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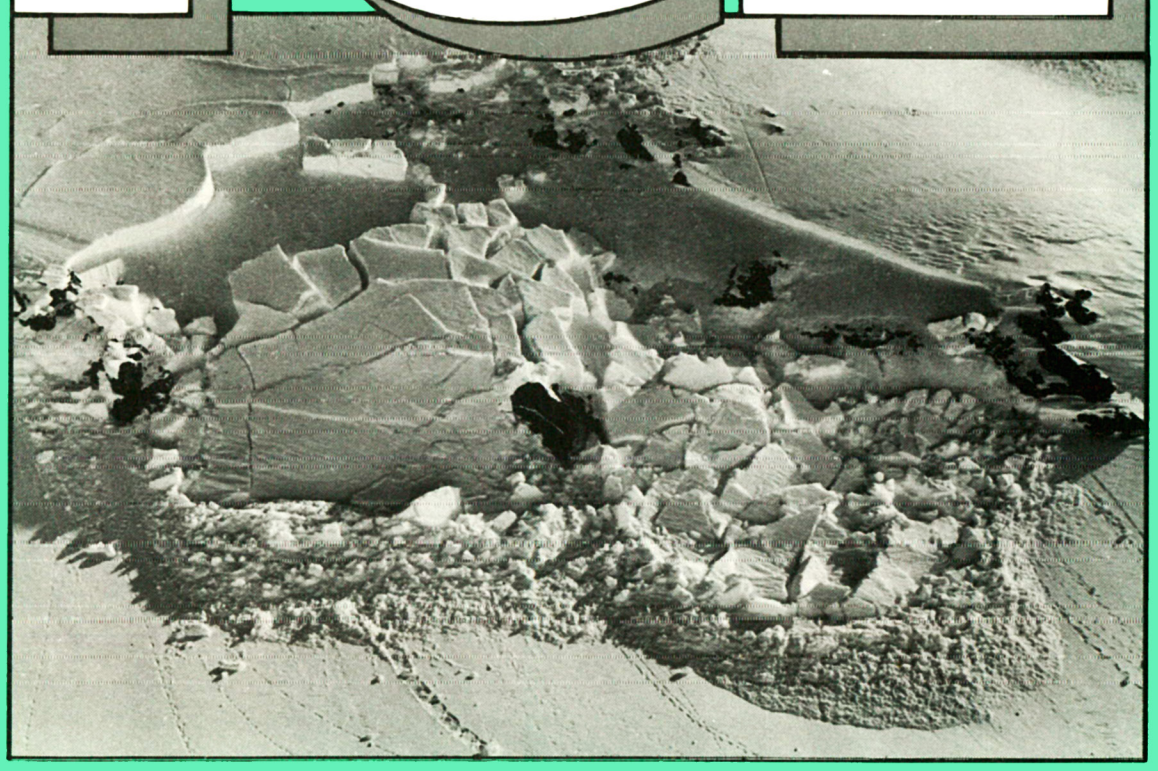

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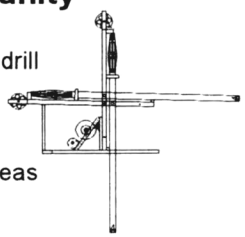

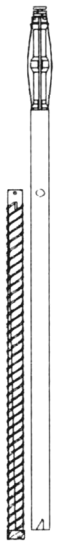

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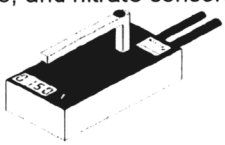

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ICE

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CONTENTS

Cover Picture: A small slab avalanche which has broken away at the sharp increase in the gradient of the slope but quickly came to rest at the foot where the gradient lessened. The large chunks of wind-packed snow and the smooth old surface upon which they slid are clearly visible. (Photograph by A. Roch No. 9100/342 © Eidg. Institut für Schnee- und Lawinenforschung, Weissfluhjoch, Davos, Switzerland.)

Scanning Electron Micrograph of the ice crystal used in headings by kind permission of William P. Wergin, Agricultural Research Service, U. S. Department of Agriculture.

RECENT WORK

CANADA

SNOW

Passive-microwave study of Arctic snow

(M.-K. Woo, D. Yang, MU; A.E. Walker EC/AES)
The development of algorithms for remote-sensing surveillance of snow-cover variation in the Arctic requires field data on regional snow distribution. Extensive surveys were conducted in central Ellesmere Island in May 1994 and 1995. The results confirmed the significant role of topography in controlling snow distribution, with snow water equivalent being greatest in gullies and valleys and lowest on exposed terrain such as wetlands, flat valley floors or rolling uplands. During the survey, Special Sensor Microwave Imager (SSM/I) passive-microwave satellite data (brightness temperatures) were acquired; each SSM/I pixel covering about 150 km^2, and the microwave-brightness temperature representing an integration of a variety of ground snow conditions. The field data were areally weighted according to the terrain components. The ground snow conditions obtained were compared against the microwave-brightness temperatures for two test pixels. The general trends exhibited by the satellite and the field data were comparable. The field technique is superior to other existing approaches for regional snow survey and warrants repeated application in the Arctic Islands to enable quantification of satellite information under a broad range of snow conditions.

Radar sensing of Alpine snowpacks

(A. (Wankiewicz) Maxfield, M.N. Demuth, G. Kite, EC/NHRI)
The application of RADARSAT to measurement of wet-snow coverage is being investigated for the Bow River watershed above Banff, Alberta. Wideswath, C-band imagery for the entire watershed is being acquired for the 1996 and 1997 runoff periods. Ground-truth measurements are being collected in alpine areas at Sunshine near Banff and at Peyto Glacier/Bow Summit. The application of remote-sensing products to streamflow forecasting will be tested using Alberta Environment's runoff models. This study will test improvements to runoff forecasting accuracy, in both lumped and distributed hydrological models, as a result of RADARSAT's frequent watershed coverage. It will apply the wet snow-cover algorithm, developed from previous studies with ERS-1 radar imagery acquired for the Rockies.

Snowmelt energy fluxes and runoff at treeline

(P. Marsh, EC/NHRI)
Field work has been carried out at two research basins in the Inuvik, NWT area. Preliminary results have demonstrated: 1) the relative importance of local advection in controlling melt rates during periods of patchy snow; 2) a method to model the spatial variation of snowmelt runoff, with the timing of runoff varying by nearly two weeks, and approximately one third of the total runoff originating from only 8% of the basin area; 3) the role of highly permeable organic pathways in controlling the transfer of meltwater to the stream channels; and 4) the application of blowing-snow, snow-surface energy-balance, snow-percolation, and snow-free evaporation models to determine annual water balance and daily water balance during the spring/summer/fall for a typical basin. The information illustrates the relative importance of all of the main water-balance terms.

Radar observation of Arctic snow and soil moisture

(A. (Wankiewicz) Maxfield, P. Marsh, J.P. Pomeroy, EC/NHRI; W. Quinton, US)
The application of radar remote sensing to permafrost terrain is being investigated in the Rocky Mountain continental divide. Its summit is the apex of the Pacific, Arctic and Atlantic drainages. Most of Snow Dome lies above the regional equilibrium line and contributes mass to the Icefields proper by flow and to other surrounding glaciers by calving. Because of the large sample volumes required, annual accumulation sequences were harvested from a crevasse wall near the summit of Snow Dome. Traditional electromechanical or thermal ice coring could not provide the large sample volumes needed. Analysis of the chemical and contaminant sequences is currently underway.

Dissolved oxygen modelling in winter, Athabasca River, Alta

(P.A. Chambers, A. Pietroniro, EC/NHRI)
During the four month period of winter ice cover, dissolved-oxygen (DO) concentrations in the Athabasca River decrease from about 12 mg l^{-1}, approx. 140 km downstream of the glacial headwaters, to as low as 6.5 mg l^{-1}, approx. 900 km downstream of the headwaters. With the increase in pulp mills in the basin from one, prior to 1988, to five, changes in land-use and increased municipal sewage, concern has focused on the role of natural versus man-made factors contributing to the decrease in DO in the Athabasca River.

Analysis of historical data shows DO concentrations improved in the 40 years following the start-up of the first bleached kraft mill; a total of 4830 kg d^{-1} BOD_5 in 1990–94 compared to >10,000 d^{-1} BOD_5 before 1977; continuous municipal sources contributed approx. 600 d^{-1} BOD_5.

Previous efforts to model under-ice DO concentrations in the Athabasca River used the DOSTOC model. Discrepancies between observed and predicted DO concentrations highlighted the need for a review and assessment of the modelling approaches. DOSTOC was implemented using revised BOD decay rates and ratios for converting BOD_5 to ultimate BOD values, measured values for sediment oxygen demand and sedimentation,

and a temperature correction from 20 to 0°C for pulp-mill BOD decay rates.

The model was reasonably successful at predicting DO for the 1990 to 1994 winters when most (≥62%) of the observed values lay within the 90% confidence limits of the model. The poorer predictions in 1988 and 1989 may relate to the limited data on tributary and sewage-treatment plant inputs and main-stem DO concentrations and to the large and erratic BOD loadings in 1989, from a new mill which had likely not equilibrated with instream processes. Comparison of rates of change in DO with distance, for the Athabasca River and other ice-covered rivers throughout the world, showed that rates for the Athabasca River were generally less than those for other ice-covered rivers receiving effluent.

Salmonid aquaculture, central coast waterways, BC

(K. Ricker, RC; W. Tupper, BCIT; John McDonald, AXYS)
This study focused on the glaciological influences on water-column stability, conservative properties and sea-floor stability for the siting of the net cages of the aquaculture industry. Fourteen biophysical parameters are evaluated for any given waterway with glacier runoff having a significant influence on several parameters (temperature, salinity, turbidity, sea floor stability). The final project area covers all waterways of the Central Coast between latitudes 51°00' and 53°00' N. The findings will be published by the BC Ministry of Agriculture, Fisheries and Food.

Biological activity related to sea ice

(C. Garrity, R.O. Ramseier, MWGOR)
During the 1993 North East Water Polynya (NEW) experiment, a detailed study of the biological activity from the ocean surface to the sea-floor bottom was accomplished. Total sea ice shows a relationship to sediment trap collections. This was quantified using sea-ice concentrations derived from SSM/I data. Sea-ice melt-water influx into the ocean, and amount of light under and between ice floes, influence the biological activity in the water column. For example, there is a 1–2 week delay from the time sea ice opens upstream from a sediment trap, to an increase in the trap contents.

Early biological primary production has been associated with the formation of new ice during the winter period as observed in the sediment collected in two traps within the NEW polynya. This conclusion was drawn from analysis of SSM/I data. A three-month field experiment is planned for the North Water Polynya (NOW) from May to August, 1996.

Arctic Ocean climate systems

(E.C. Carmack, DFO/IOS)
The prevailing view of the Arctic Ocean at the end of the last decade was that of an isolated and quiescent sea with little impact on the world ocean. We now have the image of an active and energetic ocean with strong links to the world ocean and global climate. Such a dynamic perspective of the Arctic Ocean has followed from both tundra (Trail Valley Creek) and taiga (Havikpak Creek) environments near Inuvik, NWT. A wet-snow mapping technique was developed especially for the thin, patchy snowpack that is manifested during spring snowmelt in the tundra basin. Radar backscatter is very sensitive to active-layer soil moisture during the Arctic summer. For example, the correlation between basin radar backscatter and measured streamflow for Trail Valley Creek was highly significant at the 1% level. Satellite radar can provide all-weather information on Arctic tundra processes not available from any other sensor. Work will now be extended to the taiga basin.

Interannual variability in hemispheric snow cover, 1900–96

(R.D. Brown, EC/AES)
The historical variability in hemispheric snow cover is being reconstructed using satellite and conventional data. The data will assist in understanding the role of snow cover in the climate system, and evaluating transient climate simulations from global climate models. A large volume of pre-1955 snow-depth data are being added to the Canadian snow-depth data archive. Reconstructions back to 1915 suggested that winter snow cover over North America has exhibited a gradual increase of 11.0×10^3 km^2 yr^{-1} during much of this century, while spring snow cover has decreased by an average of -6.0×10^3 km^2 yr^{-1}. These represent rather small changes in snow-covered area (<10% of current mean over a 100 year period).

Snow impact on radiation and energy exchanges

(P.M. Lafleur, TU)
The change from snow to no-snow conditions represents the largest seasonal effect on Earth surface-energy exchanges. In the high boreal forest, this is particularly important since the timing of that change-over occurs well after the vernal equinox, when sun angles are high. For two springs (1994 and 1995) we have studied radiation and energy-balance variables at a high boreal wetland near Thompson, Manitoba. The objectives are: 1) to quantify the effects of the depleting snow cover on these variables; and 2) to investigate feed backs between the surface energy exchange and atmosphere as the snow cover disappears.

Snow-cover determination with passive-microwave data

(A.E. Walker, B. Goodison, EC/AES)
Recent research has focused on improving the retrieval of snow-cover information from passive-microwave satellite data under limiting conditions such as wet snow, forest cover, and seasonal variations in snowpack structure. Development of a boreal forest snow-water-equivalent algorithm is being investigated using airborne microwave data acquired during February 1994 as part of the BOREAS (Boreal Forest Ecosystem Atmosphere Study) winter field campaign. Since 1992, special snow surveys have been conducted at Arctic and sub-Arctic sites in support of algorithm development for these landscape regions. Recently, this activity has been enhanced with the acquisition of ground-based and airborne microwave radiometers, now being used in winter field campaigns in southern Ontario. This work is a major component of the

Canadian "CRYSYS" project, a contribution to NASA's Earth Observing System (EOS) Program.

Off-site contaminant migration in ground-water systems

(J.M. Buttle, C. Labadia, TU)
Data are being acquired on the fate of road salt applied to a highway crossing the Oak Ridges Moraine, southern Ontario. They will be used for developing and testing models of road-salt transport in ground-water systems.

Road-salt inputs were determined from water and salt budgets for highway snowbanks during the 1994–95 winter. Typical salt concentrations in these snowbanks ranged from 8000 mg l^{-1} near the highway edge to 20 mg l^{-1} 15 m from the highway. Near-surface retention of road salt was determined from pre- and post-winter soil cores. Results suggest low retention of applied road salt in the upper 0.2 m of each soil type. Deep soil cores revealed salt concentrations >2000 mg l^{-1} at depths >2 m, indicating minimal dilution and/or adsorption in the unsaturated zone. Soil water from the deep cores was analyzed for O^{18}, and changes in isotopic signature with depth will be used to estimate annual recharge of water and road salt for each soil type.

Modelling runoff in a boreal forest

(R.A. Metcalfe, QU/G; J.M. Buttle TU)
Preliminary analysis has focused on the links between snowmelt and canopy structure within the basin. Daily melt was measured in 1994 and 1995 at six sites with differing canopy-density characteristics. Analysis of 1994 data revealed good agreement between relative melt intensity and canopy density, suggesting that point melt data could be distributed in the basin using ground-based or remotely-sensed measures of canopy density. 1994 results are being compared with 1995 melt data.

Snow climatology of British Columbia

(R.D. Moore, SFU/G)
Initial results, based on analysis of data from 1966 to 1992, indicate that winters dominated by an enhanced Pacific-North America circulation pattern over the North Pacific Ocean generally experienced lighter-than-average snowpack over most of the province.

SNOW/ICE ECOLOGY

Effect of snow on caribou and northern mammals
(W.O. Pruitt, Jr., I.G. Gilchrist, UM/Z)
Previous research has demonstrated the effects of snow cover on distribution, migration and behavior of several subspecies of *Rangifer tarandus* in Canada and Finland; as well as population levels and local distribution and survival of small mammals. Research continues to expand and clarify these findings.

Subnivean CO_2 effects on small mammals

(I. G. Gilchrist, W.O. Pruitt, Jr., TBA)
This study expands that by Penny and Pruitt (*Spec. Publ. Carnegie Mus. Nat. Hist.* 10, 1984) by introducing known quantities of CO_2 into the pukak space of field enclosures and tracing the reactions of *Clethrionomys gapperi* by radio-telemetry.

Ecology of snow

(H.G. Jones, INRS)
Specific projects include the study of: 1) nitrogen species in snow and the influence of physical phenomena on the dynamics of the compounds; 2) the influence of snow-cover structure on the microbiological assimilation of nutrients; 3) snow meltwater production and the emission of trace gases from the soil; 4) the effect of natural and artificial snow on vegetation. The results have shown that: 1) nitrogen compounds in snow can be degraded by intense light; 2) snow-cover algae can assimilate up to 30% of nutrient loads in snow cover during snowmelt; 3) emissions of N_20 from soil increase rapidly during the initial discharge of meltwater in spring; 4) the germination success of certain mountain plants does not seem to be affected by artificial snow meltwater. However, populations of some plants do diminish at the edge of ski runs with artificial snow compared to those with natural snow.

Boreal-forest snow hydrology

(J. Pomeroy, EC/NHRI; D.M. Gray, K. Shook, US/E/DH; G. Jones, INRS; Davies, UEA; Harding, IH; Essery, HC; Peters, USGS; M. Tranter, UB)
This work examines fluxes of radiative, sensible and latent energy during sublimation from intercepted snow, snow chemistry, nitrogen cycling in boreal snow and climate change effects on snow processes and chemistry. Sublimation consumes about one third of annual snowfall in the boreal forest and can be described by a combination of Penman-style and physical models. Nitrogen is lost over the boreal winter resulting in low nitrogen-fertilization rates during spring melt.

Contaminant deposition, Columbia Icefields

(D. Donald, EC/ECB; G. Holdsworth, AINA)
Samples have been taken on the Snow Dome to determine the long-term depositional history of organochlorine and other contaminants. This small, irregular ice dome makes up part of the Columbia Icefield which straddles strong Canadian participation and leadership in recent climate-oriented research involving icebreaker campaigns and deep-sea moorings. Selected results from the Canada/U.S.A. 1994 Arctic Ocean Section and the Canada/U.S.A. Arctic Ocean Climate Mooring illustrate this point: 1) export of freshwater components from the Arctic Ocean into the convective regions of the Greenland and Labrador Seas is now believed to influence the strength of the ocean's thermohaline circulation and thus global climate; 2) warm waters invading from the Atlantic demonstrate a strong link with the global climate system. The thermohaline interleaving driving this transition involves double-diffusive and thermodynamic processes presently unaccounted for in global climate-prediction models. The warm-water invasion has apparently displaced an equal volume of cold, relatively fresh, Pacific water. This exodus may have been in part through the Canadian Archipelago, thus affecting ocean climate in the

Labrador Sea; 3) investigations conducted during deep-sea moorings have shown that exchange between the ocean interior and the shelf regions occurs via dense-water drainage, escape of freshwater components in surface plumes, large upwelling events in submarine canyons, and large, mesoscale eddy motions; 4) recent measurements of primary productivity are an order of magnitude greater than historical estimates; 5) distinct size-fraction horizons in sedimentary records indicate that Arctic Ocean climate can change quickly.

SNOW AVALANCHES

Stability evaluation, triggering and forecasting for slab instabilities

(C.D. Johnston, J.B. Jamieson, A.N. Wilson, UC/CE)
The primary objectives of this research are to: 1) relate changes in shear strength of persistent weak snowpack layers to easily measured field properties, including analysis of microphotographs of plane sections; 2) investigate conditions under which fractures initiated by skiers in a snowpack propagate and release slab avalanches; 3) relate the depth and stiffness of skier-triggered slabs to the length of the slope and the radius of curvature at the bottom of the slope; 4) assess the compression test used by field workers for repeatability, limitations and optimal technique, including field and numerical modelling of the shear-frame test. Findings involved frame placement, loading rate, stress distribution, frame design, operator effects, variability, size effects and dependence of normal-load effect on shear strength and the microstructure of the weak layer. Other field studies have illustrated the predictive value of rutschblock and shear-frame stability indices for skier-triggered dry-slab avalanches.

Temperature effect on snow strength

Schweizer, UC/CE, SFISAR; C.D. Johnston, J.B. Jamieson, UC/CE; D.M. McClung, UBC/G; D. Skjonsberg, SRAWS)
A one-year pilot study is helping clarify the various and partly opposing effects of temperature on the mechanical properties of natural snow layers and assess the consequences on the release probability of dry-snow slab avalanches. Laboratory experiments on the mechanical behaviour of snow, under controlled shear rate, will be performed together with field studies on the temperature dependence of the shear strength of natural weak layers; stability is related to the observed avalanche activity. Numerical modelling of the stress/strain field should show the effect of short-term heat exchange on snow-slab failure.

Stability of snow piles

(B. Ladanyi, EP/CIN)
The Montréal region is known for large winter snow falls. Snow cleaned from the streets is mostly taken by trucks to a few sites in the city, where it is blown into large piles which may reach a height of over 20 m. The stability of these was studied theoretically and observed in situ. Such snow piles may remain stable at overall slope angles exceeding 35°, but local failures may occur during deposition.

Influence of avalanches on runoff from high-elevation basins

(F. de Scally, OUC/G)
Avalanches can substantially attenuate and delay the peak in snowmelt runoff. Even after 3 winters of much lower-than-average snow accumulation, and presumably also avalanche activity, in the Cascade Mountains of southern British Columbia, avalanched snow represents 10–24% of a high-elevation basin's water yield over a 11–13 week period, following the disappearance of the normal snow cover. This avalanched snow explains 16–35% of the excess of yield from this basin compared to an adjacent, avalanche-free basin. Another important reason for the different yields appears to be variations in total transpiration losses as a result of different degrees of forest cover.

Satellite snow-avalanche detection

(P.Y. Kimmel, IRCon)
This research project will attempt to: 1) improve forecasts of avalanche occurrences; 2) explore the remote sensing of snowpacks at high and low elevations; 3) further understanding of the relationship between slope aspect and the storm cycle; 4) gain knowledge of mass balance applied to second-release wet avalanches; 5) improve collection of data on avalanche occurrence, optimizing both temporal detection and spatial extent.

RIVER ICE

Anchor ice, Limestone Generating Station, Manitoba

(G. Tsang, TAI)
Manitoba Hydro's Limestone Generating Station is experiencing adverse effects from frazil and anchor ice each winter. Historic hydraulic data showed the combined effect of frazil and anchor ice led to a generation loss of 6%. Anchor-ice formation downstream led to tail-race water-level increases and related power-production inefficiencies. An innovative technique is being devised to manage and control anchor ice so hydro-power generation can be enhanced.

RIVICE model-development project

(M. Sydor, H. Cheng, T. Hamory, EC/WHC)
RIVICE is a comprehensive numerical river-ice model designed to simulate the time-varied regime and corresponding hydraulic conditions as a function of meteorological conditions, bathymetry of the river, and hydraulic/heat/ice input conditions at the boundaries of the river-channel system. The ice processes, modeled with a modified version of Environment Canada's One-Dimensional Hydrodynamic numerical model and the aid of user input parameters, are: water cooling, ice generation, transport, ice-cover formation, thickening, shoving, eroding, melting and breakup.

The global design of the model, driver and module designs and test-case planning have been completed. Current work focuses on driver and module programming/testing and linking to the model driver for test-case

evaluation. Documentation development for the entire model is at various stages of completion.

1993 Saint John River flood studies

(R.W. Carson, D.G. Judge, S.T. Lavender, ACRES)

The 1993 spring ice breakup of the Saint John River resulted in a number of ice jams with associated flooding. Since each ice-jam event provides additional information which helps to better understand the river system during ice runs, Acres International Ltd. (Acres) was commissioned by the New Brunswick Power Corporation to undertake a number of studies as part of ongoing reviews of ice-jam events. The Acres computer model simulates the backwater elevations for particular ice jams at specific locations in either the Beechwood or Mactaquac reaches for a given head-pond inflow. The model is commonly referred to as 'ICESIM'. It went through a number of re-evaluations and enhancements to incorporate a better understanding, of ice behavior during the breakup period. To improve understanding of ice-jam behavior on the Saint John River, Acres developed a new computer model "JAMSIM", to support "ICESIM" analyses. The model was used to calculate ice-jam thickness under a wide range of hydraulic and hydrologic conditions upstream of the Beechwood and Mactaquac dams. The results have helped identify the propensity for ice to jam at various locations along the Beechwood and Mactaquac reaches.

Effects of climate on breakup and jamming

(S. Beltaos, EC/NWRI)

The present study focuses on the effects of climate-controlled factors, such as flow or ice competence, and their interaction with channel morphology. Current understanding of the onset of the breakup process is limited and prediction is based on empirical, site-specific, correlations. Recent work indicates that progress can be made by taking into consideration hydraulic and morphologic features, in addition to meteorological parameters. Channel bathymetry and curvature, flow discharge and shear stress, ice thickness and strength, and freeze-up conditions are relevant to the timing of breakup. Spatial application of this finding over an entire reach would also enable prediction of the main jamming sites and determination of ice-clearing flows. Numerical modelling of breakup jams, once they are in place, is an important practical tool for computation of water levels and jam thicknesses. A recently developed model, "RIVJAM", is being applied to field data from several rivers to define the appropriate ranges of the associated coefficients. Confidence in model calibration is enhanced by the deployment of specially designed probes that remotely report jam thickness.

Saint John River ice and sediment study

(S. Beltaos, B.G. Krishnappen, EC/NWRI; B.C. Burrell, DOE/NB; S. Ismail, NBPC)

An investigation of spring ice breakup and jamming along the Saint John River from the Dickey area in Maine to Saint Leonard, New Brunswick was initiated in December 1992: 1) to obtain information to understand and quantify ice and sediment processes, their dependence on river morphology and climatic inputs, and their potential impact on the aquatic ecosystem; and 2) to acquire information needed to develop ice-management and mitigation strategies, to improve flood-warning services, and to support emergency planning and operations.

Detailed water-level measurements along ice jams, as well as, measurements of ice-jam thicknesses were obtained. The study enhances understanding of river-ice processes along the upper Saint John River, and may lead to development of general criteria on ice breakup and jamming that are transferable to other rivers.

Measurements have been made of the suspended-sediment concentration during freeze-up and breakup. These suggest that much of the suspended-sediment transport in a stream occurs during the breakup period. In addition, data on particle sizes and flocculation characteristics were obtained using the Malvern particle-size analyzer. Another aspect has been the enhancement and further development of the RIVJAM model, a steady-state numerical model, developed by NWRI, for computing ice-jam thicknesses and water levels along a jammed river reach. Field measurements have established ranges for the various coefficients used in the RIVJAM model.

River-ice modelling, Exploits River at Badger, Newfoundland

(D.B. Hodgins, FM)

In February 1993, an ice jam caused the Exploits River to flood the town of Badger. Damage was high and there was significant potential for loss of life from this and the six similar ice-jam floods which preceded it.

In 1994, this study was initiated as part of a federal-provincial program respecting water resources management, to provide an updated river-ice modeling approach for flood forecasting at Badger, and to recommend a strategy for data collection in support of the ice-jam forecasting.

Ice jams at Badger are caused by frazil ice. It was observed that sharp decreases in level (in the range of 2 m) are indicative of unusually severe frazil jam-formation/ releases in downstream reaches, followed in about 24 hours by similar and larger increases in upstream flood-water levels. So water-level observations provide valuable data for flood forecasting

It was also determined that frazil-ice generation, transport and accumulation could be successfully modeled for flood-forecasting purposes. The daily rate of frazil-ice generation contributing to ice jams at the site is directly linked to freeze-up ice elevations at Badger. Model simulation, using long-term flow and meteorological data (44 years), enabled frequency analysis of ice-generation rates and use of these relationships to forecast potential flood situations.

Ice-monitoring instrumentation, upper Niagara River

(J.R. Rossiter, CANPOLAR; L. Lalumiere, AERODAT; B. Wannamaker, SEA SEAN)

Management of ice on the upper Niagara River has significant economic importance. Of key importance is all-weather assessment of the ice discharge; i.e., ice cover, ice

speed, and ice thickness, entering the Grass Island Pool directly above Niagara Falls.

During 1994, an assessment of technologies was completed. Three technologies were recommended, in addition to the visual and low-light video monitoring already in place: 1) marine radar to determine ice cover and estimate ice speed; 2) upward-looking sonar to measure ice-keel depth; 3) radar-satellite imagery to determine synoptic conditions, particularly on Lake Erie.

In 1995, a 10 kW commercial marine-radar unit was installed on one of the hydroelectric intake towers, and an upward-looking sonar system on the riverbed in the Grass Island Pool. These instruments were operated during the ice season and results stored on computer. Preliminary analyses suggest that the data, with appropriate processing, will meet operational requirements.

Further work is continuing in 1996, including real-time telemetry of results to the Ice Control Centre. It is also expected that an initial use of RADARSAT imagery will be made.

Using ice to flood the Peace–Athabasca Delta

(T.D. Prowse, M.N. Demuth, EC/NHRI)

Flooding of deltas on large, northern rivers is usually the result of spring ice-jam events, as opposed to high flows during the open-water season. Some of the most sensitive components of such ecosystems are the perched basins: small ponds and lakes that are hydraulically isolated from the main flow system. The biological structure and productivity of these are highly dependent on flooding and flushing associated with high-stage events. Major flooding of the Peace–Athabasca Delta, has not occurred since 1974, the time of the last major ice-jam event. Prior to this, the delta experienced an extensive drying period, from 1968–1971, after one of its main rivers became regulated.

Attempts have been made to induce flooding through regulation of the natural flow system using ice. Strategic placement of artificial-ice structures at critical hydraulic nodes of the delta channel network may induce beneficial flooding provided upstream conditions are conducive to producing significant runoff. The timing and duration of runoff is crucial because the integrity of the artificial-ice structure may become marginal as spring conditions evolve. Macro-scale flooding of the entire delta would require the fragmentation of large flows from the Peace or Slave Rivers. Designing the size, configuration and placement of an artificial ice structure to aid such a fragmentation, while not inconceivable, would require a substantial environmental assessment of related impacts (e.g. the evolution of a major downstream surge upon the release of the ice jam structure).

Constructing artificial ice jams

(M.N. Demuth, T.D. Prowse, EC/NHRI; W. Graham, SANDWELL; E. Wilson, A. Hall, M. Peterson, WBNP)

To mitigate the persistent drying of a large cold-region delta, two artificial spray-ice strategies for impounding spring flood waters have been developed to assist the impoundment of spring runoff. 1) *Artificial Ice Dam*: a thick, in-channel obstruction, with significant freeboard, sprayed *in situ* through out the winter period. Jam-site bathymetry and river-bed properties are determined using ground-penetrating radar. Stability considerations, required water-level differentials and post-construction ablation, provide design criteria for the mass and geometry of the structure. This configuration would be implemented in low-slope delta channels where breakup ice runs are unlikely and winter flows are negligible. 2) *Artificial Ice Jam*: simply a zone of artificially enhanced thickness and shore attachment leading to partial grounding, that creates conditions for the dynamical interaction of upstream ice during breakup ice runs. The rubbling process promotes the formation of a jam whose configuration is similar to that of a natural breakup ice jam. This configuration would be implemented on rivers where dynamic breakup ice runs are possible and flow remains significant throughout the winter period.

Both configurations were tested within the channel network of the Peace-Athabasca Delta. Construction was complicated by the subarctic climatic conditions experienced. Aerodynamic conditions presented by near-field topography and vegetation, required close monitoring of micro-climate, ice deposition and quality, and the optimal scheduling of spraying/curing intervals.

Ice-jam formation on Peace River, Peace–Athabasca Delta

(T.D. Prowse, M. Conly, EC/NHRI)

A common perception during the 1970s and 1980s was that regulation of the Peace River by the W.A.C. Bennett Dam minimized the probability of large open-water flood events capable of inundating the perched basins of the Peace–Athabasca Delta (P-AD). A related study has confirmed that open-water floods have been ineffective in producing high-elevation floods along the Peace River. Even the historically high-flow event of 1990 did not produce a flood of sufficient magnitude to flood high-elevation portions of the delta.

This study investigated the hydro-meteorological controls on the discharge and ice regime of the Peace River and their role in the evolution of breakup ice jamming. It found that: 1) higher flows at freeze-up result in a higher freeze-up stage, an effect known to influence the timing and severity of breakup. In the lower Peace River, flow regulation seems to have produced minor changes in factors, such as ice thickness and strength, that could affect the severity of breakup and related ice-jam flooding; 2) a weak climate signal was detected suggesting that since approximately the mid-1970s the period of ice cover may have become slightly warmer and the pre-breakup melt period may have become more intense and/or more protracted; 3) flow contributions, from the point of regulation, are higher on average, at the time of breakup near the P-AD, in the post-regulation period than prior to regulation; 4) the major ice-jam floods in the 1960s, prior to regulation, and in the early 1970s, after regulation, have been associated with large runoff events from downstream tributaries.

Modelling ice-jam flooding, Peace/Slave River, Peace–Athabasca Delta

(M.N. Demuth, T.D. Prowse, T. Carter, EC/NHRI; F.E. Hicks, K. McKay, UA/CE; S. Beltaos, EC/NWRI)

This study, through field investigations and application of the numerical ice-jam model ICEJAM, attempted to simulate, for this poorly documented, remote site, the hydraulic and physical conditions that would generate significant ice-jam flooding of the Peace–Athabasca Delta . There appears to be a requirement for flows in the Peace River to exceed 2500 $m^3 s^{-1}$ to permit ice-jam backwater to enter the delta via several small to medium-sized tributaries. Evidence suggests that macro-scale flooding, such as that experienced in 1963, 1965, 1972 and 1974, may require flows in excess of 5000 $m^3 s^{-1}$. Such circumstances are characterized by extensive overland flow beyond the simple filling of the hydraulically well-connected channels and delta lakes. The simulated water levels and discharge scenarios corresponded well with ice-jam related flow fragmentation as determined from far-field hydrometric records for points upstream and downstream of the delta. A second major result is that the conveyance capacity of one of the delta tributaries under the influence of ice jamming on the Peace/Slave River was relatively insignificant. At a local scale, however, their role, in concert with secondary ice jamming, may be significant for the wetlands adjacent to their banks. This finding is particularly meaningful in light of the recent restoration of the previously blocked Claire River mouth and the possibility of deploying small-scale artificial ice structures on similar tributaries to promote localized flooding.

Restoration of the Claire River mouth, Peace–Athabasca Delta

(S. Giroux, A. Hall, S. Macmillan, WBNP; D. McGonigal, PWC; M.N. Demuth, EC/NHRI)
Activities related to a local sawmill operation resulted in the construction of berms over the channel near the mouth of the Claire River, effectively eliminating water conveyance from the Peace River to Lake Claire for all but the most extreme high-water events. Data from an extensive series of soil profiles and limited ground-penetrating radar surveys, enabled the determination of the pre-disturbance thalweg. In the 1995/96 winter, approximately 1 km of channel was mechanically restored to its pre-disturbance profile. Current work is examining the role of the restored channel under the influence of recent ice jamming on the Peace River in May of 1996.

Ice breakup and ferry operations, Mackenzie River at Fort Providence, NWT

(F.E. Hicks, UA/CE; W.R. Wiggs, GNWT)
A major roadway, leading to Yellowknife and other northern communities in the NWT from northern Alberta, encounters several major rivers and lakes crossed by ice roads in winter and by ferry during the open-water season. A significant period of time can elapse between the end of ice-road operations and the start of the open-water period. Recently, ice-breaking ferries have been launched earlier, during the ice-cover deterioration phase, so there is need for a forecasting system that can provide early warning of major ice motions. Research and operational elements of a forecasting system for ice breakup on a reach of the Mackenzie River, near Fort Providence, continue to be developed. Field determination of the hydraulic characteristics of the reach has been completed and several years of ice-thickness, ice-quality and detailed meteorological data have been collected during the pre-breakup period. Extensive observations of ice-cover motion characteristics on this part of the Mackenzie River have also been documented. An operational breakup-forecasting model is being tested.

FROZEN GROUND

Soil moisture, ground heat flux and active-layer thaw

(M.-K. Woo, S. Carey, MU)
Experimental plots were set up at two continuous permafrost sites near Resolute, N.W.T, to measure the effects of changing moisture and heat conditions on the thawing of the active layer. At a loamy-soil site, heat and water inputs were manipulated by adding carbon black to the soil surface, by increasing the snow accumulation (using a snow fence) and by artificially simulating rainfall. Comparison with control plots showed varying degrees of differences in ground thaw rates. Differences in peat properties were found to affect ground-thaw development significantly.

At all plots, heat conducted into the permafrost below the active layer consumed a large part of the incoming ground heat, while much heat was also used in the melting of the ground ice in the active layer. Only a small amount of heat was used to warm the soil. Maximum thaw depth at the end of summer varied among the plots, largely depending on the ground-ice content and the heat flux into the soils (controlled by the ground surface conditions and the thermal properties of the soils).

Geocryology Research Laboratory

(C.R. Burn, S.R. Dallimore, M.W. Smith, L.D. Dyke, M.M. Burgess, CU/G + NRCAN/GSC)
The Ottawa-Carleton Geoscience Centre–Geological Survey of Canada Geocryology Research Laboratory is a new facility dedicated to graduate study and research on geotechnical aspects of permafrost and freezing soils. The laboratory can determine soil thermal and hydrologic properties with high precision, and calibrate field instruments. Frost-heave tests may be run in the dedicated cold room. There is a technician and access to a machine shop. The laboratory was established in January 1996 with research planned on gas hydrates in permafrost, contaminant movement in frozen soils, and ice nucleation. Inquiries may be directed to Dr Chris Burn at the Department of Geography, Carleton University.

Discontinuous-permafrost hydrological response, lower Mackenzie, NWT

(A. Pietroniro, T.D. Prowse, EC/NHRI; E.D. Soulis, N. Kouwen, UW)
The primary objective is to develop components for a distributed-hydrologic model of the wetland-dominated regime in the discontinuous-permafrost zone, specifically during the spring snowmelt and near-surface permafrost-melt periods. The framework is WATFLOOD, the University of Waterloo distributed model which is ideal

because of the land-use, grouped-response unit (GRU) approach, and because of its detailed overland and streamflow routing components. The successful application of the GRU approach, in previous studies of more temperate Canadian regions, is encouraging and the first step in transferring this modeling approach to the more northerly regime. Improvements in the model simulations are underway and both the observational network and more fundamental hydrological quantification for this particular regime are being investigated.

Massive ground-ice formation

(B. Moorman, F. Michel, CU/ES)
Current projects include investigating ground ice in proglacial environments as glaciers and other surface-ice types become buried; determining the distribution and extent of buried ground ice on Bylot Island, NWT and the potential for preservation; developing criteria for determining the origin of tabular, massive ground-ice bodies and applying them in the Mackenzie Delta, NWT; developing ground-penetrating radar methods for imaging the spatial extent and internal characteristics of surface-ice bodies and ground ice; developing techniques for the direct age determination of ground ice by ^{14}C dating of trapped gases.

SAR interferometry measurement of land subsidence, Bylot Island, NWT

(P. Vachon, L. Gray, NRCAN/CCRS; B. Moorman, CU/ES)
The wasting of massive, tabular, ground-ice deposits on Bylot Island is being observed using synthetic-aperture radar (SAR) data and differential interferometric SAR (InSAR) techniques. The results will be validated using more traditional surveying methods. Concomitant work will develop algorithms and software to measure and assess land subsidence. The study is also comparing measurements over Arctic terrain of an L-band system for InSAR and C-band InSAR from ERS-1/ERS-2 and RADARSAT.

Discontinuous-permafrost mapping, Hudson Bay region

(Y. Michaud, M. Allard, GSC/PQ)
Studies continue on regional-scale mapping of base-line permafrost information for environmental-impact assessment.

Multilanguage glossary of permafrost and ground-ice terms

(R. O. van Everdingen, AINA)
Work continues on a ten-language (English, French, German, Icelandic, Italian, Norwegian, Polish, Russian, Spanish and Swedish) glossary under the auspices of the International Permafrost Association. A limited number of copies of the December 1994 edition (311 pages, not including Icelandic and Polish) are available (US$20.00), digital copies (WordPerfect 5.1 for DOS) are available on two MF2HD diskettes (US$15.00).

Mine infrastructure in discontinuous permafrost, Yukon

(M. Maxwell, B. Waddington, Karl Butler, GOLDER)
A geophysical investigation was conducted to aid the placement and design of mine infrastructure, including mill buildings and tailings dam, at a mining project in central Yukon. Specific objectives included mapping areas of discontinuous permafrost and determining depth to bedrock for foundation design purposes, and mapping faults and massive ground ice which could provide potential leakage paths under a dam. Geophysical methods employed included ground-penetrating radar for massive ground-ice detection and shallow-bedrock depth determination, electromagnetic apparent ground conductivity for fault and permafrost mapping, and seismic refraction for bedrock depth determination. Other recent glacier-related work includes the mapping of glacial deposits beneath lakes in the NWT as part of a mineral-exploration program. Similar work is expected to be carried out in 1996.

Palsas south of permafrost limit, Blanc-Sablon, Quebec

(J.-C. Dionne, UL/CEN)
MeasurementS of ground temperature and air temperature were conducted to determine conditions controlling the formation and maintenance of permafrost (palsas) outside the permafrost zone in eastern Canada.

Thermal and hydrological investigations

(C.R. Burn, CU/G)
Long-term field and laboratory studies of permafrost terrain and ground materials were conducted on the response of such sensitive terrain to site-specific and general environmental changes. In particular we consider degradation and subsidence following forest fire, ground-temperature responses to climatic variation, and growth of ground ice during seasonal freezing.

Electrokinetic phenomena

(V.R. Parameswarren, NRCC; J.R. Mackay, UNC-G; C. Burn, CU-G)
Electrical-freezing potentials, developed at the freezing front of ice lenses inside a pingo in the western Canadian Arctic, were measured for the past 8 years. The work attempts to locate experimentally the advancing front as well as the thawing boundary in seasonally freezing ground. Similar work is examining the effects of water chemistry on the freezing electrical potentials developed in lakes near Inuvik, NWT One lake is flushed annually by water; another does not receive new water other than that from precipitation in the form of rain.

Climate-warming effects on permafrost strength

(B. Ladanyi and Graduate Students, EP/CIN)
Most civil-engineering concerns linked to climate warming can be classified into those related to an increase of permafrost temperatures, those related to increases in the active-layer thickness, and those related to the degradation of permafrost. These result primarily from the decrease of its mechanical strength in its frozen and eventually thawed state. The present study is quantifying the sensitivity of frozen-ground strength to temperature increase, and proposing a simple strength-sensitivity index that can be

used for mapping zones of potentially stable and unstable permafrost, with the purpose of estimating the potential damage to existing structures and drafting design guidelines for future projects.

Cone-penetration and electrical-resistivity testing in permafrost

(B. Ladanyi, R. Fortier, EP/CIN; M. Allard, UL/CEN)
An extensive geotechnical and geophysical research program was carried out in a silty permafrost mound at Kangiqsualujjuak, northern Quebec, during the thaw period of 1992. The principal purpose was not only to evaluate the effects of permafrost warming on its physical properties, but also to determine the links between the mechanical and electrical properties of frozen ground. Load-controlled cone-penetration tests and electrical-resistivity logging on multiconductor cables, permanently buried inside the drill holes, provided the strength and resistivity of frozen silt and its variation with temperature. These properties were measured continuously over a two-month period from the surface to a depth of 2 m in permafrost. A field calorimetric method was used for a direct measurement of unfrozen water content in samples taken from the boreholes. It was found that a positive correlation exists between permafrost strength and its electrical resistivity, provided effects of strain rate on strength are properly taken into account.

Modelling permafrost energy balance and response to climate

(W.R. Rouse, J.H. Pederson, L.D. Boudreau, MU/G)
An energy-based model is being developed to predict the response of permafrost active-layer development and thaw depths to climate variation and change. The model will be field tested at Churchill, Manitoba where permafrost temperatures and the surface energy budget are being measured continuously at wetland tundra, open subarctic wetland forest, upland lichen heath and bedrock sites.

Thermal and moisture behaviour

(J. Stein, INRS; M.-K Woo, S. Carey, MU/G; L.W. Martz, US/G)
This project is studying thermal and hydrologic processes in the subarctic and providing equations suitable for modelling basin hydrology. The hydrological simulator, VSAS2, is based on the physical processes governing water movement in a basin. The input data are surficial topography, geometry of deposit, soil hydrodynamic properties and water input to the soil surface. The experimental site is in the Wolf Creek Research Watershed, southern Yukon, a subarctic basin which occupies about 220 km^2. Elevation ranges from 800 to 2250 m a.s.l. with the treeline roughly at 1300 m a.s.l., average annual precipitation is estimated at 300–400 mm yr^{-1}. Two adjacent hillslopes have been selected: a north-facing slope underlain by permafrost and a south-facing slope with only seasonal frost. These will be instrumented to study the energy and moisture fluxes under the influence of permafrost and non-permafrost conditions. Instrumentation of ground-temperature sensors and TDR probes was completed in August 1995, together with the erection of microclimatic towers. Full installation will be completed in the spring, 1996.

ICE-CORE STUDIES

Chlorinated hydrocarbons and PAHs, Agassiz Ice Cap

(D.J. Gregor, UW/ES; A. Peters, UR; J. Hoff, DU)
Current detailed measurements of contaminant deposition cannot provide a historical perspective except through long-term monitoring programs. In the Arctic, ice caps provide a well-defined historical record. Initial work began at the Agassiz Ice Cap (80°49'50"N, 72°56'30"W) in 1986, but a major effort in 1993 sampled 30 years from a snow pit. Large volume snow samples were obtained from each annual layer for determination of polychlorinated biphenyl (PCB) and polycyclic aromatic hydrocarbons (PAH). The record of deposition was extended in 1994 when four separate but contiguous cores were collected to a depth of 38 m below the 1993/1994 snow surface, approximately the year 1780. Continuous measurements of specific conductance and visual inspection were used to identify annual layers. Detailed records of PCB, PAH and ^{210}Pb concentrations and annual inventories have been determined. PCBs first appeared in the ice cap at the end of the 1950s, PAHs have always been present but peaked in the late 1960s.

Ice-core analysis, mass balance, and snow pollution

(R.M. Koerner, D.A. Fisher, J.C. Bourgeois, B. T-Alt, NRCAN/GSC)
The spatial and temporal changes in $\delta^{18}0$, melt layers, chemistry, pollen are being determined. Work here by the University of New Hampshire (UNH, USA), the Japanese National Institute of Polar Research (Tokyo) and Nagaoka Institute of Snow and Ice Studies (NISIS) will be included in their respective national reports. In the past three years, surface-snow samples have been collected for the above analyses, on the Russian Islands, the Canadian high Arctic and Penny Ice Cap, and the Arctic Ocean sea-ice snow cover between Canada and Russia. Spatial variations show much higher concentrations of all components on the Eurasian side of the Arctic Ocean, including trace metals (not measured in the ice cores). Joint Japanese investigations show seasonal variations of ion components in areas that suffer snow scouring on Agassiz Ice Cap.

The Penny Ice Cap was the main site of the 1994 field work. A 334 m ice core from surface to bedrock was drilled from the top of this ice cap in April, 1995. The ice shows Pleistocene and last interglacial ice near its bed. NISIS is to study the post-industrial-revolution chemistry. UNH will study the chemistry of the entire core. GSC will cover the $\delta^{18}0$, melt-layer and pollen changes with depth/time.

The mass balance of Melville, Meighen, part of Agassiz and NW Devon Ice Cap was measured in March 1995. These data provide the balance components for the balance year ending August 1994. No trends are yet discernible in any of the balance components for these ice caps which cover up to 33 years of measurements.

GLACIERS AND ICE SHEETS

Modelling water stability in glaciers and ice sheets

(K. Szilder, E.P. Lozowski, UA/EAS)
Work continues in modelling the stability of water flow in glaciers, emphasizing unsteady flow in glacier conduits.

Mass balance of high Arctic glaciers

(P.M. Wolfe, M. Sharp, UA/EAS)
An intensive field program at John Evans Glacier, Ellesmere Island, NWT will use shallow ice cores (10–15 m), drilled in the long-term superimposed ice zone, to reconstruct a 30–40 year mass-balance history. The accumulation and ablation processes at the drill sites (especially the formation of superimposed ice), will be monitored throughout the melt season, and analyzed using solid electrical conductivity, ice density, bubble content, size and shape, microparticle content, and anion chemistry methods to identify and interpret annual layers. Radioactive peaks from the start of atmo-
spheric bomb testing (1963) and Chernobyl (1986) will also be used to determine annual boundaries in the cores. The records will be compared with meteorological data to determine mass balance-climate relationships and to test mass-balance model predictions. If the annual stratigraphy cannot be identified, the 1963 and 1986 layers will be used to calculate 34 and 11 year net mass balances respectively. A borehole gamma-ray detector may be able to identify the depths of radioactive layers in situ, thereby allowing a more extensive field survey.
(M. Sharp, P.M. Wolfe, A. Arendt, UA/EAS)
Energy-balance and degree-day models for mass balance simulation are being developed and calibrated in the field on John Evans Glacier. Long-term simulations will be carried out for this glacier and tested against shallow ice-core data. Simulations are also planned for White Glacier, Axel Heiberg Island. Models will be used to investigate regional patterns of mass-balance/climate sensitivity in the Canadian high Arctic.

Hydrochemistry of glacierised carbonate terrains

(M. Sharp, M. Skidmore, R.Creaser, UA/EAS)
Studies of the major-ion content and solute-isotope composition (Sr, B, C, S) of glacial meltwaters are used to investigate chemical weathering of limestone and carbonate sequences in the Canadian Rockies and Ellesmere Island. Processes and rates of weathering and CO_2 consumption in different hydrological sub-environments are being investigated.

Borehole-based glacier hydrology

(M. Sharp, S. Gordon, UA/EAS)
Boreholes are used to investigate englacial/subglacial hydrological conditions at Haut Glacier d'Arolla, Switzerland. Work focuses on winter-borehole trace experiments, analysis of time series of water pressure and basal water-quality parameters, and borehole-video investigations of englacial channels.

Wedgemount and Overlord Glaciers, Garibaldi Park, BC

(Karl Ricker, RC; W. Tupper, BCIT; J. McDonald, AXYS)
From the climax position of the two glaciers, the change in snout position and ice volume is being monitored through the 20th century. The "nest" of moraines around each glacier are being dated to construct a history of glacier fluctuation from the Late Pleistocene to the present. The influence of such parameters as elevation, aspect, presence and absence of lakes at the glacier terminus are also evaluated in the variations of glacier oscillations. Oscillations are compared to the local climate record, and to global atmospheric disturbances such as El Niño and volcanic eruptions. A summary on variations from 1890 to present will appear in the 1996 edition of the *B.C. Mountaineer* (a journal for climbers). Past reports have been published in 1988, 1990, 1992 and 1994 and in the *Canadian Alpine Journal* (1976–1986).

Glacier snowline mapping using radar imagery

(S. Adam, US; M. Brugman*, A. Pietroniro, EC/NHRI; *now with CMIE)
A study was completed to delineate the snowline, taken as the wet-snow/glacier-ice boundary, by normalizing topographically induced errors (radiometric and geometric) inherent in SAR imagery of rugged terrain. Wet snow, glacier ice, and bedrock facies can be separated at all incidence angles. The snowline and glacier outline can be mapped to within 100 m and 50 m, respectively, of their true position. Glacier ice gives a low return, very similar to wet snow, in isolated areas that are marked with crevasses and runnels. Because of this, glacier ice can be mistaken for wet snow in these areas.

Hydrology of glacierized catchments, Rocky Mountains, Alberta

(G.J. Young, C. Schuster, J. Reynolds, A. Zawadzki, C. Hopkinson, A. Wallace, WLU/CRRC)
The reconstruction of glacier extents during the 20th century for selected glaciers is being conducted using historical aerial photography, maps and recent geodetic surveys. The work places an emphasis on Peyto and Athabasca Glaciers for which rates of volumetric change and glacier contribution to runoff are estimated.

Glacier-runoff modelling, Columbia River basin

(M. Brugman*, A. Pietroniro, G. Kite EC/NHRI; *now with CMIE)
This study investigates runoff from a typical test basin within the Columbia River system, and the Illecillewaet Glacier. The glacier was instrumented for energy-balance, accumulation, ablation and runoff measurements. A digital-elevation model, using LANDSAT TM, was applied to mapping glacier facies. Historic glacier changes and estimates of ice thickness, mass balance and volume changes have been documented. Field data and remote-sensing information are incorporated into the development of a glacier component for distributed-type hydrologic models.

Glacier variations monitoring and assessment network

(M.N. Demuth, D.R. Mackay, EC/NHRI; D.S. Munro, UT; G. Cogley, W.P. Adams, M. Ecclestone, TU; G.J. Young, WLU/CRRC)

The Canadian Glacier Variations Monitoring and Assessment Network (CGVMAN) currently resides at the National Hydrology Research Institute. Initiated in 1992, this is a renewed effort to revitalize glacier-related environmental monitoring and assessment in Canada. CGVMAN is a joint government-university effort centered on studies at four mass-balance network sites (remnants of the IHD network). These include: 1) White Glacier (Axel Heiberg Island, eastern high Arctic; 2) Peyto Glacier (East Slope of the Rockies); 3) Place and Helm Glaciers (Southern Coast Mountains, BC). Glacier mass-balance field data are collected using methodology standardized by Østrem. Data reduction is largely automated using an image analysis framework and PC-based water-equivalent mapping routines augmented by remote sensing (ERS-1 and RADARSAT SAR) at the close of summer-balance season. Reporting of data and assessments for the CGVMAN "benchmark" glaciers continues in the WGMS Glacier Mass Balance Bulletin. A WWW page for the network is under construction.

Mass balance of White and Baby Glaciers, Axel Heiberg Island

(J.G. Cogley, W.P. Adams, M.A. Ecclestone, TU/G)

Measurements of mass balance made from 1960 to 1991 have recently been reappraised. Balance normals for this period are -100 ± 48 mm a^{-1} (White Glacier, 29 years) and -112 ± 91 mm a^{-1} ((Baby Glacier, 19 years). In neither case is there any evidence of a trend in mass balance. However trends of plausible magnitude would not be detectable given the errors associated with stake-based measurements. For the White Glacier, the ELA averages 974 m and the AAR 0.65. Global Positioning System technology is now being used to locate stakes and to monitor retreat of the White Glacier terminus. A record of this retreat is being assembled from earlier publications and from airborne imagery at visible and radar wavelengths. Mass-balance measurements continue on both glaciers.

Snow-cover dynamics and runoff from glacierised basins

(D. S. Munro and Graduate Students, UT/G)

Using field work, remote sensing, and modelling, climate and weather are being related to glacier mass-balance change and daily summer runoff from melting. Three objectives must be met: 1) incorporation of hourly in-basin measurements of solar radiation, temperature and wind speed to force the modelling scheme; 2) integration of field and remote-sensing measurements of albedo to produce spatially representative surface-reflectance fields which are sensitive to changing cloud conditions; 3) creation of spatially complex patterns of snow-cover change during the melt season which correspond to observed patterns.

The theoretical background for the first objective has been established through several seasons of micrometeorological field work at Peyto Glacier, Alberta with supplementary work at Place Glacier, BC, and South Cascade Glacier, Washington. An automatic weather station, established at Peyto Glacier in 1987, has provided data without interruption since the summer of 1992. The next step is to drive a suitable modelling scheme with the data using knowledge gained from the micro-meteorological work. Field measurements of albedo for various ice covers and snow-cover at Peyto Glacier agree reasonably well with values derived in a related remote-sensing study using Landsat imagery. Work continues on simulating spatially complex patterns of snow-cover change commensurate with topographic influences.

Peyto Glacier, Alberta, mass balance and climatology

(M.N. Demuth, EC/NHRI)

Detailed studies of annual and seasonal mass balance at Peyto Glacier began in 1965 when G. Østrem and S. Jonssen established a transect of mass-balance glaciers in western Canada for the IHD. Detailed studies at two of the original five Cordilleran sites (Peyto and Place) continue. The long-term mean Activity Index for Peyto Glacier, a dry, continental site, is 0.8 (dB_w/dh in m w.e./100 m elevation at the ELA). The spatial mass-balance patterns here are strongly influenced by terrain shading and glacier topography. A significant shift in the annual and seasonal mass balance time series appears to have occurred in the mid 1970s. Recent work shows the net winter balance has been lower than average since 1976, commensurate with shifts in synoptic-scale winter climatology for the region.

Peyto Glacier, Alberta, ice thickness and volume

(G. Holdsworth, AINA; M.N. Demuth, EC/NHRI)

A reassessment and summary of all radar echo-sounding measurements from Peyto Glacier has been conducted to provide the first estimate of ice volume for this well-studied Cordilleran glacier. The lower glacier-bed topography is characterized by a marked overdeepening which should, at the current rate of terminus retreat, markedly influence the terminal geometry of the glacier snout and water quality for Peyto Creek within 15–20 years. Current work is examining the historical volumetric change of Peyto Glacier as it relates to past-century and recent changes in the energy fluxes associated with glacier melting.

Glacier contributions to reservoirs in the Rockies

(M.N. Demuth, EC/NHRI)

Of the 1298 glaciers within the Nelson River Drainage Basin (4*5) portion of the eastern-slopes montane eco-zone (ESME), approximately 75% contribute flow to a network of reservoirs which serve the hydro-electric and irrigation needs of the semi-arid regions east of the continental divide. For the North Saskatchewan River basin, the relevance of glacier contributions with respect to reservoir-storage characteristics and the seasonality of virgin glacier discharge prior to fragmentation and river regulation has been illustrated. The perimeter-area characteristics of glaciers within this basin (4*5D) have been described and a

conceptual model developed with which to assess possible changes in the nature of glacier contributions under a persistent regional pattern of drying, shifting equilibrium line and glacier downwasting/retreat. Work towards establishing similar information for other basins of the Canadian ESME continues.

Cause and mechanics of glacier surging

G.K.C. Clarke, U.H. Fischer, J.L. Kavanaugh, G.E. Flowers, D.H.D. Hildes, (UBC/GA).
The emphasis of this study is on continuous year-round monitoring of subglacial hydrological and mechanical processes to observe the changes associated with the onset of surging of Trapridge Glacier, YT, and identify the cause and triggering mechanism of surges. Continuous observations of subglacial water pressure and turbidity date back to summer 1988. Those on subglacial mechanical processes were initiated in 1990. New instruments developed for this study
include: devices to measure turbidity and conductivity of subglacial water; devices to measure glacier sliding, subglacial deformation and the ploughing interaction between the glacier and its bed.
See also: http://www.geop.ubc.ca/Glaciology/glaciol.html

Climate and change detection, Barnes Ice Cap, Baffin Island

(J.D. Jacobs, E.L. Simms, A. Simms, MUN/G)
Research on the Barnes Ice Cap in the 1960s indicated sustained recession of the northwest margin and suggested the ice cap was not in equilibrium with present climate. Our project commenced in 1989, with the objectives of: 1) updating earlier findings on marginal position/recession; 2) establishing a basis for long-term monitoring using remote sensing and a digital-levation model; and 3) obtaining sufficient information on the climate of the ice cap to permit extrapolation from permanent stations in the region in the context of long-term responses to global climate change.

Results confirmed sustained retreat at the northwest margin, even though a regional climatic cooling had been underway since the mid-1960s. Subsequent analysis of Landsat imagery of the southern half of the ice cap showed general marginal retreat there, consistent with negative mass-balance findings reported by other workers. These studies are to be extended to the entire ice cap using RADARSAT SAR imagery, in conjunction with Landsat TM data. Studies of the ice-cap climate continue, using data from automatic climate stations that operated at the ice-cap margin and on its summit between 1989 and 1995, along with older expeditionary data.

Quaternary glaciation and deglaciation, southern Quebec

(J.-M. Dubois, Ushe)
In the Eastern Townships, a detailed model of deglaciation is being developed related to the distribution of proglacial lakes. For Îles-de-la-Madeleine, the extent of deglaciation and its relation to changes in the relative marine limit have been established. Research on areas of glacier outburst floods has been completed. A permafrost outlier in the Îles-de-Mingan is also being studied.

Thermomechanical model of Laurentide ice sheet dynamics

G.K.C. Clarke, S.J. Marshall, N. Arnold, G.E. Flowers (UBC/GA), D.A. Fischer, A Dyck (NRCAN/GSC).
The model of the dynamics of the Laurentide ice sheet being developed is based on the continuum theory of mixtures and treats sheet ice and stream ice as distinct mixture components. Once completed it will become a module in a comprehensive model of the climate system that will include interactions between the ocean, atmosphere, cryosphere and lithosphere, being jointly sponsored by the Natural Sciences and Engineering Research Council of Canada and AES.
See also: http://www.geop.ubc.ca/Glaciology/glaciol.html

Global glaciology

(J.G. Cogley, W.P. Adams, M.A. Ecclestone, TU/G)
A dataset containing annual mass-balance time series for some 230 small glaciers has been compiled. A substantial proportion of the information is not in the standard publications of the World Glacier Monitoring Service, Zürich. The series extend from as early as 1887 to the present, but most begin after 1957. Most are very short, but 46 are longer than 20 years. The total number of measurement years is about 2100. Statistical analyses of the data are in progress. Relevant electronic files are available from ftp@trentu.ca; details can be provided by Email. A hydrographic dataset, called GGHYDRO, is also available from the above. Consisting of global grids at 1° resolution, it contains estimates of the areal extent of various hydrographic terrain types, including glacier ice and permafrost. The glacier-ice estimates have recently been revised and improved.

Glaciers fluctuations and climate, Tien Shan

(J. Schmok, GOLDER; V. Kuzmichinok , GIK)
The Tien Shan mountains have an extreme continental climate where most precipitation occurs in summer, yet the region has significant glaciation due to the large land surface above 4000 m. Glacier measurements here were recorded as early as the 1920s and continuous climate measurements began in 1930. Average annual valley-bottom air temperatures are –10°C, precipitation averages only 30 cm yr^{-1}, relative humidity is usually well below 50%, and solar flux exceeds 400 W m^2 on many summer days. Typical valley glaciers have lost 30% by volume since the Neoglacial maximum, with minor terminus advances in the mid 1970s. Vertical air photos from 1943 have been compared photogrammetrically to photos from 1977 to produce maps of area and elevation changes. Surge-type glaciers are clearly revealed by very large reservoir/receiving zone elevation changes.

LAKE ICE

Lake restoration with artificial polynyas

(P.F. Hamblin, EC/NWRI)
Some lakes suffer winter fish kill from low levels of dissolved oxygen. Adequate levels of DO may be maintained by natural replenishment through artificially

made polynyas. Mathematical models of polynya formation are being developed and integrated with standard water-quality models for ice-covered lakes.

Passive-microwave observation of lake freeze-up and breakup

(A.E. Walker, M.R. Davey, EC/AES)

Work continues to determine the potential of SSM/I data for observing the spatial and temporal patterns of ice freeze-up and breakup for large lakes in Canada. SSM/I brightness-temperature data have been acquired in near real-time for Great Slave and Great Bear Lakes during ice freeze-up and breakup seasons since 1992. Results have shown that it is possible to discriminate between areas of ice cover and areas of open water using the 85 GHz channels and therefore observe the process of ice formation and breakup over the two lakes. Observation of Great Lakes ice conditions during the 1993/94 winter were achieved using the same techniques. Current research is focused on the analysis of brightness-temperature time series for determining the effects of atmospheric and ice surface conditions on the 85 GHz data. A time series of SSM/I satellite data, available since 1987, is being compiled to document the earlier freeze-up and breakup history of ice on Great Slave and Great Bear Lakes.

Under-ice circulation in northern lakes

(B. Kenney, EC/NHRI)

Northern freshwater lakes have a density maximum at 4°C and stratify under ice. Experiments begun in 1991 have established the existence of an under-ice circulation between Waskesiu Lake and Waskesiu Bay, Saskatchewan driven by solar energy that penetrates the ice and snow covering in spring. It is likely that the penetration of solar radiation produces a gravity current between regions of varying depths in all lakes. This baroclinic current is a dominant physical process in winter because ice cover insulates lakes from the usual turbulence sources such as breaking surface waves and near-surface shear produced by the wind. The current forms a directed circulation from the littoral zone to the center of the lake that is an important distribution mechanism for nutrients and other chemical biological constituents. Heat transported by the current degrades the ice cover and makes surface travel hazardous. The thinning of the ice cover is most severe at the inlet to isolated bays with mean depths that differ significantly from the lake. At the mouth of shallow bays, the circulation forms a two-layer current with outflow from the bay occurring near the bottom. Using both vertical and horizontal thermistor chains, the temperature structure was measured in the strait separating Waskesiu Lake from a large shallow bay. The reduced gravity was two orders of magnitude less than that typically found in the ocean. The outflow was dominated by a succession of progressive internal bores which repeated approximately hourly. The amplitude of the temperature fluctuations decreased overnight and with increasing cloud cover. Trains of solitary internal waves were also observed that were an order of magnitude shorter in wavelength and period than is typical of open-water conditions. The wavelength of the solitary waves was the same as the length of the horizontal thermistor chain (5 m). The amplitude of the first solitary wave in each train was typically 0.75 m.

SEA ICE

Effect of ice on beach profile, Miscou Island, NB

(P.R. Hill, J.-D. Bouchard, UQAR)

The beach site was monitored on a monthly basis from July 1994 to May 1995 to determine if the presence of sea ice had a major effect on the seasonal cycle of beach-profile variations. The most active period was the freeze-up in early winter when ice frost began to form and storms were frequent. The ice foot underwent several stages of accretion and destruction related to storm activity, air temperature and frazil/slush ice conditions before finally becoming stabilized by the presence of offshore ice. Before final freeze-up, the developing ice foot acts as a sea-wall to incoming storm waves and substantial erosion of the shoreface was observed. Most sediment incorporated into the ice foot is deposited directly on the beach by melt out in the spring.

Dynamics and thermodynamics of Labrador/Newfoundland sea ice

(C.C.L. Tang, DFO/BIO)

A three-dimensional coupled ice–ocean model has been developed to study the movement and coverage of sea-ice off the Labrador and Newfoundland coast. The ice model is similar to the Hibler model, and the ocean model is a diagnostic one with a given density distribution and boundary conditions. Ice is coupled to the ocean through an Ekman layer. With surface wind as input, the model outputs ice velocity, concentration, thickness, and ocean current. Results have been compared with ice-drift data collected with satellite-tracked ice beacons, and the agreement is excellent.

Related work involves the measurement and modelling of ice growth and melt. Labrador pack-ice thickness has been measured with an acoustic device. This consists of a vertical pole through the ice and two acoustic distance sensors attached at the ends of two horizontal arms connected to the vertical pole. Changes of distance from the sensors to the ice surface and the bottom are measured. The measured growth and melt rates are compared with predictions of a theoretical model, which consists of a layer of ice, an oceanic surface layer and a deep layer with depth-dependent temperature and salinity. A coupled sea-ice mixed-layer model is used to compute the growth and melt rates, and the change of mixed-layer properties.

Snow catchment model for sea ice with SAR-derived ice topography

(J. Iacozza, D.G. Barber, UM/CEOS)

This research, part of SIMMS (Seasonal Sea Ice Modelling and Monitoring Site) located on the sea ice between Lowther Island and Resolute Bay, NWT, will study snow-distribution patterns over an icescape to further studies of the climate and biology of the Canadian high Arctic. A statistical method (variogram) will be used to model the distribution patterns; different ice types have been shown to have characteristic variogram models. These models will be modified and then applied to corresponding ice types in a SAR image of the area.

Shore–ice processes, St. Lawrence estuary

(J.-C. Dionne, UL/CEN)

Work continues on the quantitative evaluation of the importance of shore–ice processes in the evolution of the shoreline.

Sea-ice mechanics

(D. Farmer, Y. Xie, DFO/IOS)

Hydrophones were deployed in the Beaufort Sea to investigate the mechanical and acoustical response of ice to different conditions of mechanical and thermal forcing, and study the behaviour of overlying sea-ice sheets that move relative to each other. Acoustical measurements were acquired simultaneously with video recordings. A prominent feature of the data are 'slip-stick' signals associated with two ice sheets in contact while moving. The slip-stick signals, analogous to those investigated in earthquake mechanics, contain repeated pulses simultaneously over a wide frequency range, allowing analysis in the context of nonlinear forced oscillations.

Under-ice plume spreading, Beaufort Shelf

(R.W. MacDonald, E.C. Carmack, DFO/IOS)

Observations of salinity and oxygen-isotope composition ($\delta^{18}0$) were made for the Beaufort Shelf-Mackenzie estuary waters in September 1990, just prior to ice formation, and for both the water column and ice in April-May 1991, at the end of winter. These measurements are used to determine the apportioning of fresh water in the estuary between its two main sources, runoff and sea-ice melt. Changes in disposition of water between seasons and amounts frozen into the growing ice sheet are also derived. Two domains are considered in order to construct a freshwater budget for the Mackenzie Shelf, the nearshore within which landfast ice grows in winter and the outer shelf. Most of the winter inflow from the Mackenzie River appears to remain impounded as liquid under the ice within the landfast zone at the end of winter, and about 15% of it is incorporated into the landfast ice. $\delta^{18}0$ in ice cores from across the shelf record the progress beneath the ice of new Mackenzie inflow as it invades the nearshore throughout the winter. Rates of spreading are about 0.2 cm s^{-1} away from the coast and 1.3 cm s^{-1} along the coast. As this inflow spreads across the shelf, it progressively shuts off convection driven by brine production at locations within the landfast ice. Salinity and $\delta^{18}0$ in the offshore water column suggest that about 3 m of sea ice was formed in the outer shelf domain. Since both brine and newly formed sea ice can be advected off the shelf, a complete budget for brine or sea-ice production cannot be established without first measuring the advection of one of these two components.

Real-time sea ice information

(C. Garrity, R..O. Ramseier, MWGOR)

Using real-time Special Sensor Microwave/Imager (SSM/I) and Advanced Very High Resolution Radiometer (AVHRR) satellite data, navigation through sea ice, and planning of scientific stations has been achieved during numerous experiments on international ships. The most recent example is the joint Canadian/USA 1994 Arctic Ocean Section (AOS'94) to the North Pole. The key word is "real-time". A new algorithm, developed at the SCRIPPS Institute for Oceanography, San Diego, CA, provides an ice product using the 85GHz channel of the SSM/I sensor. Using this channel, over conventional SSM/I channels, the resolution has been doubled and the best correlation achieved in comparison with other algorithms. The SSM/I and AVHRR sensors are compatible, as they will be with RADARSAT. A RADARSAT image over a ship for example, can be augmented with SSM/I data for a large distance in front of the ship. An AVHRR image is useful for weather information and a view of the sea ice conditions for a large area when there is not a thick cloud cover. The aim is to introduce such a real-time receiver, to the CCG/DFO in order to aid navigation/safety and scientific projects along with reducing the cost for ice information by orders of magnitude compared to the present costs.

Ice-subsurface characterization

(H. Melling, DFO/IOS)

Instruments have been maintained on moorings at three sites in the Beaufort Sea continuously since 1990 (4000 instrument days) to acquire detailed draft profiles of pack ice for application to concerns in engineering, environment and climate. During this time, more than 25,000 km of topographic profile have been acquired during all seasons. The deepest ice draft observed to date has been 35 m, attributed to a weathered multi-year pressure ridge.

OTHER

Radar investigations, McMurdo Dry Valleys, Antarctica

(J. Schmok, GOLDER; R. Wharton, DRI; A. Fountain, USGS)

The McMurdo Dry Valleys are extremely dry, remaining ice-free despite annual average temperatures of –20°C (sublimation exceeds precipitation). In support of the Long Term Ecological Research project there, ground-penetrating radar in a range of frequencies, polarizations, antenna designs, and acquisition modes, was used to image the subsurface at a number of sites. These included perennially ice-covered lakes, deep subsurface water bodies, permafrost alluvium, and subglacial structure. The perennial lake ice is extremely bubbly and anisotropic, likely due to gases produced by water-column algae and bacteria being incorporated in the ice as it grows downward. As a result, this ice strongly scatters radar energy at higher frequencies. At other sites, radar sections revealed subsurface water pockets at depths exceeding 19 m. The strong radar reflection from these water pockets suggests saline water perhaps containing similar gas-producing organisms, resulting in the characteristic upwarping of the mostly flat-lying radar stratigraphy.

Cryospheric System (CRYSYS) to Monitor Global Change

(B. Goodison, R. Brown, L. Sterling, A.E. Walker, EC/AES; D. Barber, UM; M. Bernier, UQ; M. Brugman, EC/NHRI; C. Duguay, UO; J. Falkingham, EC/IC; G. Flato, CCMA; H.

Granberg, Ushe; A. Judge, R. Koerner, NRCAN-GSC; E. LeDrew, UW; M. Lewis, DU; T. Pultz, M. Manore, NRCAN-CCRS; L. Mysak McGU; M.-K.Woo, MU)
CRYSYS is a Canadian contribution to EOS, hosted and funded by Canadian agencies and universities, and led by the Atmospheric Environment Service of Environment Canada. CRYSYS investigations use remote sensing, modelling, field studies and data integration to improve monitoring of the state of the cryosphere, and provide greater understanding of cryospheric processes and variability. CRYSYS has realized benefits for the Canadian cryospheric research community by focusing limited human and financial resources on important goals and objectives. Thus the Canadian community has been able to contribute and strengthen its significant scientific and technical expertise in remote sensing and conventional analyses of the cryosphere. CRYSYS has five major research components: sea–ice, lake-ice, snow, permafrost and glaciers/ice caps. See also: http://www.on.doe.ca/CRYSYS/.

COLD OCEAN AND POLAR ENGINEERING

Large-scale hull loading — INSROP

(S.J. Jones, R.E. Gagnon, NRCC/IMD; D.M. Masterson, SANDWELL)
The International Northern Sea Route Programme (INSROP) is studying the feasibility of using the Northern Sea Route on a regular basis for shipments from Europe to the Far East. The programme is sponsored by Japan, Norway and Russia. The present experiment, conducted in collaboration with Sandwell Inc., Calgary, used a flat jack, a thin-walled, flat envelope of steel which is fitted into an ice slot and into which fluid is pumped to achieve the failure load of the ice, to load large areas of ice at relatively low cost. Tests previously conducted with these flat jacks to areas of 4.5 m^2 showed the strength of competent, intact ice did not change significantly with the size of loaded area. However, the flat jacks were thought to be too compliant and so it was reasoned that if a stiff plate were placed in the ice slot alongside the flatjack, the resulting stress concentrations from the stiff plate would result in a lower failure pressure more reasonably approximating that measured on large structures and ships. Phase 1 of Project I.1.7 investigated: 1) the effect of such a stiff plate; and 2) the feasibility of using cheaper, gas-filled flat jacks instead of the more expensive, liquid-filled ones. The results showed that the gas-filled flat jacks worked very well. An aluminum plate 1.5 m × 0.2 m × 76 mm produced pressures of around 5.5 Mpa. Meanwhile, average pressures on large structures due to global loading of 1 to 2 Mpa have been measured. Two tests with the rigid indentor were run in pre-damaged ice and the pressures obtained averaged 1.5 Mpa, a value in line with global pressure measured on large structures. This constitutes a very important observation and provides concrete direction for further tests in Phase II.

Ice-propeller interaction

(S.J. Jones and others, NRCC/IMD)
A major international project has been going on for 4 years on propeller-ice interaction as part of joint Canadian (IMD) and Finnish (VTT) research project. Physical model tests have been conducted both at IMD and VTT to measure the forces on a propeller blade due to both contact and non-contact phenomena. These data have then been compared to theoretical calculations based on hydrodynamics, and to full-scale results in the literature. They have also been used as input to a simulation model of the interaction process. The uniaxial compressive strength of sea ice and freshwater ice at high strain-rates has been measured as input to the simulation model. A design-load model is now under development which will enable designers and regulators to determine the expected loads on a propeller blade in typical ice conditions for the planned route. The object is to incorporate the results in revised machinery regulations for shipping in the Canadian Arctic and the Baltic Sea.

Modelling ships and marine systems in ice

(F.M. Williams, NRCC/IMD)
The operation of aluminum-hulled ships in ice was the focus of a project completed in 1995. Literature is available from IMD (williams@minnie.imd.nrc.ca). Model test observations and performance evaluations were also conducted for the WAGB-20.

Measurement and modelling of ice conditions

(F.M. Williams, B.L. Parsons, NRCC/IMD)
Work continues in a variety of areas concerning the measurement of ice mechanical properties, including the role of scale and size effect in governing the flexural strength of ice. Some of this work has focused on ice features in the Northumberland Strait as they relate to the Northumberland bridge.

Ice loads due to first-year ridges and rubble fields

(K.R. Croasdale, B. Rogers, T. Brown, G. Timco, R. McKenna, J. Weaver, M. Metge, B. Wright, KRCA)
The aim of this work is to improve ice-load prediction models for the interaction of first-year ridges and rubble fields with offshore platforms. The models which currently exist in the literature have neither been critically reviewed nor compared with full-scale loads and physical tests. Furthermore, the various load models which exist predict loads which can vary by factors of 2 to 3 for the same input parameters. The study combines mathematical modelling with physical tests on both ice and analogues of ice. Full-scale loads from offshore structures in the Canadian Beaufort Sea are being used in the calibration and verification of the models.

Ice-load consensus

(K.R. Croasdale; KRCA, + 15 collaborators)
The prediction of ice loads on offshore structures is still subject to wide variation in methods and results. Even for the same set of ice parameters and structures it has been shown that different experts will predict loads which can be different by almost an order of magnitude. The objective of this study is to understand why these differences occur, and by a process of dialogue between the experts, narrow the differences or define what work might be done to reach consensus. The project involves ice engineers from Russia, North America and Europe.

Iceberg-impact loads

K.R. Croasdale, G. Crocker, KRCA; with others from C-CORE)
Offshore structures and vessels for oil development off the east coast of Newfoundland have to be designed and/or operated with the possibility of collisions with icebergs in mind. Although many floating production systems can be moved out of the way of larger icebergs, they should be designed for the impact of smaller icebergs which may not be detected. This study is improving methods of iceberg-impact load prediction and obtaining relevant iceberg-crushing pressures. An instrumented load panel was mounted on a cliff face on an island off the coast of Labrador and small icebergs were towed into it using a pulley and pendulum system. The loads obtained are being analyzed.

Ice-structure interaction

(A.P.S. Selvadurai, McGU/CEAM)
Discrete-element techniques are being applied to the study of moving ice sheets and stationary offshore structures which are either rigid or flexible. The work involves modifying an existing distinct-element code to include processes such as viscoplastic softening and improved criteria for the initiation of fragment development. Other modifications will address the influence of scale on the nature of fragment development. The computational modelling is applied to the analysis of a variety of problems involving ice-structure interaction which takes into consideration the spatial variations in the properties of the ice feature and the role of either impact or farfield-induced ice movement on the ice-structure interaction process. The work is also being extended to examine the interaction of ice floes with landfast ice.

Arctic marine transportation model

(J. Tseng, SANDWELL/SWD)
Sandwell developed an Arctic marine-transportation computer-simulation model in early 1995 that simulates the loading and transport of hydrocarbons by ice-capable tankers from an Arctic export terminal to an import terminal in a temperate zone. An advanced object-oriented computer code is used and permits the user to interact with the simulation during a run. Operational issues such as transiting through various ice conditions and ice-related delays at the Arctic loading terminal can be examined A follow-up project will enhance the simulation model.

East Coast sea-ice program

(S.J. Prinsenberg, I.K. Peterson, G. Fowler, S. Holladay, DFO/BIO)
Helicopter-towed electromagnetic/laser sensors have been used successfully to measure ice-plus-snow thicknesses and ice-cover surface roughness over the mobile pack ice, along the Canadian East Coast and landfast ice of the Canadian Archipelago, during surveys in 1994 and 1995. The Canadian technology, developed by Aerodat Ltd. (S. Holladay), has become an operational tool for the Canadian Coast Guard in their efforts to escort ships more efficiently through ice in Canadian waterways. The data set is also used by investigators at BIO, EC/IC and NRCAN/CCRS to evaluate remotely-sensed SAR data collected by fixed-wing airplanes and the ERS-1 and RADARSAT satellites. Expendable GPS-ARGOS ice beacons are being used to monitor ice-pack drift and convergence and divergence rates. The Canadian-built beacons (Seimac Ltd.) use Global Position System receivers (GPS) to monitor their position and the ARGOS satellite as a data-transmission link. Relative distance accuracy between beacons range from 1 to 2 m when positions are based on the same constellations (50–60% of the time) to 10 to 15 m when all constellation pairs are used.

Expendable ice-pressure beacons are being developed at BIO to quantify the ice pressure inferred from ice-convergence data obtained by the GPS-ARGOS beacons. Both non-directional (1994/95) and directional (1995/96) pressure beacons are being developed and field tested using the ARGOS data link. Field surveys are monitoring oceanographic and atmospheric parameters to determine the pressure contributions by wind and current forcing. Numerical modeling continues to develop improved coupled ice–ocean models in support of the Ice Centre's efforts to better forecast pack-ice conditions along the East Coast. Models are also used to understand the inter-annual variability of the pack-ice extent here and its relation to ocean climate and the variability of fish stocks. Extreme ice years coincide with large spatial scale and persistent variation in the Icelandic Low which increases the frequency of cold temperatures and northwesterly winds. These conditions enhance southwards ice drift and local ice growth.

Ice-force panels, Northumberland Strait bridge

(I. Weir-Jones, WJE)
Weir-Jones Engineering Ltd. Supplied the Department of Public Works with 28 IDEAL™ 1 × 2 m (nominal) ice-force panels for mounting on the Northumberland Strait bridge piers. Each panel contains 8 independent 0.5 × 0.5 m sensing zones, capable of measuring a maximum normal compressive stress of 12 Mpa. Analog signals are sent to a central data-acquisition system. The panel-response frequency is >3 Hz and the panels can withstand a maximum compressive stress of 20 Mpa over an area of 0.25 × 0.25 m. The anticipated duration of the instrumentation program is in excess of 10 years. Weir-Jones Engineering Ltd. Have supplied ice-force monitoring systems to clients for almost fifteen years.

Sea-ice landing strip, northern Greenland

(N.K. Sinha, NRCC/IERT)

Field measurements and the application of elasto-delayed-elastic (EDE) and elastic models, enabled the estimation of bearing capacity and time-dependant deflections for a proposed sea-ice landing strip in the Frederick Hyde Fjord, northern Greenland. A fully loaded Boeing-727 was landed there in support of commercial mining exploration. Sixteen landings were made over the course of seven days. Ice-cover temperature and cracking activity were monitored as well as deflection measurements when the aircraft was parked. Model results compared favorably with measured deflections resulting from short-term loading. The EDE-elastic model estimates ice-cover stresses that develop immediately upon load application. Parking time is determined from knowledge of ice type and governing operational requirements (i.e., aircraft loading and available freeboard).

ATMOSPHERIC ICING

Atmospheric icing of structures

(J.A. Druez, ERIGS)

Research projects include studies on atmospheric icing of structures at the Mt. Valin natural-icing test site. Much of the work is supported by a climatic-testing and icing-simulation laboratory and an atmospheric-icing data base (glaze, wet snow, in-cloud icing). The mechanical behavior of atmospheric and spray ice have been investigated as they relate to the icing of structures, power lines and communication networks (ice and wind loads, ice accretion and shedding, statistical analysis and modelling, reliability).

Aircraft static-test program

(INSTRUMAR)

From January 1995 to April 1995, five evenings were selected to perform a total 14 static tests at St. John's International Airport. The main objective was to evaluate and compare the failure of de-icing fluids on aircraft wings to de-icing fluids on flat plates. Union Carbide XL54 Type I fluid was the only de-icing fluid used. The results, based on trends observed within the limited data set, appear to show a correlation between the failure of flat plates (de-iced with 20°C XL54 Type I de-icing fluid poured on the plates from a hand held container) and 10% aircraft wing fluid failure. The outer leading and trailing edges of the aircraft wing appear to be the first sites of observed fluid failure. The trailing edge in general appears to be the most likely wing area for the observation of 10% fluid failure. Contained within the boundary of the representative surface of the DC-9 aircraft is a triangular raised panel. This seems to be a susceptible site for the onset of fluid failure. There also appears to be a relationship between fluid failure on the aircraft wings and flat plates with the environmental parameters of precipitation rate and wind speed. As the precipitation rate increases, the failure times of the aircraft and flat plates decrease. As the wind speed increases, the failure times of the aircraft increase. The wind speed did not appear to effect the flat plates as much.

Ship icing and stability

(E. Lozowski, T. Forest, K. Szilder, A. Kobos, V. Chung, R. Blackmore, J. Shi, UA/EAS)

The primary aim of this research was to develop a better understanding of ship icing and its interaction with ship dynamics, to improve the design, regulation and safety of ship operations under icing conditions. To achieve this, a computer-simulation model was developed to predict the freezing-spray ice-load distribution, in three-dimensions, over the stern trawler *Zandberg*. A time-dependent ship dynamic-simulation model was used, in conjunction with the ship-icing model, to predict the motions of the ice-loaded vessel. Using these two computer simulations, it has been possible to examine the effect of a spray-ice load on the *Zandberg's* stability, without having to endanger the ship or its crew. Special computer models have also been developed to investigate and simulate other aspects of the ice-accretion process, which had previously been poorly understood.

The most important findings to date are: 1) particularly severe icing can occur when either the atmosphere or the ocean surface contains ice crystals; the spray droplets do not supercool, lose heat rapidly, and hence form more ice; 2) the rate of freezing-spray production depends on the third power of the ship speed; modest reductions in ship speed can reduce the rate of ice formation considerably; 3) icicle formation and the incorporation of unfrozen brine into the ice accretion (sponginess) can more than double the rate of ice formation on a ship; innovative computer models have been developed to simulate this; 4) asymmetrical ice loads accreted with even slightly off-head winds can cause rapid listing and instability of the vessel. Thus it would seem imperative to perform a dynamic-stability simulation and analysis, under realistic, predicted asymmetrical ice loads, in order to certify the safety of a vessel under icing conditions; 5) a simulation of the icing and dynamical behaviour of the *Zandberg*, under conditions similar to those encountered by the missing side trawler *Blue Mist II*, on the night of February 6, 1966. After three hours of icing, the computer model of the *Zandberg* capsized and sank. This piece of evidence adds to the circumstantial evidence collected at the time, suggesting that icing was the principal cause of the loss of the *Blue Mist II* with all hands.

Ice-accretion process and experimental verification

(K. Szilder, E.P. Lozowski, UA/EAS)

Work continues on a wide variety of research topics related to atmopheric icing, including the microstructure of ice accretion, icicle growth, freezing-rain simulation and modelling ice accretion on objects of complex geometry.

ICE AS A MATERIAL

Cracks in columnar-grain ice

(L.W. Gold, NRCC)

For strain rates greater than 10^{-7} s^{-1}, grain-boundary and transcrystalline crack populations have well-defined statistical characteristics. The proportion of transcrystalline cracks in the total number of cracks, tends

to increase with increase in grain size, decrease in strain rate, increase in strain and increase in temperature. At a strain rate of about $10^{-3}s^{-1}$, most of the cracks occur at grain boundaries with at least one of the crack edges at a triple point. For strains of up to about 10^{-3}, both grain-boundary and transcrystalline crack widths can be described with a good level of certainty, by the lognormal distribution. For compressive stress applied perpendicular to the long direction of the grains of columnar-grain ice, with the crystallographic axes of the grains tending to have a random orientation in the plane of the stress, crack initiation is a random process.

First-year sea-ice scattering layer

(M. Johnston, UL/CE; N.K. Sinha, NRCC/IERT)
Systematic methods for the analysis and digitizing of photographed images of thin sections have been established for examining the macrostructure of sea ice. The fundamental macrostructural parameters of the scattering layer, defined as the upper 15 cm of the ice sheet, are herewith determined. The scattering layer was of special interest as it is the region most relevant to C-band microwave remote sensing.

Abbreviations used

ACRES	Acres International Ltd., Niagara Falls, Ont.
AERODAT	Aerodat Inc.
AES	Atmospheric Environment Service, Downsview, Ont.
AINA	Arctic Inst. Of North America, Calgary, Alta
AXYS	AXYS Group (formerly Seakem Oceanography Ltd.)
BCIT	British Columbia Inst. Of Technology
BIO	Bedford Inst. Of Oceanography, Dartmouth, NS
C-CORE	Centre for Cold Ocean Research and Engineering
CANPOLAR	Canpolar Inc., Toronto, Ont.
CCMA	Centre for Climate Modelling and Analysis
CCRS	Canada Centre for Remote Sensing
CE	Civil Engineering
CEAM	Civil Engineering and Applied Mechanics
CEOS	Centre for Earth Observation Science
CMIE	Columbia Mtn Inst. Of Ecology, Revelstoke, BC
CRRC	Cold Regions Research Centre
CU	Carleton Univ., Ottawa, Ont.
DFO	Dept. of Fisheries and Oceans
DOE/NB	New Brunswick Dept. of the Environment, Fredericton
DRI	Desert Research Inst., Reno, NV
DU	Dalhousie Univ., Halifax, NS
E/DH	Engineering/Division of Hydrology
EAS	Earth and Atmospheric Sciences
EC	Environment Canada
ECB	Environmental Conservation Br., Prairie and Northern Region, Regina
EP/CIN	École Polytechnique/Centre d'Ingénierie Nordique, Montréal, PQ
ERIGS	Équipe de Recherche en Ingénierie du Givrage des Structures/Dépt. Des Sciences appliquées, UQ à Chicoutimi, PQ
ES	Earth Sciences
FM	Fenco MacLaren Inc., Willowdale, Ont.
G	Geography
GA	Geophysics and Astronomy
GIK	Geodetic Inst., Krygystan
GNWT	Government NWT, Transportation, Marine Operations, Yellowknife
GOLDER	Golder Associates, Burnaby, BC
GSC/ONT	Geological Survey of Canada, Ottawa, Ont.
GSC/PQ	GSC, Quebec
GT	Dépt. de géographie et télédétection
HC	Hadley Centre, UK
IC	Ice Centre, Ottawa, Ont.
IERT	Inst. for Environmental Research and Technology, Ottawa, Ont.
IH	Inst. of Hydrology, UK
IMD	Inst. for Marine Dynamics, St. John's, Nfld.
INRS	Inst. national de la recherche scientifiqueEau (UQ), Sainte-Foy, PQ
INSTRUMAR	INSTRUMAR Ltd., St. John's, Nfld
IOS	Inst. of Ocean Sciences, Sidney, BC
IRCon	Incline Research and Control, Revelstoke
KRCA	K.R. Croasdale & Associates Ltd., Calgary
McGU	McGill Univ., Montréal, PQ
MU	McMaster Univ., Hamilton, Ont.
MUN	Memorial Univ. of Newfoundland, St. John's
MWGOR	Microwave Group-Ottawa River, Inc., Ont.
NBPC	New Brunswick Power Corp., Woodstock
NHRI	National Hydrology Research Inst., Saskatoon
NRCAN	Natural Resources Canada, Ottawa, Ont.
NRCC	National Research Council of Canada
NWRI	National Water Research Inst., Burlington, Ont.
OUC	Okanagan Univ. College, Kelowna, BC
PWC	Public Works Canada, Winnipeg, Man.
QU	Queens Univ., Kingston, Ont.
RC	Ricker Consulting, Vancouver, BC
SANDWELL	Sandwell Inc., Calgary
SANDWELL/SWD	Sandwell Inc./Swan Wooster Division, Vancouver, BC
SEA SEAN	Sea Sean
SFISAR	Swiss Federal Inst. for Snow and Avalanche Research, Davos, Switzerland
SFU	Simon Fraser Univ., Burnaby, BC
SRAWS	Snow Research and Avalanche Warning Section, Glacier and Mount Revelstoke National Parks, Revelstoke, BC
TAI	Tsang & Assoc. International, Saskatoon, Sask.
TBA	Taiga Biological Station, Bissett, Man.
UA	Univ. of Alberta, Edmonton
UB	Univ. Bristol, UK
UBC	Univ. of British Columbia, Vancouver, BC
UC	Univ. of Calgary, Alta
UEA	Univ. of East Anglia, UK
UM	Univ. of Manitoba, Winnipeg
UO	Univ. of Ottawa, Ont.
UQ	Univ. du Quebec, PQ
UQAR	Univ. du Quebec à Rimouski, PQ
UR	Univ. of Reading, UK
US	Univ. of Saskatchewan, Saskatoon
USGS	United States Geological Survey, Portland, OR
USher	Univ. de Sherbrooke, Sherbrooke, PQ
UT	Univ. of Toronto, Erindale Campus, Ont.
UW	Univ. of Waterloo, Ont.
WBNP	Wood Buffalo National Park, Fort Chipewyan
WHC	Water and Habitat Conservation, Ottawa, Ont.
WJE	Weir-Jones Engineering Ltd., Vancouver, BC
WLU	Wilfrid Laurier Univ., Waterloo, Ont.
Z	Zoology

Submitted by M. Demuth

For abbreviations see end of report

GLACIOLOGICAL MODELLING

Flow beneath ice shelves

(A. Jenkins, A. Bombosch, BAS; D.M. Holland, Lamont Doherty Earth Observatory)
The inaccessibility of cavities beneath ice shelves to direct observation places a high premium on the use of numerical models to understand the processes that control the present-day ocean circulation there and to predict how it might respond to a changing climate. The Miami Isopynic Coordinate Ocean Model is being adapted to handle the unique conditions beneath an ice shelf. The study covers the entire Weddell Sea and includes the effects of regional-weather conditions on sea-ice production and the resultant pre-conditioning of continental-shelf water masses. An important aspect of the interaction between ice shelf and ocean is the effect of changing climate on the shape of the ice shelf itself: in the extreme case of an ice age, the ice is grounded to the continental shelf edge and there is no ice shelf at all. A simpler, two-layer sub-ice-shelf circulation model is under construction that can be run over much longer periods and coupled to a model of the flow of the ice shelf itself. This should allow a study of the interaction between the geometry of the ice shelf, which is affected by the oceanographic conditions beneath it, and the oceanographic conditions themselves, which are in turn affected by the geometry of the ice shelf.

Adaptive grid systems applied to ice-sheet models

(A. Starr, M.J. Siegert, P.L. Olivier, H. Holstein, UWA)
The centre of large ice sheets can be described adequately by simple physics and large cell widths within the grids of ice-sheet models. However, within ice streams and the floating/grounding transition zone (and possibly above sub-glacial lakes) ice dynamics become complicated by the dominance of basal processes and longitudinal stress components. In order to model ice-sheet behaviour in these regions, cell widths need to be reduced substantially from the widths of those required in the ice-sheet interior. However, to keep computer-modelling time to a minimum, the largest possible grid cells are desired. We are applying an adaptable grid system to an ice-sheet model to predict those regions of the ice sheet where relatively narrow cells are required. Such a model may be useful in determining the small changes in glacial extent that occur as a result of climate change.

Dynamics of ice streams

(T. Payne, USG)
The overall evolution and dynamics of ice streams within ice sheets is being investigated. Initial work indicates the thermomechanical flow of ice is unstable and can lead to the spontaneous development of streaming. The modelled streams share some features in common with real ice streams. In particular, they show spatial evolution and switching behaviour. The initial experiments with simplified boundary conditions will be extended to simulations of the West Antarctic ice streams.

Simulation of the Laurentide ice sheet

(T. Payne, USG)
An appreciation of the dynamics of the Laurentide Ice sheet (LIS) has recently become important in understanding the stability of climate in the circum-North Atlantic area. The discovery of Dansgaard–Oeschger events in Greenland ice cores and Heinrich layers in North Atlantic sediments has been interpreted as evidence for the large-scale instability of the LIS. The development of a numerical ice-sheet model of the LIS will allow such a hypothesis to be tested. Initial findings run contrary to the ideas of MacAyeal and indicate no potential for large-scale surging.

EISMINT Ice Sheet Model Intercomparison

(T. Payne, USG)
The performance of existing ice-sheet models is being compared in a number of benchmark experiments. The first phase sought to identify the effects of differences in the models' numerics using simplified experiments. The second, current phase, will identify differences in models when they are applied to more complex problems. Examples include the effects of including full thermomechanical flow and application to the Greenland ice sheet.

Ice sheets and drainage

(A. Fowler, Mathematical Inst., Oxford Univ.)
In association with E. Schiavi (Madrid), we are developing numerical methods to solve 2-d ice-sheet models, where drainage and sliding over deformable till is included in as realistic a way as possible. The evidence is that these models cause major ice-sheet surges (thence Heinrich events), but that numerical solution is a very delicate matter.
In association with F. Ng, we are developing theories for subglacial drainage, allowing for the presence of sediments, and transient effects. Particular applications are to the continued understanding of jökulhlaups.

Together with C. Vasquez and mathematicians at the University of Vigo (Spain), we are developing numerical methods for the solution of ice-sheet models, when realistic basal polythermal conditions occur.

Antarctic ice sheet

(J.L. Bamber, UBG; P. Huybrechts, Vrije Univ., Brussels)
A quantitative analysis of the ice dynamics in a 3-d thermomechanical model of the Antarctic ice sheet is being carried out. The velocity field produced by the model is being compared with velocities derived from conservation of mass (balance velocities) and measured surface velocities. The boundary conditions required to calculate balance velocities are surface slope, accumulation and ice thickness. There are significant errors associated with the latter two

variables; in a large part of East Antarctica the uncertainty in ice thickness is up to 25%. However, in other regions the boundary conditions are relatively well known. Here differences between the modelled, measured and balance velocities will be due to a number of possible causes including poor representation of ice rheology and/or basal processes in the model or a non-steady-state ice sheet. An investigation of these differences will help identify weaknesses in the thermomechanical model and regions where the ice sheet is substantially out of equilibrium.

Ice-sheet modelling

(R.C.A. Hindmarsh, BAS)
Work on linearised ice-sheet models has been extended with a detailed study of a perturbation around the classic Vialov-Nye solution for a steady-state ice sheet. The decay-rate for the slowest mode is approximately the same as that predicted by the zero dimensional theory. This (normalised) decay rate is very similar for different ice-sheet configurations, indicating that linearised models, which are suitable for short-term predictions, may be able to short-circuit much of the tuning process required for more computer-intensive non-linear models. Work has continued with modelling of flow patterns in the divide regions of ice sheets where ice cores are drilled for palaeoclimate purposes, and in modelling erosional processes which occur at the base of ice sheets. A natural variability in snow accumulation can cause the ice divide (and zone of anomalous flow) to migrate back and forth randomly, affecting stratigraphic models used to date ice. If this effect is important it is much smaller than the resolution of present-day ice-sheet models, so a specialised linearisation technique has been employed to quantify the influence of accumulation-rate variability. The study suggests the variability has significantly influenced the ice chronology at divides in the Antarctic Peninsula and possibly also in Greenland. Curiously, the noise may ease interpretation, as the disrupting influence is spread over a broader area and its effect thereby diluted.

Mass balance of NW Spitsbergen glaciers and responses to climate change

(K.M. Fleming, Australian National Univ., Canberra; J.A. Dowdeswell, UWA; J. Oerlemans, Univ. of Utrecht)
An energy-balance model is used to calculate mass balance and equilibrium-line altitudes (ELAs) on two NW Spitsbergen glaciers whose mass balances are at present negative, and for which >20-year records of mass-balance data are available. The model takes meteorological data, ice-mass area distribution with altitude, and solar radiation as inputs. Modelling uses mean daily meteorological data from a nearby weather station, adjusted for altitude. Average net balances modelled for 1980-1989, using models tuned to the decade's average, were -0.44 and -0.47 m w.e. for Lovénbreen and Brøggerbreen respectively, compared with the measured averages of -0.27 and -0.36 m. Sensitivity tests on glacier response to greenhouse warming predict a net balance change of -0.61 m a^{-1} per deg. of temperature rise relative to today, and a rise in ELA of 90 m per deg. Modelling Little Ice Age conditions in Spitsbergen suggests a 0.6°C cooling or a precipitation increase of 23% would yield zero net balance mass balance for Lovénbreen and that further cooling would increase net balance by 0.30 m a^{-1} per deg.

Glacial sediment transport to the Late Weichselian Polar North Atlantic Margin

(D. Howell, M.J. Siegert, J.A. Dowdeswell, UWA)
During the last glaciation, a large ice sheet may have existed within the Barents Sea. During this time, the western margin of the Barents Shelf was subject to significant glaciomarine sedimentation. This sediment was derived largely from the action of ice streams within topographically defined regions such as the Bear Island Trough. Sediments built up at the mouths of such troughs form sedimentary fan systems. This study uses a numerical model of ice-sheet flow, coupled to numerical models of ice-stream behaviour and glacial-sediment transport, to calculate the flux of sediment delivered to fan regions during glacial cycles. Geophysical information from such glacial fans will provide boundary conditions for modelling.

Ice motion over a deformable substrate, Austfonna, Svalbard

(L.G. Watts, J.A. Dowdeswell, UWA; T. Murray, ULG)
Two models, a finite-element model and a subglacial-layer model, have been developed and applied in a study of the dynamics, thermodynamics, and basal boundary conditions of a flowline on the ice cap Austfonna, Svalbard. A number of glaciological data sets, from satellite, airborne and field surveys provide boundary conditions for the modelling and suggest that the bed consists of potentially deformable sediments beneath at least part of the ice mass. The finite-element model incorporates iteratively-linked calculation of velocity and temperature solutions, and provides a simulation of present-day velocity and temperature distributions on the flowline. The subglacial-layer model provides indications of the thickness of the effective subglacial layer and can be used to assess whether subglacial water pressures are sufficient to indicate the potential for surge-type behaviour.

Numerical modelling

(L.W. Morland, School of Mathematics, Univ. of East Anglia)
Current ice-sheet studies include: development of axially symmetric solutions of the isotropic, thermally uncoupled, reduced-model equations to investigate the influence of surface and basal conditions, and determine the heat source which would induce an assumed temperature field; test solutions for direct numerical algorithms; evolution of fabric (induced anisotropy) in polar ice sheets, in collaboration with BAS, CNRS (Grenoble) and Technische Universität (Darmstadt).
Other studies include: numerical investigation of sea-ice dynamics equations in material co-ordinate formulation to explore the situation at interfaces between converging and diverging zones; and, interacting continua descriptions of 3 and 4 constituent snow packs which include phase change, and in particular phase change at singular surfaces which arise at external boundaries and internal interfaces.

REMOTE SENSING

Russian KATE-200: morphology and dynamics of ice masses in the European high Arctic

(J.A. Dowdeswell, M.R. Gorman, UWA; Y.Y. Macharet, A.F. Glazovsky and M.Y. Moskalevsky, Inst. of Geography, Russian Academy of Sciences)

Imagery from the Russian Cosmos series of near-polar orbiting satellites is now more widely available. We have obtained KATE-200 photographic imagery of ice caps in the archipelagos of Franz Josef Land and Svalbard, and from the Greenland ice sheet. This visible-band imagery is of high spatial resolution (nominal 15 m) and each image covers about 60,000 km^2. KATE-200 products are first-generation film positives, first-generation film negatives, and prints. No calibration standards or grey scales are provided. A number of ice-surface topographic features can be extracted. Examples include flow directions in the Greenland ice sheet and drainage-basin ice divides on Svalbard ice caps. The large area covered by each KATE-200 image, almost twice that of a Landsat scene and over 15 times that of SPOT, is an advantage when monitoring the occurrence of glacier surges.

Improved Antarctic topography

(J.L Bamber, UBG)

Work continues to improve the Antarctic digital-elevation model, initially produced in 1993 from ERS-1 radar-altimeter data. A 5 km DEM has now been produced from the geodetic phase of ERS-1, using the full 336 days of data, providing an across-track spacing of 4 km at 60°S. On the Ross Ice Shelf, the subtle flow stripes and relict flow features (approximately 50 cm in magnitude) were clearly resolved in the dataset. In high-relief regions (such as the Transantarctic Mountains) the radar-altimeter data are not reliable. The project will continue to focus on improving the model in these regions and methods for improving the representation south of the latitudinal limit of ERS-1. In particular, the use of photo-clinometry (shape from shading) is being considered.

Greenland ice-sheet topography and ice physics

(J.L. Bamber, J. Milroy, UBG)

A high-resolution (2.5 km) and high-accuracy digital-elevation model (DEM) of the Greenland ice sheet has been produced from a dense coverage of ERS-1 radar-altimeter measurements. The comprehensive validation of these data, using airborne-laser altimetry, indicates the accuracy of the DEM is at the decimetre level in the interior of the ice sheet. With this accuracy and resolution it is possible to study short-wavelength features in the DEM related to basal topography, ice dynamics and ice rheology. The goal is to investigate ice rheology and basal conditions by inversion of the DEM. A supplementary dataset, required for this work, is ice thickness and a revised bed-elevation dataset has been compiled from the latest available radio echo-sounding data. Other data used include in situ surface-velocity measurements and displacement fields derived from interferometric synthetic-aperture radar.

SAR interferometry, Ellsworth Land

(C.S.M. Doake, R.M. Frolich, A. Jenkins, E.M. Morris, BAS)

The technique of SAR interferometry has been demonstrated using ERS-1 images acquired six days apart over Rutford Ice Stream and Carlson Inlet. Over 100 calibrating tie-points are available in this area from ice movement and topographic surveys carried out between 1978 and 1996. An interferogram has been calibrated to agree with the ground truth to within a mean error of 1 cm, or less than a quarter of the radar wavelength. Failure to fit the tie-points exactly can be attributed to a combination of interferometric phase noise and errors in the ground surveys. Results suggest there has been no change in ice movement between 1978 and 1992. The upper 50 km of Carlson Inlet has been confirmed to flow at less than a tenth of the speed of the neighbouring Rutford Ice Stream. To improve the calibration of SAR data, radar reflectors have been set up on Rutford Ice Stream, Carlson Inlet and Evans Ice Stream. More detailed survey work was completed in the shear margin between Rutford Ice Stream and Carlson Inlet. Here the differential motion is too great to yield a simple interference pattern. With a detailed knowledge of the velocity profile it will be possible to test algorithms for unravelling this complex part of the interferogram.

Surging-glacier velocities from SAR interferometry, Svalbard

(D. Wingham, B. Unwin, Mullard Space Science Lab., Univ. College London; J.A. Dowdeswell, A.-M. Nuttall, UWA)

Techniques developed at MSSL for studying the dynamics of Austfonna, Nordaustlandet, are being applied to the recently surging, valley glacier Fridtjovbreen, S Spitsbergen. The technique will enable us to monitor velocity changes through the initiation of the surge. Several pairs of ERS-1 images, with a 1-day repeat interval, have been processed to produce interferograms, and the resulting fringes will be used to produce velocity maps for each image pair.

Glacier drainage basins and balance velocities, East Greenland

(A.-M. Nuttall, J.A. Dowdeswell, UWA)

Twenty Landsat MSS images have been used to identify drainage-basin divides for 70 tidewater glaciers in central East Greenland. Where an entire basin is covered by the imagery, its area can also be determined. Using estimates of accumulation rates and terminus thickness, the balance velocity can be estimated by calculating the mass flux across the equilibrium line, which is generally close to the terminus in this region. Field measurements of velocity are sparse in this part of Greenland making these calculated balance velocities particularly useful for mass-balance estimates of the region as a whole.

Surge-type glaciers identified from digital satellite imagery, Russian high Arctic

(J.A. Dowdeswell, M. Williams, UWA)

Landsat digital imagery was used to search Franz Josef Land, Severnaya Zemlya and Novaya Zemlya for the presence of looped medial moraines characteristic of past

glacier surges. The imagery provides almost complete summer-time coverage of the 60,000 km^2 of ice in these archipelagos. Very few surge-type glaciers are identified: none in Franz Josef Land, three in Novaya Zemlya and two on Severnaya Zemlya. This contrasts greatly with Svalbard, to the west, where over 35% of the ice masses are inferred to surge. The strong climatic gradient across the Eurasian high Arctic, with decreasing moisture eastward, may provide a gross control on this pattern. Warming since the end of the "Little Ice Age", leading to negative mass balances may also have restricted geometric build-up towards new surges.

SNOW-TOOLS

(A. J. Standley, A.R. Harrison, UBG)
SNOW-TOOLS is a project for the "Research and development of remote sensing methods with the main focus on snow hydrology", proposed by T. Guneriussen (Norut IT Ltd, Norway), R. Solberg (Norwegian Computing Center, Norway), K. Sand (SINTEF, Norway), M. Hallikainen (Helsinki Univ. of Technology, Finland), E. Barrett (Univ. of Bristol, EK), C. Matzler (Univ. of Bern, Switzerland) and J. Noll (ESA/ESTEC, Netherland). It will develop generic methods for correcting and interpreting optical and microwave data, with the aim of generating high-level products, improving the information content, and developing techniques for information extraction specific to snow hydrology. In the UK, the work is being undertaken by the Center for Remote Sensing (CRS) on the use of passive-microwave and optical data for snow hydrology.

Reconstructions of the last British ice sheet

(W.A. Mitchell, Dept. of Geology, Univ. of Luton; C. Clark, Dept. of Geography, Univ. of Sheffield)
Using remote-sensing imagery, particularly within the radar band, large-scale patterns of glacial bedforms have been plotted with particular attention to different flow units and their cross-cutting relationships. This will form a basis for targetting detailed field mapping to areas where such cross-cutting relationships have been identified and allow a more detailed and accurate reconstruction of the flow patterns and dynamics of the last ice sheet.

ICE CORES

Ice-core and radio-echo data, Berkner Island

(W.D. Miners, BAS; A. Hildebrand, FPG; S. Gerland, AWI; N. Blindow, FPG; D. Steinhage, FPG)
In the 1994/95 Antarctic field season, a 180 m ice core was retrieved from Thyssenhöhe, Berkner Island. By combining density data from the core and the dielectric profile, it has been possible to construct a model of the electrical properties for the top part of the ice sheet. This model has been used to predict the expected return from a radio-echo survey. The prediction has been compared with a surface radio-echo profile collected near the drill site. Many of the expected features were visible, but an improved comparison awaits better information about the shape of the radar pulse.

Drilling and analysis of ice cores, Berkner Island

(R. Mulvaney, D.A. Peel, N. Holman, W.D. Miners, E.C. Pasteur, BAS; C. Arrowsmith, NIGL; H. Oerter, S. Gerland and others, AWI)
In the 1994/95 Antarctic field season, ice-core drilling took place at several sites on Berkner Island, in collaboration with the Alfred-Wegener-Institute (AWI). The goal is reconstruction of the climate and atmospheric conditions of the Weddell Sea region over the past millennium. At the northern dome (Reinwarthhöhe), a new BAS drill was used to recover ice cores to a depth of 150 m (an estimated 500 years). At the southern dome (Thyssenhöhe), the AWI drill reached 180 m, representing about 900 years. The two main cores were backed up by a series of shorter ones. The processing and analysis of the Berkner Island cores continues as a collaboration between BAS and AWI. Approximately half of the Reinwarthhöhe core has been sub-sampled at annual resolution, and shorter sections at a seasonal resolution. The upper parts of the deeper cores have been sectioned and analysed for stable isotopes to reveal the mean annual temperatures and in some sections sub-annual temperatures over the past 50 years. The spatial variability in the temperature and accumulation data across Berkner Island has been estimated; for accumulation rate, annual horizons in the two deep ice cores were detected through continuous electrical-conductivity profiling, and beta-radioactivity measurements have given added confidence to the assignments. Chemical analyses by ion-chromatography are now well underway.

Sulphur compounds in Antarctic ice cores

(E.C. Pasteur, BAS)
The two main sulphur-bearing species in Antarctic snowfall, sulphate and methane sulphonate, are both produced as degradation products of dimethyl sulphide from marine phytoplankton, but sulphate has several other sources, including most notably sea salt and volcanic activity. A record of the concentration of methane sulphonate over the past 340 years has been produced, using samples from the Dolleman Island ice core to investigate the possible use of the data as a surrogate for marine biological activity in the Weddell Sea. The data show short-term variability, but no long-term trend. It is not yet clear whether the variation is due to changes in biological activity from year-to-year, or due in some part to transport effects or changes in the region of the moisture source.

Climate trends and variability, Antarctic Peninsula

(D.A. Peel, BAS)
Stable-isotope data from several ice cores drilled at lower-altitude sites and influenced by conditions in the Weddell Sea appear to show that the warmest conditions of the past 250 years occurred in the mid- to late 19th century, and were followed by a broad 'cooling' trend leading to the start of the instrumental records in the 1940s. This feature most probably arises because the isotopic signal is sensitive both to the proximity of the regional ice edge and to the precipitation of moisture drawn from high latitudes, possibly from sources inside the pack-ice zone that developed under

conditions of weak atmospheric circulation in the mid-19th century. Ice-core evidence from the higher-altitude sites of the Peninsula plateau including Dyer Plateau, which seem to be less affected by local changes within the marginal ice zone, probably provides a better representation of true temperature changes. The ice-core evidence indicates that the coldest period of the past 300 years occurred at most sites around A.D. 1760-1780. A reappraisal, with J. Jouzel (CE-Saclay, France) and others, of the validity of the temperature reconstruction from stable isotope analysis of the ice shows that a simplistic linear relationship with temperature cannot be presumed for the lower elevation margins of the ice sheet, but the data can provide important qualitative information on the changes in moisture source, an additional climate diagnostic.

Electrical studies and acidity, GRIP ice core

(E.W. Wolff, BAS; J.C. Moore, Univ. of Lapland; C.U. Hammer, H.B. Clausen, Univ. of Copenhagen)
The Greenland Ice-Core Project (GRIP) completed drilling of a 3028 m core at Summit, Greenland, in 1992. Even after removal of large volcanic peaks, the electrical records of the last 100,000 years are dominated by the acidity of the ice, which varies strongly from acidic in warm periods (such as the pre-industrial period) to alkaline in cold periods (such as the last glaciation). During interstadials, periods of the ice age when the temperatures were warmer, there is a fine balance, and often the snow alternates from acidic to alkaline rapidly within years. The changes are due mainly to variations in the amount of alkaline dust in the atmosphere, but it is not clear if the neutralisation occurs in the atmosphere en route to the ice-core site, or whether it occurs during and after deposition. The changes between acid and alkaline ice apply to all of Greenland, and probably to much of North America, when covered by the Laurentide ice sheet. The changes in precipitation acidity would have had important effects on the ecology of freshwater, and on the uptake of other chemicals by the snow surface. If the acidic particles were neutralised in the atmosphere, both chemical and radiative effects in cloud would have to be reconsidered.

SNOW PROPERTIES

Surface reflectance of snow

(E.M. Morris, R. Ladkin, P.S. Anderson, BAS; R. Gurney, G. Glendinning, Dept. of Geography, Univ. of Reading)
Work continued on the surface reflectance of snow. The SNTHERM model, developed by R Jordan of CRREL, was tested for polar snow, using data collected at Halley Station during the STABLE II experiment. Investigations were made into ways of coupling this model to radiation-transmission models for snow and the atmosphere. Field measurements were made of surface reflectance on Uranus Glacier, Alexander Island. Simultaneous upper-air measurements were made nearby at Fossil Bluff and satellite data were collected via the ARIES system at Rothera. With the meteorological data from the AWSs on the Uranus Glacier, these field data will be used to validate the models being developed.

Air/snow chemical transfer functions

(J.S. Hall, E.W. Wolff, BAS)
Analysis has continued of a two-year series of aerosol filters, surface snow samples and associated ice cores. A comparison with meteorological data exposes some interesting features. For example, sea-salt ions show a winter maximum in both air and snow, dominated by a few episodes of very high concentrations. This result implies that storminess and transport are more important than sea-ice extent in determining sea-salt concentrations in aerosol at this site. Although there is often no snowfall on the days with high salt events, surface snow and fresh snowfall concentrations show a similar seasonality to aerosol. Individual events of high concentration will be studied to determine the precise meteorological conditions for salt events. A new automated aerosol sampler (ASSAY) has been tested to allow similar studies to be carried out at remote ice-core sites.

Sublimation of blowing snow

(J.C. King, BAS; M.C. Smith, S.D. Mobbs, Univ. of Leeds)
The analysis of the surface-energy and water fluxes during the 1991 winter at Halley was completed with an assessment of the importance of blowing-snow sublimation in the surface mass budget. A model has been developed which can calculate blowing-snow sublimation rates from profiles of wind speed, temperature and relative humidity. When applied to data collected during the 1991 STABLE II experiment, the model indicates that blowing-snow sublimation is not a significant source of mass loss from the surface at Halley during winter. However, the calculations and observations show that 70-100% of the (small) total sublimation over the winter takes place from blowing-snow particles rather than directly from the surface. This, together with the rapid increase in sublimation rate with increasing wind speed predicted by the model, suggests that sublimation of blowing snow may contribute significantly to the surface mass balance in other, windier parts of Antarctica.

ANTARCTIC

Fluctuations of the East Antarctic ice sheet and the Transantarctic Mountains

(A.R. Kerr, UEG; P. Huybrechts, Vrije Univ., Brussels; D.E. Sugden, M.A. Summerfield, UEG)
A suite of modelling experiments is used to examine the relationship between the tectonic development of the Transantarctic Mountains and the East Antarctic ice sheet. There is a particular focus on the deglaciation of the sub-glacial basins adjacent to the Transantarctic Mountains. The results are compared with extensive geomorphological and palaeontological evidence from ice-free areas in the mountains. On geological time scales the tectonic-glaciation problem is coupled by the on-going erosion of troughs through the mountain range.

Radar sounding, Antarctic Peninsula

(H.F.J. Corr, M.C. Walden, M. Popple, BAS)
The BAS radio-echo sounding system was upgraded to include a pulse-compression mode and improve the range resolution. In 1994/95, 30,000 radar km were flown from the remote field camps of Ski-Hi and Haag Nunataks with approximately 7 gigabytes of data recorded. The radar was used to examine basal conditions beneath the Rutford and Evans Ice Streams, map regions of the Ronne Ice Shelf where marine ice has been accreted, and support an airborne gravity survey. In 1995/96, twenty sorties, collecting data along 1600 line kilometres, were flown. Radar ice-thickness data, from Rutford and Evans Ice Streams, will be used to map variations in the volume of ice either melting from, or freezing onto, their base. A joint project with P. Skvarca (Instituto Antartico Argentina) operating from Vicecomodoro Marambio, Seymour Island (Argentina) collected ice-thickness data over James Ross Island, and obtained ice-thickness profiles along Larsen Ice Shelf.

Stability of Antarctic Peninsula ice shelves

(D.G. Vaughan, C.S.M. Doake, BAS)
A large iceberg-calving event off the Larsen Ice Shelf occurred between mid-January and mid-February 1995. The ice shelf slightly further north suddenly broke up at about the same time, and the ice shelf in Prince Gustav Channel connecting the mainland to James Ross Island also disappeared. This adds to the observations that around 8000 km^2 of ice shelf in the Antarctic Peninsula had been lost since the 1950s. The variation in ice shelves around the Antarctic Peninsula, based on data from historical records, aerial photographs and satellite images has been catalogued. This has demonstrated for the first time that there exists a climatic limit of viability for ice shelves, which has been pushed southwards by warming over the past few decades. The observation implies that the ice sheet in the Antarctic Peninsula is vulnerable to even brief periods of climate warming. A further warming will threaten other marginal ice shelves. The cause of these events is attributed to a regional warming trend that has been identified in the temperature records at neighbouring meteorological stations.

Glacial history of the Antarctic Peninsula ice sheet and Filchner–Ronne Ice Shelf

(M. Bentley, UEG with BAS and ETH, Zürich)
Using a combination of geomorphological mapping and cosmogenic surface-exposure age dating, the extent and timing of the most recent ice expansion in the Weddell Sea embayment is being determined. This area represents a key unknown in reconstructions of the volume of Antarctic ice at the last glacial maximum, and thus is important for determining the Antarctic contribution to global sea-level change at the end of the last glaciation. By mapping and dating glacial modification of nunataks it is intended to provide constraints on the contribution of this region to global sea-level change. The main field sites are in the southern Antarctic Peninsula,.

Correlating palaeoclimate ice-core records using radio-echo layering

(M.J. Siegert, R. Hodgkins, J.A. Dowdeswell, UWA)
Antarctic radio-echo sounding data, acquired by the SPRI/TUD/NSF collaboration in the 1970s, shows clear internal horizons in the ice sheet which can be traced continuously across large regions of East Antarctica. Our work involves correlating the RES internal layer signal at Vostok with the palaeoclimate information derived from the deep ice core at this site. In addition, by analysing the internal layering between Vostok and the new ice-core site at Dome C, we will provide RES information to compare the palaeoclimate signal between Vostok and Dome C, and future ice cores.

ICE–OCEAN INTERACTIONS

Antarctic sea-ice–Southern Ocean coupling

(E. Hanna, J. L. Bamber, UBG)
Passive-microwave radiometric satellite data (SMMR and SSM/I) and a new hybrid sea-ice algorithm, which utilises the advantages of conventional NASA/Team, Comiso and AES-York algorithms, is being used to derive a temporal sea-ice concentration and extent series from 1978 to present. Other satellite sensors such as AVHRR and SAR and possibly *in situ* data will be used for validation, and comparison will be made with conventional sea-ice algorithms. The sea-ice extent record thus derived will be statistically compared with spatially-gridded temporal data of relevant climatological variables, including sea-surface temperature (SST), wind speed and possibly ocean currents, for high-latitude Southern Ocean. A water-balance model, based on ocean-pycnocline stability, will be constructed from the key parameters of precipitation, evaporation, SST, windspeed and atmospheric boundary-layer water vapour, and the amount of melting sea ice. Time-series analyses will be conducted to assess how the coupled Antarctic sea-ice/Southern Ocean system is driven by global climatic forcing factors of an internal (ENSO and Asian monsoon cycle) or external (solar irradiance variability) nature.

Sea-ice modelling, Bellingshausen Sea

(J. Turner, S.A. Harangozo, S.R. Leonard, T.A. Lachlan-Cope, BAS)
The EU PELICON project, completed during the year, was devised to develop a new algorithm to derive sea-ice extent and concentration from passive-microwave satellite data; as well as he effects of individual storms on the sea-ice environment. The importance of systematic changes in the meridional circulation changes in controlling ice extent was revealed. Recent efforts have concentrated on development of a more objective picture of the effects of depressions using the AWI sea-ice model driven by winds from the Meterological Office atmospheric model. The first model runs covered the July to September 1994 when a major ice retreat, followed by an advance, took place in the Bellingshausen Sea. The model correctly simulated the retreat, but could not reproduce the advance. This discrepancy has led to a study of how the model is formulated so that it can ultimately be used in studies of the coupled ocean–atmosphere–sea-ice system.

Ice-shelf–ocean interactions, Amundsen and Bellingshausen Seas

(A. Jenkins, D.G. Vaughan, M.R. Johnson, BAS; S.S. Jacobs, Lamont Doherty Earth Observatory; H.H. Hellmer, AWI; J.R. Keys, New Zealand Dept. of Conservation)
The high-salinity, near-freezing waters produced in most coastal regions are absent from the Amundsen and Bellingshausen Seas. This allows warm Circumpolar Deep Water (CDW) to intrude onto the continental shelf, and beneath the floating ice masses, leading to basal melt rates at least an order of magnitude higher than those estimated for the larger Antarctic ice shelves. A study of Pine Island Glacier, which drains into the Amundsen Sea, using ice-thickness measurements from the early eighties, and velocities estimated from sequential ERS-1 SAR images, has revealed that about 10 m a^{-1} must be melted from the glacier base to maintain a steady state. Oceanographic measurements at the ice front confirm the estimated melt rate, the magnitude of which appears to be the main factor limiting the extent of ice shelf cover in the region. In 1995/96, a programme of physical oceanography, which included 50 conductivity-temperature-depth stations, was undertaken in the south-east Bellingshausen Sea. Over 400 water samples were taken for oxygen-isotope, helium and salinity measurements, from which the concentration of meltwater in the ocean can be determined.

Hot-water drilling near Korff Ice Rise

(K.W. Nicholls, K. Makinson, M.R. Johnson, BAS)
In January 1996, a hot-water drill was used to create an access hole through 825 m of ice at a site 17 km west of Korff Ice Rise. The access hole was kept open for several days. Conductivity-temperature-depth (CTD) probes were used to obtain profiles of the 500 m deep seawater column, samples were obtained from the water column and the mud at the sea floor, and a string of current meters and conductivity-temperature instruments was deployed in the hole to provide a long-term record of the water characteristics and flow. Data from the instrument string are both logged on a data logger, and transmitted back to Cambridge via satellite link. The observations suggest that the bottom 150 m of the water column is travelling towards the deep grounding lines at about 0.04 m s^{-1} and consists mainly of dense water that has been preconditioned north of the ice front. The estimated flux of 200,000 m^3 s^{-1} would be capable of melting over 600 m^3 s^{-1} of ice.

Basal melt rates from seismic measurements

(A.M. Smith, BAS)
The analysis of seismic-reflection data from the grounding line of Rutford Ice Stream has provided a new method of measuring the rate of basal melting. The geometry of a reflecting horizon within the ice was used in a steady-state model to calculate the basal melt rate where the ice stream begins to float. Melt rates of up to 7 m a^{-1} were calculated, slightly higher than previous estimates based on survey data. Although the possible errors in the results of this preliminary study are fairly high (± 2.4 m a^{-1}), these can be significantly reduced during future experiments

Seismic measurements on Ronne Ice Shelf

(M.R. Johnson, A.M. Smith, BAS)
During the 1994/95 field season, seismic measurements were made of the ice and water-column thickness at 15 km intervals along a 2300 km traverse covering the southern and western Ronne Ice Shelf and the Evans Ice Stream; areas from which little seafloor data previously existed. Seismic measurements of ice thickness and water-column thickness were used to compile the first map of seabed topography for the area based on reasonable data coverage. The new map reveals a wide area with much shallower seabed and thinner water column in the southern part of the ice shelf than was previously thought. The shape of the sub-ice shelf model domain has been improved using these measurements.

Tidal modelling, Weddell Sea

(A. Robinson, K. Makinson, BAS)
A tidal model, developed by the Proudman Oceanographic Laboratory, has been applied to the Weddell Sea and Filchner-Ronne Ice Shelf. It was modified to include the presence of an ice shelf overlying the water column, the effects of an additional frictional interface, and the effect of ice-shelf bending near the grounding lines. Investigations have been made into the model's sensitivity to a variety of parameters such as friction and eddy viscosity, and also to variations in bathymetry. The model appears to fit known tidal data for the area and outputs will be used to provide a tidal correction for ERS-1 altimeter data. Models of the sub-ice-shelf oceanographic regime need to include the effect of tides. Important is the magnitude of the mixing energy available from tidal action that can help raise the denser, pre-conditioned water so it can interact with the base of the ice shelf. A tidal model for the area has been run on a fine-resolution grid and created a data set of mixing energy that can be used by numerical models of the sub-ice-shelf flow. There is a 30,000 km^2 area south of the ice front west of Berkner Island in which the water-column depth is less than 200 m. The model suggests this area is a very large sink of tidal energy, accounting for as much as half of the total tidal-energy budget. The tidal-energy dissipation beneath Ronne-Filchner Ice Shelf is modelled to be an order of magnitude greater than that beneath the similarly sized Ross Ice Shelf. This could be important in explaining the profound differences in the oceanographic regimes beneath the two ice shelves.

SEDIMENTS AND SEDIMENTATION

Scoresby Sund fan, East Greenland: evidence from GLORIA and 3.5 kHz records

(J.A. Dowdeswell, UWA; N.H. Kenyon, Southampton Oceanography Centre; J.S. Laberg, Univ. of Tromsø)
A major submarine fan (gradient about 2°), offshore of the Scoresby Sund fjord system, is indicated by the crescentic shape of the shelf break. GLORIA long-range side-scan sonar imagery was obtained over about 20,000 km^2 of the fan along with 1,000 km of 3.5 kHz records. Three acoustic

facies were defined from GLORIA backscatter signatures and sea-floor morphology and sediment acoustic character on 3.5 kHz records. The interpreted debris flows are basic building blocks in the long-term development of the Scoresby Sund Fan. Glacier-influenced fan volume is about 15,000 ± 5,000 km^3, based on seismic-reflection studies. During full glacials in East Greenland, the inland ice sheet advances to fill the Scoresby Sund fjord system and extends across the shelf to reach the shelf break in some glacial cycles. Debris flows form in areas of most rapid sediment flux. The Scoresby Sund Fan is relatively similar to the Storfjorden Fan on the eastern Polar North Atlantic margin, but differs from the larger Bear Island Fan in having a steeper fan gradient, much smaller debris flows and no large-scale slides.

Large-scale sedimentation, Polar North Atlantic margins

(J.A. Dowdeswell, M.J. Siegert, UWA; A. Elverhøi, Univ. of Oslo; F.-J. Hollender, Christian-Albrechts Univ. zu Kiel; N.H. Kenyon, Southampton Oceanography Centre; J.S. Laberg, Univ. of Tromsø)

Long-range, side-scan sonar (GLORIA) imagery of over 600,000 km^2 of the Polar North Atlantic provides a large-scale view of sedimentation patterns on this glacier-influenced continental margin. High-latitude margins are influenced strongly by glacial history and ice dynamics and, linked to this, the rate of sediment supply. Extensive glacial fans (up to 350,000 km^3) were built up from stacked series of large debris flows transferring sediment down the continental slope. The fans were linked with high debris inputs from Quaternary glaciers at the mouths of cross-shelf troughs and deep fjords. Where ice was slower-moving, but still extended to the shelf break, large-scale slide deposits are observed. Where ice failed to cross the continental shelf during full glacials, the continental slope was sediment starved and submarine channels and smaller slides developed. A simple model for large-scale sedimentation on the glaciated continental margins of the Polar North Atlantic has been developed.

Internal structure of high Arctic glaciers using GPR

(J. Woodward, T. Murray, ULG; M.J. Hambrey, LJMU; G.W. Stuart, ULES)

GPR (ground penetrating radar) can determine shallow subsurface structure in geologic materials such as sediments and rock. It is being used to map the internal structure of polythermal glaciers in Spitsbergen. Surveys at Bakaninbreen and Kongsvegen have included closely spaced 3-d grids. They show detailed englacial and basal sediment structure, allow investigation of the mechanisms forming surface sediment features (such as sediment dykes) and an assessment of the role of englacial sediment transport in the formation of proglacial landforms and sediment assemblages. The applicability of seismic-processing techniques in 3-d of GPR data from glacial environments will be investigated.

Sediment-transport pathways and moraine formation, south Iceland

(N. Spedding, Dept. of Geography, Univ. of Aberdeen; A.J. Dugmore, H. Gudmondsson, UEG)

Work continues on the relationships between bedrock topography, ice dynamics, drainage networks and sediment delivery to the ice margin. Current study sites include Gigjökull (Thorsmork) and Kviarjökull (Öræfi). The intention is to use the relationships identified at these and other glaciers to create a conceptual model of moraine formation which can be used to inform studies of Holocene glacier fluctuations and environmental change. Research focuses on the role of terminal overdeepenings, and the possible impact of these in forcing drainage to take up an englacial route. This seems to create both extensive englacial debris bands of water-worked material, and thick basal-ice sequences. This means a high proportion of sediment is delivered to moraines currently forming at the ice margins, rather than being washed away. It is believed that similar behaviour in the past can help explain the formation of large rampart-type moraines. Their sheer size (60–100 m tall) represents something of a puzzle. By combining a process model with dating constraints from tephrochronological studies, we hope to shed light on features which represent an important aspect of Iceland's Holocene geomorphic record.

GLACIER BASAL PROCESSES

Alpine basal-ice metamorphism

(B. Hubbard, UWA; J.-L. Tison, L. Janssens, Univ. Libre de Bruxelles; B. Spiro, NIGL)

Ice coring and meltwater sampling has been undertaken to assess the extent to which the physical and chemical composition of ice is altered at it deforms over a rough glacier bed. Five cores were retrieved from the margins of Glacier de Tsanfleuron, Switzerland, in August and September 1996. These varied in length from 4 to 46 m. Each core extended from the ice surface to the glacier bed and included: 1) bubble-foliated glacier ice; 2) clean, bubble-poor basal ice; and 3) debris-rich, bubble-poor basal ice. The cores will be analysed at a high resolution for their stable-isotope composition, solute content, included-gas concentration and composition, included-debris concentration and texture and ice crystallography. Together, these physical characteristics will be used to calibrate a model of ice metamorphism close to the glacier bed and to assess the implications of such alteration for subglacial hydrochemistry.

Debris incorporation into basal ice

(P.G. Knight, Dept. of Earth Sciences, Keele Univ.)

Work continues in the low-temperature laboratory on the dynamics of sediment transport into and through the intergranular vein network. Field data from Greenland and Iceland are being used to constrain simulations of debris entrainment under a range of pressure conditions using different unconsolidated substrates. The experiments cast light on the origin of debris-bearing basal ice, on the flow of water through ice close to the bed, and on the rheological continuum between basal ice and glacier substrate. New

observations of basal ice have been made at the recently surged Skeiðararjökull, Iceland.

Basal conditions from Rutford Ice Stream

(A.M. Smith, BAS)

Seismic reflection and wide-angle data have been used to study the relative importance of basal sliding and soft-bed deformation on Rutford Ice Stream. The acoustic impedance along three lines perpendicular to ice flow varies between being greater than and less than that in the ice. Areas of low bed impedance are probably dilated, deforming sediments, whereas, in areas of high impedance, basal sliding is believed to be more important than bed deformation. The proportion of the ice stream width exhibiting subglacial sediment deformation increases downstream. In places, basal conditions across the bed of the ice stream are very variable on a scale of a few kilometres, or less.

Generation of ice-rafted debris

(R.C.A. Hindmarsh, A. Jenkins, BAS)

The role of ice shelves in mediating the relationship between the marine geological record and the nature of land glaciation has been considered. A model of ice-rafted debris (IRD) event generation has been proposed, where the principal factor determining whether sediment reaches the ice front is the total melt at the base of the ice shelf. High basal melting implies that IRD-source sediment must be incorporated high into the ice column. Such debris injection can come from valley-side supra-glacial deposition, but glacier over-riding, leading to direct englacial injection, could also be important. These mechanisms of debris injection are likely to be confined to fjord areas close to the continental shelf break, i.e., the North Atlantic margins. The implication for Heinrich type events is that they are not indicators of glacial instability, nor can glacial stability be inferred from the absence of Heinrich events.

Tectonism in the distribution and appearance of basal ice

(R. Waller, J. Hart, USG)

Current research is focused on three themes: 1) identification of styles of tectonism associated with basal ice and assessment of the information these may provide about the comparative rheology of different basal ice facies; 2) analysis of the manner in which tectonism actively "creates" different basal-ice facies from an initially entrained sediment source; and 3) quantitative assessment of flow patterns within the basal-ice layer.

GLACIER HYDROLOGY AND HYDROCHEMISTRY

Dye-tracer investigations of subglacial drainage

(P. Nienow, P. Thomson, UEG)

In August 1996, dye was injected hourly, between 0800–2000 hrs, into the proglacial meltwater stream emerging from Haut Glacier d'Arolla, Switzerland. The dye was detected using automated fluorometry at a site 550 m downstream. Simultaneous photos were taken of the proglacial outwash plain between injection and detection sites to observe the routing of the proglacial stream as braiding characteristics altered with variations in discharge. Analysis of dye breakthrough curves will be undertaken to determine whether the curves can be used to infer the routing/structural changes observed in the proglacial stream and the findings will have implications for using dye breakthrough curves to make inferences about the structure of subglacial-drainage systems.

Runoff hydrochemistry from a 'cold-based' glacier in the high Arctic

(R. Hodgkins, UWA; M. Tranter, UBG; J.A. Dowdeswell, UWA)

Representative samples of meltwater from Scott Turnerbreen, 78°N in Svalbard, were analysed for major-ion chemistry. Laboratory dissolution experiments, using suspended sediment from the meltwater, were also conducted. The runoff contains significant concentrations of crustal SO_4, and is characterised by high SO_4: (SO_4+HCO_3) and high $p(CO_2)$. Runoff hydrochemistry is controlled by: 1) seasonal variations in solute input from snow- and ice-melt; 2) proglacial solute acquisition from an icing (naled/aufeis); and 3) subaerial chemical weathering within a saturated, lateral moraine adjoining subaerial drainage channels at the glacier margins, sediment and concentrated pore water from which are entrained by flowing meltwater. Explanation of meltwater routing requires only one major flowpath: subaerial, ice-marginal channels. These channels are analogous neither to dilute supra-/englacial nor to concentrated subglacial flow components.

Perturbation of atmospheric CO_2 by glacial fluxes of water, ice, sediment and solutes

(M. Tranter, UBG)

Work to date, with M.J. Sharp (Edmonton) and P. Huybrechts (Brussels), has demonstrated the potential of chemical weathering reactions in glacial runoff to cause significant reductions in atmospheric CO_2 during glacial advance. These reactions may be first-order controls on atmospheric CO_2 levels on timescales of ~20-80 Kyrs There is also the potential for glacial runoff to cause short-term decreases in atmospheric CO_2 during the last glacial-interglacial transition. Future work will focus on how glacial fluxes may stimulate the oceans to release CO_2 during the glacial—interglacial transition.

Suspended sediment in an Alpine proglacial channel

(A. Seagren, G.H. Brown, B. Hubbard, UWA)

Research at Haut Glacier d'Arolla aims to assess the nature and significance of solute acquisition in the channelised and variable-pressure axis (VPA) of the subglacial hydrological system. Between June and September 1996, intensive automated sampling of suspended sediment was undertaken in the proglacial stream to define diurnal and seasonal variations in the reactive surface area and mineralogy. These characteristics are important controls on the magnitude and timing of so-called post-mixing reactions, whereby solute is

acquired by meltwaters during transit through the subglacial conduit system. Additionally, samples were collected from the base of boreholes drilled to the glacier bed to determine the chemical signature and evolution of VPA waters. In conjunction with samples of bulk-meltwater chemical variability, these field data will be used to model the magnitude and timing of solute acquisition at the glacier bed.

Presence and character of englacial drainage pathways

(B. Hubbard, M. Kennett, B. Kulessa, UWA; A. Binley, L. Slater, Inst. of Environmental and Biological Sciences, Univ. of Lancaster)

Relatively little is known about how surface-derived meltwaters are routed through glaciers. Polarised radio-echo sounding (RES) and Electrical Resistivity Tomography (ERT) were used to investigate the englacial-drainage system of Haut Glacier d'Arolla, Switzerland during July and August 1996. Preliminary results from RES at 10 and 20 MHz suggest a concentration of linear internal reflectors at depths of between 20 and 35 m. Relatively few reflectors were recorded either above or below this depth range. While no cross-borehole ERT contacts were achieved, within-borehole resistivity experiments revealed anomalous increases in resistivity at 18 to 28 m below the ice surface. This enhanced resistivity also appears to cycle at a diurnal timescale. These RES and ERT data are interpreted as indicative of locally concentrated englacial channels 20 to 30 m below the surface of the ablation area of Haut Glacier d'Arolla; a model that will be refined with further RES and borehole investigations in 1997.

Locating englacial water using GPR, Falljökull, Iceland

(T. Murray, ULG; T.L. Dion, G.W. Stuart, ULES)

Falljökull is a small, steep, valley glacier situated in southeast Iceland. A ground-penetrating-radar (GPR) survey at 50 MHz was undertaken close to the margin, in conjunction with hot-water drilling and bore-hole video, to assess GPR in temperate ice and to attempt to characterise the englacial and basal-water system. The surveys were characterised by scattering throughout the depth of the ice with rather few distinct reflectors apparent. The reflectors seen correlated with englacial water bodies seen on bore-hole video. Analysis of e.m. propagation velocity by a variety of methods suggested a mean velocity of 0.110 m ns^{-1} in the glacier ice increasing with depth: this very low velocity may result from high water content within the glacier ice. The results show that GPR can identify water bodies within temperate glaciers, but that the results are dominated by scattering and may require careful processing and interpretation.

Borehole investigations of subglacial hydrology, Haut Glacier d'Arolla, Switzerland

(B. Kulessa, B. Hubbard, UWA)

During August 1996, subglacial electrical self-potential, electrical resistivity, water pressure, and electrical conductivity were recorded in a dense array of fluctuating boreholes drilled to the bed of Haut Glacier d'Arolla. Unconsolidated sediments are believed to be present beneath this part of the glacier, encompassing a major subglacial drainage channel inferred from previous studies. Four lead electrodes were used to measure the subglacial electrical self-potential in a square borehole array relative to a reference electrode buried in sediment exposed at the glacier margin. Basal-water pressure and electrical conductivity were recorded at several locations around the square. Preliminary results reveal systematic and stochastic variations in electrical self-potential. Systematic changes correspond (with a time lag) to variations in subglacial water pressure and electrical conductivity. Subglacial electrical resistivity was measured hourly on August 9/10 and 19/20 using different combinations of the five electrodes. Electrical resistivity varied systematically on both occasions and appears to be closely related to subglacial water pressure and electrical conductivity. Time-series analyses and interpretations are currently being undertaken.

Solute acquisition in subglacial environments

(G. Pugh, G.H. Brown, R. Fuge, UWA)

Investigations of fundamental subglacial chemical weathering reactions have found that coupled reactions involving trace minerals (e.g. carbonates, sulphides) in the bedrock provide much of the solute. However, knowledge of the rates and controls on the coupling of sulphide oxidation and carbonate dissolution now needs laboratory investigation if *in situ* field observations of meltwater chemistry are to be used to deduce variations in hydrological parameters. This project will characterise the controls, rate and magnitude of coupled reactions in the subglacial environment through a suite of laboratory dissolution experiments, constrained by measured field parameters. This will facilitate a direct evaluation of potential chemical-weathering processes operating in a known hydroglacial system.

Snow chemistry, Austre Okstindbreen, Norway

(W. Theakstone, P. Raben, UMG)

We collected 700 samples of snow from five pits on Austre Okstindbreen between March and August 1995. Pit altitudes ranged from 825 m to 1470 m. The total input of ions was calculated from the pre-melt sample data and the depth of winter-accumulated snow. In order to calculate the ionic output from the catchment, 700 water samples were collected from the river draining it between late-May and mid-August. Analysis of the data revealed that 72% of the Na^+ and Cl^- ions which had accumulated in winter drained from the snowpack in June, with 12% of the meltwater. Input and output calculations for the two ions indicated that the drainage time for the first meltwater from the highest part of the glacier's accumulation area was 6–7 weeks. Ions moved downwards through the pack even when there was little surface melting and no addition of liquid precipitation. Changes of oxygen-isotopic composition in the pack were delayed in relation to those of ionic concentrations. Early in the melt season, the isotopic stratigraphy remained relatively unaltered, and isotopic homogenisation of the pack proceeded much more slowly than did ionic purification.

Sediment and water fluxes through the glacial hydrological system

(M.D. Crabtree, T. Murray, P.J. Ashworth, ULG; G.W. Stuart, ULES)

Using bore-hole instrumentation and sampling at the outlet, the hydrological system of a small outlet glacier of Vrffajökull, Iceland has been investigated. Two summers' field data show that, while there is a highly efficient channelised drainage system, with through-flow velocities of >0.25 m s^{-1}, its spatial extent is unknown, and some form of distributed system occupies the rest of the glacier. There also appears to be a predominance of englacial-drainage pathways over subglacial ones, which might be a result of the glacier resting in an overdeepened basin. The development of an acoustical system to measure fluxes of both water and sediment through glacial conduits will hopefully provide insight into the complex pressure-flux relationship which varies between different drainage morphologies.

Borehole video investigations of englacial sediment and hydrology transfer

(A.M. Hiatt, T. Murray, ULG)

A borehole camera system was used to examine and contrast the englacial sediment and hydrological characteristics of a high Arctic glacier (Bakaninbreen, Svalbard) and a temperate glacier (Falljökull, Iceland). Work revealed the presence of upthrust basal sediment layers at depth within bulk glacier ice on Bakaninbreen, which seem to be actively purging both water and sediment from the glacier bed. Falljökull's englacial drainage system has multiple englacial channels, many of which were observed to be active. The sediment content is less compared to Bakaninbreen, and little banding was observed by video. For both glaciers the capacity for englacial water supply and removal to and from the bed is suggested by bore-hole impulse tests which are characterised by multi-frequency responses, indicating that boreholes are hydraulically connected to a number of discrete systems. GPR work on the two glaciers has shown a high degree of coincidence with the borehole camera observations; all the above methods thus producing a detailed record of englacial sediment and hydrological features.

Trace elements in glacial environments

(G.H. Brown, R. Fuge, UWA)

Determinations of variations in the major dissolved ions and dissolved oxygen in glacial meltwaters have provided new insight into solute provenance, chemical-weathering rates and processes in glacial environments. At Haut Glacier d'Arolla, Switzerland the potential of trace metals as indicators of solute provenance and routing in the subglacial environment are being evaluated and sampling procedures adopted in the study of meltwater quality examined.

Glacier hydrological modelling

(I. Willis, N. Arnold, K Richards, B. Rule, H. Jones, UCG; B. Brock, Dept. of Geography, Univ. of Dundee; M. Sharp, Univ. of Alberta).

Work continues on development of a semi-distributed, physically-based model of glacier hydrology using data collected at Haut Glacier d'Arolla, Switzerland. The model has 3 components: surface melt, surface routing, and subglacial routing. The surface-melt component uses energy-balance theory to calculate hourly variations in ablation in 20 x 20 m grid cells across the glacier. It accounts for the effects of changing patterns of surface albedo on the net-radiation fluxes using a simple parameterisation scheme. The latest version of the melt model uses the bulk-transfer technique to calculate turbulent fluxes, Monin-Obukhov similarity theory to account for atmospheric stability, and a simple parameterisation scheme to account for changing patterns of surface roughness. The albedo and roughness parameterisations are based on extensive field surveys of these variables across the glacier throughout two summer melt seasons. The surface-routing component uses simple snow-hydrology theory to route water down through unsaturated snow and laterally through saturated snow, and Manning's equation to route water across ice. In this way, surface-derived water is routed to moulins. The development of the snow routing model forms the basis of ongoing work. Field measurements in a supraglacial catchment of: 1) surface melt; 2) water content, capillary pressure, and vertical water flux in unsaturated snow; 3) depth of the saturated zone; and 4) catchment outflow discharge will be used to develop and test a more sophisticated finite-difference snow routing routine which incorporates the effects of capillary pressures. The subglacial-routing component routes water from moulins through a dendritic conduit network to the glacier snout. The conduits enlarge and shrink due to melting by flowing water and ice creep respectively. The model can be used to calculate patterns of water pressure, water velocity and water discharge along the subglacial-drainage network and water discharge in the proglacial stream. Over the next 3 years, we plan to improve the subglacial routing model to account for the diurnal and seasonal transfer of water between conduits and the adjoining distributed system. We also plan to incorporate suspended sediment and solute transport into the model.

GLACIER MOTION / SURGING

Geomorphological, sedimentological and isotopic signatures of glacier surging

(S. Church, T. Murray, ULG)

It remains unknown whether fast flow during a surge is a result of sliding or bed deformation. Refreezing of regelation melt from sliding should change the isotopic signature of basal ice. Sediments are effectively labelled as a result of physical and morphological changes during deformation. This project will work in the forefield areas of surge-type glaciers to investigate the mechanism of surge advance. Techniques will include scanning-electron microscopy and optical microscopy of thin sections at the micro-scale. Larger-scale features will be investigated using field mapping and GPR. Samples of basal ice will be collected for isotopic analysis. Field seasons in Iceland and Svalbard are planned.

Basal conditions beneath Bakaninbreen

(T. Murray, ULG; P.R. Porter, UMG; D.L. Gooch and G.W. Stuart, ULES; J.A. Dowdeswell, UWA)

Bakaninbreen is a 17 km long surge-type glacier in southern Spitsbergen which began surging between the springs of 1985 and 1986, forming a surge-front where fast moving surge-ice meets non-surging ice. This surge-front has propagated 6 km down-glacier over the period to 1995. During 1994-95 a variety of bore-hole instruments were emplaced beneath the glacier and GPR surveys were undertaken. Data collection is on-going. The results give an extremely good picture of year-round basal conditions beneath this glacier as it reaches the end of its active phase: 1) the bed is comprised of soft sediments at least 1-3 m in thick. Sediments have been collected from the bed and SEM examination suggests sediment transport has been in a highly dilated and thus actively deforming state; 2) physical properties of basal sediments beneath the glacier surge-front have been measured; values for these properties are shear strength 17-87 kPa and viscosity 1.1-4.3 x 10^{10} Pa s; 3) above the surge-front basal sediments are deforming whereas below the surge-front the sediments are unlikely to be deforming. Sediments accumulate in this area, and are thought to be purged through the formation of sediment-laden thrust faults; 4) motion of the surge-front down glacier has resulted from a combination of vertical thickening and thrusting of the glacier ice; and, 5) a thick region of basal ice has formed beneath the surge-front which is faulted or folded at its upper surface.

Environmental controls on the global distribution of surge-type glaciers

(H. Jiskoot, T. Murray, P.J. Boyle, ULG)

The non-uniform spatial distribution of surge-type glaciers suggests that environmental conditions control surging. Factors responsible for the global distribution of surge-type glaciers are being isolated to provide a method for testing and validating existing theories on the mechanisms of surging. Initially we examined 504 surge-type and normal glaciers in Svalbard. The relation between glacier surging and a number of glacial and geological variables was tested by applying a generalised linear model using a logit link function. From these analyses the following conclusions may be drawn: 1) roughly 13.4% of the glacier population of Svalbard are surge-type, covering approximately 46.5% of the total glacierized area; 2) glacier length and lithology appear to be most strongly related to surging if the variables are analysed separately. However, none of the variables tested separately was able to explain glacier surging in a satisfactory way; 3) in the multiple variate logit analysis, glacier length, surface slope, geological age and aspect of the ablation area appear significantly related to surging. Results indicate that long glaciers with relatively steep slopes, overlying shale or mudstone have the highest chance of being of surge-type. Future research will use predictive tests to identify unusual surge-type glaciers and their spatial clustering. Furthermore it is planned to expand the database by including other regions with surge-type glaciers.

Hydrological influences on basal-flow dynamics, Haut Glacier d'Arolla

(P.W. Nienow, A.L. Hubbard, UEG; D.W.F. Mair, I.C. Willis, UCG)

A detailed ice-motion study of the Haut Glacier d'Arolla, Switzerland, is being made to determine the influence that changes in the subglacial drainage system have on basal motion. Regular surveys of an extensive surface stake network were undertaken during the summer melt seasons of 1994 and 1995 and during shorter visits in winter 1995 and 1996 and summer 1996. Averaged summer velocities were typically 150-200% times faster than in winter. However, velocities were not consistent throughout the melt seasons and in both 1994 and 1995, there was one major glacier-wide speed-up event in mid-late June. The event in 1994 exhibited slightly different characteristics at the individual stakes but several points are of particular interest: 1) the relative amplitude of the event varied with distance upglacier; 2) the timing of peak velocity varied between stakes; and 3) there was a clear slowdown at each stake (relative to subsequent velocities) at the end of the event. The event appears to have been triggered by a major increase in meltwater input to the en/subglacial drainage system. This resulted from enhanced supraglacial runoff induced by a föhn wind and is assumed to have resulted in some form of decoupling at the ice-bed interface due to rapid increases in basal water pressure. A combined approach involving both analysis of field data and high-resolution 3-d modelling is being used to determine the mechanism by which the observed velocity event propagated throughout the glacier.

Quiescent-phase surge-type glacier, Finsterwalderbreen

(A.M. Nuttall, J.A. Dowdeswell, UWA; J.O. Hagen, Univ. of Oslo)

The time-dependent behaviour of Finsterwalderbreen, a surge-type glacier in Svalbard, has been investigated through its quiescent phase. The glacier last surged around 1900 and has now attained a profile similar to that in 1898, just before the surge. Comparison of measured velocities and mass balance shows that the present velocities are not sufficient to transport the accumulated mass to the ablation area. Radar soundings and hydrological studies indicate that the glacier has warm ice at the bed, and this is supported by the fact that summer velocities are higher than winter velocities by a factor of two, indicating that basal sliding is taking place. The glacier may therefore be building up towards a new surge.

Structural evolution of a surge-type polythermal glacier, Hessbreen, Svalbard

(M.J. Hambrey, LJMU; J.A. Dowdeswell, UWA)

Hessbreen is a small valley glacier which last surged in 1974, and is typical of many polythermal glaciers in Svalbard. The present ice surface displays a wide range of structures that can be attributed to either quiescent-phase or surge-phase deformation. During quiescent-phase flow,

primary stratification becomes slightly deformed into low-amplitude open folds, while a completely new structure, longitudinal foliation, develops in axial-planar relationship to these folds. The propagation of a surge front is associated with the formation of thrusts; however, not all of these break through to the surface. As the surge progresses, and the ice behind the surge-front becomes extensional, the surface of the glacier breaks up into numerous crevasses, of which several hundred metre-long transverse crevasses, convex upglacier, are dominant. After a period of quiescence, these become degraded into crevasse traces, planar structures which are steeply dipping and have many different orientations. Overall, most ice which reaches the snout has not undergone significant cumulative strain, as indicated by the lack of deformation of both the primary structures and the later crevasse traces.

GLACIER MASS BALANCE

Okstindan Glacier Project

(W. Theakstone, F. Jacobsen, P. Raben, UMG; N.T. Knudsen, Univ. of Aarhus)

Mass-balance studies at Austre Okstindbreen, the largest of the Okstindan glaciers, entered their eleventh year in 1995. The 1994-95 net mass balance was +0.46 m w.e., the sixth positive balance in the last nine. However, the glacier continues to retreat. Long-term observations of surface velocity and strain-rates on the lower part of Austre Okstindbreen were continued, as were studies of surface flow above the icefall.

Okstindan was the test-site for snow in an area of Alpine-type topography during the European Space Agency-funded European Multi-sensor Airborne Campaign (EMAC-94/95). The EMISAR imaging radar (developed at the Electromagnetics Institute, Univ. of Copenhagen), a fully polarimetric C-band/L-band synthetic-aperture radar (SAR) was flown over the test-sites at an altitude of 41000 feet. ERS SAR data were acquired at dates as close as possible to three aircraft flights. Surface data relating to snow temperature, density, liquid-water content, grain-size distribution and surface roughness were obtained for each occasion. GPS was used to fix the position of ground data-collection sites. In July 1995, FJ and WHT fixed over 2200 points in less than six and a half hours via a snow scooter-based differential GPS survey of the glacier's surface topography. The data were handled in a GIS, and a Triangular Irregular Network Digital Terrain Model of the glacier surface was prepared. Maps combining surface gradient and aspect have been produced. Comparison with a second survey, conducted in May 1996, will assist in determining the utility of GPS surveys for calculating values of annual glacier net mass balance.

Glacier calving in freshwater lakes

(M.P. Kirkbride, Dept. of Geography, Univ. of Dundee; C.R. Warren, Dept. of Geography, Univ. of St Andrews)

Empirical evidence suggests that calving speeds at glaciers ending in freshwater are about an order of magnitude less than in tidewater. Physical explanations of this contrast remain elusive, and are hampered by an absence of detailed process studies of calving. During the austral summers of 1994 and 1995, calving processes were studied at six glaciers in the Southern Alps of New Zealand. Short-term ice velocities near the termini, and patterns of terminus change were recorded at all sites. The bathymetry of the proglacial lakes was mapped, and variations in vertical water-temperature profiles were measured, together with lake stage and meteorological data. Additionally, at Maud Glacier, the annual velocity field was mapped using aerial photogrammetry, and short-term evolution of the calving cliff was studied with terrestrial photogrammetry.

Results confirm there is a strong correlation between calving rates and water depth in freshwater lakes (as in tidewater) and that, for any given water depth, these rates are much lower than those in tidewater. However, the detailed observations of calving do not support existing theories which focus on bending shear. Instead, thermal undercutting at the waterline is proposed as a rate-controlling mechanism. This, however, raises the question of why a correlation between calving rate and water depth exists when calving speed is apparently driven by the rate of waterline melting. Future research will involve longer-term monitoring of calving rates and terminus evolution using aerial photography supplemented by ground survey.

Glaciation of western Himalaya

(W.A. Mitchell, Dept. of Geology, Univ. of Luton; L.A. Owen, RHUL)

Investigations of glacial responses to climate change in Lahul, Zanskar and Ladakh have been based on detailed field mapping of specific valley systems. This has allowed the establishment of a sequence of three major glaciations and later Holocene advances which are progressively less extensive with time. OSL dates are being used to restrict these glaciations within a chronology. The study aim is to evaluate the changing glacial response to climate during the Pleistocene with respect to changes in the axis of uplift which has migrated southwards with time and which has increasingly restricted the northwards migration of the summer monsoon. Attention is now being focussed on how this has affected westerly air currents and their control on glaciation, particularly in the northern part of the region.

Abbreviations:

AWI	Alfred Wegener Institüt, Germany
BAS	British Antarctic Survey
FPG	Forschungsstelle für Physikalische Glaziologe, Universität Münster
LJMU	School of Biological and Earth Sciences, Liverpool John Moores Univ.
NIGL	NERC Isotope Geosciences Lab., Nottingham
UBG	Dept. of Geography, Univ. of Bristol
UCG	Dept. of Geography, Univ. of Cambridge
UEG	Dept. of Geography, Univ. of Edinburgh
ULES	Dept. of Earth Sciences, Univ. of Leeds
ULG	School of Geography, Univ. of Leeds
UMG	Dept. of Geography, Univ. of Manchester
USG	Dept. of Geography, Univ. of Southampton

Submitted by Bryn Hubbard

GLACIER GEOPHYSICS

Global distributions of glacier properties

(D.B. Bahr, CU/INSTAAR)

A scaling analysis of the constitutive law and mass/momentum conservation shows that many dynamical and geometrical properties of a glacier can be scaled as a function of glacier or ice-sheet surface area. Scaled quantities include characteristic velocity, flux, response time, thickness, and volume. Using the scaling relationships, world-wide distributions of glacier properties can be linked to world-wide distributions of surface areas. For example, the probability distribution of expected glacier-response times (world-wide) can be predicted as a function of surface-area distributions. Recent work has focused on deriving theoretical explanations for the observed power law and exponential distributions of glacier surface area, and then linking these explanations to predictions for response times, ice volumes, etc. in the Alps and other regions. The goal is to predict (in a probabilistic sense) the properties of glaciers which have not been directly observed in the field.

Response time of glaciers

(D.B. Bahr, W.T. Pfeffer, C. Sassolas, M.F. Meier, M. Dyurgerov, CU/INSTAAR)

A simple interpretation of the traditional definitions of glacier and ice-sheet response time (e.g., thickness divided by mass-balance rate) might suggest that response time increases as a function of glacier size. However, a scaling analysis of the continuum-mechanical description of flowing ice shows that the response time of valley glaciers decreases as a function of increasing size (when other variables are held constant). In essence this is because larger valley glaciers push further into the ablation zone, and ablation increases more rapidly than the thickness. On the other hand, ice sheets have different mass-balance regimes than valley glaciers, and as they grow larger the mass balance does not increase faster than the thickness. Therefore, as ice sheets grow larger the response time increases. Finite-element modeling experiments (still in progress) appear to confirm this unexpected response-time behavior for valley glaciers.

Ice flow near the Greenland Summit

(K. Cuffey, P. Jacobson, N. Nereson, C.F. Raymond, Th. Thorsteinsson, E.D. Waddington, UW/GP; G. Clow, USGS/MP; J. Bolzan, OSU; K. Taylor, UN; D. Dahl-Jensen, N. Gundestrup, C. Schøtt-Hvidberg, UC/NBI)

The two deep ice cores, GRIP and GISP2, have stimulated research on glaciological flow problems related to ice-core interpretation. Ice-flow models were used to convert measured annual-layer thicknesses in the GISP2 core to past accumulation records. Data from high-resolution borehole temperatures (1 mK level) were used to calibrate the stable-isotope paleothermometer in central Greenland, showing that the glacial/interglacial temperature difference was approximately 15° C; larger than previously deduced from the isotopes alone. These climate records are helping us understand ongoing changes in Greenland ice dynamics due to the changing temperature field and the recent history of accumulation-rate variations.

Radar internal layering near the core sites fails to show a large upwarp in the isochrones characteristic of the pattern expected under a steady ice divide, suggesting that either the ice divide has been actively migrating during the past 10,000 years or Glen's flow law (with n=3) is not appropriate at the low deviatoric stress levels found under the ice divide. The flow law has never been calibrated at stress levels below a few tenths of a bar. Our current ice-flow modelling addresses these possibilities.

Borehole tilt at GISP2 shows the ice in the lowermost 800 m (mid-Wisconsin glaciation) is soft in bed-parallel shear, but the enhancement factor decreases toward the bed. This agrees with data on ultrasonic velocity anisotropy on the ice core, suggesting that evolution of crystal fabric is responsible for the observed deformation pattern. Repeated inclination logs will be necessary to reveal ice rheological properties higher above the bed.

Stratigraphic disturbances in the ice cores have stimulated interest in folding near ice divides. Simple criteria have been derived that predict where perturbations or "wiggles" introduced on stratigraphic layers will overturn, and where they will attenuate without folding. Ongoing work assesses mechanisms to generate "wiggles" in the stratigraphic layering. Due to the development of preferred vertical orientation of the c-axes in ice sheets, ice is anisotropic for flow. Variations in crystal fabric may generate internal instabilities that contribute to wiggles and folding. Fabric anisotropy inferred from borehole sonic logging can account for the main features of flow enhancement seen by bore-hole tilting measurements deep in the Dye 3 bore hole (southern Greenland), although other processes affecting the flow-law "softness" A may also be needed to fully match the borehole data.

Glacier geophysics and paleoclimate at Taylor Dome, Victoria Land, Antarctica

(E.D. Waddington, D. Morse, M. Balise, P. Balise, S. Douglass, H.-P. Marshall, R. Hawley, T. Gades, H. Conway, K. Cuffey, P. Trowbridge, B. Peterka, T. Neumann, J. Orf, UW/GP; G. Clow, USGS/MP; D. Blankenship, UT/GP; J. Dibb, UNH)

In 1994, an ice core spanning the past 140,000 years was recovered from Taylor Dome. To select the ice-core site, and better understand the glaciological and depositional characteristics of Taylor Dome, a broad geophysical data-collection and interpretation program was carried out over the past 6 years.

A drill site, with relatively simple internal layer stratigraphy, was selected using airborne and surface radar. A network of 6 automatic weather stations, recording wind, air and snow temperature and visible radiation, complements the pit and shallow-core studies of local geochemical spatial variability, and documents the extent of temperature microclimate zones on Taylor Dome. A combination of stake burial rates and burial depths of nuclear-bomb-test fallout layers, identified from measurements of gross β activity was used to measure the

accumulation pattern. It is closely related to current topography and wind patterns.

Borehole temperatures have been measured at high resolution (1 mK) in the deep (554 m) fluid-filled hole on Taylor Dome, in a 100 m dry hole 35 km down the slope toward Taylor Glacier, and in a 280 m hole (DVDP-11) in Taylor Valley left from the Dry Valley Drilling Project. Regional temperature trends and climate gradients are being derived from these data.

Ice motion at the surface was measured in a wide network of approximately 200 poles to understand and calculate ice dynamical effects on layer thinning and borehole-temperature patterns, using a combination of optical, Transit satellite and Global Positioning System (GPS) techniques. Marker bands and a down-hole video camera were also used to measure vertical strain rate in the upper 130 m in a dry hole near the main (554 m) fluid-filled corehole. All these ice-deformation data are used to support an ice-flow modelling program to enhance interpretation of the geochemical ice-core record.

Radar and remote sensing studies in West Antarctica

(R. Jacobel, SO)

Ice-penetrating radar and satellite imagery is used to study the ice streams of the Ross Embayment and answer questions about ice dynamics and the history of the West Antarctic ice sheet (WAIS). With collaborators from UW and CU, these tools were deployed in studies of Siple Dome, a now stagnant inter-ice-stream ridge, which will be drilled for a climate core in 1996–1998. Its summit region is a source of slow-moving ice which contributes little to the mass flux into the Ross Ice Shelf. But portions of the dome appear to have been overridden by inland ice draining the West Antarctic ice sheet. Evidence for a relict ice stream traversing the flank of Siple Dome resulted from radar studies of the internal stratigraphy, showing that the configuration of ice streams is not fixed.

Field studies were also carried out around Siple Dome summit to characterize the surface, bed and internal stratigraphy beneath the ice-core drilling area. More than 100 km of radar traverses were completed in a 10 km^2 grid centered on the summit, and echo times from the bed and several prominent internal layers were measured to produce contour maps of these surfaces. Because these layers represent time horizons, they can reveal much about the ice dynamics and history of the dome via modeling work being carried out by N. Nereson (UW).

With T. Scambos (NSIDC), enhanced satellite imagery has been used to examine other relict features which appear to exist throughout this area. Changes in the configuration of ice flow argue for a reexamination of the paradigm of fixed drainage paths from the WAIS, and need to be better understood before predictions of its future can be made.

Flow history of Siple Dome, Antarctica

(C.F. Raymond, N. Nereson, T. Gades, H. Conway, UW/GP; R. Jacobel, SO; T. Scambos, CU/NSIDC)

The geometry of the internal stratigraphy of Siple Dome contains a record of past ice flow. This is relevant to interpreting the deep ice core, planned near the summit of the dome, and to deducing the past behavior of Ice Streams C and D that bound it. In 1994, the geometry of the surface, bed, and internal layers were measured across most of the width of the dome with ice-penetrating radar and GPS. Additional measurements from 1996 will complete the transect and allow calculation of surface velocity for markers placed in 1994. The geometry of internal layers measured in 1994 has already been useful for selecting a deep ice-core site. The layers near the summit indicate the Siple Dome divide has been migrating toward Ice Stream D at about 0.2–0.3 m yr^{-1} for the last several thousand years. Truncation of the internal layers beneath a surface scar on the NE side of the dome shows the configuration of streaming flow was different several thousand years ago compared to the present.

Columbia Glacier dynamics

(R. Krimmel, USGS/T)

Sequential vertical photography was used to monitor the continuing Columbia Glacier retreat. Retreat was about 0.5 km a^{-1} in 1994 and 1995. Speeds near the terminus have ranged from 15–25 m day^{-1}. The surface level of the lower glacier is reduced by about 20 m yr^{-1}. In late 1995, the forebay was briefly clear of ice. Several lines of bathymetry were obtained to within a few hundred meters of the terminus. Maximum forebay water depths were 360 m.

GLACIER-BED PROCESSES

Basal hydraulic system of Ice Stream B

(H. Engelhardt, B. Kamb, CIT/GL&PS)

Hot-water drilling and borehole geophysics have been used to study the basal water system of Ice Stream B. It has been possible to constrain the basal water pressure and to examine the physical characteristics of the basal water system. The high basal water pressure is thought to be responsible for the rapid movement of the ice stream. Several borehole experiments have been performed. A pressure-pulse propagation experiment shows that any gap between ice and bed is much less than 1 mm thick. A salt-tracer experiment found that downstream transport has a speed of 7.5 mm s^{-1}. One possibility is that the fairly high transport velocity and spatially varying basal effective pressures are caused by a system of relatively large "canal" conduits, spaced about 50 to 300 m apart. There are large temporal variations in basal effective pressure, but these have little effect on the ice-stream velocity, suggesting that the observed pressure variations are local and that the basal motion of the ice stream is dependent on a wide areal average of these variations

Basal sliding of Ice Stream B

(H. Engelhardt, B. Kamb, CIT/GL&PS)

Basal sliding of Ice Stream B has been measured using a "tethered stake" instrument. This is a metal stake placed in the top of the till and connected by a "tether" line to an electrical pay-out unit in the bottom of the borehole. Results indicate basal sliding averaged 69% of the total motion over a 26 day period. If a period of very slow apparent sliding, which may be anomalous, is omitted, the basal sliding

averaged 83% of the total motion. More borehole observations are needed to assess how representative this one observation is of the motion occurring broadly over the base of the ice stream and over extended periods of time.

Sedimentary record and basal mechanics of ice streaming, West Antarctica

(S. Tulaczyk, B. Kamb, CIT/GL&PS)

Sedimentological analysis of several cores recovered from beneath Ice Stream B, provides new insights into the origin of the subglacial till that underlies the ice stream. This till is a clay-rich, unsorted, fossil-bearing diamicton that bears no evidence of subglacial crushing, abrasion, or comminution. Therefore, it is not a close sedimentological analogue of the Late Pleistocene continental tills whose debris has been largely generated by these mechanical processes. Instead, the till consists of material recycled from subjacent Tertiary glaciomarine sediments of the Ross Sea sedimentary basin which extends beneath this part of the West Antarctic ice sheet. Perhaps surprisingly, the very fast motion of Ice Stream B over the subglacial till does not significantly influence the sedimentological properties of the sedimentary debris. The results question the proposition that subglacial deformation under low driving stresses is a ubiquitous primary till-forming process. Instead, it may be a secondary process that takes place only if pre-existing tills or unconsolidated marine/lacustrine sediments are present beneath overriding ice.

A series of undrained triaxial tests on undisturbed and remoulded samples of Ice Stream B till show it behaves as a Mohr-Coulomb frictional/plastic material whose shear strength at failure is linearly dependent on effective confining pressure. The tests confirm the conclusion, drawn previously from shear box tests, that the strain-rate dependence of the till strength is extremely small and that this behavior does not change fundamentally with changing effective pressure (at least within the tested range: ~25 kPa to ~250 kPa). The plastic till rheology is consistent with the recent finding that ice-stream motion is accommodated by sliding and/or subglacial till deformation in a very thin (few cm) shear zone beneath the ice base. It is, however, difficult to reconcile with a model in which several meters of till deform continuously and pervasively beneath the ice.

Laboratory studies of till rheology

(N.R. Iverson, T.S. Hooyer, UMM/GL&GP; R.W. Baker, UWisc)

The stability of ice masses that rest on sediment and the distribution of shear strain in such sediment should depend, to some extent, on sediment rheology. A ring-shear device was constructed to study the rheology of several tills collected from the beds of modern and past glaciers. Unlike traditional soil-testing devices, this shears a large annular specimen (70 x 115 mm in cross-section) to infinitely high strains under steady rates that may be varied through the full glacial range. High strains are essential to reach the steady (residual) strength of some sediment. Two tills, 4% and 32% clay by weight, respectively, have been tested extensively. As expected, they have different frictional properties, with residual friction angles of 26° and 18° respectively. Of greater significance is that, for deformation rates increasing through two orders of magnitude, neither till exhibits an increase in residual strength, a result inconsistent with the common suggestion that till is a viscous fluid. Furthermore, strain is focused at the sample center to differing extents in both tills, but does not focus under identical conditions in tests on a linear-viscous putty. The results, and absence of cogent micromechanical reasons for viscous behavior of quasi-static granular flows, suggest that frictional plastic behavior, although an idealization, is a better assumption for till deformation than linear-viscous flow.

Fabric development in shearing till

(T. S. Hooyer, N. R. Iverson, UMM/GL&GP)

Glacial geologists have inferred from field observations that till fabrics resulting from subglacial deformation of till are weaker than those resulting from lodgment at the ice/till interface. To test this hypothesis, various tills are being deformed to different shear strains using a ring-shear device. Before an experiment, prolate clasts are either placed at random orientations in the till or in a strongly preferred orientation. The till is then saturated with water, loaded under a small but reasonable effective normal stress (about 100 kPa), and sheared at a steady rate between 15 and 800 m a^{-1}. In contrast to the Jeffrey theory of clast rotation in a shearing viscous fluid, very few clasts rotate through the plane of shearing. Instead, most rapidly rotate into the plane of shearing and stay there with continued deformation up to shear strains as large as 750. This may be a result of slip between the till matrix and clasts that is not considered by the theory. The result is that a strong till fabric develops at low shear strains (<10) from an initially random fabric, and an initially strong fabric remains strong at high strains. We are, thus, skeptical that till fabic can be used to distinguish lodgment till from so-called deformation till.

Tunnel evolution, Storglaciären, Sweden

(P.M. Cutler, UMM/GL&GP)

The seasonal evolution of a subglacial tunnel cross-section has been examined using a 2-D finite-element model. The tunnel is currently assumed to lie directly over bedrock, and can be of any initial shape from semi-circular to broad and low. Calculated variations in water input from the glacier surface drive the simulation. Predicted water-pressure variations under the lower part of the ablation area of Storglaciären agree well with a borehole water-level record from 1993. Pressurized flow was dominant early in the ablation seasons of 1992 and 1993, though open-channel flow was possible during the later half of both summers. Tunnels expanded at a varying rate for the first two months of the summer. They adjusted over periods of 2–4 days in response to large water inputs from storms, but tended not to fluctuate in size on a sub-daily time scale. Tunnel aspect ratio increased through the summer, even without the influence of frictional resistance to lateral ice creep at the bed. Ongoing model development includes treatment of lateral variations in energy dissipation from the water, inclusion of friction at the ice–bed interface, examination of the role of till in tunnel development, and examination of the impact of downstream changes in the drainage network on tunnel evolution.

Basal processes at sub-freezing temperatures, Meserve Glacier, Antarctica

(H. Conway, A.M. Gades, C.F. Raymond, UW/GP; K. Cuffey, B. Hallet, R. Sletten, UW/GL)
The basal ice of Meserve Glacier, first investigated by Gerald Holdsworth and colleagues in the late 1960s, was examined during the 1995–96 field season. A new, 20 m long tunnel was excavated into the tongue to better understanding the rheology and origins of dirty basal layers in sub-freezing ice. Ice stratigraphy and structures were mapped and ice samples collected to characterize spatial variations of physical and chemical (including stable-isotopic) properties of the basal ice. Motion within the ice and between the ice and the bed were also studied. The measurements will be used to examine the physical processes responsible for the formation and diagenesis of the basal layer.

ICE MECHANICS

Mechanical properties of sea ice

(R. Brown, MSU)
The differences between some mechanical properties of sea ice and fresh-water ice are being investigated. A series of experiments have quantified the differences in material strength, viscosity, flow stress and other properties. The brine pockets in sea ice produce excess dislocations during phase change relative to non-saline ice. Theoretical and finite-element modeling have provided a measure of the production of dislocations in sea ice.

Ice core studies on Ice Stream B

(M. Jackson, B. Kamb, CIT/GL&PS)
Several cores have been obtained from Ice Stream B and one of its shear margins using a hot-water ice corer. Stress–strain experiments and fabric studies are being performed on them. The experiments have shown there is little enhancement of the flow law within the shear margins, despite the high strain rates occurring there. Studies from within the margin reveal a two-maximum fabric. This is what would be expected for ice that has undergone a relatively small amount of shear strain parallel to the margin, not the very large strain that can be estimated from the surface velocities.

MASS BALANCE AND RUNOFF

Dry Valleys, Antarctica

(A.G. Fountain, USGS/D; K.J. Lewis, CU/INSTAAR; G. Dana, UN; P. Langevin, JPP)
The mass balance of 4 glaciers in Taylor Valley, in the McMurdo Dry Valleys, is being measured to help identify the magnitude of mass loss. To identify ablation components, evaporation/sublimation during the summer months is measured directly using eddy-correlation instrumentation. Knowing total ablation, and the fraction lost to the atmosphere, meltwater flow can be estimated. Glacier melt is the only source of water to the streams and lakes of Taylor Valley. Results indicate evaporation/sublimation represents about 70% of the ablation, with the remaining 30% lost to melt. The melt rate is most sensitive to the angle of the ice surface relative to the sun. Vertical ice faces, which more directly face the sun, ablate 5–10 times more than the horizontal ones. Within Taylor Valley, there is a strong gradient in the elevation of the equilibrium line, although the valley is only about 50 km long. The ELA rises with distance away from the ocean in response, we believe, to a decrease in precipitation. Variations in precipitation may be governed by local topography which blocks clouds from the upper valley.

Relations between climate and glacier variations, Blue Glacier, Washington

(D.S. Battisti, A. Boudreaux, H. Conway, H.-P. Marshall, L.A. Rasmussen, C.F. Raymond, UW/GP)
A physically based mass-balance model is being tested against the 40-year record of surface measurements of meteorological and glaciological variables at Blue Glacier. The model is driven by gridded upper-air temperature, humidity, and wind, available from the NCEP/NCAR 40-year reanalysis project. Results are also compared with long-term volume changes determined from glacier mapping by vertical aerial photogrammetry in 1939, 1952, 1957, 1987, and by aerial-laser profiling in 1996 by K. Echelmeyer, University of Alaska, Fairbanks.

Synthetic-aperture radar detection of changing melt patterns on Alpine glaciers

(L.C. Smith, UCLA/G)
Maximum snowline elevation, which can be used as an approximation of glacier equilibrium-line altitude, may be extracted from late-summer SAR imagery to provide information about long-term trends in glacier mass balance. Patterns and timing of melt, in particular, respond to seasonal forcings of temperature and radiation. Close temporal monitoring of glacier-surface conditions with SAR will increase our knowledge of the current climatic regimes over poorly known glacier systems, improve our ability to predict streamflow in glacierized basins, and assist efforts to monitor long-term trends in glacier mass balance.

Mass balance at South Cascade Glacier, Washington

(R. Krimmel, USGS/T)
Winter and net balance was measured at South Cascade Glacier in 1995 to continue the record begun in 1958. Supplemental data included water discharge from three adjacent basins or sub-basins, air temperature, precipitation, and wind measurements. Vertical aerial photography was used to produce a digital-elevation model and define the glacier perimeter. Balance records from South Cascade, combined with those from Gulkana and Wolverine Glaciers, have been analyzed with respect to each other and climatic indicators.

Stable isotopes , Taylor Valley, Antarctica

(B.H. Vaughn, CU/INSTAAR, A.G. Fountain, USGS/D)
In conjunction with glacier mass-balance studies by A.G. Fountain (USGS/D) and K. Lewis (CU/ INSTAAR),

samples of snow, ice and runoff were collected for isotopic analysis, to define the patterns of precipitation, ice, and runoff in the closed basin.

During 1993, 1994, and 1995, several hundred samples were gathered. Those from snow pits on Commonwealth and Howard Glaciers range 120 per mil in δD (deuterium), and indicate some seasonality in snow layers sampled to 1 m depths. Surface samples of snow gathered between 50 and 1000 m elevation on Canada, Howard, and Commonwealth Glaciers indicate no distinct correlation between isotopic concentration and elevation. However, the age of the snow sampled was unknown and samples taken likely represent only a short precipitation history of one or several events.

Stable isotopes of hydrogen and oxygen in ice samples from the ablation zone of Canada Glacier were measured from the ice powder produced from drilling holes for ablation stakes, representing ice from the top half meter of the glacier. They show a distinct flow pattern of the lower glacier with a 50 per mil difference in δD between the glacier center and the margins. This may result from ice originating at different elevations, reflecting a isotopic elevation gradient. However, isotopes from the snow, in pits, or from the surface do not show sufficient differences to account for the entire observed gradient. This pattern may represent ice from the late Holocene, coinciding with that found in the Taylor Dome isotope record (by P. Grootes and E. Steig). We hope that ice velocities currently being collected will help to define the dynamics of Canada Glacier for the purpose of identifying the location of the source of ice sampled in the ablation zone and the approximate age of the ice.

Asian glaciers and hydrological cycles

(V. Aizen, E. Aizen, UCSB/ICESS)

Four high-mountain glacial basins in the arid and semi-arid regions of central Asia (Tian Shan) and the high mountain basins of the tropical monsoon belt in S and SE Asia (N Himalayas and SE Tibet), have been studied to identify processes controlling continental glaciers, to estimate the heat, water and mass balance, and to determine glacial interaction with the external hydrological cycle over Eurasia.

The major climatic feature here is the moisture entering during summer, resulting in decreased air temperature and thus decreased snow- and ice melt. Total annual precipitation increases with altitude up to the crest lines on the northern periphery of central Asia, while on the southern periphery this is observed only up to a certain elevation.

Radiation accounts for 86–96% of the energy involved in snow- and ice melt. Turbulent heat exchange is significant in the heat balance only in SE Tibet. Evaporation and condensation are either mutually compensatory or negligible at the northern periphery. At the southern periphery, on the N slope of the Himalaya, evaporation exceeded condensation during the melt period, but in SE Tibet, condensation exceeded evaporation. Comparing the four regions, the intensity of melt is least for the Xixibangma glacier (3.2 mm $°C^{-1}$) and greatest (12.5 mm $°C^{-1}$) in the central Tian Shan.

The major factors controlling glacier systems on the northern periphery are the amount of solid precipitation and the low mean summer air temperature. For a given amount of precipitation, glacier systems are largest where the air temperature is lowest. The Pobeda-Khan Tengry, the largest glacier system at the northern periphery of central Asia, has an area of 4320 km^2. At the southern periphery, the main climatic control is the monsoon circulation, manifested by heavy precipitation and relatively weak solar radiation at the glacier surface. The solar radiation intensity for the ablation zone of SE Tibet is only one-sixth of that theoretically possible. On the northern slope of the Himalayas, the continuous katabatic airflow suppresses precipitation, but increases evaporation, thus reducing glacial melt and runoff.

In all cases, the net glacier mass balance is negative, indicating large-scale degradation of modern glaciers in central Asia. The long-term average mass-balance values are estimated to be –319 kg m^{-2} for the Pobeda-Khan Tengry glaciers, –150 kg m^{-2} for the Ala Archa glaciers, –99 kg m^{-2} for the Gongga massif, and –33 kg m^{-2} for the Xixibangma glaciers. In closed basins of the northern and central Tian Shan (the Ala Archa and Pobeda-Khan Tengry glaciers), about 0.1–2.4% of the total external atmospheric moisture and 150–318 kg m^{-2} of water are stored annually for a long time in the Aral-Caspian and Tarim hydrographic systems. About 0.22–0.24% of the external water cycle is transferred annually to open glacial basins of the Xixibangma glacier (N slope of Himalayas) and Gongga glacier (SE Tibet). The glaciers of these regions return 0.25–0.30% of the external water cycle per year to the Pacific and Indian Oceans; 0.03–0.06% of this external moisture is taken from the Gongga and Xixibangma glaciers.

Isotopic measurements of precipitation on central Asian glaciers

(V. Aizen, E. Aizen, J. Melack, UCSB/ICESS; T. Martma, IGEAS)

Isotopic $\delta^{18}O$ and δD data were obtained over three years in three climatic regions: Gongga massif (SE Tibet, windward slope of summer monsoon), Xixibangma massif (N slope of the Himalaya, leeward of summer monsoon), and the massifs of Pobeda-Khan Tengry (central Tian Shan, exposed to western airstreams). The survey provided information from atmospheric precipitation, snow pits and a 23 m ice core.

The significant differences of isotopic ratios (from –25.1 to –9.5 per mil) indicate the Indian and Pacific Oceans as well as the Atlantic Ocean are sources of moisture here. Sharply changing isotopic ratios in precipitation corresponded to changing wind direction and were associated with different sources of air masses.

Among the three regions on the periphery of central Asia, the lightest $\delta^{18}O$ ratios are typical for the northern slope of Xixibangma (–36 per mil) and the heaviest for the Tian Shan on the Inylchek Glacier (–2 per mil). A relatively small variation of oxygen ratios in atmospheric precipitation during expeditionary observations, and the absence of apparent periodic anomalies of $\delta^{18}O$ composition in a 23-m ice core in the central Tian Shan, suggest only one source of moisture, that the precipitation was

derived from the Caspian or Mediterranean Seas. Within Eurasia, air masses which develop over the Atlantic with zonal direction advance farther than those from the Pacific and Indian Oceans. This effect is partly responsible for the existence of local glaciation on the central Tibetan Plateau above 6000 m.

There is a good linear relationship between mean air temperatures during deposition and $\delta^{18}O$ ratios in atmospheric precipitation originating from the same moisture source. We have revealed trends in $\delta^{18}O$ isotopic ratios with elevation. The analysis of the 23 m ice core with 186 strata could be explained by an increase of air temperatures in the central Tian Shan.

Snow hydrology, central Asian mountains

(V. Aizen, E. Aizen, J. Melack, UCBS/ICESS)
Evaluation of snow accumulation and melt in alpine watersheds typical of much of the central Tian Shan, Susamir River basin, was based on expeditionary and long-term data. Snow accumulation has been extrapolated from point measurements to different-scale river basins to quantify the influence of the topography. For basins with areas of about 500 km^2, the main factor is elevation and maximum snow water equivalent; the dates of maximum accumulation and the duration of snow cover are "parabolic" function of elevation. For basins with areas >500 km^2, the effects of rain shadow are strengthened during the cold season and precipitation decreases with distance from a mountain crest at the same elevation. However, during the warm season, the main factor is still elevation. For basins with areas <500 km^2, the exposure has a significant influence on snow redistribution. However, there is a similarity in snow distribution in spite of differences in size or the angle of inclination of slopes. The highest correlation occurred at a 50–60 km horizontal distance in the subalpine meadows and up to 1.0 km in altitude. Solar radiation contributed 74% of energy for snowmelt and evaporation, and turbulent heat contributed 26%, in May, 1992. Average daily evaporation was 0.28 mm and used 10% of available energy while snow melt used 90%. Runoff in the Susamir River basin is primarily from melt of the seasonal snowcover and summer precipitation, 90% of which occurs as snow. Melt of summer snow between snowfalls creates the high river levels observed during this season.

The basin of the Ala Archa, in the Aral-Caspian closed hydrographic region, is the most investigated in the northern Tian Shan, and it is acceptable to extend hydrological conditions of this basin to the whole of the northern Tian Shan. Air temperature is a good predictor of glacial melt there. Typical hydrographs have two floods: one from melt of the seasonal snow cover; the other from glacier melt. The second is usually larger than the first. In the N Tian Shan, direct runoff from rainfall averages about 7–12% of annual volume. Glacier runoff is 18–28% of average annual runoff in basins with glacierized areas of not less than 30–40%, but during summer it can increase to 40–70% of average annual runoff. Surface runoff from seasonal snow melt during spring and summer is 18% of average runoff, the ground-water component is 34–38% of average annual runoff.

CLIMATOLOGY/ PALEOCLIMATOLOGY

Northern Hemisphere combined snow-cover and sea-ice extent

(R. L. Armstrong, M.J. Brodzik, CU/NSIDC)
The National Snow and Ice Data Center (NSIDC), CU, has produced a Northern Hemisphere weekly data set of combined snow-cover and sea-ice extent for October 1978 to June 1995; including monthly climatologies describing average extent, probability of occurrence, and variance. The data set is provided in an azimuthal, equal area (25 km) projection (NSIDC EASE-Grid) on CD-ROM. Snow-cover extent (1972–1995) is based on the digital NOAA-NESDIS weekly Northern Hemisphere snow charts, revised by D. Robinson (Rutgers University), derived from the manual interpretation of AVHRR, GOES and other visible-band satellite data. Sea-ice extent (1978–95) is based on the existing NSIDC sea-ice product derived from SMMR and SSM/I passive-microwave data. These data are being applied to investigate the relationship between Eurasian snow extent and the timing and magnitude of the Indian monsoon.

Sierra snowpack and ENSO

(E.J. Carter, R.W. Carter, Firnspiegel)
The relation between El Niño-Southern Oscillation (ENSO) events and the 20th century climate in the northern, central and southern Sierra Nevada is expected to vary dramatically because effects vary greatly along the latitude span of the Sierras. The correlations (or anti-correlations) of ENSO events and snow elevation, precipitation and temperatures are being analyzed. Extreme events are being studied using meteorological, snowpack, and radar data and AVHRR (Advanced Very High Resolution Radiometer) images.

Snow-covered area and grain size from remotely-sensed spectral data

(T.H. Painter, D.A. Roberts, UCSB/ICESS; R.O. Green, JPL; J. Dozier, UCSB/SESM)
Spectral-mixture analysis of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data have been used to simultaneously solve for sub-pixel snow-covered area and grain size in mountainous terrain. AVIRIS measures solar-reflected spectral radiance from 400 to 2500 nm at 10 nm intervals and 20 m spatial resolution. Mixture analysis determines the fractions of the pure spectral reflectance signatures (end-members) of snow, vegetation, rock, and soil necessary to best model a reflectance spectrum incident at AVIRIS. The spectral fraction of snow is considered to be that of the areal fraction on the ground. The spectral reflectance of snow is sensitive to grain size. Therefore, to properly determine the snow contribution to a mixed reflected spectrum incident at AVIRIS, we must use the pure spectral reflectance of snow of grain size of the snow on the ground. The snow end-member of appropriate grain size optimizes the estimate of sub-pixel snow cover. The grain size of the optimal snow end-member in turn provides the grain-size estimate. Where-as previous efforts at mapping snow grain size have relied on the assumption that pixels are

entirely snow, this technique provides an estimate for any non-zero sub-pixel snow fraction.

To make the technique portable to any snow-covered region, we are replacing image end-members with modeled snow spectra and library spectra for vegetation, rock, and soil. In that form the technique will be used to characterize seasonal snowpacks with data from global coverage instruments such as the Earth Observing System Moderate Resolution Imaging Spectroradiometer (MODIS) and the TRW Lewis imaging spectrometer.

Global land-ice monitoring from space

(Hugh Kieffer, Bruce Raup, Jeffrey Kargel, David Mackinnon, USGS/F)

Global Land-Ice Monitoring from Space (GLIMS) is an international project to monitor the world's glaciers primarily using data from ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer), a Japanese-built imaging system, scheduled for launch in June 1998. In the time remaining, we hope to have in place: 1) a set of software tools to the track glaciers' areal extent, snowline, ice velocity, and terminus; 2) a global network to monitor local glaciers; and 3) a database to store and manipulate some 82 gigabytes of data per year for the 5-yr duration of ASTER.

An international consortium of glaciologists will participate in the analysis of glacier interannual changes. NSIDC (CU) will maintain a GLIMS data archive. If you are interested in joining GLIMS, consult our website for details.

See: http://wwwflag.wr.usgs.gov/GLIMS/glimshome.html

Greenland ice sheet climatology

(K. Steffen, J. Box, W. Abdalati, CU/CIRES)

The Greenland Climate Network (GC-Net) was established in spring 1994 to monitor climatological and glaciological parameters at various location on the ice sheet over a period of at least 5 years. The GC-Net automatic-weather-station (AWS) network will: 1) Assess daily, annual and interannual variability in accumulation rate, surface climatology and surface energy balance at selected locations on the ice sheet where high sensitivity of the ice-sheet mass balance to climate anomalies is predicted by models; and 2) assess accurate surface elevation, location, near-surface density at the AWS location for temporal information for dynamic ice-sheet modeling. There are 9 AWS transmitting 300 parameters hourly via satellite link. The GC-Net is a core project of PARCA (Program for Arctic Regional Climate Assessment). See: http://cires.colorado.edu/parca.html.

POLES: oceans–ice–atmosphere interaction

(D.A. Rothrock, UW/APL)

POLES (Polar Exchange at the Sea Surface) is a NASA Earth Observing System (EOS) interdisciplinary project investigating the exchange of mass and energy at the air–ice–ocean interface in the polar regions. 8 investigators hope to assimilate a rich array of observations into polar ocean–atmosphere models, refining the treatment of surface exchange processes, and quantifying the roles of horizontal transports, oceanic mixing, and deep convection.

POLES has produced a number of data sets and data processing tools to show the present state of the polar climate and how it works, and to establish a baseline against which to assess climate change. These include improved polar algorithms for the TIROS-N Operational Vertical Sounder (TOVS) and for the Advanced Very High Resolution Radiometer (AVHRR); a Cloud and Surface Parameter Retrieval System (CASPR) for polar AVHRR data; surface-radiative-flux data sets from the International Satellite Cloud Climatology Program; ice-motion data from satellites and drifting buoys; a gridded 2-m air-temperature data set, and surface-salt fluxes to the Arctic Ocean, 1979–1985.

See: http://psc.apl.washington.edu/poles/POLES.html.

Atmospheric and surface processes at South Pole

(S. Warren, UW/AS)

Results from experiments on atmospheric and surface processes at South Pole Station during the winter of 1992, are being analyzed by S. Warren and colleagues (V. Walden, S. Harder, R. Brandt, A. Mahesh, and L.Tuttle). Work is continuing on spectral long-wave climatology and cloud radiative forcing, surface-based remote sensing of clouds, aerosol deposition and lifetime, bidirectional reflectance of snow, and size distribution of atmospheric ice crystals.

Denrochronological data from central Asia

(V. Aizen, E. Aizen, J. Melack, UCSB/ICESS; J. Michaelsen, UCSB/DG)

Analysis of Schrenka spruce and Turkestanian juniper on the northern slope of Kirgizskiy Alatoo in the Ala Archa and Kok Shaal Too in the Inylchek valley allowed reconstruction of the summer air temperatures for the past 200 years and annual precipitation for the past 150 to 300 years. There are significant relations between spruce rings and annual precipitation, and between the juniper rings and temperatures. Opposite changes in the two point to the negative relation between summer air temperatures and annual precipitation in the Tian Shan. Favourable periods of glacier advance in the Tian Shan were the end of the 18th and beginning of 19th centuries, when annual precipitation increased and summer air temperature had negative deviations. The latter had their minimum during the end of the Little Ice Age in the northern Tian Shan, but a precipitation maximum occurred at the same time in both the northern and central Tian Shan. Reconstructed data from the Ala Archa basin show summer air temperatures have increased about 0.83°C during the past 200 years, and annual precipitation has decreased about 53 mm; about 10% of the total average during the past 171 years, particularly from 1821–1933. Around Inylchek Glacier, in the central Tian Shan, there were no significant trends in annual precipitation during the past 300 years. Fluctuations of annual precipitation are associated with the change of predominant circulation patterns. The primary zonal circulation patterns favor transport of cyclonic moisture into central and northern Tian Shan; strengthening the Siberian anticyclone decreases precipitation there.

SNOW

Low-density snow rheology

(H. Conway, UW/GP)

In situ measurements of the snow help in understanding the rheological properties of low-density snow. The rate of deformation increases with temperature and is especially rapid in the presence of liquid water. Creep rates decrease rapidly as the snow densifies. The slope-parallel shearing component of motion is much smaller than expected from the usual constitutive assumptions for snow. Experiments in progress are designed to examine how metamorphic processes and "capillary strain" (in the presence of liquid water) affect the pattern and rate of deformation of snow.

Flow properties of avalanches

(J. Dent, E. Adams, S. Schmidt, J. Burrell, T. Jazbutis, MSU/CE)

Instruments have been designed and built to measure flow properties in dry-snow avalanches moving through a small avalanche path near the Bridger Bowl Ski Area in SW Montana. They includes optical sensors to measure velocity and density profiles, a capacitance probe also to measure density profiles, a mechanical gauge to measure flow depth, and a strain-gauged plate mounted in the avalanche running surface to measure shear and normal stress. These properties have been measured for avalanches up to 1.5 m deep and moving faster than 10 m s^{-1}. The information collected is being used to help develop and test models of avalanche movement.

Electrostatic forces in blowing snow

(S. Schmidt, R.A. Schmidt, J. Dent, MSU/CE)

Instruments have been constructed to measure the electric field above a blowing-snow surface and the electrostatic charge on individual wind-blown snow particles. Together these allow the electrostatic force on wind-blown snow particles to be found. Recent experiments indicate this force can be as large as the gravity force when blowing-snow particles are near the snow surface. Particles of different charge and even different sign are found together in the same event.

Microstructure in snow

(R. Brown, MSU/CE)

An automated software system has been developed to calculate the many microstructural properties which affect mechanical and physical properties of snow. These include mean grain size, mean bond size, 3-d coordination number, mean neck length, specific free surface area, and other properties. Work is currently under way to evaluate statistical distributions of some of these variables.

Metamorphism of snow

(R. Brown, MSU/CE)

Modern mixture theories are being used to model both equi-temperature and temperature-gradient metamorphism of snow. The mixture theory is developed in terms of the microstructure of the material to enable one to predict how microstructure affects metamorphism and how the internal structure of the material changes under the influence of different temperature and load environments.

Meltwater flow through snow, Niwot Ridge LTER site, Colorado

(M. Williams, CU/INSTAAR; R. Sommerfeld, USFS; T. Pfeffer, CU/INSTAAR; T. Illangesakare, CU/CE)

To develop more detailed knowledge of the physics of snow hydrology for models and predicting snowmelt runoff, we are quantifying the spatial and temporal variation of meltwater flow through snow using an extensive array of 116 snow lysimeters that determines: 1) the characteristic correlation lengths of snowmelt runoff; 2) the spatial variance of meltwater flow; and 3) the effective hydraulic conductivity of the snowpack. Aerial photographs, at near-IR wavelengths, will be used to infer the onset and degree of heterogeneous infiltration from remote-sensing observations, and more accurately predict the discharge hydrograph of a ripening snowpack. The evolution of internal flowpaths is being constructed from non-destructive temperature and conductance probes and from destructive measurements of snowpack stratigraphy and dye tracers. Snow characteristics will be used to parameterize an existing meltwater infiltration model coupled with the development of a second model that explicitly includes the dynamics of preferential flowpaths.

Snow–atmosphere energy fluxes, Niwot Ridge, Colorado, and Greenland ice sheet

(M. Williams, D. Cline, K. Steffen, CU/INSTAAR)

Energy fluxes over snow are being measured to validate and calibrate energy-balance snowmelt models, particularly SNTHERM.89 developed by the US Army at CRREL. These measurements will complement existing equipment to measure snowmelt quantity and timing, including 18 snowmelt lysimeters currently installed and another 116 to be installed in summer 1997. Additionally, we will include a comparison of the Aerodynamic Profile Method (APM) and the Eddy Correlation Method (ECM) to measure turbulent fluxes in order to derive a site specific Monin-Obukov similarity relation for the inexpensive APM from the expensive and intensive ECM that can then be generalized over a wide range of snow conditions and areas. These energy-flux measurements are being conducting at Alpine (Niwot Ridge, CO) and Arctic (Greenland) sites to assess simularities and differences between these environments.

Biogeochemical and hydrologic controls in Alpine watersheds

(M. Williams, S. Schmidt, CU/INSTAAR; C. Kendall, USGS/MP; R. Bales, UA; J. Baron, USGS/FC; D. Campbell, USGS/D)

A multidisciplinary approach, combining stable and radiogenic isotopic tracers, plot-level experiments, process-level modeling, and field research to constrain the modeling results, is being used to determine what geochemical and biogeochemical processes are important at the watershed scale in Alpine basins. The objectives include understanding biogeochemical and geochemical processes and examining the responses of test basins to possible anthropogenic perturbations. Geochemical, biogeochemical,

and hydrologic processes are interconnected at the watershed scale and should be studied together. Isotopic tools will be used, in combination with field measurements of water quality and quantity, to 1) separate the relative contributions of atmospheric and soil-derived sources of nitrate in streams (analysis of nitrate for $\delta^{15}N$ and $\delta^{18}O$); 2) increase understanding of the reactions controlling alkalinity (carbon and strontium isotopes); and 3) provide insights into the dynamics of sulfur deposition (stable and radiogenic isotopes of sulfur).

A robust model for solute transport will be developed, accurate enough to predict the fate of various chemical constituents at many sites and under a variety of conditions. The algorithms will provide an integrated approach to modeling the hydrology and biogeochemistry of seasonally snow-covered Alpine basins.

Interaction of a hot grain flow with snow

(J.S. Walder, USGS/CVO)

Hot, dense grain flows (pyroclastic flows) constitute significant hazards at volcanoes that erupt explosively. Pyroclastic flows may erode and entrain the substrates over which they move. Where the substrate consists of snow or glacier ice, the pyroclastic flow commonly transforms to a water-saturated slurry, or lahar, which may travel great distances and be extremely destructive. Sometimes it comes to rest on the snow- or ice surface without transforming to a lahar, even though snow and ice may have been incorporated. Contacts between pyroclastic deposits and snow or ice vary greatly: some contacts show substantial small-scale relief, whereas others are free of irregularities and are almost planar. Unfortunately traditional stratigraphic principles are of limited use, for learning about the mechanics of interaction between the pyroclastic density current and the frozen substrate., because an ice- or snow substrate can be thermally eroded — or more simply, melted — by an overlying pyroclastic deposit even when that deposit is at rest. The contact geometry will inevitably be altered. Therefore, experimental studies are probably the most useful.

Experiments on the flow of hot sand over artificial snow in a tilted flume have been described previously. Recently a layer of hot, fine-grained sand was emplaced without relative shear motion on a bed of artificial snow. This experiment reveals that there is a purely thermally driven mechanism by which snow can be incorporated into an overlying pyroclastic layer and a slurry produced. This must operate in addition to any process of mechanical scour. For a given sand temperature (T_s) and grain size (D), vapor bubbles caused the sand immediately to convect, scour and melt the snow, and become a slurry, for a finite range of sand-layer thicknesses; but for sufficiently thin or thick sand layers, the sand passively melted downward. A physically based theory predicts these observations. Vapor flux tends to fluidize the sand, but because the uniformly fluidized state is unstable, bubbles form and cause the sand to overturn. Predicted vapor flux depends upon T_S, D (a proxy for sand permeability), sand-layer thickness, and snow permeability. Bubbling does not occur in very thin sand layers because the meltwater escapes into the snow instead of being engulfed and vaporized. Sufficiently thick sand layers are stable against bubbling because the overburden load suppresses fluidization. The observed process of thermally driven, fluidization-induced scour, even in the absence of relative shear motion, should occur in pyroclastic flows moving over snow, and may be enhanced by the fluidizing effect of exsolved volcanic gases and heated, entrained air. Purely mechanical erosional processes, as opposed to the observed thermally driven erosional process, are probably also important during the movement of pyroclastic flows over snow.

ICE CORES

Accumulation rates, northern Greenland

(K. Steffen, A. Nolin, CU/CIRES; J. White, CU/INSTAAR

The spatial and temporal variations of snow accumulation rates are the prime objectives for the shallow ice-core project in northern Greenland. Shallow ice cores, taken in conjunction with the emplacement of automatic weather stations (AWS), will be analyzed to determine past and present accumulation rates and their spatial and temporal variability. During the 1995 season, six cores were retrieved from Humboldt camp, NW Greenland (78.58°N, 57.21°W, 2000 m); two at the camp (160 m, 25 m depth) and four in four cardinal directions 25 km away (25 m depth). Preliminary isotope versus depth analyses for the base ice cores revealed an average accumulation rate of 18 ± 0.3 cm w.e. for the past 34 years. A total of nine shallow ice cores were retrieved in 1996 from the low-accumulation area in NE Greenland (Tunu-North: 78.0°N, 34.0°W, 2000 m). They were drilled within an area of 100 x 100 km^2. At base camp, a 70 m ice core was retrieved, and 25 km and 50 km from the camp in four cardinal directions cores were drilled to 15 m depth.

Isotopic measurements in East and West Antarctica

(E. Steig, CU/INSTAAR)

Cosmogenic ^{10}Be and stable-isotope measurements on Taylor Dome ice core (78 50°S, 155°E) are revealing the climate history in the McMurdo Sound/Dry Valleys region. The core extends to marine-isotope stage 6 or beyond, and may record the waxing and waning influence of the West Antarctic ice sheet on the atmospheric circulation and precipitation patterns in this region. Stable-isotope measurements at high resolution during the Holocene and Younger Dryas show significant Holocene cooling since 6 ka, and suggest coastal East Antarctica was no cooler during the Younger Dryas than it is today. Stable-isotope measurements are also being made on shallow WAIS and Siple Dome cores to determine accumulation rates and stratigraphic preservation in preparation for the planned deep drilling.

REMOTE SENSING AND GLACIER GEOPHYSICS

Ice velocity and topography of Greenland and Antarctica using radar interferometry

(I. Joughin, R. Kwok, JPL; M. Fahnestock, UMa)
SAR interferometry provides a means for measuring ice-sheet topography and velocity. Research is focused on improving interferometric techniques and interpretation of the results. Much of this work has concentrated in Greenland where interferometrically derived maps of velocity and topography have been made for the Petermann, Humboldt, and Ryder Glaciers using ERS-1/2 data. A mini surge on Ryder Glacier was detected via interferometry. The combination of interferometric velocity data with ice thickeness data from the University of Kansas coherent-radar depth sounder (CORDS) allowed precise measurement of ice flux upstream of the Petermann grounding line. Future research will focus on using interferometry to study the NE Greenland Ice Stream and on mapping discharge rates for other major outlet glaciers.

Inventories of the Patagonian glaciers

(E. Rignot, JPL; G. Casassa, UMC)
SAR data are being used with conventional ground surveys (GPS receivers and ice-sounding radars) to yield a first estimate of the mass discharge from the Patagonian icefields.

Radar images collected by the Shuttle Imaging Radar C, in late 1994, were used to map the velocity and surface topography of 4 major glaciers of Hielo Patagónico Norte, and the velocity of glaciers along an E-W transect of Hielo Patagónico Sur. In October-November 1995, ERS-1/2 tandem data were successfully collected over the entire Patagonian icefield by the European Space Agency. Although the interferometry results are deceiving, due to the prevailing summer conditions on the icefield, innovative feature-tracking techniques were used to produce velocity maps for most outlet glaciers. Field campaigns in 1996–97 will provide estimates of ice thickness on several glaciers of Hielo Patagónico Sur, and first-order estimates of the ice discharge from the Patagonian icefields are expected in 1997–1998.

Grounding line, ice flux and melt rate of northern Greenland glaciers

(E. Rignot, JPL)
ERS-1 radar data are utilized to determine the grounding line and ice flux of all glaciers of N and NE Greenland using a multiple-pass interferometry technique. Results from Petermann Gletscher showed the the grounding line can be mapped with a 20-80 m accuracy, and tidal displacements can be measured with millimetric precision. Ice discharge at the grounding line, calculated using a combination of ice-sounding radar data and an existing topographic map produced by the Danish Institute KMS, was found to be 20 times larger than the ice flux calculated at the glacier front by Higgins. The difference is attributed to pronounced basal melting of the glacier tongue. The basal melt rate averages ~10 m a^{-1}, with peak values exceeding ~20 m a^{-1} near the grounding line. Thus even in Greenland, basal melting is a significant process of mass loss from the inland ice. The analysis has now been extended to the entire N sector of Greenland. The results show that although the configuration of Petermann Gletscher is somewhat exceptional, numerous other glaciers have large floating sections where basal melting is significant and where the ice flux at the grounding line is 2 to 10 times larger than that calculated at the ice front. Consequences for the estimation of the mass balance of the Greenland ice sheet are obvious.

Ice-shelf tearing and flow separation at ice-stream outlets

(E. Rignot, JPL; D. MacAyeal, UCh/GP)
A combination of ERS radar interferograms and finite-element modelling is used to investigate ice flow and rifting where the Ronne Ice Shelf's calving front meets Berkner Island. It is suggested that the Hemmen Ice Rise stabilizes the ice front by restricting the length scale and propagation pattern of ice-shelf rifts that are the progenitors of Antarctica's largest tabular icebergs. This has been investigated by studying patterns of ice displacement associated with creep and tidal flexure, as revealed by ERS SAR interferometry. A finite-element model is used to compare ice-shelf stress patterns in various ice-front/ice-rise configurations.

Ice-sheet morphology and dynamics

(T. Scambos, CU/NSIDC)
Current work focuses on the development and application of three remote-sensing tools for ice-sheets analysis. The ice-velocity mapping technique uses pairs of high-resolution satellite images to look for displacement in surface features. Photoclinometry (also called 'shape-from-shading') improves the topography in digital-elevation models (DEMs) by deriving the quantitative relationship between image brightness and surface slope. Data cumulation is a method of combining several digital images of an area into a single scene with better resolution than is possible with a single scene. All three techniques are best applied to large ice sheets, such as Greenland and Antarctica, where more traditional techniques for measuring ice velocity and the morphology of the surface are difficult to apply.

Recent work has focused on Siple Dome in West Antarctica, the NE Greenland flow feature, and snow dunes on the East Antarctic Plateau.

SEA ICE

Microwave observations of characteristics and dynamics of Antarctic sea ice

(M.R. Drinkwater, JPL)
Two collaborative projects with the European and Canadian space agencies, allow satellite radar data acquisition in Antarctica; primarily the Weddell and Ross Seas. ERS synthetic-aperture radar (SAR) and scatterometer images are being used together with Radasat wide-swath SAR images, NSCAT scatterometer images and SSM/I passive-microwave data to monitor Southern Ocean sea ice. Images spaced at regular 3-day intervals have been generated for the December 1991 to the present. Several major Antarctic field experiments within this period allowed buoys and field camps to be deployed, and various ice-surface measurement datasets to be acquired. Combined data analysis is allowing ice dynamics to be measured and monitored for the entire Southern Ocean, and enabling study of the dynamic and

thermodynamic components of ice growth and the seasonal cycle to be determined.

Arctic summer sea-ice melt processes

(B. Holt, JPL)

This research project is examining freshwater flux during the Arctic summer sea-ice melt process to further understand its role in controlling the depth of the Arctic surface waters (or halocline). The approach is to study summer melt by quantifying sea-ice conditions and dynamics from the central pack to the marginal zones, with the Arctic considered as source (Laptev Sea), sink (Chukchi Sea), and multiyear regions (Beaufort Sea). The primary research tool is satellite SAR imagery from ERS and Radarsat. Parameters currently being examined include the onset of melt and freeze and floe size distribution. An extensive study using ERS-1 SAR of the spatal and temporal evolution of floe-size distribution in the Beaufort and Chukchi Seas is nearing completion. Future studies will incorporate geophysical products derived from RADARSAT including summer open-water fraction.

Comparisons of modelled Weddell Sea ice with satellite-microwave and in situ sea-ice observations

(M. Kreyscher,AWI, and M. Drinkwater, JPL)

Comparisons are being made between results from a dynamic–thermodynamic sea-ice model and satellite microwave results from the above study. The interannual cycle of ice production is being investigated in relation to changes in the dynamics of sea-ice drift and circulation in the Weddell Gyre. Grounded icebergs in regions of shallow bathymetry are demonstrated to have a significant impact on the sea-ice production, and therefore also the net annual salt production in shelf regions. Interannual fluctuations in observed bottom-water outflow are being investigated in relation to the model results. Further investigations focus on the correlation of the "circumpolar wave" with the deep water production in the southern Weddell Sea, which might be an important
feedback loop between mid- and high-latitude processes.

Mass balance of Arctic Ocean sea ice

(R. Kwok, JPL)

The mass balance of Arctic Ocean sea ice is being estimated using data products from the RADARSAT Geophysical Processor System (RGPS). The ice mass balance is defined as the difference between ice production and the sum of ablation and ice export from the Arctic Ocean. Over an annual cycle, there is no net accumulation of ice mass if they are equivalent. This is a rather straightforward calculation if the sea-ice motion field and ice-thickness distributions are known exactly. With the RADARSAT SAR data, the RGPS produces weekly ice-motion maps of the Arctic Ocean but provides estimates of only the thin end (<1.5 m) of the thickness distribution in the winter. Thicker ice is categorized as first-year or multi-year ice. The thicknesses of the older ice types, in different parts of the Arctic Ocean, will be estimated with available submarine measurements, upward-looking sonar (ULS) and historical datasets. These, and the motion fields from the RGPS, will then be used to estimate and summarize the mass budget for different regions (Beaufort Gyre, Trans-polar Drift Stream and peripheral seas) as well as the flux of ice through the various straits and passages. Of particular importance is the flux through Fram Strait due to its possible effects on the strength of the thermohaline circulation. The sensitivity of the mass budget will be analyzed in view of parameters which are not directly observed, e.g. mean thickness of multiyear ice. The result will be a better quantification of mass balance in terms of ice flux, accumulation and ablation, using two years of RGPS products and contrasting the interannual variability. A baseline for long-term monitoring the mass budget of Arctic Ocean sea ice by satellite data is important for model validation and detection of changes due to climate.

Lady Ann Strait polynya study with ERS-1/2 SAR imagery

(K. Steffen, J. Heinrichs, CU/CIRES)

Polynyas have a major influence on the heat and energy balance of ice-covered seas. A time series of ERS-1/2 SAR low-resolution imagery for several winters (1992–95) has been acquired for Lady Anne Strait, NW Baffin Bay. Despite difficulty in resolving ice motions (the 3-day time interval of the ERS-1 ice orbit does not permit this), the SAR data have allowed observation of the variability of the ice cover in the polynya over a relatively long period. By examining backscatter values along transects within the polyna, further understanding of how backscatter varies with ice growth for very young sea ice has been gained.

LAKE ICE

Ice covers of McMurdo Dry Valley lakes, Antarctica

(E.E. Adams, S.R. Smith, S.L. Brackman, MSU/CE; J.C. Priscu, C.F. Fritsen, MSU/B)

The structure and metamorphism of the permanently ice-covered lakes of the McMurdo Dry Valley lakes is being investigated. The ice exhibits a distinct stratigraphy that undergoes extensive seasonal metamorphism. A conspicuous stratigraphic feature in the ice covering several lakes is a characteristic zone of high sediment concentration. The predominately sand-sized particles, which have migrated downward from the surface, occur in discrete pockets. Morphology of vapor inclusions and cracks within the ice may be generally divided into a zone below the sediment, a complex region associated with the sediment, a region extending upward to just below the surface and a region near the top surface.

FROZEN GROUND

Permafrost data and information

(R.G. Barry, CU/NSIDC)

The Working Group on Permafrost Data and Information of the IPA and World Data Center-A for Glaciology are developing a prototype Global Geocryological Database (GGD). The data priorities and organizational structure of the GGD were decided at workshops in Oslo, 1994

(published in Glaciological Data Report GD-28) and Potsdam, 1995. With specialists from several Russian institutions and the Geodata Institute, University of Southampton, UK, plans are underway for a CD-ROM of permafrost data and information to be available for the July 1998 International Conference on Permafrost. National IPA representatives and individual scientists are encouraged to propose and submit data sets for inclusion on the CD.

Rock glacier, Wyoming

(E.J. Steig, W.T. Pfeffer, CU/INSTAAR; D.H. Clark, IU/GL; N.F. Humphrey, UWy/GL&GP; N. Potter, Jr., DC/GL)

Studies of an active, ice-cored rock glacier at Galena Creek, Wyoming have commenced. The project includes borehole-deformation and surface-velocity measurements, ice-core analysis, and characterization of rock and ice mass-balance ratios. Results from a preliminary hand-augered ice core show that clean glacier ice underlies this rock glacier. Isotopic profiles indicate the seasonal stratigraphy is preserved, suggesting that there is potential for using rock glaciers as archives for geochemical–paleoclimate studies.

GLACIAL GEOLOGY

Laurentide ice sheet during Heinrich events: record in Lake Superior region

(H.D. Mooers, C.L. Matsch, UMD/GL; J.D. Lehr, DNR)

The glacial stratigraphy of the western Lake Superior region (WLSR) records a complex sequence of Late Wisconsinan ice advances and retreats from accumulation centers in Quebec and Hudson Bay. All of these ice-marginal oscillations can be associated with three main Late Wisconsinan events, and each is documented by stratigraphic and geomorphic evidence. Each major events was marked by gradual build-up of ice, formation of a prominent moraine, and followed by rapid ice retreat. These events culminated at approximately 22,000, 15,500, and 13,000 radiocarbon yr B.P. This evidence is consistent with the "binge/purge" behavior suggested by MacAyeal (1993). Progressive southward shift in the position of the ice divide is recorded by indicator rock types in drift associated with each event. We suggest that each Heinrich event resulted in a drawdown of the central Laurentide ice sheet causing southward displacement of the ice divide and rapid retreat of ice margins in the WLSR.

Spatial variations in till sheet sediment-ology: the importance of comminution, dilution, and changes in source region

(S. DeLong, H.D. Mooers, UMD/GL)

Variations in sedimentological parameters of an extensive till sheet have been used to suggest that dilution by erosion of pre-existing drift was a major factor controlling till characteristics. However, laboratory experiments on crushing and abrasion have shown that the observed changed in till sedimentology more likely arose from progressive comminution of sediment during transport. Graphical and statistical methods have been developed to display sedimentary properties of till that greatly aid in analysis of processes of comminution and dilution.

Abbreviations used

APL	Applied Physics Laboratory
AS	Atmospheric Sciences
AWI	Alfred Wegener Inst., Bremerhaven, Germany
B	Biology
CE	Civil Engineering
CIRES	Center for Cooperative Research in Environmental Sciences
CIT	California Inst. of Technology, Pasadena, CA
CU	Univ. of Colorado, Boulder, CO
DC	Dickinson College, Carlisle, PA
DNR	Dept. of Natural Resources, Div. of Minerals, St. Paul, MN
Firnspiegel	Firnspeigel, Carnelian Bay, CA
G	Geography
GL	Geology
GP	Geophysics Program
ICESS	Inst. for Computational Earth Systems Science
IGEAS	Inst. of Geography, Estonian Academy of Sciences, Tallinn, Estonia
INSTAAR	Inst. of Arctic and Alpine Research
IU	Indiana Univ./Purdue Univ., Indianapolis, IN
JPL	Jet Propulsion Laboratory, Pasadena, CA
JPP	Jasper Provincial Park, Jasper, Alta, Canada
MSU	Montana State Univ., Bozeman, MT
NSIDC	National Snow and Ice Data Center
OSU/BPRC	Byrd Polar Research Center, Ohio State Univ., Columbus, OH
PS	Planetary Sciences
SESM	School of Environmental Science & Management
SO	St. Olaf College, Northfield, MN
U Ch	Univ. of Chicago, Chicago, IL
U Ma	Dept. of Meteorology, Univ. of Maryland, College Park, MD
U Wisc	Dept. of Plant and Earth Sciences, Univ. of Wisconsin, River Falls, WI
UA	Dept. of Hydrology and Water Resources, Univ. of Arizona
UC/NBI	Neils Bohr Inst., Univ. of Copenhagen, Copenhagen, Denmark
UCLA	Univ. of California, Los Angeles, CA
UCSB	Univ. of California, Santa Barbara, CA
UMC	Univ. de Magellanes, Punta Arenas, Chile
UMD	Univ. of Minnesota, Duluth, MN
UMM	Univ. of Minnesota, Minneapolis, MN
UN	Desert Research Inst., Univ. of Nevada, Reno, NV
UNH	Glacier Research Group, Univ. of New Hampshire, Durham, NH
USFS	U.S. Forest Service, Rocky Mountain Forest and Range Experimental Station, Fort Collins, CO
USGS/CVO	U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA
USGS/D	U.S. Geological Survey, Denver, CO
USGS/F	U.S. Geological Survey, Flagstaff, AZ
USGS/FC	U.S. Geological Survey, Fort Collins, CO
USGS/MP	U.S. Geological Survey, Menlo Park, CA
USGS/T	U.S. Geological Survey, Tacoma, WA
UT	Univ. of Texas, Austin, TX
UW	Univ. of Washington, Seattle, WA
UWy	Univ. of Wyoming, Laramie, WY

Submitted by J. Walder

INTERNATIONAL GLACIOLOGICAL SOCIETY

JOURNAL OF GLACIOLOGY

The following papers have been accepted for publication in the *Journal of Glaciology*:

R E BRANDT AND S G WARREN
Temperature measurements and heat transfer in near-surface snow at the South Pole

D DAHL-JENSEN, N S GUNDESTRUP, K R KELLER, S J JOHNSEN, S P GOGINENI, C T ALLEN, T S CHUAH, H MILLER, S KIPSTUHL, R H THOMAS AND E D WADDINGTON
A search in north Greenland for a new ice-core drill site

J A DOWDESWELL AND M WILLIAMS
Surge-type glaciers in the Russian High Arctic identified from digital satellite imagery

R F ELCONIN AND E R LACHAPELLE
Flow and internal structure of a rock glacier

H ENGELHARDT AND B KAMB
Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations

U H FISCHER AND G K C CLARKE
Clast collision frequency as an indicator of glacier sliding rate

S J FITZSIMONS
Depositional models for moraine formation in East Antarctic coastal oases

L W GOLD
Statistical characteristics for the type and length of deformation-induced cracks in columnar-grain ice

K GOTO-AZUMA, R M KOERNER, M NAKAWO AND A KUDO
Snow chemistry of Agassiz Ice Cap, Ellesmere Island, Northwest Territories, Canada

R GREVE
Large-scale ice-sheet modelling as a means of dating deep ice cores in Greenland

S HASTENRATH AND L GREISCHAR
Glacier recession on Kilimanjaro, East Africa, 1912, 1953, 1976 and 1989

U C HERZFELD AND H MAYER
Surge of Bering Glacier and Bagley Ice Field, Alaska: an update as of August 1995 and an interpretation of brittle deformation patterns

J F HIEMSTRA AND J J M VAN DER MEER
Pore-water controlled grain-fracturing as indicator for subglacial shearing in tills

A IKEN AND M TRUFFER
The relation between subglacial water pressure and velocity of Findelengletscher during its advance and retreat

M JACKSON AND B KAMB
The marginal shear stress of Ice Stream B

T JÓHANNESSON
The response of two Icelandic glaciers to climatic warming computed with a degree-day glacier mass-balance model coupled to a dynamic glacier model

J KLEMAN, C HÄTTESTRAND, I BORGSTRÖM AND A STROEVEN
Fennoscandian paleoglaciology reconstructed using a glacial geological inversion model

S KUMAR AND D P DOBHAL
Climatic effects and bed rock control on the quick fluctuation in Chhota Shigri Glacier, northwest Himalaya

B LEGRÉSY AND F RÉMY
Surface characteristics of the Antarctic ice sheet and altimetric observations

V YA LIPENKOV, A N SALAMATIN AND P DUVAL
Bubbly ice densification in ice sheets. 2. Applications

M E MANLEY AND E M SCHULSON
On the rate sensitivity of columnar ice

J A PIOTROWSKI AND A M KRAUS
Response of sediment to ice-sheet loading in northwestern Germany: effective stresses and glacier bed stability

M POURCHET, S K BARTARYA, M MAIGNAN, J JOUZEL, J F PINGLOT, A J ARISTARAIN, G FURDADA, V M KOTLYAKOV, E MOSLEY-THOMPSON, N PREISS AND N W YOUNG
Distribution and fallout of ^{137}Cs and other radionuclides over Antarctica

T RUOTOISTENMÄKI AND J LEHTIMÄKI
Estimation of permafrost thickness using ground geophysical measurements and its usage for defining vertical temperature variations in continental ice and underlying bedrock

A N SALAMATIN, V YA LIPENKOV AND P DUVAL
Bubbly ice densification in ice sheets. 1. Theory

W SCHÖNER AND M SCHÖNER
Effects of glacier retreat on the outbursts of Goësvatnet, southwest Spitsbergen

E M SCHULSON, S QI, J S MELTON AND E T GRATZ
Across-column cracks and axial splits in S2 saline ice under compression

C C SMART AND D B KETTERLING
A low-cost electrical conductivity profiler for glacier boreholes

A M SMITH
Variations in basal conditions on Rutford Ice Stream, West Antarctica

L C SMITH, R R FORSTER AND B L ISACKS
Seasonal climatic forcings on alpine glaciers revealed with orbital synthetic aperture radar

C VINCENT, M VALLON, F PINGLOT, M FUNK AND L REYNAUD
Snow accumulation and ice flow at Dôme du Goûter (4300 m) Mont-Blanc area

I M WHILLANS AND C J VAN DER VEEN
The role of lateral drag in the dynamics of Ice Stream B, Antarctica

A V WILCHINSKY AND V A CHUGUNOV
Modelling ice-divide dynamics by perturbation methods

YI CHAOLU
Subglacial comminution in till: evidence from microfabric studies and grain-size distributions

ANNALS OF GLACIOLOGY

The following papers have been published in Volume 24, *Papers from the International Symposium on Changing Glaciers* held at Fjærland, Sognefjord, Norway, 24–27 June 1996:

JOHN NYE
The Cambridge Austerdalsbreen expeditions, 1954–63

HANS KERSCHNER
Statistical modelling of equilibrium-line altitudes of Hintereisferner, central Alps, Austria, 1859–present

OLIVIER GAGLIARDINI AND JACQUES MEYSONNIER
Flow simulation of a firn-covered cold glacier

ANDREY N. SALAMATIN AND CATHERINE RITZ
A simplified multi-scale model for predicting climatic variations of the ice-sheet surface elevation in central Antarctica

ELISABETH SCHLOSSER
Numerical simulation of fluctuations of Hintereisferner, Ötztal Alps, since AD 1850

URS H. FISCHER, G. K. C. CLARKE
Stick–slip sliding behaviour at the base of a glacier

KEVIN M. FLEMING, JULIAN A. DOWDESWELL, JOHANNES OERLEMANS
Modelling the mass balance of northwest Spitsbergen glaciers and responses to climate change

ANNE-MARIE NUTTALL, JON OVE HAGEN, JULIAN DOWDESWELL
Quiescent-phase changes in velocity and geometry of Finsterwalderbreen, a surge-type glacier in Svalbard

Z. ZUO, J. OERLEMANS
Numerical modelling of the historic front variation and the future behaviour of the Pasterze glacier, Austria

J. OERLEMANS
A flowline model for Nigardsbreen, Norway: projection of future glacier length based on dynamic calibration with the historic record

J. F. PINGLOT, M. POURCHET, B. LEFAUCONNIER, M. CRESEVEUR
Equilibrium line and mean annual mass balance of Finsterwalderbreen, Spitsbergen, determined by in situ and laboratory gamma-ray measurements of nuclear test deposits

KATSUHISA KAWASHIMA, TOMOMI YAMADA
Experimental studies on the transformation from firn to ice in the wet-snow zone of temperate glaciers

RENJI NARUSE, PEDRO SKVARCA, YUKARI TAKEUCHI
Thinning and retreat of Glaciar Upsala, and an estimate of annual ablation changes in southern Patagonia

PEDRO SKVARCA, RENJI NARUSE
Dynamic behavior of Glaciar Perito Moreno, southern Patagonia

BEVERLEY UNWIN, DUNCAN WINGHAM
Topography and dynamics of Austfonna, Nordaustlandet, Svalbard, from SAR interferometry

KRZYSZTOF SZILDER, EDWARD P. LOZOWSKI, MARTIN J. SHARP
Glacial lake drainage: a stability analysis

RICHARD S. WILLIAMS, JR, DOROTHY K. HALL, ODDUR SIGURDSSON, JANET Y. L. CHIEN
Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973–92

J. R. REYNOLDS, G. J. YOUNG
Changes in areal extent, elevation and volume of Athabasca Glacier, Alberta, Canada, as estimated from a series of maps produced between 1919 and 1979

REGINE HOCK, CHRISTIAN NOETZLI
Areal melt and discharge modelling of Storglaciären, Sweden

GEORG KASER, CHRISTIAN GEORGES
Changes of the equilibrium-line altitude in the tropical Cordillera Blanca, Peru, 1930–50, and their spatial variations

V. M. KOTLYAKOV, G. B. OSIPOVA, D. G. TSVETKOV
Fluctuations of unstable mountain glaciers: scale and character

TSUTOMU KADOTA, KOJI FUJITA, KATSUMOTO SEKO, RIJAN B. KAYASTHA, YUTAKA AGETA
Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya

CECILIE ROLSTAD, JOSTEIN AMLEIN, JON-OVE HAGEN, BENGT LUNDÉN
Visible and near-infrared digital images for determination of ice velocities and surface elevation during a surge on Osbornebreen, a tidewater glacier in Svalbard

ANDRES RIVERA, HEINER LANGE, JUAN CARLOS ARAVENA, GINO CASASSA
The 20th-century advance of Glaciar Pio XI, Chilean Patagonia

ATSUMU OHMURA, MARTIN WILD AND LENNART BENGTSSON
Present and future mass balance of the ice sheets simulated with GCM

GINO CASASSA, HENRY BRECHER, ANDRES RIVERA, MASAMU ANIYA
A century-long recession record of Glaciar O'Higgins, Chilean Patagonia

CHARLES R. WARREN, ANDRES RIVERA, AUSTIN POST
Greatest Holocene advance of Glaciar Pio XI, Chilean Patagonia: possible causes

MARTIN P. KIRKBRIDE, CHARLES R. WARREN
Calving processes at a grounded ice cliff

KEITH A. BRUGGER
Predicted response of Storglaciären, Sweden, to climatic warming

TAVI MURRAY, DANIEL L. GOOCH, GRAHAM W. STUART
Structures within the surge front at Bakaninbreen, Svalbard, using ground-penetrating radar

JOHN WOODWARD, MARTIN SHARP, ANTHONY ARENDT
The influence of superimposed-ice formation on the sensitivity of glacier mass balance to climate change

WENDY LAWSON
Spatial, temporal and kinematic characteristics of surges of Variegated Glacier, Alaska

VINCENT ROMMELAERE, DOUGLAS R. MACAYEAL
Large-scale rheology of the Ross Ice Shelf, Antarctica, computed by a control method

NICK HULTON, DAVID SUGDEN
Dynamics of mountain ice caps during glacial cycles: the case of Patagonia

RICHARD R. FORSTER, LAURENCE C. SMITH, BRYAN L. ISACKS
Effects of weather events on X-SAR returns from ice fields: case-study of Hielo Patagónico Sur, South America

O. S. SAVOSKUL
Modern and Little Ice Age glaciers in "humid" and "arid" areas of the Tien Shan, Central Asia: two different patterns of fluctuation

MICHAEL J. HAMBREY, JULIAN A. DOWDESWELL
Structural evolution of a surge-type polythermal glacier: Hessbreen, Svalbard

BRANCH NEWS

Nordic Branch Meeting, 24–26 November 1996, Copenhagen, Denmark

The branch meeting took place at the newly renovated Rockefeller Complex in Copenhagen. In January 1996 the Department of Geophysics and its glaciology group became a department of the Niels Bohr Institute for Astronomy, Physics, and Geophysics and moved closer to this Institute. This now provides an opportunity to arrange international meetings.

The meeting was attended by 80 participants from the Nordic countries. Unfortunately no one from Iceland was present; not surprising as the great Icelandic jökulhaup had just started! Students were strongly represented and it was good to see that Nordic glaciology is now a field with a substantial number of female researchers and students.

A mixture of student reports, research reports, and unpublished material was presented. During the plenary closing session, the importance of presenting exciting and new results was mentioned; such contributions give the younger researchers inspiration and interest in attending the branch meetings.

The success of this Branch Meeting would not have been possible without close coordination and contact between Peter Jansson, Jon Ove Hagen, John Moore, and the undersigned. Funding for student travel was found and accommodation and meals were covered by the Geophysical Department.

The Branch dinner took place on board the old ferry *Sjælland* in Copenhagen harbour; dancing afterwards attracted many glaciologists. On Saturday, 24 people went on an historic-glaciological excursion in 6 private cars to the landscape around *Roskilde*, visited the historical Roskilde Cathedral and ended, just before it started raining, at the Viking Ships' Museum there. Most were surprised to see the great difference between the war ships and those for trade; the former, extremely long, slim, and flexible - clearly signalling speed and a war machine even after 900 years.

Although the weather was a bit humid and cold, everybody listened enthusiastically to Ole Humlum, the tour guide from the Geographical Institute of the University of Copenhagen. He chose an exciting and beautiful route through the country with dead-ice holes, moraines, tunnel valleys, outwash plains, and old Viking burial sites. In some ways, all we saw and heard about during the excursion was related to a time when the events and people were truly of Nordic origin.

Claus Hammer

Nordic Branch Meeting 30–31 October 1997, Oslo, Norway

The two-day Nordic Branch Meeting will be hosted this year by the Norwegian Water Resources and Energy Administration (NVE), the Norwegian Polar Institute (NP), and Oslo University's Geography Institute. It will be held Thursday and Friday, October 30–31, 1997, in the NVE and NP building on Middelthunsgate 29, Oslo.

The format will be strictly informal, with no abstracts required and no published volume to appear after the conference. We anticipate 40–50 participants, 20–30 minute talks with no flashing red lights, and plenty of coffee breaks. Presentations and discussions can be either in a Scandinavian language or in English The emphasis is on exchange of ideas and furthering cooperation between glaciological communities in the Nordic countries. Despite this Nordic thrust, researchers from anywhere in the world are encouraged to attend. Subject matter from all areas of glaciology are welcome, including glaciers, snow, sea ice, permafrost, glacial geology, polar meteorology, polar hydrology, etc.

Please register as soon as possible, no later than 1 September. We will be seeking funds to subsidize, either wholly or in part, lodgings and travel costs for Nordic participants. Those who register before the deadline will be eligible to have their costs reimbursed. Those who come at the last minute may not even get a chair!

Contact:
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Email: Jack.Kohler@nve.no

International Glaciological Society

INTERNATIONAL SYMPOSIUM ON GLACIERS AND THE GLACIATED LANDSCAPE

Kiruna, Sweden, 17–20 August 1998
Co-sponsored by City of Kiruna

FIRST CIRCULAR — February 1997

You are invited to attend the symposium. Please fill out the form below and return it to the Society as soon as possible. The Second Circular will give information about accommodation, the general programme, and preparation of summaries and final papers. Requests for the Second Circular should be sent to the Secretary General.

LOCAL ORGANISING COMMITTEE: Per Holmlund, Peter Jansson, Johan Kleman

TOPICS: The following topics will be open for discussion:

- Ice-covered landscapes
- Interpretation of glaciated landscapes
- Creation, reshaping and survival of subglacial forms
- Spatial and temporal variations in thermal regime
- Controls of wet base/cold base flow regimes
- Ice–substrate interaction

PAPERS: Papers from the Symposium will be published by the Society in the *Annals of Glaciology*. All papers (including poster papers) will be refereed and edited according to the Society's usual standards before being accepted for publication.

EXCURSIONS: A three-day post-symposium tour (21–23 August) by bus is planned which will cover an area from the Norwegian coast to the interior of Sweden. More details will be given in the second circular.

A one day pre-symposium excursion (16 August) will be available for a small number of participants. The tour includes a helicopter flight around the Kebnekaise mountain, landing on Storglaciären, and a short hike down to the Tarfala Research Station (TRS) where lunch will be served.

INTERNATIONAL GLACIOLOGICAL SOCIETY
SYMPOSIUM ON GLACIERS AND THE GLACIATED LANDSCAPE
Kiruna, Sweden, 17-20 August 1998

Family Name:		Tel:	
First Name(s):		Fax:	
Address:		Email:	
I hope to participate in the Symposium in August 1998	☐	I hope to join the post-symposium tour	☐
I expect to submit a summary of a proposed paper	☐	I wish to participate in the pre-symposium tour	☐

Secretary General
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NEWS

AWARDS

Mark Meier received the Horton Medal at the American Geophysical Union Fall Meeting in San Francisco in December 1996. It is awarded by the AGU for "outstanding contributions to the geophysical aspects of hydrology" and is the highest honour that Society can bestow upon hydrologists. Robert Horton was an outstanding American hydrologist who, among other things, developed the Horton–Strahler scheme for stream ordering. Mark Meier is the first glaciologist to receive this award.

Richard B. Alley has received the 1996 Horton Award from the Hydrology Section of AGU. This award is "given for an outstanding contribution to the science of hydrology".

Willy Weeks has been awarded the Ufi Belli Prize of the University of Alaska for research.

Glaciological Diary

1997

11–13 June

* Workshop on Remote Sensing of Planetary Ices: Earth and other Solid Bodies, Flagstaff, Arizona, U.S.A. (Wendy Calvin, United States Geological Survey, 2255 North Gemini Drive, Flagstaff, AZ 86001, U.S.A. Tel: [1](602)556-7000; Fax: [1](602)556-7014; calvin@flagmail.wr.usgs.gov; http://wwwflag.wr.usgs.gov/USGSFlag/Space/RSIce/rsice.html)

1–9 July

Glaciers of the Southern Hemisphere, Melbourne, Australia (A.G. Fountain, U.S. Geological Survey, PO Box 25046 MS–412, Denver, CO 80225, U.S.A. Tel: [1](303)236-5025; Fax: [1](303)236-5034; andrew@usgs.gov)

8–31 July

** IGS Western Alpine Branch, Tournée Bolivie (François Valla, CEMAGREF, B.P. 76, F-38402 Saint-Martin-d'Hères, France Tel: [33]76-76-27-21; Fax: [33]76-51-38-03; francois.valla@cemagref.fr)

13–18 July

* International Symposium on Antarctica and Global Change, University of Tasmania, Hobart, Australia (Antarctica and Global Change Symposium, Mures Convention Management, Victoria Dock, Hobart, Tasmania 7000, Australia Tel: [61](3)6234-1424 Fax: [61](3)6234-4464: http://www.antcrc.utas.edu.au/antcrc/events/antsymp.html)

5–8 August

2nd International Conference on Cryogenic Soils, Syktyvkar, Russia (Prof. I.V. Zaboeva, Institute of Biology, Komi Center, Russian Academy of Sciences, 167610 Syltuvkar, Komi Republic, Russia Tel: [7](821)22-25213; Fax: [7](821)22-25231; gilichin@issp.serpukhov.su)

18–22 August

11th Northern Research Basins Symposium and Workshop, Prudhoe Bay to Fairbanks, Alaska (D.L. Kane, Water Research Center, University of Alaska, Fairbanks, AK 99775-5860, U.S.A. Tel: [1](907)474-7808; Fax: [1](907)474-7979; dlk@aurora.alaska.edu)

10–12 September

IGS British Branch Meeting, University of Keele, U.K. (Andrew J. Russell, Department of Earth Sciences, Keele University, Keele, Staffs ST5 5BG, UK Tel: [44](1782)584303; Fax: [44](1782)715261; a.j.russell@keele.ac.uk)

20–25 September

Polar Regions and Quaternary Climates: Coupling between Northern and Southern Hemisphere Climates during the Last Climatic Cycle, Acquafredda di Maratea, Italy (Dr Josip Hendekovic, European Science Foundation, 1 quai Lezay-Marnésia, F-67080 Strasbourg Cedex, France Tel: [33]88 76 71 35; Fax: [33]88-36-69-87; euresco@esf.org; http://www.esf.org/euresco)

23–27 September

Workshop on River Ice, Fredericton, New Brunswick, Canada (Brian C. Burrell, Environmental Planning and Sciences Branch, Environment New Brunswick, P.O. Box 6000, Fredericton, New Brunswick, E3B 5H1, Canada Fax: [1](506)453-2390; brianb@gov.nb.ca)

30–31 October

** IGS Nordic Branch Meeting, Oslo, Norway (Jack Kohler, NVE, Glacier and Snow Section, P.O. Box 5091, Majorstua, N-0301 Oslo, Norway Tel [47](22)95-93-57; Fax: [47](22)95-90-81; jack.kohler@nve.no)

3–6 November

Polar Processes and Global Climate, Rosario Resort, Orcas Island, WA, U.S.A. (Roger Colony, International ACSYS Project Office, P.O. Box 5072 Majorstua, N-0301 Oslo, Norway Tel: [47](22)95-96-05; Fax: [47](22)95-95-01; acsys@npolar.no)

8–12 December

Special Session on Fast Glacial Flow, AGU Fall Meeting, San Francisco, CA (Peter U. Clark, Dept. of Geosciences, Oregon State University, Corvallis, OR 97331, U.S.A. Fax: [1](541)737-1200, clarkp@ucs.orst.edu; http:\\www.agu.org)

1998

9–11 January

Glacial Debris Transport and Deposition: Processes and Products. Joint meeting of the IGS British Branch, Quaternary Research Association, British Geomorphological Research Group and British Sedimentological Research Group, University of Leeds, UK (Tavi Murray, School of Geography, University of Leeds, Leeds, LS2 9JT, U.K. Fax: [44](113)233–3308; tavi@geog.leeds.ac.uk; http://www.geog.leeds.ac.uk/conferences/glacial98/glacial.htm)

13–17 February

4th Circumpolar Ecosystems in Winter Conference, Churchill, Manitoba (Michael Carter, Churchill Northern Studies Centre, P.O. Box 610, Churchill, Manitoba, R0B 0E0, Canada) Tel: 1-204-675-2307; Fax: 1-204-675-2139; director@cnsc.mb.ca; http://www.cnsc.mb.ca/CNSC)

14–16 May

25 years of Snow Avalanche Research at NGI, Voss, Norway (Meeting Management AS, Niels Juelsgt. 39, N-0257 Oslo, Norway Tel: [47]22-55-50-11; Fax: [47]22-56-35-10; kl@ngi.no)

24–29 May

8th International Offshore and Polar Engineering Conference, Montréal, Que, Canada (ISOPE-98, P.O. Box 1107, Golden, CO 80402–1107, U.S.A. Fax: 303-420-3760)

8–11 June

8th International Workshop on Atmospheric Icing of Structures (IWAIS), Reykvavík, Iceland http://www.rarik.is/iwais98/

23–27 June
7th International Conference on Permafrost, Yellowknife, N.W.T., Canada (J.A. Heginbottom, Terrain Sciences Division, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada Tel: 1-613-992-7813; Fax: 1-613-992-2468; heginbottom@gsc.emr.ca)

27–31 July
14th IAHR International Symposium on Ice, Potsdam, New York (H.T. Shen, Dept. Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699-5710, U.S.A. Tel: [1](315)268-6606; Fax: [1](315)268-7985; htshen@sun.soe.clarkson.edu)

17–21 August
** International Symposium on Glaciers and the Glaciated Landscape, Kiruna, Sweden (Secretary General, International Glaciological Society, Lensfield Road, Cambridge, CB2 1ER, UK)

24–28 August
* Symposium on Global Changes in the Polar Regions, Tromsø, Norway (IASC Secretariat, Postboks 5072, Majorstua, N–0301 Oslo, Norway Tel: [47]22-95-96-00; Fax: [47]22–95–96–01; iasc@npolar.no)

5–9 September
* Sixth International Symposium on Antarctic Glaciology (SISAG), China (Qin Dahe, Lanzhou Institute of Glaciology and Geocryology, Academia Sinica, 174 West Donggang Road, Lanzhou, Gansu 730000, People's Republic of China Tel: [86](931)882-2813; Fax: [86](931)888-5241; icecore@ns.lzb.ac.cn)

14–19 September
25th International Conference on Alpine Meteorology, Turin, Italy (ICAM 98 Scientific Secretary, Regione Piemonte - Servizio Meteoidrografico, C.so Unione Sovietica 216, I-10134 Torino, Italia Fax: [39](11)31-81-709; meteoidro@regione.piemonte.it)

5–8 October
* Snow Hydrology: The Integration of Physical, Chemical and Biological Systems, Hanover, NH, U.S.A. (Janet P. Hardy, Cold Regions Res. and Engineering Lab., U.S. Army Corps of Engineers, 72 Lyme Road, Hanover, NH 03755–1290, U.S.A. Tel: [1](603)646-4306; Fax:[1](603)646-4785; jhardy@crrel.usace.army.mil)

1999

22–25 August
* 6th International Symposium on Thermal Engineering and Sciences for Cold Regions, Darmstadt, Germany (Dr. Kolumban Hutter, Institut für Mechanik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany Tel: [49](6151)16-2991; Fax: [49](6151)16-4120; hutter@mechanik.th-darmstadt.de)

** IGS Symposium
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Recent and Future Meetings (of other organizations)

Workshop on Remote Sensing of Planetary Ices: Earth and other Solid Bodies

Flagstaff, Arizona, 11–13 June 1997.

The primary goal of the workshop is to bring together the terrestrial and planetary science communities whose focus is remotely sensed surface-ice research, including all icy solid bodies in the solar system. The workshop will address issues such as the current problems and objectives in surface-ice studies, methods and technologies currently employed, and future requirements for instrumentation, field studies, supporting laboratory measurements and theoretical modelling.
For further information see:
www.flag.wr.usgs.gov/USGSFlag/Space/RSIce/rsice.html
Wendy M. Calvin (wcalvin@flagmail.wr.usgs.gov)

Glaciers of the Southern Hemisphere (JMPH 18)

Melbourne, Australia, 7–9 July 1997

This symposium, convened by the International Commission on Snow and Ice under the auspices of IAHS, will highlight the programs and results of studies on alpine glaciers and ice caps in the Southern Hemisphere, including the tropics. The theme is glacier response to a changing climate. Papers addressing the mass balance, hydrology, hazards, global sea level, tidewater glaciers, and climate are encouraged. Site-specific and regional studies are of interest as well as those providing a long-term perspective of glacier change based on glacial-geologic studies and modeling efforts. A proceedings volume will be produced.
For more information see:
http://www.dar.csiro.au/pub/events/assemblies/
Andrew G. Fountain (fountaina@pdx.edu)

NATO School on Ice Physics

A NATO-sponsored Advanced Study Institute on "Ice Physics in the Natural and Endangered Environment" will be held 7–19 September 1997 at the Hotel Villa del Mare, in Maratea, Italy. Information on the rationale, the speakers and topics of the meeting, and application forms for attendance can be obtained at the Web site:
http://www.apl.washington.edu/natoice/natoice.html.

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