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How does the ocean surrounding the Greenland ice sheet impact its surface mass balance ?

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Abstract. *During summer 2012, surface melt record was observed over the Greenland Ice Sheet (GrIS). It most certainly results from more frequent negative phases of the North-Atlantic Oscillation (NAO) favouring warmer conditions over the GrIS. Anomalies in sea ice cover (SIC) and sea surface temperature (SST) during last summers (Table 1) don't seem to be involved in these recent GrIS melt records (2007-2012). To demonstrate this hypothesis, a set of sensitivity experiments on SIC and SST has been carried out to estimate the impact of these variables on the GrIS surface mass balance (SMB) over 2007-2012. These sensitivity experiments consist of single or coupled fluctuations of SST and SIC, using the regional climate model MAR forced by the ERA-INTERIM reanalysis. These sensitivity experiments show that changes in SST and SIC surrounding Greenland don't have any significant impact on the GrIS SMB (Table 2) due to katabatic winds. Those are strong enough to prevent the synoptic oceanic wind, influenced by SIC and SST variability, from penetrating into the GrIS (Fig. 4). Slight SMB fluctuations, associated to oceanic forcings, are restricted to coastal regions (Fig. 1 and 3), where katabatic winds weaken. However, anomalies in SST and SIC could have affected the general circulation over Greenland, favouring warmer conditions.*

Methodology. To evaluate the impacts of oceanic forcings on the GrIS SMB, a set of 12 sensitivity experiments were carried out, using the MAR model *(Fettweis et al., 2007)*.Those experiments were forced by the ERA-INTERIM reanalysis over 2007-2012 and were performed at spatial resolution of 40 km, sufficient to display katabatic winds over the GrIS. Those experiments consist of :

- **Tests 1 – 4** : SST -2, -4, +2, +4°C and respectively SIC +3, +6, -3, -6 peripheric pixels.
- **Tests 5 – 8** : SST -2, -4, +2, +4°C with no variation of SIC (Fig. 2 b).
- **Tests 9 – 12 :** SIC +3, +6, -3, -6 peripheric pixels with no variation of SST (Fig. 2 a).

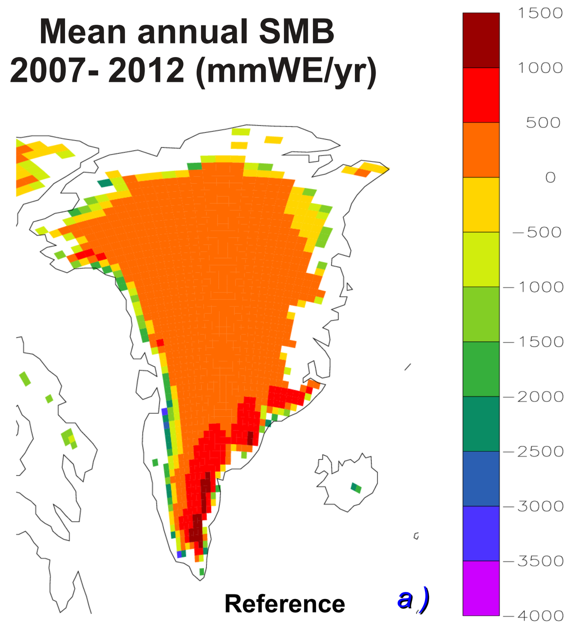
Results. This research focuses on annual SMB fluctuations over the GrIS due to oceanic forcings. The SMB is calculated as : **SMB =** Snowfall **SF +** Rainfall **RF** – Runoff **RU** – Sublimation **E**. However, those experiments show that only **SF**, **RF** and **RU** fluctuate significantly with changes in SIC and SST (Table 2). This generates slight anomalies in the GrIS SMB, especially along the western and southeastern coasts. Those anomalies are respectively driven by changes in **RU** and **SF** (Table 2).

Role of oceanic forcings. **No significant impacts on the GrIS SMB** (Table 2).

- **↗ in SIC (annual) :** ↘ in evaporation and air temperature results in a sharp ↘ in **SF** with no significant **RU** and **RF** anomaly. This ↘ the **GrIS SMB** (Fig. 1 b). Opposite results are observed for **↘ in SIC** (Fig. 1 e).

- **↗ in SST (annual) :** ↗ in evaporation and air temperature results in a slight ↗ in **SF** and **RF** overstriped by a sharp ↗ in **RU**, leading to a ↘ in the **SMB** (Fig. 1 d). Opposite results are observed for a **↘ in SST** (Fig. 1 g).

- **↗ in SST (summer) :** ↗ in evaporation and air temperature results in a slight ↘ in **SF** (partially turned into **RF**). Opposite results are observed for a **↘ in SST** during summer (Table 2).



Coupled effects of SIC-SST.

- **Annual :** Changes in **SMB**, induced by combined SIC-SST anomalies, are **compensated**. An ↗ in SIC (↘ **SMB**), associated with a ↘ in SST (↗↗ **SMB**), leads to a resultant slight ↗ in the **SMB** (Fig. 1 c). Opposite results are observed for ↘ in SIC and ↗ in SST (Fig. 1 f).

- **In summer :** Combined SIC-SST anomalies **amplify** **SF** and **RU** changes, impacting the **SMB**. An ↗ in SIC, associated with a ↘ in SST, leads to a resultant ↗ in **SF** and sharp ↘ in **RU** (Fig. 3 b). Opposite results are observed for ↘ in SIC and ↗ in SST (Fig. 3 c).

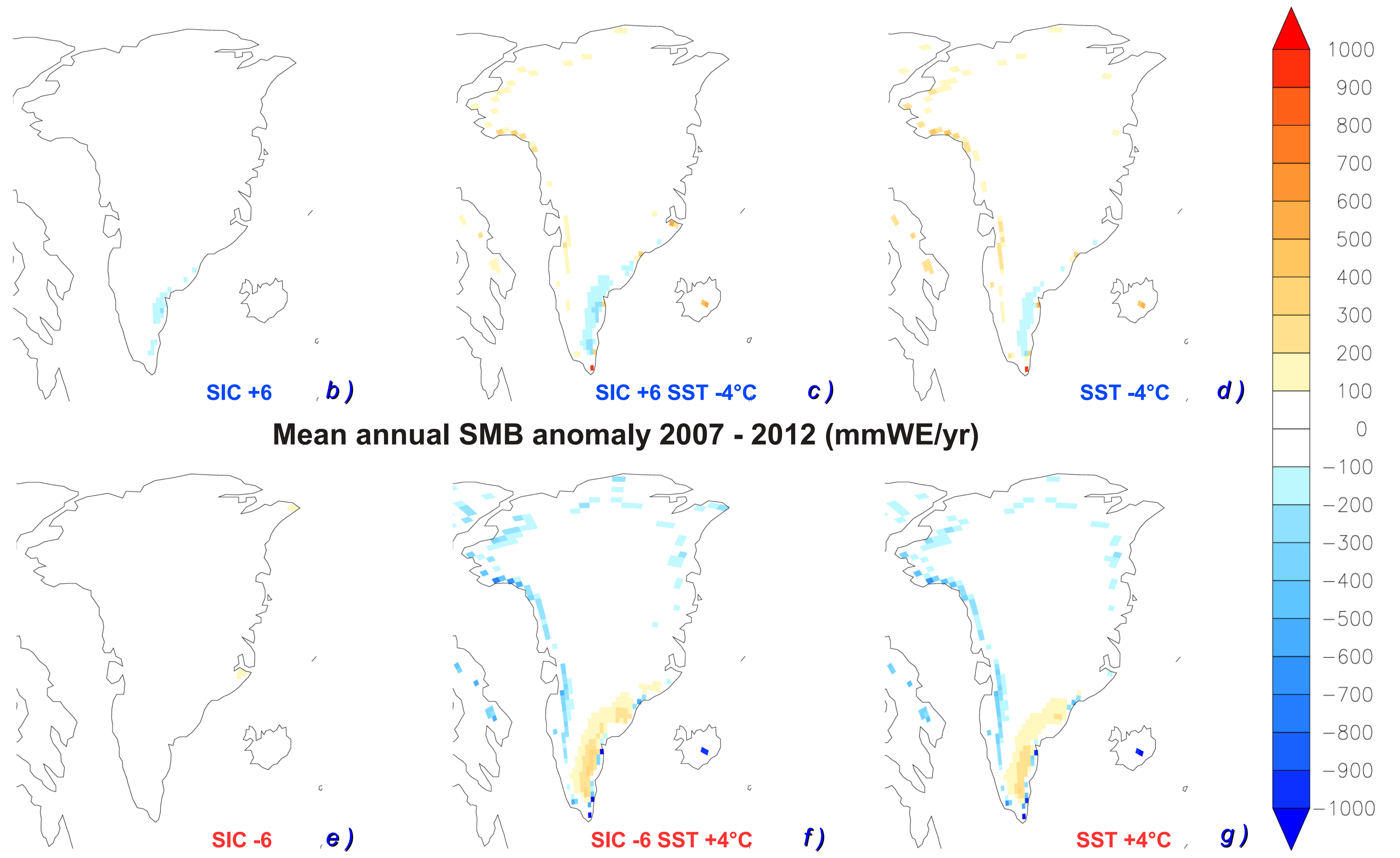


Fig. 1 a) *Mean annual cumulated SMB (mmWE/yr) for the reference run, using the MAR model, for the period 2007-2012. Difference in the SMB (mmWE/yr) between the most extreme sensitivity experiments **b)** SIC +6 **peripheric pixels, c)** SIC +6 peripheric pixels and SST +4°C, **d)** SIC -6 peripheric pixels, **e)** SST +4°C, **f)** SIC -6 peripheric pixels, **g)** SST +4°C and the reference run over 2007-2012. Those simulations were carried out using a 40 km spatial resolution to enable the MAR model to simulate the katabatic winds. The MAR model was forced by the ERA-INTERIM reanalyses (1° x 1°) over the period 2002 -2012. The integration domain (Fig. 2) was selected wide enough to prevent boundaries forcing from affecting the GrIS region.*

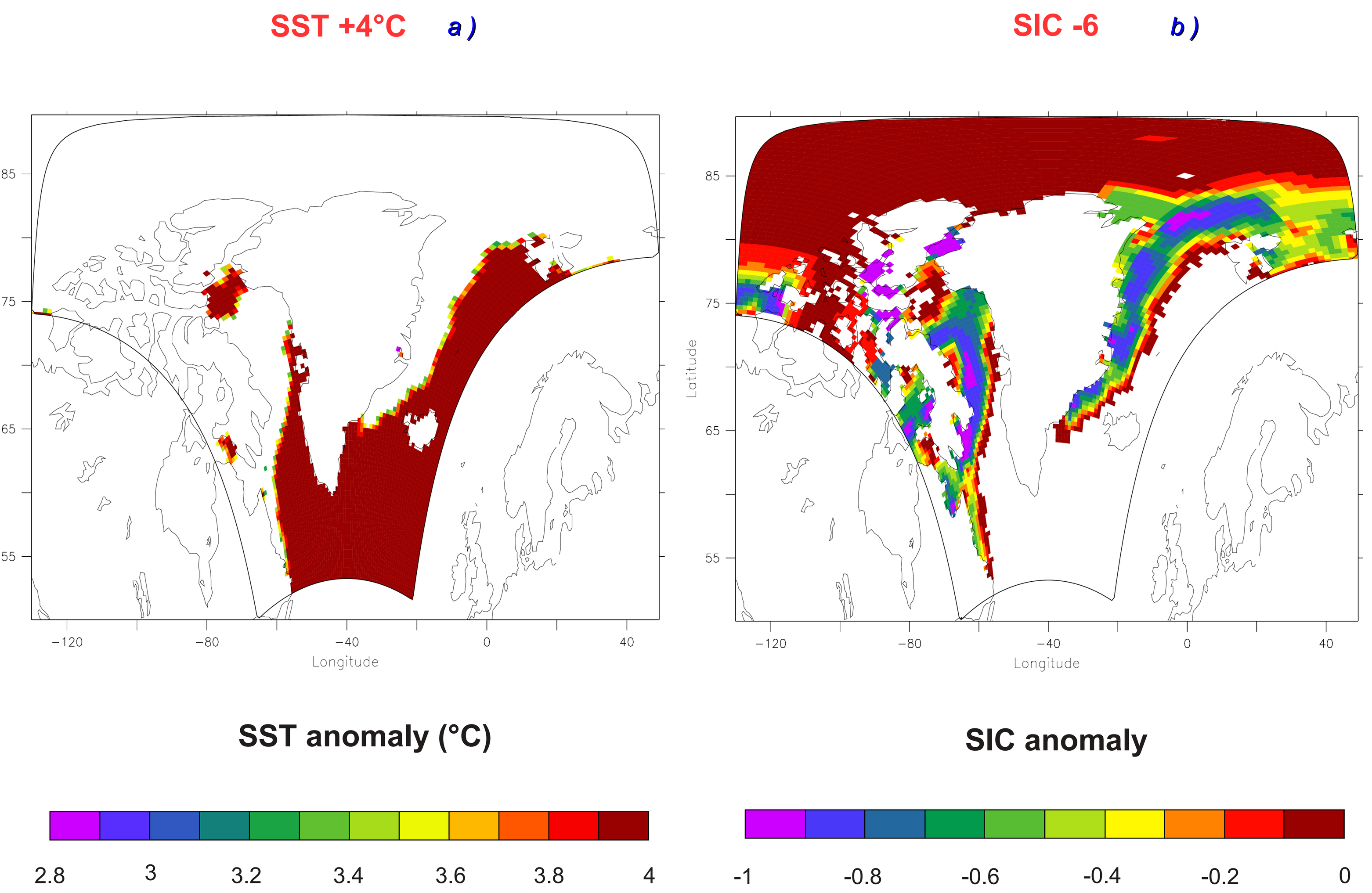


Fig. 2 a) *Difference between SST (°C) from the sensitivity simulation SST +4°C and the reference run for the 1st of June 2012. Only ice free oceanic pixels (SIC ≤ 20%) are subjected to SST variations. **b)** Difference between SIC from the sensitivity simulation SIC -6 and the reference run for the 1st of June 2012. The SIC value of each sea ice pixel is computed as the min SIC value from a distance range of 6 pixels surrounding the current one.*

JJA anom 2012	Reference	SIC +3	SIC +6	SIC -3	SIC -6
SIC (10³ km²)	-635,4	30,4	589,5	-1274,5	-1670,8
SST (°C)	1,2				

Table 1) *This table lists the 2012 JJA SI extent anomalies for the reference simulation and SIC sensitivity runs over the integration domain (Fig. 2) with respect to those from the ERA-INTERIM reanalyses (1979-2000). The 2012 JJA SST anomaly is also listed for the reference run.*

Annual (2007-2012)						JJA
Mean (Gt/yr)	**SMB**	**Snowfall**	**Rainfall**	**Runoff**	**Melting**	**Snowfall**
Reference	237	555	28	354	585	117
Difference (Gt/yr)	**SMB**	**Snowfall**	**Rainfall**	**Runoff**	**Melting**	**Snowfall**
SIC+3 / SST -2°C	-1	-14	-2	-14	-10	4
SIC+6 / SST -4°C	2	**-19**	**-4**	**-22**	**-15**	**7**
SIC -3 / SST+2°C	1	23	4	26	24	-4
SIC -6 / SST+4°C	-7	**48**	**10**	**64**	**58**	**-10**
SST -2°C	8	-7	-2	-17	-13	5
SST -4°C	**15**	**-12**	**-4**	**-29**	**-22**	**8**
SST +2°C	-5	17	4	25	23	-4
SST +4°C	**-13**	**37**	**9**	**59**	**54**	**-9**
SIC +3	-8	-7	-0,2	1	1	1
SIC +6	**-15**	**-16**	-1	-1	-1	2
SIC -3	10	9	0	-2	-2	1
SIC -6	**16**	**13**	0	-3	-4	2

Table 2) *This table lists **(top)** the mean annual cumulated GrIS SMB (Gt/yr) and its components (Gt/yr) for the reference run (2007-2012). This table also lists **(bottom)** the difference in the SMB and its components (Gt/yr) between each sensitivity experiments and the reference run over 2007-2012. The last column shows the mean JJA cumulated snowfall (Gt/3months) over the GrIS for the reference run **(top)**, as well as the difference in snowfall (Gt/3months) between the sensitivity runs and the reference one **(bottom)** over 2007-2012. Significant variable changes are displayed in bold for the most extreme tests. Positive (resp. negative) SMB anomalies are displayed in green (resp. in red).*

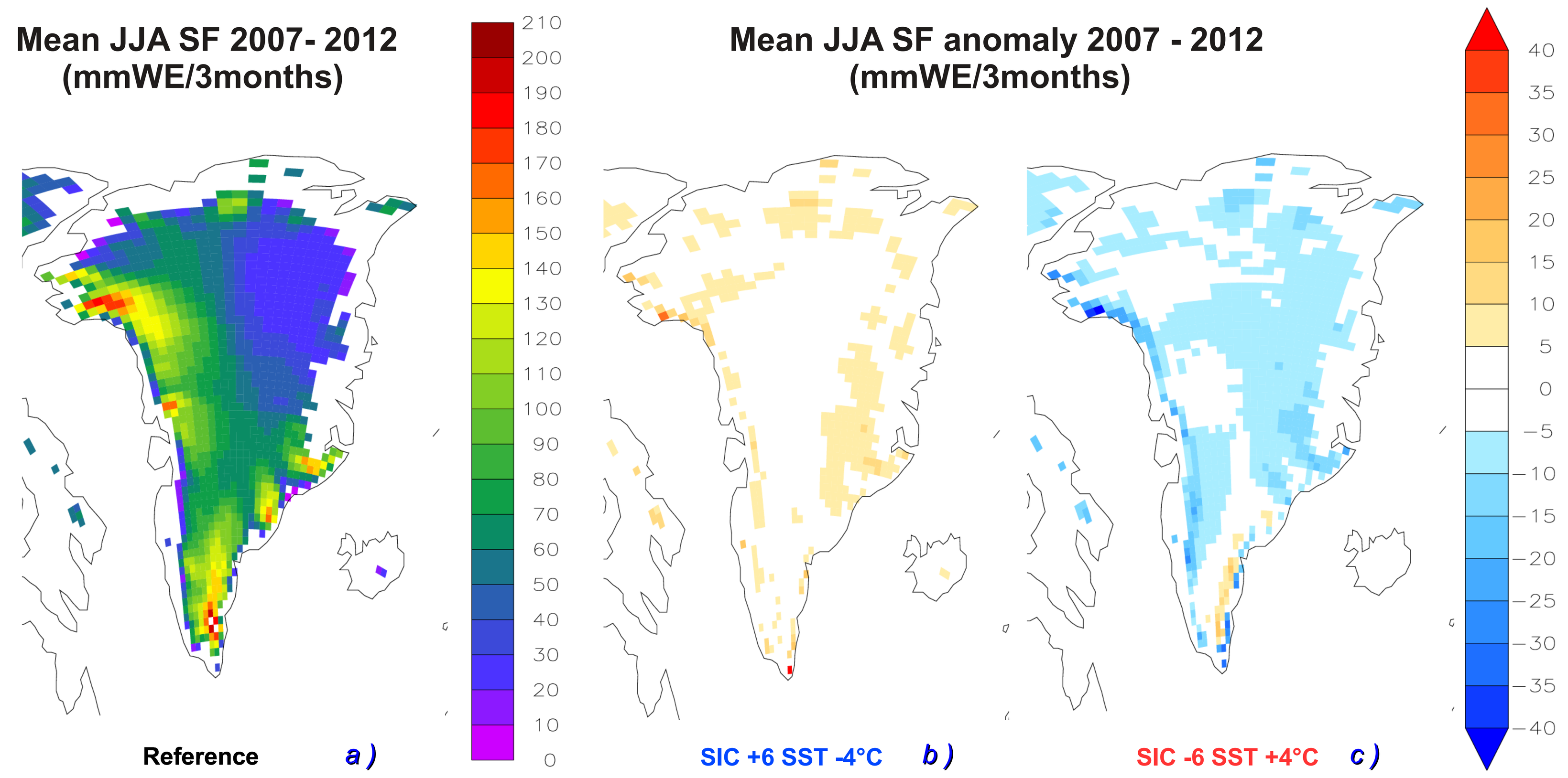


Fig. 3 a) *Mean JJA cumulated snowfall SF (mmWE/3months) for the reference run, using the MAR model, over the period 2007-2012. Difference in SF (mmWE/3months) between the most extreme coupled sensitivity experiments **b)** SIC +6 peripheric pixels and SST -4°C, **c)** SIC -6 peripheric pixels and SST +4°C and the reference run over 2007-2012.*

Role of Katabatic winds. The oceanic forcings influence on the GrIS SMB is restricted to the coastal regions. Katabatic winds are strong enough to prevent oceanic air from affecting the GrIS SMB. However, this thermal wind becomes weaker towards the coastal tundra regions as the surface slope decreases. Moreover, the western coast is more subjected to oceanic forcings as it presents the weakest katabatic winds because of its slighter topography. Finally, enhanced impacts of oceanic forcings are observed in summer, since katabatic winds weaken during this season (Fig. 4).

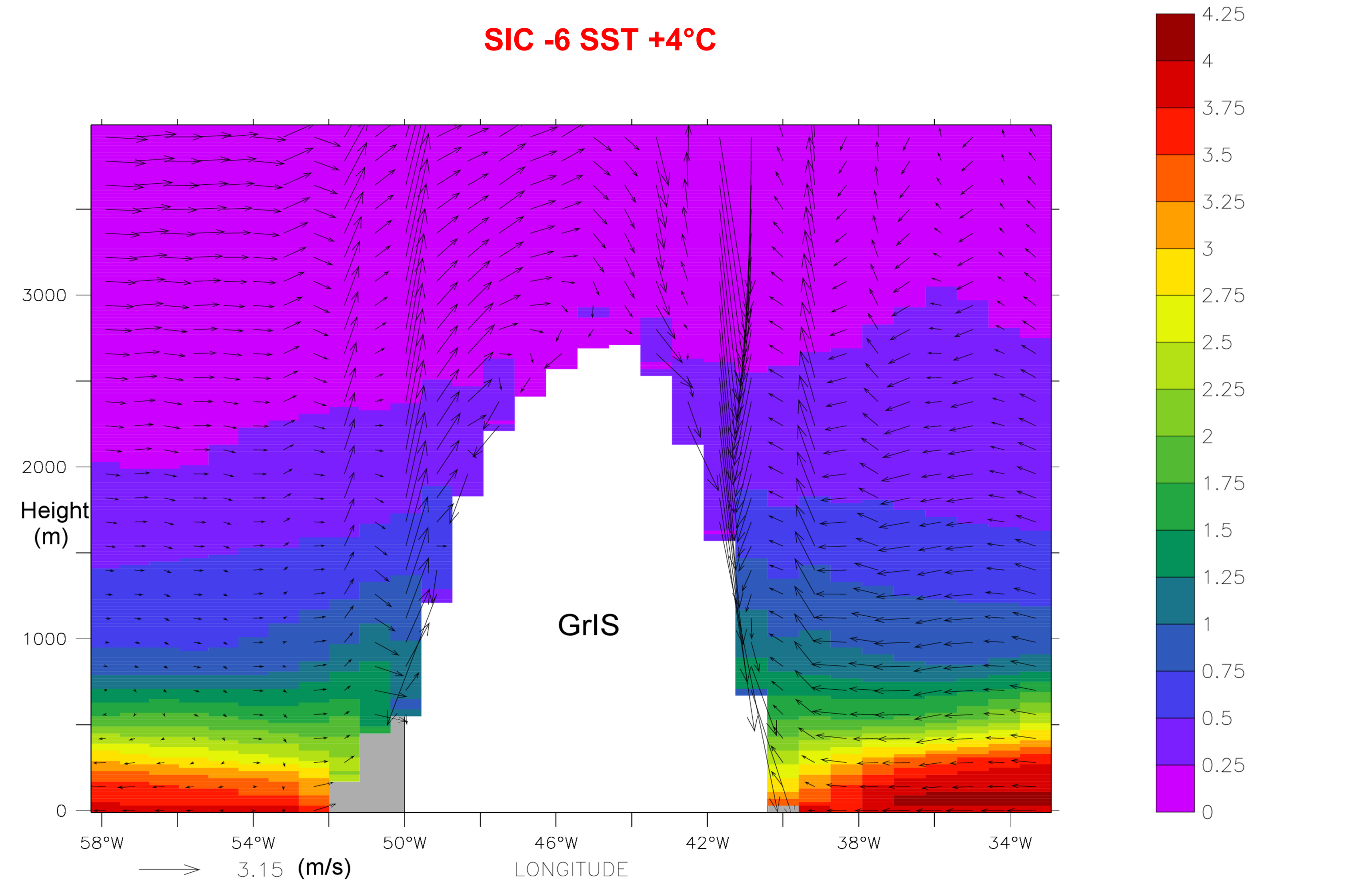


Fig. 4 *Longitudinal GrIS section (60°N), showing the mean JJA wind speed (m/s) and direction from the reference run over 2007–2012. The wind speed and direction were interpolated every 200 m from the MAR vertical grid. The wind speed (m/s) can be estimated using the arrow beneath the graph. The figure background corresponds to the difference between the mean JJA air temperature from the coupled sensitivity experiment SIC -6 peripheric pixels, SST +4°C and the reference run. The greyish area corresponds to the tundra region surrouding the GrIS, where katabatic winds decelerate and further dissipate. This figure also shows the contrast of katabatic winds intensity between the western and eastern coast of the GrIS.*

Conclusion. Oceanic forcings are not directly involved in the melting records observed over the GrIS since 2007 (Table 2). Katabatic winds prevent the near-surface oceanic synoptic air, influenced by SIC and SST variability, from penetrating into the GrIS centre and further affecting its SMB (Fig. 4). However, oceanic forcings may have slightly contributed to SMB anomalies in coastal regions, where katabatic winds almost dissipate. Actually, the melting records are more likely associated with the recent shift in negative NAO phases. This generates a persistent anticyclonic circulation pattern over the southern part of the GrIS. Therefore, this allows more frequent upper-levels southeasterly warm air advections to cross the western part of the GrIS, resulting in enhanced melting *(Fettweis et al., 2013)*.

Reference.

- Fettweis, X.:Reconstruction of the 1979-2006 Greenland ice sheet surface mass balance using the regional climate model MAR, *The Cryosphere*, 1, 21-40, doi:10.5194/tc-1-21-2007, 2007.
- Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M., and Gallée, H.: Brief communication "Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet", *The Cryosphere*, 7, 241-248, doi:10.5194/tc-7-241-2013, 2013.