Author comments on
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Enhanced Atlantic subpolar gyre variability through baroclinic threshold in a Coarse Resolution Model
by M. Mengel , A. Levermann , C.-F. Schleussner and A. Born

September 9, 2012

Dear Prof. Dr. Keller,
thank you very much for handling the review process of our manuscript. Below we answer the two referee comments published during the open discussion of the manuscript. We thank both referees for their constructive and helpful comments. Please find the referees' comments, quoted in italic, and our corresponding statements below. We attach a new version of the manuscript with changes highlighted in blue, so our updates are fast to identify.

With kind regards,
Matthias Mengel

Referee #1

This paper adds one piece to the important puzzle regarding the variability of the subpolar gyre. The result that the subpolar gyre circulation can be brought to a threshold position, where is becomes highly sensitive to freshwater and wind stress forcing, is very interesting. And if this holds true, it might improve our ability to predict the marine climate and ecosystems in the subpolar Atlantic. The result that it is freshwater forcing over the Nordic Seas that regulates this threshold is both puzzling and interesting. But the paper appears rather unfinished to me. The linkage between the freshwater forcing over the Nordic Seas and the SPG, and the internal feedback loops in the North Atlantic do, unfortunately, not make clear sense to me. Maybe this becomes clearer after the questions below are answered.

In response to the helpful comments of referee # 1, we expanded the discussion of the linkage between freshwater forcing and SPG and decided to completely rework the section on the mechanism of the SPG transition.

Our model results back the linkage between Nordic Seas Inflow of North Atlantic Current (NAC) waters and the freshwater forcing in the Nordic Seas that has been described by *Hansen et al.* (2004). The strength of this inflow couples with the SPG strength through its influence on the recirculation of saline waters in the subpolar basin. See the manuscript and our answers to the specific comments for details.

The reworked section about the mechanism of the SPG transition now discusses a simplified scheme with one feedback loop. It is well backed by literature and our model data. See the manuscript and our answers to the specific comments for details.

Specific comments

The freshwater forcing over the Nordic Seas regulates the threshold SPG variability. It is mentioned that causality go via the overflows, but this is all. The discussed baroclinic changes in the SPG occur within the upper 1000m, while the overflows flow deeper than this. So how can changes in the overflow strength induce the described changes in the SPG? Please describe.

Hansen et al. (2004) argue that thermohaline forcing drives the Atlantic inflow to the Nordic Seas. The inflow balances the deep overflows and depends on the deepwater production rate in the Nordic Seas. Reducing the deep water production through freshwater forcing leads to diminished inflow and more water recirculates in the subpolar basin. This is consistent with the signal of warmer and saltier upper 1000m waters at the southern GSR, that is the predominant early response to freshwater forcing in the Nordic Seas in our model. See lines 114-124 on page 4.

P 264, L 21: *In this paper, it said that the NAC and the subarctic front shift south-eastward and the paper by Bersch is cited. Care should be taken here. Bersch, Hatun et al, 2005 and others show that the NAC actually shifts north in the Newfoundland Basin-Mid-Atlantic ridge area, during periods when the SPG is strong. Please confer with the literature once more, and clarify accordingly*

The description of subarctic front shifts has been unclear, we revised the discussion. See lines 138-142 on page 5:

"The general spatial expansion is in line with observations and model studies (*Bersch et al.*, 2007; *Häkkinen and Rhines*, 2009; *Häkkinen et al.*, 2011a). However, the southward extension (*Hátún et al.*, 2005; *Bersch et al.*, 2007) associated with a south-north aligned SPG during weak state differs from the behaviour in our model. The southward shift of the NAC during strong gyre circulation may thus be model specific."

P 265, L16-19: *I do not understand loop 3. It is said that an increased SPG leads to a longer pathway spiraling around and into the gyre. This shall lead to more heat loss, a cooler gyre center and thus a stronger center-rim temperature difference (stronger baroclinicity). 1) How is the rim defined? One should expect that a long stretch along the rim would also be colder, and the temperature difference between the center and rim would thus be unaltered. Please explain.*

Due to the several good comments on feedback loops we decided to rework the section and reduced the feedback loops to one. It incorporates the dominating processes and is backed up by several other studies. Please note that the rework of this section does not change the central argument of the paper. See lines 155-167 on page 5/6.

We may define the rim by its role of encompassing the center, with the center covering the convective regions at 33.75° W to 26.25° W and 52.5° N to 60° N. Because we only discuss differences between rim and center this is a sufficient definition here.

Loop 1 and 2 rely on a fact that a strong SPG induces increased temperatures and salinities in the NE Atlantic/rim or in the Sub polar Mode Water (SPMW). On decadal time scales, it has been shown that a strong SPG is associated with lower temperature and salinities in the SPMW (due to less influence of the warm and saline eastern waters)(e.g. Hatun et al, 2005). Is there a question of time scales here? Please bring this into your discussion.

Indeed, this is a question of time scales as well as atmospheric coupling. *Lohmann et al.* (2009) have shown that on sub-decadal to decadal time scales a strong positive NAO forcing leads to the cooling of SPMW waters (*Lohmann et al.* (2009), Fig. 7a) through high atmospheric heat loss. The same signal is seen in the NCEP/NCAR driven simulations in *Hátún et al.* (2005). However, the response on longer than decadal scale is dominated by the increased transport of warm NAC waters into the region (*Lohmann et al.* (2009), Fig. 7b), resembling the pattern we show in Fig. 2a of our paper. See lines 126-132 on page 4/5.

The gyre becomes unstable when a freshwater anomaly of 15 mSv is added It is not obviously clear to me how to interpret this What average is this anomaly relative to? How would the authors know what the right 1000-years average is, and thus what importance should be ascribed to the number 15. Is it important that there is threshold off-set or is number 15 important?

The main point here is that a small change in the freshwater balance of the Nordic Seas, well within the range of natural variability or changes that may occur under ongoing changing climate, can bring the SPG to the threshold. The number of 15 mSv flux is model dependent and its exact value of minor importance. The average net surface freshwater flux over the Nordic Seas in our control simulation is 47.4 mSv, comparable to the 54 mSv estimated by *Dickson et al.* (2007). The applied anomalies are similar in magnitude to the estimates given in *Curry and Mauritzen* (2005), Fig. 2 for the second half of the 20th century. Future changes in the Nordic Seas freshwater budget may easily exceed the 15 mSv forcing applied here, as discussed by *Dickson et al.* (2007). Still, we can not rule out that the 1000 year average state of the ocean has deficiencies and the distance to the SPG threshold exceeds the value presented here.
We added lines 114-115 on page 4 and 259-262 on page 8 to clarify this issue.

Referee #2

This is an interesting paper, which explains with simplified model experiments the importance of buoyancy fluxes for explaining the Subpolar Gyre (SPG) variability. In the face of a freshwater threshold, the amplitude of variability is highly increased. It relies on similar mechanisms previously published by the authors (e.g., Levermann and Born, 2007; Born and Leverman, 2010) to explain that the SPG variability in terms of temperature and salinity advection northward. The paper would benefit from some better explanation of the model biases and simulations, internal ocean mechanisms involved in the SPG (c.f., Rossby waves, ice feedback) and comparison with other mechanisms.

In response to the helpful comments of referee #2 we added a description of model biases and a brief discussion on the ocean's adjustment mechanism to the manuscript. We argue that advection dominates the adjustment process in our model because we do not find a response on time scales shorter than 25 years. A short section on further mechanisms of North Atlantic variability has been added to account for the vast range of literature. See also our answers to the specific comments below.

Specific comments

1- Is the location of the water forcing selected because of biases in the water formation and deep convection regions of the model, like in Msadek and Frankingnoul (2009)? Would be good to have a brief description of model biases in the model section.

We choose the forcing region to perturb the model state without directly affecting the subpolar convection. We do not select it to counteract model biases. Relevant model biases are now discussed in the text, see lines 82-88 on page 3:
"The gyre circulation does not extend to the Labrador Sea due to the coarseness of our model. This leads to too fresh surface conditions in this region and too saline conditions at the outflow region of the Labrador Current east and southeast of Newfoundland. The East Greenland Current is fresher and broader than observed. This leads to the eastward shift of the region of subpolar deep convection to the central Irminger basin. The area of deep convection in the Greenland Basin compares well with observations of mixed layer depth (*De Boyer Montégut et al.*, 2004). "

2- The mechanism described here does not include ice melting and atmospheric variability, in which increased temperatures in the subpolar regions could decrease salinity through ice melting of precipitation. For example, some studies suggest that a stronger heat transport would decrease salinity in the northern seas by increasing precipitation (Timmermann et al., 1998). It seems that these mechanisms play a secondary role here, but some explanation is needed in the text.

We added a paragraph to the discussion section to provide a short perspective on mechanisms of North Atlantic variability. A number of studies explore mechanisms of variability that originate from the interaction between atmosphere and ocean. The focus of this paper is, however, on ocean dynamics with the major statement that the baroclinic threshold in the ocean suffices to trigger high variability in the North Atlantic. See lines 235-242 on page 8.

3- A better discussion on the timescales of variability would strengthen the paper. For example, some models show that the relationship between AMOC strengthening and temperature response in the Arctic would take about 3-4 years (Huck et al., 1999; te Raa and Dijkstra,2002), and the delay between the salinity and temperature responses through Rossby wave mechanisms would generate different decadal variabilities, with the longer (40-70 years) linked to salinity anomalies. The time delay between the adjustments has been recognized to be greatly responsible for the multidecadal variability (c.f., Lee and Wang, 2010). In a nutshell, a better description of the baroclinic adjustment mechanisms is needed here.

The aim of this paper is to show the role of the baroclinic threshold in amplifying prescribed signals of variability, we do not focus on internal modes of variability. In chapter 4 we explore the model response to the different time scales of forcing (Fig. 5 and 6). We tested forcings with periods shorter than 25 years and they do not yield the same increase on variability as shown for the 50 to 200 year periods. We thus argue that the signal transport on advective, inter-decadal time scales dominates the dynamics in this study, similar to *Lee and Wang* (2010); *Zhang et al.* (2011).

Still, we can not rule out that the adjustment through planetary waves may influence the dynamics. We expanded the discussion on time scales of variability to take into account this helpful suggestion of the referee. See lines 208-211 and 248-258 in the manuscript.

Technical Corrections, Referee #1

Page 260 Line 11
freshwater forcing of varying, but small amplitudes and multidecadal to centennial periodicities
corrected in manuscript.

Page 260 Line 19
Might consider to used the name Arctic Mediterranean instead of the Nordic Seas, since deep water formation is also formed outside the Nordic Seas.
Deepwater formation also occurs in the Arctic Ocean, but the dominant part of deepwater forms in the Nordic Seas (*Dickson and Brown*, 1994). We leave this unchanged in the text.

Page 260 Line 20
Over the GSR
corrected in manuscript.

Page 260 Line 23
Introduced the AMOC abbreviation here and add a reference
We added the abbreviation and refer to *Rahmstorf* (2002) and *Kuhlbrodt et al.* (2007).

Page 260 Line 26
The strength
corrected in manuscript.

Page 261 Line 1
Add ref to the wind stress var.
We refer to *Hurrell* (1995).

Page 261 Line 2
...Atlantic...
corrected in manuscript.

Page 261 Line 5
Use fewer refs
We drop *Myers et al.* (1996).

Page 261 Line 9
...the variations...
corrected in manuscript.

Page 261 Line 14
The Hakkinen et al. Ref is not the right one when referring to the salinity increase. Better

ones are for example Curry and Mauritzen, 2005 or Hatun et al, 2005. And this salinity increase started in the mid-1995, and not in 2001.
The reference was wrong, corrected it to *Holliday et al.* (2008).

Page 261 Line 16
observations. reduction → decline a SPG circulation strength
Changed 'reduction' to 'decline' at line 15, added 'circulation strength' at line 17.

Page 261 Line 26
time scales
corrected.

Page 262 Line 6
140 yrs
corrected

Page 262 Line 9-13
Improve sentence
Sentence changed to 'The baroclinic response of the SPG to surface wind-stress forcing can depend on the existence of the GSR overflows and lead to two dynamically distinct regimes of the SPG in glacial and interglacial climate (*Montoya et al.*, 2011).'

Page 262 Line 20
the model, the experiments
corrected

Page 262 Line 22
By analyzing the...
We changed this sentence already.

Page 262 Line 23
loops that potentially lead...
added, 'We then outline the feedback mechanism that potentially leads...'

Page 262 Line 26
define distance
changed to "ocean state's distance".

Page 263 Line 13
sinusoidal
corrected.

Page 263 Line 14
forcing of (1) → forcing of surface freshwater

corrected.

Page 263 Line 16
applied within the Nordic Seas (63.75-78.75, 11.25W-10E).
corrected.

Page 263 Line 17
gyre → SPG (there are gyre within the Nordic Seas as well)
We deleted the sentence because of the more detailed discussion on the freshwater forcing and its linkage to SPG dynamics, see major comments.

Page 263 Line 18
Nordic Seas and thus weakening overflow.
We deleted the sentence because of the more detailed discussion on the freshwater forcing and its linkage to SPG dynamics, see major comments.

Page 263 Line 22-27
The description from L12 and forward seems to be reiterated here (although with more detail). What about just using just one (detailed) version of experiment description?
We restructured and merged the description.

Page 263 Line 25
200 yrs. A general comment is to write yrs and not yr when referring to several years.
We substituted 'yrs' by 'years' in the manuscript.

Page 263 Line 26
Spell out NCEP-NCAR
corrected.

Page 264 Line 1
... <u>are</u> continued by <u>their</u> time-reversed...
corrected.

Page 264 Line 3
presently sounds like yesterday. Use other term. Remove 'to be able to'
We use 'of the 1948-2009 variability. We removed 'to be able to'.

Page 265 Line 1
remove together tropical NAC → the warmer NAC waters
corrected.

Page 265 Line 3
refer to Fig. 2g
done.

Page 265 Line 23
late 1990s → mid-1990s
done

Page 265 Line 25
AMOC introduced before
corrected.

Page 265 Line 25-26
weaker... Than what?
We now write '... 6.5% weaker in the strong circulation regime than in the control simulation of our model.'

Page 265 Line 26-28
Unclear sentence
Modified the sentence to 'The AMOC weakening during the increase of SPG transport is consistent with the observational data of (*Zhang*, 2008) and the model results of (*Zhang*, 2008; *Manabe and Stouffer*, 1999).'

Page 266 Line 12
sea surface height obs
corrected.

Page 266 Line 14
25% of what?
We now write '... 10 Sv transport variability or 25% of the long-term average.'

Page 266 Line 16
the previous chapter → chapter 3.
corrected.

Page 266
Line 22 the SPG
corrected.

Page 266
Line 27 The Variability
corrected.

Chapter 4 is generally confusing. Please write this chapter clearer
We think that a restructuring would not make the chapter clearer. We leave it unchanged.

Page 267 Line 25

Add reference
We added *Häkkinen et al.* (2011b).

Page 268 Line 4
similar processes... Please be more specific here
Changed sentence to
'In fact, the abrupt weakening of the SPG during the 1990s has been associated with the decay of the density difference between inner and exteriour gyre through thermohaline forcing (*Häkkinen and Rhines*, 2004).'

Page 268 Line 14-17
... Than what. Please improve sentence
Changed sentence to
'Model studies and observations found a threshold behaviour for the Labrador Sea convection and the SPG circulation (*Legrande et al.*, 2006; *Wu and Wood*, 2008; *Thornalley et al.*, 2009; *Born et al.*, 2011). This indicates the robustness of our results though artifacts due to the low resolution or deficiencies in the density structure cannot be ruled out.'

Fig. 1
Write weak state in red (warm) and strong state in blue (cold). Add Sv and mSv to the axes in the inset as well. Caption: 15 mSv freshwater forcing
Corrected plot and caption.

Fig. 2
Add units to the colorbars, add m to depth axis, add longitude and latitude to geographical axes. Panel h is too crowded and unclear Better emphasis on the gray rectangle
We added units to the colorbars and labeled the axes. We deleted the strong circulation from Panel h to make it less crowded. We changed the rectangle color to green.

Fig. 3
Cooler temperature → lower temperature
corrected. Figure was reworked.

Fig. 4
It took me quite some time to decipher this figure + text. What are the upper two panels and the two panels below? Please refer clearer to the figure.
We made the caption text clearer.

Fig. 5
Add yrs to the figures (e.g. $T = 50$ yrs). Maybe use the same SPG amplitude scale in all panels. This would better show that the wind stress forcing is inferior to the freshwater forcing
We added yrs to the figure, and mention the different scale in the text.

Minor Comments, Referee #2

The word entrainment is generally associated with vertical movements of waters into the upper layers or mixed layer. It makes more sense to use the word horizontal advection or similar for the transport of NAC waters into the SPG.
We do not use 'entrainment' in the updated text, except for the introductory sentence on deepwater formation in its proper sense.

Page 264 Line 22
It would make it easier to understand the equilibrium experiment (1) if the authors described how the strength of the freshwater forcing was varied (varying +-??mSv every ?mSv).
We added the sentence 'We run the model to equilibrium (at least 1000 years of integration) with freshwater forcing in the interval ±200 mSv with steps of 5 mSv and refine the steps near the threshold.' to the reworked description of the experiments.

Page 262 Line 1
NAO is the main "northern hemisphere" mode of wind stress variability.
corrected.

Page 266 Line 7
I would say NAC transports subtropical instead of tropical waters. Subtropical waters are known to have higher salinity through strong E-P fluxes and NAC is northern part of the subtropical gyre.
We do not use 'tropical' in the updated text.

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Enhanced Atlantic subpolar gyre variability through baroclinic threshold in a Coarse Resolution Model

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Abstract. Direct observations, satellite measurements and paleorecords reveal strong variability in the Atlantic subpolar gyre on various time scales. Here we show that variations of comparable amplitude can only be simulated in a coupled climate model in the proximity of a dynamical threshold. The threshold and the associated dynamic response is due to a positive feedback involving increased salt transport in the subpolar gyre and enhanced deep convection in its center. A series of sensitivity experiments is performed with a coarse resolution ocean general circulation model coupled to a statistical-dynamical atmosphere model which in itself does not produce atmospheric variability. To simulate the impact of atmospheric variability, the model system is perturbed with freshwater forcing of varying, but small amplitude and multi-decadal to centennial periodicities and observational variations in wind stress. While both freshwater and wind-stress-forcing have a small direct effect on the strength of the subpolar gyre, the magnitude of the gyre's response is strongly increased in the vicinity of the threshold. Our results indicate that baroclinic self-amplification in the North Atlantic ocean can play an important role in presently observed SPG variability and thereby North Atlantic climate variability on multi-decadal scales.

1 Introduction

Most northern deep water formation occurs in the Nordic Seas in combination with strong overflows over the Greenland-Scotland ridge (GSR) and associated entrainment of surrounding water masses (Hansen et al., 2004). This deep water formation is a crucial part of the Atlantic Meridional Overturning Circulation (AMOC), an important element of the global climate system , Rahmstorf (2002); Kuhlbrodt et al. (2007). Simulations with a high resolution ocean model suggest that the Atlantic inflow into the Nordic Seas is modulated significantly by the strength of the subpolar gyre (SPG) south of the GSR (Hátún et al., 2005). Surface wind stress has strong influence on the strength and variability of the SPG and the gyre strength has been linked to the northern hemisphere main mode of wind stress variability (Hurrell, 1995), the North Atlantic Oscillation (NAO) (Curry et al., 1998; Böning et al., 2006) and the Atlantic Multidecadal Oscillation (AMO) (Häkkinen et al., 2011a,b). However, part of the gyre circulation is controlled by baroclinic adjustments and thereby the density structure in the region (Greatbatch et al., 1991; Penduff et al., 2000; Eden and Willebrand, 2001).

Current diverging trends of NAO and SPG transport suggest that the classical picture of an NAO driven gyre is incomplete. Häkkinen et al. (2011a,b) argue that the frequency of atmospheric blocking and associated SLP anomalies in the eastern North Atlantic more closely resemble the variations in the SPG. A decoupling due to baroclinic effects is discussed by (Hátún et al., 2009; Lohmann et al., 2009b). Direct measurements reveal a strong freshening of the region during the last four decades of the 20th century (Reverdin, 2010; Yashayaev, 2007; Häkkinen and Rhines, 2009; Curry and Mauritzen, 2005; Dickson et al., 2002; Blindheim et al., 2000) with a reversal towards higher salinities in the Eastern North Atlantic after 2001 (Holliday et al., 2008). Satellite observation of sea surface elevation suggest a rapid decline in SPG strength between 1992 and 2003 (Häkkinen and Rhines, 2004).

Observations, higher-resolution models and fully coupled climate models with atmospheric variability exhibit strong variations of the SPG circulation strength. Inter-annual variability can reach up to 25% of the long-term mean and variability on multi-decadal time-scales can be even stronger (Treguier et al., 2005; Hátún et al., 2005; Häkkinen and Rhines, 2009; Böning et al., 2006). However, due to their complexity the dynamical cause of the variability is often difficult to identify in these models.

In order to understand the SPG's past role in climate variability (Born and Levermann, 2010; Thornalley et al., 2009) and to project its future evolution, the gap between simulations on short time scales with high spatial resolution and those on long time scales and lower resolution needs to be overcome. The coarse-resolution climate model CLIMBER-3α, which we apply in this study, exhibits a threshold behaviour of the Atlantic SPG with respect to surface freshwater forcing (Figure 1) that has been related to baroclinic feedbacks in the region (Levermann and Born, 2007; Born and Mignot, 2011). Similar abrupt changes in Labrador Sea convection and the SPG have been observed in a number of models of varying complexity (LeGrande and Schmidt, 2008; Wu and Wood, 2008; Jongma et al., 2007; Weijer, 2002; Born et al., 2011) as well as sea surface temperature and sea ice reconstructions over the last 140 years (Dima and Lohmann, 2011). The SPG dynamics of four comprehensive coupled climate models of the CMIP3 intercomparison project are dominated by the baroclinic feedback mechanism (Born et al., 2012). The cessation of Labrador Sea convection and a subsequent weakening of the SPG is a prominent feature in 21st century global warming simulations with Atmosphere-Ocean General Circulation Models (AOGCMS) (Yin et al., 2010; Landerer et al., 2007).

The appreciation of the SPG's non-linear and feedback driven dynamics has proven useful for the understanding of historic climate events. The baroclinic response of the SPG to surface wind-stress forcing can depend on the existence of the GSR overflows and lead to two dynamically distinct regimes of the SPG in glacial and interglacial climate (Montoya et al., 2011). Paleoclimatic time series in the North Atlantic suggest that a transition of the SPG from a predominantly weak to a strong state has occurred during the so-called 8.2 ka event at the beginning of the present interglacial (Born and Levermann, 2010) when a meltwater outburst from North American proglacial lakes weakened the Atlantic overturning circulation and led to widespread cooling over Europe. Furthermore, the SPG likely delayed the last glaciation over Scandinavia by controlling the Atlantic inflow into the Nordic Seas (Born et al., 2010, 2011).

After a brief description of the model and the experiments, we present the threshold behaviour for the SPG under stationary preindustrial boundary conditions exhibiting two distinct regimes. We then outline the feedback mechanism that potentially leads to the threshold behaviour through self-amplification in our model. We propose that this self-amplification plays a crucial role in multi-decadal gyre variability, as illustrated by the SPG response to time-dependent variations in surface freshwater flux and wind-stress as a function of the ocean state's distance from the threshold.

2 Model and Experiments

The coupled climate model CLIMBER-3α applied in this study comprises interactive atmosphere, sea ice and ocean components (Montoya et al., 2005). The oceanic general circulation model is based on the GFDL MOM-3 code (Pacanowski and Griffies, 1999), with 24 variably spaced vertical levels, a coarse horizontal resolution of $3.75°$, a background vertical diffusivity of $\kappa_h = 0.3 \cdot 10^{-4} m^2 s^{-1}$ and an eddy-induced tracer advection with a thickness diffusion coefficient of $\kappa_{gm} = 250 m^2 s^{-1}$. If not denoted differently wind stress is prescribed to climatology (Trenberth et al., 1989). We apply an improved version of the model used in (Levermann and Born, 2007) that exhibits a more realistic strength of the meridional overturning circulation. The gyre circulation does not extend to the Labrador Sea due to the coarseness of our model. This leads to too fresh surface conditions in this region and too saline conditions at the outflow region of the Labrador Current east and south-east of Newfoundland. The East Greenland Current is fresher and broader than observed. This leads to the eastward shift of the region of subpolar deep convection to the central Irminger basin. The area of deep convection in the Greenland Basin compares well with observations of mixed layer depth (De Boyer Montégut et al., 2004).

The statistical-dynamical atmosphere model (Petoukhov et al., 2000) does not produce internal variability. We explore this shortcoming using three sets of experiments:

(1) equilibrium simulations with constant anomalous surface freshwater forcing. We run the

model to equilibrium (at least 1000 years of integration) with freshwater forcing in the interval ±200 mSv and steps of 5 mSv and refine the steps near the threshold. The freshwater flux is applied within the Nordic Seas (63.75-78.75°N and 11.25°W-10°E).

(2) sinusoidal freshwater forcing in addition to the constant freshwater forcing freshwater of (1). Amplitudes are varied between 5 and 30 mSv (1mSv = 10^3 m^3/s) and periods are 25 to 200 years. The freshwater forcing is applied in the same geographical region as (1).

(3) time-varying surface wind stress reanalysis forcing in addition to (1). We add surface wind stress anomalies from the National Centers for Atmospheric Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996) to the climatology (Trenberth et al., 1989). Wind stress anomalies were computed as the annual mean minus the average over the full period from 1948 to 2009. In order to avoid drifts and discontinuities, the anomalies time series from 1948-2009 are continued by their time-reversed time series. The resulting 122-years-long time series is cyclic and is used as a long-term representation of 1948-2009 variability. In order to let the simulation run into a dynamic equilibrium this forcing is repeated several times.

Note that no freshwater forcing is applied on the convection sites south of the Greenland Scotland Ridge and thereby no direct influence on the SPG is induced. We will show here that the remote forcing, however, induces strong shifts in the SPG dynamics.

3 SPG threshold behaviour and mechanism of transition

In response to a constant surface freshwater forcing we identify a threshold behaviour with two distinct regimes of circulation (Fig. 1). Within the explored forcing interval between ±200 mSv (inlay in Fig. 1) we find a sharp increase of 40% (from 20 Sv to 28 Sv) in SPG volume transport, measured as the maximum absolute value of the horizontal stream function in the gyre region, at 15 mSv anomalous freshwater forcing. This value is well within the range of natural variability (Curry and Mauritzen, 2005) and may easily be exceeded under global warming (Dickson et al., 2007).

We find warmer and saltier upper 1000m waters at the southern GSR as the predominant early response to freshwater forcing in the Nordic Seas in our model. In contrast, the deep overflow density shows little changes. Hansen et al. (2004) argue that thermohaline forcing drives the Atlantic inflow to the Nordic Seas. The inflow balances the deep overflows and depends on the deepwater production rate in the Nordic Seas. Reducing the deep water production through freshwater forcing leads to diminished inflow and more water recirculates in the subpolar basin. This is consistent with the signal of warmer and saltier waters at the southern GSR. We thus argue that the forcing signal does not trigger subpolar changes through the overflows but through its influence on the Atlantic inflow.

The strong circulation regime is characterized by a cooler SPG center and a warmer northern rim

(Figure 2a and b). Lohmann et al. (2009a) have shown that on inter-annual to decadal time scales a strong positive NAO forcing leads to a stronger SPG and the cooling of subpolar mode waters (their Fig. 7a) through high atmospheric heat loss. The same signal is seen in the NCEP-NCAR driven simulations in Hatun et al. (2005). This does not contradict our results because the response on longer than decadal scale is dominated by the increased transport of warm NAC waters into the subpolar mode water region (Lohmann et al. (2009a), Fig. 7b), resembling the pattern we show in Fig. 2a.

Surface salinities are higher along the path of waters advected from the North Atlantic Current (NAC) at the northern part of the gyre (Figure 2c and d) with positive anomalies extending into the SPG center. The density increase over the whole upper 1000m in the center (Figure 2e and f) is, however, dominated by lower temperatures (compare to Fig. 2a and b).

The cooling, freshening and density increase at the southern part of the SPG reflects the southeastward shift of the NAC due to the intensification and associated spatial expansion of the SPG (Fig. 2h). This expansion is in line with observations and model studies (Bersch et al., 2007; Häkkinen and Rhines, 2009; Häkkinen et al., 2011a). However, the southward extension (Hátún et al., 2005; Bersch et al., 2007) associated with a south-north aligned SPG during weak state differs from the behaviour in our model. The southward shift of the NAC during strong gyre circulation may thus be model specific. A prominent feature of the strong circulation is a southward expansion of the winter convection at the SPG center (Fig. 2, gray rectangles). The heat flux to the atmosphere increases over the northern SPG region (Figure 2g) and ensures that the additional heat that is advected with the warmer NAC waters is released to the atmosphere in such a way that there is a net cooling in the center of the SPG. The strong negative heat flux anomaly at the southern SPG rim (Fig. 2g) is due to a southward shift of the NAC.

The intensification of the transport is in geostrophic balance with the density changes in the gyre. Consequently, the stronger gyre is associated with an enhanced density difference between its denser center and the relatively light outer rim of the gyre. This finding has been discussed in detail by Levermann and Born (2007). Since we find a threshold behaviour in equilibrium simulations, the nonlinear transition between the weak and the strong gyre state has to be linked to positive feedbacks within the system.

Feedback mechanisms that drive SPG dynamics through the density difference between center and rim have been identified in earlier studies. Levermann and Born (2007) state that enhanced salinity import from the tropics to the gyre center when gyre circulation is strong drives further densification of the center. This is consistent with Hátún et al. (2005) who find increased salt-inflow in the Nordic Seas for periods of a weak SPG in a high-resolution model. The anomalous advection of salt and subsequent stronger convection in the Irminger basin has been identified as a possible source of multi-decadal AMOC fluctuations (Msadek and Frankignoul, 2009). Born et al. (2012) identified four CMIP3 AOGCMs where this salinity-advection feedback drives SPG dynamics through enhanced convection.

Consistent with these studies, in our model a stronger SPG imports more saline waters from the NAC that are transported to the SPG center (Fig. 2 c,d). That enables stronger winter convection and leads to a colder SPG center (Fig 2a,b). The increased density contrasts between center and exterior gyre causes a stronger gyre circulation that captures more saline waters.

Even though our coarse resolution model fails to represent North Atlantic ocean-atmosphere dynamics in their full complexity, the mechanism reported here is consistent with the relation between the cessation of subpolar deep convection in the mid-1990s and a slowing down and westward contraction (Bersch et al., 2007; Häkkinen and Rhines, 2004, 2009; Häkkinen et al., 2011a) of the SPG which is speculated to be induced by internal dynamics (Lohmann et al., 2009b).

We diagnose the AMOC to be 6.5% weaker in the strong circulation regime than in the control simulation of our model. The AMOC weakening during the increase of SPG transport is consistent with the observational data and model results (Zhang, 2008; Manabe and Stouffer, 1999), also on high resolution eddy-permiting scale (Zhang et al., 2011).

4 Role of Threshold for SPG Variability

In order to investigate the role of the threshold behaviour for SPG variability we introduced temporal variations in surface freshwater and wind stress forcing (Fig. 4). In the standard simulation, i.e. without a constant off-set in freshwater forcing and thereby far away from the threshold, the application of the observed wind stress anomalies results in relatively weak SPG variability of less than 2 Sv. Similarly low variability is obtained for sinusoidal surface freshwater flux variations with 20 mSv amplitude and a period of 100 years.

The SPG response drastically increases when the system is brought closer to the threshold by application of a constant freshwater flux off-set. In this case both forcings induce a high SPG variability of 10 Sv for wind-stress and 15 Sv for sinusiodal freshwater forcing, respectively. Similar values were obtained from satellite sea surface height observations (Häkkinen and Rhines, 2004, 2009) and model results (Böning et al., 2006) yielding 10 Sv transport variability or 25% of the long-term average.

Spatial patterns of variability for temperature, salinity and density mimic the anomaly patterns we discussed in chapter 3. Thus, the increase of variability originates from the feedback driven dynamical regime in our model. The high correlation of center temperature, center density and SPG strength in Fig. 4 supports this finding. Salinity plays an important role in modulating convection but does not drive density changes directly, it is anticorrelated with density in the upper 1000m average.

The robustness of the variability increase is detailed in Fig. 5 where the SPG mean and standard deviation are plotted over the respective freshwater flux off-set. Different colors correspond to different forcing amplitudes of the sinusoidal freshwater flux. The qualitative behaviour is best seen for a forcing amplitude of 100 years: SPG variability shows an abrupt increase at an off-set similar to the threshold for constant freshwater forcing of 15 mSv. The variability decreases when we move away from the threshold towards higher offsets. The increase of mean and variability are not tightly linked. Variability is high for runs near the threshold because the SPG meanders between the two equilibrium states. Mean strength monotonically increases with higher offsets, analogous to the equilibrium simulations. This particular feature illustrates the dynamic core of the variability. Though the transition of the time-dependent behaviour reflects the equilibrium threshold of Fig. 1, it is not equivalent to the equilibrium response but reflects a dynamical behaviour as expressed in the variance. The dynamical transition occurs over a large interval of forcing amplitudes and is largely independent of this forcing amplitude.

The model's response to external forcing increases with the period of the freshwater forcing from 8Sv (50 years period) to more than 23Sv (200 years period) forcing (Fig. 5 and Fig. 6). Forcings with periods shorter than 25 years do not yield the same variability increase. We thus argue that the signal transport on advective, inter-decadal time scales dominates the dynamics in this study.

For reanalysis surface wind stress forcing (Fig. 5, lower panels) we observe a similar behaviour. SPG variability is relatively constant at a low level as long as the SPG is too far from the threshold. At the threshold of 15 mSv of constant freshwater off-set the amplitude of the time-varying response increases and stays strong beyond the threshold.

The SPG variability induces an atmospheric response pattern that resembles the large scale air pressure pattern of a positive NAO phase (Figure 7). We thus speculate that the mechanism of oceanic variability identified in this study may reverberate in the large scale atmospheric variability patterns of the Northern Hemisphere. A similar footprint has been detected in atmosphere general circulation model simulations forced with observed sea surface temperature anomalies (Rodwell et al., 1999) and experiments with a fully coupled AOGCM (Yoshimori et al., 2010).

5 Conclusion and Discussion

Here we present simulations with a coarse-resolution climate model to better understand the mechanisms of SPG variability. In equilibrium, the SPG exhibits a threshold behaviour with respect to surface freshwater flux which results from a positive baroclinic feedback within the subpolar region. It is important to note that the freshwater is not applied on the SPG but north of the Greenland Scotland Ridge. The SPG response is thereby induced by circulation changes through the baroclinic feedback. This non-linear behaviour enhances SPG variability drastically for variations in surface freshwater forcing with a magnitude comparable to observed changes in precipitation in the region.

Wind-stress forcing from reanalysis data only produces gyre transport variability similar to observations if the system is brought close to the threshold. The observed high variability of SPG transport (Häkkinen et al., 2011b) may thus indicate a near-threshold gyre circulation. A near-threshold gyre circulation might collapse into a permanent weak SPG circulation as found in model simulations under global warming scenarios (Yin et al., 2009).

The presented mechanism of variability provides an alternative approach to these derived from fully coupled simulations to explain North Atlantic multidecadal variability. See Grossmann and Klotzbach (2009) for a review. The export of sea ice to the subpolar North Atlantic has been found to induce AMOC variability through its influence on subpolar convection, see for example Holland et al. (2001). Oka et al. (2012) suggest a thermal threshold originating from the interplay of Nordic Seas sea ice cover, convection and the AMOC strength. Timmermann et al. (1998) identified a delayed negative feedback between North Atlantic surface water temperatures, the North Atlantic Oscillation and convection to foster variability through a coupled air-sea mode.

While it is clear that our results are not directly applicable to presently observed variability on interannual time scales, they suggest a potential role of the associated baroclinic feedback on multidecadal time scales. In fact, the abrupt weakening of the SPG during the 1990s has been associated with the decay of the density difference between inner and exteriour gyre through thermohaline forcing (Häkkinen and Rhines, 2004).

In our simulations the SPG does not respond to forcing shorter than 25 years, pronounced variability is found for periods of 50 years and longer. The signal transport on advective, inter-decadal time scales thus dominates. Time delayed advective adjustment has been proposed to drive NA variability (Lee and Wang, 2010) and Zhang et al. (2011) showed that the baroclinic adjustment on advective time scales can dominate also in high resolution eddy-permitting models. The increasing amplitude with the length of the forcing period further supports the dominance of long adjustment time scales. A general problem of coarse resolution models is the dilution of temperature and salinity signals due to the large grid boxes. We thus hypothesize that the time scales in our model might be larger than they would be at higher resolution where the adjustment through planetary waves may come into play. In that case strong variability of shorter period than 50 years might be possible and mechanisms of variability on sub-decadal scale may come into play (Lee and Wang, 2010).

The average net surface freshwater flux over the Nordic Seas in our control simulation is 47.4 mSv, comparing well to the 54 mSv estimated by Dickson et al. (2007). Still, we can not rule out that the 1000 year average state of the ocean has deficiencies and the distance to the SPG threshold exceeds the value presented here.

Model studies and observations found a threshold behaviour for the subpolar convection and the SPG circulation (Legrande et al., 2006; Wu and Wood, 2008; Thornalley et al., 2009; Born et al., 2011). This indicates the robustness of our results though artefacts due to the low resolution or deficiencies in the density structure cannot be ruled out. Analyses of higher resolution models with and without atmospheric variability are necessary to confirm our results.

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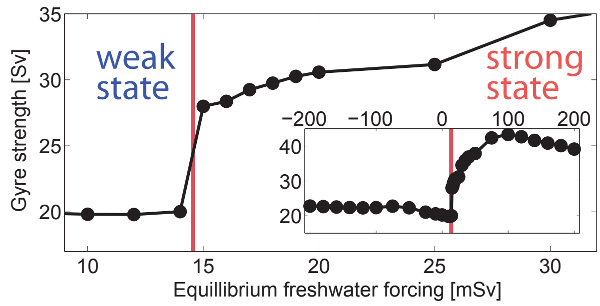

Fig. 1. Equilibrium threshold behaviour of Atlantic SPG volume transport in response to constant surface freshwater flux. The SPG exhibits a threshold behaviour at 15 mSv freshwater forcing strength where it intensifies by more than 40%. The inlay shows its response in the entire forcing interval of ±200 mSv.

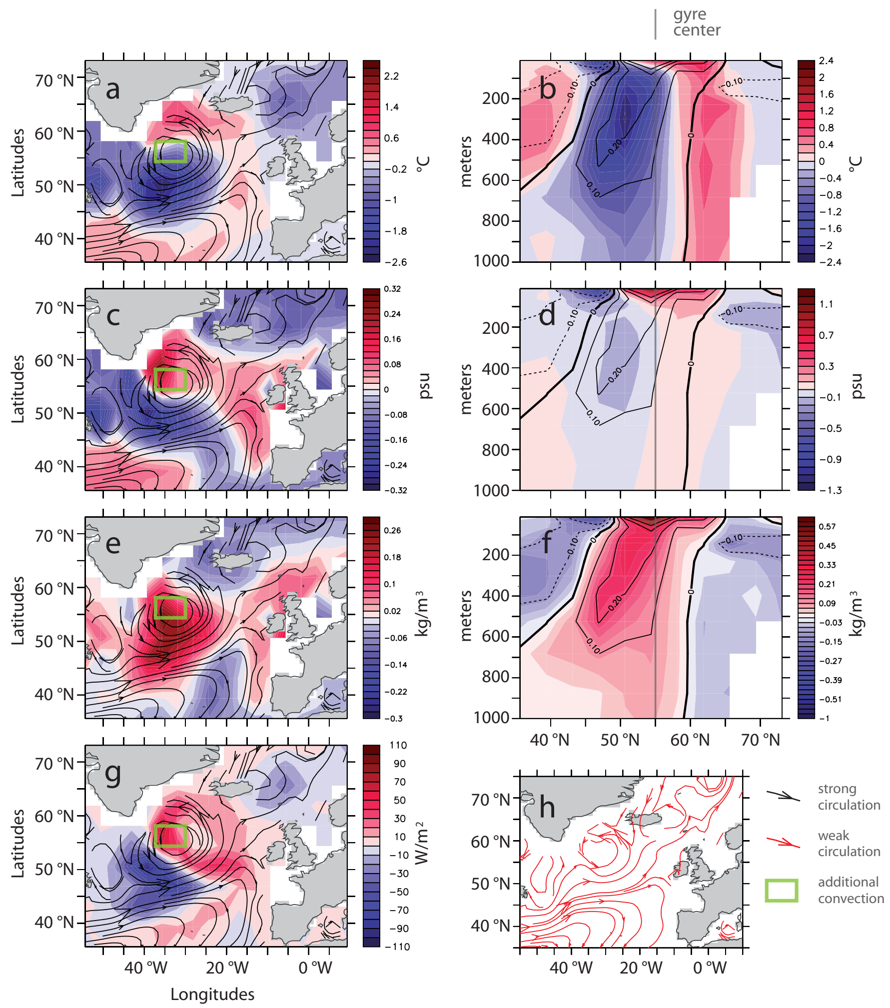

Fig. 2. Difference between the strong (15mSv forcing) and weak (control) SPG circulation. Panels (a,b) show temperature, (c,d) salinity, (e,f) density and (g) heatflux. Panels (a,c,e) show averages over the upper 1000m, black flowlines in panels (a,c,e,g) show upper 1000m strong state velocities. Panel (h) shows weak upper 1000m velocities as flowlines in red. Panels (b,d,f) show zonal averages between 37.5° and 18.75°W with density anomalies as contours and the approximate gyre center as a grey line.

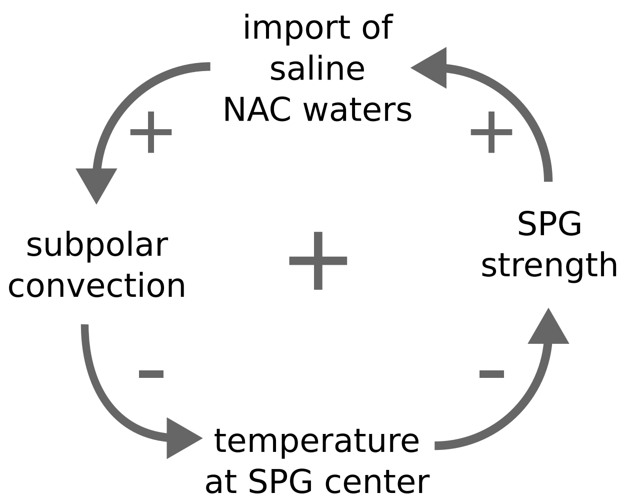

Fig. 3. The feedback loop that leads to the self-amplification of the SPG transport as described in the text. The stronger SPG imports more warm and saline water from the North Atlantic Current, this increasing the surface salinity in the subpolar region, which fosters winter convection and thereby leads to lower temperatures at the SPG center. This increasing the center-rim density contrast and thus geostrophic SPG transport.

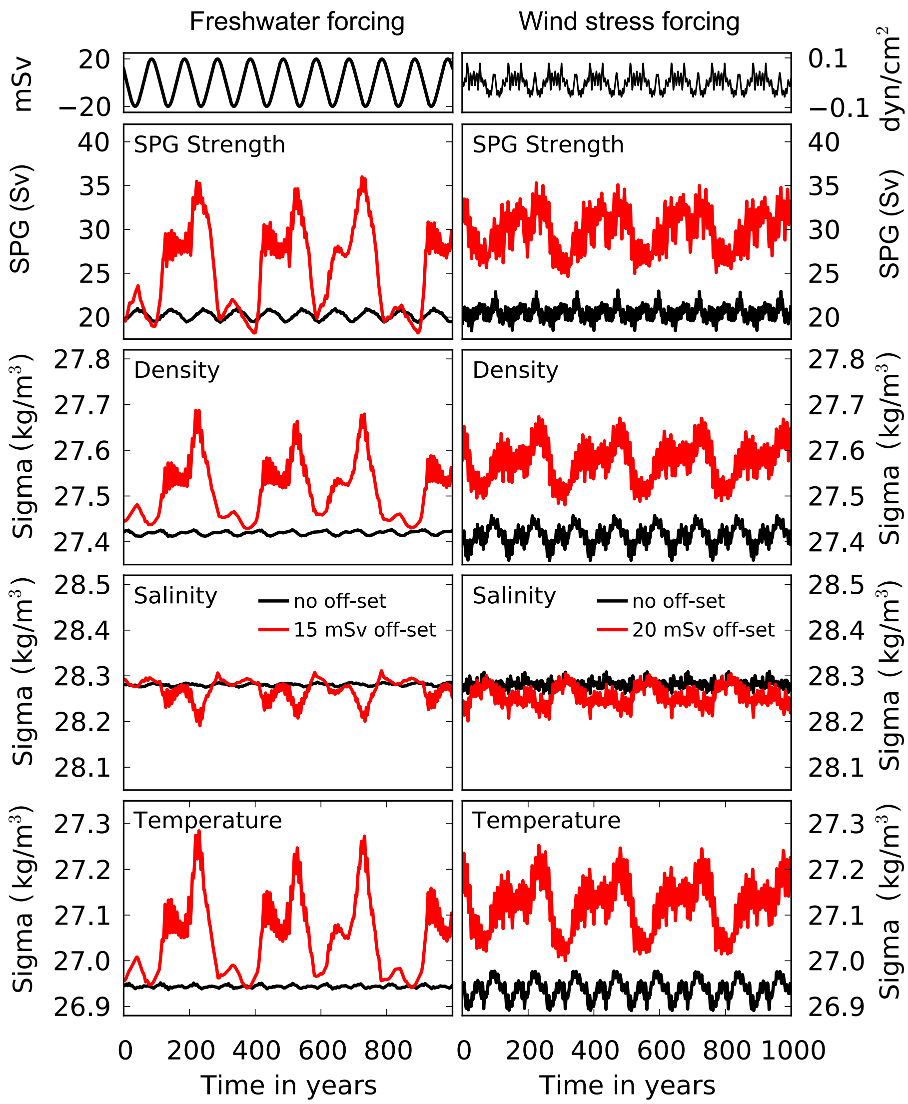

Fig. 4. Time series of SPG strength showing enhanced variability near the dynamical threshold due to the baroclinic feedback. Left panels show the response to sinusoidal freshwater forcing with 20 mSv amplitude and a period of 100 years, right panels to NCEP-NCAR surface wind stress anomaly. Red curves are with constant freshwater off-set of 20 mSv and black curves are without off-set. Narrow upper two panels show the time-varying forcing. The large panels show from top to bottom SPG strength, density variations, density variations due to salinity alone and density variations due to temperature alone. Averages are taken between 37.5°W-18.75°W and 45°N-60°N in the upper 1000 m. In both the cases of freshwater and wind forcing the SPG variability is significantly weaker than observed when the system is far from the threshold (black curves). In the vicinity of the dynamical threshold of Fig. 1, the SPG variability is drastically increased. The main density signal is produced by temperature variations. Major salinity changes are restricted to the surface layers, but play a key role in the process of self-amplification (see Figure 3).

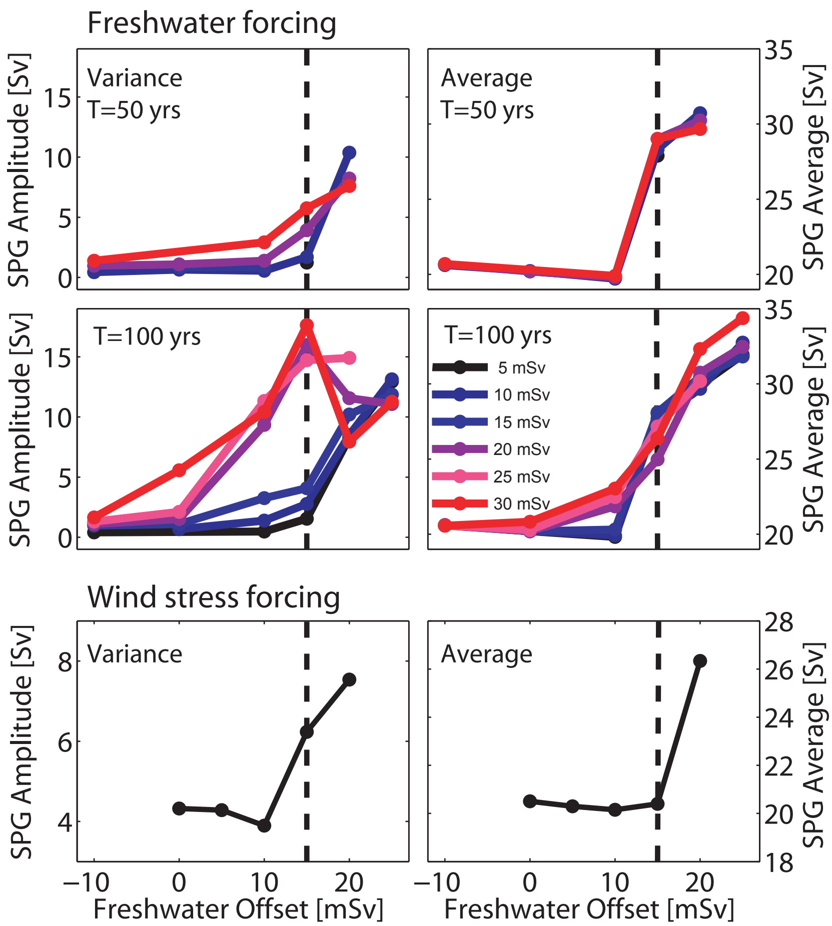

Fig. 5. Upper and middle panels: Mean SPG strength and its variability for different constant off-set in surface freshwater flux. Different lines correspond to the forcing amplitudes as denoted in the legend. Lower panels: Wind induced variability of the SPG for different constant freshwater off-sets. The dashed vertical line marks the position of the equilibrium threshold at 15mSv (compare to Fig. 1). The amplitude of SPG variations increases when approaching the threshold for both time-varying freshwater and wind stress forcing. This is best seen for the 100 year period freshwater forcing, but still present on the shorter time scales (50 year period and wind stress forcing). Even close to the threshold the system's response to NCEP wind stress variability is significantly smaller than its response to centennial scale freshwater variations. The lower panels have a different y-scale.

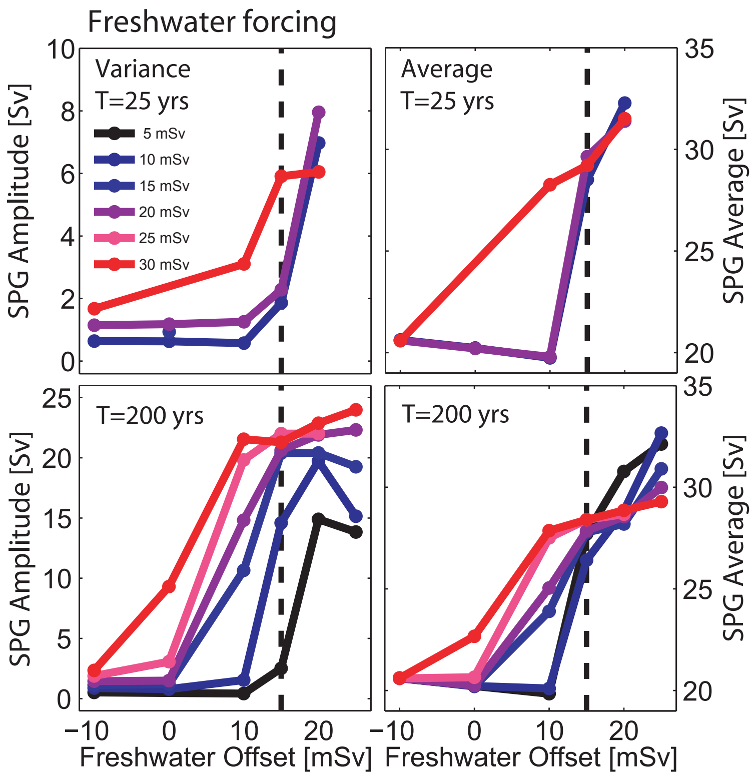

Fig. 6. Mean SPG strength and its variability for varying perturbation amplitude corresponding to figure 5, but for periods of 25 and 200 years. Different lines correspond to different forcing amplitudes as denoted in the legend.

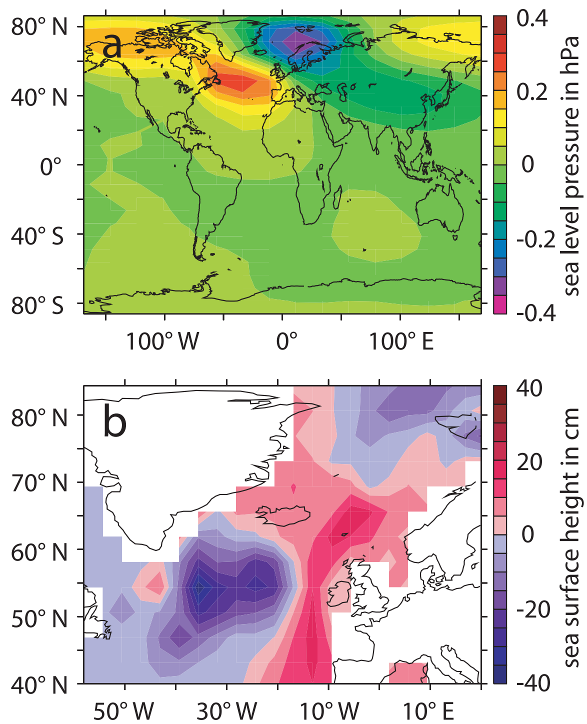

Fig. 7. Sea level pressure (a) and sea surface height (b) difference of strong minus weak SPG state with 100 year period sinusoidal freshwater forcing of 20 mSv amplitude.