Lagrangian Analysis of the Dynamical and Thermodynamic Drivers of **Greenland Melt Events 1979-2017**

in review (Weather Clim. Dynam.)

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Short summary

Greenland melt events are episodes of enhanced mass loss, also affecting regions of the Greenland Ice Sheet (GrIS) above 2000 m, which is often 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 near-surface warming – not subsidence within the present atmospheric blocking. We give new insights into the well-documented melt event of July 2012 and answer the following key questions:

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

Conclusions

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 (see *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 mass origin: Unusually low latitude and/or low altitude, but not itself anomalously warm

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

Summary incl. cloud radiative effects

Strong poleward moisture fluxes

GrIS-wide additional melt potential

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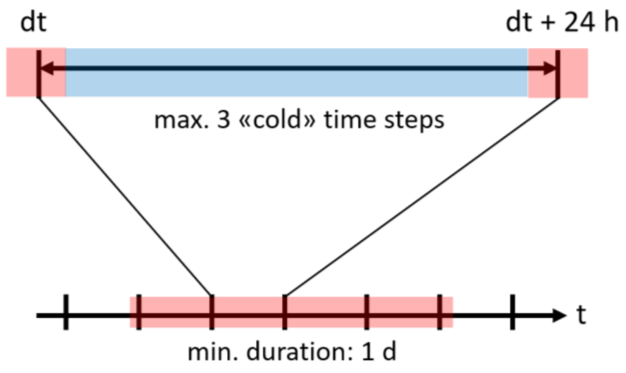
Data & methods

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

6-hourly during June-August (JJA) 1979-2017
Grid spacing: 1×1°, 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



Melt event identification:

Melt: skin temperature ***SKT* ≥ -1°C** *(as in e.g., Nghiem et al., 2012)*
Melt event: Starting (end) date defined as the first (last) time step when melt was detected over **an area above 2000 m of at least 5% of the GrIS area**, but not preceded (followed) by melt for more than 24 hours. Duration has to be at least one day.

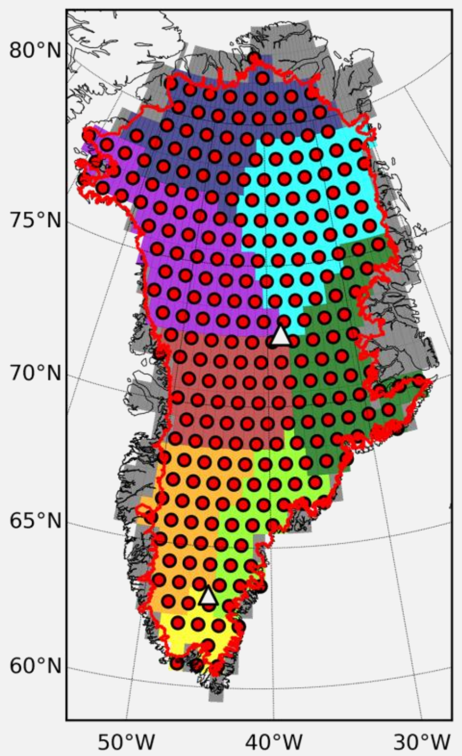


Figure: Starting points (red) over all ERA Interim grid points over Greenland with center inside the ice outline after *Zwally et al. (2012)* (outline in red, drainage basins in color).

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Trajectories & illustration

Trajectories:

… started during all 77 melt events (mean duration of 4.05 days)

… compared to "trajectory climatology": median air streams of JJA 1979-2017

Temperature modifications:

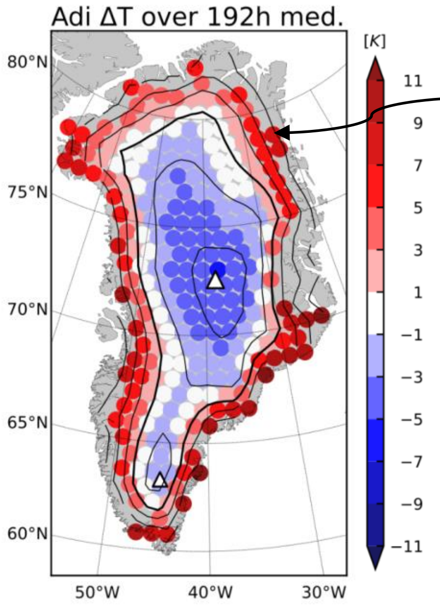
Thermodynamic energy equation *(e.g., Holton & Hakim, 2012)*:

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

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

Lagrangian forward projections (LFP):

… projects trajectory information onto the starting point



"The air stream arriving here over the northeastern GrIS warmed adiabatically by ~10 K during the 192 hours prior to arrival."

In this study, each circle typically represents the average or median (depending on the variable) over the three vertical layers (20, 40, 60 hPa agl) and over time (e.g., during all time steps in JJA 1979-2017)

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The #1 melt event

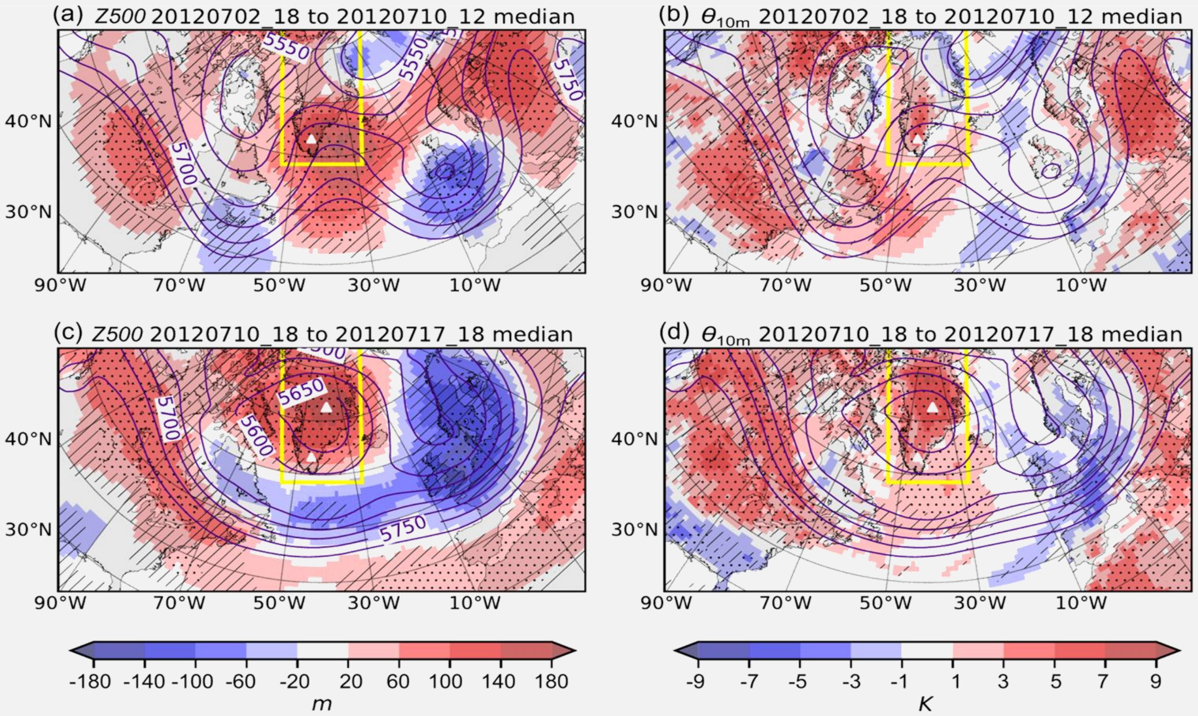

Figure: Median over (a) 18 UTC 2 July to 12 UTC 10 July, and (c) 18 UTC 10 July to 18 UTC 17 July of 500 hPa geopotential height (contours) and its anomalies (colors) wrt. 1979-2017 climatology. Anomalies of potential temperature on the lowest model layer is shown in (b) and (d) for the respective periods. 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)*
- **Phase II:** cutoff centered over the GrIS *(Fig.c)* → distribution of the warmth over the entire GrIS *(Fig.d)*

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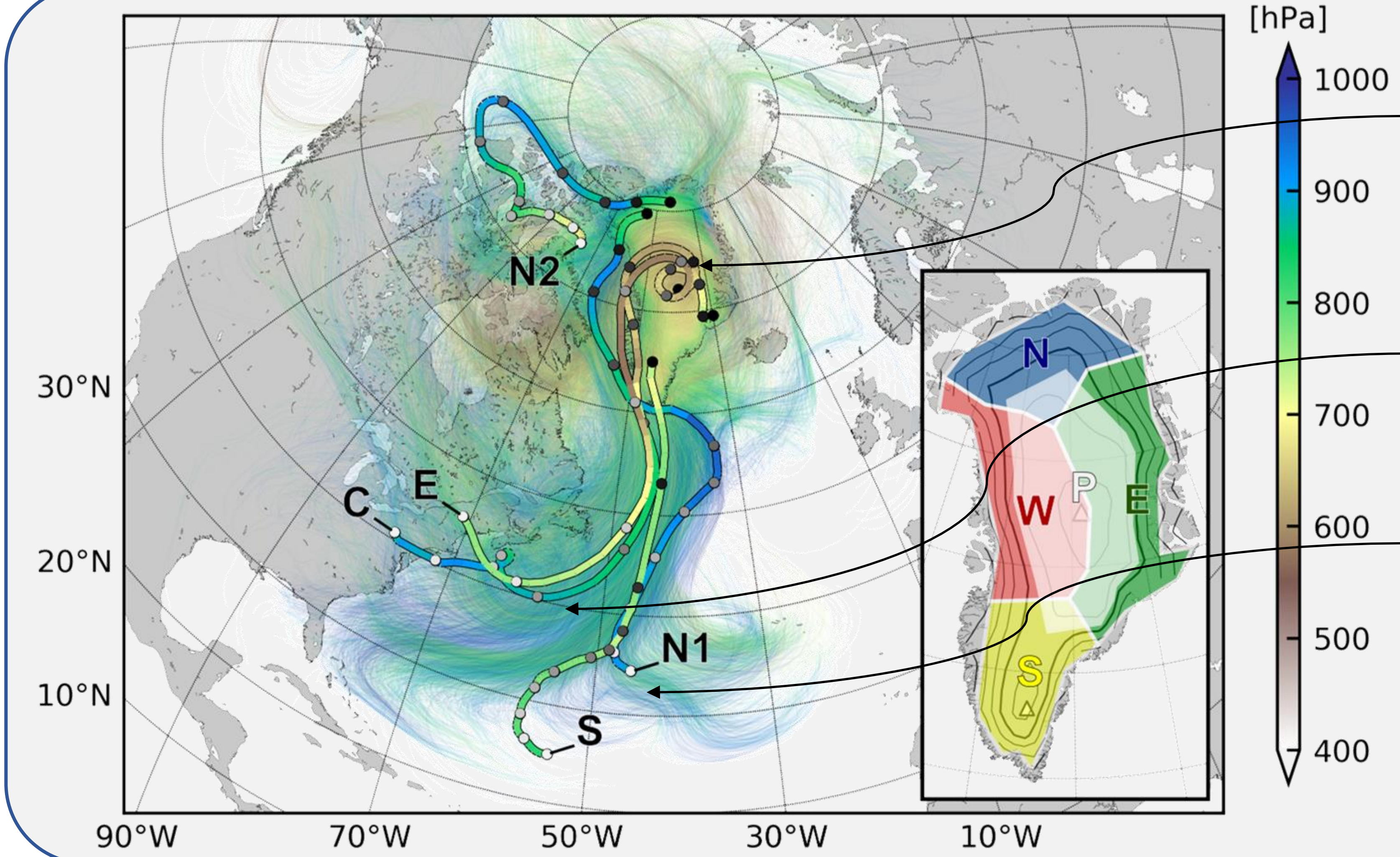
#1: characteristic air streams



Some anticyclonic descent in the high-pressure system along air masses C (central) and E (eastern). The induced adiabatic warming, however, will prove to be of no importance to the temperature anomaly.

The dominant colors are blue-green: Except for few regions of the central and eastern GrIS, air masses originate from by about 30-100 hPa lower levels

Especially over the GrIS plateau, air masses originate from 15-25°lat further south than the climatological summer air mass.

Figure: All 10-day backward trajectories arriving over melting ice during this event, colored according to their pressure. Labels C, E, N1, N2, and S show characteristic air streams of this event, and circles indicate 24 h time steps, colored from *t = -240* h (white) to *t = 0* h (black).

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#1: Concurrent U.S. heat wave

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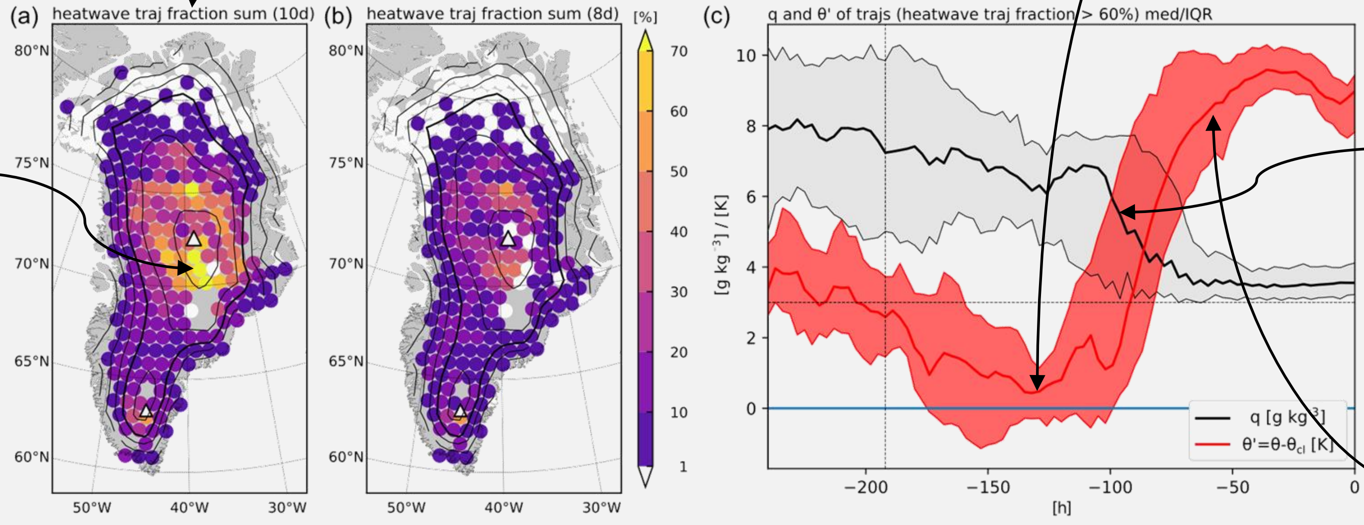
Investigation of air mass transport from the record heatwave over the U.S. Great Plains and its importance for the #1 melt event *(Neff et al., 2014)*, as well as the role of moisture transport from the western subtropical North Atlantic *(Neff et al., 2014; Bonne et al., 2015)*.

A "heatwave trajectory" travelled over the U.S. continent being more than +3 K warmer than the local climatology.

The heatwave trajectories lose their temperature anomaly almost entirely.

In some regions near Summit (where also only few air masses arrive over melting ice), most arriving air masses originate from over the U.S. heatwave.



The θ-anomaly, θ', grows while specific moisture decreases, illustrating condensation and with that diabatic heating occurring during ascent to the GrIS (see ALLEVs).

θ' further grows due to rapid (meridional) transport into a climatologically colder region

Figure: LFP maps of the trajectory fraction being associated with the North American heat wave, for (a) the extended 10-day or (b) 8-day trajectories; (c) shows the median (solid line) and inter-quartile range (shading) of specific humidity q (grey) and θ' wrt. θ_{cl} (red) of heat wave trajectories arriving at locations with a heat wave trajectory fraction >60%. Dashed lines in (c) indicate t = *-192* h and θ' = +3 K. The contours indicate elevation in 500 m intervals with the 2000 m isoline in solid. Summit and Southdome are marked with triangles.

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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 anticyclonically 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

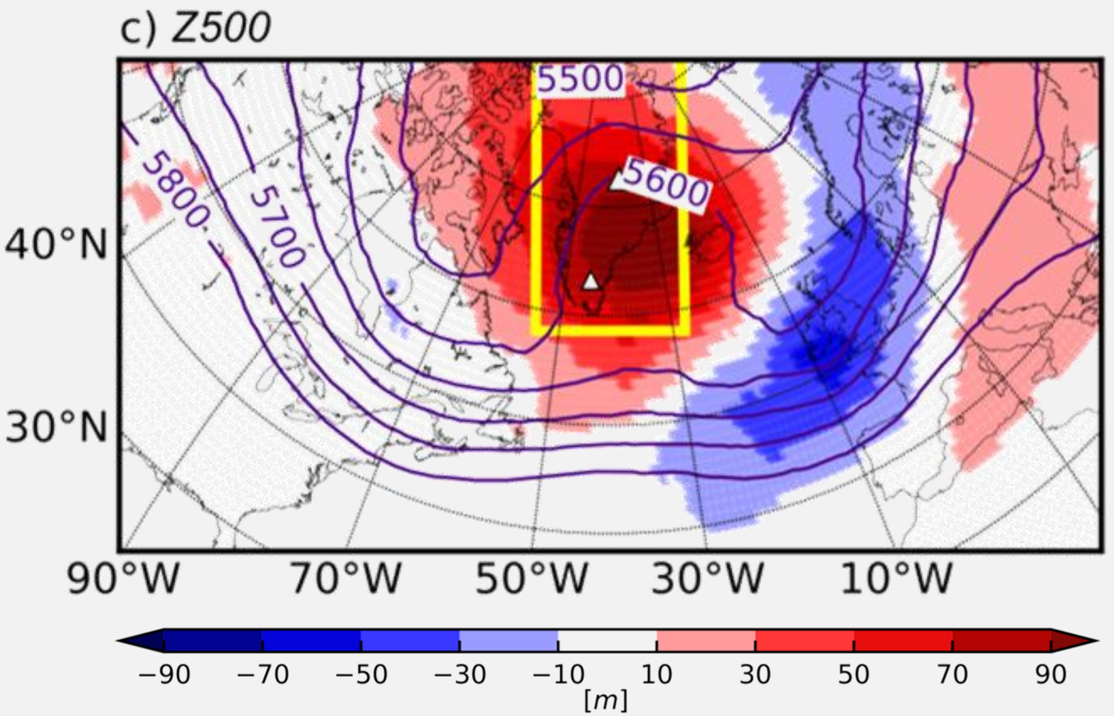

Figure: Median composite of 500 hPa geopotential height *Z500* in contours and its anomalies wrt. climatology in colors for all melt event time steps. The yellow box indicates the location of the GrIS.

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Temperature changes

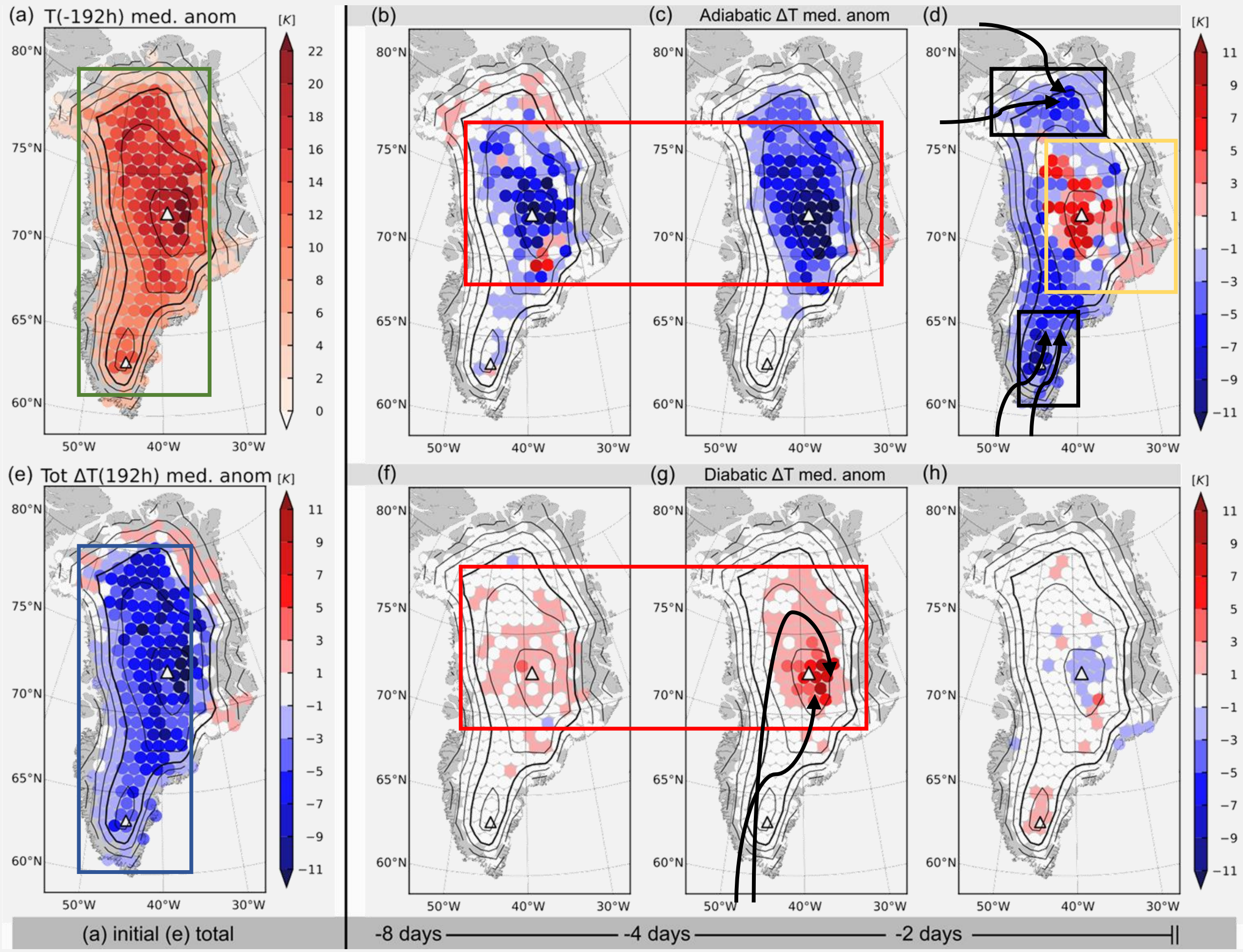

Figure: LFP anomaly maps of the (a) initial temperature at $t = -192$ h, and (b-d) adiabatic, (f-h) diabatic, and (e) total temperature change over eight days wrt. the climatological summertime air streams. The adiabatic and diabatic temperature change anomalies are split up in the periods (b,f) $t =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

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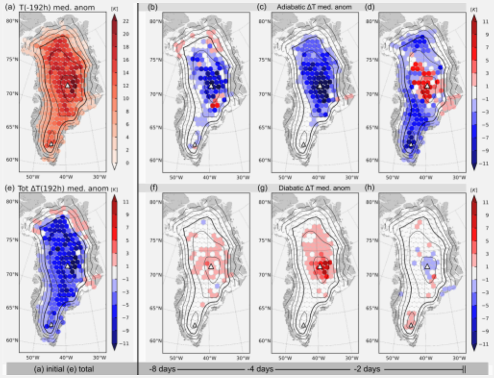
Summary

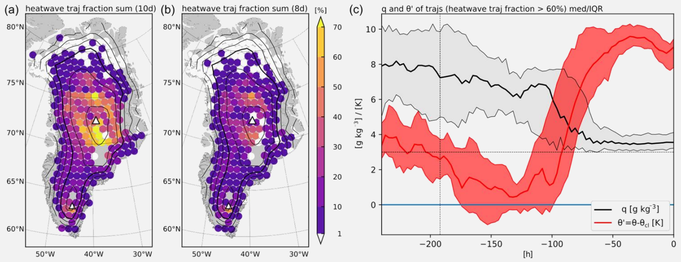
Details will follow soon in the publication feeding this presentation (in prep. for Weather Clim. Dynam.)

Transport & diabatic heating



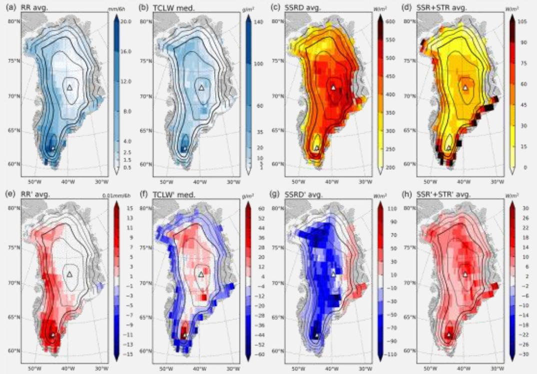
The essence of our trajectory analysis is, that air masses being responsible for Greenland melt events cool stronger wrt. climatological air masses. They acquire their warm anomaly from **strong meridional transport** and higher than usual **latent heating** during cloud formation. This contrasts with Artic 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 South.

#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 vapour 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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For exchange, additional information, or suggestions please get in touch

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