Heat Waves, Hurricanes, and the Melting of Greenland

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Abstract

1. **Introduction**

[*Neff et al.*, 2014] identified a continental heat wave over North America as the source of warm air that traveled over the Atlantic Ocean and carried heat and moisture via an Atmospheric River (AR) to the Greenland Ice sheet (GIS) resulting in the two major melting episodes in July 2012. [*Doyle et al.*, 2015] identified a cyclonic rainfall event on the western margin of the GIS in late August 2011 that accounted, in 4 days, for 10% of the annual mass loss from the GIS via surface runoff and ice flow acceleration. [*Neff*, 2018] later identified that this event was initiated by an AR (similar to that in 2012 that brought subtropical moist air with its distinct isotopic signature to Greenland [*Bonne et al.*, 2015]). Interestingly, Hurricane Irene in 2011 followed the AR to Greenland and may have provided the additional moisture source for the heavy rainfall as it decayed to an extratropical cyclone near the tip of Greenland. More recent reports have emerged in 2019 of major melt episodes over the GIS in mid-June and then again in late-July following the major European heat wave [*Shepard*, 2019]. In this paper we will examine ARs as well as other transport pathways impacting Greenland and their relationship to extreme events such as heat waves and hurricanes that can facilitate the melting of the GIS via large circulation anomalies and enhanced moisture transport.

1. **Background**

ARs, as conveyers of heat and moisture, are of particular importance in the Arctic given the dramatic environmental changes associated with the reduction in sea ice extent and the increased discharge of fresh water from Greenland’s coastal glaciers and associated decrease in Greenland’s mass balance. ARs are thin filaments of high-moisture air often occurring at frontal boundaries and represent an efficient poleward transport mechanism for warm moist air [*Newell et al.*, 1992] to the Arctic [*Bonne et al.*, 2015; *Neff et al.*, 2014] and the Antarctic [*Gorodetskaya et al.*, 2014]. Of note, the melting of the Greenland ice sheet has accelerated since the early 1990s [*Graeter et al.*, 2018]. Such increases in the melting rate also coincide with increasing moisture transport to the Greenland Ice Sheet associated with ARs [*Mattingly et al.*, 2018; *Mattingly et al.*, 2016; *Neff*, 2018], warming in recent decades as seen in δ18O signatures in ice cores for northwestern Greenland [*Masson-Delmotte et al.*, 2015], potential sea level increases [*Noël et al.*, 2017], particularly along the U.S. southeast coast associated with increasing Greenland melting [*Davis and Vinogradova*, 2017], as well meltwater impacts on the oceanic ecosystem that lead to phytoplankton growth and increases in primary productivity in the Labrador Sea [*Oliver et al.*, 2018]. At the same time clouds and warm air associated with transport events can play a key role in the melting of the sea ice via changes in the surface radiative balance [*Yang and Magnusdottir*, 2017].

An opportunity to determine trends in moisture transport events has also come with recent historic reanalyses covering longer time scales. For example, [*Neff et al.*, 2014] examined the 2012 summer Greenland melt episode and compared it to the last episode in 1889 using the Twentieth Century Reanalysis [*Compo et al.*, 2011], finding similar factors at work. A key factor in 2012 was the presence of an Atmospheric River (AR) that transported warm air from a mid-continent heat wave lying over North America and thence over the Atlantic Ocean and then to the west coast of Greenland and then over the ice sheet with a confirming water vapor isotopic signature [*Bonne et al.*, 2015]. Some common characteristics of the events in 1889 and 2012, in addition to the expression of poleward moisture transport as an AR, included continental heat anomalies in the trajectory source regions as well as a trough-ridge pattern that focused transport along the west coast of Greenland. The latter consisted of a trough of low-pressure situated to the west, generally over Baffin Island and Hudson Bay, and a high-pressure ridge impinging on the southeast coast of Greenland. This type of trough-ridge pattern was also implicated in the major rain event in late summer of 2011 along the western margin of the Greenland ice sheet that accelerated the flow of ice into the ocean [*Doyle et al.*, 2015] which was initiated with an AR [Neff, 2018] and provided a pathway for moisture associated with Hurricane Irene to follow. Similarly, enhanced winter precipitation over Spitzbergen [*Serreze et al.*, 2015] was associated with an AR. Extreme moisture transport into the Arctic in winter along the west coast of Greenland (with an AR like structure) has been identified as an artifact of Rossby Wave breaking [*Liu and Barnes*, 2015]. In particular, as concluded by Liu and Barnes, cyclonic wave breaking (CWB) during the negative phase of the North Atlantic Oscillation (NAO) favors moisture transport along the west coast of Greenland [*Doyle et al.*, 2015]; conversely, anticyclonic wave breaking (AWB) favors moisture transport into the Norwegian Sea. ARs have also been identified in transport of warm moist air across the entire Arctic during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment [*Persson et al.*, 2016]. The NCEP-NCAR reanalysis has been used to identify the significant contribution of low-frequency variability to moisture transport to the Arctic and moisture convergence over Greenland from synoptic scale systems (high frequency variability) [*Newman et al.*, 2012]. Newman et al. thus identified a major pathway from the extratropics to Greenland through the western Atlantic during summer. This pathway is consistent with the results of [*Bonne et al.*, 2015; *Neff et al.*, 2014] for the 2012 Greenland melt episode. Bonne et al., in particular, showed that the 2012 melt episodes bore the water-vapor isotopic signature of subtropical air arriving over Greenland.

In this paper we take a broader view of the larger-scale synoptic environments that facilitate the transport of warm (and often moist air) to the GIS and, in particular, northward transport of moisture as ARs along the southwest coast of Greenland. The rationale for this focus lies in recent observations of increasing mass loss from SW Greenland in GRACE observations [*Bevis et al.*, 2019] coincident with an increased frequency of strong ARs since 2000 [*Mattingly et al.*, 2018]. In the course of these analyses, we compared the efficacy of three reanalyses (ERA-I, NCEP-NCAR, and 20CR) in identifying the presence of moisture transport events along the west coast of Greenland (see Supplemental Material where we show consistent results from the three reanalyses). Our study of events on the west coast of Greenland also exploits the topographic barrier effect of the 3-km high ice sheet that channels southerly flows along the SW coast. We also find that Atlantic hurricanes at times follow the same pathway from the extratropics as does AR moisture as the hurricanes decay into extratropical cyclones in the vicinity of Greenland. In particular, we explore the role of Hurricane Irene in late summer of 2011 that coincided with the extreme melt episode reported by *Doyle et al.* (2015) as well as hurricanes Earl and Igor in 2010 and compare with a similar event, namely the Outer Banks Hurricane of 1933, using the 20CR. Furthermore, we will examine circulation anomalies and transport events that have their origins in heat anomalies over other land masses such as that of Europe and northwest Africa in the summer of 2019.

1. Identification of west-coast transport events
   1. Classification method
   2. Frequencies
   3. Synoptic patterns with strong transport events
2. Hurricanes
   1. 2011 Irene
   2. 2010 Igor and Earl
   3. 1933 Outer Banks Hurricane
3. The European/African Heat Waves of 2019
   1. June 2019 -- Origins off northwest Africa
   2. July 2019 -- Origins in Central Europe and North Africa
4. Discussion

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