Barents Sea inflow shutdown: A new mechanism for rapid climate changes

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[1] A new mechanism for rapid climate transitions in the high latitudes is presented which involves complex ocean-sea ice-atmosphere interactions. A shutdown of the Barents Sea Inflow (BSI) which carries a vast amount of heat into the Arctic Ocean is at the heart of the mechanism. The BSI shutdown is studied in a multi-millennium integration with a global climate model forced by periodically (1000 yr) varying solar constant (±2 W/m^2). A positive feedback between the inflow and sea ice cover is revealed in the model, which triggers rapid climate changes. The BSI shutdown events are associated with strong cooling in the northern latitudes and subsequent rearrangement of the Arctic Ocean surface current system. The results reveal the existence of a bifurcation point in the Arctic climate system and demonstrate that rapid climate transitions may be caused by local feedbacks and restricted to confined areas without significant global impacts. **Citation:** Semenov, V. A., W. Park, and M. Latif (2009), Barents Sea inflow shutdown: A new mechanism for rapid climate changes, *Geophys. Res. Lett.*, *36*, L14709, doi:10.1029/2009GL038911.

1. Introduction

[2] The Holocene is the present warm period that started about 11,500 years ago. It is characterized by a relatively stable climate, as opposed to the climate of the last glacial which exhibited a number of strong and rapid climate changes on regional, hemispheric and even global scale. However, proxy records from the North Atlantic, Nordic and Barents Seas reveal some rapid climate shifts of several centuries duration [*Bond et al.*, 1997; *Duplessy et al.*, 2005; *Hald et al.*, 2007] also during the Holocene. In particular, abrupt fluctuations of water temperature and salinity are indicated by sea sediment cores along the Norwegian Current and in the Barents Sea [*Voronina et al.*, 2001]. Lake sediments and tree ring reconstructions also indicate rapid temperature changes over Scandinavia and north-western Eurasia [*Allen et al.*, 2007; *Andreev and Klimanov*, 2000]. While only moderate global climate variations can be directly explained by changes in solar irradiance on millennium timescales [*Crowley*, 2000], the role of solar forcing in sharp and strong regional climate changes is still poorly understood. A feasible and compelling way to obtain further insight into the dynamics of such events is to simulate them in a realistic climate model, run either in unforced or forced mode. Abrupt climate transitions simulated by climate models in the high northern latitudes were mostly attributed so far to a rearrangement of deep oceanic convection in the North Atlantic and Nordic Seas in response to an external freshwater forcing [*Manabe and Stouffer*, 1995; *Rahmstorf*, 1994], to changes in solar irradiance [*Goosse et al.*, 2002; *Renssen et al.*, 2007], or to a strong and persistent internal atmospheric fluctuation [*Goosse et al.*, 2003; *Hall and Stouffer*, 2001].

[3] The Barents Sea inflow is a major surface current carrying roughly one half of the Atlantic waters entering the Arctic Ocean. The Barents Sea inflow (BSI) is defined here as the net eastward transport between North Cape, the northern tip of Norway, and Svalbard (Spitsbergen), which is dominated by the transport of relatively warm and salty Atlantic waters by the North Cape Current [*Loeng*, 1991; *Loeng et al.*, 1997]. The latter is primarily wind driven on interannual to decadal time scale [*Adlandsvik and Loeng*, 1991; *Bengtsson et al.*, 2004; *Loeng*, 1991; *Loeng et al.*, 1997], but may be also influenced by the multi-decadal variability of the Atlantic meridional overturning circulation [*Bengtsson et al.*, 2004; *Semenov*, 2008]. Variations of the inflow of warm and saline Atlantic waters to the shallow Barents Sea have a strong impact on the sea ice cover in winter. Historical observations and climate model simulations suggest that BSI variability might have been a major contributor to climate changes in the Barents Sea and even the entire Arctic, especially during the early 20th century warming [*Bengtsson et al.*, 2004; *Goosse and Holland*, 2005; *Semenov and Bengtsson*, 2003; *Semenov*, 2008].

[4] In this study, we show that complex ocean-sea ice-atmosphere interactions in the Barents Sea region may result in positive feedback between sea ice and the BSI. This feedback is responsible for the events of rapid inflow shutdown and associated climate changes, which were simulated in a multi-millennium integration with a global climate model forced by varying solar constant.

2. Model Simulation

[5] A 4200 year long simulation with the state-of-the-art coupled atmosphere-sea ice-ocean general circulation model KCM (Kiel Climate Model) [*Park et al.*, 2009] was analyzed. The model consists of the ECHAM5 [*Roeckner et al.*, 2003] atmosphere general circulation model run at T31 (3.75° × 3.75°) horizontal resolution and the NEMO [*Madec*, 2008] ocean-sea ice general circulation model with horizontal resolution based on a 2° Mercator mesh (see detailed description by *Park et al.* [2009]). No form of flux correction or anomaly coupling was used. The model was forced by a periodically varying solar constant. The period of 1000 years

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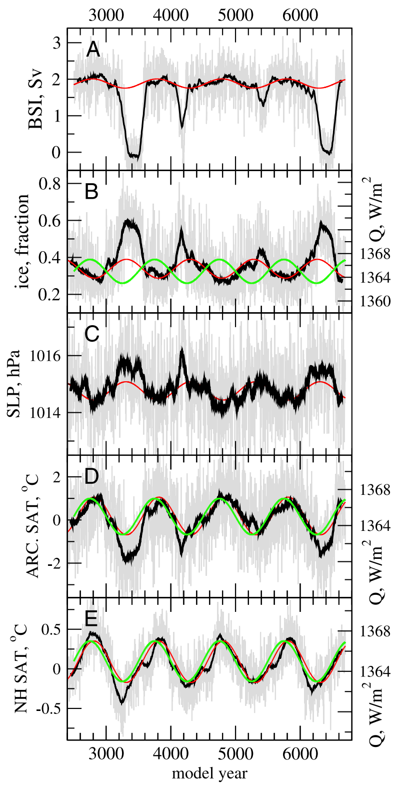

Figure 1. (a) Simulated time series of Barents Sea inflow, BSI, (b) ice extent fraction in the western Barents Sea (15°E–35°E, 70°N–80°N), (c) sea level pressure over the western part of the Barents Sea, and (d) surface air temperature anomalies over the Barents sea region (10°E–60°E, 65°N–85°N) region and (e) for the Northern Hemisphere. Grey lines are annual mean values, thick black lines represent 100 year running means, and red sinusoids depict a harmonical fit (with 1000 yr period) to corresponding time series with excluded periods of the BSI shutdown. Green lines on Figures 1b, 1d, and 1e are solar constant evolution.

and the amplitude of ±2 W/m^2 of the solar forcing (Figure 1) were chosen to idealistically represent millennial-scale total solar irradiance (TSI) variations during the Holocene. Such variations are suggested by splicing the TSI reconstructions for the last millennium [*Bard et al.*, 2000; *Lean et al.*, 1995] into extended TSI proxies based on cosmogenic radionuclides [*Stuiver et al.*, 1998; *Vonmoos et al.*, 2006; *Weber et al.*, 2004].

[6] An important feature of the oceanic model component is the relatively high horizontal resolution, which is less than 100 km in the Nordic and Barents Seas. In comparison to previous studies, this allows a more realistic representation of the coupling between the atmosphere, oceanic currents and sea ice extent in the Atlantic opening of the Arctic. KCM realistically simulates the mean oceanic circulation in the Barents Sea (Figure 2a), with a cyclonic circulation in the south, countercurrents between Novaya Zemlya and Franz Josef Land and an indication of the East Spitsbergen Current. The simulated BSI, defined as difference of the barotropic streamfunction between North Cape and Spitsbergen, amounts to 1.9 Sv, which is consistent with the range of 1–3 Sv obtained from observations and other models [*Goldner*, 1999; *Loeng et al.*, 1997; *Maslowski et al.*, 2004].

3. Results

[7] Two complete BSI shutdowns were simulated in response to the periodic solar forcing (Figure 1a). The transition to a zero BSI state takes several decades and the shutdown lasts for about 300 years with a subsequent sharp return to the "normal" state. During the shutdown, the Atlantic surface waters do not enter the Barents Sea but turn westward thereby intensifying the Greenland Sea Gyre and then re-circulate along the East Greenland coast (Figures 1b and 1c). A strong anti-cyclonic circulation anomaly develops in the Barents Sea, and the net inflow of the Barents Sea waters to the Kara Sea between Novaya Zemlya and Franz Josef Land is replaced by a westward outflow of the Arctic

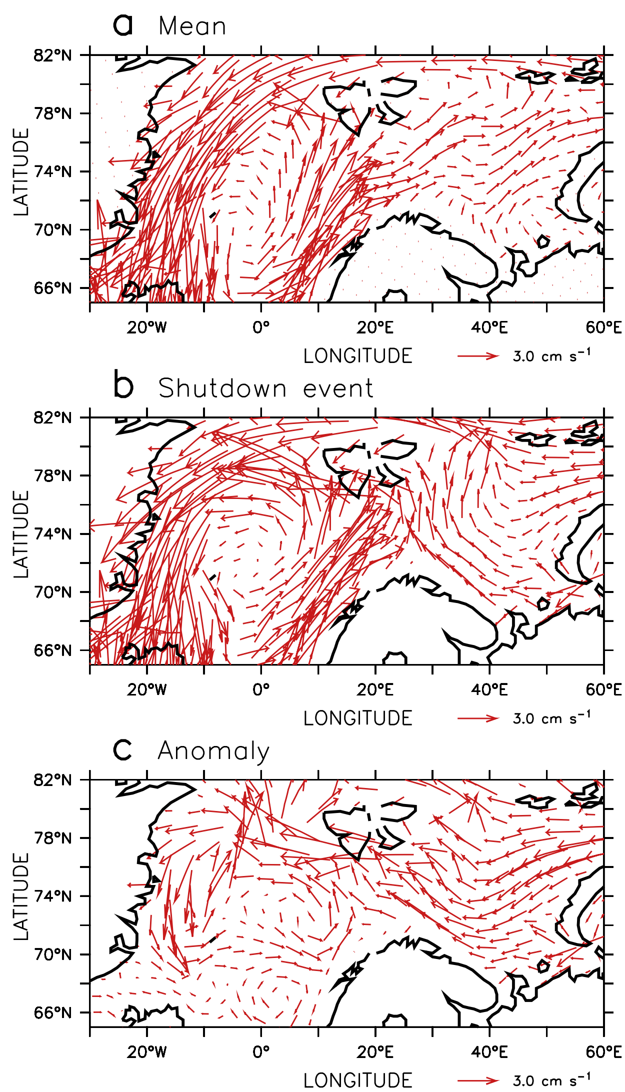

Figure 2. Annual mean upper ocean (15 m depth) velocities averaged (a) for the whole simulation duration, (b) for the first BSI shutdown event, model years 3321–3550, and (c) their difference.

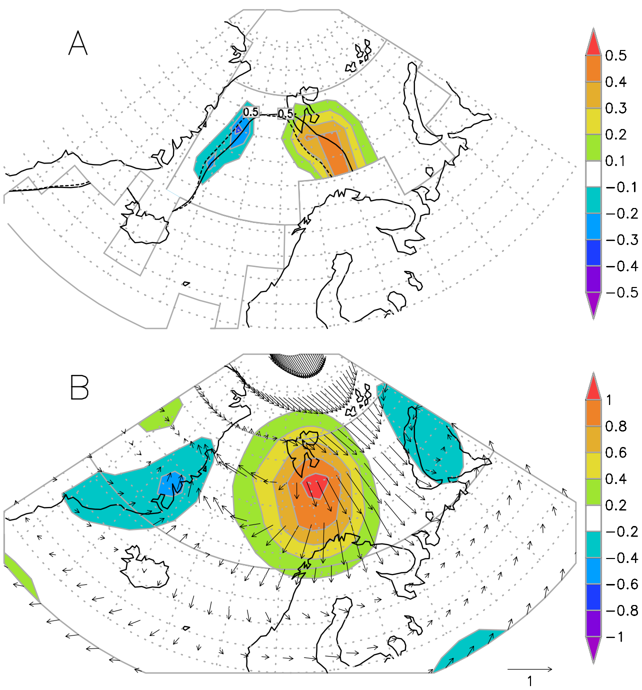

Figure 3. (a) Simulated changes (relative to the whole simulation average) of sea ice concentrations (fraction) and (b) sea level pressure (hPa) and 10 m wind (m/s, unit vector is 1 m/s) averaged for winter (Nov–Apr), during the BSI shutdown period. Solid and dashed lines in Figure 3a depict 50% sea ice extent averaged for the whole simulation and for the BSI shutdown periods, respectively.

waters (Figures 2a and 2b). The net outflow through the Fram Strait decreases thereby keeping the Arctic Ocean water mass balance, as simulated changes of the Bering Strait inflow amount to only about 0.1 Sv. The BSI shutdown is accompanied by a sharp increase of the ice cover (Figure 1b) covering practically the whole Barents Sea extending close to the 15°E meridian during the winter months, November through April (Figure 3a). The comparison to the mean sea ice climatology (not shown) reveals that winter sea ice conditions during the BSI shutdown persist for almost the whole year except in August and September. Accordingly, sea level pressure (SLP) increases (Figure 1c) and surface air temperature drops by about 1°C over the Barents Sea and adjacent land areas in the annual mean (Figure 1d), with stronger changes in winter than in summer (Figure 4). The events are also visible in Northern Hemisphere averaged temperature (Figure 1e), with a drop of about 0.2°C during the first event around model year 3200 relative to the average response given by the corresponding harmonic fit.

4. Shutdown Mechanism

[8] The BSI behavior (Figure 1a) is a good illustration of the classical stochastic resonance theory which was put forward almost 30 years ago to explain strong paleo-climate variations in response to weak orbital (Milankovich) forcing [*Nicolis*, 1982]. According to this concept, a "double-well" potential climate system may perform quasi-periodic transitions between the two stable states that are driven by a modest periodic lowering of the potential barrier in the presence of a stochastic forcing [*Benzi et al.*, 1981]. An essential requirement for such a behavior is the existence of a positive feedback. In the climate model simulation, a positive feedback operates between the BSI, the sea ice, and the oceanic and atmospheric circulation, and both observations and other modeling studies support its existence [*Adlandsvik and Loeng*, 1991; *Bengtsson et al.*, 2004; *Ikeda*, 1990; *Mysak and Venegas*, 1998]. Sea ice extent anomalies are associated with changes in the turbulent heat loss from the sea surface. An anomalously strong (weak) BSI drives a reduced (increased) sea ice extent and a surface heating anomaly that forces a cyclonic (anti-cyclonic) circulation anomaly in the atmosphere. This leads to stronger (weaker) surface westerly winds reinforcing the initial inflow perturbation, thereby further increasing (decreasing) both the oceanic and atmospheric heat transports into the region. This effect was modeled with an atmospheric model and was found to be an amplifier of the multidecadal climate variations in the North Atlantic-Arctic Sector [*Bengtsson et al.*, 2004]. Here, the instability arises when the sea ice cover expands (Figure 1b) and approaches the western opening to the Atlantic (Figure 3a) in response to a decrease in the solar constant. The instability threshold for the western sea ice border extension in the model is about 25°E (in the central part of the western opening of the Sea, Figure 3a). An anti-cyclonic atmospheric circulation anomaly develops over the ice covered sea surface in the western part of the Barents Sea (Figures 1c and 3) weakening the south–westerly winds north of Norway (Figure 3b) and thereby decreasing the BSI. This causes a further westward extension of the Barents Sea ice, which is limited by the relatively warm and salty Norwegian Current to the west of North Cape-Spitsbergen meridian. When the solar forcing increases the sea ice extent diminishes, which enhances the probability of the system to return to the stable state with a BSI (Figure 1a).

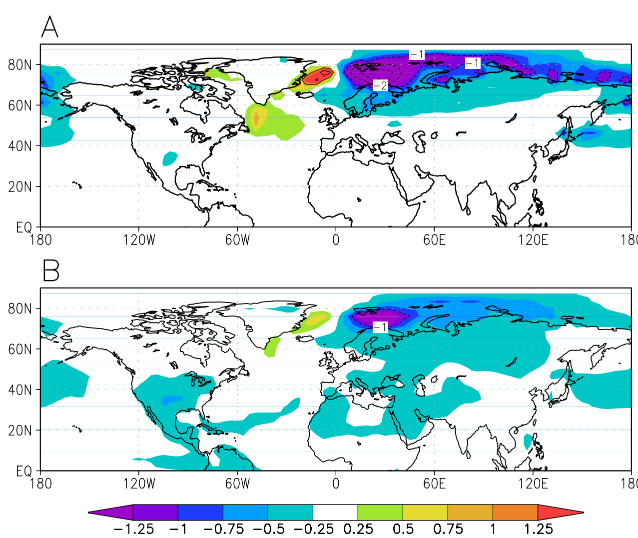

Figure 4. Surface air temperature anomalies (°C) corresponding to the BSI shutdown event as simulated by the KCM for (a) winter (Nov–Apr) and (b) summer (May–October).

The feedback is most pronounced in winter (Figure 4), when the winds over the Barents Sea and the associated surface heat loss are strongest.

5. Discussion

[9] Several studies previously highlighted that positive feedback between the sea ice and oceanic inflow to the Barents Sea may amplify climatic changes in this region [*Arzel et al.*, 2008; *Bengtsson et al.*, 2004; *Goosse et al.*, 2003; *Guemas and Salas-Melia*, 2008]. Our results present the first evidence from state of the art climate model simulation that this feedback mechanism may cause a complete shutdown of the Barents Sea inflow leading to rapid regional climate changes.

[10] Substantial cooling is simulated during the events of BSI shutdown and increased sea ice cover in the Barents Sea (Figure 4a). The cooling is stronger in winter reaching -2°C over northern Norway. Interestingly, the anomalously cold temperatures are contrasted by a positive temperature anomaly to the east of Greenland (Figure 3a). This can be readily explained by oceanic circulation changes (Figure 2). An intensified Greenland Sea Gyre and a stronger recirculation of warmer Atlantic waters during the BSI shutdown cause a reduction in ice extent in the north–western Greenland Sea (Figure 3a) with higher surface air temperatures (Figure 4a).

[11] The North Atlantic Oscillation (NAO) plays an important role in climate variability in the northern high latitudes [e.g., *Dickson et al.*, 2000]. However, the connection between the NAO and Arctic climate is highly nonstationary [*Goosse and Holland*, 2005; *Semenov*, 2008]. In the analyzed simulation, no apparent link was found between the NAO and BSI shutdown events.

[12] KCM considerably overestimates the extent and underestimates the variability in the sea ice of the Barents Sea relative to the present climate so that its climate is closer to the instability point, where the above described positive feedback yields rapid climate transitions. Historical data of winter Barents Sea ice extent [*Shapiro et al.*, 2003] show a strong sea ice retreat from the middle of 19th century to the end of 20th century. Thus, the proposed mechanism may be more applicable to preindustrial times, for example to the Little Ice Age and rapid climate pulses during the Holocene. The Barents Sea Inflow shutdown leads to a significant redistribution of the Arctic Ocean water mass balance. Particularly important are the halt of the Atlantic water inflow to the Barents Sea and the enhanced Arctic water outflow from the Kara Sea (Figure 2b). Indications of such rapid changes are indeed found in sediment records [*Duplessy et al.*, 2001, 2005; *Lubinski et al.*, 2001]. Thus, the presented mechanism may provide a new perspective for understanding rapid climate changes in the northern high latitudes during the Holocene. The results also demonstrate that rapid climate transitions may be caused by local feedbacks and restricted to confined areas without significant global impacts.

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