Introduction to the world glacier inventory

F. Müller and K. Scherler

Abstract. The development of the world glacier inventory project is reviewed and its main objectives – water balance, practical application, and monitoring of climate – are discussed. Some of the problems still awaiting solution are appraised.

Introduction à l'inventaire mondial des glaciers

Résumé. Le développement de l'inventaire mondial des glaciers est tracé et ses buts principaux – bilan hydrologique, surveillance du climat, emploi pratique – sont discutés. Quelques problèmes à résoudre sont présentés.

HISTORIC NOTES

The first efforts to organize a standardized assessment of the amount and distribution of the perennial snow and ice masses on a worldwide scale were made in 1955 by the Comité Spécial de l'Année Géophysique Internationale, preparatory to the 1957 *International Geophysical Year* (IUGG, 1956). Member countries having glaciers within their national boundaries were asked to record, as a minimum: location and elevation, area, volume, activity measurements and any other observations of glaciological and meteorological value.

Subsequently, eight countries prepared glacier inventories, though of different levels of completeness and detail: Mexico (Lorenzo, 1959), Canada (Falconer *et al.*, 1958), Italy (Comitato Glaciologico Italiano, 1959–1962), Argentina (Bertone, 1960; Colqui, 1962), USA (Meier, 1961), Norway (Hoel and Werenskjold, 1962), USSR (Vinogradov and Psareva, 1965) and France (Vivian, 1967).

Amongst the various pre-International Hydrological Decade attempts to provide a global summary of the existing snow and ice masses (Flint, 1963; Thiel, 1962; Corbel, 1962; Bauer and Lorius, 1964), that compiled by Shumskiy *et al.* (1964) may be considered the most reliable. The large differences in values cited in these summaries (some 10 per cent range in total area covered by ice and as much as 20 per cent for the non-polar glacierized areas, i.e. those most important to man) must be attributed to incompatibility of assessment methods, map quality and instrumentation. All too frequently, rough estimates were incorporated for the lesser known areas without clear indication.

The *International Hydrological Decade (IHD, 1965–1974)* brought new impetus to the glacier inventory: the Coordinating Council for the IHD recommended on the basis of Resolution I-12, that member states undertake 'mapping of permanent snow and ice masses and the compilation and assemblage of data for publication in order to obtain the elements necessary for the establishment of the regional distribution of permanent snow and ice in various territories and the degree of accuracy in each area' (UNESCO, 1964). In May 1966, the International Commission on Snow and Ice (ICSI), asked by UNESCO's IHD Secretariat to organize this task, set up a working group under the chairmanship of F. Müller to prepare guidance material. The resulting *Guide for the Compilation and Assemblage of Data for a World Inventory of Perennial Snow and Ice Masses,* published by UNESCO/IAHS (1970a), prescribes standard measurements for some 40 glacial parameters and includes a matrix type classification. Part II gives instructions for an inventory of ice beneath the surface.

A most timely *Symposium on Glacier Mapping,* held in Ottawa in September 1965, jointly sponsored by ICSI/IAHS and the Canadian Associate Committee on Geodesy and Geophysics of the National Research Council, encouraged glacier mapping at different scales and with sufficient accuracy to serve as a basis for the IHD glacier inventory task (NRC, 1966). A photogrammetric-cartographic documentation of as many glaciers as possible, particularly of those near human habitation, was advocated. At the same time, attention was drawn to the great potential of satellite imagery and other remote sensing techniques for the assessment of glaciers in remote areas and in particular for the large ice sheets of Antarctica and Greenland. Thus the Symposium on Glacier Mapping must be considered an important forerunner to the present Workshop on the World Glacier Inventory. Recently, a highly successful innovation has further advanced glacier mapping: the orthophoto and stereo-orthophoto technique (Blachut, 1976).

At the 1970 mid-IHD *World Water Balance Symposium* held in Reading, UK, an encouraging status report on the world glacier inventory was presented (Müller and Ommanney, 1971). Many countries had inaugurated a national glacier inventory and a few had made substantial progress: the USSR reported 30 of a series of about 100 volumes of glacier inventory data completed; Norway had recorded approximately half of the glaciers in accordance with the UNESCO guide (Østrem and Ziegler, 1969), and for Canada, large areas had already been documented (Ommanney, 1969; Ommanney *et al.,* 1969).

Since May 1968, the ICSI officers at their annual meetings with UNESCO consistently expressed their firm believe that a *Temporary Technical Secretariat (TTS)* was needed to:

- coordinate and assist national inventories
- collect and standardize the data
- make the data computer compatible in one system
- produce a global summary
- initiate analysis.

In May 1973, ICSI/IAHS submitted a resolution to this effect to the IHD Coordinating Council, which was passed. Though the financing of the TTS was not yet fully solved, ICSI appointed F. Müller (Zürich) as director, to start this task as soon as possible. A subsequent resolution passed by IUGG at the August 1975 International Congress in Grenoble recommended 'that member countries, and the relevant international organizations (ICSU, UNEP, UNESCO and WMO) cooperate with the TTS, and assist ICSI in obtaining financial support'. This support was forthcoming from UNEP, UNESCO and some member states, so that in October 1976 TTS could commence operations at the Swiss Federal Institute of Technology, in Zürich.

THE OBJECTIVES

The importance of the world glacier inventory was recognized to be threefold:

(1) To increase the knowledge of the local, regional and global *water cycle and balance.*
(2) To serve as a data base for *practical purposes,* such as the planning of fresh water resources, hydropower, irrigation, disaster prevention and recreational facilities.
(3) To provide data for the *study of climatic processes* and for *monitoring climatic change.*

The *hydrological balance* equation, broadly formulated by Müller and Ommanney (1971) as

$$\left|\begin{matrix}\text{water}\\ \text{input}\end{matrix}\right|_{\text{net}} + \left|\begin{matrix}\text{snow and}\\ \text{ice input}\end{matrix}\right|_{\text{net}} + \left|\begin{matrix}\text{change in}\\ \text{liquid storage}\end{matrix}\right| + \left|\begin{matrix}\text{change in snow}\\ \text{and ice storage}\end{matrix}\right| = \text{water yield}$$

assigns a decisive role to the seasonal snow cover, the perennial snow and ice masses and to sea, lake and river ice. The guides prepared by ICSI working groups and published by UNESCO/IAHS (1969, 1970a and 1971) prescribe, in fact, the recording of all snow and ice members of the above equation. The assessment of snow and ice at the global level is highly complex due to the wide range in duration (hours to thousands of years) of various snow and ice bodies and the large spatial changes (from a few per cent to a quarter of the earth's surface). However, as about 80 per cent of the fresh water on the earth is stored in the form of snow and ice (99 per cent of the latter in glaciers), there is a rapidly growing practical need for a snow and ice, or rather in the first place, a glacier inventory. Batisse (1964) predicted, based on a pre-IHD study by UNESCO, that the growth of world population, industry and agriculture would double the water requirements in 20 years; recent trends are corroborating this. Thus, the world glacier inventory with the practical objectives of contributing to the better assessment of the fresh water reserves and furthering their more rational utilization becomes an integral part of UNESCO's IHP (International Hydrological Programme), the follow-up of the IHD.

The importance of the glacier inventory for the study of climate is discussed in detail below.

A TOOL FOR MONITORING CLIMATE AND CLIMATIC CHANGE

In a recent paper, Radok (1978) reviews the climatic roles of ice and snow. UNEP and WMO convened a Government Expert Meeting on Climate-Related Monitoring, in Geneva in April 1978, to discuss basic concepts, objectives and proposals for future action programmes (UNEP/WMO, 1978). Climate-related monitoring was recognized as an integral part of the even larger international programme known as GEMS (Global Environmental Monitoring System). Monitoring of changes in the cryosphere is to be given considerable attention. How can the world glacier inventory serve this purpose?

For more than 200 years (see Walcher, 1773), glaciers have been referred to as 'climatoscopes', sensitive indicators of climatic change. Though there is no doubt about the general validity of this statement, the quantitative assessment of the relationship between glaciers and climate still needs considerable clarification. A schematic, qualitative representation (Fig. 1) reveals in the chain of causal dependences the complexity of this relationship and demonstrates the need for long-term measurements of mass balance and climatic parameters on the mesoscale, as prescribed by the ICSI working group on Combined Heat, Ice and Water Balances at Selected Basins (UNESCO/IAHS, 1970b and 1973). Clearly, this task is outside the range of the glacier inventory project. But the inventory can, as shown below, be used to evaluate the representativeness of the glaciers selected for mass balance and tongue fluctuation measurements.

The main contribution of the inventory to the study of the glacier–climate relationship will derive from the *statistical* analysis of the first and the last members of the chain shown in Fig. 1. (For the intermediate members there are rarely enough data available for statistical treatment.) The *investigation of the spatial distribution and the changes in time of both the regional and local climate and the glacier dimension parameters* necessitates sets of comparable data to be analysed according to the Fig. 2 flow diagram. Consequently, glacier inventories must be repeated at carefully chosen

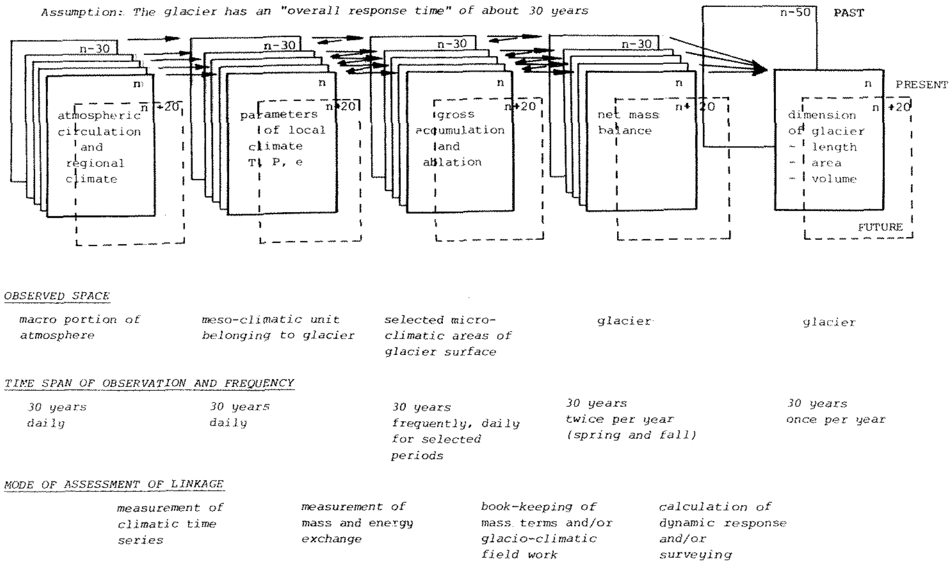

FIGURE 1. Relationship between climate and glacier.

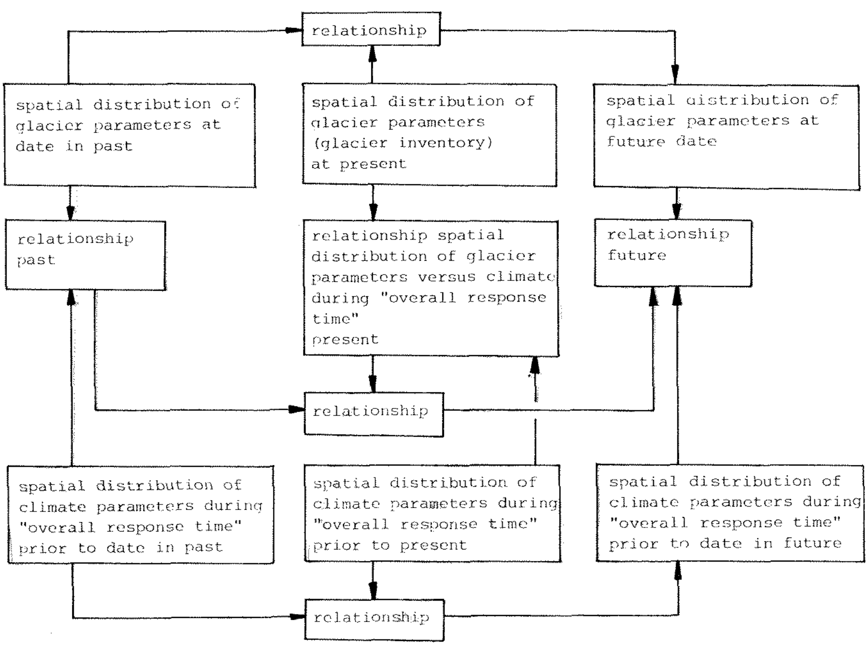

FIGURE 2. Flow diagram for glacier–climate relationship study (modified from Müller *et al.*, 1973).

times in the future and during the interim periods the data from detailed monitoring of tongue position, area and mass balance of selected glaciers, recorded by the Permanent Service on the Fluctuations of Glaciers (PSFG), will provide the linkage.

This model, as simple and convincing as it may seem at first sight, embodies some difficulties: as indicated by the Fig. 1 scheme, the dimensions of a glacier at a given time are the result of interactions of various climatic, glaciological and also orographic parameters, over as many preceding years as the 'overall response time' demands. The length of this 'influence time' varies primarily with the size of the glacier. For a snow patch, it may be only one year, for a medium-sized glacier some tens of years and for a large glacier centuries to millennia. It is a *sine qua non* of inventory analysis that only comparable data sets are collated, i.e. the data must be grouped in classes preparatory to the relationship studies depicted in Fig. 2.

One of the most effective methods for the quantitative assessment of spatial distributions is *trend surface analysis.* Until recently, lack of adequate data precluded its use in the study of the glacier–climate relationship. A possible application of this technique is shown in Fig. 3. The spatial distribution of each parameter (1 to *n*) for a given area, e.g. the Swiss Alps, can be described by a main trend and then explained with the aid of the other parameters (*a* to *z*). Discrete trends can be obtained for individual regions, giving more precise information on the spatial distribution of particular parameters, e.g. the median elevation of glaciers. The division into regions and subregions is based on a critical analysis of the main trends of the next larger unit. The deviations of individual or group values from the calculated trend surface (i.e. the residual values) reveal important local effects. Using this method, both representative glaciers and those with unusual characteristics can be selected and thus appropriate monitoring programmes can be set up much more successfully than previously.

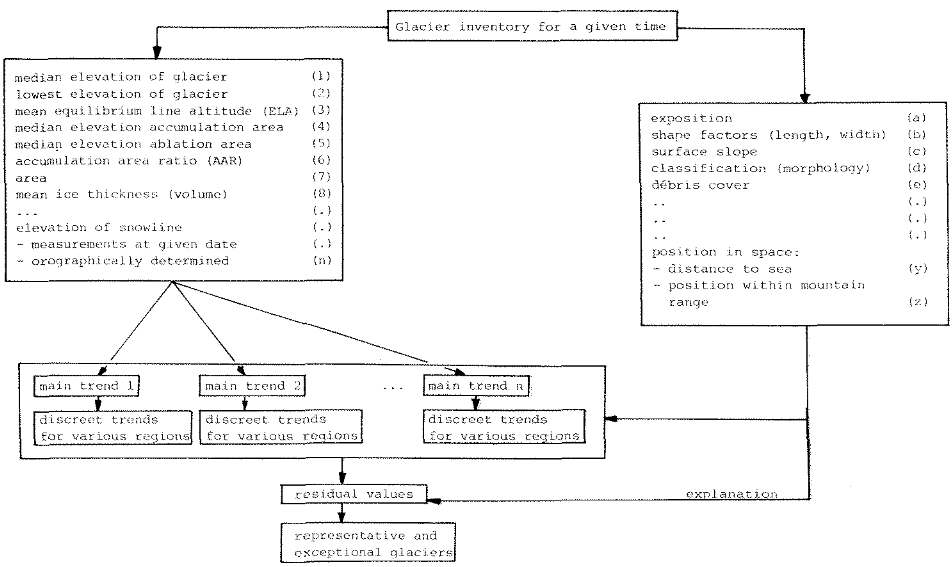

FIGURE 3. 'Trend surface analysis' diagram for the quantitative study of the spatial distribution of the glacier parameters (modified from Müller *et al.*, 1973).

SOME DIFFICULTIES

Timing

The required 'comparable data' would be best obtained by the various national inventories being carried out for one particular year. This is clearly not feasible. The differences in age of the available resource materials (maps, air and ground photographs, field measurements) are such that a time span of several decades must be accepted. For many of the current inventory projects, source materials dating back to the 1950s and 1960s are being utilized. Other countries will only start their inventories in the 1980s. It is still hoped that the current world glacier inventory can be labelled with a clear peak date. The main purpose of the present effort, however, is to establish a datum on which it is possible to build backwards and forwards in time. Unfortunately, owing to shifts in the timing of the inventory work in different areas the results are likely to be more suitable for regional than for global analysis.

Source material
The quality differences from region to region in the maps, photographs etc. on which the inventory is based are such that strongly heterogeneous data will result, again more appropriate for regional than global analysis. For future research, it is vitally important to identify and record in detail the quality and date of the base material.

Snow line
The identification of the snow line depends on the availability of photographs of suitable quality. Very few countries can arrange a special photographic air survey at the time of highest elevation of the transient snow line as was done for the Swiss inventory (Müller *et al.,* 1976). Meier (1973) demonstrated that satellite pictures may be able to supply the required data. The Swiss investigations indicate, however, that there are limitations to the snow line as a glacier parameter. The climatic snow line and the more readily available mean and/or median elevations of the glacier are possibly of greater relevance for the inventory programme. This does not mean that efforts to obtain snow and firn line data should cease.

Mean glacier depth
The empirical relationship between the surface area and the mean depth according to a primary classification, as advocated by the UNESCO/IASH (1970a) guide and discussed by Lagarec and Cailleux (1972), may produce useful volume data, though of limited accuracy. The development of glacier volume formulae based on the plasticity theory and flow laws of ice, commenced by Brückl (1970, 1973), is an urgent necessity. For this purpose, more test data than presently available from different regions are required.

Adaptation of the guide
As the inventory guide was applied in new areas, shortcomings of the original instructions (UNESCO/IAHS, 1970a) came to light. Hesitantly, and only after careful consideration, a revised guide was issued (Müller *et al.,* 1977). Improvements and clarifications were made in the identification system, the delineation of glaciers and in the instructions for data presentation. For a project with some 40 participating countries, however, changes to the instructions must be kept to an absolute minimum. The present workshop provides opportunity for discussion of some pending problems in applying the guide. Further adjustments are only warranted if they are globally applicable. Where national or regional requirements demand changes, this should be reported when the data are submitted to TTS.

RELATIONSHIP OF TTS TO PSFG

For the purpose of compiling the steadily growing amount of mass balance and glacier fluctuation data which form an essential counterpart to the glacier inventory, the Permanent Service on Fluctuations of Glaciers (PSFG) was established in 1967 in Zürich, Switzerland. This archive and data bank contains records on glacier tongue fluctuations started by ICSI in 1895 and serves as a depository for the mass balance data of some 100 glaciers around the world. These are predominantly located in three chains: one stretching through the western mountains of the Americas from Arctic

Alaska to the Antarctic Peninsula, one extending from the Tien Shan and Pamir Mountains westward through Europe to the west coast of North America in the latitudinal belt 35° and 55°N, and the third extending from the Polar Urals westward through Scandinavia, Iceland and Greenland, and then swinging northward through the Canadian Arctic Archipelago. The PSFG publishes a summary of this global set of data at five-yearly intervals. So far, in addition to the early ICSI records, three volumes have appeared (Kasser, 1968, 1973; Müller, 1978).

For the glacier–climate relationship studies it is important to make parallel progress with both the world glacier inventory and the work of the Permanent Service on Fluctuations of Glaciers. Fortunately, PSFG and TTS are – and should remain – located together, at present in the ETH Zürich, thus fostering close cooperation between the two organizations. When the present world glacier inventory draws to an end in a few years' time, it is mandatory that the data be deposited and amalgamated with that of the PSFG.

Acknowledgement. Countless discussions with and hard work by Toni Caflisch, Gerhard Müller and many other members of the TTS office staff, as well as the fine collaboration of colleagues and experts from around the world – as one of many, C. S. L. Ommanney (Canada) is mentioned – have shaped and advanced the world glacier inventory. Particular thanks go to C. C. Wallén (UNEP), J. A. da Costa (UNESCO), J. A. Rodier (IAHS), M. F. Meier, J. F. Nye and U. Radok (all ICSI), who untiringly supported this endeavour.

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The World Glacier Inventory contains information for over 130,000 glaciers. Inventory parameters include geographic location, area, length, orientation, elevation, and classification. The WGI is based primarily on aerial photographs and maps with most glaciers having one data entry only. The data set can be viewed as a snapshot of the glacier distribution in the second half of the twentieth century. It was founded on the original WGI from the World Glacier Monitoring Service. Acknowledgements. The National Snow & Ice Data Center continues to work with the World Glacier Monitoring Service t ABSTRACT. The World Glacier Inventory (WGI) was conceived half a century ago as an activity to be completed during the International Geophysical Year, 1957/58. It consisted until very recently of nearly 70 000 glacier records covering slightly less than one-quarter of the glacier ice outside the ice sheets. A complete WGI must be a compromise if it is to be available and usable soon.Â INTRODUCTION. I present here an enlarged version of the World Glacier Inventory (WGI), in which several recently published, some rescued and some new regional inventories are assimilated into the original material. The new inventory has an extended format which promotes ease of use by prescribing low-level details of data storage, giving it its acronym, WGI-XF. Glacier inventories provide essential baseline in-formation for the determination of water resources, glacier-specic changes in area and volume, climate change impacts as well as past, potential and future contribution of glaciers to sea-level rise.Â 1 Introduction. Glaciers and ice caps (GIC in the following) are key indica-tors of climate change (e.g. Lemke et al., 2007), important water resources and their melt water could potentially make a substantial contribution to sea-level rise during this cen-tury (e.g. Meier et al., 2007; Hock et al., 2009; RadicÂ´ and Hock, 2010).Â Due to the lack of complete inventory data (the DCW was never used for that purpose) the total area covered by local GIC on Greenland has been assessed by a range of (not al-ways fully documented) techniques.