The IIASA Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness on a Global Terrestrial Grid

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Foreword

The projects within the Environment Program of the International Institute for Applied Systems Analysis (IIASA) are devoted to investigating the interaction of human development activities and the environment, particularly in terms of sustainable development of the biosphere. The research is policy-oriented, interdisciplinary, and international in scope and heavily dependent on collaboration with a network of research scientists and institutes in many countries. The importance of IIASA's Environment Program stems from the fact that the many components of the planetary life-support systems are being threatened by increasing human activity, and that these problems are not susceptible to solution by individual governments or even international agencies. Instead, resolution of the difficulties will demand concerted and cooperative actions by many governments and agencies, based on essential understanding of the earth's environmental systems. Establishment of a basis for international cooperation, and production of accurate global environmental perceptions are both hallmarks of IIASA's Environment Program.

Foremost among the global issues of concern are those involving increasing concentrations of *greenhouse* gases and the associated climatic change. Solutions to the problems will only become apparent after collection and analysis of pertinent data, testing of relevant hypotheses, development of mitigation strategies, and investigations of the efficacy of the strategies that are developed. All of these activities can be supported by appropriate mathematical models of the biosphere. The Biosphere Dynamics Project has, therefore, focussed on the creation of models that can describe processes in the biosphere that result in vegetation dynamics. Models are being designed to define the biotic and ecological results of measures suggested to slow or stop increases in *greenhouse* gases. The models must be capable of documenting whether vegetational communities would benefit from mitigation actions, and if so by how much, as well as describing how the terrestrial biosphere will respond in its role as carbon source and sink.

The models are all heavily depending on high-quality global data in digitized form. Few data sets were available prior to beginning the work in Spring, 1988. Since then, global databases on vegetation, soil, topography and hydrology have been collected and developed. Although many compilations have been made of weather records, few global databases have been developed to be linked with different types of models. This report presents the generation of a comprehensive climate database, based on weather records, for all continents. As the database is part of a geographic information system, BIOGIS, world maps showing climatic characteristics can be easily generated. Models can be linked to the database and combined with climate scenarios. As such, the climate database has become the most central database within the Biosphere Dynamics Project.

Bo R. Döös
Leader
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Allen M. Solomon (IIASA Biosphere Dynamics Project Leader, 1987–1990) stimulated the development of the climate database and provided the opportunities to collect much of the basic data. William Emanuel generously supplied his collection of weather records. Michael Ter-Mikhaelian and Ruiping Gao supplied missing data from the USSR and North-Eastern China, respectively. Brian McLaren entered many weather records into the appropriate computer format and checked many records for their locations and typos. Without the generously provided data sets and Brian's energy, the data set would be of lesser quality. We appreciate the fruitful discussions of Sandy P. Harrison and I. Colin Prentice on the topics of data quality and interpolation. Helpful review comments from P.D. Jones, R.A. Monserud, and H.H. Shugart are also much appreciated.

Summary

A database for current climate for a global terrestrial grid has been created using weather records from many different sources. Average monthly temperature, precipitation, and cloudiness values are included in the data set. The weather records were mostly constrained to include at least five observational years from the period 1931–1960. In order to achieve reliable data coverage in regions with especially sparse data, this constraint was not always strictly adhered to. The selected weather records were interpolated onto a grid with a resolution of 0.5° longitude and latitude using a triangulation network followed by smooth surface fitting. Temperature values were corrected to mean sea level using an estimated moist adiabatic lapse rate and a global topography data set. This technique has enhanced the quality of the data set, especially for temperature in data-sparse mountainous areas. Precipitation was not corrected, due to the more complex relationships between precipitation and altitude. The cloudiness data set, defined as the number of recorded bright sunshine hours as a percent of its potential number, is based on fewer stations and often derived from estimated rather than computed data. Although the major annual cloud dynamics are shown, the regional reliability of the data is low. The final database can be improved by including more weather records and by using local correction methods, especially for precipitation. The final data set is considered appropriate for use in agricultural, geographical, biogeographical, and ecological studies.

Contents

1. Introduction

Historical climatic records show that climate has been changing on different time scales. During the last century, for example, a global, steady warming trend occurred from the late 1890s through the 1940s, followed by a minor cooling trend in the late 1940s and the 1950s. Until the mid-1970s the climate was relatively steady, followed by a warming during later years (Jones *et al.*, 1986). The warmest five years of their 134-year weather record all occurred during the last decade.

Climatologists have tried to characterize climate using relatively long-term averaged weather records to determine the "normal climate" of a station or region. In the context of constantly changing climate, such climatic "normals" may be misleading. There is no particular value of average weather to which climate will always return (Gribbin and Lamb, 1978). The observed historical record is important in providing information on the underlying mechanisms of climate dynamics which interact to produce the complex weather pattern, while climatic "normals" are crucial for describing the interactions between climate and other parts of the earth's system, e.g., the vegetation patterns within the biosphere.

A major driving force in climatic change has been recognized in several recent studies. Increasing amounts of so-called *greenhouse* gases (CO_2, CFCs, CH_4, nitrogen compounds, and others) in the atmosphere trap more heat and eventually change the global climate (Ramanathan *et al.*, 1985; Ramanathan, 1988). Anthropogenic emissions of these gases will continue to increase during the next decades (Harvey, 1989) and continued global warming due to the *greenhouse* effect seems unavoidable. Presently different global climate simulations with general circulation models (GCMs) agree on an average annual global warming of 2.5 to 5°C [Houghton *et al.* (1990); for a discussion see also Schlesinger and Zhao (1989); Harrison (1990)]. The spatial and temporal pattern of this warming, however, will not be evenly distributed over the globe. The warming is likely to be most pronounced during the winter season in high latitude areas. Combined with such global warming, precipitation is likely to increase, but there is less agreement between the different models concerning spatial patterns, due to the close and complex interactions and feedbacks between temperature, clouds, evapotranspiration, and precipitation. Part of the reason behind the poor simulation of the spatial pattern of precipitation is that the resolution of the GCM-grid can not realistically simulate the real world.

Within the Biosphere Dynamics Project at IIASA, the impacts of clima change on a global scale was studied. Earlier studies elsewhere have emph sized sea-level rise (e.g., Robin, 1986; Hekstra, 1989), impacts on agricultu (Parry *et al.*, 1988), and shifts in the distribution of biomes (Emanuel *al.*, 1985a and 1985b). We limit ourselves to impacts on natural vegetatio which change major aspects of vegetation, like structure and physiognom biome and species distributions and which directly result from vegetatio dynamics (see Prentice *et al.*, 1989).

On a global level the physiognomy and structure of vegetation is largel determined by climate, although regional deviations from a climatically determined vegetation can occur. Such deviations can be caused by local an regional differences in geology, topography, vegetation history, and anthropogenic influences. Biogeographers have often used available climate information to define boundaries between plant types and to draw maps of th major distributions of vegetation and plant types based on climate (e.g. Box, 1981). Climatologists have classified different climates by implicitl including recognized boundaries between vegetation types into their classifications (e.g., Köppen, 1936). The use of such interrelations for mapping purposes, however, was limited to the availability of data from weather stations and expeditions and the resulting maps were therefore often based o fragmentary and limited data.

A major deficiency in the development of global ecology has been the availability of relevant climate data with an appropriate coverage. In this report we present a global database for terrestrial climate derived from instrumental weather records. The database consists of monthly averaged values for temperature, precipitation, and cloudiness. The resolution of the data set is 0.5° longitude and latitude. This resolution is appropriate to show regional spatial and seasonal patterns of climate and can be overlaid with results of the somewhat coarser resolutions of the current GCM climate models to obtain consistent climate change scenarios. The data coverage for large parts of this global climatic grid is good (especially for Europe, USA, Japan, India, and Africa) and interpolation techniques can be used reliably to estimate the intermediate values between the stations. Climate data from many other regions, however, are derived from a sparser weather station network. Here interpolation will be less reliable. Using a topographic correction, we improved the data quality. (New data will be included in the database and updated interpolated versions will be produced. In the collection of new data we will focus on the regions with sparser data coverage.)

Earlier compilations of global climate databases (e.g., Wernstedt, 1972; Willmott *et al.*, 1981a and 1981b; Spangler and Jenne, 1984) do not give very satisfactory space-time coverage for a terrestrial grid and are mainly developed for use within climatology. We have therefore tried to define a typical climate for each terrestrial cell in relation to topographical and ecological features. The data set presented here is primarily developed for use within biogeography, agrometeorology, and (terrestrial) ecology. For example, data from stations in extreme locations (e.g., at the top of mountains), although important for the determination of global climate and climatic trends, are often not representative of their immediate surroundings and were therefore excluded from our data set.

The main application of our database for climate change impact studies has lead to the limitation that the data set should contain weather records for which no *greenhouse* effect has yet been recognized. Although the general consensus is that this effect will not be significantly recognized from natural climate variation before the first decades of next century (e.g., Briffa *et al.*, 1990), others believe that it is already detectable now (Jones *et al.*, 1988; Wigley and Raper, 1990). Much of the disagreement in this discussion depends on the spatial and temporal scale of the arguments. Jones, *et al.* (1988) and Wigley and Raper (1990) use global trends within centuries, while Briffa *et al.* (1990) focus on local decadal trends.

Here we are trapped in a troublesome dilemma. Principally, we define current climate as that prevailing before any climatic effect due to anthropogenic emissions of *greenhouse* gases. These emissions significantly increased after 1860, and emission rates accelerated after the late 1940s (Keeling *et al.*, 1982). We cannot efficiently use weather records from the nineteenth century, because there was no adequate global coverage of weather measurements to compile a reliable global database. Data coverage during this period was too poor to produce a data set like the present one. Besides, this era was near the end of the so-called "little ice age" and was significantly colder than early this century (Gribbin and Lamb, 1978), which points to the amount of climatic variability that can occur naturally.

Our approach has been to define "current climate" (or "normal climate") as the average climate of the period 1941–1960. The climate of this period was rather stable (cf. Jones *et al.*, 1986) and probably no anthropogenic *greenhouse* effect was detectable. Global coverage of measurements series for this period is relatively good and there are several sources with digitized weather records available for this period. Although most of our collection of selected weather records is from this period, we have, for some areas with very sparse data coverage, chosen to violate the observation perioc limitation. In some cases we have decided that coverage was more importan than the constraint on observation period.

This report includes a short description of different data sources we hav reviewed during the creation of our global climate data set. We also giv the procedures for checking, correcting, and selection of the stations used fo interpolation to the global terrestrial grid. Finally we discuss the quality o the data set and present world maps of all the climatic indices included.

2. Collected Weather Records

2.1 World Weather Records

The *World Weather Records*, as published by the US Weather Bureau (1959), contains monthly averaged temperature and precipitation values for 2,583 stations measured during a period between 1941–1950. The stations are characterized by their longitude, latitude, and altitude. Global data coverage is good, especially since many weather records from islands in the Pacific and the Southern Atlantic Ocean are listed. Many altitude values are missing, however, and the averaged monthly data is only available for very short observation periods, often less then five years. *Figure 1* gives the global distribution of the weather stations included in this collection.

2.2 The Climate Atlas of Walter and Lieth

This data set represents a digitized form of the standardized climate diagrams of the *Klimadiagramm-Weltatlas* by Walter and Lieth (1960–1967). The digitizing of all climate diagrams was completed by Emanuel *et al.* (1985a and 1985b) at Oak Ridge National Laboratory in the USA. The database contains monthly averaged values for temperature and precipitation for 6,720 stations. Longitude, latitude, altitude, and the total observation period is given for each station and climate variable respectively. Longitude and latitude are only given to one decimal point which makes a precise location of a station difficult. The data quality of the stations differs greatly. Central Europe is overrepresented, while continental Asia is poorly covered. Many stations have observation periods of less than six years, while others extend over a period of more than 50 years. The actual observation period is not specified. *Figure 2* gives the global distribution of the stations.

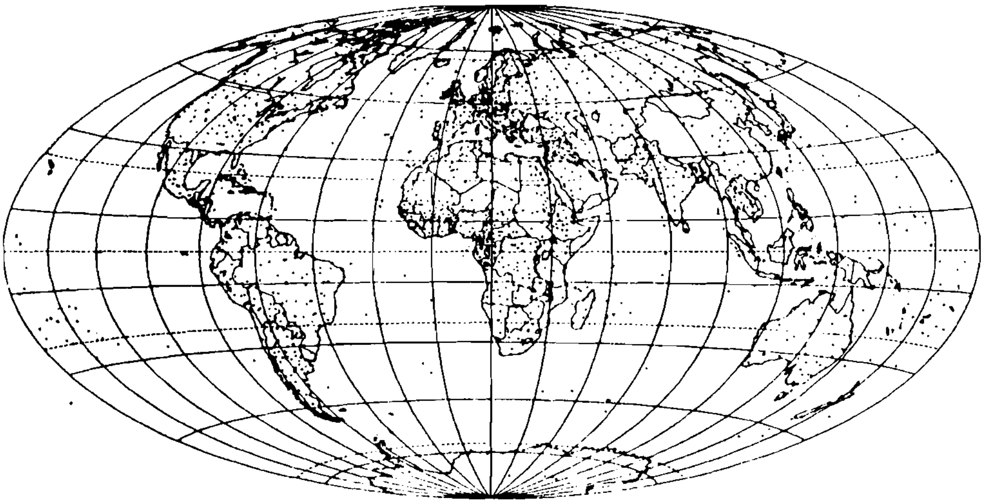

Figure 1. Distribution of stations (2,583) for the US Weather Bureau climate data set: *World Weather Records 1941–1950.*

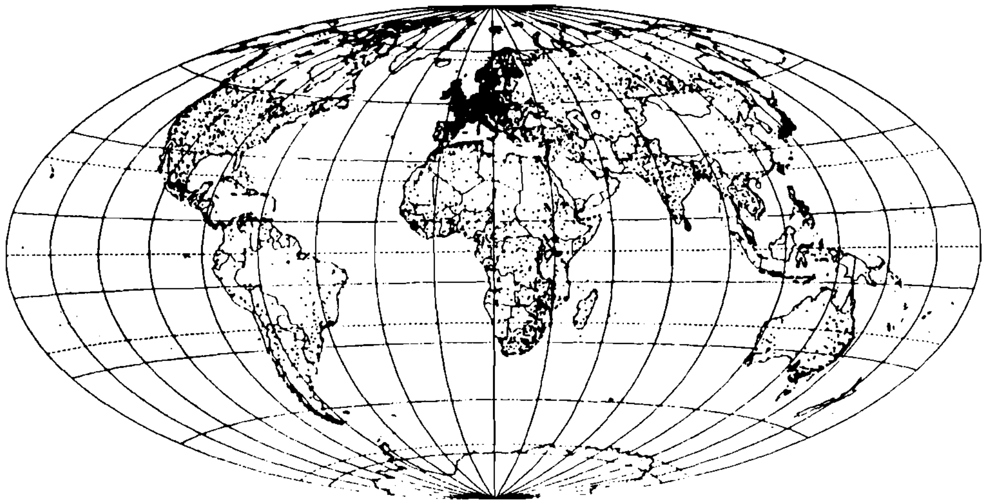

Figure 2. Distribution of stations (6,612) for the Walter and Lieth *Klimadiagramm-Weltatlas* (1960–1967).

Time sequences of the climate diagrams are organized by the vegetation season (winter to winter on either hemisphere). The original digitized data set is not corrected for this feature, which means that the monthly sequence for the Northern Hemisphere is January until December and the Southern Hemisphere July until June. We corrected this before including the data set into our collection.

2.3 Selected Global Climatic Data for Vegetation Science

The data set consists of 1,057 meteorological records, especially collected in order to achieve a meaningful geographical distribution of climate data for vegetation science by Müller (1982). Most of the data is based on the UK Meteorological Office series (1966–1983) and the World Survey of Climatology (Landsberg, 1969–1981), but some other sources have been investigated and, if necessary, included as well. For most stations the series of observations are based on a standard record length obtained for the period 1931–1960. The weather variables in the data set are:

1. Mean daily temperature (°C)
2. Average maximum and minimum temperature (°C)
3. Absolute maximum and minimum temperature (°C)
4. Mean relative humidity (%)
5. Mean precipitation (mm)
6. Minimum and maximum monthly precipitation (mm)
7. Maximum precipitation in 24 hours (mm)
8. Days with more then 0.1 mm precipitation (mm)
9. Sunshine duration (hours)
10. Amount of radiation (ly/day)
11. Potential evapotranspiration according to Thornthwaite and Mather (1957) (mm)
12. Mean wind velocity (m/s) and direction.

For many stations most of the climatic variables are available, only data on maximum and minimum precipitation are rare. All stations are characterized by their longitude, latitude, and altitude. Besides this standard characterization, their names and the appropriate class of Köppen (1936) and Troll and Paffen (1964) are given. *Figure 3* gives the global distribution of stations in this data set.

Although this data set contains only relatively few stations (1,057), the quality of the data is high. No information is included on cloudiness. We have used an algorithm developed by Swift (1976) to derive this variable from the location of each weather station and the total number of bright sunshine hours. Using this algorithm, high latitude regions with short periods of sunlight, cloudiness may be overestimated. This is due to extended measurement periods of sunshine during the polar summer. Swift's algorithm does not correct for this feature. In these cases cloudiness was truncated to 100 percent.

2.4 Precipitation and Temperature Data for the Northern Hemisphere

The data are obtained from the long-term climatic data bank for the Northern Hemisphere land areas (Bradley *et al.*, 1985). Their aim was to obtain a high-quality data set using the maximum number of long-term weather records available. Tight selection criteria are based upon the known history of single stations and the measurement methods for obtaining the raw data. The final data set consists of data on seasonally and yearly precipitation and temperature of 1,200 and over 700 records respectively. The data spans a very long observational sequence from 1851–1984. The data are transformed into a 10° longitude and 5° latitude grid for temperature and precipitation anomalies by Bradley *et al.* (1987). Distribution over different periods are given on maps in Bradley *et al.* (1985). We have selected the 1931–1960 period from the data set and computed the climatic normals for this period from the original data set.

2.5 Selected Weather Data from the Meteorological Office

Cramer and Prentice (1988) have digitized a weather data set for Europe. This data set contains 632 selected European stations published by the UK Meteorological Office (1972). During the 1989 Young Scientist's Summer Program at IIASA stations from other volumes were entered. We especially selected stations from regions with sparse data coverage. The data set contains mean monthly values for maximum and minimum temperature, precipitation, and percentage cloudiness. Stations are characterized by longitude, latitude, altitude, and the observation period. The quality for precipitation and cloudiness values of this data set are generally high. The temperature values are only accurate to whole degrees fahrenheit. We have estimated

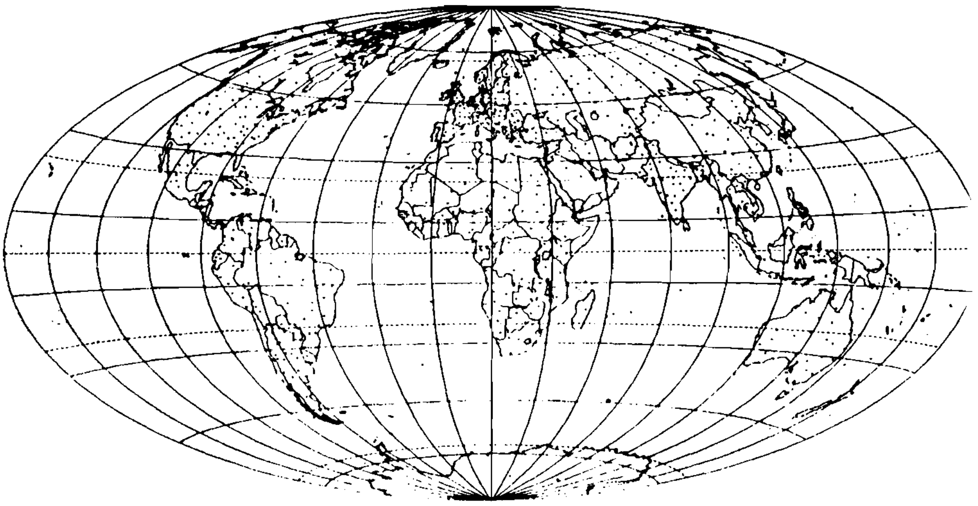

Figure 3. Distribution of stations (1,062) for the Müller (1982) climat data set: *Selected Climatic Data for Vegetation Science.*

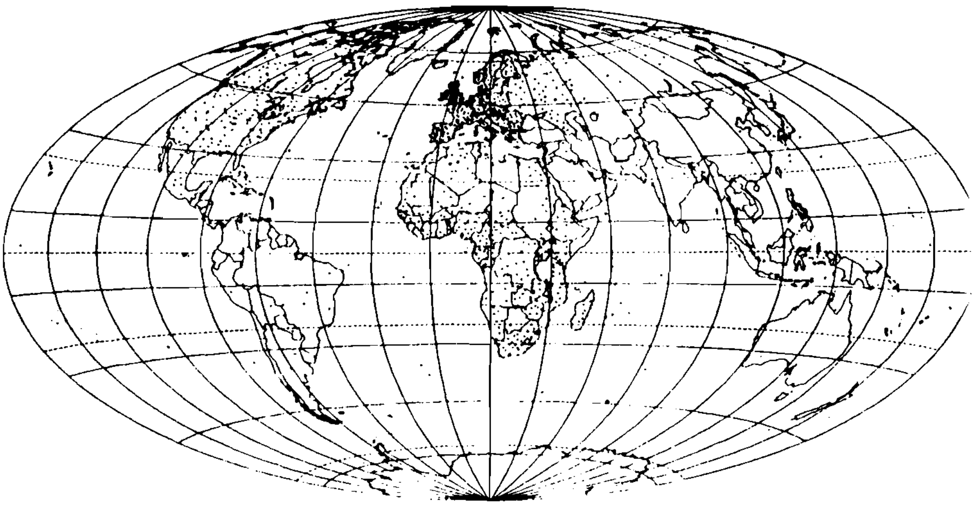

Figure 4. Distribution of stations (1,538) for the UK Meteorological Offic (1966–1983) climate data set.

mean monthly temperature by taking the average of the maximum and the minimum temperature. This could lead to a deviation from the temperature records of other data sets.

Other volumes in the UK Meteorological Office series are presently being digitized and, when completed, will be included in later versions of this data set. *Figure 4* gives the distribution of all stations included in the present data set.

2.6 Thornthwaite and Mather's Temperature and Precipitation Data

Willmott and Rowe (1985) used the Thornthwaite and Mather (1957) and Mather (1962–1965) precipitation records combined with temperature and other precipitation records (Willmott *et al.*, 1981a and 1981b) to create a global climate database of monthly temperature and precipitation. The complete data set consists in total of 14,765 stations with an uneven distribution (*Figure 5*). The USA, Japan, and Western Europe are well covered, while high latitude regions, Australia, and most of the developing world are underrepresented. The stations are characterized by longitude and latitude. Altitude values are missing and no observation period is given. Taking into account the length of time taken for the collection of this data (it started in the 1940s) the observation period is probably not very homogeneous.

Legates and Willmott (1990a and 1990b) combined this climate data set with the databases of Wernstedt (1977) and Spangler and Jenne (1984) and added ocean estimates. Using this array they created a gridded global climate data set on 0.5° longitude and latitude. The data were checked for coding errors, and redundant stations were removed. The total database consists of 17,986 independent terrestrial station records and 6,955 oceanic grid-point records. The data were interpolated towards a 0.5° longitude and latitude grid by using a spherically-based interpolation algorithm. They have also created two versions of the precipitation database, one interpolated and a gauge-corrected interpolated grid. The strength of this data set is the immense number of stations, resulting in a reliable spatial data quality for large regions. The data does not represent any climatic normal period, although most of the data is selected from the period 1920–1980 with a bias towards the data-rich latter years (Legates and Willmott, 1990a and 1990b).

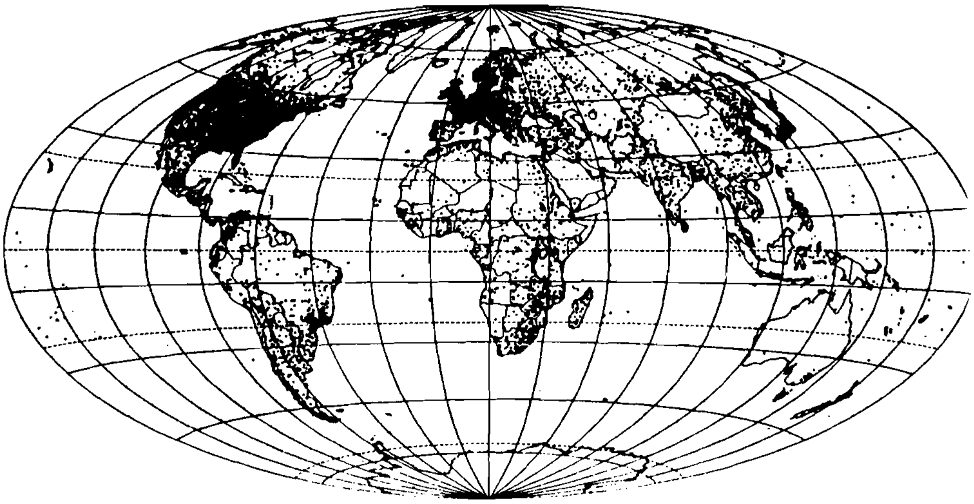

Figure 5. Distribution of stations (13,332) for the Legates and Willmot (1990a and 1990b) climate data set.

2.7 Soviet Temperature and Precipitation Data

Kirikova (1977) and Trophimemko (1981) have prepared a data set with monthly temperature and precipitation data from 148 Siberian weather stations. The stations are characterized by their Soviet ID-number and altitude. Longitude and latitude values can be derived from an accompanying map. The precision of digitized position values would be less than 1°. The data gives a data sequence with monthly values, spanning 1910–1980. We have selected the period 1931–1960 from this database and computed the monthly climatic normals.

2.8 Chinese Temperature and Precipitation Data

During the summer of 1989, Ruiping Gao collected weather records for the boreal part of North-Eastern China. The source of these data is the Institute of Ecology, Academia Sinica in Shenyang-Lianoning, China. The data consists of 50 stations, characterized by longitude, latitude, and altitude. The climate variables included are average monthly temperature and precipitation. The averaged data is mainly from the observation period 1950–1960. Much of the earlier observations are unfortunately not maintained in the Chinese records.

3. Creation of the Global Climate Database

3.1 Quality Check and Selection Algorithm

All data sets were first transformed to the IIASA Biosphere Dynamics Project file standard (see Appendix 1). Thereafter all stations were separately checked for coding errors by evaluating extreme values and averages, and by comparing each station with other stations in the immediate surroundings. If unreliable extremes or large differences were located, the data from that station were manually checked for inaccuracies. The longitude and latitude of each station (location) was checked to see if it was actually located in the given country and, if possible, if the location was in agreement with the known name of the station. The latter was checked by using the *Times World Atlas* (Bartholomew *et al.*, 1988).

The altitude of each station was checked against a topography database. This 0.5*0.5° topography database was created especially for this purpose at IIASA by combining several cells of another global data set on topography (National Geophysical Data Center, 1988). The new topography data set consists of minimum, maximum, and modal elevation in meters, together with percentage land for each cell. Altitudinal values of all weather stations were checked against the given range in the topography data set. The most common error spotted during this comparison was a difference of a factor of three in altitudinal values. Although some sources stated that their altitudes were given in meters, no transformation from feet had been made before the publication of those records. We have corrected these inconsistencies. Stations with missing altitude values were assumed to be located at an elevation similar to the modal value in the topography data set.

All stations were merged into a single database and sorted according to longitude and latitude. The Soviet data set was not included since the location of the data was known to be inaccurate (Kirikova, 1977; Trophimemko, 1981). Also the original data sets of Legates and Willmott (1990a and 1990b) have been excluded. This was not only because of their nonhomogeneous observation period, but mostly because we wanted to have a data set with which to compare our data set in order to evaluate its quality.[1] Finally, the data set was separately screened for station selections for the creation of the

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[1] The interpolated Legates and Willmott (1990a and 1990b) data set is the only gridded database with a comparable resolution. The authors used a different interpolation technique. This makes their data set ideal for comparison.

gridded temperature, precipitation, and cloudiness data set. The selectior criteria, however, were similar.

The first step was to remove redundant stations (stations with multiple entries in the database). This was evaluated on the basis of longitude latitude, and altitude. Because of differences in the accuracy of the given location of the original data sets, we checked all stations within 0.1° longitude and latitude apart. A secondary criterium for the evaluation of redundant records were the names of the stations.

Together with the length of the observation period, the initial data sets were ranked according to our estimated quality assessment. The quality of the data set was based on the known observation period (long-term historical records including 1931–1960 were preferred over compilations of climatic normals) and the quality and clarity of the documentation of the data set. The data sets collected by Bradley *et al.* (1985) ranked first, Müller (1982) second, followed in sequence by the UK Meteorological Office (1966–1983), the Chinese collection, the Weather Bureau (1959), and finally Walter and Lieth (1960–1967). If redundant records were found, and both were within our definition of the "current-climate" period, the record with the longest observation period was selected in favor of the shorter one. If an observation period of a record extended outside the observation period, while the other qualified our "current climate" constraint, the latter was favored over the first. If the other criteria were inconclusive, the quality ranking determined which station was deleted. If records still were of equal quality, one of them was chosen randomly. The next selection-step was to remove stations with observation periods shorter than six years and longer than 30 years. Long records were deleted because we wanted to exclude long-term climatic change trends.

Finally, a terrestrial 0.5° longitude and latitude grid was created, using the above mentioned topography data set. Using the variable "percentage land" in this data set, terrestrial cells were defined as having at least 60% land. The resulting terrestrial data set was checked for inconsistencies in the coastline against the World Database II (CIA, 1972), as it is incorporated in the computer graphic libraries from UNIRAS (1989). Most erratic terrestrial or water cells were corrected.

The weather records were further delimited by determining the "most typical station" of each terrestrial cell. We wanted only one station per cell to allow for a consistent topography correction scheme (see below). The most typical station should be located closest to the modal altitude of a cell. If more stations were available per cell, the most central one could determine the climate of that cell statistically relatively well, although it could be located towards the topographical extremes of the cell. We listed all cells with several available stations together with minimum, maximum, and modal altitude. By evaluating the altitude of the stations, the observation periods, and the quality ranking (see above), we selected the most typical station for the cell. This tedious process was done manually first and included in an automatic selection program later. We did not consider averaging, because stations close to the extreme altitude could become dominant.

The resulting data set consisted of 6,280 records with temperature values, 6,090 records with precipitation values, and only 1,597 records with cloudiness values. Initially we had 13,118 stations in our merged database, but many stations were not selected because of an irrelevant observation period or because they were located with better stations in a single grid cell. The latter was especially true for precipitation stations, especially in mountainous regions. Good data coverage was obtained for Europe, the USA, Southern Canada, East Asia, and Japan. Africa and Australia have somewhat poorer data coverage, while high latitude, arid, and mountainous regions had low data coverage. The selection procedure has lead to areas with good station densities being determined by stations with observation periods within our defined current climate, thus with a high quality for database usage objectives. The other regions have a somewhat poorer coverage quality, but probably still adequate for our purposes. Regions with sparse data coverage are often characterized by stations with short observation periods and outside our "current climate' period. This leads to a poor data coverage in these areas'.

3.2 The Interpolation Technique

Spatial interpolation is the estimation of the function that represents the entire surface from a given set of spatial data. This function can be used to predict values at other points. The result of such interpolation from any sets of points can either be exact or approximate. Exact methods preserve the values of the original points, while the latter do not (Wren, 1975). Several algorithms for point interpolation have been developed and reviews on interpolation are presented by Lam (1983) and Ripley (1981).

Interpolation techniques differ when using stations located in cartesian two-dimensional space or on a sphere. Willmott *et al.* (1985) have compared these two methods and concluded that the spherical method was superior when using the interpolation for a sparse data network. Their studies showed that a cartesian two-dimensional network could display large distortions after the actual interpolation, especially if values were estimated outside the original data grid. The distortion was dependent on the type of projection and was most severe when using cylindrical projections. Their analysis was, however, based on a different interpolation routine than the one we used (Shepard, 1984). Their method has less extrapolation capabilities than our methods and it also becomes more sensitive to distortions in data-sparse areas, like the high latitudes. Besides, many weather stations in our database are situated along the coastal edges of continents and we only want to estimate the values of terrestrial areas. These reasons minimize our need for extrapolation and thus also minimize distortion. Distant extrapolation only occurred for Northern Greenland and a small area of Central Siberia (see *Figures 1* to *5*), where no stations were available.

Although the spherical interpolation intuitively is appealing, an argument against it is that distances on a sphere are mostly defined as the great circle distances. Because of this, spherical interpolation methods often cross the poles. Although climatic polar interaction cannot be neglected, it is of lesser importance than the interactions within any latitudinal belt. The rotation of the earth causes the climate due east of any point to be more influenced by that point than in any other direction.

The interpolation technique we used is a triangulation of all data points (according to the algorithm developed by Green and Sibson, 1978) followed by a smooth surface fitting (Akima, 1978). We used a cartesian two-dimensional space in which we directly used the actual longitude and latitude values (with minutes converted to decimals). This defines a sinusoidal projection for both the data points and the resulting grid. To obtain climatic influence between Alaska and the Eastern part of Siberia (180°E and 180°W) we duplicated the monthly climatic normals of stations within 20° of this discontinuity with a 180°E or 180°W mirrored image. This reduced extrapolation errors for this part on the globe.

3.3 Correction Scheme for Altitudinal Differences

Temperature and precipitation values in general decrease and increase respectively with elevation. This observation could be used to improve the data reliability in mountainous areas with sparse data coverage. These altitudinal correction factors are called lapse rates. Moist adiabatic lapse rates for temperature are physically determined and range from -0.5°C to -0.8°C per 100m (Strahler and Strahler 1987). Application of temperature lapse rates to long-term monthly means involves a rough approximation within this physically-determined narrow range. Lapse rates for precipitation are more difficult to estimate for a global application. They would differ largely from region to region and need not be monotonous along a local altitudinal gradient. Apart from depending on altitude, they also depend on the orographic position of the station and the main direction of the wind, rain shadows, distance to oceans, and air humidity. Therefore, up to now only local precipitation lapse rates have been determined and implemented in very detailed studies (e.g., Delijaniec, 1972; Khurshid Alam, 1972).

We have thus only implemented a moist adiabatic lapse rate correction for temperature. Before any monthly temperature was used in the interpolation, the value was corrected as if the station was located at sea level using a lapse rate of –0.6°C per 100m altitude. All records were then entered into the interpolation as if they were at sea level. The resulting values for the terrestrial grid were estimates at the same level. These values were then corrected towards the modal altitude of the grid cell using the same lapse rate and the topographical database. (If needed we can provide a version of the temperature data set without the topography correction.)

We explored a similar procedure for precipitation, but a satisfactory global orographic lapse rate could not be defined. The resulting precipitation data set had few similarities with the uncorrected precipitation patterns from the Legates and Willmott (1990b) database. We decided not to implement a correction for orographic processes because of their complexity. Precipitation data was therefore interpolated without accounting for differences in altitude. Future updates of the database, however, could involve algorithms to empirically determine local lapse rates for precipitation as well (e.g., Hutchinson, 1989).

4. Quality of the IIASA Climate Database

Monthly average temperature patterns are presented in *Figures 7* to *18* (Legend in *Figure 6*). The seasonal patterns can clearly be observed on the maps. By comparing the different monthly values with the database of Legates and Willmott (1990a) we find that most patterns are similar. We have obtained a more detailed pattern in most of the Southern Hemisphere. This is probably due to our more dense network of stations in this area. Also the different mountainous areas are more clearly distinguished in our database. This is mainly due to the temperature lapse rate correction, but this probably has some disadvantages. We have consistently obtained a colder climate for high altitude regions, e.g., the Plateau of Tibet. This could be the result of a too high estimate of the average annual moist adiabatic lapse rate for the whole altitudinal range. But this is difficult to check. because there are only very few weather stations in these regions and none are located on a clear altitudinal gradient.

There is another concern about the general quality of the current data set, which also applies to the Legates and Willmott (1990a) data set. The sources are nonhomogeneous and monthly mean temperature could have been defined and/or derived in different ways. For example, measurements are made in °F and °C and the conversion into °C could easily generate a precision of less then one decimal point. This is especially true for the UK Meteorological Office (1972) data set. The best solution to this problem is to take an approach similar to Bradley *et al.* (1985), who collected long-term measurement sequences; from this a better quality assessment can be achieved and comprehensive normal periods can be computed. The creation of such an accurate collection is very time consuming and goes beyond our ambitions and capabilities.

Although the major patterns are captured in both databases, our database seems to have, on average, a better regional resolution than the Legates and Willmott (1990a) data set. The use of our database for ecological/biogeographical applications is thus likely to reveal a reliable pattern and lead to valid conclusions on crop and vegetation distribution patterns.

Monthly average precipitation patterns are presented in *Figures 19* to *30* (Legend in *Figure 6*). Precipitation data display the major global patterns. Going southward from the Sahara in Africa, there is a steep increase in precipitation. The major arid areas of the world can clearly be located. The wettest areas in the Northern Hemisphere are on the SW coast of Norway and in the American NW. Similar patterns can be observed in the uncorrected Legates and Willmott (1990b) database. The latter database displays a more local pattern in the USA. This is due to their dense network of stations in this part of North America. For the rest of the world, data coverage is similar. We can assume that global data quality is about equal for both data sets.

As a result of the straight interpolation of measured values, the quality of the database will be less in regions with sparse data coverage. The actual values in the data set could also be underestimated, because of the undercatch of rain-gauges. This was done for one of the Legates and Willmott (1990b) data sets and this led to particularly higher precipitation values at high latitude and high elevation areas, where large proportions of annual precipitation comes as snow. A simple version of such correction schemes could, of course, be implemented on the precipitation data set by users separately.

Monthly average cloudiness patterns are presented in *Figures 31* to *42* (Legend in *Figure 6*). Cloudiness demonstrates particularly well the major seasonal patterns of the monsoons and other wet seasons. The arid areas are clearly distinguishable from the wetter areas. If these areas are combined with the temperature data set, we see a clear correlation with temperature. The highest temperatures are observed in the arid areas with little cloudiness, and not in the tropics, where there is a more continuous cloud cover. No comparisons can be made with other cloudiness data sets because no such data set was available to us.

As coverage was low, i.e., only 1,597 stations, regional quality is probably low..This quality is further decreased by the heterogeneity of the input data. We have defined cloudiness as the mean monthly percentage coverage of the sky. These values were often obtained from other types of measurements, like sunshine hours (e.g., Müller, 1982), and the conversion towards cloudiness leads to further quality loss. Although appropriate for global applications, we do not recommend the use of the cloudiness data set for regional and local applications.

The cloudiness database shows slight distortions that are likely to be caused by the interpolation routine. In the high latitude areas some unexpected patterns occur, which cannot be explained by the underlying data. Few stations were available for these areas and larger parts had to be extrapolated, leading to more distortions (Willmott *et al.*, 1985).

The climate data set is presently embodied in a Geographic Information System (GIS) that permits almost instant visualization of current climatic conditions and data manipulations for a wide range of applications. This GIS system has been developed at IIASA and is especially designed to interface global databases with different global vegetation models. Its visualization routines are based on the graphics software libraries of UNIRAS (1989). The figures in this report are drawn using this dedicated global GIS.

5. Future Developments

The IIASA-climate database has reached a quality suitable for use in general applications within the fields of ecology, biogeography, agriculture, and climate change impact studies and is already applied at different research centers around the world. It will also soon be included in the global ecosystems database, compiled by the US-EPA and NOAA (1991). However, there are some limitations to the current version of the data set. For example, in linking climate to vegetation by using different climate classifications (e.g., Holdridge and Tosi, 1967; Box, 1981), the temperature-determined vegetation patterns in areas with a particular topography are clearly captured. The finer scale pattern in precipitation is not always evident, which often leads to an arid environment with increasing altitude as compared with reality.

These small-scale changes in the climate pattern can be captured. Bartlein (personal communication, 1990) has shown that regional precipitation patterns can be improved considerably by using a scheme based on interpolation of only weather records within specific altitudinal ranges. Other interpolation schemes that directly take local topography into account (e.g., Hutchinson, 1989) could also be feasible. We plan to test more elaborate interpolation schemes for use in future versions of the database.

Besides the potential improvements by more elaborate interpolation procedures, the main limitation is still inappropriate data coverage for large areas. Good data coverage is especially important for capturing the regional and local patterns of precipitation and the overall improvement of the relatively few cloudiness records. The main areas with inappropriate data coverage are the high latitude regions (especially Siberia and Canada, while Alaska and Fennoscandia have better coverage), Australia, South America, Mongolia, China, and the Plateau of Tibet. These regions with sparse data coverage will be improved by the incorporation of other data collections.

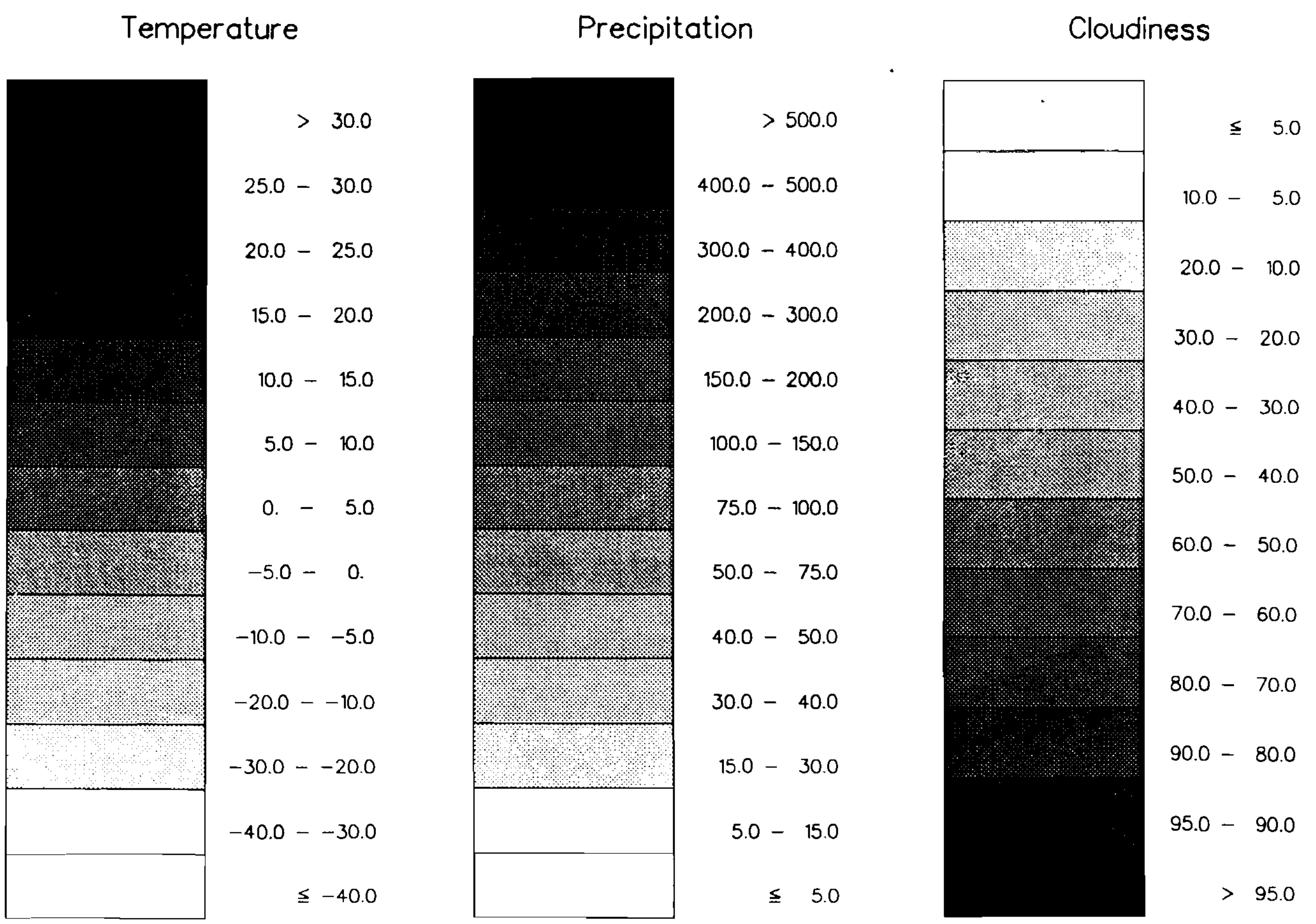

Figure 6. Legend for *Figures 7* to *42*.

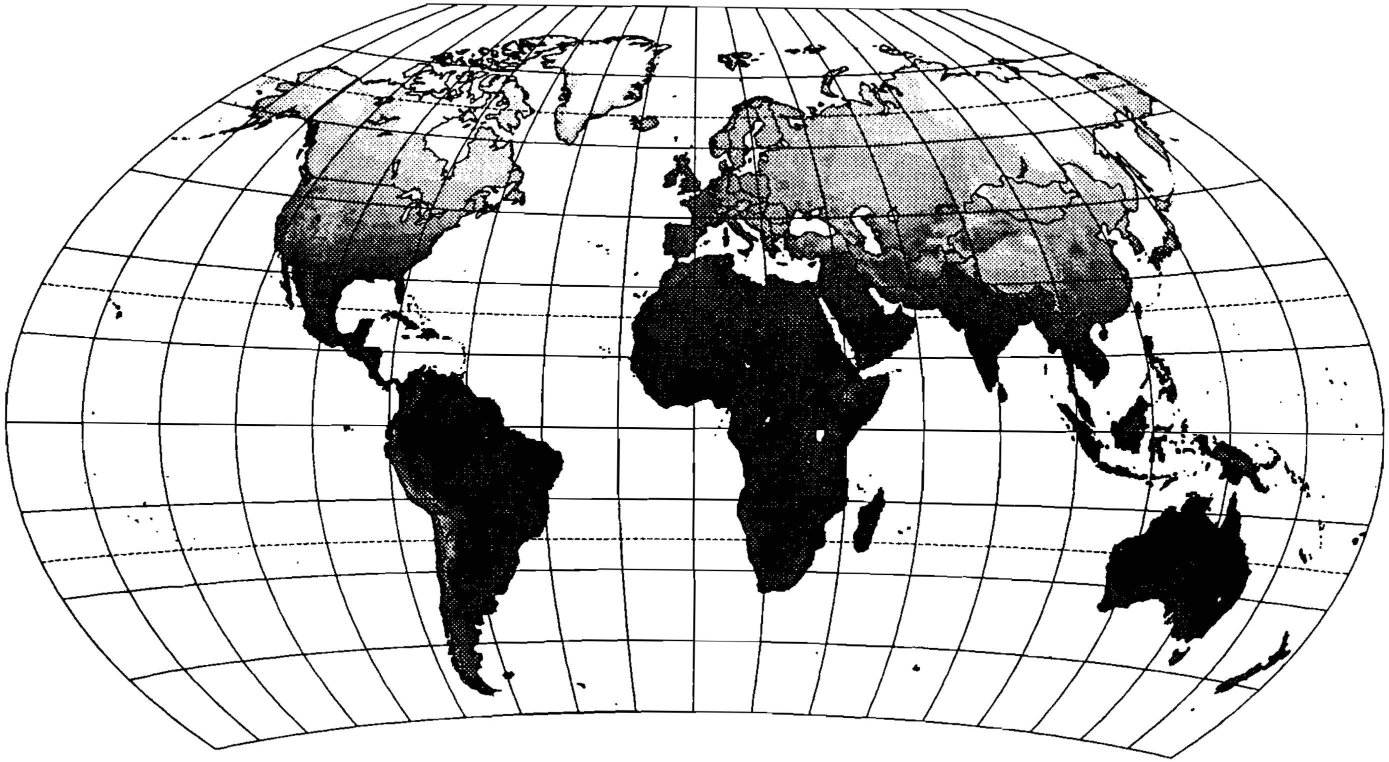

Figure 7. Mean monthly temperature for January (°C).

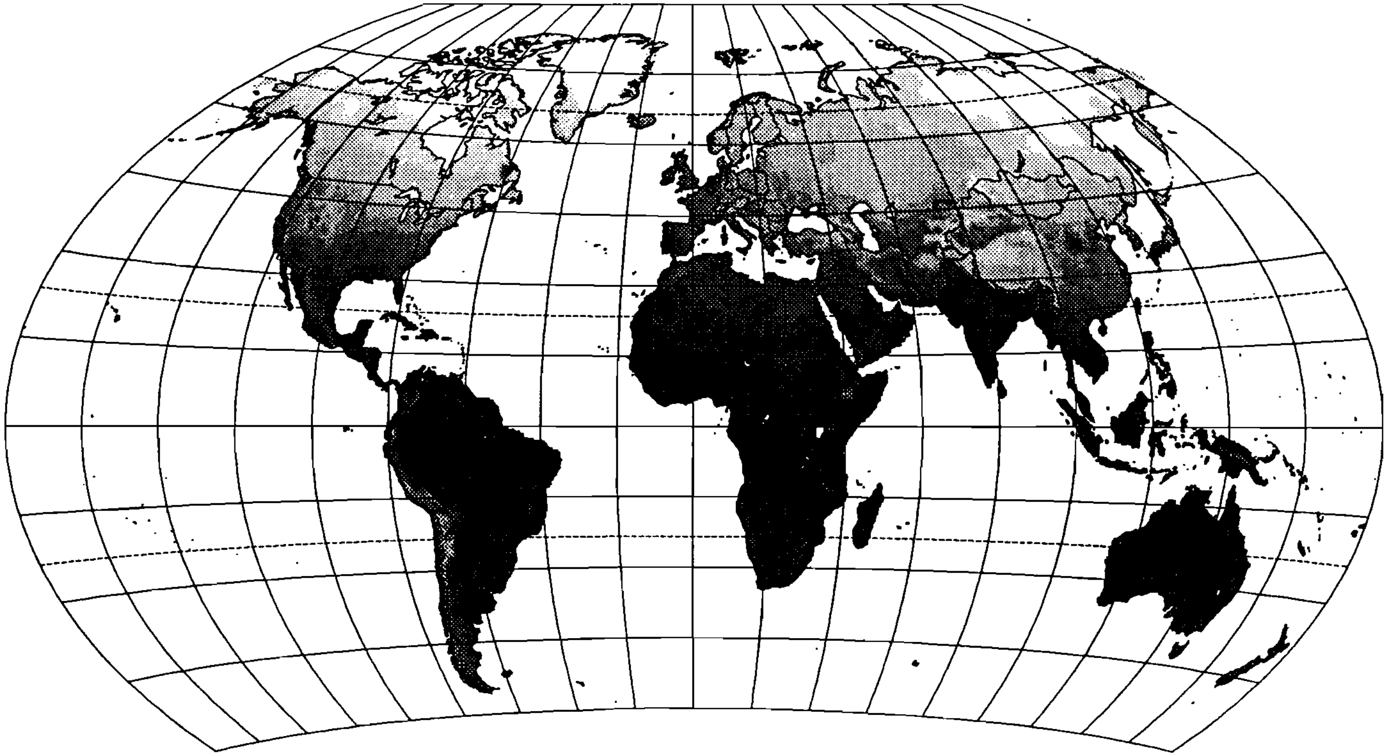

Figure 8. Mean monthly temperature for February (°C).

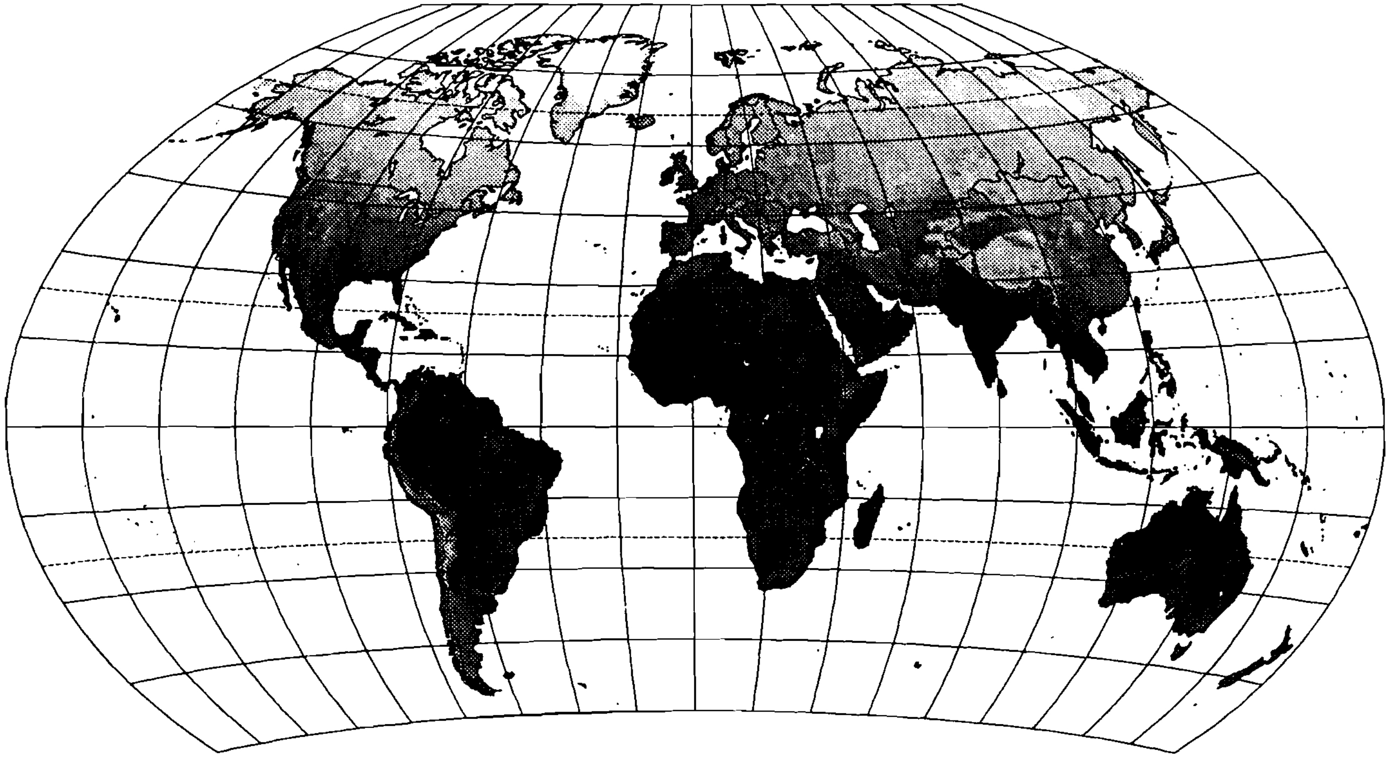

Figure 9. Mean monthly temperature for March (°C).

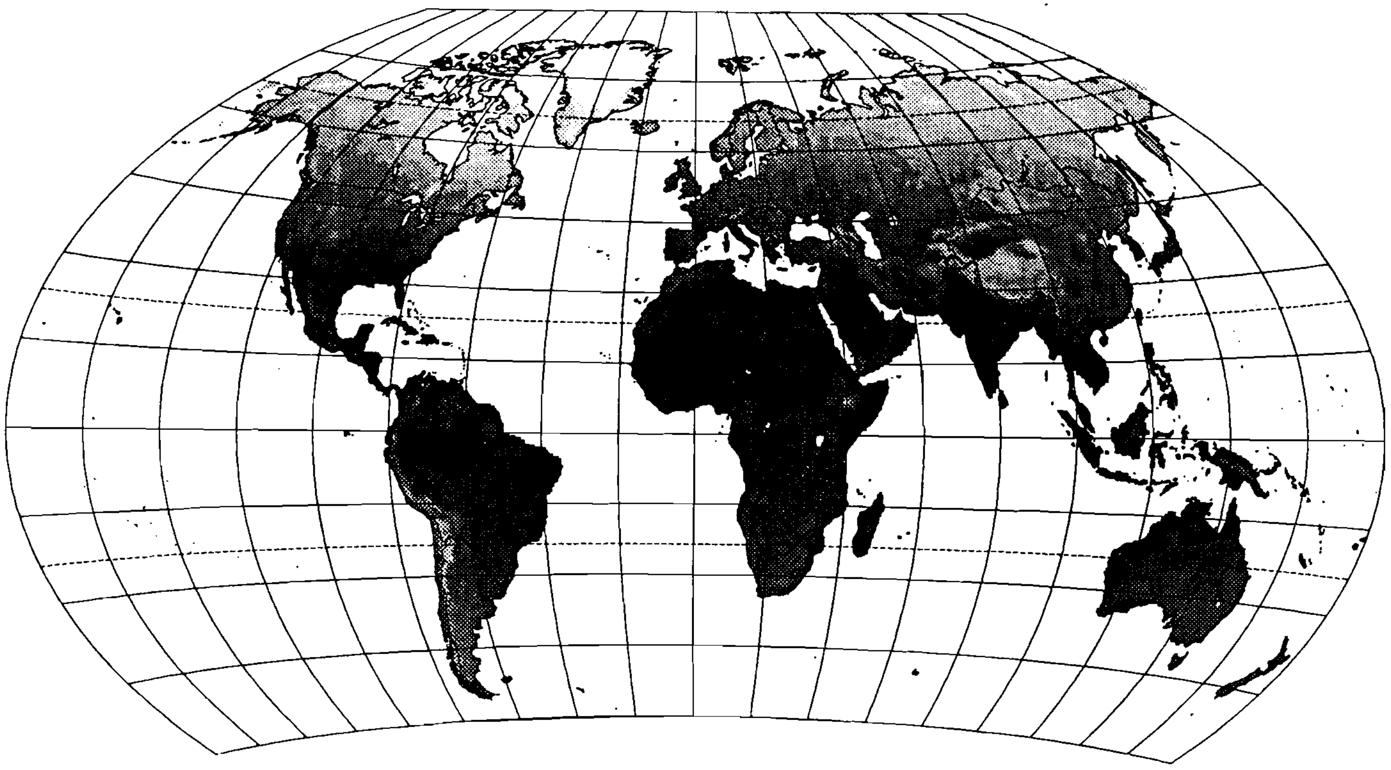

Figure 10. Mean monthly temperature for April (°C).

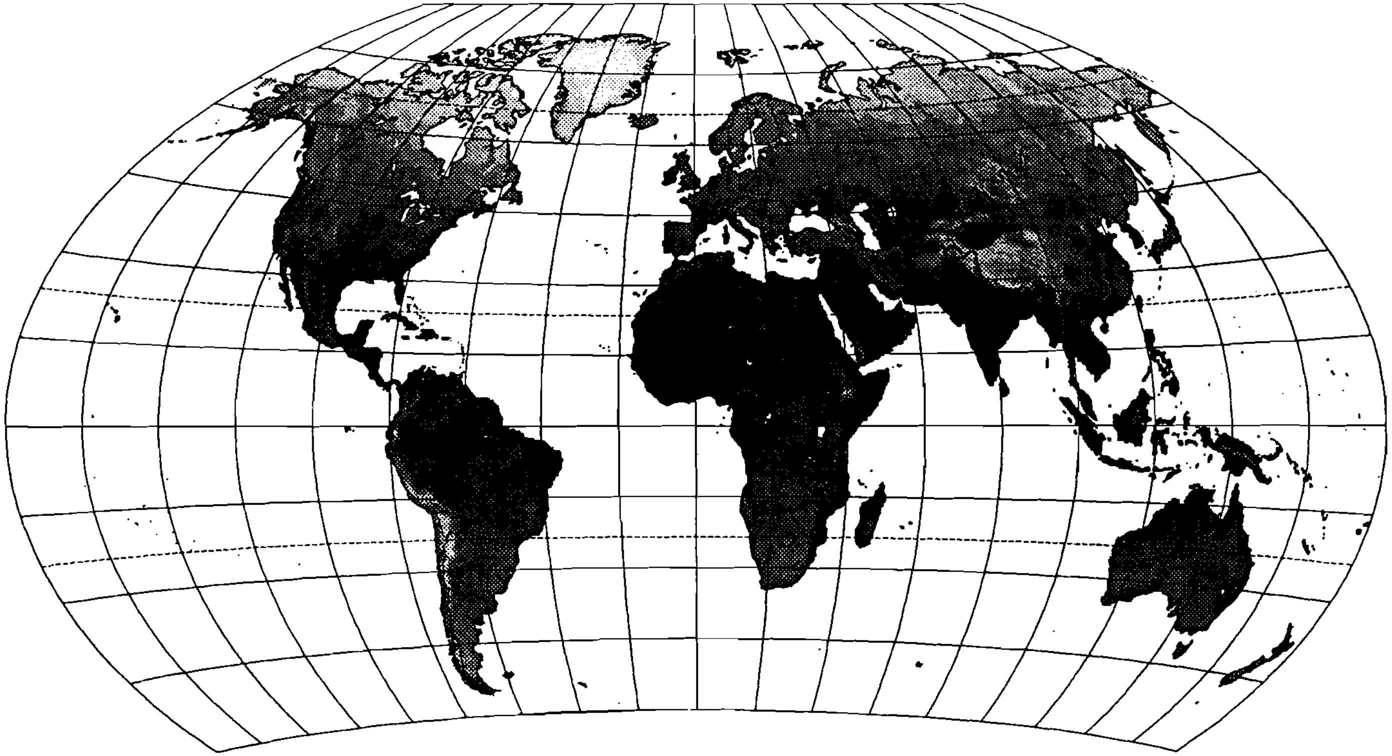

Figure 11. Mean monthly temperature for May (°C).

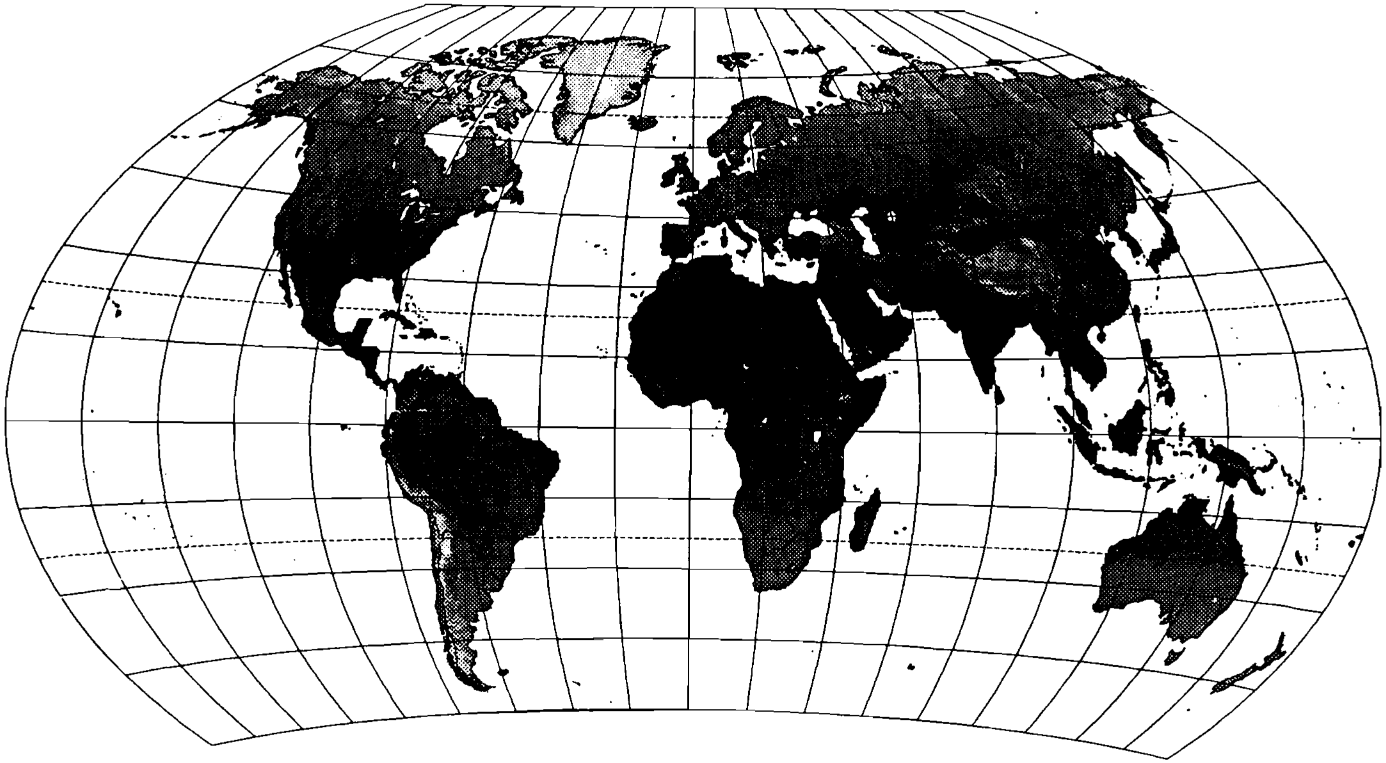

Figure 12. Mean monthly temperature for June (°C).

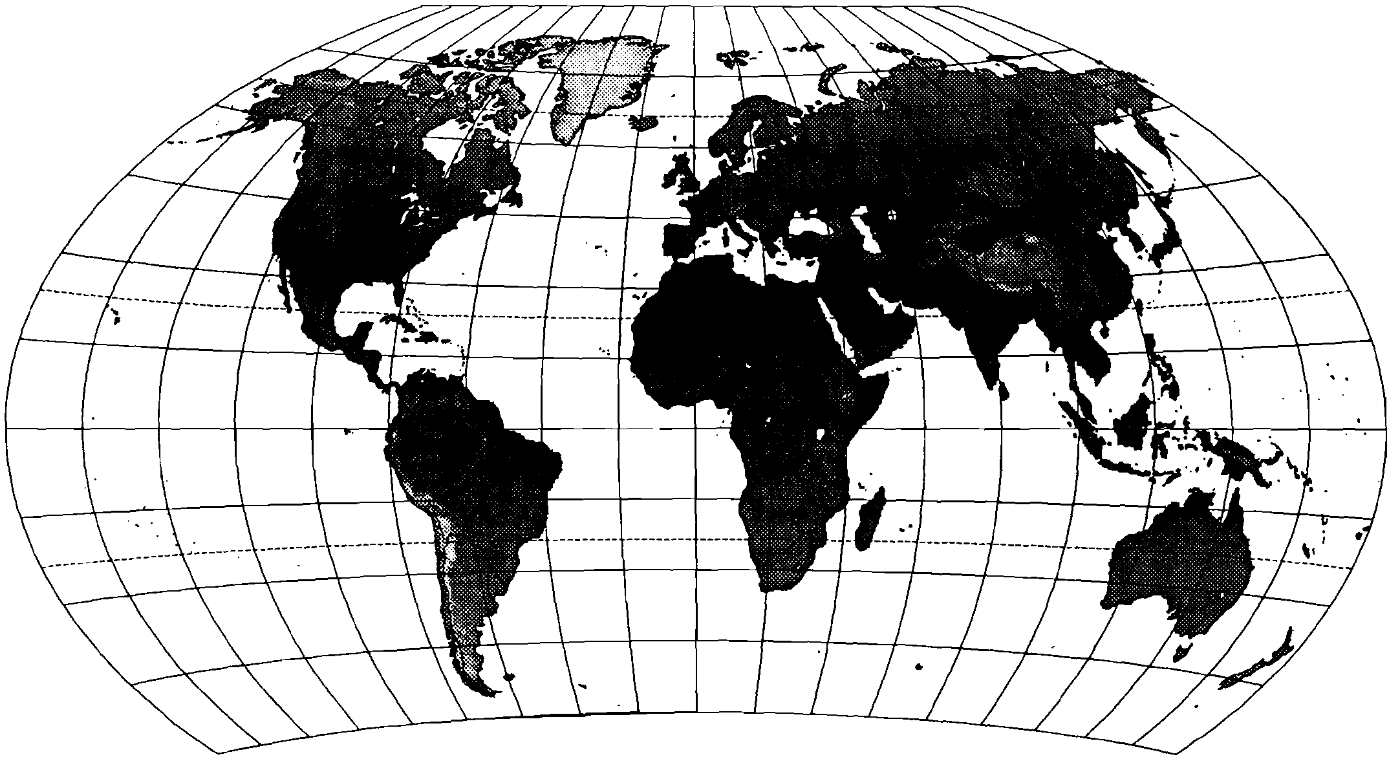

Figure 13. Mean monthly temperature for July (°C).

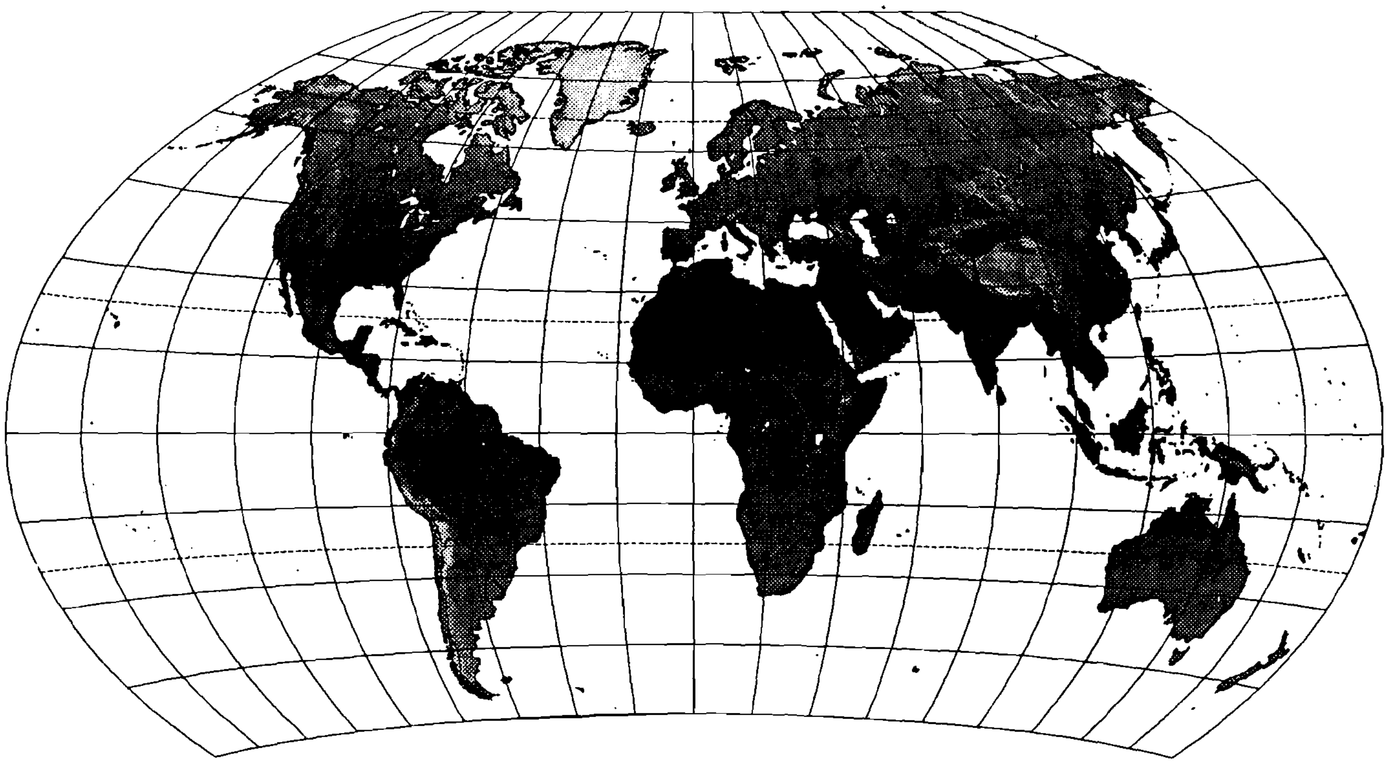

Figure 14. Mean monthly temperature for August (°C).

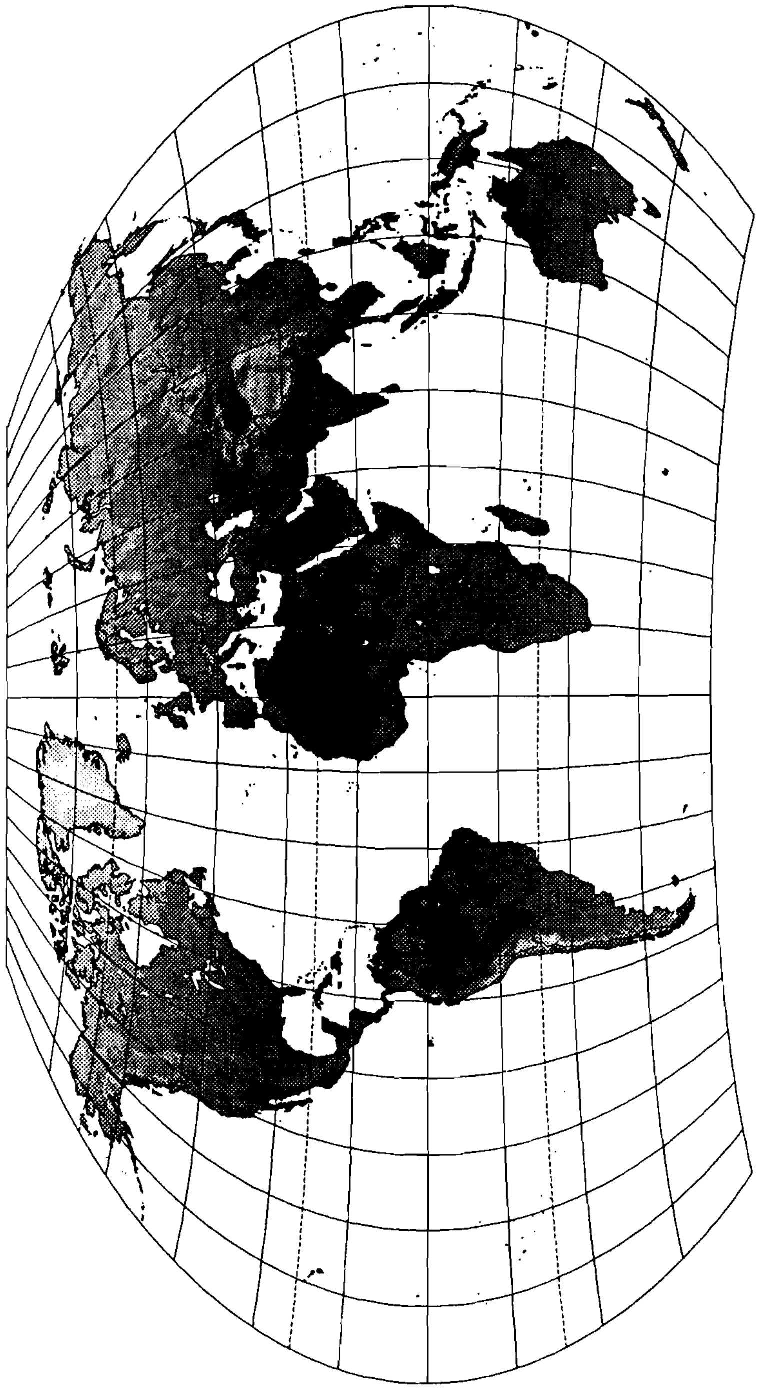

Figure 15. Mean monthly temperature for September (°C).

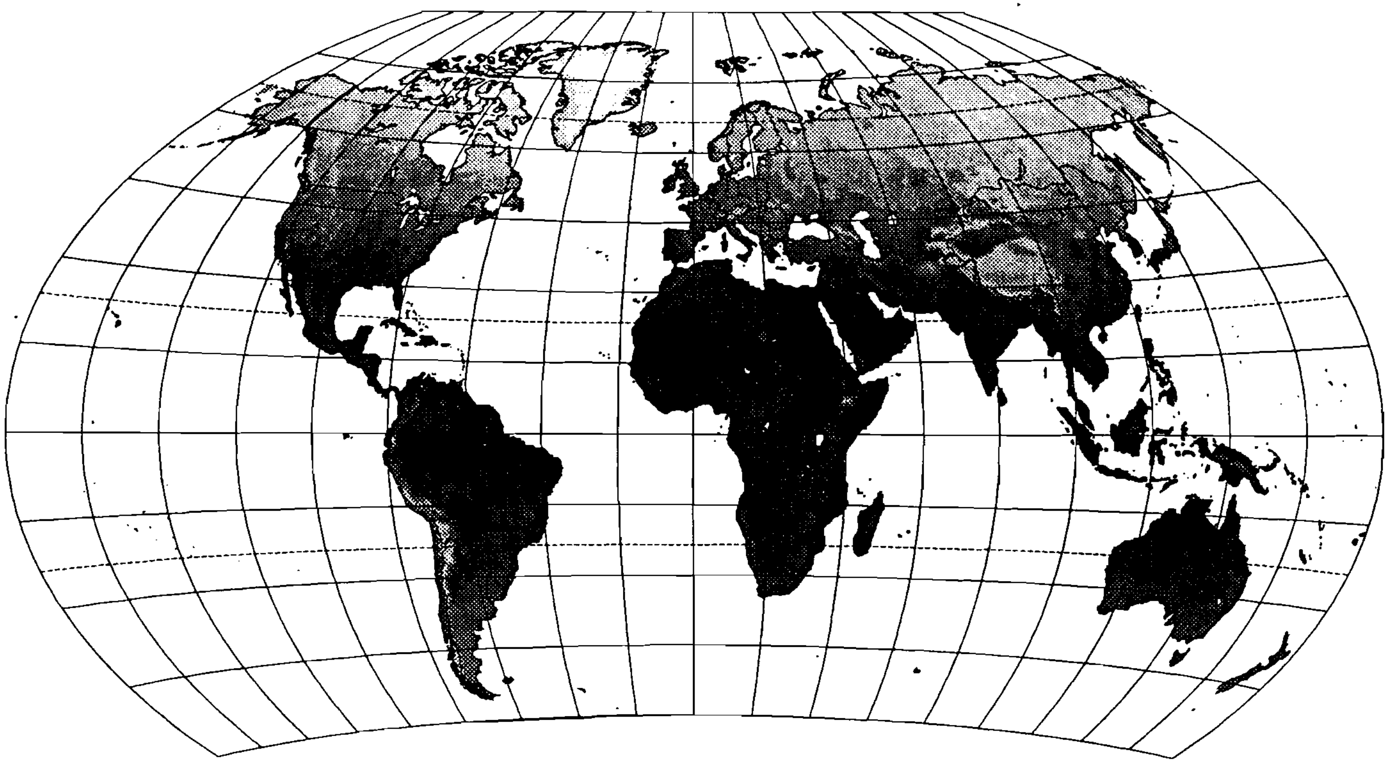

Figure 16. Mean monthly temperature for October (°C).

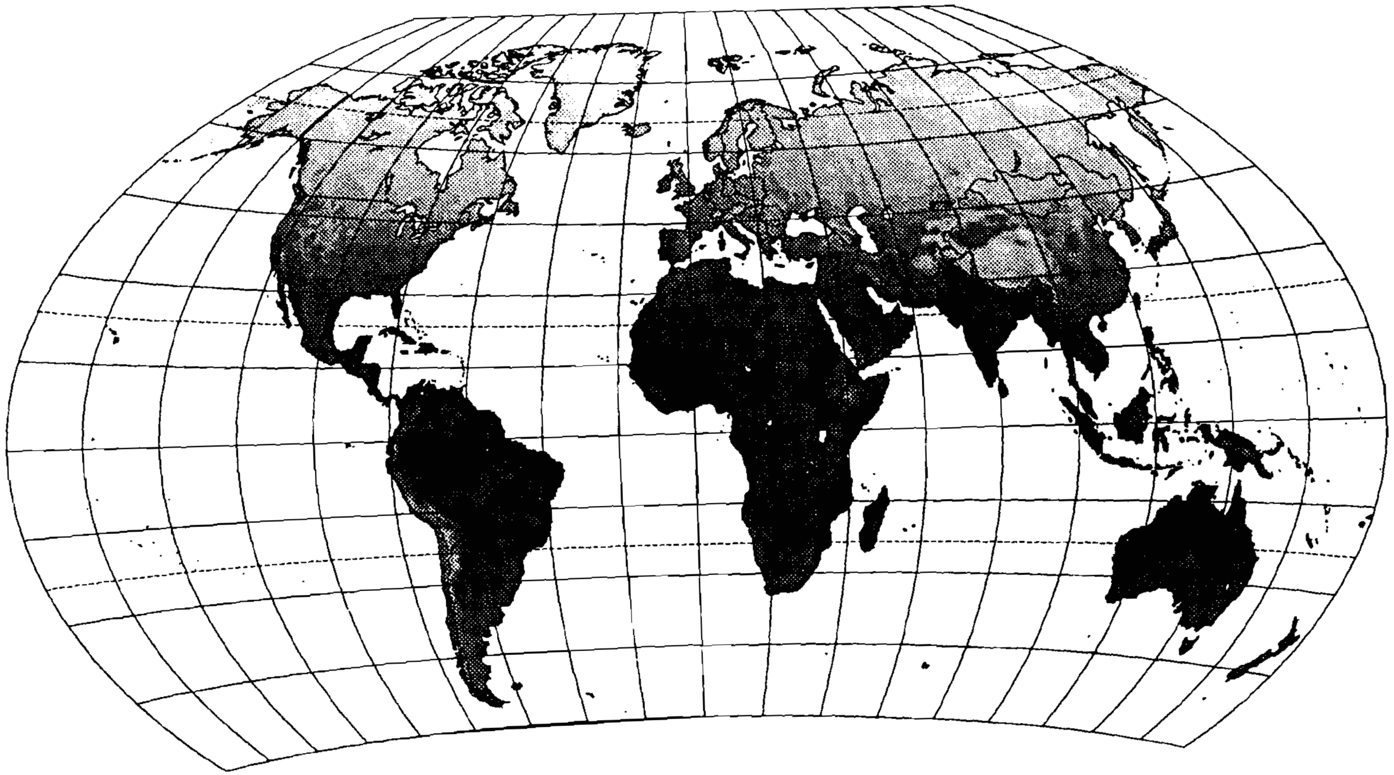

Figure 17. Mean monthly temperature for November (°C).

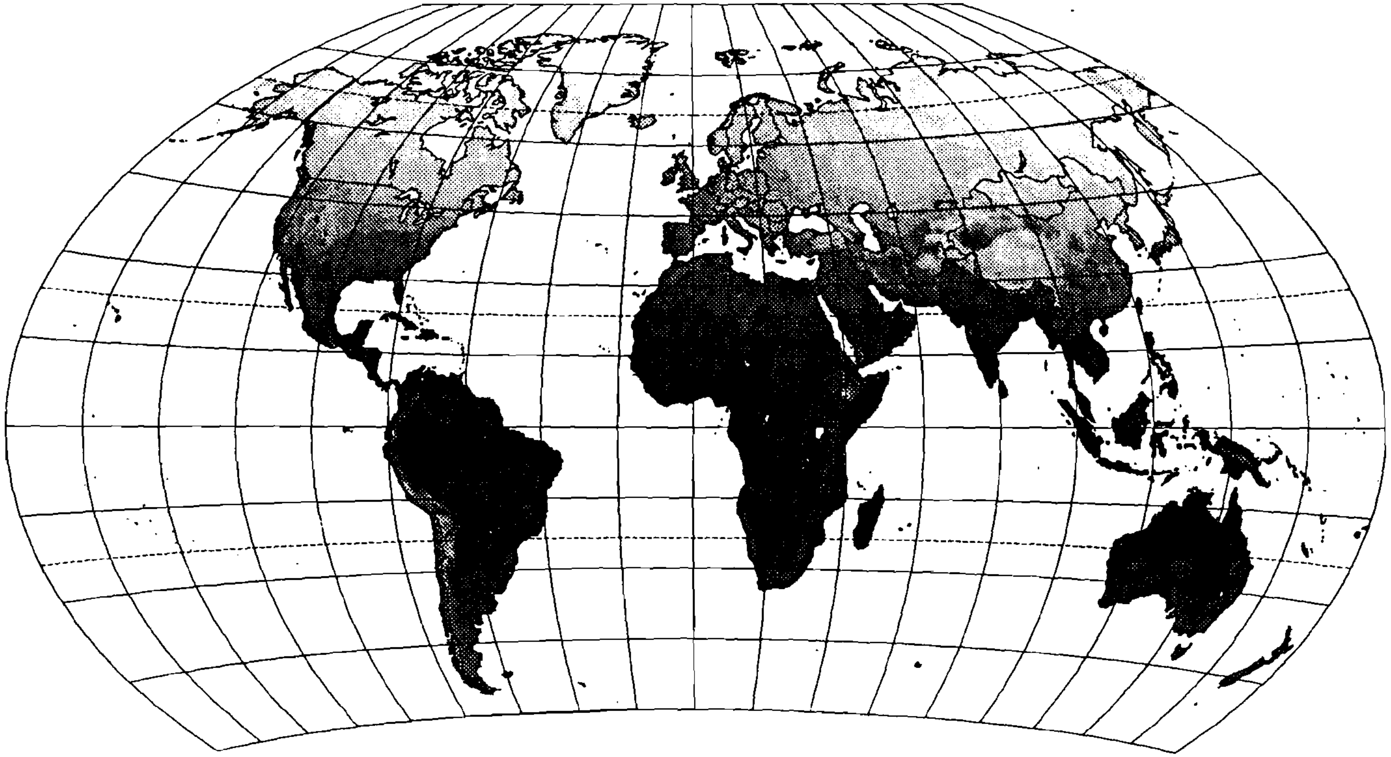

Figure 18. Mean monthly temperature for December (°C).

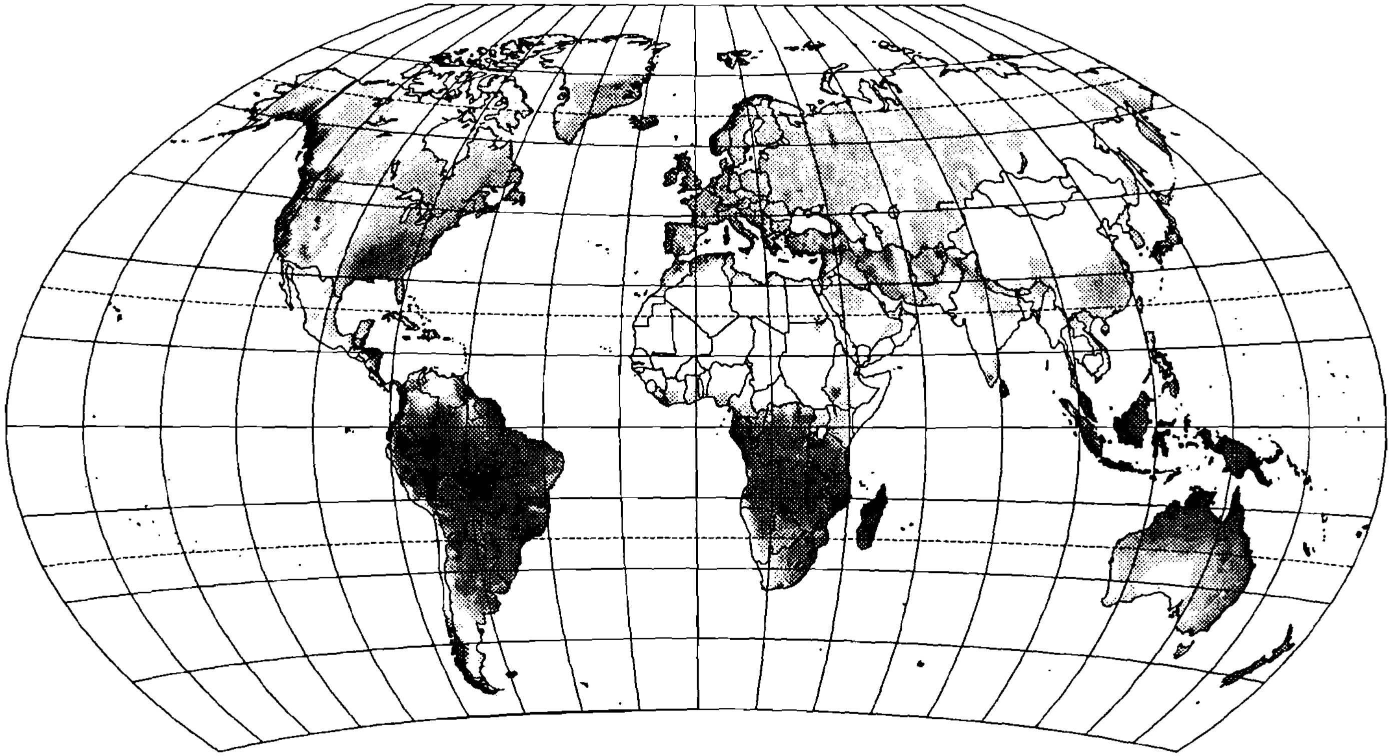

Figure 19. Mean monthly precipitation for January (mm).

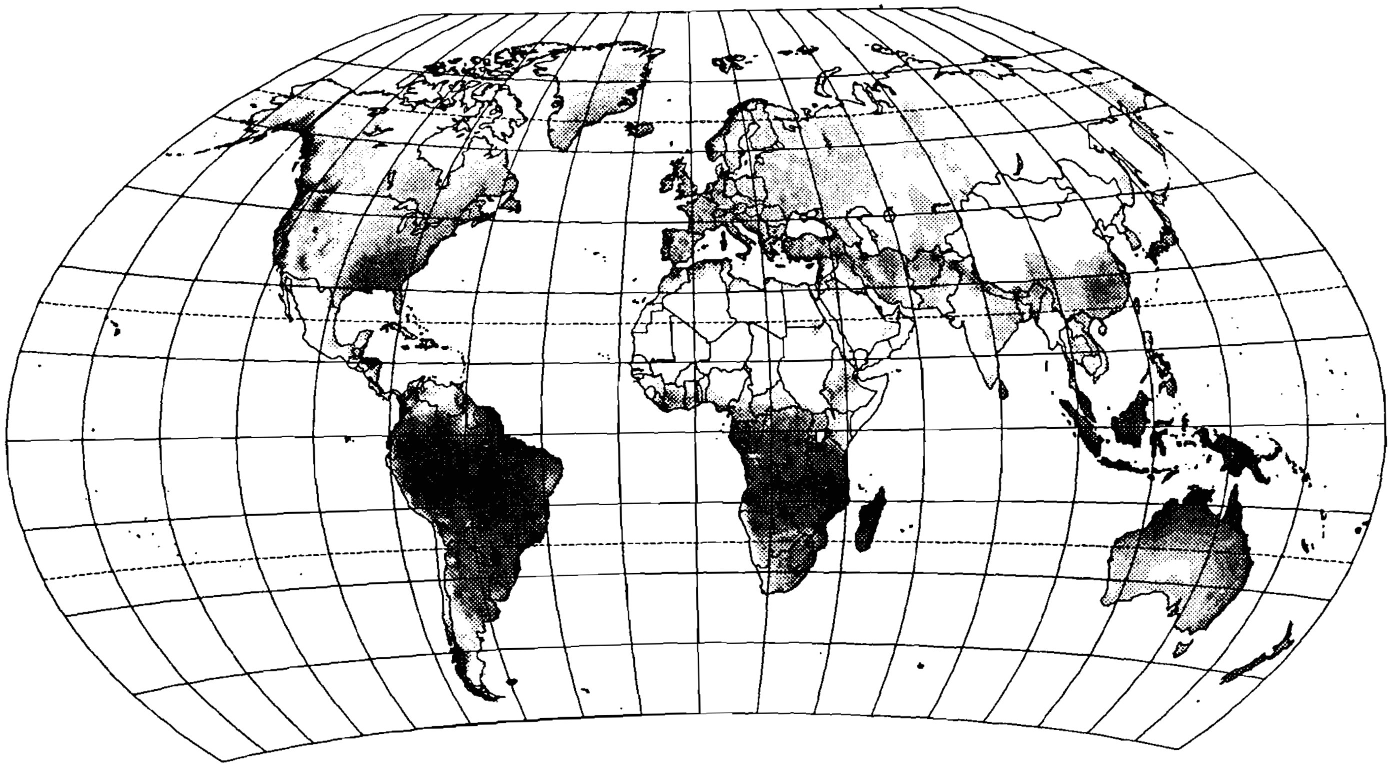

Figure 20. Mean monthly precipitation for February (mm).

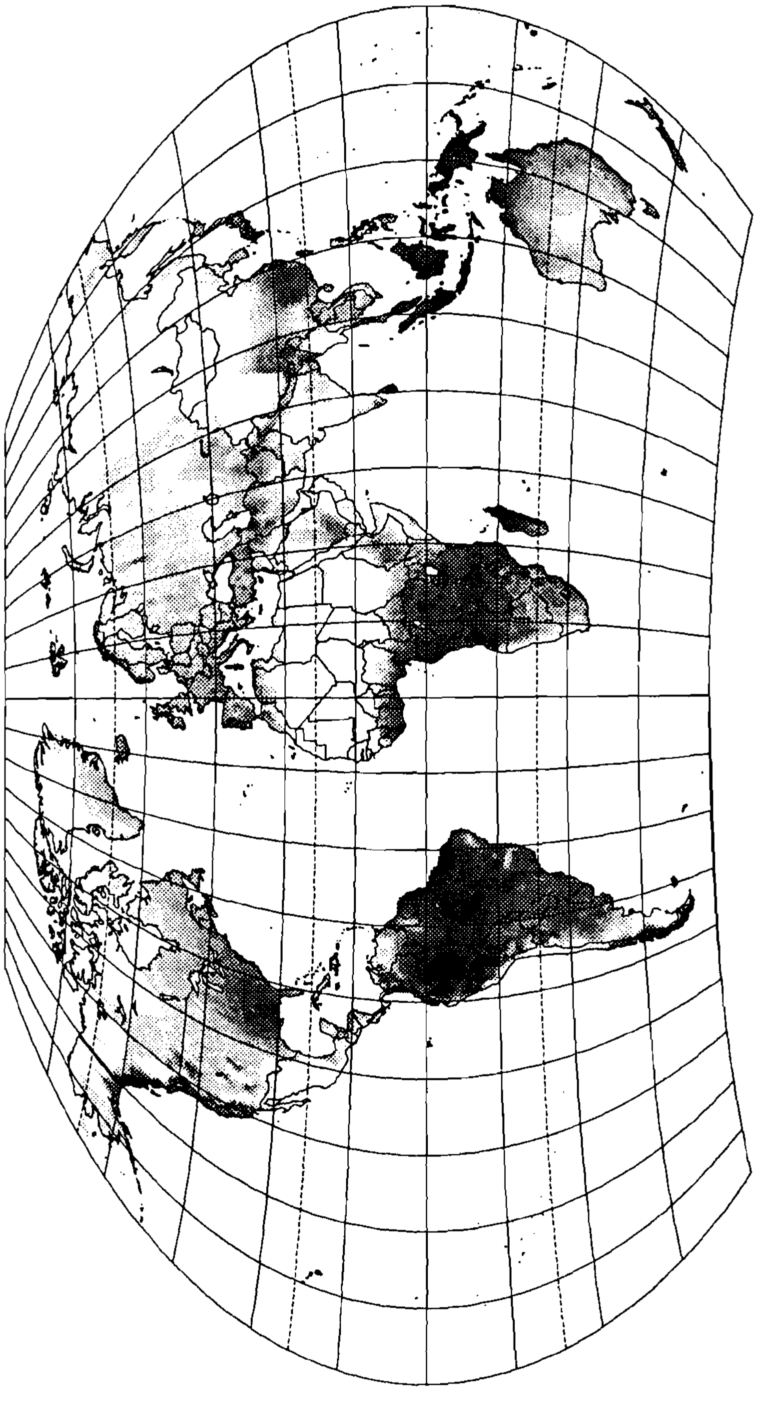

Figure 21. Mean monthly precipitation for March (mm).

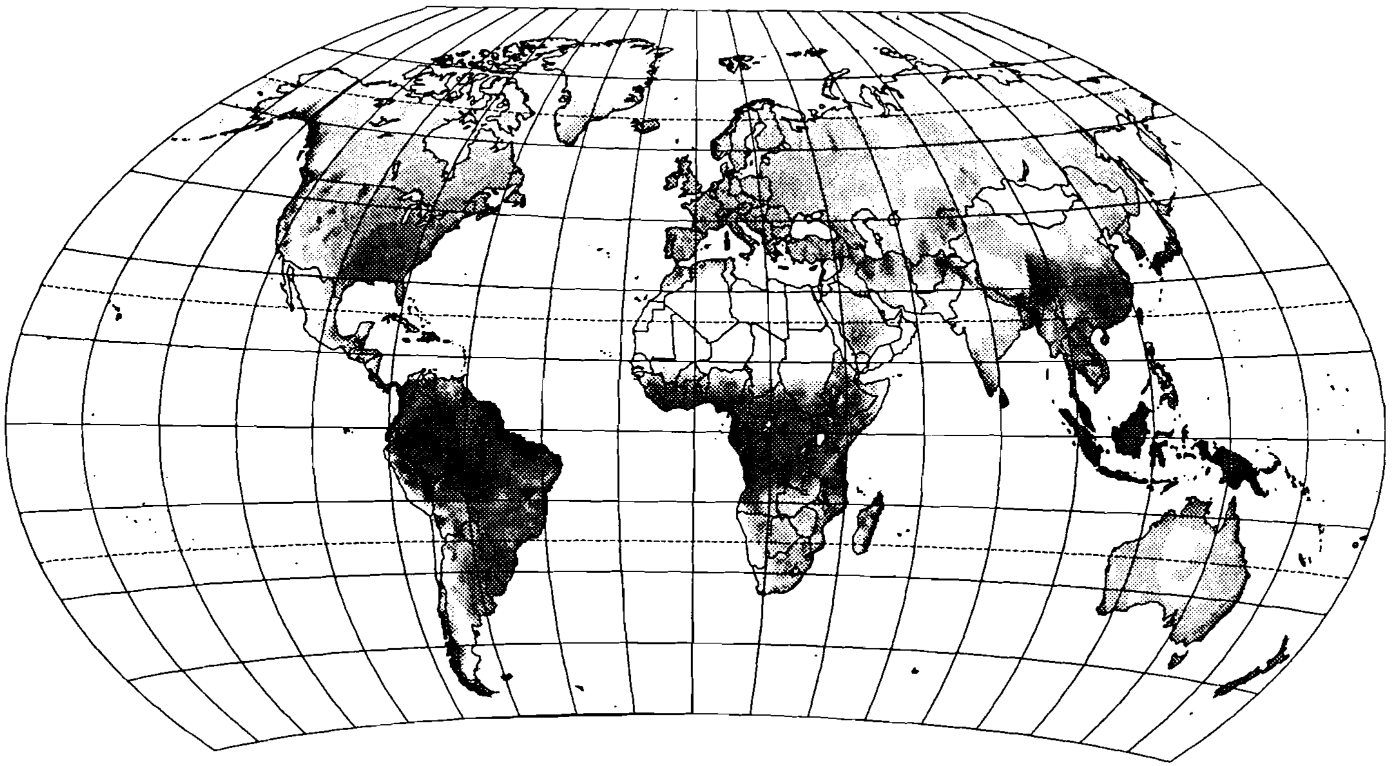

Figure 22. Mean monthly precipitation for April (mm).

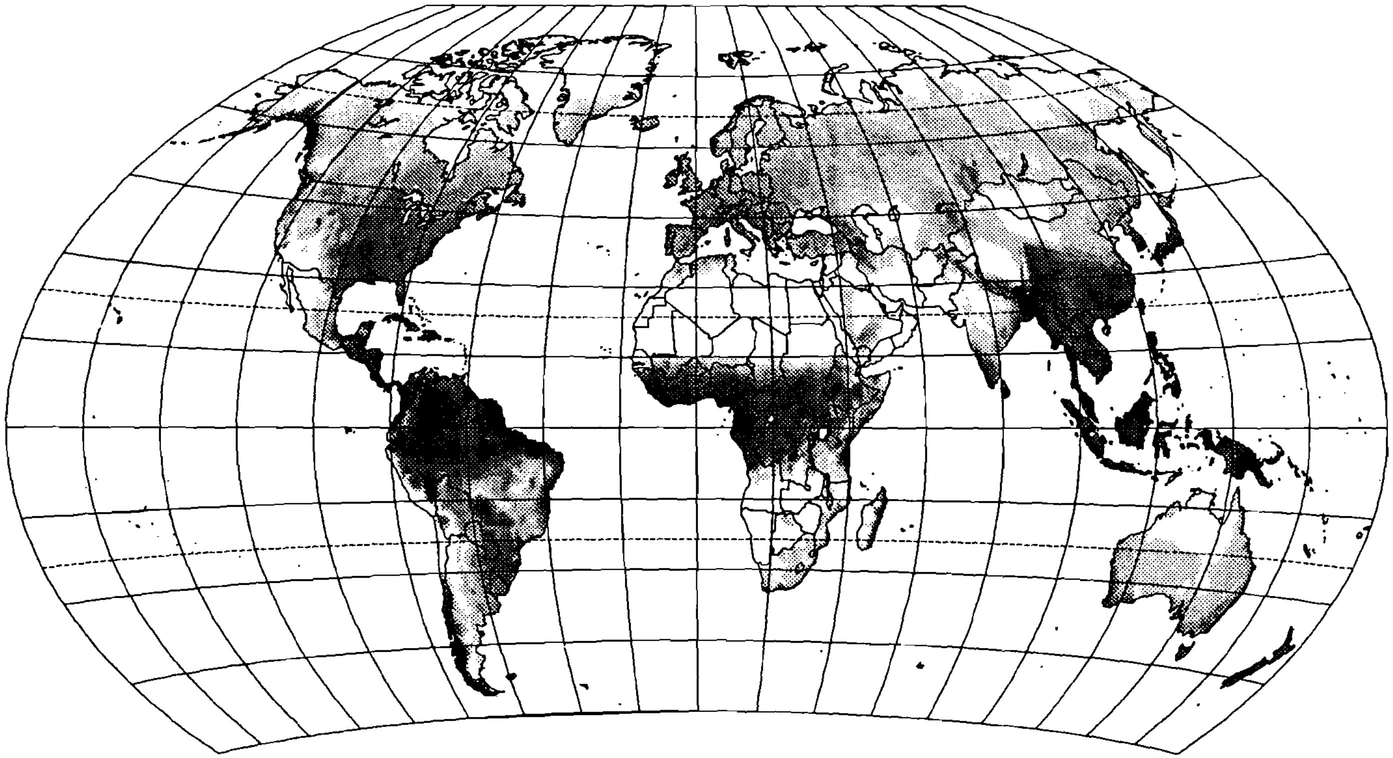

Figure 23. Mean monthly precipitation for May (mm).

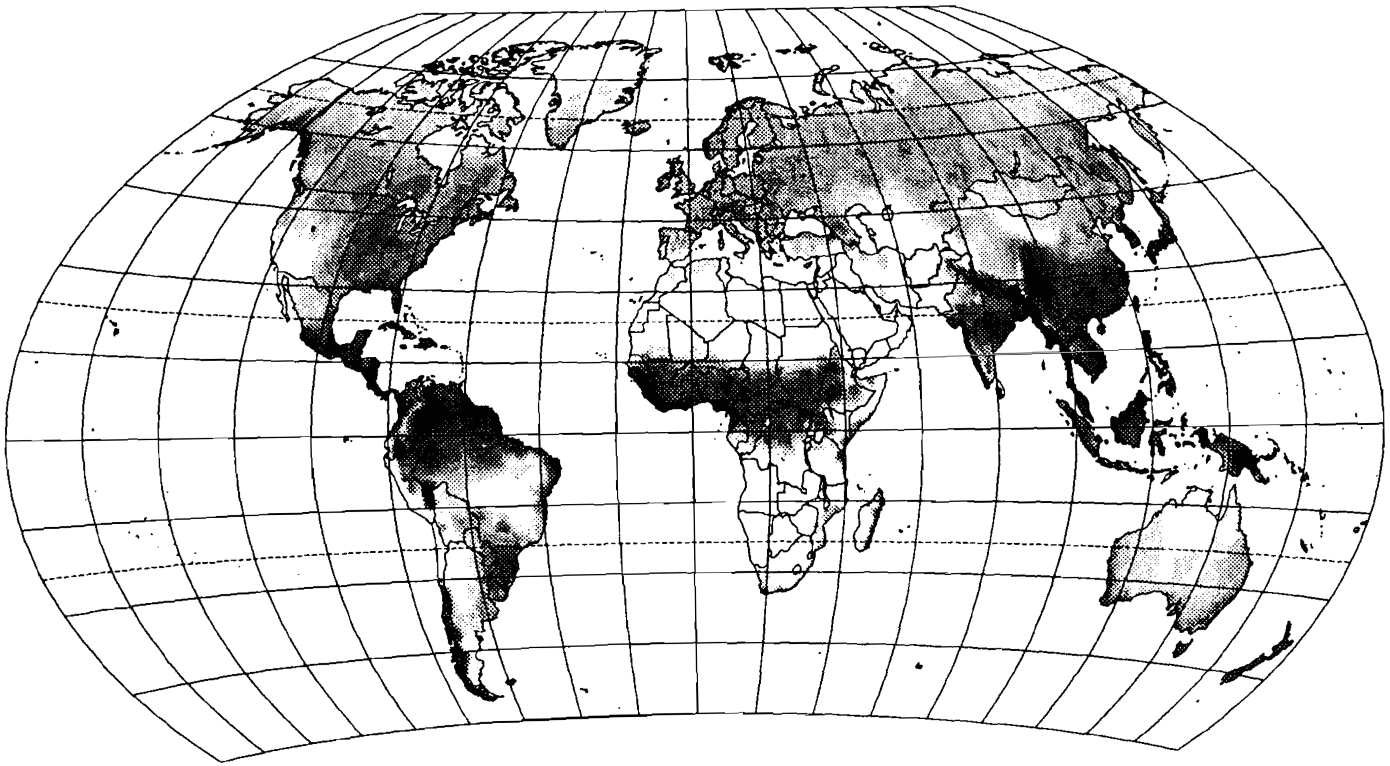

Figure 24. Mean monthly precipitation for June (mm).

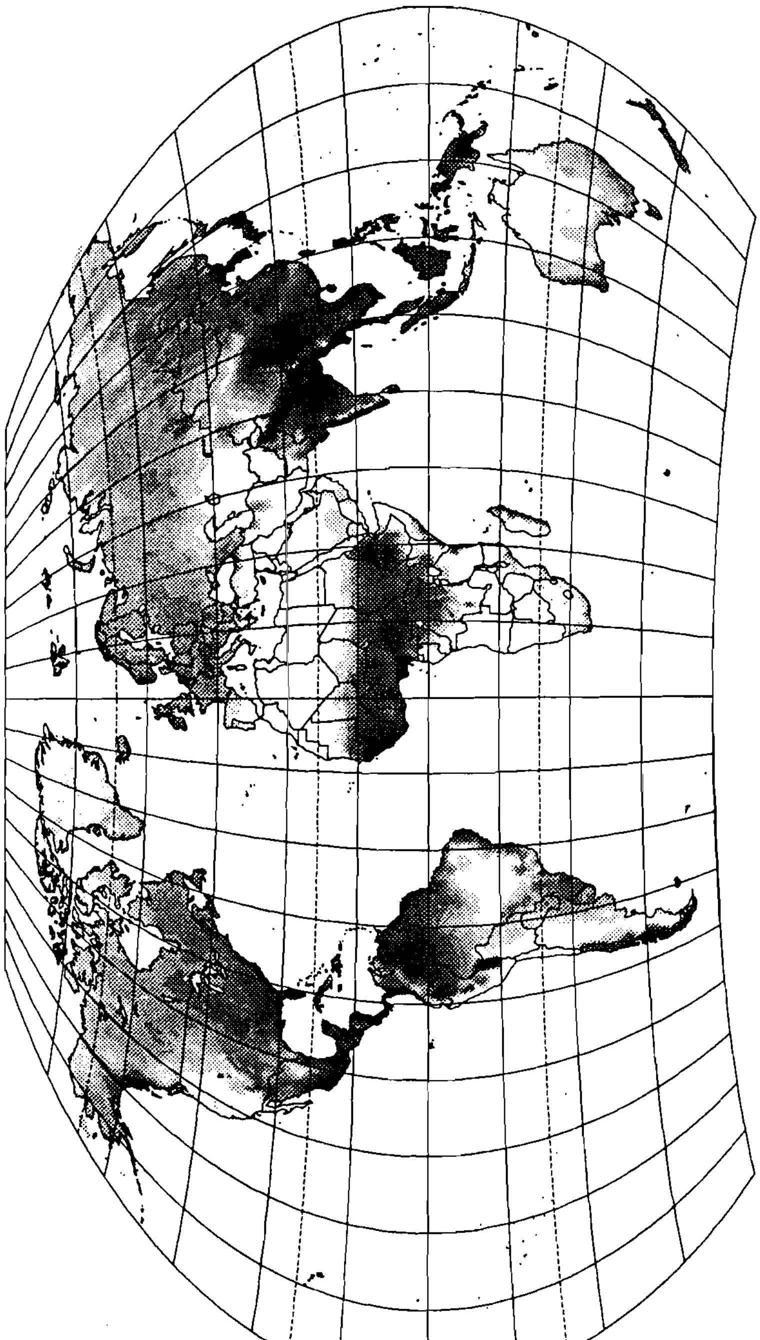

Figure 25. Mean monthly precipitation for July (mm).

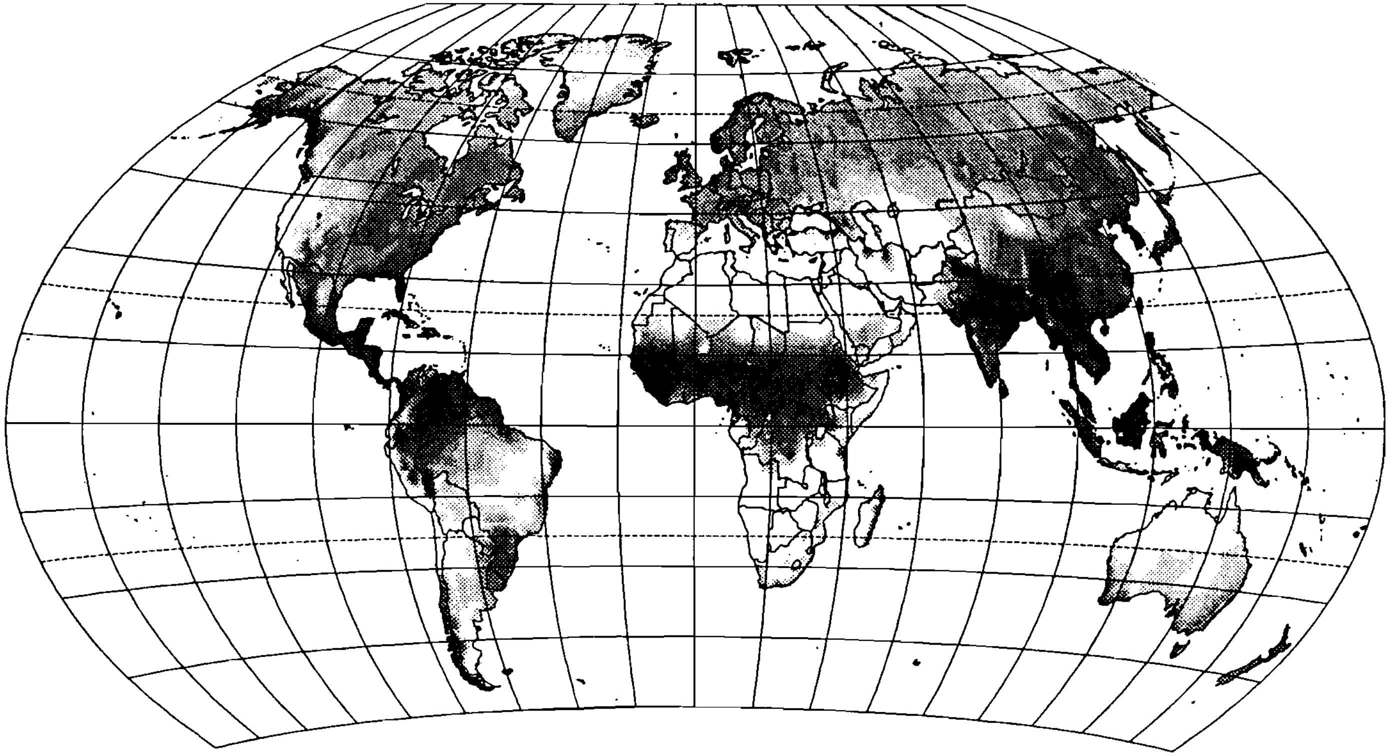

Figure 26. Mean monthly precipitation for August (mm).

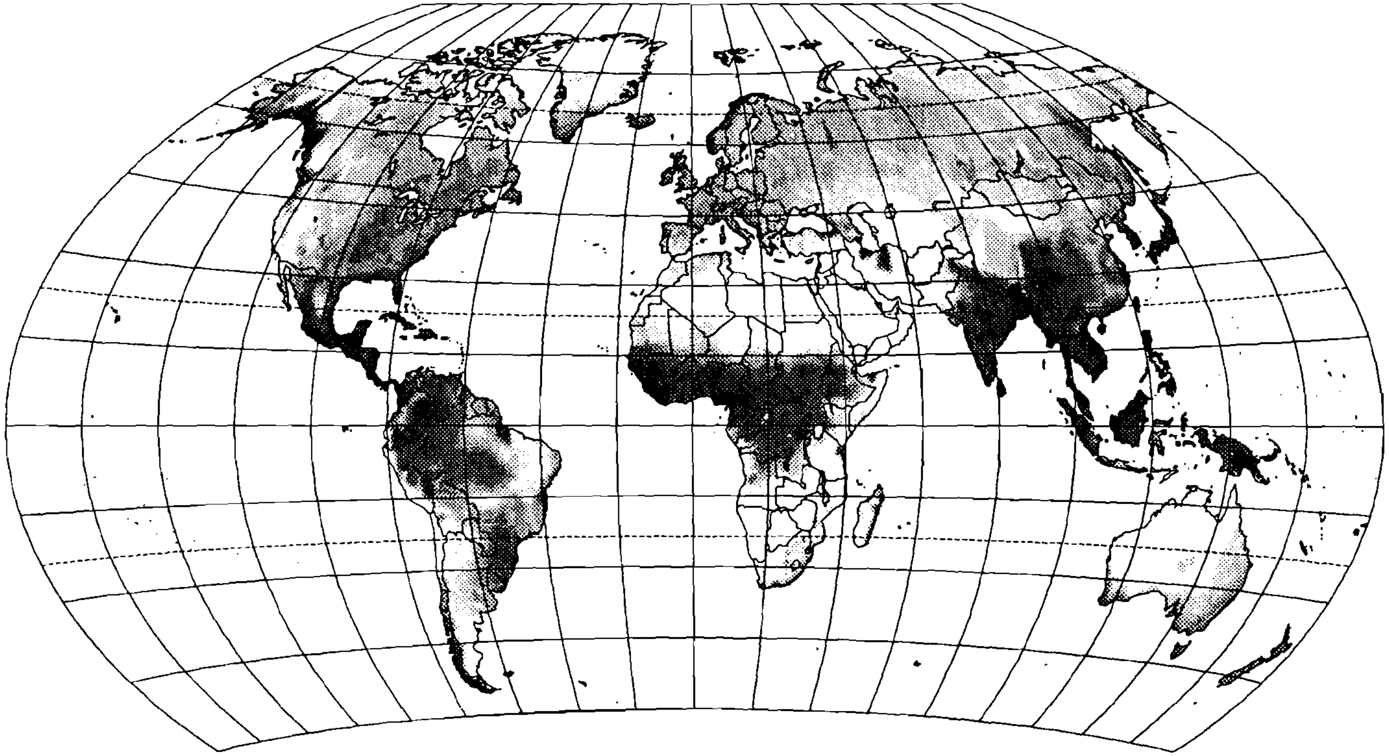

Figure 27. Mean monthly precipitation for September (mm).

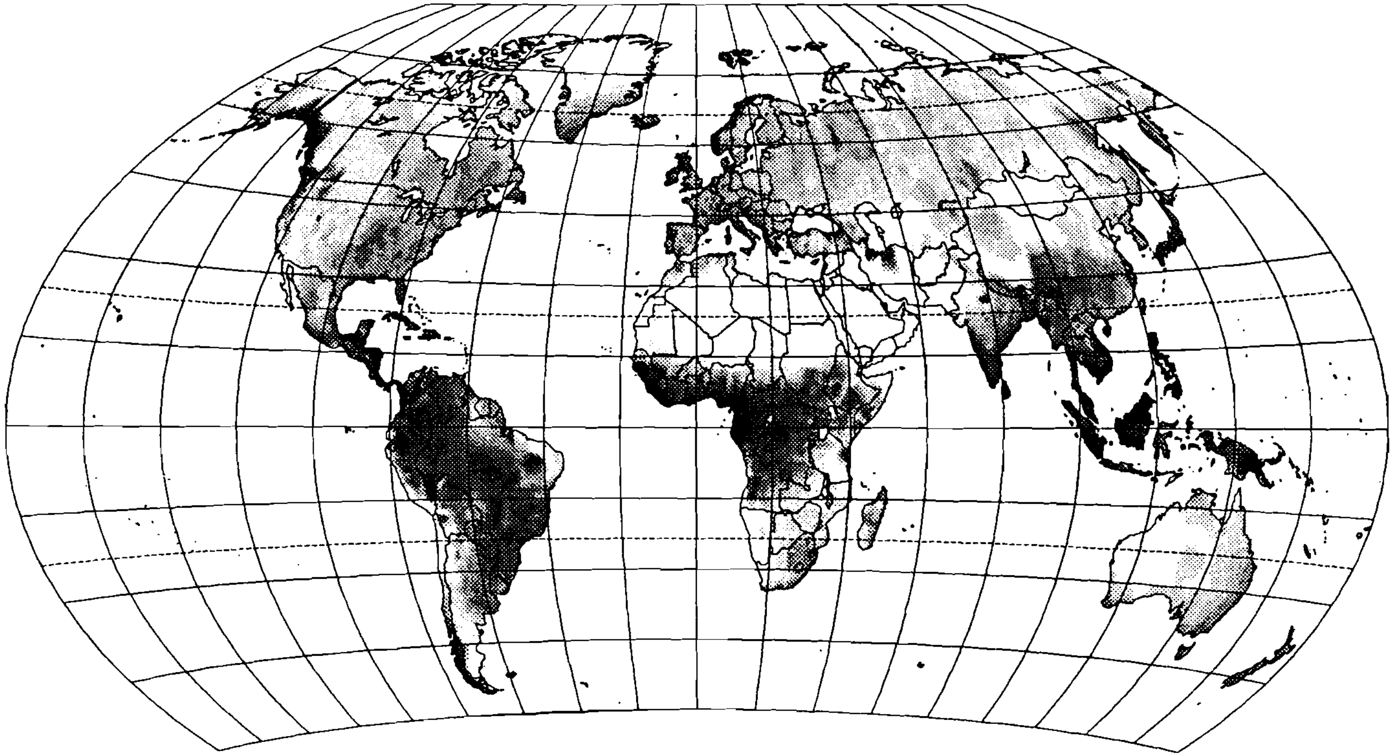

Figure 28. Mean monthly precipitation for October (mm).

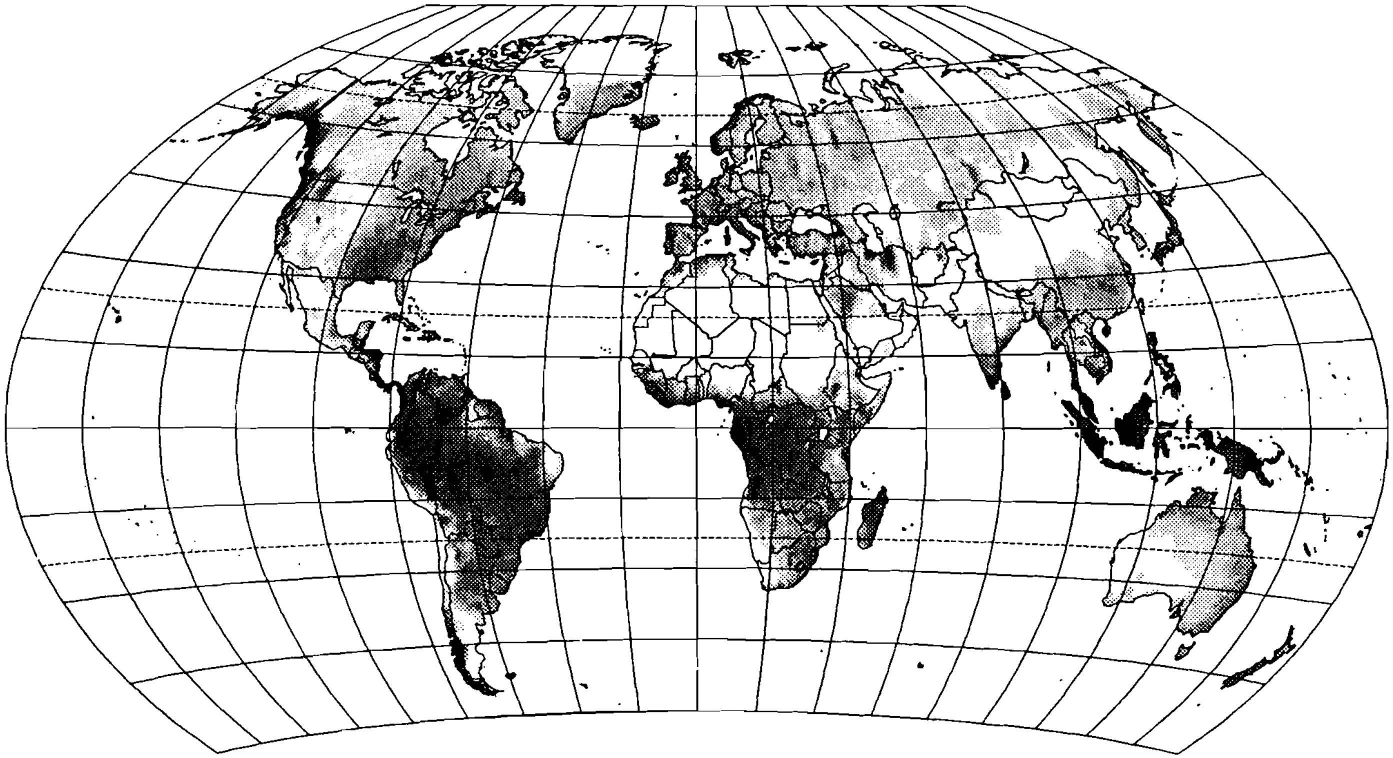

Figure 29. Mean monthly precipitation for November (mm).

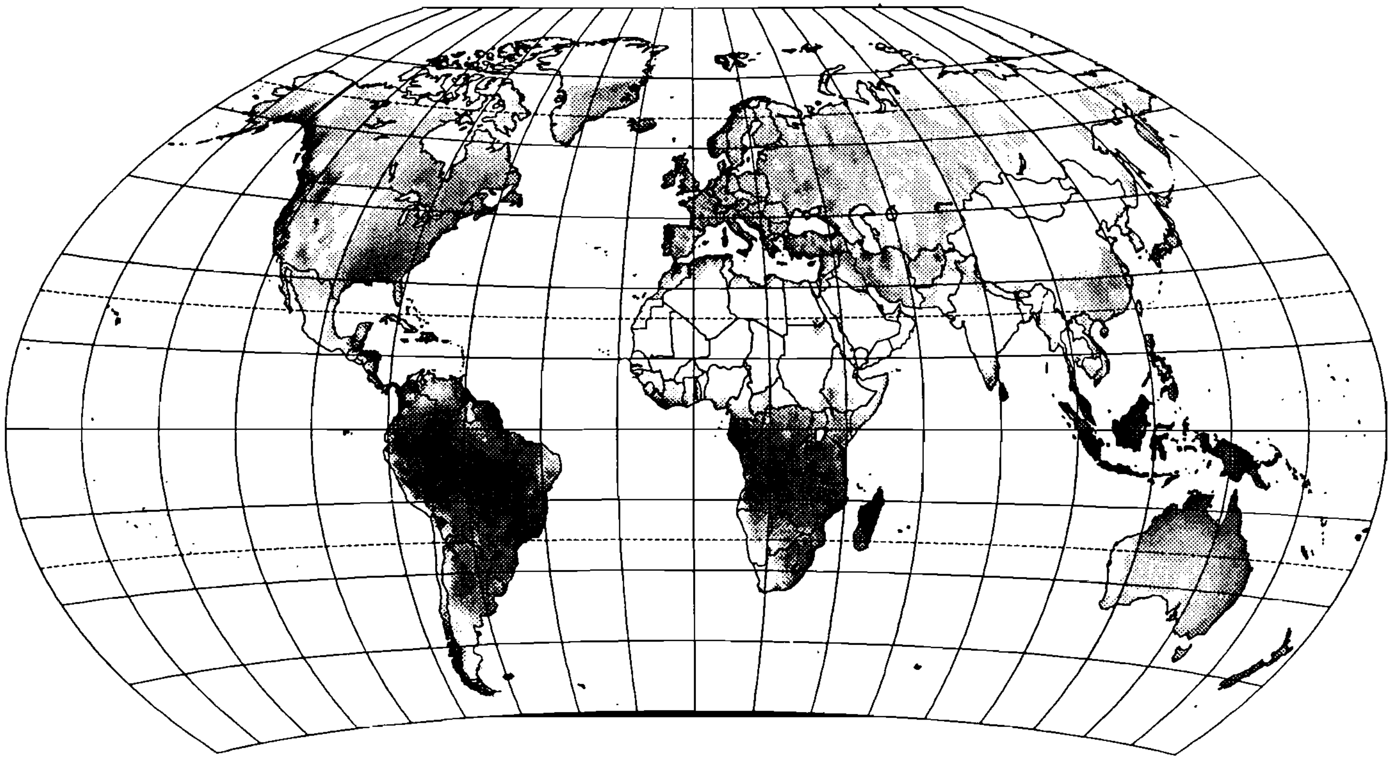

Figure 30. Mean monthly precipitation for December (mm).

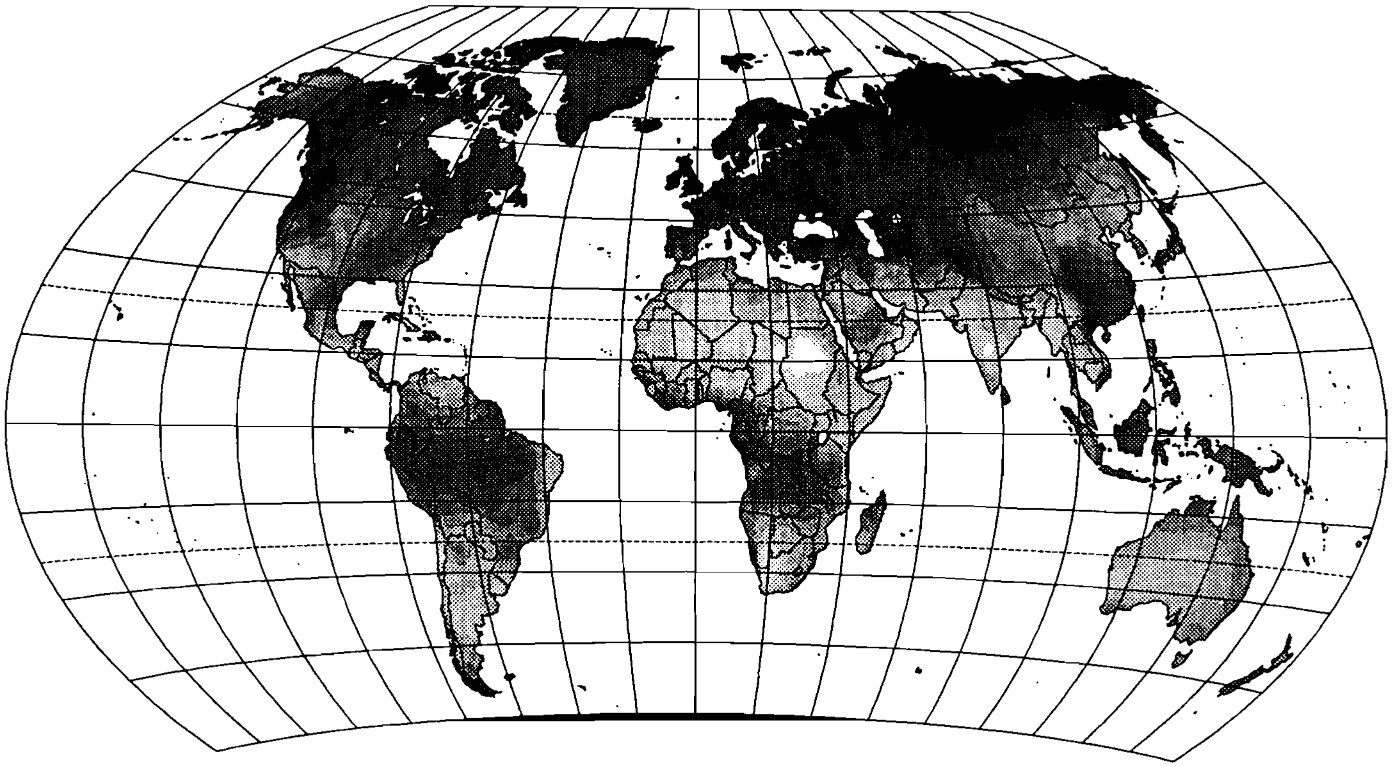

Figure 31. Mean monthly cloudiness for January (%).

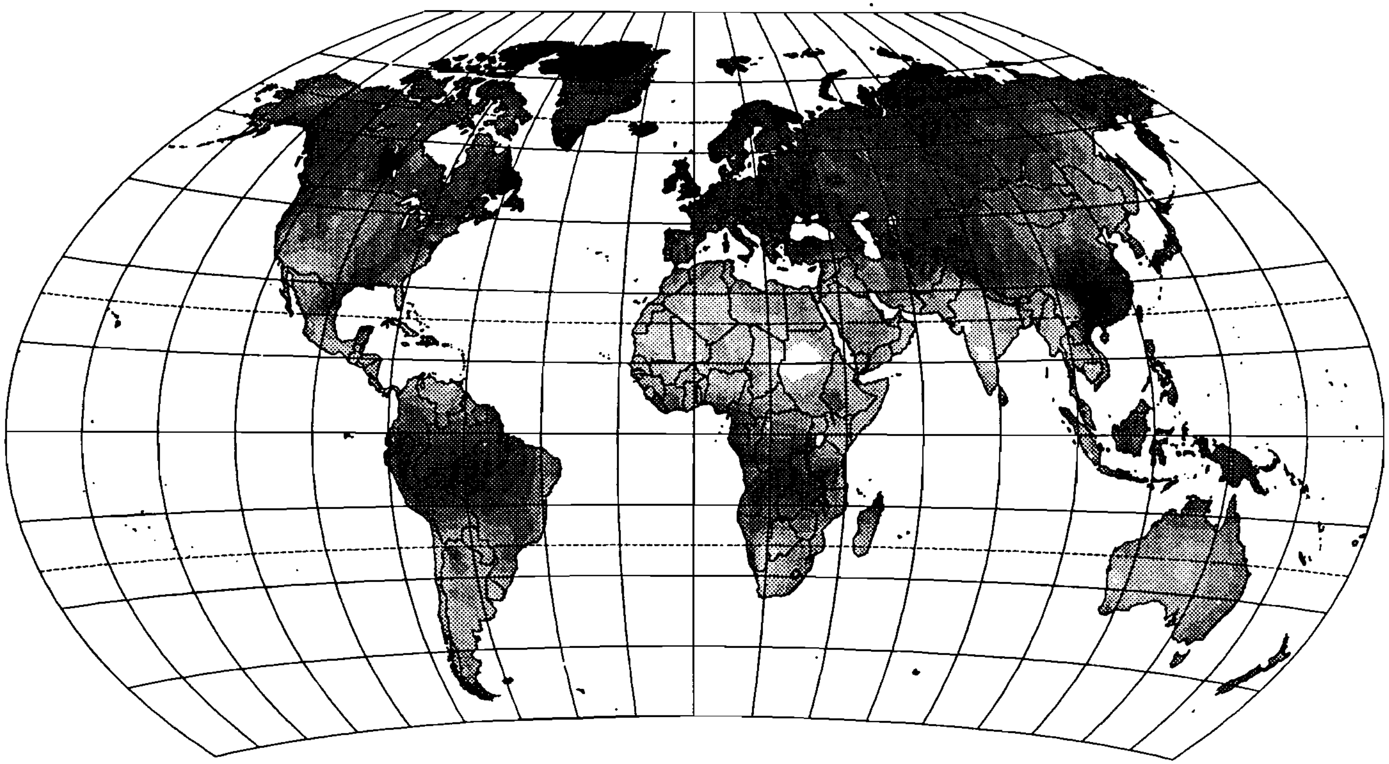

Figure 32. Mean monthly cloudiness for February (%).

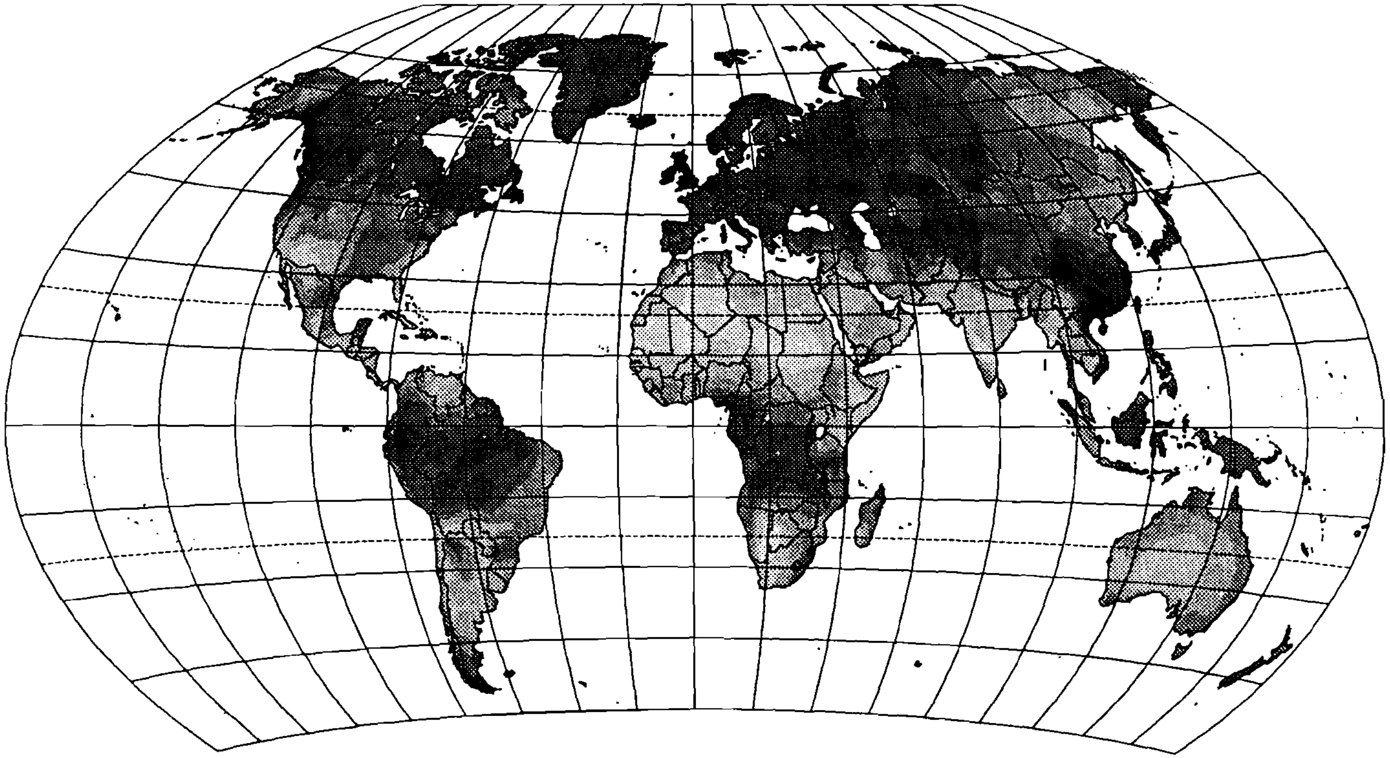

Figure 33. Mean monthly cloudiness for March (%).

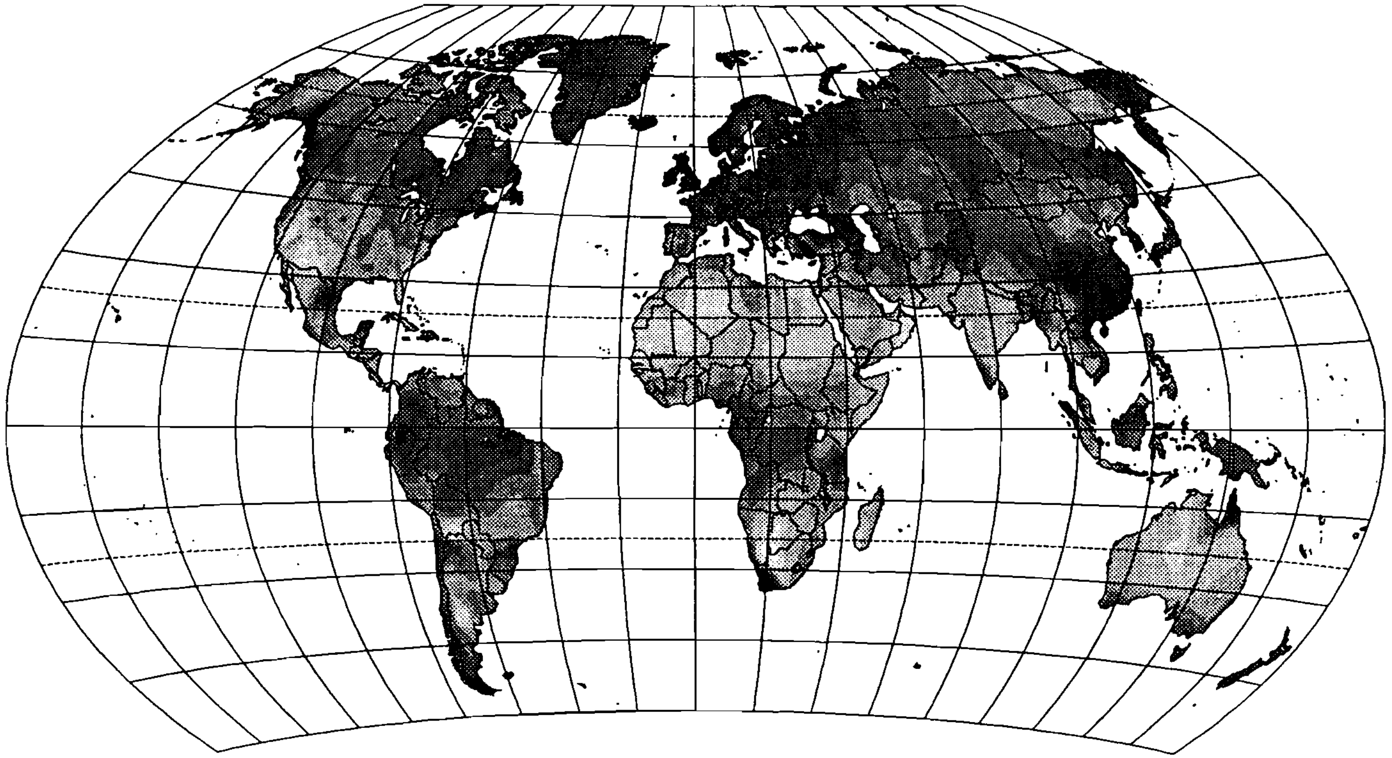

Figure 34. Mean monthly cloudiness for April (%).

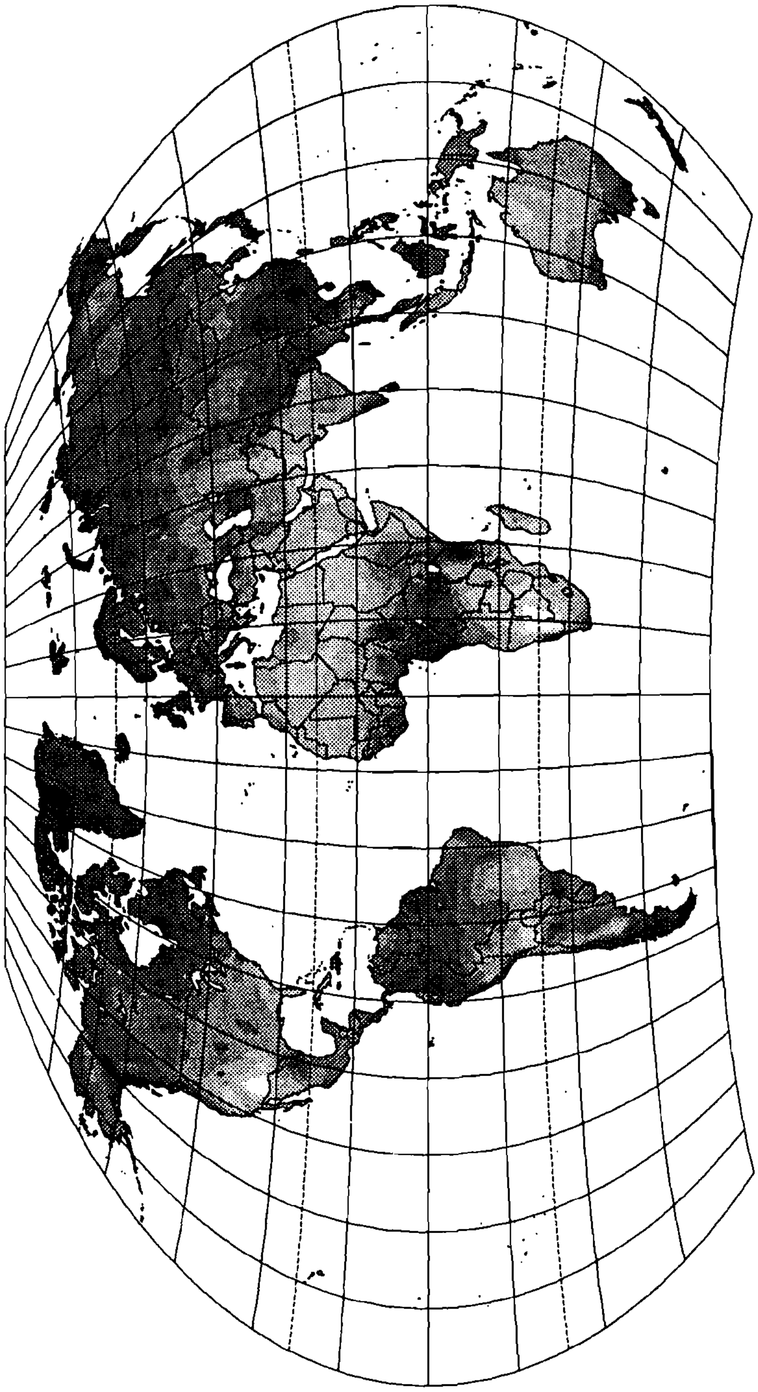

Figure 35. Mean monthly cloudiness for May (%).

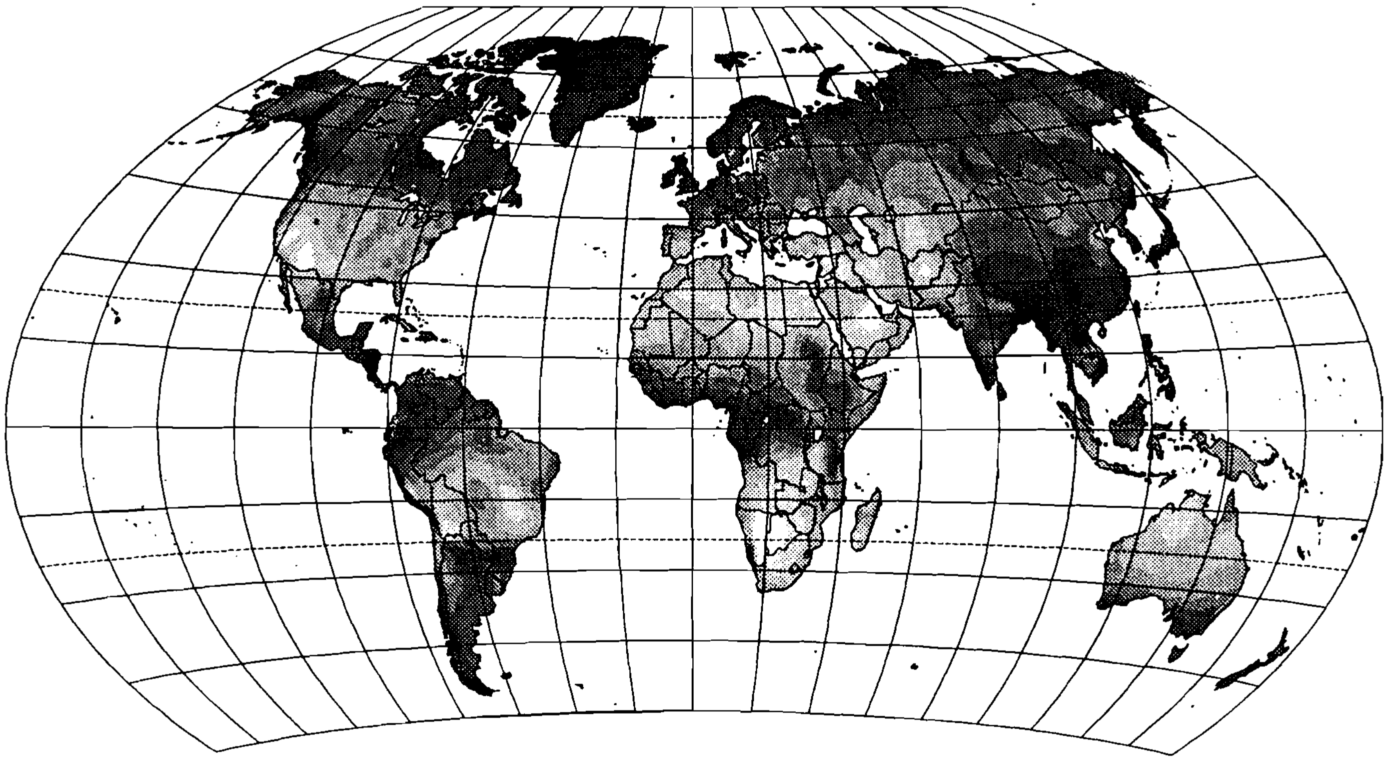

Figure 36. Mean monthly cloudiness for June (%).

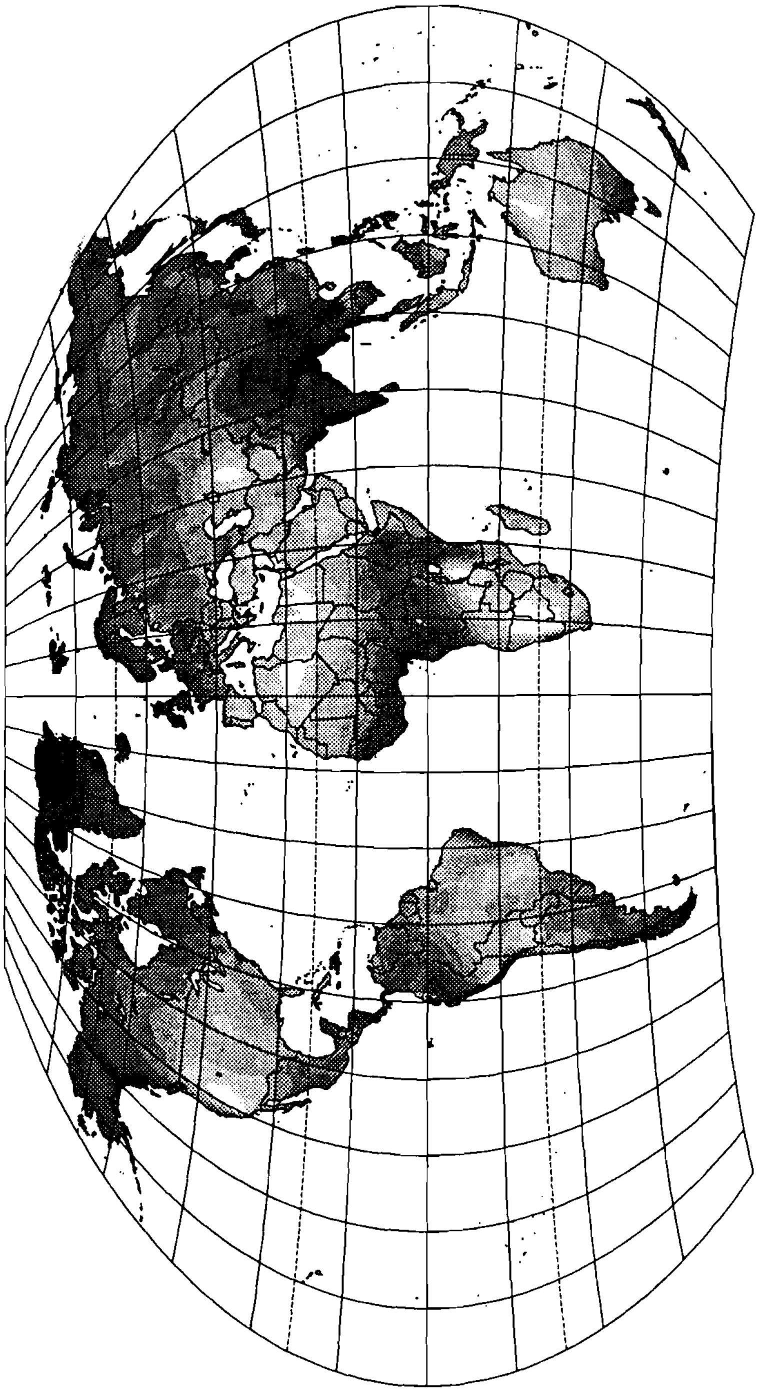

Figure 37. Mean monthly cloudiness for July (%).

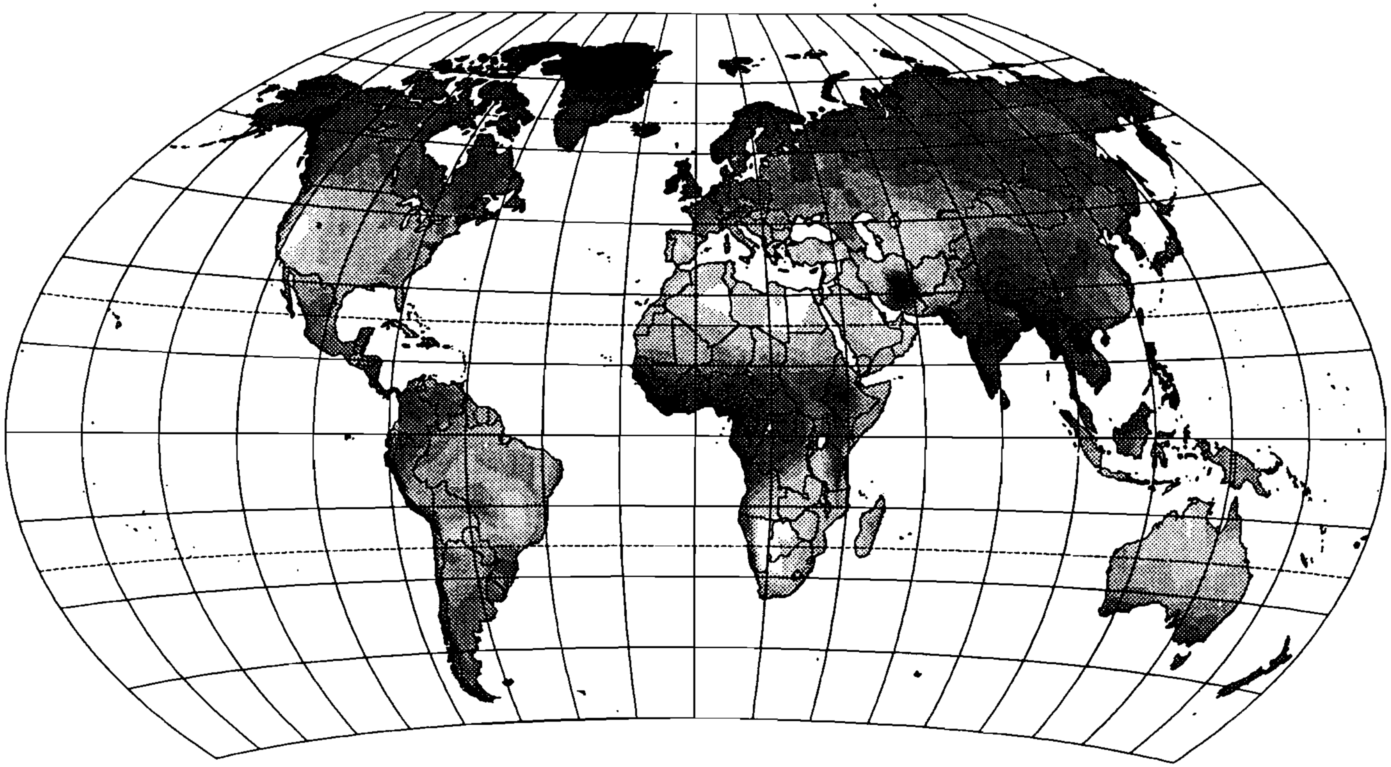

Figure 38. Mean monthly cloudiness for August (%).

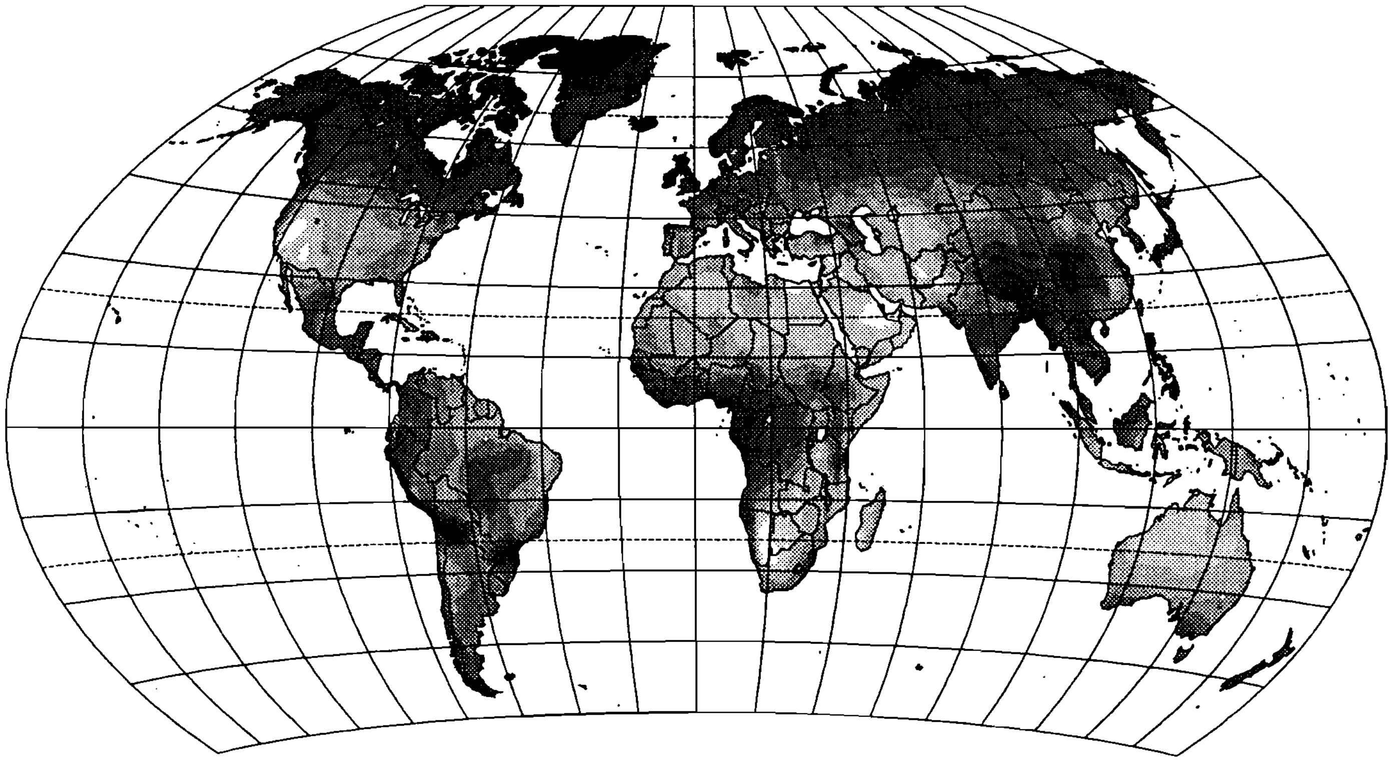

Figure 39. Mean monthly cloudiness for September (%).

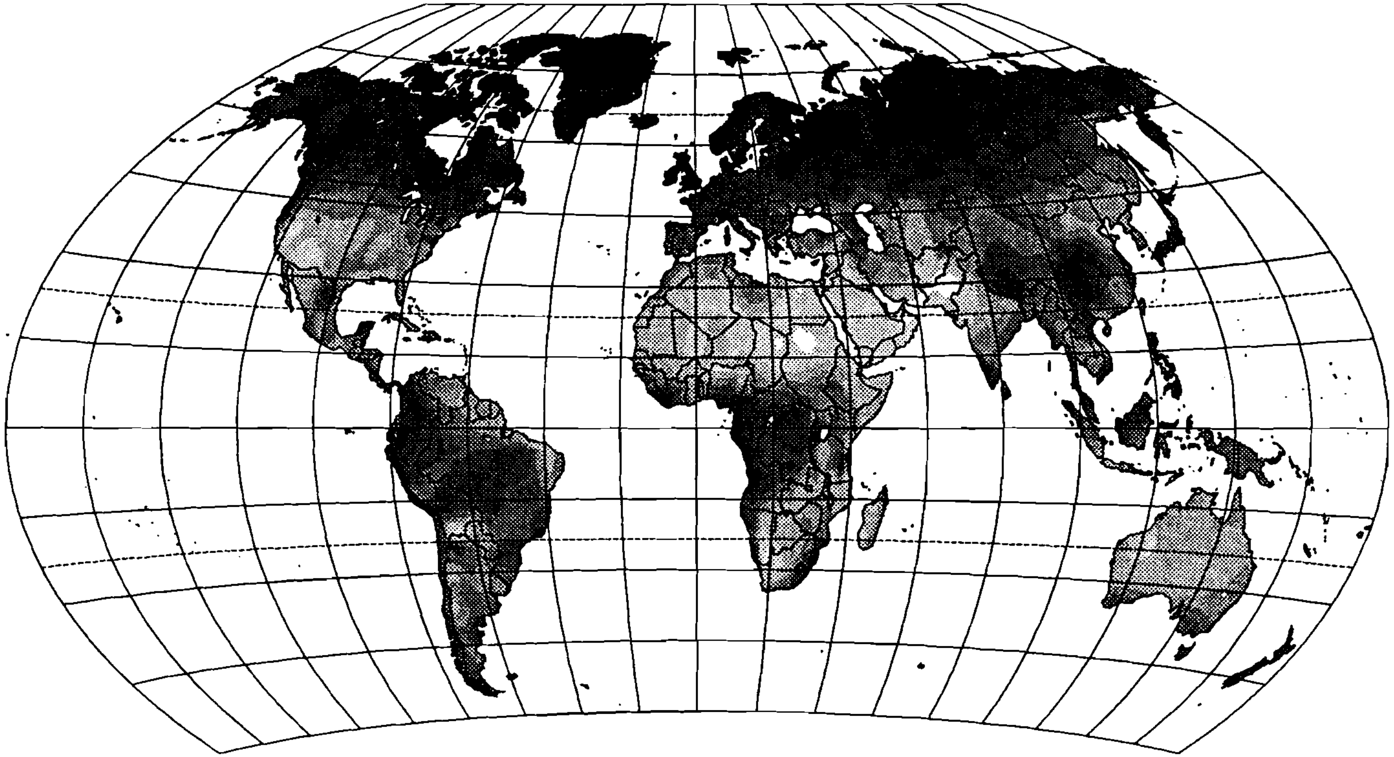

Figure 40. Mean monthly cloudiness for October (%).

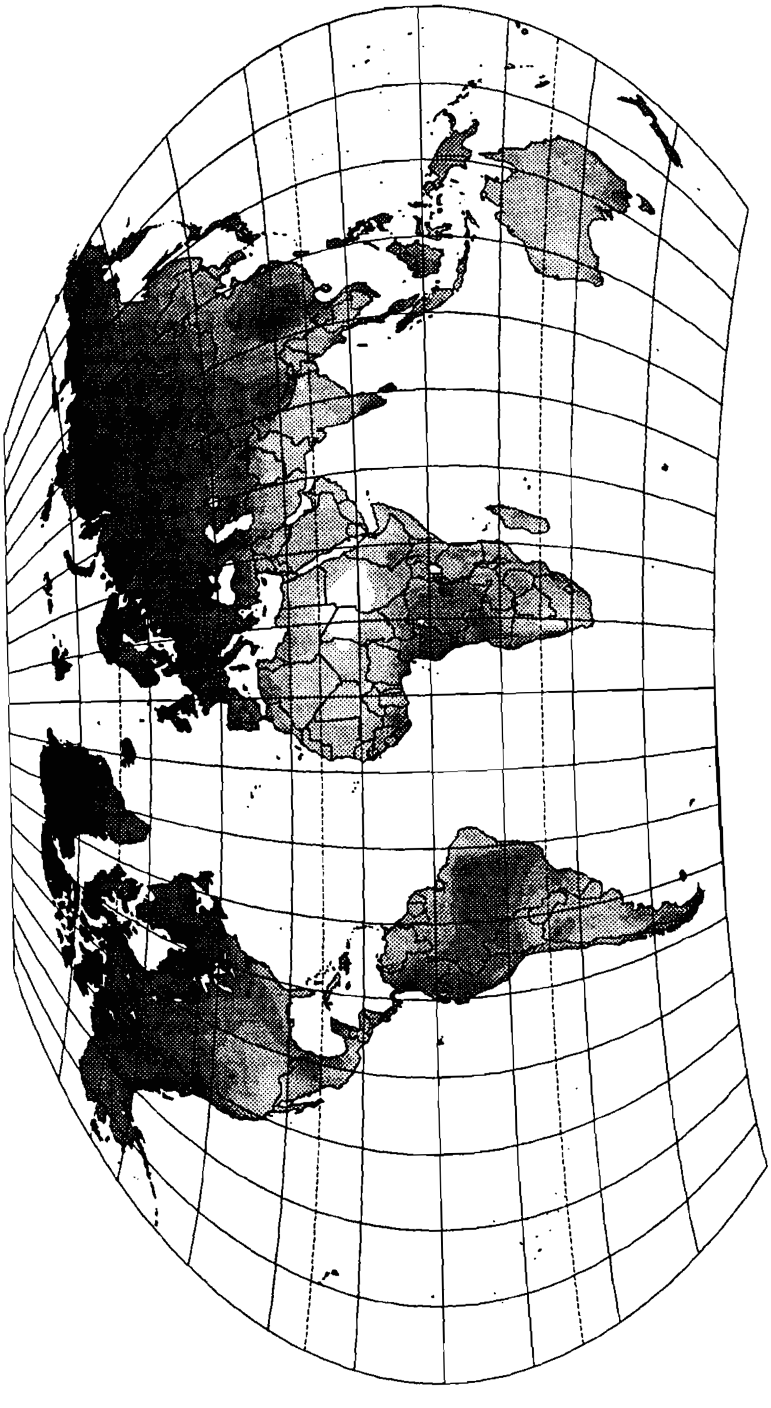

Figure 41. Mean monthly cloudiness for November (%).

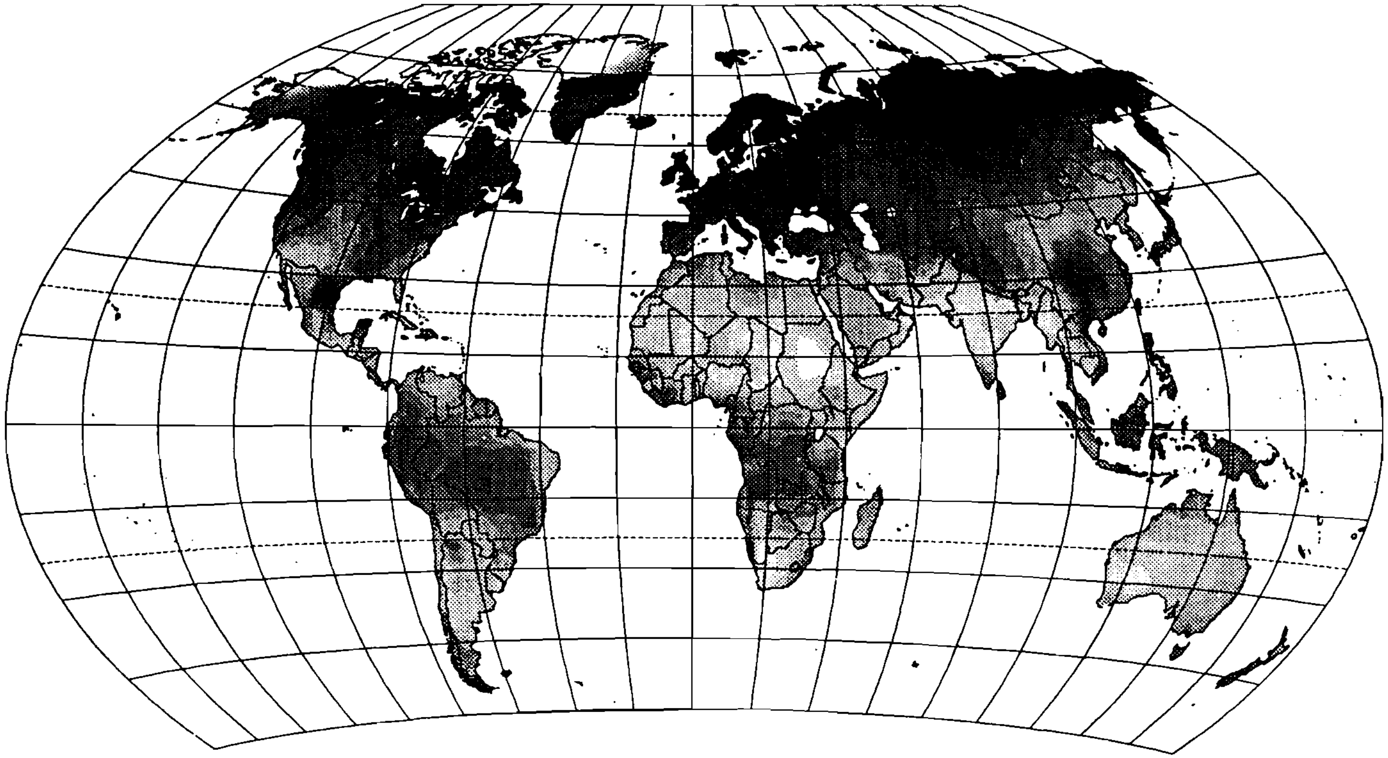

Figure 42. Mean monthly cloudiness for December (%).

Appendix 1. Format of the Raw Databases

All data from the different sets with weather stations have been transformed into a unified format for the checking, selecting, and interpolation algorithms. All raw databases are available in this format from the IIASA Biosphere project.

Each station has a descriptive line with its position (longitude, latitude, and altitude), station name, and country and source. For the Müller data set, the remainder of the line is used for extra information such as station number and climatic classification class codes (Köppen, 1936; Troll and Paffen, 1964). Longitude and latitude values are given in degrees and decimals. Longitude ranges from −180.0 (West of Greenwich) to 180.0 (East of Greenwich), while latitude ranges from −90.0 (Southern Hemisphere) to 90.0 (Northern Hemisphere). The next lines contain the actual climate data, one climatic variable per line. Only climatic variables are listed which consist of one or more values; variables with only missing values are left out. Each variable line consists of 14 values: first the variable code, then 12 monthly values, and finally the length of the observation period. If single values are missing, they are set to −99. In order to save space in the files all items on each line are separated by only one space (' ') and trailing decimal points and zeros are removed. The lines can thus easily be read with the so-called list directed or FORTRAN free format. An example of a station from the Müller raw data set is:[1]

```
16.37 203 15 Wien Austria Mueller 124 Cfb III,3
1 -1.4 .4 4.7 10.3 14.8 18.1 19.9 19.3 15.6 9.8 4.8 1 30
2 .9 3.2 8.4 14.5 19.2 22.6 24.6 23.8 20.1 13.5 7 2.8 30
3 -3.8 -2.5 .9 5.7 10 13.5 15.3 14.7 11.4 6.5 2.6 -1 30
4 13.2 18.5 24 27 32.6 36.1 38.3 34.2 31.6 27.8 19.6 16.5 30
5 -21.9 -22 -11.2 -3.2 -.3 4.1 8.8 8 -.1 -3.1 -8.8 -15.3 30
6 79 76 71 66 68 67 68 70 74 79 81 82 50
7 39 44 44 45 70 67 84 72 42 56 52 45 30
8 93 110 208 148 180 155 203 242 181 212 136 120 50
9 5 5 2 2 11 8 14 24 8 1 1 6 50
10 21 44 41 38 93 66 67 76 85 54 45 50 30
11 15 14 13 13 13 14 13 13 10 13 14 15 30
12 57 84 138 184 235 249 266 250 199 129 55 45 30
14 0 2 21 49 89 112 127 111 75 40 15 2 50
15 3.2 3.2 3.2 3.1 3.1 3.1 3.2 2.8 2.7 2.6 3.1 2.9 30
16 270 270 270 270 270 270 270 270 270 270 270 270 30
```

---

[1] During the digitalization of the Müller data set some choices had to be made. Two of them concerned non-number values (tr for trace, >1, etc.). These values were all set to zero. The predominant wind direction is given in numeric values (0 = North, 90 = East, 180 = South, and 27 = West). Sometimes it was impossible to assign one single value, because of variable directions. In such cases the value is set to missing (−99).

Appendix 2: Format of the Interpolated Databases

The databases consist of monthly values of temperature, precipitation, and cloudiness, obtained from an irregular array of weather stations from different sources. All data is screened for outliers, doublets, and unreliable stations. The remaining stations are interpolated towards a 0.5*0.5° longitude and latitude grid for the terrestrial earth surface. In total there are 62,483 cells.

The formats of all three data sets are identical: one cell per line, each line contains longitude, latitude, and 12 climatic variables. Each climatic data set is distributed in one or more files, depending on the magnetic distribution media. The file format is ASCII and all decimal points are removed. Only integer values are listed. The first line gives a specific FORTRAN-77 format statement to read the data set (position 1-20, to read the data as real values; position 21-40 to read the data as integer values).

The total file size of each data set is approximately 3.5 MB in ASCII-format. Reading speed and access time are greatly improved if the data is transferred into one single binary file with a more machine-efficient format. Each file occupies here only 1.7 MB. A conversion program, CONVERT, is supplied to change automatically between the two formats and split or combine files according to different sizes of magnetic media-types. The source code (CONVERT.FOR) gives FORTRAN examples of how to read the data in either format.

Before using longitude and latitude from the binary file integer format, they must be converted to floating point values and divided by 10.0 to get the appropriate value. Negative longitude values denote West of Greenwich. Negative latitude values denote locations South of the equator. Both longitude and latitude values give the position of the lower left corner of a cell.

Temperature values are given with one decimal point. Before using them from the integer format in the binary files, they must be converted to real values and divided by 10.0. Precipitation and cloudiness values have no decimals and require no transformation. The file names of the databases are defined as follows:

first 3 characters	TMP	monthly temperature (° Celsius)
	PRC	monthly precipitation (mm)
	CLD	monthly cloudiness (%)
character 5 to 7	CUR	current climate
character 8	#	file number for split ASCII files
File extension	ASC	a plain ASCII file with real (character 1–20) and integer (character 21–40) input-format on first line; longitude, latitude, 12 data values on all other lines.
	BIN	binary file (unformatted, sequential, 14 integer*2 data-values per line[2])

---

[2] Longitude, latitude, and temperature values should be divided by 10.0 and the cloudiness values by 100 and all values must be converted to real values to use that data set.

The files will be distributed in DOS-PKZip auto-compressed format, so that they occupy less storage space. Copy these files to your harddisk and type each filename at the DOS-prompt. They will uncompress automatically. The resulting files are the binaries and could be converted to plain ASCII by using the CONVERT program. This could take some time.

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