Presentation Script

Slide 1: Hello everyone and welcome to our discussion on Bjerknes Compensation under the abrupt-4xCO2 CMIP6 experiment.

I want to go through some basic concepts first, so I'll start with the obvious:

Slide 2: What is Bjerknes Compensation?

This is a plot from Jacob Bjerknes' 1964 paper.

Here, we can see the Ocean, Atmosphere and total, Top Of the Atmosphere (TOA) heat transports and their changes in the Northern Hemisphere (NH).

So Bjerknes noticed that when the Ocean Heat Transport (OHT) changes, the Atmosphere Heat Transport (AHT) changes in the opposite way or, in his own words:

Slide 3: "The anomalies of heat flux in oceans and atmosphere are assumed to cancel, leaving total heat flux and radiation unchanged".

This statement is now known as Bjerknes Compensation.

Slide 4: Another thing I need to explain beforehand is what is the x4CO2 experiment.

So, phase 6 of the Couple Model Intercomparison Project consists of 2 big sets of runs: the historical runs…

Slide 5: and the DECK runs.

The DECK runs are used for evaluating and diagnosing the climate behavior and the x4CO2 experiment is one of those runs.

In this experiment, we force the system by abruptly quadrupling the CO_2 in the atmosphere at year 1 and then we let the system equilibrate for the rest of the time.

Slide 6: For example, this is the albedo at 66N, the Arctic Circle. As you can see, it goes through a steep decline in the beginning of the x4CO2 forcing and then it reaches an equilibrium…

Slide 7: in contrast with, for example, the pre-industrial, or piControl, run where the system behaves the same along time, as there is no external forcing.

We'll be using the piControl run for comparisons.

Slide 8: So, how does a forcing like this affect the system?

Slide 9: If the system was in balance, the heat equation at the TOA, which is about 10km above sea level, would look like this. Here…

Slides 10-14: the first term is the area of each latitude belt, S is the incoming solar radiation, part of which gets reflected back into space by the albedo, α, I stands for the thermal emissions of the Earth into space and F is the TOA heat transport.
Slide 15: So, when the system is in balance, we can directly calculate the TOA heat transport just from the TOA heat fluxes.

Slide 16: But now, in the x4CO2 scenario, the system is not in balance anymore.

Indeed, we have this extra term on the left hand side, which stands for the heat getting pumped into the system because of a change in temperature, based on the firt law of thermodynamics.

Slide 17: Now, because the heat transport must be 0 at the poles…

Slide 18: If we integrate this equation from the South Pole (SP) to the North Pole (NP),

Slide 19: we end up with an imbalance term.

Slide 20: This indicates that, because of this forcing, we cannot evaluate the TOA heat transport just from the TOA heat fluxes anymore, as we did in the balanced case.

Slide 21: So instead, we evaluate it as the sum of the atmosphere and ocean heat transports.

Slide 22: To visualize this imbalance, we plot both approaches of calculating the TOA heat transport. In the blue curve, we see the TOA heat transport calculated using only the heat fluxes. In the orange curve, we see the total, TOA heat transport, calculated as the sum of the atmosphere and ocean heat transports, therefore including the imbalance term.

Slide 23: So, basically, we can evaluate the imbalance by taking the difference of those 2 curves. If we take their difference in the NP…

Slide 24: and plot it over time, we see that **the imbalance of the TOA exponentially declines. This, eventually becomes heat storage in the ocean**.

Slide 25: So let's see what happens across latitudes, given the setting we just established.

Here we have the plots of the (x4CO2-piControl) heat transport differences for the Ocean, the Atmosphere and the TOA. The blue curves are for the first 30 years of the runs and the orange curves are for the last 30 years, that is years 120-150.

Slide 26: If we focus on the NH, we see the following:

Slide 27: The OHT decreases

Slide 28: The AHT increases

Slide 29: The decrease of the OHT is bigger than the increase of the AHT, indicating that the ocean is still adjusting-it's not fully evolved yet.

And the atmosphere is trying to compensate for the dying ocean circulation.

Slide 30: So, in the NH, the ocean is leading the atmosphere and, because the ocean is too slow to adjust, the total, TOA heat transport is not so well- compensated, it should be closer to 0.
But why is the ocean leading in the NH?

Slide 31: Well, it's because of **AMOC**! This plot is edited from [Madan et al. 2023]. Here, we can see that the relative AMOC strength decreases with time.

Slides 32-34: This leads to a decrease in the OHT, which triggers an increase in the AHT and, eventually, BJC.

Slide 35: This comes in agreement with a previous study by [Povea-Pérez et al.], where they found that AMOC is the driver of BJC. This is AMOC along time and you can see that when it picks, the OHT picks as well.

Slide 36: Now, moving on to the SH:

Slide 37: Here, we see that:

1. The AHT is negative, so there's heat transported towards the SP now.
2. The AHT does not change much through time. It increases immediately and stays there.

Slide 38: The OHT in the SH, now, is positive, meaning there's less heat transported towards the SP, so the OHT in the SH is dying in response to the increase in the AHT.

Slide 39: So, in the SH, it's the atmosphere that leads the ocean!

Slide 40: This happens because the temperature gradient along latitudes is larger in the SH and it happens in shorter timescales.

Slides 41: So these are my conclusions. Thank you for your attention and I'd be happy to take any questions or comments.

Appendix II: A timescales discussion

Slide 49: As we saw earlier, AMOC drives BJC. If we take an exponential fit to the multi-model mean of relative AMOC strength, we see that is has an e-folding timescale of about 20 years.

Slide 50: This is a plot of the (x4CO2-piControl) OHT, correlation with the (x4CO2-piControl) AHT, over time, separately for each hemisphere. For the Northern Hemisphere, we see that BJC happens with an e-folding timescale of about 15 years.

In the Southern Hemisphere, the atmosphere leads the ocean, because the temperature gradients there are stronger and happen in a timescale of less than 1 year. However, as we can from the bottom plot, the OHT/AHT correlation and therefore BJC, has an e-folding timescale of about 13 years, very similar to the one in the NH.

Slide 51: So, we can distinguish 3 timescales in the system:

1. AMOC timescale of about 20 years
2. Temperature gradient timescale of less than 1 year and
3. The coupled (ocean-atmosphere) system timescale, about 15 years.

The incredible thing here is how BJC keeps the same timescale in both hemispheres, although the mechanisms that drive it are completely different!