Dear Editor,

Please find below in this cover letter a summary of our responses to the two anonymous referees' comments and one interactive comment by M. Pelto, for the paper entitled "Increased glacier runoff enhances the penetration of warm Atlantic water into a large Greenland fjord" by A. J. Sole et al. submitted to The Cryosphere Discussions. A detailed response to all of the referees' comments is appended after the cover letter. We would like to thank the reviewers and M. Pelto for their constructive and detailed comments, which have led to many improvements to the manuscript. We believe we have addressed all the major comments from both reviewers, as well as the many minor and technical corrections, and hope that you will now find the manuscript suitable for publication in The Cryosphere.

M. Pelto writes in his interactive comment that we "reach a critical conclusion that supports the ongoing evolution and quantification of the role and interaction of warm ocean water penetrating at depth to reach marine outlet glacier termini, and glacier runoff". He believes we present "another step in quantification of the glacier runoff reinforcing AW [Atlantic Water] circulation to the glacier front process that deserves our attention". Reviewer 1 states that our work is "a well-written manuscript describing an interesting and important natural phenomenon" but that the context is "too limited" (Reviewer 1, General Comments). Reviewer 2 finds "the different circulation regimes forced by the tides, the local winds and the glacier runoff" interesting but they too suggest that we "neglect the most likely driver of change in fjords such as KF [Kangerdlugssuaq Fjord]- which are fjord/shelf gradients in density and thickness" (Reviewer 2, General Comments). However, in agreement with M. Pelto, we suggest that the basis for these assessments (observations at Sermilik Fjord (SF) by Straneo et al., 2010) "is now an outdated result" (M. Pelto, Interactive Comment). We have collated more recent and substantial evidence (e.g. Straneo et al., 2011; Sutherland and Straneo, 2012) which counters the assertions of Reviewer 1 that Kangerdlugssuaq Fjord is likely to be "flushed so rapidly by external forcing that the water properties in the fjord always essentially match shelf properties" and that it is therefore "hardly possible for subglacial discharge to enhance the penetration of shelf waters" (Reviewer 1, General Comments). We have also described several key differences between SF and KF (e.g. fjord mouth bathymetry and width) which suggest that wind-driven exchange with the shelf is less likely to dominate at the latter than the former.

Nevertheless, in order to fully address these concerns, we have, as suggested by Reviewer 1, conducted several new modelling experiments which incorporate the potential effects of wind-driven intermediary circulation as observed at SF (Straneo et al., 2010). We find that while this prescribed forcing does have a significant impact on water flow and heat transport in KF, the process is not required to bring in warm Atlantic Water (AW) from the fjord mouth over a single year. Moreover, the addition of glacier runoff to the experiment with wind-driven intermediary circulation further enhances along fjord heat transport, supporting our finding that rising ice sheet runoff increases the sensitivity of KG and other Greenland marine terminating glaciers to ocean warming. We have added a new section (Section 4.4 'Wind event-driven intermediary circulation') to the manuscript which describes the design and discusses the results of these new experiments.

As a result of the comments from both reviewers, we have removed from the manuscript the section in which we had estimated ice melt rates from heat transport. However, the main conclusions of the paper – that glacier runoff alone is sufficient to draw in warm AW from the coast, and that rising ice sheet runoff increases the sensitivity of KG and other Greenland marine terminating glaciers to ocean warming – are entirely independent from the ice melt estimates and still stand.

We have also clarified our conclusions to allay the suggestion by Referee 2 that the paper "makes unsubstantiated claims that glacier runoff is the dominant control on transport of water within the fjord" (Reviewer 2, comment 2). While our findings do highlight the potential importance of glacier runoff for impacting fjord water circulation, we certainly do not believe that it is the only forcing that matters. Clearly at SF, and to a lesser extent at KF, wind-driven intermediary circulation is also a key control on water flow. These two forcings act (and thus influence water flow) on different timescales; glacier runoff over several months during a melt-season and individual wind events over several days (Sutherland and Straneo, 2012) and their influence also varies for different parts of the fjord. We suggest that while external forcings, such as synoptic pressure gradients (Christoffersen et al., 2011) and wind-driven intermediary circulation (Straneo et al., 2010), dictate which water masses are present at the mouth and within KF, heat transport along the inner part of the fjord towards the glacier terminus is most sensitive to variations in glacier runoff.

Below, we have provided a detailed response to the Reviewers' comments including those of M. Pelto. The Reviewers' comments are in italics with our response immediately beneath each in bold.

Kind regards.

Andrew Sole (on behalf of all authors.)

Interactive comment on "Increased glacier runoff enhances the penetration of warm Atlantic water into a large Greenland fjord" by A. J. Sole et al.

Anonymous Referee #1

Received and published: 16 December 2012

General Comments

This is a well-written manuscript describing an interesting and important natural phenomenon: the transfer of heat through Kangerdlugssuaq Fjord (KF) towards the Kangerdlugssuaq Glacier (KG) at the head of the fjord. The paper takes as its starting point earlier published temperature, salinity, and velocity data for the fjord waters in 1993 and 2004. The Bergen Ocean Model (BOM) is configured to simulate KF in order to understand the controls on the heat transfer up the fjord as the conditions at the mouth changed from cold (1993) to warm (2004). After spinning up the model with 1993 water properties, various experiments are carried out which purport to show that ocean warming at the mouth of the fjord has a more significant influence on melting at the terminus of KG when there is substantial melt-water runoff entering the fjord from under the glacier. I think the paper adequately reports its model results and does a good job putting the importance of the question of fjord dynamics in context by citing relevant references.

The work is successful in showing, in a certain context, that subglacial runoff enhances heat transfer and therefore increases the sensitivity of the glacier to ocean warming beyond the mouth of the fjord. However, I think it is a much too limited context in which this conclusion is meaningful. It was shown in (Straneo 2010, Nature Geosci.) that vigorous wind-driven baroclinic currents flush Sermilik Fjord in a matter of days. As a result of this externally forced 'intermediary circulation', Straneo concludes that water properties in Sermilik Fjord track sub-seasonal changes of water properties on the shelf. If KF, which like Sermilik lacks a shallow sill, is flushed so rapidly by external forcing that the water properties in the fjord always essentially match shelf properties (with a lag of no more than a few weeks) then it is hardly possible for subglacial discharge to enhance the penetration of shelf waters. The paper under review does not adequately simulate the effect of external forcing on ocean circulation in KF and is therefore unable to demonstrate that subglacial runoff has a significant effect on water properties in KF beyond the massive effect that external forcing already likely has on fjord properties.

We disagree with this assessment of the context of our work for two reasons. Firstly, wind-driven intermediary circulation is no longer considered to be the principal seasonal control on water circulation in SF close to the fjord head (e.g. Sutherland and Straneo, 2012). Secondly, there are several key differences between Sermilik Fjord (SF) and KF which could explain why wind-driven exchange with the shelf is less likely to dominate at the latter than the former.

Although Straneo et al. (2010) did show the importance of baroclinic intermediary flows caused by along shore winds which 'pile up' (Straneo et al., 2010, pg. 2) water against the fjord mouth at SF, the data on which this conclusion was based, extended to within only 50 km of the terminus of Helheim Glacier (HG) and the top 300 m of the fjord (Straneo et al., 2011). As such, their results only provided evidence that intermediary circulation was important in the outer part of the fjord, and not that this type of circulation either caused warm water to come into contact with Helheim Glacier or represented the longer-term average circulation in the fjord. As noted by Mauri Pelto in his interactive comment on our submission, more recent work (for example Straneo et al., 2011; Straneo et al., 2012, Sutherland and Straneo, 2012) indicates that intermediary circulation, although important, is not the dominant control on heat transport in Greenland fjords. Sutherland and Straneo (2012, pg. 55) state, 'it appears that the circulation in Sermilik Fjord, though heavily modulated by synoptic variability, does have an estuarine-like structure when one accounts for the dominant mode of variability. The presence of stratification and deep subglacial discharge complicate the estuarine flow, however, creating multiple residual circulation cells.' This characterisation of circulation agrees qualitatively with our model results for KF. See for example Figure 2d from Sutherland and Straneo (2012) which clearly shows a 'multiple cell residual circulation' (Sutherland and straneo, 2012, pg. 55) very similar to our Figure 5f (albeit in 1D rather than 2D).

We have added the flowing to the Introduction to clarify current knowledge about circulation in SF: 'Preliminary data from Sermilik Fjord in 2008 suggested that an along-shore wind-driven intermediary circulation dominated fjord-shelf exchange (Straneo et al., 2010). However, the data presented in Straneo et al. (2010) extended to within only 50 km of the Sermilik Fjord head and were limited to the top 300 m of the fjord (Straneo et al., 2011) so could not confirm that the intermediary circulation controlled water flow either close to Helheim Glacier or at the depth of the glacier's grounding line (thought to be approximately 600 m). Several more years of observations from SF have now revealed that water flow close to HG is controlled by a multilayer circulation pattern affected by seasonal runoff from the glacier (albeit heavily modulated by synoptic variability) with freshwater glacier outflow both at the surface and at the stratification maximum (Straneo et al., 2011; Sutherland and Straneo, 2012).'

KF is much wider at its mouth (16 km) so is likely to be in geostrophic balance whereas SF is narrower (9 km) and therefore rather more likely to respond strongly to winds (see response to Referee 1 Comment 1). Secondly, KF has a clear cross shelf trough and a single deep entrance rather than a complex entrance like SF (Schjøth et al., 2012).

It may be that subglacial runoff does significantly enhance melting at the glacier terminus (as argued in Jenkins 2011, JPO) but this has to do with the enhancement of heat transfer over the last few meters of ocean next to the ice. This is a rather different question from the question of how ocean heat is transported into the fjord in the first place.

I would strongly recommend that model experiments be carried out to investigate whether subglacial runoff has a significant effect on heat transport into the fjord beyond that which would be accomplished by externally forced intermediary flows. For instance, it would be straight-forward to apply a boundary condition at the fjord mouth where the pycnocline is artificially oscillated up and down with an appropriate amplitude and period to simulate the effect of wind events. The paper's main conclusion is not adequately supported unless an experiment of this nature is carried out that *could potentially rule-out the dominance of the externally-forced fjord flushing mechanism presented in (Straneo 2010).*

The main conclusion of our paper concerned the magnitude of circulation that could be driven by glacier run-off; i.e. that it alone was sufficient to propagate Atlantic Water (AW) from the fjord mouth to KG over a year. The argument here is whether at KF glacier runoff forcing is secondary to the wind-driven intermediary circulation observed at SF by Straneo et al. (2010).

We acknowledge that in order to assess this we should include some experiments that represent the effects of coastal wind events (Straneo et al., 2010). This we have done by simulating synchronous multi day increases in sea surface height (by 0.4 m - Straneo et al., 2010 Supplementary Material) and concurrent depressions in the halocline at the fjord mouth. The outputs from these experiments show that while this forcing does have a significant impact on water flow and heat transport in KF, it is not required to bring in warm Atlantic Water (AW) from the fjord mouth over a single year. Moreover, the addition of glacier runoff to the experiment with wind-driven intermediary circulation further enhances along fjord heat transport, supporting our finding that rising ice sheet runoff increases the sensitivity of KG and other Greenland marine terminating glaciers to ocean warming. We have added a new section (Section 4.4 'Wind event-driven intermediary circulation', included below) to the manuscript which describes the design and discusses the results of these experiments.

4.4 Wind event-driven intermediary circulation

Straneo et al. (2010) found that coastal wind-driven intermediary circulation can govern exchange of fjord and shelf waters in the top 300 m of the outer 50 km of Sermilik Fjord (SF). Wind events, which increased sea surface height and depressed the halocline at the fjord mouth, established a pressure gradient between the fjord and the shelf which drove an inflow in the upper layer and an outflow at depth (Straneo et al., 2010). To investigate the importance of this type of exchange at KF we conducted several experiments to simulate coastal wind events for which we prescribed cyclical increases in sea surface height (by 0.4 m Straneo et al. (2010) Supplementary Methods) accompanied by freshening in the top 500 m in the FRSZ to represent observed halocline depression (Figure 8).Wind events occurred every 20 days and consisted of: a two day 'build up' (during which sea surface height and salinity linearly increased and decreased respectively to their wind event values); the wind event itself which lasted a further two days and; a two day 'wind down' (during which sea surface height and salinity linearly relaxed to their normal values). When only intermediary forcing was (IF) included (i.e. no tides, surface winds or glacier runoff CF1-TF0-WF0-RF0-IF1), the simple intermediary circulation envisaged by Straneo et al. (2010) resulted during the build up and wind down of a wind event (Figure 9). However, velocities were significantly lower than those observed in SF by Straneo et al. (2010) with the result that individual wind events were not of sufficient duration to enable AW and PSWw to reach the fjord head. In the absence of any other forcing, successive wind events did (after 300 days) result in AW reaching KG at the fjord head (c.f. experiment CF1-TF1-WF1-RF1 where AW reaches KG on day 230). The low velocities may be due to limitations in the model (for example caused by viscosity parameterisations), but the same limitations also apply to the circulation established by glacier runoff suggesting that the relative effects of each forcing are correctly represented.

We conducted one experiment which incorporated intermediary forcing along with all other forcings apart from glacier runoff (CF1-TF1-WF1-RF0-IF1), and a further experiment which also included glacier runoff (CF1-TF1-WF1-RF1-IF1). The effect on net heat transport through section 2 can be see in Figure 7a. The inclusion of wind events and the resulting intermediary circulation enhances mean annual (summer) along fjord heat transport by 19.7 (17.5) % for CF1-

TF1-WF1-RF0-IF1 and 17.3 (1.5) % for CF1-TF1-WF1-RF1-IF1. Intermediary forcing leads to a rise in heat transport because wind events in the early part of the year, prior to glacier runoff, hasten the along fjord advance of AW and PSWw, while wind events after the cessation of runoff favour the retention of AW and PSWw further along the fjord. Closer to the fjord mouth (Figure 7b-d), the impact of intermediary circulation increases. At section 2a (15 km from KG) the addition of intermediary forcing enhances heat transport by 22.9 %, at section 2b (43 km from KG) by 37.8 %, and at section 3 (58 km from KG) by 36.9 %. At sections 2a and 2b these changes are greater than those caused by a doubling of glacier runoff.

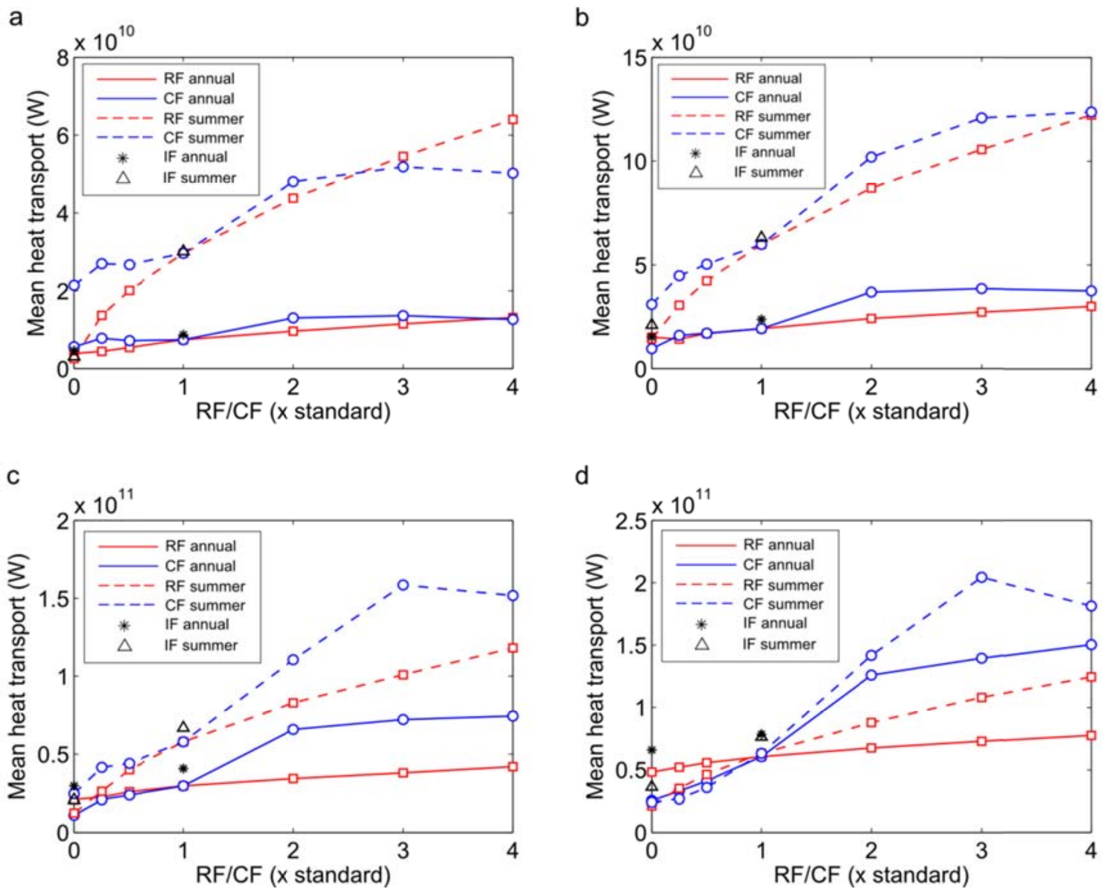

Fig. 7. The effect of varying RF and CF on mean annual and summer along-fjord heat transport (Q) from 0-500 m depth through: (a) section 2 (5 km from KG); (b) section 2a (15 km from KG); (c) section 2b (43 km from KG) and; (d) section 3 (58 km from KG)(see Figure 2 for locations).

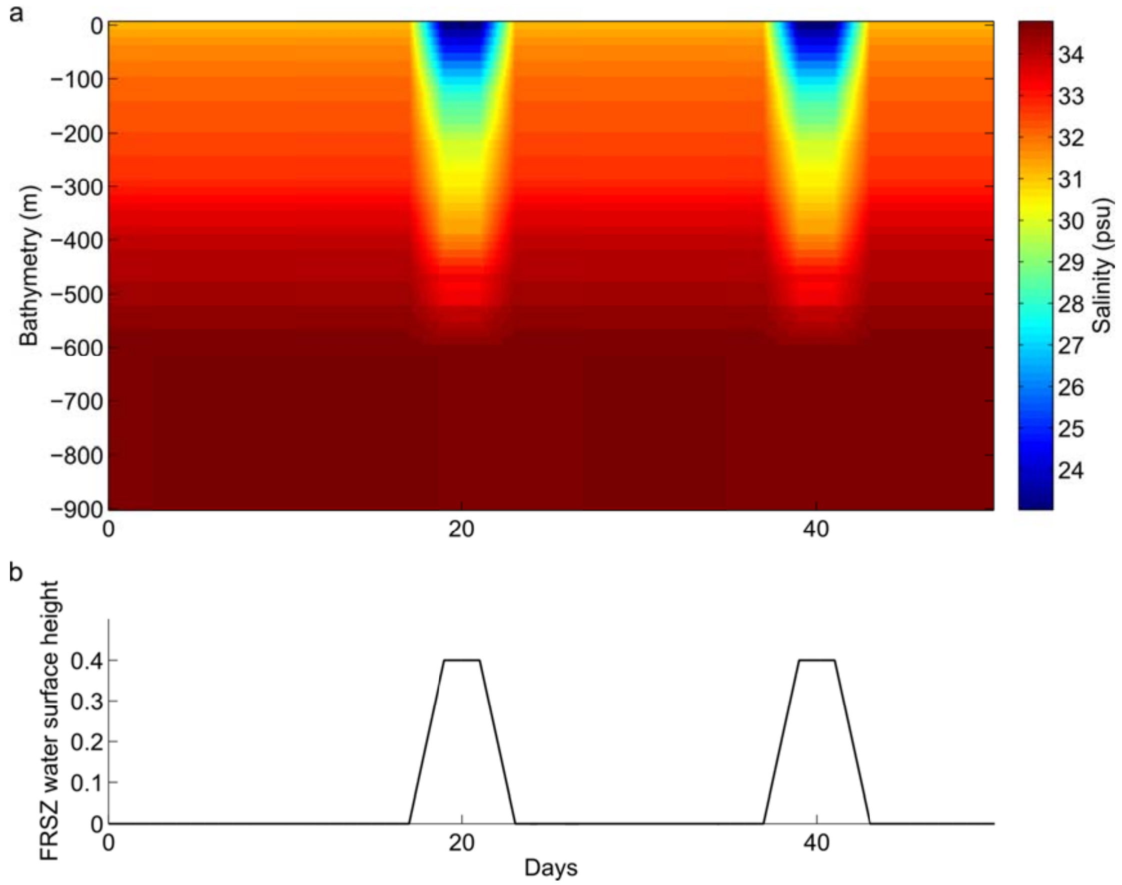

Fig. 8. An example (day 1 to day 50) of forcing in the FRSZ for the experiments that simulate wind-driven intermediary circulation. a, 'coastal' salinity; b, water surface height in the FRSZ (in addition to the effect of tides in experiments where TF=1). The day 20 wind event starts with a 'build-up' period from day 17 which lasts two days, followed by the wind event itself from day 19 to 21, and then a 'wind down' period for a further two days.

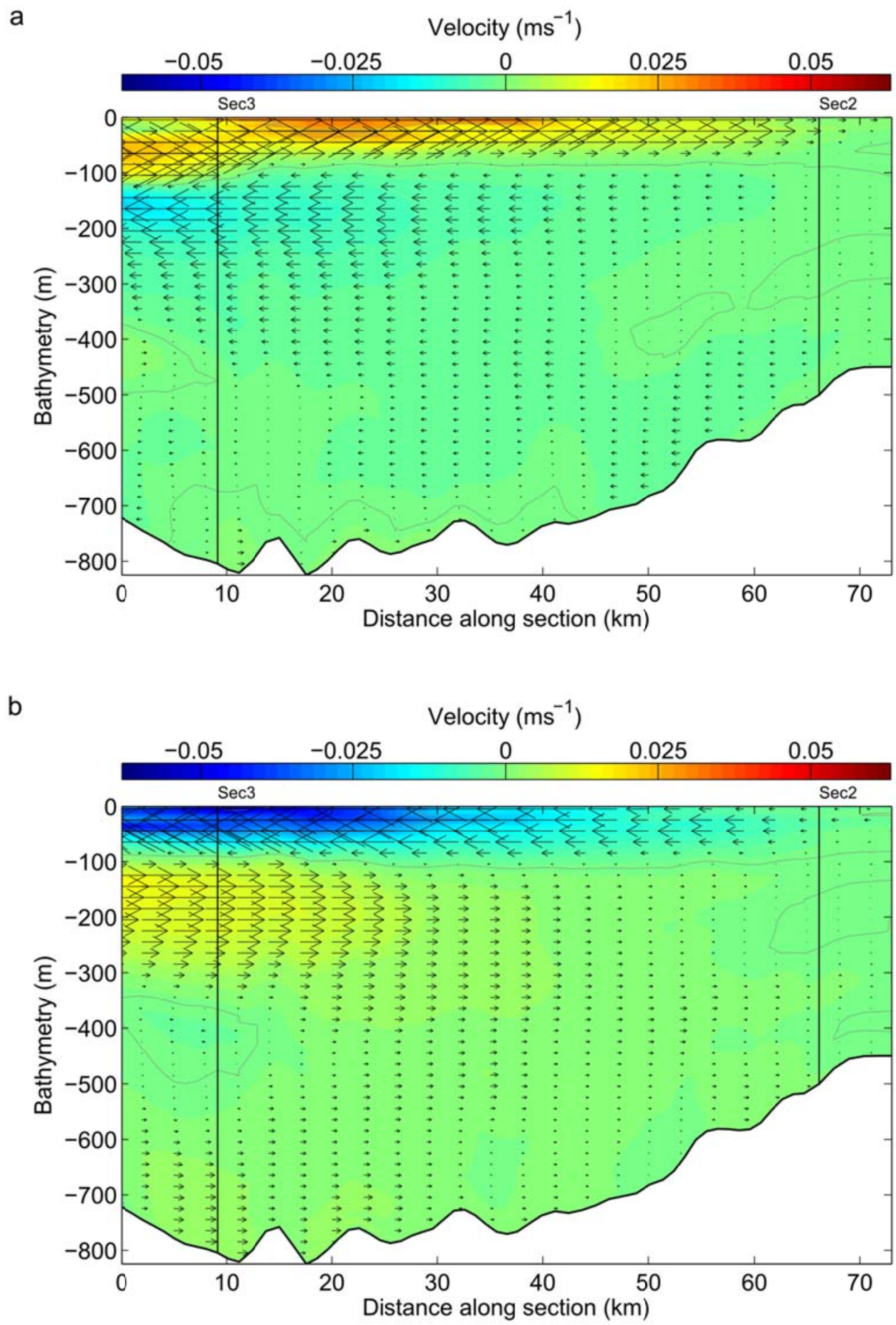

Fig. 9. Along fjord (section 1) velocities that result from the forcing depicted in Figure 8 for the 'build-up' and 'wind down' periods. a, mean of days 18 and 19, a coastal 'wind event' increase water surface height and depresses the halocline at the fjord mouth driving an inflow in the upper 100 m and outflow at depth; b, mean of days 21 and 22, as the wind decreases and the shelf returns to pre-wind event conditions and the fjord relaxes through the reverse circulation.

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*A second general deficiency is the paper's discussion of glacial melt rates. The paper calculates the area-integrated heat flux Q along the fjord at a certain flux gate (it wasn't clear to me where along the fjord the chosen flux gate was) and then assumes that this energy is completely consumed as latent heat in order to obtain a total melt rate of ice. My objections are two-fold. First, when water temperatures in the fjord volume between the glacial terminus and the flux gate are not steady, the method is not valid. Energy conservation would say that Q = c*dT/dt + E where dT/dt is the rate at which the mean water temperature T is increasing and E is the rate at which melting consumes energy (from which melt rate can be inferred). Perhaps the flux gate in the paper is close enough to the terminus that the proportionality constant c is tiny, but this isn't demonstrated. Otherwise, and especially in a fjord that is rapidly flushed, you would expect Q and c*dT/dt to both be quite large in magnitude and nearly equal to each other, with E being essentially uncorrelated to Q. My second objection is, why not just show melt rates as calculated by the model? The paper does not describe the model's treatment of the ice-ocean interface and the omission of directly calculated melt rates suggests there may be some deficiency there, which is not properly discussed.*
We agree that our conversion of heat transport into glacier melt rates is oversimplified and we have therefore removed reference to quantitative assessment of melt rates from the paper. While we have removed these estimates of melt rates, we still report the heat delivered to the fjord head and show how this is amplified by stronger fjord circulation resulting from increased subglacial runoff.

I have several specific comments:

1. If there is no forcing in the spin-up period, why doesn't the model relax to a state of no motion? Is it that melting at the terminus drives a circulation, even in the absence of subglacial runoff?
The residual motion is caused by the coriolis force acting on the water in the fjord creating eddies at the fjord mouth and in the wider part of the fjord towards its inland margin (see our response to Comment 1 by Referee 2 for a plot of the circulation). KF is approximately 15 km wide at its mouth, 6 km wide for much of its length and 10 km wide towards its inland margin. Using the 1993 CTD data (as used for the spinup experiment) we estimate the internal Rossby radius of the fjord waters to be smaller than the typical fjord width. Thus KF can be considered 'broad' meaning that rotational forces are important relative to stratification (Cottier, 2010). In order to clarify this, we have added the following text to Section 3, 'Model Boundary and Initial Conditions': 'The remaining circulation in the fjord is dominated by a series of slow-flowing (< 0.02 m s^{-1}) eddies driven by the coriolis force which form in the widest parts of the fjord located just inside the fjord mouth and near its head. The internal Rossby radius of the KF waters in 1993 is smaller than the typical fjord width, such that KF can be considered 'broad' meaning that rotational forces are important relative to stratification (Cottier et al., 2010). The volume averaged kinetic energy resulting from this circulation is 0.04 J m^{-3}, less than one tenth of the typical values for an experiment incorporating tidal, wind or glacier runoff forcing.'

2. Line 35-36: I am not convinced by this paper that reduced buttressing from sea-ice and ice mélange will be less important than undercutting. This claim goes beyond the scope of the model results, in my opinion.
We accept this point and have removed relevant sections from the manuscript.

3. Line 126: It would be appropriate to point out that a non-hydrostatic model would have diminished accuracy in simulating narrow buoyant plumes.
Although we do not attempt to model narrow plumes because our standard model experiments are on a 1 km grid, we have added the following to Section 2 'Model description': 'While hydrostatic ocean models are not ideal for simulating narrow buoyant plumes because vertical

velocities are limited, they give significant computational time savings over non-hydrostatic models. Comparisons with non-hydrostatic models suggest that the BOM is able to reproduce the major features of several test flows (Berntsen et al., 2006). The BOM has also been previously used to model the effect of artificial upwelling on primary productivity in fjords (Berntsen et al., 2002).'

4. Line 132: There ought to be a description of how ice-ocean interactions are represented in the model.
Ice-ocean interactions are not included in the model. In other words, the fjord water does not 'see' that the fjord head boundary is ice.

5. Line 201: What are the velocity boundary conditions during the spin-up? This is potentially important. If north-south velocity is set to 0 during the spin-up then the large transient velocities during phase 'a' in Figure 4 may due to the change in boundary condition rather than the commencement of forcing.
The boundary conditions at the fjord mouth during the spinup experiment are the same as those during the subsequent model runs (see main text for details). The large transient velocities in Figure 4ai are caused by the initiation of wind and tidal forcing.

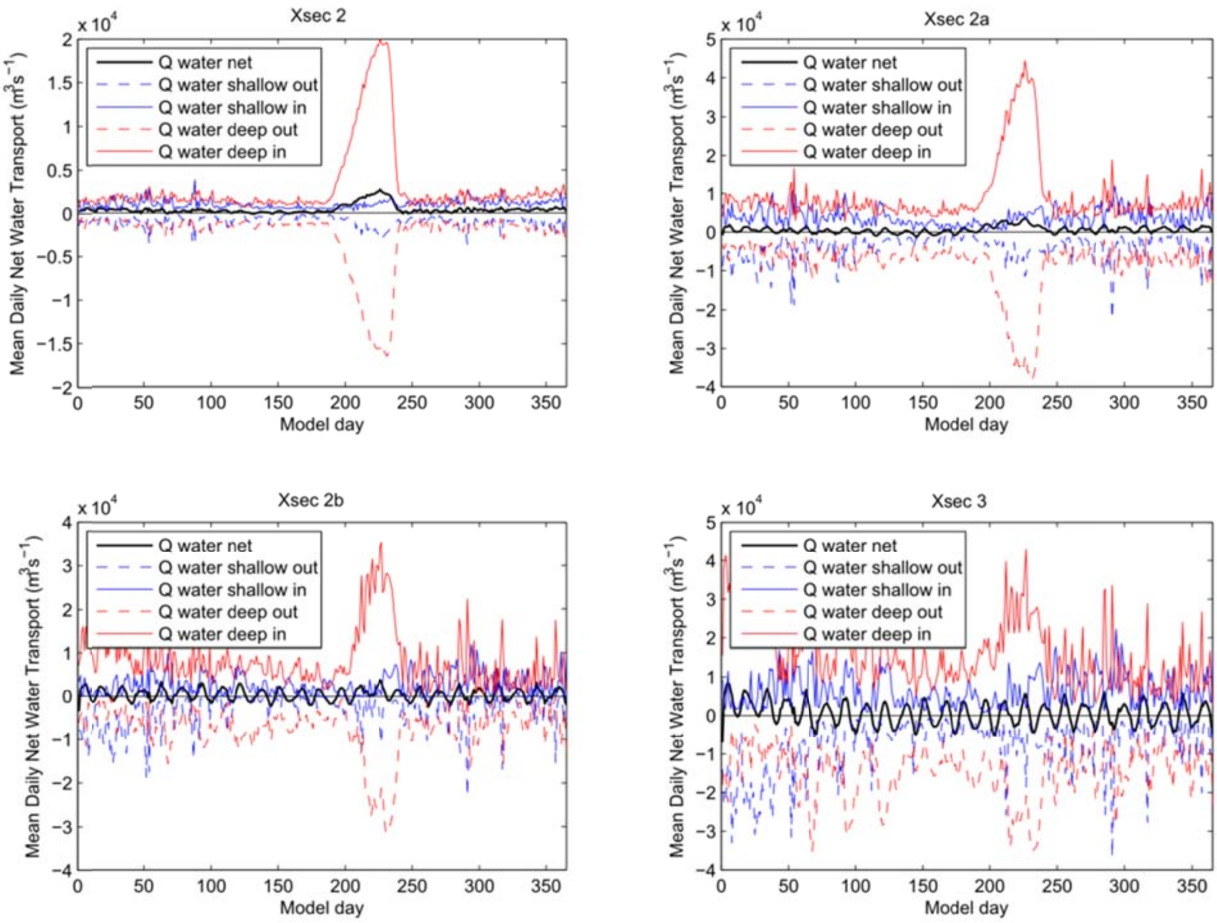
6. I think lines 211 to 219 should be re-written carefully. To make a suggestions, perhaps what is meant is: "For y=0 to y=7, model-generated velocities are adjusted towards prescribed external values (u_EXT,v_EXT,w_EXT) with a relaxation time constant T which varies from T=0 at y=0 (instantaneous adjustment) to T=1 at y=7 (no adjustment)."
We have reworded this section to: "The relaxation time constant α varies linearly from α =0 at y=7 (no adjustment to external values), to α =1 at y=0 (instantaneous adjustment to external values)."

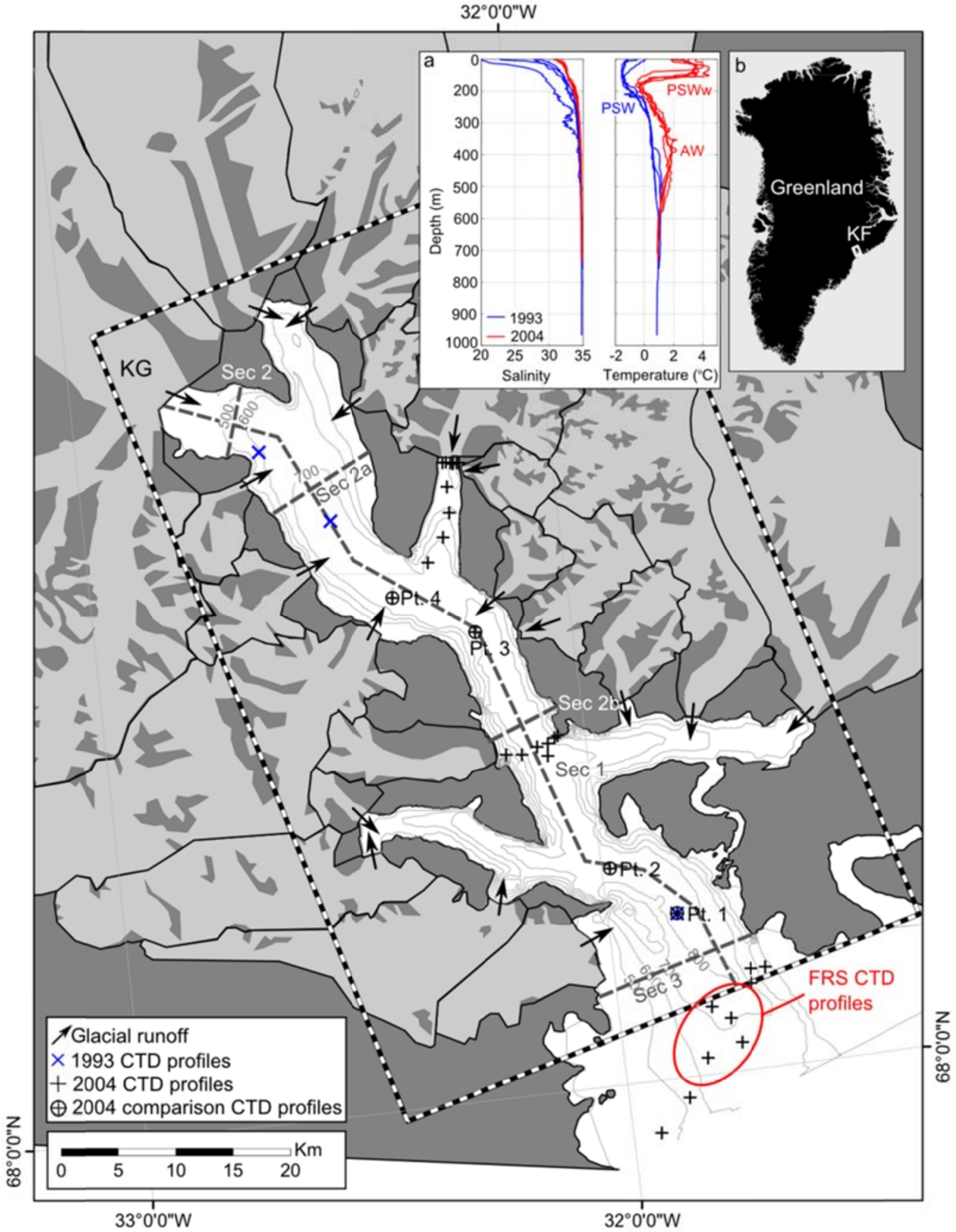
7. Figures 2 and 3 give contradictory impressions of the fluid domain in the model. Figure 2 has realistic coastlines but Figure 3 looks like a rectangular fluid domain.
Figure 3 simply shows the model domain outline without the coastline. It is also not to scale so it is not appropriate to include the coastline in this figure. We have added the following to the figure caption to make this clear: 'The fjord coastline is contained within the domain but is not shown.'

8. Figure 10: The difference between a,b,c, and d for temperature and salinity are quite small and are not really discussed in the text. It may be better to omit the salinity plots altogether to make more space. For temperature plots, perhaps show anomalies relative to the initial conditions. For the velocity plot, the arrows are too small to be legible at actual figure size. Show streamlines of across-fjord-integrated along-fjord velocities instead. Streamlines could be plotted overlain on the temperature anomalies.
We have removed salinity plots from figures 4, 6, 10 and 11. We also now show temperature anomalies relative to initial conditions to better illustrate the along fjord progression of AW and PSWw. We did experiment with using streamline plots, but decided that velocity magnitude with overlying directional arrows showed the pattern of water flow more clearly. However, we have increased the size of the arrows to make them more legible.

9. To show how the heat transport varies seasonally, a plot of the strength of the overturning circulation in the lower cell as a function of time would be very illuminating. In particular, the overturning in phase 'a' of Figure 4 ought to be highlighted and explained since it occurs in the absence of subglacial runoff and then goes away in phase 'b'.
We have made some plots of up- and down-fjord water flux throughout the experiment CF1-TF1-WF1-RF1 (Figure 1). This figure is also now included in the paper as Supplementary Material Figure 13. The influence of glacier runoff on the overturning circulation is (as expected) much greater

closer to KG. Near the fjord mouth, there is little difference between water transport with and without glacier runoff forcing. Most of the water circulation here is controlled by tides with alternating flow in and out of the fjord. The overturning circulation in (original submission) Figure 4a(i) is caused by the initiation of the wind forcing. Indeed, for the first part of the model experiments (i.e. before the onset of glacier runoff on day 180) the intermediate AW does advance along the fjord even without glacier runoff forcing. We now make this point more strongly in the text. However, without including glacier runoff, the AW does not reach KG over a single year.





10. Line 419: You have shown that wind-induced intermediary circulation is not necessary to bring about the temperature changes from 1993 to 2004. But you cannot conclude that subglacial discharge is the dominant driver of heat transport. If KF flushes in a matter of weeks like Sermilik fjord (which we cannot check due to limited data) it is probably not subglacial runoff that drives the main fjord circulation and it may have very little effect on heat transport.

We have modified this sentence as follows: "We suggest that while external forcings, such as synoptic pressure gradients (Christoffersen et al., 2011) and wind-driven intermediary circulation (Straneo et al., 2010), dictate which water masses are present at the mouth and within KF, heat transport along the inner part of the fjord towards the glacier terminus is most sensitive to variations in glacier runoff." We do not believe that observations from SF are necessarily applicable at KF. Please see our response to the General Comments from Reviewer 1 for details.

With a model, you could attempt to show that wind driven intermediary flows are not sufficient to deliver heat to KG at the minimal rate that observations imply (although I suspect a model would not, in fact, show that).
We have conducted several new experiments which incorporate the effects of wind-driven intermediary circulation that has been observed at SF (Straneo et al., 2010). These show that while wind-driven intermediary circulation does have a significant impact on water flow and heat transport in KF, it is not required to bring in warm Atlantic Water (AW) from the fjord mouth over a single year. Moreover, the addition of glacier runoff to the experiment with wind-driven intermediary circulation further enhances along fjord heat transport, supporting our finding that rising ice sheet runoff increases the sensitivity of KG and other Greenland marine terminating glaciers to ocean warming. We have added a new section (Section 4.4 'Wind event-driven intermediary circulation') to the manuscript which describes the design and discusses the results of these experiments (see our response to Reviewer 1, General Comments above).

11. Line 465: At the risk of being repetitive: the claim that subglacial runoff "increases the sensitivity" of KG to temperature changes beyond the fjord mouth is un-proven since the model can not disprove the default hypothesis (in light of what is know at Sermilik fjord) that KG is already always in contact (with a delay of just a few weeks) with whatever water mass appears outside the fjord.
As far as we are aware, Straneo et al. (2010) did not show that HG is in contact with AW, just that conditions to within 50 km of the head of SF in the top 300 m track conditions on the shelf. Please refer to our reply under 'General Comments' above and the interactive comment by M. Pelto for details of the most recent findings from SF. We have now run some experiments which simulate coastal wind events and intermediary circulation. Please see the new Section 4.4 'Wind event-driven intermediary circulation' which describes the design and discusses the results of these experiments.

Minor/technical corrections:

1. line 12: change "transmission of this warming" to "transfer of oceanic heat"
Changed as suggested.

2. line 20: The word "estuarine" should perhaps be retired from discussions of glaciated fjords like KF/KG since it is becoming clear that such fjord are not like estuaries (river-fed embayments). Here the more general label "buoyancy-driven flow" is perhaps appropriate.
Changed as suggested.

3. Line 35: "in agreement with obs, that maximum submarine melt rates occur... present at the fjord mouth" suggests that direct obs. of submarine melt rates exist for KG, but this is surely not the case.
We have removed the reference to observations (which were of glacier velocity etc with inferences about submarine melt rate).

4. Figure 1 caption: "AVHHR 4km" is undefined. There is no reference for the ocean current schematic.
The figure 1 caption now starts: 'The sub-polar gyre (based on Figure 16 of Sutherland and Pickart (2008)). Background colour shows mean annual AVHRR (Advanced Very High Resolution Radiometer) 4 km sea surface temperature for 2004'.

5. Figure 2: Missing labels "A" and "B" on inset figures.
The inset labels have been added to Figure 2.

6. Line 135. Punctuation. Change "extent of the fjord, water" to "extent of the fjord.

Water"
Changed as suggested.

7. Figure 3 caption: "FRSZ" is not defined yet in the main text when Figure 3 is first referenced. To correct this, just put panel 3d in its own figure and move the reference to it somewhere after the point where FRSZ is defined in the text.
We have added 'Flow Relaxation Scheme Zone' to the Figure 3d caption. Figure 3d is not referred to until after the FRSZ is defined in the text. We would rather limit the number of figures and leave Figure 3d as part of Figure 3.

8. Line 168: remove the period
Changed as suggested.

9. Equation 1: a. units are in italics, change to non-italics
b. 1.2x10^{-3} should be typeset as $12ntimes 10^{-3}$ to get the correct 'x'
c. |W_x|W_x|W_x should be |W_x|^2 W_x
d. |W_y|W_y|W_y should be |W_y|^2 W_y
a. Units and italics changed as suggested.
b. typesetting of 'x' changed to '\times' which produces the correctly formatted 'x'.
c. Changed as suggested.
d. Changed as suggested.

10. Line 179: what is the treatment for basins other than KG shown in Fig 1?
A rate of runoff in m^3 km^{-2} s^{-1} was derived for KG as described in the text. This value was then multiplied by the basins' area to give an estimate of runoff. This probably slightly underestimates actual runoff because the hypsometry of the smaller basins is different from KG with a greater proportion of the basin area at lower elevations. This runoff flowed into the fjord at the surface and base of these glacier termini as for KG.

11. Line 182: "constant" means "vigorous"?
Changed as suggested.

12. Line 186: "external forcing of across shelf properties" is awkward
Changed to 'external forcing of shelf water properties'.

13. Line 199 The symbols CF, TF, RF, and WF are only defined implicitly. It only becomes clear later in the text that these are not just acronym labels and not just logical true/false flags, but actually variables that will later be set equal to various values. The variables are not really necessary in section 3.1. Perhaps introduce them later.
We have removed reference to 'RF' etc. from section 3.1. They are now first introduced in section 4 (Results).

14. Line 202: does "stable" mean "steady" or "stable in the sense of stratification"?
"stable" means "steady", we have changed the text to reflect this.

15. Line 201: The sentence "While we acknowledge : : :" is unnecessary.
We have removed this sentence.

16. Line 207: How long does the spin-up take?
Approximately 100 days for the quasi constant energy state to be reached, but each spinup experiment was run for a full year to confirm the model stability.

17. Line 212: Does "at each time step" mean "after each time step"?
Yes, and we have modified the text accordingly.

18. Line 214: "From within the fjord" is unclear. Does this actually mean "the velocity produced by the model after the current timestep" or does it mean "the velocity generated by the model at y=7 (or 8, or : : :)"?
We have removed "From within the fjord" and now simply refer to the "the velocity produced by the model after the current timestep" which is defined in the next sentence: "For our experiments, the external velocities u_{EXT} , v_{EXT} and w_{EXT} are set to be the mean of modelled *u*, *v* and *w* from *y*=8, to *y*=10, i.e. the mean velocities with depth for the three rows of grid cells immediately up-fjord of the FRSZ for each timestep; $u,v,w_{EXT} = u,v,w_{INT}$"

19. Line 214: change "contains" to "refers to". Also, "unrelaxed" is undefined here and unclear.
We have changed "contains" to "refers to" as suggested. "unrelaxed" has been deleted as per correction 18.

20. Caption of 3d is redundant with lines 216 to 221 (ie "The external: : :")
This part of the caption now reads: "The external velocities U_{EXT}, V_{EXT} and W_{EXT} are updated after each timestep as described in the main text."

21. Line 216: Previously the paper states that (u,v,w) at the boundary were set equal to tidal values, so shouldn't phi_EXT simply be these tidal values?
***u*, *v* and *w* in the FRSZ are initially computed according to the tidal constituents, and then these velocities are relaxed towards the specified external values. If the external values were set equal to the tidal *u*, *v* and *w* there would be no way of simulating the net flow of water through the open boundary at the fjord mouth.**

22. The notation u,v,w_EXT = u,v,w_INT should be written (u_EXT,v_EXT,w_EXT)= (u_INT,v_INT,w_INT) if that is indeed what is meant. It is unclear as it is.
Changed as suggested

23. Line 227: What is the boundary condition for sea-surface height?
Sea surface height is a function of time and the amplitudes and phases of the tidal constituents in the FRSZ.

24. Line 242: define RF,CF,TF, and WF here.
Changed as suggested.

25. Line 253: Citing (Jenkins 2011) after "as observed elsewhere" is inappropriate since that paper is theoretical and does not present new observations.
The reference to (Jenkins 2011) has been removed as suggested.

26. Line 257-260: This sentence seems like a cut-and-paste error since CM and CM2D are not defined yet and this is more of a model-internals remark.
The sentence now reads: "The 3-D (C_M) and 2-D (C_{M2D}) viscosity coefficients are set to 5 and 250 respectively."

27. Figure 5: Please indicate the time of these model outputs. Day 365?

The model outputs are a mean for day 240, immediately following the cessation of glacier runoff forcing. We believe this is most representative of the CTD surveys carried out between the 1st and 10th September.

28. Figure 6: The color scale for velocity is bad (ie too much green).
Although we agree with this comment, the colour scale used is necessary to aid visual comparison of the velocity fields for each stage (panels a-d). The colour scale is set to accommodate panel d) which displays higher velocities.

29. Line 286-290: Is the correlation calculated at a fixed time (ie day 365) or is it a time mean?
The model outputs are a mean for day 240, immediately following the cessation of glacier runoff forcing. As noted above, we believe this is most representative of the CTD surveys carried out between the 1st and 10th September.

31. Line 290: CF appears to mean the scaling factor in: P_model_2004(z) = P_obs_1993(z) + CF(P_obs_2004(z) – P_obs_1993(z)). This should be written in the text, if correct.*
We have added this to the text

32. Line 297: "intrusion" is misspelled.
Corrected.

33. Table 1: Shallow salt agreement is better at most points when WF=0. Can you explain?
We believe that the discrepancy in shallow salinity is due to the lack of representation of freshwater from melting icebergs in the model which would dilute the relatively salty inflowing PSWw. Thus, the experiments which bring in less PSWw display better agreement with observations. However, we are convinced that wind forcing is important, because without it, the fit to the temperature observations is not as strong.

34. Line 314: What does "standard" mean?
"standard" here refers to velocities from the 'standard' model experiment, i.e. CF0-TF1-WF1-RF1. We have made this more clear in the text: "A comparison between measured (Figure 5e) and velocities from the standard experiment…"

35. Line 339: Spelling of "equivalent".
The section on ice melt has been removed based on comments from Referees 1 and 2.

36. Line 340-343: This is mistaken reasoning, I think. If the entire energy flux Q is assumed to be converted to melting, then convection at the icefront is not relevant unless it increases or decreases the amount of energy available for melting at the end of the day (since the energy argument is agnostic about the dynamics of how heat is delivered to the ice). Introducing buoyant meltwater at the grounding line does introduce gravitational potential energy that could possibly contribute to melting, but that is not quantified here (or elsewhere, if I'm not mistaken) so can not be used in support of the claim "This calculation is a minimum estimate of submarine melt rates".
The section on ice melt has been removed based on comments from Referees 1 and 2.

37. Line 346: Model outputs at which time?
This sentence has been removed based on comments from Referees 1 and 2.

38. Line 348: "3x10ˆ9" should say "3x10ˆ10" I believe.
Corrected.

39. Line 351: Summer melt rates which are four times the annual average suggests that there is essentially 0 melting in the three non-summer seasons: (0+0+0+1)/4 = 1 4 . If it is true that melting is essentially absent without subglacial discharge, that ought to be made clear at some point.
The section on ice melt has been removed based on comments from Referees 1 and 2.

40. Figure 8 caption: The vertical axes are labeled "mean heat transport". Is this the time mean over the entire 365 day simulation?
Yes. Caption now reads: "Sensitivity of mean annual along-fjord heat transport through section 2 to parameter uncertainties".

41. In the calculation of Q, which flux gate is being used, section 2?
Yes. This is stated in the main text: "Modelled mean annual (summer: day 180 - 240) net along-fjord heat transport through section 2". The captions for Figures 7 and 8 now read: "The effect of varying RF and CF on mean annual and summer along-fjord heat transport (Q) through section 2" and "Sensitivity of mean annual along-fjord heat transport through section 2 to parameter uncertainties" respectively.

42. Line 402: The sentence "Although: : :" is unnecessary.
We have removed this sentence as suggested.

43. Line 408: "barotropic" is incorrect here. The intermediary circulation is generated by baroclinic pressure gradients created by moving the isopycnals up or down at the fjord mouth.
This sentence now reads: "Observations show that wind-driven intermediary circulation controls water exchange in the top several hundred metres of SF (Caceres et al., 2002; Straneo et al., 2010)."

Interactive comment on "Increased glacier runoff enhances the penetration of warm Atlantic water into a large Greenland fjord" by A. J. Sole et al.

Anonymous Referee #2

Received and published: 7 January 2013

This study uses a numerical ocean model to investigate the circulation in Kangerdlugssuaq Fjord (KF), East Greenland. Its goal is to investigate if ocean variability played a role in the retreat and speedup of Kangerdlugssuaq Glacier (KG) in the mid 2000s. The model used is a three dimensional fjord forced by tides, local winds, property changes at the mouth and glacier runoff. It is initialized with hydrographic data collected in 1993.

The main thrust of the paper is to investigate the changes in heat transport associated with various forcings and especially with the (discrete) change in ocean conditions from those observed in 1993 to those observed in 2004. The conclusion, stated in the title, is that increased glacier runoff enhances the penetration of warm Atlantic water in KF and, therefore, of the submarine melt rate of KG. The model runs presented are interesting and relevant to understanding the circulation in a Greenland fjord, but there are major flaws in the analysis presented and in the conclusions drawn from them (which I describe below). Because of this, I do not recommend publication of this paper. I do believe that these model runs could be used to address a different set of questions and that an appropriate analysis would increase our understanding of the dynamics of glacial fjords. I make some recommendations to this regard below after detailing the problems with this paper.

There are two major problems with this study:

1) It attempts to address a question which is beyond the scope of the model set-up: 'What caused the change in properties in KF from 1993 conditions to 2004 and how did that impact KG?' The logic of the authors has been to set up a fjord model in which the circulation is driven by glacier runoff, surface winds and tides and initialized it with 1993 conditions. Then they step-change the properties at the mouth to those observed in 2004 and watch the progressive advection of 2004 properties into the fjord. Since glacier runoff is the main driver of the fjord circulation, they then conclude that the change from 1993 to 2004 properties is due to glacier runoff.

This conclusion is unsupported by the evidence presented. To conclude that the circulation driven by glacier runoff is the main driver of changes in KF (i.e. the intrusion of warmer AW) the authors would need to compare all (or at the very least the more likely) drivers of fjord/shelf exchange. Instead, their set-up effectively includes only a limited number of drivers (tides, surface winds and glacier runoff) - only one of which (glacier runoff) is actually capable of driving a significant fjord circulation. It is worth noting that the circulation driven by submarine melting of the glacier itself is also excluded. More importantly, they neglect the most likely driver of change in fjords such as KF - which are fjord/shelf gradients in density and thickness (see for example the recent review of fjord dynamics by Stigebrandt, 2012, and references therein). This is even more troubling given that in the nearby Sermilik Fjord, previous studies have shown these exchanges to dominate the renewal of fjord waters (Straneo et al. 2010). The question which these model runs address is: 'how long does it take for KF waters to be renewed if the waters at the mouth change AND the exchange is governed only by the circulation driven by glacier runoff? This is an interesting question, but is not the question which the authors claim to be answering and its relevance to the observed change in KF from 1993 to 2004 is not substantiated by any discussion presentedhere.
We disagree with this assessment for two reasons. Firstly, wind-driven intermediary circulation is no longer considered to be the principal seasonal control on water circulation in SF close to the

fjord head (e.g. Sutherland and Straneo, 2012). Secondly, there are several key differences between Sermilik Fjord (SF) and KF which could explain why wind-driven exchange with the shelf is less likely to dominate at the latter than the former (please see our response to Referee 1, General Comments for more details).

The main conclusion of our paper concerned the magnitude of circulation that could be driven by glacier run-off; i.e. that it alone was sufficient to propagate Atlantic Water (AW) from the fjord mouth to KG over a year. The argument here is whether at KF glacier runoff forcing is secondary to the wind-driven intermediary circulation observed at SF by Straneo et al. (2010).

We acknowledge that in order to assess this we should include some experiments that represent the effects of coastal wind events (Straneo et al., 2010). This we have done by simulating synchronous multi day increases in sea surface height (by 0.4 m - Straneo et al., 2010 Supplementary Material) and concurrent depressions in the halocline at the fjord mouth. We have added a new section (Section 4.4 'Wind event-driven intermediary circulation') to the manuscript which describes the design and discusses the results of these experiments (see our response to Reviewer 1, General Comments above).

2) The second, more concerning, flaw of this paper has to do with the interpretation of the heat transports and equating them with submarine melt rates (which is really the focus of the paper). Estimating a submarine melt rate without a glacier representation of sorts (i.e. a heat sink that accounts for the amount of heat taken up by a glacier) makes no physical sense. Consider for example the fjord model run for a long enough time (with constant forcings and boundary conditions) so that it reaches steady state. Then the modelled heat transport would necessarily be zero (since heat has to be conserved in the model runs). Yet we definitely would not expect the submarine melt rate to be zero as long as the waters are above freezing temperatures near the glacier. Thus the modeled and the submarine melt rate are not equivalent. The heat transport estimated in the model runs is, instead, related to changing the heat content of the fjord above the section they are estimated across. It is the heat transport associated with the progressive change in properties in the fjord model from the 1993 initial condition to the 2004 imposed condition at the mouth. This heat transport is going into warming the fjord, it is not going through the northern wall into the glacier. Again, it cannot be used as a measure of submarine melting. Very likely submarine melting will increase as the fjord warms up, but these thermodynamics are absent in this model.

The modeled heat transport thus is different from that derived from observations by Johnson et al. 2011 or Sutherland and Straneo 2012 who are implicitly assuming that the rate of change in heat content of the fjord is small on the time scales considered. To give another example of why the modeled heat transport cannot be equated to a submarine melt rate, consider the following scenario. If the model with the 2004 open boundary conditions is run for long enough, the modeled heat transport will decrease since the fjord has largely equilibrated to the 2004 properties – yet we expect the submarine melt rate to stay high since the water in the fjord remains warm.
We agree that our conversion of heat transport into glacier melt rates is oversimplified and we have therefore removed reference to quantitative assessment of melt rates from the paper. Please see our response to Referee 1 above regarding the same issue.

Less Major Problems (but still problems):

1) What does the 'spun-up' circulation look like? Is there a circulation? If so why? It seems like in the absence of forcing, and with the fjord equilibrated to the shelf conditions the fjord circulation should be zero. If it is not zero, because there is mixing, then the authors must quantify and describe what this circulation is.

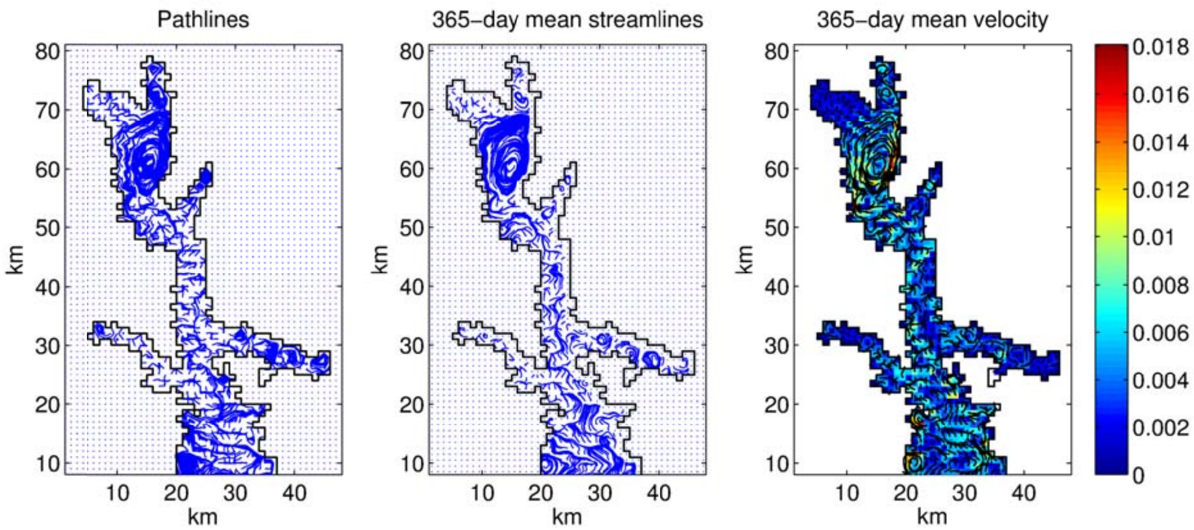


Fig 3: Circulation during spinup experiment

Please see our response to Comment 1 by Referee 1.

2) The paper makes unsubstantiated claims that glacier runoff is the dominant control on transport of water within the fjord. It is the dominant control amongst those explored in these model runs but it leaves it entirely open that other drivers (e.g. fjord/shelf gradients) may dominate if included in the simulations. Please do not draw conclusions on things you have not studied.

As stated in our original submission, we simply show that 'the commonly observed estuarine fjord circulation alone can explain the exposure of KG to warm AW and that intermediary circulation, as observed in Sermilik Fjord after storms (Straneo et al., 2010), may not be required. The latter could, however, greatly increase circulation in the fjord, but this remains to be confirmed' (Original submission, Section 6: Discussion). We acknowledge however that we need to also assess the influence of intermediary circulation, which we have done by simulating alongshore wind events such as those observed by Straneo et al. (2010). We have added a new section (Section 4.4 'Wind event-driven intermediary circulation') to the manuscript which describes the design and discusses the results of these experiments (see our response to Reviewer 1, General Comments above).

3) It is unclear what velocity is used to estimate the heat transports – the absolute modeled velocity or the modeled velocity with a barotropic component subtracted to impose a zero volume flux (as described in Johnson et al. 2011 which the authors cite). Their results suggest that it is the latter. Removing a barotropic component is incorrect given that there is a net volume flux through a section due to the glacier runoff. If glacier runoff is present and a barotropic flow is removed, this gives rise to an artificial positive heat transport. This seems to be the case with the 1993 runs (CF=0) and varying glacier runoff.

The heat transports are estimated using the absolute modelled velocity.

4) The data/model comparisons presented do not, in my opinion, support the conclusions drawn. First of all the velocity section observed by Autosub and the modelled are different!

While we agree that the Autosub and modelled velocity sections are quantitatively different, we maintain that they are qualitatively similar in that they both show a multi layered estuarine-type circulation with alternating inflow and outflow. Such a circulation pattern is more complex than the relatively simple two layer flow which would be expected from baroclinic intermediary circulation. Furthermore, a similar circulation pattern is also evident in Sermilik fjord once short-term baroclinic flows are removed (Sutherland and Straneo., 2012).

In general, it makes little sense to compare a velocity snapshot with a modeled velocity where only slow varying processes (except for the tides) are included.

While we agree that the comparison is not ideal, we believe that a comparison with observations, even a snapshot, is preferable to no comparison at all. The Autosub transect is one of very few velocity measurements which have been made in Greenlandic fjords. The fact that the flow characteristics generated by the model are qualitatively similar (both show a multi layered estuarine-type circulation with alternating inflow and outflow) to those observed by Autosub must give more credence to the model than if the results were presented in isolation without any comparison to real world fjord observations. Furthermore, we expect that most referees would have wanted to see our model results compared with those that are available from the field if we had chosen *not* to show the Autosub results.

Secondly, the CTD data comparisons are also misleading. All they show is that fjord conditions change from the 1993 conditions to the 2004 conditions once the open boundary conditions of 2004 are imposed. And that the speed at which they do depends on the magnitude of the fjord circulation. This is hardly surprising, since they cannot do anything else – and hardly evidence that the model is capturing the correct dynamics. Even a diffusive process would, eventually, have produced the same results.

We do not agree with this view. Take for example the observed and modelled CTD comparison shown in Figure 5a-d. The dark blue line in each panel represents the experiment without glacier runoff forcing. It is clear that this simulation misrepresents the depth at which warm water flows into the fjord, with the modelled AW intrusion being consistently too shallow (this is particularly prominent in 5c). Once glacier runoff is included, the agreement between the observed and modelled AW layer increases significantly, indicating that this may be an important feature of water flow in the fjord. Furthermore, the same plots show that, without the inclusion of wind forcing, the observed surface warming is not correctly simulated.

Interesting Results from the Model Runs

What I think is interesting in this study are the different circulation regimes forced by the tides, the local winds and the glacier runoff. These model runs have revealed an interesting interaction between these different forcings which merits to be analyzed in more detail. The authors could quantify the relative role of these different forcings and examine their role in dominating the variability on different time scales.

We believe that we have already done this to some extent. The only reason we know about which forcings control which circulations is from our comparison between observed and modelled CTD data which the referee describes as 'misleading'.

Effectively the circulation driven by the glacier runoff is a modified estuarine circulation. As such it must depend on mixing, yet there is little or no discussion of the role of mixing on the magnitude and character of the circulation (the only sensitivity discussion mostly focuses on melt rates which are not a good diagnostic of the circulation).

The sensitivity analysis actually focusses on heat transport rather than melt rate. Certainly the referee is correct that in many fjords (e.g. Inall and Gillibrand, 2010) a strong baroclinic estuarine circulation is driven largely by vertical mixing between the out-flowing freshwater and the in-flowing intermediate waters. However, it is unclear that this is the case in fjords terminated by a glacier. The reason for this is that there exists a large store of potential energy in the form of the submerged calving front (approximately 450m deep in this case). As this melts a convective mixing zone develops in the vicinity of the calving front which has the potential to drive a baroclinic exchange without the need for strong mixing between the interfacial layers along the full axis of the fjord.

I think these runs merit a more in-depth (but sound) analysis and this would really advance our understanding of how these fjords work.

Interactive comment on "Increased glacier runoff enhances the penetration of warm Atlantic water into a large Greenland fjord" by A. J. Sole et al.

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Sole et al (2012) provide a detailed examination of the heat flux into and out of the KF and the resulting amount of subglacial melt of KG and the role of KG subglacial runoff in that process. KG is one of the three large Greenland outlet glaciers with detailed oceanographic observations. The authors reach a critical conclusion that supports the ongoing evolution and quantification of the role and interaction of warm ocean water penetrating at depth to reach marine outlet glacier termini, and glacier runoff. The following sentence from the paper is of such importance that it warrants publication of the paper. "Along-fjord heat transport towards KG increases significantly with both glacier runoff and coastal water temperature. A doubling of glacier runoff produces a 29% (48 %) amplification of mean annual (summer) heat transport towards the KG terminus, increasing estimated mean annual (summer) submarine melt rates from 211 to 273 (842 to 1244)myr−1." There is certainly room for improvements in the model going forward, but this is another step in quantification of the glacier runoff reinforcing AW circulation to the glacier front process, that deserves our attention. This paragraph reviews three recent papers that highlight the evolution of the concept of glacier runoff enhancing the penetration of warm AW to marine calving glacier termini in Greenland, and how Sole et al (2012) adds to this discussion. Straneo et al (2011) observed for Helheim Glacier, Greenland that the melting circulation within the fjord and at the ice front is influenced by seasonal runoff from the glacier and by the fjord's externally forced currents and stratification. Rignot et al (2012) identified a positive feedback with glacier runoff, "A doubling in subglacial runoff should increase subaqueous melt by 25% according to the model simulations." Note this compares well to the 29-48% increase modeled here. Straneo et al (2012) further found that examination of oceanic water properties identified the melting by AW and the influence of subglacial discharge on water properties in the summer. Straneo et al (2012) found that KG was quite complex, warranting a detailed examination, and that KG had higher volumes of glacier runoff modified water in the upper circulation zone and less of a PW signature than other glaciers. The complexities of the circulation system outlined in the papers above, are impossible to model based on existing field data alone. Sole et al (2012) use an appropriate ocean model combined with one of the richest fjord data sets in Greenland to further quantify and discern the complexities of the fjord circulation at KG.

The critical result of Sole et al (2012) provides a more detailed quantification of glacier runoff, and the potential role of glacier runoff in the net flow of warmer AW to the glacier face. Numerous papers have identified the acceleration of marine terminating outlet glaciers in southeast, southwest, and northwest Greenland during the past decade. This acceleration and retreat has coincided with increased melting and hence glacier runoff. The mechanism of glacier runoff strengthening the circulation of AW to the glacier front provides a mechanism for the similar response of so many glaciers. The glaciers are scattered across a wide enough region that the actual oceanic conditions at the fjord mouths are less likely to have changed as similarly. The anonymous referee #1 observes that "It was shown in (Straneo 2010, Nature Geosci.) that vigorous wind-driven baroclinic currents flush Sermilik Fjord in a matter of days. As a result of this externally forced 'intermediary circulation', Straneo concludes that water properties in Sermilik Fjord track sub-seasonal changes of water properties on the shelf. If KF, which like Sermilik lacks a shallow sill, is flushed so rapidly by external forcing that the water properties in the fjord always essentially match shelf properties (with a lag of no more than a few weeks) then it is hardly possible for subglacial discharge to enhance the *penetration of shelf waters." I disagree with this analysis. The citation is true, but is now an outdated result. Straneo et al (2010) was a preliminary result based on data from just 2008, whereas Straneo et al (2011) relied on data from two more field season and their conclusion as noted above does not support the rapid baroclinic flushing model. Instead Straneo et al (2011), Straneo et al (2012) and Rignot et al (2012) support the highly stratified basic circulation described by Sole et al (2012) with glacier runoff volume as an important component.*

Specific Comments:

4863-13: Relatively synchronous acceleration of most marine terminating outlet glaciers even the ones that are not large should be emphasized.
This sentence now reads: "The recent widespread thinning, acceleration and retreat of many GrIS marine-terminating outlet glaciers were caused by changes at their calving fronts"

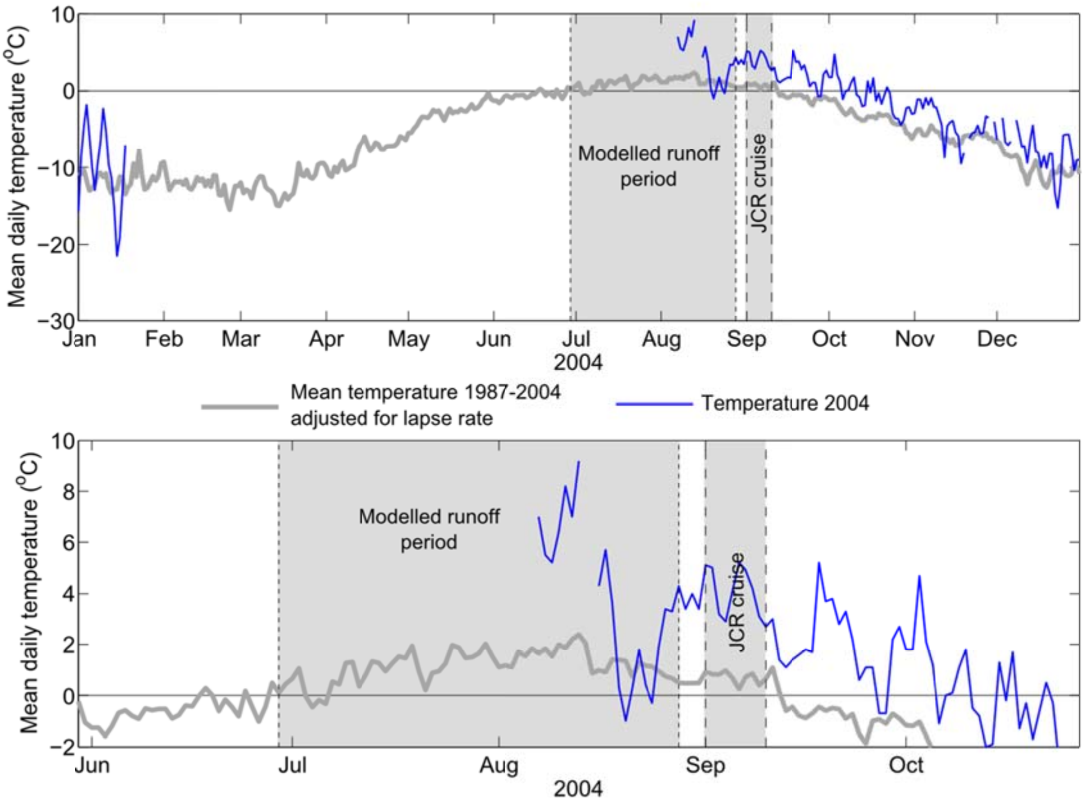
4864-14: A table indicating the characteristics of the various water masses would be useful. This would ideally include both shelf water characteristics and the various in fjord water mass characteristics.
We have added the below table and caption to the text.

Water mass		Year	Typical depth range (m)	Characteristic temperature (°C)	Characteristic salinity (psu)
PSW		1991	0-100	< 1.3	< 32
		1993		-1.5	< 32
	(PSWw)	2004		< 2.8	< 32
AW	(RAW)	1991	100-600	1.8	34.9
		1993		1.1	34.9
		2004		1.5	34.9
Deep ambient		1991	> 600	1.4	34.9
		1993		1.0	34.9
		2004		1.0	34.9

Kangerdlugssuaq Fjord typical water mass characteristics; 1991, 1993 and 2004. Data from Christoffersen et al. (2011) and Christoffersen et al. (2012) with water mass classification based on Rudels et al. (2002).

Figure 9 provides a useful depiction of the modeled general circulation. I would rather this simple depiction be early in the paper.
We would rather keep Figure 9 where it is because it summarises the circulation simulated in our experiments and should therefore not preempt the results section.

4867-12: Do acquisitions in September lead to any bias?



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Acquisitions in September likely represent conditions when surface melting is decreasing at the end of the summer season (Figure 4) and therefore show the net effect of a full melt season of glacier runoff on fjord temperature and circulation. This is why we make comparisons between these data and the model outputs which are generated following a full melt season of simulated glacier runoff.

4868-15: Is the melt season duration long enough ((Figure 3c- 60 days) given the results from recent years, with extensive June melt? Note Figure 2a from the Tedesco et al (2012).

The modelled melt-season was based on mean air temperature data, between 1987-2004 from a site close to the fjord mouth (Aputiteeq, World Meteorological Organisation station code 04351), with a lapse rate applied to represent the Kangerdlugssuaq basin. This 'mean' melt-season is unlikely to be long enough to capture the extreme melting that has been observed in recent years (particularly 2010 and 2012), although both longer and warmer melt-seasons would only increase the effect of glacier runoff on fjord circulation (as shown by the experiments in the paper with artificially inflated melt rates). Varying the melt season duration would of course be an interesting extension to this work in the context of changes in the regional climate and is something that we would like to investigate in the future.

4686-18: Beyond this paper having a temporally varying glacier runoff input to the model would be useful, as the large melt spikes seen in 2012 for example would certainly alter the glacier runoff impact on circulation. What would such amazing spikes in melt and runoff as in July 2012 due to the circulation of AW? Of course the lag in the runoff and the dampening of this spike are difficult to identify currently.

We agree that this would be an interesting experiment. We would expect significant spikes in runoff to result in temporary enhancement of the along fjord circulation. A series of such spikes throughout a melt season could result in a considerable net increase in heat transport towards KG. It would be interesting to see whether the absolute volume or temporal variability of glacier runoff has more influence on along fjord heat transport.

4872-15: Peak in intermediate flow?

Yes. The sentence now reads: "This results in significant seasonal variation of the intermediate circulation with a peak in summer and minimal flow during winter."

4873-15: Figure to illustrate this?

See graphs made in response to Comment 9 by Referee 1 (Figure 1) and Figure 12, Supplementary Material.

4873-18: The wind driven importance relates to the observations of Christofferson et al (2011), should be referenced.

Christoffersen et al. (2011) concentrate on the links between along shore winds and shoreward heat flux rather than winds in the fjord itself. We therefore do not agree that Christoffersen et al. (2011) should be cited here.

4875-13: How does the runoff calculated here compare to Mernild et al (2012) for Sermilik Fjord per unit area? This should be used for comparison.

We could not find a reference to glacier runoff in Mernild et al. (2012). Straneo et al. (2010, Supp. Info.) use a runoff estimate from Helheim Glacier, based on ablation stake measurements of ~5 Gt yr^{-1} for in 2008.

4875-16: Provide quantities from the other studies for comparison. The reported here seem high.

The sentence now reads: 'Our modelled heat transport and melt rates are broadly comparable with estimates based on observations from other Greenland fjords (e.g. 1.7 +/-0.3 to 85.8 +/-14 x 10^9W Rignot et al. (2010) and 24 x 10^9W Sutherland and Straneo (2012)).'

4877-21: What is the likely difference between KF and Sermilik Fjord?

There are several key differences. Firstly, KF is much wider at its mouth (approx. 16 km vs. 9 km) so is likely to be in geostrophic balance whereas SF is narrower and therefore rather more likely to respond strongly to winds (see response to Referee 1 Comment 1). Secondly, KF has a clear cross shelf trough and a single deep entrance rather than a complex entrance like SF (Schjøth et al., 2012).

Figure 9: This could benefit from being more detailed in terms of illustrating not just the basics but also the water mass characteristics in a fashion like Straneo et al (2011) Figure 2b and c.

More detailed water properties are incorporated into Figure 2 and the new Table 1.

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