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The Cryosphere Discussions

Interactive comment on "Warming of waters in an East Greenland fjord prior to glacier retreat: mechanisms and connection to large-scale atmospheric conditions" *by* P. Christoffersen et al.

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We are very pleased by the positive and encouraging comments from the associate editor (AE) who wrote "I strongly agree that a graphical comparison between model and in situ data is needed. In addition, I suggest adding bathymetry to one of the figures (possibly as the background for Figure 2) so that the trough, and potentially others on the SE coast can be identified, as well context given to the circulation patterns discussed. Further, I think an expanded discussion of the results in terms of the broader context of forcing of recent glacier change in Greenland is desperately needed."

To address the points raised by the AE, we have:

1. Included a graphical comparison of ocean reanalysis data and in situ observations.

2. Added bathymetry as a background colour for Figure 2

3. Expanded the discussion of results in terms of broader context of forcing of recent glacier change, particularly in southeast Greenland

The first point raised by the AE has been addressed by adding a new figure to the paper. This new figure (Figure 6) shows a very good agreement between modelled ocean properties for September 1993 and September 2004 and water mass properties observed during the same months at nearby stations. To be consistent, we made the comparison for the same outer continental shelf area used to show temporal variability of water masses in terns of temperature and salinity (Figures 5 and 7) as well as heat flow (Figure 7c).

Due to the inclusion of a new figure, we added the following text to section 3.2 entitled 'Shelf water exchange in the ocean reanalysis':

"Temperature profiles for September 1993 and September 2004, as seen in the ocean reanalysis, are plotted in Figures 6a and 6b together with temperature profiles from station measurements in the same months and nearby locations. The comparison of reanalysis data and observations is favourable in that the former falls within the variability of the latter. The ocean reanalysis profiles are calculated for the box shown in Figure 6c, which is the same box used to illustrate temperature and salinity variations in Figures 5 and 7. When observations are averaged across the approximate same area, we find a very good fit between modelled and observed temperature and salinity (Fig. 6d)."

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The second point raised by the AE was addressed simply by improving the bathymetry shown in Figure 2. We also added a colour scale. Since the circulation patterns of major currents are illustrated in Fig. 1, we prefer to not include these patterns in this figure.

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To address the third point by the AE, we expanded section 6 entitled ‘Synthesis’.

The AE wrote: “Similarly, it seems strange that these oceanographic patterns should be discussed in terms of only changes at one glacier, albeit that’s where the CTD data is. Couldn’t these forcing explain changes along the entire SE coast, as documented in the works cited? Finally, little change has been observed to the north of the Denmark Strait. Is this consistent with the spatial-temporal pattern of forcing you elucidate?”

To answer this, we have included a second new figure. This figure (Figure 11) shows changes in the position of calving margins for 30 glaciers in East Greenland together with subsurface temperatures from the ocean reanalysis. The data are from Seale et al. (2011). The figure clearly shows the connection between synoptic atmospheric pressure variations and properties of coastal water, and that it is not only valid for the Kangerdlugsuaq Trough region, but for the wider southeast coast south of 69°N. We included this modified figure because it clearly shows the connection between ΔP and ocean temperature. Seale et al. (2011) do not show ΔP and do not discuss the role of winds. Hence, we include the modified figure, rather than simply citing Seale et al. (2011).

The following paragraph was added to describe the new figure:

“The wider effect of ΔP on coastal water temperature and glacier dynamics are shown in Figure 11. The figure shows changes in the frontal position of 30 marine-terminating glaciers fronts in East Greenland, as reported by Seale et al. (2011). The figure clearly shows that retreats were common in 2000-05 for glaciers south of 69°N (Fig. 11a), whereas glaciers further north remained largely unchanged (Fig. 11b). The retreat of the southern glaciers coincides with major warming of the entire water column at adjacent coastal sites (Fig. 11c). Furthermore, the connection between ΔP and water mass change, as discussed above, remains intact when assessed on a regional scale (Fig. 11c). The role of the geostrophic wind and the mechanisms of water mass exchange between the Irminger Sea and KTr thus apply to the shelf seas of East Greenland south of 69°N, causing impact on outlet glaciers along the entire southeast coast of Greenland. The setting of glaciers north of 69°N is considerably different in that temperature of coastal waters are largely below 0°C (Fig. 11d). The unchanged position of northern glaciers may thus be explained by cold properties of coastal shelf waters (Seale et al., 2011). The cold state of shelf waters north of Denmark Strait is associated with transport of cold polar waters and sea ice from the Arctic Ocean and a much more limited and distant supply of AW."

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Editor: "The results essentially extend those of Holland et al. 2008 from the west coast to the east, providing a more global perspective on widespread change. This should be pointed to."

We addressed this point by adding the following short paragraph as the final conclusion:

"Our findings show that the geostrophic wind should be regarded as a key factor in the oceanographic forcing of the Greenland Ice Sheet. The connection between the position of the IL and ΔP and its influence on coastal waters apply to the shelf seas south of 69°N, causing impact on outlet glaciers along the entire southeast coast of Greenland. The same mechanism explains the warming observed in coastal waters along the west coast (Holland et al., 2008), as coastal waters from East Greenland are transported to the west coast in coastal currents. Khan et al. (2010) report a shift in the centre of ice-sheet mass losses, from southeast to northwest Greenland after 2007, and these losses may comprise a delayed response of north-western tidewater glaciers to warm coastal waters originating from the east coast."

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Editor: “In summary, I ask the authors perform minor revisions on this work in line with my comments above, detailed points below, and those of the reviewers. In addition, please respond to each review as a reply to the discussion in the TCD thread.“

This has now been done.

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Below are responses to the detailed comments by the AE:

Editor: In numerous places: "East Greenland" or "East Coast" should only be in caps if a proper noun, but not a modiïňĄer. Should be "east Greenland" and "east coast".

Response: We have replaced ‘East Coast’ with ‘east coast’ throughout the text, but have retained ‘East Greenland’. East Greenland is an officially named region of Denmark. In Danish it is Østgrønland; not øst Grønland. East Greenland should therefore be correct.

Editor: page 2/line 2: "with ocean reanalysis *model estimates*" ? need to deïňĄne "reanalysis"

Response: The ocean reanalysis is a reanalysis because in situ measurements of temperature and salinity were assimilated in the simulation. This differs from a ’hindcast’ simulation which would be a free-run of the model with no assimilation of data. We added this sentence to section 2.2 entitled “Ocean reanalysis”:

“The ocean model simulation is referred to as reanalysis (rather than a hindcast) because it assimilates in situ measurements of temperature and salinity.”

Editor: 2/3: "east Greenland"

Response: Retained, see comment above.

Editor: 2/4: misleading. the hydrographic data only show that 2004 survey was warmer than a survey in 1993, while "warming" implies a trend.

Response: The first two sentences of the abstract have been revised to:

“Hydrographic data acquired in Kangerdlugssuaq Fjord and adjacent seas in 1993 and 2004 are used together with reanalysis from the NEMO ocean modelling framework to elucidate water-mass change and ice-ocean-atmosphere interactions in East Greenland. The hydrographic data show that the fjord contains warm subtropical waters and that fjord waters in 2004 were considerably warmer than in 1993. . ..”

Editor: 2/7: again, "reanalysis" of what? I suggest actually naming the model in line 2 and then you need only name it later.

Response: See comment immediately above.

Editor: 2/21: "long term" is ambiguous. Why not just say it was "close to balance"?

Response: Revised as suggested

Editor: 2/23: why "can"? They do.

Response: Revised as suggested

Editor: 3/12: "timescales"

Response: Time scale is as far as we know two words. We left this unchanged.

Editor: 4/6: "...2004, together with..."

Response: Corrected

Editor: 4/6: write out acronym "NEMO"

Response: Revised as suggested.

Editor: 4/7: "...model, to..."

Response: Corrected

Editor: 4/7: "...elucidate air-sea and ice-ocean interactions." Vague. We already know

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they interact, so what about the interactions will be elucidated?

Response: To be more precise, we changed this sentence to " .... to establish the connection ice-ocean interactions in a glaciated fjord and offshore air-sea interactions."

Editor: 4/8: NAO already deïňĄned.

Response: Corrected

Editor: 4/9: "...and, furthermore, the latter data were acquired..." or, better, break into 2 sentences with the 2nd beginning with "Furthermore, the latter data ...".

Response: Changed as suggested

Editor: 5/9: "...icebergs allowed the station..." Awkward. \

Response: Revised

Editor: 5/26: what makes it "primitive"? relative to what?

Response: Removed

Editor: Section 2.2: Much of this description seems unnecessary for the scope of the paper - I suggest removing much of the model detail, since it is given in the cited works, and focusing only on the relevant and/or novel attributes of the model to this application.

Response: We have shortened section 2.2 by removing some technical and non-essential sentences. However, we do want to make it clear what the ocean model is, and what it is capable off. We have therefore left most of this section unchanged. Physical oceanographers will presumably appreciate this.

Editor: 9/10: "...both meaningful and informative." Vague. Exactly how is it meaningful and informative for your analysis?

Response: We changed this sentence to: "Although the absolute value of this flux is not definitive, as it is calculated on the basis of a reference value and because there is a net volume flux across the transect, its relative temporal variability is here both meaningful and informative because it specifies the relative significance of warm inflow and cold outflow."

Editor: 11/16: "This delay between ocean warming (from SST's) and glacier retreat/acceleration for the entire SE coast has been previously noted (Howat et al. 2008, J. Glac.) and was attributed to the effect of basal topography, as initially slow retreat from basal highs could lead to faster, larger retreats into over-deepenings. This progression is supported by modeling work (e.g. Nick et al. 2009, Nature Geoscience)."

Response: Although we do not disagree with the findings of Howat et al. (2008) and Nick et al. (2009), we question whether a topographic over-deepening is a prerequisite for fast glacier retreat. The widespread retreat in the southeast and the unchanged position of northern outlet glaciers implies an environmental cause since it is unlikely that over-deepenings should only exist south of 69°N (see comment above).

To address this comment, we added the following short paragraph to section 4 entitled "The abrupt retreat of KG in 2004-05":

"The delayed retreat of KG relative to peak heat flow into KTr is similar to the delayed retreat of glaciers farther south relative to peaks seen in sea-surface temperature data (Howat et al., 2008). Howat et al. (2008) suggest the delay is connected to initial slow retreat over topographic high points and subsequent fast retreat across over-deepened troughs with reverse bed slopes. Whereas Helheim Glacier retreated across an over-deepening (Nick et al., 2009), it is not certain that glaciers undergoing significant retreat are necessarily positioned over topographic over-deepenings. The observed delays may in general be connected to the period over which water masses travel from deep ocean, across the continental shelf and into fjords, as well as the sensitivity of individual glaciers to oceanographic change...."

To address a related comment by J. Amundsen (referee) we finish this paragraph by stating:

“. . . The latter is beyond the scope of this study, but includes the influence of glacier geometry and calving-related processes, such as ice-front melting (Rignot et al., 2010) and presence of proglacial ice melange and sikussak (Reeh et al., 2001, Joughin et al., 2008b; Amundson et al., 2010).”

Reeh et al. (2001) and Joughin et al. (2008b) was added to our list of references.

Editor: 11/25: "east Greenland"

Response: Unchanged (see comment above).

Editor: 11/25: would this effect the entire east Greenland coast, or should this be speciïňĄed more narrowly? (i.e. central and southern east Greenland?). This is important considering the differing of behavior of northeastern glaciers.

Response: Addressed by adding a new figure (Figure 11). See response to related comment above.

Editor: 12/10: "east coast"

Response: Corrected

Editor: 12/15: give these statistics of signiïňĄcance.

Response: Correlation coefficient included (r=0.64).

Editor: 14/15: Same issue with "warming... between 19993 and 2004" as in the abstract. The model estimates are what’s needed to establish this as a trend and not temporally random variability.

Response: To avoid ambiguity, we changed this sentence, which is the first in the summary section, to:

“Hydrographic surveys conducted in KFj and in transects along KTr show warm properties of fjord waters in 2004 relative to 1993.”

Editor: 15/1: "Subtropical waters ... *are* found....".

Response: Corrected

Editor: 15/13: "subtropical waters *ïňĆow* "

Response: Corrected

Editor: 15/28: Seems appropriate somewhere soon after this statement to link this conclusion to the similar result of Holland et al. 2008, Nature Geosci, providing a more regional context for this forcing.

Response: Revised as suggested. See comment above describing a new paragraph added to the conclusions, i.e. the paragraph starting with "Our findings show that the geostrophic wind should be. . ."

Editor: Figure 2: What is the color scale representing?

Response: This figure has been revised as described above.

Editor: Figure 8: The arrows are almost illegible. Maybe make them white, expand the ïňĄgures and/or make the arrows smaller?

Response: This figure has been increased in size as suggested. The arrows are now more legible.

Interactive comment on The Cryosphere Discuss., 5, 1335, 2011.

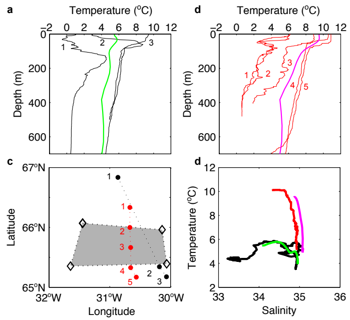

Figure 6. (a) Temperature profile for September 1993 as seen in ocean reanalysis (green) and observations (black) at the outer continental shelf and slope. Numbers refer to stations whose location is shown in (c). (b) Same as (a) but for September 2004. Ocean reanalysis data are shown by magenta line and red lines are observations. (c) Location diagram with black diamonds and grey shading illustrating area used derive modelled temperature profiles as shown in (a) and (b). The same area is used to derive the water mass properties shown in Figure 5. Black dots and dashed line show station transect and location of stations in 1993. Red dots and dashed line show station transect and location of stations in 2004. (d) Potential temperature and salinity for water masses as seen in ocean reanalysis for September 1993 (green) and September 2004 (magenta), and the mean of nearby observations from September 1993 (black) and September 2004 (red).

Fig. 1. New figure (Figure 6). See caption above.

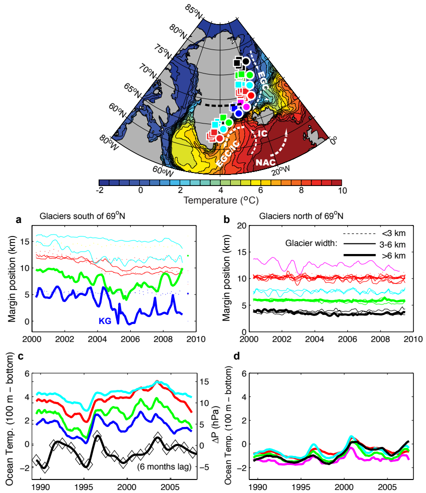

Figure 11. Map of Greenland and surrounding seas (top) with coloured squares showing locations of marine-terminating glaciers whose frontal positions are shown in (a) and (b). Coloured dots show adjacent locations where subsurface temperatures are examined in ocean reanalysis (c-d). The colour scale show sea surface temperature averaged for 2004. (a) Changes in the position of calving fronts for glaciers south of 69°N. The colours represent three glaciers in Mogens Fjord (red), Tingmjarmiut and A. P. Bernstoffs Gletscher (cyan); Helheim Glacier (green), and three glaciers in KFj including KG (blue). (b) Same as (a) but for glaciers north of 69°N. The glaciers are Borggraven (magenta); eight glaciers in Scoresbysund including Daugaard-Jensen (red); Hisingers and Nordenskjorlds Gletscher near Mestervig (cyan); four glaciers in and around Kejser Franz Joseph Fjord (green), and four glaciers near Danmarkshavn (black). Colours match locations shown on map (top). (c) Subsurface temperature from ocean reanalysis averaged from 100 m to bottom for sites near glaciers south of 69°N. Seasonal temperature variations are excluded by filtering the time-series of monthly means with a 12-month-moving average. Colours correspond to those in (a) and locations shown on map (top). Black diamonds and solid black line show winter atmospheric pressure difference across Denmark Strait (ΔP) as seen in station records from Tasiilaq and Stykkishólmur (see Fig. 1 for location). (d) Same as (c) but temperature is for sites near northern glaciers. Modified from Seale et al. (2011).

Fig. 2. New figure (Figure 11). See caption above.

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