VIII Terrestrial component of the cryosphere

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1 Background

The terrestrial component of the cryosphere includes the seasonal snow cover, mountain glaciers, terrestrial ice sheets, frozen ground including permafrost (ground that remains frozen for more than one year) and seasonally frozen ground. In conjunction with projected changes in climate associated with enhanced atmospheric concentrations of greenhouse gases, the global areal extent and volume of these elements of the terrestrial cryosphere are expected to be substantially reduced (Climate Change: The IPCC Impacts Assessment, 1990). These reductions, when reflected regionally, could have significant impacts on related ecosystems (both natural and managed) and on social and economic activities. For example, the projected reductions in the area and volume of seasonal snow cover (including changes in the length of the season) and the recession of glacial ice sheets will impact on local and regional water resources. In the case of permafrost, projected increases in the thickness of the freeze-thaw layer above the permafrost and recession of permafrost to higher latitudes and altitudes could lead to increases in terrain instability, erosion and landslides in those areas which currently contain permafrost. These changes could alter overlying ecosystems and affect existing human settlements (structures) and development opportunities.

The study of the impacts of climate change on the terrestrial components of the cryosphere is in its infancy and there are many uncertainties regarding the relationships and sensitivities of snow and ice masses to climate and climate changes especially at the local and regional levels.

Limitations also exist in terms of our understanding of the environmental impacts (Koster 1991) and of socioeconomic consequences of changes in snow and ice masses. Addressing these uncertainties and limitations is essential to the development and implementation of appropriate response strategies.

2 Progress since the IPCC Impacts Assessment in 1990

2.1 Snow cover

Recent analyses (Cess et al. 1991) of the differences in the behaviour of General Circulation Models (GCMs) suggest that snow feedbacks include both the simple, direct positive feedback and indirect negative affects. The positive feedback hypothesis suggests that a decrease in snow cover makes the earth less reflective, causing it to warm as it absorbs more solar radiation and reflects less back out to space. Recent analyses reveal that some models suggest that clouds could redistribute themselves to cover those areas which were covered with snow thus reducing to some degree the positive feedback. Some of the models also suggest that decreases in snow cover could increase the amount of long-wave radiation emitted at the top of the atmosphere, which would lead to cooling of the Earth.

Robinson and Dewey (1991) examined a 20-year data set of satellite derived snow cover and found the extent of northern hemisphere snow to be at record low levels since the middle of 1987. The largest negative snow anomalies of late are occurring in the Spring.

Meteorological data gathered along the Mackenzie Valley in Canada over the past 50 years shows a long-term warming trend of up to 1°C (Stuart et al. 1991). Analysis of this data shows that along with this increase in air temperatures, snow cover has decreased in the Mackenzie Valley. Under this combination of climatic changes permafrost could grow, not diminish, in this region (Stuart and Judge 1992).

2.2 Permafrost

The raising of mean annual air temperatures by 2°C is projected to result in a shift of the southern boundary of permafrost areas in Russia approximately 250–300 km to the north and northeast. A warming of this magnitude is also expected to cause the receding of permafrost areas on the plateaus of Tjyan Shan and the vanishing of those in Pamir with only spotty discontinuous areas remaining. Based on mathematical models, permafrost could lose 2–6% of its 'cold reserves' during the period 1990–2040 as a result of projected global warming.

The above normal temperatures throughout much of the Northern Hemisphere in 1989 led to the initiation of extensive active layer detachment slides in Ellesmere Island, Canada, and in the Yamal Peninsula in the Russian Arctic. A thicker active layer intersected the top of massive ice triggering the failures which are continuing to spread in these areas. This condition, at least in the Yamal Peninsula, has led to the damming of streams, increased sediment loads in streams, and has initiated ongoing thaw and further failures.

Allen et al. (1988) have identified the growth and decay of permafrost in the Mackenzie Delta, Canada, over the past 75 000 years based on deep temperature records and the palaeoclimatic history. Rozenberg et al. (1985) have documented multilayered permafrost in the Mackenzie Delta, and Collett et al. (1988) have shown a similar structure over several thousand km^2 on the North Slope of Alaska.

Anisimov and Nelson (1990) and Stuart and Judge (1992) have used the frost index model to examine the circumpolar distribution of permafrost and to compare it for Eurasia and Amerasia. The advantage of the frost index is that it accounts for and couples both temperature and precipitation (snow cover). Further calculations have examined the change as predicted by the various GCMs.

Field studies using deep temperature records from boreholes (Taylor et al. 1989 and Taylor 1991) have demonstrated that recent sea-level changes in the arctic are preserved in these temperature records and that these temperatures can be used to estimate the retreat or advances of shorelines.

Studies of the isotope chemistry of carbon in the atmosphere suggests that up to 30% derives from old carbon (or earth) sources. In the tundra and northern taiga ecosystems there is an abundant reserve of carbon stored in moss, peat, and soil duff. The potential release of this carbon as a result of global warming and the associated increase in soil temperatures, increasing depth of the seasonal thaw layer, and improved drainage suggest increases in CO_2 emissions from these regions as a result of global warming. Currently, CO_2 data from global systematic observations identifies a maximum of annual mean CO_2 concentrations over the tundra and northern taiga regions around 70°N latitude and not between 20–60°N where the greatest majority of the emissions from human activities occurs.

Recent experiments indicate that a sharp increase in CO_2 emissions from deep freezing soil monolits occurs by warming them 4°C. This conclusion is supported by the increase in emissions that is observed in April as the temperature of the upper horizon of frozen deposits increases from -8°C to -4°C.

Emissions of methane from the earth's surface are currently estimated at 540x1012 g/year including 35x1012 g/year from tundra areas (Khalil and Rasmussen 1990 and Melnikov 1991). The annual flow rate of methane into the atmosphere from present-day sources within permafrost regions in Russia are estimated to be 9.2x107 m^3 or 6.1x104 tonnes (Glotov, in press).

The amount of methane within permafrost has not been extensively studied (examples of some studies, Archangelov and Novgoroda 1991 and Kvenvolden et al. 1992) with the majority of studies having been carried out in oil and gas fields for which methane is the target indicator. Recent investigations in Kolimo-Indigirka lowland area, have found methane in borehole samples at concentrations from 3.2 to 63.7 ml/dm^3 with the greatest concentrations in the turl-organic horizons. It appears that the stable zone of gas hydrate deposits in permafrost lies more than 100 metres below the surface where the temperature are between -10°C to -12°C.

In some regions of the arctic there is evidence which suggests that the continental shelves are warming as permafrost degrades. In the Canadian Beaufort Sea, shallow sediments are very gassy and several plumes emerging from the Russian shelves have been attributed to sudden emissions of methane due to hydrate degradation. Such emissions may themselves contribute to climate change in the short term and may indicate a trend towards accelerating hydrate decomposition on northern shelves. Climate warming accompanied by shelf warming as a consequence of increased meltwater input will accelerate this decomposition (Neave et al. 1978; Clarke et al. 1986; and Nisbet 1990).

2.3 Ice sheets

Some glacier-mass budget record lengths are now sufficient to be useful as a climate change indicator tool, having reached or exceeded the 'thirty-year norm' criteria. They can therefore serve as a background to test the climate change projections over broad areas. For example, there is good evidence now (Koerner and Brugman 1991) that glaciers in the Northern Hemisphere polar and subpolar regions are receding at a slower rate than previously suggested. In addition, all glaciers measured in Iceland between 1930 and 1960 were receding. Between 1960 and 1990, however, 25% have advanced.

The longest glacier record from northern Sweden identified only eight positive balance years between 1946 and 1980. In the ten years since then, six years have shown a positive balance. In the Canadian high Arctic (Koerner and Brugman 1991), thirty years of mass balance on two ice sheets show slightly negative balances with no significant trends. This evidence, which is substantial, is the opposite to that found from two years of similar measurements taken earlier—one in the 1970s and the other in the 1980s.

Observations from Kasakhstan (High Mountain Geocryological Laboratory) indicate that between 1955–1979 the glaciated area reduced by 13.7%, the number of glaciers diminished by 15.2% and the general volume of ice in glaciers reduced by 10.8%. During the same period, the volume of water flow from the glaciers increased from 295 to 340 billions m^3 annually (ie 15% increase). Continuing this rate of glacial ablation would suggest that the glaciers in Zailiisky Alatau would vanish over the next 200 years.

Although the Southern Hemisphere record is not as detailed as that for the Northern Hemisphere, work by Ruddell (1990) has shown that several New Zealand glaciers have retreated since the mid 1800s. In particular, a decrease in the volume of the Tasman Glacier is attributed to a warming in the order of 0.75°C, accompanied by a decrease in precipitation of about 10% since the middle of the last century.

3 Information and data gaps

In addition to those uncertainties associated with climate change (IPCC 1990), the limited state of knowledge and understanding of the sensitivity of polar and high-altitude regions, especially with respect to climate change, is restricting our capabilities to estimate the environmental impacts and therefore, socioeconomic consequences, of climate change as a result of changes in these components of the terrestrial cryosphere. Despite the large volume of literature, there is a limited number of accessible relevant datasets for scientific research. Future systematic observations and associated research should give priority to designing and implementing programs to provide the necessary data and, thereby, to increase our understanding of:

- basic cryospheric processes and phenomena;
- slope processes and mass movements;
- the emission and storage of carbon by polar and high-altitude ecosystems; and
- the associated changes in vegetation and wildlife community structures and functions.

With respect to permafrost, causes of changes in ground temperature profiles need further theoretical and field study to provide greater insight into when permafrost degradation will begin, at what rate it will occur and to what depth.

GCMs do not adequately incorporate atmospheric and cryospheric energy fluxes for polar regions encompassing vegetative terrain, snow cover, and ice sheets, with the complications of freeze/thaw. The coupling between the atmosphere and the cryosphere is therefore not well represented, leading to uncertainty in projecting the location, timing (including rate) and extent of snow cover disappearance, ice sheet ablation, soil temperature and moisture profiles, soil moisture movement and permafrost degradation.

Current efforts towards systematic observations and examining impacts of global change within the terrestrial cryosphere are not always undertaken in a coordinated fashion. The Arctic, for example, is largely omitted from the IGBP Planning Documents despite the enormous heat storage and release capabilities of the cryosphere. There are programs, however, which deal with many of these shortcomings. For example, WCRP is developing an Arctic Climate System Study (ACSYS) program and efforts are being made by IASC and the US NSF (Arctic System Science). These efforts and those with similar goals need to be encouraged and strengthened.

The number and areal coverage of long-term systematic observation sites in high-latitude and high-altitude regions are insufficient to provide more than qualitative and theoretical assessments of components of the terrestrial cryosphere and the impacts of climate change on them individually and together. Some such systematic observational efforts have been undertaken for permafrost (eg Mackay in the Mackenzie Delta of Canada, Pewe in the Fairbanks, Alaska, area and research by Pavlov and Melnikov in Russia). Existing observation programs need to be maintained and, where necessary, enhanced to provide the required long-term observation records. Additional sites, however, are required throughout the high-latitude and high-altitude regions. Particular emphasis should be given to addressing data gaps within priority areas, including the main population centres and transportation routes, providing areal coverage to encompass a linear transect through the discontinuous and continuous permafrost, and including areas in which there are major sheets and adjacent terrestrial and marine environments. Every attempt should be made to encourage the operation of these types of programs in a manner that promotes international cooperation and involvement, thereby providing the opportunity for intercomparison.

Comprehensive spatial data that will allow analysis of trends and spatial distribution of elements of the terrestrial cryosphere are especially limited. Remotely sensed data, although not yet fully developed, ultimately should provide the best approach to assessing responses and identifying potential risks over large areas quickly and frequently. A regional example of this type of program is the CRYSYS program developed by USA and Canada. The CRYSYS program has been conceived as a part of the Earth Observation Satellite Programme designed specifically to evaluate the impact of global change on the cryosphere.

As pointed out under the previous section, an important factor in the relationship between climate change and permafrost degradation appears to be the decomposition of marine gas hydrates, which results in the release of radiatively important gases to the ocean and atmosphere. Little is currently known about their distribution, chemistry and kinematics.

Uncertainties exist in our understanding of the relationship between glacier mass balance and climatological conditions. These uncertainties must be resolved to improve estimates of ice sheet ablation contributions to sea-level change and to local/regional hydrological regimes (especially important for those areas which depend on meltwater from the terrestrial cryosphere).

Our knowledge of the effects of the major ice masses on changing sea-level in the event of global warming is limited as a result of the uncertainties regarding the mass balance of the Greenland and Antarctic ice sheets. In fact, changes in the mass balance of the Greenland and Antarctic ice sheets are not certain even as to sign. A recent compilation of data concerning the Antarctic mass budget (areas of the Antarctic Peninsula have not been included in these calculations) by Bentley and Giovinetto (1991) has, however, concluded that the ice sheet currently exhibits a positive balance (ie an excess mass input) of 80 to 400 Gt/year, contributing a drop of 0.2 to 1.1 mm/year to sea-level change.

With respect to Antarctica, major deficiencies in the knowledge base can be attributed to lack of knowledge of the accumulation rate over most of Antarctica, the basal melting rate of the ice shelves, and the ice calving rate along the entire margin of Antarctica. For the Greenland ice sheet, insufficient information is available about the ablation rate (currently restricted to a few years of measurements at a few points) and the calving rates at the fast moving outlet glaciers (eg Jakobsavn).

These deficiencies make it virtually impossible to relate changes in the global glacier mass balance to sea-level change, either in the past or in the near future. Modelling cannot answer these questions until annual-to-decadal data on the surface profile of both Greenland and Antarctica are available. This data requirement will be realised only if and when the new generation of satellite altimeters are put into orbit some time in the next century. For Antarctica there is an additional need to improve the information available on snow accumulation rates and how they relate to synoptic weather patterns each year.

Historical accumulation data obtained retrospectively from ice cores can provide the perspective on natural accumulation rate variability which is needed to assess the significance of more recent changes. An essential aspect of this as well as other sampling or systematic observation programs, however, is communication of the resulting data or information. One notable shortcoming in this area for Antarctica is that accumulation rates for stations occupied since 1957 still remain unpublished (Jacka 1991, personal communication).

4 Responses to close information and data gaps

The collection, through internationally coordinated programs, of basic data on snow cover extent and volume, glacier behaviour, and permafrost temperatures, ice content and thickness is of utmost importance to improve our understanding and to improve models of climate-cryosphere relationships. Where possible, existing time-series of observations should be compared with recent and historical climate records to study the cryospheric responses to recent warming and specific climatological conditions. Current observational programs should be continued, while the extension of the global network with observations at new locations (particularly in the Southern Hemisphere) and by remote sensing (eg satellite, radar and photogrammetry) is strongly recommended.

Integrated research should be carried out on the side effects of fluctuations in snow cover, glacier size, and permafrost dynamics on, for example, the stability of slopes, runoff, the supply and transport of sediment, timberline ecotones, food chains, and on wildlife migration.

4.1 Snow cover

The natural variability and trends, if any, of continental snow cover changes is poorly known because of the short length of comprehensive data records (ie satellite observations from the 1970s to the present). To enhance these records, appropriate protocol to integrate surface observations with recent satellite data is needed to expand the temporal coverage. This is required not only for snow cover, but also for the other components of the terrestrial cryosphere.

Specific efforts should be directed at collecting the required data to help identify areal and altitudinal snow cover change trends. The required observation programs include continued systematic observations of snow extent and duration both by field observations and remote sensing, improved observation of snow depth/volume and water equivalent, and collection of data on mountain snow pack characteristics.

Work must also continue on assembling and analysing historic station-based observations of snow cover in order to provide a greater historic perspective to recent snow behaviour without having to wait decades to assemble a satellite set of suitable length. Of course, this can be accomplished only on a regional scale, but even on this scale the work would prove useful.

For remote sensing of snow cover extent and depth/volume, the hope is that microwave satellite data will provide the necessary information. This technique currently shows some promise but still requires some 'tuning' before reliable snow cover volumes can be obtained (eg in boreal forests and over tundra).

Another approach which should be applied to future snow observations employs geographic information systems techniques. These permit the amalgamation of remotely sensed data with traditional ground-based station observations, topographic data, vegetation information etc.

Further research towards understanding the impacts of climate change on regional and hemispheric snow covers is needed; research is also needed on the impacts of a changed snow cover on the climate system. Relationships between snow cover, surface and upper atmospheric temperature, precipitation, air mass characteristics and atmospheric circulation need further exploring with lengthy and spatially extensive datasets. Modelling efforts are also needed, with equilibrium and transient runs analysed for snow dynamics and additional runs geared specifically towards snow cover issues.

Snow cover research should examine the regional impacts of heat islands and land use on snow cover extent and duration. This information would be useful in the assessment of regional climate impacts, as well as establishing the stability of sites when it comes to analysing long-term records of snow.

Research is also needed to determine how variations in snow cover thickness and duration affect plant growth, food chains and wildlife migration.

4.2 Permafrost

Most, if not all, of the research gaps in permafrost and permafrost processes can be filled through implementation of internationally conceived and managed programs of geocryological systematic observations designed to provide the necessary data. Such programs should involve the full spectrum of support of international programs and agencies (eg International Permafrost Association, WMO and IGBP) as well as national agencies. The required observation program should allow for the collection of the data necessary to calibrate permafrost/atmospheric temperature and energy flux models, indicate something of the scale of permafrost changes, both temporally and aerially, and allow climate change projections to be verified.

The required observation program should comprise three basic components with observations distributed throughout the major permafrost areas of the globe including continuous, discontinuous, marginal and marine permafrost zones, as well as alpine permafrost areas in both the northern and southern hemispheres:

- a number of first order sites (primary nodes) similar to the current sites in Canada, the Gydan, Yamal site of VSEGINGEO and the stations of the Permafrost Institute in the USSR;
- second order sites which would help generalise observations at the primary nodes; and
- remotely sensed data to provide a more comprehensive picture (although this data has the lowest level of accuracy and resolution, it does provide the broadest areal coverage).

The objective of this program should be to provide the data necessary to answer questions concerning basic permafrost processes and the depth, rate and extent of permafrost changes that can be expected as a result of projected climate change.

Early in the international collaboration, common protocols for systematic observational processes and equipment need to be established for all three components of this observation program to allow for intercomparison of observations. Procedural guidelines for analysis and establishing quality and reliability will also be needed. Data collected should be reasonably accessible.

The observation program at the 'primary node' sites should consist of year-round meteorological observations of air temperature, precipitation, snow cover and surface radiative, sensible, latent energy fluxes, widespread observations of ground temperature, active layer depth, soils, vegetation, hydrology and ground ice characteristics.

Within the context of global change and the permafrost regions, it will be necessary to maintain systematic observation at the sites for at least ten years (preferably 20 years), depending on the data taken and the scale of the changes observed.

Widespread observations at 'second order' sites are needed to generalise the observations taken at the 'primary node' sites. Integral to the observation programs at these sites are frost-tubes which can measure the greatest depth of active layer development and thus provide an indication of the amount of energy absorbed by the near surface over a season. Boreholes drilled to a depth of 60–100 m should also be included as part of the observation program at these sites. Data from these boreholes can provide information on the historical characteristics of any ice present, on how the ground temperatures have changed over the past century and determine the presence and distribution of ice (especially when coupled with ground probing radar surveys).

With respect to the third component of the observation program—remote sensing—the use of surface geophysical methods such as electromagnetic soundings and ground probing radar are beginning to provide knowledge of the local continuity of permafrost and ground-ice conditions. Several recent papers have demonstrated this capability (Rozenberg et al. 1985; LaFleche et al. 1987; and Todd et al. 1992). Repeated surveys with such equipment can provide early warning of changes in the subsurface, especially in the vicinity of structures (Judge et al 1991).

Both the primary and secondary component sites of the suggested observation program can also provide the ground-truthing for airborne and satellite-borne observations of landscape, snow, ground temperature, vegetation and shallow permafrost conditions.

Systematically observing the temperature, geometry and creep of permafrost at selected sites in alpine regions is a necessary component. Internationally coordinated systematic observation programs should be developed in various mountain areas of the world, especially with respect to borehole data and rock glacier photogrammetry.

National, regional and international integrated research programs should be directed at examining the processes and dynamic changes and interaction between the atmosphere, the biosphere and the cryosphere. This research should include modelling the heat and energy balance of permafrost; conducting integrated research on the impact of permafrost changes on terrestrial and coastal ecosystems (ie on the interrelations in the atmosphere - buffer zone - permafrost system); identifying processes causing changes in ground temperature profiles; and improving methodologies to observe changes systematically in permafrost extent and thickness, to determine ice content of permafrost (globally) and to determine the chemical characteristics of ground ice/permafrost areas.

Attempts to measure and model the heat and energy balance of mountain permafrost must accompany systematic observational activities in order to reach a better understanding and interpretation of the collected data. Sensitivity studies concerning the thermal and mechanical reaction of ice-rich permafrost on slopes in relation to reasonable scenarios of projected climate change will be possible in the near future. Such an approach requires systematic collection of the increasing amount of information on permafrost occurrence, and the design of computer-compatible algorithms for predicting permafrost distribution in mountain areas using digital terrain models in combinations with geographic information systems and—preferably infra-red—aerial photography. The same models would be able to show where anticipated warming trends could lead to rapid active layer thickening or even complete permafrost degradation. The corresponding information would form an important basis for directing attention towards especially sensitive areas and for improving systematic observation programs as a whole.

For impacts research studies, efforts should be directed towards systematic observations of structures (linear and buildings) within permafrost areas and the impacts of changes in the underlying permafrost on the stability of those structures. Research should be intensified on environmental factors and physical processes (eg soil temperature, thermal conductivity of soil layers, soil-moisture balance, active layer dynamics, thermokarst erosion) and their impacts on the accumulation and decomposition of peat, and the production of carbon dioxide and methane. This includes controlled experiments in the field as well as analysis of permafrost and peat cores.

In the case of permafrost, analyses indicate that changes in its characteristics are primarily determined by changes in climate and vegetative cover. The ability to separate the influences on permafrost temperature of changes in vegetative cover from those caused by changes in climate suggests that permafrost temperature can be a reliable indicator of climate change and can be used to reconstruct past climates. Collaboration among scientists working on climate change detection and those working on permafrost dynamics is essential to tapping this potential.

4.3 Ice sheets

More statistical work is needed on the existing glacier data (two separate components of accumulation and ablation) to improve our knowledge of recent and projected climate changes, especially in the polar regions where data from other disciplines is especially sparse. Glacier-mass budget data must also be tied in with that derived from ice-core data to extend our knowledge of past climate change and place the present changes into true perspective (eg a recent study of ice cores from Wilkes Land, Antarctica, (Morgan et al. 1991) indicates increased snow accumulation since 1960, compatible with the mass input increase reported by Bentley and Giovinetto (1991)). The present warm period in the Canadian high Arctic is still considerably cooler than the climate there for over half the interglacial period beginning 10 000 years ago. The ice core record also shows that the short period immediately preceding the present warm one was the coldest for several thousand years. It appears that the present glacial recession is from major advances that took place during that cold period (Koerner and Fisher 1990). Seen in that context the present warming trend is not unusual.

Presently, the accurate measurement of the mass balance of Antarctica and Greenland is unattainable. The measurement of mass balance on small glaciers and ice sheets forms a powerful tool for detecting early signs of climate change of the nature projected by climate models as it represents an integration of the total energy flux over each glacier or ice cap. The two components of glacier balance—ie accumulation and ablation (ice or snow loss)—constitute measures of two separate parameters of the projected climate change (ie change in precipitation rate - substantially higher in the polar regions) and measurable higher ice/snow melt rates in summer. This is particularly important in polar glaciers as they are located in areas where the maximum climate change is projected to occur. To improve their effectiveness as indicators, it will be necessary to identify those changes resulting from local catchment characteristics and microclimate which can dominate climate change for many decades.

Changes of area and thickness on parts of dynamic glaciers are difficult to relate directly to climate change unless the response time of the glaciers is well known. Increasing thickness in the accumulation areas of southern Greenland (Zwally et al. 1989) contrast with decreasing thickness in the ablation zone below this (Lingle et al., in press). In the Canadian Arctic the accumulation areas of those ice sheets measured during the past 30 years show no evidence of changing elevation. Some glaciers, however, show a surface lowering in the ablation zone (Koerner 1989). Such measurements, when repeated, indicate whether precipitation and/or summer melting rates are changing. They complement mass balance observations.

It is still questionable, however, whether satellite measurements provide the desirable accuracy to detect surface elevation changes, particularly on small ice sheets where the required resolution could limit the usefulness of satellite- derived observations. Modern geodetic techniques or repeated precision-gravity measurements, coupled with GPS should be used to provide overlap with future satellite mapping using improved satellite sensors.

The gravity/GPS technique is presently being used on ice sheets in the Canadian Arctic and at seasonal Antarctic sites to detect elevation changes at the tops of ice sheet summits. Vertical (elevation) resolution also limits the use of satellite and GPS in areas where accumulation rates are low (ie <20 g cm2y−1) as changes in both the accumulation rate and elevation will be even lower.

To improve understanding of ice sheet and glacial changes and the impacts thereof, it is essential that existing long-term systematic observations programs be continued and that programs for representative glacier mass balance changes and associated climatic and hydrologic variables be expanded to provide a truly global network. This data should be supplemented with data derived from ice sheet elevation surveys by satellite (laser) altimetry such as that on the EOS/ERS series. Efforts should also be directed at improving systematic observations and assessments of iceberg calving from the Antarctic and Greenland ice sheets.

Enhanced integrated research programs at the national, regional and international levels should be directed towards examining the effects of glacier size fluctuations on the upper and lower drainage basin dynamics and continuing studies on the frequency and intensity of mass movements in relation to extreme meteorological events. Particular emphasis should placed on promoting research in the slopes of high mountain regions aimed at better hazard (flooding, slope failure) appraisal.

The means of encouraging and, where necessary, facilitating the required support for these activities should be the subject of international dialogue. Specific requirements, recommendations, priorities and their implications (globally and regionally) including considering both the needs and resource (human and monetary) requirements should be the subject of this dialogue.

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