Functioning of Svalbard glacier drainage systems from *in-situ* data, remote sensing and models

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Abstract

The drainage of meltwater and rainwater holds significant importance in understanding glacier dynamics and mass balance (MB). There is, however, a lack of comprehensive knowledge and understanding regarding the behavior of water within the internal drainage system (IDS). As the behavior of subglacial water plays a determining role in glacier dynamics, it requires particular attention, especially in the context of climate warming which intensifies ablation and leads to increased meltwater production. Furthermore, it is essential to recognize the impact of persistent high-speed events during the Arctic winter, which lasts twice as long as the summer season. These events not only represent a substantial dynamic response on the annual speed of glaciers but also a potential significant source of sea level rise. Therefore, studying and comprehending the dynamics of subglacial water and its interaction with the supraglacial and the englacial drainage system is crucial for a comprehensive understanding of glacier behavior and its implications for sea level rise.

Water originating from the surface of glaciers usually is the primary source of supply for the subglacial drainage system. This system is greatly influenced by the supraglacial and englacial drainage systems which collect meltwater and precipitation and rapidly delivers it to specific points in the glacier bed through moulins, crevassed areas known as water input areas (WIA), and englacial channels. While subglacial hydrology has received more attention due to its direct connection to ice dynamics, there has been a limited focus on understanding the supraglacial and englacial aspects. Commonly, models of subglacial channels patterns rely primarily on hydrological potential gradients, disregarding the supraglacial drainage system. Moreover, while progress has been made in identifying key features of englacial channels, several aspects of this system remain unexplored. Most studies have focused on temperate glaciers during the melt season, and the measurement techniques employed predominantly rely on indirect methods. Direct observations only offer punctual measurements and lack the ability to conduct long-term studies with high temporal resolution. Additionally, to the best of my knowledge, there have been no studies that establish a direct connection between observations of englacial water fluctuations within the channelized system and glacier speed.

The objective of this thesis is to improve the understanding of the individual components that constitute the glacier hydrological system while also examining their interconnected relationships. Additionally, the study aimed to analyze the influence of meteorological conditions on the IDS and evaluate the resulting dynamic response of the glaciers.

To achieve these objectives, a diverse range of data and methods were employed. First, the evolution of the supraglacial drainage system of two glaciers in Svalbard: the land-terminating Werenskioldbreen and the tidewater Hansbreen, was examined. This analysis was conducted on both annual and decadal timescales, utilizing very high resolution remote sensing images. Then, subglacial channel patterns were modeled for two those glaciers, specifically during the 2015 melt season. Two different modeling approaches were employed: one incorporating a spatial water recharge and the other considering a discrete water recharge, enabling a comparative analysis between them. Also, an innovative pressure transducer installation method was developed to instrument the central section of englacial channels, including ice caves and moulins, within Hansbreen. This pioneering approach enabled the continuous measurement of water fluctuations within the englacial channels, with a temporal resolution of 30 minutes, over a period up to two hydrological years. Consequently, by linking englacial water fluctuations to meteorological data, four distinct periods were identified, collectively representing a complete hydrological year. Finally, by combining water fluctuations in the englacial channels with speed measurements on the Hansbreen, direct relationships were found.

It was found that surface meltwater has a more substantial impact on glacier runoff compared to precipitation. Secondly, changes in the supraglacial drainage system over several decades have resulted in corresponding adaptations in the subglacial drainage system, mainly influenced by the activation or deactivation of WIAs. However, the consistent alignment of WIAs along the same subglacial axes suggests that fundamental reorganization within the subglacial system is absent. Furthermore, the presence of a well-developed snow cover on the glacier surface delays the increase in englacial water levels and reduces the rate at which englacial channels are filled. Additionally, observations of water flowing from the subglacial system to the englacial system confirms theoretical knowledge. The hydraulic capacity of the subglacial drainage system is affected by the history of water recharge, and periods of increased hydraulic capacity are characterized by events of englacial water storage. It is worth noting that during the winter season, the subglacial system is not necessarily inefficient, as water draining events occur. This indicates that the subglacial drainage system remains somewhat active even in winter, challenging the notion of its specific inefficiency during this season. However, this does not imply that it is never inefficient or poorly efficient. Also, most of the winter water persists in the englacial system. The transition period from winter to summer, as well as significant warm winter events, lead to changes in the efficiency of the subglacial drainage system. During these periods, the system shifts from an inefficient or poorly efficient state to an efficient state, facilitating increased water flow and drainage. Throughout the summer season, the subglacial drainage system consistently operates efficiently. However, it constantly adjusts its hydraulic capacity to accommodate the varying volumes of water recharge, which exhibit significant variations. The subglacial drainage system demonstrates an impressive ability to handle the dynamic nature of water recharge during the summer months, adapting its capacity within a day to maintain efficiency throughout the season. Rainfall events consistently trigger englacial flooding, particularly when positive air temperatures are relatively low as the system is less efficient. Furthermore, there is a clear relationship between fluctuations in englacial water levels and glacier speed. The magnitude of the glacier's dynamic response is influenced by the volume of water recharge and the effectiveness of the subglacial drainage system. Warm winter events can significantly impact glacier speed, depending on the initial state of the glacier's internal drainage system (IDS). The efficiency state of the IDS plays a crucial role in mitigating the effects of warm winter events. The greater the efficiency, the less time the water is stored and the less the dynamic response of the glacier, and vice versa. For this reason, understanding the dynamic response of a glacier to external conditions requires consideration of the prior state and evolution of the glacier's hydrological system. Finally, collecting data with a fine temporal resolution is crucial to capture the complete extent of englacial water dynamics, as filling and draining events often occur within shorter time intervals than a day.

In summary, it is crucial to be cautious about the representativeness of punctual measurements due to the substantial temporal variability in the effectiveness of the IDS during the melting season. Future hydrological and dynamic models should incorporate the significantly higher dynamics of the IDS than previously acknowledged. Neglecting the potential impact of warm winter events and failing to properly constrain the glacier's response to water fluctuations within the IDS in glacier dynamic models can result in inaccurate predictions of the magnitude of dynamic changes. This, in turn, leads to limitations in accurately estimating the rise in sea levels.