Reversibility of Historical and Future Climate Change with a Complex Earth System Model

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Abstract

The reversibility of a wide range of components of the earth system was investigated by comparing forward and time-reversed historical and future simulations of a coupled earth system model known as the Beijing Normal University earth system model. Many characteristics of the climate system, including the surface temperature, ocean heat content (OHC), convective precipitation, total runoff, ground evaporation, soil moisture, sea ice extent and Atlantic Meridional Overturning Circulation, did not fully return to their initial values when the historical or future natural and anthropogenic forcing agents were reversed. The surface temperature and OHC declines lagged behind the decline in greenhouse gases (GHGs). Reverses in other variables occurred in direct response to the decline in GHGs. The sea level increased, even after all of the forces returned to the original values. Furthermore, most of the climate variables did not return to their original values because of thermal inertial. The end states of variables, other than those related to thermal storage, mainly depended on the original state of the natural and anthropogenic forces, and were unaffected by the future growth rate of the GHGs. The climate policy implication of this study is that climate change cannot be completely reversed even if all the external forces are returned to their initial values.

Introduction

Recent global warming has largely been induced by human activities that have increased CO₂ and other radiatively important gas emissions (Nicholls and Cazenave, 2010; Piao et al., 2010). It has had significant negative effects on marine and terrestrial systems and human wellbeing, both regionally and on a global scale (Stoll et al., 2011). Global temperature and sea level will continue to increase as future economic development leads to increased greenhouse gas (GHG) emissions (Grinsted et al., 2013; Jevrejeva et al., 2012; Villarini and Vecchi, 2012). Thus, climate mitigation and adaptation to avoid potentially dangerous anthropogenic climate change is challenging, and it is essential to determine whether the climate system is reversible if atmospheric CO₂ concentrations can be effectively reduced by geo-engineering approaches.

The reversibility of the climate system once GHG emissions have been reduced has been investigated using climate models of varying complexity. The consensus is that anthropogenically induced climate warming and its effects on sea level and ocean acidification will continue on millennial time scales (Eby et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Lowe et al., 2009; Mikolajewicz et al., 2007; Plattner et al., 2008; Solomon et al., 2009; Wu et al., 2015; Dana and Kirsten, 2017; 2018; Li et al., 2020). These studies focused on the long-term effects on the climate and carbon cycle caused by the long lifetime of atmospheric CO₂ perturbation. For example, Solomon et al. (2009) investigated the reversibility of atmospheric warming, sea level rise, and precipitation for the zero emission case with an earth system model of intermediate complexity. Additionally, Frölicher and Joos (2010) determined the multi-century reversible and irreversible effects of anthropogenic emissions on global mean temperature, regional precipitation, sea level rise, and carbon–climate feedback using a coupled carbon cycle–climate model. A

few studies have attempted to understand the response of a climate system to an idealized CO₂ concentration reduction scenario (Boucher et al., 2012; Samanta et al., 2010). For example, Boucher et al. (2012) examined the degree of climate system reversibility by comparing a scenario wherein CO₂ increased by 1.0% yr⁻¹, starting from pre-industrial levels (286 ppm) and finishing at four times the initial level (1,144 ppm), with four scenarios wherein CO₂ decreased at a rate of -1% yr⁻¹, starting at 1.5, 2, 3, and 4 × the pre-industrial CO₂ concentration.

However, most previous research on the climate reversibility have focused on either idealized scenarios where atmospheric CO₂ decreased at a fixed rate (Samanta et al., 2010; Boucher et al., 2012; Dana and Kirsten, 2018) or scenarios with immediate zero emissions (Frölicher and Joos 2010; Gillett et al., 2011; Dana and Kirsten, 2017), and most have used an earth system model of intermediate complexity (Eby et al., 2009; Solomon et al., 2009; Dana and Kirsten, 2017; 2018; Li et al., 2020). No research has focused on whether or to what extent the climate can be restored to a previous state by reversing the historical and future natural and anthropogenic forcing agents, especially on future scenarios associated with carbon reduction commitment made at a Climate Change Conference, by using a complex earth system model. Understanding this type of climate reversibility deepens our knowledge of climate change mechanisms and enriches our understanding of whether geoengineering methods such as CO₂ capture are effective at reverting climate back to its original state useful (Matthews, 2010). In this study, we quantified the reversibility of sensitive climate indicators under historical and future natural and anthropogenic forcing conditions. Simulations were conducted forwards and backwards in time with a state-of-the-art coupled earth system model, the Beijing Normal University earth system model (BNU-ESM). Aerosol forcing and all relevant natural and anthropogenic GHGs were taken into account in these simulations.

Materials And Methods

The BNU-ESM model

Simulations were performed using the BNU-ESM, a fully coupled atmosphere–land–ocean–ice earth system model. The BNU-ESM simulations forms part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Bellenger et al., 2014; Fyfe et al., 2012; Grinsted et al., 2013; Scheff and Frierson, 2012). This model can reliably model historical climate change (Wei et al., 2012; Dong et al., 2013) and is widely used in the climate projection and attribution (Tian et al., 2016; Yang et al., 2016, 2018). The atmospheric component of BNU-ESM is CAM3.5 from the National Center for Atmospheric Research (NCAR). The land component model is the BNU CoLM, which incorporates the Lund–Potsdam–Jena dynamic vegetation model. The ocean component model is MOM2, developed by the Geophysical Fluid Dynamics Laboratory (GFDL) with the ecosystem-biogeochemical module (IBGC). The sea ice model is CICE4.1 from the Los Alamos National Laboratory. These four component models are fully coupled using the CPL6.0 from the NCAR. The atmosphere model has a horizontal resolution equivalent to T42 spectral truncation and 26 vertical levels with detailed parameterizations of physical processes. The ocean model has 50 vertical

levels with a horizontal resolution of $1^\circ \times 1^\circ$. A detailed description of the BNU-ESM model can be found in a study by Wu et al. (2013).

Experimental design

We designed two kinds of simulations (forward and reversed) with the BNU-ESM. The forward simulations included one historical simulation from 1850 to 2005 and four future simulations from 2005 to 2100. For the forward historical simulations (Hist), covering the period 1850–2005, the BNU-ESM was forced with natural forcing (such as solar irradiance and volcanoes), GHG concentrations (such as CO_2 , CH_4 , and N_2O), and aerosol concentrations of black carbon, organic carbon dust, and sulfates. This experiment followed the CMIP5 historical simulation requirements and was extended to include four forward future simulations (H, M1, M2, and L) to 2100 under different CO_2 scenarios. These scenarios, H, M1, M2, and L, typically represent high-, middle- and low-emission pathways, respectively. These pathways correspond to CO_2 concentration scenarios that quantify the responsibilities of developed and developing countries' for CO_2 mitigation, and are described in detail by Wei et al. (2012). That is, (1) H: all countries pursue business as usual and ignore their Cancun pledges; (2) M1: developed countries pursue business as usual, while developing countries follow their Cancun pledges; (3) M2: developed countries follow their Cancun pledges, while developing countries pursue business as usual; (4) L: all countries follow their Cancun pledges. In 2100, the CO_2 concentrations were 457.4, 547.7, 684.6, and 786.2 ppm in the L, M1, M2, and H scenarios, respectively (Fig.1). Other forcing agents, including solar irradiance, non- CO_2 GHGs (such as CH_4 and N_2O), aerosols, and volcanoes, were taken from RCP4.5 (Van Vuuren et al., 2011).

Generally, the Hist and four future simulations were run forward in time and followed regular experimental design. The corresponding reversed simulations Hist-R, L-R, M1-R, M2-R, and H-R were also performed. The reversed simulation Hist-R was forced by the same natural and anthropogenic forcing agents as the Hist simulation, but time-reversed and using the end (2005) results of the Hist simulation as the initial conditions. Thus, the Hist-R simulation was run from 2005 back to 1850. The L-R, M1-R, M2-R, and H-R simulations were reversed in a similar way, but using the end (2100) results of the H, M1, M2, and L simulations, respectively, as the initial conditions.

Results

Reversible variables with hysteresis

The global mean surface temperature (GMST) increased at different rates in the forward simulations of the historical and four future scenarios. At the end of the 21st century (2081–2100), the GMST of the L, M1, M2, and H simulations was 2.9°C, 3.4°C, 3.9°C, and 4.4°C higher, respectively, than pre-industrial levels. In the corresponding time-reversed simulations, the GMST decreased in response to the time-reversed forcing, especially due to the decline of GHG concentrations (Fig.2). The GMST did not decrease immediately as the GHG forcing decreased, it continued to increase slowly for the first 10 years of the

reversed simulations. The higher the CO₂ concentration, the longer the GMST lag time. In addition, the GMST decreased at a slower rate than it increased in the forward simulations. Therefore, the GMST remained about 0.6°C and 1.4°C above its original value at the end points of the reversed historical and future simulations, respectively. Furthermore, the GMST returned to the same value in all of the future simulations, even though they led to different degrees of warming in 2100 because of the differences in CO₂ concentrations. This indicates that the reversed GMST state depended mainly on the initial GHG concentrations. Similar surface temperature inter-annual variability was also seen in the historical and future reversed experiments.

The upper ocean heat content (OHC, 0-700 m) also showed hysteresis over different time scales in the reversed simulations. The OHC increased by about 30×10^{22} J in the forward historical simulations, and it continued to increase in the first 20 years of the corresponding reversed simulations (Fig.3a), then began to slowly decline. The OHC was only restored by 8×10^{22} J when all of the forces were returned to their 1850 states. The OHC in the future simulations showed a nearly linear growth trend. The OHC growth was 0.78×10^{22} J yr⁻¹, 0.97×10^{22} J yr⁻¹, 1.0×10^{22} J yr⁻¹, and 1.28×10^{22} J yr⁻¹ in the L, M1, M2, and H simulations, respectively. At the end of the 21st century, the OHC had increased by 70–120 $\times 10^{22}$ J in the four forward simulations (Fig. 3b). The OHC continued to increase in the early stages of the reversed simulations, and showed a small decline and convergence in the final stage. However, the final OHC in three of the forward simulations (those other than the H-R simulation), was still higher than that at the end of the 21st century in the forward simulations. Moreover, the OHC did not return to its initial states, and there was a disparity of about 10×10^{22} J between the two adjacent reversed simulations.

As the OHC is mainly determined by the potential temperature of the ocean, we can infer that the potential temperature is irreversible. The spatial patterns of the potential temperature (fig.4) show that the CO₂ scenario affects the recovered ocean-temperature states. These patterns indicate that the higher the CO₂ concentration, the more difficult it is for ocean temperature to return to its initial value, especially in high-latitude oceans where the positive sea ice feedback is relatively large. The maximum difference between the start of the H and the end of the H-R experiments exceeded 2°C, while that between the L and L-R experiments was less than 1.5°C.

Reversible variables without hysteresis

Climate variables affect various physical, biological and chemical processes, and have different roles in controlling global energy transfer and the carbon and hydrological cycles. Hence, the degree of reversibility of these variables differs. We investigated the reversibility of variables such as total runoff, soil moisture, and convective precipitation.

As CO₂ concentration increased and consequently temperatures increased, there was a significant increase in globally averaged total runoff and convective precipitation and a decrease in soil moisture, ground evaporation, sea ice extent, and Atlantic Meridional Overturning Circulation (AMOC) (Fig.5). The

higher the CO₂ concentration, the larger the increase (or decrease) of these variables in the future simulations (Fig. 6). Generally, the total runoff was reversible, and the magnitude of the change in the reversed simulation was close to that in the forward historical and future simulations (Fig.5b and 6b). A similar phenomenon was observed for the convective precipitation in the historical simulation (Fig.5a). However, the convective precipitation did not return completely to its original states in the four future simulations, and there remained a small disparity of about 0.07 mm/day⁻¹. The ground evaporation recovered almost completely in the historical and future simulations (Fig.5c and 6c). The soil moisture and sea ice extent in the northern hemisphere is more sensitive to increases in CO₂ concentration, and both exhibited weak reversibility. The returned sea ice extent was about 1.0 million and 3.0 million km² less than its original state in the historical and future simulations, respectively. This suggests it is difficult for the soil moisture and sea ice extent to recover from reductions caused by global warming. The AMOC showed greater reversibility in the historical and future simulations (Fig.5f and 6f). In contrast with the GMST, these variables reversed in direct response to the decline of the GHGs.

Furthermore, as with the GMST, the higher the CO₂ concentration, the greater the rate of increase or decrease of the climate variables in the forward future simulations (Fig.6), which led to different climate states in 2100. However, these variables returned to the same value in all four of the reversed future simulations. This indicates that for most of the variables, the returned states mainly depended on the original states of the natural and anthropogenic forces rather than their final states.

Irreversible variables

The steric sea level increased in the forward historical and future simulations. However, unlike other variables in the climate system, it did not appear to be reversible and continued to increase after all of the forces were reversed (Fig.7). This phenomenon was consistent with other work focused on sea level reversibility under the stabilization of CO₂ concentration in the atmosphere or zero CO₂ emissions (Matthews, 2010; Mikolajewicz et al., 2007; Solomon et al., 2009). The sea level had increased by 0.26, 0.28, 0.30, and 0.32 m by the end of the 21st century in the four forward simulations. It demonstrated a further increase of 0.2 m during the four corresponding reversed simulations. Hence, the returned states of the sea level were about 0.5 m higher than the original states in the future simulations, and about 0.27 m higher in the historical simulations (Fig.7). However, as the sea level continued to rise in the four reversed simulations, it showed the same disparity (about 0.02 m) in the final states of the four reversed simulations. This was the most significant difference between the changes in global sea level and other variables in the climate systems.

Conclusions And Discussions

We investigated climate system reversibility with the BNU-ESM using forward and reversed time simulations forced by one historical and four future natural and anthropogenic conditions. The GMST, potential temperature of the ocean, sea ice extent, and other quantities analyzed in this study exhibited varying degrees of reversibility, as their responses to changes in atmospheric CO₂ are on different time

scales. Climate variables with longer response timescales typically exhibit poorer reversibility. Generally, land surface variables reverse quicker than ocean variables, in agreement with most previous studies (e.g., Frölicher and Joos 2010; Gillett et al., 2011; Boucher et al., 2012; Li et al., 2020). However, most of the variables could not be restored to their original values by reversing all of the natural and anthropogenic forces, particularly for future scenarios with large levels of peak CO₂ concentration (Frölicher and Joos 2010; Li et al., 2020). The surface temperature showed hysteresis in response to the reversal of the external forces. Its end values in the reversed simulations were about 0.6°C and 1.4°C above its initial value in the historical and future simulations, respectively. Variables related to land surface and hydrological processes (such as the total runoff, ground evaporation, and soil moisture extent) declined or increased directly with changes to the external forces in both the historical and future simulations. These variables were mostly related to ecological or biological processes that occurred on land, and as such did not contribute significantly to global heat storage. Furthermore, these variables returned to very similar states in all four of the reversed simulations. However, they had significantly different values in 2100 in the forward simulations forced by different CO₂ conditions.

The sea ice extent in the northern hemisphere and the AMOC also reversed in direct response to the decline of GHGs. The final sea ice extents in the northern hemisphere were about 1.0–2.0 million km² less than their initial values. Due to the ocean's vast mass and larger heat capacity than the land (Domingues et al., 2008; Levitus et al., 2000; Levitus et al., 2012), variables related to ocean heat storage and thermal inertia, such as the sea level and OHC, showed weak reversibility and did not return to their initial states in the four reversed future simulations. The sea level increased by about 0.14 and 0.2 m in the historical and future reversed simulations. Its final states were 0.27 and 0.5 m higher than its original states in the historical and future simulations, respectively. Although the OHC declined during the last stage of the reversed simulations, it was only restored by 8×10^{22} J in the historical reversed simulations, and the final states of the OHC in three of the reversed simulations (those other than the H-R simulation) were larger than its initial states in 2100. Moreover, the OHC showed a 10×10^{22} J disparity between the two adjacent reversed simulations at the end of the reversed future simulations.

However, the degrees of reversibility of other important physical and biological quantities, including monsoon systems, soil carbon, and terrestrial and oceanic ecosystem biodiversity, were unclear. Further research on these topics is required.

The time scales of the forward experiments were the same as those of the reversed experiments. Therefore, the end states of the reversed experiments did represent an equilibrium state. Further experiments are necessary to investigate reversed equilibrium states.

Overall, the results of this study show that if the concentration of GHGs in the atmosphere could be significantly reduced using geoengineering approaches, the effects of global warming would be reduced. However, they would not be eliminated. For example, the sea level rises caused by thermal expansion would still be significant. Hence, it would be better to protect the climate and mitigate global warming in advance, rather than attempt to control or reverse the changes later.

Declarations

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Author contributions

SL Y and WJ D designed the study, SL Y, T W, D T, JM C, and X Z performed analyses and carried out the simulations. SL Y and D T wrote the initial draft of the manuscript and contributed equally to this work, all authors discussed the results and reviewed the manuscript.

Code availability

Not applicable. Software application or custom code is not involved in this study.

Data availability statement

The datasets analyzed during this study are available from the corresponding author on reasonable request.

Ethics approval

Complied with the Ethical Standards of TAAC Journal.

Consent to participate

All authors give their consent for participate of this paper.

Consent for publication

Informed consent to publish has been obtained from all authors.

Conflict of interest

The authors declare no conflict of interest.

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Figures

Figure 1

Global CO2 concentration in L, M1, M2, and H scenarios

Figure 2

Globally and annually averaged surface air temperature simulated by (a) Hist and Hist-R and (b) L, L-R, M1, M1-R, M2, M2-R, H, and H-R. The time axis runs from right to left for all of the reversed simulations. The annual time series was filtered by a 5-yr running mean.

Figure 3

Globally and annually averaged 0–700 m ocean heat content (OHC) simulated by (a) Hist and Hist-R, and (b) L, L-R, M1, M1-R, M2, M2-R, H, and H-R. The time axis runs from right to left for all of the reversed simulations. The annual time series was filtered by a 5-yr running mean and is normalized to 1850.

Figure 4

Latitude–depth sections of differences in ocean potential temperature for (a) Hist-R minus Hist averaged over 1850–1859, (b) H-R minus H, (c) M2-R minus M2, (d) M1-R minus M, and (e) L-R minus L. In (b)–(e) the temperatures are averaged over 2006–2015.

Figure 5

Globally and annually averaged (a) convective precipitation, (b) total runoff, (c) ground evaporation, (d) soil moisture content, (e) sea ice extent in the Northern Hemisphere for July–September, and (f) AMOC, simulated by Hist and Hist-R. The time axis runs from right to left for all of the reversed simulations. The annual time series was filtered by a 5-yr running mean.

Figure 6

Globally and annually averaged (a) convective precipitation, (b) total runoff, (c) ground evaporation, (d) soil moisture content, (e) sea ice extent in the Northern Hemisphere for July–September, and (f) AMOC, simulated by L, L-R, M1, M1-R, M2, M2-R, H, and H-R. The time axis runs from right to left for all of the reversed simulations. The annual time series was filtered by a 5-yr running mean.

Figure 7

Globally and annually averaged steric sea level simulated by (a) Hist and Hist-R, and by (b) L, L-R, M1, M1-R, M2, M2-R, H, and H-R. The time axis runs from right to left for all of the reversed simulations. The annual time series was filtered by a 5-yr running mean.