MELTWATER DRAINAGE AND SEDIMENT TRANSPORT IN A SMALL GLACIARIZED BASIN, WANDA GLACIER, KING GEORGE ISLAND, ANTARCTICA

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ABSTRACT - Basal sediment transport by efficient subglacial drainage systems is widely assumed to dominate the sediment budget of most temperate glaciers in glacimarine environments. Hydrological characteristics of the drainage system and mechanisms of basal sediment transport in Wanda Glacier, King George Island, were examined by the analyses of temporal variations of discharge and sediment load in the proglacial channels. In the investigation about the variability of sediment load transfer to Admiralty Bay, we analyzed the control of the drainage system, thermal conditions, ice flow velocity, topography and meteorological conditions in the period. Data collected on January 2010 and 2011 show the control of the subglacial drainage configuration on rates of basal sediment evacuation and delivery by subglacial meltwater to glacimarine environment. Thus, such data demonstrate a strong relation between suspended sediment load, water discharge and air temperature, radiation and precipitation rate. High sediment concentrations recorded in proglacial channels are related to efficient rates of basal sediment transport, thus, indicate sediment yield availability to Martel Inlet glacimarine environment. Direct measurements of sediment in proglacial channels allowed the estimation of the actual sedimentary contribution of 19.49 kg s-3 to the glacimarine environment. Sediment load is an indicator of erosion and sediment yield processes beneath the glacier. These processes are interconnected with the high summer temperatures presented, responsible for the relatively high rates of meltwater production and the sediment supply to glacimarine environment and with consequences for the sediment dynamics of the study area.
Keywords: subglacial hydrology; sediment evacuation; suspended sediment; climate variability.

RESUMO - O transporte de sedimentos subglaciais por uma eficiente rede de drenagem subglacial é amplamente considerado como a forma dominante de descarga sedimentar na maioria das geleiras temperadas em ambientes glacimarinhos. Características hidrológicas do sistema de drenagem e mecanismos de transporte de sedimentos basais na geleira Wanda, ilha Rei George, foram examinados por meio de análises das flutuações temporais da descarga de água de degelo e sedimentos em canais proglaciais. Foram realizadas relações entre o sistema de drenagem, as condições termais, a velocidade de fluxo de gelo, a topografia e as condições meteorológicas no período observado. Dados coletados em janeiro de 2010 e 2011 demonstram o forte controle da configuração dos sistemas de drenagem no grau de remoção sedimentar e transferência para o ambiente glacimarinho. Desta forma, resultados indicaram uma forte relação entre a carga de sedimentos em suspensão, descarga de água de degelo, temperatura do ar, radiação solar e precipitação. Altas concentrações sedimentares registradas em canais proglaciais estão relacionadas ao eficiente grau de transporte sedimentar e, indicam a produção sedimentar disponibilizada ao ambiente glacimarinho da enseada Martel. Medidas da concentração de sedimentos em suspensão em canais proglaciais permitiram estimar a atual produção sedimentar de 19.49 kg s^{-3} pela geleira Wanda. A carga de sedimentos em suspensão é um indicador de processos de erosão e produção sedimentar na zona subglacial da geleira Wanda. Estes processos estão conectados com as altas temperaturas no verão responsáveis por relativos altos graus de produção de água de degelo e suprimento sedimentar para o ambiente glacimarinho e com consequências para a dinâmica sedimentar na área de estudo.
Palavras-chave: hidrologia sublgacial; remoção sedimentar; sedimento em suspensão; variabilidade climática.

INTRODUCTION

Meltwater is an important component of subglacial erosion and sediment yield in wet bed glaciers (Sugden & John 1976, Swift et al. 2005, Eyles 2006). These glaciers produce efficient debris transport by abrasion, quarrying and fragmentation processes (Drewry 1986, Swift et al. 2005). Subglacial meltwater runoff in temperate glaciers results from geothermal and friction heat, rainfall and flush-out of storage water (Boulton 1974). Meltwater runoff may also enter glacial drainage systems by supraglacial meltwater, ice and snow, acessing the glacier bed through crevasses and moulins (Benn & Evans 2010).

Hydraulic erosion enhances sediment transport, and is related to the balance between the water flow capacity and competence (according to basal sliding, subglacial drainage configuration and development) and nature of sediment and its availability (Alley et al. 2003). Topographic gradients may influence this process (Shreve 1972, Paterson 1994, Swift 2006).

The pattern of a subglacial hydraulic system is controlled, in part, by runoff meltwater. Drainage system development is controlled by: (a) ice mass type, morphology and topography, (b) thermal conditions, (c) ice mass balance, (d) ice flow velocity, (e) basal conditions and (f) amount of debris transported (Menzies 1995).

Seasonal changes and canalized drainage variations may increase erosion capacity and contribute to glacial sediment yield variability. Subglacial conduits tend to form or enlarge near the terminus in the spring and early summer and extend further upglacier as the melting season proceeds (Nienow et al. 1998, Anderson et al. 2004). Abrupt discharge increases during summer, along short time-periods such as days or hours are important for erosion and sediment discharge (Drewry 1986). The evacuation efficiency is greater in the ablation area where the streams reach their maximum extension (Swift 2006). Runoff tends to be minimum in winter due to the collapse of channels formed by previous ablation (Hubbard & Glasser 2005). Thus, seasonal changes in the glacier sediment transport system are strongly controlled by the evolution of this subglacial drainage system (Nienow et al. 1998).

Several researches have focused on Alpine and Arctic glaciers, but subpolar glaciers hydrology in the Antarctic Peninsula region have received little attention. These glaciers represent a powerful source for hydrological studies due to their temperate thermal regime influence on the hydrological processes.

This work presents an investigation on the mechanisms of basal sediment evacuation in Wanda glacier King George Island, South Shetland Islands, Antarctica (Figures 1 and 2), and specifically determines its suspended sediment contribution to the Martel Inlet glacimarine environment. This study integrates geomorphological, hydrological, glaciological and meteorological aspects that affect suspended sediment transport and yield. The interpretation of the transport processes may contribute to our understanding of temperate glaciers in maritime and sub-Antarctica region.

In the investigation about the variability of sediment load transfer to Admiralty Bay, the drainage system control, thermal conditions, ice flow velocity, topography and meteorological conditions were also analyzed.

STUDY AREA

Wanda glacier (Figure 1) is characterized by its proglacial front and a proglacial lake. The glacier has 1.56 km² of the area (based in a QUICKBIRD image obtained in 2006) and has a thin glacier front (4 meters thick maximum). In the ablation areas, crevasses observed on glacier surface are connected to subglacial conduits where meltwater flows downward to the subglacial zone. Subglacial conduits emerge at the front of the glacier and fine sediments are transported towards Martel Inlet through a proglacial lagoon (Rosa et al. 2009).

Several studies have provided evidence for a general glacial retreat in the Martel Inlet since 1950 (Simões & Bremer 1995, Park et al. 1998, Bremer 1998, Simões et al. 1999, Aquino 1999, Braun & Gossmann 2002, Vieira et al. 2005, Rosa et al. 2009). The retreat processes of those glaciers can be related to the present regional atmospheric warming recorded (Blindow et al. 2010). For the past 30 years, the number of days with liquid precipitation has increased in the summer. These processes accelerated the snowmelt and increased the negative mass balance of local glaciers (Braun et al. 2001; Ferrando et al. 2009).

Wanda glacier retreat may increase sediment supply and also result in a high runoff by developing proglacial streams. Proglacial meltwater streams transport significant amounts of sediments, mainly during the summer season which may contribute for sedimentation processes in Admiralty Bay.

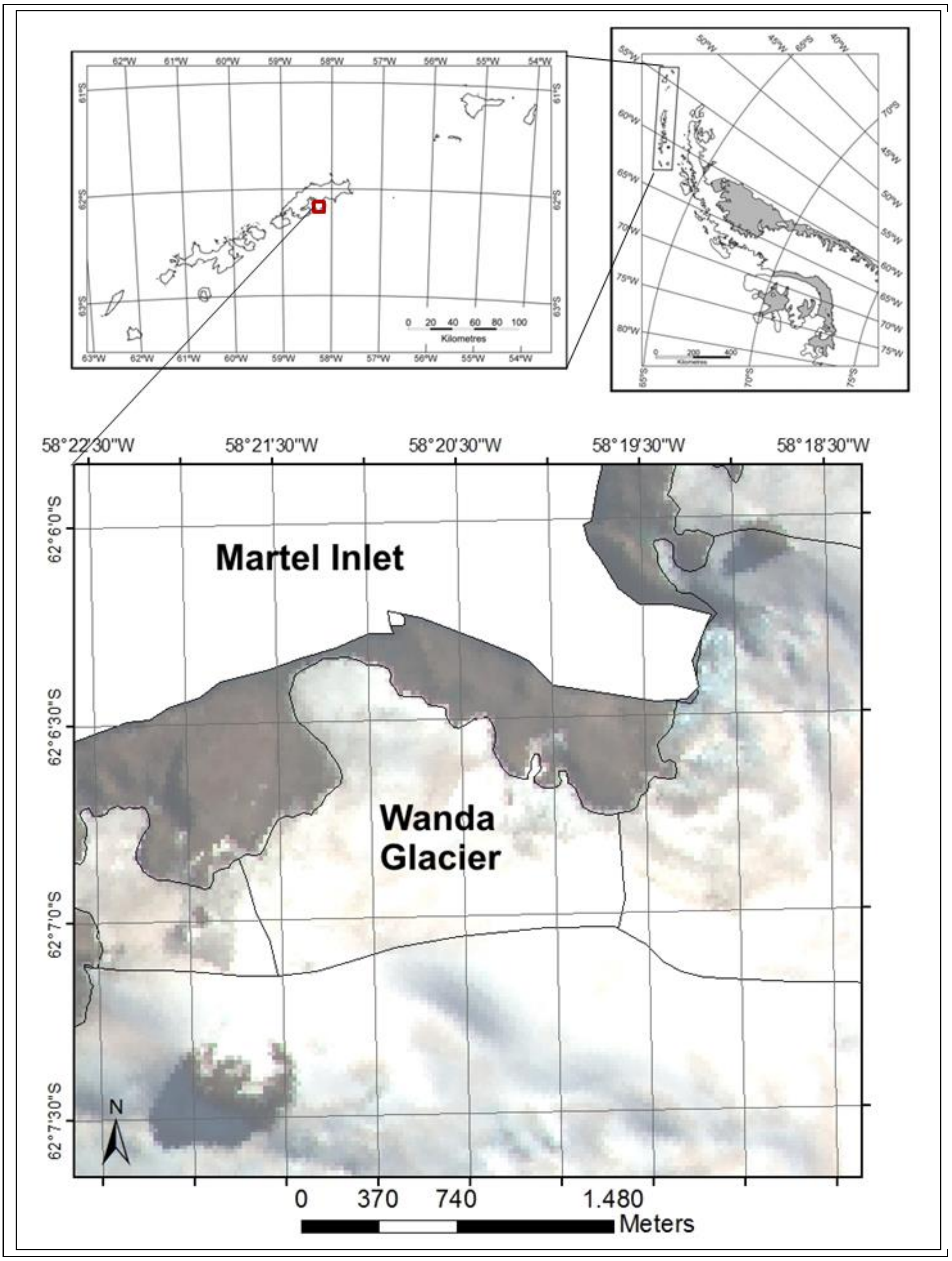

Figure 1. Location map of Wanda glacier, Admiralty Bay, King George Island, South Shetland Islands (based on SPOT image obtained in 2000).

DATA SOURCES AND METHODS

Monitoring of sediment transport from subglacial drainage system of Wanda glacier was carried out in January 2010 and February 2011 to characterize the efficiency of sediment evacuation and to investigate the subglacial drainage configurations. Time-series of daily discharge and sediment load in proglacial streams were used to explore the relationship between discharge, sediment load, and glacial drainage systems within the glacier. The observed variability was related to meteorological conditions (radiation, precipitation and air temperature) in the period (the database was updated using the continuous meteorological record from the Brazilian Antarctic Station – *Estação Antártica Comandante Ferraz*, EACF, 62°05'S, 58°23.5'W.

Meteorological stations maintained by the Brazilian *Instituto Nacional de Pesquisas Espaciais* (INPE), and their data are available at the following Internet address: ''http://www.met.inpe.brhtmldoc/antarctica).

Figure 2. Wanda Glacier, viewed from Admiralty Bay, KGI in the summer of 2011.

Hydrological characteristics of englacial and subglacial drainage systems in Wanda Glacier were examined by analyzing temporal variations of discharge and sediment load in the proglacial streams.

Proglacial streams daily discharge (Q) was estimated by multiplying the cross-sectional area (A) with water flow velocity (Vm) (Q= A.Vm) according to Santos et al. (2001), Collischon (2005) and Correa (2006). In order to estimate the partial discharge value of each section (Figure 3), the area of influence was calculated in accordance to Equation 1.

The water sample is collected in the field and filtered to extract suspended matter. The filtered material is then dried, weighed and divided by the sample volume to obtain SSC concentration (mg/L). The total sediment load transported in proglacial streams was quantified by multiplying the total discharge by the sediment load in January - February in 2010 and 2011. This methodology aims to investigate runoff processes in the proglacial streams and suspended sediment supply variability for Martel Inlet. According to Rubin & Topping (2001) and Morehead et al. (2003), the sediment load in proglacial streams will predict correctly the sediment bulk transported by glaciers if the sediment transport is regulated only by meltwater discharge.

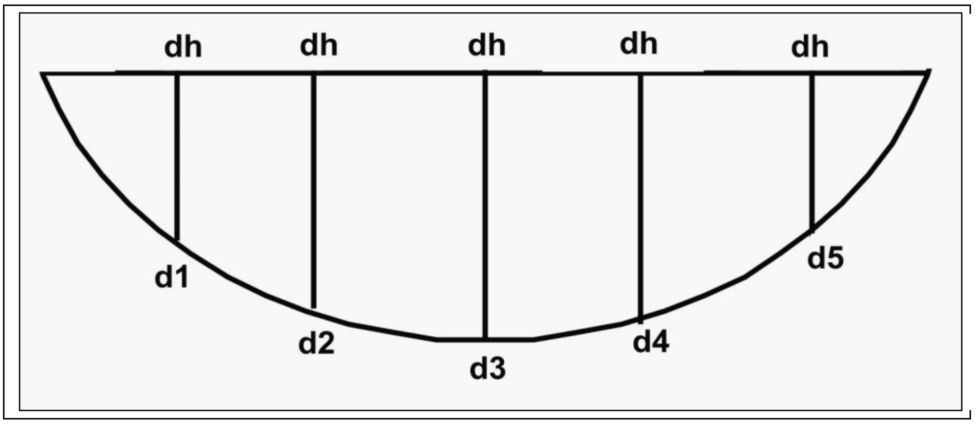

Figure 3. Cross sections channel measurements for partial discharge estimative. The partial discharge of each section (dh) was estimated by multiplying the water flow velocity by its influence area (A.Vm).

Equation (1) for partial discharge estimative.

$$A_i = \left(\frac{d_1 + d_2}{2}\right).dh + \left(\frac{d_2 + d_3}{2}\right).dh$$

The partial discharge of each section (dh) was estimated by multiplying the water flow velocity by its influence area (A.Vm).

The SSC (Sediment Suspended Concentration) temporal variability was used to infer glacial ablation processes, considering that the meltwater is sensitive to those processes. Sediment supply is an important proxy for erosion action related to subglacial thermal conditions (Ritchie & Schiebe, 1986). According to Benn and Evans (2010), ice temperature controls several glacial processes, including glacier motion, meltwater flow, and subglacial erosion and deposition.

RESULTS

Hydrological characteristics were examined by analyzing temporal variations of suspended sediment and discharge in the proglacial meltwater channels (Figure 4) of Wanda Glacier in January 2011, which are influenced by fluctuations of air temperature, radiation and precipitation rates (Figure 5).

Each curve gradient reflects the relationship with sediment transport capacities, which are related linearly with discharge, mainly during early ablation season. There are considerable temporal changes in proglacial suspended sediments due to high variability of the local meteorological conditions in the studied period. Low discharges are associated with low temperatures, lower snowfall, and little radiation in early morning, when the channels can still be occluded. Higher values of surface air temperature and solar radiation induce high meltwater and sediment supply to the glacimarine environment. Days with high SSC are related to two periods of rainfall and positive air temperatures. Rainfall induces occasional runoff peaks. According to Benn and Evans (2010), the highest weather-related discharges tend to be associated to high rainfall during summer storms and runoff in the basin, and therefore contribute to snow and ice melting. The increase in the correlation between runoff and incident radiation probably reflects the removal of the ablation area snowpack. Relatively poor correlation between runoff and meteorological variables during some days probably reflects a more complex relationship between meteorological variations and meltwater generation during periods of high precipitation. Since incident radiation generally outleads air temperature by a couple of hours, this may have contributed to the decline in lag between runoff and meteorological variables.

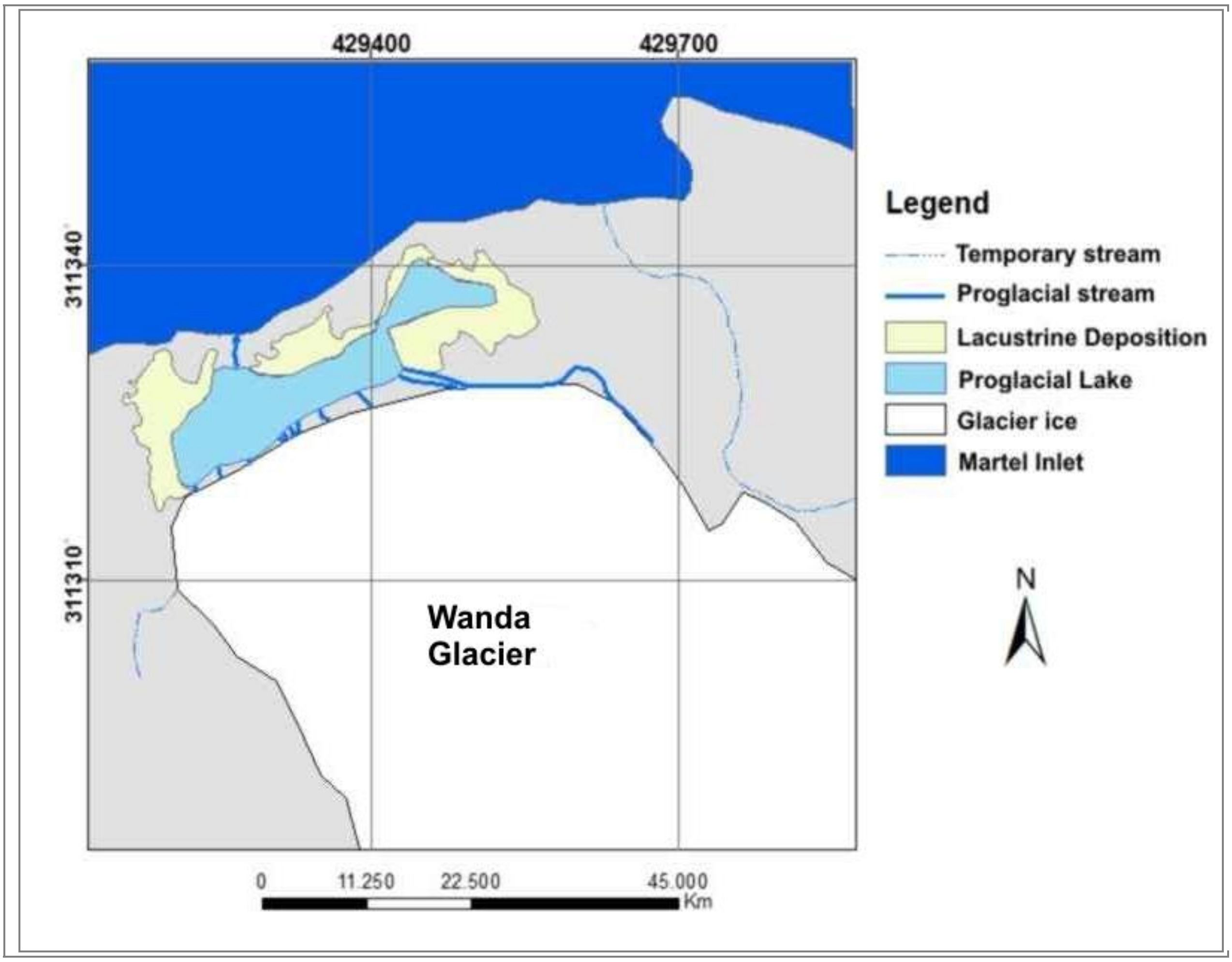

Figura 4. Localization map of the Wanda glacier proglacial channels.

Discharge fluctuations during the studied period have an impact on the morphology of the proglacial channels cross section (Figure 6) and on the development of proglacial multiple channels at glacier front. Thus, it has hydrological implications for geomorphologic studies in the area.

Analysis of proglacial streams flow records (Figure 7), near the ablation area of Wanda Glacier, during two consecutive years in the same month (January) has shown an increase in SSC and an enlargement of the cross section channel, which reflects an increase in meltwater processes.

DISCUSSION

The correlation between the hydrological and sedimentological processes in proglacial area of the Wanda Glacier is demonstrated in the results and the configuration of the meltwater drainage system and basal sediment transport rate in the study area are interpreted. The glacial meltwater is the main water component in proglacial streams throughout the melting season in the proglacial area. Other possible sources of water include proglacial snowmelt in the melting season and rainfall. Observations show that subglacial zone cavities are connected to the englacial zone, but meltwater has predominantly a subglacial origin.

With high discharge rates in proglacial channels, the flow of meltwater becomes sufficiently concentrated to develop channeled subglacial drainage systems. Thus, in summer, with a wider surface melt and rainfall registered in the study area, there is the formation of efficient and developed meltwater channels towards the ablation area.

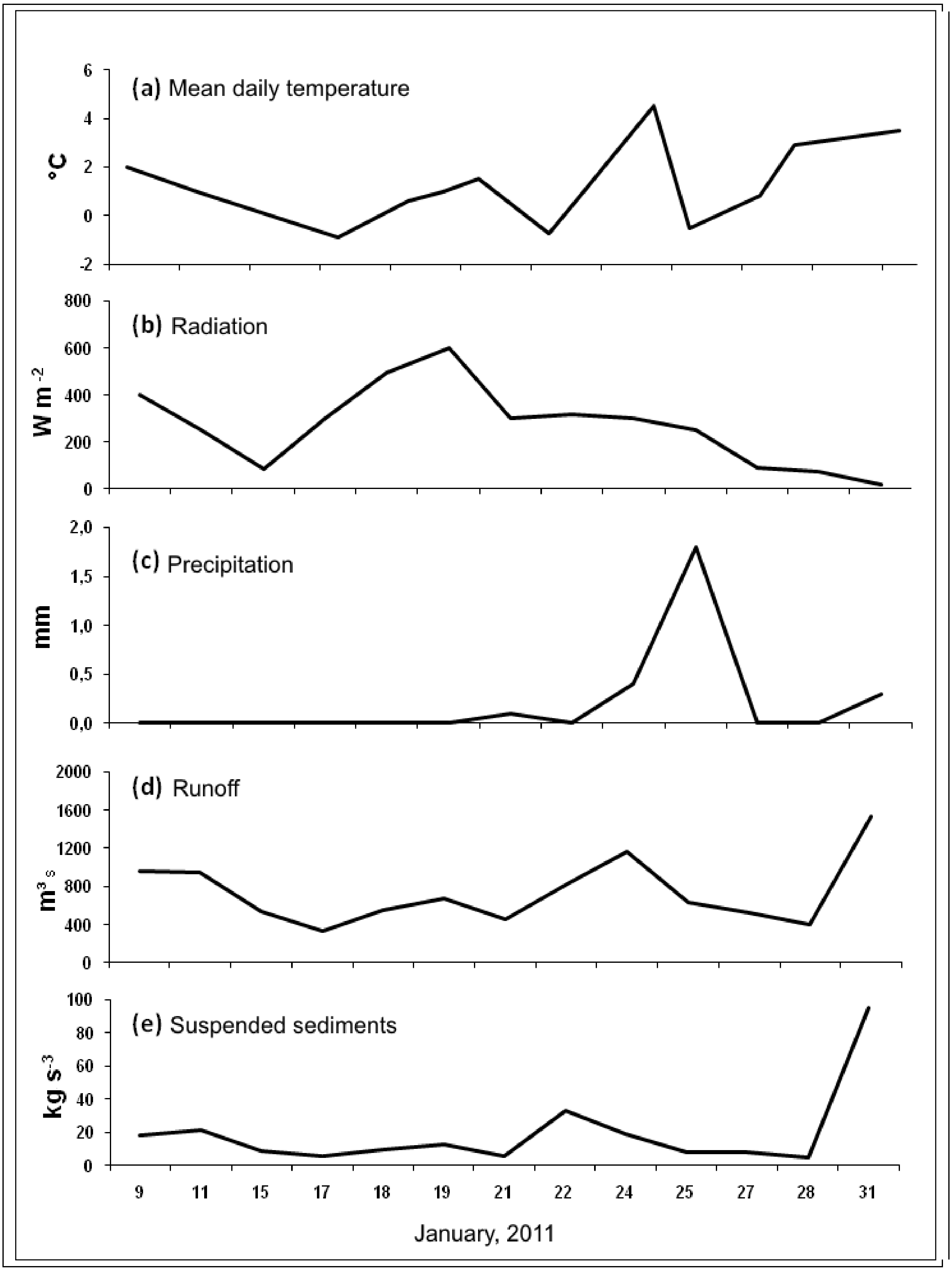

Figure 5. Temporal variations of air temperature (a), radiation (b) and precipitation rate (c), runoff (d) and suspended sediment loads (e) at site in January, 2011.

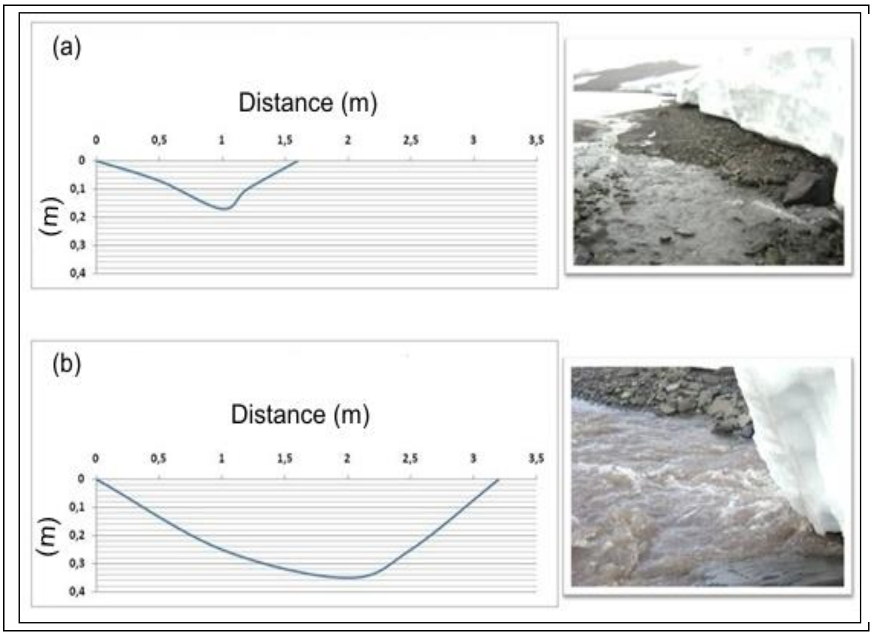

Figure 6. Fluctuations of the channel cross section morphology due peaks in proglacial discharge (a) obtained on January 2010 and (b) obtained on January 2011.

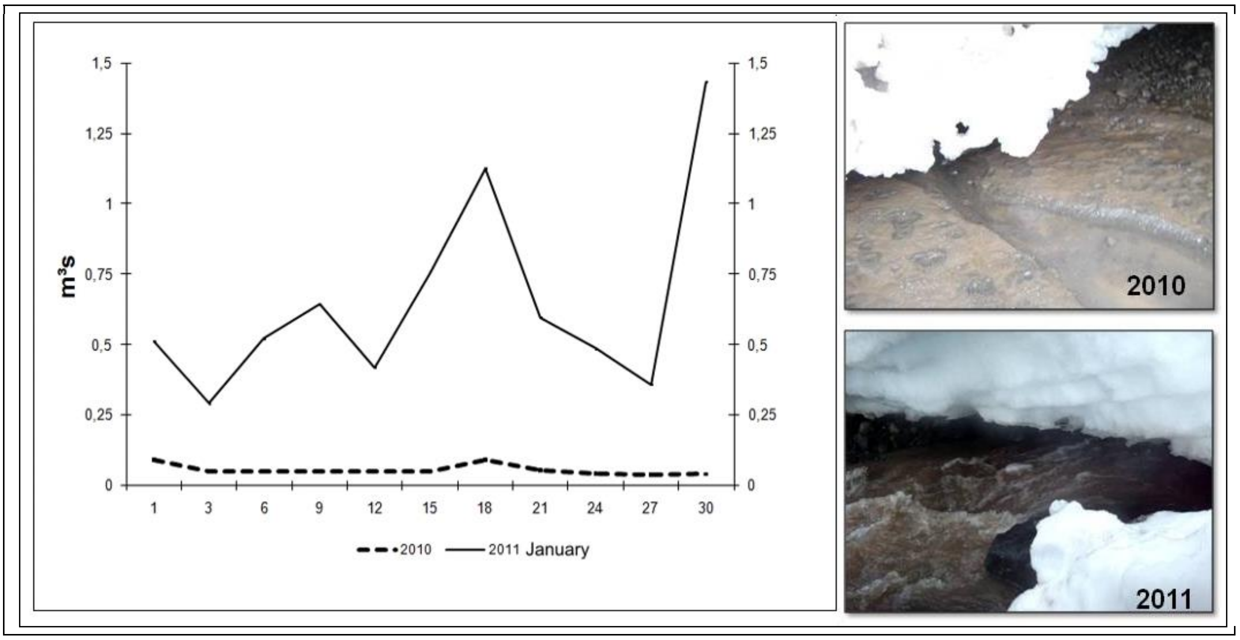

Figure 7. Discharge in proglacial channels when comparing January 2010 and 2011.

According to Menzies (1995), the nature and configuration of the subglacial drainage system are controlled by meltwater runoff rates. According to Nienow et al. (1998) and Swift et al. (2005), distributed drainage systems exist where meltwater is derived only from basal melting and predominates during spring and summer in temperate glaciers. The internal glacier drainage system expands as increasing volumes of meltwater are delivered to it near late spring and summer (Hooke 1989, Richards et al. 1996, Nienow et al. 1998, Anderson et al. 2004). The release of stored water is thought to induce a change in the subglacial drainage system, from distributed to channelized structure (Fountain & Walder 1998, Nienow et al. 1998).

Channelized systems are composites for efficient hydraulic conduits that transport high volumes of basal sediments. This channelized conduits, observed in the study area, suggest that they are large enough to transport sand grains during large flow velocity events. The distributed drainage system is likely to control the mobilization and transport of basal sediments. Data (Figure 5) show that the peak of suspended sediment concentration occurred during increased discharge.

According to Tranter et al. (1996), this occurs due to changes in some parts of the subglacial drainage system during these events. Channelized and distributed drainage systems differ markedly in terms of hydraulic efficiency; the configuration of the subglacial drainage system is probably a critical control on the basal sediment evacuation efficiency (Alley et al. 1997, Swift et al. 2005).

The variability in the basal sediment availability, according with SSC in proglacial channels, reflects the presence of a hydraulically efficient subglacial drainage in the studied glacier.

Swift et al. (2005) indicate that the drainage system configuration exerts high control over glacial erosion rates, sediment yield, glacial sediment transport pathways and ice-marginal sedimentation. High sediment concentrations in proglacial channels can indicate seasonal development of an efficient subglacial drainage configuration (Clifford et al. 1995, Swift et al. 2005, Riihimaki et al. 2005).

Velocities were high during those periods of high-peaked runoff cycles that produced highly efficient basal sediment evacuation. The highest sediment availability, therefore, occurred during January, but a reduced efficient basal sediment evacuation results in limited transport capacity. Runoff cycle evolution during January 2011 resulted in increased efficiency in the basal sediment evacuation due to the establishment of hydraulically efficient channelized subglacial drainage. Increasingly peaked runoff cycles also appear to increase basal sediment availability, probably due to high diurnal water pressure variation within subglacial channels.

Observed discharge variations recorded significant changes in Wanda Glacier drainage patterns during the analyzed period, which are related to meteorological conditions.

Direct measurements in proglacial channels, which communicate the glacier proglacial lagoon to Admiralty Bay, allowed estimating a sedimentary contribution of 19.49 kg s^{-3} to the glacimarine environment. Sediment load in meltwater is an indicator of erosion and sediment yield processes beneath the glacier. Sediment discharge from glacier melting reflects variations in sediment supply as meltwater pathways change. Our results suggest limited subglacial storage and agree with observations of rapid meltwater transfer from the ice bed interface at the peak of the melting season.

Runoff fluctuations in the study area might, therefore, exert a significant control on glacial erosion rates and sediment yields. Increasing diurnal discharge variations within subglacial channels may also have enhanced basal sliding rates and, hence, sediment yield.

CONCLUSIONS

Hydrologic data from proglacial channels in Wanda Glacier obtained in January – February 2010 and 2011 indicate variations in meltwater discharge and the transport of subglacial sediment load. Subglacial events, as observed in 2011, are probably controlled by meteorological conditions during the melting season; meltwater input into the glacier could induce peaks of SSC and discharge. Long-term observations of discharge and sediment load are thus needed to clarify if the climate variability could induce an increase in sediment yield due to strong melting processes in the study area.

High sediment concentrations in proglacial channels are related to efficient rates of basal sediment transport. This process is controlled by a developed subglacial drainage system, and quantifies the Wanda Glacier sediment contribution to Martel Inlet.

The abundant amount of fine sediments in the proglacial channels in Wanda Glacier shows the presence of the meltwater in ice-bedrock contact. These sediments result from erosive glacial action and are transported by a subglacial developed drainage system, probably from a wet basal thermal regime, in an accelerated and continuous process of retraction.

Wanda Glacier has a high sediment supply (19.49 kg s^{-3}), derived from processes of glacial erosion and deposition. These processes are interconnected with high summer temperatures presented, responsible for the relatively high rates of meltwater production and sediment supply to glacimarine environment with consequences for the sediment dynamics of the study area.

ACKNOWLEDGMENTS

The FAPERGS (1996-2551/13-0) Center for Studies in Marine and Coastal (CECO/UFRGS) and Brazilian Antarctic Program (PROANTAR) provided the support for this research.

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Manuscrito recebido em: 11 de Abril de 2012
Revisado e Aceito em: 15 de Abril de 2014