The Ocean Physics behind Net Zero

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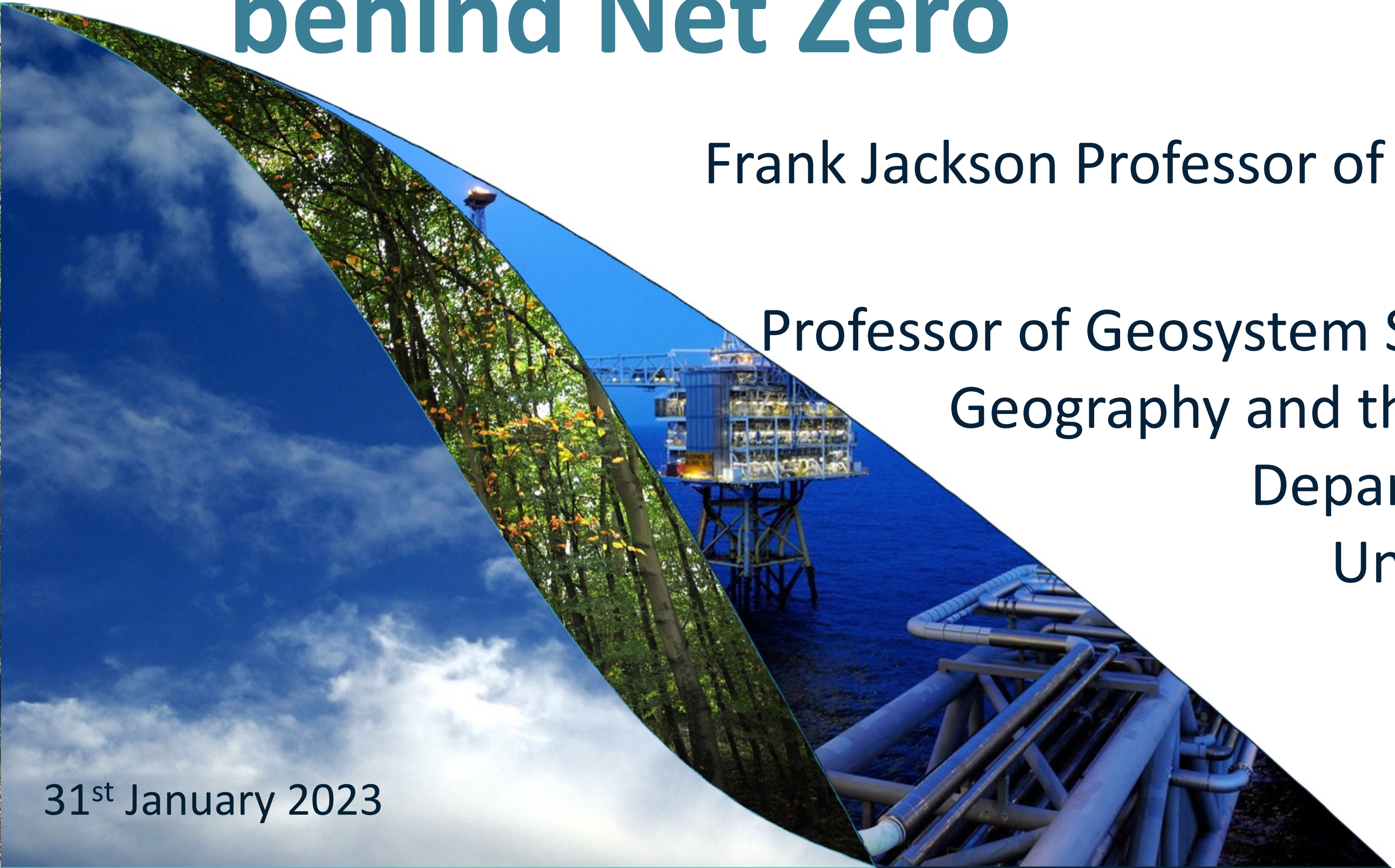

31st January 2023

Why is the deep ocean cold?

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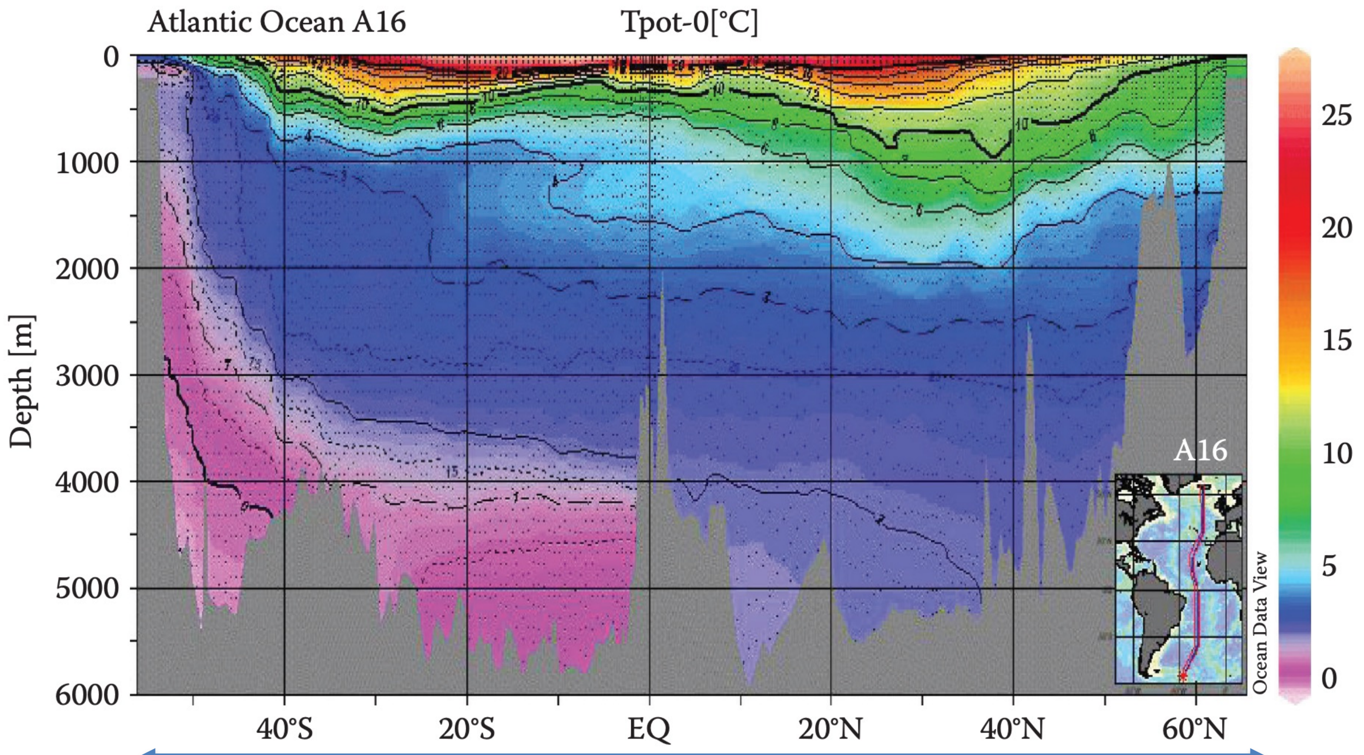
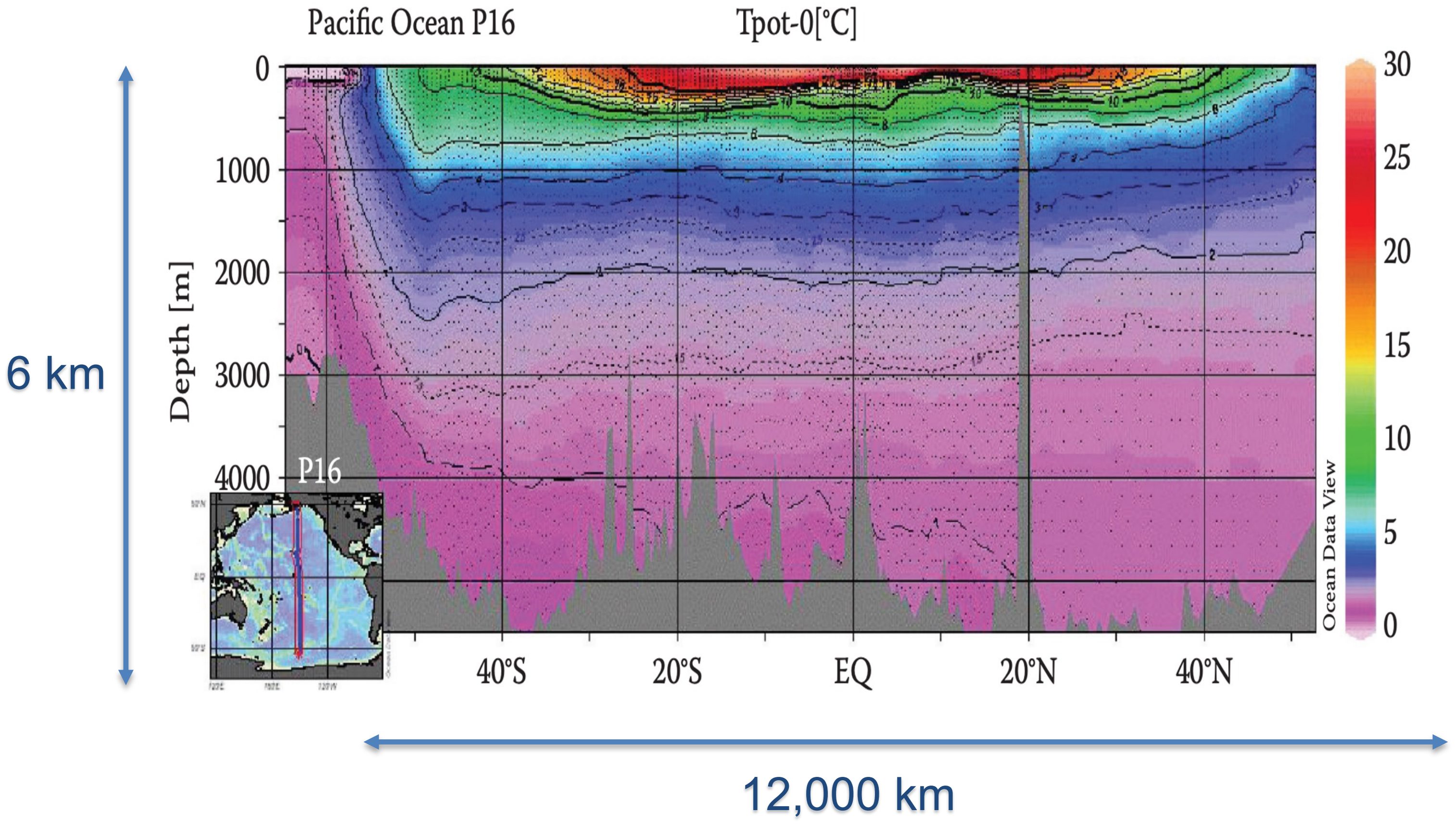


6 km

12,000 km

Why is the deep ocean cold?

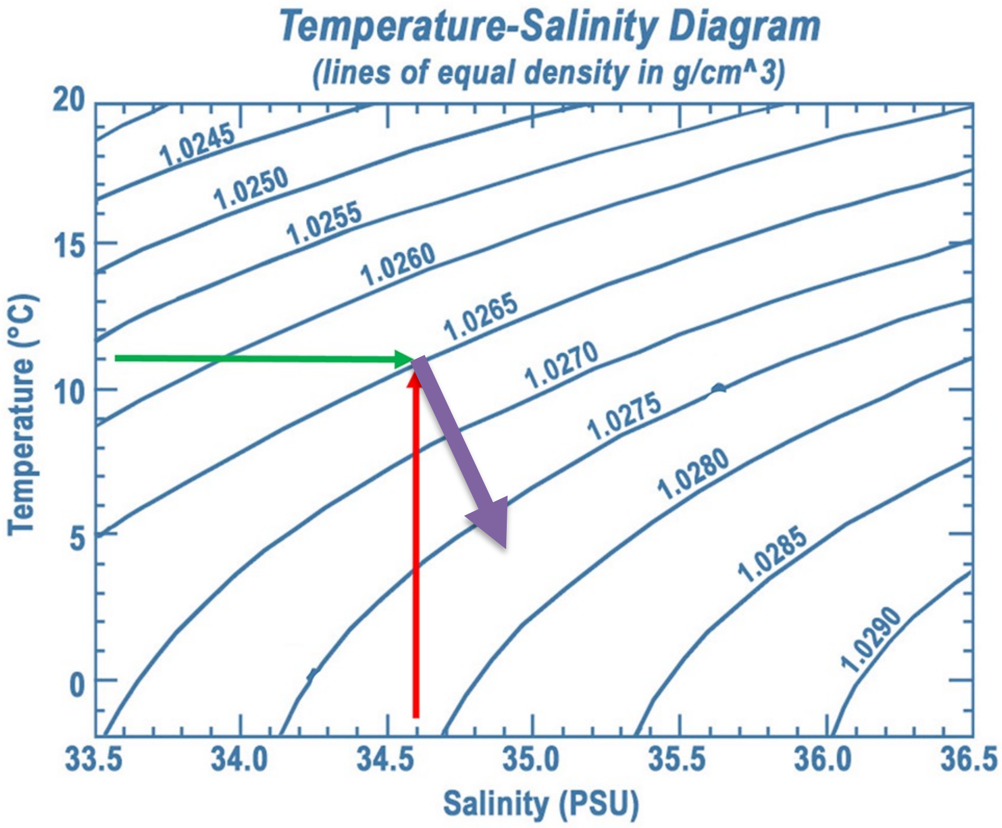


Why is the deep ocean cold?

- Temperature isn't the only factor affecting the density of sea water.

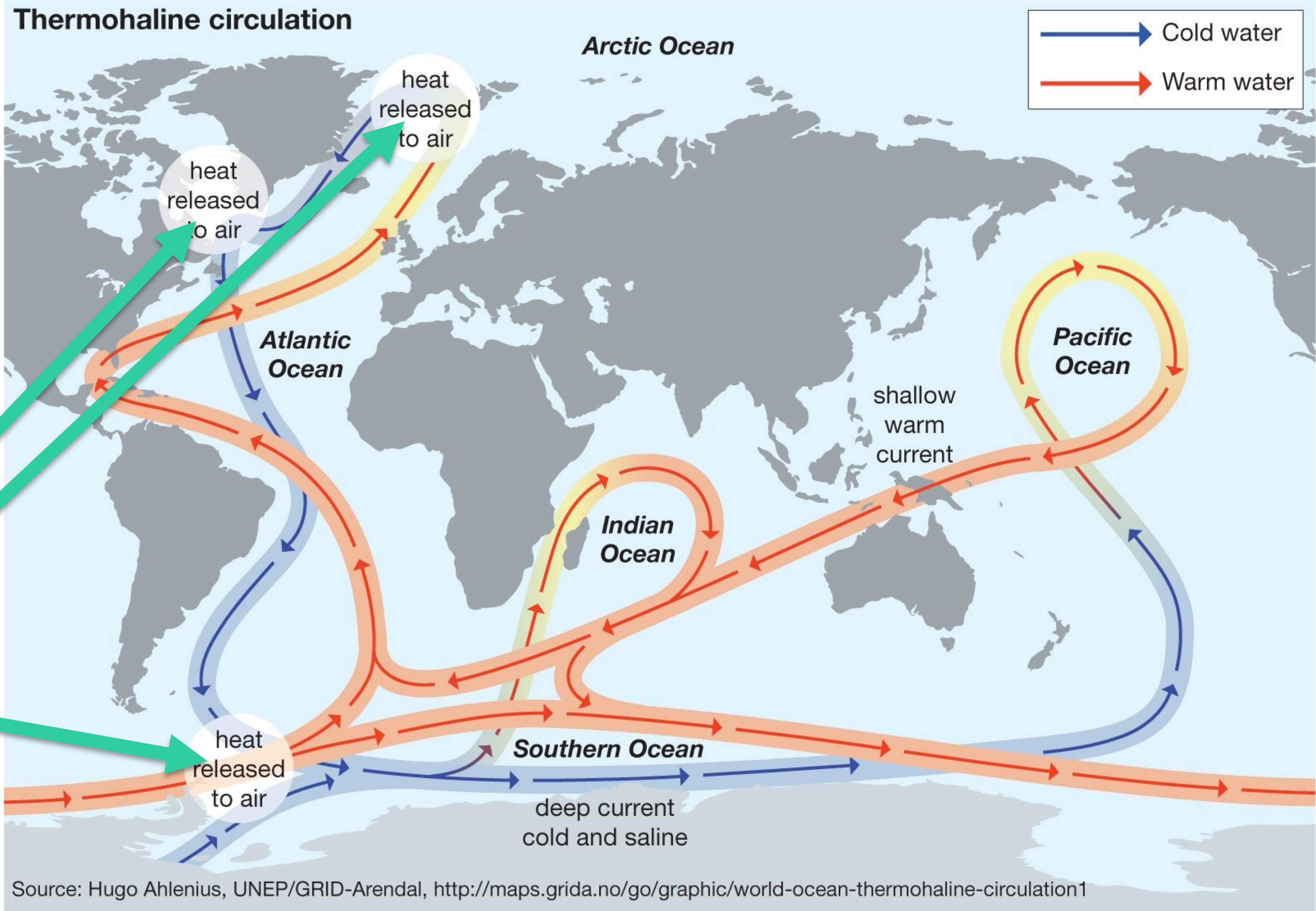
Why is the deep ocean cold?

- Temperature and salt-content, or salinity, affect density of sea water.
- Cooling, evaporation & ice-formation make water denser.
- So surface waters escape to depth only in very cold regions.



Deep water formation

The great ocean conveyor



Deep water formation regions

So what has this got to do with net zero?

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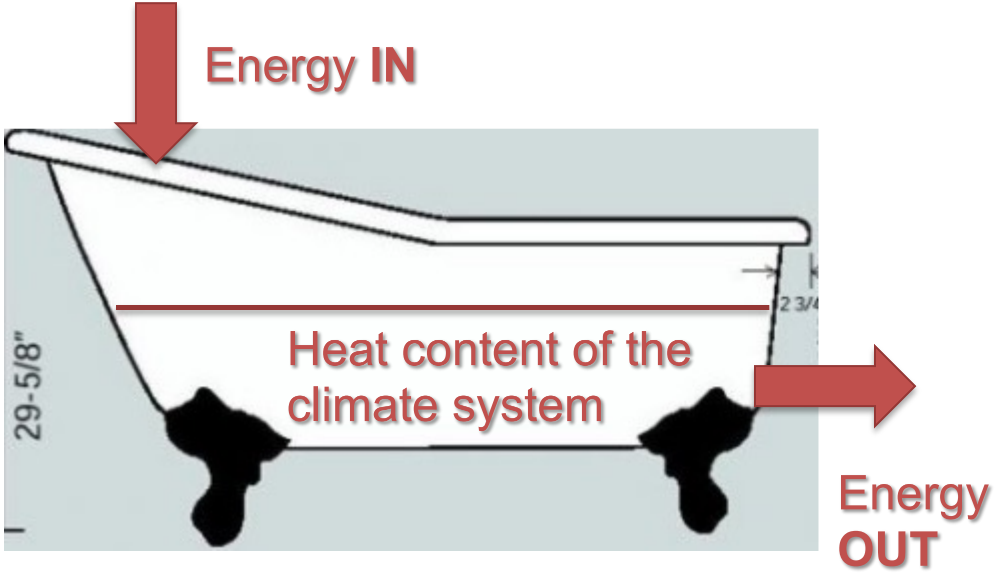
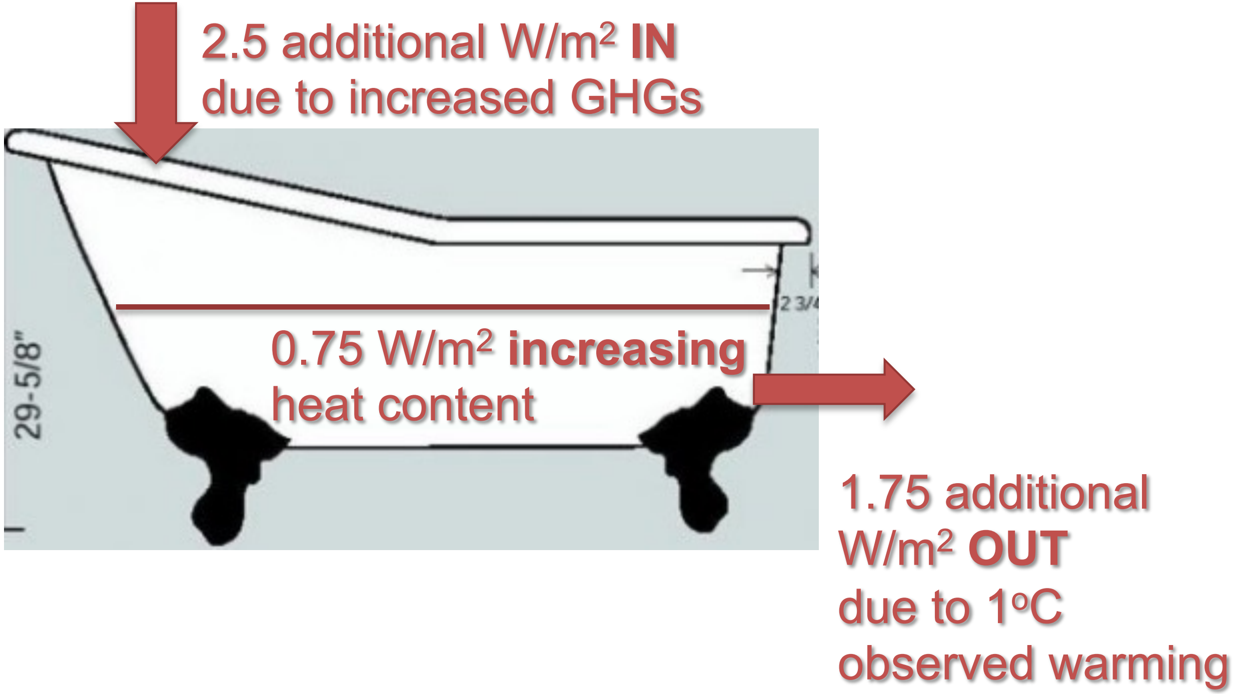
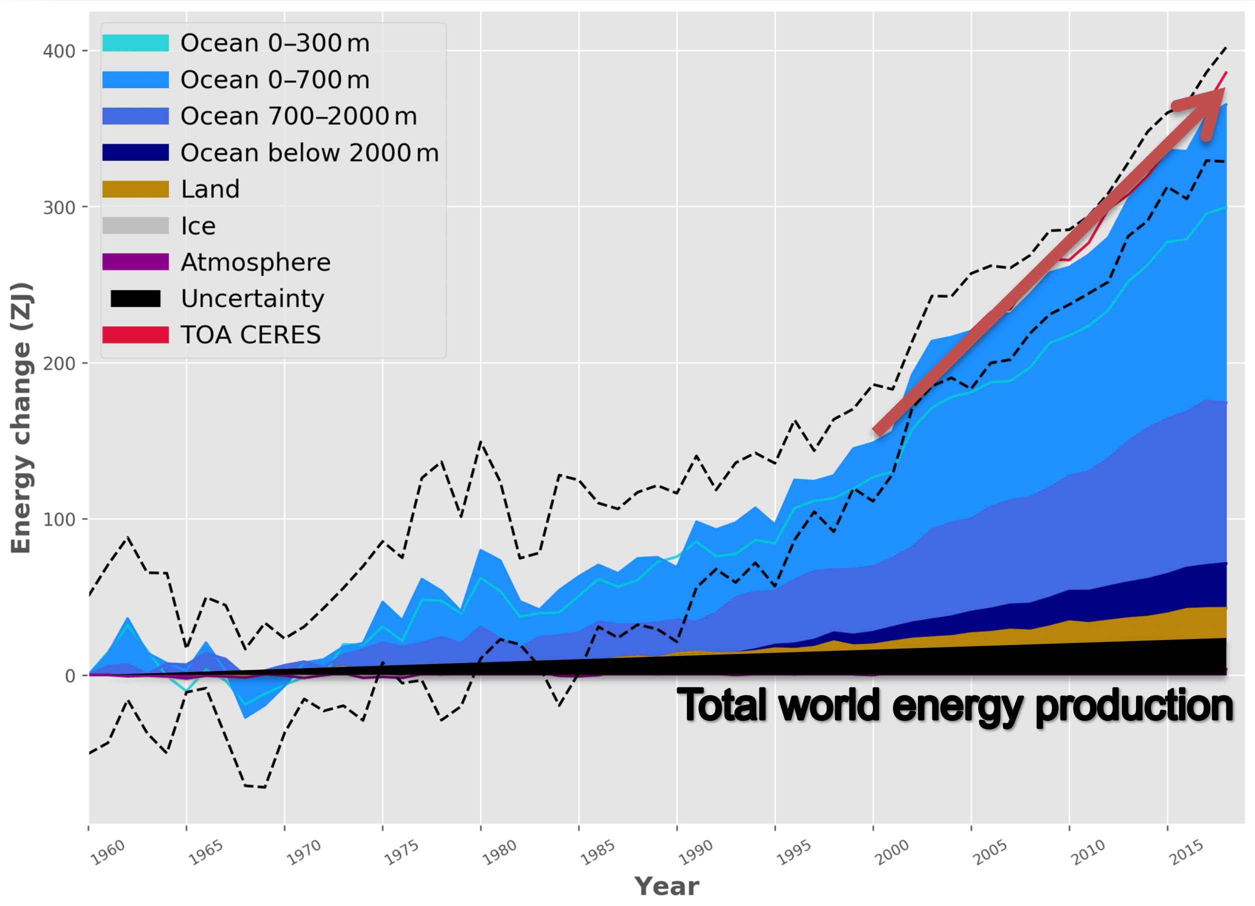


So what has this got to do with net zero? It determines how heat energy is distributed in the climate system



Where heat energy is going

Heat energy accumulation in the climate system since 1960

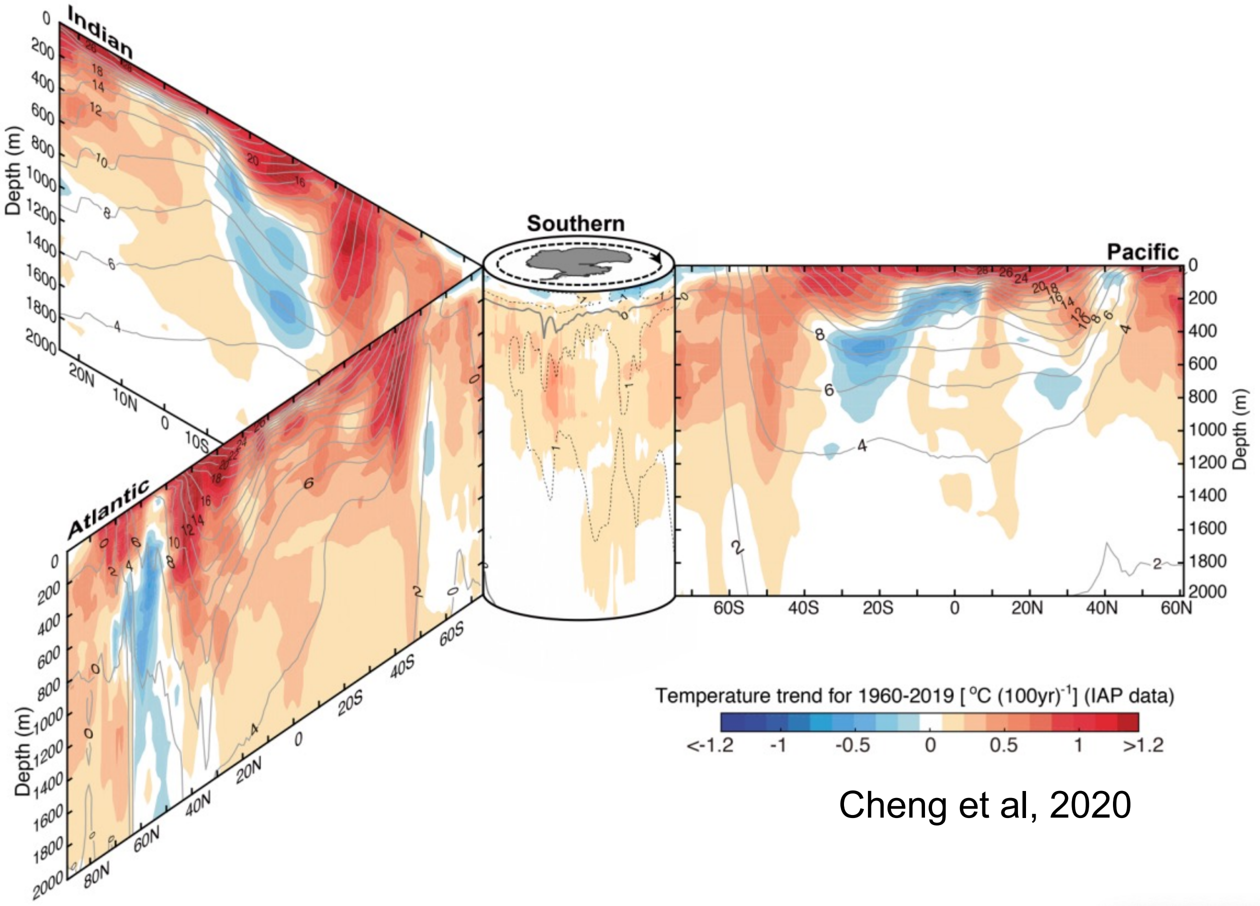


$0.75 W/m^2$

von Schuckman et al, 2020

Where heat energy is going

Ocean temperature trends 1960-2019



Cheng et al, 2020

Back to our Gresham climate model

- A plastic tube with an open outlet pipe:

$$F = k \times h$$

  - F is the additional rate of fluid flowing in, above “background” flow.
  - h is the increased water depth above the initial equilibrium level.
  - k is the openness of the outlet pipe.

Back to our Gresham climate model

- The Earth's climate system in equilibrium:

$$F = \lambda \times T$$

  - F is net additional energy flow in due to increased greenhouse gases.
  - T is global average surface temperature increase above pre-industrial.
  - λ is efficiency with which Earth gets rid of excess energy to space.

Back to our Gresham climate model

- A plastic tube with an open outlet pipe:

$$F = k \times h$$

  - F is the additional rate of fluid flowing in, above “background” flow.
  - h is the increased water depth above the initial equilibrium level.
  - k is the openness of the outlet pipe.

Gresham climate model, Mk. 2

- A plastic tube with two open outlet pipes & an “infinite pool”:

$$F = (k + k_2) \times h$$

  - F is the additional rate of fluid flowing in, above “background” flow.
  - h is the increased water depth above the initial equilibrium level.
  - k is the openness of the outlet pipe flowing out to “space”.
  - k_2 is the openness of the outlet pipe flowing into the “ocean pool”.

Gresham climate model, Mk. 2

- The Earth's climate in equilibrium with an infinite deep ocean:

$$F = (\lambda + \gamma) \times T$$

  - F is net additional energy flow in due to increased greenhouse gases.
  - T is global average surface temperature increase above pre-industrial.
  - λ is efficiency with which Earth gets rid of excess energy to space.
  - γ is efficiency of excess surface energy transport to the deep ocean.

Gresham climate model, Mk. 2

- A model of slow changes in water depth:
$$\Delta F = (k + k_2) \times \Delta h$$
  - ΔF is the *change* in rate of fluid flowing in over a time-interval.
  - Δh is the *change* in water depth, after initial rapid adjustment.
  - k and k_2 are constant.

Gresham climate model, Mk. 2

- A model of slow changes in global temperature:

$$\Delta F = (\lambda + \gamma) \times \Delta T$$

  - ΔF is the *change* in energy flow in due to *change* in greenhouse gases.
  - ΔT is the *change* global average surface temperature.
  - λ & γ are constant.

Gresham climate model, Mk. 2, rearranged

- A model of slow changes in water depth:

$$\Delta h = \kappa \times \Delta F$$

  - Δh is the *change* in water depth, after initial rapid adjustment.
  - ΔF is the *change* in rate of fluid flowing in over a time-interval.
  - κ is a constant, $1/(k + k_2)$.

Gresham climate model, Mk. 3

- Changes in water depth with adjustment of ocean pool:

$$\Delta h = \kappa \times \Delta F + \kappa_2 \times \bar{F} \times \Delta t$$

  - Δh is the *change* in water depth, after initial rapid adjustment.
  - ΔF is the *change* in rate of fluid flowing in over a time-interval.
  - $\bar{F}$ is the *average* rate of fluid flowing in over that time-interval.
  - Δt is the length of the time-interval.
  - κ and κ_2 are constants.

Gresham climate model, Mk. 3, rearranged

- Changes in water depth with adjustment of ocean pool:

$$\Delta h = \kappa \times (\Delta F + \rho \times \bar{F} \times \Delta t)$$

  - Δh is the *change* in water depth, after initial rapid adjustment.
  - ΔF is the *change* in rate of fluid flowing in over a time-interval.
  - $\bar{F}$ is the *average* rate of fluid flowing in over that time-interval.
  - Δt is the length of the time-interval.
  - κ is a constant "Transient Level Response to Flow".
  - ρ is a constant "Rate of Adjustment to Constant Flow".

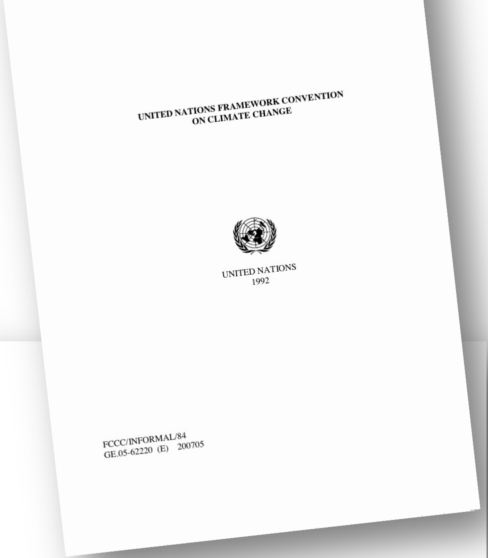
Gresham climate model, Mk. 3, rearranged

- Changes in temperature over decade to century timescales:

$$\Delta T = \kappa_F \times (\Delta F + \rho_F \times \bar{F} \times \Delta t)$$

  - ΔT is the *change* in global average surface temperature.
  - ΔF is the *change* in energy flow in due to *change* in greenhouse gases.
  - $\bar{F}$ is the *average* energy flow in due to *level* of greenhouse gases.
  - Δt is the length of the time-interval.
  - κ_F is a constant “Transient Climate Response to Forcing”.
  - ρ_F is a constant “Rate of Adjustment to Constant Forcing”.

So what does stabilization achieve?


UNITED NATIONS FRAMEWORK CONVENTION
ON CLIMATE CHANGE

UNITED NATIONS
1992

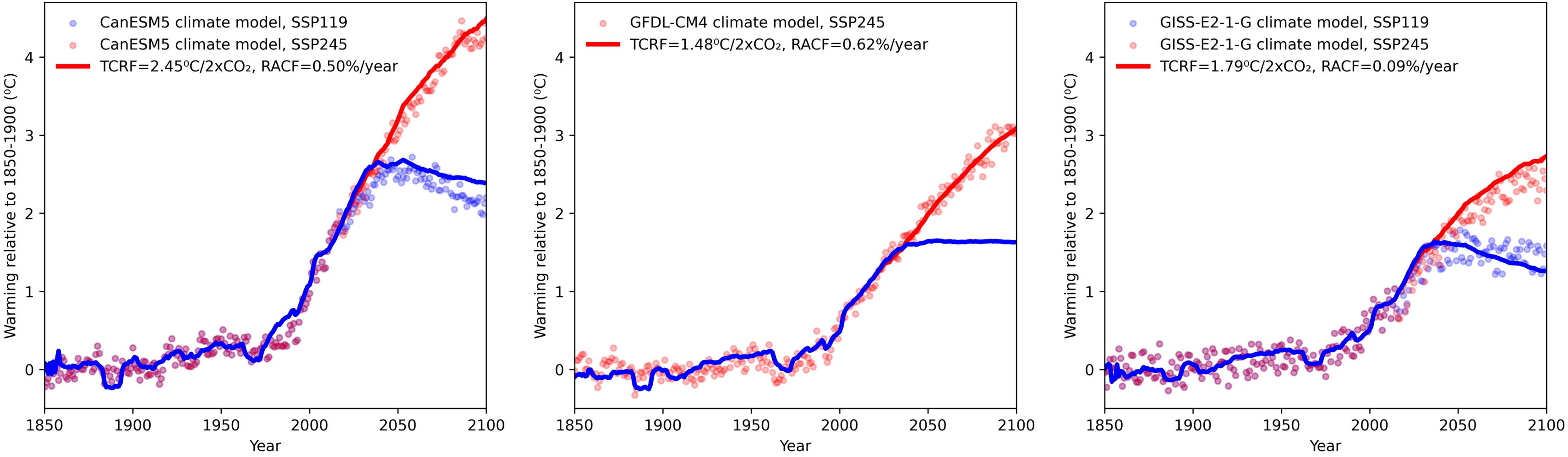
FCCC/INFORMAL/84
GE.05-62220 (E) 200705

Article 2

OBJECTIVE

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, **stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.** Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

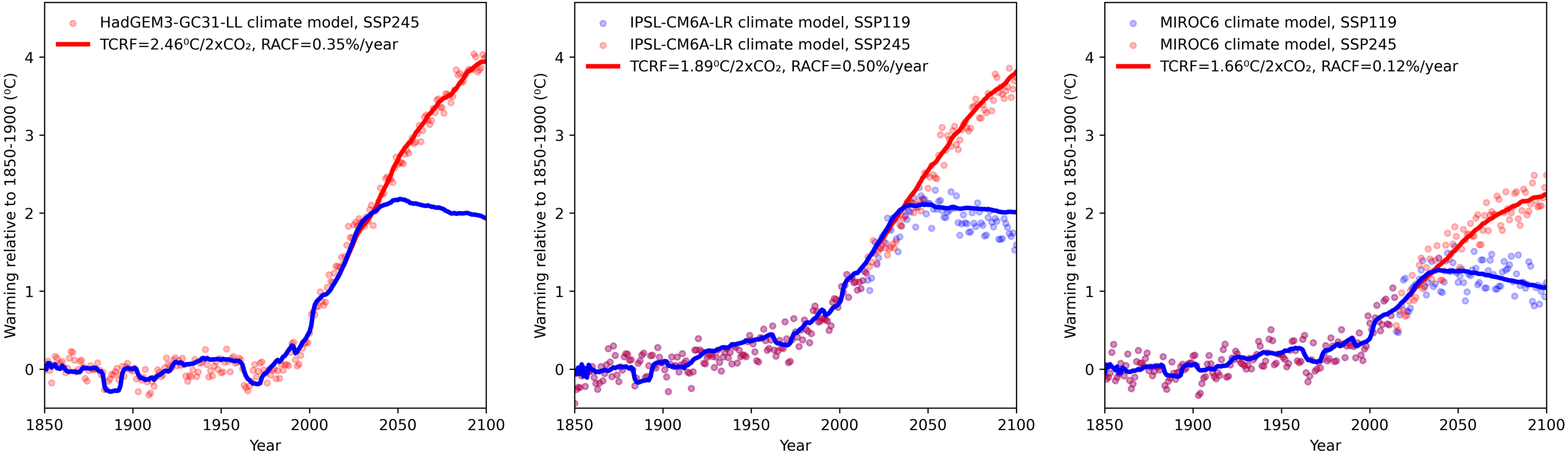
So how well does this work?



Full-complexity climate models take millions of processor-hours per simulation

Solid lines: $\Delta T = \kappa_F \times (\Delta F + \rho_F \times \bar{F} \times \Delta t)$

So how well does this work?



Full-complexity climate models take millions of processor-hours per simulation

Solid lines: $\Delta T = \kappa_F \times (\Delta F + \rho_F \times \bar{F} \times \Delta t)$

So what will it take to halt the warming?

- Changes in temperature over decade to century timescales:

$$\Delta T = \kappa_F \times (\Delta F + \rho_F \times \bar{F} \times \Delta t)$$

  - We want $\Delta T = 0$, meaning no further surface temperature change.
  - So either $\bar{F} = 0$, meaning atmospheric composition is back to pre-industrial, or…

$$\frac{\Delta F / \Delta t}{\bar{F}} = -\rho_F$$

  - So global energy imbalance needs to *decline* at a fractional rate equal to the RACF, or about 0.3% per year.
  - Not constant, but declining, concentrations of greenhouse gases.

A good-enough model for climate policy

- Changes in temperature over decade to century timescales:

$$\Delta T = \kappa_F \times (\Delta F + \rho_F \times \bar{F} \times \Delta t)$$

- Warming over a multi-decade time-interval is proportional to:

1. the *change* in global energy imbalance due to any *change* in greenhouse gas levels over that time-interval plus
2. a contribution from the gradual adjustment to the current *level* of energy imbalance relative to pre-industrial.

An enthusiasts' model of global temperature response to energy imbalances, from 5 to 500 years

Rate of increase in near-surface heat content

Energy imbalance due to increased greenhouse gases

Additional energy flow to space due to surface warming in equilibrium

Additional energy flow to deep ocean due to climate disequilibrium

$$C_s \frac{dT_s}{dt} = F_{\mathrm{ext}} - \lambda T_s - \gamma (T_s - T_d) - \lambda' (T_s - T_d)$$

$$C_d \frac{dT_d}{dt} = \gamma (T_s - T_d)$$

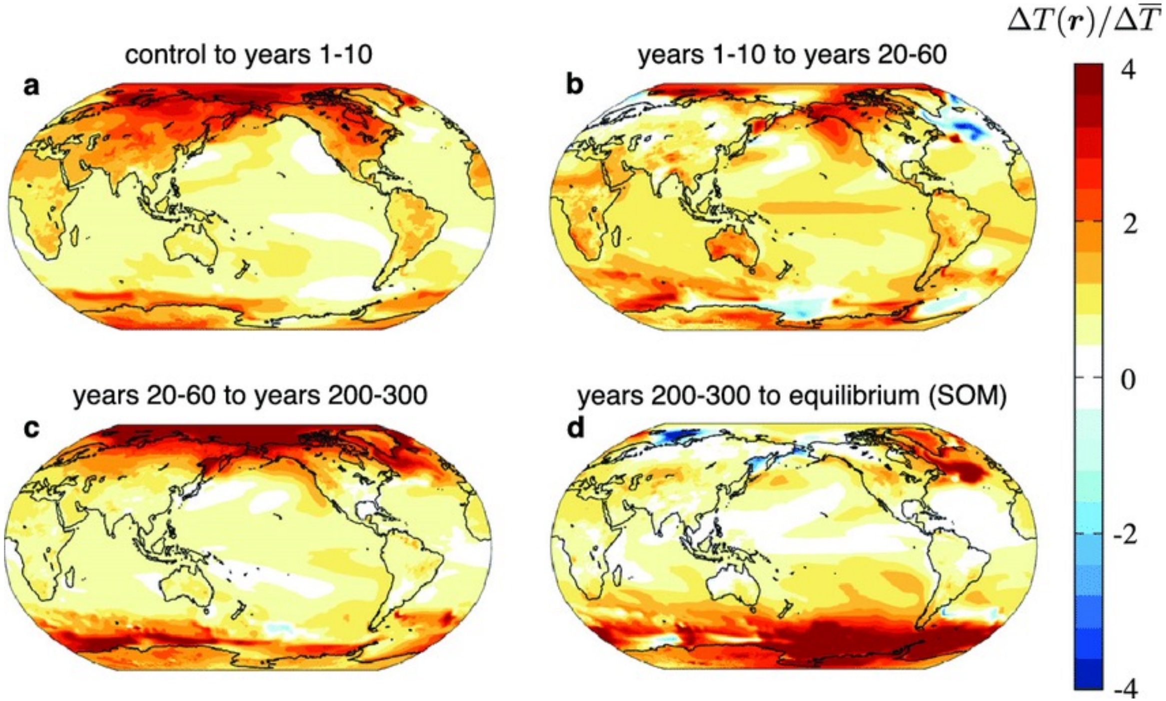
Rate of increase in deep-ocean heat content

Additional energy flow to space due to climate being out of equilibrium

Indomitable nerds see: [Net Zero: Science, Origins, and Implications]

M. R. Allen, P. Friedlingstein, C. A.J. Girardin, S. Jenkins, Y. Malhi, E. Mitchell-Larson, G. P. Peters, L. Rajamani
Annual Review of Environment and Resources 2022 47:1, 849-887

Another slow adjustment: pattern of warming changes as climate re-equilibrates, affecting energy loss to space



Armour et al, 2013

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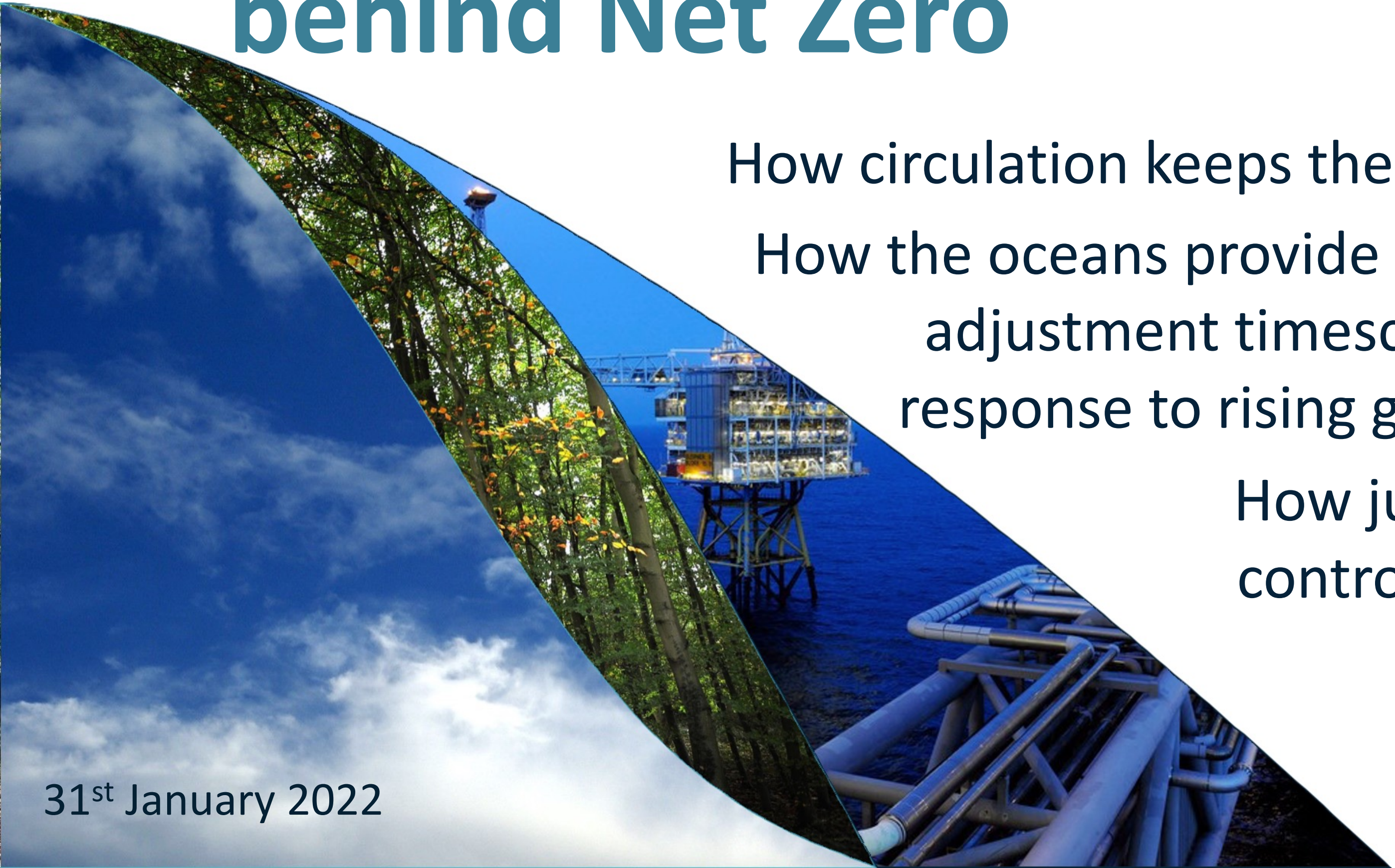
NET ZERO

UNIVERSITY OF OXFORD



How circulation keeps the deep ocean cold.

How the oceans provide the multi-century adjustment timescale in the climate response to rising greenhouse gases.

How just two quantities control global warming.

31st January 2022

EST. 1597

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