

A Lagrangian analysis of the dynamical and thermodynamic drivers of large-scale Greenland melt events during 1979–2017

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a short
summary

Short summary

Large-scale Greenland melt events are episodes of enhanced surface melt, also affecting the accumulation zone of the Greenland Ice Sheet (GrIS), which are strongly atmospherically forced. Our analysis reveals that **anomalous poleward transport** of moist-warm air masses and **latent heat release** during ascent are the key processes contributing to the air mass warming – not subsidence within the present upper-tropospheric ridge. We give new insights into the well-documented melt event of July 2012 and answer the following key questions:

- 1) How often did large-scale melt events occur over the GrIS during 1979-2017?
- 2) What is the synoptic flow configuration and the air stream pathways during these events?
- 3) Which thermodynamic air stream modifications and radiative effects over the GrIS caused these melt events?



Click to find
an overview
of the study

Conclusions

Click to
find out
more

The #1 melt event

July 2012 | 15.25 days | 95% melt extent

Dynamics: transport of up to 45°lat in 8 days 

Thermodynamics: latent heat from stronger than usual ascent (see melt event climatology)

Melt event's warm anomaly not directly related to the US heat wave (Neff et al., 2014) 

Data & methods

ERA-Interim
Melt event identification
Backward trajectories 

Melt event climatology synoptic situation & air streams

Synoptic: Upper-level ridge induces strong meridional transport affecting the entire GrIS

Air stream evolution: Stronger ascending motion, accompanied by overall cooling, and diabatic heating 

Anomalous evolution: Originating from warmer regions than usually (low latitude/altitude): rapid transport, latent heat release 

Summary incl. cloud radiative effects

Strong poleward moisture flux

GrIS-wide additional melt potential

Contact





Data & methods

ERA Interim reanalysis data (Dee et al., 2011):

6-hourly during June-August (JJA) 1979-2017

Grid spacing: $1 \times 1^\circ$, 60 vertical levels

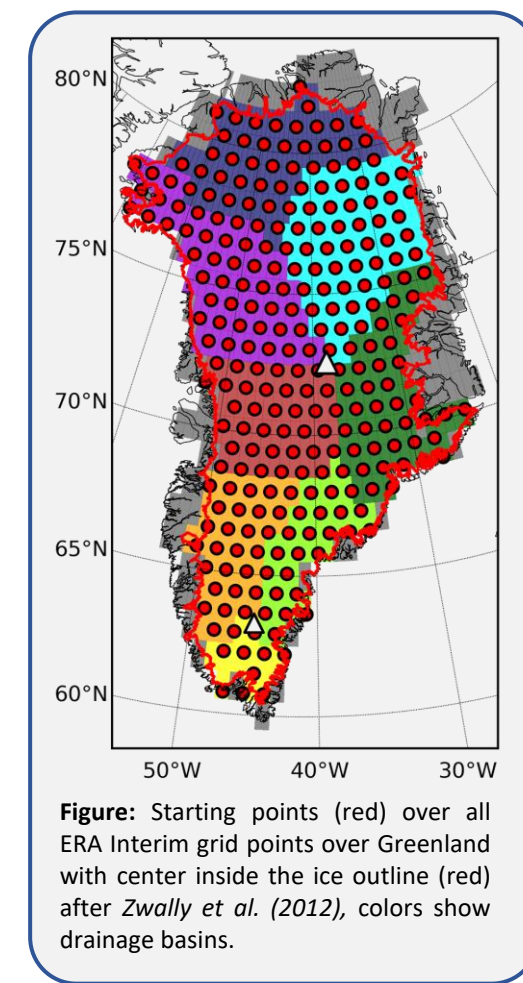
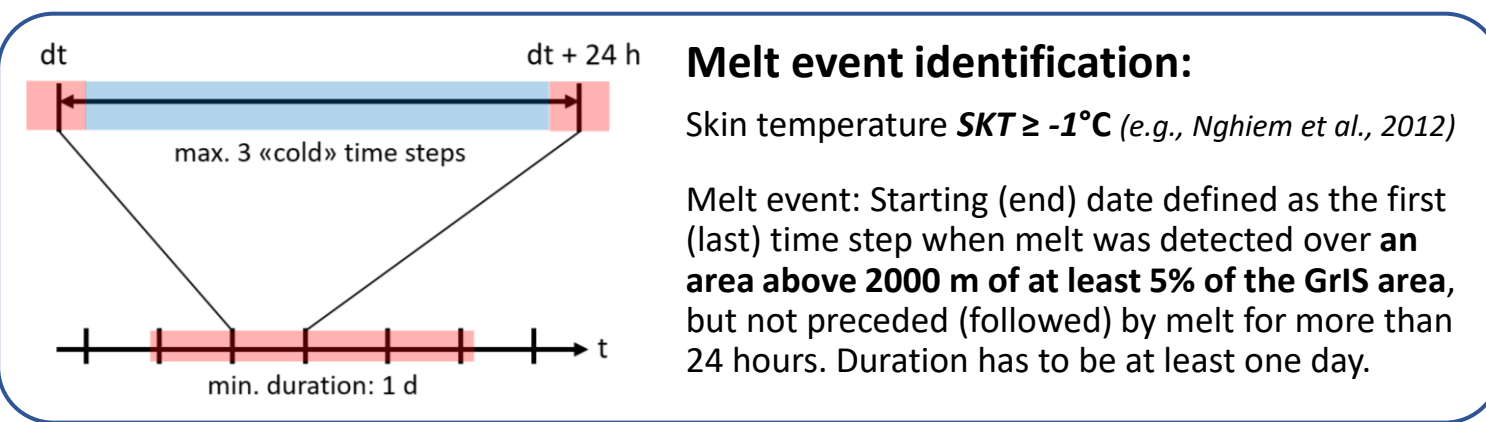
Trajectories calculated with the Lagrangian analysis tool LAGRANTO

(Wernli & Davies, 1997; Sprenger & Wernli, 2015):

Time: 8 or 10 days backward (depending on analysis)

Starting points: Equidistantly spaced over the GrIS, $dx = 80$ km

Starting points: 20/40/60 hPa above ground level



How were the
trajectories
further
evaluated?

Trajectories & illustration

Trajectories:

- ... started during all 77 melt events (mean duration of 4.05 days)
- ... compared to “air mass climatology”: median air streams of all 6-hourly JJA 1979-2017 trajectories

Temperature modifications:

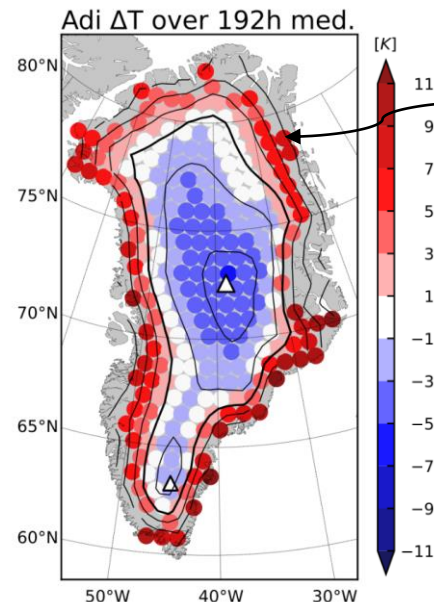
Thermodynamic energy equation (e.g., Holton & Hakim, 2012):

$$\frac{DT}{Dt} = \underbrace{\frac{\kappa T \omega}{p}}_{\text{adiabatic contribution}} + \underbrace{H \left(\frac{p_0}{p} \right)^{-\kappa}}_{\text{diabatic contribution}}$$

→ We calculate adiabatic/diabatic air mass warming from the sum of these terms along each trajectory, by approximating DT/Dt and H numerically (from 3-hourly trajectory output).

Lagrangian forward projections (LFP):

- ... projects trajectory information onto the trajectory starting point (i.e., the air mass end point)



“The air mass arriving here over the northeastern GrIS warmed adiabatically by ~10 K during the 8 days prior to arrival.”

In this study, each circle typically represents the mean over three vertical layers (20, 40, 60 hPa above ground level) and over time (e.g., during all time steps in JJA 1979-2017 for the air mass climatology)

The #1 melt event in July 2012

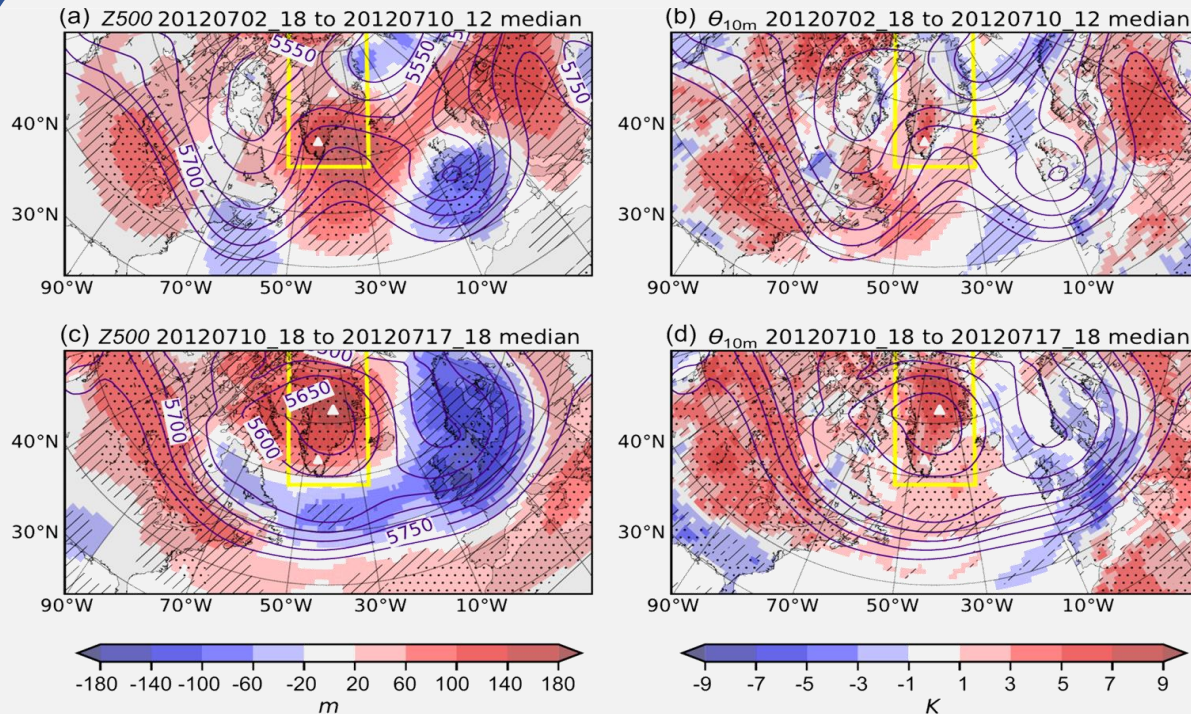


Figure: Median over (a) 18 UTC 2 July to 12 UTC 10 July, and (c) 18 UTC 10 July to 18 UTC 17 July of 500 hPa geopotential height (contours) and its anomalies (colors) wrt. 1979-2017 climatology. Anomalies of potential temperature on the lowest model layer is shown in (b) and (d) for the respective periods. Hatching indicates anomalies outside the 25-75th, stippling those outside the 10-90th percentile range.

Well-studied melt event in early July 2012 with record melt extent and melt at Summit Station (~3216 m) (Nghiem et al., 2012; Bennartz et al., 2013; Tedesco et al., 2013; Neff et al., 2014; Bonne et al., 2015;...)

Confirmation of these findings by our melt event definition:

- 18 UTC 2 July – 18 UTC 17 July (15.25 days)
- Max. melt extent of 94.8% (highest among all events)
- Melt at highest grid point near Summit (3175 m)

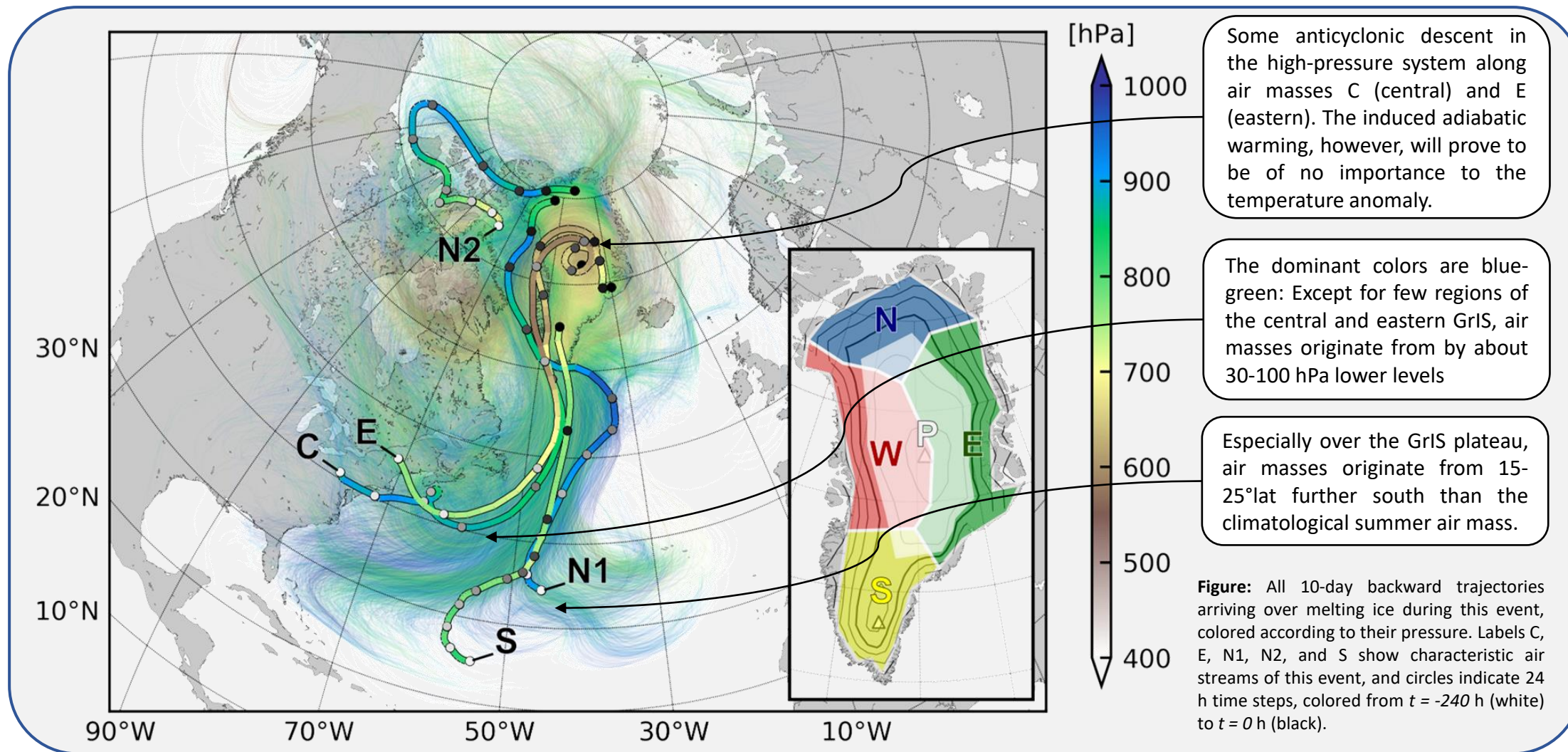
Synoptic situation: blocking-dominated

- **Phase I:** blocking ridge southeast of Greenland (Fig.a) → poleward advection of moist/warm air masses to Southwest Greenland (Fig.b), high IVT at west coast
- **Phase II:** cutoff centered over the GrIS (Fig.c) → distribution of the warmth over the entire GrIS (Fig.d)



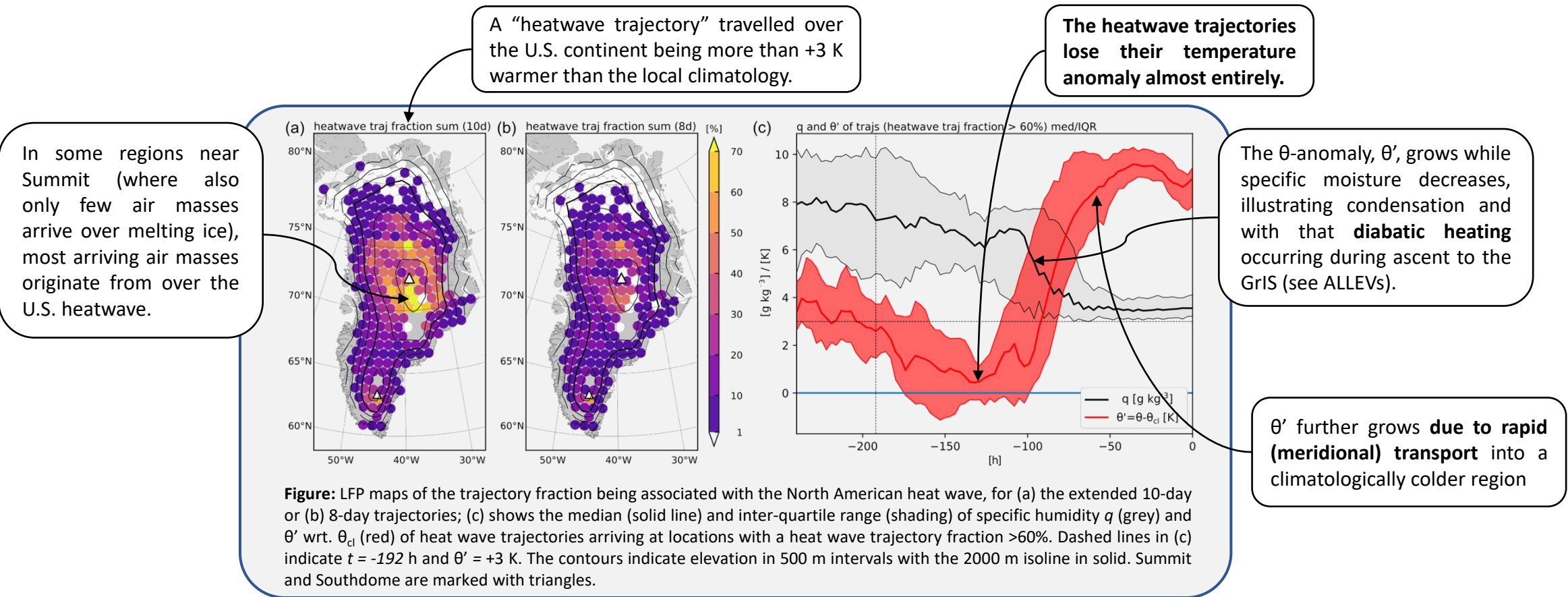
Go to the
Lagrangian
perspective of
this event

#1: characteristic air streams



#1: Concurrent U.S. heat wave

Regions of the central GrIS were fed by air masses from the record heatwave over the U.S. Great Plains (Neff et al., 2014; Bonne et al., 2015). However, they did not carry this temperature anomaly to the GrIS, but arrived anomalously warm due to rapid poleward transport and condensational heating.



Greenland melt event climatology

Strong agreement of the synoptic pattern and the melt air mass sources, transport and temperature changes between the #1 and all melt events.

General flow pattern:

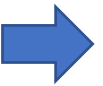
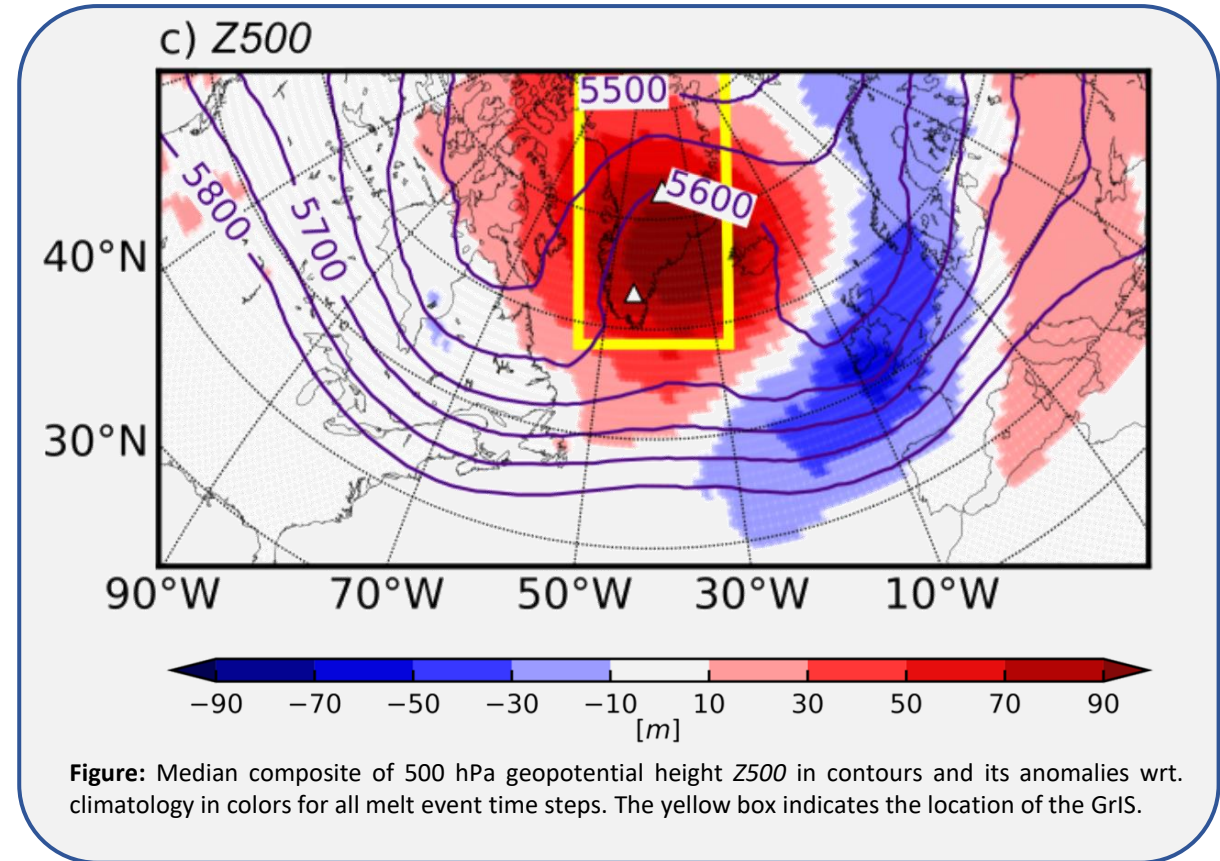
The upper-level ridge and associated surface high pressure system southeast of Greenland are favorably located to induce strong poleward air mass transport to the western GrIS, followed by the distribution of these air masses anti-cyclonically over the entire GrIS.

Air mass origin:

The air masses originate from lower latitude and/or lower altitude wrt. the climatological summertime air parcel. They, however, do not originate from an anomalously warm source region (wrt. local climatology).

Air mass temperature changes:

See next slide



What about the
air mass
warming?

Temperature changes

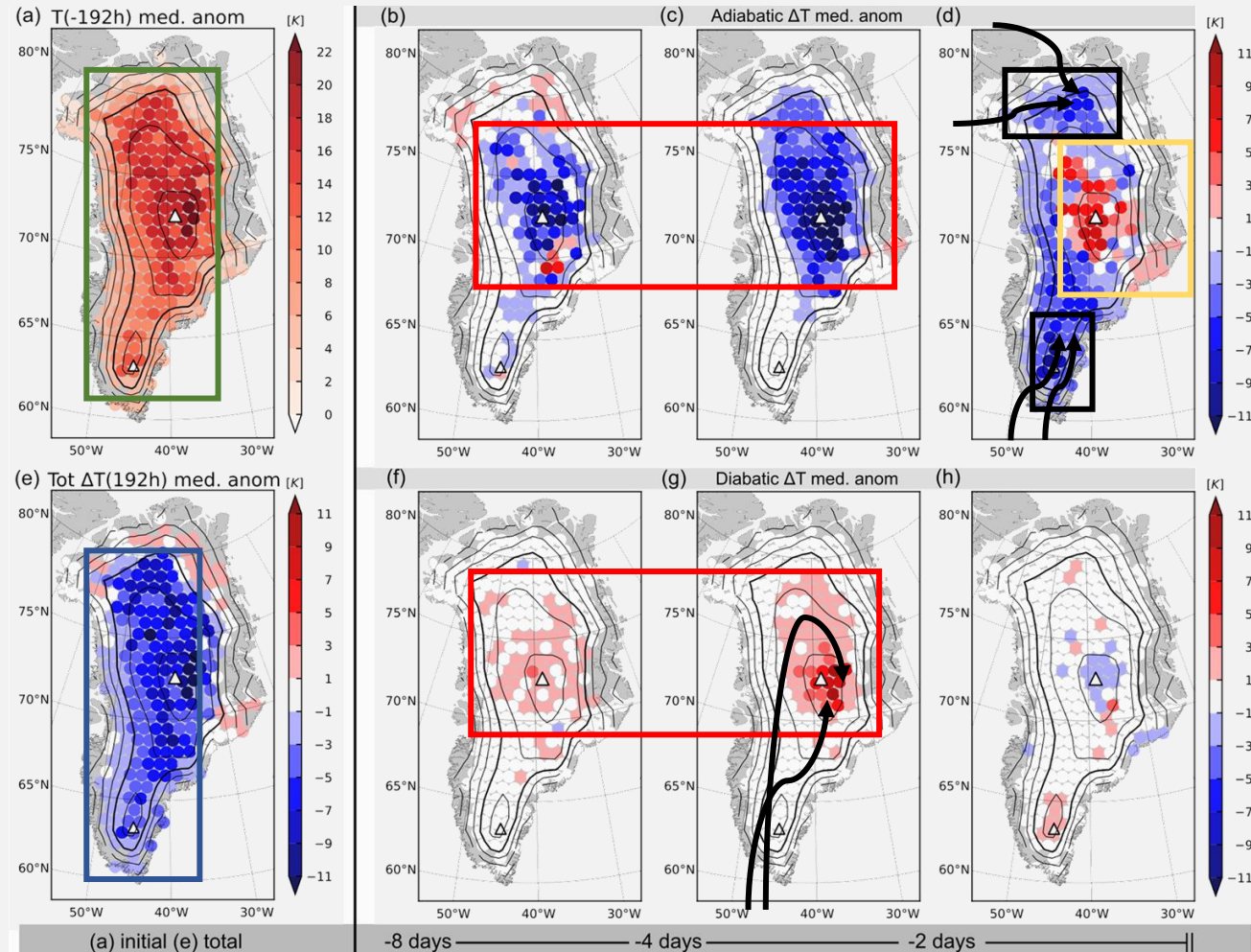


Figure: LFP anomaly maps of the (a) initial temperature at $t = -192$ h, and (b-d) adiabatic, (f-h) diabatic, and (e) total temperature change over eight days wrt. the climatological summertime air streams. The adiabatic and diabatic temperature change anomalies are split up in the periods (b,f) $t = -192$ h to $t = -96$ h, (c,g) $t = -96$ h to $t = -48$ h, and (d,h) $t = -48$ h to $t = 0$ h.

Melt event air masses arriving over melting ice compared to the JJA 1979-2017 climatological air mass arriving at these locations!

- **Warmer than usual air mass origin** (lower in elevation or latitude; **not** anomalously warm wrt. local climatology)
- **Stronger overall cooling** (also related to the warmer origin)
- **Stronger ascending motion** (at the S-tip of the GrIS): stronger adiabatic cooling & diabatic warming than usual
- Final subsidence over the Central & Eastern GrIS (not resulting in a temperature anomaly – not shown)
- Final ascent onto the GrIS (in S- and NW-Greenland)



Find out more
about the air
masses

How do these
LFP maps come
about?

What was the
synoptic
situation?

Anomalous evolution

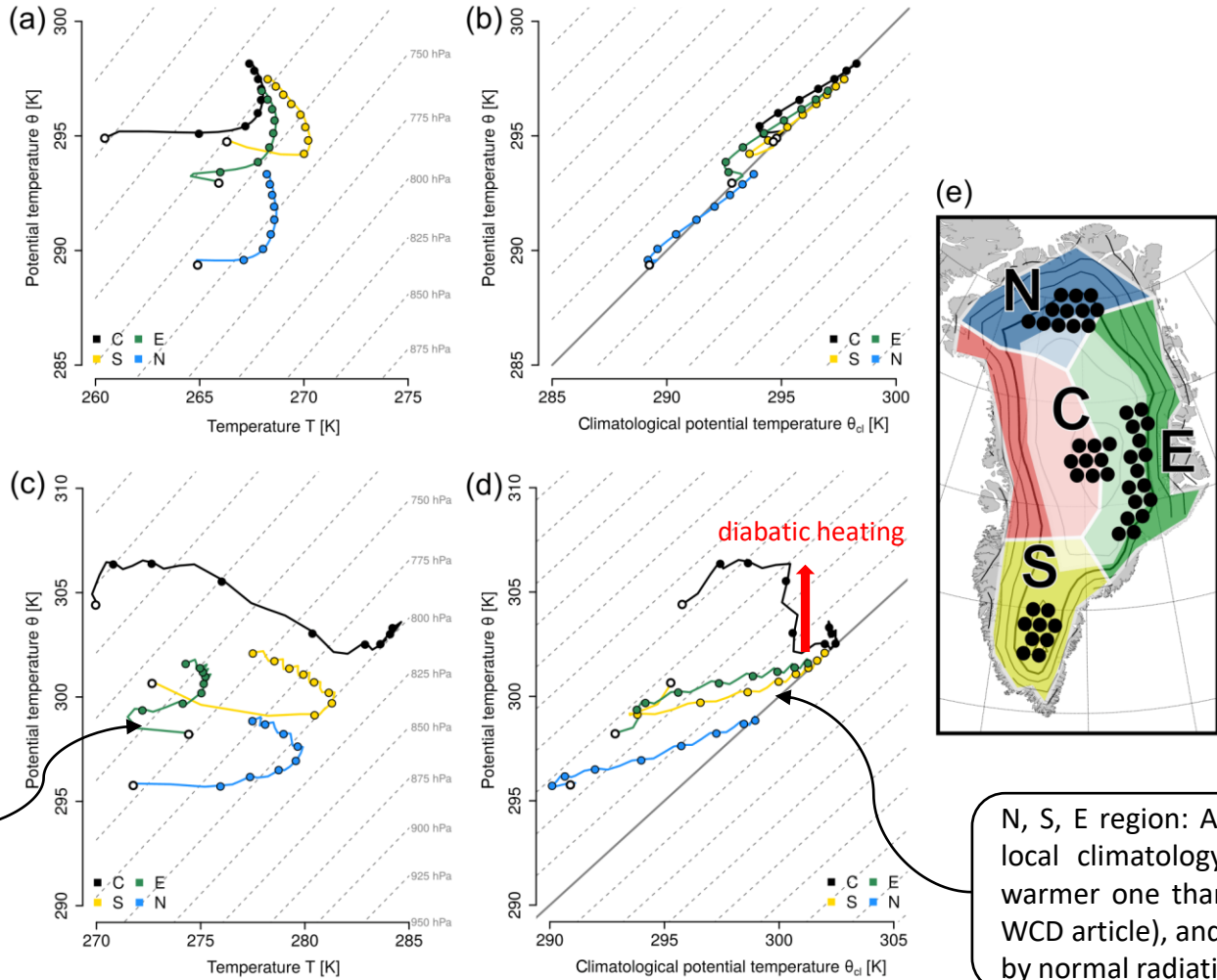


Figure: Thermodynamic evolution of backward trajectories from selected starting points (see e) representative of regions C, E, S, and N. Shown are medians for each trajectory category, summarized as one air parcel, in (a,c) θ -T and (b,d) θ - θ_{cl} space. Grey dashed lines indicate isobars in intervals of 25 hPa (a,c) and isolines of constant potential temperature anomaly in intervals of 2 K (b,d). Panels (a) and (b) represent all climatological summertime air masses, and panels (c) and (d) represent melt air masses only. Circles along the lines indicate time in 24 h intervals, with an empty circle at the trajectory end point at $t=0$ h. Note that the axis limits of (a)-(d) are not identical.

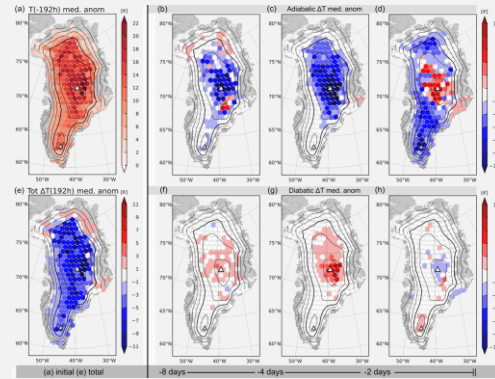
What was the contribution of a/diabatic T-changes?

Only in E region: slight subsidence-related adiabatic warming during the last 24h..

N, S, E region: Air masses were not anomalously warm wrt. the local climatology, but the region itself was a climatologically warmer one than usual (lower and further south; see Fig. 10 in WCD article), and the following **horizontal transport** accompanied by normal radiative cooling.

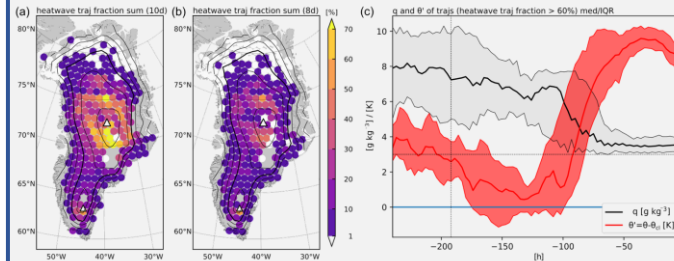
Summary

Transport & diabatic heating



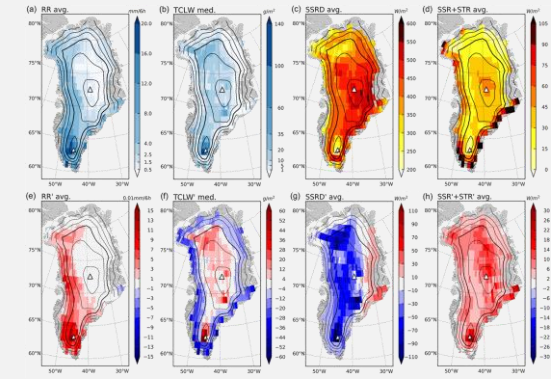
The essence of our trajectory analysis is that air masses being responsible for large-scale Greenland melt events cool stronger wrt. climatological air masses. They acquire their warm anomaly from **strong meridional transport** and higher than usual **diabatic heating** during ascent. This contrasts with Arctic and midlatitude heat extremes that require subsidence-induced adiabatic warming. The upper-level ridge, in most events identified as a block, favors these processes through the induced poleward flow from low latitudes.

#1 melt event



The most extensive melt event that occurred in July 2012 was in many ways representative for Greenland melt events. The **air mass origin** was a peculiarity, being 15-20 K warmer than usually. This is due to its location **up to 45°lat further south** and lower in the atmosphere than climatological summertime air masses. Especially in central Greenland, air masses originated from a concurrent **U.S. record heat wave**. They, however, **did not carry their initial warm anomaly to the GrIS**, but rather got anomalously warm due to strong poleward transport, and diabatic heating from condensation of water vapor during ascent.

(Cloud) radiative effects



The evaluated air masses go along with strong **poleward moisture transport** and are forced to ascend over the southern and western GrIS. Cloud formation and rain go along with a shift of the cloud phase from ice to liquid wrt. climatology. This causes additional downward longwave radiation west of the ice divide. On the eastern side, in the clear-sky regions, downward shortwave radiation is enhanced. The net effect of long- and shortwave radiative anomalies results in an on average by **+2.1 cm ice day⁻¹ increased melting potential**.



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