Hillslope Hydrological Linkages: Importance to Ponds within a Polar Desert High Arctic Wetland

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ABSTRACT

Arctic wetland environments are considered to be sensitive to ongoing climate change (Hinzman *et al.* 2005) but they have received limited attention despite their ecological importance. To better understand and quantify the hydrologic processes which are leading to the sustainability and demise of High Arctic ponds, a water balance framework was employed on several ponds situated in two broad geomorphic areas near Creswell Bay, Somerset Island (72°43'N, 94°15'W). These ponds are also linked to an upland area through a range of linear features: stream, late-lying snowbeds and frost cracks. This study assesses the importance of these features with respect to the sustainability of these wetland ponds.

A pond's position in the moraine landscape was important in determining its connectivity to a nearby stream and late-lying snowbed. Close proximity to a stream draining a large upland snow-covered catchment ensures steady water levels during the snowmelt period. Once discharge slows, a late-lying snowbed continues to supply the pond and others with meltwater. The deeply thawed, sandy coastal zone is characterized by frost cracks which run both across and perpendicular within the wetland zone. These cracks function primarily as 'sinks' and serve to deprive small and medium-sized ponds of water during dry periods, often leading to their desiccation.

KEYWORDS

High Arctic wetland complexes; hydrologic linkages; permafrost landscape; polar desert environments; sustainability

1. INTRODUCTION

High Arctic wetlands are important ecosystems in Northern Canada with their ability to store, regulate and cleanse water flow. They provide homes and resting grounds for northern fauna and migratory birds. While, our understanding of small, patchy wetlands existing in polar desert environments has been improved recently (e.g. Woo and Young 2003), our understanding of extensive wetland systems existing within polar oasis and polar desert regimes is still limited (e.g. Woo and Guan 2006).

Various types of patchy wetlands exist and are governed by different aspects of topography, hydrology, vegetation, and frost conditions (Woo and Young 2006). Through surface depressions some wetlands are able to capture and maintain sufficient quantities of spring snowmelt maintaining a prolonged saturation long after snowmelt. Other wetlands have hydrologic linkages to late-lying snowbeds, streams and subsurface ground ice melt. These sources of water are critical in sustaining these wetlands during short-term shifts in climate (warm, dry summers) but are themselves vulnerable to shifting climatic conditions, particularly the loss of late-lying snowbeds and near-surface ground ice supplies during persistent warm summers. Woo and Guan (2006) recently investigated the hydrology of tundra ponds existing in a polar oasis environment (warm/dry). They found that meltwater inputs from the surrounding landscape was important in replenishing ponds during a high snow year but this role diminished during a year with little snow. The tundra thaw ponds instead relied on late summer rains to rejuvenate water levels to near snowmelt levels.

It has recently been suggested that climate change will influence numerous hydrological and ecological processes in wetlands (e.g. Bridgham *et al.* 1995; Rouse *et al.* 1997; Prowse *et al.* 2006). In fact, it has been documented that ponds and lakes are disappearing in Alaska and Siberia in response to recent climate warming (Fitzgerald *et al.* 2003; Smith *et al.* 2005). Alterations in water movement due to climate change will impact on the delivery of carbon and nutrients to ponds, ultimately influencing their productivity levels and ecology. Limited understanding about the hydrology of larger wetland complexes found in the High Arctic islands makes it difficult to predict how these systems will sustain themselves under a changing climate (Woo and Young 2006).
In this study we examine the role of different modes of lateral water inflow into a low-gradient wetland from adjacent hillslopes and uplands and discuss their importance in the sustainability of a suite of ponds situated here. These linear features can take a variety of forms: streams draining uplands, meltwater from late-lying snowbeds, and frost cracks which can channel water from hillslopes into wetlands and/or capture water back from ponds (reversal of flow), thereby depriving ponds of water during drought conditions. A sound understanding of the interactions between wetland ponds and upslope linkages is critical as we begin to anticipate how High Arctic wetland systems will respond to future climate warming.

2. STUDY AREA

The study occurred within an extensive, low-gradient wetland lying south of Creswell Bay on Somerset Island (72°42'N 94°15'W). The area can be described as having a polar desert climatic regime (cool/wet) comparable to Resolute Bay, Cornwallis Island about 100 km to the north. Here a government weather station exists. The study spanned two seasons: May to mid- August, 2005 and May to late-July, 2006. While three study sites were selected within this glacial till terrain, two are discussed here (Figure 1).

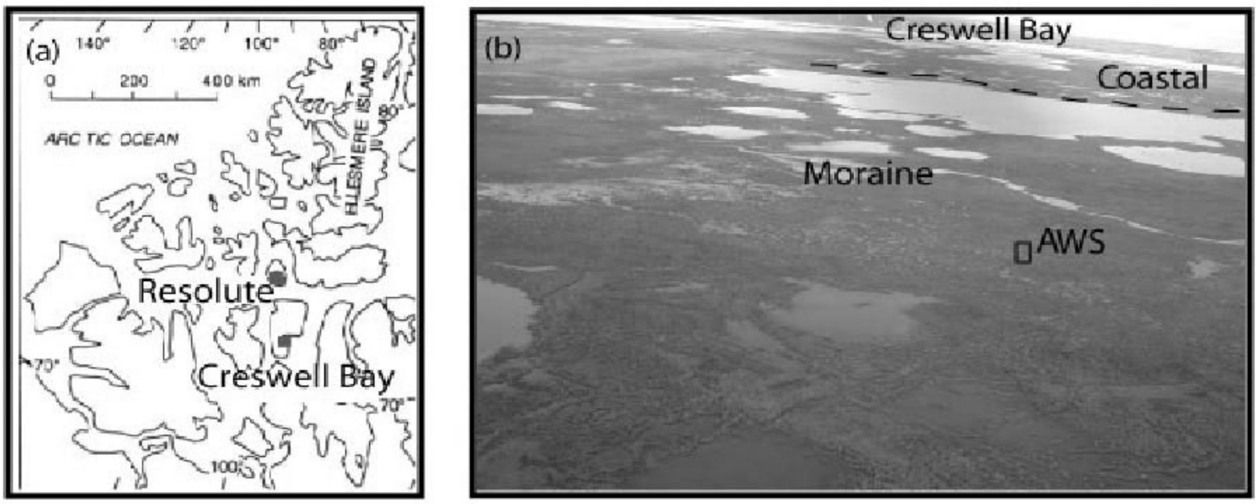

Figure 1. Location of the study area south of Creswell Bay (a) and a photograph of the general study area, August 2004 (b). The main Automatic Weather Station (AWS) is indicated and a dashed line approximately separates the Moraine wetland zone from the Coastal area.

The Moraine site contains lakes and ponds that formed as a result of glacial action, remnants of ponds formed behind an ancient lagoon and ponds likely created by thermokarst action (Brown and Young 2006). Here two ponds were selected, one fed by a late-lying snowbed and the other fed by a stream and a late-lying snowbed (Figure 2). The Coastal site with numerous ponds and lakes evolved over time being subjected to continual isostatic rebound. It contains very distinctive hydrological features, notably frost cracks, running both horizontally and linearly throughout the area. One medium-sized pond with a frost cracking running beside it is discussed in this study.

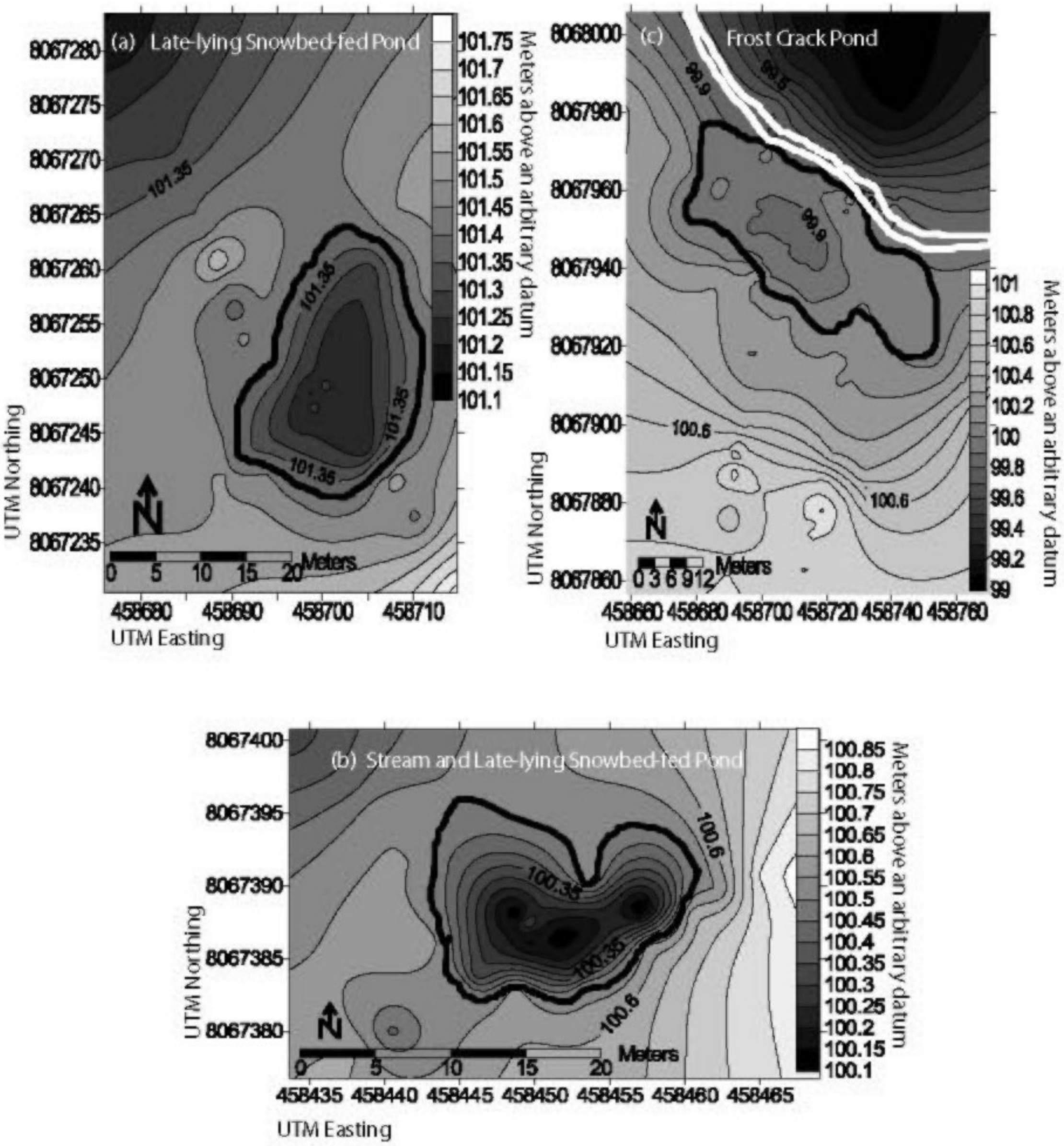

Figure 2. Topographic maps of the study ponds (a-c) and photographs of the linear features (d-f) described in the study.

3. METHODOLOGY

To better understand the hydrologic dynamics of ponds and their sustainability in a polar desert climatic setting, a detailed water balance framework was used during the summer seasons of 2005 and 2006. Here,

$$dS/dt = Sn + R - E \pm Q \tag{1}$$

where dS/dt is used to describe the change in storage (here we consider volume of water in the pond). The sum of Sn and R is precipitation input of snowfall (Sn) and rainfall (R), E is evaporation output, and Q is inflow to the pond or outflow (both surface and subsurface) (Woo *et al.* 1981). Owing to detailed data collection, water balance components are evaluated in more detail for the stream, snowbed-fed pond and the frost crack pond.

Snow comprises a large percentage of the annual precipitation in High Arctic regions and seasonal snowmelt remains one of the most important sources of water to wetland systems and consequently to ponds (Young and Woo 2004). At the end-of the winter period, a snow survey at each pond site (see Woo 1997) was conducted. A series of transects (n = 6) were laid across each pond and surrounding catchment and snow depth was taken every 2 m with a metric ruler or a longer snow rod if the snow depth > 1 m. Snow density was taken at 3 to 4 locations along each transect with a Meteorological Survey of Canada (MSC) snow corer and then averaged. Snowmelt was estimated directly (see Heron and Woo 1977) and indirectly with a snowmelt model described by Woo and Young (2003). Once the snowmelt season ceases, patches of late-lying snow often remain in lee of slopes, these features being common in these wind-swept environments (Young and Lewkowicz 1990). One of these late-lying snowbeds persisted adjacent to one of the study ponds and a detailed snow survey of it was made. Rate of retreat was monitored daily along 11 transects and photographs were taken twice weekly.

Summer precipitation (snow and rain) were measured with a tipping bucket raingauge geared into a CR10X datalogger at the main AWS (Figure 1). Manual raingauges were placed near each study site and regularly checked. Evaporation was evaluated using the Priestley-Taylor approach which has been found to work well in a range of arctic environments (e.g. Young and Woo 2003; Woo and Guan 2006). Its robustness was recently evaluated in a recent study where it was found to perform surprisingly well in comparison to other techniques (Rosenberry *et al*. 2004). In our study, an α=1.26 was applied. The AWS measured the following variables: Q*, K$\downarrow$, K$\uparrow$, U and direction, T_a, RH, T_s (1 cm, 10 cm), Q_g and PPT. An additional weather station monitoring: Q*, K$\uparrow$, U, T_a, T_w and Q_g rotated amongst the study sites every few days. Both stations provided climate data to estimate snowmelt, evaporation and ground thaw at the pond sites.

Groundwater inflow/outflow was evaluated using Darcy's law (e.g. Young and Woo 2003). A series of screened water wells dissected each pond site and the adjacent catchment. Wells were installed down to the permafrost table the previous year. In areas where water wells could not be easily inserted (e.g. frost cracks), dowels allowed surface water tables to be assessed. Water and frost tables were monitored regularly and hydraulic conductivity estimates (after Luthin 1966) were carried out at each site, at least once per season. Near-surface soil moisture (0-60 mm) in the pond catchment was measured with a Theta probe and confirmed with direct volumetric soil moisture measurements. These data quantified the degree of saturation in the pond catchment.

The stream draining the upland area (catchment size of 7 hectares, c.a. 45 m a.s.l) emptied into the moraine wetland area (c.a. 28 m a.s.l). The stream carved a well-defined channel for about 100 m within the wetland and then it spilled into a wet meadow zone. Stream discharge at the entry and exit of the wetland complex was monitored in both years using the area-velocity approach. Stage measurements together with current metering allowed discharge to be determined. In 2005, no water level recorder was available, so only 2 to 3 daily estimates of discharge were available. In 2006, water level in the stilling wells was monitored continuously with Ecotone water level recorders. During high flow periods, the floatation approach was used to determine stream velocity (Dunne and Leopold 1978). Again, 2 to 3 discharge measurements were made daily during the high flow period and less frequently during low flow.

To estimate the hydrological role played by frost cracks in pond sustainability, three frost cracks in the coastal zone were monitored during 2005 and 2006. The selection of the frost cracks was associated with their proximity to the observed ponds at the Coastal site and included both minor (1 m in width) and major-sized cracks (up to 2 m in width). Monitoring consisted primarily of regular measurements of water table and frost table. Finally all sites were surveyed in July 2005 with a Total Survey System.

4. RESULTS AND DISCUSSION

4.1 Climatology

Weather conditions near Creswell Bay in 2005 and 2006 are very similar to those of Resolute Bay (see Figure 3), confirming a polar desert climate designation (Woo and Young 2003). Mean temperature from Creswell Bay was slightly higher than Resolute Bay in 2005 (3.7^{o}C vs. 2.7^{o}C) and in 2006 (2.8^{o}C vs. 1.5^{o}C). Summer precipitation was slightly lower at Creswell Bay in 2005 (47 mm) than in 2006 (68 mm) and there was differences in the timing of rainfall. Rainfall was greater in July, 2005 but higher in June, 2006. Winds were generally from the west and averaged 3.6 m/s. End-of-winter snowcover at the AWS was 162 mm in 2005 and only 108 mm in 2006. Snowmelt was delayed in 2006 due to poor weather conditions and steady snowmelt did not commence until June 10 (JD 162) and lasted for 10 days. Growing degree-days were larger in 2005 (187) than in 2006 (102) when the same time period was compared.

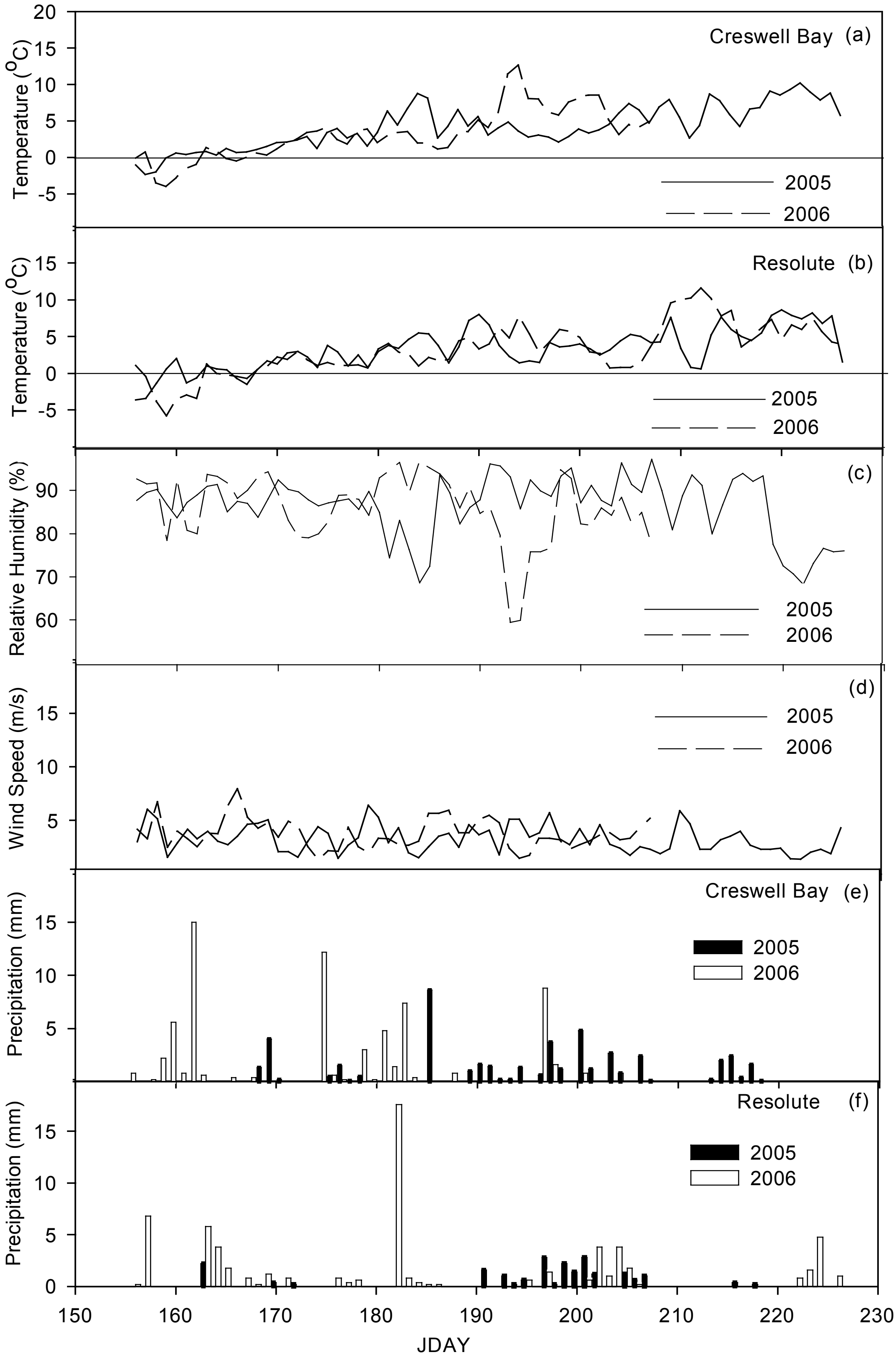

Figure 3. Seasonal pattern of mean daily air temperature at Creswell Bay (a) and Resolute Bay (b); mean daily relative humidity (c); mean daily wind speed (d); and daily total precipitation at Creswell Bay (e) and Resolute Bay (f). Note data collected at Creswell Bay was not complete in 2006 (only from June 1 to July 26).

4.2 Hillslope linkages

4.2.1 Single: Moraine zone-Late-lying snowbed-fed pond

This snow-bed fed pond is located near the lee of a slope and receives more snow than exposed ponds (280 mm in 2005 vs. 284 mm in 2006). Deeper snow here delayed snowmelt until June 21, 2005 (JD 173) and June 24, 2006 (JD 176) and snowmelt persisted here for 14 days in both years. Figure 4 indicates that water tables remained stable in both years (189±19 mm in 2005 and 175±35 mm in 2006) largely due to steady water contributions from the melting late-lying snowbed during favourable weather conditions (sunny, warm periods) and episodes of significant rainfalls (6.6 mm from JD 214 till JD 218 in 2005). Soil moisture in the adjacent catchment was also high varying between 55 to 60 % in both years due to prolonged meltwater contributions. However, some water loss from the pond did occur as the snowbank and water supplies diminished.

Young and Woo (2003) have previously shown the importance of late-lying snowbeds in providing meltwater to downslope patchy wetlands long after the seasonal snowmelt has disappeared. They note that these snow-beds buffer wetlands from variable climatic conditions, especially during warm, dry summers. However, snowbeds are also vulnerable to shifts in climate and can shrink dramatically during warm, dry summers (Woo and Young 2006). Future climate warming may see the disappearance of these features along with their ability to sustain near-by ponds and their adjacent wet meadows. Brown and Young (2006), using historical air photos showed that in the past ponds disappeared from this landscape when adjacent late-lying snowbeds also disappeared.

4.2.2 Multiple: Moraine zone-Stream-fed and Late-lying snowbed-fed pond

Evaluation of the water balance components of a second moraine pond demonstrated the importance of multiple water sources in this wetland system (Figure 2). Initially, linkage of the pond with the upland stream contributes to elevated water levels during the spring flood (Figure 5). Once snowmelt waters are drained from both the lowland and upland, the pond looses its connectivity with the stream and its water level drops to its seasonal level (see Figure 5). However, meltwater inputs from a late-lying snowbed (c.a. 180 m away) continues to provide additional meltwater as the season progresses ensuring steady water levels in both the pond and saturated conditions for the adjoining catchment. Examination of the water budget demonstrates that storage remains positive despite high surface outflow during the snowmelt season, deep thaw and evaporation losses during the post-snowmelt season.

The timing and magnitude of rain events coupled with the degree of connectivity of a pond to its landscape is another important consideration in terms of recharge. A late season rain event (10.4 mm) in 2006 elevated water levels higher than estimated, suggesting that additional water inputs came from the surrounding landscape (i.e. stream, late-lying snowbed and saturated catchment) (Figure 5).

Other wetland researchers (e.g. Soranno *et al.* 1999 and Van Hove *et al.* 2006) have also remarked on the importance of linkages with the landscape to buffer the losses of water due to climatic influences. Ponds which are isolated, having limited connection to their surrounding basin (snowbeds, streams, saturated ground) are generally more dependent on meteorological conditions (snowfall, summer rains) for their survival. Seasons with little snow and rain result in these ponds drying out quickly (Woo and Guan 2006). Large rainfall events occurring at critical periods may recharge the ponds if storage deficits can be satisfied. Without adequate inputs, these ponds can be viewed as intermittent and in time may cease to exist. Multiple water linkages appear to be one of the best strategies for arctic ponds to survive changing climatic conditions. In this study, the overlapping contributions of streamwater and late-lying snowmelt water inputs allows this particular pond to maintain a positive water storage despite variable climatic conditions.

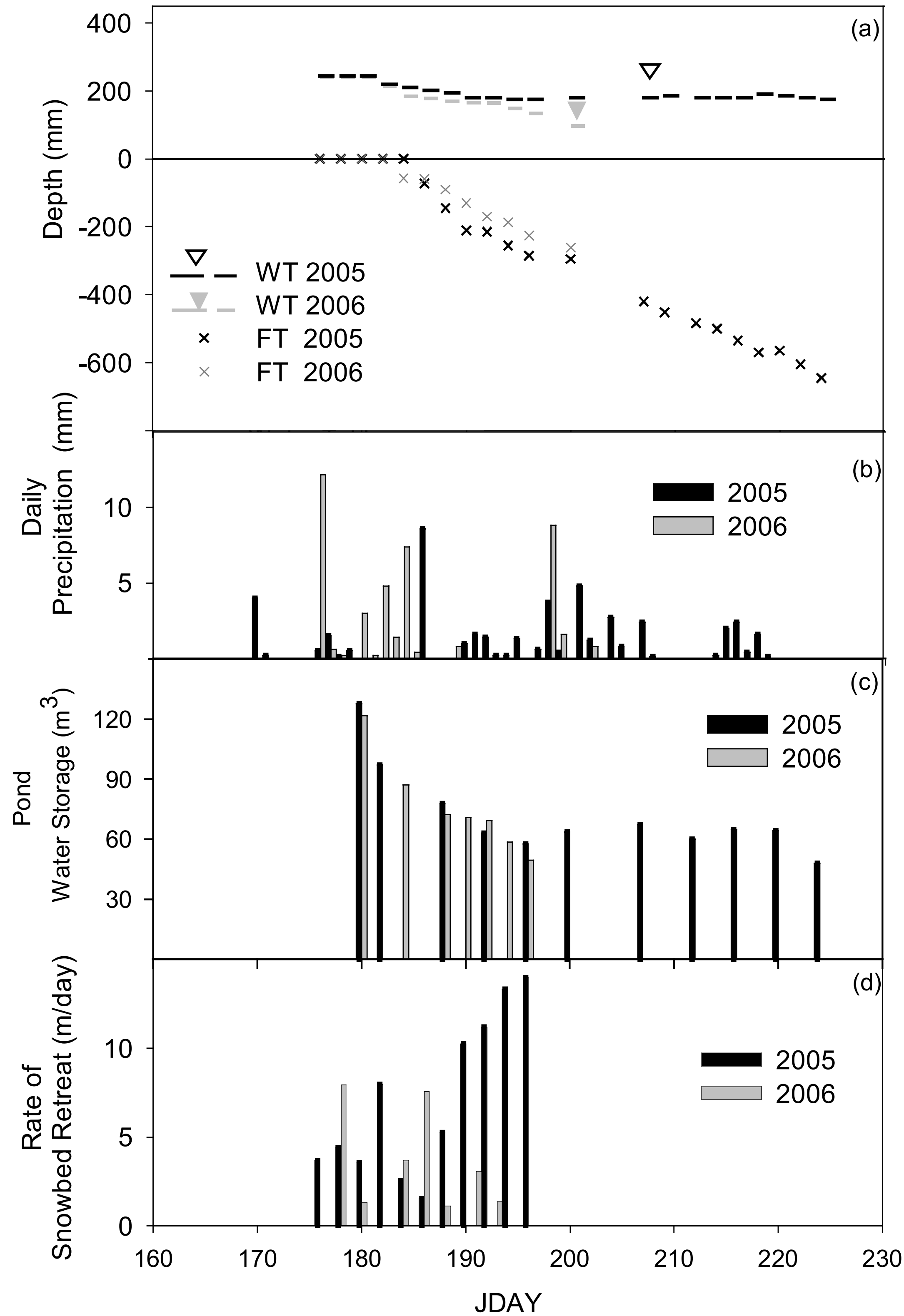

Figure 4. Seasonal regime of ground thaw (mm) and water table response (mm) at the Snowbank-fed pond (a); daily total precipitation amounts (mm) (b); daily pond storage change (m^3) (c), and late-lying snowbed retreat (m/d) in 2005 and 2006 (d). Note data collected at Creswell Bay was not complete in 2006 (only from June 1 to July 26).

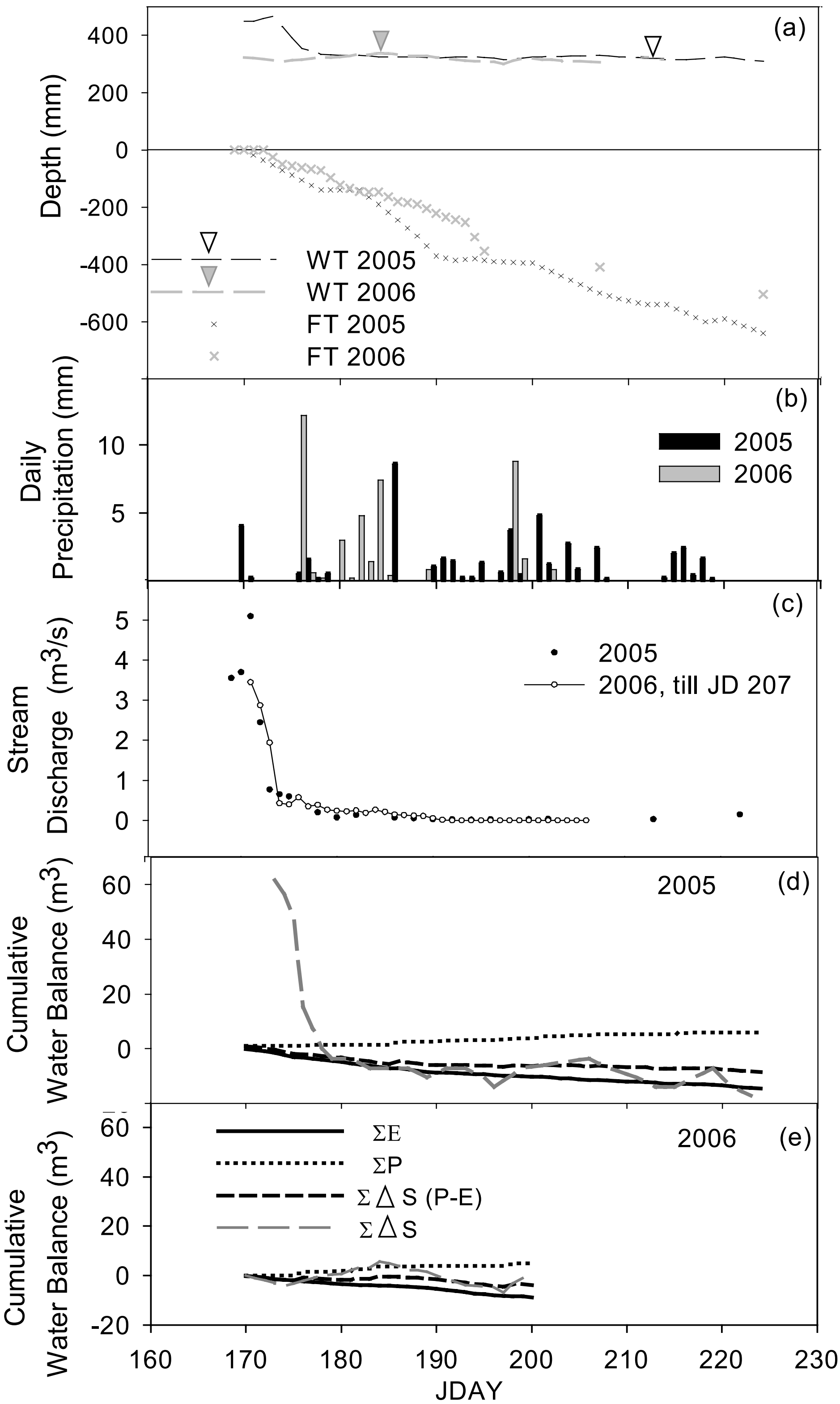

Figure 5. Seasonal regime of ground thaw (mm) and water table response (mm) at the Moraine Medium pond (a); daily total precipitation amounts (mm) (b); stream discharge into the wetland in 2005 and 2006 (c); cumulative water balance components (m^3) in 2005 (d) and 2006 (e). Note data collected at Creswell Bay was not complete in 2006 (only from June 1 to July 26).

4.2.3 Dual role: Coastal zone - frost crack pond

The coastal zone is characterized by coarse sandy soils which thaw rapidly after snowmelt and frost cracks which dissect the area. These cracks run from the slopes that border this wetland zone and are orientated parallel and perpendicular to the wetland. They are in response to isostatic rebound and to the maximum ground temperature gradient arising from the contrast between land and sea (Lachenbruch 1962). These frost cracks appear to play a dual role. At the time of snowmelt and large rainfall events they are conduits for water draining from slopes and are effective in funneling this water further out into the coastal zone. However, their major role in the post-snowmelt period is to serve as ‘sinks’ and enhance pond drainage and desiccation, especially for small and medium-sized ponds. For instance, Figure 6 shows the water table and frost table pattern for a medium-sized pond in both 2005 and 2006. The strong link of the pond to the frost crack when water tables are compared ($R^2 = 0.76$, $p< 0.05$) results in seepage of subsurface water from the pond to the crack and subsequent water losses.

The presence of near-by frost cracks is just one more feature compounding to water losses from these coastal-type ponds. For instance, these ponds show little relief and cannot capture as much snow as other sites (155 mm in 2005 vs. 125 mm in 2006). Shallow (mean depth = 0.22 m) and warm water (6.71 ^{o}C) triggered by a dark blue-green substrate which can absorb much radiation enhances evaporation losses (about 2.5 mm/day) (Oke 1987). The sandy texture also enhances much groundwater flow through deep thaw (0.89 m) and high hydraulic conductivity (e.g. $K = 2.6$ m/d).

The role of frost cracks in pond hydrology was recently described by Woo and Guan (2006). At their study site a frost crack was formed due to thermokarst processes after an exceptionally warm summer with little rain. They concluded that a warmer climate increases the probability for thermokarst occurring along pond rims helping to create natural channels for pond drainage. This response is a slightly different situation than in our study but does help to provide additional evidence of the numerous roles played by frost cracks in high arctic wetland environments.

5. CONCLUSIONS

There are many factors which determine a pond’s ability to sustain itself in polar desert environments. Some of these are position in the landscape and size with large ponds, generally receiving water from larger catchment areas. Topography and soil texture are also critical. Depression-type ponds can capture and hold onto more snow than broad, shallow ponds which tend to be windswept. Ponds with sandy soil will have deeper and earlier thaws than silty soils with high ice contents. Here, we consider a few selected ponds in the context of hillslope linkages (i.e. late-lying snowbed, stream and frost cracks). Our study has shown that connectivity to a water source is important in sustaining ponds during variable climatic conditions (2005 vs. 2006) and can help buffer ponds against seasonal water losses (runoff and evaporation). Multiple water linkages provide the best strategy for ponds to sustain themselves over the long-term. Streamwater together with meltwater from late-lying snowbeds provide overlapping sources of water which sustain pond water levels throughout the summer season. A pond dependent on only one water source (e.g. late-lying snowbed) could be vulnerable in the future if this supply disappears in response to a warmer climate (Woo and Young 2006). Ponds not well connected to a reliable hydrological system are the most vulnerable to climatic shifts and are prone to desiccation (e.g. small and medium Coastal ponds). Here, landscape features such as frost cracks also serve as ‘sinks’ rather than water ‘sources’, helping to deprive ponds of even more water.

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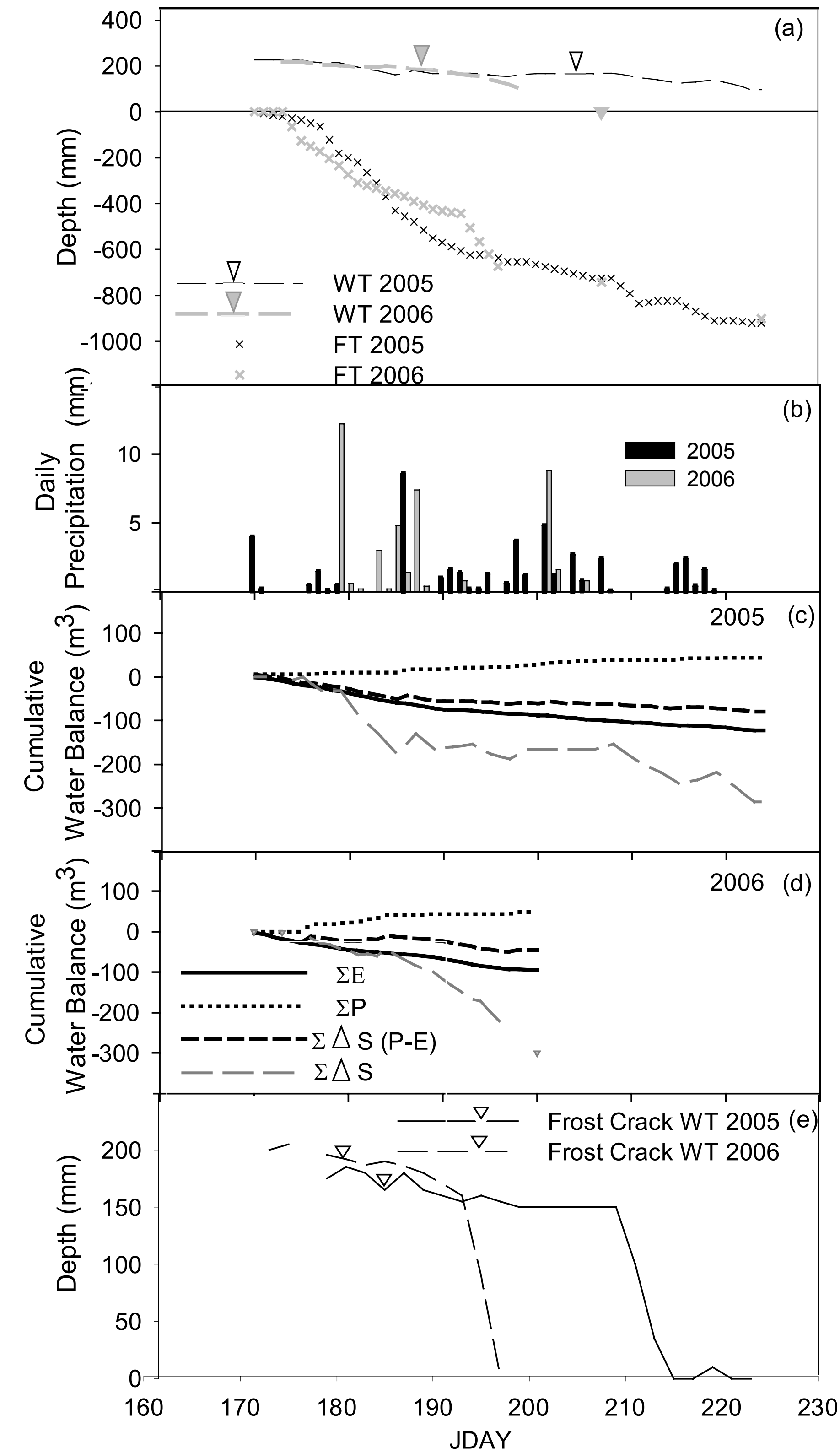

Figure 6. Seasonal regime of ground thaw and water table response at the Coastal Medium pond (a); daily total precipitation amounts (b); cumulative water balance components (m^3) in 2005 (c) and 2006 (d), and seasonal regime of water table at the nearby frost crack 2005 and 2006 (e). Note data collected at Creswell Bay was not complete in 2006 (only from June 1 to July 26).

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