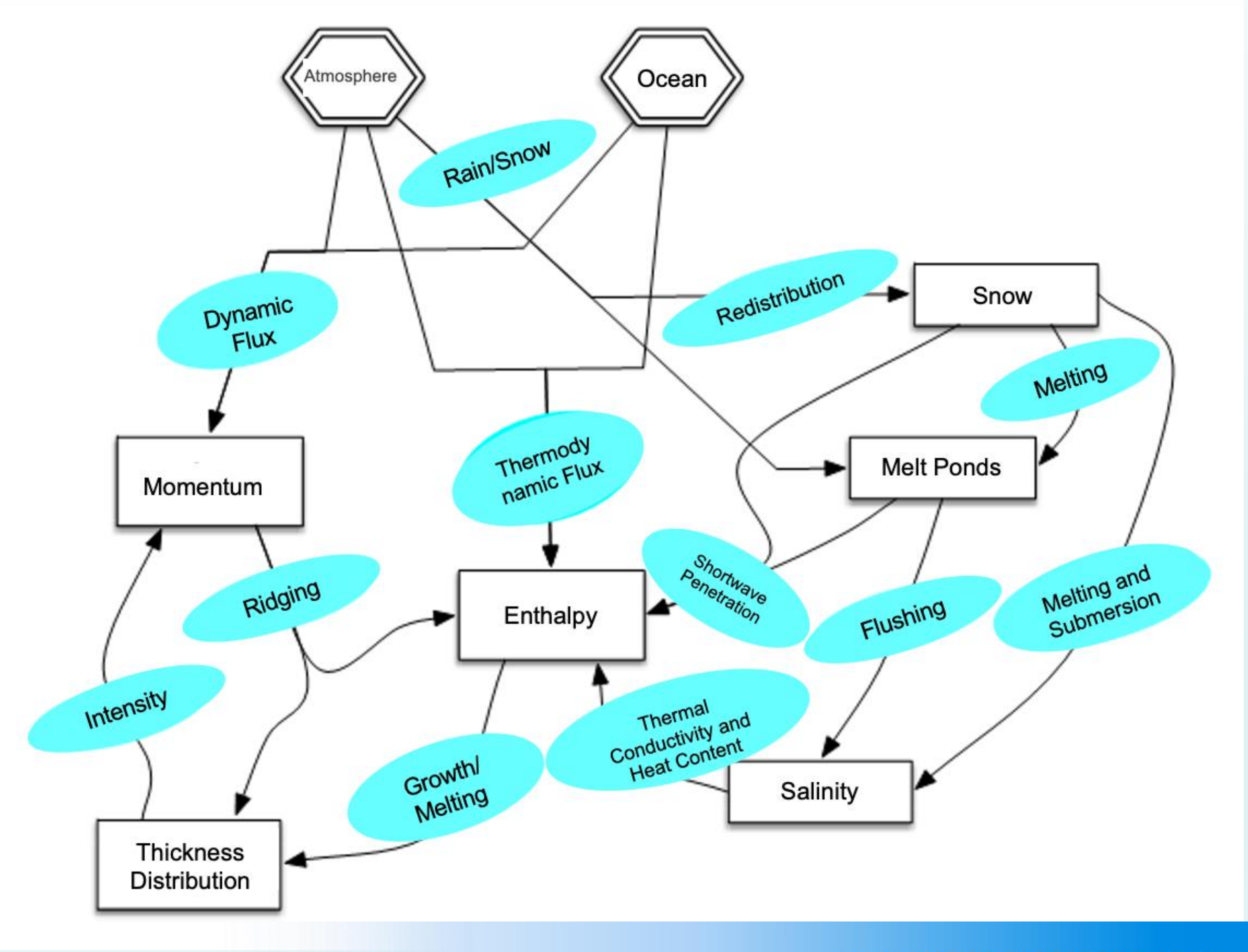
- ✓ The dynamic processes mainly include: Sea ice rheology, momentum exchange in the boundary layer , sea ice ridging & rafting, advection, and other related processes.

Sea Ice Model

Optical observations of Melt Ponds and Polynyas in sea ice → **Distribution Patterns of Solar Radiation in the Ocean-Air-Ice System** → **Contribution to Sea Ice Melt** → **Improving Parameterization Schemes for Melt Ponds, Polynyas, and Albedo**



Key Prognostic Variables in Sea Ice Models and Their Interrelationships



- ✓ The main prognostic variables in sea ice models include ice thickness distribution (ITD), heat content (enthalpy), velocity, snow depth, and snow heat content.
- ✓ Additionally, more complex models may also forecast variables such as salinity, snow distribution, and melt pond distribution, depending on the configuration.