

Climate sensitivity in the northern high latitudes using the Brazilian Earth System Model

Sensibilidade climática em altas latitudes do Hemisfério Norte usando o Modelo Brasileiro do Sistema Terrestre

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ABSTRACT

An expressive number of scientific publications including the recent IPCC-AR6 report have warned about the effects of the ongoing and the projected climate change in the northern high latitudes as response to CO_2 forcing. Here we investigate the response of the Arctic region to an increase in atmospheric CO_2 concentration using the Brazilian Earth System Model and other three state-of-the-art Global Climate Model from the CMIP5 project. We evaluated the Arctic climate sensitivity through the Polar amplification using two numerical experiments. Our results showed that the northern high latitudes are described as the most climatically sensitive areas of the world, with strongest warming occurring in winter (DJF) and autumn (SON). The Arctic climate sensitivity is linked to changes in sea ice extent and sea ice thickness. Considering this scenario, it is expected that the Arctic will become ice-free in summer time and covered only by first-year-sea ice in the remaining months. We suggest that the projected sea ice albedo feedback will reinforce the Arctic warming with lack of understanding effects beyond the Arctic region.

Keywords: Climate change; Polar Amplification; Climate Models; Future Scenarios; CMIP

RESUMO

Um expressivo número de publicações científicas, incluindo o recente relatório do IPCC -AR6 chama atenção para os efeitos das mudanças climáticas em altas latitudes e projeções em resposta ao forçamento de CO₂. Nesse artigo investigamos o efeito do aumento de CO₂ atmosférico, no Ártico, utilizando o Modelo do Sistema Terrestre Brasileiro e outros três Modelos Climáticos Globais considerados estado da arte, pertencentes ao CMIP5. Avaliamos a sensibilidade climática do Ártico através da Amplificação Polar utilizando dois experimentos numéricos. Nossos resultados indicam que as altas latitudes do hemisfério norte são as regiões climáticamente mais sensíveis no mundo, com amplificado aquecimento ocorrendo durante o inverno (DJF) e outono (SON). A sensibilidade climática no Ártico é associada a mudanças na

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extensão e espessura do gelo marinho. Considerando esse cenário, espera-se que o Ártico fique sem gelo no verão e coberto apenas pelo gelo de primeiro ano nos meses restantes. Sugerimos que o feedback projetado do albedo-gelo marinho reforçará o aquecimento no Ártico com efeitos ainda não conhecidos além das regiões Árticas.

Palavras-chave: Mudanças Climáticas; Amplificação Polar; Modelos Climáticos; Cenários Futuros; CMIP

INTRODUCTION

The climate sensitivity refers to the effects of carbon dioxide (CO₂) increases on the global temperature after the change in the climate system, for instance: the response of global mean temperature to abrupt 4xCO₂ forcing (Huusko et al, 2021). Polar regions are more sensitive to climate change than the rest of the world. The Arctic is warming at a rate of almost twice of the global average over the last decades (Casagrande et al., 2020; Smith et al., 2019; Serreze & Barry, 2011). This phenomenon is known as Arctic Amplification and is linked with changes in sea ice, cloud cover and both atmospheric and oceanic heat transport (Dai et al., 2019; Goosse et al., 2018; Serreze & Barry 2011; Alexeev et al., 2005; Cai, 2005).

The Arctic amplification has been the central theme of several studies in recent years. Both observations and state-of-the-art Global Climate Model simulations have shown that the Arctic Amplification is an intrinsic feature of the Earth's climate system as a response to greenhouse gas (GHG) forcing (IPCC, 2021; Casagrande et al., 2020; IPCC, 2019; Overland et al., 2019; Dai et al., 2019; Stuecker et al., 2018; Screen & Williamson, 2017; Pithan & Mauritsen, 2014; Serreze & Barry, 2011; Holland & Bitz, 2003).

Previous and most recent studies, using distinct data set (observational and climate simulations) agree with the emergence of the Arctic climate change and the climate sensitivity (Casagrande et al., 2020; Overland et al. 2019; IPCC, 2019; Screen & Williamson 2017). Bekryaev et al., (2010) using extensive observational data from meteorological stations at high northern latitudes (> $60^{\circ}N$) found a warming rate of $1.36^{\circ}C$ century⁻¹ for the period from 1875 to 2008. The trend is almost double that of the Northern Hemisphere trend (0.79 °C century⁻¹), with an accelerated warming rate in the most recent decade. Holland & Bitz (2003) using a set of 15 state-of-the-art global climate

models found that the range of simulated Arctic warming as response to an increase of 2xCO₂ concentration varies largely between the models and it is from 1.5 to 4.5 times the global mean warming. The large bias among the models is related to differences in simulating ocean heat transport, polar cloud cover and sea ice (e.g a simulation with thinner sea ice cover obtains higher polar amplification). The previous and most recent CMIP simulation (Coupled Model Intercomparison Project, Version 5 and 6) suggested that the polar amplification will continue to intensify with effects extending beyond the Arctic region (Cai et al., 2021; Cai et al. 2021; Davy & Outten 2020; Jung et al. 2020; Pithan & Mauritsen 2014; Bintanja et al., 2013; Serreze & Barry, 2011).

The way by the polar climate will change as response to an external forcing depends deeply on feedback processes, which operate to amplify or diminish the effect of climate forcing. These feedbacks depend on integrated coupled processes between ocean-atmosphere-cryosphere in a non-linear response over a large spectrum of spatial and temporal scales making the quantification more complicated (Boeke et al., 2021; IPCC, 2021; IPCC, 2019; Pithan & Mauristsen, 2014).

The mainly intertwined feedbacks involved in the polar amplification process are: albedo-sea ice feedback (Thackeray & Hall, 2019; Hall, 2004; Curry et al., 1995), temperature feedback (Pithan & Mauristsen, 2014), water vapor and cloud feedback (Graversen & Wang 2009; Vavrus, 2004) and lapse rate feedback (Boeke et al. 2021; Bintanja et al 2013). The albedo-sea ice feedback is often cited as the major contributor of the polar amplification. As temperature rises, sea ice is reduced, decreasing the surface albedo and increasing the amount of sunlight absorbed by the upper ocean. This increase in absorbed solar radiation contributes to continued and accelerated warming (Thackeray & Hall, 2019; Curry et al., 1995). However, Graversen & Wang (2009) found that albedosea ice feedback is a contributing, but not a dominating mechanism underlying the Arctic warming. The authors, using simulations with locked surface albedo suggested that an increase in water vapor and cloud cover lead to a greenhouse effect, which is more intense in northern high latitudes. Pithan & Mauritsen (2014), using CMIP5 models suggested that the temperature feedback is causing more enhanced Arctic warming than albedo-sea ice feedback.

Indeed, the physical processes involved the climate sensitivity in the northern high latitudes are not necessarily independent of each other and involve complicated structures occurring at many scales. The combination between complexities of linked multiples processes; uncertainties of global climate models and absence of observational data sets deviate the climate projections from more realistic simulations and is still a subject of debate. Nevertheless, even with inherent limitations and uncertainties, the global climate models are the most powerful tools available for simulating the climate response to GHG forcing and to provide future scenarios to help decision makers, the governments and the community (IPCC, 2021; IPCC, 2019; O'Neill et al., 2016; Taylor et al., 2012).

Recent studies have shown the advances in the Arctic climate predictions over the last few years. The improvements include better performance for simulating sea ice conditions, clouds and energy balance (Shen et al, 2021; Shu et al. 2020; Wild, 2020; Li et al., 2020). According to Stroeve et al. (2012) and Liu et al. (2012) the future advances need to incorporate improvements in the cloud parameterization schemes since the cloud feedback is the primary source of uncertainties in the polar regions (Wei et al., 2021).

In this paper we evaluated the seasonal Arctic climate sensitivity under abrupt 4xCO₂ numerical experiments and the coupled ocean-atmosphere-sea ice processes related. The results presented here are based on the Brazilian Earth System Model, Version 2.5 (BESM-OA2.5) simulations and three other Coupled General Circulation Models participating in the Coupled Model Intercomparison Project, Phase 5 (CMIP5). The main goal is to investigate the Arctic climate sensitivity through polar amplification and the coupled processes underlying the seasonal Arctic warming. This paper is organized as follows: section 2 provides a description of the climate models and experimental design[s] used in this work, focusing on the BESM-OA2.5 model description (Veiga et al., 2019; Nobre et al., 2013). Section 3 examines the seasonality of the Arctic surface warming and compares the different CMIP5 climate models for the same numerical experiment. Section 4 provides an analysis of coupled ocean-atmosphere processes and feedback mechanisms. In a final Section the results are summarized.

DATA SOURCES

Numerical Design

This study uses two CMIP5 numerical experiments: (i) piControl (pre-industrial fully-coupled control, run for a hundred of years) and abrupt $4xCO_2$ (as piControl but run for 150 years, following an instantaneous quadrupling of the atmospheric CO_2

concentration). The design of both experiments follows the CMIP5 protocol described in Taylor et al. (2009; 2012).

We compared our BESM-OA2.5 polar warming results (changes in surface air temperature) with the following climate models: CCSM4 model (Community Climate System Model Version 4) from National Centre for Atmospheric Research (NCAR), described in Gent et al. (2011); GFDL-ESM2M (Earth System Model 2M), from National Oceanic and Atmospheric Administration – Geophysical Fluid Dyanmics Laboratory (GFDL), described in Delworth et al. (2006) and Griffies et al. (2011) and MPI-ESM-LR model from Max Planck Institute for Meteorology (MPI), described in Marsland et al. (2003). The comparison was made considering the same numerical experiment.

Brazilian Earth System Model (BESM-OA2.5)

The BESM-OA model has been set up at the Brazilian National Institute for Space Research (INPE) and is part of CMIP5. The model is composed of the INPE/CPTEC atmospheric general circulation model (AGCM) coupled to NOAA/GFDL's Modular Ocean Model version 4p1 (MOM4p1) oceanic general circulation model (OGCM) via GFDL's Flexible Modular System (Bottino & Nobre, 2015; Nobre et al., 2013; Griffies, 2009).

The INPE/CPTEC AGCM has a spectral horizontal resolution truncated at triangular wave number 62, giving an equivalent grid size of 1.8758 degrees of latitude and longitude and 28 sigma levels unevenly spaced in the vertical (i.e., T062L28). The exchanges of heat, moisture and momentum between the surface and atmosphere in INPE/CPTEC AGCM over the ocean and continents are computed differently by various physical processes that define the surface fluxes.

The ocean model MOM4p1 (Griffies, 2009) from GFDL, includes the Sea Ice Simulator (SIS), described in Winton (2000). The SIS is a dynamical model with three vertical layers (two ice and one snow), and five ice thickness categories. The elasticviscous-plastic technique of Hunke & Dukowicz (1997) is used to calculate ice internal stresses, and the thermodynamics is a modified Semtner's three-layer scheme (Semtner, 1976). SIS calculates the concentration, thickness, temperature, brine content, and snow cover of an arbitrary number of sea ice thickness categories (including open water) as well the motion of the complete pack. Additionally, the model is responsible for calculating ice/ocean fluxes and communicating fluxes between the ocean and atmosphere models globally.

The MOM4p1 horizontal grid resolution is set to 1° in the longitudinal direction, and in the latitudinal direction the grid spacing is 1/4° in the tropical region (10°S - 10°N), decreasing uniformly to 1° at 45° and to 2° at 90° in both hemispheres. For the vertical axis, 50 levels are adopted with a 10 m resolution in the upper 220 m, increasing gradually to about 370 m of grid spacing in deeper layers. We used FMS to coupling MOM4p1 and CPTEC/AGCM. Thus, wind stress fields are computed, using Monin-Obukhov scheme within MOM4p1, from the field 10 meters above the above the ocean surface. Adjustments were done to the Monin-Obukhov boundary layer scheme, whose parameters were tuned according to the wind fields output by the CPTEC AGCM. The AGCM receives the following two fields from the coupler: sea surface temperature (SST) and ocean albedo from ocean and sea ice models at an hourly rate (coupling time step).

RESULTS AND DISCUSSION

Polar amplification

Here we present results from BESM-OA2.5 compared with three state-of-the-art CMIP5 models, using the abrupt 4xCO₂ numerical experiment to assess the seasonality of polar amplification and the coupled processes involved. The main processes linked to the polar amplification are related to changes in Surface Air Temperature (SAT), sea ice, ocean heat content and surface energy budget and are closely associated with feedback processes (Pithan & Mauritsen 2014; Screen & Simmonds, 2010; Serreze & Francis, 2006).

Figure 1 shows the seasonality of the Arctic amplification (change in zonally SAT average) as simulated by BESM-OA2.5 and three other CMIP5 models. This gives us a measure of the warming difference between low and high latitudes and the Arctic climate sensitivity.

An increase in the zonal mean surface temperature at high latitudes is evident with strongest warming in winter (DJF) and Autumn (SON), which exceeds the summer warming (JJA). These results are in agreement with observational and model simulations for both present-day and abrupt $4xCO_2$ numerical experiment (Casagrande et al. 2020;

Pithan & Mauritsen 2014; Bintanja & Linden, 2013; Serreze et al., 2009; Serreze & Francis, 2006). BESM-OA2.5 and MPI-ESM-LR models show high climate sensitivity through the simulated enhanced warming in winter and summer, compared to the GFDL-ESM-LR and NCAR-CCSM4 models.

Figure 1 – Zonal mean surface temperature (°C) for the last 30 years of quadrupling atmospheric CO_2 numerical experiment compared to the last 30 years of the piControl run for the following climate models: (a) BESM-OA2.5, (b) NCAR-CCSM4, (c) GFDL-ESM-LR and (d) MPI-ESM-LR. Winter time (DJF) is represented by blue lines, spring (MAM) is represented by black lines, summer (JJA) is represented by red lines and autumn (SON) is represented by green lines.



Source: authors' authorship (2021)

The comparative simulated values in winter for the Arctic polar amplification are close to 30°C (BESM-OA2.5 and MPI-ESM-LR) and 20°C (GFDL-ESM-LR and NCAR-CCSM4). For summer the values of the Arctic polar amplification are close to 7°C (BESM-OA2.5) and 3°C (NCAR-CCSM4). In the abrupt 4xCO₂ simulations (CMIP5) presented by Pithan and Mauristsen (2014), the Arctic warming for winter (summer) is

close to 16°C (6.5°C). Which indicates that all of the models overestimate the Arctic winter warming in relation to the CMIP5 ensemble mean, with more pronounced warming for both BESM-OA2.5 and MPI-ESM-LR. Holland & Bitz (2003), using CMIP2 simulations, included the NCAR model (NCAR-CCSM2) in a separated group of models with "high" Arctic warming, i.e, high climate sensitivity to increase in CO₂ forcing. According to Bintanja & Linden (2013), the CMIP5 models' outputs tend to underestimate the Arctic winter warming and overestimate summer warming over the last decades when compared to observational data. For long-term simulations the magnitude of simulated Arctic warming winter varies considerably among CMIP5 simulations. The differences are in part related to feedback mechanisms, parameterizations, ocean heat uptake and sea ice conditions (Bintanja & Linden, 2013).

Figure 2 shows the spatial difference of surface temperature between abrupt $4xCO_2$ and piControl numerical experiments, considering only the last 30 years of each simulation in BESM-OA2.5 and three other CMIP5 models. This allows the comparison of the spatial response of CO₂ forcing in surface temperature from different regions of the world and the climate sensitivity.

The amplified winter warming at northern high latitudes appears as an inherent characteristic of climate models. Accessing the response of quadrupling atmospheric CO₂ in polar regions, the southern high latitudes warming is modest in relation to northern high latitudes warming and is most pronounced in summer (JJA), with higher values found in the BESM-OA2.5 and GFDL-ESM-LR simulations. The delayed (accelerated) warming in the Antarctic (Arctic) as a response to an increase in GHG forcing is a consequence of anomalous advection of heat out of (into) the region by the ocean (Marshall et al., 2014). Furthermore, considering that CO₂ forcing is the same for both poles, large ozone depletion only occurs in the Antarctica. Marshall et al. (2014) suggest that the initial response of Sea Surface Temperature (SST) around southern high latitudes to ozone depletion is one of cooling and only later contribute to the GHG forcing warming trend as upwelling of sub-surface warm water linked with stronger surface westerlies impacts surface properties.

Figure 2 – Spatial difference of SAT (°C) between the abrupt 4xCO₂ and piControl numerical experiments, considering only the last 30 years of each simulation for annual and seasonal time frame. BESM-OA2.5 annual (top) and below the annual and seasonal cycle of the following models: BESM-OA2.5, NCAR-CCSM4, GFDL-ESM-LR and MPI-ESM-LR for winter (DJF), spring (MAM), summer (JJA) and autumn (SON).





The main reason for the high Arctic climate sensitivity to increase in CO_2 forcing is related to sea ice loss. According to Serreze et al. (2009), during summer the energy is used to melt sea ice and increase the sensible heat content of the upper ocean. The atmosphere loses heat to the ocean during summer whereas the flux of heat is reversed in winter. The sea ice loss in summer allows a large warming of the upper ocean but atmospheric warming is modest. The excess heat stored in the upper ocean is subsequently released to the atmosphere during winter (Serreze et al., 2009).

Coupled ocean-atmosphere-sea ice processes

The main physical processes underlying the Arctic climate sensitivity and the polar amplification will be discussed below using simulations from BESM-OA2.5. One of the main features of the Arctic Ocean is the presence of sea ice cover that isolates the atmosphere from the warmer ocean and is highly sensitive to CO_2 forcing. The Arctic sea ice has decreased dramatically since 1980, faster than forecasted and unprecedented in the past 1.5 millennia (Stroeve et al., 2012; Stroeve et al., 2007).

Most of the state-of-the-art global climate models simulations have suggested that the Arctic will become ice-free in summer in approximately 30 years as response to increase in CO₂ concentration. Figure 3 shows the seasonal cycle of Sea Ice Extent (SIE) and Sea Ice Thickness (SIT) over the area between 70°N and 90°N, considering only the last 30 years of each simulation (piControl and abrupt $4xCO_2$). The SIE is often defined as the area of the ocean with a Sea Ice Concentration (SIC) of at least 15%.

For piControl climate simulations, the mean of SIE ranges from $3x10^6$ km² to $16x10^6$ km², and the mean of SIT ranges from 0.2 m to 1.6 m. Previously studies showed that BESM-OA2.5 represents quite well the seasonal cycle of Arctic SIE even with an overestimation in winter (Casagrande et al., 2016).

The growth and melting of sea ice have an important effect on the heat balance, salinity and ocean heat content. The SIT changes tend to reinforce the warming by altering the transfer of heat and moisture from the ocean to the atmosphere (Holland & Bitz, 2003).

The response of a quadrupling of CO_2 on Arctic Sea ice concentration is a sharp decrease in SIE and SIT followed by a decrease in annual amplitude, with outstanding ice-free conditions from July to October (Figure 3). The SIT has the maximum difference between piControl and abrupt 4xCO₂ in May (close to 1 m) after the winter Arctic warming. The end of the melting period (when sea ice reaches its minimum annual value) is expected for July instead of September associated with a large winter decrease in SIT and contributing to a delay in sea ice formation (in Autumn). In this scenario the Arctic Ocean will become covered only by first-year-sea ice (sea ice that does not survive to summer melt season). This thin sea ice is more vulnerable to melting away making the region more sensitive dynamically and thermodynamically to temperature changes. Furthermore, we suggest an increase in lead and polynyas (regions of open water surrounded by sea ice) that promotes a very efficient exchange of heat and moisture between the relatively warm ocean and cold atmosphere.

Figure 3 – Seasonal cycle at northern high latitudes (70°N-90°N) of (a) surface air temperature (°C), (b) albedo, (c) sea ice extent (million km²) and (d) Sea ice thickness (meter) for the last 30 years of the quadrupling atmospheric CO₂ numerical experiment compared to the last 30 years of the piControl run, using BESM-OA2.5.



Source: authors' authorship (2021)

The SIT simulated in both BESM-OA2.5 and the CMIP5 ensemble mean are too thin compared to observational data (no shown), resulting in enhanced melt and underestimation of summer SIE (Casagrande et al., 2016; Shu et al., 2015; Stroeve et al., 2012). Thin sea ice conditions in the control climate simulations typically resulted in amplified warming at 4xCO₂ conditions, given that it is easier for sea ice to melt in a warmer climate (Rind et al., 1997; Rind et al., 1995). According to Rind et al. (1997), the climate sensitivity depends more on SIT than SIE from control climate simulations. Thus, we suggest that the enhanced polar warming present in BESM-OA2.5 and MPI-ESM-LR (Figure 1) is associated with thin sea ice piControl conditions presented in Figure 3.

The close relationship between sea ice loss and decrease in albedo results in an increase of heat exchanges between the ocean and atmosphere. This is because the high sea ice albedo (>0.7) reflects most of the incoming solar radiation back to space. When sea ice melts, the darker ocean (low albedo, ~0.06) is exposed to solar radiation and absorbs more energy, thus warming the ocean.

Winter albedo for piControl (abrupt $4xCO_2$) climate simulations varies from 0.69 to 0.72 (0.1 to 0.52), which represents a significant increase of nearly 60% in energy absorption by the ocean in December. For summer the differences between piControl and abrupt $4xCO_2$ are lower since the SIE in piControl presents a small area of SIC (close to $3x10^6 \text{ km}^2$).

The net energy fluxes are represented by the sum of net radiative fluxes (SW radiation from the sun and LW radiation emitted from the surface and by the atmosphere), sensible and latent fluxes (Bourassa et al., 2013). Freshwater fluxes into the ocean are due to precipitation, runoff and evaporation (P+R-E) (North et al, 2014; Stossel el al., 2011; Bourassa et al., 2013).

According to Bourassa et al. (2013) the latent heat flux is the rate at which energy associated with the phase change of water is transferred from the ocean to the atmosphere, the main terms related are wind speed and humidity. Similarly, the sensible heat flux is the rate at which thermal energy (associated with temperature, but without a phase change) is transferred from the ocean or sea ice to the atmosphere. The main terms are the difference between ocean and atmosphere and wind speed.

The response of the Arctic warming in heat fluxes (Sensible + Latent fluxes) over high northern latitudes is an increase for all seasons, stronger in winter (Figure 4a). The

seasonal cycle simulated by piControl (abrupt 4xCO₂) ranges are from approximately 10 W.m⁻² in winter to 25 W.m⁻² in summer. The large increases are found for the same period of strong Arctic warming (autumn and winter). The response of the Arctic warming to changes in Freshwater fluxes into the ocean (Precipitation minus Evaporation) over northern high latitude is an increase for all seasons, meaning that precipitation exceeds evaporation with an accentuated rise in summertime (Figure 4b). The Freshwater fluxes have a quite well-defined seasonal cycle. The piControl (abrupt 4xCO₂) simulations vary from 10 mm (35 mm) in winter to 45 mm (80 mm) in summer (Figure 4b). According to Bintanja & Selten (2014) the projected changes in precipitation over the Arctic Ocean as response to GHG forcing is more than 50 %. This marked increase is among the highest globally projected precipitation changes and is associated with enhanced poleward moisture transport from the lower latitudes (Kug et al., 2010).

Figure 4 – Seasonal cycle at northern high latitudes (70°N-90°N) of (a) heat fluxes (sum of sensible and latent fluxes) and freshwater fluxes (precipitation – evaporation) for the last 30 years of quadrupling atmospheric CO₂ numerical experiment compared to the last 30 years of the piControl run, using BESM-OA2.5.



Source: authors' authorship (2021)

Feedback processes in the climate system may act to amplify or damp the initial radiative perturbation, such changes in CO₂ concentration. The Radiative Kernel is a powerful technique used for calculating the climate feedbacks in Global Climate Models, allowing a robust analysis of climate sensitivity (Jonko et al., 2012; Soden et al., 2008). To quantify the feedback, the kernel is multiplied by the change in the variable interest (e.g albedo, temperature, cloud), typically normalized by the change in global mean

surface temperature (SODEN et al., 2008). We applied the NCAR Radiative Kernel in BESM-OA2.5 for accesses the seasonal impact from different feedback mechanisms at northern high latitude (The Radiative Kernel NCAR are available in https://climatedataguide.ucar.edu/climate-data/radiative-kernels-climate-models.





The Radiative Kernels presented below (Figure 5) were calculated for the water vapor, lapse rate, temperature and albedo feedback for both clear sky and all sky (Shell et al., 2008). Figure 5 shows the contribution of each feedback mechanism to the Arctic warming. Positive values are contributing to the Arctic warming while negative values are indicating cooling. The surface albedo feedback describes the response of downward shortwave radiation at the Top of the atmosphere (TOA) to a 1% additive rise in surface albedo (Soden et al., 2008). The large contribution of albedo feedback is evident from April to August with more accentuated values for clear sky. This result reinforces the simulated decrease in SIE and albedo for the same period presented in Figure 3. The water vapor feedback is not so evident because BESM-OA2.5 underestimated the cloud for northern high latitudes (Casagrande et al., 2016). Even so, water vapor feedback, associated with large changes in clouds is one of the most important climate feedbacks

under global warming. From November to March the lapse rate feedback contributes for the Arctic warming and the planck feedback, in opposition contributes to a cooling (Figure 5).

Conclusions

We have examined the quadrupling of CO₂ numerical experiment in order to assess the Arctic Climate sensitivity (through the Polar amplification) and the coupled ocean-atmosphere-sea ice processes associated. The amplified warming at high latitudes appears as an inherent characteristic of climate models with strongest warming in winter (DJF) and Autumn (SON), which exceeds the summer warming (JJA). The Arctic warming is linked with changes in SIE and SIT. The effects of abrupt 4xCO₂ in sea ice is a sharp decrease in SIE and SIT followed by a decrease in annual amplitude, with outstanding ice-free conditions from July to October. In this scenario the Arctic Ocean will become covered only by first-year-sea ice (sea ice that does not survive to summer melt season). This thin sea ice is more vulnerable to melting away making the region more sensitive dynamically and thermodynamically to temperature changes and increasing the heat fluxes. The albedo sea ice feedback reinforces the polar warming with marked contributions from April to August for both all sky and clear sky. Future progress in the climate sensitivity and the polar amplification are essential to better understand the effects of climate changes in high latitudes and the related coupled ocean-atmosphere processes.

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