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DETECTING THE CLIMATIC EFFECTS OF INCREASING CARBON DIOXIDE

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3. DATA BASES FOR ISOLATING THE EFFECTS OF THE INCREASING CARBON DIOXIDE CONCENTRATION

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CONTENTS

3.1 INTRODUCTION

The debate over the climatic significance of anthropogenically produced carbon dioxide (CO_2) began with Callendar's (1938, 1949) studies of worldwide temperature increases in the 1930s and 1940s. Empirical studies of long-term instrumental climatic data have continued to play an important role in attempts to identify causative factors in climatic variations. Instrumentally recorded data have been used in five major types of studies:

1. To produce spatially averaged time series of temperature for large areas (e.g., Northern Hemisphere averages, which are generally derived for continental areas only, or zonal averages for latitudinal strips around a hemisphere, again generally continent based) (e.g. Callendar 1961; Mitchell 1963; Vinnikov and Groisman 1981; Yamamoto 1980; Jones et al. 1982);
2. To identify modes of climatic anomaly, often using principal components analysis of temperature or precipitation data, and to relate these to changes in circulation pattern and determine if changes in anomaly patterns have occurred through time (van Loon and Williams 1976; Gray 1981; Tabony 1981; Jones and Kelly 1983);
3. To verify computer simulations of hemispheric or zonal temperature trends in relation to various forcing factors including CO_2 increase, solar output variations, volcanic aerosol loading of the atmosphere (Reitan 1974; Schneider and Mass 1975; Robock 1979; Hansen et al. 1981; Gilliland and Schneider 1984).
4. To examine empirically the effects of forcing factors (particularly volcanic aerosols) on the instrumental record of climate (Miles and Gildersleeves 1978; Yamamoto and Hoshiai 1980; Kelly and Sear 1984);
5. To derive scenarios of the possible climatic effects of CO_2-induced warming by identifying warm-year or warm-season anomalies in the long-term instrumental data set and using these as analogs for future climate (Wigley et al. 1980; Williams 1980; Pittock and Salinger 1982; Jäger and Kellogg 1984).

In almost all of these types of studies, the focus has been on mean monthly temperature data from Northern Hemisphere continental stations. Only recently have efforts been made to incorporate long-term air temperature data from over the oceans to derive more representative hemispheric averages (Folland et al. 1984; see also Chapter 4 of this volume). Here, we discuss briefly the history of instrumentally recorded temperature data and review some of the limitations of the data and the methods used in deriving large-scale averages. This is followed by a brief discussion of long-term precipitation and pressure data sets and the limitations of these data sets. A final section discusses data on volcanic aerosol loading of the atmosphere and solar irradiance variations, both of which may have played an important role in recent temperature variations.

Chapter 4 describes analyses of the surface and free air temperature data bases. Later chapters in this volume extend the scope of the search for the CO_2-induced signal to include other climatic variables, including changes in the ocean (Chapter 5), changes in snow and ice extent and other cryospheric variables (Chapter 6), and changes in precipitation (Chapter 7). The data bases needed for these analyses are described in those chapters.

3.2 TEMPERATURE DATA

3.2.1 History of Worldwide Instrumentation Network

Although various experiments to record temperature had been made earlier, the first reliable thermometers were not developed until the mid-18th century (Gerland 1896). Only careful analyses have been able to extend records back further into the past, and these require a great deal of faith in the early instruments and their calibration scales (e.g., Manley (1974) compiled a central England temperature series commencing in 1659) (also see Dettwiller 1981; Schaake 1982). Some attempts to organize regional observations in a systematic way began in the late 18th century, the best-known example of this being the network coordinated from Mannheim, West Germany (the measurements from which were published as the *Mannheim Ephemerides* for 1781–1785 [Kington 1974]). Similarly, the Société Royale de Medicine de France coordinated another network during the same interval (1780–1790) (Kington 1970). However, there was no major expansion of temperature recording networks until a century later, following the Vienna Meteorological Congress of 1873. This meeting provided the impetus for the expansion of recording networks worldwide and for the international exchange of data that continues today under the auspices of the World Meteorological Organization (WMO). While national meteorological agencies were established in the late 19th century, observing networks expanded, instruments and instrument shelters were standardized, and uniform instructions to observers were issued. As a result, a reasonably comprehensive global network of temperature-recording stations emerged, many of which have continued in operation to the present. Unfortunately, standardization of measurements did not extend to a universally adopted observation time policy so that, even today, vastly different protocols are followed in deriving daily temperature averages. This problem is discussed in more detail below. Further discussion on the history of instrumentation has been presented by Lamb and Johnson (1966), von Rudloff (1967) and Middleton (1966, 1969).

3.2.2 Data Inhomogeneities

> A numerical series representing the variations of a climatological element is called homogeneous if the variations are caused only by variations of weather or climate (Conrad and Pollak 1962, p. 223).

Although observers may take readings with meticulous care, nonclimatic influences can easily affect the readings. Some factors, such as the type of instrument, its exposure, and the method of measurement, may be under the control of the observer; other factors, such as observation times and the station environment, may not. Figure 3.1 illustrates the relative magnitude of error introduced by these various factors according to Mitchell (1953). The following sections discuss the most important causes of inhomogeneity:

- Changes in instrumentation, exposure, and measurement technique;
- Changes in station location (both position and elevation);
- Changes in observation times and the methods used to calculate monthly averages;
- Changes in the environment of the station, particularly with reference to urbanization.

After this discussion, methods of data homogenization are considered.

3.2.3 Changes in Instrumentation, Exposure, and Measuring Techniques

For land-based temperature data, the effects of changes in instrumentation are slight (at least after the early 19th century). More important is the change in exposure of the instruments. Thermometers are now located in louvered screened enclosures, which are generally painted white. Earlier readings often were from shaded wall locations and need correction. The effects of changes in thermometer type and screen, however, are considered to be slight (Mitchell 1953).

Changes in the techniques for measuring sea surface temperatures (SSTs) over the last 100 years have significantly affected readings. From the early 19th century, an increasing number of ships took daily readings of SST, air temperature and sometimes pressure, wind speed and direction, and other weather observations (Fletcher 1984). Until about 1940, SST was measured using the so-called bucket method. The values were recorded in log books together with the ship's position. With the increasing size of ships, SSTs began to be measured with thermometers located in the ship's cooling water intakes. These injection temperatures are estimated to be 0.3 to 0.7°C higher than bucket temperatures because of the internal warmth of the ship and elimination of evaporative cooling effects (Saur 1963; James and Fox 1972; Tabata 1978; Folland et al. 1984; see also Chapter 5 of this volume).

Many observations in the world data bank are supposed to be either all bucket or all injection SST data, but the analysis of Barnett (1984) shows that many contain both types of observations. Barnett concluded that better estimates of the temperature conditions over the oceans may be gained using the air temperatures measured on ships. Although these may contain the effects of increasing ship size, specific location of the instruments on board the ship, and the color of the louvered screen, these errors are more likely to be reduced by averaging

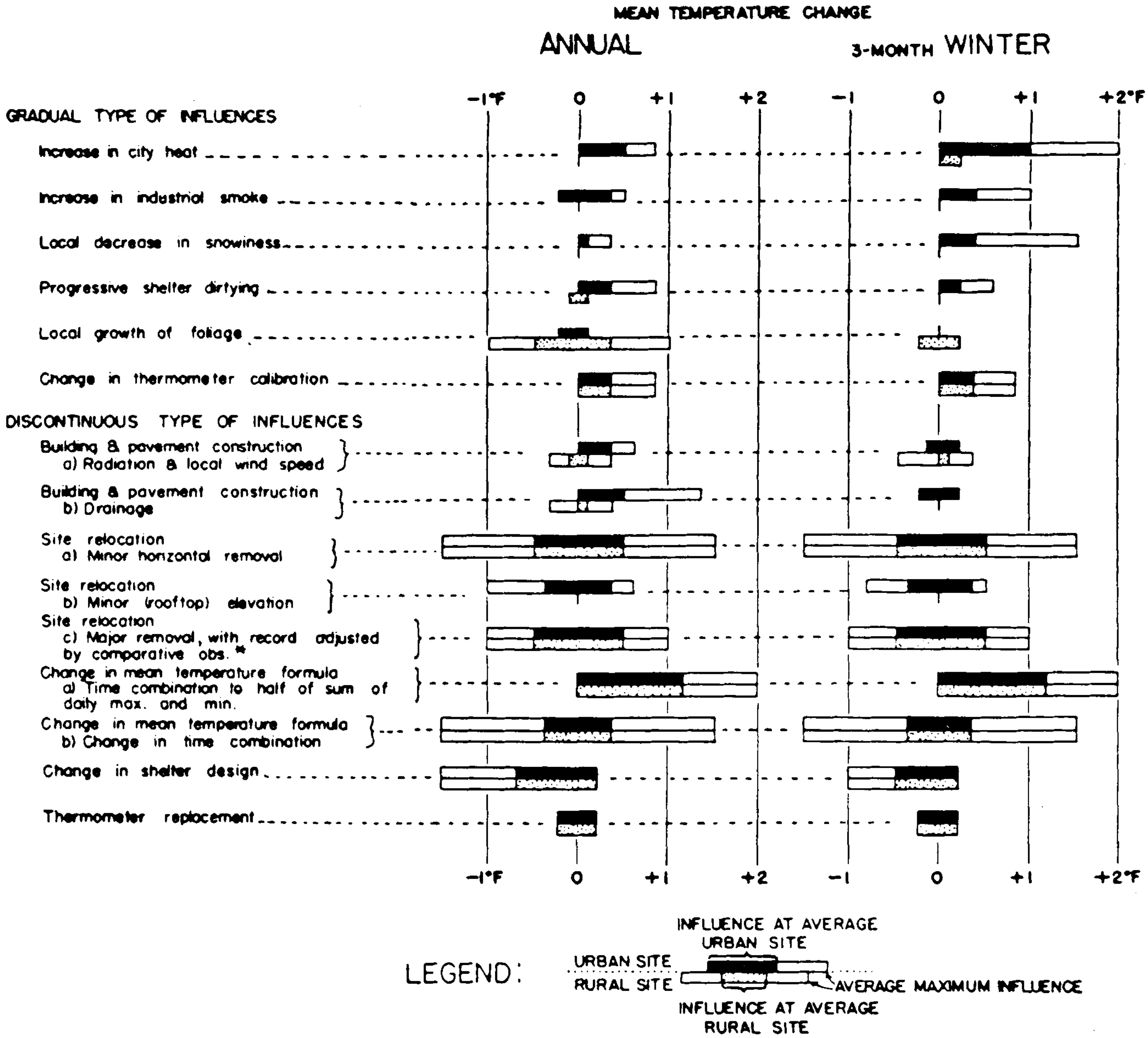

Figure 3.1. Estimated worldwide average and average extreme magnitudes of instrumental and local environmental influences on secular records of annual and winter mean temperatures over a 100-year period, based on observational and environmental changes typical of the past century. Source: Mitchell (1953).

than are systematic errors apparent in SST measurements (cf. Ramage 1984). One such systematic bias (toward higher temperatures in recent years) may be present as a result of improved weather forecasts, which have enabled ships to avoid bad weather, thereby increasing the number of observations taken under fair conditions.

3.2.4 Changes in Station Location

In any data bank, the specified station location and height probably will be that in current use. Earlier locations of the station, if any, can be found by consulting the meteorological archives or the written information available with a data set, such as the volumes of World Weather Records (WWR). Information concerning station moves is of primary importance to homogenization. The significance of moves can only be assessed station by station in the homogenization process (see Section 3.2.7).

3.2.5 Changes in Observation Times and Methods Used to Calculate Monthly Averages

In the late 19th and early 20th centuries, there was considerable discussion in the climatological literature concerning the best method of calculating true daily and, hence, monthly average temperatures (e.g., Ellis 1890; Donnell 1912; Hartzell 1919; Rumbaugh 1934). Many different schools of thought existed, and unfortunately, no one system prevailed in all regions.

The publication *Reseau Mondial,* which issued monthly mean data in yearly volumes from 1910 to 1934, used correction factors to reduce readings to means based on observations every hour (a 24-hour mean). In most cases, however, the corrections used are not given. In the United States, many sets of observation times were devised by the various supervising authorities and it was not until 1890 that a widespread policy of computing daily means—(maximum + minimum)/ 2—was introduced. However, despite this use in locally published material in the United States, data published in WWR for the United States are corrected to 24-hour means using factors derived by Bigelow (1909). In WWR these adjustments continued until 1940 or 1950. After this time, adjustments were not made and the measurements were simply calculated by (maximum + minimum)/2.

In the United States it is possible to unravel the effects of such adjustments and to correct the data sets accordingly. In other countries the situation is more chaotic with numerous changes to (maximum + minimum)/2 from fixed hours or vice versa. Examples for almost all countries have been described by Bradley et al. (1985). Only in 15 countries has a consistent methodology been followed since the 19th century. Of these, the most important (spatially) are those from Canada and India.

At present, there is no uniform system, although the (maximum + minimum)/2 method is used by over half of the members of WMO. The remainder calculate monthly means from observations at fixed hours or use complex formulae that employ station constants. Norway, for example, bases mean daily temperatures on the formula:

$$T = \frac{1}{3}(08 + 14 + 19) \ + C$$

where 08, 14, and 19 refer to the temperatures at these local times (in hours), and C is an empirically derived station constant which varies from month to month. For countries that use the maximum/minimum formula, the time of observation during the day can affect monthly mean values (Baker 1975; Blackburn 1983). In the United States the time of maximum/minimum observation at cooperative stations has changed from morning to evening, and this may result in a spurious cooling trend in temperature data (Schaal and Dale 1977).

To correct all readings to a common standard (e.g., [maximum + minimum]/2) would be extremely difficult. Such an effort is not necessary however if monthly temperature values and hemispheric estimates are calculated as *anomalies* from a selected reference period. Using this approach, one can assume that departures from differently derived mean values are comparable, provided that the observing system has remained internally consistent.

3.2.6 Changes in the Station Environment

The most important change that can affect a particular station is the growth of towns and cities around the site (the urbanization effect). Other changes at a site resulting from deforestation and irrigation are important only at single sites and generally not over entire regions.

Increasing urbanization around many stations may introduce a warm bias into computed regional temperature trends. Dronia (1967) calculated urban/rural differences by using 67 station pairs and by classifying the stations used by Mitchell (1963) into urban/rural categories based on population. His results showed an average urban warming trend of about 0.08°C per decade. Applying this correction to Mitchell's curve, he concluded that the mean hemispheric temperature in the 1960s was lower, not higher, than during the 1880s and 1890s. However, the spatial distribution of the stations used, the large distances of up to 2000 km separating the paired stations, and the paucity of data from the late 19th century make his conclusions questionable.

Other estimates of the magnitude of urban warming are made either on a regional basis or for a single city (e.g., Kukla et al. 1985). Most results suggest an urban effect from about 0.10 to 0.30°C per decade and refer to cities with populations greater than 100,000. However, because it is very difficult to separate any urban bias from other station inhomogeneities, these results should be viewed as a combined impact of both processes.

Recent studies of gridded temperature data from Northern Hemisphere land areas indicate that in studies of large-scale temperature trends, urbanization effects are relatively insignificant (Jones et al. 1985, 1986a). Indeed, those regions that are most important in contributing to hemispheric temperature trends are in high latitudes, north of 55°N, where urbanization effects are probably small (Jones and Kelly 1983).

3.2.7 Data Homogenization Techniques

Evaluation of the homogeneity of a data set can be accomplished in two stages. Data errors, generally from mistakes made in keypunching of handwritten records for computer entry, can be found by checking on outliers and flagging values that are at least three standard deviations from monthly means. (Alternatively, outliers could be flagged from 30-year filtered series.) These can be checked with original documents and with neighboring stations to decide whether the observation is correct. After such checking, the data can be considered "clean," although the data set may still not be homogeneous.

Many methods have been proposed for testing the homogeneity of station records relative to those at adjacent stations (Kohler 1949; Conrad and Pollak 1962; WMO 1966). Generally, tests of homogeneity involve the null hypothesis that a time series of differences between adjacent observation sets will exhibit the characteristics of a random series (Mitchell 1961; Bradley 1976; Craddock 1977; Jones 1983; Jones et al. 1986a).

These methods use climatological data (long-term series of monthly mean values) and make the assumption that non-climatic factors influencing one record will become apparent when the record is compared with a similar record (or group of records) from neighboring sites. If differences between observations are plotted against time, an abrupt nonlinearity in the plot may reveal where a station moved or a change in instrumentation or observation time at one of the stations occurred (Figure 3.2). When stations are analyzed in a small area it may become apparent which station or stations are in error. The station history information concerning the errant station can be checked for confirmations of a change. With this type of abrupt error, corrections can be made easily. However, if the graphs reveal that the changes at one station are gradual, increasing urbanization may be causing a gradual rise in monthly mean temperatures at one of the sites. With these types of subtle, time-dependent errors, corrections are difficult to apply, and part or all of the record should be removed from subsequent analyses.

This method of homogenization is only possible for monthly mean data. The corrections made on a monthly basis are not applicable to the daily data, such as for a time series of daily maximum and minimum air temperatures; such series are still nonhomogeneous. The method can be easily computerized, but the final deletion/correction/acceptance of a record can only be made by a careful subjective analysis.

This approach also requires that station records be from a dense network so that the stations are close together, although the appropriate distances depend on the region and on meteorological variables. For precipitation, which is generally more spatially variable, a denser network is required. For many parts of the world and many early periods, an adequate station density is not available. However, station networks since the 1880s are dense enough over the midlatitude regions of North America and Europe. In these regions homogeneity tests will be particularly important, because here the effects of urbanization may be large (Dronia 1967; Kukla et al. 1985).

Although further and more detailed analyses of temperature records are possible, such detail is considered impractical and unnecessary for the calculation of averages over large areas. The tests outlined above are considered to be adequate for this task. They are not, however, adequate for the analysis of individual station records.

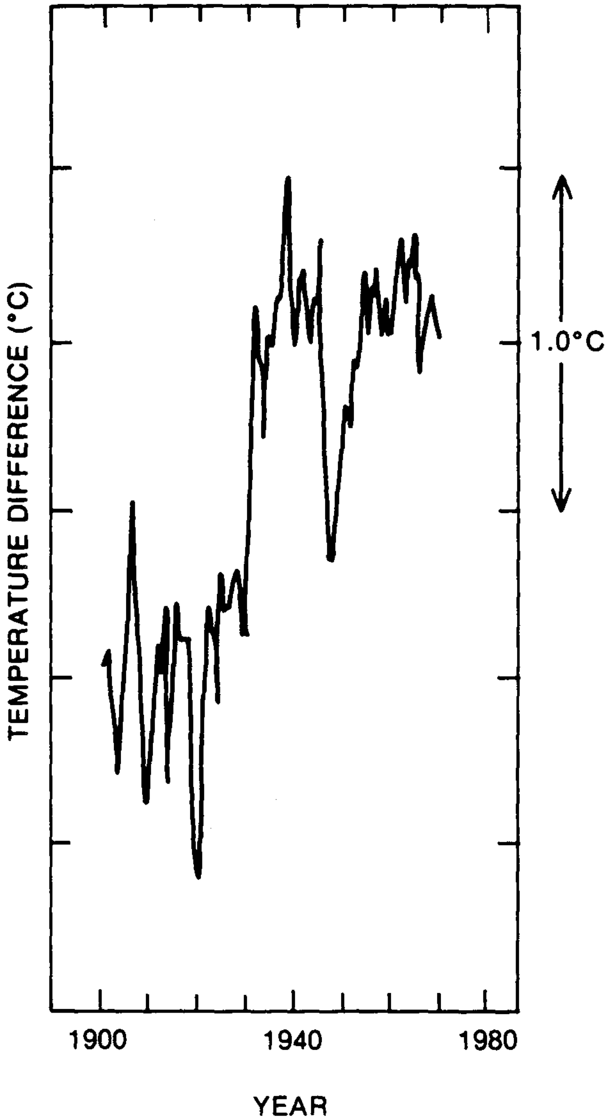

Figure 3.2. Station temperature difference time series: Reykjavik (64.0°N, 22.0°W) minus Vestmannaeyjar (63.4°N, 20.3°W), 1901–1970. The plot identifies Vestmannaeyjar as the errant station because a similar jump also occurs in 1931 when the station is compared with Stykkisholmur (65.0°N, 22.8°W). WWR station history data reveal that the station was moved in 1931.

In certain instances the analysis of long and isolated records from particular parts of the world is important. An example is the record from Sitka, Alaska (57.1°N, 135.0°W), where temperature, precipitation, and pressure were measured between 1832 and 1887. The unique position of this site (no records are available from the western half of North America until the 1850s in California and the 1870s in Washington State) make it ideal for further study. Detailed analyses of the record by Parker (1981, 1984) may allow the record to be used in hemispheric and regional analyses. The examination of station history information is very important for such single-site analyses.

Similar detailed studies of air temperature records have led to the production of many long temperature series; for example, in central England (Manley 1974), Paris (Dettwiller 1970), Berlin (Schaake 1982), and Philadelphia (Landsberg et al. 1968). There is the potential for similar research on long temperature records from other areas of the world.

3.2.8 Data Compilation

The best-known set of climatological data is generally referred to as World Weather Records (WWR). The project to produce this compilation initially was led by H. H. Clayton and funded by the Smithsonian Institution, Washington, D.C. Data were published by the Smithsonian Institution in 1927, 1934, and 1947, and updates containing 10 additional years of data were published by the U.S. Weather Bureau (various volumes from 1959–1982). These records have been recently digitized, and copies can be obtained from the National Center for Atmospheric Research (NCAR) (Jenne 1975). The individual station records that make up this data set are not homogeneous and contain many basic errors, but this data set has been used widely to study temperature variations over the last 100 years (Yamamoto and Hoshiai 1979; Hansen et al. 1981; Jones et al. 1982).

The selection of data for inclusion in WWR, however, was somewhat arbitrary. Before 1920 data were requested through personal contacts and not in any exhaustive fashion. This resulted in rather unrepresentative spatial coverage, with certain countries dominating the records in early years. For example, in the 1880s, half the temperature records came from three countries (the United States, U.S.S.R., and India). It is apparent that many long-term records were not included in these compilations.

Initial efforts to homogenize the records from before 1950 that comprise WWR were undertaken in cases for which the editors could gain sufficient information from the country concerned. The disproportionate information given by some countries can be seen in the station information section that

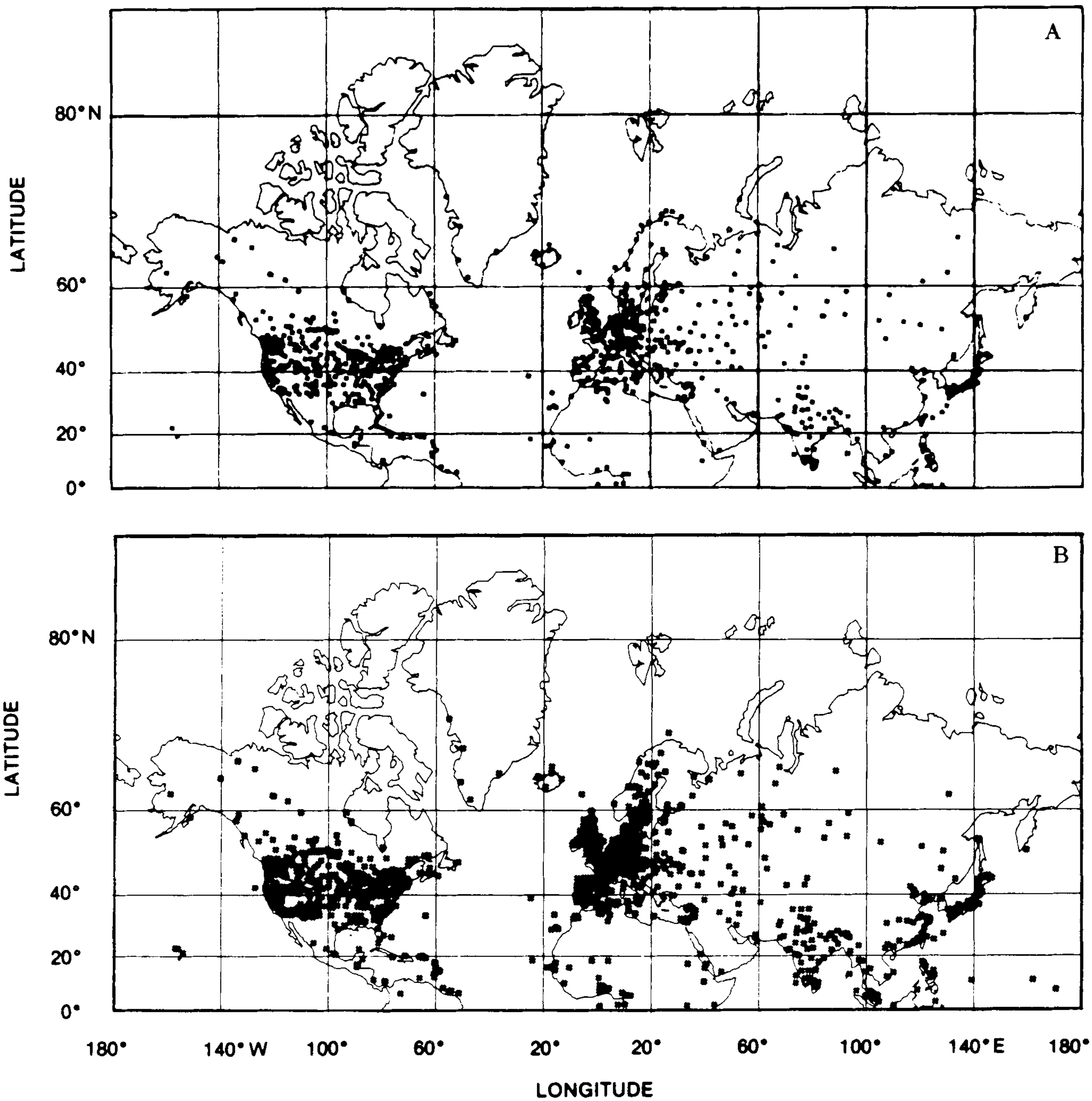

Figure 3.3. Locations of 19th century station records of 10 years or more in the Department of Energy Data Set. All stations shown have at least 10 years of data before 1900 and are generally continuous through at least 1960. (A) Temperature stations; (B) precipitation stations.

precedes each volume (see Bradley et al. [1985] for further details). After 1951, the data are simply those submitted through WMO by member countries. Any homogenization performed has been done in the individual country, and it must be assumed, in some cases, that no checks have been made.

The WWR data set formed the basis for the Department of Energy (DOE) temperature and precipitation data set produced by Bradley et al. (1985). Improvements were made for the period 1850 to 1900 by searching national meteorological archives for both published and unpublished materials. These data were key punched and added to the data set, extending existing records or forming new ones (Figure 3.3).

Many published compilations of early records were found in the course of this work. Two are particularly important, and while these were available to Clayton, neither was included in WWR. Between 1881 and 1890 the Central Physical Observatory at St. Petersburg (now Leningrad) published a set of volumes entitled *Repertorium für Meteorologie* (Wild 1887). These gave all climatological data (temperature, precipitation, and air pressure) collected for Russian territory and some adjacent areas, particularly China. The source extends instrumental data for the U.S.S.R. back to about the 1830s and significantly earlier in European parts of the U.S.S.R. Because no data for the U.S.S.R. are available in WWR before 1881, all analyses of hemispheric temperature trends have been constrained to begin in 1881 (surprisingly even those of the Russians themselves; Gruza and Ran'kova 1979; Vinnikov et al. 1980).

The most significant source of early temperature records for the world (pre-1860 to 1870) were published by Döve between 1838 and 1868. By correspondence, he built up a network of stations throughout the world. His network contained more than 1700 stations (although not all were operating at the same time); this number of stations has only been exceeded since 1951. However, most records were from Europe and eastern North America. He diligently gave his sources for every site (sometimes these are in very obscure journals), observation times, and units. No check was made on station homogeneity. This data set formed the basis of the first attempt to produce hemispheric temperature averages (Köppen 1873).

3.2.9 Methods of Producing Hemispheric Temperature Estimates

A world map of the locations of station temperature records shows that there are areas where station density is high (e.g., Europe, United States), areas where density is extremely low (Tibetan China, Antarctica, and the Amazon Basin), and ocean areas where there are no stations at all. Therefore, to produce hemispheric or regional estimates of mean temperatures, adjustments need to be made so that each area for which temperature records exist receives proper weighting. Another problem facing analysts is that temperature stations are at different altitudes and therefore may have quite different mean temperatures. Ideally, one would like to factor out the altitude effect, perhaps by extrapolating all data to a common level such as mean sea level (although topoclimatic factors would still be important). This, unfortunately, is extremely difficult to accomplish. Almost all analysts, therefore, subtract a reference period mean from station data. These anomaly values are comparable and contourable (see, for instance, *Die Grosswetterlagen Europas*, which publishes monthly a Northern Hemisphere map of temperature anomalies from the 1931 to 1960 normal reference period). The choice of reference period is especially important because a station can be used only if it has a record that is long enough to produce a reference period mean. Many workers (e.g., Yamamoto and Hoshiai 1980) select either the period 1881 to 1980 or 1881 to 1975. With a long reference period, one is immediately faced with deciding how many years need to have measurements before a reliable reference period mean can be produced. The choice of the almost 100-year period omits much station data and allows very few low-latitude (<30°N) data records to enter any subsequent analysis. To use most of the available data, it is easiest to select a reference period that has the best data coverage. Jones et al. (1982) selected the period 1946 to 1960, from which the maximum number of station records are available.

Many techniques have been used for forming hemispheric average temperature values.[1] Mitchell (1961, 1963) divided the world into 10° latitude zones, averaging all the zones (with area weighting). Hansen et al. (1981) divided the Northern Hemisphere into 40 boxes of equal area. Yearly temperature estimates were formed for each box, with the average of all available box values being the hemispheric estimate. Yamamoto and Hoshiai (1979) organized the data onto a regular but extremely coarse grid network, using the method of optimum interpolation, which was introduced into the field of meteorology by Gandin (1963). They then averaged the grid point values, with cosine latitude weights, using zero for all grid points with no data. This last step is

[1] Analysis of time series produced by various authors is discussed in Chapter 4 of this volume.

of dubious validity and causes a considerable damping of the variability. Jones et al. (1982) organized the data onto a 5° latitude by 10° longitude grid using an inverse distance-weighted, best-fit plane (for stations within 300 km) and then produced a hemispheric average using the weighted (by cosine latitude weighting) average of all the grid point values.

The last technique discussed here is that used by a team at the State Hydrological Institute, Leningrad, under Vinnikov et al. (1980). All available station data are plotted on maps and contoured by trained analysts. This is done routinely in Leningrad for forecasting purposes. The Soviet scientists have digitized the temperature anomaly charts by reading off interpolated values at 5° latitude by 10° longitude on the 1200 monthly charts. They have managed to use most of the available data (even short records) by changing the reference period mean three times over the period 1881 to 1980. Their method has been discussed at length by Jones et al. (1982) and Robock (1982).

Which method is best? Is there a best method? Undoubtedly the Russian method (Vinnikov et al. 1980) has certain advantages. The maps highlight data errors, but the contouring is subjective, and there may be differences among analysts in the extrapolation technique over areas with poor data. The Russians extrapolate their analyses over the ocean areas of the Northern Hemisphere, even though only isolated island data are available. This procedure is dubious and gives a false impression of the true data coverage. Tables and figures of the gridded area, as given by Jones et al. (1982), are more informative. The significance of the missing areas can be assessed, but this is fraught with danger, as highlighted by the analysis of Jones and Kelly (1983).

All the analyses discussed so far purport to be for the Northern Hemisphere (Jones et al. 1982). However, the area for which hard data are available is, at best, only 57% of the surface area of the Northern Hemisphere (Figure 3.4), dropping to less than 8% in the 1850s. The problem is worse when the Southern Hemisphere is considered; Hansen et al. (1981) produced a "global average," but when the number of stations in the Southern Hemisphere is considered, it is clearly inadequate. Global estimates cannot be produced until temperature trends over the oceans of the world are considered. Recently, estimates that include the ocean areas as well have been produced by Paltridge and Woodruff (1981), Folland and Kates (1984) and Folland et al. (1984), and by Barnett (1984); see also Chapter 4 of this volume. The results of these analyses show trends similar to those derived from the land series records, although there is still considerable controversy over the quality and homogeneity of ocean area air temperature data (Barnett 1984; Ramage 1984).

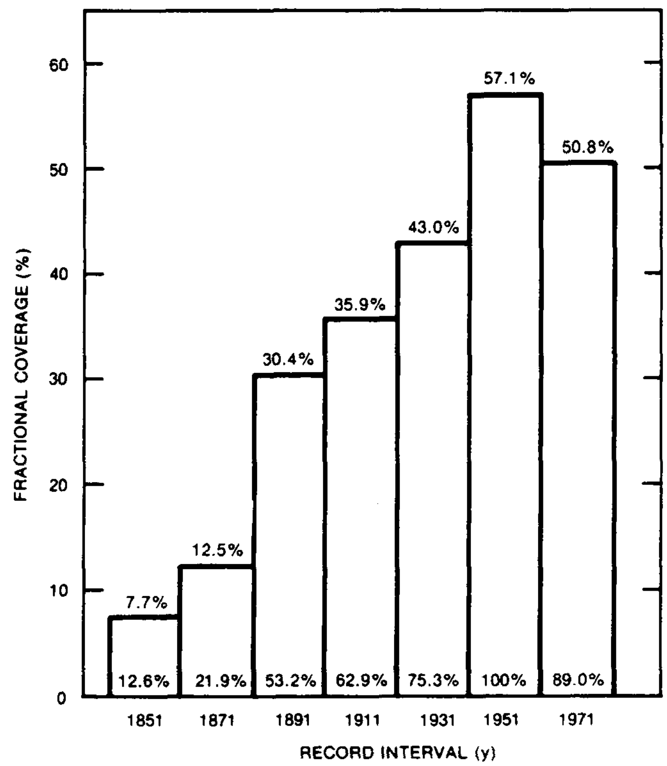

Figure 3.4. Percentage of the surface area of the Northern Hemisphere represented by gridded land-based temperature data, at 20-year intervals, in the Department of Energy Data Set. The numbers within the vertical bars indicate the relative coverage (in percent) compared to the maximum coverage achieved during the period centered on 1951.

Improvements are under way to rectify many of the shortcomings of recent analyses. Work by Bradley et al. (1985) has considerably increased the digitized land-based station data for the last century and increased the areas of the Northern Hemisphere where gridded estimates of air temperature can be made. Analyses of the global SST and air temperature data from ocean areas are being undertaken at the National Oceanic and Atmospheric Administration (NOAA)/University of Colorado Cooperative Institute for Research in Environmental

Sciences (Fletcher et al. 1984; Slutz et al. 1985; Woodruff 1985), at the U.K. Meteorological Office (Shearman 1983) and at the Scripps Institution of Oceanography (Barnett 1984). The combination of the new land estimates and ocean estimates from ship-based air temperatures will produce the best possible hemispheric estimates. The inclusion of Southern Hemisphere ocean area temperature data in time will improve global estimates (see Chapter 4 of this volume). An important development in this field is the new estimates of hemispheric and global surface temperatures that recently have been calculated from information from polar-orbiting satellites (Chahine et al. 1983). Such estimates may give an improved picture, but only after they have been checked and calibrated against dense arrays of surface observations. This approach will not provide any historical information, but it may enable the representativeness of limited area averages (such as those from continental land areas) to be assessed.

3.3 OTHER INSTRUMENTALLY RECORDED DATA BASES

Three other data bases are considered here. The precipitation and pressure data sets are comparable in length to that for temperature. However, upper air analyses, which give tropospheric and stratospheric measures of change, are only available since about 1950. All three data bases are discussed with respect to their errors, homogeneity, and potential significance in evaluating the climatic effect of increasing CO_2 concentrations.

3.3.1 Precipitation

Precipitation stations throughout the world far outnumber those for temperature, but the distribution is similar, with a plethora of records from Europe and North America. As with temperature, many precipitation site records are not homogeneous. There are problems because of changes in precipitation gauge size, gauge shielding, the height that the gauge is located above the ground, the growth of vegetation near the gauge, or the construction of buildings. All these factors can impair the performance of the gauge or alter the efficiency of the catch. Furthermore, various methods have been devised to deal with the difficulties of accurately measuring snowfall. This is a particularly acute problem at high latitudes and high elevations. Rodda (1969) has reviewed the possible errors and inhomogeneities that can result in precipitation records.

The total of these problems, coupled with the greater spatial variability of precipitation data, makes the problem of precipitation record homogenization significantly more difficult than that for temperature. Precipitation networks are not dense enough to allow the homogenization checks proposed in Section 3.2.6 to be easily undertaken. Analysis of precipitation records should not be undertaken on single-site records because of the high spatial variability of precipitation. Instead, analyses should be based on regional precipitation averages, formed by aggregation of many records in an area (Bradley et al. 1983; see also Chapter 7 of this volume).

The basic data source is again World Weather Records (WWR); improvements to the data set have been made by Bradley et al. (1985) by incorporating many new records, including 350 station records from the western United States (from Bradley et al. 1983), 180 homogenized station records for western Europe (Tabony 1980), many early records for the U.S.S.R. (Wild 1887), and the approximately 1000 records collected for Africa by Nicholson (1976).

The changes in precipitation patterns that are likely to accompany CO_2-induced climate changes are extremely important but have not been the focus of much research to date. Most CO_2 experiments suggest that global total precipitation will rise (National Research Council 1983), although precipitation may decrease in some areas. It is these regional-scale changes, especially on seasonal and shorter time scales, that are of most importance (Revelle and Waggoner 1983). Unfortunately, such resolution is not yet possible from available models, nor is it likely to be so in the near future. The only means of assessing future precipitation levels on these scales at present is the use of scenario studies (Lough et al. 1983; Webb and Wigley 1985).

3.3.2 Surface Pressure

Pressure data have an advantage over the temperature and precipitation data bases because they are routinely analyzed onto regular grid networks for weather forecasting purposes. Monthly mean data for the Northern Hemisphere extend back to 1873, but for the Southern Hemisphere routine analysis only began in the late 1940s.[2]

The Northern Hemisphere data, however, are not truly homogeneous. There are several different data sets (produced by the United Kingdom Meteorological Office [UKMO], the National Oceanic and Atmospheric Administration [NOAA], Deutscher Wetterdienst, and Soviet sources). Most data sets are the same for 1899 to 1939, but since 1945 they are generally different because of different interpolation algorithms. Analyses of the UKMO and NOAA data sets by Williams and van Loon (1976) and of the NOAA data set by Trenberth and Paolino (1980) have revealed that in many areas the gridded data do not agree with monthly mean station data. Further comparison of the different data sources has been undertaken by Parker (1980). Differences are most apparent over highland areas such as the Rockies and the Himalayas. Furthermore, it is suspected that early analysts overemphasized the "Arctic High," particularly over North America before 1920. Pressure values here are thought to be 2–4 mb (0.2–0.4 kPa) too high compared with mean values from recent periods (Namias 1958).

Jones et al. (1983, 1986b) derived a method to extend pressure data further back in time and to estimate values in data-poor regions. The method uses multiple regression techniques to transform between principal components of the gridded sea level pressure and principal components of station pressure data. The regression equations developed with data from the 20th century can then be applied to earlier periods, depending on the availability of station pressure data (back to the 1850s over Europe and North America). Extension back to even earlier times (~1780) is possible over Europe using a mixture of station pressure, temperature, and precipitation data instead of station pressure data alone. For Europe, continuous monthly mean pressure series have been produced for Paris, Edinburgh, Trondheim, and Milan back to the late 18th century (see Jones et al. [1986b] for details).

Station pressure data are also available from WWR.[3] The pressure data have all the problems of temperature data with station moves, observation time changes, correction to true means, and instrumentation problems. Further difficulties arise because all pressure readings should be corrected for temperature and for gravity at 45°N; the height of the instrument must also be known unless the observation is reported as mean sea level pressure. Jones et al. (1983) analyzed 32 pressure sites over Europe, and although WWR authors noted that corrections had been made in all cases, only five records were found to be error free. The most common problem was because of a station move, with subsequent data being corrected to a new height.

3.3.3 Upper Air Analyses: Heights, Temperature, Thickness

Since 1945, worldwide measurements of upper level pressures, winds, and temperatures have been made with radiosondes, rocketsondes, and, more recently, satellite-derived data. There are many different types of sonde manufactured, and their use differs from country to country. The data obtained from these instruments are extremely important meteorologically for weather forecasting purposes. As a result, the data come to climatologists secondhand after their operational use. Interpolated daily grid-point values of heights and temperatures at certain fixed pressures are averaged to form monthly mean values. The thickness of the atmosphere between any two levels is directly related to the average temperature of the layer. Analysis of free air temperature measurements is discussed in Chapter 4 of this volume.

Because they are affected by changes in instrumentation and changes in correction procedures, upper air data are far from being error free. Over data-sparse oceanic regions, the grid point analyses are dependent on the dynamic model that provides the "first guess" pressure field (Parker 1980). Spurious trends therefore may be introduced into grid point time series by changes in analysis procedures.

[2] The routine synoptic analysis of the Southern Hemisphere was started at the end of the 1940s in South Africa and was taken up in the early 1960s by the International Antarctic Analysis Center in Melbourne, Australia. The U.S. Weather Bureau prepared its own analysis in the 1960s and 1970s in support of the Apollo project.

[3] In numerous cases, station and sea level pressure data sets published in WWR appear to have been reversed.

Although changes related to sonde type may not be apparent from day to day, climatological analysis has unearthed some slight, but important, changes. For example, Parker (1980) has analyzed sonde data from Arctic regions and found that data from U.S.S.R. stations bordering Norway were abruptly different at the same time as similar changes were noted on the eastern border of the U.S.S.R. with Japan. It was concluded that the change in sonde manufacture had affected the U.S.S.R. sonde data. Such checks between stations in adjacent countries need to be conducted on a continuing basis to ensure the homogeneity of the data set in the future. Parker (1980) also compared the routinely analyzed charts of surface pressure and upper level analyses performed by national meteorological agencies in the U.S.S.R., the United States, West Germany, and the United Kingdom. Some important differences were revealed, but by using the station data it was possible to select the most correct chart for any particular case. However, there was no consistent pattern in selecting the optimum analysis.

3.4 VOLCANIC AEROSOLS

Several studies of the effects of a CO_2 buildup on the climate during the last 100 years have pointed to the importance of isolating the significance of volcanic aerosol loading of the upper atmosphere (Schneider and Mass 1975; Miles and Gildersleeves 1978; Hansen et al. 1981). Because this factor is possibly the most important variable affecting temperature variations on the time scale of 1 to 10^2 years, the following section discusses various data sets concerned with stratospheric aerosol loading. A similar review has been provided by MacCracken (1983).

Although the idea that volcanic eruptions might influence climate far from the eruption site was proposed over 200 years ago (Franklin 1789), serious attention was not directed to the question until the early 20th century (Abbott and Fowle 1913; Humphreys 1913; Arctowski 1915). The first attempt at a comprehensive catalog of explosive eruptions was that of Lamb (1970), who compiled historical data on known eruptions (tephra volume) and records of unusual post-sunset sky coloration as a proxy of eruptions that had injected aerosols into the stratosphere. Using the fairly comprehensive studies of Krakatoa (Symons 1888) as a reference standard (to which he assigned a dust veil index [DVI] of 1000), Lamb made estimates of the magnitude of other, less well-known eruptions, and even of unknown eruptions observed via the sky coloration records in historical literature. This approach recently has been applied to years earliler than 630 A.D. using European (principally Roman and Greek) literature sources (Stothers and Rampino 1983). Lamb's DVI often has been criticized because of the occasional use of temperature records to assess eruption magnitude (by reference to the extent of cooling after an eruption) (Robock 1981). However, this is only true for a few cases; according to Newhall and Self (1982), of Lamb's 250 DVI estimates, only 5% are solely based on temperature estimates. The majority (48%) are based on qualitative descriptions of eruptions or post-sunset sky coloration and another 42% are based either on Sapper's (1927) semiquantitative estimates of tephra volume or on later, more detailed calculations of tephra volume. A small percentage of values (5%) are based on actual radiation data. Lamb recognized the dangers of circular reasoning in using the DVI to assess the effect of explosive eruptions on temperature and was careful to isolate any data derived from climatological reasoning (Figure 3.5). He also pointed out explicitly that his estimates were probably only good to within one order of magnitude. This is discussed further by Kelly and Sear (1982).

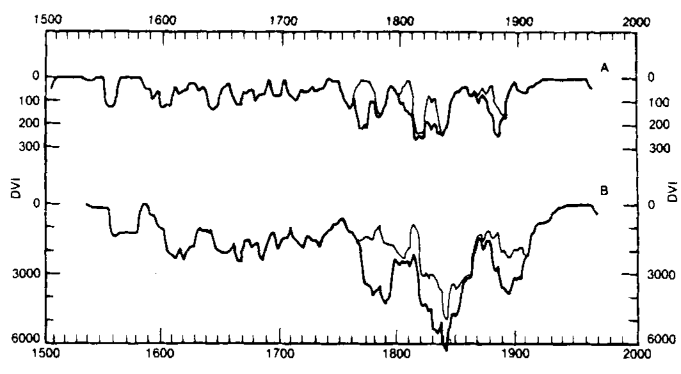

Figure 3.5. (A) Ten-year running means of Lamb's DVI plotted at the middle of each decade. (B) Twenty-five-year cumulative DVI. In (A) and (B) the finer lines indicate values obtained by ignoring cases of dust veils assessed solely on evidence of temperature anomalies. Source: Lamb (1970).

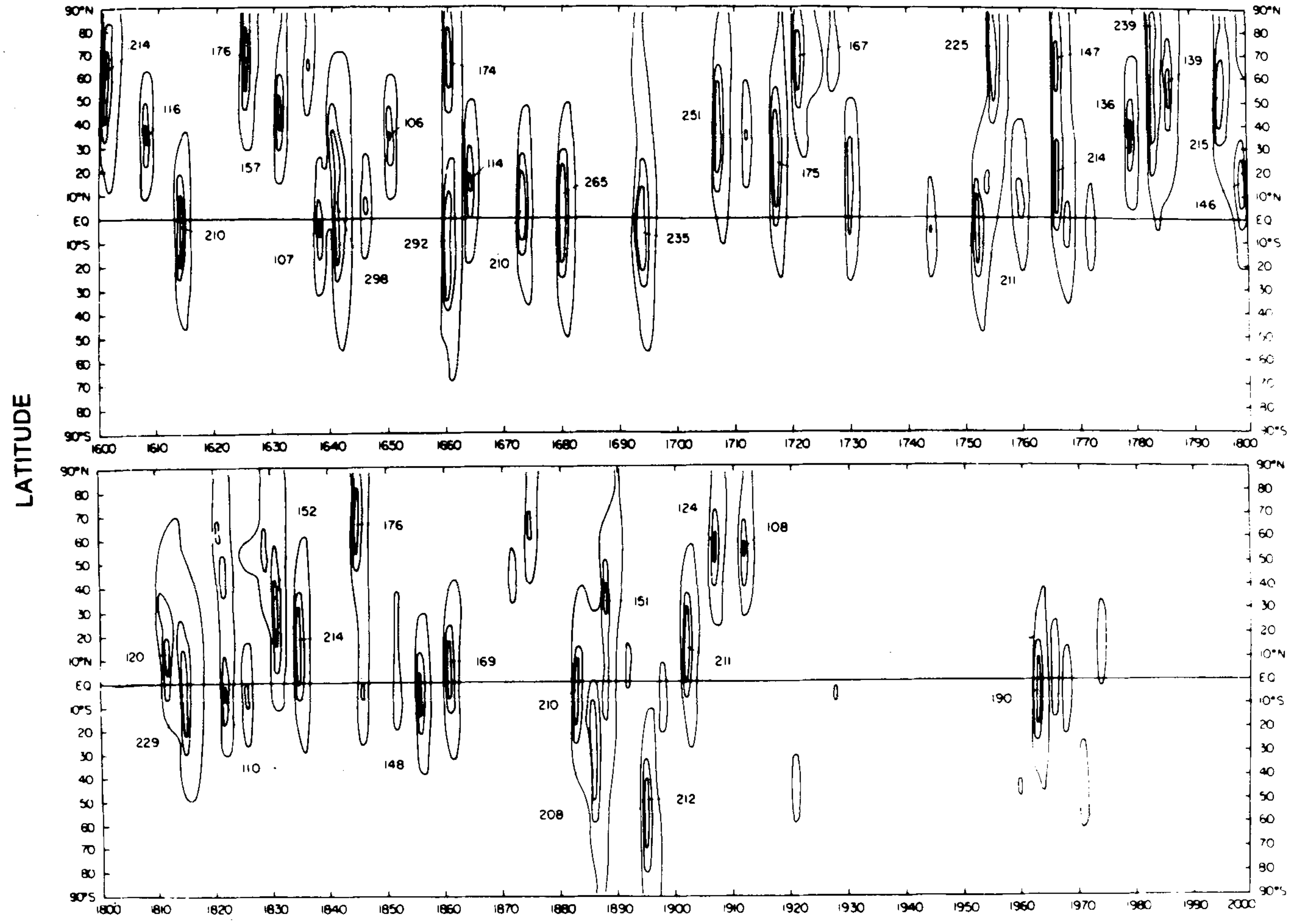

Figure 3.6. Latitudinal distribution of volcanic DVI, calculated from the adjusted data of Lamb (1970). Contours are at DVIs of 20, 60, and 100; the maximum value at the center is also given. Source: Robock (1981).

Since that time, authors have made minor adjustments in Lamb's chronology, revising the magnitude of certain eruptions based on more recent information (Mitchell 1970, 1972; Oliver 1976). An attempt also has been made to assess the latitudinal and temporal dimensions of aerosol clouds, recognizing that the location of eruptions is important in subsequent aerosol dispersion history, and that aerosols may remain dispersed for several years following an eruption (Robock 1981). Robock's model of DVI is shown in Figure 3.6.

A more detailed chronology of volcanic eruptions has been compiled by Hirschboeck (1980), with data spanning the interval from 2227 B.C. to A.D. 1969. Hirschboeck's chronology contains an order of magnitude more eruption events, but the vast majority are rated as minor or moderate, which are unlikely to have been of climatic significance. Indeed, even some of those rated as great eruptions were too small to have been of climatic significance (Newhall and Self 1982).

The most extensive compilation of worldwide volcanic eruptions is that of Simkin et al. (1981), who used geological criteria to rank eruptions on a scale of 0 (small) to 8 (massive) to form a volcanic explosivity index (VEI). Although this provides an objective chronology of eruption magnitude, the ratings were not designed to indicate potential climatic significance. The 1980 eruption of Mt. St. Helens, for example, was given a rating of 5, whereas the 1963 eruption of Mt. Agung, known to be of far greater climatic significance, was rated only as a 4. It would be useful to develop an index of climatically important explosive eruptions that would take into account eruption magnitude (volume and size of material, and injection height) as well as tephra composition, particularly sulfate content (Devine et al. 1984; Rampino and Self 1984). Other factors such as season of eruption, latitude, and vent elevation are also of significance.

All these factors notwithstanding, analysis of the VEI chronology provides some insight into the major characteristics of all eruption chronologies:

1. A total of 75% of major eruptions (VEI > 5) are recorded as occurring in the Northern Hemisphere (Table 3.1).

Table 3.1
Major Volcanic Eruptions (with VEI $\geq$ 5) Since 1600.

Volcano	Latitude	Date of Eruption	VEI
Awu	3.67°N	January 1641	5
Usu	45.5°N	August 1663	5
Tarumai	42.7°N	August 1667	5
Long Island	5.4°N	1700±100	6
Tarumai	42.7°N	August 1739	5
Katla	63.6°N	October 1755	5
Tambora	8.3°S	April 1815	7
Galunggung	7.3°S	October 1822	5[a]
Cosiguina	12.98°N	June 1835	5
Sheveluch	56.78°N	February 1854	5
Askja	65.0°N	March 1875	5
Krakatoa	6.1°S	August 1883	6
Tarawera	38.2°S	June 1886	5
Santa Maria	14.75°N	October 1902	6
Ksudach	51.8°N	March 1907	5
Novarupta (Katmai)	58.28°N	June 1911	6
Quizapu (Cerro Azul)	35.67°S	April 1932	5
Bezymianny	56.07°N	March 1956	5
St. Helens	46.2°N	May 1980	5

[a] Considered questionable.
Source: Simkin et al. (1981).

2. The record is incomplete and biased toward areas with good historical records. Prior to 1800, most reports of large, high-latitude eruptions were from Iceland and Japan, whereas in the late 19th and 20th centuries more high-latitude eruptions were reported from Alaska, the Aleutian Islands, and Kamchatka. This strongly suggests that many other eruptions occurred in these areas during historical times, but were never reported. Even today, eruptions in the Aleutian Islands may not be noticed for weeks to months. High latitude Southern Hemisphere eruptions are virtually unknown; only two major eruptions poleward of 30°S have been recorded, in 1886 and 1932.
3. Because of the probable bias in reporting, the maximum eruption density (eruptions per unit area) for eruptions with a VEI $\geq$ 4 occurs in latitude zone 60°–65°N (1.4 eruptions per 10^6 km^2 for the period 1500–1980). In view of other potentially unrecorded eruptions in this zone, this in fact may be true, but only further volcanological studies will be able to confirm it.
4. Although reports of eruptions have increased toward the present, it is, nevertheless, clear that the interval 1923–1950 was relatively free of major eruptions. The number of large eruptions (VEI $\geq$ 4) has doubled since the early 1950s, with an average of two major eruptions every 3 years since then (Simkin et al. 1981).

Because of the limited historical and volcanological data available and the inherent difficulties of assessing eruption magnitude ex post facto, the value of a precise proxy for volcanic eruptions is clear. Recently, the potential for using ice core electrolytic conductivity data as a proxy of explosive sulfate-rich eruptions has been demonstrated. Gases such as hydrogen sulfide and sulfur dioxide injected into the stratosphere are rapidly dispersed around the hemisphere. They are photochemically oxidized en route and combine with water molecules to form sulfuric acid, which is eventually washed out in precipitation, thereby raising the conductivity of snow (and eventually ice layers) in polar ice caps. Using Lamb's dust veil index (DVI) as a check, Hammer (1977) and Hammer et al. (1978, 1980) have demonstrated that highly acidic layers, significantly above background acidity values, reveal a record that closely matches eruptions of known ages. However, the ice core record is biased toward high-latitude eruptions because the washout of acidic precipitation is greater near the source. For example, in the Greenland Crête ice core, the highest acidity levels in the last 2000 years resulted from the eruptions of Lakagigar, Iceland, in 1783 and Eldgja, Iceland, in 934 A.D. ± 2. However, the most explosive eruption in the last millennium (and also perhaps the eruption of greatest climatic significance) was that of Tambora in 1815, a low-latitude event (8°S) rated 7 in the VEI (Stothers 1984). Perhaps a Southern Hemisphere ice core acidity record will provide a better perspective of the magnitude of these equatorial eruptions, even though they appear to have been of climatic significance in both hemispheres (Dunwiddie and LaMarche 1980; LaMarche and Hirschboeck 1984). Perhaps, the greatest value of ice core acidity records is the prospect of constructing a unique chronology of explosive eruptions back into prehistoric times.

The principal value of all these chronologies is as an estimate of the potential climatic effect of eruptions through their effect of reducing the solar radiation that reaches the lower atmosphere. A more direct index of volcanic aerosol loading may thus be long-term actinometric measurements of solar radiation (Pivovarova 1977). Although there are uncertainties in the quality of these records over time (World Meteorological Organization 1984a) they have been used as an index of stratospheric aerosol loading by Bryson and Goodman (1980), who have analyzed actinometric data for 42 Northern Hemisphere stations between 20° and 60°N on cloud-free days. These data were converted into mean aerosol optical depth as a measure of turbidity in the overlying atmospheric column (Figure 3.7). The early data in the record show relatively sharp year-to-year changes that appear to be correlated with the volcanic record. However, the later data seem to be much less related to volcanic eruptions. Because the data cannot be used to distinguish between tropospheric and stratospheric aerosol loading, the effect of urbanization and industrial and agricultural activity may be important factors in this time series. The data also include any effects of solar variability.

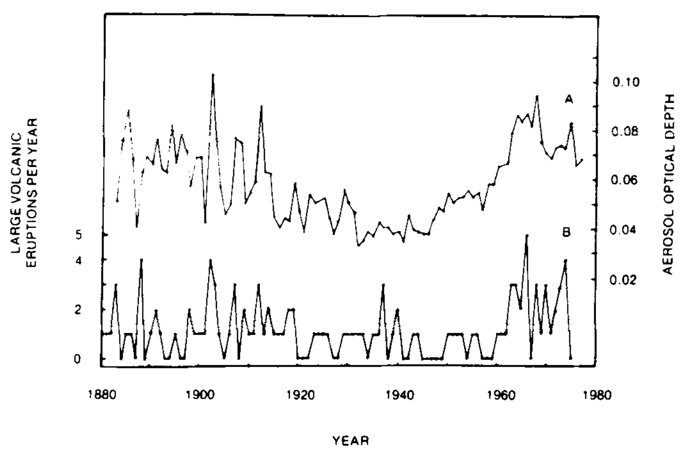

Figure 3.7. (A) Mean annual aerosol optical depth, based on 42 stations between 20° and 65°N, and (B) the number of Northern Hemisphere volcanic eruptions of large magnitude per year. Source: Bryson and Goodman (1980).

In view of the wide variety of volcanic aerosol indices, it is interesting to compare them for the period of overlap. Correlation coefficients are shown in Table 3.2.[4] Correlations between most series are statistically significant at a level <5 percent after accounting for autocorrelation. Pivovarova'sactinometric index is inversely correlated with the other indices because it is a direct measurement of solar radiation received at the surface rather than of aerosol loading. Also shown are correlations between the various indices and the Northern Hemisphere continental temperature data set of Jones et al. (1982). All series (except Pivovarova's) show statistically significant negative correlations with the temperature records. This analysis suggests that a better understanding of volcanic aerosol effects on climate will be needed to adequately assess CO_2-climate relationships in the future.

3.5 SOLAR IRRADIANCE

Until recently (i.e., since the availabiltiy of satellites) there have been no accurate measurements of solar irradiance. However, a number of proxy indicators have been used in solar climate studies: sunspots, atmospheric carbon-14 concentrations and solar diameter (see Wigley [1981] for a thorough discussion of these proxy indicators of solar irradiance and also Repin et al. [1980]; papers concerning solar-climate relationships are the focus of Centre National d'Etudes Spatiales [1978, 1980]).

Sunspots were rediscovered by Galileo in 1611, shortly after the invention of the telescope, even though the dark spots or blemishes had been seen on the face of the Sun with the naked eye for many centuries. Long records of sunspot activity can be gleaned from descriptions of the Sun and aurorae in Chinese records (Youji et al. 1983), but these are imprecise. Sunspots vary greatly in size, with some being as large as one-twentieth of the visible area of the Sun, and they occasionally occur in groups.

Since the 17th century, the number of sunspots has been counted by a regular network of observatories around the world. Wolf began a compilation of the sunspot counts on a monthly basis (known as the Zurich relative sunspot number), which has been continually updated. The sunspot numbers

[4] S. Clegg and T.M.L. Wigley; personal communication.

Table 3.2.
Correlations Between Different Series of Volcanic Forcing[a]

Source[b]	1	2	3	4	5	6	7	8
9	−0.36	−0.44	−0.54	−0.29	−0.48	−0.66	(0.31)	−0.47
8	0.28	0.37	0.44	0.30	−0.36	0.52	(−0.50)	
7	−0.48	−0.32	−0.46	(−0.15)	−0.47	−0.43		
6	(0.26)	0.43	0.63	−0.25	−0.56			
5	0.65	(0.16)	0.81	0.65				
4	0.61	0.30	0.63					
3	0.56	0.41						
2	0.23							
9	(−0.48)	(−0.67)	(−0.67)	(−0.35)	(−0.61)	(−0.75)	(0.33)	(−0.57)
8	(0.25)	(0.45)	(0.58)	(0.48)	(0.53)	(0.62)	(−0.40)	
7	(−0.51)	(−0.33)	−0.68	−0.51	(−0.72)	(−0.47)		
6	(0.44)	(0.63)	(0.72)	(0.49)	(0.60)			
5	0.70	(0.18)	(0.84)	0.66				
4	0.80	(0.33)	(0.54)					
3	(0.62)	(0.51)						
2	(0.39)							

[a] In the lower half of the table, the volcanic data have been subjected to a low pass (3 year) binomial filter. Values in parentheses are not significant at the 5% level after accounting for autocorrelation.

[b] Sources are as follows:
1. Simkin et al. (1981); VEI.
2. Hammer et al. (1980); ice core acidity.
3. Lamb (1970); DVI.
4. Mitchell (1970); based on Lamb's (1970) DVI.
5. Oliver (1976); based on data from Lamb (1970) and Mitchell (1970).
6. Bryson and Dittberner (1976); alternative DVI.
7. Pivovarova (1977); strength of direct solar beam (actinometric).
8. Bryson and Goodman (1980); mean annual aerosol optical depth (cf. Pivovarova 1977).
9. Northern Hemisphere temperatures from Jones et al. (1982).

vary in a periodic way with roughly 11 years between each sunspot maxima, although the cycle has had lengths ranging from 7.3 to 17.1 years over the last 300 years (see Sonett [1983] for a discussion of the sunspot index spectrum). The sunspot record extends back to 1749 with high reliability (Eddy 1976), but is less reliable before and extremely sketchy prior to 1700. Part of the reason for this sketchiness is due to the belief that there were no sunspots for certain periods during the 17th century. This period has come to be known as the Maunder Minimum (1654 to 1714). It is now generally believed that there were some sunspots, although the numbers were reduced compared with those counted after 1800. Earlier sunspot minimum periods are also believed to have occurred (e.g., the Spörer [1416 to 1534] and Wolf [around 1280 to 1350] minima).

The area of the Sun covered by sunspots has been measured since 1874. The umbral/penumbral ratio (the ratio of the size of the inner to the outer ring of the spot) has also been measured since that time because it was thought that it might be a more useful irradiance proxy than the sunspot number (Hoyt 1979). The area time series has been used by Eddy et al. (1982) to reconstruct values of the solar irradiance. Such a series may be a more reliable indicator of variations of solar irradiance received by the Earth than is the number of sunspots.

Another indicator of solar output variations is the amount of radioactive carbon-14 in the atmosphere. Such variations can be measured by comparing carbon-14 dates with accurate calendrical dates of tree rings. As carbon-14 production is influenced by solar flare activity and the strength of the solar wind (Stuiver and Quay 1980), it is a valid proxy measurement of solar activity, but its relationship to irradiance is uncertain. Major variations in atmospheric carbon-14 are associated with modulations in the amplitude of the 11- and 22-year solar sunspot cycle and may allow periods similar to the Maunder Minimum to be identified back many thousands of years. The variability of atmospheric carbon-14 provides firm evidence of solar variability on the century time scale, but as noted above, the link with irradiance has not yet been determined.

The relationships between variations in sunspot activity, sunspot area, solar flare activity, and solar irradiance are still a matter of debate (Newkirk 1983). The issues cannot be resolved until long and accurate time series of satellite-measured irradiance become available. Such direct measurements of solar irradiance have been made with the aid of satellites only since 1975. Earlier rocket-based or ground-based data are considered inadequate for estimating decadal time scale changes (Willson 1984). The results from the many satellite missions since 1975, in particular the Solar Maximum Mission, have been summarized by Smith et al. (1983) and Willson (1984). Correlations on daily to annual time scales between solar irradiance and sunspots have been demonstrated (Willson et al. 1981; Eddy et al. 1982; Smith et al. 1983). These data suggest that there may be irradiance changes of ±0.05 percent associated with the sunspot cycle. The associated change in global mean temperature would almost certainly be less than ±0.1°C if due account is taken of transient response effects (Hoffert and Flannery 1985).

Extrapolation of the satellite record to longer periods suggests that solar variability may vary by up to 0.2% over a 40-year period. Such variations may be more important for climatic studies, partly because of the amplitude of such changes and partly because the transient response damping would be less for lower frequency forcing. These variations appear to be in accord with astronomical evidence that the solar diameter varies on the decadal to century time scale. Parkinson et al. (1980) and Gilliland (1981) suggest that the diameter of the solar disk varies with an approximately 80-year cycle. There is also evidence of such a periodicity in the modulations of the 11- and 22-year sunspot cycle over the last 250 years. Although the quantitative link is still uncertain (to within two orders of magnitude according to Gilliland 1981), changes in solar diameter should be reflected by changes in solar irradiance. Smith et al. (1983) have suggested that some of the observed changes in irradiance from satellite data might be caused by such changes.

Global mean temperature changes of up to ±0.2°C appear to be possible as a result of solar irradiance changes, consistent with recent satellite observations (Willson 1984). However, the shortness of the satellite record precludes any definitive statement at present. Changes of ±0.2°C would be extremely difficult to detect in the observational record. Nevertheless, the magnitude is consistent with the empirical estimates of Gilliland (1982) and Gilliland and Schneider (1984), even though their results are not statistically significant. Almost all proposed solar-climate relationships have been found to be statistically unsound when analyzed critically (Pittock 1978, 1983), but the possibility of solar influences on the climate cannot be dismissed. The effects are almost certainly small on the interannual time scale, but they may still be significant on the 10 to 100 year time scale.

Determination of the significance of solar irradiance change on climate and the relationship between solar irradiance and the proxy measurements discussed above require a relatively long and continuing record of accurate measurements from satellites. The present Earth Radiation Budget satellites will probably not be operative after 1987–1988. After 1993, a new generation of satellites will become operational (World Meteorological Organization 1984b). There will therefore be a gap in the hitherto continuous record of broad-spectrum radiation measurements from satellites between 1988 and 1993 (World Meteorological Organization 1984b). To avoid such a gap, immediate action is required. The contingency measures suggested by the World Climate Research Programme (World Meteorological Organization 1984a) to bridge this gap may not provide the required accuracy.

3.6 SUMMARY AND RESEARCH RECOMMENDATIONS

Almost all data used in studies of long-term climatic variations have significant limitations arising from the fact that the data were never collected for this purpose. Table 3.3 summarizes the most important data sets that have been assembled and that are in machine-readable form. Users of these data sets who wish to isolate the effect of increasing CO_2 concentrations or to understand climatic variations of the past must carefully consider the data quality and spatial and temporal resolution of the data, as discussed above. Only with such a realistic appraisal of these data can meaningful conclusions be reached.

Compilation of a detailed land-based temperature and precipitation data set extending back to 1851 has recently been accomplished. It is unlikely that a significant improvement in the spatial coverage of this long-term set can be achieved. Studies of the homogeneity of the data sets, particularly of precipitation and pressure data, are needed, however. Both sea surface and marine air temperatures need to be carefully homogenized and merged with land-area data to provide a more comprehensive view of hemispheric and global temperature variations. The record of large explosive volcanic eruptions (i.e., those likely to be of climatic significance) is poor and improvements are needed to more fully understand the effects of these events on the long-term climatic record. In particular, the chemical characteristics of past volcanic emissions and their relationship to atmospheric optical depth through time are areas requiring further study. Satellite measurements of solar irradiance are also extremely

Table 3.3
Sources of Data Sets Useful for Detecting CO_2-Induced Climate Change.

Variable	Region	Source and Availability of Data Set	References and Remarks
Surface Air Temperature (land stations only)	Global	World Weather Records (WWR)—NCAR, Boulder, CO	Jenne (1975) and updated current NCAR documentation
Surface Air Temperature (land stations only)	Northern Hemisphere	U.S. Dept. of Energy Data Bank—Carbon Dioxide Information Center (CDIC), Oak Ridge, TN	Bradley et al. (1985). 19^{th} century records in WWR are a subset
Gridded Air Temperature (5° latitude by 10° longitude for land areas	Northern Hemisphere	U.S. Dept. of Energy Data Bank—CDIC, Oak Ridge, TN	Jones et al. (1986a). Gridden version of station data in Bradley et al. (1985) and WWR
Marine Data (including sea surface and ocean air temperature)	Global	Comprehensive Ocean-Atmosphere Data Set (COADS)—NCAR or CIRES, Boulder, CO	Slutz et al. (1985). Data set contains many other variables (e.g., windspeed, sea level pressure, cloudiness)
Marine Data (sea surface and ocean air temperature only)	Global	U.K. Meteorological Office	Folland et al. (1984)
Station Precipitation (land areas only)	Global	WWR-NCAR, Boulder, CQ	Jenne (1975) and updated current NCAR documentation
Station Precipitation (land areas only)	Northern Hemisphere	U.S. Dept. of Energy Data Bank—CDIC, Oak Ridge, TN	Bradley et al. (1985) (19^{th} century records in WWR are a subset)
Sea Level Pressure (gridded)	Northern Hemisphere	NCAR (1899-), Boulder, CO	Jenne (1975). See remarks concerning homogeneity in Williams and van Loon (1976) and Trenberth and Paolino (1980)
Sea Level Pressure (gridded)	Northern Hemisphere	U.K. Meteorological Office (1873-)	See Williams and van Loon (1976)
Upper Air Analyses (various levels [1000–100 mb], heights, and temperatures)	Northern Hemisphere	NCAR, Boulder, CO	Jenne (1975). Most standard levels available although 500 and 700 mb are of longer duration (since ~1946) and are probably most reliable
Sea Level Pressure (gridded), Upper Air Analyses (various levels (1000–100 mb), and heights)	Southern Hemisphere	Australian Bureau of Meteorology, Melbourne Australia	Only available since 1972

important and it is critical that these observtions be continued, particularly over the next decade.

Improvements in large area and long-term data sets have been and continue to be made. Analysis of these data should provide new insights into the variability of past climate and the importance of various factors in producing the variability. This will be a major step towards isolating the effects of the increasing CO_2 concentration on climate.

REFERENCES

Abbott, C. G., and Fowle, F. E. 1913. "Volcanoes and Climate." *Smithsonian Institution Miscellaneous Collection 60*(29):Washington, D.C.

Arctowski, H. 1915. "Volcanic Dust Veils and Climatic Variations." *Annals of the New York Academy of Science 26:*149.

Baker, D. G. 1975. "Effect of Observation Time on Mean Temperature Estimation." *Journal of Applied Meteorology 14:*471–476.

Barnett, T. P. 1984. "Long Term Trends in Surface Temperature Over the Oceans." *Monthly Weather Review 112:*303–312.

Bigelow, F. H. 1909. "Report on the Temperature and Vapor Tensions of the United States." *Bulletin S, Weather Bureau.* U.S. Department of Agriculture, Washington, D.C.

Blackburn, T. 1983. "A Practical Method of Correcting Monthly Average Temperature Biases Resulting from Differing Times of Observations." *Journal of Climate and Applied Meteorology 22:*328–330.

Bradley, R. S. 1976. *Precipitation History of the Rocky Mountain States.* Westview Press, Boulder, Colorado.

Bradley, R. S., Barry, R. G., and Kiladis, G. 1983. "Climatic Fluctuations of the Western United States During the Period of Instrumental Records." *Contribution No. 42.* Department of Geology and Geography. University of Massachusetts, Amherst, Massachusetts.

Bradley, R. S., Kelly, P. M., Jones, P. D., Goodess, C. M., Diaz, H. 1985. "A Climate Data Bank for Northern Hemisphere Land Areas, 1851–1980." (DOE/EV/10739-2). Carbon Dioxide Research Division, U.S. Department of Energy, Washington, D.C. Available from NTIS, Springfield, Virginia.

Bryson, R. A., and Dittberner, G. J. 1976. "A Non-Equilibrium Model of Hemispheric Mean Surface Temperature." *Journal of the Atmospheric Sciences 33:*3094–3106.

Bryson, R. A., and Goodman, B. M. 1980. "Volcanic Activity and Climatic Changes." *Science 207:*1041–1044.

Callendar, G. S. 1938. "The Artificial Production of Carbon Dioxide and its Influence on Temperature." *Quarterly Journal of the Royal Meteorological Society 64:*223–237.

Callendar, G. S. 1949. "Can Carbon Dioxide Influence Climate?" *Weather 4:*310–314.

Callendar, G. S. 1961. "Temperature Fluctuations and Trends Over the Earth." *Quarterly Journal of the Royal Meteorological Society 87:*1–12.

Centre National d'Etudes Spatiales. 1978. *Evolution of Planetary Atmospheres and Climate of the Earth.* Centre National d'Etudes Spatiales, Toulouse, France.

Centre National d'Etudes Spatiales. 1980. *Sun and Climate.* Centre National d'Etudes Spatiales, Toulouse, France.

Chahine, N. T., Haskias, R., Susskind, J., and Reuter, D., 1983. "Remote Sensing of Weather and Cloud Parameters." *Proceedings of the International Union of Geodesy and Geophysics XVIII General Assembly,* Hamburg, Federal Republic of Germany. I.U.G.G. Publications Office, Paris, France.

Conrad, V., and Pollak, L. D. 1962. *Methods in Climatology.* Harvard University Press, Cambridge, Massachusetts.

Craddock, J. M. 1977. "A Homogeneous Record of Monthly Rainfall Totals for Norwich for the Years 1836–1976." *Meteorological Magazine 106:*267–278.

Dettwiller, J. 1970. "Evolution Seculaire Du Climat De Paris. Influence Del'Urbanisatin." *Memoire de la Meteorologie 82.*

Dettwiller, J. 1981. "Les Temperatures Annuelles A Paris." *Bulletin d'Information 83.* Direction de Meteorologie, Boulogne, Billencourt.

Devine, J. D., Sigurdsson, H., Davis, A.N., and Self, S. 1984. "Estimates of Sulfur and Chlorine Yield to the Atmosphere from Volcanic Eruptions and Potential Climatic Effects." *Journal of Geophysical Research 89:*6309–6325.

Donnell, C. A. 1912. "The Effect of the Time of Observation on Mean Temperatures." *Monthly Weather Review 40:*708.

Döve, H. W. 1838 and later. "Über Die Geographische Vebreitung Gleichartiger Witterungerserscheinungen (Uber Die Nichperiodischen Anderungen Der Temperaturverteilung Auf Der Oberflache Der Erde)." *Abh. Akad. Wiss. Berlin.* I. Teil (1838) 37, 285; 38, 286; 39, 245. II Teil (1839) 40, 306–307. III Teil (1844) 41, 127. V Teil (1852) 42, 3–4.

Dronia, H. 1967. "Urban Influence on Worldwide Temperature Trends." *Meteorological Treatises 7*(4) [Institute for Meteorology and Geophysics of the Free University of Berlin, Berlin, Federal Republic of Germany].

Dunwiddie, P. W., and LaMarche, V. C. 1980. "A Climatically Responsive Tree-Ring Record for *Widdringtonia cedarbergensis,* Cape Province, South Africa." *Nature 286:*796–797.

Eddy, J. A. 1976. "The Maunder Minimum." *Science 192:*1189–1202.

Eddy, J. A., Hoyt, D. B., and White, O. R. 1982. "Reconstructed Values of The Solar Constant from 1874 to the Present." 29–34. In J. London and C. Frohlich (eds.) *Extended Abstract Volume of the Symposium on the Solar Constant and the Spectral Distribution of Solar Irradiance.* IAMAP Third Scientific Assembly. National Center for Atmospheric Research, Boulder, Colorado.

Ellis, W. 1890. "On the Difference Produced in the Mean Temperature Derived From Daily Maxima and Minima as Dependent on the Time at which the Thermometers are Read." *Quarterly Journal of the Royal Meteorological Society 16:*213–218.

Fletcher, J. O. 1984. "Clues from Sea-Surface Records." *Nature 310:*630.

Fletcher, J. O., Slutz, R. J., and Woodruff, S. D. 1984. "Towards a Comprehensive Ocean-Atmosphere Data Set." *Tropical Ocean-Atmosphere Newsletter 20:*13–14.

Folland, C. K., and Kates, F. E. 1984. "Changes in Decadally Averaged Sea Surface Temperature Over the World 1861–1980." 721–727. *Proceedings of the Symposium on*

Milankovitch and Climate. Lamont-Doherty Observatory, New York, New York.

Folland, C. K., Parker, D. E., and Kates, F. E. 1984. "Worldwide Marine Temperature Fluctuations 1856–1981." *Nature 310:*670–673.

Franklin, B. 1789. "Meteorological Imaginations and Conjectures." *Memoirs of the Literary and Philosophical Society, Manchester 2:*373–377.

Gandin, L. S., 1963. "The Objective Analysis of Meteorological Fields." *Gidrometoizdat, Leningrad Israel Program of Scientific Translations, 1965.*

Gerland, E. 1896. "Historical Sketch of Instrumental Meteorology." 687–698. *Report of the International Meteorology Congress, Weather Bureau Bulletin II, Part III.* Department of Agriculture, Washington D.C.

Gilliland, R. L. 1981. "Solar Radius Variations Over the Past 265 Years." *Astrophysics Journal 248:*1144–1155.

Gilliland, R. L. 1982. "Solar, Volcanic and CO_2 Forcing of Recent Climatic Change." *Climatic Change 4:*111–131.

Gilliland, R. L., and Schneider, S. H. 1984. "Volcanic, CO_2 and Solar Forcing of the Northern and Southern Hemisphere Surface Air Temperature." *Nature 310:*38–41.

Gray, B. M. 1981. "On the Stability of Temperature Eigenvector Patterns." *Journal of Climatology 1:*273–281.

Gruza, G. C., and Ran'kova, E. Ya. 1979. *Data on the Structure and Variability of Climate. Air Temperature at Sea Level, Northern Hemisphere.* Central Institute for the Collection of Hydrometeorological Information-World Data Centre, Obninsk, U.S.S.R. (in Russian).

Hammer, C. U. 1977. "Past Volcanism Revealed by Greenland Ice Sheet Impurities." *Nature 270:*482–486.

Hammer, C. U., Clausen, H. B., Dansgaard, W., Gundestrup, N., Johnsen, S.J., and Reeh, N. 1978. "Dating of Greenland Ice-Cores by Flow Models, Isotopes, Volcanic Debris and Continental Dust." *Journal of Glaciology 20:*3–26.

Hammer, C. U., Clausen, H. B., and Dansgaard, W. 1980. "Greenland Ice Sheet Evidence of Post-Glacial Volcanism and its Climatic Impact." *Nature 288:*230–235.

Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D., and Russell, G. 1981. Climate Impact of Increasing Atmospheric Carbon Dioxide." *Science 218:*957–966.

Hartzell, F. Z. 1919. "Comparison of Methods for Computing Daily Mean Temperatures." *Monthly Weather Review 47:*799–801.

Hirschboeck, K. K. 1980. "A New Worldwide Chronology of Volcanic Eruptions." *Palaeogeography, Palaeoclimatology, Palaeoecology 29:*223–241.

Hoffert, M., and Flannery, B. 1985. "Model Projections of Time-Dependent Response to Increasing CO_2 Concentrations." Chapter 4 in M.C. MacCracken and F. Luther (eds.) *Projecting the Climatic Effects of Increasing Carbon Dioxide,* (DOE/ER-0237). U.S. Department of Energy, Washington, D.C. Available from NTIS, Springfield, Virginia.

Hoyt, D. V. 1979. "Variations in Sunspot Structure and Climate." *Climatic Change 2:*79–92.

Humphreys, W. J. 1913. "Volcanic Dust and Other Factors in the Production of Climatic Changes and Their Possible Relations to Ice-Ages." *Journal of the Franklin Institute 176:*131.

Jäger, J., and Kellogg, W. W. 1984. "Anomalies in Temperature and Rainfall During Warm Arctic Seasons." *Climatic Change 5:*39–60.

James, R. W., and Fox, P. T. 1972. "Comparative Sea-Surface Temperature Measurements." Report No. 5, *Marine Science Affairs No. 366.* World Meteorological Organization, Geneva, Switzerland.

Jenne, R. 1975. "Data Sets for Meteorological Research" (NCAR Technical Report 1A-111) National Center for Atmospheric Research, Boulder, Colorado.

Jones, P. D. 1983. "Further Composite Rainfall Records for the United Kingdom." *Meteorological Magazine 112:*19–27.

Jones, P. D., and Kelly, P. M. 1983. "The Spatial and Temporal Characteristics of Northern Hemisphere Surface Air Temperature Variations." *Journal of Climatology 3:*243–252.

Jones, P. D., Wigley, T. M. L., and Kelly, P.M. 1982. "Variations in Surface Air Temperatures: Pt. 1 Northern Hemisphere 1881–1980." *Monthly Weather Review 110:*59–71.

Jones, P. D., Wigley, T. M. L., and Briffa, K. R. 1983. "Reconstructing Surface Pressure Patterns Using Principal Components Regression on Temperature and Precipitation Data." 4.2.1–4.2.8. *Proceedings of the International Meeting on Statistical Climatology.* Instituto Nacional de Meteorologia e Geofisica, Lisbon, Portugal.

Jones, P. D., Kelly, P. M., Bradley, R. S., Diaz, H. F., and Goodess, C. M. 1985. "Effects of Urbanization and other Sources of Inhomogeneity on the Northern Hemisphere Surface Air Temperature Average." 19–20. *Preprints of the Third Conference on Climate Variations and Symposium on Contemporary Climate, 1850–2100.* American Meteorological Society, Boston, Massachusetts.

Jones, P. D., Raper, S. C. B., Bradley, R. S., Diaz, H. F., Kelly, P. M., and Wigley, T. M. L. 1986a. "Northern Hemisphere Surface Air Temperature Variations, 1851–1984." *Journal of Climate and Applied Meteorology.* In press.

Jones, P. D., Wigley, T. M. L., and Briffa, K. R. 1986b. "Reconstructions Using Objective Techniques of Grid Point Pressure Data over Europe (Back to 1780) and North America (1858)." University of East Anglia, Norwich, United Kingdom.

Kelly, P. M., and Sear, C. B. 1982. "The Formulation of Lamb's Dust Veil." In A. Deepak (ed.), *Atmospheric Effects and Potential Climatic Impact of the 1980 Eruptions of Mount St. Helens.* Conference Publication 2240, Scientific and Technical Information Branch, National Aeronautical and Space Administration, Washington D.C.

Kelly, P. M., and Sear, C. B. 1984. "Climatic Impact of Explosive Volcanic Eruptions." *Nature 311:*740–743.

Kington J. A. 1970. "A Late Eighteenth Century Source of Meteorological Data." *Weather 25:*169–175.

Kington, J. A. 1974. "The Societas Meteorological Palatina: An Eighteenth Century Meteorological Society." *Weather 29:*416–426.

Kohler, M. A. 1949. "On the Use of Double Mass Analysis for Testing the Consistency of Meteorological Records and for Making Required Adjustments." *Bulletin of the American Meteorological Society 30:*188-189.

Köppen, W. 1873. "Über Mehrjahrige Perioden der Witterung, Insbesondere Über die 11 Jahrige Periode der Temperature." *Zeitschrift der Österreichischen Gesellschaft für Meteorologie:*241-256, 257-267.

Kukla, G., Gavin, J., and Karl, T. R. 1985. "Impact of Urban Heating on Recent Temperature Trends in Eastern and Central North America." 23-24. *Preprints of the Third Conference on Climate Variations and Symposium on Contemporary Climate 1850-2100.* American Meteorological Society, Boston, Massachusetts.

LaMarche, V. C., and Hirschboeck, K. K. 1984. "Frost Rings in Trees as Records of Major Volcanic Eruptions." *Nature 307:*131-126.

Lamb, H. H. 1970. "Volcanic Dust in the Atmosphere." *The Philosophical Transactions of the Royal Society of London A266:*426-533.

Lamb, H. H., and Johnson, A. I. 1966. "Secular Variations of the Atmospheric Circulation Since 1750." *Geophysical Memoirs 110:*London (HMSO for Met. Office).

Landsberg, H. E., Yu, C. S., and Huang, L. 1968. "Preliminary Reconstruction of a Long Time Series of Climatic Data for the Eastern U.S." (Technical Note BN-571). Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park, Maryland.

Lough, J. M., Wigley, T. M. L., and Palutikov, J. P. 1983. "Climate and Climate Impact Scenarios for Europe in a Warmer World." *Journal of Climate and Applied Meteorology 22:*1673-1684.

MacCracken, M. C. 1983. "Have We Detected CO_2-Induced Climate Change? Problems and Prospects." V3-V45. *Proceedings of Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus.* Berkeley Springs, West Virginia. September 19-23, 1982. (CONF-820970) U.S. Department of Energy, Washington D.C. Available from NTIS, Springfield, Virginia.

Manley, G. 1974. "Central England Temperatures, Monthly Means, 1659-1972." *Quarterly Journal of the Royal Meteorological Society 100:*389-405.

Middleton, W. E. K. 1966. *Invention of the Meteorological Instruments.* Johns Hopkins Press, Baltimore, Maryland.

Middleton, W. E. K. 1969. *A History of the Thermometer and Its Use in Meteorology.* Johns Hopkins Press, Baltimore, Maryland.

Miles, M. K., and Gildersleeves, P. D. 1978. "Volcanic Dust and Changes in Northern Hemisphere Temperature." *Nature 271:*735-736.

Mitchell, J. M., Jr. 1953. "On the Causes of Instrumentally Observed Secular Temperature Trends." *Journal of Meteorology 10:*244-261.

Mitchell, J. M., Jr. 1961. "The Measurement of Secular Temperature Changes in the Eastern United States" (Research Paper No. 43). U.S. Department of Commerce, Weather Bureau, Washington, D.C.

Mitchell, J. M., Jr. 1963. "On the World-Wide Pattern of Secular Temperature Change." 161-181. *Proceedings of the UNESCO/WMO Symposium on Changes of Climate.* UNESCO Arid Zone Research Series 20, UNESCO, Paris, France.

Mitchell, J. M., Jr. 1970. "A Preliminary Evaluation of Atmospheric Pollution as a Cause of the Global Temperature Fluctuation of the Past Century." 139-155. In S.F.Singer (ed.), *Global Effects of Environmental Pollution.* Springer Verlag, New York. D. Reidel, Dordrecht, The Netherlands.

Mitchell, J. M., Jr. 1972. "The Natural Breakdown of the Present Interglacial and Its Possible Intervention by Human Activities." *Quaternary Research 2:*436-445.

Namias, J. 1958. "The General Circulation of the Lower Troposphere Over Arctic Regions and Its Relation to the Circulation Elsewhere." Polar Atmosphere Symposium, Pt. 1, Meteorology. Pergamon Press, New York, New York.

National Research Council 1983. *Changing Climate.* National Academy Press, Washington, D.C.

Newhall, C. G., and Self, S. 1982. "The Volcanic Explosivity Index (VEI): An Estimate of Explosive Magnitude of Volcanic Eruptions." *Journal of Geophysical Research 87:*1231-1238.

Newkirk, G. Jr., 1983. "Variations in Solar Luminosity." *Annual Reviews of Astronomy and Astrophysics 21:*429-467.

Nicholson, S. E. 1976. "A Climatic Chronology for Africa: Synthesis of Geological, Historical, and Meteorological Information and Data." Ph.D. Thesis, Dept. of Meteorology, University of Wisconsin, Madison, Wisconsin.

Oliver, R. C. 1976. "On the Response of Hemispheric Mean Temperature to Stratospheric Dust: An Empirical Approach." *Journal of Applied Meteorology 15:*933-950.

Paltridge, G., and Woodruff, S. 1981. "Changes in Global Surface Temperature From 1880 to 1977 Derived from Historical Records of Sea Surface Temperature." *Monthly Weather Review 109:*2427-2434.

Parker, D. E. 1980. "Climatic Change or Analyst's Artifact?- A Study of Gridpoint Upper Air Data." *Meteorological Magazine 109:*129-152.

Parker, D. E. 1981. "Early Meteorological Observations at Sitka, Alaska." *Meteorological Magazine 110:*161-162.

Parker, D. E. 1984. "Collation and Improvement of Early Meteorological Data for Sitka, Alaska." Met. 013, *Branch Memorandum No. 139,* Meteorolgical Office, Bracknell, United Kingdom.

Parkinson, J. H., Morrison, L. V., and Stephenson, F. R. 1980. "The Constancy of the Solar Diameter Over the Past 250 Years." *Nature 288:*548-551.

Pittock, A. B. 1978. "A Critical Look at Long-Term Sun Weather Relationships." *Reviews of Geophysics and Space Physics 16:*400-420.

Pittock, A. B. 1983. "Solar Variability, Weather and Climate: An Update." *Quarterly Journal of the Royal Meteorological Society 109:*23-57.

Pittock, A. B., and Salinger, J. 1982. "Towards Regional Scenarios for a CO_2-Warmed Earth." *Climatic Change 4*:23–40.

Pivovarova, Z. I. 1977. *Radiation Characteristics of Climate of the USSR*. Gidrometeoizat, Leningrad (in Russian).

Ramage, C. S. 1984. "Can Shipboard Measurements Reveal Secular Changes in Tropical Air-Sea Heat Flux." *Journal of Climate and Applied Meteorology 22*:187–193.

Rampino, M. R., and Self, S. 1984. "Sulphur-Rich Volcanic Eruptions and Stratospheric Aerosols." *Nature 310*:677-679.

Reitan, C. H. 1974. "A Climate Model of Solar Radiation and Temperature Change." *Quaternary Research 4*:25–38.

Repin, R. O., Eddy, J. A., and Merrill, R. B. 1980. "The Ancient Sun Fossil Record in the Earth, Moon and Meteorites." *Proceedings of the Conference on the Ancient Sun: Fossil Record in the Earth, Moon and Meteorites.* Boulder, Colorado, October 1979. Pergamon Press, Oxford, England.

Revelle, R., and Waggoner, P. 1983. "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies." 419–432. In *Changing Climate*. Board of Atmospheric Sciences and Climate, National Research Council, National Academy Press, Washington, D.C.

Robock, A. 1979. "The Little Ice Age: Northern Hemisphere Average Observations and Model Calculations." *Science 206*:1402–1404.

Robock, A., 1981. "A Latitudinally Dependent Volcanic Dust Veil Index, and Its Effect on Climate Simulation." *Journal of Volcanology and Geothermal Research 11*:67–80.

Robock, A. 1982. "The Russian Surface Temperature Data Set." *Journal of Applied Meteorology 21*:1781–1785.

Rodda, J. C. 1969, "The Rainfall Measurement Problem." 215–231. (Publication No. 78) International Association of Scientific Hydrology, IAHS, Wallingford, Oxfordshire, United Kingdom.

Rumbaugh, W. F. 1934. "The Effect of Time of Observations on Mean Temperature." *Monthly Weather Review 62*:375–376.

Sapper, K. 1927. *Katalog der Geschichtlichen Vulkanausbruche*. K.J. Trubner, Strasbourg, France.

Saur, J. F. T. 1963. "A Study of the Quality of Sea Water Temperatures Reported in Logs of Ships Weather Observations." *Journal of Applied Meteorology 2*:417–425.

Schaake, P. 1982. "Ein Beitrag zum Preussenjahr 1981 in Berline." *Beilage zur Berliner Wetterkarte*. Institut für Meteorologie der Freien Universitat Berlin, Berlin, Federal Republic of Germany.

Schaal, L. A., and Dale, R. F. 1977. "Time of Observation Bias and 'Climatic Change'." *Journal of Applied Meteorology 16*:215–222.

Schneider, S. H., and Mass, C. 1975. "Volcanic Dust, Sunspots and Temperature Trends." *Science 190*:741–746.

Shearman, R. J. 1983. "The Meteorological Office Main Marine Data Bank." *Meteorological Magazine 112*:1–10.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J.H. 1981. *Volcanoes of the World.* Hutchinson Ross, Stroudsbourg, Pennsylvania.

Slutz, R. J., Lubker, S. J., Hiscox, J. D., Woodruff, S. D., Jenne, R. L., Joseph, D. H.. Steurer, P. M., and Elms, J. D., 1985. "Comprehensive Ocean-Atmosphere Data Set (COADS)." Release 1, NOAA/ERL Special Report, Boulder, Colorado.

Smith, E. A., Vonder Haar, T. H., Hickey, J. R., and Maschheff, R. 1983. "The Nature of Short Period Fluctuations in Solar Irradiance Received by the Earth." *Climatic Change 5*:211–235.

Sonett, C. P. 1983. "Is the Sunspot Spectrum Really so Complicated?" 607–613. In B.M. McCormac (ed.), *Weather and Climate Responses to Solar Variations*. Colorado Associated University Press, Boulder, Colorado.

Stothers, R. B. 1984. "The Great Tambora Eruption 1815 and Its Aftermath." *Science 224*:1191–1198.

Stothers, R. B., and Rampino, M. R. 1983. "Volcanic Eruptions in the Mediterranean Before A.D. 630 From Written and Archaeological Sources." *Journal of Geophysical Research 88*:6357–6371.

Stuiver, M., and Quay, P. D. 1980. "Changes in Atmospheric Carbon-14 Attributed to a Variable Sun." *Science 207*:11–19.

Symons, G. J. (ed.). 1888. *The Eruption of Krakatoa and Subsequent Phenomena*. Harrison and Tribner, London, United Kingdom.

Tabata, S. 1978. "On the Accuracy of Sea Surface Temperatures and Salinities Observed in the Northeast Pacific Ocean." *Atmospheric Oceanography 16*:237–247.

Tabony, R. 1980. "A Set of Homogeneous European Rainfall Series." U.K. Meteorological Office Mo. 13 Branch Memo. 104, Bracknell, United Kingdom.

Tabony, R. C. 1981. "A Principal Component and Spectral Analysis of European Rainfall." *Journal of Climatology 1*:283–291.

Trenberth, K. A., and Paolino, D. A. 1980. "The Northern Hemisphere Sea Level Presure Data Set; Trends, Errors and Discontinuities." *Monthly Weather Review 108*:855–872.

van Loon, H., and Williams, J. 1976. "The Connection Between Trends of Mean Temperature and Circulation at the Surface. Part 1. Winter." *Monthly Weather Review 104*:365–380.

Vinnikov, K. Ya., and Groisman, P. Ya. 1981. "The Empirical Analysis of CO_2 Influence on the Modern Changes of the Mean Annual Northern Hemisphere Surface Air Temperature." *Meteorologiya i Gidrologiya 11*:30–43.

Vinnikov, K. Ya., Gruza, G. V., Zakharov, V. G., Kirillov, A. A., Kovyneva, N. P., and Ran'kova, E. Ya. 1980. "Contemporary Variations of the Northern Hemisphere Climate." *Meteorologiya i Gidrologiya 6*:5–17.

von Rudloff, H. 1967. *Die Schwankungen und Pendelungen des Klimas in Europe seit dem Beginn der Regelmassigen Instrumenten Beobachtungen (1670)*. F. Vieweg and Sohn, Braunschweig, Federal Republic of Germany.

Webb, T., and Wigley, T. M. L. 1985. "What Past Climates Can Tell Us About a Warmer World." In M. C. MacCracken, and F. M. Luther (eds.), *Projecting the Climatic Effects of Increasing Carbon Dioxide* (DOE/ER-0237). U.S. Department of Energy, Washington, D.C. Available from NTIS, Springfield, Virginia.

Wigley, T. M. L. 1981. "Climate and Paleoclimate: What We Can Learn about Solar Luminosity Variations." *Solar Physics 74*:435–471.

Wigley, T. M. L., Jones, P. D., and Kelly, P. M. 1980. "Scenarios for a Warm High-CO_2 World." *Nature 283*:17–21.

Wild, H. 1887. *Repertorium für Meteorologie.* Supplement bands, St. Petersburg, Russia.

Williams, J. 1980. "Anomalies in Temperature and Rainfall During Warm Arctic Seasons as a Guide to the Formulation of Climate Scenarios." *Climatic Change 2*:249–266.

Williams, J., and van Loon, H. 1976. "An Examination of the Northern Hemisphere Sea Level Pressure Data Set." *Monthly Weather Review 104*:1354–1361.

Willson, R. C. 1984. "Measurements of Solar Total Irradiance and Its Variability." *Space Science Reviews 38*:203–242.

Willson, R. C., Gulkis, S., Janssen, M., Hudson, H. S., and Chapman, G. A. 1981. "Observations of Solar Irradiance Variability." *Science 211*:700–702.

Woodruff, S. D. 1985. "The Comprehensive Ocean-Atmosphere Data Set." 14–15. *Preprints of the Third Conference on Climate Variations and Symposium on Contemporary Climate: 1850–2100.* American Meteorological Society, Boston, Massachusetts.

World Meteorological Organization (WMO). 1966. *Climatic Change.* (Technical Note No. 79). Geneva, Switzerland.

World Meteorological Organization (WMO). 1984a. *Scientific Plan for the World Climate Research Programme* (WMO/TD-No. 6. WCRP Publication Series No. 2). World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization (WMO). 1984b. *Satellite Systems to Measure the Earth's Radiation Budget, Parameters and Climate Change Signals* (WCP-70). World Meteorological Organization, Geneva, Switzerland.

Yamamoto, R. 1980. "Change of Global Climate During Recent 100 Years." *Proceedings of the Technical Conference on Climate—Asia and Western Pacific Report No. 578.* World Meteorological Organization, Geneva, Switzerland.

Yamamoto, R., and Hoshiai, M. 1979. "Recent Changes of the Northern Hemisphere Mean Surface Air Temeprature Estimated by Optimum Interpolation." *Monthly Weather Review 107*:1239–1244.

Yamamoto, R., and Hoshiai, M. 1980. "Fluctuations of the Northern Hemisphere Mean Surface Air Temperature During Recent 100 Years." *Journal of the Meteorological Society, Japan 58*:187–193.

Youji, D., Barorong, L., and Youngming, F. 1983. "Periodic Peaks of Ancient Solar Activities." 545–557. In B. M. McCormac, (ed.), *Weather and Climate Responses to Solar Variations.* Colorado Associated Unversity Press. Boulder, Colorado.