Record-breaking rain falls at Greenland summit controlled by warm moist-air intrusion

Min Xu, Qinghua Yang∗, Xiaoming Hu, Kaixin Liang and Timo Vihma

1 School of Atmospheric Sciences, Sun Yat-sen University, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People’s Republic of China
2 Finnish Meteorological Institute, Helsinki, Finland
∗ Author to whom any correspondence should be addressed.
E-mail: yangqh25@mail.sysu.edu.cn

Keywords: Greenland summit, rain, moisture transport

Abstract
On 14 August 2021, rain fell on the peak of Greenland for the first time on record. The atmospheric circulation and water vapour transport responsible for the rain were investigated. A high-pressure ridge favoured southwesterly advection of warm and moist air, the intrusion of which contributed to the rainfall. At the same time, Summit station observed above-freezing temperatures, which was the third time in a decade, after summers 2012 and 2019. The previous two warm events also included influxes of moisture, but no rainfall. Comparison between them and the 2021 event show different atmospheric pressure fields and water vapour transports. In 2021, the moisture from the southwest ascended the sloping ice sheet, whereas in the prior events moisture was transported from the southeast in smaller amounts. The sufficient supply of warm and moist air was the key factor in the 2021 rain event.

1. Introduction
Greenland is the largest island on the Earth and mostly covered by ice and snow. It has undergone rapid warming (Hanna et al. 2012, 2021) and acceleration of the Greenland ice sheet (GrIS) mass loss (Rignot et al. 2011) in recent years, gaining more concerns for the risk of sea-level rise.

The continuous warming over Greenland not only leads to ice-sheet melt (Hanna et al. 2020) but also influences the precipitation phase (Screen and Simmonds 2012, Sankare and Theriault 2016), which plays an important role in the mass balance of the GrIS (Noël et al. 2015). In high-elevation areas of Greenland, the air temperatures are generally below the freezing point, and the precipitation has always fallen as snow. However, on 14 August 2021, rain fell on the peak of GrIS for the first time, with above-freezing temperatures observed at Summit station (72.58° N, 38.46° W, 3216 m above sea level). The station is located near the apex of the GrIS and is the only high-altitude, high-latitude, inland station in the Arctic. Rainfall can accelerate snow and ice melting by affecting the snow morphology and surface albedo (Aoki et al. 2003). Therefore, exploring the potential effects on rainfall is crucial for projecting the ice-sheet melt and the related sea-level changes.

In the last decade, above-freezing temperatures occurred at Summit also in 2012 and 2019. In 2012, the Greenland blocking, warm southerly winds, and changes in radiation contributed to an extreme melting event (Tedesco et al. 2013, Hanna et al. 2014). In 2019 the runoff from Greenland was the second highest after 2012. The excessive melt was also driven by an atmospheric blocking, with enhanced absorption of solar radiation and the flow of warm, moist air (Hanna et al. 2020, Tedesco and Fettweis 2020). There was no rainfall at Summit station in the two warm events, indicating that the rainfall cannot be simply attributed to warmer air. The 2021 event provides a unique opportunity to explore the relevant atmospheric dynamic and thermodynamic processes. By data analysis and comparison with the previous two melt events, we try to reveal the sufficient conditions for the formation of the rainfall observed at Summit station.

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2. Data and methods

The hourly average observations of 2 m air temperature and relative humidity at Summit station applied in this study are taken from the Global Monitoring Laboratory of the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratories. The data are screened for instrument malfunctions and non-physical values, both by visual inspection and automated algorithms.

The atmospheric conditions during this specific event are obtained from ERA5 reanalysis data. ERA5 is the most recent reanalysis product of the European Center for Medium-Range Weather Forecasts (ECMWF) that combines large amounts of historical observations into global estimates using advanced model systems and data assimilation (C3S; Hersbach et al. 2020). The ECMWF ERA5 reanalysis products have demonstrated significant improvements in Greenland regions (Delhasse et al. 2020, Mattingly et al. 2020). ERA5 provides hourly data on 37 pressure levels (from 1000 to 1 hPa, interpolated from data on 137 model levels) with a horizontal resolution of 0.25° × 0.25° over the period from 1979 to present. Variables used from ERA5 in this study are air temperature and specific humidity, wind components, geopotential height, and cloud cover at various pressure levels.

Most of the water vapour transport across 70° N is via transient eddies (Jakobson and Vihma 2010). The long, narrow corridors of strong water vapour transport are referred to as atmospheric rivers (ARs) (Newell et al. 1992). ARs over the northern polar regions are identified in terms of the integrated water vapour transport (IVT) calculated as:

$$\text{IVT} = \sqrt{\left(\frac{1}{g} \int_{1000 \text{ hPa}}^{200 \text{ hPa}} qu \, dp\right)^2 + \left(\frac{1}{g} \int_{1000 \text{ hPa}}^{200 \text{ hPa}} qv \, dp\right)^2}$$

(1)

where $g$ (m s$^{-2}$) is the gravitational acceleration, $q$ is the specific humidity (kg kg$^{-1}$), $u$ and $v$ are the zonal and meridional wind components (m s$^{-1}$), respectively, and $dp$ (hPa) is the difference between adjacent pressure levels. IVT (kg m$^{-1}$ s$^{-1}$) is vertically integrated between the 1000 hPa and 200 hPa levels at six-hourly time steps using ERA5 reanalysis data. The thresholds of IVT we applied for AR identification are the 85th percentile of the monthly climatological value over the period of 1979–2020 and the magnitude exceeding 150 kg m$^{-1}$ s$^{-1}$ (Guan et al. 2015, Mattingly et al. 2018).

3. Results

3.1. Atmospheric conditions when it rained

Figure 1(a) shows the time series of 2 m air temperature and relative humidity from 12 to 18 August 2021. They both increased fast from 13 August and peaked on 14 August when the rain fell. Before the temperature reached the freezing point, the relative humidity increased to 100% at 05 UTC. Then, the air humidity decreased during the rainfall as the water vapour condensed to raindrops. The air temperature exceeded 0°C and rain started at 07 UTC, continuing for several hours, and observers at Summit reported seeing water droplets on surfaces near the camp (NSIDC 2021). Winds were from the southwest with a mix of freezing and non-freezing rain at about 14 UTC (NSIDC 2021). The temperatures were above 0°C for 9 h from 07 UTC to 16 UTC (grey bar).

The distribution of air temperature and temperature anomalies at the 650 hPa level (slightly above Summit station, where the surface pressure was 680 hPa) at 07 UTC is depicted in figure 1(b). The air temperature and its anomalies have similar patterns showing exceptionally warm air south of the station over Greenland. The strongest warm advection was related to the northward flow from the North Atlantic to southern Greenland and the Denmark Strait. Bounded by the summit, air temperatures over the windward slope were distinct from those over the leeward slope, indicating the influence of orography on the warm moist-air intrusion. On the one hand, the orography limits the poleward airflow in the low troposphere. On the other hand, due to the uplift of the terrain, the airflow will rise and form the precipitation. Furthermore, we searched...
the summer days in the broad period 1950–2021 for 650 Pa temperature and humidity fields similar to this event in the region 45°–85° N, 100° W–0° (the similarity was measured by the Euclidean distance between two maps) and found no pattern with similar combinations of high temperature and humidity, indicating the unique warmth and humidity in this event.

To illustrate the atmospheric circulation responsible for the high air temperatures and rain, figure 2 depicts the mean sea level pressure and 500 hPa geopotential height fields at 07 UTC from 11 to 14 August. On 11 August, the low pressure near the Hudson Bay started to form, and then moved eastward and generated a cyclone (minimum surface pressure of about 980 hPa) centred over the Hudson Bay on 12 August. On 13 and 14 August, the cyclone shifted northward towards Greenland. Moreover, in the mid-troposphere on 14 August when the rain started, a pronounced high-pressure ridge extended northward from the western Atlantic to Greenland, flanked by the low-pressure centre and a trough south of it. This synoptic structure facilitated the southwesterly flow that transported mid-latitude air masses to Summit station, supplying moisture for cloud formation.

Heat and moisture were transported northward onto the ice sheet. For insight into the atmospheric conditions at 07 UTC on 14 August, the vertical cross-sections of the specific humidity and potential temperature (figure 3(a)) at 72.5° N around Summit station were further examined. On the west slope of the ice sheet, the specific humidity was more than 6 g kg\(^{-1}\) and the relative humidity (not shown) was nearly 100%, indicating saturated air. The warm air extended to about 700 hPa level over the ice sheet, around which the isotherms were not parallel to the isobars, demonstrating the role of baroclinic forcing in ascent. The air on the east side was drier and colder.

The precipitation was linked to extensive atmospheric water content visible as clouds. The advection supplied enough moisture for the cloud
Figure 4. Vertically integrated water vapour transport (kg m\(^{-1}\) s\(^{-1}\)) at (a) 18 UTC on 13 August, (b) 00 UTC on 14 August, (c) 06 UTC on 14 August, and (d) 12 UTC on 14 August. The blue line encloses areas where the IVT magnitude exceeds both the 85th percentile and 150 kg m\(^{-1}\) s\(^{-1}\), which are commonly used as criteria for an atmospheric river. Summit station is marked with a red dot.

formation. Indicated by the proportion of a grid box covered by clouds, the vertical distribution of clouds (figure 3(b)) shows a high cloud coverage over the west slope in the lower and upper troposphere. The liquid water droplets were in the low clouds close to the ice sheet where the air was warm. We hypothesize that collisions between hydrometeors resulted in rainfall. In addition, the cloud base height over the station was low (~30 m), so the distance to the ice sheet surface was too short for the raindrops to evaporate, which allowed the rain to reach the surface.

The extent of the moisture inflow is illustrated by the six-hourly variations of IVT (figure 4). During the period from 13 h before to 5 h after the occurrence of rain at Summit station, there were large areas where the IVT exceeded the threshold of the AR detection. Focusing on the core of the IVT, at 18 UTC on 13 August (figure 4(a)), the maximum IVT of more than 800 kg m\(^{-1}\) s\(^{-1}\) occurred over the Davis Strait, and the IVT over the southwest coast of Greenland exceeded 400 kg m\(^{-1}\) s\(^{-1}\). At 00 UTC on 14 August, the northward IVT strengthened (figure 4(b)). The regions with the maximum values reached Baffin Bay and the southwest coast of Greenland. An hour before the rainfall (figure 4(c)), more moisture reached ashore over western Greenland, and the IVT offshore weakened. At 12 UTC on 14 August (figure 4(d)), the IVT larger than 400 kg m\(^{-1}\) s\(^{-1}\) extended farther inland but its shape became narrow. In brief, the IVT peaked before the rainfall, when its core was still offshore, and the rainfall at Summit station occurred during the period of the maximum IVT over the ice sheet.

3.2. Comparison with above-freezing events in the past

2021 marks the third year with above-freezing temperatures at Summit in the past decade. The air temperatures in summers 2012 and 2019 were higher than in the 2021 event but without rain. We compared the atmospheric circulation and IVT at the times when the highest temperature occurred in the two prior events with the 2021 case. The two events have obvious differences in synoptic patterns from the 2021 event. The atmospheric circulations (figures 5(a) and (b)) show the contribution of the high pressure to the high surface temperatures. In 2012, the high pressure was centred near the station. West of the anticyclonic circulation was an extensive low pressure extended to the Labrador Sea. In 2019, the high pressure centred over the east of the station was stronger than in 2012. The low pressure over the Labrador Sea was relatively
weak and dispersed, making the belt of westerly winds around 55° N distorted.

The high pressure also affected the moisture transport in both events (figures 5(c) and (d)). Compared to 2021, less moisture was delivered along the clockwise airflow to the station from the east of Greenland in 2012 and 2019. In 2012, it passed through the Davis Strait and the Baffin Bay. The IVT over the station was less than 100 kg m⁻¹ s⁻¹, outside of the AR areas. In 2019, the IVT was relatively stronger with a shorter path than that in 2012. The moisture originated from higher latitudes and crossed the Denmark Strait to Greenland. Both events lacked an abundant supply of water vapour needed for rain, indicating the importance of the atmospheric humidity affected by the moisture transport. In the 2021 case, the role of air humidity was pronounced. The 650 hPa specific humidity over Summit station was 6.3 standard deviations above the climatological mean value while the temperature anomaly was only 3.3 standard deviations above the mean.

4. Conclusions

The precipitation usually falls as snow on Greenland’s Summit station due to the below-freezing air temperature. On 14 August 2021, rain fell on the peak of Greenland for the first time since Summit station was established there in 1989. At the same time, the temperatures at the station exceeded 0 °C. By analysing near-surface and mid-tropospheric circulation, we found that a high-pressure ridge over the east side and a trough over the west side of Greenland caused warm, southwesterly airflow to Summit station, carrying excessive amounts of moisture. With the orographic lift and cooling, the warm and humid air was saturated. The water vapour condensed to clouds, and consequently the rain fell. As shown in the vertically IVTs, the rain was made possible by the favourable circulation transporting extensive amounts of moisture to Summit station.

In the last decade, Summit station has observed above-freezing temperatures three times: the summers of 2012, 2019 and 2021, the case in 2021 was the only one accompanied by rainfall. The three events differ in mechanisms and impacts. Although the previous events also experienced water vapour transports, they were weaker and originated from southeast of Greenland. The two previous events were linked to large anomalies in the North Atlantic Oscillation (NAO) index (Tedesco et al 2013, Hanna et al 2014), which was −1.32 (−1.43) in July 2012.
(2019), but during the 2021 event the NAO index was close to zero (−0.28), and the event was controlled by synoptic-scale dynamics. Heat and, in particular, moisture advection were the main drivers of this event with the formation of warm clouds producing rain.

In the 2021 event, the melt peak extent was more than 800 000 km² on 14 August, which was later in summer than all previous melt events of this scale in the satellite record (NSIDC 2021). Rainfall decreases the surface albedo, maximizing the solar radiation absorbed in snow/ice when the sky becomes clear again, and hence contributing to the acceleration of the ice melt (Fettweis et al. 2013). In addition, the heat released by rain freezing into the surface snowpack can enhance the melt (Doyle et al. 2015). Also, an anomalously strong moisture transport can result in ice melt by enhancing the downward longwave radiation (Maksimovich and Vihma 2012, Mattingly et al. 2018). Due to the future atmospheric warming, rain is projected to become the dominant form of precipitation in the Arctic (Landrum and Holland 2020), which will reinforce future Arctic warming by decreasing the surface albedo (Bintanja and Andry 2017). Rain will become more frequent over Greenland (Fettweis et al. 2013) and fall more often also at high elevations where the ice sheet is responsive to increasing runoff (Doyle et al. 2015).

This study explained the causes of a single rainfall event. Considering the future evolution of GrIS, one of the key issues is that the occurrences of temperatures above 0 °C in high altitudes of the ice sheet are closely related to the cloud cover (Gallagher et al. 2020). More attention is needed on both large-scale atmospheric dynamics and cloud physical processes to explore the future changes of rain over GrIS and its impact on ice melt.

Data availability statement

The data that support the findings of this study are openly available. The ERA5 reanalysis data can be accessible from Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/home). The observations at Summit station are obtained from Global Monitoring Laboratory (https://gml.noaa.gov/afput/data/meteorology/in-situ/sum/met_sum_insitu_1_obop_hour_2021.txt). The North Atlantic Oscillation (NAO) index is available from www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table.

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This study is supported by the National Natural Science Foundation of China (Nos. 41922044, 41941009 and 42075028), the Guangdong Basic and Applied Basic Research Foundation (No. 2020B1515020025), the Fundamental Research Funds for the Central Universities (No. 19lgzd07), the Academy of Finland (No. 317999), the Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (No. SML2021SP302). We thank the European Centre for Medium-Range Weather Forecasts (ECMWF) for the ERA5 reanalysis data, the NOAA’s Global Monitoring Laboratory for the observations at Summit station. We thank the National Snow and Ice Data Center (NSIDC) for the event report. This is a contribution to the Year of Polar Prediction (YOPP), a flagship activity of the Polar Prediction Project (PPP), initiated by the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO). We acknowledge the WMO WWRP for its role in coordinating this international research activity.

ORCID iD

Timo Vihma https://orcid.org/0000-0002-6557-7084

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