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TipESM

Exploring Tipping Points and their Impacts Using Earth System Models

Climate Modelling and Safe Emission Pathways

Les Gustins Summer School – 08.08.2025

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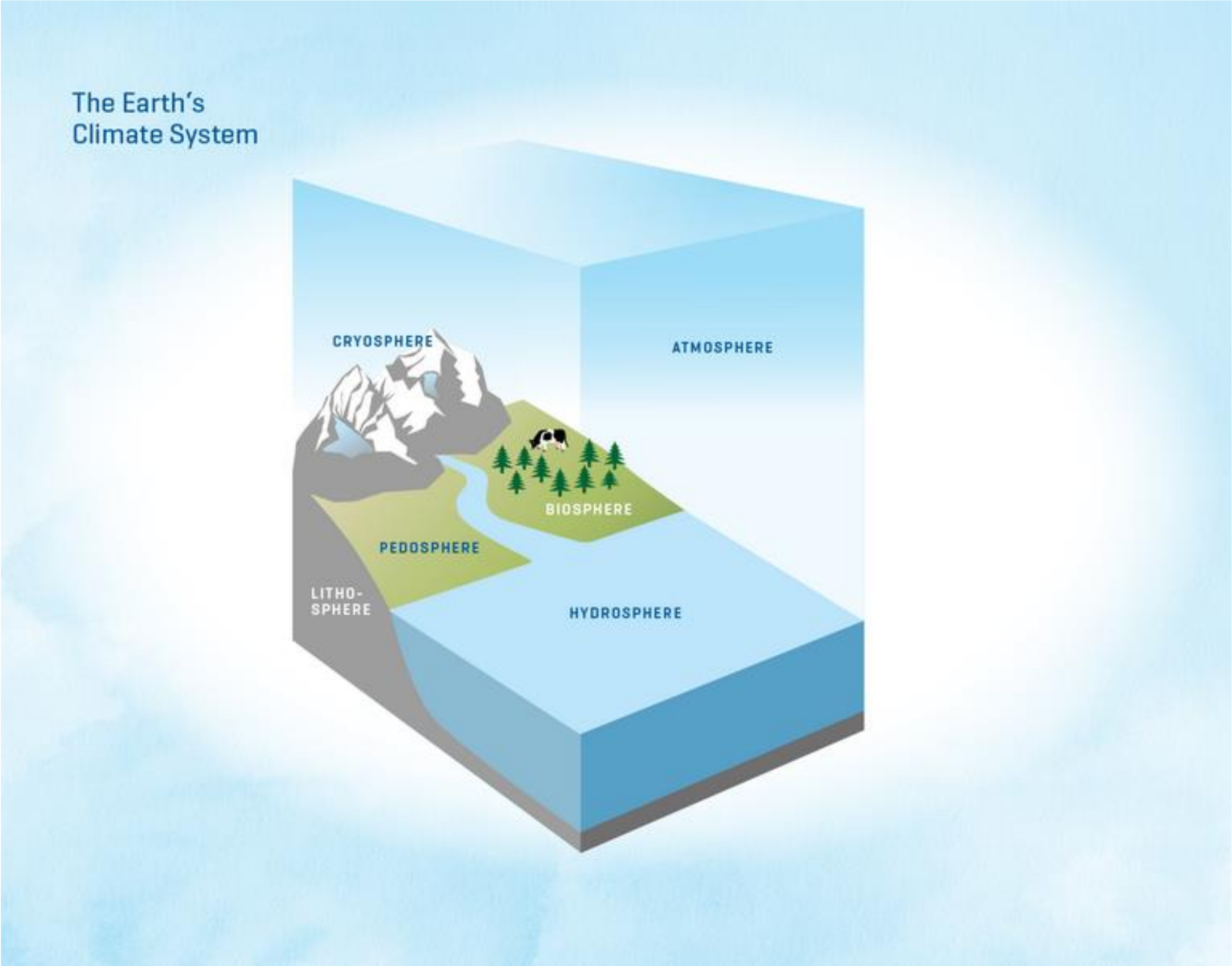
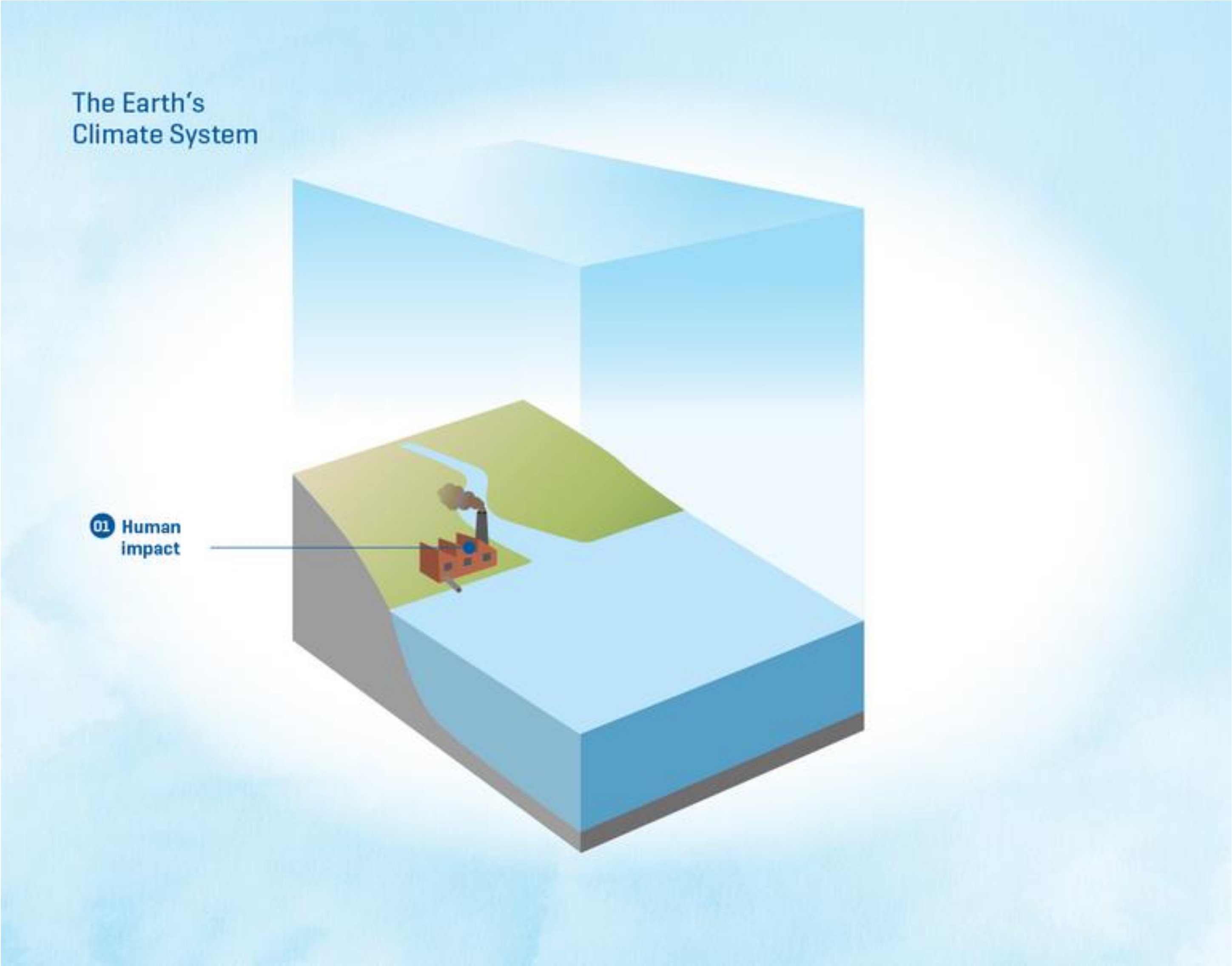
1. **Climate Modelling**
2. **Carbon Cycle**
3. **Safe Emission Pathways**

Earth’s Climate System Components



The Earth's Climate System, Geomar

Earth’s Climate System Components



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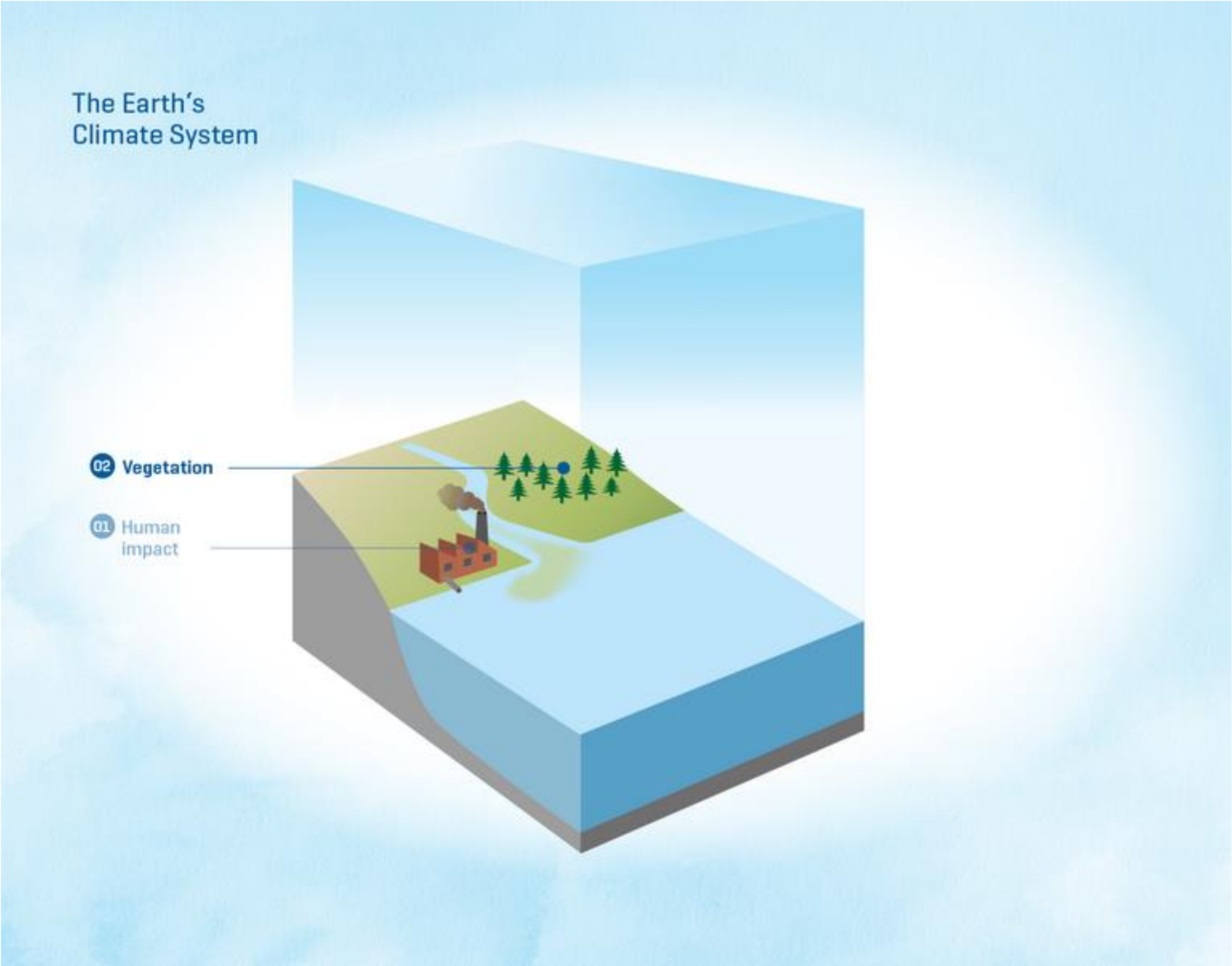

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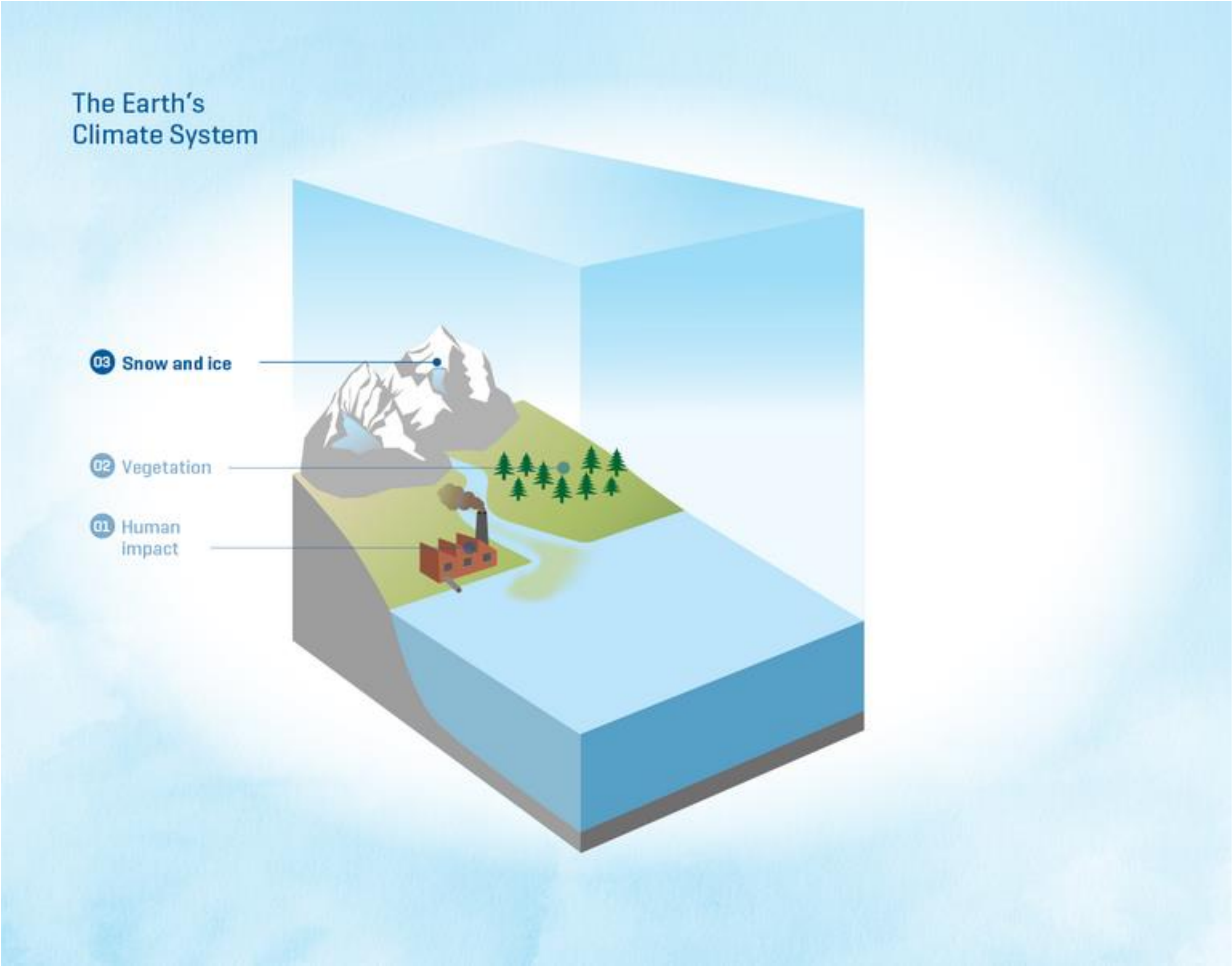

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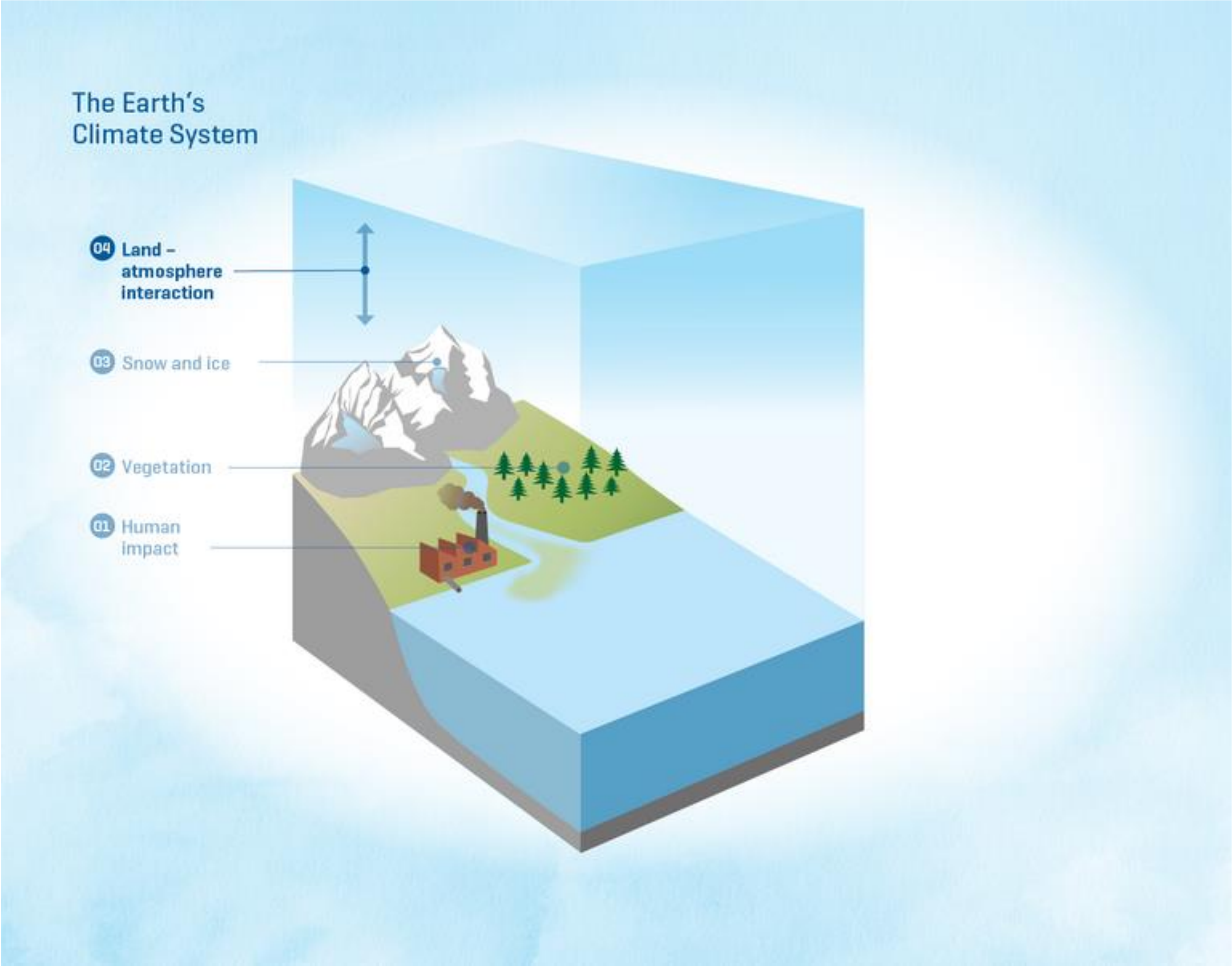

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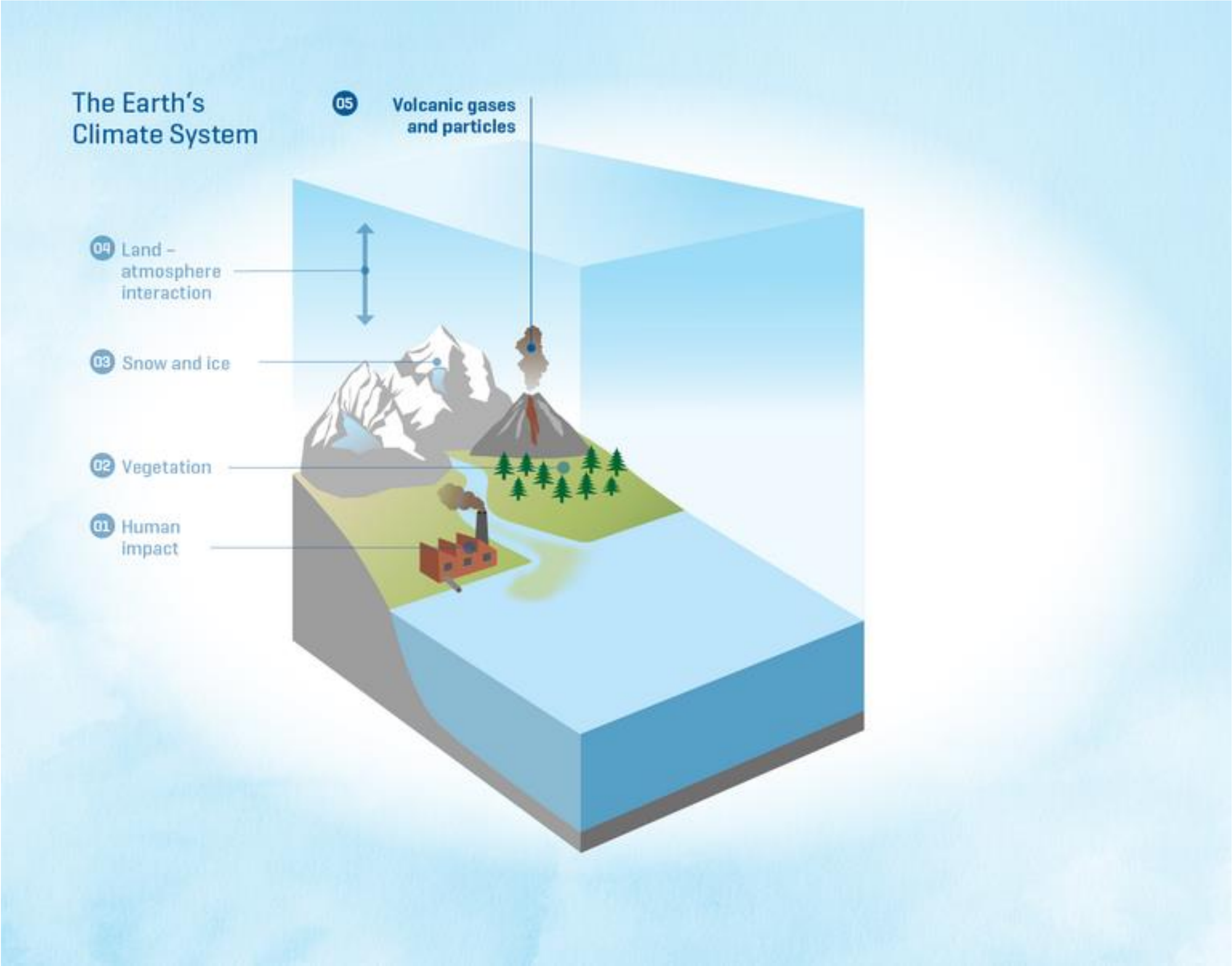

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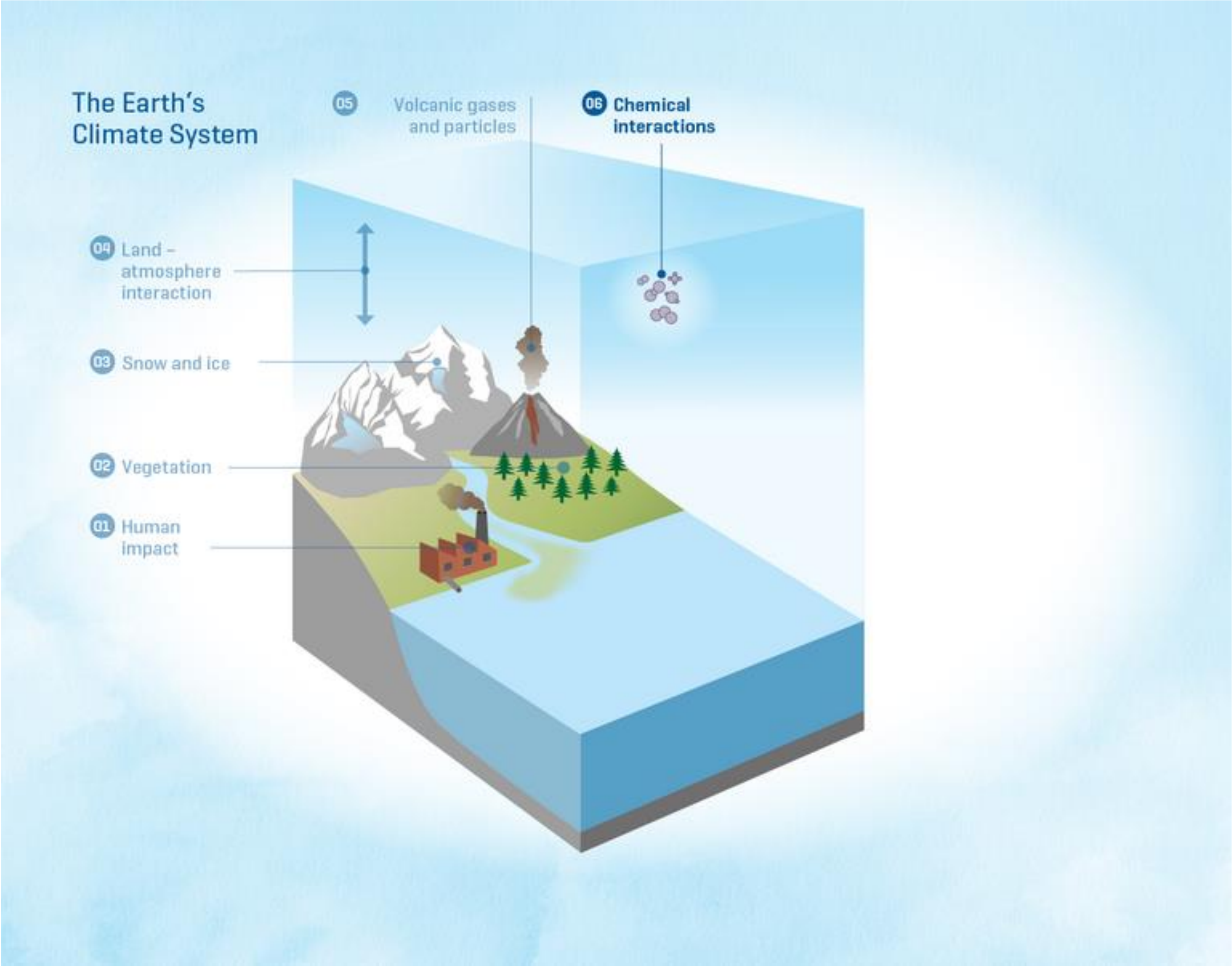

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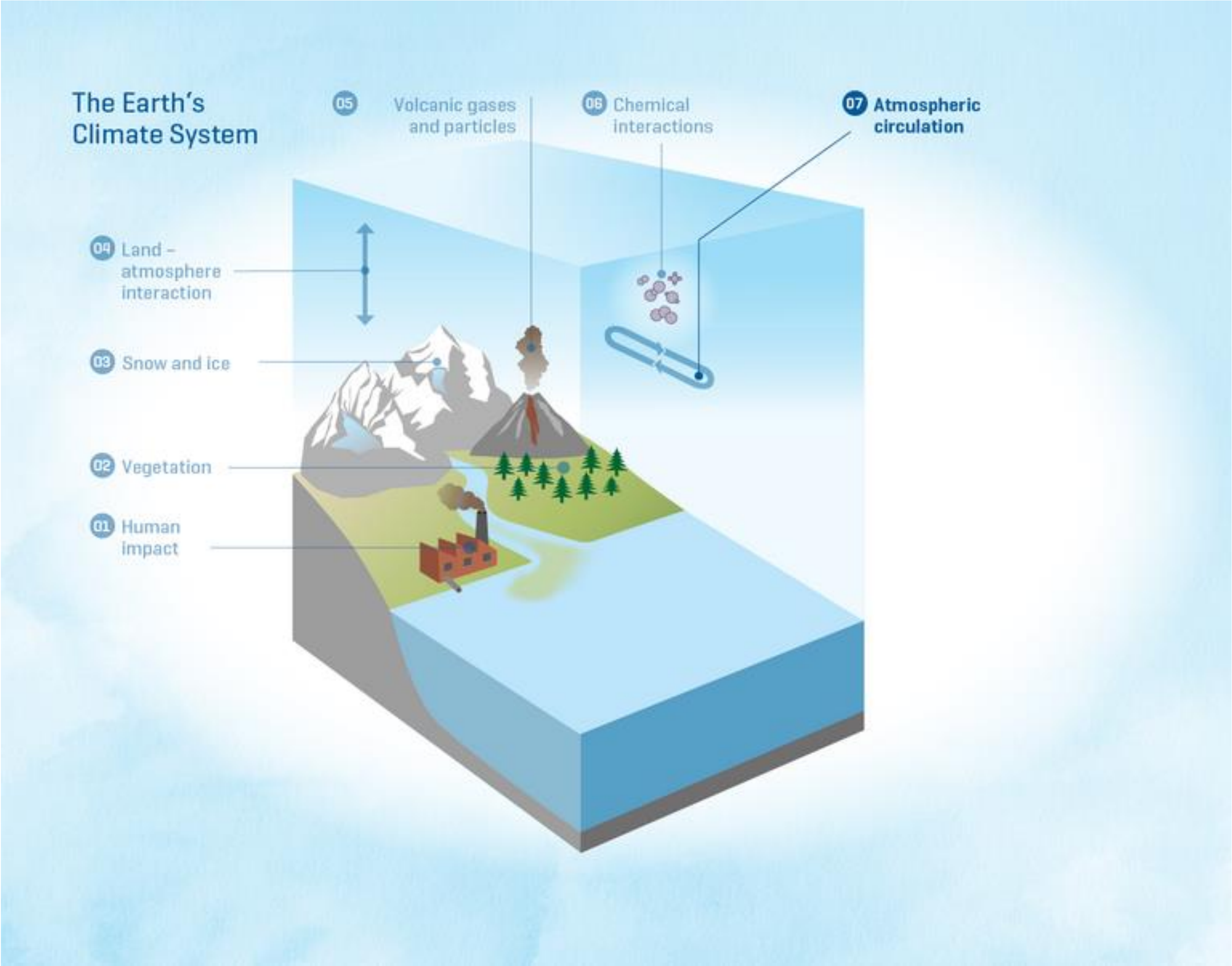

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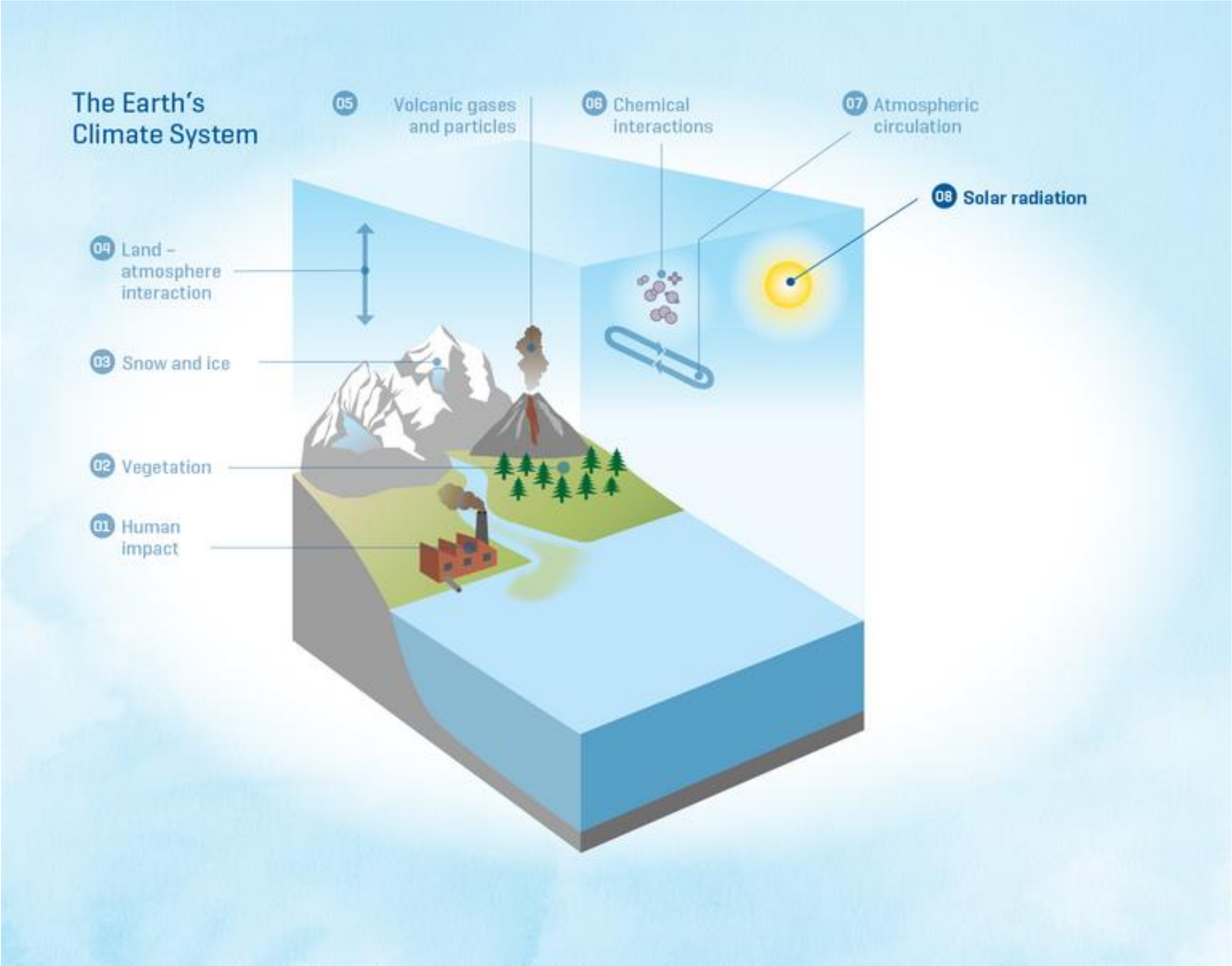

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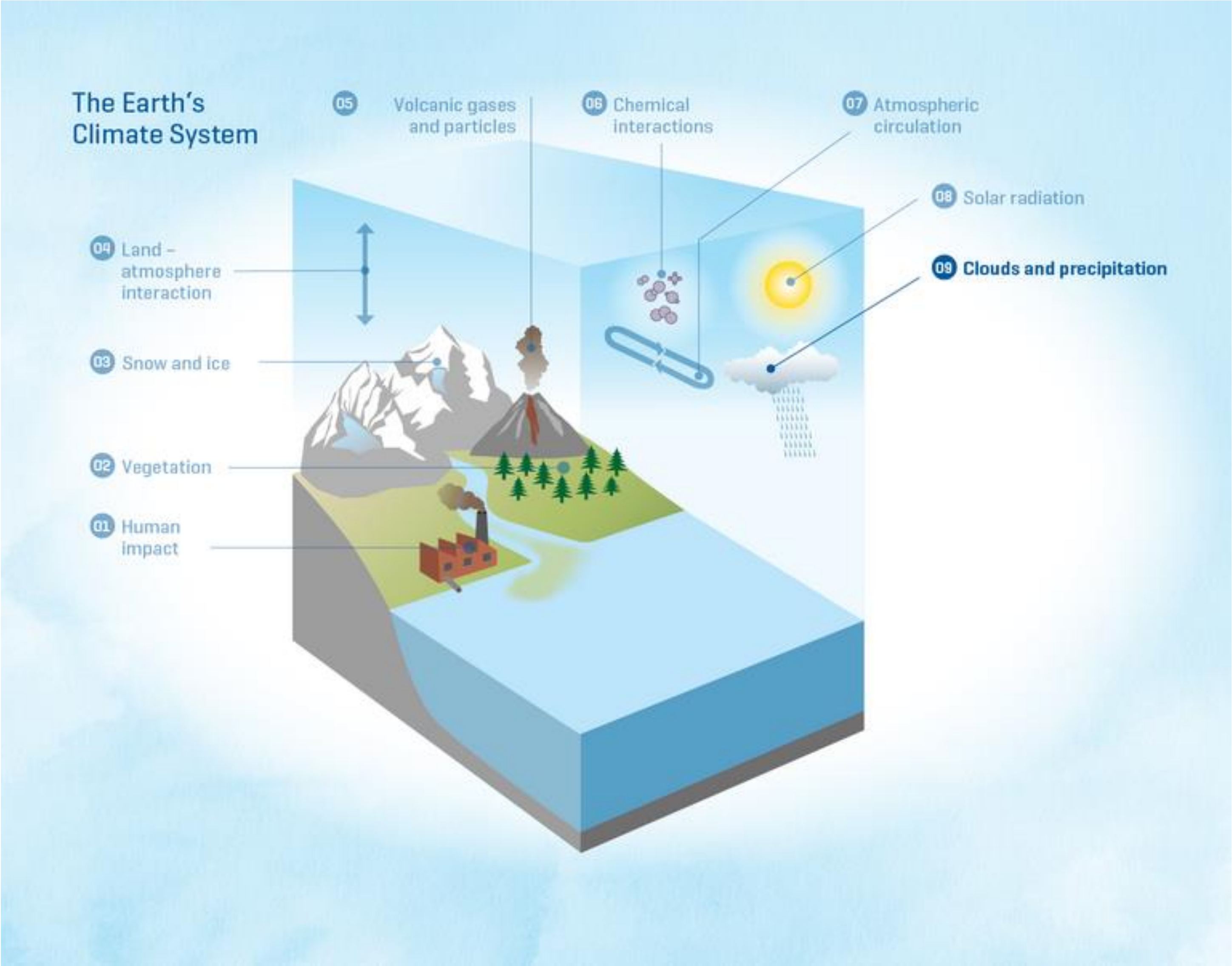

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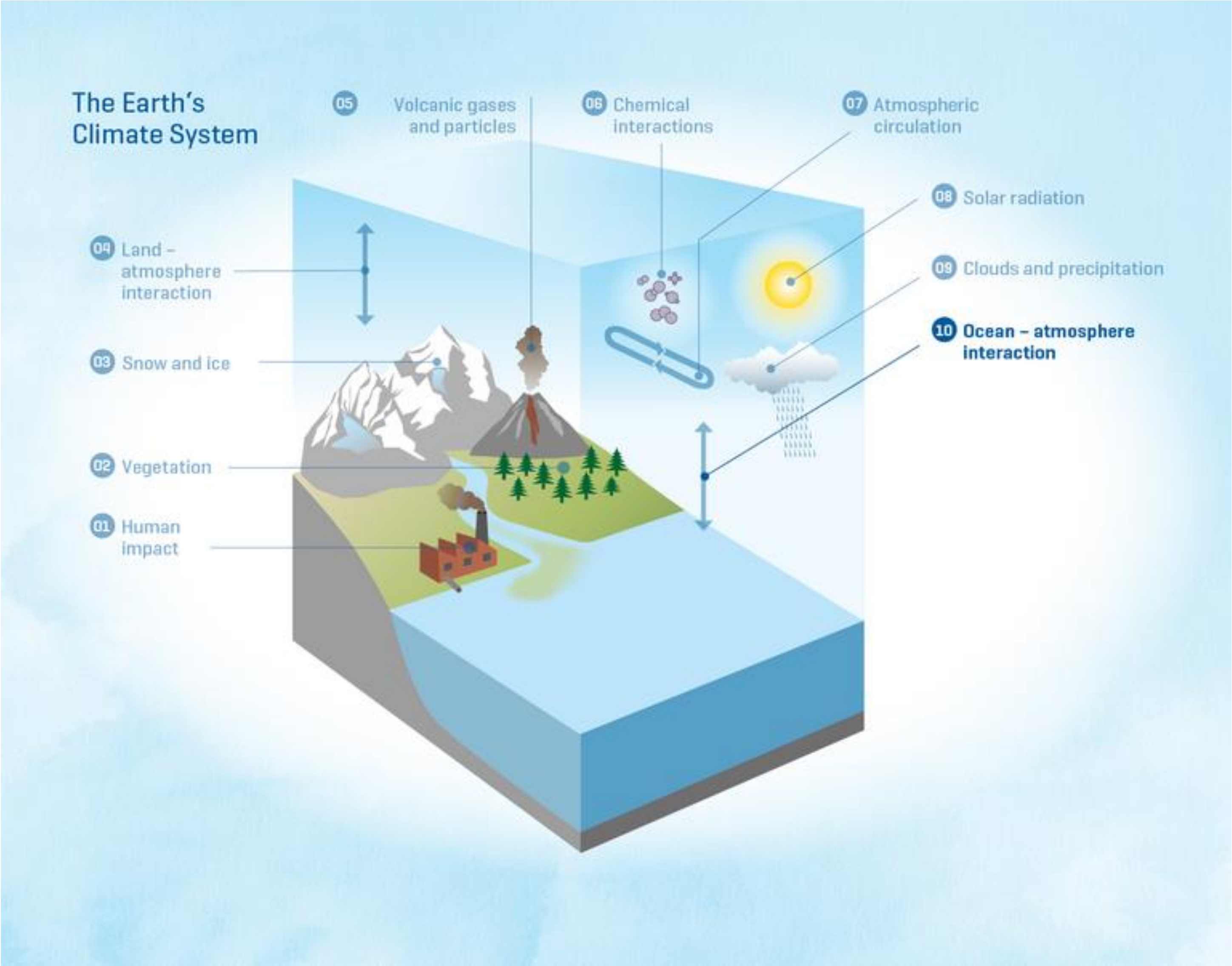

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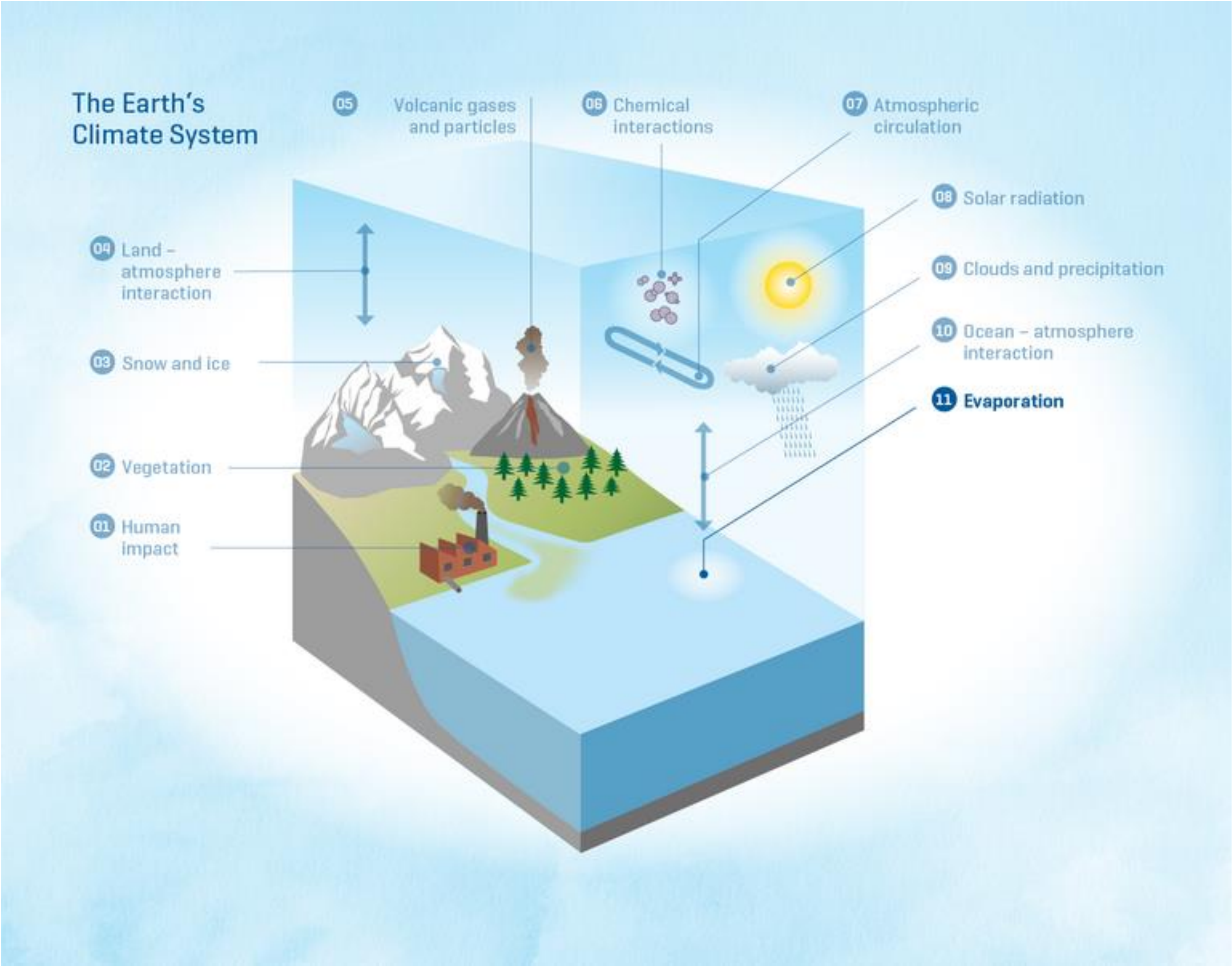

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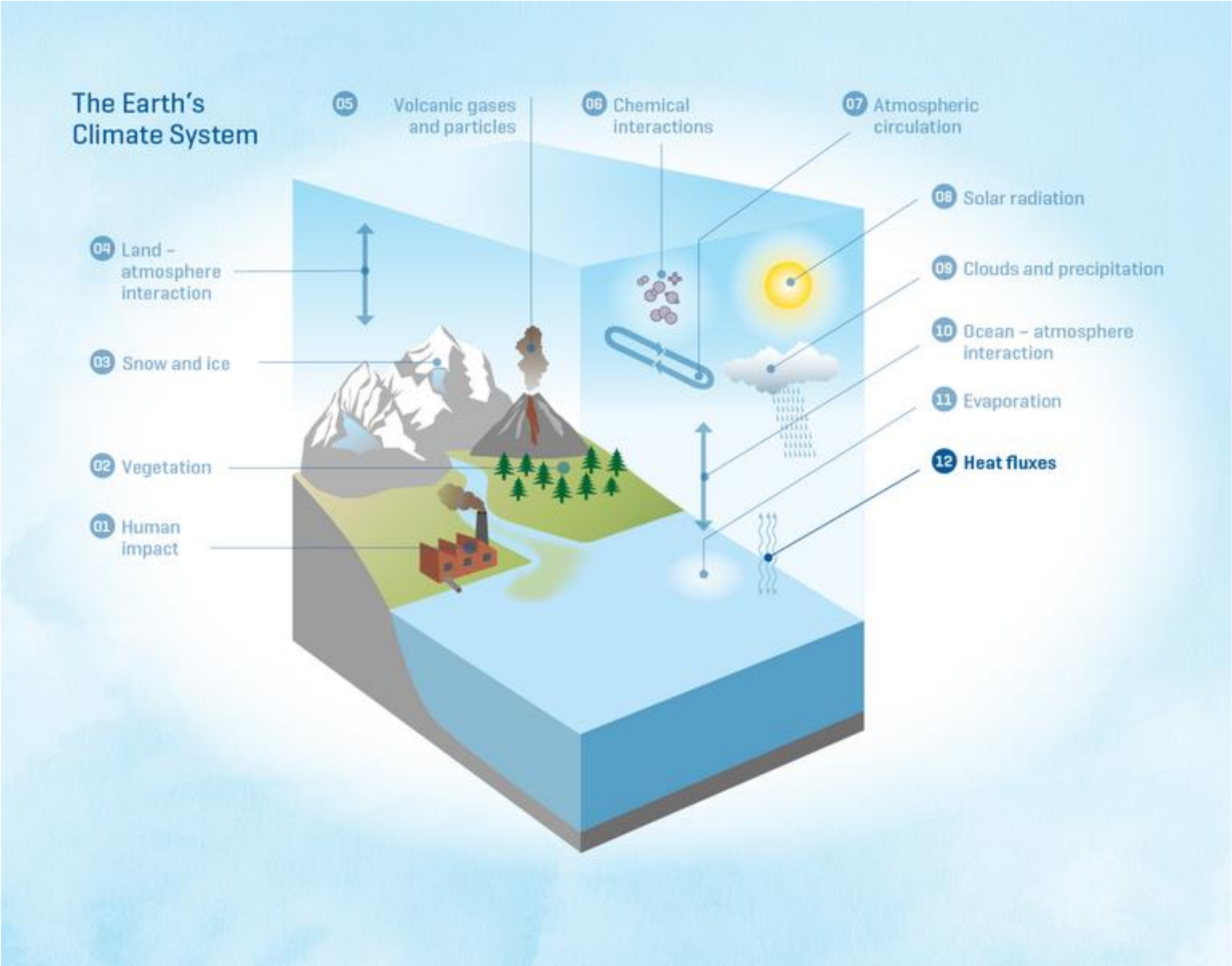

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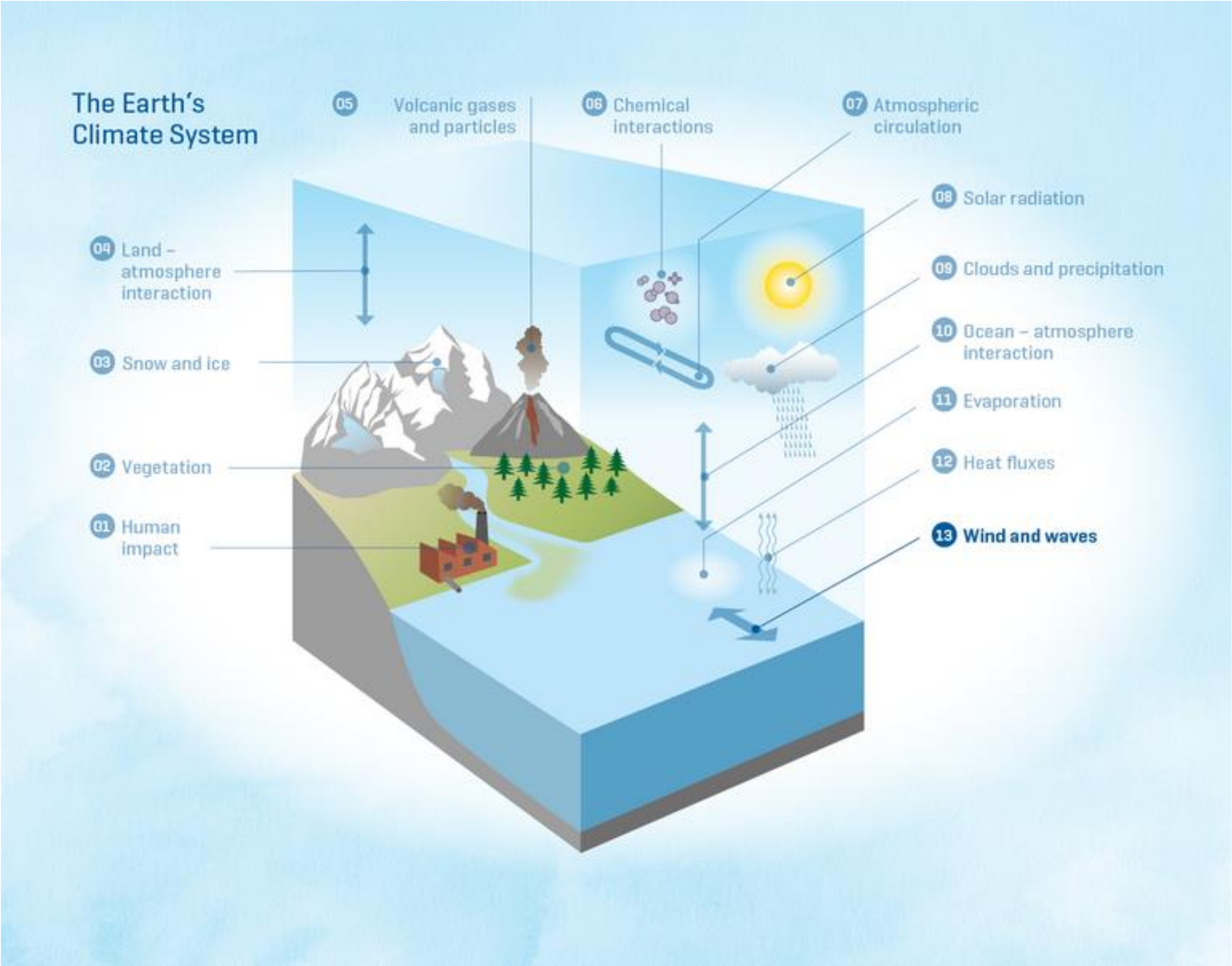

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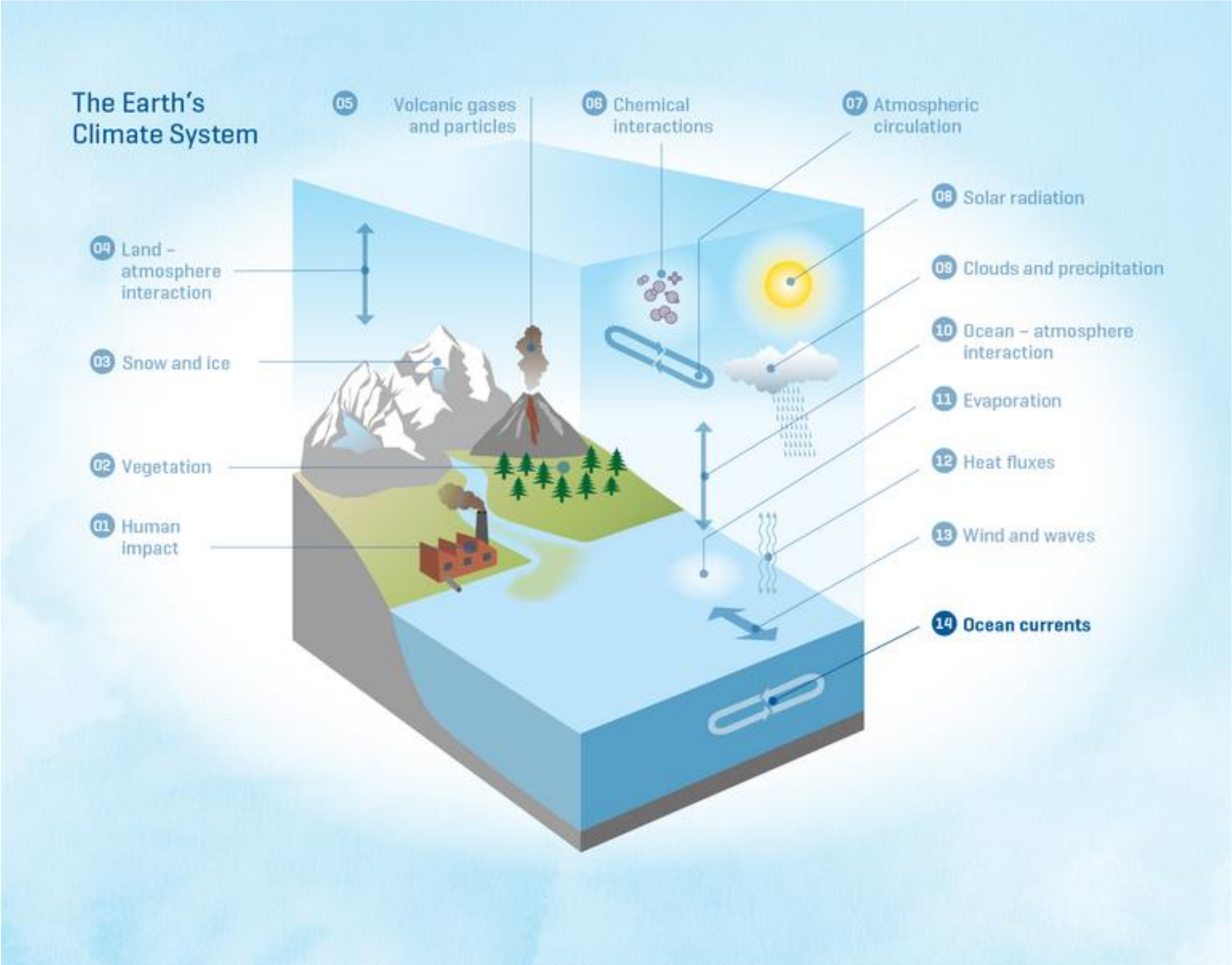

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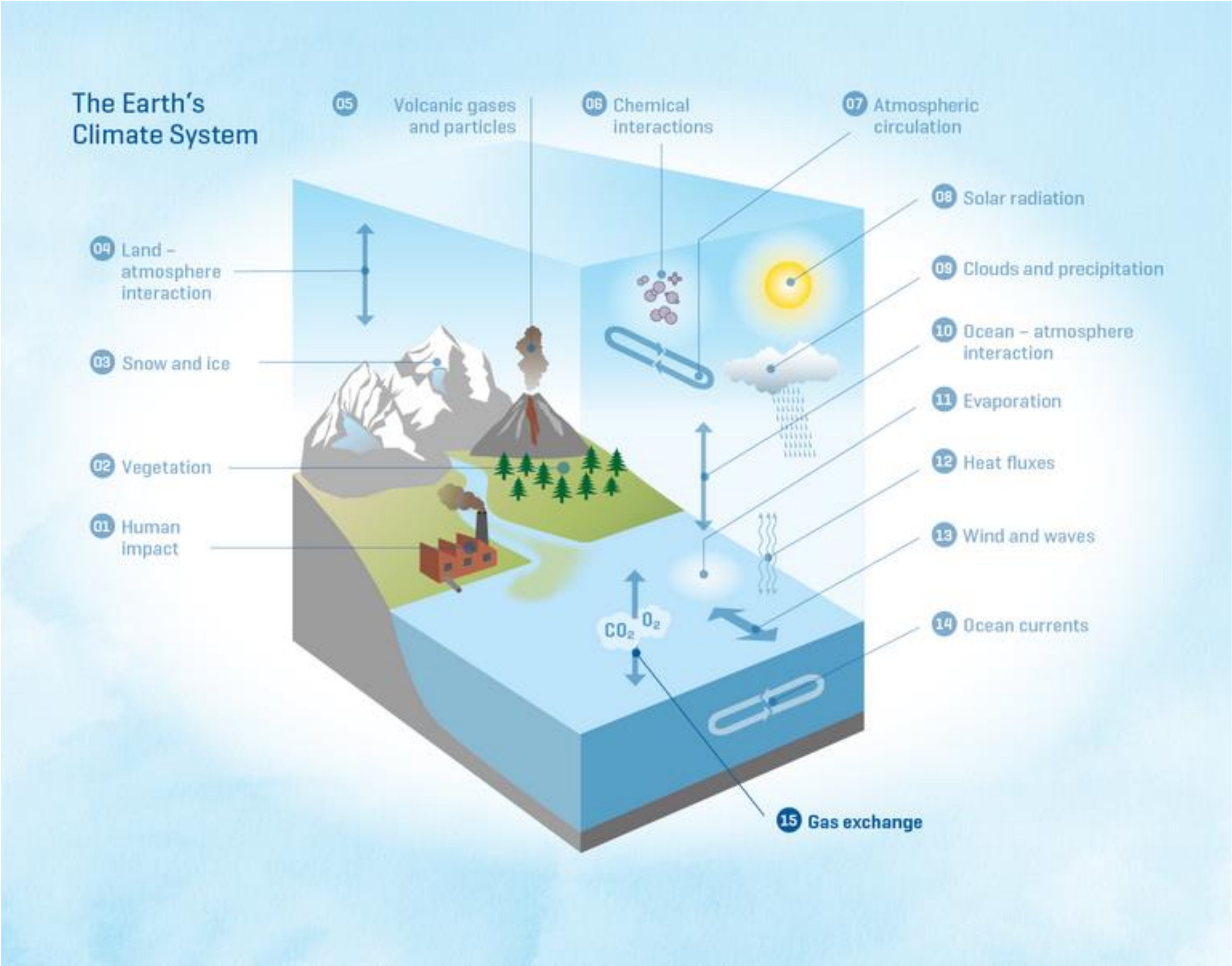

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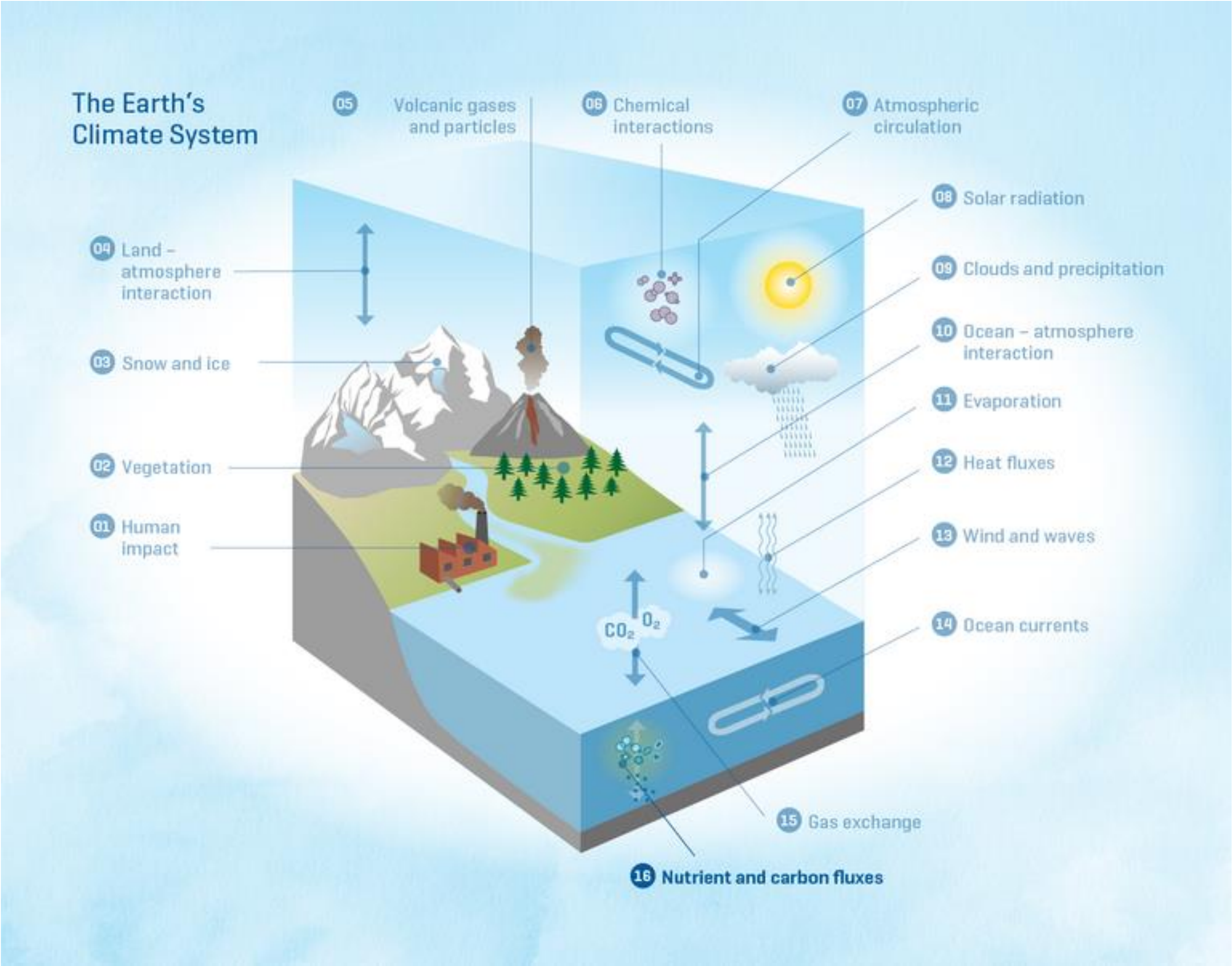

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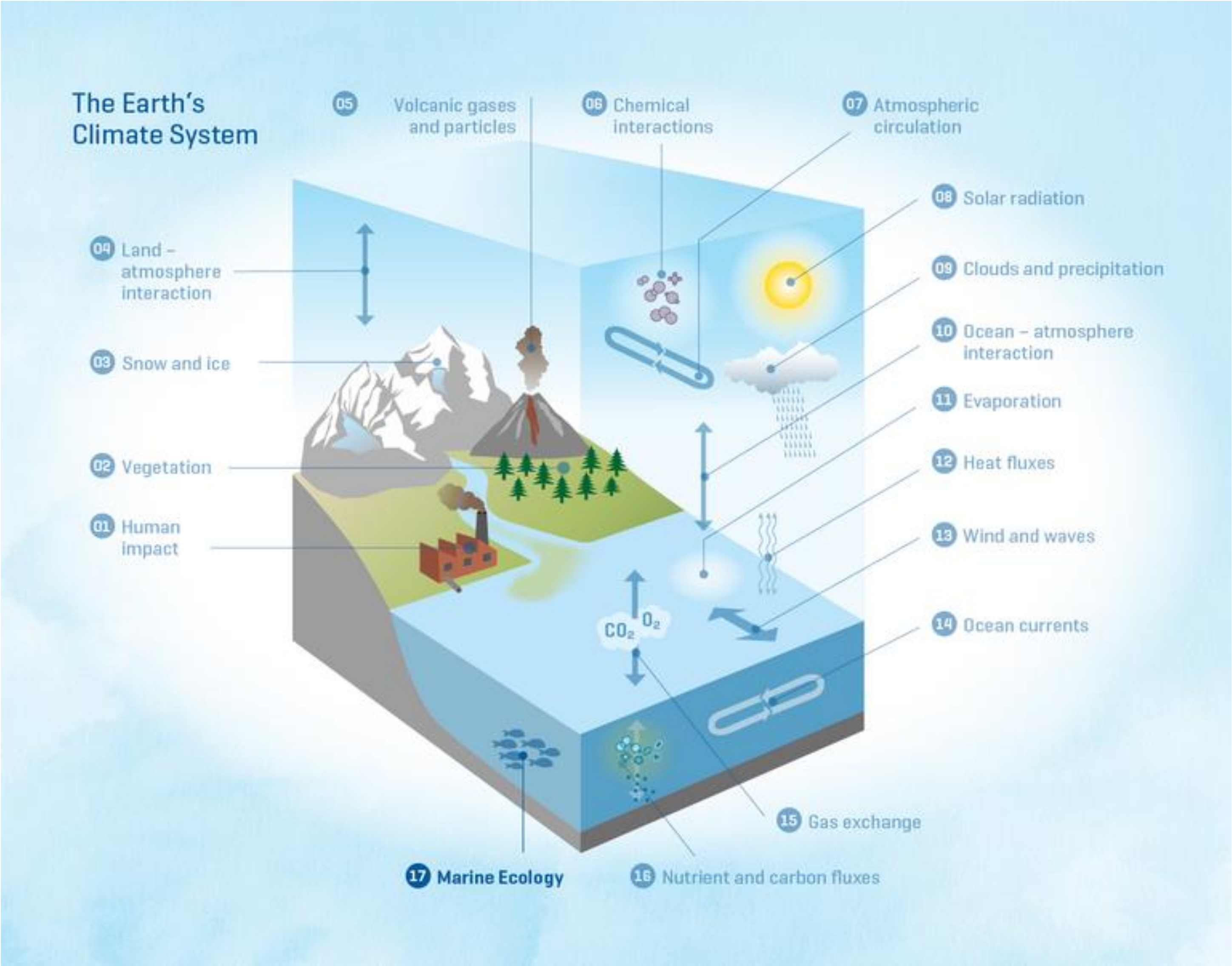

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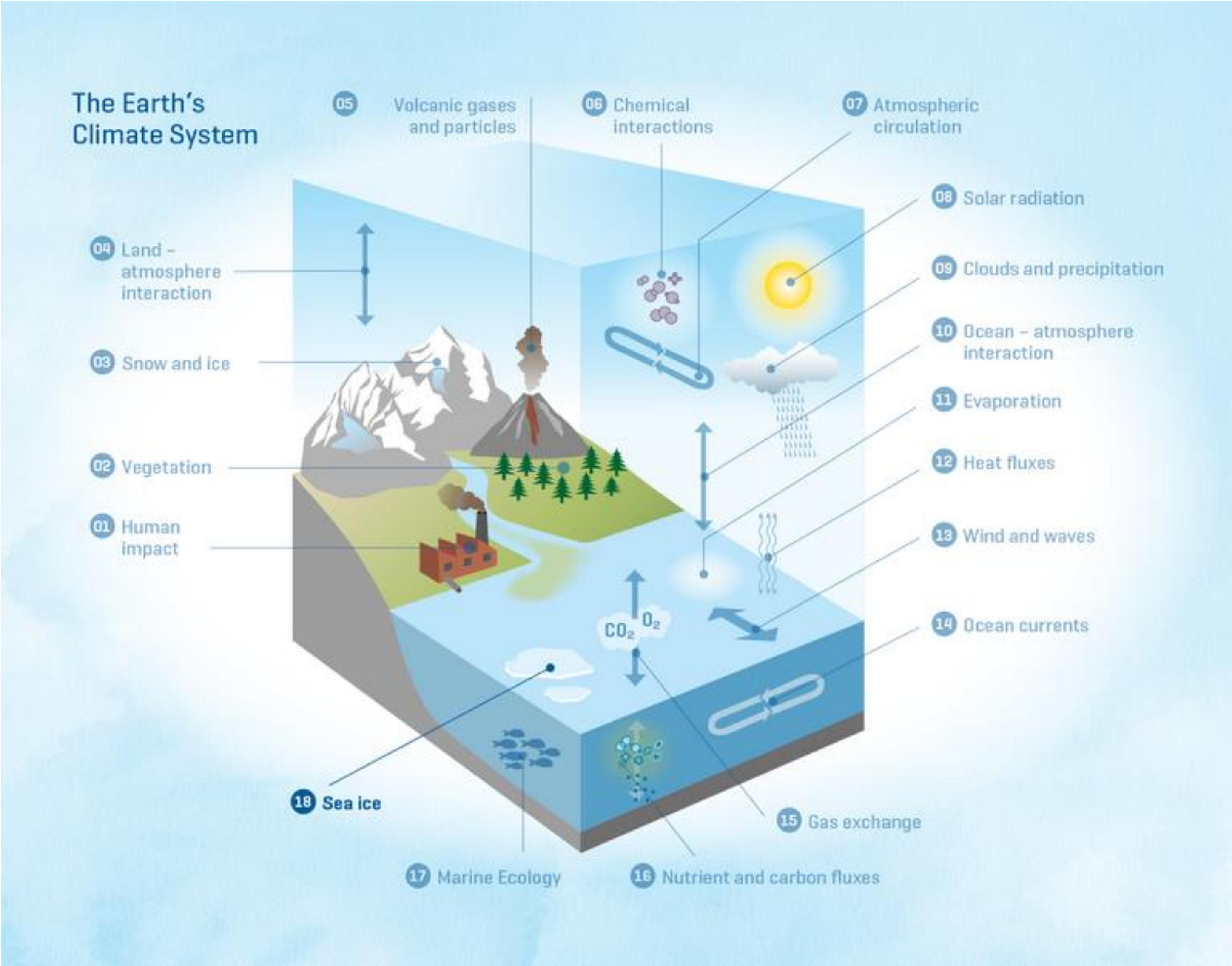

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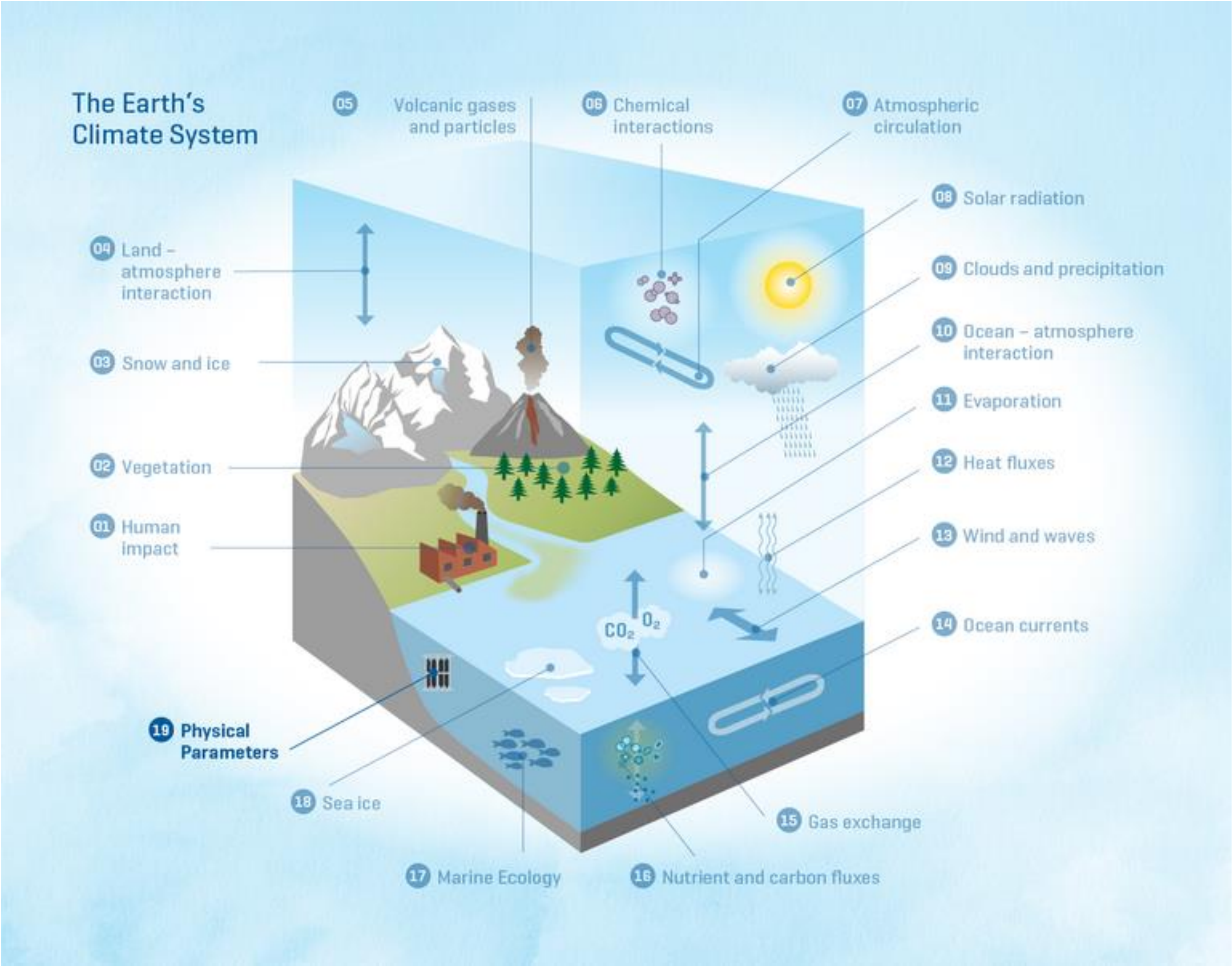

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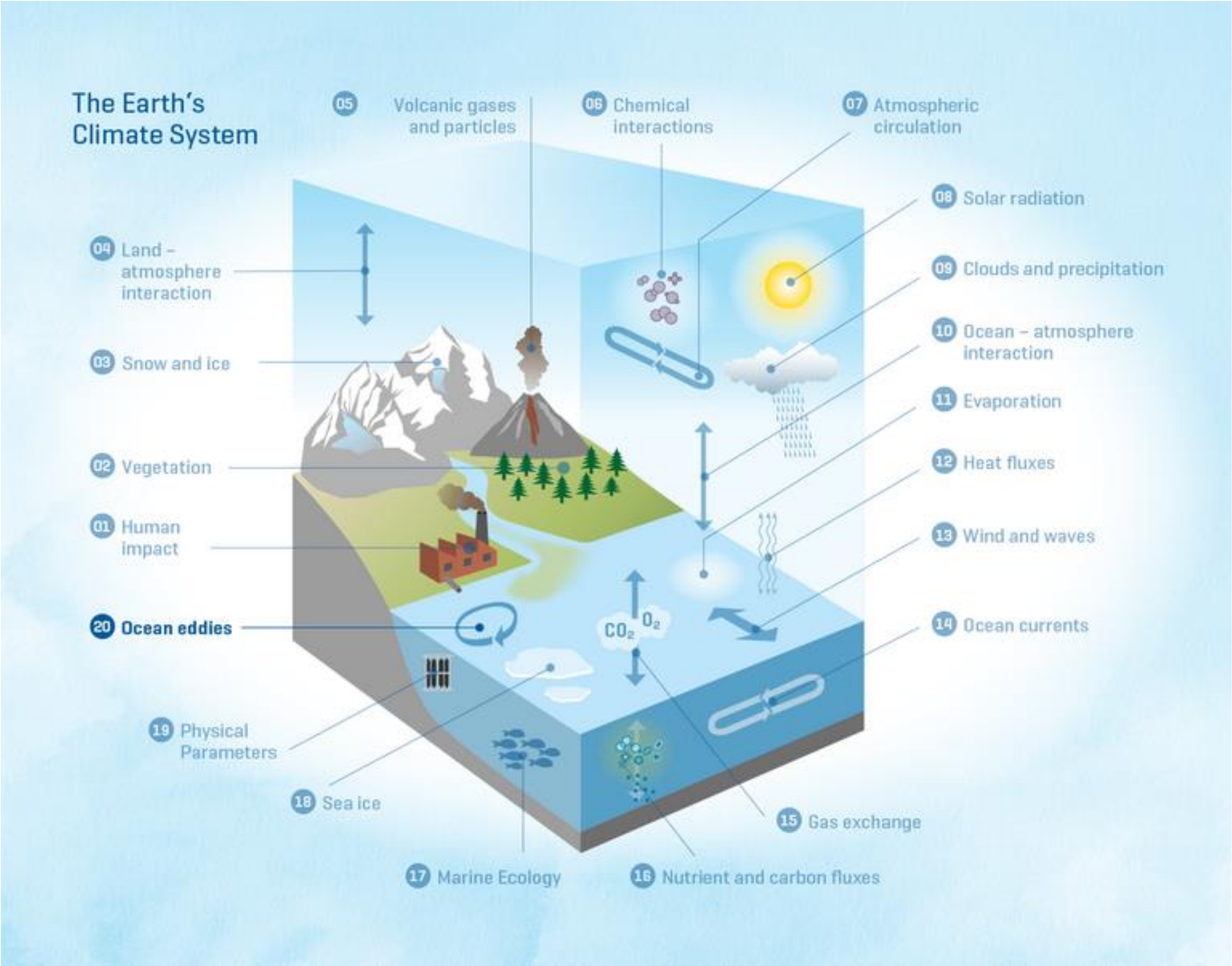


The Earth's Climate System, Geomar

Climate Models

Climate ≠ weather

Numerical implementation of many **physical processes**

Complex **interactions** between the different climate components

Globe divided into **grid cells** → spatial resolution

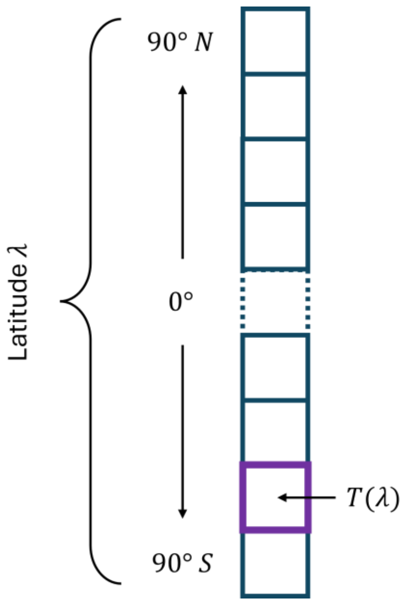
Differential equations solved for each **time step** → temporal resolution

Model **resolution** = **compromise** between simulation **accuracy** and computational **efficiency**

Climate Models

Climate model **hierarchy**

- 1D energy balance model (EBM)
- ...
- General circulation model (GCM, concentration driven)
- Earth system model (ESM, emission driven)



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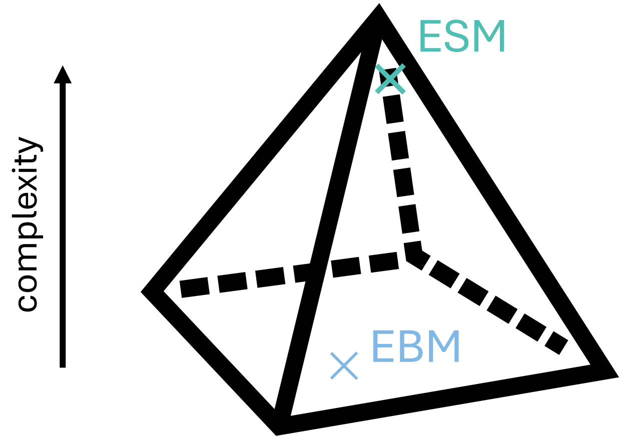

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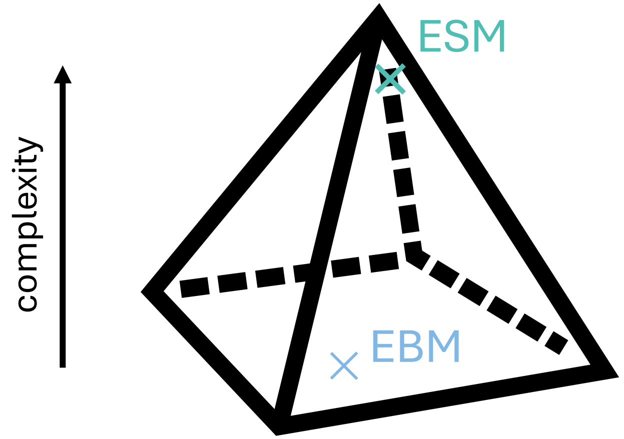


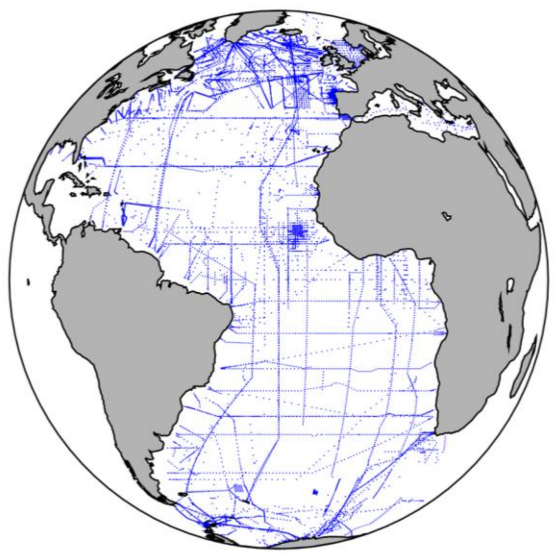
Earth system model

- **Physical climate** components (atmosphere, land, ocean, sea ice, ...)
- **Biogeochemical cycles** (carbon, nitrogen, water cycles)

Using and Testing Earth System Models

Earth system models are used for:

- **Attribution** studies
- **Process** understanding
- Comparison with, or completion of sparse **observations**
- Future climate **projections**



Olsen et al., 2019

Climate model intercomparison project (CMIP):

- Large **collaboration** of modelling centres
- **Compare** model outputs based on a set of **common experiments**
- Assess **model performance** and **uncertainties**

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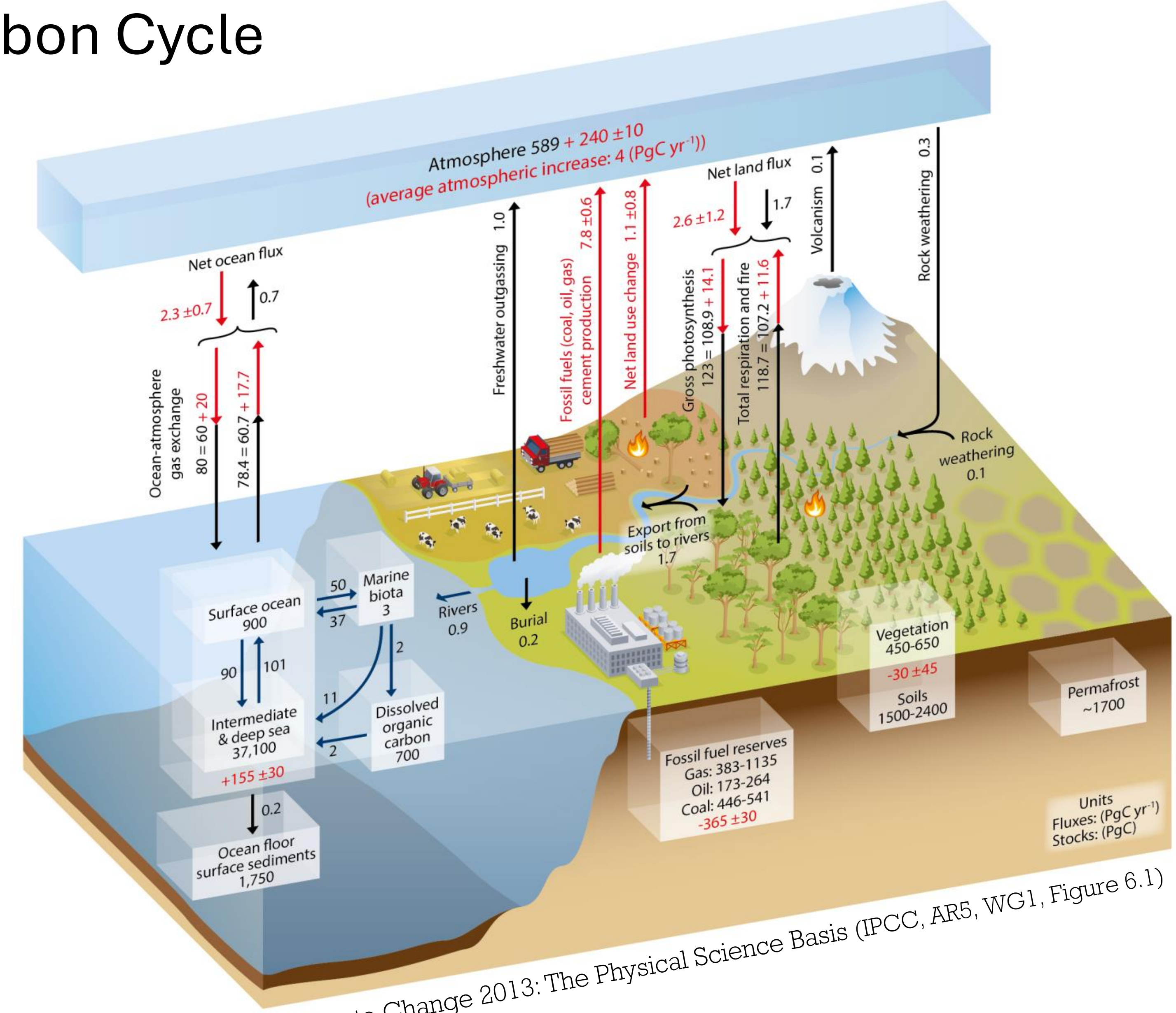
Global Carbon Cycle



Climate Change 2013: The Physical Science Basis (IPCC, AR5, WG1, Figure 6.1)

1. **Climate Modelling**
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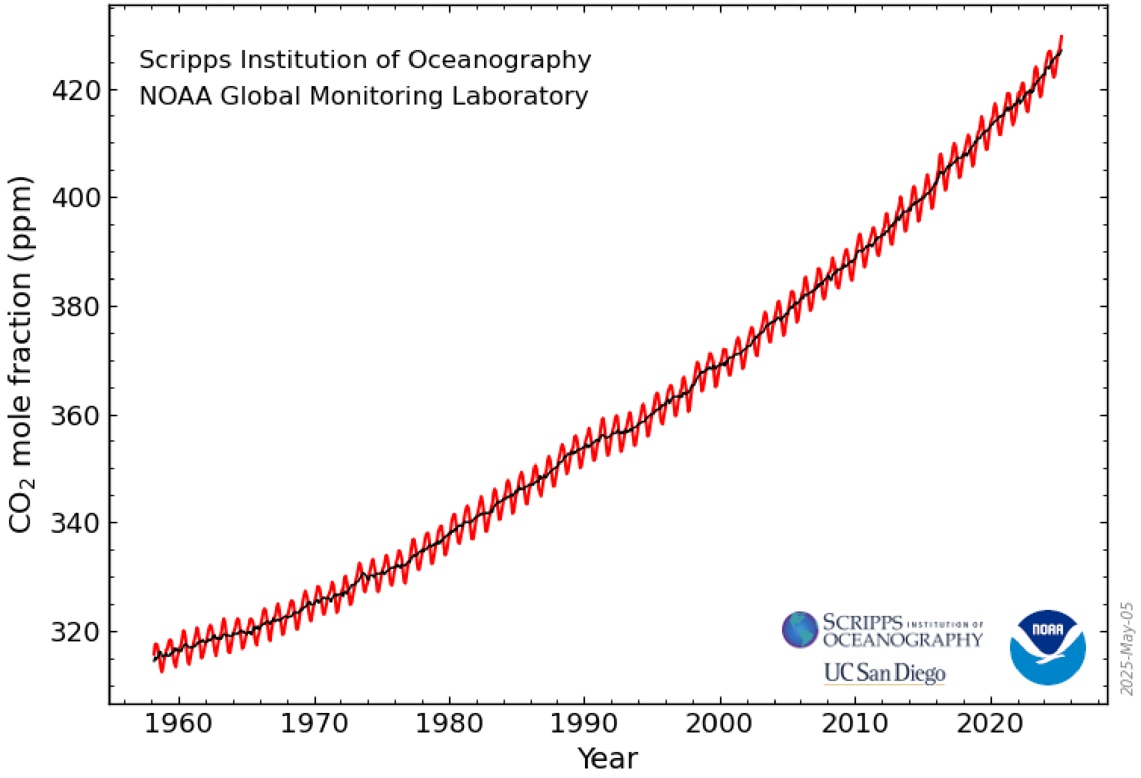
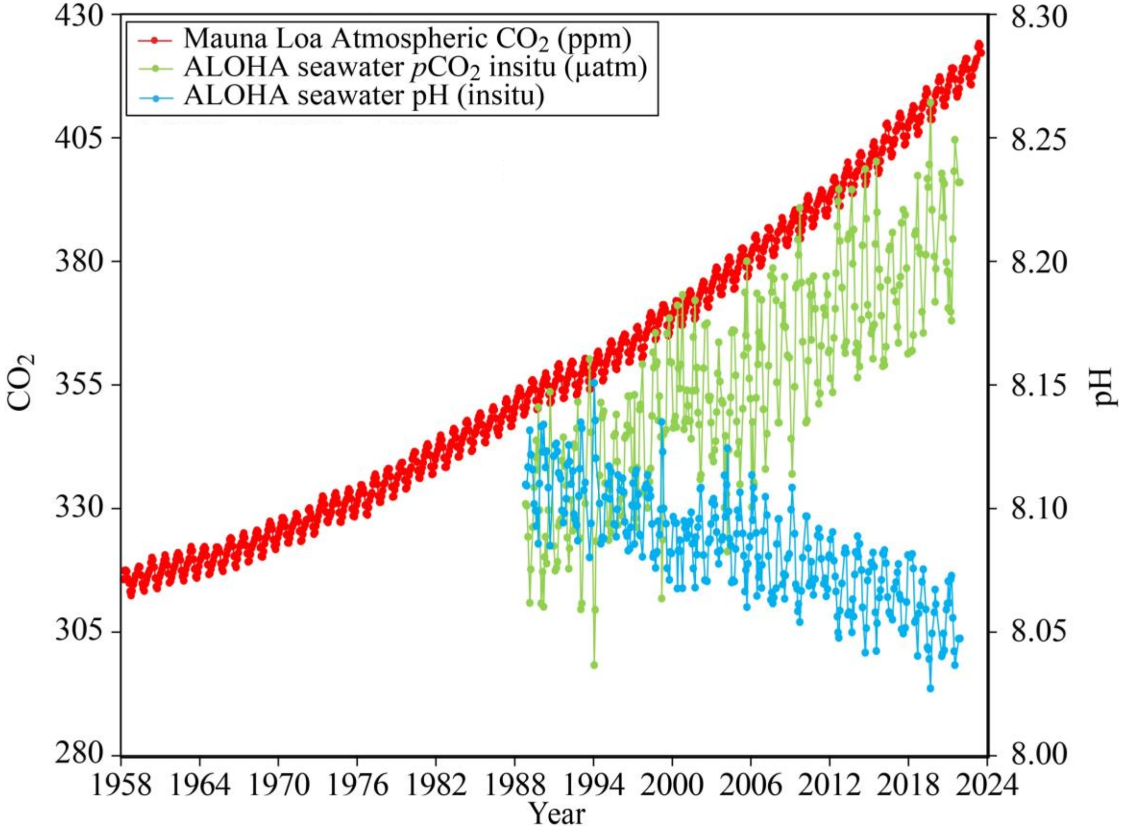
Atmospheric CO_2 increases since preindustrial period



CO_2 uptake by the ocean causes ocean acidification

Part of **atmospheric CO_2 dissolves** in seawater.



Data: Mauna Loa (https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt) ALOHA (https://hahana.soest.hawaii.edu/hot/hotco2/HOT_surface_CO2.txt)
ALOHA pH & pCO_2 are calculated at in-situ temperature from DIC & TA (measured from samples collected on Hawaii Ocean Times-series (HOT) cruises)
using co2sys (Pelletier, v25b06) with constants: Lueker et al. 2000, KSO4: Dickson, Total boron: Lee et al. 2010, & KF: seacarb

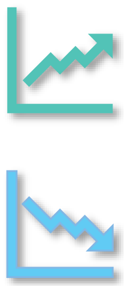
Impacts on **seawater chemistry** and decrease of **pH**

CO_2 uptake by the ocean affects seawater chemistry

Part of atmospheric $\mathbf{CO_2}$ **dissolves** in seawater:

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{carbonic acid}}{H_2CO_3} \longrightarrow \underset{\text{bicarbonate}}{HCO_3^-} \;;\; \underset{\text{hydrogen ion}}{H^+}$$

$$\underset{\text{hydrogen ion}}{H^+} + \underset{\text{carbonate}}{CO_3^{2-}} \longrightarrow \underset{\text{bicarbonate}}{HCO_3^-}$$



$[\mathbf{H^+}]$ **increases** ⇔ **pH decreases**

$$pH = -\log([H^+])$$

$[\mathbf{CO_3^{2-}}]$ limits **calcification** process:

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$$

Ocean acidification impacts marine calcifying organisms

Pteropods

Peijnenburg et al., 2020

Calcifying species:
- Corals
- Plankton
- Pteropods (e.g. sea butterfly)

Effects:
- Reduced calcification rate
- Reduced growth rate
- Species-specific

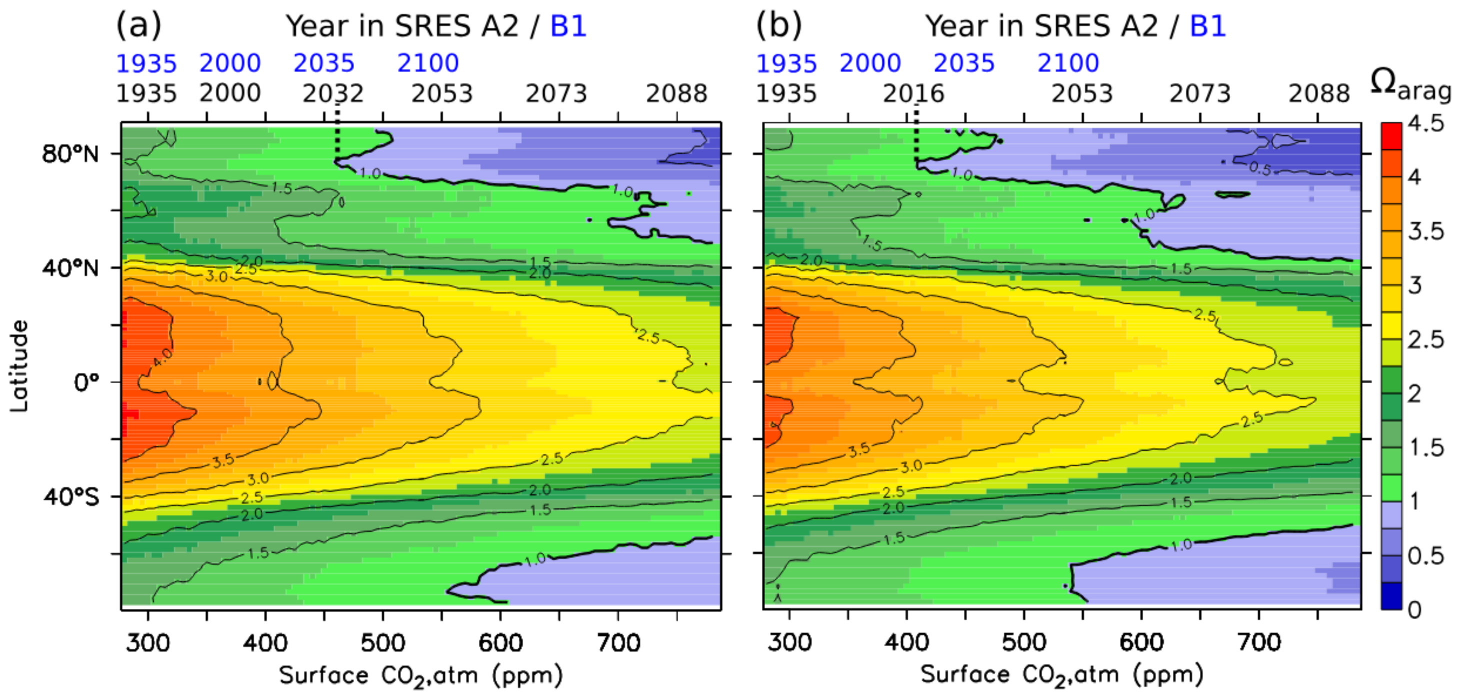
Aragonite saturation state:

$$\Omega_{\mathrm{arag}} = \frac{[\mathrm{CO_3^{2-}}][\mathrm{Ca^{2+}}]}{[\mathrm{CO_3^{2-}}]_{\mathrm{sat,\ arag}}[\mathrm{Ca^{2+}}]_{\mathrm{sat,arag}}}$$

$\Omega_{\mathrm{arag}} > 1$, inorganic precipitation
$\Omega_{\mathrm{arag}} = 1$, equilibrium
$\Omega_{\mathrm{arag}} < 1$, inorganic dissolution

The Arctic is projected to become undersaturated soon

a) Annual-mean
b) Lowest monthly mean

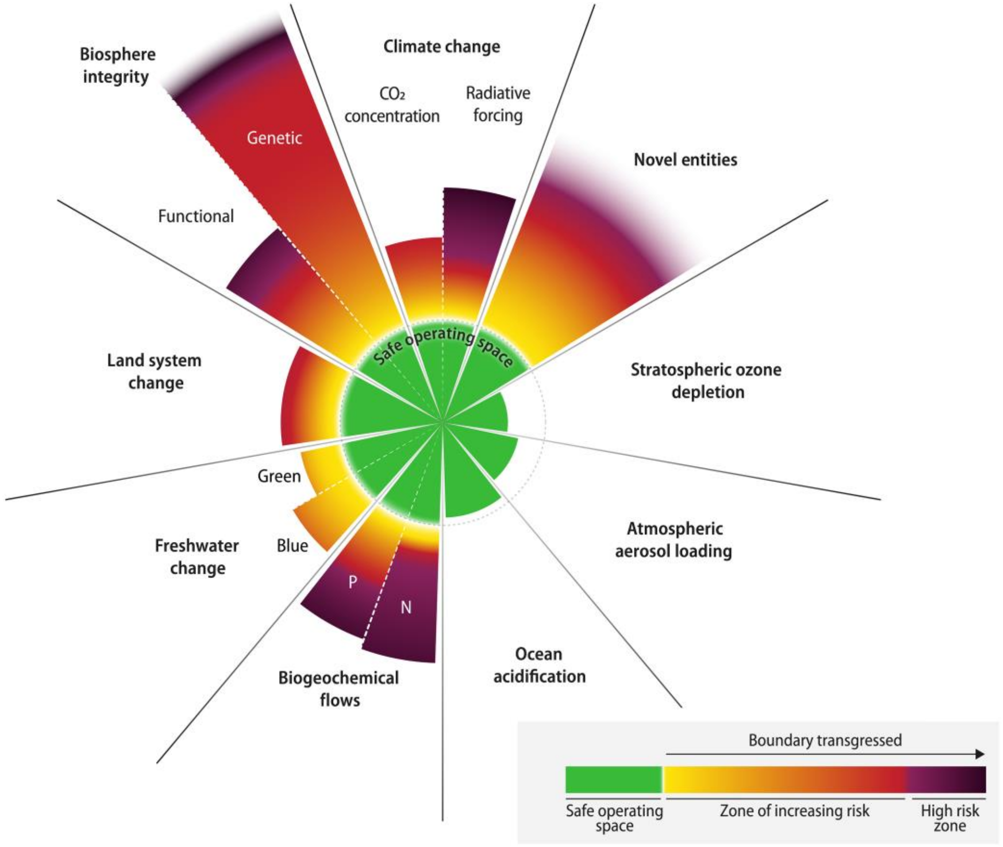


Steinacher et al., 2009

Projections for surface water **undersaturation** in the **Arctic**: within a few **decades**.

Many planetary boundaries are outside their safe operating space

Status in **2023** of **control variables** for nine planetary boundaries



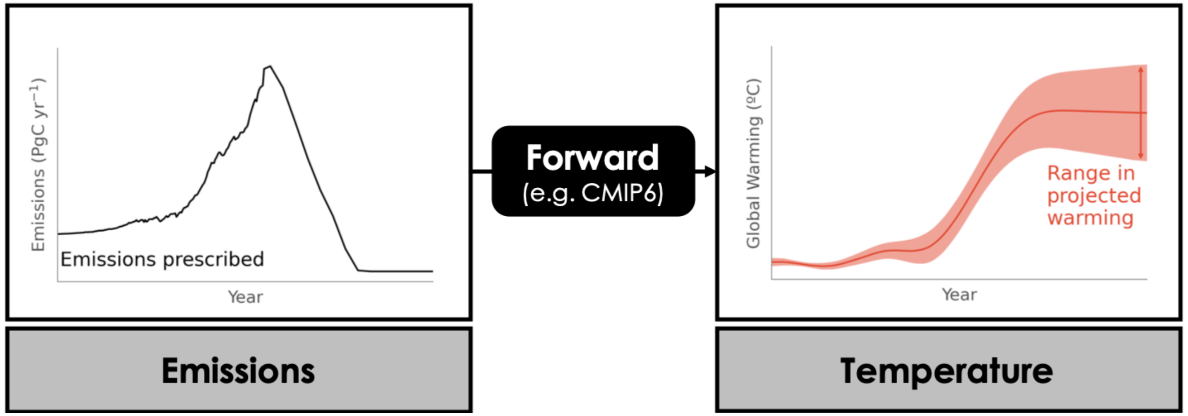
Richardson et al., 2023

Rockström et al., 2009

Ocean acidification is **approaching** its boundary.

Climate model projections should provide safe emission pathways

Currently, most climate projections are based on **prescribed emission pathways**.



Silvy et al., 2024
Terhaar et al., 2022

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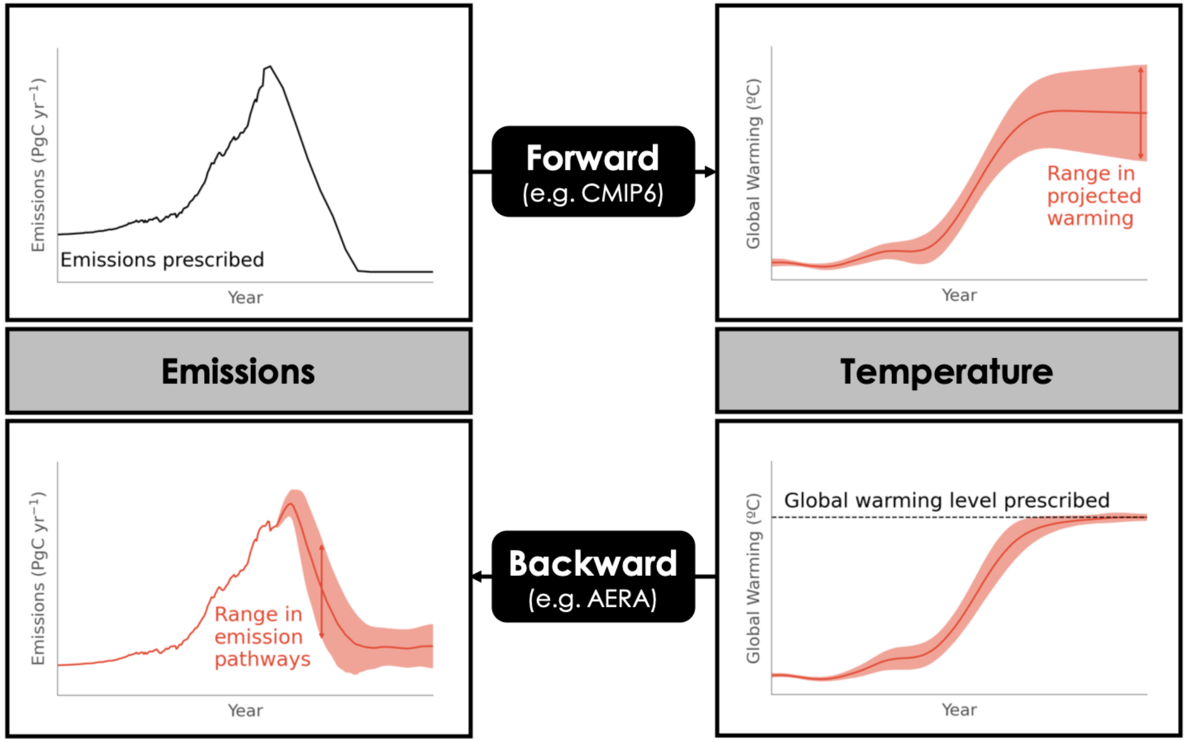
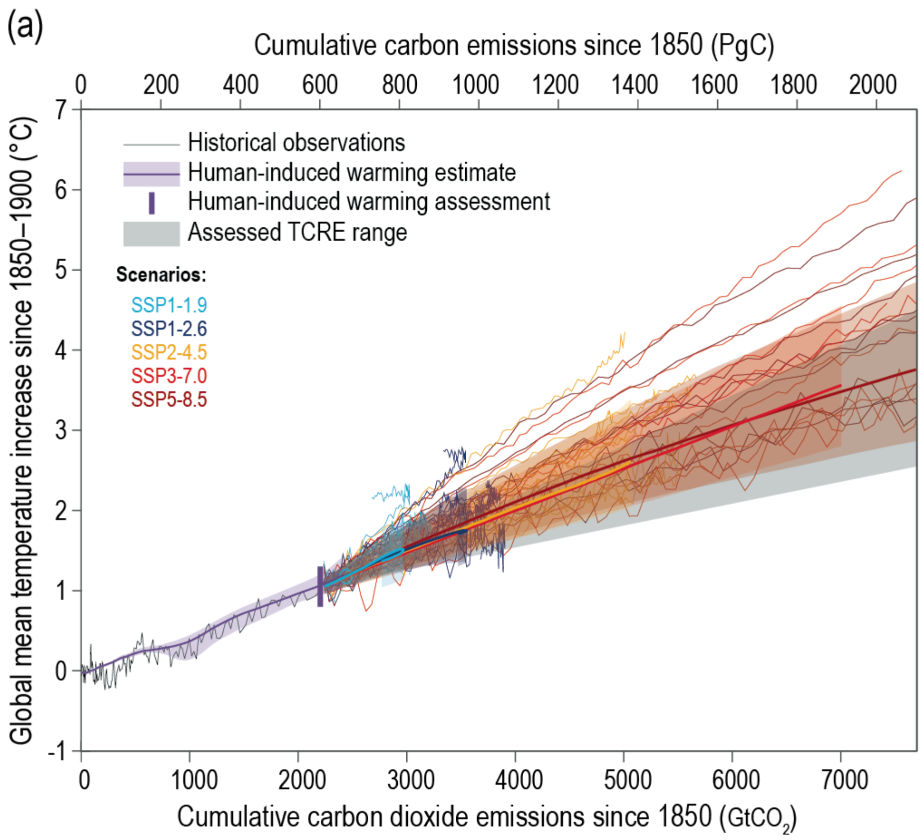


Silvy et al., 2024

Terhaar et al., 2022

AERA determines the emission pathways allowing global warming to **stabilise at the threshold**.

Estimate remaining emission budget from cumulative emissions and global warming



Climate Change 2021: The Physical Science Basis (IPCC, AR6, WG1, Figure TS.18 & Chapter 5.5.1)

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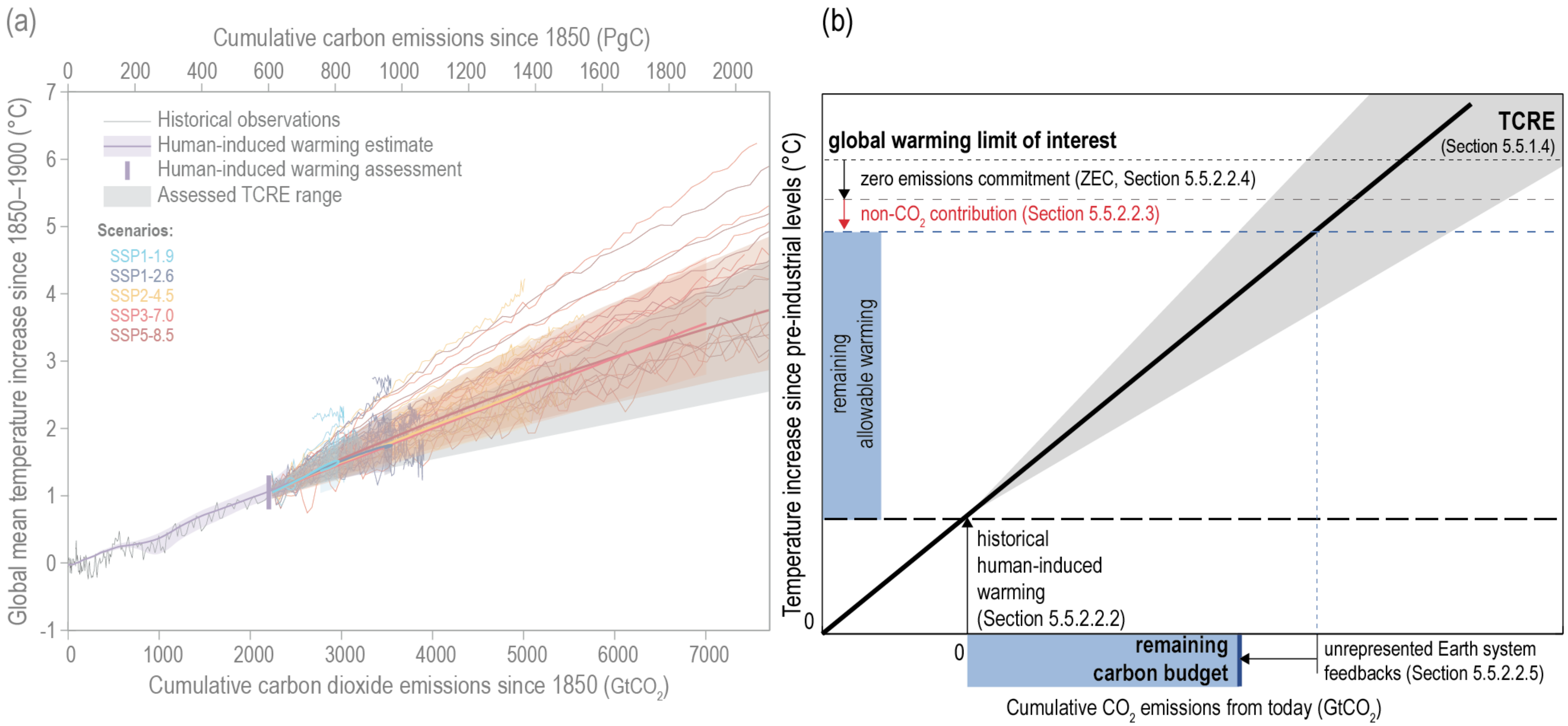


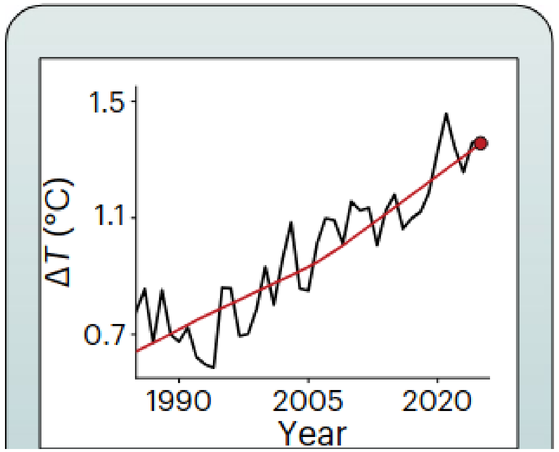
Climate Change 2021: The Physical Science Basis (IPCC, AR6, WG1, Figure TS.18 & Chapter 5.5.1)

Adaptive Emission Reduction Approach

Terhaar et al., 2022

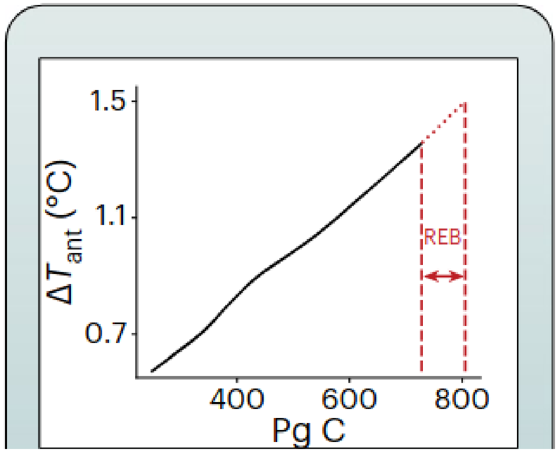
Step 1

Estimating anthropogenic warming (ΔT_{ant})



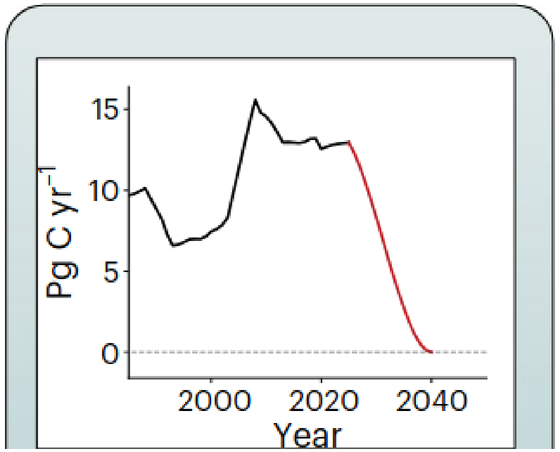
Step 2

Estimating the remaining CO_2-fe budget (REB)

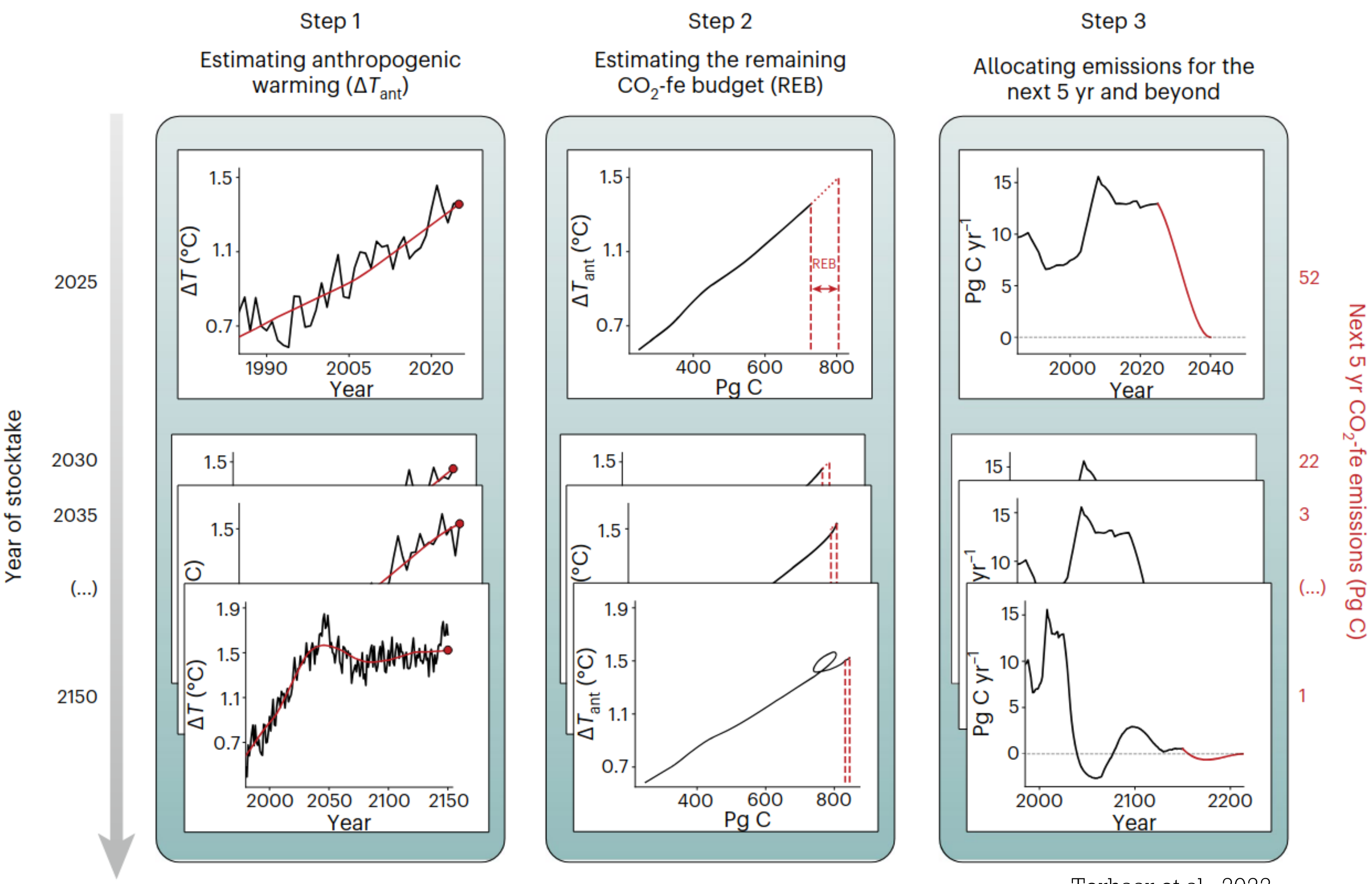


Step 3

Allocating emissions for the next 5 yr and beyond



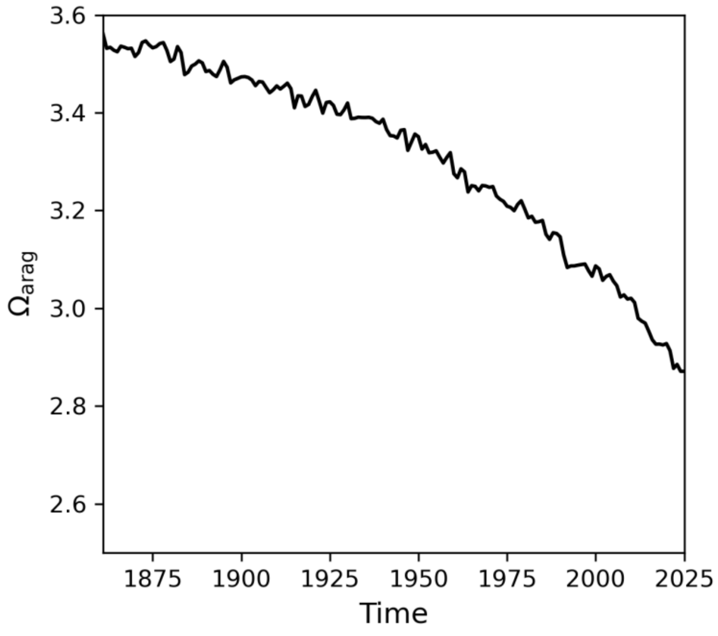
AERA provides emission pathways that stabilise global warming



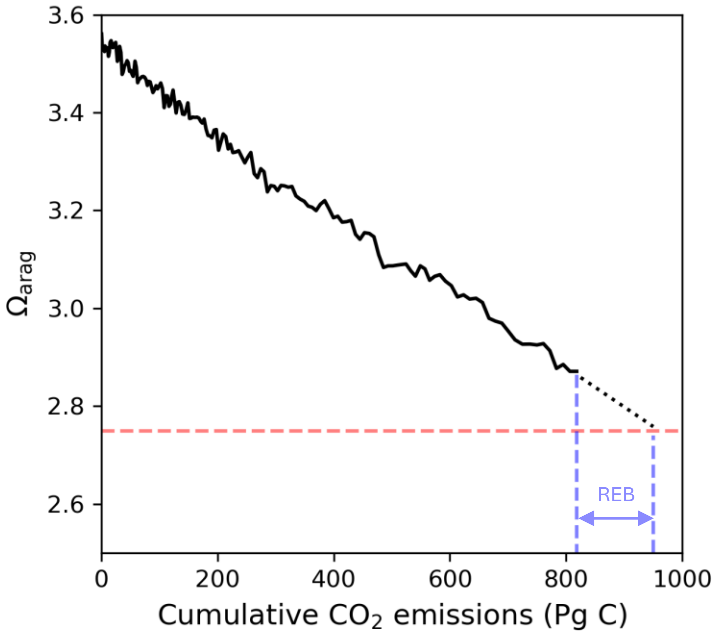
Terhaar et al., 2022

We want to extend AERA to an ocean acidification target

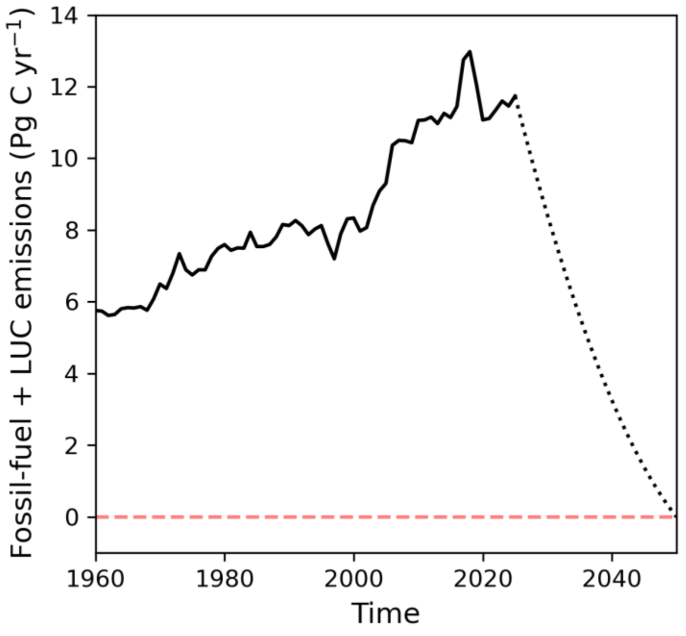
Step 1
Estimate the decrease in aragonite saturation state



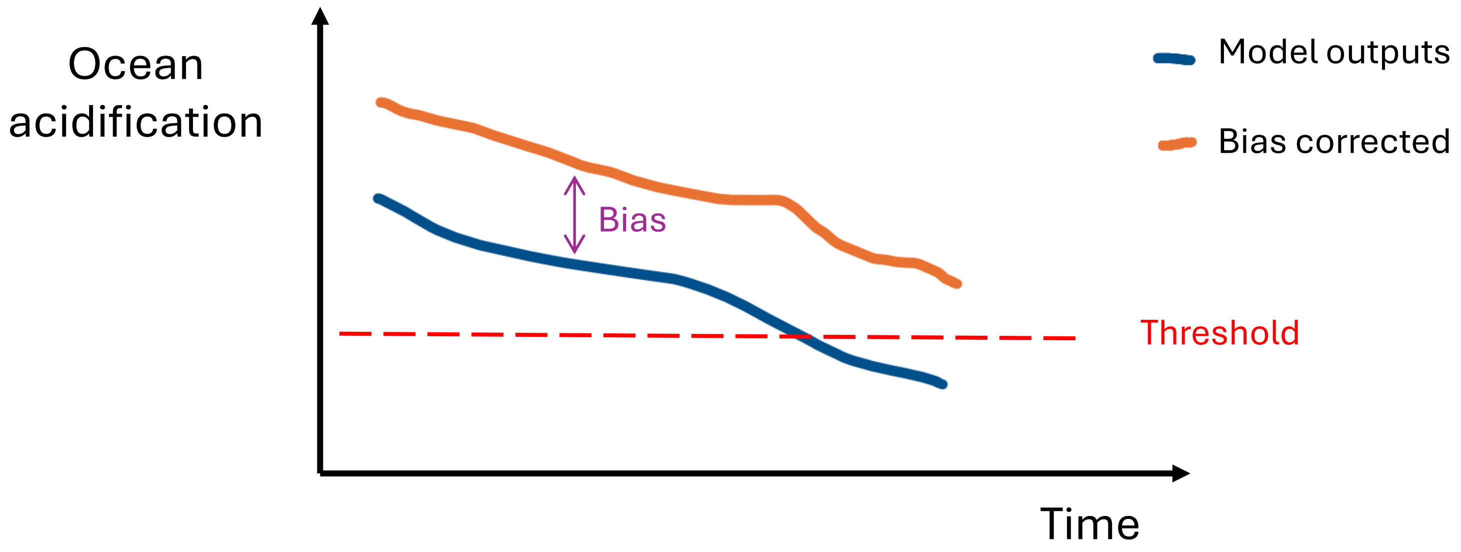
Step 2
Estimate the remaining CO_2 emission budget (REB)



Step 3
Allocate emissions for the next five years and beyond



Real-world acidification targets require model bias correction



Positive / **Negative**	bias	↔	Control variable in the model is	**higher** / **lower** than observations.

The bias correction is performed on ocean acidification drivers

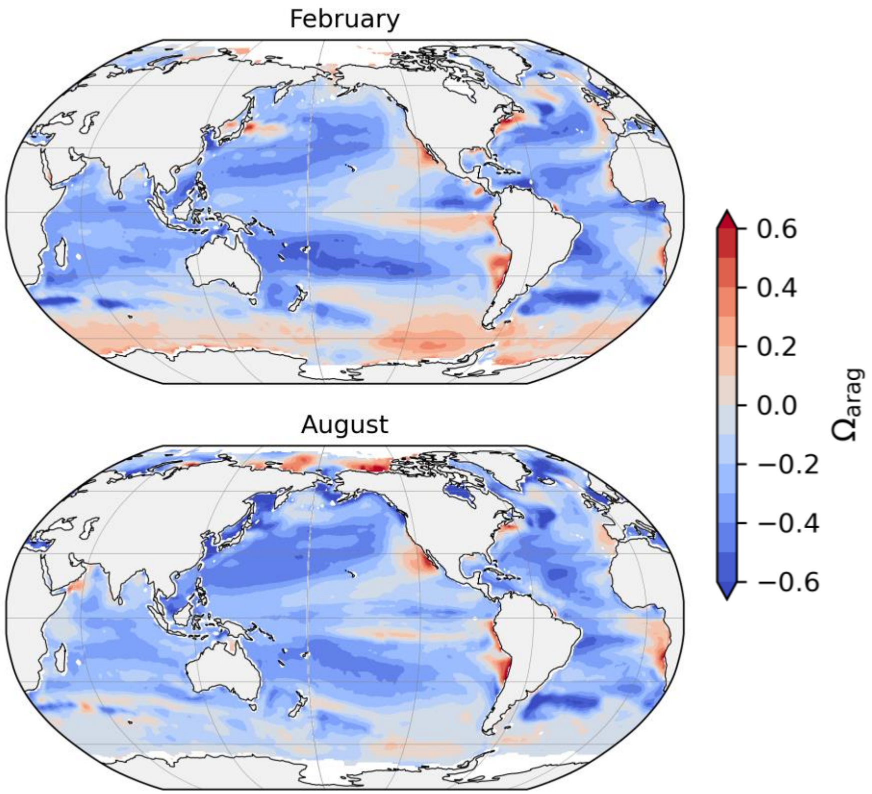
Ocean acidification **drivers**:

- Sea surface temperature
- Dissolved inorganic carbon
- Alkalinity
- Salinity
- Silicate
- Phosphate

Observation **datasets**:

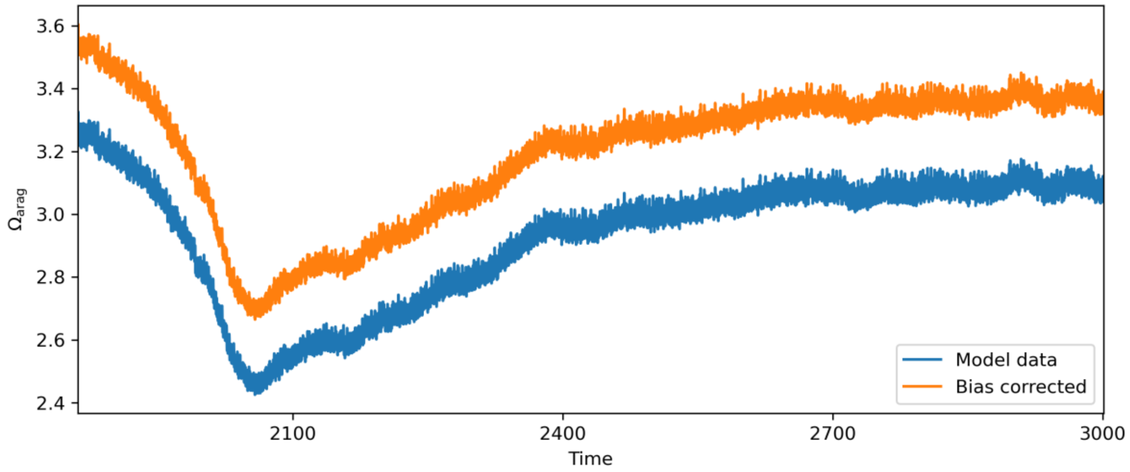
Gregor & Gruber, 2021 (OceanSODA-ETHZ, 1993-2022)
Garcia et al., 2024 (WOA, 1991-2020)

Aragonite saturation state, monthly bias
(Sim-Obs 1993-2022)



Satellite-based **observations → missing data** under **sea ice**

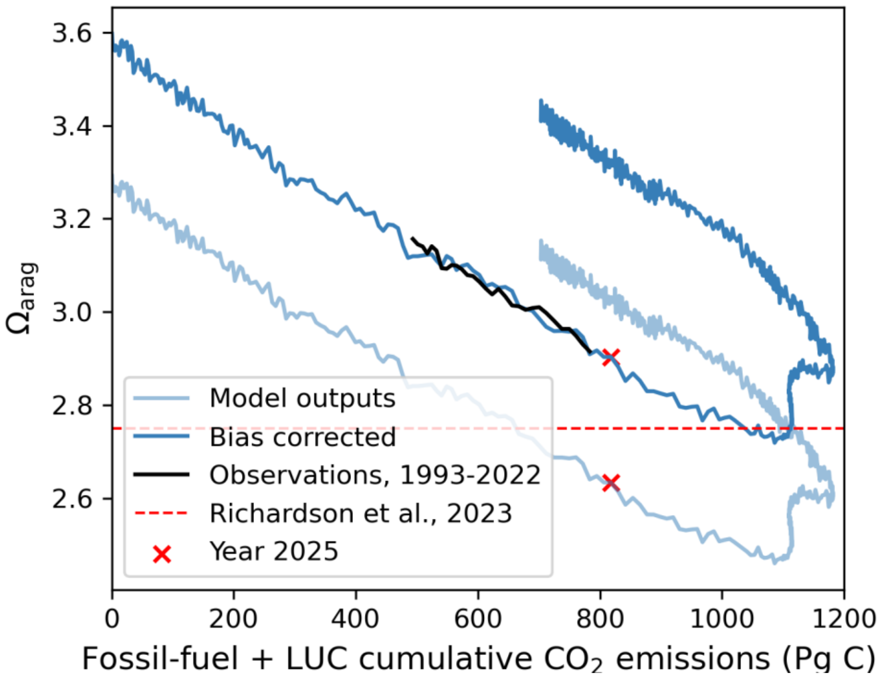
Ω_{arag} scales linearly against cumulative CO_2 emissions



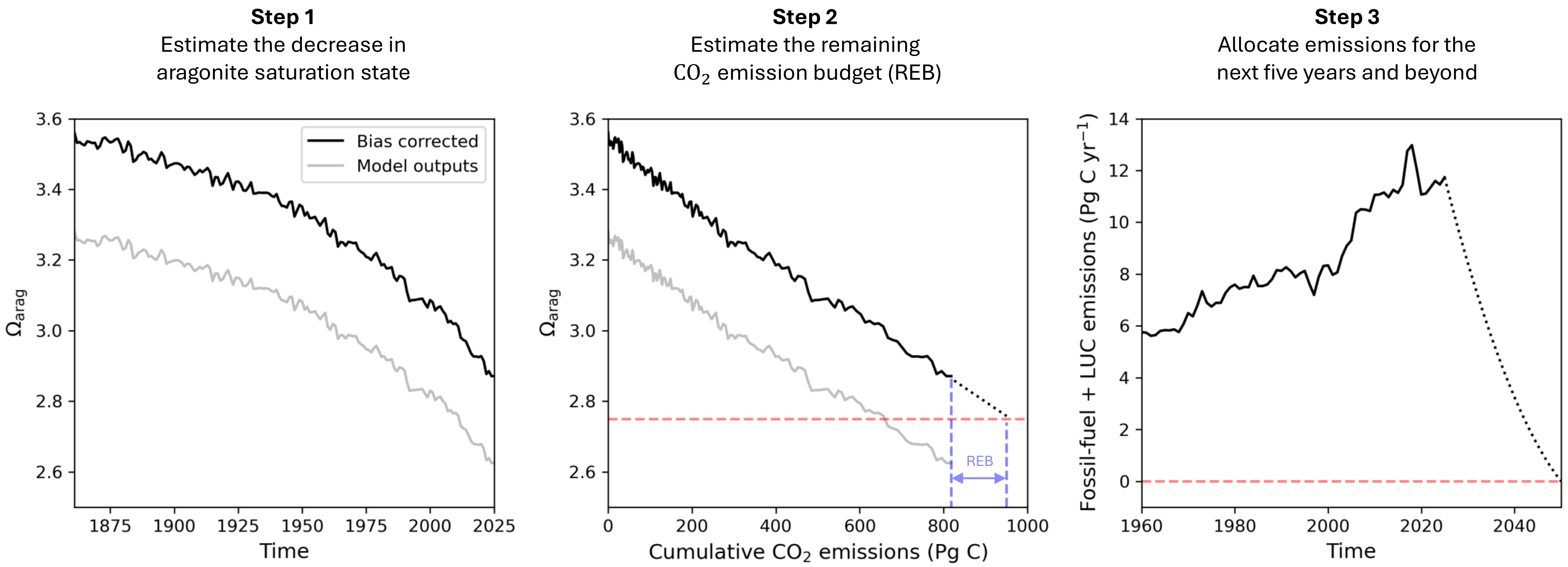
Before emission stabilisation:
Linear regime (TCRE)
Condition required by AERA

After emission stabilisation:
Hysteresis

GFDL-ESM2M Ω_{arag} time series is **negatively biased**.



Next step: implement acidification target in AERA



Take home messages

Ocean acidification impacts **calcifying organisms** and threatens **high latitudes** ecosystems.

Global warming scales **near-linearly** with cumulative CO_2 emissions.

Earth system models can be used to compute **safe emission pathways** for global mean **temperature**.

We extend the **adaptive emission reduction approach** to ocean **acidification targets**.

Real-world acidification **thresholds** require **model bias correction**.

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Thank you for your attention!

References

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Figure 9 (b)

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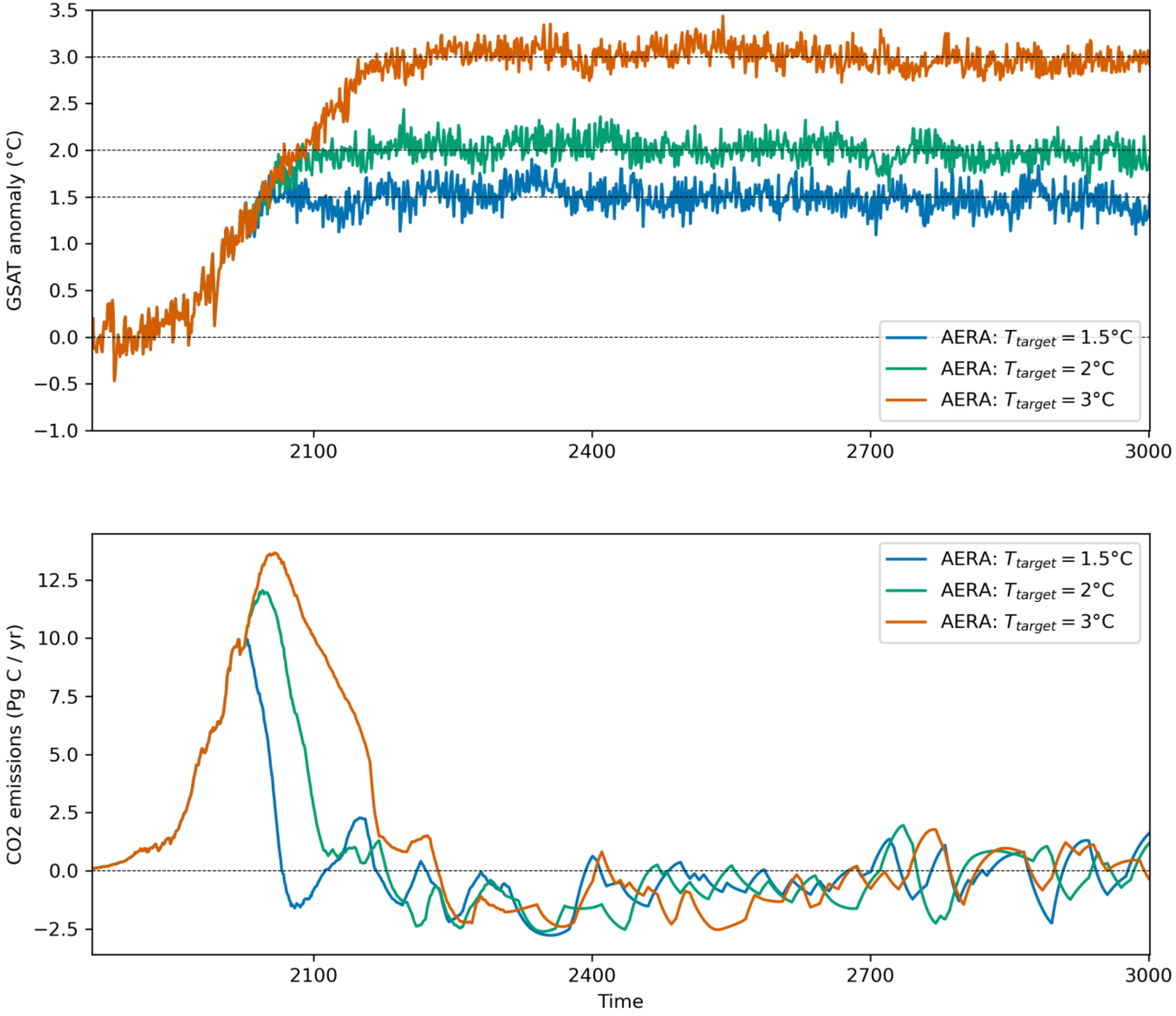
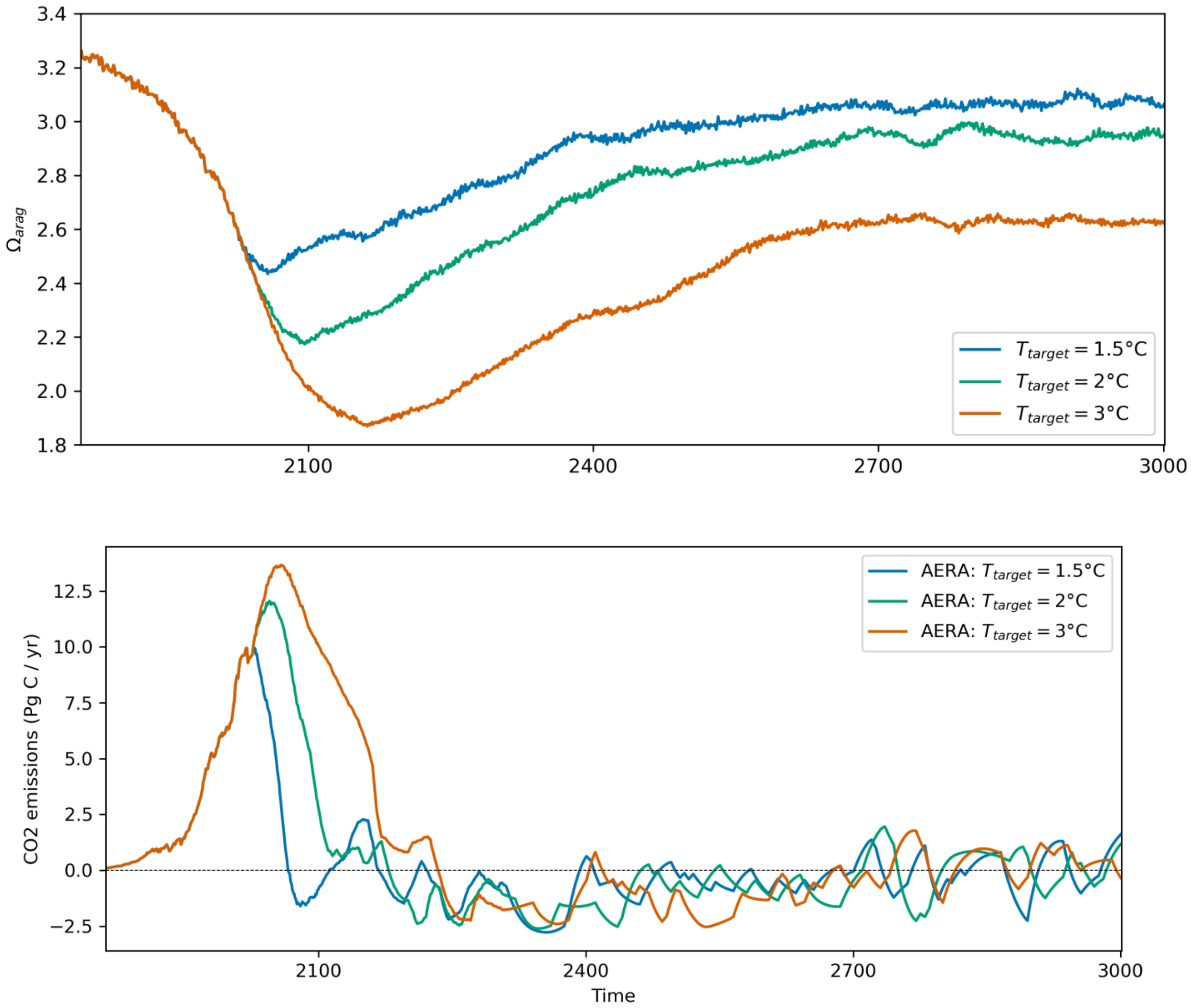
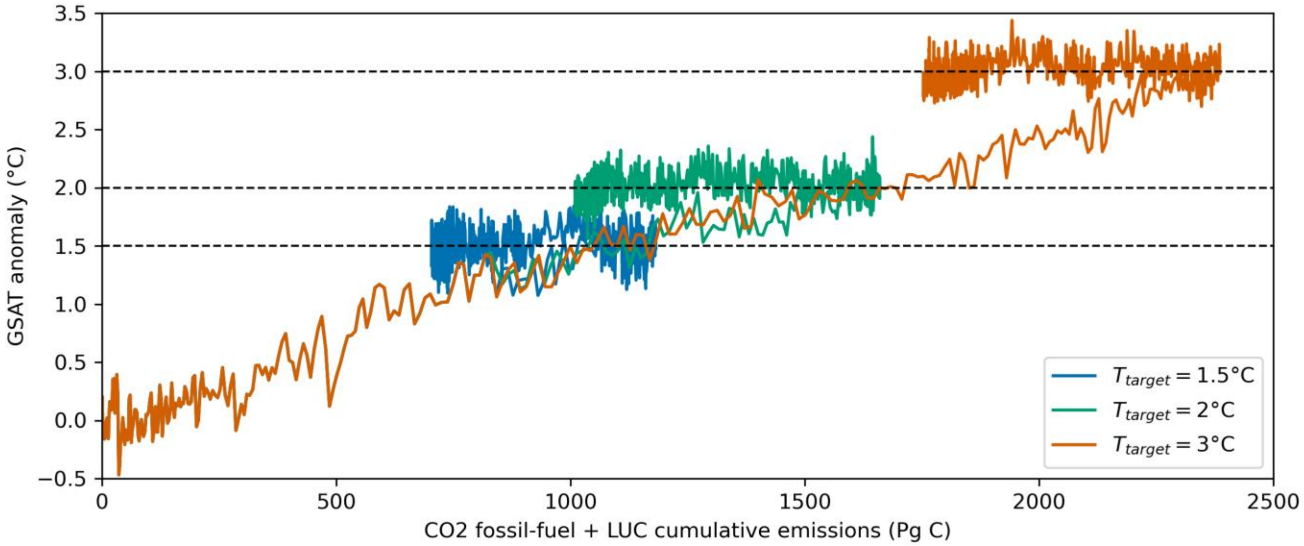
Additional slides

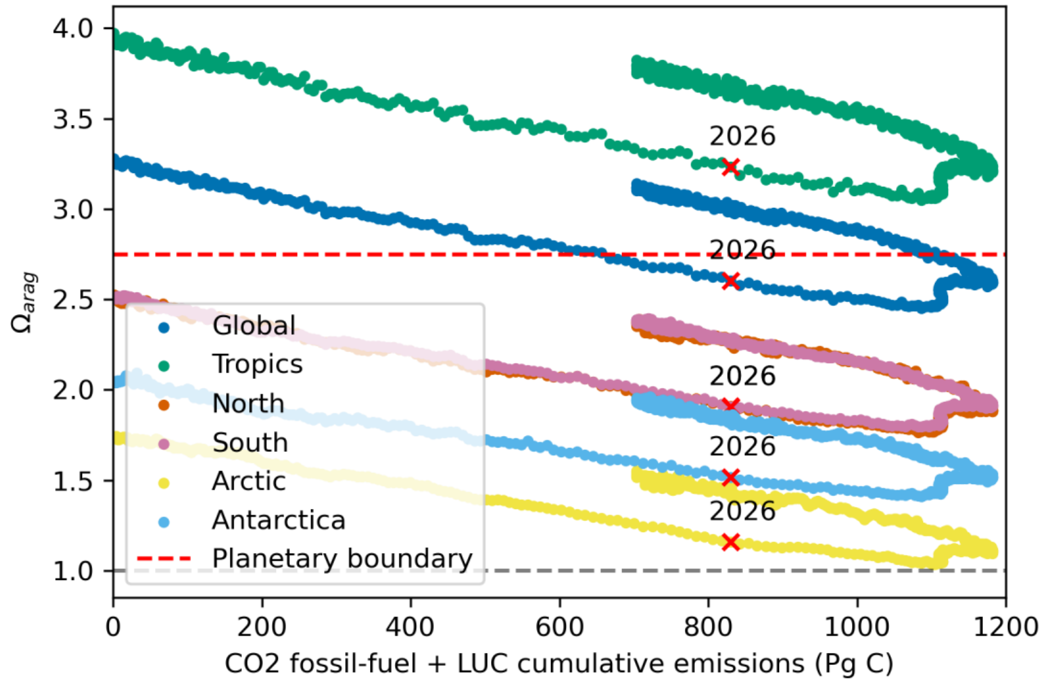


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
GSAT anomaly (°C)
2100
2400
2700
3000
AERA: T_{target} = 1.5°C
AERA: T_{target} = 2°C
AERA: T_{target} = 3°C
12.5
10.0
7.5
5.0
2.5
0.0
−2.5
CO2 emissions (Pg C / yr)
2100
2400
2700
3000
Time
AERA: T_{target} = 1.5°C
AERA: T_{target} = 2°C
AERA: T_{target} = 3°C

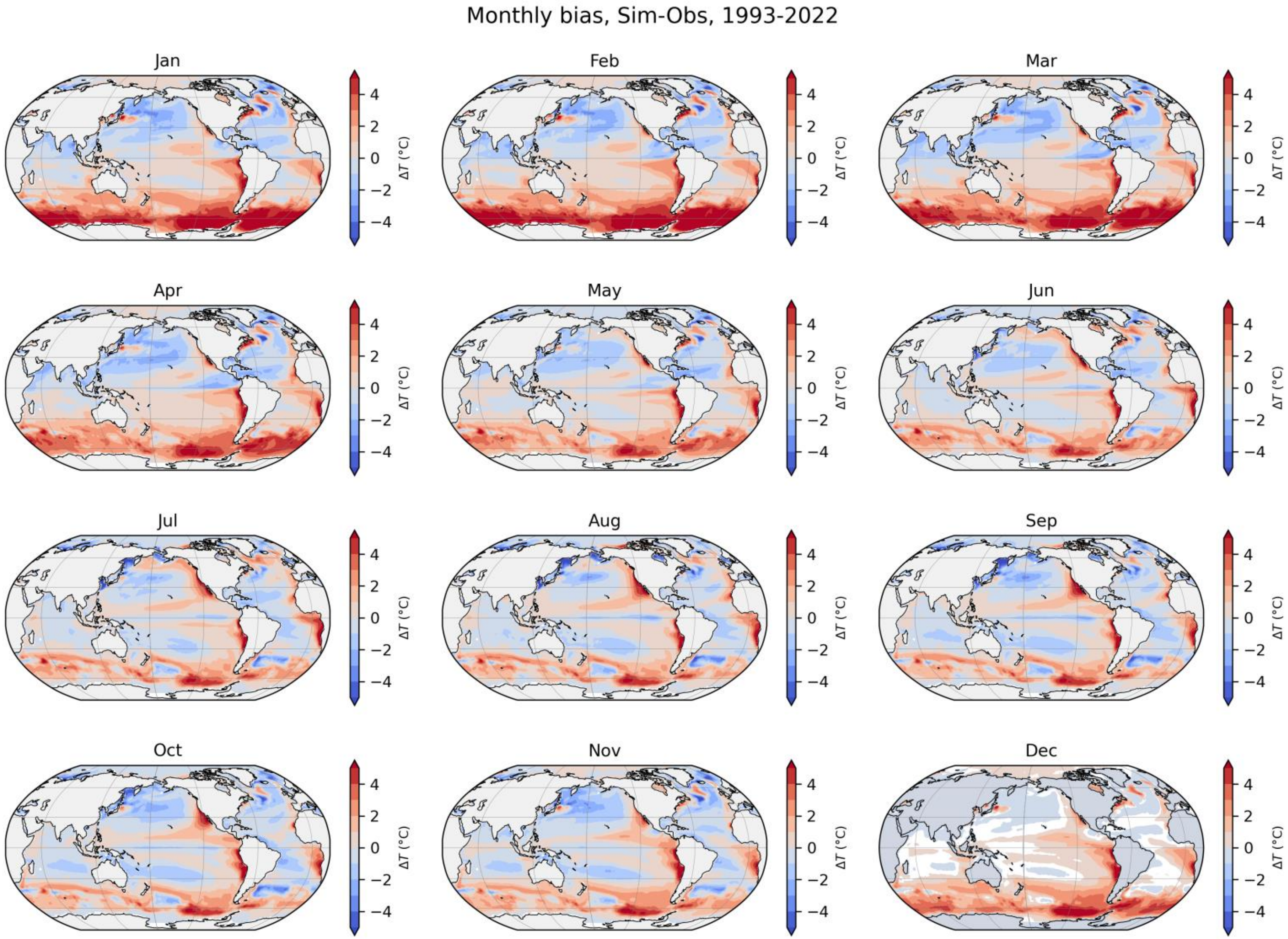


3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
Ω_{arag}
2100
2400
2700
3000
$T_{target} = 1.5°C$
$T_{target} = 2°C$
$T_{target} = 3°C$
12.5
10.0
7.5
5.0
2.5
0.0
−2.5
CO2 emissions (Pg C / yr)
AERA: $T_{target} = 1.5°C$
AERA: $T_{target} = 2°C$
AERA: $T_{target} = 3°C$
2100
2400
2700
3000
Time


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
GSAT anomaly (°C)
0
500
1000
1500
2000
2500
CO2 fossil-fuel + LUC cumulative emissions (Pg C)
$T_{target} = 1.5°C$
$T_{target} = 2°C$
$T_{target} = 3°C$



4.0
3.5
3.0
2.5
2.0
1.5
1.0
Ω_{arag}
0
200
400
600
800
1000
1200
CO2 fossil-fuel + LUC cumulative emissions (Pg C)
2026
2026
2026
2026
2026
Global
Tropics
North
South
Arctic
Antarctica
Planetary boundary


Monthly bias, Sim-Obs, 1993-2022
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
ΔT (°C)
4
2
0
−2
−4