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Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution

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ABSTRACT

Locally grounded features in ice shelves, called ice rises and rumples, play a key role buttressing discharge from the Antarctic Ice Sheet and regulating its contribution to sea level. Ice rises typically rise several hundreds of meters above the surrounding ice shelf; shelf flow is diverted around them. On the other hand, shelf ice flows across ice rumples, which typically rise only a few tens of meters above the ice shelf. Ice rises contain rich histories of deglaciation and climate that extend back over timescales ranging from a few millennia to beyond the last glacial maximum. Numerical model results have shown that the buttressing effects of ice rises and rumples are significant, but details of processes and how they evolve remain poorly understood. Fundamental information about the conditions and processes that cause transitions between floating ice shelves, ice rises and ice rumples is needed in order to assess their impact on ice-sheet behavior. Targeted high-resolution observational data are needed to evaluate and improve prognostic numerical models and parameterizations of the effects of small-scale pinning points on grounding-zone dynamics.

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1. Introduction

Small-scale topographic features occur wherever ice shelves ground locally on the elevated seabed. These features are called “ice rises” where the flowing ice shelf is diverted around the grounded region, and “ice rumples” where the ice shelf flows over the grounded region (Figs. 1 and 2). Numerous ice rises around the edge of the Antarctic Ice Sheet are in fact miniature ice sheets — independent entities with many of the characteristics shared with the larger, main ice sheet (Robin, 1953). Being smaller and numerous, ice rises represent a far larger sample of possible ice sheets. Each one is relatively simple, but the population provides much variety. As such, they provide a convenient platform for conducting geophysical and glaciological observations and model experiments to develop concepts about ice sheets.

Understanding the role of ice rises in the evolution and future of the Antarctic Ice Sheet is important for three primary reasons. First, glacial-interglacial changes in the extent and configuration of the Antarctic Ice Sheet are largest at the margins, so knowledge from ice rises provide powerful constraints on the timing and amount of thickness changes (e.g., Conway et al., 1999; Brook et al., 2005; Waddington et al., 2005; Martin et al., 2006; Mulvaney et al., 2007). Second, relatively high surface mass balance (SMB) and close proximity to the storm track that circulates Antarctica make ice cores from ice rises well suited to examine highly regional, circumpolar variations in Antarctic climate and sea ice, and their tele-connections (e.g., Goodwin et al., 2014; Sinclair et al., 2014). Finally, the mass balance of Antarctica is dominated by grounding-zone dynamics and ice-shelf/ocean interactions, which are influenced by ice rises and rumples. For example it is thought that recent un-grounding of an ice rumple within the ice shelf of Pine Island Glacier in the Amundsen Sea Embayment has contributed to the ongoing retreat and thinning in the region (Jenkins et al., 2010a; Gladstone et al., 2012). Losses from the Amundsen Sea Embayment dominate the current mass deficit of the Antarctic Ice Sheet (Pritchard et al., 2012; Joughin et al., 2014; Rignot et al., 2014). Ice rumples are much smaller than ice rises, but provide significant buttressing to the ice shelf with potential for rapid ice-dynamical changes in cases of grounding or un-grounding.

Here, we review current understanding of ice rises and rumples in terms of their morphology, distribution, history, and impact on the evolution of Antarctica. Section 2 first defines ice rises and rumples and then shows their distributions, and their geological, oceanographic, and climatological settings. We also discuss their formation mechanisms. Section 3 reviews the roles of ice rises and rumples in ice-sheet dynamics and mass balance. Section 4 provides an overview of current knowledge of the Holocene retreat of the Antarctic Ice Sheet, with emphasis on the records and roles of ice rises. Finally, in Section 5, we discuss major knowledge gaps, and key directions and needs for future research.

2. Settings

2.1. Definition of ice rises and rumples

Ice rises and ice rumples are locally elevated, grounded features surrounded fully or partially by ice shelves or ice streams (Figs. 1 and 2). Other terms such as ice hill, ice dome, ice promontory, ice ridge, and inter-ice-stream ridge have also been used to refer to ice rises (depending on which characteristic is being emphasized), so we include them in our definition here. We follow MacAyeal et al. (1987) to distinguish ice rises and rumples.

Ice rises are built mostly from locally accumulating snow. They consist of radial ice-flow centers or divides separate from the main ice sheet. They are typically several hundred meters higher than the surrounding ice shelves or ice streams. In cross section (Fig. 2), the surface topography is quasi parabolic with flank slopes extending from a blunt peak (Martin and Sanderson, 1980). Local snow accumulation and negligible horizontal ice flow make the flow divide or center an excellent site to extract ice cores to determine coastal Antarctic climate. Examples of ice rises of various types include (see Figs. 1 and 3 for locations): (#1) Roosevelt Island in the Ross Sea Embayment and Korff Ice Rise in the Weddell Sea Embayment are isles completely surrounded by ice shelves; (#2) Fletcher Promontory in the Weddell Sea Embayment is a promontory of the ice sheet protruding into the ice shelf; (#3) Siple Dome in the Ross Sea Embayment is an inter-ice-stream ridge; and