Authors' response to comments on paper: How does sea ice influence $\delta^{18}O$ of Arctic precipitation?

Anne-Katrine Faber et al.

We thank the referees and the editor for their comments made to our manuscript. We appreciate the constructive feedback on our manuscript and have made substantial changes to the manuscript.

Response to anonymous referee # 1:

1.1 Abstract misleading - Focus on Greenland

Question:
The abstract emphazing the influence of sea ice on δ 18O of Arctic precipitation except on central Greenland is misleading

Changes in manuscript:
Changes in sea ice and sea surface temperatures have different impact in Greenland and the rest of the Arctic. The simulated changes in central Arctic sea ice does not influence $\delta^{18} O$ of Greenland precipitation, only anomalies of Baffin Bay sea ice. However, this does not exclude that simulations based on other sea ice and sea surface temperature distributions might yield changes in Greenland $\delta^{18} O$ of precipitation.

Question:
Same in the conclusion. e.g. l 317-320: "significant changes", but it should be emphasized that they are mainly local, not where most of the ice cores are.

Changes in manuscript:
Conclusion:
The geographical variations in the $\delta ^{18} O$ response to changes in Arctic sea surface conditions show that the isotopic composition of Arctic precipitation is sensitive to the spatial distribution of the sea ice and SST changes, however not at Greenland
….
The isotopic composition of Greenland precipitation are unaffected by the imposed changes in central Arctic sea ice cover in all experiments. Only conditions near Baffin Bay influence Greenland.

Question:
L313: relatively -> completely?
Changed.

1.2 Need for model evaluation in the Arctic.

<u>Question:</u>
Before using a model, some evaluation of this model is necessary. Can you add a figure showing the distribution of precipitation δ 18O in the Artic compared to precipitation data wherever they are available? (GNIP, snow samples, ice cores...)

<u>Changes in manuscript:</u>
A figure is added where data from ice cores and coastal Greenland GNIP stations are compared to the CTRL run

Question:
If the model features some biases what are the consequences on the conclusions. For example, is the absence of large-scale isotopic response specific to this model, and can it be linked to the representation of the large-sale circulation or of boundary layer processes?

<u>Comments:</u>
The model is positive biases producing to enriched d18O over Greenland as many other models.
To answer whether the absence of a large-scale isotopic response is specific to this model would require model-intercomparison study. Currently no model-intercomparison studies of isotope-enabled GCM are published for Arctic conditions.

1.3 Sea surface conditions rather than sea ice cover
<u>Request:</u>
Use the term sea surface conditions rather than sea ice cover

<u>Changes to manuscript</u>
This is changed through out the paper. Either sea ice cover and sea surface temperatures are used together, or the term sea surface conditions is used the describe both.

1.4 Questions on precipitation weighting.
<u>Changes to manuscript</u>
All d18O values from model output are shown as precipitation weighted. This is now corrected in the manuscript.

1.5 d18O-Temperature relationships.
<u>Comments:</u>
Reviewer 1 discusses the importance in the differences in the intercept values for the different experiments. In the previous version of figure 5, the plot "All experiments" where each experiment were plotted with different colors. Therefore due to the plotting routine the differences in intercepts for each experiment incorrectly looked more pronounced. Therefore the plot "All experiments" in fig. 5 now plots all values with the same color. However, the differences in the intercepts values, especially for experiments "2012" is now added to the manuscript

The reviewer disagrees with the implications for the interpretation of the d18O p signal. This part is now only briefly mentioned in the paper, and the manuscript now only mentions that the slope of $\delta ^{18} O_{p}$-temperature relationship is found to be insensitive to changes in the perturbations of sea ice.

No further analysis on this topic is conducted as the focus on this manuscript is directed towards a discussion on the causes of changes in the isotopic response.

<u>Changes in the manuscript</u>
In this study, the slope of $\delta ^{18} O_{p}$*-temperature relationship is found to be insensitive to changes in the perturbations of sea ice. Differences in the intercept values of the regression is noted, most pronounced for the experiment "2012" where the offset of* $\Delta \delta ^{18} O_{p}$ *is* $-0.39 \permil$*.*

1.6 The link with vapor origin is not clear
& 1.7 Clarify the link with large-scale circulation
<u>Comments:</u>
We clearly agree with the reviewer on this comment. Further analysis has been made and the results and discussion sections have been rewritten in order to improve this link.

<u>Changes in the manuscript</u>
To clarify the influence of the observed simulated change in d18O and the connection to either change in air mass origin or local temperature then analysis of the vertical distribution of T and d18O have been made. The zonal cross sections at latitude band 77 N have been added to the manuscript (fig 8 and fig 9). The given latitude has been selected to match the nearest grid point to the location of the ice core drilling site NEEM at Greenland. NEEM is selected rather than central Greenland due to several reasons. First, because the latitude band 77N covers a circumpolar band with regions of large sea ice changes all over the Arctic. Second, recent observations from Steen-Larsen 2011 find a connection between the isotopic signal at NEEM and Baffin Bay sea ice extent.

Furthermore spatial fields of d18Ov are added to the appendix. These show d18Ov at two different pressure levels, 950hPa and 700 hPa (thus representing different layers in the vertical) and show that clear surface based signal is found all over the Arctic and not just at the given selected 77 N latitude band as shown in the cross section plot.

In short we find that anomalies of d18Ov are surface based and connected to grid points of changes in sea ice. But changes are also seen for temperature near the surface.
We cannot separate the effect of temperature and changes in moisture source in this study due to the lack of moisture tracking. Therefore the discussion in this paper is now treating the possibilities of either changes in moisture source or temperature – but no conclusion is made.

Structural changes have been made to the manuscript in order to separate the findings from this set of model experiments and speculations based on findings from other studies.

2. Miscellaneous.

L18: Add more references, including key historical ones
<u>Changes in the manuscript</u>
Since the pioneering work by Dansgaard (1964), the understanding of stable water isotopes as a proxy for temperature has significantly advanced. It has become clear that the isotopic composition of precipitation is a complex signal, influenced by both local and regional climate conditions (Vinther et al., 2010; Steen-Larsen et al., 2011; Sjolte et al., 2011; Sodemann et al., 2008b; White et al., 1997; Johnsen et al., 1989)

L32: Demonstrate -> suggest OK
L64: Citations are wrong for isoCAM3:
<u>Comments:</u>
A model release paper does not exist for isoCAM3 thus it chosen to refer to Noone and Sturm 2010 as also done by other studies.
<u>Changes in the manuscript</u>
More details of isoCAM3 can be found in Noone and Sturm (2010)

L67: What is third generation isotope scheme?
This is now removed as this is not relevant

L156 – precipitation weighted d18Opwgt,
Corrected
Fig 3 and figure 4 caption – are these annual means?
Yes, corrected

L205 – latent heat flux as a proxy for evaporation

<u>Changes in the manuscript</u>

Changes in local evaporation are here investigated based on the surface latent heat flux

Figure 8 (now figure 10).
Additional statistical information required for this analysis.
<u>Changes in the manuscript</u>
The number of grid points of reduced sea ice is as follows; 1980: 217, 1996: 444, 2007:1148, and 2012: 2116. And the number of grid points of increased sea ice; 1980: 1508, 1996: 1024, 2007:554, 2012: 437.

L246 Weakening of the jet stream for separate years…
<u>Comments:</u>
Investigating the differences in the variability within the weakening of the Jetstream could yield information on the control of the sea surface conditions on jet stream variability. However given the model setup in this experiments with artificially constructed ocean data sets consisting of an Arctic section and a non-semi Arctic mean values section (as described in L109-L116) it is found not favorable to focus on Jetstream conditions as it is uncertain whether the potential artificially introduced SST gradients near 37 N in the Atlantic might alter the representation of the jetstream

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How does sea ice influence $\delta^{18}O$ of Arctic precipitation?

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Abstract. ~~In this study we investigate the influence of variations in sea ice cover on the isotopic composition of precipitation in~~ This study investigates how variations in Arctic sea ice and sea surface conditions influence $\delta^{18}O$ of present-day Arctic precipitation. This is done using the model isoCAM3, an isotope-equipped version of the National Center for Atmospheric Research Community Atmosphere Model version 3. Four sensitivity experiments and one control simulation are performed with prescribed ~~SSTs~~ SST and sea ice. Each of the four experiments simulates the atmospheric and isotopic response to Arctic oceanic conditions for selected years after the beginning of the satellite era in 1979.

~~Results show that the isotopic composition of Arctic precipitation~~ Changes in sea ice and sea surface temperatures have different impact in Greenland and the rest of the Arctic. The simulated changes in central Arctic sea ice does not influence $\delta^{18}O$ of Greenland precipitation, only anomalies of Baffin Bay sea ice. However, this does not exclude that simulations based on other sea ice and sea surface temperature distributions might yield changes in Greenland $\delta^{18}O$ of precipitation. For the Arctic, $\delta^{18}O$ of precipitation and vapour is sensitive to ~~changes in sea ice extent~~local changes of sea ice and sea surface temperature and the changes in vapour are surface based. Reduced sea ice extent yields more enriched isotope values, while increased sea ice extent yields more depleted isotope values. ~~Results also demonstrate that the configuration~~ The distribution of the sea ice ~~cover anomalies are important~~ and sea surface conditions is found to be essential for the spatial distribution of the ~~isotopic response. The configurations of sea ice change used in these simulations did not show a change in~~ simulated changes in $\delta^{18}O$~~for central Greenland. However, results indicate that other configurations of sea ice changes could yield different results for Greenland.~~ .

1 Introduction

~~Stable~~ Records of stable water isotopes from polar ice cores have been widely used to reconstruct past climate variability. Since the pioneering work by **?**, the understanding of stable water isotopes as a proxy for temperature ~~have undergone a significant development~~has significantly advanced. It has become clear that the isotopic composition of precipitation is a complex signal~~both influenced by~~ , influenced by both local and regional climate conditions ~~(??)~~ (??????) . The isotopic composition of the precipitation is ~~an integrated measure of the regional climatic and atmospheric conditions throughout the transport of moisture~~ integrated along the moisture transport pathway from source to deposition. ~~Accordingly~~ As a result, there is a need for a detailed process-based understanding of the factors that can alter the isotopic composition of the transported moisture.

~~The physical and dynamical processes that influence the isotopic composition of precipitation have been investigated~~ Studies using models, ice cores, snow and ~~vapor measurements . Results indicate that variations~~ vapour measurements have investigated the physical and dynamical processes influencing the isotopic composition of precipitation. Variations in local Greenland temperatures, conditions at source regions ~~, North Atlantic Oscillation (NAO) and air mass trajectories~~ and atmospheric circulation all influence the isotopic composition of Greenland precipitation ~~(???????) . Based on studies of Antarctic and non-Greenland Arctic ice cores, sea ice extent have been qualitatively estimated to be essential for the isotope composition of precipitation (????) .~~ (??????) .

Several ~~general circulation model (GCM) studies have stressed the importance of sea ice as essential for understanding the~~ model studies highlight sea ice changes as important for understanding changes in the isotopic composition ~~in precipitationover Greenland both~~ of precipitation. Sea ice changes in the Arctic were investigated during Dansgaard-Oeschger events (**?**) and for exceptionally warm climates (**?**). ~~Currently no model studies exist of the isotopic response to the recent observed drastic decline in Arctic sea ice or for observations in Antarctica. However in the latter the isotopic response to~~ For Antarctica, the impact of sea ice changes ~~has been investigated by modeling idealized~~ were studied using idealized reductions of the circular shaped sea ice cover (**?**) . None of these model studies investigate sea ice perturbations comparable to present-day observations. Measurements from ice cores spanning this period suggest that sea ice ~~changes (?) . Results herein showed that the sea ice~~ changes ~~led to changes in diabatic heating of the atmosphere which influenced atmospheric circulation. The large spatial differences in~~ can influence the isotope composition of precipitation (????) .

A study of idealised changes of Antarctic sea ice show a non-uniform spatial distribution of the modelled isotopic response over Antarctica ~~was~~ (**?**) . The heterogeneity of the response is suggested to reflect the existence of different processes driving local and long range moisture transport to coastal and high elevation regions of Antarctica. Due to differences in the configuration of landmasses, open ocean and sea ice, it is ~~however~~ difficult to directly transfer findings of **?** from ~~Antarctica~~ Antarctic to the Arctic.

The ~~study of (?) have investigated the sea ice influence on isotopes in Greenland. It was found that different~~ impact of changes in sea ice and connected sea surface temperatures (SST) of the Arctic ocean were studied by **?** . The sea ice conditions were created using an experiment where a coupled climate model was forced by respectively $2\times$, $4\times$ and $8\times CO_2$. Hereafter the sea ice and SST conditions were used to force the applied atmospheric isotope models. Differences in the configurations of sea ice extent and ~~the corresponding warming of the Arctic ocean was~~ SST were found to be essential for the resulting large variability in the isotope-temperature slope of $0.1-0.7$ ‰$/C$ for the Greenland ice sheet. While ~~the $2\times, 4\times$ and $8\times CO_2$ forced model-setup of **?** disallows for~~ these CO_2 changes used by **?** do not allow direct comparison with present-day Arctic conditions, the results ~~highlights~~ highlight processes that might be important for ~~other climateconditions too. Hence results suggest that the differences in spatial distribution of the sea ice and ocean warming can control the relative influence~~ present day climate.

The recent decades of rapid Arctic sea ice decline provide an interesting opportunity to study how $\delta^{18}O$ respond to realistic changes of sea ice ~~change at the given location.~~

~~The results from **?** and **?** suggest that there are spatial differences in the response to sea ice changes. Accordingly this has implications for the interpretation of ice cores. Understanding of how sea ice influences the isotopic composition can thus potentially improve the isotope-based climatereconstructions. Using model-based experiments to investigate this topic are an important addition to observational studies because the use of an isotope-enabled AGCM makes it possible to scrutinize the physical processes causing the simulated isotopic response. This has the advantage that such studies yields information on the spatial differences in the response that would not be possible with ice core data only. Therefore the isotopic response can be analyzed at all grid points in the model instead of the response at the very few locations where ice cores were drilled.~~

and sea surface temperatures of present-day climate. We here present results from ~~isotope~~ isoCAM3 model simulations forced with observed Arctic sea ice and sea surface temperature (SST) conditions derived from observations. This paper will address how the sea ice ~~extent is influencing the isotopes~~ and sea surface conditions influence the $\delta^{18}O$ in precipitation in the Arctic, and ~~if the response depends on the~~ the role of the spatial configuration of the sea ~~ice changes. Furthermore the processes causing the changes in the isotopes will be investigated. This is done for several configurations of sea ice to asses the robustness of the response to different magnitudes of sea ice concentration changes and spatial patterns. The focus of the analysis of isotopic response is in this study limited to $\delta^{18}O$ only~~surface changes. The structure of the paper is as follows; (1) The model and experiments are described, (2) Results of the simulations are presented, (3) The influence of atmospheric moisture processes is discussed.

2 ~~The model and experiments~~Experimental configuration

2.1 The model ~~isoCAM~~isoCAM3

The simulations of the isotopic composition of precipitation and water ~~vapor~~ vapour in this study are conducted with isoCAM3~~(???) .~~. This is an atmospheric general circulation model (AGCM) enabled with the ability to trace the various species of water isotopes. The model is based on the Community Atmosphere Model version 3 (CAM3) (**?**)~~with a third-generation isotope scheme.~~

~~The hydrological cycle in CAM3 has been found to be efficient in simulating the overall structure of the hydrological cycle (?) . The performance of the isotope-module in~~, and the isotope module was developed by David Noone, University of Colorado. More details of isoCAM3 ~~has been investigated with a model-data comparison (?) . The present-day simulations from this study showed a good agreement on global and regional scales with observed spatial isotopic patterns from the database Global Network of Isotopes in Precipitation (GNIP). Furthermore~~ can be found in **?** The model isoCAM3 has been applied in several studies that investigated the isotopic response to past climate changes ~~(??????)~~ (???????) .

2.2 ~~The experiments~~

~~To investigate the influence of changes in the Arctic sea ice cover on stable water isotopes, four sensitivity experiments and one control simulation are performed.~~ The horizontal resolution of the model is T85 ($\sim 1.4^\circ$ x 1.4°) with 26 hybrid-sigma levels in the vertical. ~~All of the simulations are run for 15 years (excluding one year for spin-up). Every run has identical modern day boundary conditions for orbital configurations, ice sheets and greenhouse gases (GHGs), the latter~~ In this study the SST and sea ice concentrations are specified, thus the only surface temperatures that are calculated interactively are land and sea ice surface temperatures. This configuration allows no feedback between atmospheric circulation and open ocean SST. Greenhouse gases, vegetation, ice sheets are all set to modern conditions. More specifically greenhouse gasses are set to the following CAM3 default levels (year 1990): CO_2: 355 (ppmv), CH_4: 1714 (ppbv), N_2O: 311 (ppbv). The solar constant is set to ~~the CAM3 default settings corresponding to GHG levels in~~ 1365 (Wm^{-2}) and orbital configurations are set to the year ~~1990. Only the Arctic oceanic surface boundary conditions differ between the runs.~~ 1850.

2.2 Ensemble design

We perform a set of four sensitivity experiments and one control simulation to investigate how observed variations in Arctic sea surface conditions influences $\delta^{18}O$. Every model integration is run for 15 years (following one year for spin-up). Each of the four ~~runs simulates the atmospheric and isotopic~~ sensitivity experiments simulates the $\delta^{18}O$ response to sea ice ~~conditions~~ concentration and sea surface temperature (SST) for selected years in the time period 1979-2013 within the satellite era~~(1979-2012). The years are chosen as the~~. The 12-month time periods are selected based on the four most extreme cases of ~~sea ice changes based on satellite data of~~ high and low September sea ice extent ~~(~~recorded during the time period (1979-2012) by the NSIDC Sea ice Index ~~(?) updated daily. The two years with highest September sea ice extent is 1980: 7.8 mio. km^2 and 1996: 7.9 mio km^2. The two years with lowest~~ (?, updated daily) . The control simulation (CTRL) simulates the $\delta^{18}O$ response using the 12 months climatology of sea ice concentration and SST for the full time period April 1979 to March 2013. Only the Arctic oceanic surface boundary conditions differ between the runs. An overview of the model experiments are given in table **??**.

We force the model isoCAM3 with an annual cycle of monthly mean SST and sea ice conditions obtained from ERA-Interim (?) . This annual cycle goes from April to March thus spanning the full sea ice cycle related to the selected cases of September sea ice extent~~is 2007: 4.3 mio. km^2 and 2012: 3.6 mio. km^2~~. Here after the model runs for 15 years (following one year of spin up) with repeated annual cycle. The re-analysis data are interpolated bilinearly from the ERA-Interim (1° x 1°) to the CAM3 T85 resolution, and hereafter checked for consistency.

~~Changes in SSTs in the Arctic region~~

Overview of model experiments

Experiment	**Prescribed SST and sea ice**
"1980"	ERA-Interim monthly mean: April 1980-March 1981
"1996"	ERA-Interim monthly mean: April 1996-March 1997
"2007"	ERA-Interim monthly mean: April 2007-March 2008
"2012"	ERA-Interim monthly mean: April 2012-March 2013
CTRL	ERA-Interim monthly mean climatology: April 1979-March 2013

Table 1. Overview of model experiments

Changes in Arctic SST are in nature an inseparable part of the sea ice changes. Keeping the ~~SSTs~~ SST constant and only simulating the atmospheric response to sea ice changes, would therefore lead to unrealistic temperature gradients ~~. See~~ (see **?** for further discussion on this topic~~. Therefore~~). Therefore, we chose that these experiments are based on both changes in sea ice and ~~SSTs. Data are obtained from ERA-Interim (?) To~~ SST. A masking of the SST data is applied to eliminate remote influences from extra-polar climate patterns (e.g. from the El Niño Southern Oscillation or Pacific Decadal Oscillation)~~the model is forced with prescribed SSTs and sea ice~~. This masking is constructed so that only the conditions near the Arctic differ from experiment to experiment. Hence~~this global data ocean data set~~, this global ocean data is divided in an Arctic and a non-Arctic region. The Arctic region refers to the region of ocean/sea ice conditions expected to influence the Arctic climate and is therefore rather semi-Arctic. Due the geographical configuration of the

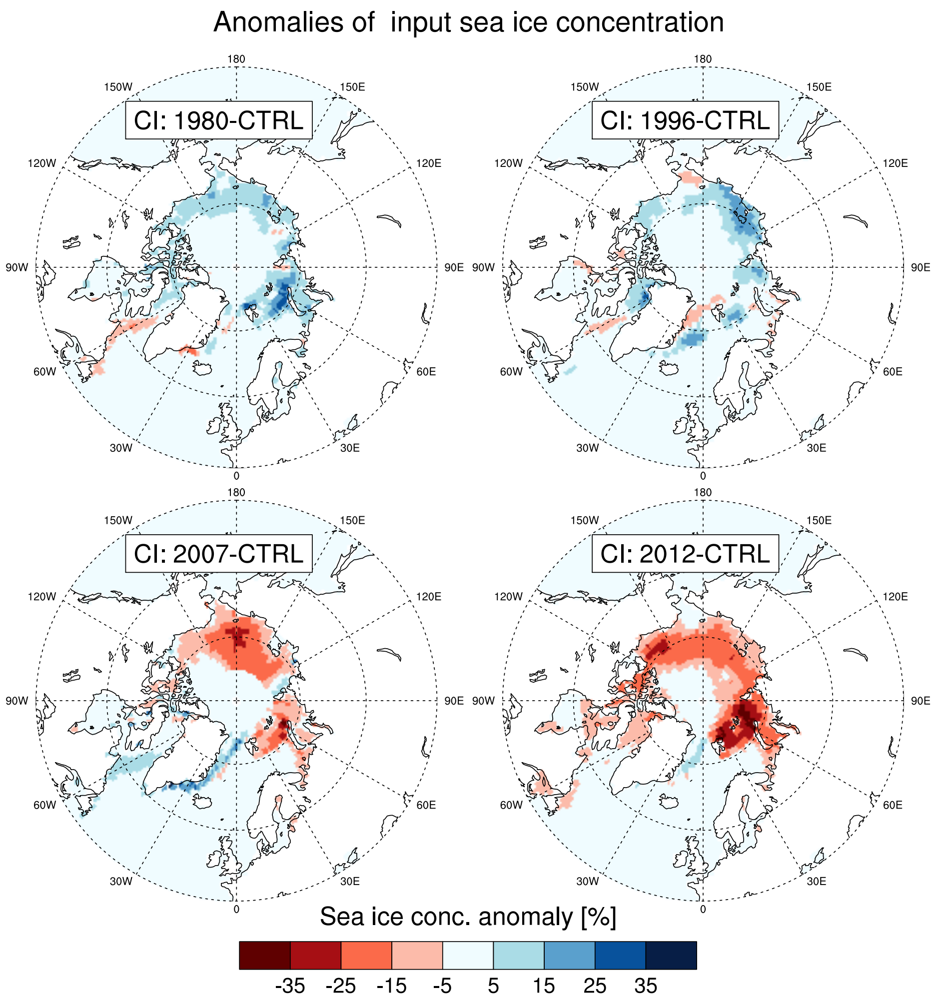


Figure 1. *Annual mean anomalies of sea ice concentration (CI) used to force the model* See tab. **??** for details. Red colours represent a decrease in sea ice compared to the CTRL run. Blue colours represent an increase in sea ice compared to the CTRL run (mean April 1979 to March 2013).

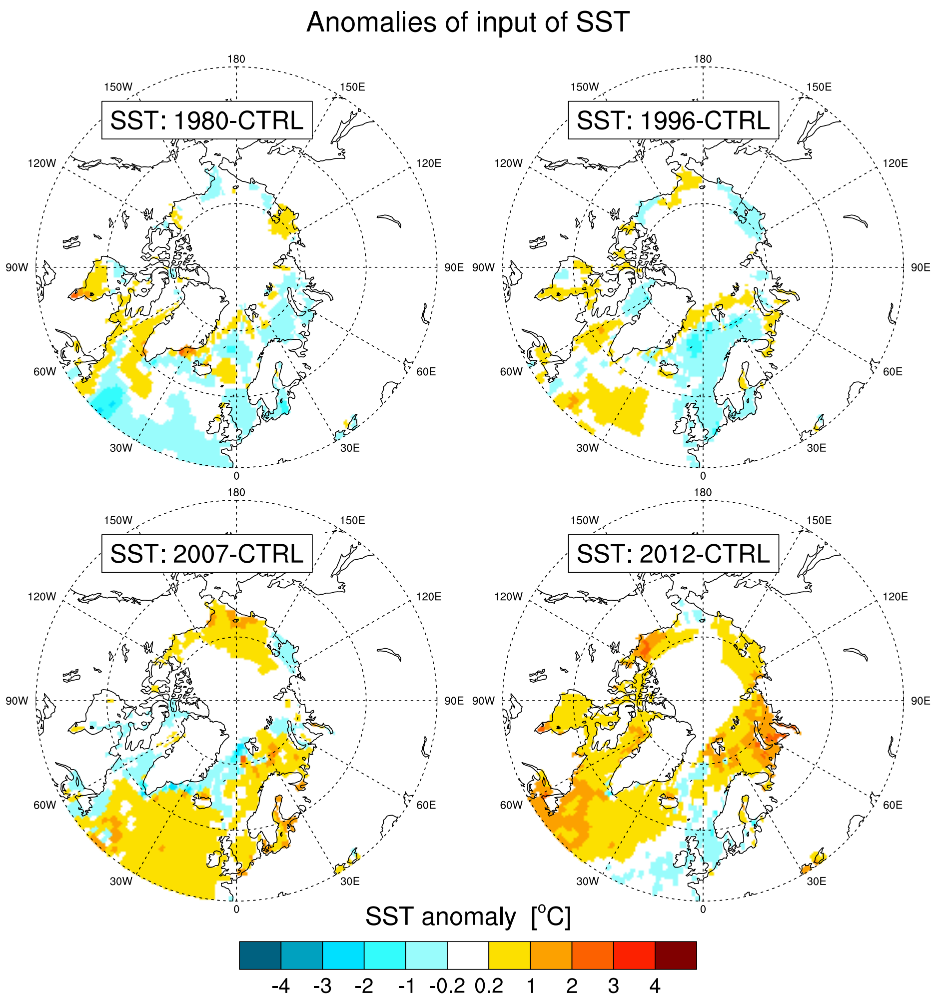


Figure 2. *Annual mean anomalies of sea surface temperature (SST) used to force the model* See tab. **??** for details. Red and yellow colours represent a increase in SST compared to the CTRL run. Blue colours represent a decrease in SST compared to the CTRL run (mean April 1979 to March 2013).

continents it is chosen to confine this region ~~by~~ with southern boundaries of $66°N$ and $37°N$ for the Pacific and Atlantic sector respectively~~(Note that this relative~~. The relatively southern definition of the semi-Arctic region in the North Atlantic is chosen to also include the ~~southern~~ southern-most position of sea ice export in the Newfoundland area~~). Each experiment has different values~~.

Each experiment is forced by different SST and sea ice conditions in the (semi-)Arctic region corresponding to the values for the selected year. The non-Arctic part of the dataset is identical for all the different experiments and ~~have~~ has values from the mean climatology of ERA-Interim 1979-2012. ~~No smoothing is applied~~ The area between the Arctic and non-Arctic ~~as this would also smooth out~~ part in the North Atlantic have strong naturally occurring SST gradients.

~~All prescribed oceanic conditions are constructed based on monthly mean data of SSTs and sea ice cover for 12 months (April to March) . This makes it possible to examine a full sea ice cycle from maximum extent one year to maximum extent the year after. The data are interpolated bilinearly from ($\sim 1°$ x $1°$) to T85 resolution, and hereafter checked for consistency.~~

~~Annual mean anomalies of sea ice concentration from ERA-Interim used to force the model. Red color represent a decrease in sea ice compared to the CTRL run. Blue color represent a increase in sea ice compared to the CTRL run (mean 1979-2012).~~

~~Annual mean anomalies of SST data from ERA-Interim used to force the model. Red and yellow colors represent a increase in SST compared to the CTRL run. Blue color represent a decrease in SST compared to the CTRL run (mean 1979-2012).~~

To avoid smoothing of natural SST gradients, then no smoothing is applied to the constructed oceanic data set. The sea ice concentrations and ~~SSTs~~ SST used to force the model are ~~seen~~ shown in Fig. **??** and Fig. **??** here displayed as annual mean anomalies between the respective experiment and the CTRL run. ~~In the simulations SSTs and sea ice concentrations are specified according to re-analysis data, so the only temperatures that are calculated interactively are land and sea ice surface temperatures. This configuration thus allows no feedback between atmospheric circulation and open ocean SST. Greenhouse gases, vegetation, ice sheets are all set to modern values. More specifically greenhouse gasses are set to the following CAM3 default levels: CO_2: 355 ppmv, CH_4: 1714 ppbv, N_2O: 311 ppbv. The solar constant is set to 1365 (Wm^{-2}) and orbital settings to the year 1850.~~

3 Atmospheric response to changes in sea ice extent

~~Here we present results from the four sea ice change experiments. Results for all variables are presented as the annual mean difference between the respective experiment and the CTRL run.~~

3.1 Atmospheric response

~~All experiments clearly show that changes~~ Changes in sea ice ~~cover and the connected SSTs yield~~ concentration and SST forces a strong local response in surface air temperature (T_{2m}) (see Fig.

??) ~~. As expected this response is strongly correlated with the distribution of SSTs and sea ice concentration in the prescribed ocean conditions. This demonstrates that the configuration of the sea ice change is very important for the resulting atmospheric conditions. The experiments with large sea ice extent simulates air temperatures colder than mean and vice versa. Comparing our simulations to existing work that analyses the atmospheric response to observed present-day sea ice it is found that the simulated temperature change~~ with cooling where sea ice extent is increased, and warming where sea ice extent is decreased. The simulated temperature changes are in agreement with other ~~modeling~~ modelling studies that have investigated the ~~simulated~~ atmospheric response to prescribed reanalysis-based ~~sea ice changes (**???**) . See also review papers by **??** .~~

~~Surface air temperature (T_{2m}) for the four simulations compared to the CTRL run. Only anomalies statistical significant to the 95confidence level are shown.~~

~~Because of the generally short persistence time of atmospheric processes it is reasonable to regard our 15-year experiments as ensembles of 15 independent annual cycles. The influence of internal variability on results is found to be of minor importance by comparing ensemble mean field of temperature of the experiments "2007" and "2012" with the ensemble mean field of the 60 member ensemble of CAM3 simulated by **?**~~ changes (**???** , see also reviews **??**). Changes in annual mean precipitation amount is found negligible (see appendix).

3.2 Isotopic response

The ~~isotopic response to the sea ice changes (Fig. **??**)clearly shows~~ CTRL run is compared to values of $\delta^{18}O$ observations from ice cores and GNIP stations for Greenland and a positive bias is found (see figure in appendix). As a consequence this study only investigates anomalies and not absolute values. All sensitivity experiments clearly show that changes in sea ~~ice~~ surface conditions influence the modelled ~~isotopic composition~~ $\delta^{18}O$ of Arctic precipitation ~~.~~ (Fig. **??**). Decreased (increased) sea ice ~~extent and concentration~~ concentration and connected SST results in enriched (depleted) $\delta^{18}O$ values of precipitation (hereafter referred to as $\delta^{18}O_p$). ~~The spatial distributions of the isotopic response are~~ Annual means of $\delta^{18}O_p$ are computed as precipitation weighted annual means. The spatial distribution of changes in $\delta^{18}O_p$ is similar to the ~~atmospheric temperature response and match the pattern of the changed sea ice cover. In the "2012" experiment the isotopic response to sea ice changes has a spatial extent of the response larger than the other experiments. These results display~~ spatial distribution of changes in simulated surface air temperature.

This shows that the spatial ~~distribution of the isotopic response to sea ice changes are~~ response of the simulated $\delta^{18}O_p$ to changes in sea surface conditions is controlled by the ~~configuration of the sea ice~~ distribution of theses changes. The distribution of the $\delta^{18}O_p$ response to the ocean conditions depends on the sea ice and SST configuration in the different experiments. As ~~seen~~ shown in Fig. **??** the $\delta^{18}O_p$ of the precipitation over central part of Greenland appears unaffected by the simulated changes in sea ice cover in all experiments whereas $\delta^{18}O_p$ changes over the Pacific-Arctic and the Barents/Kara Sea region depend on the ~~configuration~~ distribution of sea ice in the given experiment.

The experiments "1980" and "1996" both have increased sea ice extent and colder SSTs compared to the CTRL experiments, yet the spatial ~~configuration~~ distribution of the sea ~~ice changes~~ surface conditions in the Arctic Ocean are very different. This is observed in the Barents/Kara Sea region, in the Baffin Bay and near the northern coast of Greenland. The corresponding isotopic response match the differences in spatial pattern ~~as~~ observed in sea ice cover.

The two experiments with low sea ice extent compared to the CTRL experiments (the "2007" and "2012" experiments) similarly show that sea ice ~~configuration are~~ distribution is important for $\delta^{18}O_p$. The Labrador/Baffin region does not experience any significant change in the isotopic composition of precipitation in the "2007" experiment~~but it does in the "~~. Conversely, significant changes are simulated in the "2012~~" experiment ,~~" experiment where the sea ice changes in this region ~~is~~ are much more pronounced. For the Barents Sea ~~regions both experiments display~~ region both experiments yield positive $\delta^{18}O_p$ anomalies, but the amplitude of the anomalies ~~are~~ is different. Interestingly~~this amplitude difference are also displayed~~ , this difference in amplitudes is also found in the sea ice concentration anomalies used to ~~simulated~~ simulate the isotopic response. Thus this ~~suggest that both configuration~~ suggests that both distribution and magnitude of the ~~sea ice changes~~ changes in sea surface conditions are important for the ~~sea ice controlled~~ change in $\delta^{18}O_p$.

3.3 $\delta^{18}O_p$-temperature relationship

From a climate reconstruction perspective it is interesting to examine whether the isotope-temperature relationship ($\delta^{18}O_p$-T~~slope~~) is sensitive to changes in sea ice cover and SST. Scatter plots of annual mean anomalies of $\Delta\delta^{18}O_p$-ΔT are shown in Fig. **??**~~and **??**. The latter with $\delta^{18}O_p$ mean weighted with precipitation.~~ . Only grid points in the Arctic ($60°N$ - $90°N$) ~~is~~ are included in the analysis.

Linear regression ~~show~~ shows that the spatial $\Delta\delta^{18}O_p$-ΔT slope ~~all lies~~ for each of the experiment all are within the range of 0.38 to 0.53 ~~permil~~‰/$°C$ for all experiments. Linear regression for all experiments together (Fig. **??** "All experiments") ~~produce~~ show a larger range of values of anomalies and ~~yield~~ yields a slope of 0.57 ‰ /$°C$ with $R^2 = 0.761$. For experiments with high sea ice extent the slope is 0.38 ‰/$°C$ with $R^2 = 0.59$ for "1980" and 0.53 ‰/$°C$ with $R^2 = 0.575$ for "1996". The cases with low sea ice extent have values of the slope, 0.42 ‰/$°C$ with $R^2 = 0.732$ for "2007" and 0.48 ‰/$°C$ with $R^2 = 0.635$ for "2012".

~~Results of linear regression using $\delta^{18}O_p$ mean weighted with precipitation is seen in Fig. **??**. Using precip weighted anomalies the regression yields values of R^2 in the range of 0.3 - 0.6 for the individual experiments. Best fit is achieved for regression using all experiments together, where there is larger range of values of anomalies. Here the slope is 0.51 ‰/$°C$ and $R^2 = 0.668$.~~

In this study~~the~~ , the slope of $\delta^{18}O_p$-temperature relationship is found to be insensitive to changes in the pertubations ~~in~~ of sea ice. ~~Interpreting $\delta^{18}O_p$ changes to temperature changes using an Arctic~~

~~$\delta^{18}O_p$~~

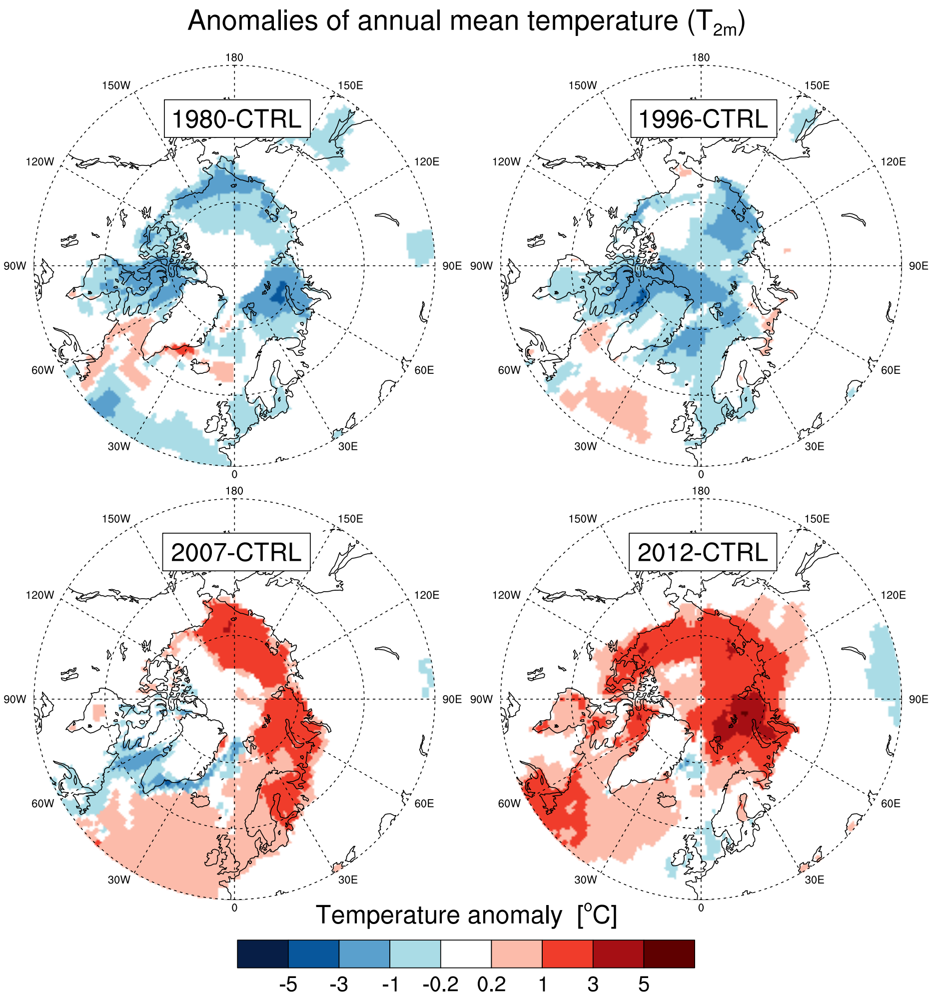


Figure 3. *Annual mean anomalies of surface air temperatures (T_{2m})*
Annual mean anomalies for the four simulations compared to the CTRL run. Red colours represent a increase in T_{2m} compared to the CTRL run. Blue colours represent a decrease in T_{2m} compared to the CTRL run Only anomalies statistical significant ~~to~~ at the 95% confidence level are shown.

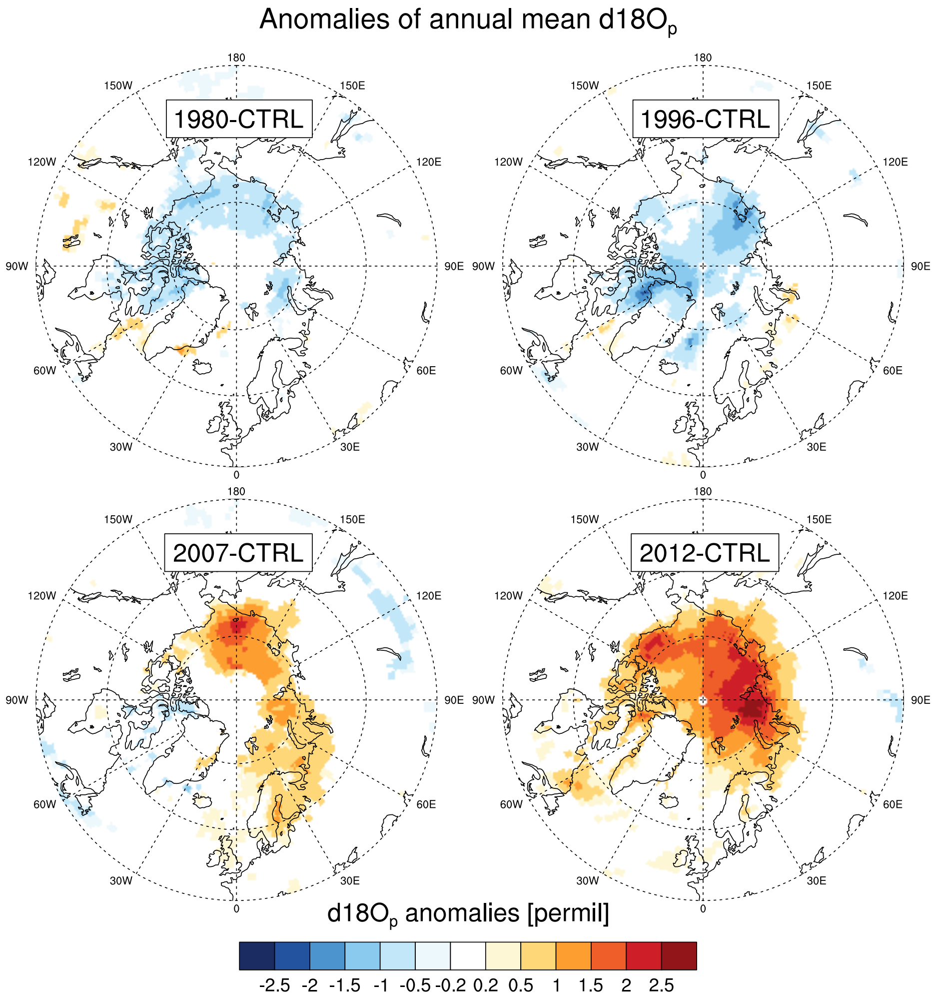
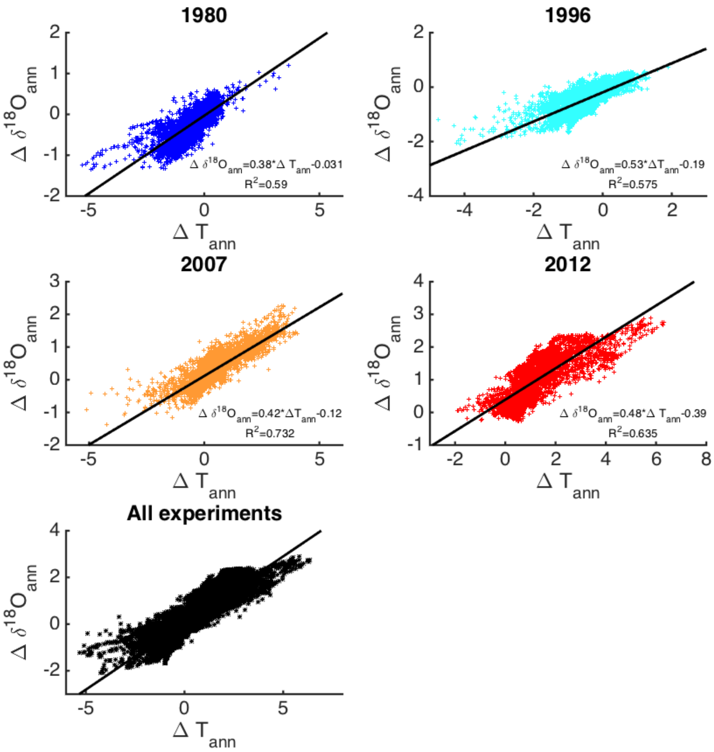


Figure 4. *Annual mean anomalies of $\delta^{18}O$ of precipitation ($\delta^{18}O_p$)*

Annual mean anomalies for the four simulations compared to the CTRL run. Only anomalies statistical significant at the 95% confidence level are shown. Red and yellow colours represent an increase in $\delta^{18}O_p$ compared to the CTRL run. Blue colours represent a decrease in $\delta^{18}O_p$ compared to the CTRL run.

~~spatial slope will therefore not be dependent on the sea ice configuration in the climate where the spatial slope is estimated. However the results here show that configuration still plays a major role, as the isotopic composition of precipitation at one location might not represent the regional conditions~~Differences in the intercept values of the regression is noted, most pronounced for the experiment "2012" where the offset of $\Delta\delta^{18}O_p$ is -0.39‰.



~~Scatter~~

Figure 5. *Scatter plots of anomalies of annual mean surface temperature (ΔT) versus $\Delta\delta^{18}O_p$ anomalies* The plots show scatterplots of ~~anomalies of annual mean surface temperature (ΔT) versus $\Delta\delta^{18}O_p$ anomalies of~~ all grid points from $60°N$ - $90°N$ for the different experiments compared to CTRL. The ~~colors~~ colours refer to the different experiments~~and the~~. The regression lines ~~in identical colors~~ for the individual experiments are shown with colours matching the ~~corresponding regression lines~~colours of the markers. Dark blue refers to experiment "1980", light blue to experiment "1996", orange to experiment "2007" and red to experiment "2012". Black colors show results from all experiments. Note that the scale of the x and y-axes are different for each plot.

~~Same as figure 5 but for annual mean temperature (ΔT) versus precipitation weighted $\delta^{18}O_p$ anomalies ($\Delta\delta^{18}O_{p,wgt.}$)~~

3.4 Atmospheric moisture processes

~~Changes in sea ice and SST alters the air-ocean-ice interaction. This can induce changes in atmospheric moisture processes resulting in changes in isotopic compositions of the moisture on both local, regional and remote scales. Investigation of the~~ The $\delta^{18}O_p$ response to sea ice changes ~~show that the responses~~ (Fig. **??**) shows that the response is predominantly local, yet with the "2012" experiment showing a more regional response. ~~For the local response~~ We here broadly define a local response as a situation where the grid points in close proximity to regions of sea ice change experience large changes in $\delta^{18}O_p$, ~~whereas regions~~ and where grid points without sea ice change show no pronounced changes in $\delta^{18}O_p$. ~~This local response suggest that the~~ Similarly, a regional response is here used to describe a response where changes in $\delta^{18}O_p$ ~~response to sea ice change is very sensitive to local changes in sea ice extent and SSTs. Changes in evaporation of local ocean water have been suggested by **??** as important for sea ice induced changes in $\delta^{18}O_p$. Evaporation is important for the control of isotopic composition of the moisture because water evaporated locally in the Arctic Ocean has a different isotopic composition than the surrounding vapor that has been depleted during transport from remote moisture sources.~~

~~Investigation of possible causes of a local response to~~ both occur at grid points in close proximity to regions of sea ice changes~~are done by examining the role of sea ice cover in controlling the evaporation.~~, but also at neighbouring grid points without sea ice changes.

Examination of the anomalies of isotopic composition of the water vapour ~~compared to the CTRL run~~ yields insight into the ~~evaporation and moisture mixing and transport processes that occur in the atmosphere~~isotopic composition of the Arctic moisture. Fig. **??** shows the anomaly of isotopic water vapour composition at the 850 hPa level (here after referred to as $\delta^{18}O_v$). The anomaly is plotted ~~together~~ with the 850-hPa level wind field anomaly overlayed. Similarly to the isotopic composition of precipitation, the isotopic composition of ~~vapor~~ vapour at the 850 hPa level reveals local anomalies at the same locations as anomalies of sea ~~ice occurs~~ surface conditions occur for all experiments. Locations with decreased (increased) sea ice extent and concentration ~~matches~~ are co-located with locations of enriched (depleted) water ~~vapor.~~

~~This suggest that an increase in local Arctic Ocean evaporation contributes with heavily enriched water to the ambient vapourresulting in vapour that has a higher value of $\delta^{18}O_v$. In the case of an increase in sea ice cover then the decrease in the contribution of local enriched water would result in ambient vapour with a lower value of $\delta^{18}O_v$~~vapour. The wind vectors in Fig. **??** show that the changes in advection at the 850 hPa level can not explain the change $\delta^{18}O_v$. Interestingly the highest wind anomalies are found in the "2012" experiment which is also the experiment which displayed a more widespread and regional isotopic response to sea ice changes. The slight increase in local wind anomalies ~~here~~ could indicate that advection ~~are~~ is responsible for larger spatial extent of the isotopic response.

~~$\delta^{18}O_v$~~

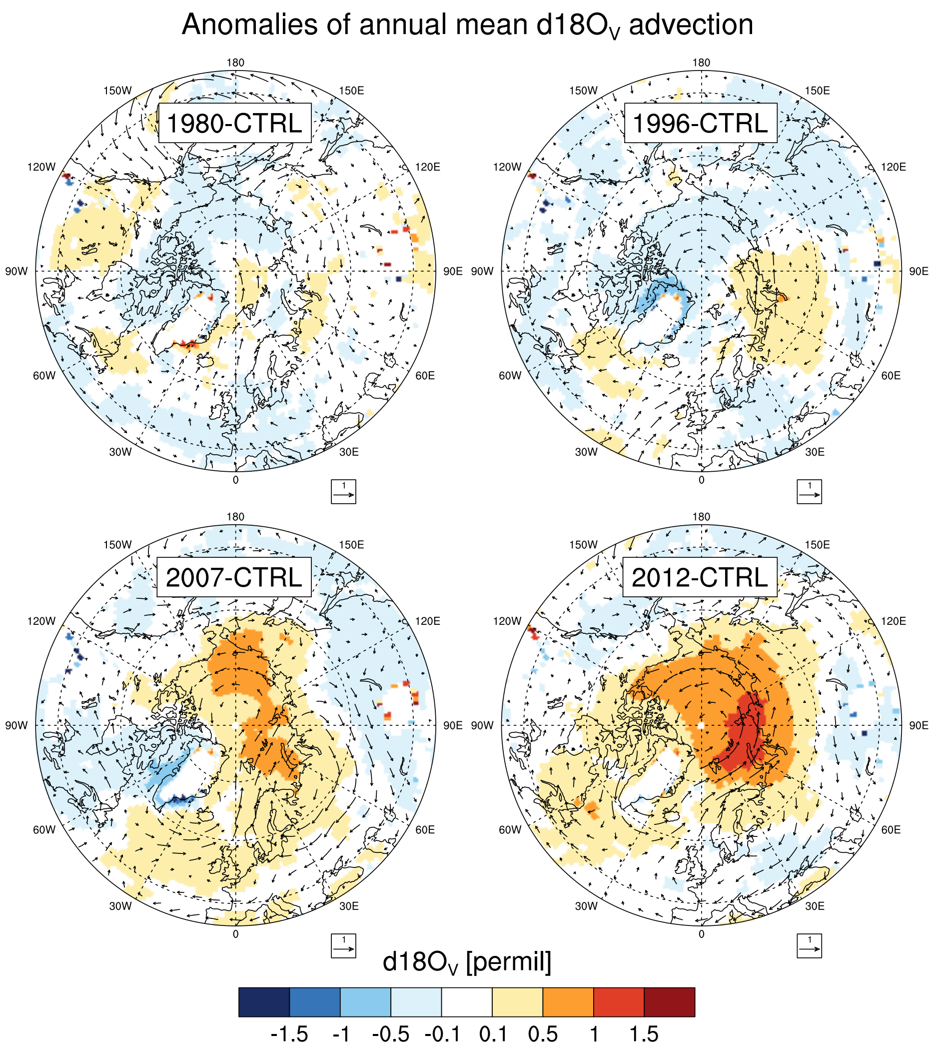


Figure 6. *Annual mean anomalies of $\delta^{18}O_v$*
Anomalies for the four simulations compared to the CTRL run. The arrows show the wind anomalies between the experiments and the CTRL run at the 850 hPa level.

~~Examining the role of sea ice cover as a control on the evaporation is here done using~~ Changes in local evaporation are here investigated based on the surface latent heat flux ~~as proxy for the local evaporation~~over ocean and ice. To compare how changes in sea ~~ice cover~~ surface conditions change the amount of total local evaporation, only locations with grid points of strongly reduced sea ice (change bigger than 20 %) were selected and the amount of total latent heat flux per year for all grid points between $60° N$ - $90° N$ was calculated for all experiments. To account for different numbers of grid points with sea ice change for each experiment the comparison to the CTRL run ~~are done using the~~ is done using identical locations of the grid points, such that non-local effects in evaporation changes were excluded. As observed in Fig. **??** the amount of local evaporation is remarkably stronger ~~in~~ for grid points where sea ice is reduced and weaker where sea ice is increased.~~Thus it is argued that the changes in $\delta^{18}O_p$ over regions of sea ice change is strongly connected to changes in local evaporation.~~ The number of gridpoints of reduced sea ice are as follows; 1980: 217, 1996: 444, 2007:1148, 2012: 2116. And the number of gridpoints of increased sea ice; 1980: 1508, 1996: 1024, 2007:554, 2012: 437.

The two experiments with low sea ice extent ("2007" and "2012") have warmer temperatures, more intense evaporation and higher values of $\delta^{18}O_v$ than the CTRL experiment. This ~~is in contrast to~~ contrasts the two remaining experiments ("1980" and "1996") ~~,~~ which have sea ice extent larger than ~~in~~ the CTRL run (based on 1979-2012 mean). In these experiments lower temperatures are observed as well as less intense evaporation and lower values of $\delta^{18}O_v$ ~~than in~~ compared to the CTRL experiment. Our results confirm that sea ice concentration and ~~SSTs controls~~ SST control the ability of the ocean to evaporate ~~ocean~~ water to the atmosphere. ~~This is in agreement with the thorough analysis of 37 CMIP5 projections (?) , which found that the projected strongly intensified local surface evaporation in the Arctic was primarily caused by retreating winter sea ice.~~

4 Discussion

~~In this analysis it is~~ For isoCAM3, it is here found that changes in sea ice ~~yields~~ and sea surface temperatures yield local changes in the ~~amount of relative contribution of vapor originating from localmoisture sources, and the location of these anomalies results in changes in~~ $\delta^{18}O$ of Arctic precipitation. The isotopic response is sensitive to the spatial configuration of the sea surface conditions and the response of the changes are primarily local. Differences in the isotopic response in Greenland and the rest of the Arctic thus exist for both vapour and precipitation. The experiments show no changes of $\delta^{18}O$ for Greenland precipitation. Investigation of the vertical distribution of $\delta^{18}O_v$ anomalies are show in fig. **??** and **??**. The zonal vertical cross sections of temperature and $\delta^{18}O_v$ ~~. Since no statistical significant changes are observed in the amount of precipitation it is assumed that the local moisture mix with existing vapor. An illustration of~~ along the latitude 77 ° N show that the changes in the ~~found connection between sea ice, SSTs and isotopic composition is seen in fig~~

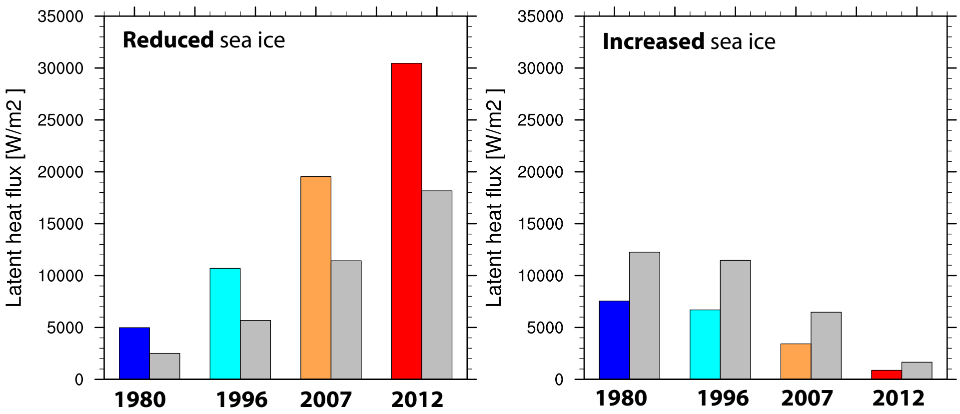


Figure 7. *Latent heat flux for sea ice changes*
Grid points of strongly reduced sea ice (~~change~~ anomaly bigger than 20 %) in each experiment were compared to identical grid points in the CTRL run and the amount of total latent heat flux per year for all grid points between $60^{\circ}N$ - $90^{\circ}N$ was calculated for both experiments and the CTRL run. The same was done for grid points of strongly increased sea ice. The ~~colored~~ coloured bars represent the latent heat flux over sea ice change regions for the different experiments and the grey bars adjacent to the ~~colored~~ coloured bar represent the latent heat flux for the identical grid points in the CTRL run.

~~??~~$\delta^{18}O_v$ and temperature is a surface based signal. This is also found in the spatial fields of $\delta^{18}O_v$ at different pressure levels in the vertical (see appendix). The precipitation anomalies are not occurring together with anomalies in the mid-troposphere $\delta^{18}O_v$ as seen vertical meridional cross sections of $\delta^{18}O_v$ (not shown). While the anomalies of vapour and precipitation at the same location does not have to be linked, it still suggest that the anomalies of precipitation is not connected to changes in air masses and large scale transport but rather to local changes.

~~This figure display the processes suggested to be the cause of the sea ice influence on the isotopic composition of Arctic moisture. The three cases a,b and c refers to three different sea ice concentrations: High, medium and low. a) In situations with high sea ice concentration all of the moisture in the lower atmosphere comes from remote sources and thus an isotopic signature referred to as~~ $\cancel{\delta_{remote}}$~~. b) In situations with medium sea ice concentration evaporation is occurring at the open ocean~~

~~water region. This water vapor has isotopic signatures which is here referred to as δ_{local}. Also moisture from remote sources are present. Mixing occurs between the two air masses which also influences to isotopic composition. c) Situations with low sea ice concentration and warmer SSTs are somehow similar to b) however as ocean is warmer the evaporation is more pronounced. Hence the relative contribution from the two moisture sources with the isotope signatures δ_{remote} and δ_{local} are changed. This also yields a more regional extent of the response.~~

~~In conclusion~~

4.1 Are the moisture sources changing?

Based on the pronounced local ~~effect observed in Fig. **??** combined with the evidence of increase in~~ structure of the isotopic response, and the evidence of an increase in ocean evaporation when sea ice is reduced and SSTs are warmed (see Fig. **??**)~~we propose that the primary mechanism behind the changed~~ , it is speculated that the pertubed isotopic composition is caused by changes in the contribution from local moisture ~~source. This is a local effect, primarily driven by local sea ice changes and not changes in the remote moisture~~ sources. ~~However, as observed in the "2012" experiment, larger changes in~~ An increase in local Arctic Ocean evaporation would contribute with heavily enriched water to the ambient vapour resulting in vapour that has a higher value of $\delta^{18}O_v$. This could explain the simulated $\delta^{18}O_v$ anomalies. In the case of an increased sea ice cover, the decrease in the contribution of local enriched water would result in ambient vapour with a lower value of $\delta^{18}O_v$. This hypothesis is supported by observational studies of the impact of Arctic sea ice ~~and more generally Arctic amplification might also induce changes in large scale circulation, which can potentially influence $\delta^{18}O_{remote}$.~~ changes on the isotopic composition of moisture (**??**) . Changes in evaporation of local ocean water have also been suggested by modelling studies as important for sea ice induced changes in $\delta^{18}O_p$ (**??**) . Furthermore, an analysis of future warming in the Arctic using state-of-the-art climate models showed changes in the hydrological cycle due to Arctic warming and sea ice changes (**?**) . In that study it was found that moisture inflow from lower latitudes played a minor role, and the changes were mainly caused by strongly intensified local surface evaporation.

~~Existing studies suggest that atmospheric processes caused by sea ice changes are; changes in cloud cover (**?**) , vertical structure of the atmosphere (**?**) , water vapor content, height of the boundary layer, convection (**?**) , , poleward energy moisture transport, latent heat flux and the connected items: jet stream, NAO and storm tracks **?** . Here we choose to focus on the effects of the jet stream only and investigate whether this is influencing our results.~~

~~It is found that the position and strength of the jet stream~~ An alternative explanation for the simulated changes in $\delta^{18}O_v$ and $\delta^{18}O_p$ is that the changes occur as result of changes in air mass characteristics. Reductions in the poleward temperature gradient would reduce the cooling and condensation that air masses experience during the northward transport. This would cause isotopic composition of the air masses to be less depleted. The sea surface conditions effect on Arctic warming is seen in the air temperature of this study and also the vertical cross sections (fig. **??** and **??**) can not exclude that the changes in the $\delta^{18}O_v$ is caused by changes in atmospheric temperature. Nevertheless, it is difficult to explain the spatially very local effects of $\delta^{18}O_p$ as a cause of reduction in the poleward temperature gradient. Yet, sea ice changes are connected to regions of cyclogenesis (**??**) . Thus regions of open and warmer ocean surfaces might potentially steer cyclones to follow these paths and precipitate over the these regions, thereby creating a local signal of $\delta^{18}O_p$ changes. Our experimental design can not reveal the synoptical variability and the effects of changed wind patterns are not clear from analysis of annual mean advection in the 850hPa layer in **??**. The windspeed ($\sqrt{u^2+v^2}$ ~~at~~) at the 300 hPa level ~~) (see appendix) varies in strength and position for the different experiments~~ is weakened at midlatitudes in this study, which indicate that the changes in sea surface conditions are influencing atmospheric circulation; yet no clear connection to the changes in sea ice extent is found. ~~However this calculation of annual mean position based on monthly mean output might not be representative of the actual processes occurring on shorter time scales. This is because sea ice changes have been suggested to lead to a more meandering jet stream **??** altering storm tracks, storm frequency, regions of cyclogenesis **??** moisture source region and thereby conditions during uptake and transport of moisture . All of these mechanisms have the potential to alter the~~ Based on the considerations above it is difficult to separate the effects of changes in temperature and changes in evaporation, and consequently model simulations with moisture tracking features is suggested for further investigation of this study. However, independent of the cause of the changes, it is found that changes in sea surface conditions are important for the isotopic composition of ~~the precipitation~~non-Greenland $\delta^{18}O_p$ in the Arctic.

~~Changes in isotopes in the~~

4.2 Influence on Greenland precipitation

Changes in the isotopic composition of Greenland precipitation is of special interest due to the ~~deep~~ ice core research sites in this region. Interestingly, none of the ~~experiments~~ sea ice perturbation experiments in this study display $\delta^{18}O_p$ changes over ~~Central Greenland. We argue that the robustness of the central Greenland $\delta^{18}O_p$ to changes in Arctic Ocean conditions is related to the topography of Greenland. The altitude of the Greenland Ice Sheet requires that the precipitation originates from moisture-bearing storms intense enough to endure the rainout that follow as a result of the orographic lift at the steep slopes of the ice sheets. Hence assuming that if the Arctic Ocean conditions only form~~ Greenland. Thus the vertical distribution of T and $\delta^{18}O_v$ near the location of the ice core drilling site NEEM, Greenland ($\sim$ 77 °N, 51 ° E) are used to investigate the differences in the response in Greenland and the rest of the Arctic. Fig. **??** and **??** show the circumpolar zonal vertical distribution of T and $\delta^{18}O_v$ at nearest gridpoint levels to NEEM. At non-Greenland locations the anomalies of T and $\delta^{18}O_v$ are surface based signals, sensitive to the local conditions. However near NEEM, the Baffin Bay sea ice extent and associated simulated response in $\delta^{18}O_v$ are important for the

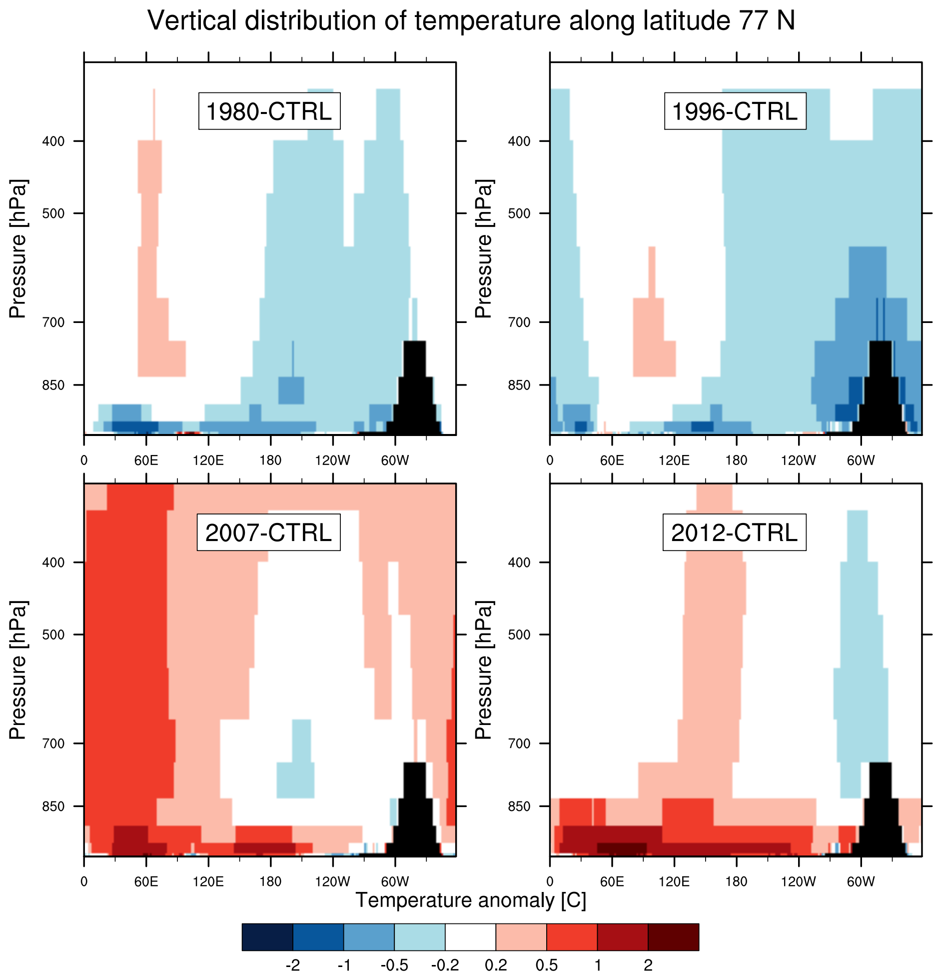


Figure 8. *Vertical distribution of annual mean anomalies of temperature at the latitude band, 77 ° N* Annual mean anomalies for the four simulations compared to the CTRL run. Red and yellow colours represent an increase in temperature compared to the CTRL run. Blue colours represent a decrease in temperature compared to the CTRL run. The topography of Greenland is marked with black

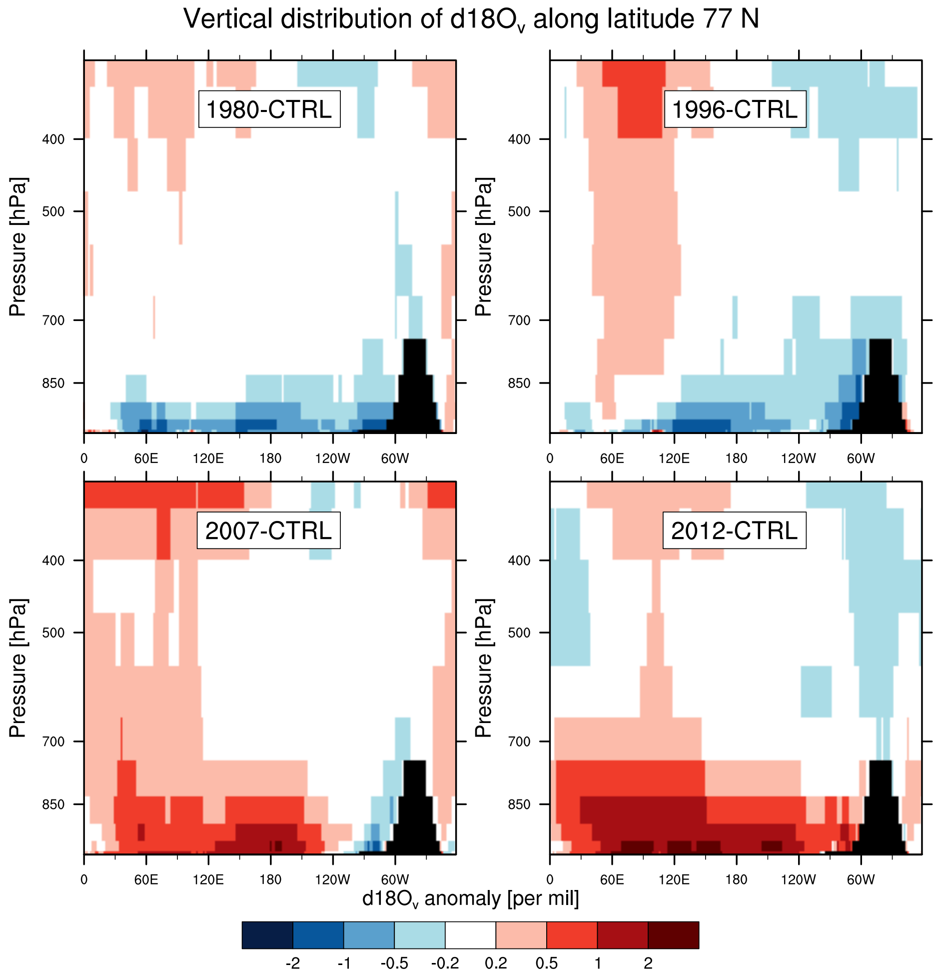


Figure 9. *Vertical distribution of annual mean anomalies of $\delta^{18}O$ of vapour ($\delta^{18}O_v$) at the latitude band, 77 ° N*

Annual mean anomalies for the four simulations compared to the CTRL run. Red and yellow colours represent an increase in $\delta^{18}O_p$ compared to the CTRL run. Blue colours represent a decrease in $\delta^{18}O_p$ compared to the CTRL run. The topography of Greenland is marked with black

$\delta^{18}O_v$ at NEEM. In experiment "~~weak~~2007" ~~precipitation systems then these are not intense enough to transport moisture to central part of the Ice Sheet. Thus weak locally produced storm systems wont influence~~ the Baffin Bay sea ice extent is increased compared to the mean values, while the near NEEM $\delta^{18}O_v$ display negative anomalies of $\delta^{18}O_v$ in the range 0.2-1 ‰, this in spite of an overall Arctic enrichment. This suggest that the local conditions at Baffin Bay, and not the general Arctic conditions, are relevant for studying the $\delta^{18}O_v$ response to sea ice changes at NEEM. Modern observations of the isotopic composition of snow and vapour from NEEM also show that variations in modern values of $\delta^{18}O$ correlates with conditions in Baffin Bay sea ice extent **?** .

The robustness of the Greenland $\delta^{18}O_p$ ~~over Greenland. Furthermore, no remarkable changes in sea ice cover are occurring in near proximity to Greenlandin this study. This attenuates the contribution of local moisture sources in the Greenland precipitation. However changes in storms tracks and similar features might also influence the location of source region and resulting isotopic signal.~~ to changes in Arctic Ocean surface conditions is argued to be related to the topography of Greenland. Specifically, the steep slopes of the ice sheet margin are associated with substantial orographic enhancement of precipitation and depletion of storm water vapour content. Processing controlling the Greenland $\delta^{18}O_p$ might be decoupled from the processes influencing the $\delta^{18}O_p$ over the Arctic ocean. The Greenland katabatic wind blocking effect (**?**) might also play a role in blocking of low level moisture to Greenland.

We note our experiments does not exhibit the strong warming observed over Greenland in 2012. The observed 2012 Greenland melting was attributed to the key factors the North American heat wave, transitions in the Arctic Oscillation and transport of warm air and vapour via an atmospheric river (**??**) . Forcing the model with only oceanic conditions can thus not expected to create a similar atmospheric-induced warming.

In contrast to ~~these results~~ the results of this study, **?** simulated $2-3$‰ changes in central Greenland $\delta^{18}O_p$ for ~~warmer than present-day climates. The main difference between the simulation~~ extremely warm climates. SST and sea ice conditions created from coupled model experiment forced by large increases in CO_2. The main differences between the simulations in this study and ~~from **?** is the existence~~ in the study by **?** is related to the distribution and magnitude of sea ice and SST changes ~~near Greenland as well as the~~ especially near northern Greenland.

In the study by **?** sea ice and SST changes also occur in the region north of Greenland. Also the magnitude of Arctic SST anomalies ~~(aprox.~~ are $8-10°C$ ~~) whereas our simulations~~ whereas the simulations in this study have anomalies of $3-5°C$. ~~Results from temperature and isotope response in our experiments (see Fig. **??** and **??**) show that years with minor perturbations in sea ice extent result in local responses whereas years with major perturbations in sea ice extent result in more regional and more amplified responses~~These differences are compelling as our experiment "2012" with the largest prescribed SST anomalies and sea ice changes also is the only experiment that simulates a regional isotopic response. This indicates that the magnitude of SST changes might control not only the amount of local evaporation, but also the regional extent of the isotopic response. ~~In our simulations as well as in previous studies,~~ Hence, it is possible that the simulated changes of $\delta^{18}O_p$ by (?) have a regional extent due to the same reasons as experiment "2012".

Warming of the lower troposphere and associated weakening of inversion layer might be important in controlling the extent of the isotopic response. As sea ice removal is ~~found to be~~ connected to intense warming of the lower troposphere ~~??, with a resulting seasonal~~ (??), it could be speculated that this warming and associated weakening of the inversion layer ~~. A~~ is controlling the extent of the isotopic response. This would be possible as a weaker inversion layer allows atmospheric convection, and ? have shown that this can occur at high-latitudes in sea ice free regions in winter. ~~Hence it can be speculated whether the regional extent of the isotope response is controlled by the strength of the inversion layer.~~ Further investigation of the mechanism causing this change requires ~~experiments designed similar to the idealised Antarctic sea ice changes used by ?~~ further idealized experiments following a similar to design to ?, so that a systematic investigation of the atmospheric processes influencing the isotopic composition of moisture is possible.

5 Conclusions

The aim of this study ~~is~~ was to investigate whether changes in sea ice ~~cover~~ and sea surface temperatures derived from observed anomalies can influence the isotopic composition of precipitation in the Arctic. Results are presented from isoCAM3 an isotope-equipped AGCM, forced with different ~~configurations~~ distributions of Arctic sea ice changes and associated ~~SSTs from the re-analysis~~ SST from the ERA-interim re-analysis product. These simulations ~~clearly shows that a changed sea ice cover influence~~ show that changes in sea ice and sea surface conditions influences the isotopic composition of Arctic precipitation with regional changes of $\delta^{18}O_p$ of up to 3‰ in the Barents ~~sea region. Independent of the spatial configuration of sea ice and SST change decreased (increased~~ Sea region. However, no changes are found for Greenland; a region relevant for isotope records from ice cores. For all experiments it is found that regions of increased (decreased) sea ice extent and concentration results in enriched (depleted) $\delta^{18}O$ values of precipitation.

~~Our simulations show that in isoCAM3 the~~ The $\delta^{18}O$ response to the ocean conditions is primarily local~~- not regional.~~. Changes in sea ice and sea surface temperatures yield local surface based anomalies of $\delta^{18}O$ of vapour. Differences in the isotopic response in Greenland and the rest of the Arctic thus exist for both vapour and precipitation. Within the same experiment large changes in $\delta^{18}O$ ~~is~~ are observed over some regions and no changes over other regions. The geographical variations in the $\delta^{18}O$ response to ~~Arctic sea ice changes~~ changes in Arctic sea surface conditions show that the isotopic composition of Arctic precipitation is sensitive to the spatial ~~configuration~~ distribution of the sea ice and SST changes, however not at Greenland. This means that different ~~configurations~~ distributions of similar sea ice areas can produce very different $\delta^{18}O_p$ values at the same location. Or conversely, that different locations respond very ~~different~~ differently in $\delta^{18}O_p$ to the same total Arctic sea ice extent.

~~For example the isotopic composition in precipitation over central part of Greenland appears~~ The isotopic composition of Greenland precipitation are unaffected by the imposed changes in central Arctic sea ice cover in all experiments. Only conditions near Baffin Bay influence Greenland. As many ice cores ~~origins~~ originate from the Greenland Ice Sheet this is an important result for the interpretation of isotope records. ~~Analysis showed that the changes in $\delta^{18}O_p$ and $\delta^{18}O_v$ could be (partly) explained by changes in local moisture sources. As the interior Greenland Ice Sheet has a continental climate with no local moisture sources it is suggested that this could explain why the $\delta^{18}O_p$ in central Greenland are insensitive to the configuration of the sea ice changes used in this model study. The spatial $\Delta\delta^{18}O_p$ - ΔT relationship was found insensitive to the configuration and magnitude of the sea ice changes in this study.~~

Previous studies have shown that large changes in the state of sea ice and SST conditions influences the isotope composition over Greenland (**?**) and Antarctica (**?**) but this study is the first model experiment to show that minor (relative to **?**) perturbations in the sea ice cover and ~~SSTs~~ SST under present-day climate ~~state~~ conditions can yield significant changes in the isotopic composition of precipitation in the Arctic, ~~except central~~ while at the same time not changing conditions in Greenland.

6 ~~Jetstream~~

~~Anomalies of strength of the jet stream ($\sqrt{u^2+v^2}$ at 300 hPa level). Blue color represent an decrease in the jet stream strength compared to the CTRL run, and red an increase. Only anomalies statistical significant to the 95confidence level are shown.~~

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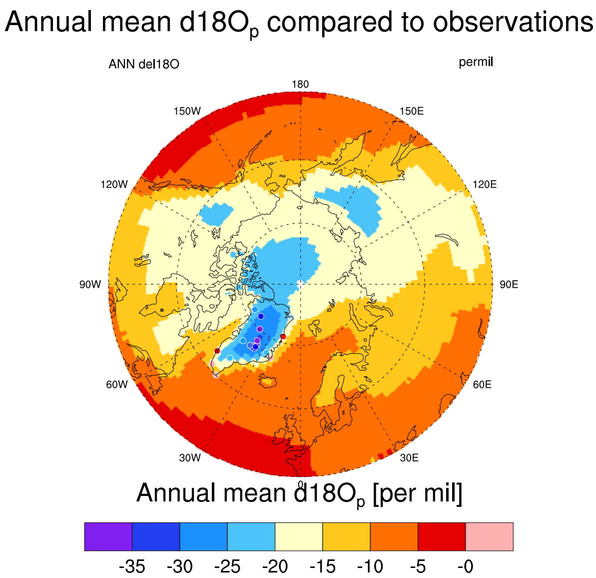

Figure 10. *Annual mean $\delta^{18}O_p$ for the CTRL run compared to observations*
Annual mean $\delta^{18}O_p$ for the CTRL run compared to observations. The circles represent annual mean values from ice core and GNIP observations.

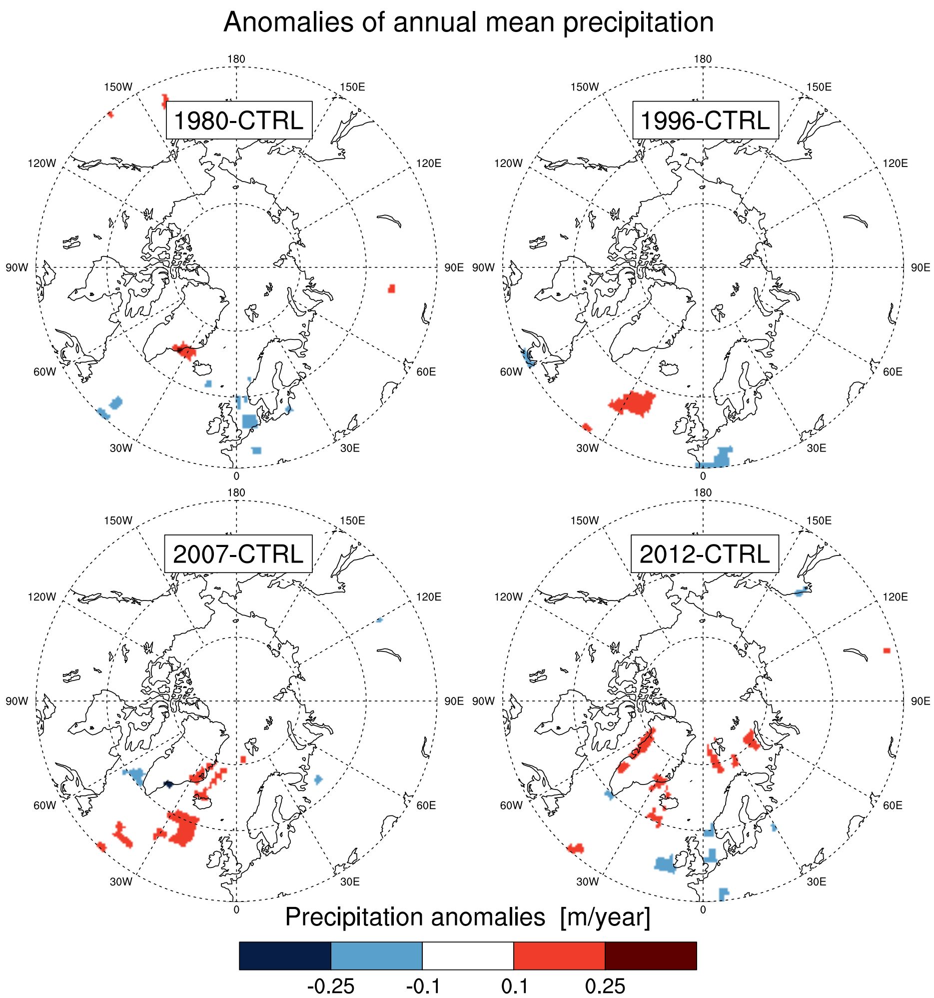

Figure 11. *Annual mean anomalies of precipitation*

Anomalies for the four simulations compared to the CTRL run.

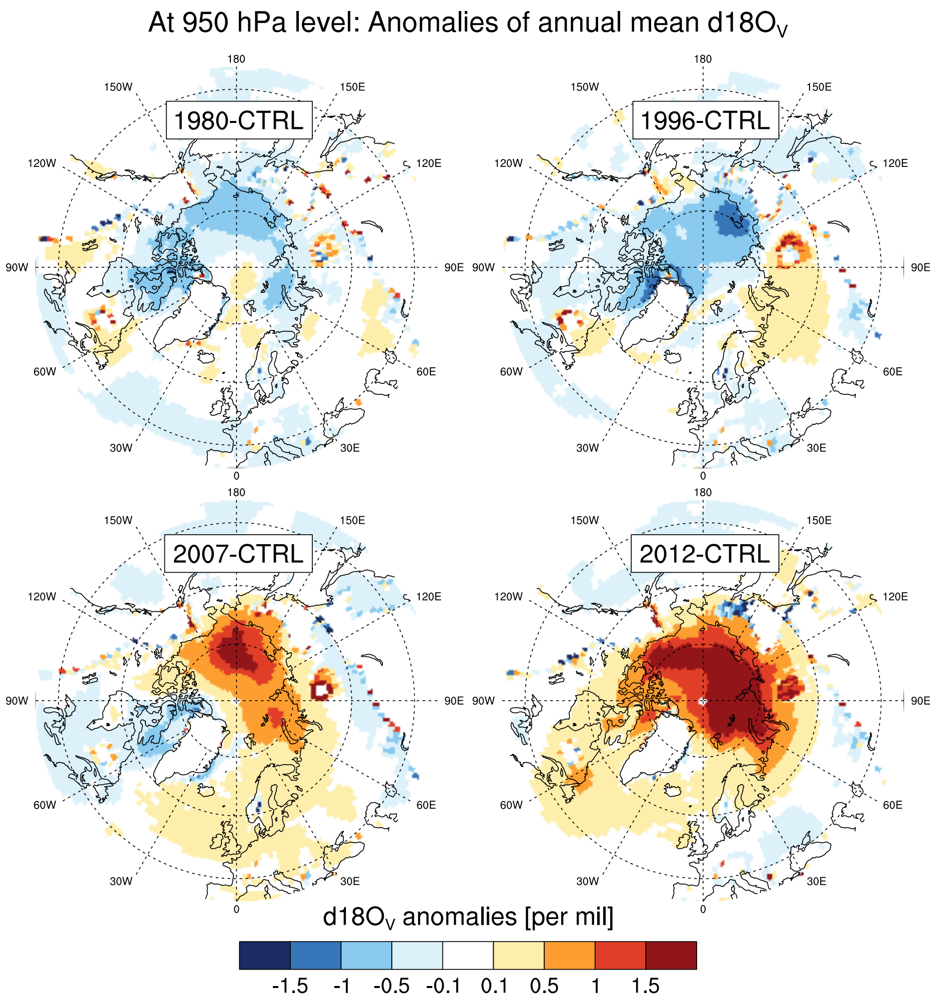

Figure 12. *Annual mean anomalies of $\delta^{18}O_v$*

Anomalies for the four simulations compared to the CTRL run. The arrows show the wind anomalies between the experiments and the CTRL run at the 950 hPa level.

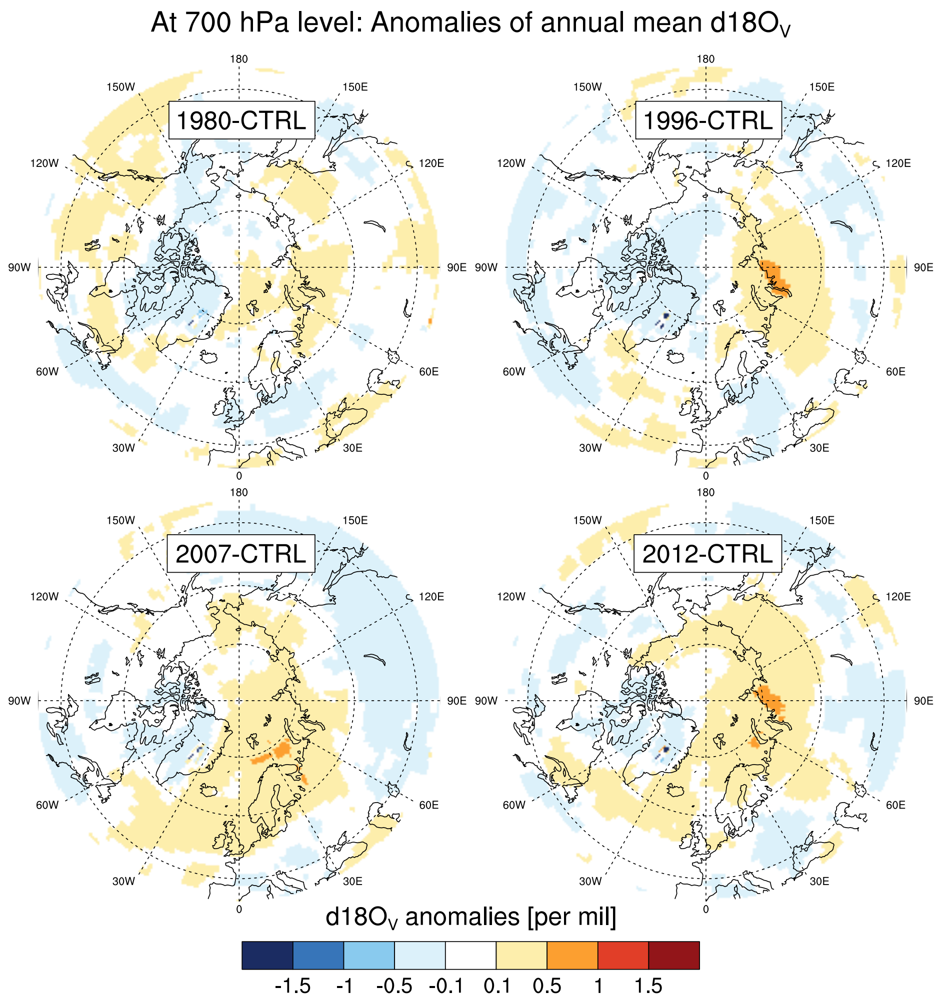

Figure 13. *Annual mean anomalies of $\delta^{18}O_v$*

Anomalies for the four simulations compared to the CTRL run. The arrows show the wind anomalies between the experiments and the CTRL run at the 700 hPa level.