From greenhouse effect to the Paris Agreement:

Exploring Manabe's Nobel-winning-work in predicting global warming

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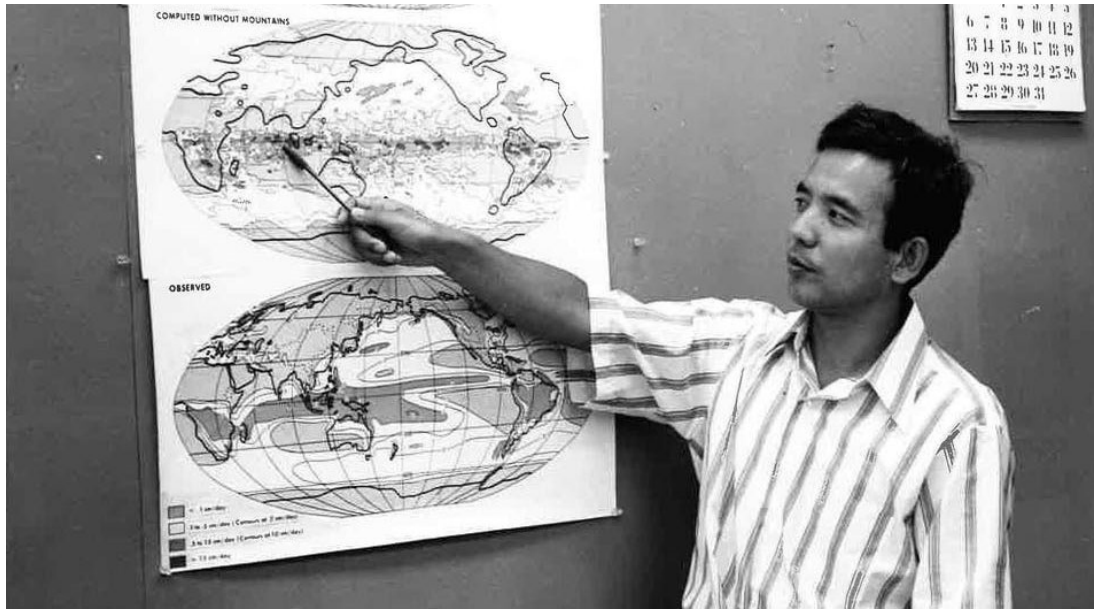
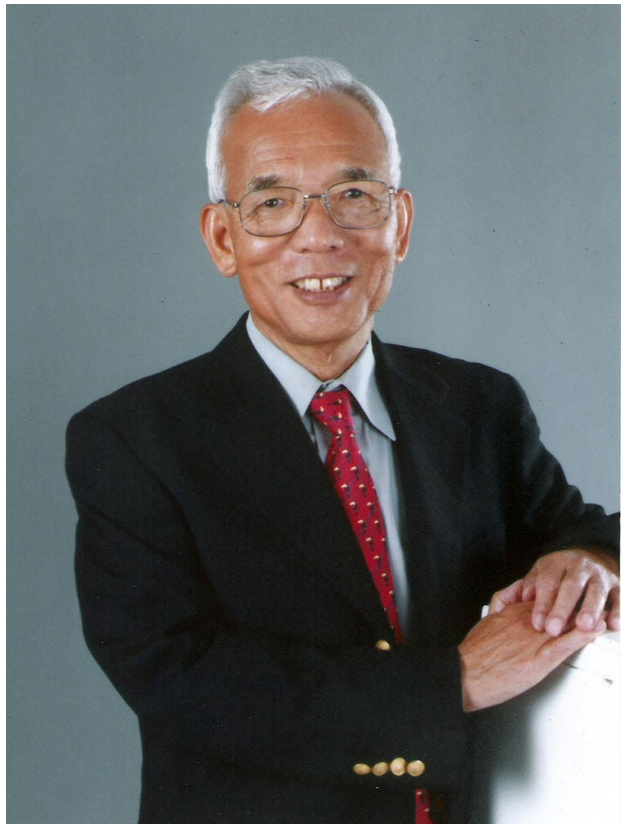
cSplash 2023

04/22/2023 (Earth Day)

Syukuro "Suki" Manabe 真鍋 淑郎



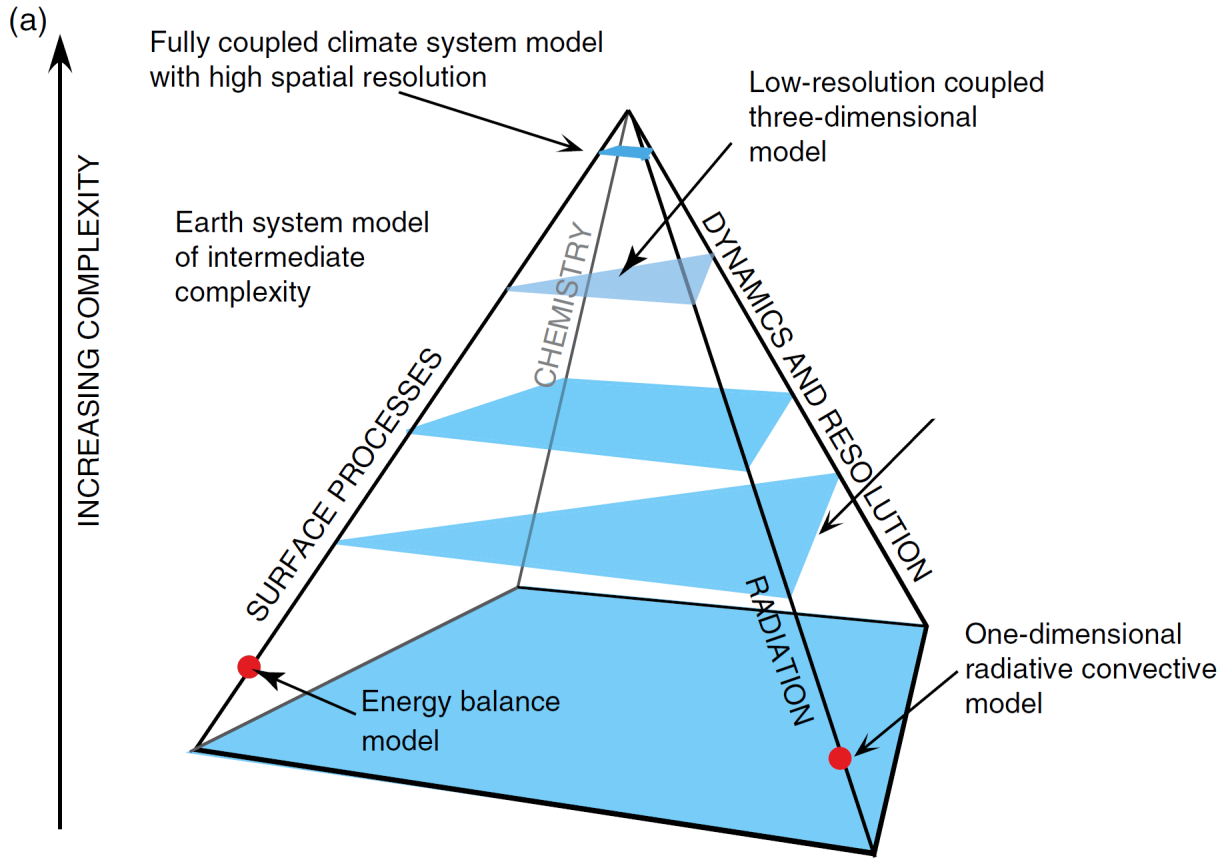


- Nobel Prize motivation: “for the physical modelling of Earth’s climate, quantifying variability and reliably predicting global warming”

Photos from Geophysical Fluid Dynamics Laboratory and Franklin Institute

Hierarchy of models

- Energy balance
  - 0D, one-layer atmosphere
  - Greenhouse effect
- One vertical column
  - Manabe and Wetherald (1967)
- 3D model
  - Manabe and Wetherald (1975)
- Earth system model
  - Use nowadays in the Intergovernmental Panel on Climate Change Assessment Report (e.g.: IPCC-AR6 published in 2022)



McGuffie, Kendal, and Ann Henderson-Sellers. 2014. *The Climate Modelling Primer*. John Wiley & Sons.

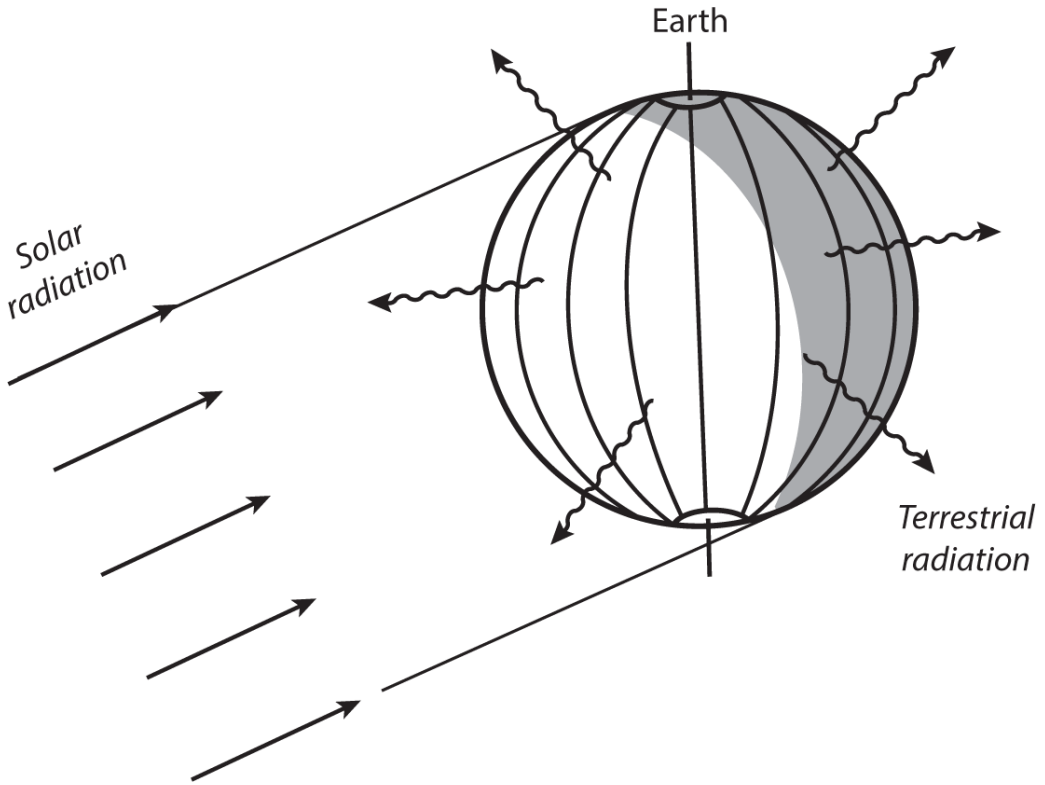
Energy balance model - Bare rock

- Energy in
  - Radiation from the sun about 340 Wm^{-2}
- Energy out
  - Reflection of solar radiation 101 Wm^{-2}
  - Radiation of the earth ???? Wm^{-2}
- Energy in = Energy out
  - Terrestrial radiation about 240 Wm^{-2}
- Stefan–Boltzmann law of radiation

$$j^* = \sigma T^4$$

$$\Rightarrow \quad T = 255 \text{ K}$$

- Effective emission temperature of the earth
  - -18.7 °C = -1.7 °F



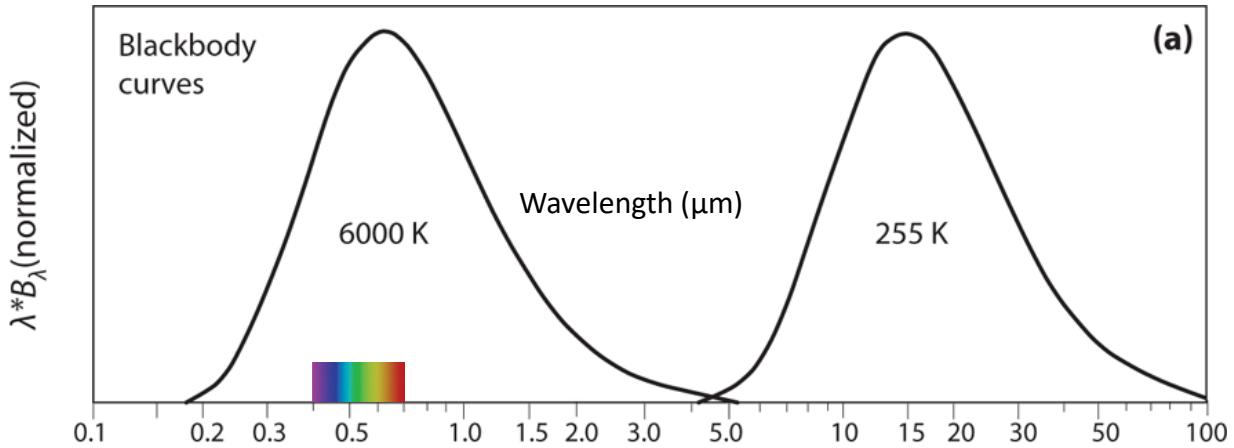
Manabe, Syukuro, and Anthony J. Broccoli. 2020. *Beyond Global Warming: How Numerical Models Revealed the Secrets of Climate Change*. Princeton University Press.

Too cold! Greenhouse effect

- Hotter object emits shorter waves

- The sun (6000 K):
  - Shortwave radiation invisible to greenhouse gases
  - Includes the visible spectrum

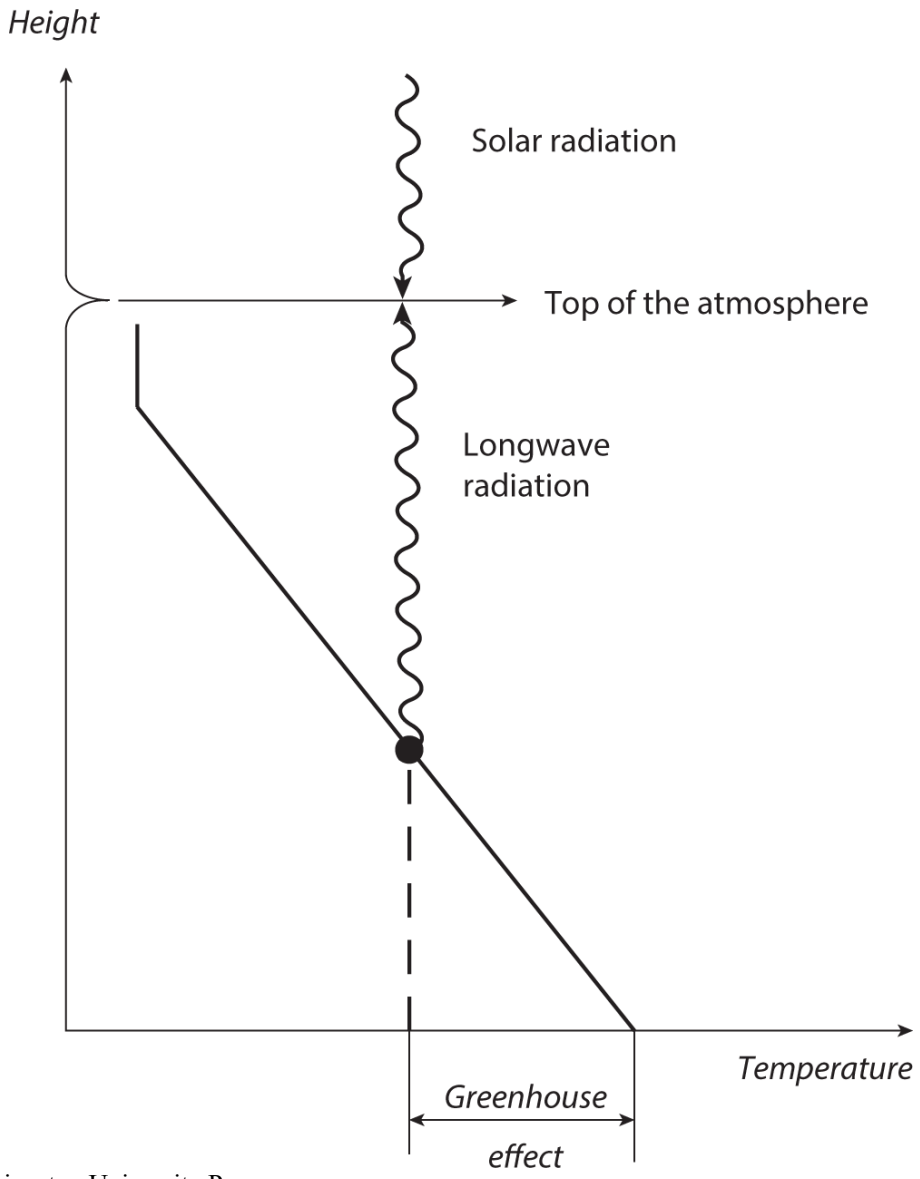
- The earth's emission temp (255 K):
  - Longwave radiation easily absorbed by greenhouse gases



Peixoto, José Pinto. 1992. *Physics of Climate*. American Institute of Physics.

A simple energy balance model

- Effective emission temperature of the earth:
  - 255 K
- "Effective emission height":
  - 5 km
- Typical lapse rate of the troposphere:
  - 6.5 K/km
- Greenhouse effect:
  - 32.5 K
- Temperature on the surface
  - 287.5K= 14.4 °C = 57.8 °F



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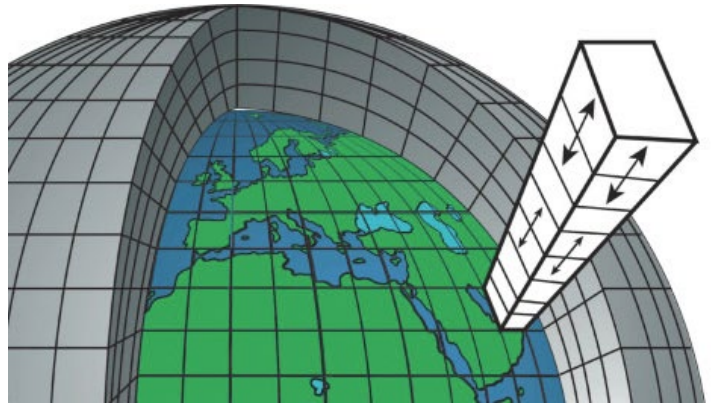
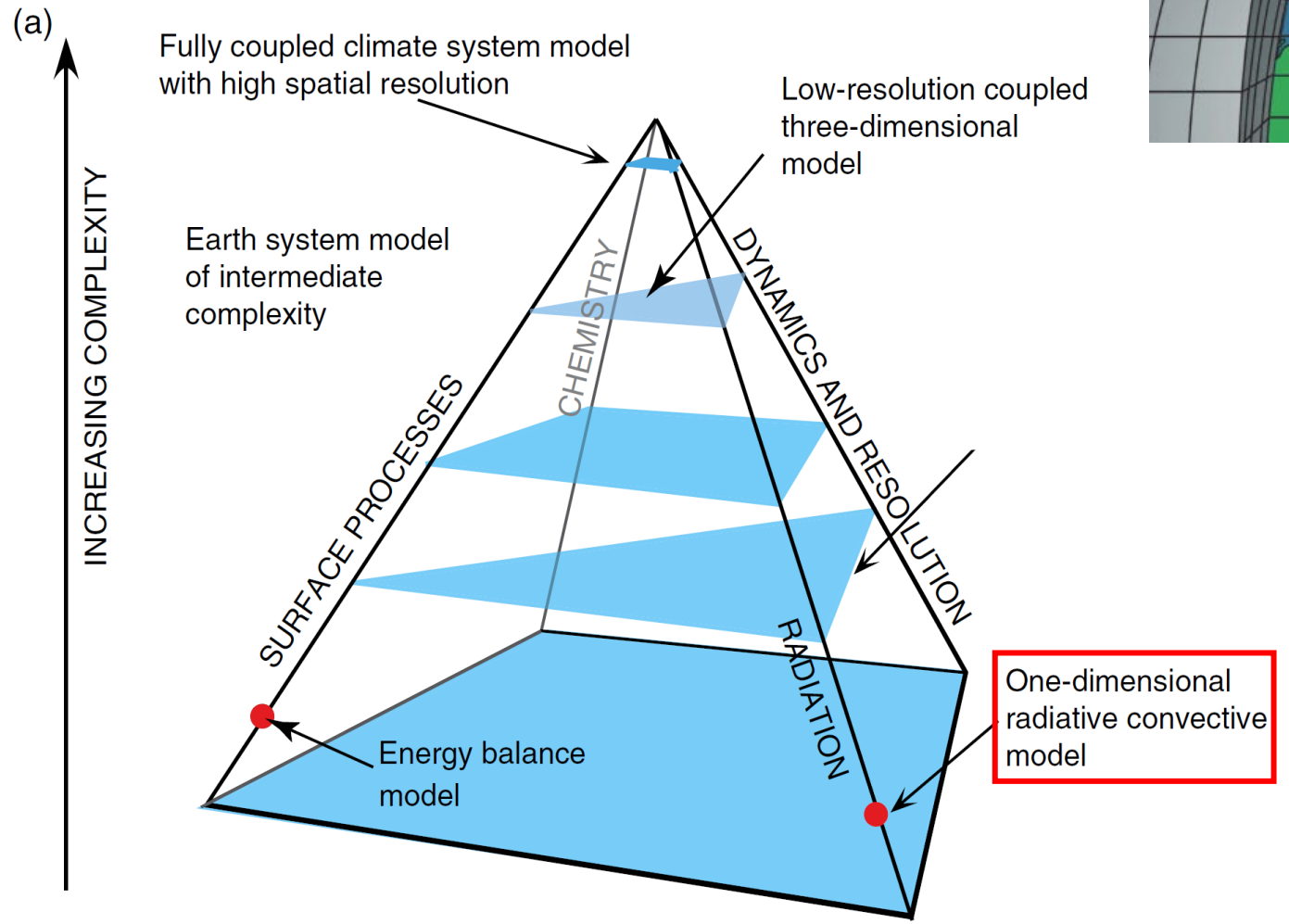
1D Vertical Column Model

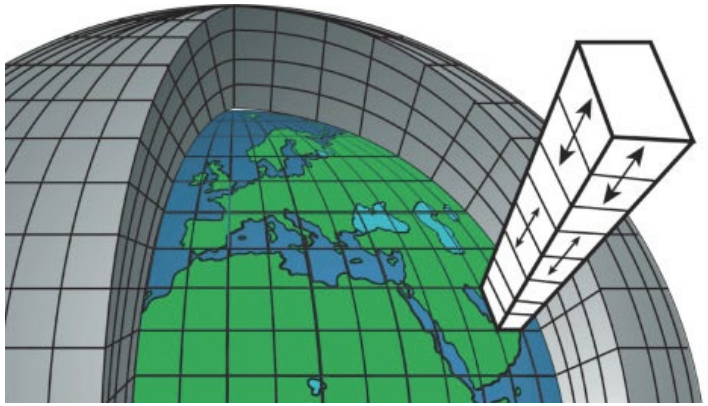




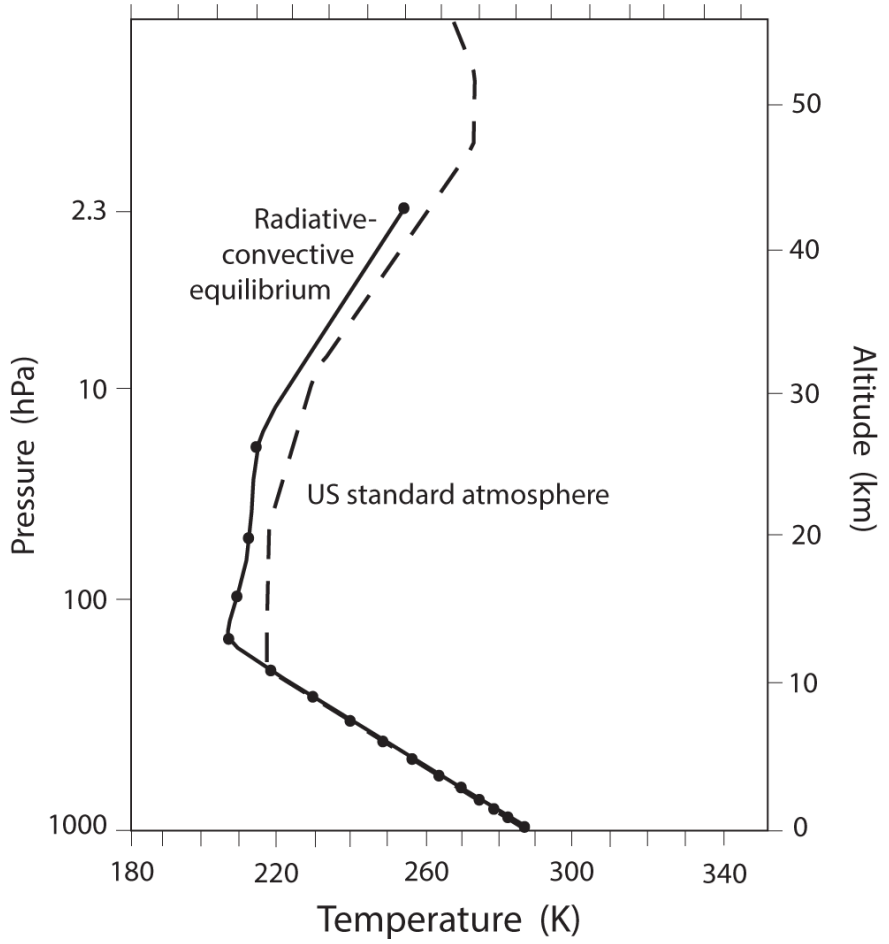
Edwards, Paul N. 2011. "History of Climate Modeling." *WIREs Climate Change* 2 (1): 128–39.

Radiative-Convective Equilibrium

- One-dimensional vertical column



- Energy balance at each vertical level
  - Absorption of shortwave radiation
  - Absorption and emission of longwave radiation
- The lapse rate cannot exceed the critical 6.5 K/km
- Equilibrium solution (no time change)
- Critical paper: Manabe and Strickler (1964)



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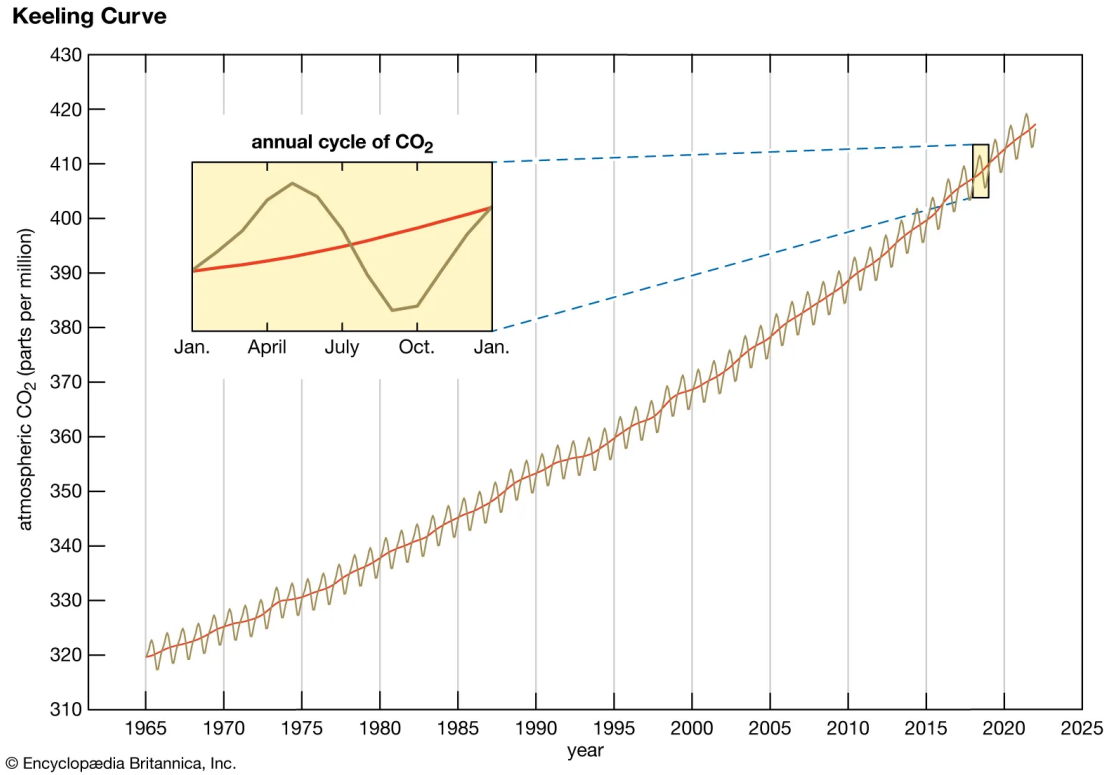
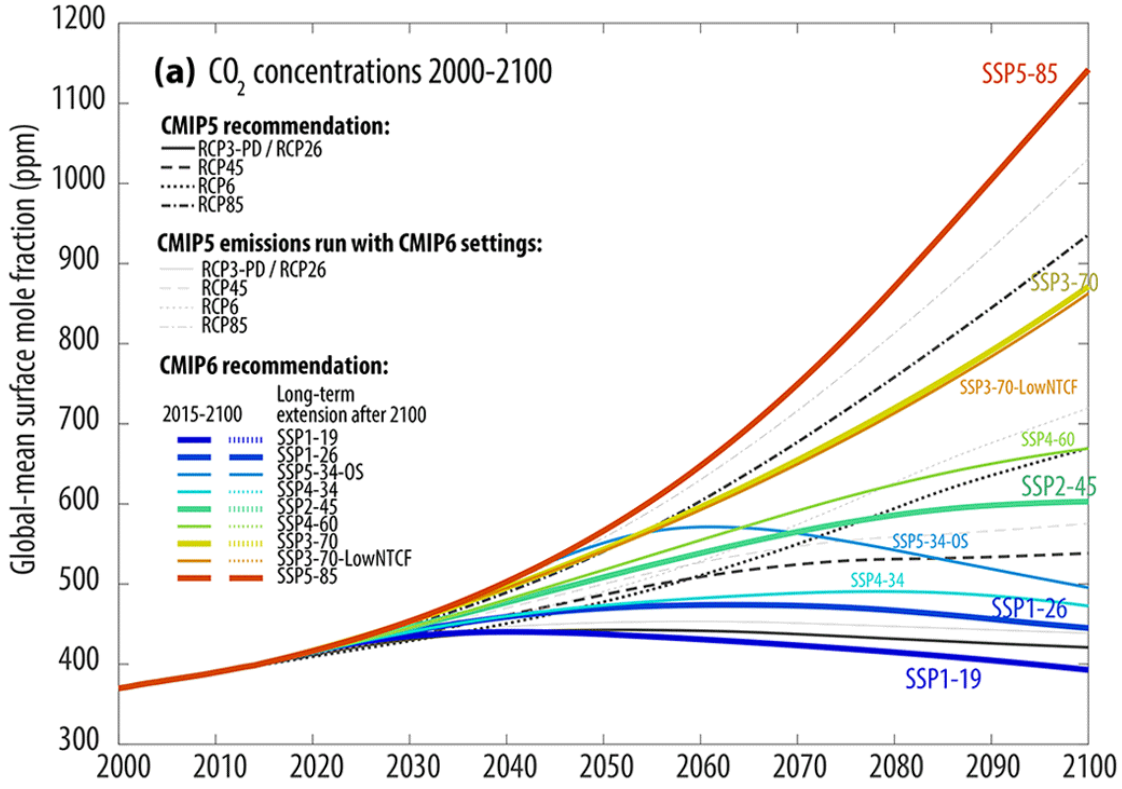
Anthropogenic CO_2

- The Keeling curve: Observed CO_2 concentration in the atmosphere
- Shared Socioeconomic Pathways (SSPs): keys future emissions scenarios





Rafferty, J. P.. "Keeling Curve." *Encyclopedia Britannica*. https://www.britannica.com/science/Keeling-Curve. Keeling curve data from Scripps Institution of Oceanography

Meinshausen, Malte, Zebedee R. J. Nicholls, Jared Lewis, Matthew J. Gidden, Elisabeth Vogel, Mandy Freund, Urs Beyerle, et al. 2020. "The Shared Socio-Economic Pathway (SSP) Greenhouse Gas Concentrations and Their Extensions to 2500." *Geoscientific Model Development* 13 (8): 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020.

Water vapor is a Greenhouse gas

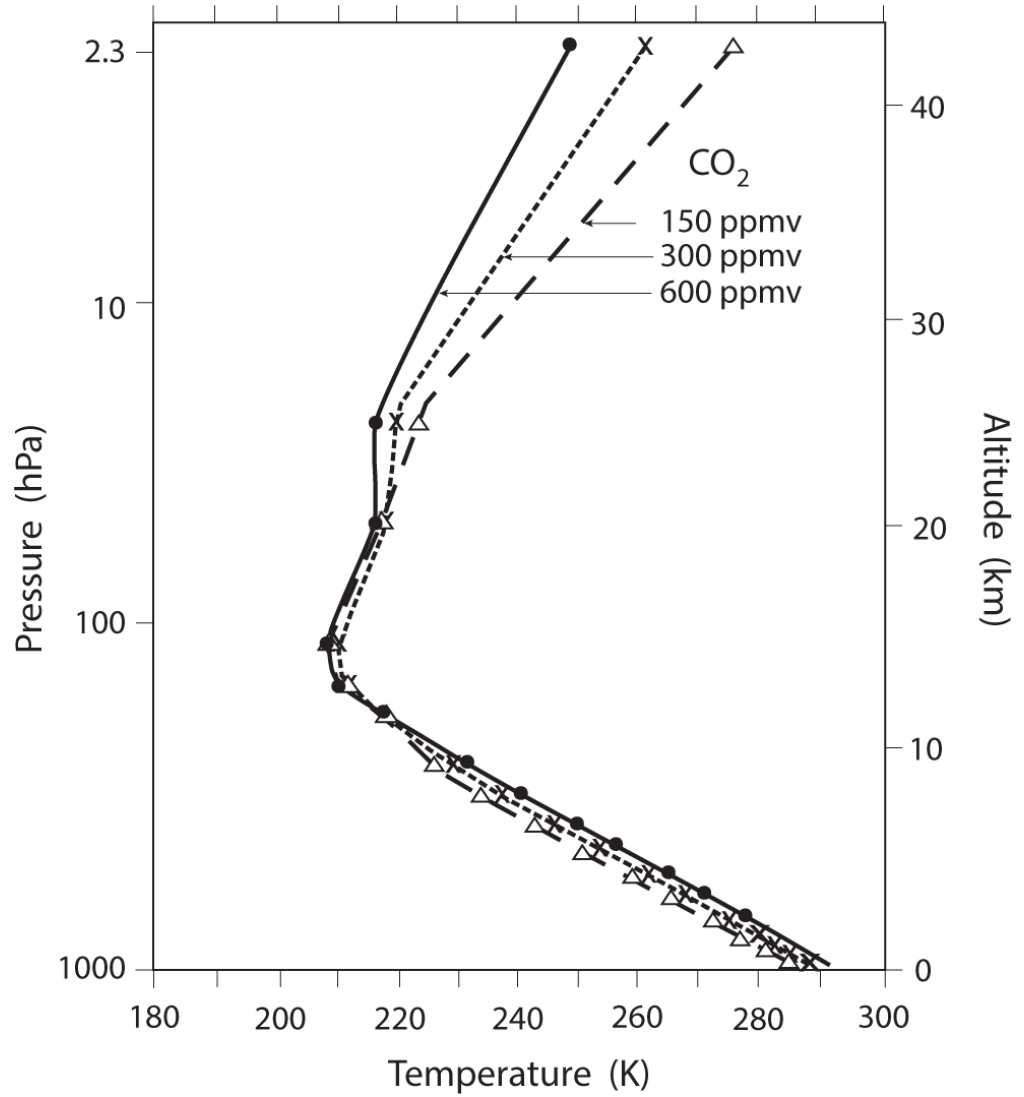
- High impact, short lived
- $$\text{Specific humidity (mass ratio)} = \text{Relative humidity} \times \text{Saturation specific humidity}$$

- Warmer air can hold more water vapor
  - Clausius–Clapeyron relation
- The relative humidity in the atmosphere does not change much as temperature changes
  - From our seasonal variation
- Assume constant relative humidity
  - More water vapor as the earth warms

Manabe, Syukuro, and Richard T. Wetherald. 1967. “Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity.” *Journal of the Atmospheric Sciences* 24 (3): 241–59.

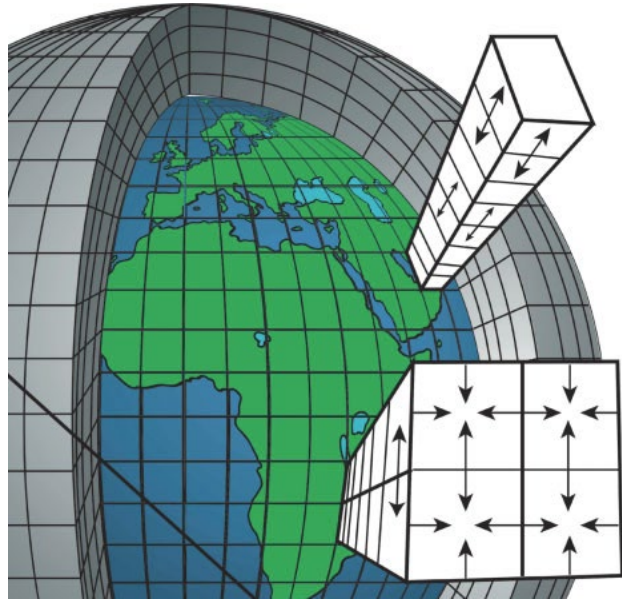
Doubling CO_2: Equilibrium Climate Sensitivity

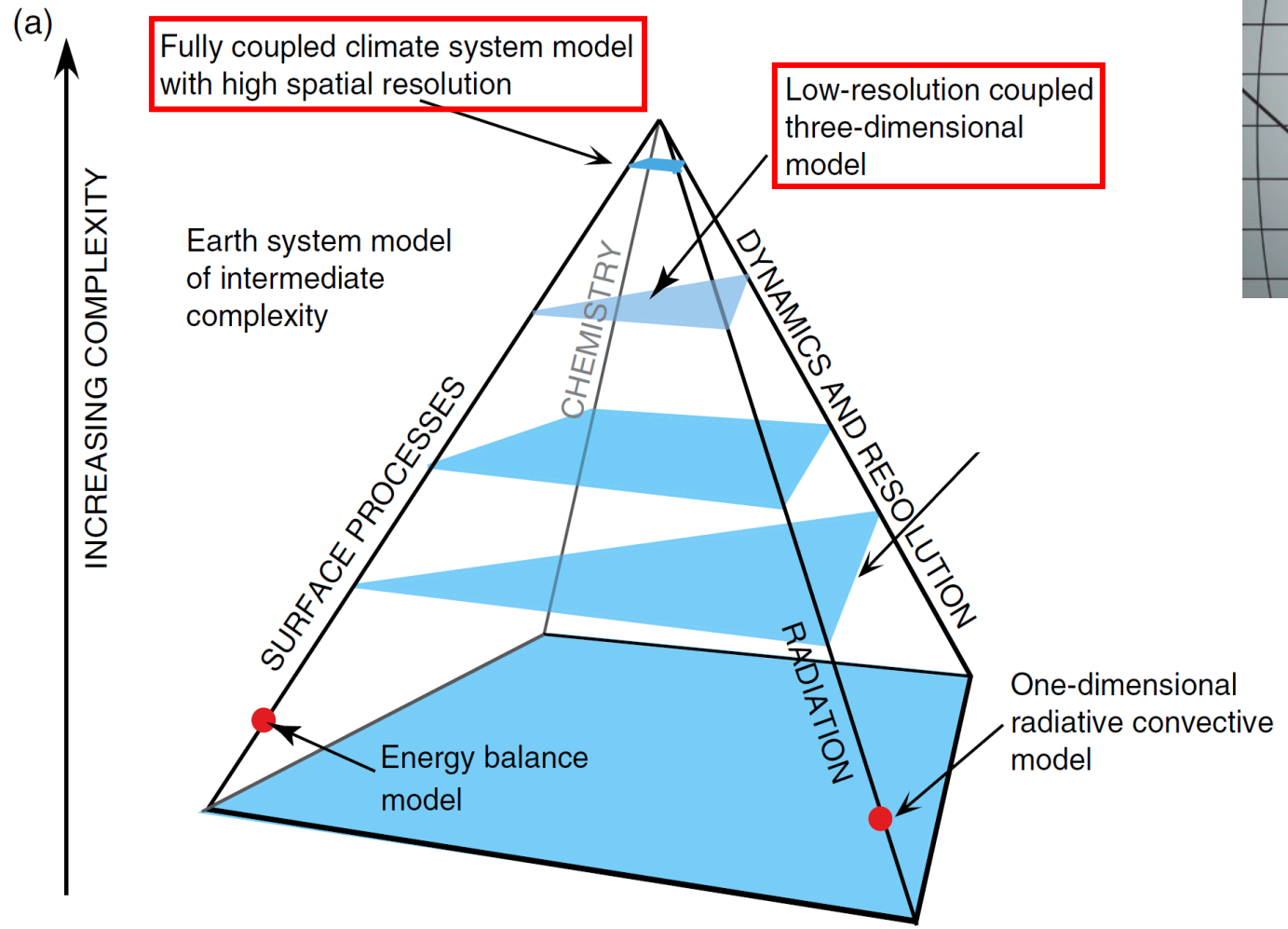
- CO_2: 300 ppmv v.s. 600 ppmv
- Water vapor (positive) feedback (on or off)
  - Fix specific humidity: 1.3 K (2.3 °F) warming
  - Fix relative humidity: 2.4 K (4.3 °F) warming
- Critical paper: Manabe and Wetherald (1967)



Manabe, Syukuro, and Richard T. Wetherald. 1967. "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity." *Journal of the Atmospheric Sciences* 24 (3): 241–59.

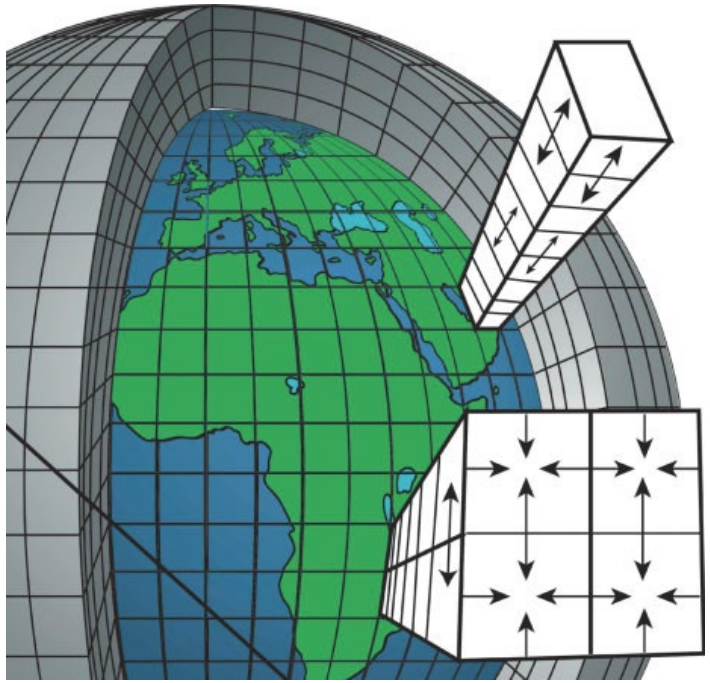
Early and current 3D global models

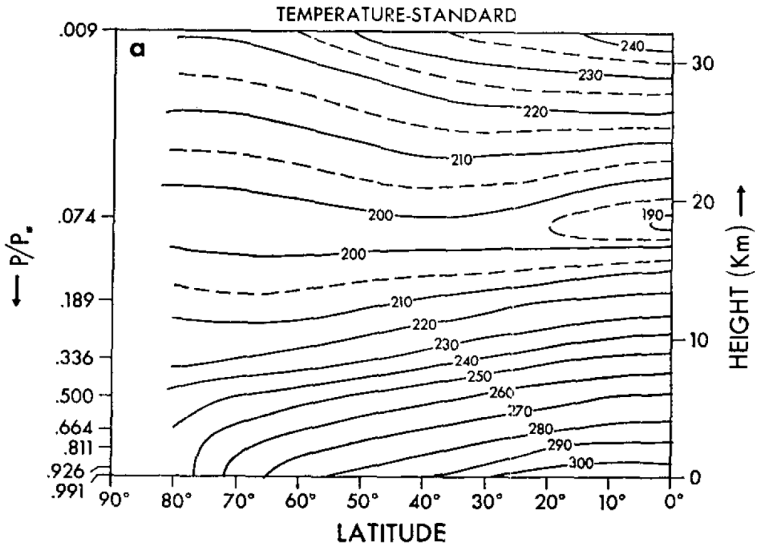


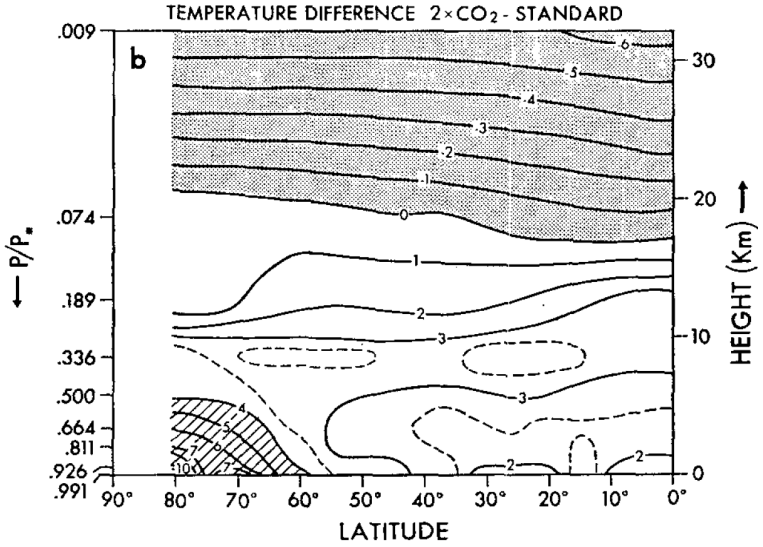


Three-Dimensional General Circulation Model

- Similar in vertical profile
- More warming near the pole due to albedo feedback
- Global average warming of 2.93 K (5.27 °F)
- Critical paper: Manabe and Wetherald (1975)





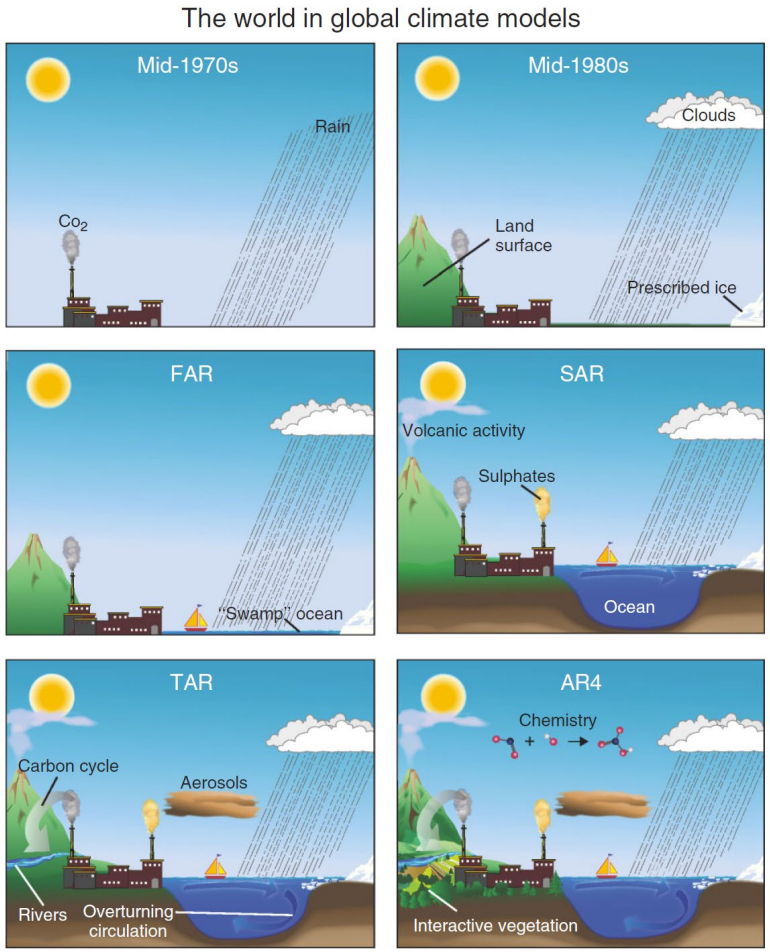


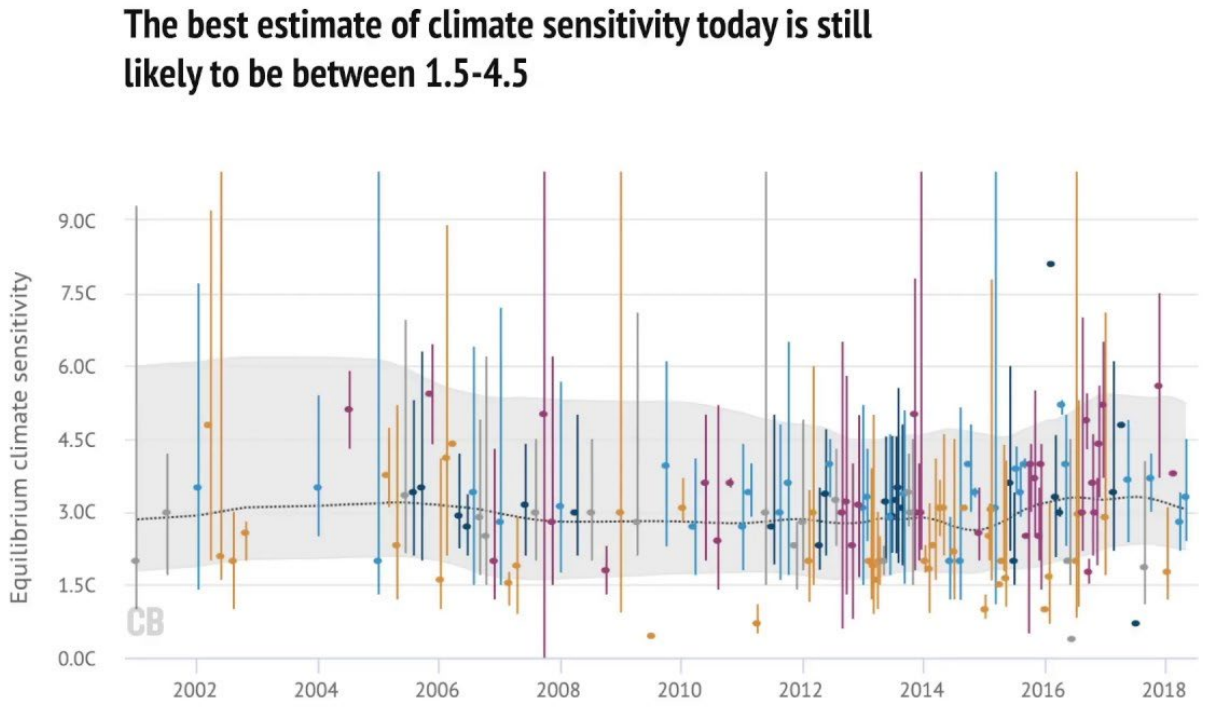
https://earthobservatory.nasa.gov/features/SeaIce

Manabe, Syukuro, and Richard T. Wetherald. 1975. "The Effects of Doubling the CO2 Concentration on the Climate of a General Circulation Model." *Journal of the Atmospheric Sciences* 32 (1): 3–15.

Earth system model

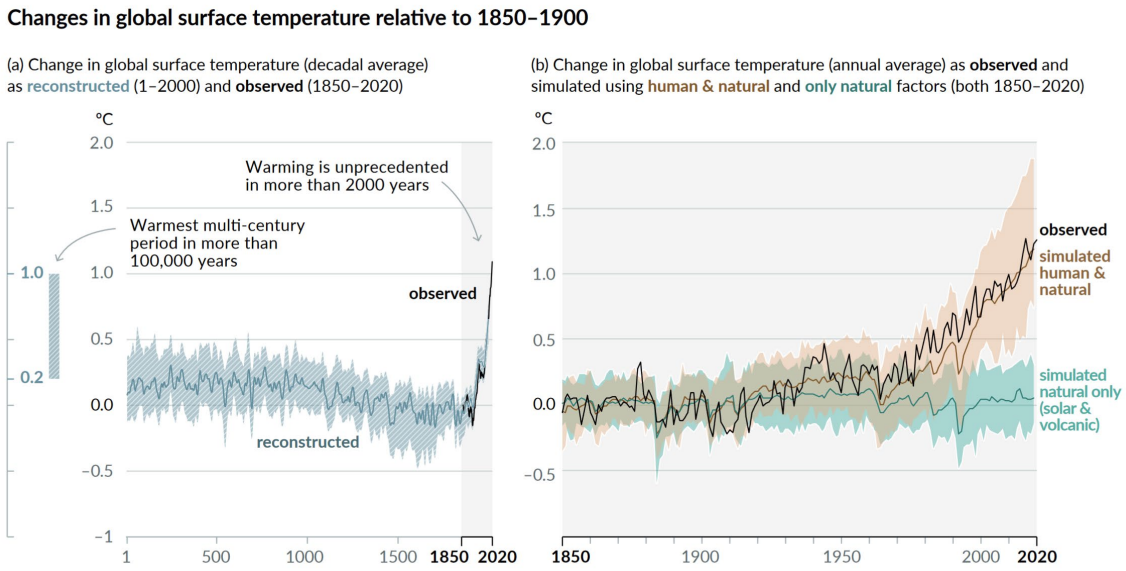
- High-resolution, multi-component models of the earth system

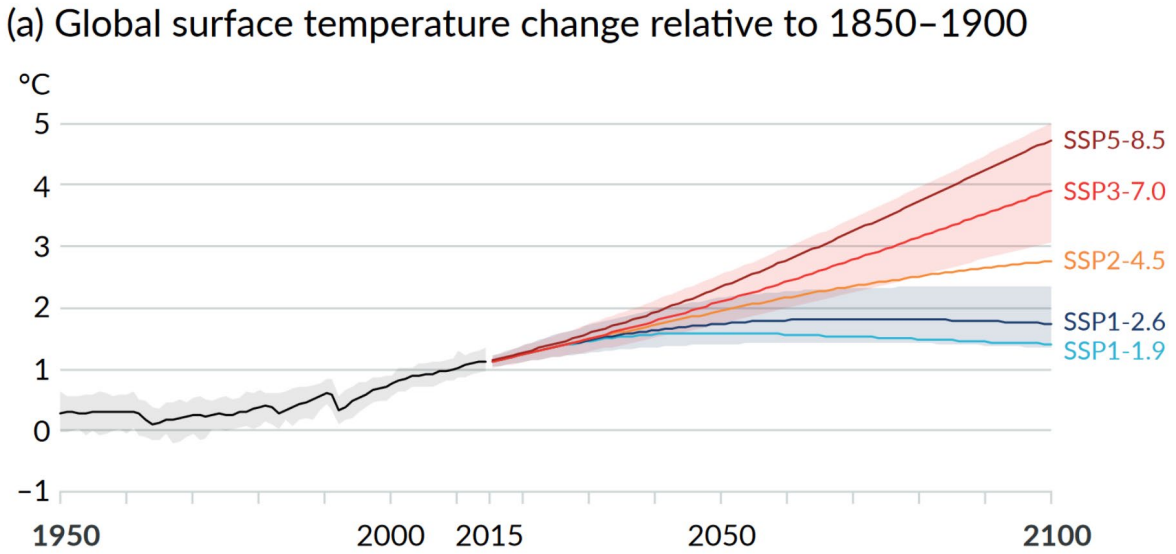




IPCC, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, NY, USA.
Pearce, Rosamund. 2018. "Explainer: How Scientists Estimate Climate Sensitivity." Carbon Brief. June 19, 2018. https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity/.
"Earth Simulator." 2022. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Earth_Simulator&oldid=1123978018.

Conclusion from the science





- "It is unequivocal that human influence has warmed the atmosphere, ocean and land."
- This is confirmed by a hierarchy of models:
  - From simple to complex
  - From pen and paper to high performance computing simulations
- Manabe "predicted" global warming before its effect is apparent.

IPCC. 2021. "Summary for Policymakers." Edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, et al. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.