The Global Distribution of the Annual and Semiannual Cycles in Precipitation

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ABSTRACT

The annual march of precipitation is documented on a global basis by mapping the amplitudes and phases of the annual and semiannual cycles in a vectorial format. The various climatic regimes proposed by Kendrew (1922) show up quite clearly in the results. In addition, the results give some indication of the seasonal variation of precipitation over the oceanic regions.

1. Introduction

The most important characteristics of the annual march of precipitation over the continents were documented more than 50 years ago. The main precipitation regimes, as proposed by Kendrew (1922), are summarized in Kendrew (1961) as follows:

1. Equatorial: Abundant rainfall throughout the year with two distinct rainfall maxima which correspond roughly to the times when the sun is overhead. This regime is prevalent only within a few degrees of latitude of the equator, and even within this narrow belt there are some stations which do not exhibit a pronounced semiannual cycle.

2. Tropical: Most rain in the hottest months when the sun is highest; winter is a pronounced dry season. Can be subdivided into:

(a) Inner Tropical: The two rainfall maxima following the overhead sun are closer in time than those of the equatorial regime, and the cool season is dry. This regime can be found in some regions between the equatorial zone and the neighborhood of 10°N and 10°S.

(b) Outer Tropical: A single maximum, similar to 2(a) except that the two maxima coalesce into a single maximum. The dry season is longer. Tends to occur poleward of the regions of inner tropical regime.

3. Monsoonal: Heavy summer rainfall and a long dry season centered on winter, much like 2(b). Prevalent in the following regions:

India except for southeast coast, southern and eastern China, western portions of Indochina, western portions of the Philippines.

Northern Australia.

Northern Africa throughout much of the latitude belt between 10° and 20°N.

Southern Africa throughout much of the latitude belt between 10° and 15°S.

Eastern Mexico and much of Central America.

4. Mediterranean: Dry summer season; a single winter rainfall maximum, or two maxima during spring and fall. This regime derives its name from the climate around the Mediterranean Sea, but it can also be found in more or less exaggerated form along the California coast, in central Chile between 30° and 37°S, along the southwest coasts of Africa and Australia and in the Spencer Gulf region of Australia.

5. Continental Interior (middle and high latitudes): Tendency for maximum rainfall during summer. The annual cycle is not so dominant as in (3) and (4).

6. West Coasts of Continents (middle and high latitudes): Abundant rainfall with autumn or winter maximum. This regime is closely associated with mountain ranges.

More precise specifications of the boundaries of these various regimes are given in Kendrew (1961).

In the earlier investigations the annual march of rainfall was usually represented in the form of tables or maps of mean monthly rainfall amounts. Horn and Bryson (1960) were the first to apply harmonic analysis in describing the climatic precipitation regimes in the United States. Their results were presented in the form of charts showing the distribution of amplitudes and phases of various harmonics of the annual cycle. These maps provided a more objective basis for delineating the boundaries of the various climatic regimes. In subsequent papers this method has been applied to other regions of the globe: many of these works are cited by Hastenrath (1968).
The observational studies cited above were largely regional in nature and limited to continental regions. Global analyses of the annual cycle in precipitation have not been undertaken because of the scarcity of quantitative precipitation data over the oceans. Thus it has not been possible to verify completely the results of recent simulations of the annual cycle with general circulation models [e.g., Manabe and Holloway (1975)] on the basis of observational data.

Although it is not possible to make a comprehensive and definitive global analysis of the annual march of precipitation on the basis of existing data, we believe that it may be useful, at this point in time, to present the existing data in a format which is completely objective and designed to convey as much information as possible concerning the global distribution of this phenomenon. For this purpose, we will display the amplitudes and phases of the annual and semiannual precipitation cycles in a vectorial format similar to the one used by Chapman (1932) in his analysis of the lunar tide in the atmosphere and Wallace (1975) in his analysis of the diurnal precipitation cycle. This vectorial display format has the virtue of being simple, objective and compact, and it conveys a substantial amount of information on the annual precipitation cycle in data sparse regions, without recourse to interpolation procedures.

2. Data

This study is based upon the following data sources:

(i) World Monthly Surface Climatological Data obtained, on tape, from the National Center for Atmospheric Research. Precipitation data are available for about 2000 stations distributed throughout the world. Most stations have records for the period 1951–70; many of the records extend much further back in time. About 700 of these stations were selected for our study.


(iii) A selection of publications, which are listed in the bibliography.

All the precipitation data derived from the above sources are for land or island stations, with the single exception of Weather Ship P (50°N, 145°W). The other weather ships do not routinely record precipitation amounts because of the technical difficulties associated with obtaining representative raingage measurements from a moving vessel. Several methods have been developed for making indirect estimates of precipitation amounts over the open oceans.

Extrapolation of data taken at coastal stations, with the amounts reduced by some constant factor. This method was used by Möller (1951) to prepare global analyses of precipitation.

Computation based on the assumption of a linear relationship between precipitation frequencies and amounts (Jacobs, 1951).

Estimation on the basis of coded surface weather reports. Tucker (1961) derived an empirical relationship between 3 h precipitation amounts and various types of surface weather (e.g., light continuous rain, rain showers, etc.) and applied it to data from weather ships in the North Atlantic. Reed and Elliott (1973) and Dorman et al. (1974) have subsequently applied the same method to weather ship data from the Pacific.

Estimation on the basis of satellite cloudiness data.

Of the first three methods listed above, the one developed by Tucker appears to be the most promising. We were able to compare the results obtained by applying this method to the surface reports for Ship P (Reed and Elliott, 1973) against the precipitation amounts derived directly from raingage data, which are contained on the NCAR tapes. The resulting amplitudes of the annual cycle differ by about a factor of 2 and the corresponding phases differ by about 2 months. In view of the size of these discrepancies we decided not to make use of rainfall estimates based on any of the indirect methods listed above. We are considering making a separate study of the annual cycle in cloudiness, as viewed by satellite, at some later date.

The period of record upon which our rainfall statistics are based varies from station to station. In processing the data on the NCAR tapes we made use of the period 1951–70 for all stations that have complete records during that interval. In areas of sparse data we included stations with records as short as 5 years. In some preliminary experiments, we found that a 5-year averaging period is usually sufficient to obtain representative estimates of the amplitudes and phases of the first two harmonics of the annual precipitation cycle. The one notable exception seems to be the stations in the equatorial Pacific which exhibit more interannual variability than seasonal variability. Further justification for the variable averaging period is the spatial consistency of the patterns that emerge when the results are mapped.

A listing of the stations used in this study, together with their respective data sources and periods of record are available, upon request, from the authors.

3. Analysis and display

Monthly precipitation data for individual years were averaged together to obtain monthly means for the 12 months of the year. These monthly means were then subjected to harmonic analysis, which yielded the
amplitudes and phases of the first and second harmonics of the annual cycle.

In studying the annual march of precipitation we are primarily interested in the degree to which the annual and semiannual cycles modulate the monthly mean precipitation in various regions, irrespective of the annual mean precipitation. Thus, it is appropriate to consider the normalized amplitudes of the annual and semiannual cycles rather than the raw amplitudes, which tend to be large at wet stations and small at arid stations. Normalized amplitudes are obtained by dividing the raw amplitudes obtained from harmonic analysis by the average monthly precipitation (i.e., one-twelfth of the average annual precipitation). Note that normalized amplitude defined in this manner can be greater than unity, as in the example shown in Fig. 1 which is for a station with a pronounced dry season. At such stations the annual and semiannual cycles tend to be "phase locked" such that the peaks of the two

Fig. 1. An example illustrating the interpretation of the semiannual cycle at a station with a pronounced dry season. See text for further details.

Fig. 2. Normalized amplitude and phase of the annual cycle in precipitation over the Northern Hemisphere. Normalized amplitude is indicated by the length of the arrows according to the scale in the figure. Phase is indicated by the orientation of the arrows. An arrow pointing from north to south indicates a maximum on 1 January, one pointing from the east indicates a maximum on 1 April, etc. Normalized amplitudes smaller than 0.075 are plotted as open circles.
Fig. 3. As in Fig. 2 except for the tropics.

cycles occur at practically the same time. In such situations the semiannual cycle is significant from a mathematical point of view, but it exists only because of the constraint that precipitation cannot be negative during the dry season. The presence of a semiannual cycle is indicative of two distinct wet seasons only at

Fig. 4. As in Fig. 2 except for the Southern Hemisphere.
Fig. 5. Normalized amplitude and phase of the semiannual cycle in precipitation over the Northern Hemisphere. Normalized amplitude is indicated by the length of the vectors (arrows without heads) according to the scale in the figure. Phase is indicated by the orientation of the vectors. A vector directed north-south indicates maxima on 1 January and 1 July; one directed east-west indicates maxima on 1 April and 1 October, etc. Normalized amplitudes smaller than 0.075 are plotted as open circles. Stations with a second harmonic of the annual cycle larger than the first harmonic are denoted by heavy dots.

stations where it is large in comparison to the annual cycle.

It should also be noted that harmonic analysis is not well suited for delineating regions characterized by two rainfall maxima separated by only a few months (e.g., Kendrew’s “inner tropical regime”). In such regions the annual cycle tends to be dominant, even though there may be a distinct break between the two wet seasons. In the following discussion we will tend to emphasize those regimes that show up clearly in the harmonically analyzed results.

Normalized amplitudes and phases of the annual cycle are displayed as arrows with midpoints coinciding with their respective stations on the map, lengths proportional to normalized amplitudes, and directions indicating the phases. The phase convention is as follows: an arrow pointing from north to south indicates a maximum in the annual precipitation cycle on 1 January, one pointing from the east indicates a maximum on 1 April, etc. Thus, the arrows rotate clockwise about 1° per calendar day. Note that with this phase convention, an arrow from the north is indicative of winter in the Northern Hemisphere and summer in the Southern Hemisphere, etc. Normalized amplitudes <0.075 are plotted as circles. The phase convention for the semiannual cycle is the same, except that the vectors are plotted without heads. Thus a vector directed north-south indicates a semiannual cycle with maxima on 1 January and 1 July, one directed east-west indicates 1 April and 1 October maxima, etc. With these plotting conventions, stations with a pronounced dry season and “phase locking” of the semiannual cycle are characterized by annual and semiannual vectors which are parallel to one another. In order to emphasize those stations with a dominant semiannual oscillation (that is, a second harmonic of the annual cycle larger than
the first harmonic) we have denoted them by heavy dots in the semiannual charts.

In order to simplify the plotting and reading of the phases, all results are plotted on conformal map projections.

4. Global results

Normalized amplitudes and phases of the annual cycle are displayed in Figs. 2–4 and those of the semiannual cycle are displayed in Figs. 5–7. From an inspection of these results the following conclusions appear to be warranted:

1) The “equatorial regime” described by Kendrew is observed only over east Africa and, to a lesser extent, over the southern part of Colombia. In these regions the maximum precipitation is observed about a month after the times when the sun is overhead.

2) Most of the equatorial belt does not exhibit a pronounced semiannual cycle in rainfall. For example, over much of the Amazon basin the annual cycle is dominant, while over Indonesia and much of the western Pacific rainfall exhibits very little seasonal variability.

3) The monsoon regime is clearly evident in all the regions mentioned by Kendrew. Not only does the annual cycle display a pronounced late summer maximum, but the semiannual cycle is “phase locked” with the annual, which is indicative of long dry seasons centered on late winter. In addition to the areas mentioned by Kendrew, Florida, Venezuela and southern Brazil also display monsoon-like characteristics, although not as pronounced as the regions mentioned above.

4) The so-called “Mediterranean regime” is evident in a broad belt extending from Spain and Morocco eastward to the border of India. Indeed, the Mediterranean region represents only a small fraction of the area within which this regime is observed. Analogous regimes are observed in all the other regions mentioned by Kendrew.

5) A tendency for wet summers is observed throughout most of the interiors of Europe, Asia and North America, as noted by Kendrew.

6) The west coasts of Europe and North and South America at temperate latitudes are characterized by maximum precipitation in late autumn or winter, as noted by Kendrew. In the Americas, mountain ranges divide this regime from the “continental interior” regime described above.

7) A pronounced semiannual modulation of precipitation is observed, not only within the equatorial belt but also in certain subtropical regions along the boundaries between the monsoon climates and Mediterranean climates (i.e., along the India-Pakistan border, over parts of southwestern United States, and in parts of Chile, Peru and Bolivia). Not only is the semiannual cycle large in comparison to the annual cycle in these regions, but it is also large in an absolute sense.

8) There is a pronounced late autumn precipitation maximum over the southeast coast of India and along the east coast of the Malay peninsula and Vietnam.

9) Many of the minor irregularities in the large-scale pattern of seasonal variability represent real climatic effects related to local topography. For example, Garcia (1975) has explained the winter maximum along the north coast of Hispaniola in the Caribbean (evident in Figs. 2 and 3) in terms of local climatic influences. A detailed documentation of these local influences is beyond the scope of this brief survey.

Precipitation data over the oceans are severely limited. Nevertheless, there appears to be sufficient consistency between the results for a large number of island stations to support the following conclusions.
concerning the annual march of precipitation:

10) In general there appears to be much less seasonal variation of precipitation over the oceans than over land.

11) There is usually no abrupt discontinuity between the annual march of precipitation at continental stations and that at adjacent island stations. Thus, for example, the “Mediterranean regime” (if it can still be called that) extends westward from Spain at least as far as the Azores, and westward from California to Hawaii [Dorman et al. (1974) have presented convincing evidence of a winter rainfall maximum at ship N (30°N, 140°W)]. Likewise the Australian “monsoon regime” extends across much of the subtropical southwest Pacific.

12) There appears to be a general tendency for late summer precipitation maxima over the western oceans and winter maxima over the eastern oceans.

13) The equatorial and high-latitude oceans display little seasonal variability. There is some tendency for very weak autumn maxima over high latitudes.

5. Discussion

There now exist sufficient data to allow us to begin to view the annual march of precipitation from a global perspective. The geographical scale of the various regimes of seasonal variability is large; much larger, in fact, than the scale of variability of mean annual precipitation. Although land-sea differences undoubtedly play a role in determining the geographical distribution of seasonal variability, there is no clear distinction between the precipitation regimes over land and sea other than the fact that land areas generally tend to exhibit more pronounced seasonal variability.

With the minor exceptions noted above, the classification scheme devised by Kendrew for describing the precipitation regimes over the continents appears to be valid and useful as a device for pointing out certain physically significant similarities between the precipitation regimes over widely scattered parts of the globe. For example, the widespread occurrence of the “monsoon” and “continental interior” regimes suggests that these climatic features should be explainable in terms
of rather simple models with highly idealized topography.

Some of Kendrew's classifications may tend to artificially group together geographical regions whose seasonal precipitation distribution is controlled by different physical mechanisms. The so-called "Mediterranean regime" is a case in point. It is not at all clear whether the same synoptic conditions that produce wintertime precipitation along the coasts of California and Chile are also prevalent along the south coasts of Africa and Australia. Nor is it certain that any of these regions are analogous to the Mediterranean area, in terms of the physical processes that govern climate. Another problem that arises in Kendrew's classification scheme is that the boundaries between adjacent regimes are sometimes somewhat artificial. For example, there is rarely any clear distinction between the "Mediterranean" and "west coast" regimes or between the "monsoon" and "continental interior" regimes. The problem is compounded when one attempts to extend the description to oceanic regions.

6. Seasonal variability over the United States

For the purpose of showing the seasonal variability of precipitation on a somewhat more localized scale we have displayed in Figs. 8 and 9 the normalized amplitudes and phases of the annual cycle in precipitation over the conterminous United States, based upon the 30-year data set described in Section 2. The geographical patterns of seasonal variability are rather smooth and can be divided into a number of well-defined regimes:

An area of pronounced winter maxima in the western states which can be identified with
Kendrew’s “Mediterranean regime” in the south and the “west coast” regime in the Pacific Northwest. A broad area of early summer maxima over the Great Plains and Great Lakes, presumably a reflection of Kendrew’s “continental interior” regime. Small areas of late summer maxima over Florida and west Texas which are probably monsoonal in character. A region of weak spring maxima over the interior of the southeastern states. A region of weak seasonal variability over the middle and north Atlantic states. A region of strong semiannual variability with February and August maxima, centered over Arizona.

These results are in close agreement with Kendrew’s (1922) detailed description of the rainfall regimes over North America.

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REFERENCES


