WORLD CLIMATE PROGRAMME

APPLICATIONS

ANALYZING LONG TIME SERIES OF HYDROLOGICAL DATA WITH RESPECT TO CLIMATE VARIABILITY

PROJECT DESCRIPTION

WCAP - 3

WMO/TD-No. 224

WORLD METEOROLOGICAL ORGANIZATION

(February 1988)

The World Climate Programme launched by the World Meteorological Organization (WMO) includes four components:

The World Climate Data Programme
The World Climate Applications Programme
The World Climate Impact Studies Programme
The World Climate Research Programme

The World Climate Research Programme is jointly sponsored by the WMO and the International Council of Scientific Unions.

1. INTRODUCTION

1.1 The World Climate Programme (WCP) was established by Eighth Congress "to assist societies to improve their capabilities to carry out various activities and to obtain maximum economic and social benefit under different climatic conditions while maintaining environmental integrity". Congress has decided that the WCP should have the following four components:

- World Climate Data Programme (WCDP): WMO

- World Climate Applications Programme (WCAP): WMO

- World Climate Impact Studies Programme (WCIP): UNEP

- World Climate Research Programme (WCRP): WMO/ICSU

The organizations having the lead role and responsibility for each being as shown above.

1.2 Climate and the world's water-resource system have a special relationship insofar as water resources depend on the hydrological cycle which is itself part of the climate system. Hence there are hydrological and water-resource aspects in all four components of the WCP. In order to facilitate the necessary co-ordination, all water-related activities in WCP are commonly grouped under the general title World Climate Programme - Water (WCP-Water). The basic aim of WCP-Water is "to meet more effectively the socio-economic needs which depend on water-resource systems, through the improved application of climate data and information."

1.3 Within WCP-Water, two projects are to be undertaken which involve the analysis of long time series of hydrological data, namely:

Project A.1 Analyzing historical hydrological and related information with respect to climate change (IAHS* responsible)

Project A.2 Analyzing long time series of hydrological data and indices with respect to climate variability (WMO responsible)

Summary descriptions of these two projects, as proposed by meetings of experts and representatives of the organizations concerned, are given in Appendix A.

1.4 Project A.1 is concerned with the study of very long time series of data, both hydrological data and proxy data, with a view to identifying and analysing changes in climate. Project A.2 is confined to hydrological and related data which normally do not extend for much more than 100 years. The latter project, which is the subject of the document, is therefore limited to a consideration of climate variability (see paragraph 2.6 for definitions).

1.5 The purpose of WCP-Water Project A.2 is to improve our knowledge of hydrological variability in the context of climate variability. As river basins integrate local meteorological variability, there is also the consideration that flow data represent filtered climate data. A more detailed formulation of the main aims of the project would be:

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* International Association of Hydrological Sciences

(a) To provide information to hydrologists and water-resource planners, concerning the effects on hydrological systems of climate variability;

(b) To provide information to meteorologists, concerning evidence of possible trends in climate variability contained in hydrological and related time series; and

(c) To encourage countries and their national agencies to store and analyse long time series of hydrological and related data so that this information is readily available for use in the planning and design of major socio-economic developments and for related research.

1.6 An additional objective of Project A.2 is related to one of the recommendations in the Supporting Documents of the Declaration of the World Climate Conference: "to develop appropriate statistical processing schemes for condensing the mass of raw climatological data down to manageable data sets" (WMO, 1979).

1.7 It is noted that, although it is hoped that Project A.2 will contribute to a better understanding of the physical processes behind climatic variability, it is not intended to analyze such physical processes or their relationship to climate variability, as this is the object of a number of other projects under the World Climate Programme.

1.8 In the great majority of countries, it is standard practice, at least for the design of large water-resource projects, to make allowance for the effects of variability in hydrological and hydrometeorological elements. These allowances are commonly based on short time series and on assumptions that are difficult, if not impossible, to check in practice. A great deal of subjective judgement enters into the decision making process involved. In addition, in the operation of such projects, it is common for very little allowance to be made for future variability. Those responsible for water-resource planning and management could therefore benefit from a comprehensive description of climate variability and the resulting variability in hydrological and hydrometeorological elements. It is hoped that this project will assist in this regard and so engender a new awareness of the importance of these factors for the efficient development of water resources.

2. DEFINITIONS: HYDROLOGY AND CLIMATE; VARIABILITY AND CHANGE

2.1 In defining the hydrology and climate of an area for the purpose of this project, it is considered appropriate to start from the definition of the term "climate". A large number of definitions of this term have been proposed at various times and so, to avoid confusion and ensure uniformity within the WCP, the following definitions are currently being used within the WCRP:

> "Weather is associated with the complete state of the atmosphere at a particular instant in time and with the evolution of this state through the generation, growth and decay of individual disturbances."

"Climate is the synthesis of weather over the whole of a period essentially long enough to establish its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state."

2.2 To parallel the above definitions, the hydrology of an area is defined for the purpose of this project as the ensemble of the long-term statistical properties (mean values, variances, probabilities of extreme events, etc.) of flows (runoff), water levels and other pertinent hydrologic characteristics, which can be considered independent of any instantaneous conditions.

2.3 The concepts of variability and change as regards both climate and hydrology are fundamental to the object of Project A.2. The two terms can be used in a loose way and could mean different things to different people. Without a clear definition of these terms the purpose of Project A.2 could be misinterpreted.

2.4 The US Committee for GARP (1975) defined variability as the variance among a number of climate states of the same kind. They spoke, for example, of monthly, seasonal, yearly or decadal climate variability. Incidentally, this definition of climate variability includes the variance of the variability of the individual climate states.

2.5 At the World Climate Conference, Hare (1979) discussed the difference between the concepts of variability and change and noted that "before the question of possible climatic change arose, climatologists adopted the practice of forming the above estimates (of statistics of climatic characteristics) for thirty-year reference periods. These were recalculated every ten years (e.g. 1931-60, 1941-70, etc.). It was found that small differences occurred between these successive reference periods. Such differences are bound to occur because of the extremely variable character of the climate's behaviour. They can be thought of as climatic noise, and their occurrence does not indicate a real climate change. Climatic variability is treated in this paper as the internal variability characteristic of the reference period". And further: "But the major question before the Conference is the possibility of real climatic variation, or change (the latter term being applied, as a rule, to larger, longer-term variations for which a definite cause can be assigned). Such variation or change will show itself as real differences between reference periods, larger than those associated with climatic noise. The main problem is to find evidence for such variation."

2.6 The definitions of "climate change" and "climate variability" used within the WCRP as the counterparts of those given in paragraph 2.1 above are:

"Climate change defines the difference between long-term mean values of a climate parameter or statistic, where the mean is taken over a specified interval of time, usually a number of decades."

"Climate variability includes the extremes and differences of monthly, seasonal and annual values from the climatically expected value (temporal mean). The differences are usually termed anomalies."

2.7 Climate and hydrological change may be considered significant or not significant on the basis of physical, economic and/or statistical criteria. In view of the lack of generally accepted physical and economic criteria for defining such changes, Project A.2 will initially only consider criteria pertaining to statistical significance. The earlier discussion and definititions imply that the terms climate variability and climate change pertain to two different concepts of the climate process, in particular to climate represented by a stationary process and a non-stationary process, respectively. It further implies that climate is viewed as a process which is non-stationary on a long time scale, but can be approximated by a stationary process on a shorter time scale of a few decades. Within this shorter time scale, it is thus considered appropriate to talk about "climate normals" representing central tendencies around which the climate fluctuates. These fluctuations constitute climate variability.

2.8 The long-term non-stationarity implies that, in fact, no long-term climate normals exist, or, to put it in another way, that they themselves exhibit irregular long-term fluctuations. These fluctuations can be approximated as changes in the quasi-constant central tendencies or normals in the successive periods of a few decades within which the stationary representation is acceptable.

2.9 To summarize, climate variability can be regarded as the variability inherent in the stationary stochastic process approximating the climate on a scale of a few decades, while climate change can be regarded as the differences between the stationary processes representing climate in successive periods of a few decades.

3. SELECTION OF THE TIME SERIES OF DATA

3.1 Types of time series

3.1.1 The process of selection of time series of data should be based on the recommendations included in the supporting documents to the Declaration of the World Climate Conference, that is : "it will be necessary to locate and to assemble instrumental observations made during the last 100 years or more, to examine the data for quality and consistency, and to arrange that the data are readily accessible and suitable for both manual and computer processing."

3.1.2 The project description (Appendix A) indicates the types of time series to be considered. It is felt that the emphasis should be laid on river discharges and lake levels. An important reason for emphasizing this type of time series is the fact that they reflect areally integrated climate inputs and therefore provide more pertinent information on climate variability and less local "weather" type variability than station records of precipitation and temperature. However, the number of time series of river flows and lake levels that have not been influenced by man is very limited, while time series of precipitation have been less subject to such influence. It should be noted that, wherever mention is made in this document to the influence of man, the reference is to man's direct impact on the element concerned in the local area and not to any indirect impact on a global scale. Finally, it is noted that time series of river levels are rarely a correct reflection of hydrological and climate variability and change because of frequent changes in cross section configuration.

3.1.3 In view of the above, the types of time series to be considered in Project I.2 are divided into two sets according to the priority to be accorded to them in the implementation of the project; namely:

Priority 1

(a) water discharge
(b) lake levels
(c) precipitation
(d) air temperature

Priority 2

(e) river stage
(f) fresh water temperature
(g) ice cover (date of break up)
(h) ice cover (total number of days during season)
(i) groundwater level

Within each set the order of priority is the order in which the types are listed.

3.1.4 For reasons given in 3.4.3 below, a standard set of information must be submitted for each time series included in the project. A description of this set of information is contained in Appendix B.

3.2 Time interval

3.2.1 Although some earlier studies have concentrated on series of annual averages, it is considered that such data are not sufficient for studying variability, and possibly not even change. Variations from one year to another in seasonal flow, precipitation or temperature could be of great significance for the variability of hydrology and climate and may even be indicative of hydrological and climate changes. They may remain completely undetected when annual time series are used. It is obvious, for example, that the effects of such changes on reliability of water supply could be significant and remain undetected if only annual time series are considered.

3.2.2 The project will therefore be carried out on the basis of monthly time series, with a pilot analysis of the differences in results obtained when a daily series is used. The aim, however, would be to carry out the data collection on a daily basis for all time series.

3.3 Data selection

3.3.1 Ideally, the time series of data used for the purpose of this project should be consistent and homogeneous. Consistency relates to the type and technique of measurement, the sampling interval and the manner of processing the data. Homogeneity relates to the constancy of the measurement site and of its environmental conditions, and to the lack of artificial disturbance of the climate and hydrological processes. Such disturbances include man's direct influence on the size of the variable measured - as in the case of creation of storage, diversions, etc - or his indirect influence, as in the case of changes in the environmental conditions, modifications of land use and land cover.

3.3.2 It is recognized that ideal consistent-homogeneous time series are hard to obtain. Therefore, quasi-consistent time series will be considered acceptable, these being time series for which adequate corrections have been introduced to account for change in measurement equipment and technique, sampling interval and data processing techniques. Homogeneous time series are to be preferred. As the number of homogeneous time series is extremely limited, non-homogeneous time series will be tentatively accepted for analysis provided that the information on causes leading to the non-homogeneity is available and is provided with the data.

3.3.3 With respect to non-homogeneity caused by water-resource development, the data owner should attempt a "reconstruction" of the natural regime data which would have been recorded if the water-resource development had not occurred. In some cases such "reconstructed" natural time series of flows are already available. It should be noted, however, that for short time periods (e.g. daily) such reconstructed flows can be extremely erroneous. The time series of minimum and maximum daily flows of such "reconstructed" time series should not be used because the errors involved are usually very large. Errors such as wrong estimates in change in storage tend to compensate over larger time periods, and it is likely that flows for monthly time intervals are not subject to great errors. Nevertheless, the analysis of such time series should be carried out very cautiously.

3.3.4 Non-homogeneous time series of data with the non-homogeneity introduced by natural factors such as fires, land slides, glacier surges will be accepted provided that the causes of non-homogeneity are readily identified.

3.4 Quality control

3.4.1 The time series of data will normally only be accepted if they satisfy the quality control requirements listed in the WMO Guide to Hydrological Practices (WMO, 1983), Sections 4.2.4.4 and 4.3.4. In addition, for computer processed data, the quality control recommendations contained in the revised WMO Technical Note 115 - Automated Processing of Hydrological Data - should also be considered.

3.4.2 Besides the above-mentioned quality control requirements, the following supplementary criteria are to be used for screening the time series of data for the project:

(i) Precipitation data which have been corrected for bias (for example using Sevruk, 1982) should have the corrections made to the whole period of record and applied in a consistent manner.

(ii) Records for rivers having ice cover in all or some winters should be corrected for the effects of ice.

(iii) Regular checks should be made of stage-discharge relationships, particularly after the passsage of floods, and the range of discharge measurements should be as great as possible.

3.4.3 The aim of the project in this regard is to include the best data sets that are available and, as a guide to their use, the data owners will be asked to supply the information listed in Appendix B and themselves grade their data sets as being:

- very good
- good
- acceptable for the purposes of the project.

3.5 Duration of time series

3.5.1 It is proposed to adopt as the minimum duration of time series to be used in Project A.2, 50 years for precipitation and air temperature and 30 years for all other data. Stations with 40 years or more of data can be used for analysis of both temporal and spatial variability. Stations with less than 40 years of record will be used only for the analysis of spatial variability. The reasons for proposing these lower limits are presented in section 4. As indicated there, the main reason for using a minimum period of 30 years for analysis of spatial variability relates to the fact that climatologists normally also use 30 years for their reference periods.

3.5.2 Few long time series are continuous but, if possible, those used in the project should not have gaps totalling more than 5% of the record and these gaps should be filled in by the data owner using recognised methods.

4. SELECTION OF REFERENCE PERIOD

4.1 The reference hydrological state will be defined for a period of 30 years. This is so as to obtain consistency with climatological reference states which are usually calculated for a 30 year period and to ensure a sufficiently large sample of data when statistical confidence limits are estimated.

4.2 It is considered preferable to use a common reference period for all stations, to the extent possible, particularly for the analysis of spatial variability. If the reference period differs, it will be difficult to separate spatial and time variability in the analysis. The actual dates defining the reference period will be selected on the basis of the descriptions of the time series to be included in the project.

5. STATISTICAL PARAMETERS TO BE OBTAINED

5.1 The most difficult part of the analysis of long time series is the formulation and testing of hypotheses concerning the existence of long-term fluctuations (trends, cycles, etc). Further analysis of the nature of these characteristics is even more complex and requires stochastic hydrological modelling.

5.2 It is therefore appropriate that during the initial stage of the investigation, several competent organizations should examine the basic statistics computed by the formulae in Appendix C using the computer program developed for this purpose.

5.3 After a number of such organizations have examined critically the basic statistics for rivers with which they are familiar, they will report on their findings, both as regards methodology and results.

5.4 After a tentative agreement on methodology is reached, a second draft of the list of formulae and the computer program will be prepared and distributed to a wider group of research organizations.

5.5 Only after that group has completed their analyses and reported their conclusions will it be appropriate for WMO to circulate the set of instructions and formulae to a wider circle of hydrologists in all member countries so that they may examine their river basins in order to determine long-term fluctuations.

5.6 At this initial stage, the following basic statistics will be computed for the periods indicated in Table 1 of Appendix C:

(A) mean

(B) standard error of mean

(C) standard deviation

(D) standard error of standard deviation

(E) coefficient of variation

(F) coefficient of skew

(G) coefficient of kurtosis

(H) ranks for each month

(I) coefficient of autocorrelation

(J) standard error of coefficient of autocorrelation

(K) cumulative periodogram

(L) variance spectrum

(M) confidence intervals for variance spectrum

(N) rescaled range

(O) Hurst's coefficient

(P) number of runs

(Q) trend in the mean

(R) trend in the variance

(S) equality of sub-period means

(T) equality of sub-period variances

(U) (1) jump in the mean (cumulative deviations)
(2) jump in the mean (Worsley)

(V) Gaussian filter.

Computations of the above statistics will be carried out for subsamples of 5, 10, 20 and 30 years which can be derived from the original time series and also for the whole series.

5.7 It is essential for the aims of the project that the statistical values derived for the different time series be comparable. A precise algebraic interpretation of statistics (A) to (V) above is therefore presented in Appendix C.

5.8 In addition to the numerical statistical parameters listed above, the graphical plots of the following should also be presented, if possible:

(i) Original data (monthly series). Filled in data to be included.

(ii) Histogram of the complete series of observations.

(iii) Mean monthly values and their standard deviations for various subperiods. The choice of the length of the subperiods depends on the individual river under study.

(iv) Autocorrelation coefficients of annual values (whole period).

(v) Autocorrelation coefficients of monthly data for various subperiods.

(vi) Spectrum function of annual values (whole period).

(vii) Spectrum function of monthly data for various subperiods.

(viii) Running sum of the differences of the monthly values from their overall mean.

(ix) Running sum of the same quantity but divided by the standard deviation of the series.

5.9 In a later stage of the project, and as special cases of time series are submitted for analysis, further consideration will be given to the statistical parameters to be obtained for special time series such as:

(a) intermittent time series (Kelman, 1977);

(b) time series with two (or more) physically and statistically distinctive precipitation or runoff generation mechanisms;

(c) time series affected by regional events (e.g. tropical cyclones);

(d) time series with non-homogeneity resulting from natural causes such as forest and savannah fires, volcanoes, glacier surges and land slides.

6. ANALYSIS OF VARIABILITY

6.1 Time variability

6.1.1 Time variability will be investigated using the following technique. A comparison will be made of the differences between the statistical parameters of the hydrological states for various equal-length periods. For this purpose the record will be divided into n periods each of m years. The statistics listed under 5.6 will be computed for the periods shown in Table 1 of Appendix C.

6.1.2 Whenever the difference between the statistical parameters for the whole period and those for the reference period is excessive when compared to the corresponding standard errors of estimates, a test will be made of the time dependency of the basic data used to estimate them. When such tests are positive, this should be followed by a search for anthropogenic causes.

6.1.3 On the basis of the above-described analysis, it will be possible to offer indications as to whether the time series have:

(a) normal variability (stationary);

(b) trends and jumps related to man's activity (anthropogenic change);

(c) trends and jumps related to local, specific natural causes (local natural change) related to non-climatic causes;

(d) other manifestations of non-stationarity;

(e) indications of hydrological and climate changes;

(f) any combination of (a) to (e).

6.1.4 The time series thus separated and with their statistical characteristics could provide inputs for investigating the causes of hydrological and climate variability and change. This is, however, beyond the scope of this project.

6.2 Assessment of variability in space

6.2.1 Variability in space will be estimated by analysing the spatial variation of the hydrological reference states (see 4.1 above), as defined by the above statistical parameters. General extension of the comparison to more than one hydrological state (defined by other 30-year periods) might be desirable, but it is not considered practical at this point in time.

6.2.2 The analyses of spatial variability will be based on plots on maps of the various statistical parameters, together with their associated standard errors. A study will be made of the resulting plots to see if there is any evidence of regional non-homogeneity and, where there is, to check whether it is related to physical characteristics of the regions so defined.

6.2.3 After the above analyses have been completed and where data availability permits, consideration may be given to additional studies such as:

(a) Derivation of values for other indices, particularly those relating to extreme events;

(b) Comparison of statistical parameters of stations located in generally recognized different climate (hydrological) regions but representing a gradual differentiation (e.g. from tropical forest to arboraceous savannah) with the purpose of relating the differences observed to criteria of climate change in time (in the sense that variation in space of certain statistical parameters for different climate regions might be commensurate with the variation in time induced by climate change);

(c) Correlation of the variation in statistical parameters within a region or of several neighbouring regions to terrain characteristics (e.g. elevation, slope, distance to sea, etc), and the elimination of the explained variance with the purpose of defining more comprehensive climate regions in which variation is mainly related to variations in terrain characteristics.

These analyses might be carried out initially using data from individual stations. However, extension to studies based on averaged values for a region in the manner carried out by Yevjevich (1977), although with a more elaborate separation into regions, or for entire river basins using data of the type provided by Deutscher Wetterdienst (1980) could also be considered. Such analyses would be of interest as the averaged time series would have a dampened local noise and might permit the detection of regional trends and fluctuations.

6.2.4 One further technique which might be considered later, data permitting, would be to calculate cross-correlation coefficients for pairs of time series. This could be used to trace, around a representative station in a region, lines of equal cross-correlation. Such isolines would indicate spatial variability of the noise component of the corresponding time series. Zones of dense concentration of such isolines are also indicative of regional boundaries.

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PROJECT DESCRIPTIONS A.1 AND A.2

Project A.1 Analyzing Historical Hydrological and related Information with respect to Climate Change

1. Background

Historical hydrological and related information concerning for example floods, low flow periods or river ice periods, is available in many countries in the form of direct information stored in archives or in the form of indirect information such as proxy-data (i.e. ice core data, dendrochronological data, sediment probes, historical records tied to climatological or hydrological parameters, etc.). This material has been used for specific studies but could be more broadly used for increasing our knowledge of variations in hydrological regimes during past centuries. Such information would be useful for analyzing climate change.

Several organizations, including some working within the framework of the WCP, have undertaken research in these fields. However, there is a need for more co-ordination between the individual research studies.

Research groups need information on existing inventories of historical hydrological data sources including proxy-data. Therefore, it would be necessary to compile information on existing data. Furthermore, a unified methodology is needed in the form of guidance material so that results of individual research groups can be compared. Hence it is necessary:

(a) to develop guidance material on the analysis of historical hydrological and proxy-data;

(b) to compile inventories of sources of historical data, including proxy-data.

2. Output

(a) Improvement of methodologies and as far as possible unification of them;

(b) Comparison of results using various approaches for specific climatological or hydrological variables and for specific periods;

(c) Support for the work of and provision of guidance to research groups.

3. Mechanism for implementation

(a) Preliminary planning;

(b) IAHS Symposium on the Influence of Climate Changes and Climatic Variability on the Hydrological Regime and Water Resources, Vancouver, August 1987;

(c) Round-table discussion at General Assembly of IUGG in Vancouver (August, 1987) on topics 1(a) and 1(b);

(d) Establishment of an ad hoc and temporary working group for liaison and to some extent co-ordination.

4. Organizations/bodies involved

IAHS responsible with co-operation from Unesco, WMO, ICSU and other interested international bodies and national institutions.

5. Tentative time schedule

Based on (a) to (c) of 3 above:

(a) 1983-86
(b) 1987
(c) 1987
(d) 1988-90.

6. Comments

This project involves the co-operation of many scientists from very different fields of research. This project started in 1983 and will become operational only after several years, at which time the project will encompass most of the related action.

Liaison necessary with Projects A.2 and A.3.

Project A.2 Analyzing Long Time Series of Hydrological Data and Indices with respect to Climate Variability

1. Background

In many countries long hydrological time series are available (e.g. for precipitation, discharge, water levels of rivers, estuaries, lakes). From these hydrological variables and relevant meteorological variables (e.g. air temperature) sets of hydrological statistics (annual mean, monthly mean, minimum values, exceedence for different time periods based on daily values, etc.) and indices (drought-index, etc.) can be obtained. This material should be used for improving knowledge of climate variability by being analyzed in that respect. In some countries relevant investigations are currently being undertaken.

Research groups need information on existing long time series. Therefore, it will be necessary to compile information on such time series and their availability. Furthermore, a unified methodology is needed in the form of guidance material so that the results of individual research groups can be compared.

Long hydrological time series are often influenced by man's activities. These effects have to be identified and eliminated in the time series so as to isolate the influence of climate change. A methodology for eliminating these effects will be developed under Project A.3.

It is necessary:

(a) to compile information on existing time series starting before 1900;

(b) to develop guidance material on analyzing long time series with respect to climatic variability.

2. Output

Round-table discussions were held in Hamburg in 1983. A preliminary proposal for the project was developed in 1984. A detailed draft methodology for the analysis of long-time series, including a computer program, was prepared in 1985.

Results of analyzing such long time series may give more detailed information on the variability of climate in time and space. The results will contribute to a better understanding of the physical processes behind climate variability.

3. Mechanism for implementation

(a) To make the results of such studies in different countries comparable with each other, a unified method is being developed and guidelines will be prepared for the use of existing statistical methods. As the problem is very complex, the appropriate methodology can be found only by trial and error (i.e. by application to concrete cases and critical analysis of the results). Consequently, it has been decided that the present set of instructions, formulae and the computer program are sufficient as a first stage. A number of institutions will undertake to apply the existing program to some basins with long records in their country and report on the results in a workshop to be convened during the IUGG Assembly in Vancouver;

(b) IAHS Symposium on the Influence of Climate Changes and Climatic Variability on the Hydrological Regime and Water Resources, Vancouver, August 1987;

(c) The round-table discussion in Vancouver referred to under 3(b) of Project A.1 could also aid in reviewing the interim progress of this project;

(d) As a result of the deliberations of the workshop referred to in (a) above, a revised form of the instructions and the programme will be prepared, to be distributed to a wider circle of research organizations;

(e) After this methodology is tested by these organizations and found satisfactory, WMO will send the final form of the instructions and the program to various countries that possess long hydrological data series;

(f) Member countries will be asked to analyze their long time series on the basis of the recommended statistical method;

(g) Results of these studies should be sent to WMO for a compilation of the results obtained in different countries.

4. Organizations/bodies involved

The project will be executed by WMO in co-operation with Unesco, IAHS and with the participation of those Members which have available long hydrological time series.

5. Tentative time schedule

Based on (a) to (g) under 3 above:

(a) 1983-87, draft of methodology completed 1985;

(b)-(d) 1987;

(e) 1988-1989;

(f) 1989-1990;

(g) 1991.

6. Comments

An expert to review all material which is published describing existing long time series of hydrological data. Countries to be asked for a compilation of this information by a questionnaire on their existing long hydrological time series. Data for the studies mentioned should be on a daily or at least monthly basis. Minimum length of records should be about 80 years. Furthermore, additional information on the stations and the catchments will be requested.

Liaison with Projects A.1 and A.3.

INFORMATION REQUIRED FOR EACH STATION

1. HEADER INFORMATION

- Station identification code number
- Station name
- Location in geographic co-ordinates (latitude/longitude)
- Altitude
- Variable measured
- Units of measurement
- Time interval of measurement
- Time interval of record elements
- First year of record
- Last year of record or last available year
- Operating authority and address
- Catchment area (if a stream gauging station)

2. HISTORY OF CHANGE IN INSTRUMENTATION AND MEASUREMENT AND IN SITE AND SITE CONDITION

- Nature and date of changes in instrumentation and/or in measurement practice, including changes in sampling interval and manner of processing the data.
- Change in operating agency.
- Details of any station relocations, in terms of geographical co-ordinates or with reference to current or previous position of the gauge.
- Details on accessibility to station.
- Site description of each location in the station's history, and details of progressive or sudden change in conditions at the site which may affect the variable being measured or the performance of the instrument, e.g. a tree growing over a precipitation gauge, or a cooling tower located near a temperature gauge.
- Photos of site through history where possible.

- Details of gaps in the record.
- Inspection history.
- Change in observer plus dates.

3. HISTORY OF CHANGE IN THE ENVIRONMENT OF THE STATION

For all types of data, a history of changes in environmental conditions (urbanisation, land use, deforestation, reforestation, irrigation development, etc.) with descriptive maps and statistics or percentage. If the station is recording stream or lake levels this history should refer to the entire catchment area.

For stream flow or lake level data, a history of water resource developments within the catchment. Statistical data on each development where available together with rules of operation. Time series data on storage accumulation and release abstractions, diversions and inter-catchment transfers. Details of natural catastrophes affecting flows or levels, such as forest, bush and savannah fires, land slides, glacier surges, volcanic eruptions etc.

4. HOMOGENEITY OF THE TIME SERIES

Has the station record been analyzed with respect to its homogeneity? If so, then what adjustments, if any, have been made to the record and what parts of the record are affected by these changes. Does the record incorporate these changes in its current form? Is the record considered homogeneous by the operator of the station? If not, why not? Are changes published, if so where?

5. ADDITIONAL INFORMATION SPECIFIC TO THE TYPE OF DATA

(i) Precipitation data

If snow represents a significant proportion of precipitation at the station, how is snow depth converted to water equivalent? Has this procedure been used consistently through the record? If not, detail other procedures.

(ii) Temperature data

How are time-averages of the data computed (e.g. [max + min]/2 or an average of values at fixed hours)

(iii) Streamflow data

Is the rating curve considered to be stable within a year and from year to year?

Is more than one rating curve used for different parts of the year, or have various rating curves been used at various periods in the record?

What are the maximum and minimum gauged flows beyond which the rating curve is an extrapolation?

Is the station significantly affected by ice or by vegetation during the year? If so, what measures are used to adjust the measurements for these effects?

Is there a variation in stage-discharge relationship during a flood? If so, how is this taken into account where estimating flows during a flood period?

(iv) Other types of gauge

6. CLASSIFICATION OF DATA SETS ACCORDING TO THE QUALITY OF THEIR DATA

GRADE	MEANING	PROPERTIES
1	Very good	Station history is known, record has been checked for homogeneity and no adjustment has been deemed necessary
2	Good	Station history is known and has been homogeneised
3	Acceptable	Station history not well known and has not been homogeneised, but is considered to be acceptable

LIST OF FORMULAE

1. The terms "annual values" and "monthly values" are used as abbreviations for the mean values for each year and month respectively.

2. In the formulae which follow it is assumed that a record of N years of monthly data is available, that it has no gaps (see note 1) and that it is divided into m subsamples of equal size. Each subsample has a length n years and m is the largest integer less than or equal to N/n.

3. The index for the month is j (j = 1,2,..., 12), for the year is i (i = 1,2,..., n) and for the subsample is k (k = 1, 2,..., m). For each subsample separate statistics are calculated.

4. In summary, the following basic notation is used:

N - total number of years

n - number of years in a subsample

m - total number of subsamples

X_{ijk} - value in year i, month j, subsample k of the variable considered

$N \geq m.n = N'$ - total length of m subsamples, each of length n

5. Basic Statistics

The formulae are given for the annual values of the k-th subsample. The same formulae are used for all other cases shown in Table 1. These formulae assume un-correlated observations (see Note 2).

(A) Subsample mean

$$\overline{X}_k = \sum_{i=1}^{n} \overline{X}_{ik}/n$$

where $\overline{X}_{ik} = \sum_{j=1}^{12} X_{ijk}/12$

The centered values of the annual time series are defined as:

$$\overline{x}_{ik} = \overline{X}_{ik} - \overline{X}_k$$

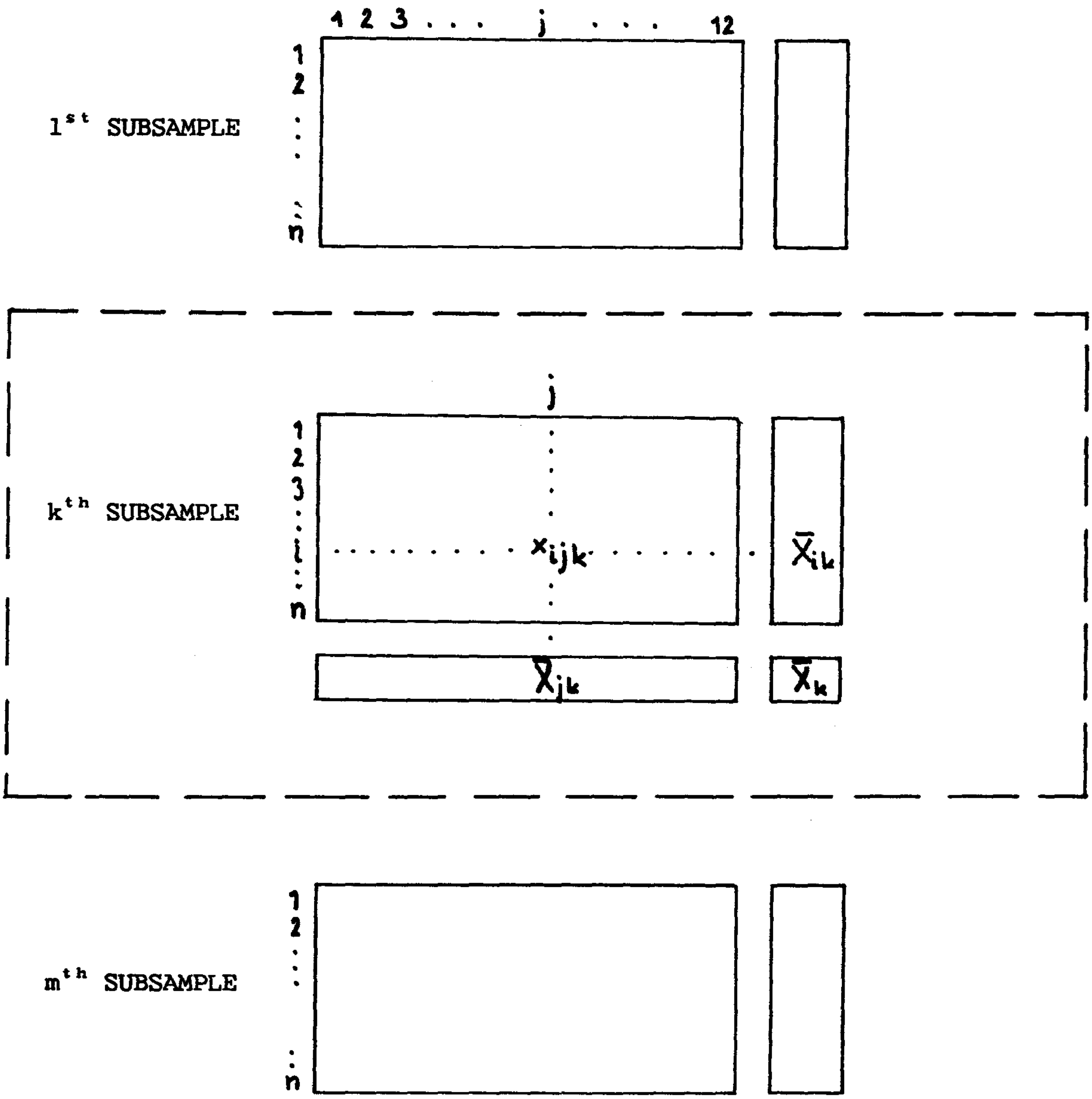

Figure 1. NOTATION

(B) Standard error of mean

$$SE(\overline{X}_k) = S_k/n^{1/2}$$

(S_k from item C)

(C) Standard deviation

$$S_k = [\sum_{i=1}^{n} \overline{x}_{ik}^2/(n-1)]^{1/2}$$

(D) Standard error of standard deviation

$$SE(S_k) = S_k/(2n)^{1/2}$$

(E) Coefficient of variation

$$CV_k = S_k/\overline{X}_k$$

(F) Coefficient of skew

$$CS_k = n/[(n-1)(n-2)] \,.\, \sum_{i=1}^{n} \overline{x}_{ik}^3/S_k^3$$

[Yevjevich (1972)]

(G) Coefficient of kurtosis

$$CS_k = n^2/[(n-1)(n-2)(n-3)] \,.\, \sum_{i=1}^{n} \overline{x}_{ik}^4/S_k^4$$

[Yevjevich (1972)]
(See Note 3)

(H) Matrix of ranks for each month

$$\begin{bmatrix} R_{1,1} & \cdots & R_{1,12} \\ \vdots & & \vdots \\ R_{n,1} & \cdots & R_{n,12} \end{bmatrix}$$

(I) Coefficients of autocorrelation

$$r_{\ell k} = [\Sigma_{i=1}^{n-\ell} (\overline{X}_{ik}-\overline{X}_k)(\overline{X}_{i+\ell,k}-\overline{X}_k)]/\Sigma_{i=1}^{n} (\overline{X}_{ik}-\overline{X}_k)^2$$

where $\ell = 0,1,2, \ldots, M$

In the program, maximum lag M is the largest integer less than or equal to (n-1)/6

[Box and Jenkins (1970)]

(J) Standard error of coefficient of autocorrelation

$$SE(r_{\ell k}) = [(1+2\Sigma_{i=1}^{q} r_{ik}^2)/n]^{1/2}$$

[Box and Jenkins (1970)]

A common practice is to let $q = 1$ for $\ell = 1$ and $q = 2$ for $\ell \geq 2$, the program prints only the value for $q = 2$.

(K) Cumulative periodogram

[Anderson (1977)]

The periodogram for the series $x_1, \ldots, x_n$ is defined as:

$$I(p) = (2/n).\left\{(\textstyle\sum_{i=1}^{n} x_i \cos 2\pi ip/n)^2 + (\sum_{i=1}^{n} x_i \sin 2\pi ip/n)^2\right\}$$

where $p = 1, 2, \ldots [(n/2) - 1]$ where [ ] denotes the "integer part of". The standardized cumulative periodogram is defined by

For $j = 1, \ldots [(n/2) - 1]$,

$$C(j) = \textstyle\sum_{p=1}^{j} I(p)/\sum_{p=1}^{[n/2]} I(p)$$

$$= \textstyle\sum_{p=1}^{j} I(p)/(n.S_k^2)$$

For $j = [n/2]$

$$C(j) = 1$$

If the series follows a white noise process, the plot of C(j) vs j/n is scattered randomly about the line from (0,0) to (0.5, 1). The Kolmogorov-Smirnov test statistic D is the maximum vertical deviation of the plot from the above line.

For $[(n-1)/2] > 35$ the 95% critical value of the statistic D is $D_{0.05} = 1.36([n/2-1])^{-1/2}$

The 95% confidence interval for a cumulative periodogram of white noise is represented graphically by drawing two parallel lines at a distance of $D_{0.05}$ above and below the empirical periodogram.

(L) Variance Spectrum

Using the truncation point M as defined in item (I), calculate the coefficients of autocorrelation for all lags ℓ up to ℓ = M.

Calculate for p = 0, 1, 2, ..., M the (normalized) variance spectrum,

$$S_{p,k} = (1/M)\ [1+2\sum_{\ell=1}^{M-1} r_{\ell k} \cos(\pi p\ell/M)+r_{MK} \cos(\pi p)]$$

with smoothing:

$$S_{o,k} = 0.5(S_{o,k} + S_{1,k})$$

$$S_{p,k} = 0.25\ S_{p-1,k} + 0.5\ S_{p,k} + 0.25\ S_{p+1,k}$$

$$S_{M,k} = 0.5\ (S_{M-1,k} + S_{M,k}).$$

[Haan (1977)]

The frequency corresponding to p is calculated from

$$f = p/(2M) \text{ (cycles per year)}.$$

(M) Confidence interval of variance spectrum

The 95% confidence interval for the normalized variance spectrum S_{pk} is given by:

$$[\nu.S_{pk}/\chi^2_{0.025}(\nu),\ \nu.S_{pk}/\chi^2_{0.975}(\nu)]$$

where the degrees of freedom of the χ^2 - distribution are given by ν = 2.667 n/M.

[Jenkins and Watts (1969)]

(N) Rescaled adjusted range

Calculate the running sum of the differences of the monthly values from their overall mean $\overline{X}$, i.e.

$$RS_{s,t} = \sum_{i=1}^{s} \sum_{j=1}^{t} (X_{ij}-\overline{X}) + \sum_{j=1}^{t} (X_{s+1,j}-\overline{X})$$

where $X = \sum_{i=1}^{N} \sum_{j=1}^{12} X_{ij}/(N.12)$

s = 0, 1, 2, ..., N - 1
t = 1, 2, ..., 12

and retain the largest and smallest $RS_{s,t}$ ($RS^+_{s,t}$ and $RS^-_{s,t}$)
The adjusted range is calculated as

$$R^* = RS^+_{s,t} - RS^-_{s,t}$$

[Yevjevich (1972)]

The rescaled adjusted range is calculated as

$$R_a^* = R^*/S_o$$

where S_o is the standard deviation of the series of monthly data, all values considered together

$$S_o = [\sum_{i=1}^{N} \sum_{j=1}^{12} (X_{ij}-\overline{X})^2/(12N-1)]^{1/2}$$

(O) Hurst's coefficient

Hurst's coefficient can be calculated from the relationship

$$h = \ln R_a^*/\ln (6N)$$

[Ven Te Chow (1964)]

(P) Test of number of runs

Define a run as a set of consecutive observations above or below the median of the observations.

Let n = number of data in the series

n_r = number of runs

Expected number of runs

$$E(n_r) = 1 + (n/2)$$

Variance of the number of runs

$$Var\ (n_r) = n(n-2)/[4(n-1)]$$

The test statistic is

$$[n_r - E(n_r)]/[Var\ (n_r)]^{1/2}$$

(Q) Mann's test of trend in the mean [Sneyers (1975)]

Given a time series $X_1, \dots X_i, \dots X_n$ we want to test the null hypothesis H_o that the observations are randomly ordered versus the alternative of monotone trend over time. Let $R_1, \dots, R_i, \dots R_n$ be the corresponding ranks of the elements of the series and define the function sgn(x) as follows:

$$sgn(x) = 1 \quad \text{for } x > 0$$

$$sgn(x) = 0 \quad x = 0$$

$$sgn(x) = -1 \quad x < 0$$

Under H_o, the statistic

$$S = \sum_{i<j} \operatorname{sgn}(R_j - R_i)$$

has mean zero and variance

$$Var\ (S) = n(n-1)(2n+5)/18$$

and is asymptotically normal.

The test statistic is

$$u(n) = S/[Var\ (S)]^{1/2}$$

The statistic u(n) can be computed for all values of i (i=1,2,..., n). A graph of u(i) versus i allows one to detect visually the points of change in the mean.

In the case of ties (i.e. $R_j = R_i$) we use the formula for σ_g^2 with tied groups presented below.

When the test is applied to the series of <u>all</u> monthly observations we must take into account the covariances between months in the computation of the variance of the test statistic (Hirsch and Slack, 1984). In this case the computation is modified as follows:

We arrange the monthly observations in the following matrix:

$$X = \begin{bmatrix} X_{1,1} & \cdots & X_{1,12} \\ \vdots & & \vdots \\ X_{n,1} & \cdots & X_{n,12} \end{bmatrix}$$

The null hypothesis H_o is that for each of the 12 months, the n observations are randomly ordered versus the alternative of a monotone trend in one or more months.

Let R be the matrix of ranks corresponding to the observations in X, where the n observations for each month are ranked among themselves:

$$R = \begin{bmatrix} R_{1,1} & & \cdots & & R_{1,12} \\ \vdots & R_{i,g} & \cdots & R_{i,h} & \vdots \\ R_{n,1} & & \cdots & & R_{n,12} \end{bmatrix}$$

The ranks should be calculated from the formula:

$$R_{j,g} = [n + 1 + \textstyle\sum_{i=1}^{n} \text{sgn}\ (X_{jg} - X_{ig})]/2,$$

which assigns the mid-rank in the event of tied values.

The Mann statistic for each month is:

$$S_g = \textstyle\sum_{i<j} \text{sgn}\ (X_{jg} - X_{ig})$$

$$g = 1, 2, \ldots, 12$$

The seasonal Mann statistic is

$$S = \textstyle\sum_{g=1}^{12} S_g$$

This statistic is asymptotically normal with mean zero and variance

$$\text{Var}\ (S) = \textstyle\sum_g \sigma_g^2 + \sum_{g,h,\ g\neq h} \sigma_{gh}$$

where $\sigma_g^2 = \text{Var}\ S_g$,

$$\sigma_{gh} = \text{Cov}\ (S_g, S_h)$$

The covariances σ_{gh} are computed as follows:

$$\sigma_{gh} = [K_{gh} + 4 \textstyle\sum_{i=1}^{n} R_{ig} R_{ih} - n(n+1)^2]/3$$

where $K_{gh} = \sum_{i<j} \text{sgn}\ [(X_{jg} - X_{ig})(X_{jh} - X_{ih})]$

In the case of ties the variance σ_g^2 is computed from the equation

$$\sigma_g^2 = [n(n-1)(2n+5) - \textstyle\sum_{j=1}^{m} t_j(t_j-1)(2t_j+5)]/18$$

where m is the number of tied groups among the X_{ig} and t_j is the size of the j th tied group. The formula for σ_{gh} remains the same except that mid-ranks are used in assigning the values $R_{i,g}$. The formula given above for the ranks has this effect.

It must be noted that, according to Hirsch and Slack (p. 731), the above seasonal test is not sensitive in the case of opposing trends in different months.

(R) Test for trend in the variance

[Sneyers (1975), p. 15]

The test for the trend in the mean (Q above) can also be used to detect a trend in the variance of the observations. For this purpose, the test is applied to the quantities

$$|R_i - (n/2)|$$

This test can also be represented graphically as in the previous case.

(S) Kruskal-Wallis test of equality of sub-period means

[Sneyers (1975)]

Let m be the number of sub-periods with lengths n_j $(j = 1,2, \ldots, m)$ and R_{ij} the rank of the i th observation of the j th sub-sample in the ordered complete sample.

Let $R_j = \sum_i R_{ij}$

$N = \sum_j n_j$

The test statistic is:

$$XS = 12\sum_j (R_j^2/n_j)/[N(N+1)] - 3(N+1)$$

Under the null hypothesis of equal sub-period means, this statistic follows the Chi-square distribution with (m-1) degrees of freedom.

In the case of t_j ties in the j th sub-period we divide XS by the quantity

$$1 - [\sum_j (t_j^3 - t_j)]/(N^3 - N)$$

(T) Test of equality of sub-period variances

[Sneyers (1975), p. 23]

The Kruskal-Wallis test can also be applied, using the same formulae, to detect differences in the variances of the sub-periods. In this case we use the ranks of the quantities $|X_i - \overline{X}|$ where $\overline{X}$ is the mean of the complete period.

(U) Test for jump in the mean

[Buishand (1982)]

The purpose of this test is to detect the existence of a jump in the mean after m observations:

$$E(X_i) = \begin{cases} \mu & i = 1, \ldots, m \\ \mu + \Delta & i = m+1, \ldots, n \end{cases}$$

The basic assumptions of these tests are that the observations are independent and normally distributed. The tests can still be applied, however, when there are slight departures from normality.

Two tests of this type are presented:

(U1) Test of cumulative deviations

Given the observations $X_1, \ldots, X_i, \ldots, X_n$, we let

$$S_o^* = 0, \; S_k^* = \Sigma_{i=1}^{k} (X_i - \overline{X}) \qquad k = 1, 2, \ldots, n$$

$$D_y^2 = \Sigma_{i=1}^{n} (X_i - \overline{X})^2/n$$

$$S_k^{**} = S_k^*/D_y \qquad k = 0, 1, \ldots, n$$

The test statistic is

$$Q = \max_{0 \le k \le n} |S_k^{**}|$$

Percentage points of the statistic Q are given in the following table

[Buishand (1982)]

		Q/n	
n	90%	95%	99%
10	1.05	1.14	1.29
20	1.10	1.22	1.42
30	1.12	1.24	1.46
40	1.13	1.26	1.50
50	1.14	1.27	1.52
100	1.17	1.29	1.55
∞	1.22	1.36	1.63

(U2) Worsley's likelihood ratio test

Let

$$Z_k^* = [k(n-k)]^{-1/2} S_k^*$$

$$Z_k^{**} = Z_k^*/D_y$$

We compute

$$V = \max_{1 \leq k \leq n-1} |Z_k^{**}|$$

The test statistic is

$$W = (n - 2)^{1/2} . V/(1 - V^2)^{1/2}$$

Worsley (1979) gives critical values for the test statistic W.

According to Buishand (1982), the tests based on the cumulative deviations and the likelihood ratio are preferable respectively in the case of a change near the middle or near the ends of the series.

For both tests, the position of maximum $|S_k^{**}|$ or $|Z_k^{**}|$ can be taken as an estimate of the change-point m.

(V) Gaussian filter

A filter is a method for smoothing a time series X_1, X_t, ..., X_n using the formula

$$X_t = \sum_{i=-m}^{+m} w_i X_{t+i},$$

where $\sum_{i=-m}^{+m} w_i = 1$,

and the weights w_i can be constant or variable.

A filter that is particularly suitable for eliminating short-term fluctuations (low pass filter) is the Gaussian filter (WMO, 1966, Schönwiese, 1983). This filter can be used to study long-term fluctuations of climatological time series.

The weights of the Gaussian filter are computed as follows:

(1) Assume that we are interested in studying the fluctuations with periods $\geq T_*$

(2) Calculate the standard deviation σ_g of the normal distribution from the equation

$$\sigma_g = T_*/6$$

(3) Calculate the raw weights

$$w_i^* = f(i/\sigma_g), \text{ for } i = 0, \pm1, \pm2, \ldots, \pm m$$

where f(z) is the ordinate of the standard normal density:

$$f(z) = (1/2\pi)^{1/2} \exp(-z^2/2)$$

and m is chosen so that $f(m/\sigma_g) < 0.05 f(0)$

(4) Standardize the weights by dividing each by their sum:

$$w_i = w_i^* / \sum_{i=-m}^{m} w_i^*$$

Examples of the application of this filter to the analysis of climatological time series are given in WMO (1966) and Schönwiese (1983).

NOTES

Note 1 In the case of missing values the user should estimate them and report in detail on the method of estimation.

Note 2 In the case of auto-correlated observations, the computed statistics should be corrected for the effect of auto-correlation, as appropriate.

Note 3 The user should be cautious in interpreting the estimated values of the coefficients of skew and kurtosis in the case of small samples.

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TABLE 1. <u>Review of subsamples and statistics</u>

(Each marked box specifies that the particular statistic is computed for given (sub)sample)

STATISTICS	COMPLETE PERIOD			SUBPERIODS 5 YEARS			10 YEARS			20 YEARS			30 YEARS		
	1*	2*	3*	1*	2*	3*	1*	2*	3*	1*	2*	3*	1*	2*	3*
(A) Mean	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
(B) S.E. of mean	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
(C) Standard deviation	x	x	x				x	x	x	x	x	x	x	x	x
(D) S.E. of standard deviation	x	x	x				x	x	x	x	x	x	x	x	x
(E) Coefficient of variation	x	x	x				x	x	x	x	x	x	x	x	x
(F) Coefficient of skew	x	x	x				x	x	x	x	x	x	x	x	x
(G) Coefficient of kurtosis	x	x	x												
(H) Ranks for each month			x												
(I) Autocorrelation coefficient	x	x	x					x			x			x	
(J) S.E. of autocorrelation coefficient	x	x	x					x			x			x	
(K) Cumulative periodogram	x		x												
(L) Variance spectrum	x	x	x		x			x			x			x	

* 1 - Annual values
2 - All monthly values
3 - Monthly values, each month individually

TABLE 1. Review of subsamples and statistics (contd.)

STATISTICS	COMPLETE PERIOD			SUBPERIODS 5 YEARS			SUBPERIODS 10 YEARS			SUBPERIODS 20 YEARS			SUBPERIODS 30 YEARS		
	1*	2*	3*	1*	2*	3*	1*	2*	3*	1*	2*	3*	1*	2*	3*
(M) Confidence intervals for variance spectrum	x	x	x		x			x			x			x	
(N) Rescaled adj. range		x													
(O) Hurst's coefficient		x													
(P) Number of runs	x		x												
(Q) Trend in the mean	x	x	x												
(R) Trend in the variance	x	x	x												
(S) Equality of sub-period means	x		x										x		x
(T) Equality of sub-period variances	x		x										x		x
(U1) Jump in the mean (cum. deviations)	x		x												
(U2) Jump in the mean (Worsley)	x		x												
(V) Gaussian filter	x		x												