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Lakes of the western Canadian Arctic: Past Controls and Future Changes

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ABSTRACT

The western Canadian Arctic is lake rich with over 40,000 lakes in the Mackenzie Delta, and thousands more to the east of the Delta in the Tuktoyaktuk Peninsula. To address unknowns concerning these lakes, Professor Mackay published at least 19 papers over the period 1956 to 2013 that dealt with various aspects of lakes in the western Canadian Arctic. These papers outlined many of the controlling processes and considered the complex interactions between lakes and the permafrost landscape. Subsequent research has built on Professor Mackay's legacy and has gradually developed a better understanding of the hydrology and ecology of these lakes, as well considered the interactions between climate, permafrost and hydrology, and developed predictive models.

RÉSUMÉ

L'ouest de l'Arctique canadien est une région avec plus de 40 000 lacs dans le delta du Mackenzie, et des milliers d'autres à l'est du delta dans la péninsule de Tuktoyaktuk. Pour répondre aux incertitudes concernant ces lacs, le professeur Mackay a publié au moins 19 articles, entre 1956 et 2013, qui traitent de divers aspects des lacs de cette région. Ces documents présentent la plupart des processus de contrôle et de considération des interactions complexes entre les lacs et le pergélisol. Des recherches ultérieures se sont appuyées sur l'héritage du professeur Mackay et ont progressivement développé une meilleure compréhension de l'hydrologie et de l'écologie de ces lacs. Elles ont ainsi examiné les interactions entre le climat, le pergélisol et l'hydrologie, en plus de développer des modèles prédictifs.

1 INTRODUCTION

Many areas of arctic Canada, Alaska and Eurasia are extremely lake-rich, and Smith et al. (2007) showed that northwards of 45°N lake abundance and lake area are higher in permafrost regions compared to non-permafrost terrain. This increase in lake occurrence is likely due to thermokarst processes which can form and enlarge lakes during warm periods (Mackay, 1992) and the aggradation of permafrost and ground ice which can both modify the surface topography and limit water drainage due to impermeable permafrost limiting groundwater flow from lakes. Many areas of the Canadian Arctic are lake rich due to other processes. For example, the Canadian Shield is often lake rich due to geologic controls. In contrast to such shield lakes, the western Canadian Arctic is lake rich due to the effect of permafrost. This is especially true for the Tuktoyaktuk Peninsula (TP), Richards Island (RI), and the Mackenzie Delta (MD) of the western Arctic (Mackay, 1992) (Figure 1), a region where Professor J. Ross Mackay focussed much of his research.

Professor Mackay greatly enhanced our understanding of lakes of the western Arctic through at least 19 papers over the period 1956 to 2013. Many of these papers considered key aspects of the controlling processes, considered the complex interactions between lakes and the permafrost landscape, and set the stage for

Figure 1: Lakes (darker bodies) of the Mackenzie Delta, Richards Island and the Tuktoyaktuk Peninsual immediately to the east of the Delta.

future research to build upon Mackay's legacy. However, one of Mackay's early achievements was simply to raise awareness of the importance of these lakes to the ecology, hydrology, and permafrost of the region, and to the communities of the MD region (Ft. McPherson, Aklavik, Tuktoyaktuk, and Inuvik). The MD, located where the Mackenzie River enters into the Beaufort Sea (Figure 1), is approximately 12,000 km^2 in area and is the largest delta in Canada and one of the largest Arctic Deltas. Unlike many deltas, the MD is extremely lake rich, with over 40,000 lakes (Emmerton et al, 2007). The formation process of these lakes has been discussed for many years, and are believed to have formed due to a combination of sedimentation, permafrost aggradation, thermokarst, and channel migration.

Mackay (1963) realized that the water level regime of MD lakes depended on the elevation that they were perched above the main channels and the connection between the lake and the channel. The controlling elevation along the connecting channel is often termed the lake sill elevation. Based on this Mackay defined lake classes as: no-, low-, and high-closure lakes. No-closure lakes are those with a low sill elevation and "open out to, are joined with, or are crossed by channels". Low-closure lakes are those that "tend to flood annually" and high closure lakes having a high sill elevation and that "flood infrequently". Marsh and Hey (1989) used observations of channel water levels and dates of lake flooding in the vicinity of East Channel near Inuvik to quantify Mackay's definitions by the flood return period. No-closure lakes were then defined as lakes that are connected to the main channels of the delta for much of the summer, with the lake sill elevation lower than the one-year return period for summer low water levels. Low-closure lakes have a sill elevation such that the lake is cut off from the main channels for some of the summer but flooded by high water during the spring breakup at least annually. Specifically they have a sill elevation greater than the one-year return period for low water levels and less than the one-year return period for spring water levels. High-closure lakes are then those that flood less than annually during spring breakup and never flood in the summer. Marsh and Hey (1989) and Marsh et al. (1999) used aerial observations and photography to map flooding levels across larger areas of the delta in order to further extend our understanding of the spatial variability of lake sill elevations and lake hydrology. Hopkinson et al. (2011) reported on an International Polar Year (IPY) project that used airborne LiDAR to accurately map lake elevations across three broad areas of the MD, further extending our understanding of the spatial variability of lake types. Such data provides essential information needed to understand the impact of changes in ice jam flooding and storm surges (Lesack and Marsh, 2007; Lesack et al., 2013) on the hydrology and ecology of these lakes. This combination of studies has resulted on a greatly improved understanding of the spatial variability of lake hydrology, and the links to aquatic ecology (Emmerton et al., 2007; Squires et al., 2009 and carbon fluxes (Tank et al., 2008). However, our predictive ability is still extremely poor. Building on these advancements, a Beaufort and Region Environmental Assessment (BREA) project has led to the next improvement in understanding MD lakes, the development of the first predictive model of MD channel water levels using a hydraulic model of the main MD channels and water levels of the Beaufort Sea (Nafziger et al., 2009; personal communication, F. Hicks and W. Perrie).

Predictive tools are essential for understanding ongoing impacts of climate change on the MD (Lesack and Marsh, 2007) and for understanding the impacts of developing the vast natural gas fields that lie below the MD and which would be the source fields for the proposed, and approved, Mackenzie Gas Project. Professor Mackay's early efforts were of great importance in setting the stage for our understanding of the delta hydrology and played a key role in carrying out the environmental assessment of the Mackenzie Gas Project.

RI and the TP, located to the east of the Mackenzie Delta, are of similar size to that of the MD and as Mackay (1992) noted, is "a land of lakes where water covers about 15 to 50% of the total surface area". Mackay (1992) showed that many of these lakes are thermokarst lakes that formed during an earlier warm period over 8 000 years ago. These thaw lakes are an important and very dynamic component of regions such as RI and the TP and the Alaskan Coastal Plain for example (Frohn et al., 2005). For these thaw lakes, lake area may change dramatically over time due to erosion and melting of the shoreline by thermokarst processes; a change in the lake water balance and therefore lake level; or increased groundwater outflow as permafrost is melted. Such changes have been described for numerous regions of the arctic. For example, Yoshikawa and Hinzman (2003) and Smith et al. (2005) found that lakes in discontinuous permafrost areas of Alaska and Siberia were disappearing, and hypothesized that this is caused by increased sub-surface drainage due to permafrost melting. Smith et al. (2005) also suggested that thermokarst processes resulted in an increase in lake numbers in the continuous permafrost areas of Siberia.

For the RI and TP regions, Mackay (1992) showed that thaw lakes have been draining, and removed from the landscape over the last 8000 years, resulting in drained thaw lake basins (DTLBs). These DTLBs have numerous effects. For example, pingos, a major research topic of Mackay over his entire research career (e,g. Mackay, 1979) only form within these drained lake basins, while van Huissstedent et al. (2011) has outlined the effect of these lakes on methane emmissions.

Mackay (1992) documented the rapid drainage of thaw lakes due to melting of an outlet channel through ice-rich permafrost. Such rapid drainage has been termed catastrophic drainage by Mackay (1992). The ongoing removal of these thaw lakes from the landscape across the arctic is extremely important as it affects permafrost, hydrology and the ecology of these regions. However, the details still poorly understood. The following sections of this paper will outline Mackay's contribution to our understanding of such lakes in the western Canadian Arctic, and consider recent contributions on this topic that build upon Mackay's efforts, and we will consider future research needs.

2. THERMOKARST LAKES OF THE WESTERN CANADIAN ARCTIC

2.1 Lake characteristics

Many of the tens of thousands (Figure 1) of lakes across RI and the TP are thermokarst lakes that developed during a postglacial warm period between 13 000 BP and 8 000 BP (Mackay, 1992). At this time, active layer depths increased, resulting in the thawing of the upper layers of ice-rich permafrost (Mackay, 1992), ground surface settlement, and ponding of water that lead to pond and lake development. Most of the existing lakes in this region are less than 5 m in depth, with a few having depths exceeding 13 m (Burn, 2002). Although this area is in the continuous permafrost zone, Mackay (1992) estimated that thaw basins exist beneath those portions of lakes where water depth exceeds approximately two-thirds of the maximum winter ice thickness (up to 2 m in thickness). In addition, Mackay (1992) estimated that if the lake diameter considerably exceeds the thickness of permafrost, the thaw basin would eventually extend throughout the depth of permafrost. Burn (2002) carried out a detailed analysis of lake size and thaw bulb configuration under equilibrium conditions, and suggested that about 25% of the lakes in this area have taliks that penetrate the permafrost. As will be discussed in the next section, these thaw lakes are prone to rapid drainage due to the melting of ice rich permafrost that surrounds these lakes.

2.2 Drainage of thermokarst lakes

Following a cooling trend that started approximately 4 5000 BP, thousands of thaw lakes across the TP have been lost from the landscape due to erosion of drainage channels through the ice-rich permafrost (Mackay, 1992), resulting in complete or nearly complete emptying of the lake (Figure 2). As Mackay (1979) has shown, pingos in the TP only form in DTLBs as permafrost aggrades in the former lake bed. A lake removal rate from the TP landscape of one to two per year over the last few thousand years has been estimated by Mackay (1988, 1992) from mapping both pingos and lake drainage between 1950 and 1985.

A common feature of DTLBs is the existence of large drainage channels (Figure 3) and large volumes of ground ice in the walls of the drainage channel (Mackay, 1992). In the vicinity of the drained lake sites discussed by Mackay (1992), Pollard and French (1980) showed that ice volume in excess of the pore volume was common, with ground ice volume in excess of 60% in the upper 2 m and with ice wedges averaging 1.5 m in width, having an average depth to width ratio of 3:1, and constituting as much as 50% of earth materials in the upper 1 m of permafrost. Most of the examples of lake drainage described by Mackay (1992) include initial lake outflow over a relatively steep and narrow drainage divide, with flow either through ice-wedge thermal contraction cracks or over areas of ice-wedge polygons. In many cases the drainage channel does not coincide with the original lake outlet (Marsh and Neumann, 2001). Mackay (1992) suggested that the occurrence of subsurface flow was clearly demonstrated by the existence of 'pool ice' in newly exposed channel banks.

Mackay (1992) suggested that a key process leading to lake drainage was the existence of ice wedges and ice wedge thermal contraction cracking over the winter. When such cracks intersected lake outlets, then lake drainage could occur the following spring or summer when water was able to flow through the crack. Mackay (1992) suggested that lake drainage is initiated during periods of high water in the spring runoff period, after periods of heavy rain, or in the spring due to the existence of a snow dam at the normal lake outlet, when water was able to flow through ice wedge thermal contraction cracks. The importance of ice wedge terrain to lake drainage is suggested by a comparison of all drained thaw lake basins and pingos across the TP (Figure 4) and the distribution of ice wedge polygonal terrain across the same area (Figure 5) as mapped by Kokelj et al., (2014). These figures show a remarkable similarity between the distribution of ice-wedge polygonal terrain and the distribution of drained thaw lake basins and pingos. Ongoing research is required in order to consider this relationship in greater detail.

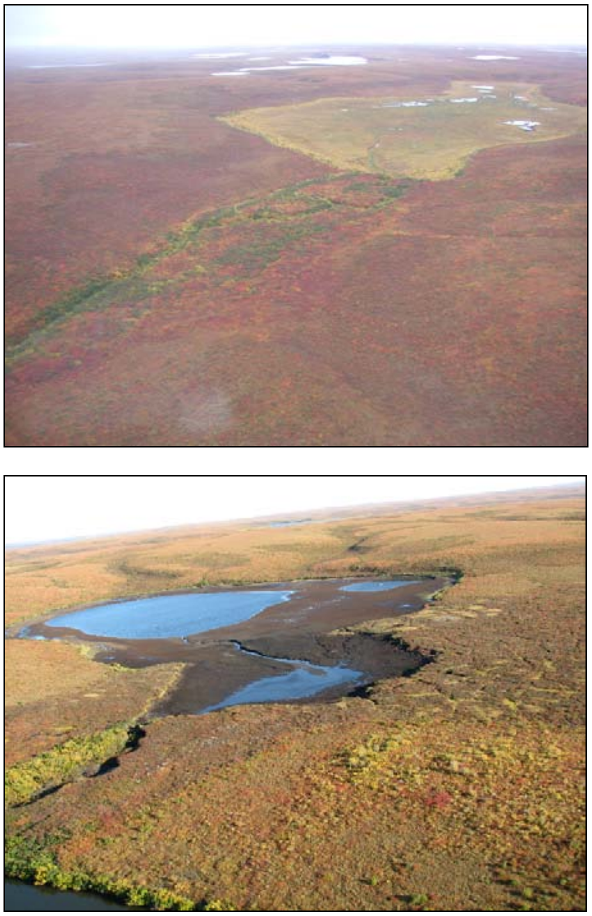

Figure 2: Example of a nearly completely drained lake (top) and partially drained lake (bottom).

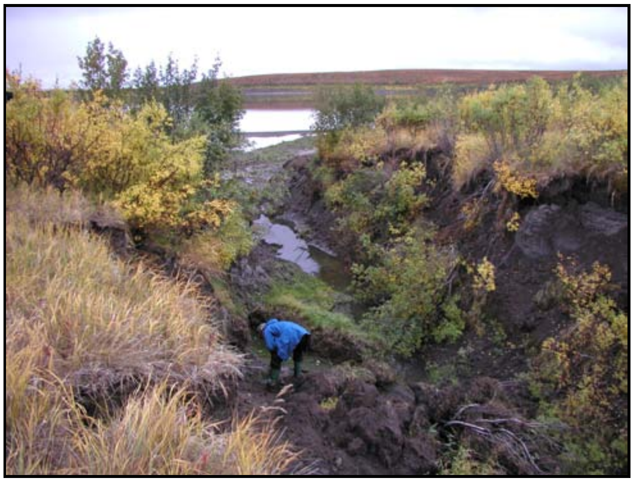

Figure 3: DTLB channel formed by a combination of ground ice melting and sediment erosion. Note person in the drainage channel for scale. It is common for the walls of these drainage channels to expose large volumes of ground ice. Such channels often follow the path of the previous lake outlet channel, and case simply deepens and widens the existing channel. In other cases, the channel does not follow the existing outlet channel.

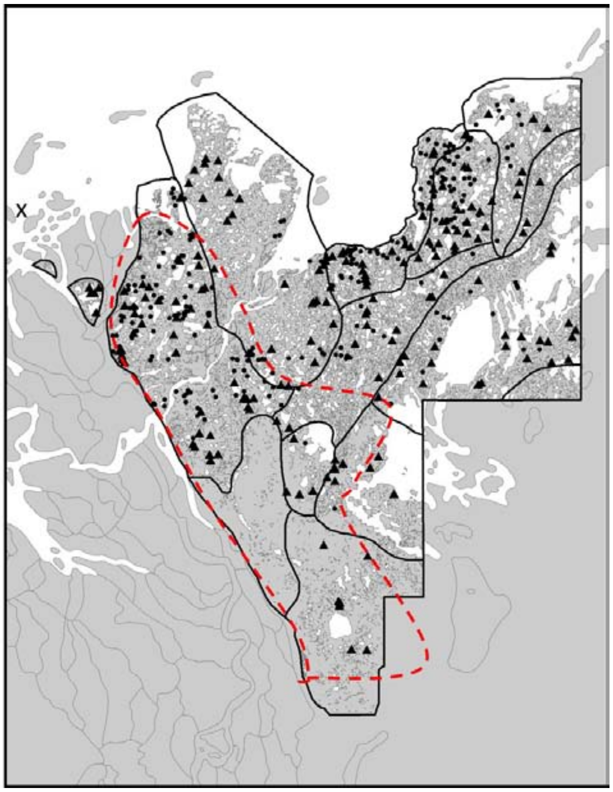

Figure 4: All drained lake thaw basins (DLTB) (shown by triangles) and pingos (closed circles) as mapped by Marsh et al. (2009). Dashed red line outlines the area of mapped polygonal terrain shown in Figure 5.

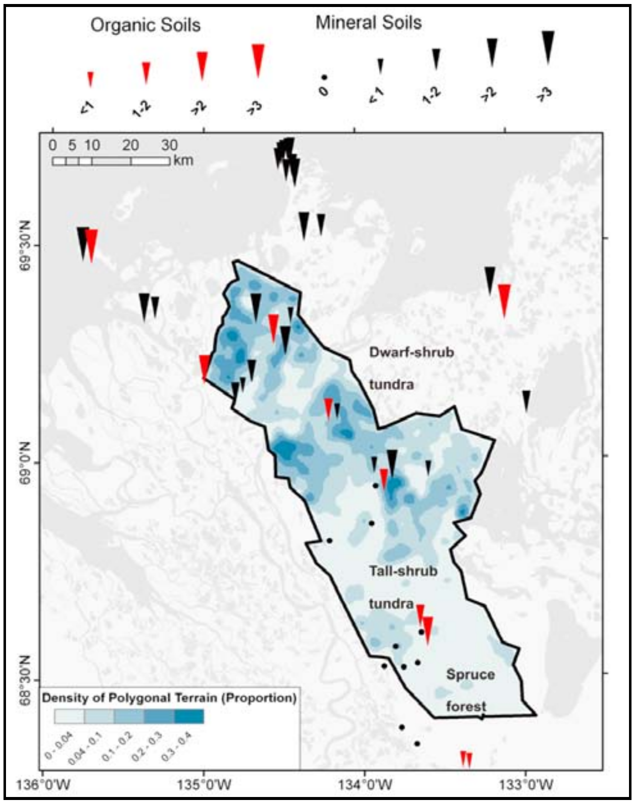

Figure 5: Density of polygonal terrain as mapped by Kokelj et al. (2014) and ice wedge characteristics for a portion of the area mapped in Figure 4. Note that areas with higher numbers of DLTBs in Figure 4, appear to coincide with areas of higher density of polygonal terrain. 2.4)

2.3 Discharge rates during lake drainage

Although Mackay (1992) outlined possible processes of lake drainage, few details were known at that time. Although the initial stages of lake drainage have not been well documented from field observations, observations after drainage (Mackay, 1992) suggest that there is typically a period of rapid or catastrophic outflow with near-complete lake drainage occurring within a few hours (Marsh and Neumann, 2001). Such a period of rapid drainage was also described for the experimental drainage of Lake Illisarvik on Richards Island in 1978 (Mackay, 1981). Although it seemed likely that lake drainage occurred due to melting of ground ice, the relative importance of thermal versus mechanical erosion during the period of rapid channel enlargement were not known. However, the importance of the melting of ground ice was suggested by the observation that ‘remarkably little sediment was deposited by the floodwater at the terminus of the gully and along the river, considering the size of the gully excavated during lake drainage’ (Brewer et al., 1993) and by ‘signs of thaw slumping of ice-rich permafrost’ in a recently formed outlet drainage channel (Mackay, 1988). Marsh and Neumann (2001) suggested that if melting of ice is important, and possibly the dominant process leading to lake drainage, then as a first approximation it could be assumed that the processes controlling the rapid enlargement of the drainage channel controlling the rate of drainage are similar to that of glacier overtopping or tunnelling controlling the sudden release of water from glacier-dammed lakes where the role of thermal enlargement has been well documented. Fortier et al. (2007) and Godin et al. (2012) described similar thermo erosional processes in the eastern Canadian Arctic.

Applying a glacial lake drainage model to two examples of lake drainage where discharge was available, Marsh and Neumann (2001) showed that modelled discharge was in fact similar to measured, and as a result, melting of ground ice was likely the dominant process controlling rapid lake drainage. Marsh and Neumann (2001) and Marsh et al. (2008) modelled discharge during lake drainage events for a number of lake sizes, and groups of lakes, reporting that lakes could in fact drain completely in less than a day and that peak discharge could be orders of magnitude larger than would occur during spring snowmelt.

Marsh et al. (2009) mapped all thaw lakes and ponds (Figure 4) in the study area using National Topographic Data Base (NTDB) map sheets based on 1950 aerial photographs and estimated the area of each water body. Mackay (1992) also used this data source for his estimates of 1950 lake boundaries in the Tuktoyaktuk Coastlands. DTLBs were identified from a series of aerial photographs taken in August 2000, including partially drained lakes. Mapped DTLBs were confirmed via field visits. DTLBs that drained since 1950 were separated from all other lakes and DTLBs, and lake drainage was then determined for the periods 1950 to 1973, 1973 to 1985 and 1985 to 2000 using available aerial photographs.

The overall drainage rate for the period 1950 to 1985, the time period used by Mackay (1992) was similar to the 1 or 2 lakes per year found in Mackay's study. However the full data set showed a decreasing rate of lake drainage as follows: for the period 1950 to 1973, the annual drainage rate was 1.13/yr, decreasing to 0.83/yr for 1973 to 1985, and only 0.33/yr for the period 1985 to 2000. There is a need to consider the drainage rate from 2000 to present and determine if it continues to decline.

The processes controlling this decline in lake drainage rates are not well understood. Pohl et al. (2009) modelled lake levels to see if a changing climate over the 1975 to 2006 period could be responsible for a decline in lake drainage. For this 32 year period, they found no trends in lake levels. Suggesting that a change in hydrology is likely not responsible for the declining lake drainage rates. Since ice wedge thermal contraction cracking plays a very important role in lake drainage, a decrease in cracking is a possible driver of the decrease in lake drainage. Kokelj et al. (2014) outlined some of the factors controlling ice wedge cracking across the TP. Although cracking is dependent on ground temperature, the impact of factors controlling ground temperature and therefore cracking are not well known. These could include winter air temperature and snow depth, with snow depth being controlled by snowfall, blowing snow and changes in vegetation, such as the expansion of shrubs across the tundra. Ongoing research is also required to consider these changes.

3) DISCUSSION

J. Ross Mackay made a significant contribution to our understanding of lakes and permafrost across the western Canadian Arctic, and highlighted the variety of processes controlling lake water level regime and changes in lake size and depth. For lakes of the Mackenzie Delta, he was the first to outline the role of lake sill elevation and main channel water level in controlling the water level regime of the lakes. Ongoing research has further quantified lake water level regime based on extreme low and high channel water level frequency. Building on this work are efforts to develop a hydraulic model of the Mackenzie Delta Channels, including the effect of off channel water storage in delta lakes, and linking lake hydrology to lake ecology. Such efforts are essential to understanding the ongoing impact of a changing climate (including Beaufort Sea level and storm surges, and discharge from the Mackenzie River basin) and future natural gas extraction on the hydrology and ecology of the Mackenzie Delta.

Mackay also outlined the key aspects of rapid drainage of lakes in the western Arctic. Such rapid drainage is a natural occurrence in this region, and has been shown to be sensitive to climate. Recent research has shown that the rate of lake drainage is declining, however it is not clear if this trend will continue. In fact it seems likely that lake drainage will increase in the future as thermokarst melting increases, and results in higher rates of lake drainage. It is expected that such a lake drainage event will occur during the summer or fall of 2015 in an area west of Ft. McPherson in the Mackenzie Delta region (S. Kokelj, person communication). This event will occur due to a massive slumping of ice rich terrain that will encroach on a small lake. It seems likely such lake drainage events will occur more often in this region as the climate warms over the coming decades.

Ongoing changes to permafrost affected lakes, either increasing or decreasing lake drainage or expansion of lake area due to thermokarst processes or changes in lake water balance, will have significant ecological implications and may impact infrastructure built in this area. Drained lakes obviously result in a significant change in habitat, with a change from lakes used by waterfowl to DTLBs being a location of enhanced shrub growth and therefore moose habitat for example. Future changes are also important for understanding the impact on linear infrastructure such as pipelines or roads such as the Inuvik-Tuktoyaktuk Highway that is currently under construction. Rapid lake drainage poses a significant risk to such infrastructure as discharge from these lakes is typically not planned for in the design of pipelines or roads, but is orders of magnitude larger than snow or rainfall generated runoff. Lake drainage would have major implications to downstream roads or pipelines. It is important to know if this risk will decrease across the TP, as it has done over the past 65 years, or will it increase with a warming climate

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