SHARP 173766

THE DYNAMIC RESPONSE OF ARCTIC GLACIERS TO GLOBAL WARMING: A CANADIAN CONTRIBUTION TO INTERNATIONAL POLAR YEAR PROJECT *GLACIODYN* (IPY 30)

BACKGROUND

IPY 30 (Glaciodyn) is led by Professors J.Oerlemans (Utrecht) and J-O Hagen (Oslo), and promoted by the International Arctic Science Committee (IASC) Working Group on Arctic Glaciology. It's goal is to investigate the role of ice dynamics in the response of Arctic glaciers and ice caps to global warming, with a view to improving our ability to predict future changes and their impact on global sea level and fluxes of fresh water to the ocean. To arrive at more accurate predictions, IPY *Glaciodyn* proposes to study the dynamics of Arctic glaciers and develop new tools to deal with this dynamic response. The key elements of this effort are (i) to *make better use of observational techniques* to assess the detailed dynamics of a key set of glaciers, and (ii) to *develop models* that can be used to aggregate data and that are sufficiently robust to have predictive power. A set of target glaciers, which covers a wide range of climatic/geographical settings and takes maximum advantage of prior long-term studies, has been identified for intensive observations (in situ and from space) for the period 2007-2010. Thus, *Glaciodyn* will involve workers from seventeen countries, working on glaciers and ice caps in Alaska, Canada, Greenland, Iceland, Svalbard, northern Scandinavia, and the Russian Arctic.

The inclusion of ice dynamics in predictive models would represent a significant advance over what was done in the Arctic Climate Impact Assessment (ACIA)[1], where a simple approach was taken to estimate the runoff from all glaciers in the Arctic for a set of climate-change scenarios. Changes in the surface mass balance were calculated without dealing with the fact that glacier geometries will change. It was also assumed that the rate of iceberg production at calving fronts would not change. Within *Glaciodyn*, it is proposed that special attention be given to tidewater glaciers. The goal is to look carefully at the interaction between surface processes and dynamics (e.g. the influence of meltwater supply on ice velocities and consequently calving rates). In a warming world some glaciers will transform from cold to polythermal, or from polythermal to temperate. It is proposed to study the effect of such transitions on glacier dynamics and rates of adjustment of glacier geometry[2]. *Model development* will be conducted in parallel with the observational programmes. The modelling work will deal with processes acting on the smaller scale (e.g. parameterization of the calving process) and on the larger scale (e.g. global dynamics of tidewater glaciers, response to climate change).

Glaciodyn contributes to the following IPY themes:

- to determine the present environmental status of the polar regions by quantifying their spatial and temporal variability
- to quantify, and understand, past and present environmental and human change in the polar regions in order to improve predictions
- to investigate the unknowns at the frontiers of science in the polar regions

The ICSU/WMO Joint Committee for the IPY considers that *Glaciodyn "includes very strong scientific components and demonstrates a high level of organisation and of adherence to the IPY themes and goals. Based on the materials provided, the Joint Committee has every reason to believe that the activity as proposed will constitute a prominent and valued part of the IPY program and therefore conditionally endorses your submission*" (letter to J.Oerlemans, 24 August 2005).

RATIONALE

Sea level rise is a major consequence of climate warming because of its impact on coastal processes, infrastructure, and ecosystems. Sea level rose by 1.5 ± 0.5 mm yr^{-1} over the twentieth century[3]. The major causes are steric expansion of ocean water (due to increased temperature or decreased salinity), and eustatic rise due to increased freshwater transfer from the continents[4]. The eustatic component is largely due to melt of glaciers and ice sheets. There is, however, a significant difference between the measured sea level rise and the Intergovernmental Panel on Climate Change's (IPCC) best estimate of the sum of the major contributions to this rise (0.7 ± 1.5 mm yr^{-1})[3-4]. This discrepancy may reflect overestimation of the rise in global mean sea level due to biases in the distribution of tide gauges[5], underestimation of the steric and/or eustatic[6] contributions, or additional contributions that have been overlooked. These uncertainties motivate improved estimates of the various contributions to sea level rise because prediction of future sea levels and their impacts demands a clear understanding of the sources of sea level change and their response to climatic forcing.

Most climate model simulations predict that the Arctic will be strongly affected by anthropogenic climate change[7]. Significant warming has occurred over much of this region during the past 40 years[8]. Outside Greenland, the largest volume of glacier ice in the Northern Hemisphere is found in the Canadian Arctic Archipelago (CAA). Glaciers and ice caps in this region have short response times relative to the Greenland ice sheet[9] and may contribute disproportionately to sea level rise in the early stages of climate warming. Furthermore, their mass balance has become significantly more negative since 1987 than it was in the period 1961-87[10]. Ice caps in the CAA have complex flow regimes, including fast-flowing outlet glaciers[11] that discharge significant volumes of ice to the ocean by iceberg calving[12]. 73% of these outlets have retreated since 1960 (by up to 9 km). Many have also undergone major changes in flow rates[13] that could have affected rates of mass loss by iceberg calving and overall ice cap mass balance. Conventional mass balance measurement programs[14], which provide the basis for most estimates of the glacier/ice cap contribution to sea level rise[15], do not detect mass loss by iceberg calving. Similarly, most model based predictions of future mass loss from Arctic glaciers and ice caps assume no change in glacier geometry, ice flow dynamics, or the calving flux. If these influences are significant, estimates of the past and future glacier contribution to eustatic sea level rise may be too low.

Variations in ice flow rates can induce substantial changes in the thickness of polar ice caps and ice sheets by altering the flux of ice to the ocean and to low elevation regions at the ice margins where rates of surface melting are highest[16]. Such changes mainly affect fast flowing ice streams and outlet glaciers, and can occur on very short timescales. It is thus important to characterize the range of time scales on which outlet glacier velocities vary and to identify the forcings responsible for the observed variations. Fast ice flow usually occurs mainly by sliding and/or deformation of subglacial sediments, so velocity variations are likely linked to changes in basal friction or the stresses applied to subglacial sediments. Possible mechanisms include freeze/melt transitions[17] or changes in meltwater lubrication at the glacier bed[18], and the occurrence of waves of failure and healing in sediments underlying the glacier[19]. The suggestion that climate warming increases penetration of surface meltwater to the glacier bed, accelerating glacier flow and leading to a positive feedback on surface melt rates is of particular interest[18,20]. Changes in buoyancy and/or back-pressure at tidewater glacier termini and the breakup and removal of floating ice tongues[21] or ice shelves[22] may affect glacier flow rates and induce large changes in glacier extent and thickness. Successful estimation of past and future contributions of Arctic ice caps to global sea level rise therefore demands an understanding of, and ability to model, the role of changes in the dynamics of fast flowing outlet glaciers in the response of these ice caps to changes in climate.

PROJECT DESCRIPTION

Choice of Field Site

Glaciodyn has selected the Devon Island Ice Cap (Figure 1) as its target ice mass in the Canadian Arctic. This is largely because of the long–term mass balance record (1961-present) collected by Koerner[14] for the NW sector of the ice cap. There are, however, numerous additional benefits to working on this ice cap, which arise from work conducted on the ice cap over the past decade by workers from the Geological Survey of Canada (GSC), NASA and the Universities of Alberta, Aberdeen, and Cambridge.

- Digital maps of the ice thickness and surface and bed topography of the ice cap have been constructed from airborne radio echo sounding[11].
- The mean mass balance of the whole ice cap has been estimated for the period 1963-2000 using a combination of net accumulation measurements from shallow ice cores and temperature index modeling[23]

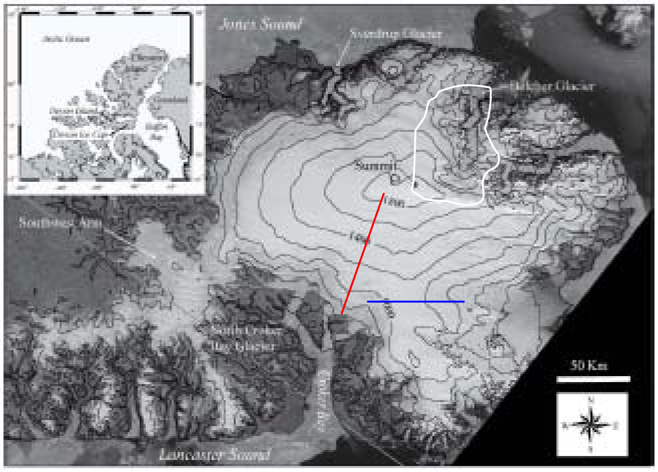

Figure 1: Landsat7 image of the Devon Island Ice Cap, showing the location of the Belcher Glacier drainage basin, the CryoSat (N/S) stake transect and the southern ice divide (E/W) stake network. A third stake network circles the 1200m contour.

- The GSC and University of Alberta operate several automatic weather stations and air temperature monitoring stations on the ice cap.
- The annual onset, duration and end of summer melt across the ice cap have been monitored since 2000 using scatterometer data from QuikScat (spatial resolution ~4km)[24].
- Changes in the extent of the ice cap from 1960-99 have been reconstructed from comparisons of aerial photography and Landsat7 ETM+ imagery and used to make initial estimates of volume changes of the whole ice cap and its major drainage basins[9]
- NASA have surveyed 2 laser altimetry transects over the ice cap in 1995, 2000, and 2005[25].
- The surface velocity field of most of the ice cap has been mapped using SAR interferometry[12] and used (along with measurements of ice thickness and terminus advance/retreat) to estimate the contribution of iceberg calving to total mass loss from the ice cap (~30%). These data have also been used to infer which parts of the bed are warm and cold-based.
- Arrays of GPS velocity stakes have been established around the 1200m contour of the ice cap (May 2005), along the CryoSat transect (Figure 1; May 2004) and across the main north-south divide in the south-east region of the ice cap (Figure 1; May 2005).
- Balance velocities and fluxes have been computed from the modeled mass balance field and surface topography and compared with observed fluxes (computed from the surface velocity and ice thickness measurements) on both the basin scale and for longitudinal profiles along major outlet glaciers in order to estimate spatial patterns of thickness changes across the ice cap since 1960 (Burgess and Sharp, in prep).

We will focus our IPY study on the Belcher Glacier drainage basin in the northeast sector of the ice cap (Figure 1). The Belcher Glacier is the largest and fastest flowing (up to 300 m yr^{-1}) outlet of the ice cap, and it terminates in about 300m of tidewater[12]. Flow stripes on the glacier surface suggest that flow is largely by basal sliding and/or bed deformation[26]. The glacier may be susceptible to hydrologically driven velocity variations, as it has a well-developed surface drainage system that includes major channels that are connected to both supraglacial and ice-marginal lakes and which sink into crevasse fields. The glacier bed lies below sea level in the lower 11km of the glacier and reaches 400m below sea level in an over-deepened basin located 2-5.5 km from the terminus. Belcher Glacier accounts for approximately half the iceberg calving loss from the ice cap (~15% of the total mass loss)[12] and its bed topography suggests that it's terminus region could become unstable in the event of further retreat. It is thus well suited for a targeted field, remote sensing, and model-based investigation of the coupling between surface mass balance, glacier hydrology, ice flow dynamics, and iceberg calving.

Objectives

The goal of this study is to develop and validate a high-resolution coupled mass balance-hydrology-dynamics model that will be used to investigate the dynamics of a large, fast-flowing, tidewater terminating ice cap outlet (the Belcher Glacier) under current conditions and to explore its likely response to future climate change scenarios. Through the experiments proposed, we will evaluate the impact of changes in ice flow dynamics, hydrology, and calving rates on the rate and magnitude of the glacier's response to climate forcing. The field and remote sensing investigations that we propose will allow us to constrain the 3-D geometry of the glacier, estimate the time-space evolution of surface meltwater production and runoff across the glacier surface and into the glacier, characterize the surface velocity and strain rate fields at high spatial resolution and investigate their temporal variability, assess the nature of the subglacial substrate and the ability of sediments to deform where they are present, and quantify the mass loss by iceberg calving and its temporal variability. We will also be able to explore the force balance of the glacier, its variation over time and its simulated evolution in response to climate warming. We will explore the potential for assimilating field data into the hydrology-dynamics model in order to improve the fidelity with which it reproduces the observed dynamics. This study will be a major contribution to the work of *Glaciodyn*, providing a new state of the art model and characterization of the dynamics and evolution of a system at the cold end of the spectrum of Arctic glacier systems.

High Resolution Model Development (Marshall, Flowers)

With (1) ice-cap geometry from GPS and radar surveys, (2) a mass balance model based on direct and remotely-sensed data, and (3) spatial and temporal ice-surface velocity constraints from a GPS network and satellite interferometry, the Belcher Glacier system will afford an excellent opportunity for the development of numerical models to explore the interactions of climate, mass balance, ice dynamics and hydrology on an Arctic ice cap. We propose the development of a suite of models (from simple flow-line to coupled three-dimensional models) that would be strongly constrained by field data and that would provide new insight into the dynamic vertical coupling of glaciological processes from surface to bed, as well as the coupling of atmosphere, ice, and ocean in the context of an Arctic ice cap.

Building on extensive prior glacier and ice-sheet modeling work, we propose the development of a 2-D cross-sectional flow line model and a 3-D Belcher Glacier system model that couple higher-order ice dynamics (sheet-, stream- and shelf-like ice flow)[27,28] with a comprehensive treatment of glacier hydrology (surface, englacial and subglacial flow systems)[29,30]. This two-step development reflects a logical progression of model complexity and capitalizes on both existing models and the unique dataset that will be collected on the Belcher Glacier. International ice sheet modelling efforts are shifting to the development of high-order ice dynamics models, which are based on a full solution to the stress balance[31-34]. High-order dynamical solutions are essential when horizontal model resolution becomes comparable to ice thickness or in complex terrain such as valley glaciers and mesoscale icefields[35]. The full stress solution is also important in dynamically complex settings such as the Belcher Glacier, which is subject to a mixed regime of slow-moving inland ice, regions of significant basal flow, and floating glacier dynamics. Transitions between regions dominated by basal versus lateral drag and the dynamics of flow across the grounding line require consideration of longitudinal stress coupling and a non-local solution to ice dynamics [31,32, 36]. These models allow free solution of the momentum/stress balance and basal velocity need not be specified. This will permit an objective coupling between ice dynamics and the subglacial water system, where the latter is incorporated into the formulation of basal friction. Such a coupled model has never been developed to date, although Flowers and Marshall have successfully coupled simpler models of ice dynamics and subglacial hydrology[37,38]. The high-order ice dynamics model for the proposed Belcher Glacier simulations will spring from prior work integrating ice-stream flow into thermomechanical sheet flow[27,28]. This continuum mixture framework will be used to couple the Belcher Glacier system in a whole-ice cap model for Devon Island (Tarasov, Marshall). The nested Belcher Glacier system can then be simulated using high-order dynamics at a proposed 1km resolution.

The thermomechanical ice model will be directly coupled to a multi-component hydrology model, where ice and water flow models are mutually influenced at the basal boundary: the hydrology model will simulate subglacial water pressure from which basal coupling (flotation fraction, p_w/pi) can be estimated**;** the ice dynamics model will calculate the rate of basal melting which in turn is a source to the water system. Prior work on polythermal Trapridge Glacier inspired the development of a four-component hydrology model, where the surface hydrology scheme was a simple representation of overland flow, englacial flow was modelled as for fractured media[39], the subglacial system was treated as a non-linear porous medium and the groundwater system was modeled conventionally [29,30]. This model has recently been adapted to the ice-cap scale and coupled to a shallow-ice flow model for simulation of the geometry, dynamics and hydrology of Vatnajökull ice cap, Iceland, in response to decadal and centennial scale climate change[37]. The major new development in this proposal will be the incorporation of thermodynamics into the hydrology model to allow for phase change and latent heat transfer and the incorporation of a more sophisticated and realistic treatment of supraglacial hydrology. The latter is targeted in this proposal because it plays a major role in the seasonal timing of water delivery to the glacier interior, and is thus a potentially important control on basal ice dynamics. Although this has long been recognized and progress has been made on modelling the supraglacial hydrology of temperate glaciers[40], little is known about how to address a Greenland-type (polythermal or cold glacier) surface hydrology. In this case, significant seasonal depression storage takes place[41] before englacial/subglacial connections are made, presumably through hydrofracturing[42]. One obvious obstacle to the general progress on this problem is the "subgrid" (small-scale) nature of supraglacial ponds and water conduits. In the ablation zone of west Greenland, each supraglacial pond drains a catchment on the order of 1 km^2 (pers. comm., P. Jansson, 2004). We intend to compare statistical and deterministic physical models of supraglacial water routing and storage, with our representation of subgrid processes guided by observations made by Boon and Sharp[42] as part of this proposal.

The hydrologically-coupled ice dynamics model will allow us to test the spatial and temporal scales of ice cap response to surface water penetration to the bed. Is there widespread flow acceleration, or is it confined to the downstream sections of the outlet glacier? Does flow acceleration depend on the location and timing of the surface water injection? Seasonal development of the subglacial drainage system may limit the efficacy of late-season water inputs. Arctic ice caps are also likely to be influenced by a complex mosaic of cold- and warm-based conditions. The effect of thermal zonation on hydrological development can be explored in the coupled model. Basal drag induced by frozen and dry patches may also limit ice dynamical response to surface water inputs. The ice dynamics model will calculate the partitioning between basal shear stresses, longitudinal stresses, and side drag, and the simulated seasonal evolution of these fields can be evaluated with the detailed surface velocity measurements that will be made from 2006-2008. This should improve our understanding of the overall controls of ice flow in the Belcher Glacier. Future simulations under a range of climate scenarios can then address the potential impacts of changing ice geometry (thinning) vs. changing outlet boundary conditions (i.e., at the calving front) vs. increased meltwater inputs to the bed.

There are a number of important glaciological processes known or expected to accompany a general climate warming. In the short term, warming results in upward migration of the equilibrium line alitude which immediately increases the ablation area of the glacier. This invites the question of whether feedbacks between surface meltwater and basal motion can accelerate the glacier response, as suggested by the somewhat controversial interpretation of a set of observations from Greenland[18]. On longer timescales, the thermal regime of the glacier may change, with implications for basal and internal dynamics. In this study, our coupled model will allow us to explore both of these issues. Recent coupled modelling on the isothermal ice cap Vatnajökull[37] has pointed to hydrologically induced acceleration of basal motion and upglacier migration of this effect with decadal- to centennial-scale climate warming. However, this acceleration is offset in almost all cases by the decrease in ice deformation rates arising from the reduced driving stress of a wasting glacier surface. This question of the competition between flow acceleration due to meltwater feedbacks and deceleration due to the decrease in driving stress is fundamental in determining the stability of an ice cap and will be pursued with the numerical tools to be developed for this project. Specifically, we plan to conduct a set of numerical experiments targeting the sensitivity of the Belcher Glacier system to short-term and prolonged warming. The former would focus our attention on meltwater feedbacks as described above and the latter would address changes in glacier thermal regime. Although ice-cap thermal response times are large, transitions from cold-bedded to warm-bedded conditions can have immediate dynamic consequences[2].

Iceberg Calving Model (Tarasov)

Calving models will be fully coupled with the ice-dynamics models. Currently no comprehensive physically-motivated ice-calving model exists[43]. As such, initial modelling will use a proximity to flotation condition[44,45]. Once detailed field data have been assembled and analyzed, the calving model will be expanded to also account for the following possible controls on terminus stability (and therefore calving rates): water temperature[46], tidal range[47], sea-ice presence[48], margin confinement, crevasse density, and crevasse depth (along with diagnostics for crevasse density and depth based on stress-strain fields near the glacier terminus). Subject to data availability, model parameters will be derived using an objective calibration procedure. Sensitivity studies using the coupled ice-dynamics/hydrology/calving model will then assess future stability of the Belcher glacier marine terminus under global warming scenarios as well as identify the key factors controlling the apparent present-day stability.

In order to adequately isolate controls on marine terminus stability, as well as validate derived models, data from a wide range of tide-water glaciers will be required. As such, Lev Tarasov aims to coordinate marine terminus and calving data standardization and collection within the Glaciodyn program. Calving model development and terminus stability analysis will focus on the Belcher terminus, but will also include model-based analyses of other glaciers within the Glaciodyn program.

Whole Ice Cap Model (Marshall, Tarasov)

The coupled hydrology and ice dynamics models need to be run at the scale of the whole ice cap to provide ice and water fluxes in the tributaries and head of the Belcher Glacier system. This model will be initialized by geologically-constrained Holocene simulations of the Devon Ice Cap (Tarasov). ERA40 and MM5-based regional climate reconstructions will then be used to drive the coupled higher-order ice model through simulations of the last 40 years, using the climate downscaling/mass balance models developed in this proposal. Available mass balance and ice velocity data from this historical period[14, 23] will be used to evaluate and calibrate the modelling insofar as is possible.

Model data requirements and integration with other project elements

The modeling component requires data to constrain the ice cap geometry, velocity, and mass balance. Present-day surface and bed topography are first-order controls on ice and water flow. Flow line surface profiles (from photogrammetry and airborne radar/laser surveys) already exist for the Belcher Glacier, so we would be poised to begin developing flow line models right away. We have the opportunity to acquire an additional laser profile up the glacier in May 2006 through links with M.Demuth (GSC) and W.Krabill (NASA). As part of the present proposal, more extensive surveys of the surface and bed topography of the Belcher system will be conducted, including cross-flow profiles and profiles across tributary junctions, which will be necessary in order to extend the modeling to two- and three-dimensions and for constraining upstream and tributary ice-flux boundary conditions. Surface velocities will be measured with direct and remote methods, which will provide an opportunity for both point- and large-scale comparisons between modeled and observed flow structure. The wireless GPS array that will be deployed in 2006 will serve to constrain sub-annual variations in surface motion along the length of the glacier (hence the temporal evolution of the system) as well as illuminate surface longitudinal strain patterns. The latter is especially relevant for local comparisons of observations with simulation results from the higher-order ice dynamics model. Interferometry and speckle tracking will provide a broader spatial picture of ice-cap flow dynamics. Accumulation patterns will be constrained by snow pit surveys, 1-GHz radar surveys and shallow (20-m) firn cores - also part of the present proposal. Field investigations of surface mass balance and hydrology will be linked directly to the modelling of ice dynamics and englacial/subglacial hydrology and to seismic reflection investigations of subglacial sediment behaviour. Results from these surveys will be used both to guide the model development (in choosing which processes to represent) and evaluate model performance.

Radio-echo sounding of Belcher Glacier (Kavanaugh)

Measurements of ice thickness and surface elevation will be obtained in order to constrain the models of Belcher Glacier. To date, ice thickness measurements of this glacier are limited to a single longitudinal profile obtained by airborne radar[11]. Bed topography could not be resolved along approximately 20 km of the ~ 48 km length of this profile[12]. Given the large number (12-15) of tributary glaciers feeding into Belcher Glacier, the basal geometry and ice flux pattern of this system are likely to be complex. A more detailed knowledge of these characteristics is required if we are to accurately model the current dynamics of the Belcher Glacier, account for the mass-balance contribution of its numerous tributary glaciers, and determine the response of this glacier system to changing climate.

Ice thickness and surface elevation data will be gathered by snowmobile-based ice-penetrating radar (IPR) surveys. Data will be recorded along a large number of transects, which will be oriented both longitudinally (1-3 transects at a given flow line distance) and laterally (15-20 transects). In addition, longitudinal and lateral transects will be obtained for each tributary, with particular interest given to the location where each enters the Belcher Valley. The extent and coverage of this survey will be largely determined by glacier surface conditions. Ice thickness measurements will be obtained with the UHF ice-penetrating radar system developed by *Narod and Clarke*[49], which was specifically designed to sound the small polar glaciers and ice caps found in the Canadian Arctic. This system has been used successfully in airborne ice thickness surveys of glaciers in Yukon[50] and on Ellesmere Island[51]. Although losses due to dielectric effects and random scattering are significant at UHF frequencies, the high-gain corner-reflector antenna employed by the system offsets much of these losses. A single, compact (1.18 m long x 0.59 m wide x 0.30 high) antenna is used for both transmitting and receiving, resulting in a system that can be transported by Komatiq sled. Because this antenna is strongly directional, valley-wall echoes will be much reduced in comparison with VHF IPR systems. Sharp's 5 MHz impulse radar[52] will be employed to obtain spot measurements in any areas where no basal reflection is obtained with the UHF system.

Ice sounding locations and surface elevation values will be determined using geodetic-quality Trimble R7 GPS receivers. Sub-decimeter positional accuracy of the radar soundings should be possible with this system. The ice thickness and surface elevation datasets obtained will be interpolated to develop digital elevation models (DEMs) of the Belcher Glacier surface and basal topographies. In addition, radar data will be used to determine the thermal and hydrological conditions at the bed of the glacier using residual bed reflection power (BRP_r) techniques[52]. Information gained from this analysis will complement surface hydrology studies by S. Boon and aid in constraining the subglacial hydrological model of G. Flowers.

Ice cap flow dynamics from SAR interferometry and speckle tracking (Copland, Gray)

Synoptic-scale mapping of the surface velocity of the Devon Island ice cap and its temporal variability is required for validation of the whole ice cap flow model, within which the high-resolution model of the Belcher Glacier system will be nested. This will be generated from synthetic aperture radar (SAR) imagery using interferometric and speckle tracking methods. Although the velocity field has previously been mapped using this approach[12], the results have several limitations:

- Surface velocities were derived using images from a single look angle. Whilst efforts were made to convert look-direction velocities to true downslope velocities, this is not possible where the flow direction is near perpendicular to the look direction. Imaging from more look angles is required to obtain true velocities for the entire ice cap.
- Existing SAR-derived velocity fields relate only to single years and winter conditions. They provide no insight into seasonal or inter-annual variability in ice flow rates, which appear to be large on outlet glaciers of Ellesmere and Axel Heiberg Islands[54]. It is important to know whether similar variations occur on the Devon Island Ice Cap (and the Belcher Glacier in particular), and to determine their causes and significance for ice fluxes and calving if we are to properly assess how the ice cap may change under future climate warming scenarios.
- The velocities were derived from satellite images from 1992 and 1996, which will be over a decade old by the time of the IPY. We need to update these velocity fields in order to determine whether there have been significant changes over the past decade.
- Improved estimates of iceberg calving rates along the eastern side of the ice cap are required to better understand the influence of these glaciers on the mass losses that have occurred since 1960. Estimated losses from iceberg calving account for up to 30% of the total reduction in ice cap size in the past 40 years[12], yet we know little about the temporal variability of calving rates.

To address these knowledge gaps, a comprehensive search of historical SAR imagery will be made to identify new scene pairs that are suitable for interferometry and speckle tracking. Where possible, data from ascending and descending pairs will be combined to improve the estimation of downslope velocity. In addition, new RadarSat image acquisition requests will be made to provide more regular monitoring of Devon Ice Cap, and to provide information on iceberg calving rates and inter- and intra-annual variations in velocity. Loss of coherence can limit the use of C-band satellite radars (like Radarsat and Envisat) to the winter or early spring period, so we will try to acquire data from the Japanese L-band SAR on ALOS (Advanced Land Observing Satellite). With the longer wavelength, L-band data are less sensitive to changing surface conditions and it may be possible to estimate velocities over more seasons than with Radarsat. Experiments will also be conducted to determine whether ice movement can be monitored using 'feature tracking' techniques with visible imagery from other satellite sensors, particularly Aster and Landsat.

Surface velocity measurements on the Belcher Glacier (Sharp, Copland, Kavanaugh)

The flow dynamics of Belcher Glacier will be investigated using ground-based measurements of ice surface velocity. A wireless network of GPS receivers will be established on the 47-km long glacier in May 2006 to provide high resolution, year-round measurements of surface velocities. The proposed network will consist of 15 stations deployed at 3km intervals along the Belcher Glacier. Each station will consist of a Motorola M12+ Oncore GPS chip, and will carry an amplified wireless Ethernet link connecting it to at least 3 other stations. The individual stations will operate at less than 5 watts average power consumption, to be supplied by photovoltaics and batteries. On-board power management electronics will hibernate the station if available power drops below necessary levels. The stations will acquire GPS data by means of a single-board computer running Linux. We plan to acquire data at a rate of one sample per second; subsequent processing will produce data records at each station precise to <10 cm at one-hour sample intervals over the duration of the deployment. With 1+ GByte of storage capacity, *each station* will maintain an up-to-date record of the GPS data *for the entire network*, updated once per day via wireless. This redundant storage scheme optimizes data recovery in case of station loss. The telemetry will use existing high-speed protocol (802.11) to permit uploading a full year of data in a single capture flight. Other critical system features include the ability to operate in reduced duty cycles to conserve power in winter, to compress data for faster recovery, and to give rapid network state-of-health reports to indicate stations in need of attention. Because this network will operate in *ad hoc* peer-to-peer mode there is no risk of server-client single-point-failure.

The GPS measurements will be used to: (i) derive the annually averaged surface velocity field along the glacier centreline; (ii) identify the time scales on which glacier velocity varies in different sections of the glacier; (iii) determine where short-term velocity events are initiated and whether/how they propagate in space; (iv) determine the relationship between velocity events, locations where surface meltwater enters the glacier, and the drainage of ice-marginal and supraglacial lakes; and (v) resolve the interactions between velocity responses to different (e.g. hydrological/tidal) forcings. The continuous wireless GPS velocity measurements will be supplemented by measurements of horizontal and vertical velocities using at least 6 geodetic grade GPS receivers at sites located up and downglacier of major water input points and in the region near the glacier terminus where tidal forcing may be significant. These measurements will allow us to identify any uplift events associated with meltwater penetration to the glacier bed. Velocities will also be measured at annual and seasonal time scales using static differential GPS for stakes on profiles across the main glacier and its major tributaries.

Calving Dynamics

The ice-calving analyses and model development will also require: seasonal measurements of calved ice-fluxes and sea-ice extent, seasonal marine temperature profiles near the calving margin, tidal range measurements, near margin bathymetry mapping, and coarse resolution measurement of crevasse density and depth at the marine terminus. We will use time-lapse photography to monitor the timing of major calving events at the glacier terminus and evaluate the sizes of bergs produced in each event. This will create the opportunity to explore linkages between variations in glacier velocity and iceberg calving events. The photography will provide information about sea ice abundance in front of the glacier, but we will supplement this with satellite observations (SSMI, and the ASTER and RadarSat imagery acquired for the remotely sensed velocity measurements). We will install a pressure transducer in the fjord in front of the glacier to monitor tidal fluctuations in water level at the glacier surface. We are exploring the possibility of using the research Icebreaker *Amundsen* (which visits northern Baffin Bay on a regular basis) as a platform from which to obtain vertical temperature, salinity and current profiles and bathymetric measurements offshore from the Belcher Glacier terminus. In the event that this is not possible, we have budgeted for purchase of a Zodiac and outboard motor to permit some measurements to be made. We will use a helicopter to access the terminal regions of the glacier to obtain video imagery of the crevassing in this area and to make local measurements of crevasse depth. We plan to obtain 4 sets of high resolution stereo *Ikonos* imagery of the terminus region in 2007 and 2008 to allow characterization of crevasse characteristics and crevasse development, determination of a detailed velocity field for this region using feature tracking techniques, and derivation of a high resolution digital elevation model for this section of the glacier that will not be readily accessible on the ground..

Seismic reflection surveys of the glacier bed (Kulessa)

The occurrence of flow stripes on the surface of Belcher Glacier[12] suggests that ice flow occurs primarily by basal sliding or bed deformation[26]. It is therefore likely that the dynamic response of Belcher glacier to climatic forcing is strongly dependant upon hydro-mechanical properties of and processes operating at the glacier bed. As a consequence, there is a need for field data to constrain the basal boundary conditions in the high-resolution model of the dynamics of Belcher Glacier. It is particularly important to answer the following questions:

1. Is the glacier resting on bedrock or unlithified sediments?
2. Where sediments are present, what is their physical state (e.g. water-saturated, deforming, frozen)?
3. Does the nature or physical state of the subglacial substrate vary spatially?

Surface-based seismic reflection surveys are comparatively inexpensive and can assess and monitor such properties and processes at spatial scales that are often representative of basal shear stress and slipperiness[55], which are fundamental to basal ice dynamics. The reflection coefficient (R; $-1 < R < 1$) and the acoustic impedance of subglacial tills is the focus of such seismic methods, based on the observations that:

- Negative phase of the reflection coefficient commonly indicates weak sediments, and its amplitude can be used to infer whether sediments are dilating and thus contribute to ice motion;
- Spatial changes in positive reflection strength can indicate transition from unfrozen to frozen subglacial sediments;
- Spatial changes in negative reflection strength can indicate the presence of water canals;
- Temporal decreases in reflection strength are potentially indicative of sudden changes in basal dynamic regime.

It is proposed to conduct seismic reflection surveys at several key locations on Belcher glacier. The locations will be identified based on a combination of surface velocity records (to be generated as part of the project), and predicted driving stress[12]. We aim to conduct seismic reflection surveys in areas likely characterized by differing basal dynamic regimes, such as e.g. those where (i) both velocity and driving stress are high; (ii) velocity is low although driving stress is high; and (iii) velocity is high although driving stress is low. Where possible seismic surveys will be repeated on weekly to annual timescales to assess potential temporal changes in the basal dynamic regime. Depending on initial field results and logistics, seismic surveys may also be able to complement radar studies in characterising the geometry of discrete subglacial water flow pathways.

The seismic reflection surveys will be conducted using a commercially widely available 48-channel system which will be provided by Kulessa's institution. The basic system consists of a Geometrics Stratavizor seismograph together with 40 Hz geophones and cables. A combination of common-offset and common-midpoint seismic surveys will be conducted to allow characterization of subglacial sediment reflectivity, depth, and geometrical properties at satisfactory spatial coverage.

Surface Mass Balance and Runoff Generation (Boon, Sharp, Copland)

For time-dependent simulations, the coupled hydrology-dynamics model requires modelling of the surface mass balance, which is a major driver of changes in glacier geometry. The mass balance model will also compute the magnitude and distribution of runoff production on the glacier under summer conditions, which is a critical input for the hydrology component of the model and for testing the hypothesis that changes in the rate of delivery of surface water to the glacier bed can result in major changes in the flow dynamics of the glacier. We therefore need to collect field data that can be used to drive and validate a mass balance model. Since long-term simulations will likely use output from climate reanalyses (such as ERA 40), or regional/global climate models, we also need to investigate how to downscale model output (temperature and precipitation) to the complex topography of the Belcher Glacier.

A surface mass balance model typically simulates 3 distinct processes: snow accumulation, surface melt, and internal refreezing. Accumulation can sometimes be specified from field measurements, but for longer-term simulations this is not possible. Climate model/reanalysis precipitation output is available at very coarse spatial resolution and has to be downscaled to the domain of the glacier model. This requires knowledge of the spatial pattern of snow accumulation across the glacier (which will be obtained from snow pits and 1 GHz radar surveys) and the relationship between modeled precipitation and the mean accumulation across the entire glacier. If these things are known then model outputs can be expressed as anomalies relative to a longer term mean and downscaling can be performed by calculating an anomaly in the glacier mean accumulation and local deviations from this mean. We plan to use both temperature index[23] and energy balance models[56] to simulate the melt component of mass balance. This requires the installation of two automatic weather stations on the glacier that will make a full suite of energy balance measurements and an array of Hobo air temperature loggers (mounted on GPS stakes) that will allow us to determine vertical lapse rates in surface air temperature and their temporal variability. Ability to predict these lapse rates as a function of season and a parameter such as local 500 hPa geopotential height is critical to successful downscaling of model-derived temperatures to the glacier domain. Previous work on Prince of Wales Icefield, Ellesmere Island, suggests that this approach has the potential to be successful[24,57]. Internal freezing can be simulated using physically based models[55] or simple parameterizations of the fraction of surface melt that refreezes[57]. With collaborators Payne and Wadham, we propose to pursue both options.

Validation of model output will require stake-based measurements of surface melt, the changing density of residual snow cover, and the evolving temperature distribution within the snow and firn. QuikScat scatterometer data (available since 1999) allow determination of the daily occurrence of surface melt across the ice cap[24] and will be used to assess whether the model is predicting an appropriate spatial distribution of melt on a given day. Time-lapse cameras will be established to monitor the migration of the summer snowline, providing another means of validating model performance. Shallow ice cores allow measurement of the long-term mean net accumulation above the equilibrium line of the glacier[23], which can be compared with model simulations. This will be achieved by drilling 20-m ice cores from sites along an elevation gradient above the equilibrium line. All core sections will be weighed and measured in order to determine a density profile for each site. In situ ^{137}Cs gamma spectrometry techniques will be used to detect the 1963 “bomb layer” (produced by the fallout from atmospheric thermonuclear weapons testing) in the boreholes from which each core was recovered. The mean net annual accumulation rate at each site is then determined from the mass accumulated since 1963 (kg), the core cross-section (m^2) and the time elapsed since 1963 (yrs).

Mass balance models will simulate the production of surface runoff in each grid cell as the difference between surface melt and internal freezing at each time step. For the purposes of the hydrological model, this runoff needs to be routed across the glacier surface until it either leaves the glacier at its sides or terminus or penetrates the glacier interior via crevasses or moulins. The potential for storage in supraglacial or ice marginal lakes also needs to be considered, as such lakes are clearly visible on images of Belcher Glacier. For the purposes of model validation, we will use 1960 aerial photography and 1999 Landsat7 imagery to compile detailed maps of the surface drainage system of

Belcher Glacier, highlighting major streams, lakes, and points where water appears to drain into the glacier. We will also map crevasse patterns so that we can explore the relationship between crevasse formation and the pattern of velocity and strain rates within the glacier. It will be necessary to understand this relationship if we are to predict where crevasses will form during time-dependent simulations of the glacier and thus continually update the location of points where water can enter the glacier. We will use time-lapse photography to monitor the filling and drainage of supraglacial and ice marginal lakes[42]. In addition, we will identify three major streams that sink into the glacier and monitor discharge through them using pressure transducers[42] and a stage-discharge relationship developed using dye dilution techniques. This will allow us to validate model simulations of runoff inputs to the englacial drainage system. Unfortunately, since the glacier terminates in tidewater, it will not be possible to use techniques such as dye tracing or measurements of meltwater chemistry to validate model assumptions about the configuration of the subglacial drainage system and its evolution through time.

WORKPLAN

Fieldwork

2 field seasons are planned, running from May 1 to August 30 in each of 2007 and 2008. Each season will have a spring (May 1-31) and summer phase (June1- August 30). As skidoo travel on the glacier will only be feasible in spring, this part of the season will be used to carry out work that requires extensive ground travel. This includes radio echo sounding and GPS traverses, shallow ice coring, snow pit and radar surveys, installation and maintenance of weather stations and time-lapse cameras, GPS stake surveys, and servicing of the wireless GPS network. The summer seasons will be used for monitoring of summer melt and snowline retreat, the filling and drainage of surface/marginal lakes, the development of surface/englacial drainage connections, iceberg calving and tidal fluctuations in the fjord in front of the glacier. Seismic reflection surveys (both seasons), and surveys of the crevasse characteristics near the calving front (2007 only) will also be conducted at this time. During this period, helicopter support will be required to make camp moves and service instrumentation and stakes. It is envisaged that the wireless GPS network and weather stations will all be serviced by helicopter towards the end of the summer season. Discussions are underway with *ArcticNet* management to determine when it might be possible to take the icebreaker *Amundsen* into the area in front of the glacier to conduct surveys of bathymetry and water column properties. If this is not possible we plan to conduct some offshore surveys from a Zodiac in 2007. Analyses of field data will commence in summer 2007. Data critical for model development and validation will be the first priority for analysis. Analysis of other datasets is likely to continue into 2009 and beyond because of the 4-year duration of Ph.D projects.

Ice Dynamics

Assuming that we succeed in installing the wireless GPS network in May 2006, we expect to have measurements of the summer centreline velocity profile (including velocity variability) by the start of the project. By the end of 2007 we should know the annual profile and have 2 summers of measurements of seasonal and shorter term variability. We should also be able to start to connect the velocity measurements to measurements of surface melt and runoff. We expect to have over-summer measurements on cross profiles by the end of 2007 and annual measurements by the end of 2008. Using these data and remotely sensed velocities we will be in a position to start analyzing strain patterns and investigating the glacier's force balance in 2008.

Remote Sensing and Radio Echo Sounding:

- New *Radarsat* and *ASTER* image acquisitions of all of Devon Ice Cap over the 2007-8 IPY years. Start date: Aug. 2006; End date: Feb 2009) (Copland).
- Determination of velocity structure across Devon Ice Cap, its spatial and temporal variability (with a particular focus on Belcher Glacier), and revised estimates of calving fluxes (Copland, Gray, Ph.D student). Fall 2006-Fall 2010 (duration of Ph.D project).
- Acquisition of *Ikonos* stereo imagery of the terminus region (May 2007-August 2008 – 4 sets), production of digital elevation model (October-December 2007) and maps of surface velocity field and crevasse patterns in this region (January 2008, October 2008) (Burgess, Tarasov)

- Fall 2008: production of the first comprehensive maps of spatial and temporal variability in accumulation patterns across the ice cap over at least the last 40 years from ice core and GPRsurveys
- Maps of ice surface and bedrock topography from radio echo sounding surveys, and derivative maps of residual bed reflection power and reconstructed subglacial hydraulic equipotential surfaces. Preliminary maps December 2007. Updated maps October 2008.
- Maps of surface drainage patterns on the ice cap will be produced by the end of 2007 from existing Landsat7 imagery and 1959/60 aerial photography.

Model Development

- Develop high-order model of ice dynamics for application to the Belcher Glacier system (Marshall): April 2006-April 2007
- Develop supraglacial hydrology model (PDF with Flowers, Marshall): Sept 2006-Sept 2007
- Couple supraglacial hydrology model with subglacial hydrology model (PDF): Oct 2007-April 2008.
- Develop model of calving dynamics (Tarasov) and couple to high order dynamics model (Tarasov and Marshall): January 2007- April 2008.
- Couple high-order ice dynamics model with subglacial hydrology model (PDF) and with whole-ice cap model (Tarasov): Sept 2007-April 2008.
- Mass balance simulations (Boon, Sharp with Payne and Wadham): single season simulations for 2007 and 2008 within 6 months of field seasons; long term simulations with ERA40 and or MM5 output (May 2008-March 2009)
- Integrated modelling of Belcher Glacier mass balance, surface-subglacial hydrology connections, and basal flow in the Belcher Glacier system (Marshall, Flowers): May 2008-March 2009.

QUALITY OF THE RESEARCH

A major outcome of the work will be a state of the art coupled model of ice dynamics and hydrology that includes the higher order stress terms. This will be validated against an unusually comprehensive set of observations of glacier velocities (derived from remote sensing and ground measurements), ice surface hydrology and mass balance from the whole of a major ice cap outlet glacier. It will be used to test hypotheses about the dynamic processes involved in the response of outlet glacier systems to climate warming, and to perform simulations of the evolution of such a system in response to recent and projected future warming. It is expected that, once developed and validated, this model will also be used to investigate the dynamics of other glaciers studied by *Glaciodyn* in order to explore regional variations in the response of Arctic tidewater outlets to climate warming. The work proposed will foster collaboration among much of the Canadian glaciological community, including senior and junior faculty members, modelers, remote sensing specialists, and fieldworkers who will pool their expertise for a concerted attack on a scientific problem of major importance. The project will provide an opportunity for training of 9 HQP at levels from undergraduate to PDF. It will be conducted within the context of a major international effort to improve our ability to predict the future response of Arctic ice caps to climate warming, an effort that is critical to our ability to better predict the consequences of such changes for global sea level.

EXCELLENCE OF THE RESEARCHERS

For many years, the glaciological community in Canadian Universities has had only 3 or 4 members. Recently, there have been a number of hirings of new young faculty and the size of the community has doubled. We propose to use the International Polar year as a vehicle to foster collaboration between many of the members of this community, with the Glaciodyn project as the focus of research activity. In addition, we want to connect Canadian glaciology to a major international initiative. Glaciodyn is well suited for this purpose because of its pan-Arctic perspective, and because it's scientific objectives demand the integration of field, remote sensing and modeling approaches. The current Canadian glaciological community is very well configured to respond to this challenge.

The research team consists of 2 modellers (Shawn Marshall (Calgary) and Gwenn Flowers (CRC, Simon Fraser), 2 remote sensing specialists (Laurence Gray (Canada Centre for Remote Sensing) and Luke Copland (Ottawa)) and 3 field workers (Martin Sharp and Jeff Kavanaugh (Alberta), and Sarah Boon (UNBC)). Four members of this group have previously conducted fieldwork in the Canadian high Arctic and there is an extensive record of collaboration between the group members. Copland and Boon did their Ph.Ds with Sharp; Marshall, Flowers and Kavanaugh were Ph.D students together at UBC. Marshall and Sharp have been collaborating on research on glacier-climate interactions in the Canadian high Arctic since 2001, and Flowers and Marshall have worked together to develop a coupled ice sheet-hydrology model that has been applied to the Vatnajökull ice cap, Iceland.

- **Sharp** has an international reputation for field-based investigations of ice dynamics and glacier hydrology. His current research focuses on glacier-climate interactions in Arctic Canada, and he has 12 years field experience in the region. He has recently co-authored 5 papers about the Devon Island ice cap.
- **Marshall** is one of the world's leading ice sheet modellers, with expertise in both large-scale ice sheet dynamics and higher-order ice stream modelling.
- **Flowers** holds a Tier 2 Canada Research Chair in Glaciology and is responsible for developing the most comprehensive model of glacier hydrology available at this time.
- **Kavanaugh** has particular expertise in glacier geophysics and the investigation of the mechanics of subglacial processes, including the coupling of basal motion and subglacial hydrology.
- **Boon** and **Copland** are previous winners of the Arctic Consortium of the United States prize for excellence in Arctic research (Physical Sciences) and have worked extensively on melt processes, hydrology and flow dynamics of Canadian high Arctic glaciers.
- **Copland** is developing a glaciological laboratory at the University of Ottawa that will focus on applications of radar interferometry, and will also provide a comprehensive equipment pool for making the field measurements discussed here (e.g., Trimble R7 differential GPS units, PulseEKKO GPR system).
- **Gray** has internationally recognized expertise in the investigation of ice dynamics using radar interferometry and speckle tracking techniques and played a significant role in the RadarSat Antarctic Mapping Mission. His recent work has involved the application of these techniques to the tracking of water flow beneath Antarctic ice streams. Gray will soon retire from the Canada Centre for Remote Sensing, but an application is underway for him to become an adjunct member of the Department of Geography at the University of Ottawa.

Collaborators

We will collaborate with Professor Tony Payne and Dr. Jemma Wadham (Centre for Polar Observation and Modelling and Bristol Glaciology Centre, UK), who are already engaged in a funded pan-Arctic mass balance-modeling program.

- **Payne** is an ice sheet modeler with an international reputation whose group has developed state-of-the-art models of ice cap mass balance that have already been applied successfully to ice caps in the Russian Arctic and Svalbard. He has also developed a general higher-order flow model for ice masses that will be of great use in guiding the development work proposed here.
- **Wadham** has special expertise in the area of meltwater refreezing, internal accumulation and superimposed ice formation, which are important themes for this project. We plan to compile a series of field and remotely sensed datasets that will be useful for validation of their models in an environment that is distinctly colder than the Eurasian Arctic, where it has been applied previously. Wadham plans to spend part of her current sabbatical at the University of Alberta (April 2006) to facilitate planning of this collaboration.

We also plan to collaborate with Dr Bernd Kulessa (Swansea) on seismic reflection studies of the glacier bed, which will be designed to assess the properties of the glacier bed and their evolution over time (see above). This collaboration will be contingent upon Kulessa finding funding to support for his involvement in the program.

- **Kulessa** is an environmental geophysicist interested in the application of surface- and borehole-based geoelectrical and seismic techniques to a broad spectrum of environmental, engineering, and glaciological problems.

In addition, through **Tarasov**, we intend to be active within *Glaciodyn* in the synthesis of data on tidewater glacier dynamics with the goal of developing and validating a global model that can be incorporated within models of ice dynamics and used for predictive purposes. At this point, however, it is not possible to be precise about the nature of this involvement because the detailed planning for *Glaciodyn* internationally is planned to take place in Obergurgl, Austria, in February 2006.

TRAINING OF HIGHLY QUALIFIED PERSONNEL

During the course of the project we plan to train 3 Post-Doctoral Fellows, 2 Ph.D students, 3 M.Sc students and 1 undergraduate student. The training is biased towards the Post-Doctoral level because of the short duration of the IPY, and the need for high level modeling expertise, personnel with prior field experience on the Devon Island ice cap, and the data management demands of the project. David Burgess will be employed as a PDF with responsibility for field logistics, GPS velocity surveys, and project data management (Alberta; 2.5 yr tenure). Burgess's Ph.D dealt with the dynamics and recent changes of the Devon Island ice cap. He has 5 seasons field experience in the area, understands the logistical challenges of working in the area extremely well and is an accomplished GPS surveyor. Lev Tarasov will be employed for 0.5 yr as a PDF (under sub-contract from Marshall to W.Peltier (Toronto)) to undertake the whole ice cap modeling, work on the development of a calving law, and be involved in fieldwork. Tarasov is a physicist with a decade of experience in model-building and data-constrained glacial systems modelling. He is currently a senior research associate in the Dept. of Physics, University of Toronto. He brings to the project an existing model that can be used to simulate the dynamics of the whole ice cap, including its mass balance. He will also contribute to efforts within Glaciodyn to develop a general calving model that can be used in both whole ice cap and higher order ice models. Support is requested by Flowers and Marshall for a postdoctoral fellow (two year tenure) to be based at SFU. This person would be responsible for the development of the supraglacial hydrology component of the model and would work with Flowers and Marshall to integrate this component into the coupled model.

Ph.D students will be supervised by Copland and Gray (dynamics of the Devon Island ice cap from remote sensing and ground based measurements) and Boon (mass balance). M.Sc students will be supervised by Kavanaugh (radio-echo sounding), Copland (snow accumulation patterns using GPR) and Boon (supraglacial hydrology). We also hope to involve one undergraduate and a student from Nunavut Arctic College in the summer fieldwork, if a suitable individual can be identified. In addition, an existing M.Sc student (Brad Danielson) supervised by Sharp will initiate work with the wireless GPS network. Danielson has a strong background in electronics and is working with R.Fatland at Vexcel Corporation on the design of the sensor network. A graduate student working with Marshall on Arctic Icefield modelling will also contribute to this project. This student is separately funded through the CFCAS Polar Climate Stability Network (2005-2009).

PROJECT AND FINANCIAL MANAGEMENT

Sharp will act as overall project leader with responsibility for financial management. He will also co-ordinate the field component of the project. Copland will lead the remote sensing component of the project, and Marshall will have overall responsibility for the modeling component. Boon will oversee the mass balance and glacier surface hydrology components of the project and be responsible for northern outreach, communication, and promotion of the project. Annual project meetings are planned to co-ordinate research activities and discuss results as they emerge. It is also planned that the project leader or designate will attend meetings of the IASC working group on the Mass Balance of Arctic

Glaciers in order to facilitate interaction with overseas collaborators and other participants in Glaciodyn. Initially budgets will be allocated to individual investigators as outlined in the budget justification section of the proposal. Deviations from this initial budget will require approval by the three component leaders (Sharp, Marshall and Copland) and will have to have a neutral impact on the overall budget.

NORTHERN INVOLVEMENT

The Devon Island ice cap is remote and no hunting or other traditional land uses are known for this area. Furthermore, local communities have existed for only ~50 years, and this results in a lack of traditional ecological knowledge (TEK) regarding the study area or the processes in which we are interested. We have, however, developed a strategy to engage Northerners in the planning, conduct, and dissemination of our research. We will obtain the appropriate research licenses from the Nunavut Research Institute, and will involve local communities and organizations in the license approval process. The local communities will be made aware of our planned research at an early stage, and will have the opportunity to comment on and contribute to our research plans. This is the standard practice we have used over the past 12 years of working in the region. To involve the communities in the work, during each field season, we plan to host a group of residents from Resolute Bay and Grise Fjord who wish to make a one-day visit to the field site in order to see and contribute to what is being done there. We also plan to liaise with Nunavut Arctic College in order to identify students with interests in environmental or earth sciences who would be interested in participating in the field program for longer periods of time. We hope to employ one such student in each year of the project.

COMMUNICATION AND PROMOTION

In addition to scientific publication in standard outlets and conference presentations, we plan a targeted community outreach program to disseminate our research plans and results. We will give outreach presentations in the communities of Grise Fjord and Resolute Bay to let northern residents know about our work. We will also visit local schools to give a poster and overview presentation about our work. We will keep northern news sources updated regarding our project, (e.g. Above 'n' Beyond, Nunatsiaq News, CBC North, Kivalliq News), and will submit our own popular articles describing our research (Boon has significant experience in scientific writing for the popular media). We propose to take award winning journalist, Ed Struzik, of the *Edmonton Journal* to the ice cap with us during one field season so that he can write a story about the project as part of a planned series of stories about Canadian IPY projects. We will also maintain a web page to keep northerners and others informed of our project plans and progress. In addition we will collaborate with local organizations interested in the promotion of science to organize public lectures in Edmonton, Calgary, Vancouver, and Ottawa to publicize IPY-related science and its significance for the general public.

DATA MANAGEMENT

Data collected or used during the project will be managed according to the IPY Data Policy. Catalogue metadata will be submitted to appropriate data archives (probably the national Snow and Ice data Center, Boulder, Colorado or the Canadian Cryospheric Information Network, University of Waterloo) once the project is funded. Complete metadata will be submitted after collection. Internationally agreed standards will be used for acquisition, processing, and final archiving of both data and metadata. We will grant free access to all data collected with minimal delay and will release preliminary versions of the data as soon as possible after collection. We will acknowledge funding agencies and all contributors of data in publications arising from the project. For the reasons outlined above, we do not envisage any use of TEK or indigenous knowledge in the project.

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