上海交通大学

SHANGHAI JIAO TONG UNIVERSITY

SJTU

上海交通大学海洋学院

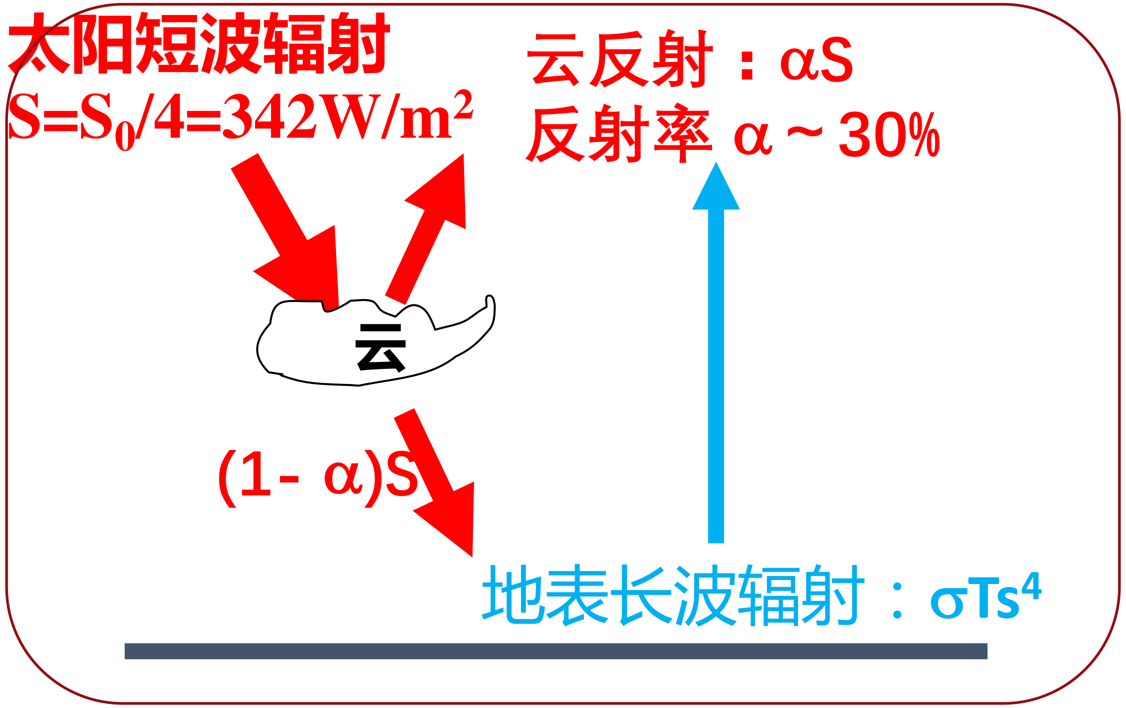
气候学与全球变化
Climate and Global Change

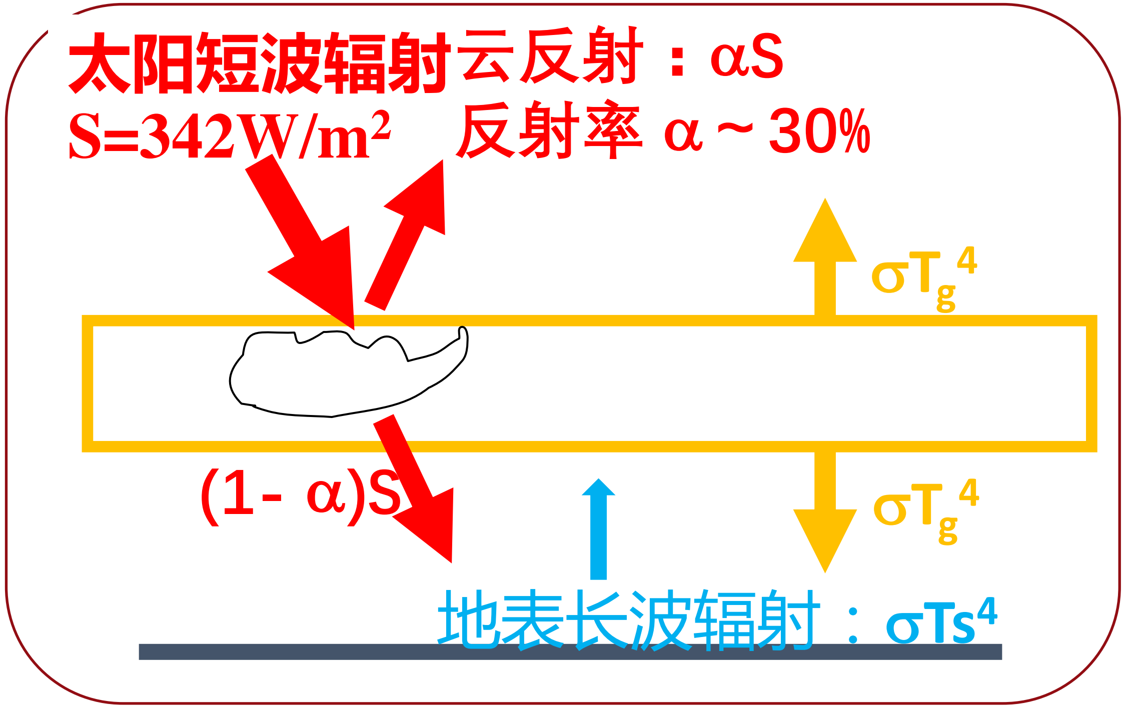
2022.05.17

SCHOOL OF OCEANOGRAPHY
SHANGHAI JIAO TONG UNIVERSITY
上海交通大学 海洋学院

What models are available?

Radiative Equilibrium Model/Energy Balance Model





$(1-\alpha) S = \sigma Ts^4$

$Ts = -18^oC$

地表：$(1-\alpha) S + \sigma T_g^4 = \sigma Ts^4$

大气：$2\sigma T_g^4 = \sigma Ts^4$

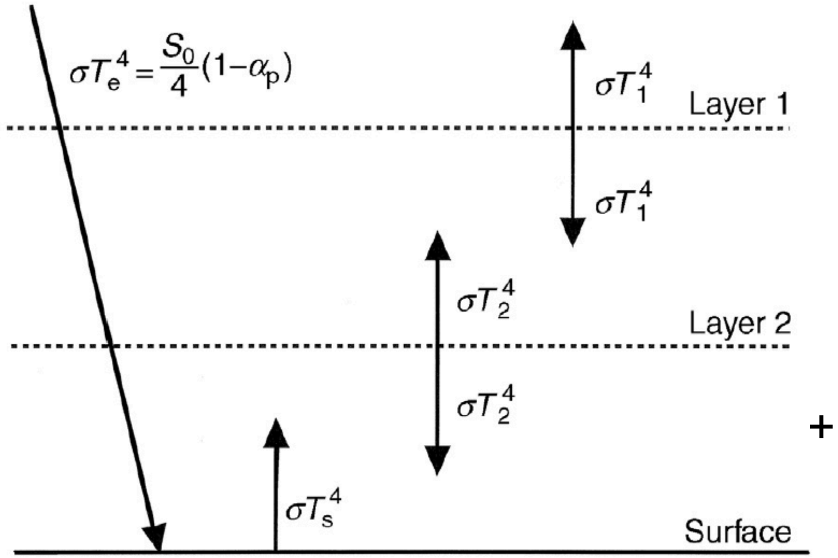
$Ts = 30^oC$，$T_g = -18^oC$

What models are available?

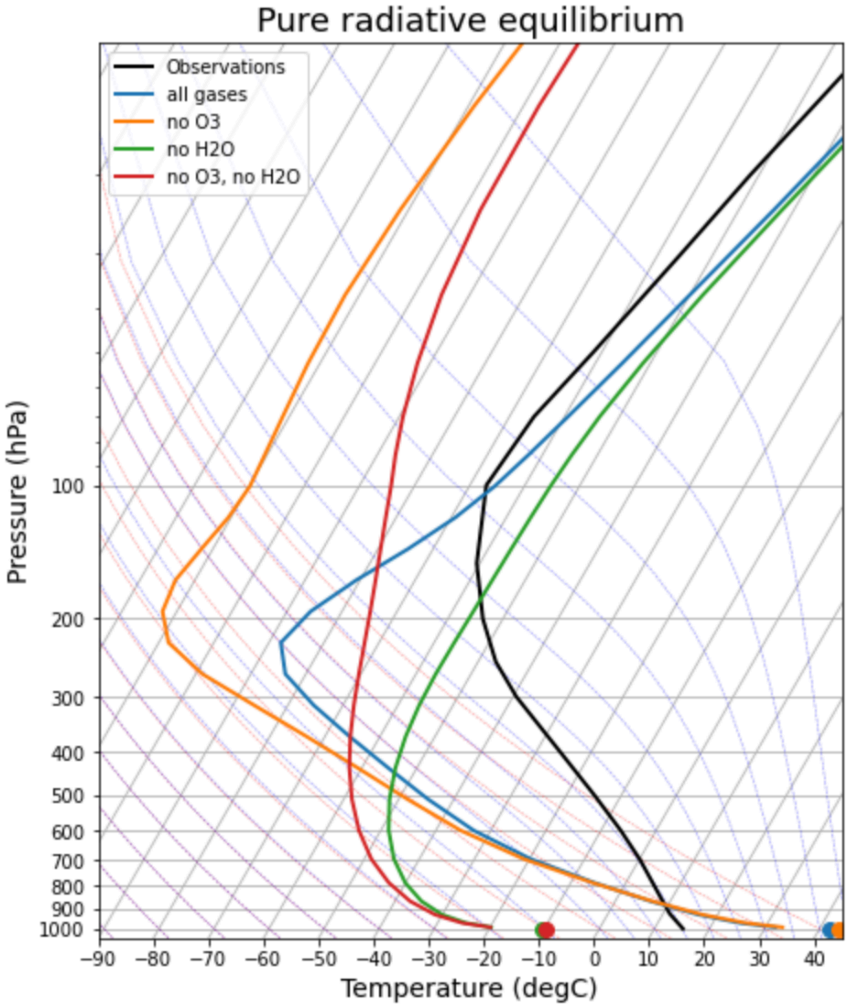
Radiative Equilibrium Model/Energy Balance Model

1-D:

T(z)



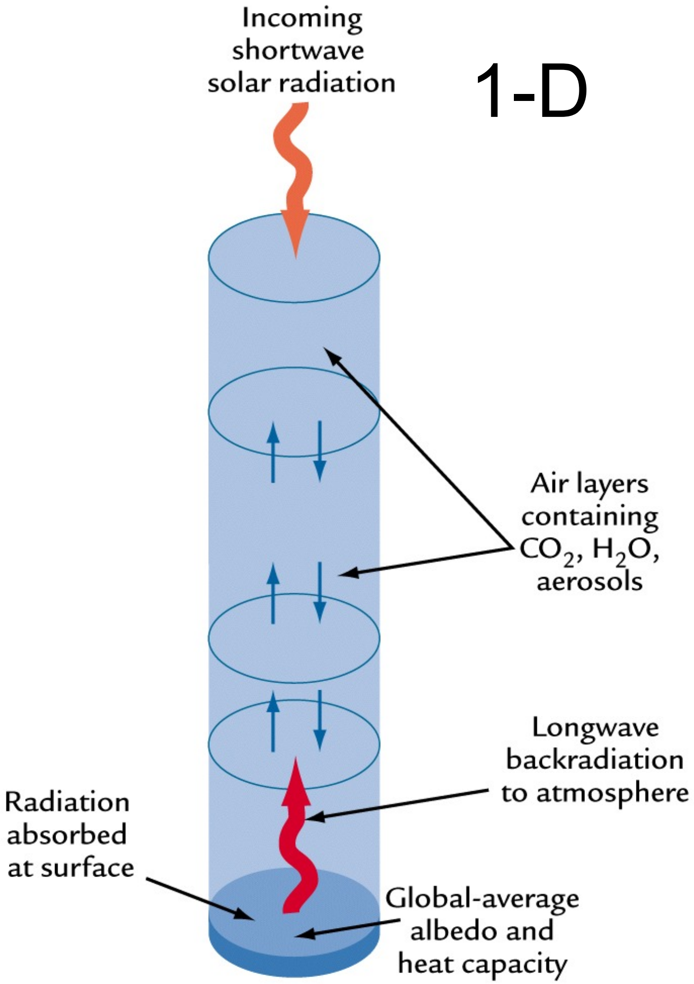
+Layer n



只考虑能量平衡

What models are available?

Radiative Convective Model

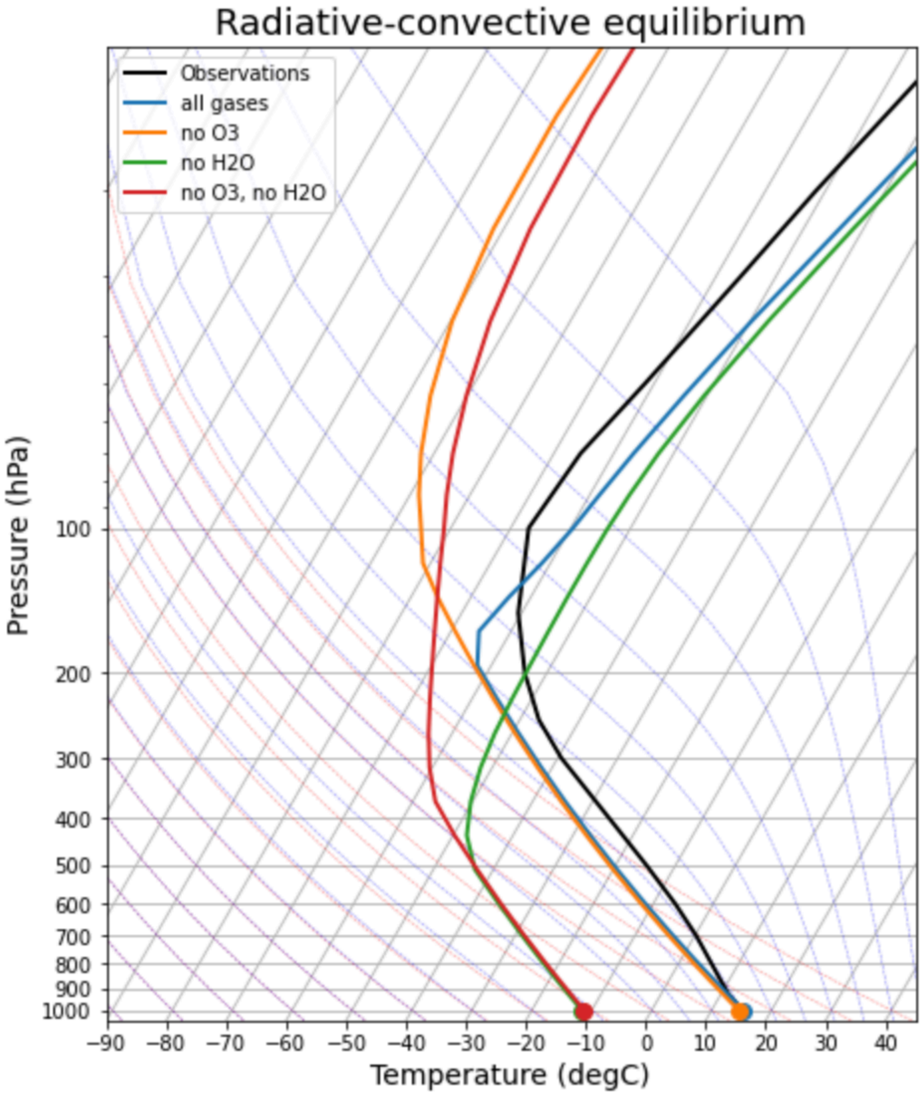


1-D

辐射能量平衡

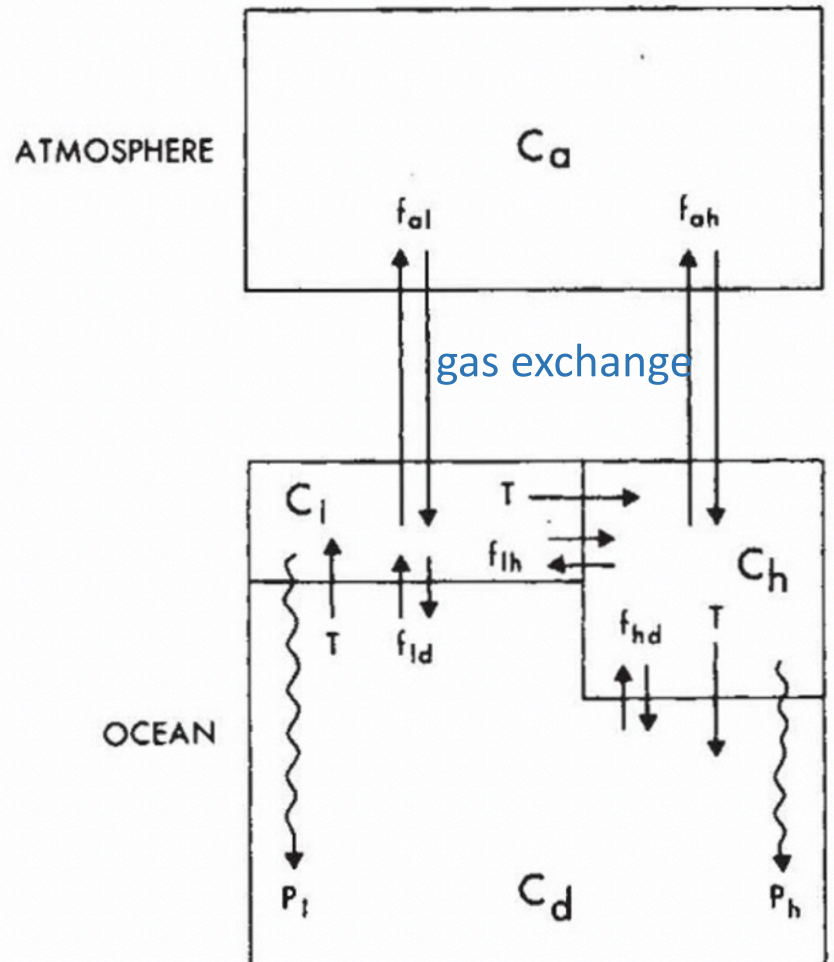
+

对流(能量传输)

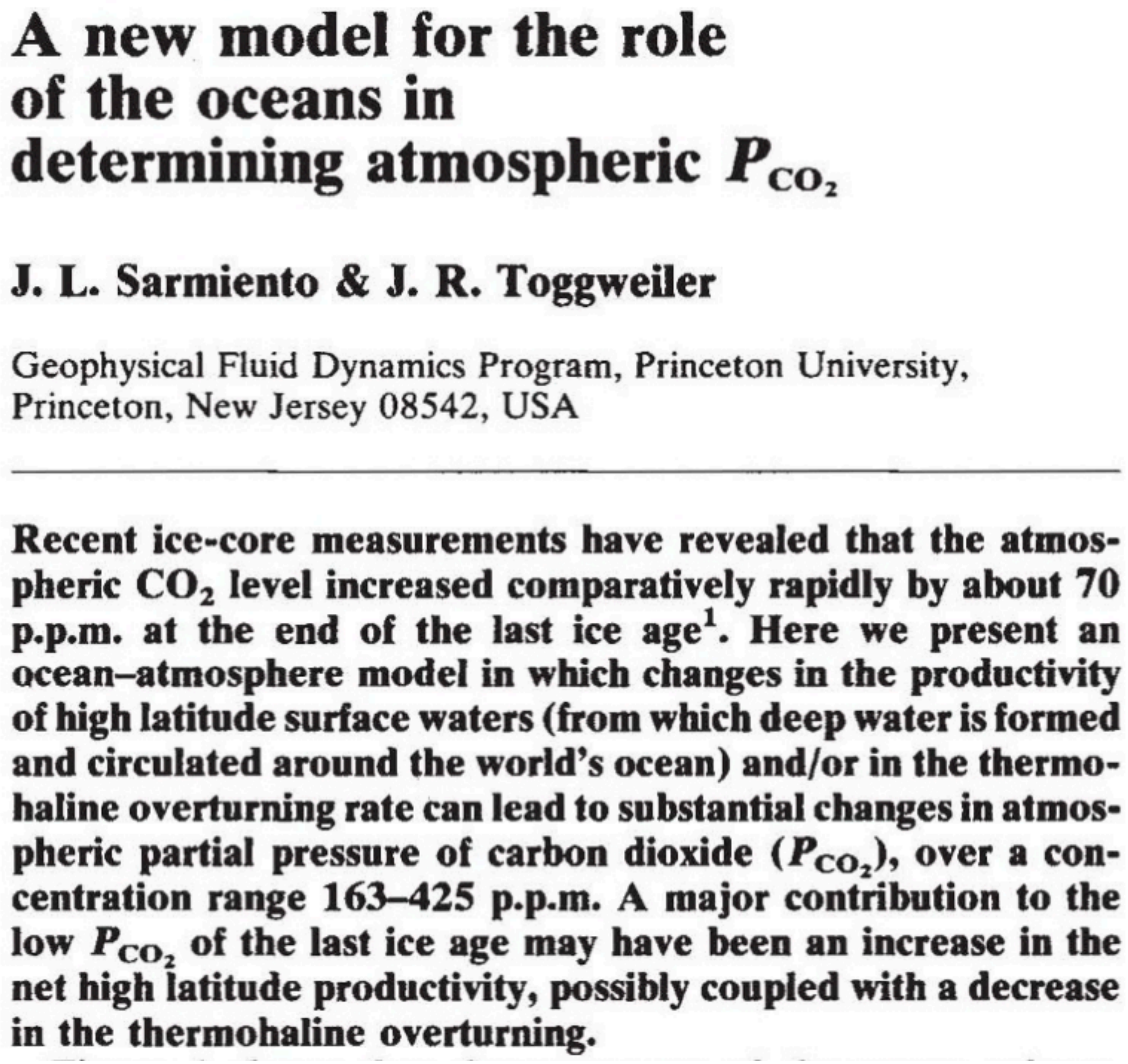


What models are available?

Box Model



Sarmiento & Toggweiler, 1984, Nature



A new model for the role of the oceans in determining atmospheric P_{CO_2}

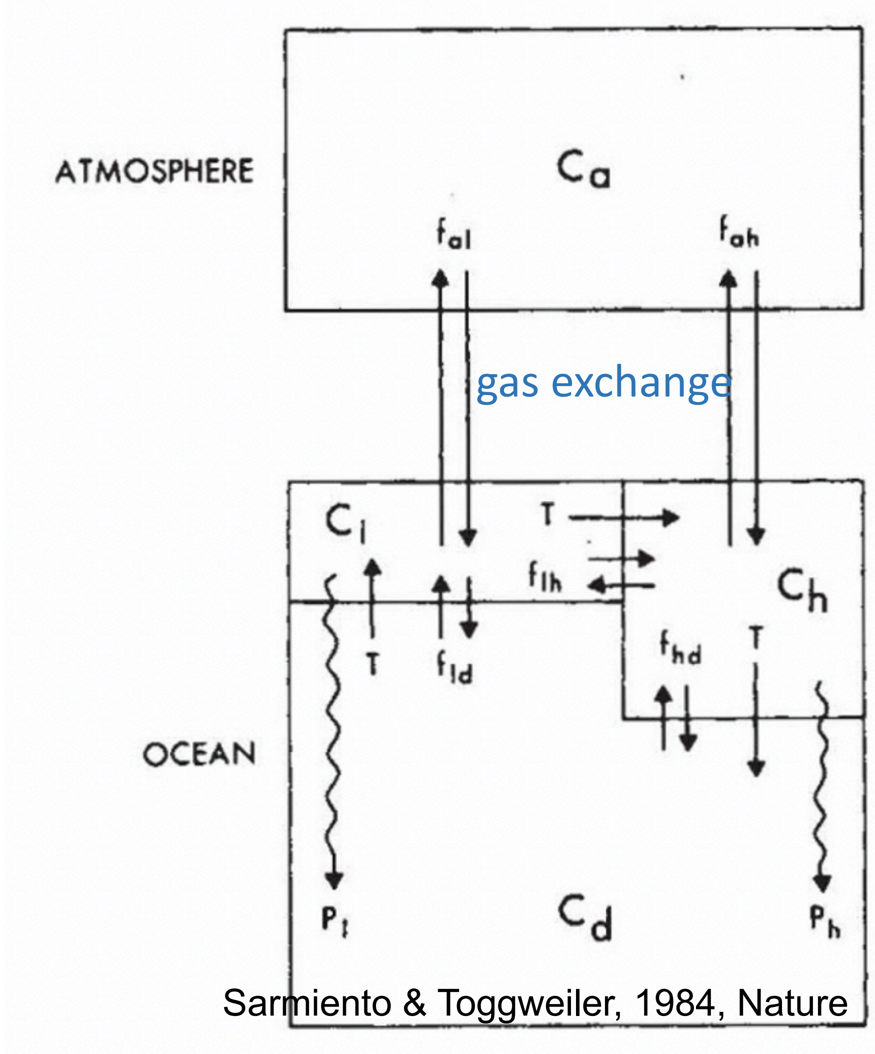
J. L. Sarmiento & J. R. Toggweiler

Geophysical Fluid Dynamics Program, Princeton University, Princeton, New Jersey 08542, USA

Recent ice-core measurements have revealed that the atmospheric CO_2 level increased comparatively rapidly by about 70 p.p.m. at the end of the last ice age[1]. Here we present an ocean–atmosphere model in which changes in the productivity of high latitude surface waters (from which deep water is formed and circulated around the world's ocean) and/or in the thermohaline overturning rate can lead to substantial changes in atmospheric partial pressure of carbon dioxide (P_{CO_2}), over a concentration range 163–425 p.p.m. A major contribution to the low P_{CO_2} of the last ice age may have been an increase in the net high latitude productivity, possibly coupled with a decrease in the thermohaline overturning.

What models are available?

Box Model



Sarmiento & Toggweiler, 1984, Nature

4-Box model: Atmosphere, Surface ocean-High Latitude, Surface ocean-Low Latitude, Deep Ocean

Variables: T, O_2, PO_4, CO_2 (+^{13}C, ^{14}C), ALK

Phosphate：

(1) $\frac{dPO_{4d}}{dt} = \frac{1}{V_d} * [f_{ld}(PO_{4l} - PO_{4d}) + (T + f_{hd})(PO_{4h} - PO_{4d}) + (P_l + P_h)]$

(2) $\frac{dPO_{4h}}{dt} = \frac{1}{V_h} * [(T + f_{lh})(PO_{4l} - PO_{4h}) + f_{hd}(PO_{4d} - PO_{4h}) - P_h]$

(3) $\frac{dPO_{4l}}{dt} = \frac{1}{V_l} * [(T + f_{ld})(PO_{4d} - PO_{4l}) + f_{lh}(PO_{4h} - PO_{4l}) - P_l]$

$R_{C:P}$ -> CO_2 equations，+ gas exchange

……

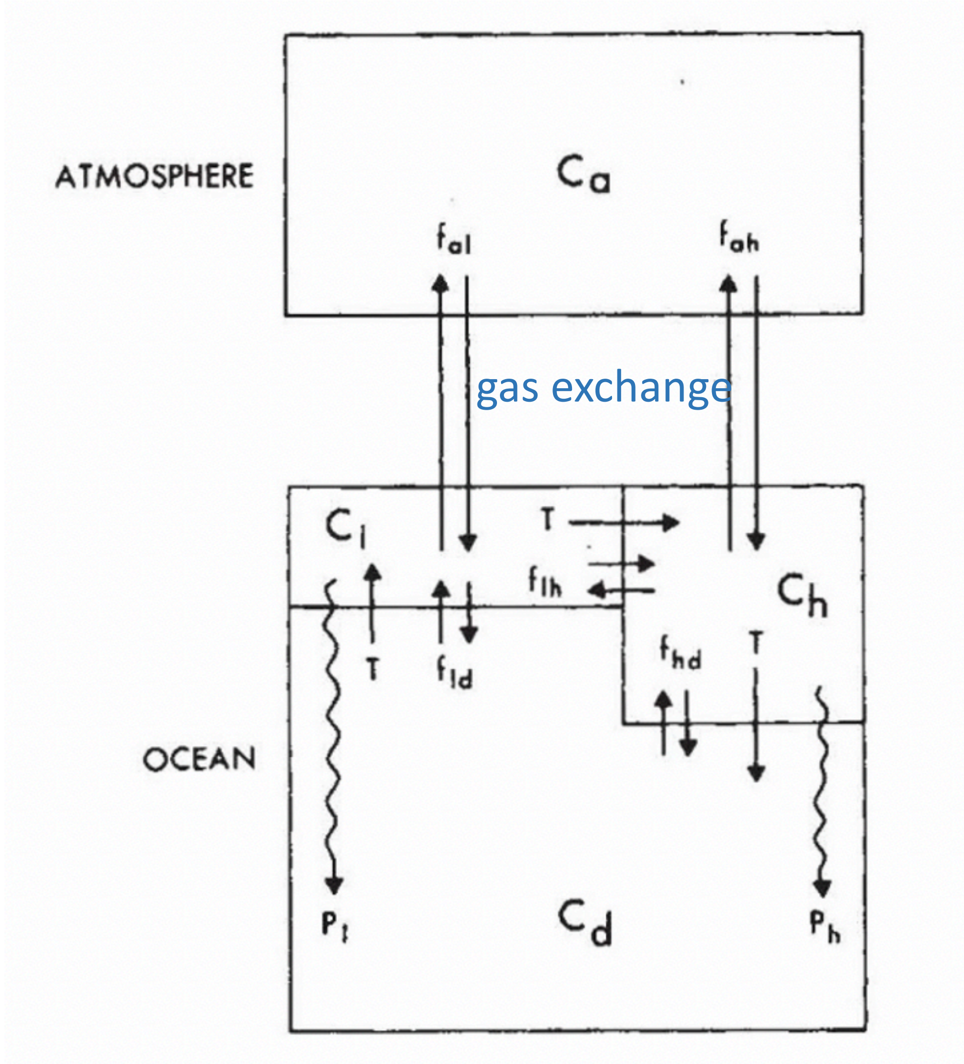
T: overturning

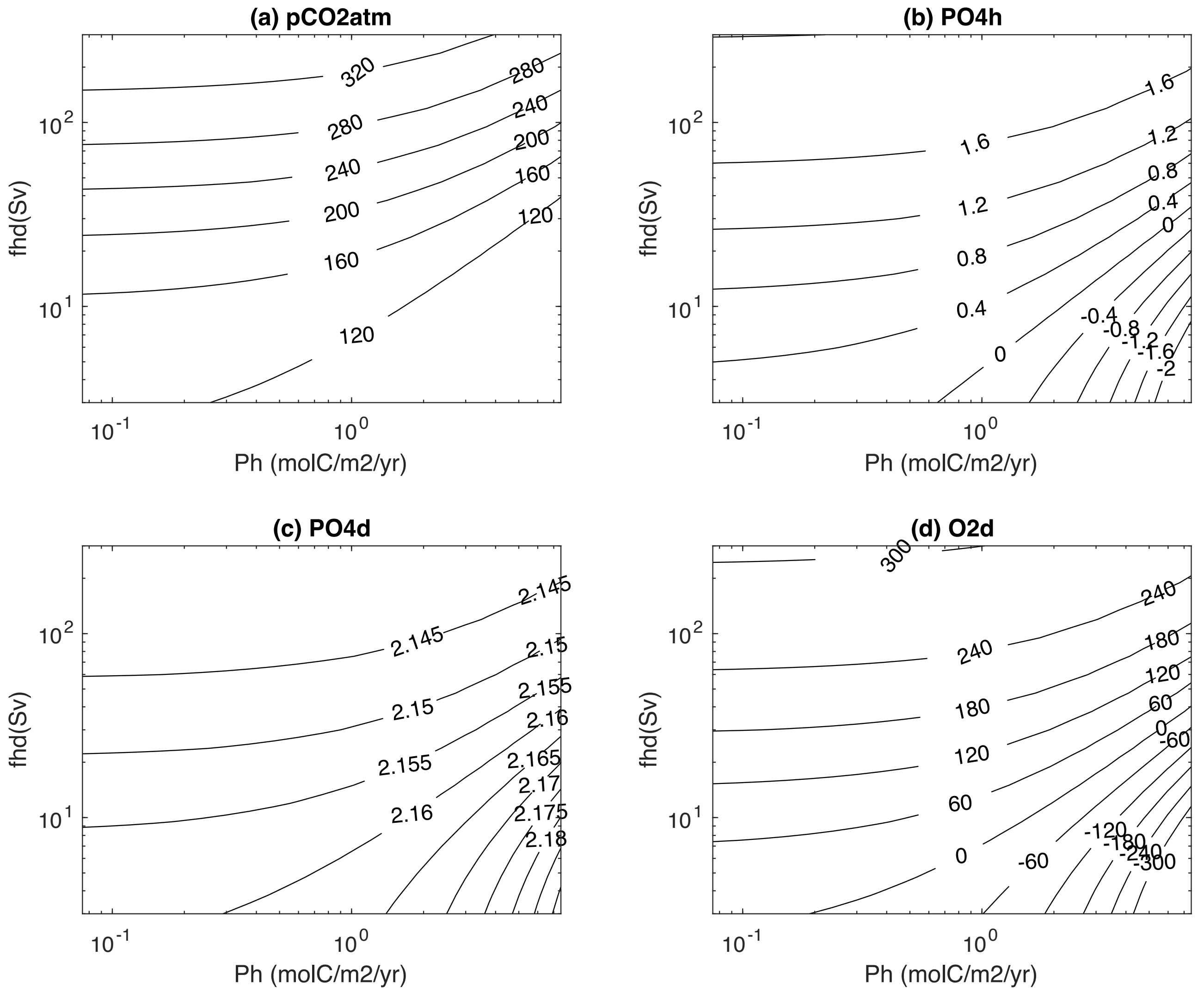
f_{hd},f_{ld}: vertical exchange

P_h / P_l: sinking PO_4 flux/productivity

What models are available?

Box Model

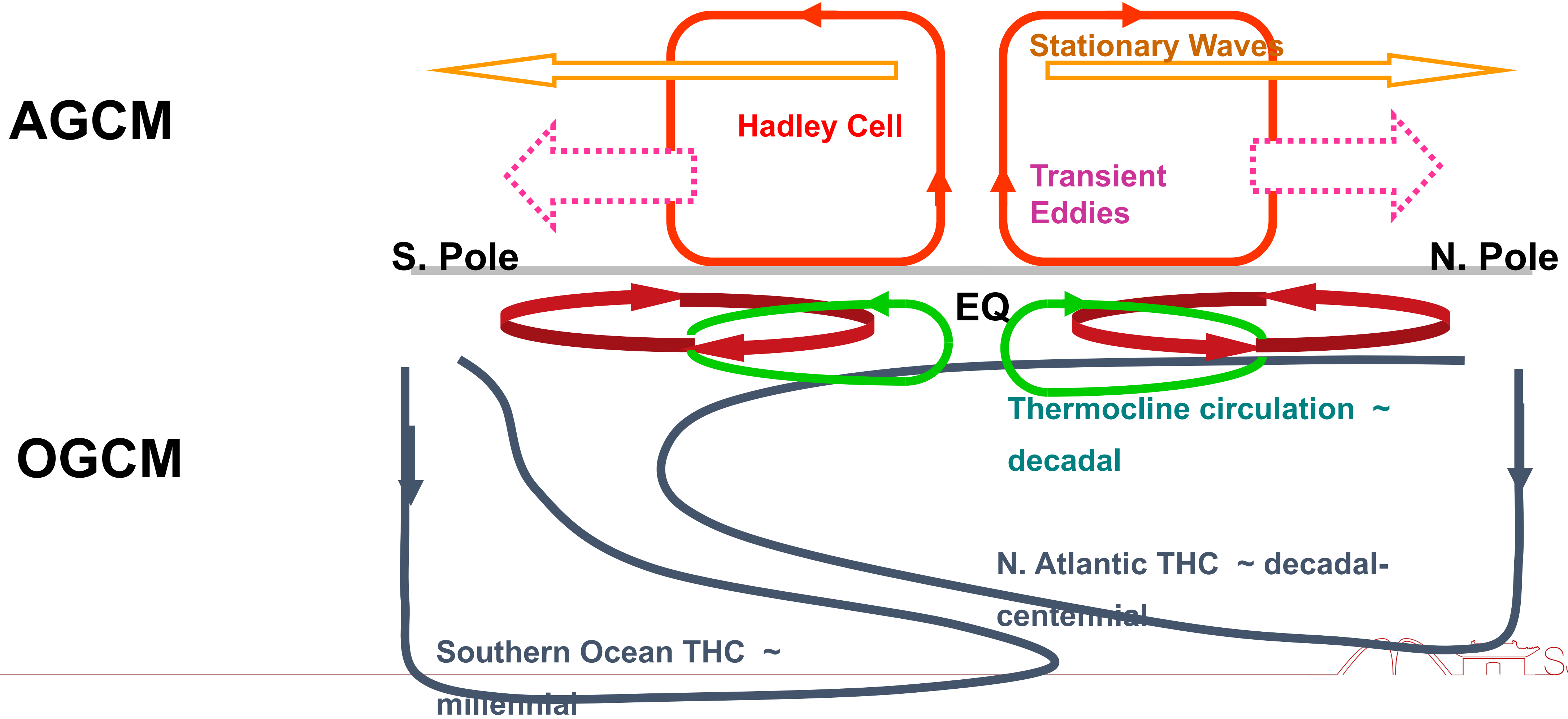




What models are available?

General Circulation Model（GCM）

The Coupled Ocean-Atmosphere System



What models are available?

General Circulation Model （GCM）

Equations

$$\frac{du}{dt} = fv - \frac{1}{\rho}\partial_x p + \frac{1}{\rho}G_x$$

$$\frac{dv}{dt} = -fu - \frac{1}{\rho}\partial_y p + \frac{1}{\rho}G_y$$

$$\frac{dw}{dt} = -g - \frac{1}{\rho}\partial_z p + \frac{1}{\rho}G_z$$

Momentum Equations

$$a = \frac{F}{m}$$

$$\frac{d\rho}{dt} = -\rho\left\{\partial_x u + \partial_y v + \partial_z w\right\}$$ **Mass Equation**

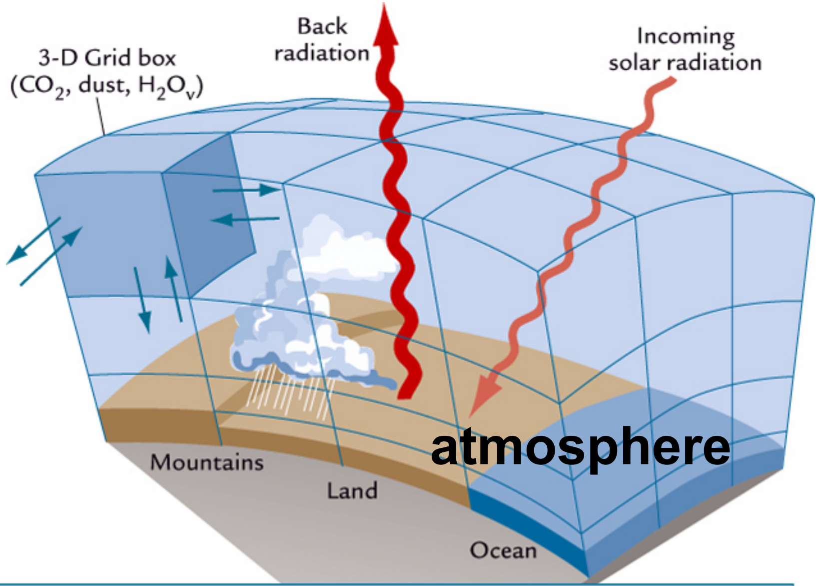
$$\frac{dT}{dt} = Q + k\nabla^2 T$$ **Heat Equation**

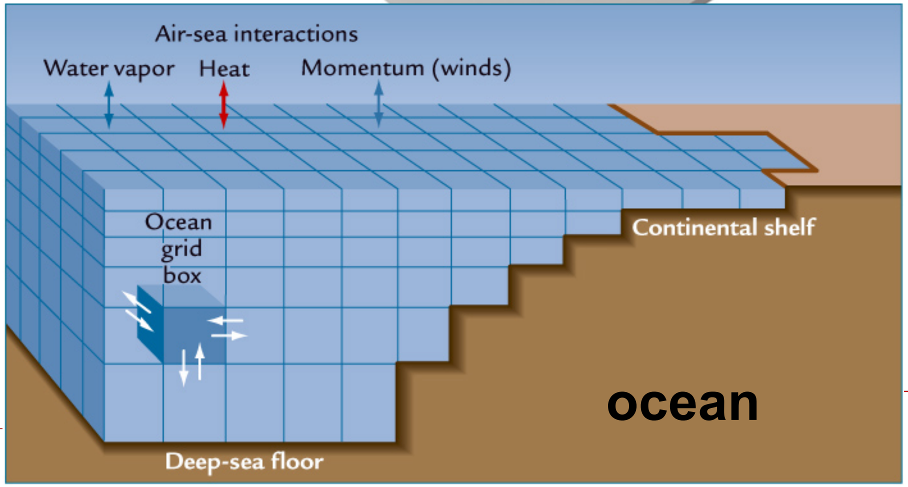
$$\rho \approx \rho_m\left[1 - \alpha\left(T - T_0\right)\right]$$ **Equation of State**

where $\frac{du}{dt} \equiv \partial_t u + u\partial_x u + v\partial_y u + w\partial_z u$

Spatial Discretization

resolution

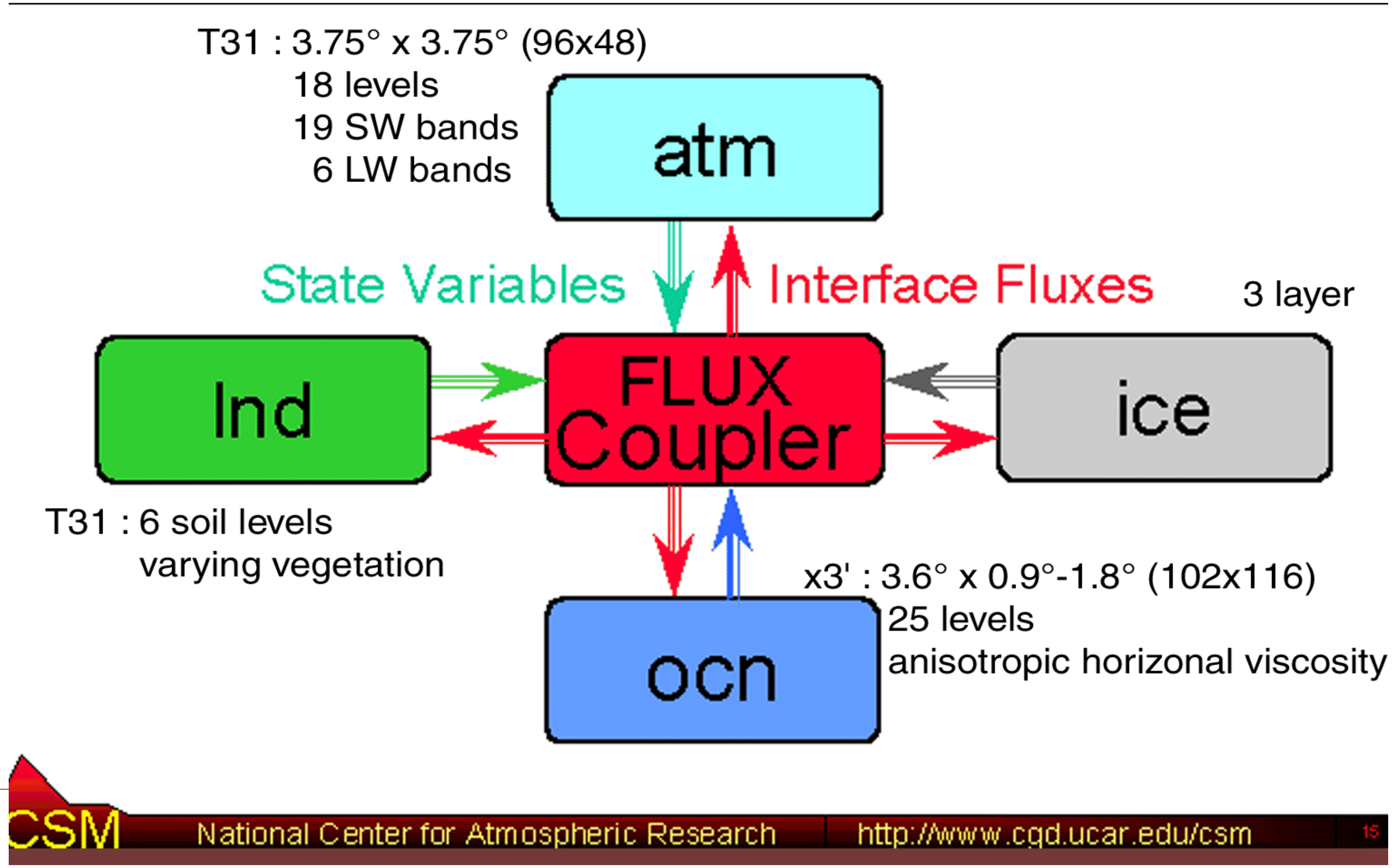


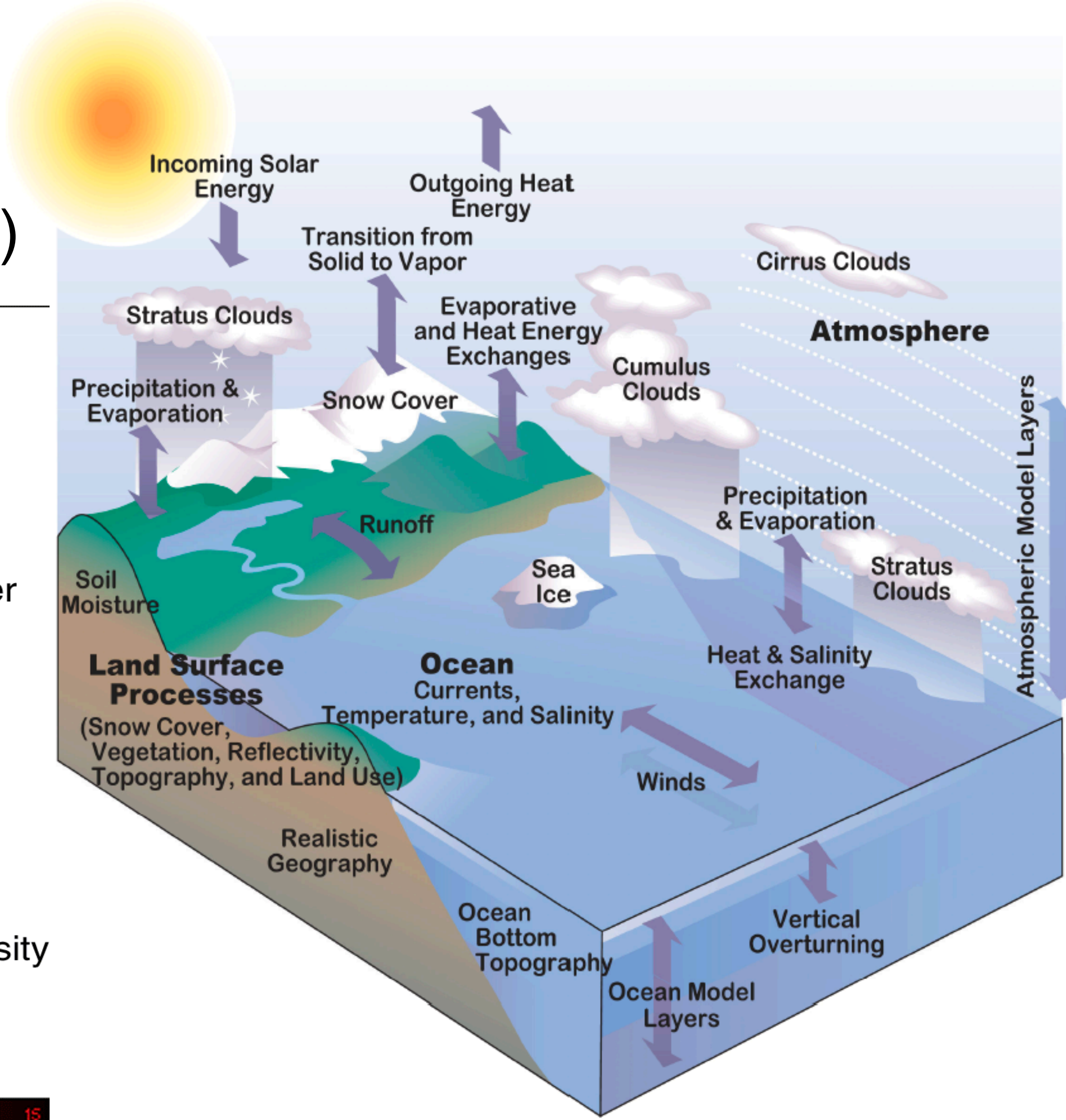


What models are available?

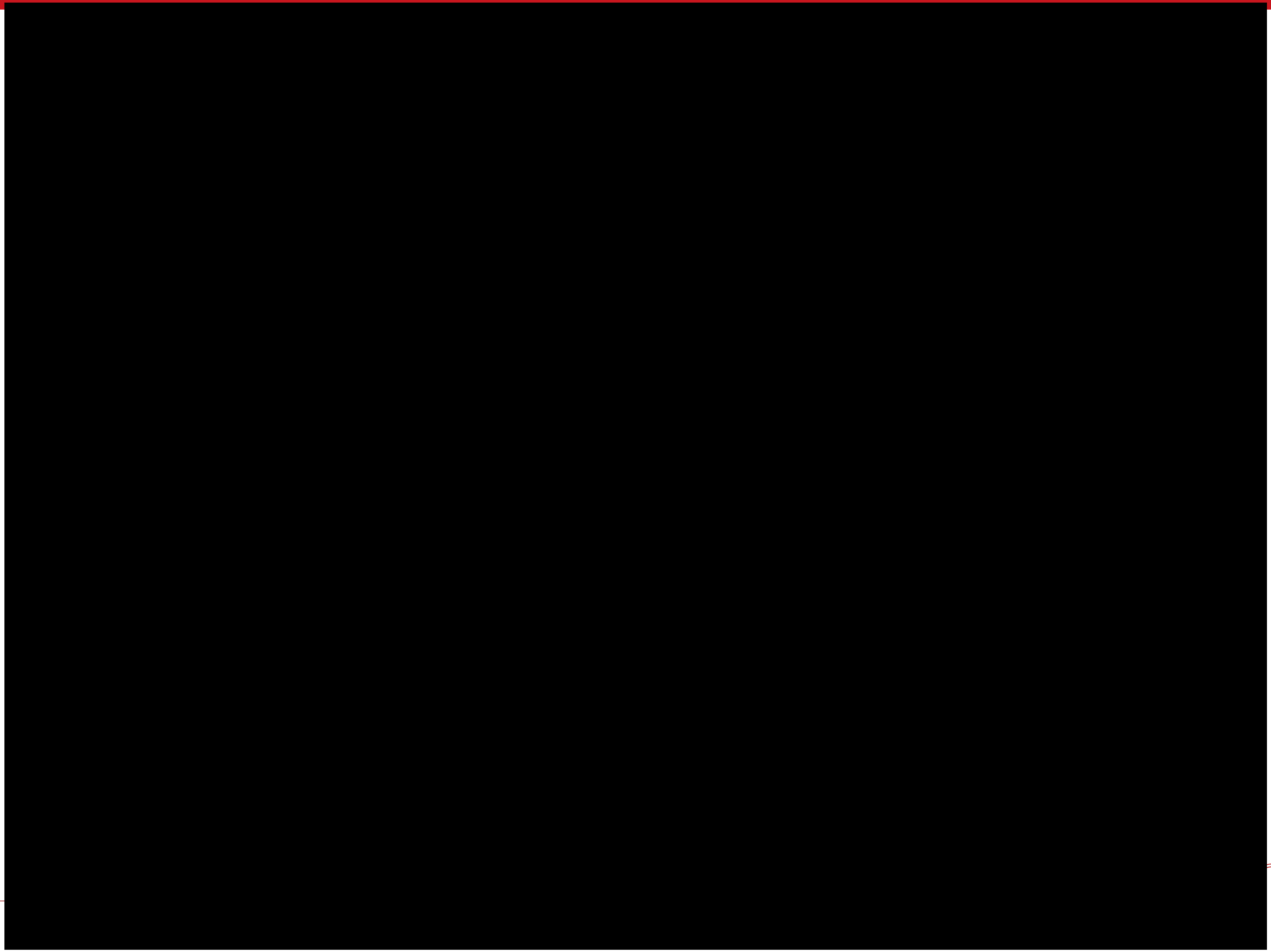
Climate System Model

NCAR Community Climate System Model (CCSM)



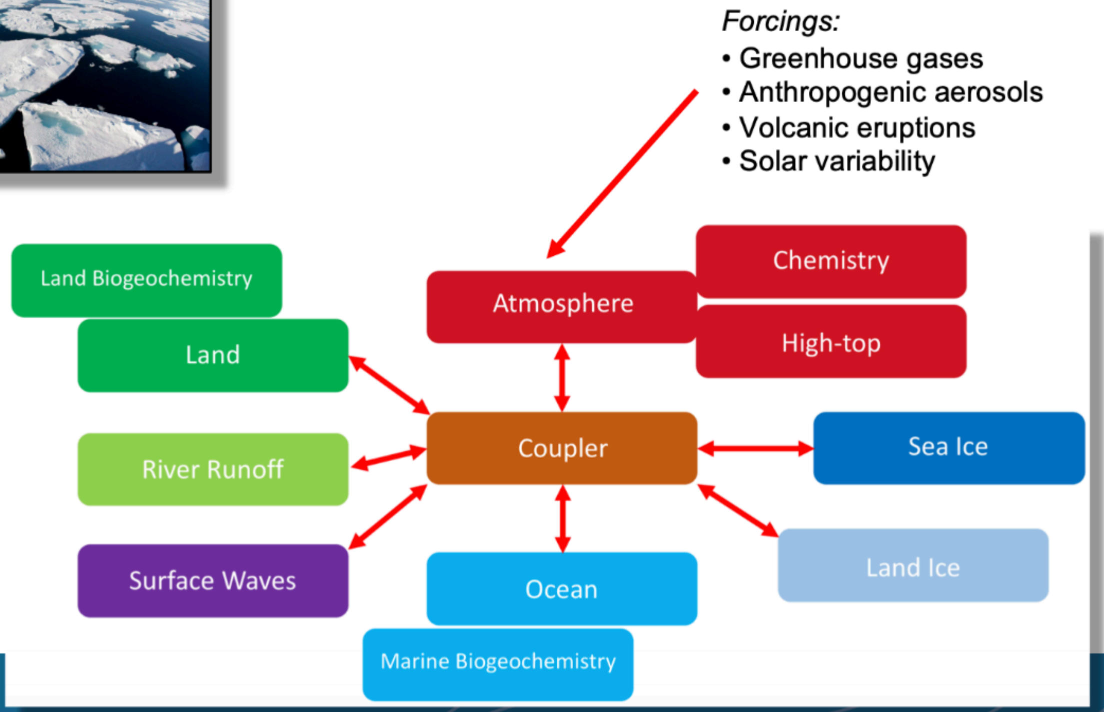


Climate Change simulated by CCSM3



What models are available?

Earth System Model



Community Earth System Model (CESM)

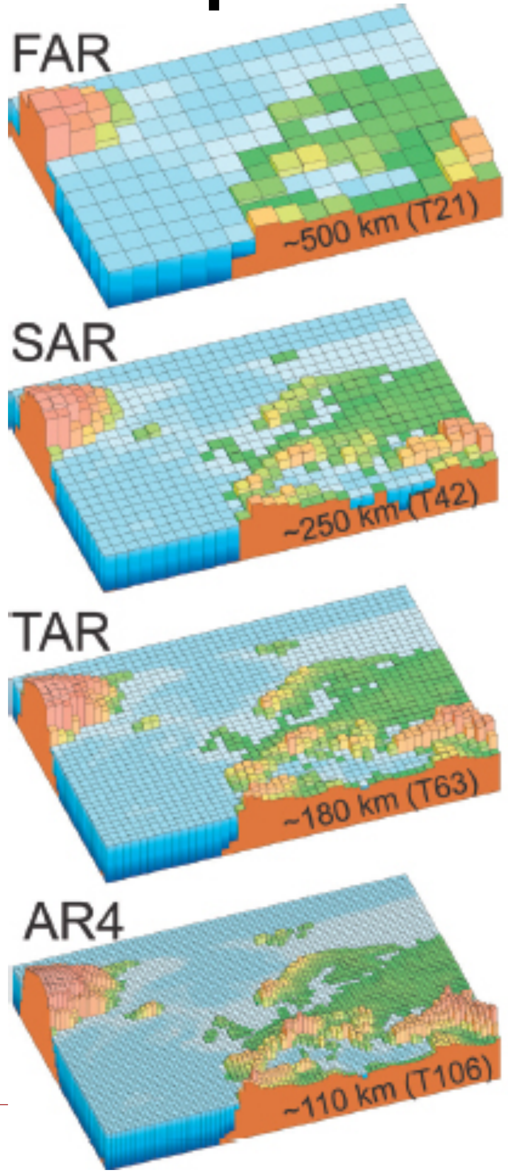
NCAR | UCAR

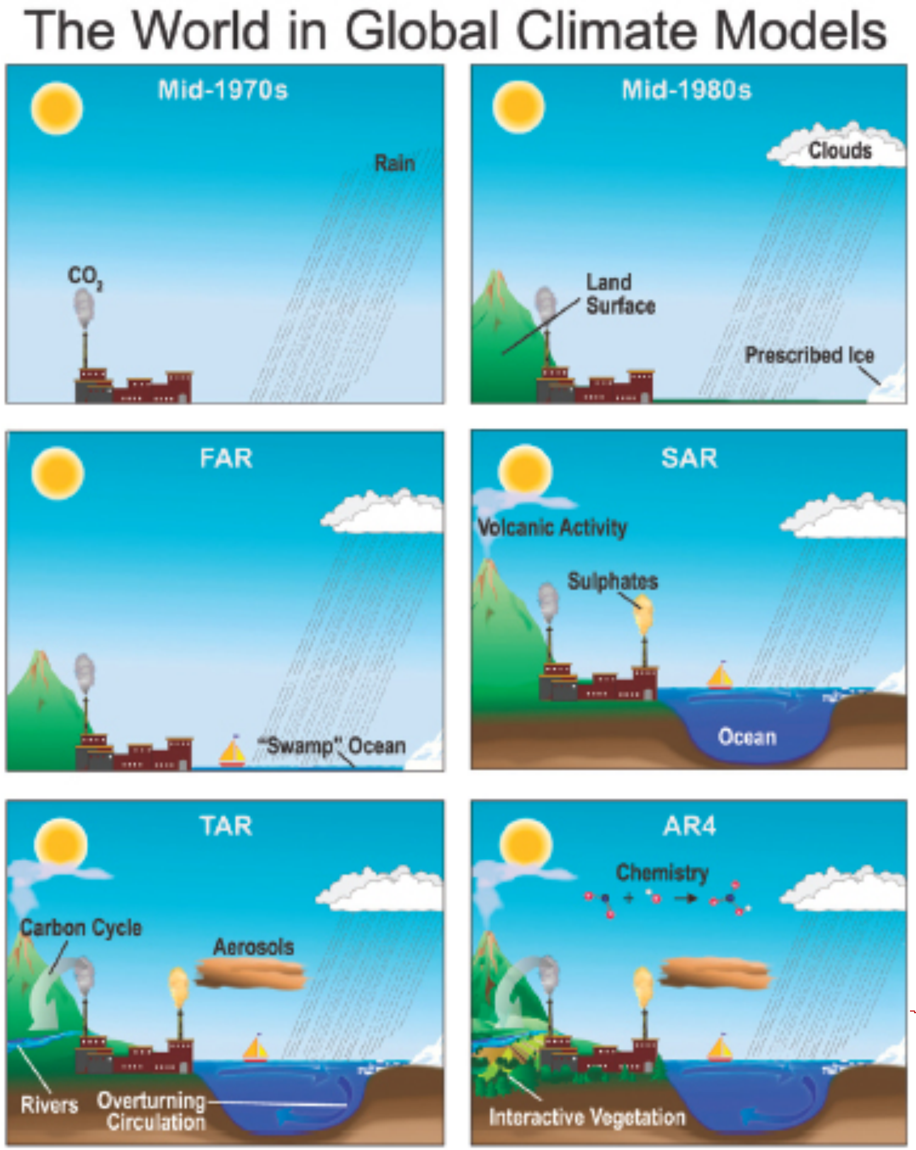
Physical Model
+Chemistry Model
+Ecological Model
+Biogeochemical Model
+Carbon cycle
+......

Interdisciplinary!

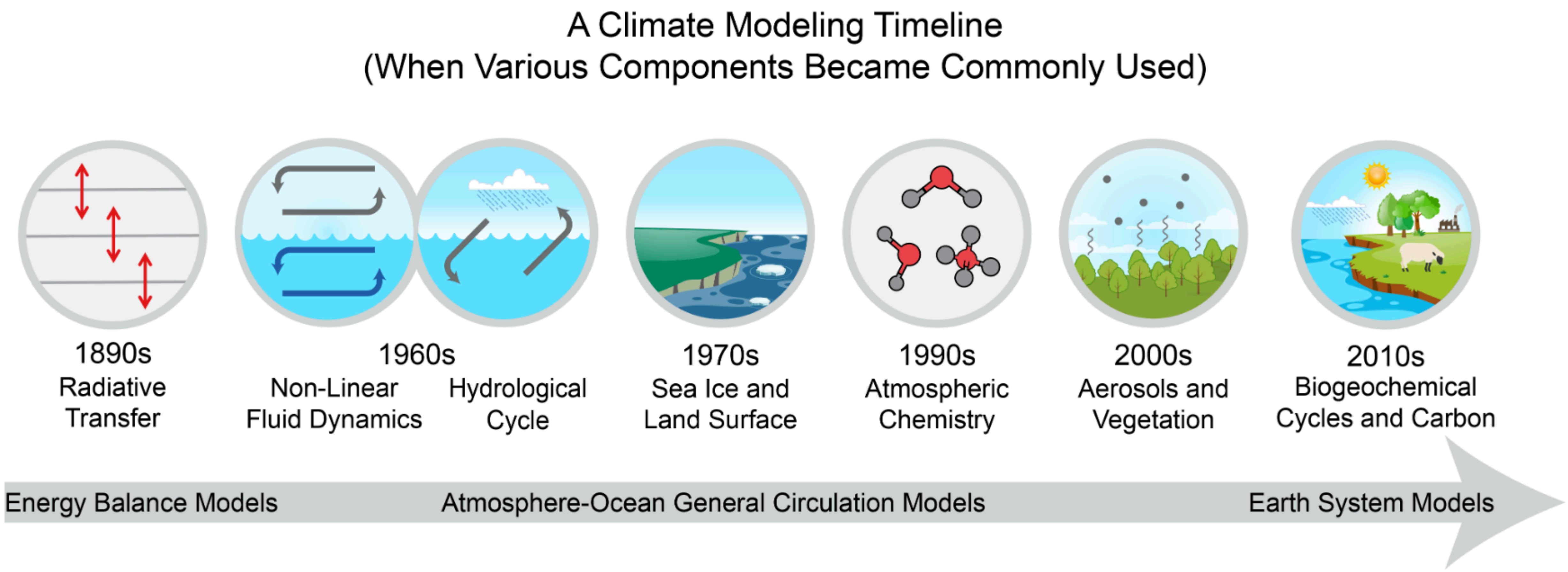
History of climate model development

Increased
Spatial Resolution
& Complexity





History of climate model development



What models are available?

Isotope Enabled Earth System Model

RESEARCH ARTICLE | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES | FREE ACCESS

Younger Dryas cooling and the Greenland climate response to CO_2

Zhengyu Liu, Anders E. Carlson, Feng He, +9, and Jiang Zhu Authors Info & Affiliations

June 25, 2012 | 109 (28) 11101-11104 | https://doi.org/10.1073/pnas.1202183109

Abstract

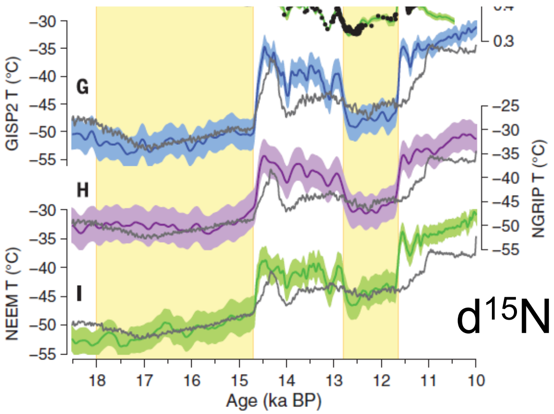
Greenland ice-core $\delta^{18}O$-temperature reconstructions suggest a dramatic cooling during the Younger Dryas (YD; 12.9–11.7 ka), with temperatures being as cold as the earlier Oldest Dryas (OD; 18.0–14.6 ka) despite an approximately 50 ppm rise in atmospheric CO_2. Such YD cooling implies a muted Greenland climate response to atmospheric CO_2, contrary to physical predictions of an enhanced high-latitude response to future increases in CO_2. Here we show that North Atlantic sea surface temperature reconstructions as well as transient climate model simulations suggest that the YD over Greenland should be substantially warmer than the OD by approximately 5 °C in response to increased atmospheric CO_2. Additional experiments with an isotope-enabled model suggest that the apparent YD temperature reconstruction derived from the ice-core $\delta^{18}O$ record is likely an artifact of an altered temperature-$\delta^{18}O$ relationship due to changing deglacial atmospheric circulation. Our results thus suggest that Greenland climate was warmer during the YD relative to the OD in response to rising atmospheric CO_2, consistent with sea surface temperature reconstructions and physical predictions, and has a sensitivity approximately twice that found in climate models for current climate due to an enhanced albedo feedback during the last deglaciation.

Liu et al., 2012, PNAS

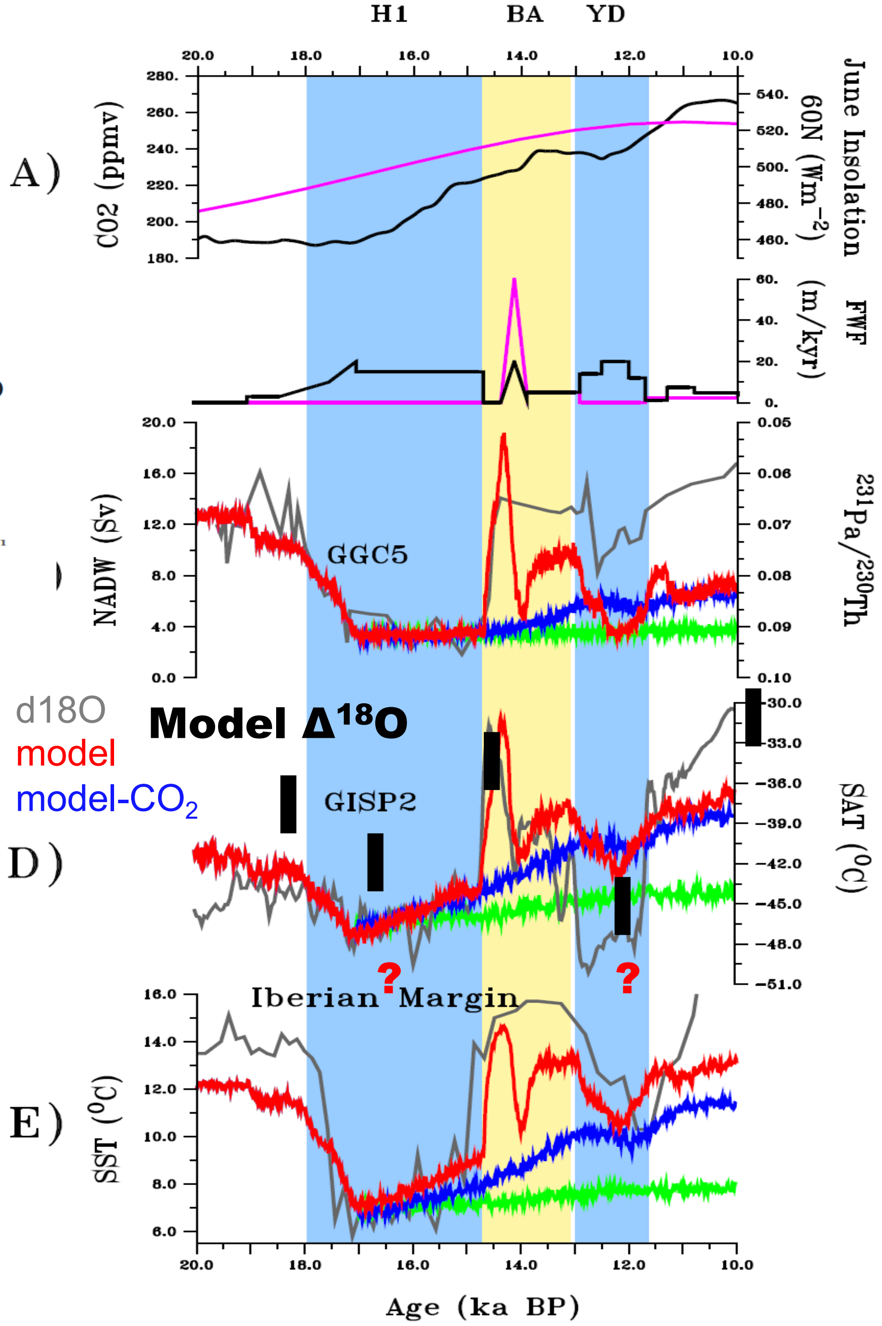
PALEOCLIMATE

Greenland temperature response to climate forcing during the last deglaciation

Christo Buizert,[1*] Vasileios Gkinis,[2,3] Jeffrey P. Severinghaus,[4] Feng He,[5] Benoit S. Lecavalier,[6] Philippe Kindler,[7] Markus Leuenberger,[7] Anders E. Carlson,[1] Bo Vinther,[2] Valérie Masson-Delmotte,[8] James W. C. White,[3] Zhengyu Liu,[5,9] Bette Otto-Bliesner,[10] Edward J. Brook[1]



Buizert et al., 2014, Science

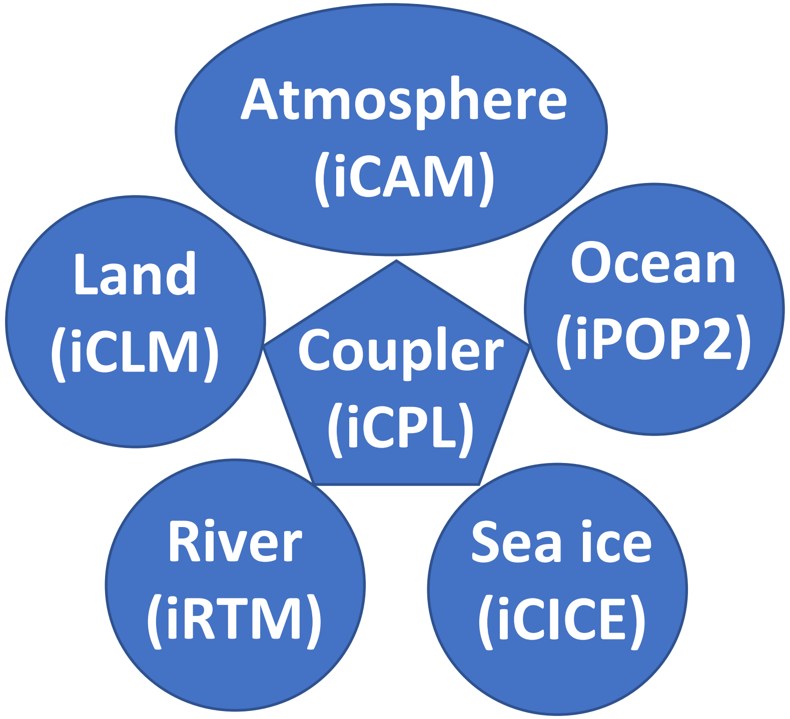


What models are available?

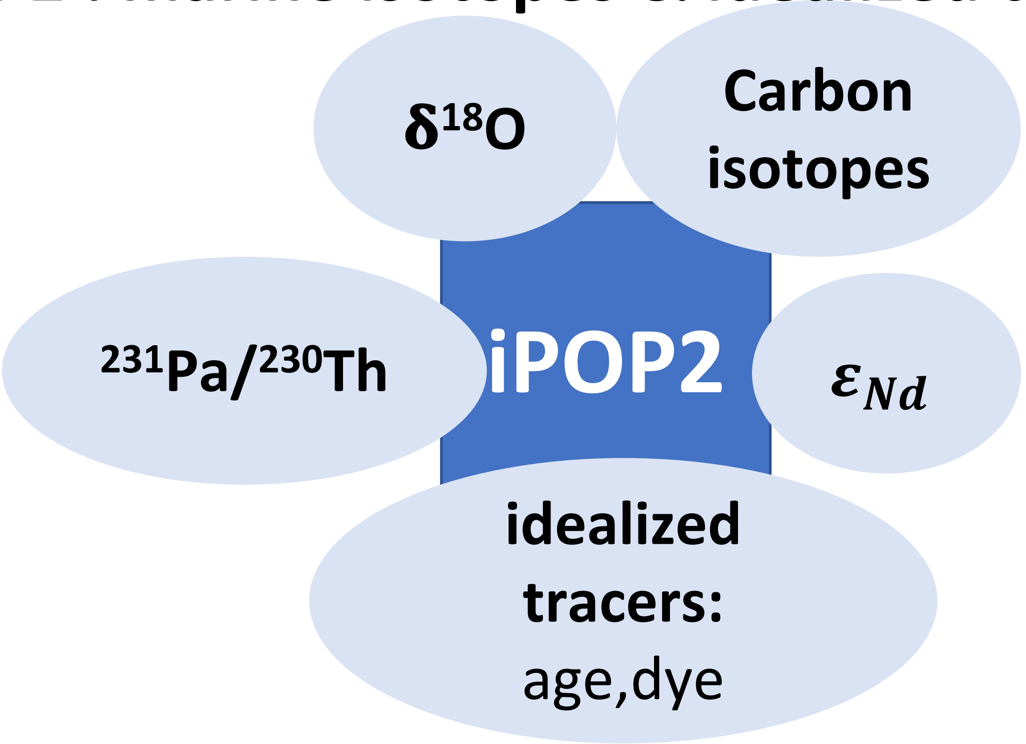
Isotope Enabled Earth System Model

- Model-data comparison
- Interpreting proxy

iCESM : $\delta^{18}O$ & Carbon isotopes



iPOP2 : marine isotopes & idealized tracers



What models are available?

Isotope Enabled Earth System Model： $\delta^{18}O$

- Ocean $\delta^{18}O$: $\boldsymbol{\delta^{18}Ow} = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{VSMOW}} - 1\right] \times 1000$

Precipitation (P,$\boldsymbol{\delta}_P$)

Evaporation (E,$\boldsymbol{\delta}_E$)

River (R,$\boldsymbol{\delta}_R$)

Land Ice Meltwater (M,$\boldsymbol{\delta}_M$)

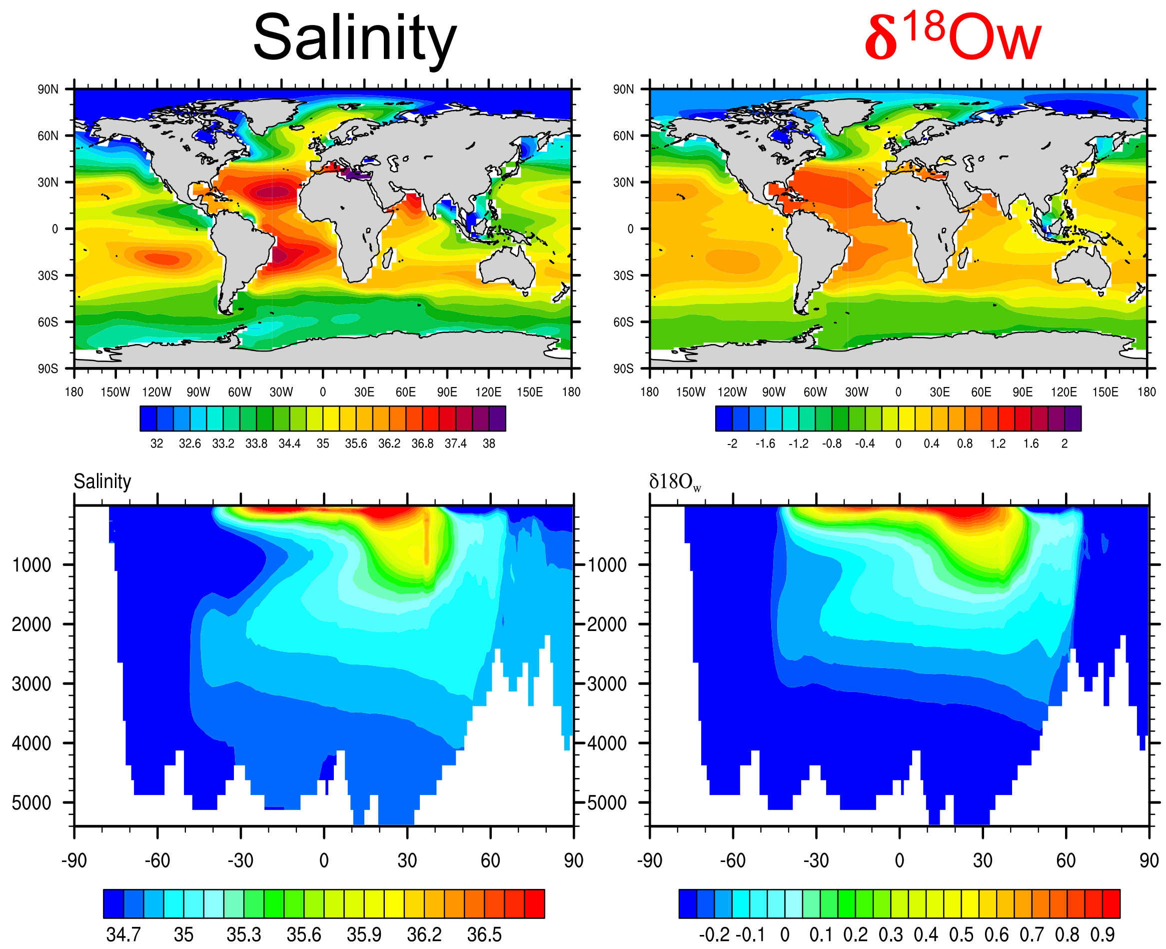
Flux$_\delta$ = $E(\delta_w - \delta_E) - P(\delta_w - \delta_P) - R(\delta_w - \delta_R) - M(\delta_w - \delta_M)$

Surface Ocean ($\boldsymbol{\delta}_W$)

Ocean Interior

$$\begin{cases} \dfrac{\partial \delta}{\partial t} = Transport(\delta) + \dfrac{F_\delta}{rho*dz} & (surface) \\ \dfrac{\partial \delta}{\partial t} = Transport(\delta) & (interior) \end{cases}$$

Zhang et al., PNAS,2017



Modern Control Simulation in CESM

What models are available?

Isotope Enabled Earth System Model：carbon isotopes

Read in atm $\Delta^{14}C$, $\delta^{13}C$ and pCO_2

air-sea gas exchange
(with fractionation)

surface dust deposition

iPOP2

Ecosystem Module

dynamic inorganic carbon chemistry

<u>7 carbon pools (each has ^{14}C and ^{13}C):</u>
DIC, DOC, $CaCO_3$, diazotrophs
small phytoplankton, zooplankton

Sinking particles:
dust, POC, opal, $CaCO_3$

PO_4

O_2

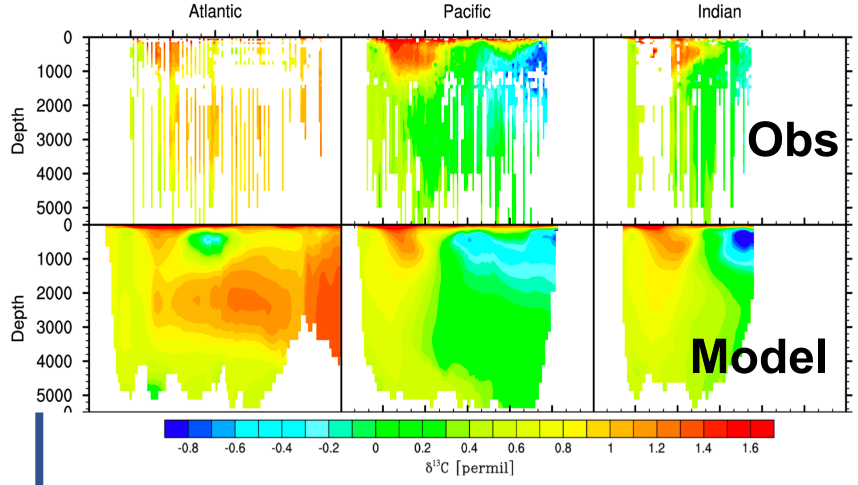
ALK

Iron

dissolved nitrate
……

ammonium

Simulated $\delta^{13}C$ under Modern climate



Jahn et al., 2015, GMD

What models are available?

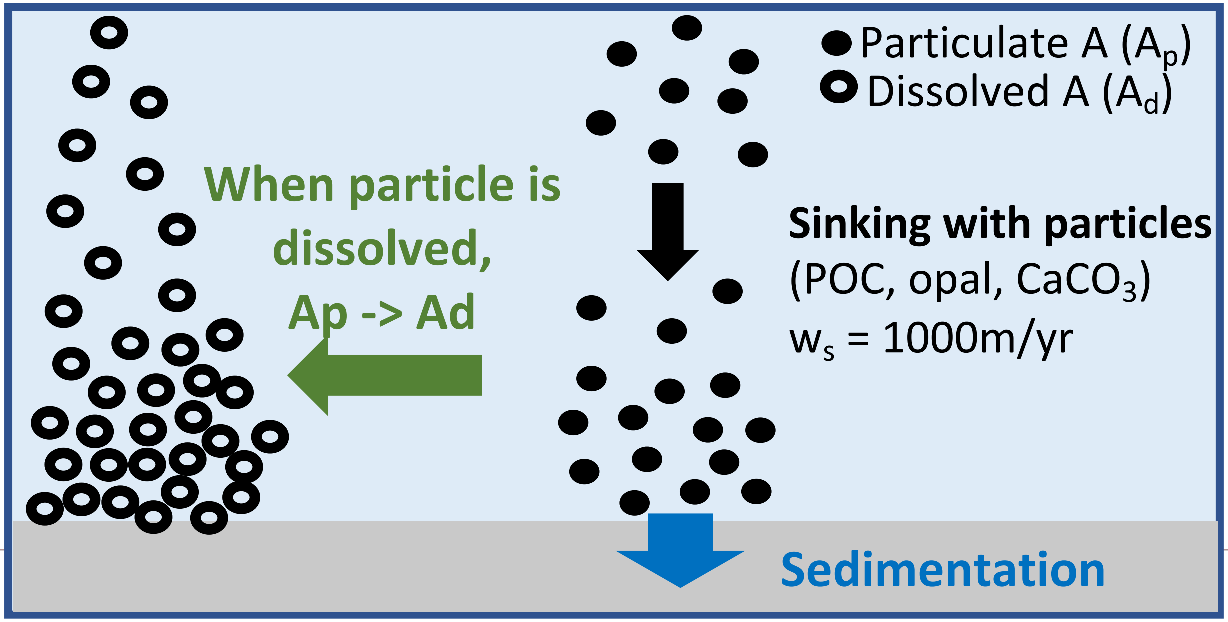
Isotope Enabled Earth System Model： $^{231}Pa/^{230}Th$

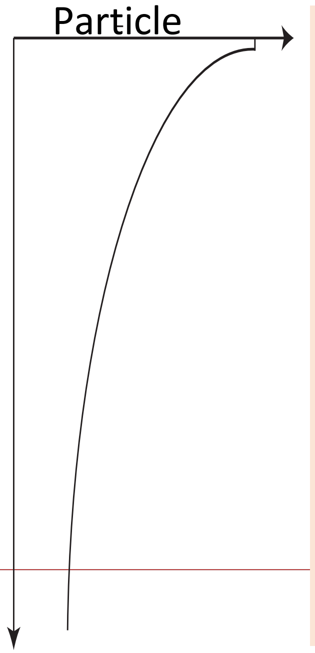
Reversible Scavenging (Bacon&Anderson, 1982):

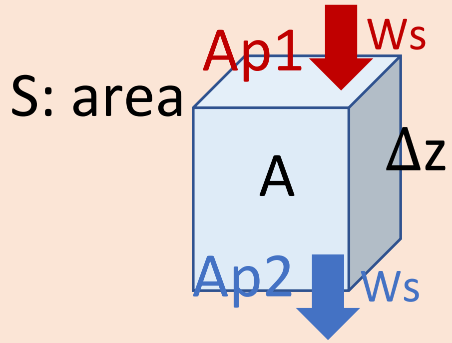
adsorption of isotopes onto sinking particles and desorption after the dissolution of particles

$$[A] = [A]_d + [A]_p,\ A{:}\ ^{231}Pa,\ ^{230}Th$$

$$\frac{[A]_p}{[A]_d} = K_i * R_i,\ i = POC, opal, Calcite,\ \mathrm{R} = \frac{particle\ concentration}{density\ of\ seawater},\quad K:\text{partition coefficient}$$







Limited time Δt:

in: Ap1*S*Ws*Δt out: Ap2*S*Ws*Δt

box change: ΔA*S*dz

=in-out=(Ap1- Ap2)*S*Ws*Δt

$$\rightarrow \frac{\Delta A}{\Delta t} = \frac{\mathrm{Ap1} - \mathrm{Ap2}}{\Delta z} w_s = -w_s \frac{\partial A_p}{\partial z}$$

What models are available?

Isotope Enabled Earth System Model： $^{231}Pa/^{230}Th$

- $^{235}U \rightarrow ^{231}Pa$, $^{234}U \rightarrow ^{230}Th$ produced with a constant rate (β) uniformly in the ocean: $\frac{\beta_{Pa}}{\beta_{Th}} = 0.093$.
- Radioactive decay ($\lambda_{Pa} = 2.13\times10^{-5}$, $\lambda_{Th} = 9.22\times10^{-6}$)
- Reversible scavenging: $-w_s\frac{\partial A_p}{\partial z}$

$$\begin{cases} \frac{\partial[Pa]}{\partial t} = \beta_{Pa} - \lambda_{Pa}[Pa] - w_s\frac{\partial[Pa]_p}{\partial z} + Transport \\ \frac{\partial[Th]}{\partial t} = \beta_{Th} - \lambda_{Th}[Pa] - w_s\frac{\partial[Th]_p}{\partial z} + Transport \end{cases}$$

$[A] = [A]_d + [A]_p$,

$\frac{[A]_p}{[A]_d} = K_i * R_i, i = POC, opal, Calcite$, $\mathrm{R} = \frac{particle\ concentration}{density\ of\ seawater}$, K : partition coefficient

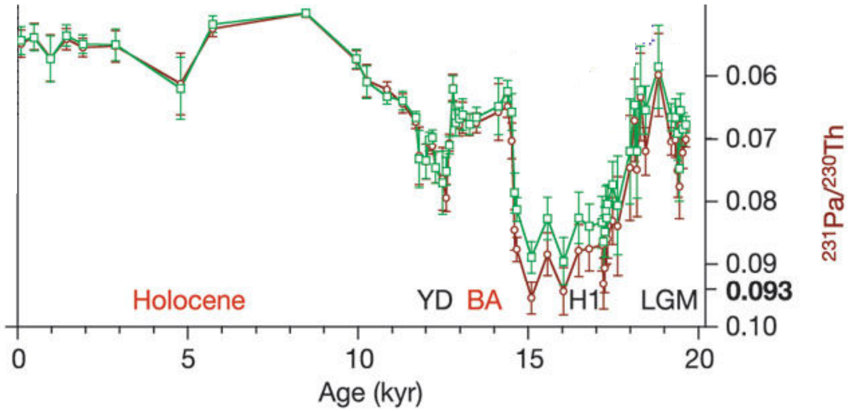
What models are available?

Isotope Enabled Earth System Model： $^{231}Pa/^{230}Th$

If **No ocean transport**, and neglect the decay term, at equilibrium

$$\begin{cases} \cancel{\dfrac{\partial [Pa]}{\partial t}} = \beta_{Pa} - \cancel{\lambda_{Pa}[Pa]} - w_s \dfrac{\partial [Pa]_p}{\partial z} + \cancel{Transport} \\ \cancel{\dfrac{\partial [Th]}{\partial t}} = \beta_{Th} - \cancel{\lambda_{Th}[Pa]} - w_s \dfrac{\partial [Th]_p}{\partial z} + \cancel{Transport} \end{cases}$$

AMOC↓,
Transport ↓
Pa/Th ↑ ,→0.093



McManus et al., 2004,Nature

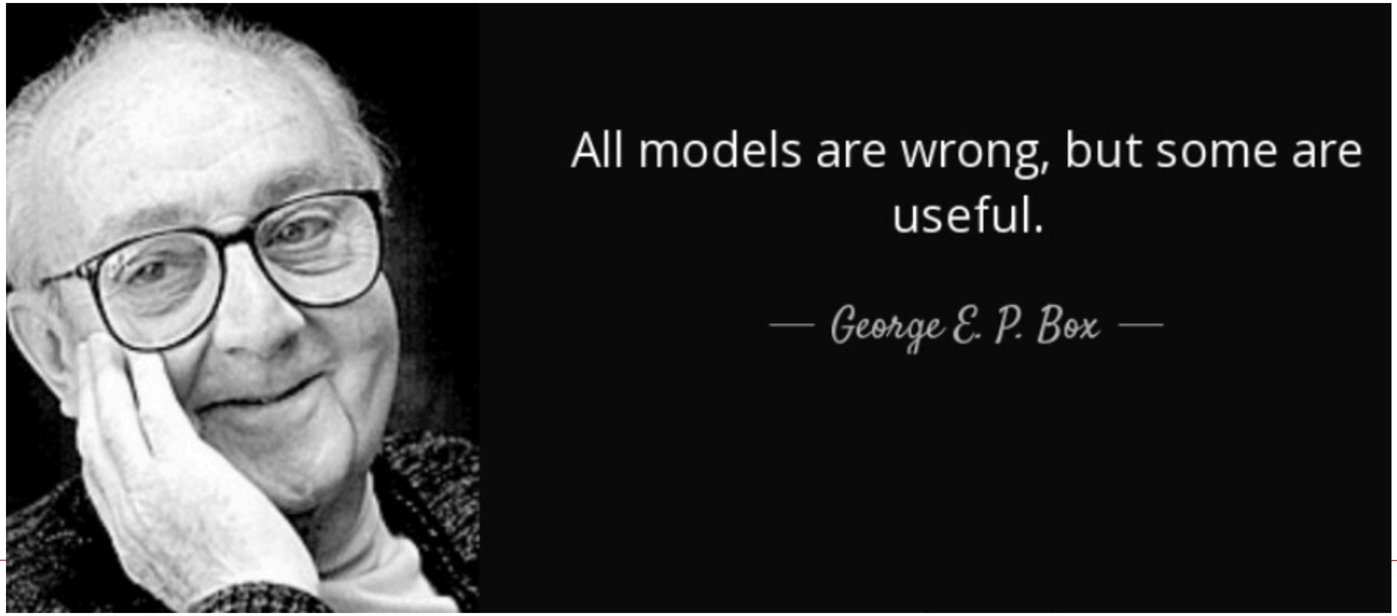
$$\begin{cases} \dfrac{\partial [Pa]_p}{\partial z} = \dfrac{\beta_{Pa}}{w_s} \\ \dfrac{\partial [Th]_p}{\partial z} = \dfrac{\beta_{Th}}{w_s} \end{cases} \xrightarrow[{[]_p \approx 0 \; at\ surface}]{} \begin{cases} [Pa]_p(z) = \dfrac{\beta_{Pa}}{w_s} z \\ [Th]_p(z) = \dfrac{\beta_{Th}}{w_s} z \end{cases}$$

$$\Rightarrow \frac{[Pa]_p}{[Th]_p} = \frac{\beta_{Pa}}{\beta_{Th}} = \mathbf{0.093}$$

What models are available?

- Radiative Equilibrium Model/Energy Balance Model
- Radiative Convective Model
- Box Model
- General Circulation Model （GCM）
- Climate System Model
- Earth System Model

No perfect model!
A model for a purpose!



Why simple models?

- **Computational Cost**

Simple models

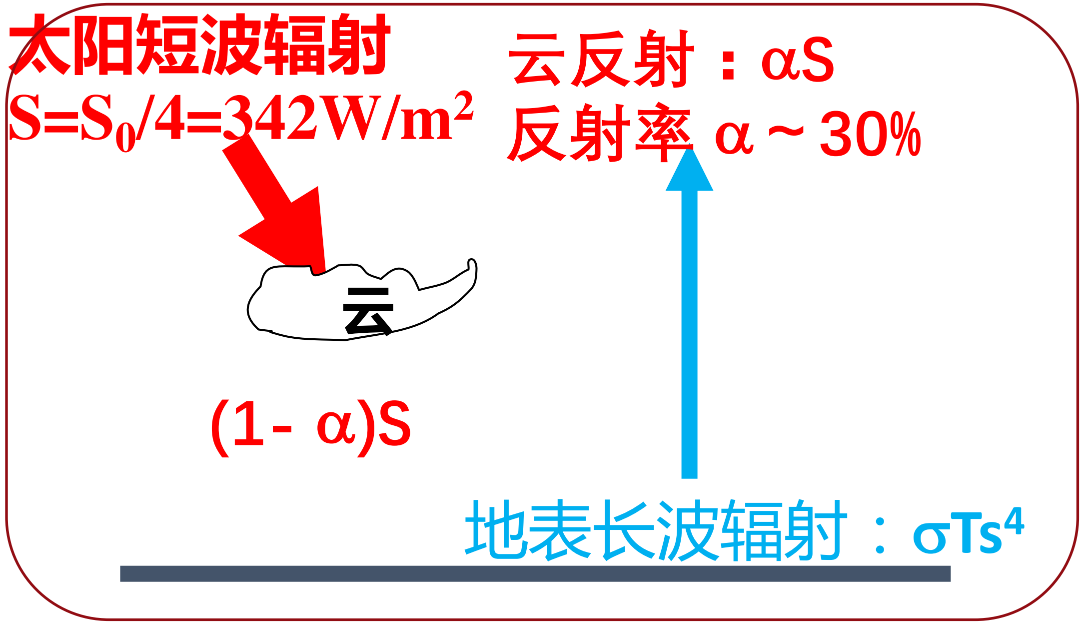
GCMS

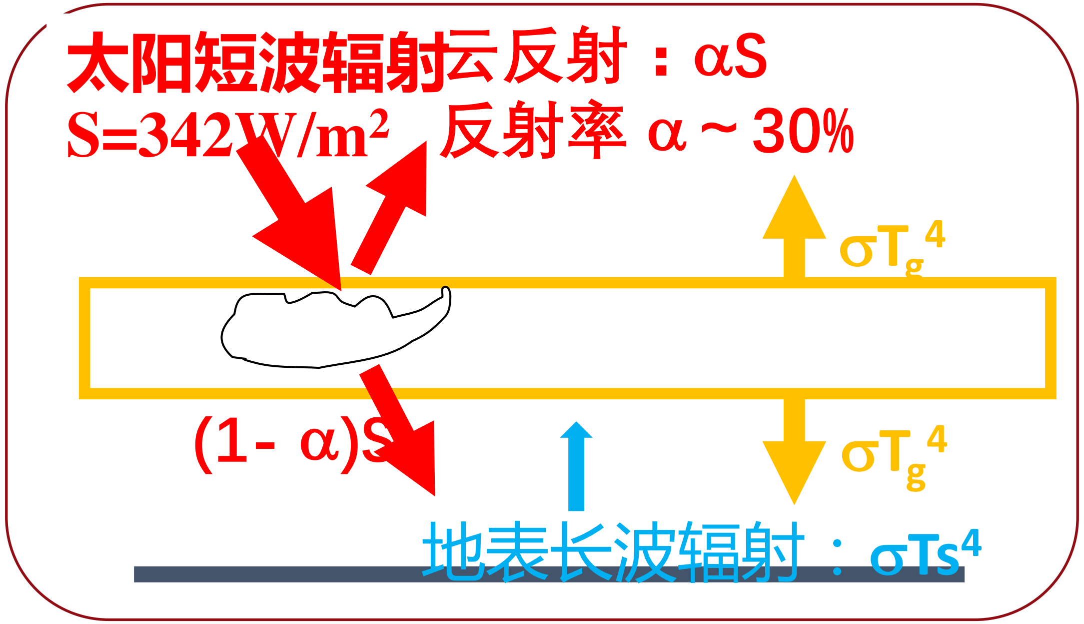
计算，存储

Why simple models?

- **Physical Insights**

Energy balance model for explaining Greenhouse effect





$(1-\alpha)S = \sigma T_s^4$

$T_s = -18^oC$

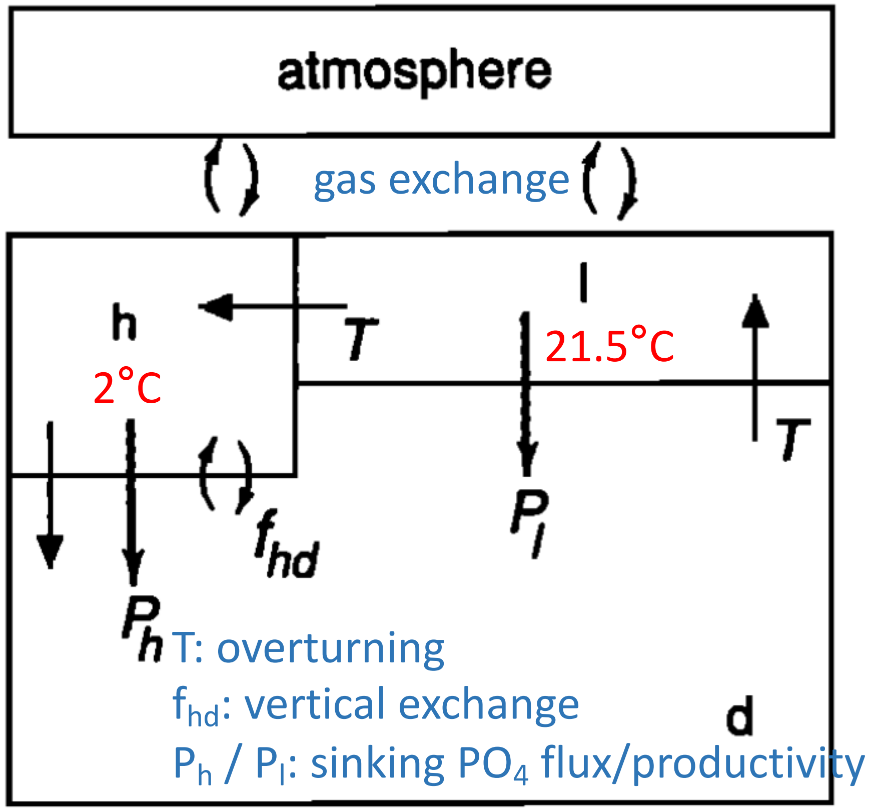
地表：$(1-\alpha)S + \sigma T_g^4 = \sigma T_s^4$

大气：$2\sigma T_g^4 = \sigma T_s^4$

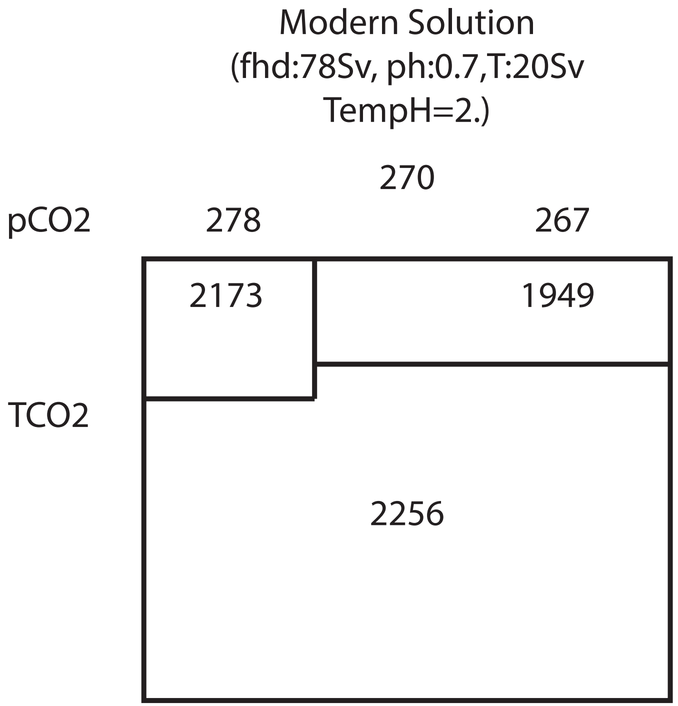
$T_s = 30^oC$，$T_g = -18^oC$

Why simple models?

- **Physical Insights** Box Model for understanding LGM CO2 drawdown



Sarmiento & Toggweiler, 1984, Nature



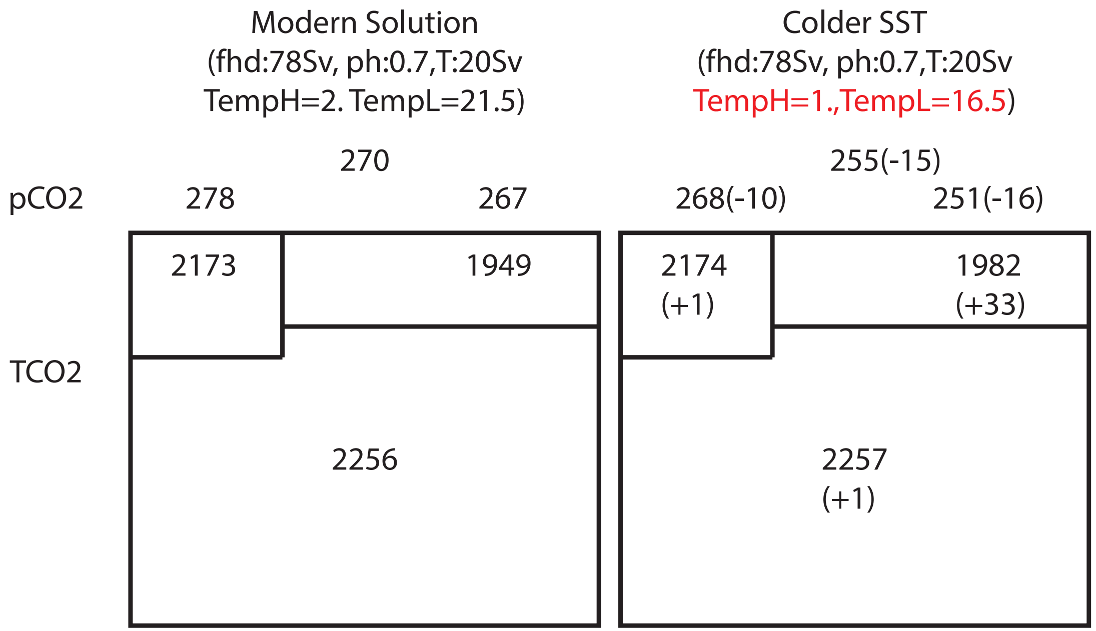
Potential Mechanism (magnitude unclear!)

- Temperature
- Stratification f_{hd}
- Gas exchange
- Productivity P_h

Why simple models?

- **Physical Insights** Box Model for understanding LGM CO2 drawdown

Colder SST, increased solubility

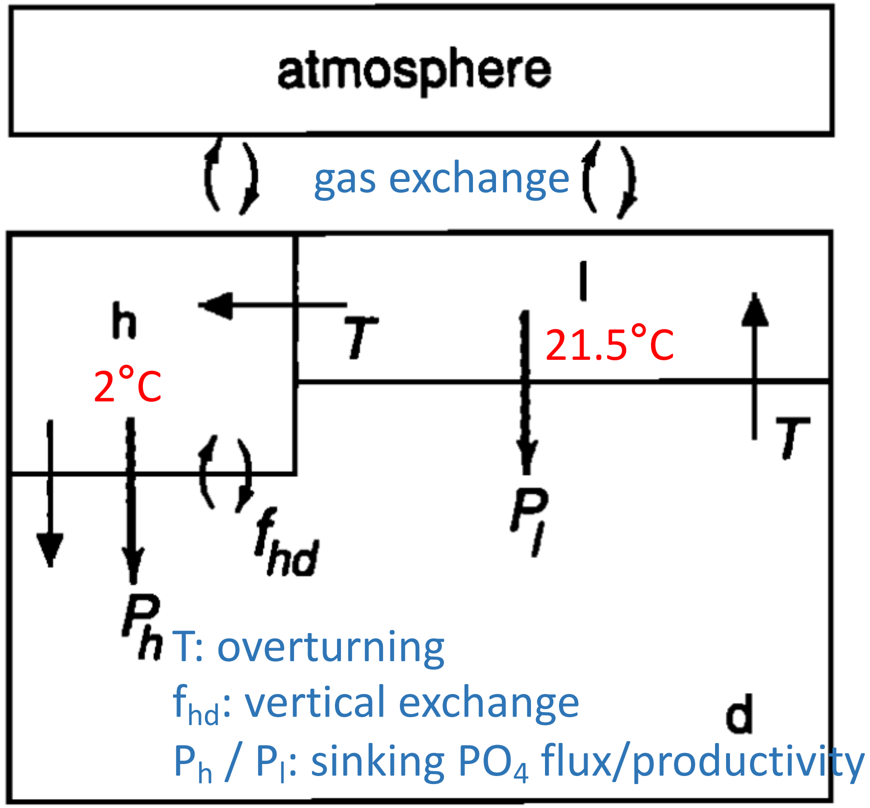


Colder temperature can explain ~10-16 ppm (e.g., Brovkin et al. 2007, Paleo; Marzocchi&Jansen, 2019, NGeo)

Very minor!

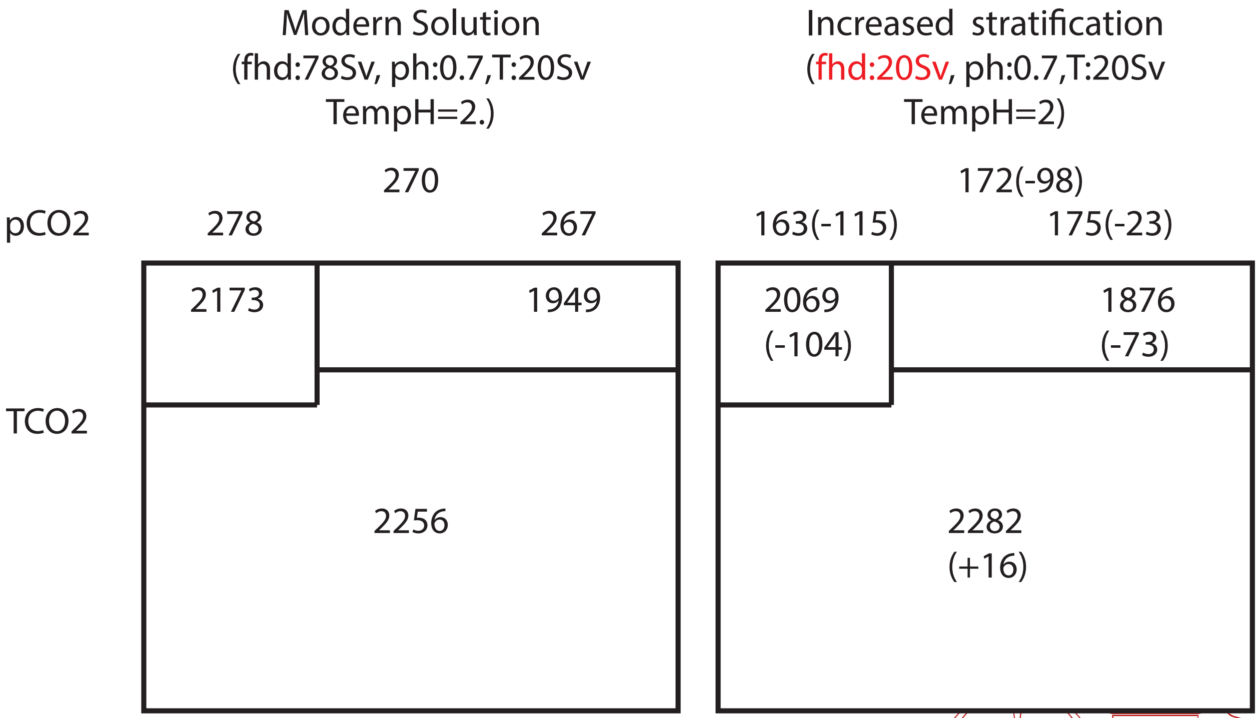
Why simple models?

- **Physical Insights** Box Model for understanding LGM CO2 drawdown



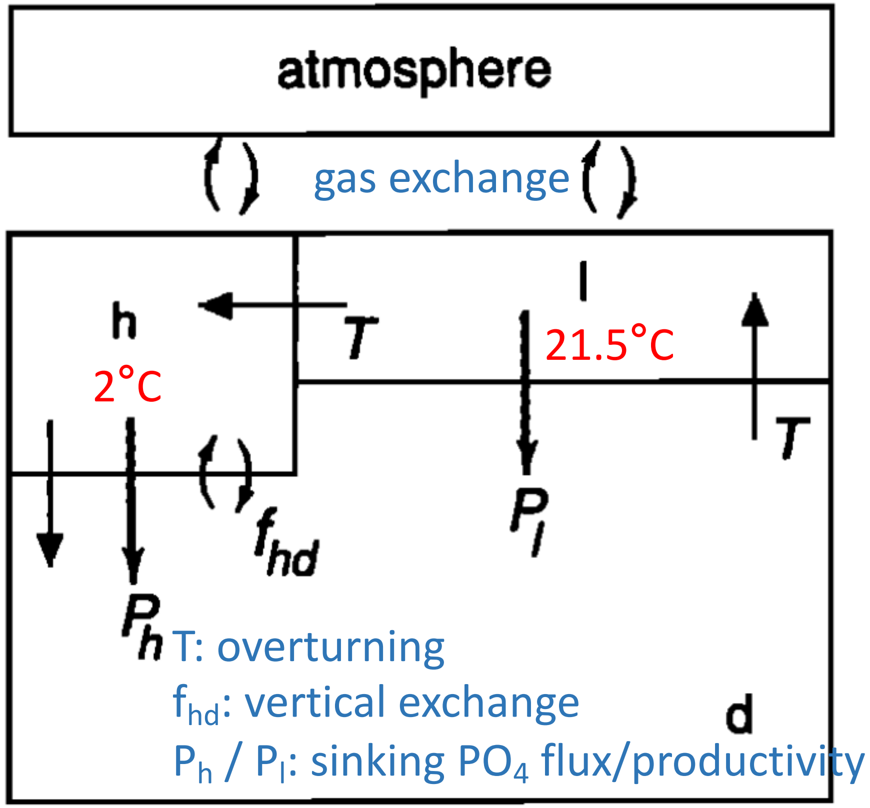
Sarmiento & Toggweiler, 1984, Nature

Increased stratification, reduced upwelling of DIC rich deep water in SO, reduced outgassing



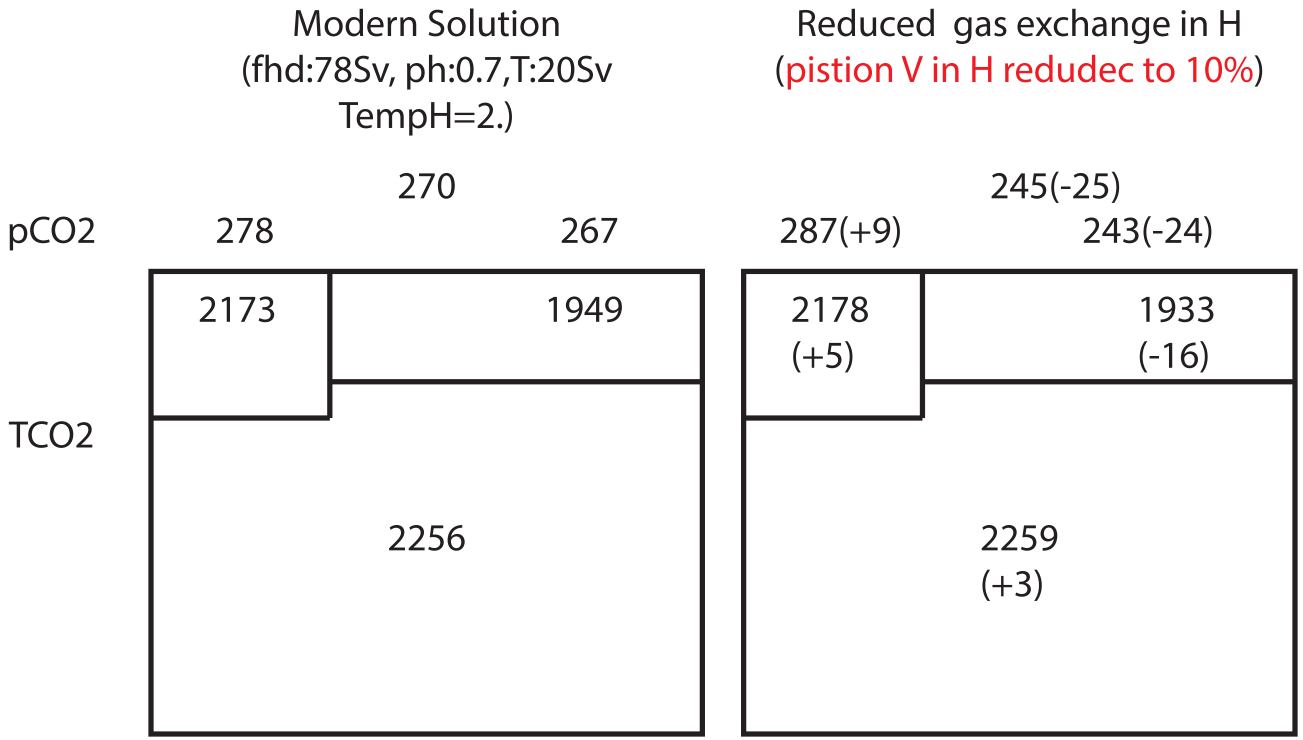
Why simple models?

- **Physical Insights** Box Model for understanding LGM CO_2 drawdown



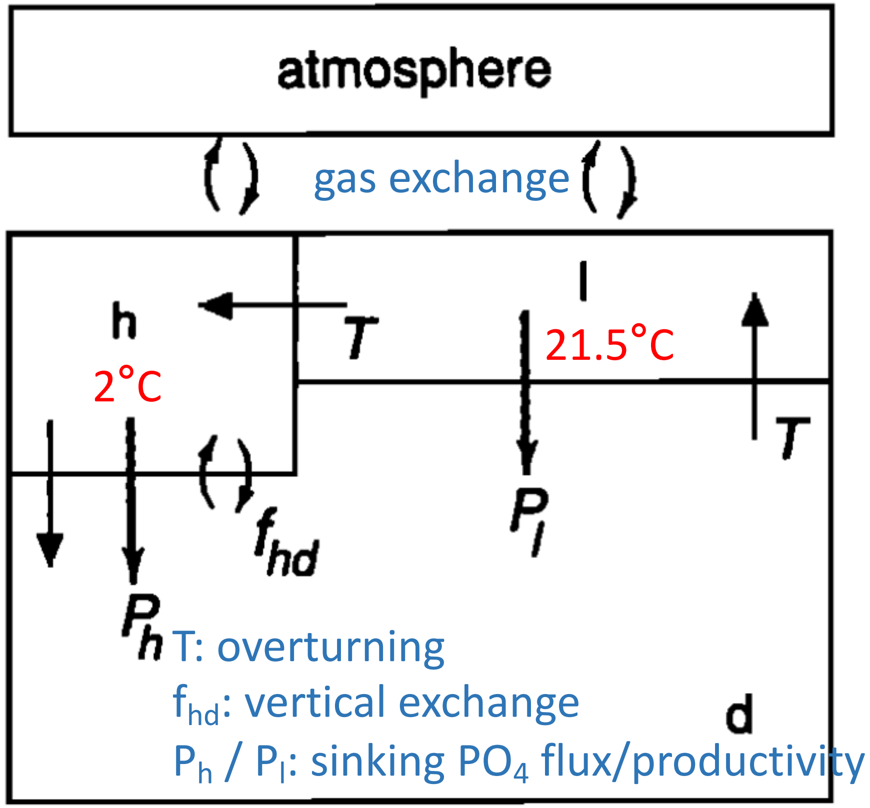
Sarmiento & Toggweiler, 1984, Nature

Reduced air-sea gas exchange, reduced outgassing



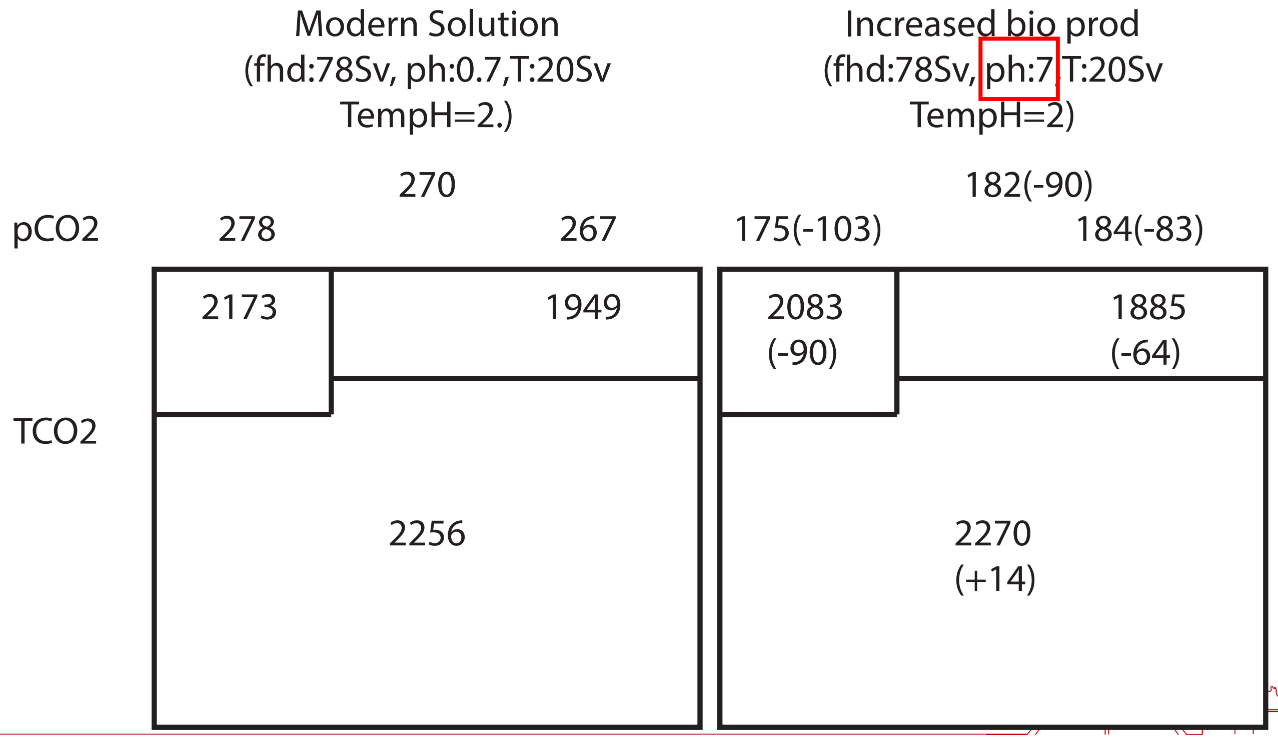
Why simple models?

- **Physical Insights** Box Model for understanding LGM CO_2 drawdown



Sarmiento & Toggweiler, 1984, Nature

Iron Fertilization, increased productivity, increased biological pump



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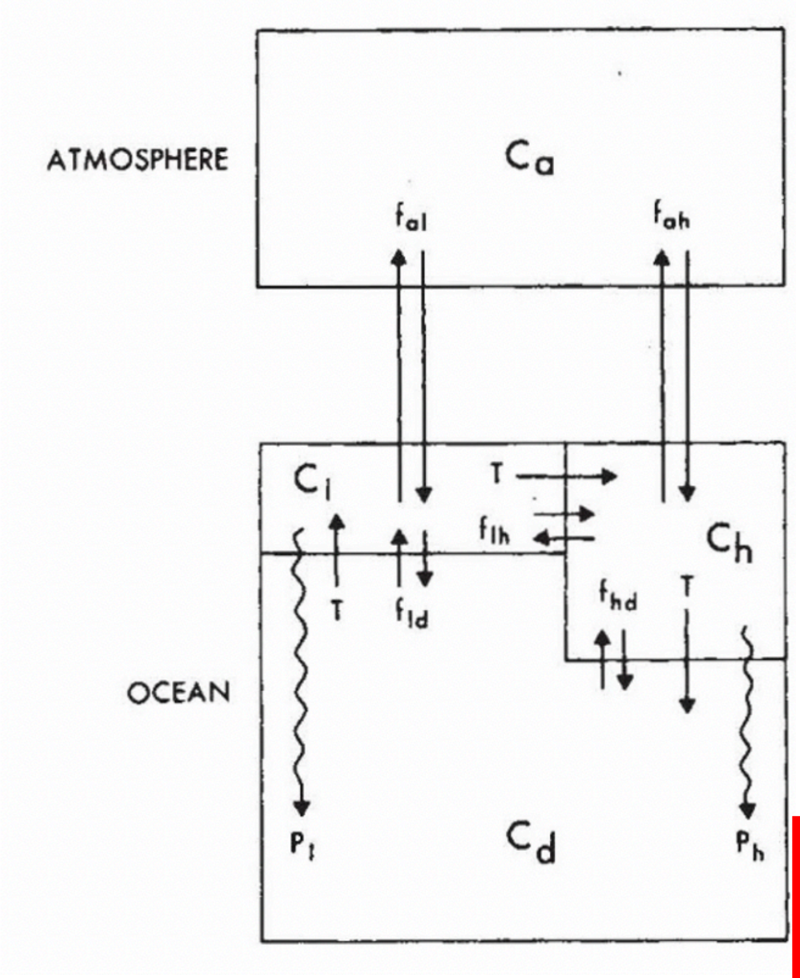

A new model for the role of the oceans in determining atmospheric P_{CO_2}

J. L. Sarmiento & J. R. Toggweiler

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Recent ice-core measurements have revealed that the atmospheric CO_2 level increased comparatively rapidly by about 70 p.p.m. at the end of the last ice age[1]. Here we present an ocean–atmosphere model in which changes in the productivity of high latitude surface waters (from which deep water is formed and circulated around the world's ocean) and/or in the thermohaline overturning rate can lead to substantial changes in atmospheric partial pressure of carbon dioxide (P_{CO_2}), over a concentration range 163–425 p.p.m. A major contribution to the low P_{CO_2} of the last ice age may have been an increase in the net high latitude productivity, possibly coupled with a decrease in the thermohaline overturning.

Potential Mechanism

- Temperature (-15)
- Stratification (-98)
- Gas exchange (-25)
- Productivity (-90)

How to evaluate models?

1. Specify input to climate model

Choose boundary conditions based on known changes of solar radiation, CO_2, ice sheets, mountains, and continent positions

→

2. Run model simulation of ocean and atmosphere

Internal operation of model based on physical laws of radiation and circulation of fluids (ocean and atmosphere)

→

3. Analyze climate-data output

Model-simulated changes in temperature, precipitation, winds, pressure

Compare: ↕

Data from Earth's climate history (sediments, ice cores, corals, tree rings, etc.)

Data from modern times (instrumental measurements)

→

Climate interpreted from independent geologic data

and reanalysis data

How to evaluate models?

Model-Data mismatch?

The Holocene temperature conundrum

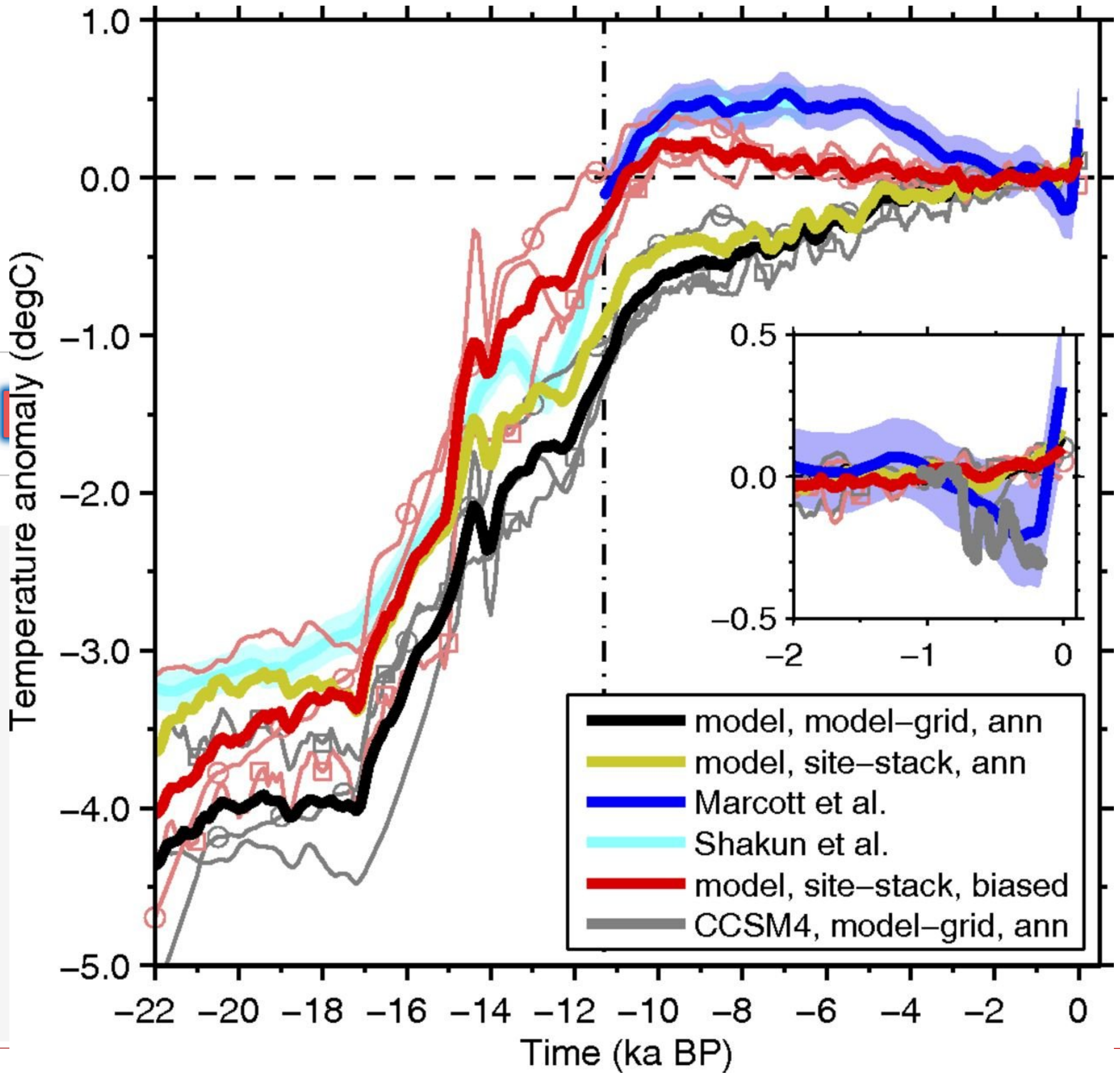
Zhengyu Liu, Jiang Zhu, Yair Rosenthal, +6 , and Oliver Elison Timm Authors Info & Affiliations

August 11, 2014 | 111 (34) E3501-E3505 | https://doi.org/10.1073/pnas.1407229111

Significance

Marine and terrestrial proxy records suggest global cooling during the Late Holocene, following the peak warming of the Holocene Thermal Maximum (~10 to 6 ka) until the rapid warming induced by increasing anthropogenic greenhouses gases. However, the physical mechanism responsible for this global cooling has remained elusive. Here, we show that climate models simulate a robust global annual mean warming in the Holocene, mainly in response to rising CO_2 and the retreat of ice sheets. This model-data inconsistency demands a critical reexamination of both proxy data and models.

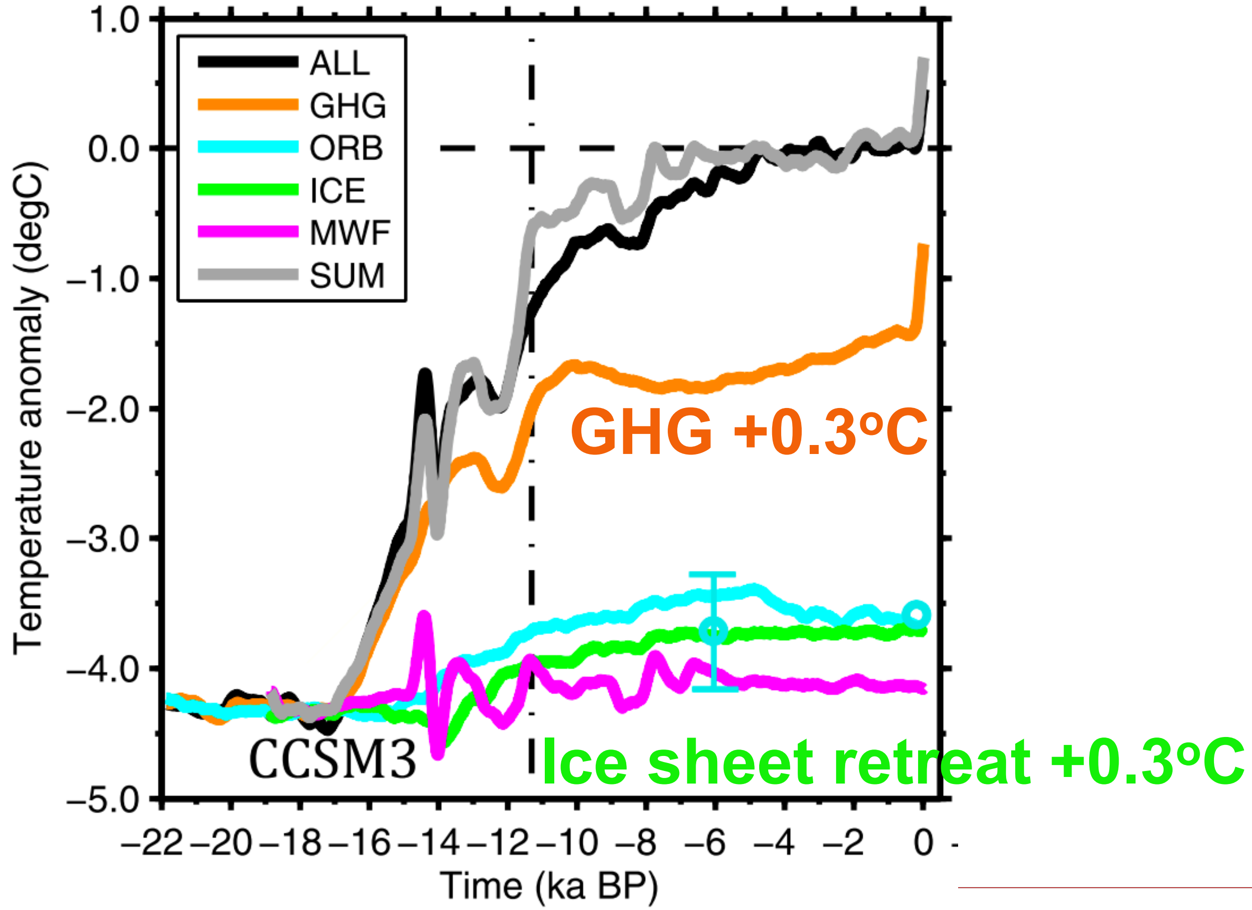
Global Mean & Annual Mean



How to evaluate models?

Model-Data mismatch?

The Holocene temperature conundrum



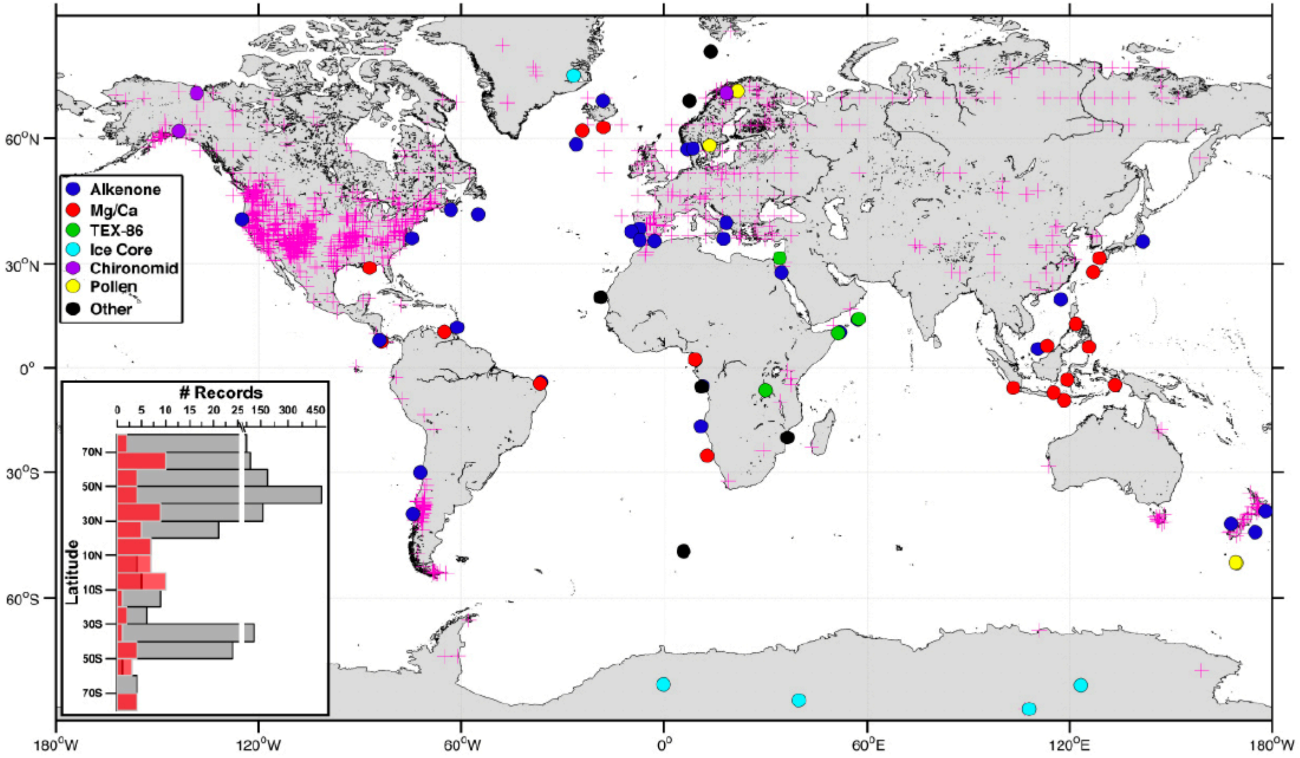
Model uncertainty?

- Missing major feedbacks?
- Dust->cooling? How big?

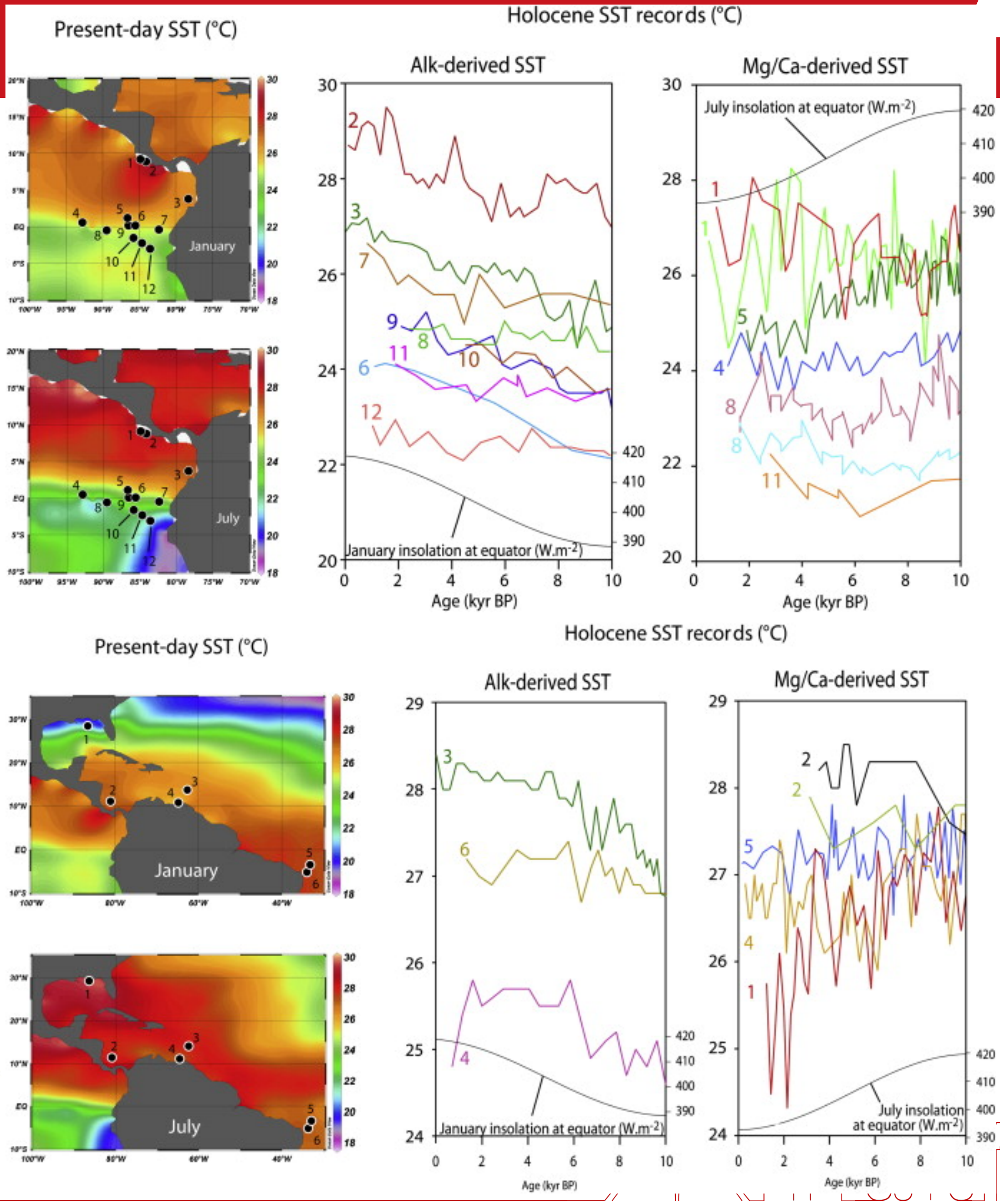
How to evaluate models?

Model-Data mismatch?

The Holocene temperature conundrum



Marcott et al., 2013, Science



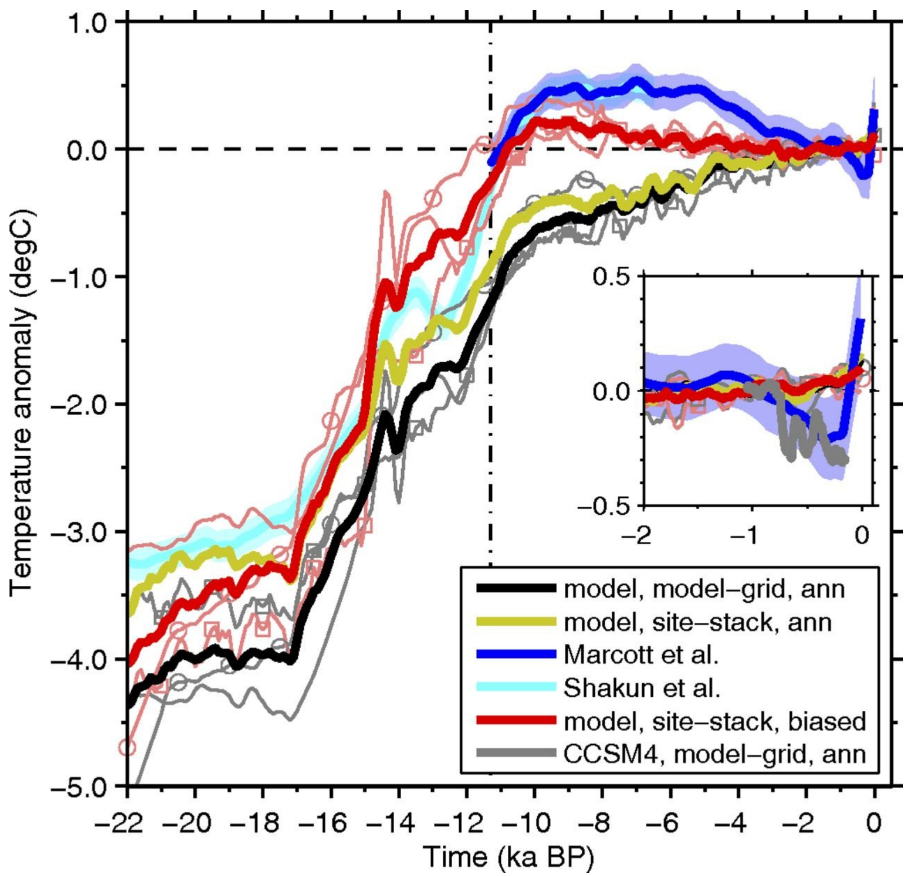
Data is seasonally biased?

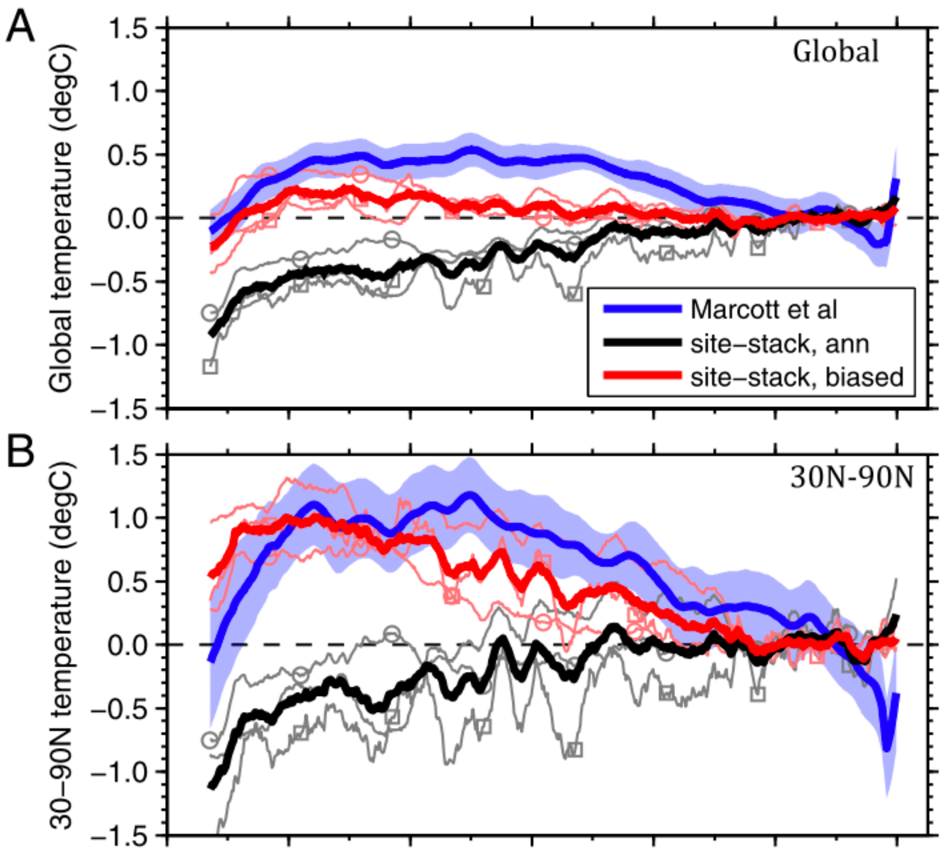
Leduc et al., 2010, QSR

How to evaluate models?

Model-Data mismatch?

The Holocene temperature conundrum





Liu et al., 2014, PNAS

How to evaluate models?

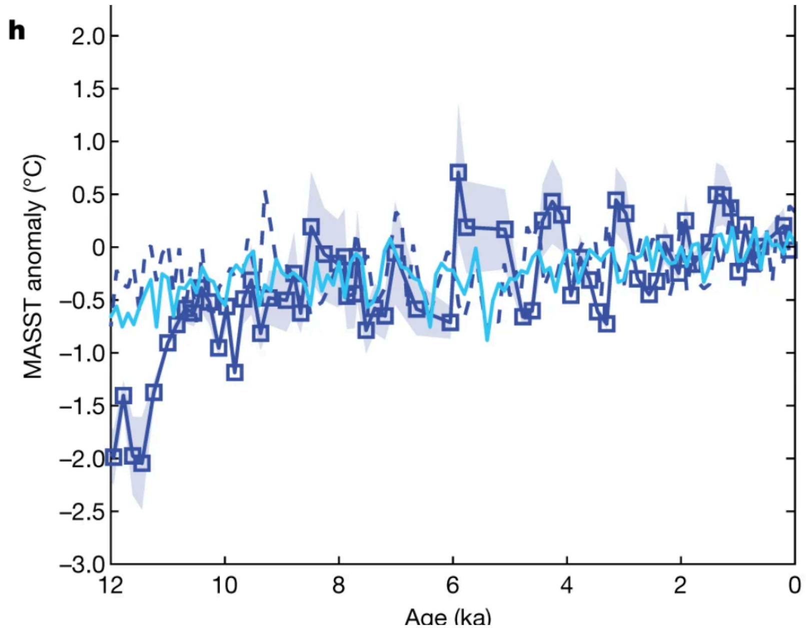
Model-Data mismatch?

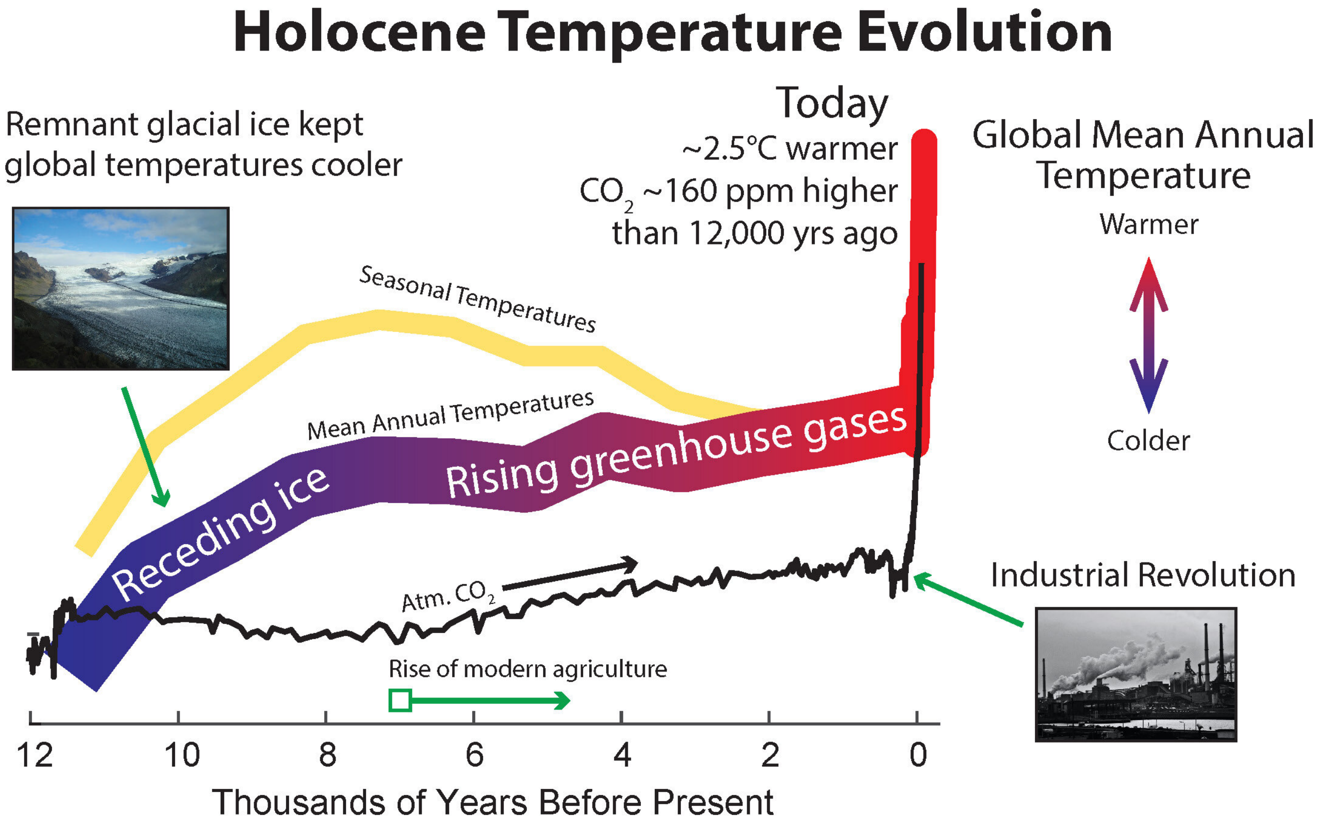
The Holocene temperature conundrum

Seasonal origin of the thermal maxima at the Holocene and the last interglacial

Samantha Bova, Yair Rosenthal, Zhengyu Liu, Shital P. Godad & Mi Yan

Nature **589**, 548–553 (2021) | Cite this article





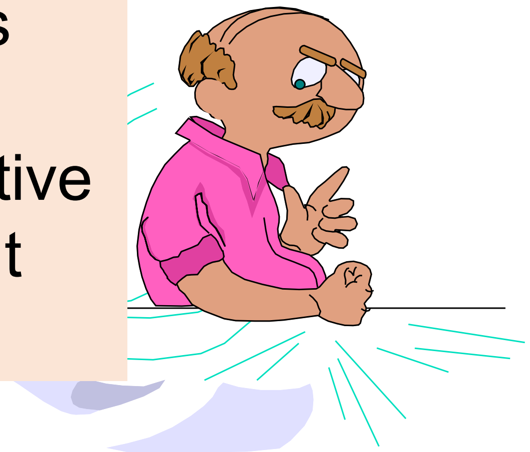
How to evaluate models?

Growing Cooperation Between Modelers and Field-Scientists

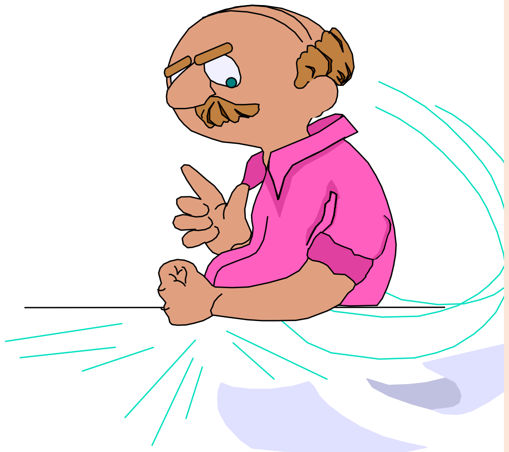
"Your tools are terribly antiquated and imprecise"

"You produce junk and waste a lot of money"

Model is a model and is never perfectly true!
But it includes quantitative physical laws consistent within the system.



Climate Modeler



Field-Geologist

Observation is always true!
But its interpretation can be wrong! (especially for paleo proxy data)

Solution: interdisciplinary collaborations!

Requirement: understanding each others 'language'

Challenges in Climate Model

- **Resolution**

spatial: more grids
temporal: smaller timestep

Very expensive for high resolution modeling!

JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2020MS002298

Key Points:

- An unprecedented set of multi-century high-resolution Community Earth System Model (CESM) simulations is described
- High-resolution CESM simulations reveal a potential role of Southern Ocean polynyas in multidecadal climate variability
- High-resolution CESM exhibits significantly improved simulations of extreme events, such as tropical cyclones and atmospheric rivers

An Unprecedented Set of High-Resolution Earth System Simulations for Understanding Multiscale Interactions in Climate Variability and Change

Ping Chang[1,2,3], Shaoqing Zhang[1,4,5], Gokhan Danabasoglu[1,6], Stephen G. Yeager[1,6], Haohuan Fu[1,7,8], Hong Wang[1,4,5], Frederic S. Castruccio[1,6], Yuhu Chen[9], James Edwards[1,6], Dan Fu[1,2], Yinglai Jia[1,5], Lucas C. Laurindo[1,6], Xue Liu[1,2], Nan Rosenbloom[1,6], R. Justin Small[1,6], Gaopeng Xu[1,2], Yunhui Zeng[10], Qiuying Zhang[1,2], Julio Bacmeister[1,6], David A. Bailey[1,6], Xiaohui Duan[8,11], Alice K. DuVivier[1,6], Dapeng Li[1,2], Yuxuan Li[11], Richard Neale[6], Achim Stössel[1,2], Li Wang[10], Yuan Zhuang[10], Allison Baker[1,6], Susan Bates[6], John Dennis[6], Xiliang Diao[1,2], Bolan Gan[1,4,5], Abishek Gopal[1,2], Dongning Jia[9], Zhao Jing[1,4,5], Xiaohui Ma[1,4,5], R. Saravanan[1,3], Warren G. Strand[6], Jian Tao[1,12], Haiyuan Yang[1,4,5], Xiaoqi Wang[1,2], Zhiqiang Wei[9], and Lixin Wu[4,5]