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Inferring the variation of climatic and glaciological contributions to West Greenland iceberg discharge in the twentieth century

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ABSTRACT

Iceberg discharge is a major component of the mass balance of the Greenland Ice Sheet (GrIS). While bulk estimates of discharge variation over time exist, inferred remotely from measurements of grounding line ice velocities or surface mass balance calculations, few detailed measurements of discharge itself from individual marine-terminating glaciers existed until recent years. Recently, it has been shown, through a combination of ocean–iceberg modelling and non-linear system identification, that the century-long record of iceberg numbers crossing 48°N in the West Atlantic is a good first-order proxy for discharge from at least south and west Greenland. Here, we explore the varying relative importance of ice sheet, oceanic and climatic forcing of iceberg discharge from these areas over the twentieth century, by carrying out sensitivity studies of a non-linear auto-regressive mathematical model of the 48°N time series. We find that the relationships are mainly non-linear, with the contribution of the GrIS surface mass balance to iceberg discharge likely to be dominant in the first half of the century. This period is followed by several decades where oceanic temperature effects are most important in determining the model variation in iceberg discharge. In recent decades, all physical processes play a non-negligible part in explaining the iceberg discharge and the model suggests that the glacial response time to environmental changes may have decreased.

1. Introduction

The total mass balance of the Greenland Ice Sheet (GrIS) comes from the net mass balance between surface accumulation/runoff, basal melting, and ice discharge through calving. The former is known as the surface mass balance (*SMB*)—the balance between net precipitation and surface ablation (surface meltwater, runoff, and sublimation)—and has been calculated by a number of groups using different atmospheric reanalysis and/or regional climate model fields as forcing for various melt/runoff/*SMB* models (e.g. Hanna et al., 2011; Janssens and Huybrechts, 2000; van den Broeke et al., 2009). While there are differences between these *SMB* models, they are second order in magnitude, and all show a distinct trend towards a reduced *SMB* over the last decade (e.g. Box, 2013; Fettweis et al., 2008; Hanna et al., 2011; Van den Broeke et al., 2009), but with considerable interannual variability (e.g. Fig. 1). This recent trend is part of a longer-term *SMB* decrease, starting around 1930 (Hanna et al., 2011). But what characterises this record throughout, both recently and over the last century or more, is high variability on an annual timescale. The ice discharge term (D) in the total mass balance, although estimated to have earlier contributed approximately equally to ice sheet mass loss as the *SMB* (Rignot et al., 2011) but more recently only a third of the latter's magnitude (Enderlin et al., 2014), has not been directly measured, but estimated empirically (e.g. Bigg, 1999; Reeh, 1994) or, more recently, inferred from a combination of satellite remote sensing of ice motion across the ice sheet's grounding line and ice thickness (e.g. Enderlin et al., 2014; Rignot et al., 2008, 2011; Sasgen et al., 2012; van den Broeke et al., 2009). While D inferred from grounding line discharges has shown a distinct upward trend in the last decade, in contrast to the *SMB* time series it is characterised by a lack of interannual variability.

However, what measures we do have for annual variations in iceberg discharge suggest that D—when taken as the calving flux from the GrIS, rather than transport over the grounding line—is actually highly variable. At the individual glacier scale, it is well known that the major glacier of west Greenland—Jacobshavn Isbrae—has long exhibited substantial changes in discharge from year to year and decade to decade (e.g. Csatho et al., 2008; Sohn et al., 1998). Similarly, there has been short-term major ice loss from northwest Greenland glaciers on different occasions in the last few decades (Kjaer et al., 2012). The International

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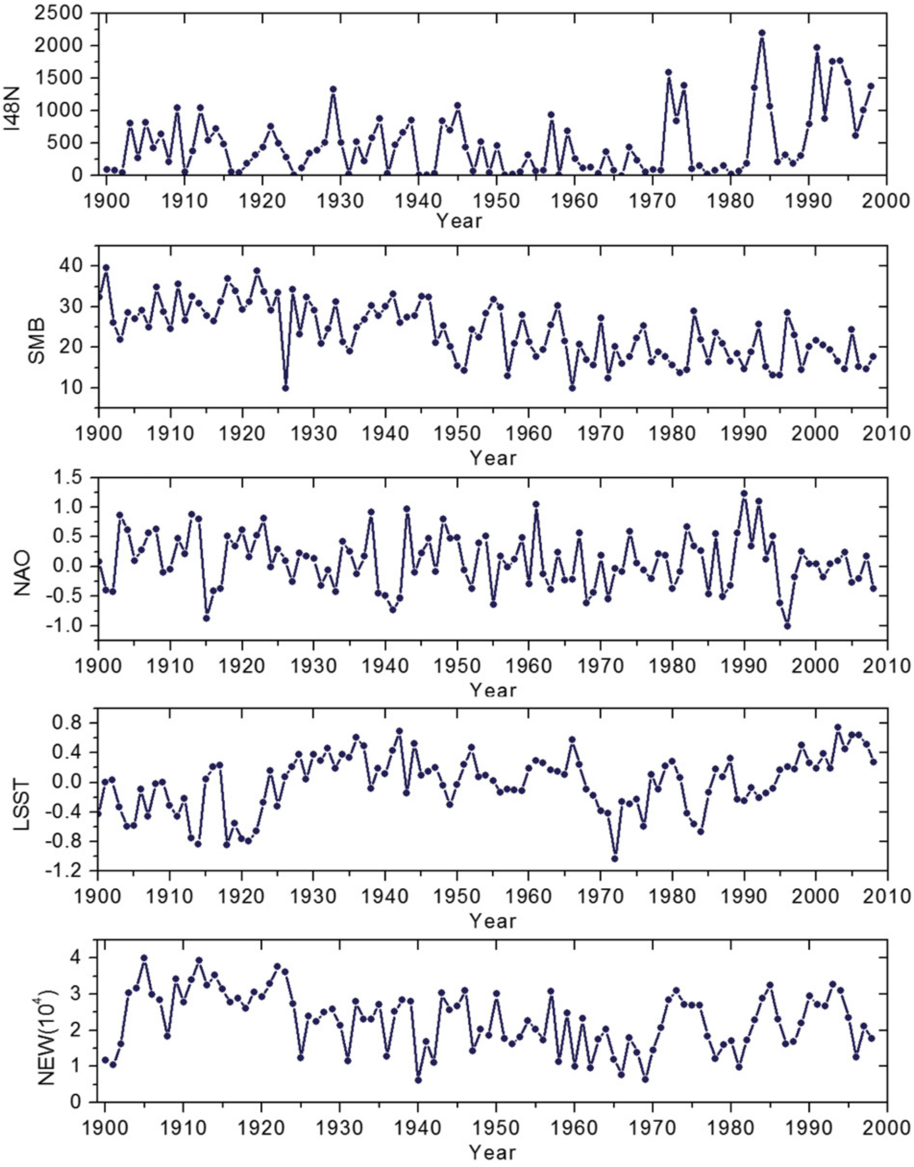

Fig. 1. The annual input and output variables for the Greenland Iceberg Calving modelling problem. Units are number (I48N), ×10 km^{3}yr^{-1} water equivalent (*SMB*), standardised value (*NAO*), °C anomaly (*LSST*), ×10,000 km^2 (*NEW*; 1900–1998 only).

Ice Patrol's (IIP) long-term record of icebergs crossing 48°N (I48N; Marko et al., 1994; Murphy and Cass, 2012), an integrated measure of iceberg flux from at least south and west Greenland (Bigg and Wilton, 2014), and one which is highly variable on an annual scale (Fig. 1), has been shown to be a first-order proxy for west Greenland iceberg discharge (Bigg et al., 2014), down to individual glacier level (Wilton et al., 2015).

The mechanisms which control glacier retreat, and therefore calving, have recently been discussed in a review article by Straneo et al. (2013). Here three categories of triggering mechanisms for retreat are presented. The first is submarine melting at the ice–ocean interface, linked to changes in ocean temperature (Seale et al., 2011) and variation in ice sheet runoff (Motyka et al., 2013; Slater et al., 2015), which can alter the ice front force balance. The second is variation in the thickness, extent, and duration of the calved ice/sea-ice melange in front of marine-terminating glaciers. This melange has been shown to hinder calving over winter and into the spring (Todd and Christoffersen, 2014; Walter et al., 2012) and is likely to be linked to a combination of glaciological and ocean and atmosphere temperature and circulation change (Mugford and Dowdeswell, 2010). The third is the nature of crevassing and sub-glacial hydrology close to the glacier's calving front. This factor will be linked to changes in surface melting and runoff via the amount and depth of water-filled crevasses and routing of runoff at the base of the glacier (e.g. Andersen et al., 2011; Moon et al., 2014).

Previously we have used a combination of ocean–iceberg modelling and the non-linear system modelling discussed below to examine these mechanisms at annual timescale (Bigg et al., 2014). In this paper, we examine in much greater detail the variation and sensitivity of these mechanisms over time by using non-linear finite impulse response (NFIR) system identification modelling of the discharge signal in I48N. The NFIR approach is described below in the Methods section, but, briefly, it is a modelling framework, derived from control engineering, which allows the user to construct linear or non-linear dynamic models between inputs (exogenous variables) and outputs (auto-regressive variables) in the presence of coloured and non-linear noise. Three physical variables that we use as model inputs to characterise the large-scale physical environment in which the Greenland marine-terminating outlet glaciers exist are the *SMB*, representing the glacier's surface runoff/accumulation balance, a measure of regional ocean temperature (the Labrador Sea Surface Temperature; *LSST*), which, indirectly