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Is the climate-carbon cycle response to CO_2 emissions path dependent?

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Abstract

Recent studies with coupled climate-carbon cycle models suggest that global mean temperature change is proportional to cumulative CO_2 emissions, independent of the timing of those emissions[1]. This finding has prompted the suggestion that climate stabilization targets, such as the 2°C target adopted by the Copenhagen Accord, can be expressed in terms of cumulative CO_2 emissions[2,3,4]. Here we examine the simulated response of a range of global and regional climate variables to the same cumulative CO_2 emissions (2500 PgC) released along different pathways using a comprehensive Earth system model. We find that the response of most surface climate variables is largely independent of the emissions pathway once emissions cease, with the exception of variables with long response timescales, such ocean heat content and thermosteric sea level rise. Peak responses of many climate variables, such as global mean temperature, precipitation and sea ice, are also largely independent of the emissions pathway, except for scenarios entailing cumulative emissions overshoot, i.e. net removal of CO_2 from the atmosphere. By contrast, peak responses of atmospheric CO_2 and surface ocean pH are found to be dependent on the emissions pathway. We conclude that a CO_2 mitigation framework based on cumulative emissions is well suited for limiting changes in many impact-relevant climate variables, but is less effective in avoiding impacts directly associated with atmospheric CO_2 whose peak response is dependent on the rate of emissions.

Methodology

The model

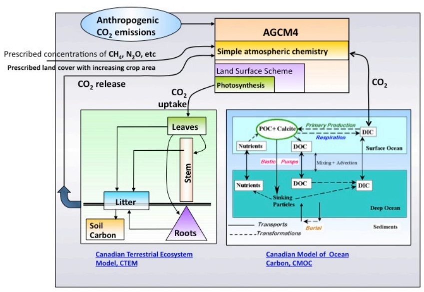

Figure 1: The Canadian Earth System model[5].

Model simulations

HIST is a historical simulation (1850-2000) with atmospheric CO_2 prescribed according to observations and non-CO_2 forcings fixed at pre-industrial values.

Three 400-year (2001-2400) simulations with freely evolvingCO_2 are initialized from the HIST simulation, all forced with cumulative emissions of 2500 PgC (Fig. 2a):

A2+: CO_2 emissions follow the IPCC SRES A2 scenario until 2100. Thereafter emissions continue to increase at the average rate of the last decade of the 21st century until a cumulative total of 2500 PgC is reached and are then set to zero.

OVSHT: CO_2 emissions deviate from the A2 scenario around 2070, peak in 2085 (20 PgC yr^{-1}) , reach a minimum in 2250 (-7.7 PgC yr^{-1}) and reach zero in 2300.

UNSHT: CO_2 emissions deviate from the A2 trajectory around 2050, peak in 2060 (15 PgC yr^{-1}) and decline thereafter reaching zero in 2270.

PULSE: 2500 PgC are instantaneously injected into the pre-industrial atmosphere.

Results

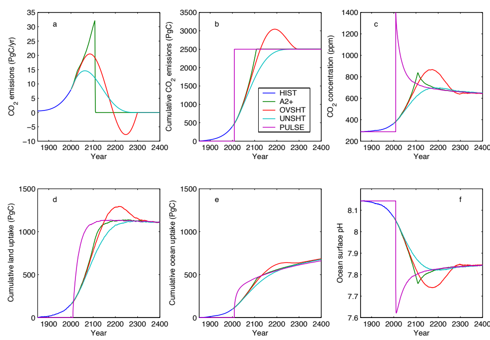

Figure 2: Time series of biogeochemical variables. (a) CO_2 emissions, (b) Cumulative CO_2 emissions, (c) Atmospheric CO_2 concentration, (d) Cumulative land uptake, (e) Cumulative ocean uptake, (f) Surface ocean pH.

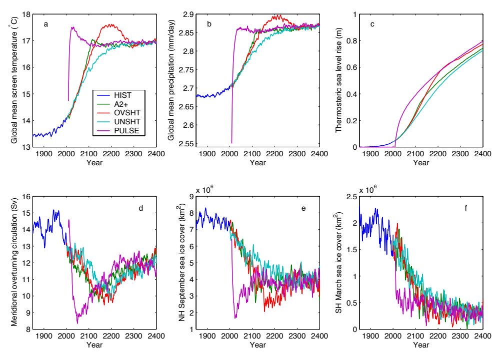

Figure 3: Time series of physical climate variables. (a) Global mean screen temperature, (b) Global mean precipitation, (c) Thermosteric sea level anomaly, (d) North Atlantic meridional overturning circulation, (e) Northern Hemisphere March sea ice cover, (f) Southern Hemisphere September sea ice cover. Data was smoothed using a 5-year running mean (except for (c)).

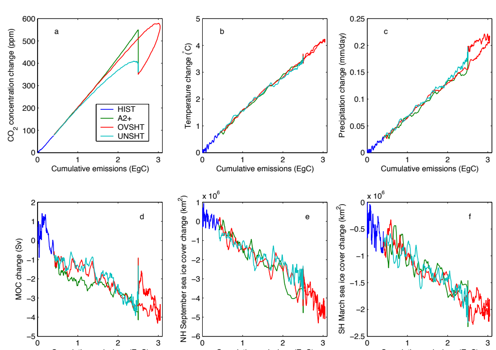

Figure 4: Changes in climate variables as a function of cumulative CO_2emissions, given in EgC (1 EgC = 1000 PgC). (a) Atmospheric CO_2, (b) Global mean temperature, (c) Global mean precipitation, (d) North Atlantic meridional overturning circulation, (e) Northern Hemisphere September sea ice cover, (f) Southern Hemisphere March sea ice cover. Data was smoothed using a 5-year running mean. Results for the PULSE experiment are omitted from this figure.

Variable	Year-2400 response path dependent?	Peak response path dependent?
CO_2, pH	No	Yes
Temperature	No	No (except for OVSHT)
Precipitation	No	No (except for OVSHT)
Sea level rise	Yes	--
MOC	Slightly	Yes
NH Sea Ice	No	Yes

Table 1: Path dependence of year-2400 and peak response

- The century-scale global mean climate response after cessation of CO_2 emissions is determined solely by the total cumulative emissions, except for climate variables with response timescales of several centuries, such as deep ocean temperature and thermosteric sea level rise.
- For scenarios without cumulative emissions overshoot, peak responses of many climate variables are also largely determined by total cumulative emissions. Exceptions are atmospheric CO_2 and surface ocean pH whose peak values are dependent on the timing of emissions.
- Under "overshoot" scenarios, i.e. scenarios entailing net sequestration of CO_2 from the atmosphere, peak climate responses are better correlated with maximum rather tan total cumulative emissions.

Conclusions

- The linear relationship between changes in climate variables and cumulative carbon emissions holds for many impact relevant climate variables. It is less applicable to climate variables with long response timescales, or variables such as atmospheric CO_2, whose peak values are dependent on the rate of emissions.
- We conclude that a CO_2mitigation framework based on cumulative emissions targets is effective in limiting changes in many physical climate variables but is less suited for limiting impacts that are related directly to atmospheric CO_2 levels.

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Acknowledgments: We acknowledge the work of Canadian Centre for Climate Modelling and Analysis members who developed CanESM1 including, as well as the second author, G. J. Boer, C. L. Curry, J. R. Christian, K. Zahariev, K. L. Denman, G. M. Flato, J. F. Scinocca, W. J. Merryfield and W. G. Lee. We also thank Duo Yang and Fouad Majaess for help with processing model output and technical support.