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Climate Variability and Ecosystem Response

Proceedings of a Long-Term Ecological Research Workshop

Boulder, Colorado August 21 - 23, 1988



Cover photo: Hurricane Hugo, which snapped trees and dumped salt water on South Carolina forests in September 1989, suddenly and dramatically altered a pime ecosystem. W.T. Swank photo was taken in the vicinity of the North Inlet LTER Site.

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Southeastern Forest Experiment Station P.O. Box 2680 Asheville, North Carolina 28802

CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE

Proceedings of a Long-Term Ecological Research Workshop

Niwot Ridge/Green Lakes Valley LTER Site

Mountain Research Station

University of Colorado

Boulder, Colorado

August 21-23, 1988

Edited by David Greenland and Lloyd W. Swift, Jr.

Department of Geography, University of Colorado, Boulder, CO and Coweeta Hydrologic Laboratory, Forest Service, Otto, NC

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INTRODUCTION TO LTER WORKSHOP

ON CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE

David Greenland and Lloyd W. Swift Jr. 1

The Intersite Climate Committee of the Long-Term Ecological Research (LTER) Program, which is sponsored by the National Science Foundation, has the mission of facilitating investigations of the atmospheric environment in LTER ecosystems. The Committee has developed standards for meteorological measurements at LTER sites (Greenland 1986; Swift and Ragsdale 1985) and has summarized the climates at the first 11 LTER sites (Greenland 1987). This climate summary demonstrated the obvious: very different ecosystems have very different climates. This report, and discussions at the LTER Data Processing Workshop at Las Cruces in January 1986. suggested that moisture (including soil moisture) and climate variability were distinctive forcing variables at each site. The Climate Committee decided to defer investigations of water budgets and to concentrate first on climate variability. This decision recognized the LTER network's potential importance to research on the global climate change question and the growing public interest in that question.

Eleven of the 15 sites then in the LTER network attended a workshop on Climate Variability and Ecosystem Response. Ten sites are represented by papers in this volume. Each site was invited to examine its longest time series of climatic data for temporal variability and to comment on the relation of that variability to ecosystem responses. The variability of many data sets was characterized by multiyear climatic periods punctuated by strong and dramatic responses to specific weather events. All sites found duration of record and spatial representativeness to be limiting factors in assessing variability.

The workshop was held in August 1988 at the Mountain Research Station of the University of Colorado, the field headquarters for the Niwot Ridge-Green Lakes Valley LTER site. The keynote address on Global Warming and Ecosytem Response was given by Dr. Stephen Schneider of the National Center for Atmospheric Research. Following this and formal presentations of papers, the authors and Dr. Gary Cunningham from the Jornada LTER site met as the LTER Climate Committee to review the

research and our understanding of climate variability and ecosystem responses of the LTER sites. The discussions reported in the overview chapter concluded that recognition and utilization of time and space scales are keys to understanding response phenomena.

The papers in this volume represent a variety of ecosystems, environments, and approaches to our topic. This variety represents one of the riches of the LTER program, although it makes standardization and generalization difficult. The volume starts with information from three forest sites. Federer examines the record at the Hubbard Brook Experimental Forest in New Hampshire in order to determine whether real variation in the climate can be deduced from existing records. A powerful statistical technique, the Z-T extreme event analysis, is employed by Swift and others to determine the uniqueness, or return period, of extreme events in streamflow and precipitation data from the Coweeta Hydrologic Laboratory in North Carolina. Viereck and Adams infer effects of climate warming on vegetation patterns from data on spatial variation in microclimate and related plant successional development at the Bonanza Creek Experimental Forest.

Aquatic ecosystems were represented by the North Inlet South Carolina and the Northern Lakes Wisconsin LTER sites. Michener and others show impacts of chronic and acute climate events upon the estuary ecosystem and how the scale of climatic variability affects productivity. paper was written before the North Inlet site was severely impacted by Hurricane Hugo in September 1989. At the Wisconsin site, Robertson demonstrates how historical data for fresh-water lakes can be used as a measure of longer term climatic change. Predominantly agricultural landscapes were addressed by Wendland and by Crum. Wendland summarizes the history and quality of Illinois weather observations that supported the former Illinois Rivers LTER site. Crum found little or no indication of climate change in 100year temperature and precipitation records and was able to relate corn yield to midsummer precipitation at the Kellogg Michigan LTER site.

Three sites represented landscapes where extreme climates limit vegetation cover. Greenland describes a marked variation in the temperature and precipitation record on the alpine tundra at the Niwot Ridge-Green Lakes Valley Colorado site, but this variation was not well correlated to obvious ecosystem responses. In contrast, Kittel reports that climate variability

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¹ Professor of Geography, University of Colorado, Boulder, CO; and Research Meteorologist, Coweeta Hydrologic Laboratory, Forest Service, U.S. Department of Agriculture, Otto, NC.

in the shortgrass steppe ecosystem at the Central Plains Experimental Range site in Colorado is well related to ecosystem function. The final site paper, by Hayden, describes how storm events at the Virginia Barrier Island site move and reform coastal terrain and influence vegetation distribution. The latter point was a good demonstration of the contrast between time and space scales, which must be recognized in any attempt to relate climate variability to ecosystem response.

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CHANGE, PERSISTENCE, AND ERROR

IN THIRTY YEARS

OF HYDROMETEOROLOGICAL DATA

AT HUBBARD BROOK 1/

C. Anthony Federer $\frac{2}{}$

Abstract.—Daily precipitation, air temperature, and solar radiation data have been collected on the Hubbard Brook Experimental Forest, New Hampshire, for over 30 years. A tradeoff occurs between cost and accuracy. Various instrument errors can make real climatic variation difficult to detect. Periods of above or below "normal" temperature or precipitation persist for up to several years, but their ecosystem effect is probably slight. Rare hurricanes cause the greatest ecological response to any weather events.

Keywords: Temperature, precipitation, solar radiation.

INTRODUCTION

The Hubbard Brook Experimental Forest (HBEF) in New Hampshire is a recent addition to the Long-term Ecosystem Research (LTER) network, but its weather records and its research history extend for more than 30 years. Only in the last couple of years has the Hubbard Brook weather record been organized on a computer in such a way that long-term analysis is relatively simple.

In this paper I will examine possible long-term change or variation in the Hubbard Brook record, to see whether real variation can be separated from errors. The possible effects of climatic variation on the ecosystem are briefly discussed.

The differences among weather, climatic variation, and climate change are differences of time scale. The climate of a place is usually defined in terms of means over a 30-year period. Climate change, therefore, takes place over decades; weather, on the other hand, over days to weeks. This leaves open the question of whether a drought or cold period of several to many months should be considered as weather or climate. Though I would prefer such phenomena

to be classed as weather variation, the term "climatic variation" is now commonly used for such phenomena that have time scales of months to several years.

Variation or Error?

Most of us know, when we read an instrument, that the reading may be slightly incorrect. With weather instruments and data analysis, there are several sources of error, some of which can be confused with climatic variation and even climate change.

Mistakes are human-induced by misreading or miscopying. If they are large enough, they may be caught by eye or by a computer program, but smaller ones will always exist and will be merged in with the randomness inherent in weather data. Modern electronic data collection systems may be able to eliminate mistakes. The effect of random mistakes on analysis of climatic variation and change is probably negligible. However, persistent mistakes that bias data could be interpreted as real variation.

Other sources of error are more important when evaluating climate variation. Sensor calibrations change, sensors are replaced, instrument exposure changes or instruments are moved, and processing procedures change. Each of these error sources causes apparent, but not real, long-term variation in the data. I will point out several possible instances in the Hubbard Brook data set.

There is little question about how to minimize such errors in weather data. With enough equipment and technicians (i.e.

 $[\]frac{1}{P}$ Presented at the LTER Climate Committee Workshop on Climate Variability and Ecosystem Response, Nederland, CO, August 22-23, 1988.

 $[\]frac{2}{\text{Principal Meteorologist, USDA Forest Service,}}$ Northeastern Forest Experiment Station, P.O. Box 640, Durham, NH 03824

money), highly accurate and complete data could be produced. But at ecological research sites, our main objective is not data collection but research. We must decide on the tradeoff between accuracy and cost. We must decide what sort of error rate or amount is tolerable. At Hubbard Brook over 30 years, the demand for or use of weather data, aside from watershed precipitation, has been minimal, though not quite non-existent. We have put a great deal of effort into collecting some data that have never been used. Concern for error reduction is wasted on data that will not be used.

HUBBARD BROOK HISTORY

The Hubbard Brook Experimental Forest was established by the USDA Forest Service (Northeastern Forest Experiment Station) in 1955. HBEF is a single, oval-shaped basin of 3,160 ha located in the White Mountain National Forest of central New Hampshire (Fig. 1). Basin elevation ranges from 222 to 1,015 m. HBEF is drained from west to east by Hubbard Brook, which has many similar-sized tributaries on opposing south-facing and north-facing slopes. The area was selected specifically for small watershed research; stream gages were built on eight of these tributaries between 1956 and 1967. The gaged watersheds range in area from 12 to 76 ha. Three of them have been treated by cutting the 70-year-old northern hardwood (beech-birch-maple) forest that covers virtually all of HBEF.

Instrumentation

Collection of precipitation and air temperature data began immediately after establishment of HBEF. Openings were cut in the forest to eliminate tree crowns above a 45° angle from the precipitation collectors. The network density of standard rain gages is about 1 per 20 ha; 11 are on adjacent south-facing watersheds 1-6, and 9 are on the adjacent north-facing watersheds 7 and 8. Weighing recording gages are located at five of these locations, and hygrothermographs in standard weather shelters are at three of them (plus one at Headquarters). All gages are mounted high enough to clear up to 2 m of snow, and are equipped with Alter-type windshields. Each weather shelter also includes maximum, minimum, and standard thermometers.

Electric line power and telephone communications have never been available anywhere at HBEF except at Headquarters. All precipitation, streamflow, and temperature recorders are spring-wound or battery operated. Spring-wound analog recorders have proven very reliable for year-round operation in the -30 to +40°C environment. Visitors to Hubbard Brook are usually surprised by our "primitive" approach to hydrometeorological data collection. The fundamental reasons for this are a philosophy that prefers to spend available money on research rather than on data collection, and a belief that inexpensive mechanical systems are more reliable than expensive electronic ones.

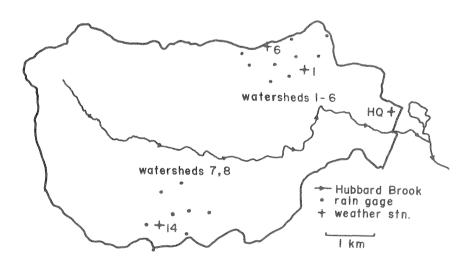


Figure 1.--Map of the Hubbard Brook Experimental Forest showing rain gage and weather station locations.

Data Processing

Data processing, on the other hand, has changed drastically over time. In the 50's and early 60's, all data were picked from charts by eye and tabulated manually using rotary calculators. In 1964, we began digitizing streamflow charts and processing data by computer. Over the years, we have used six different mainframe and mini computers (GE-265, IBM 1620, IBM 360, DEC-10, PRIME-750, and DG-MV4000). 3/Our Fortran programs migrated rather easily. Input and output data were stored for many years on punch cards. Now, most of our streamflow and meteorological data are stored on magnetic tapes in ASCII files; this method has been chosen because it moves easily to new machines.

Precipitation and temperature data continue to be read from charts by eye, but are processed by computer. Only daily total precipitation and daily maximum and minimum temperatures are obtained routinely.

In early years, when the amount of data was less and labor was cheap, every data point and every calculation was checked by a second person. Now computer programs catch only the grossest errors. There is certainly a possibility that our random error rate now is higher than it used to be.

Headquarters Weather Station

At Hubbard Brook, we emphasize what happens on the gaged watersheds. The foot of the lowest and closest of these is 3 km away and 200 m higher than our Headquarters (HQ) office. Though a weather station has been maintained at Headquarters, data from it have not always been processed. For instance, we have miles of unprocessed charts from a tipping bucket rain gage, and from an anemometer and wind vane. Headquarters data provide neither complete nor representative values for weather on the gaged watershed areas. This raises a question of which weather station or stations to use as a climatic standard for HBEF.

A weather station meeting LTER Level 2 standards was established at HQ (where power is available) in 1981. A variety of problems

have beset this system, and there are many gaps in the record. For example, a week was lost once when I forgot to push the ON button. Sensors, tape recorder, and data logger all fail occasionally. Lightning damage has been frequent, though we keep trying to improve protection. Repair and maintenance of this station has not had top priority. Although the daily data that it produces have sometimes been used, there have never been any requests for its hourly data.

Data Amount and Availability

Data piles up over the years. About one and a half million values are now contained in the routine hydrometeorological data set at Hubbard Brook (Table 1). And each of these has a time and location attached to it. Yet, we still get requests to "send us all your precipitation and streamflow data!"

Our philosophy has been to provide this data to anyone who requests it. We have recently established the Hubbard Brook Bulletin Board. Anyone with an MS-DOS microcomputer and a modem (300, 1200, or 2400 baud) can obtain many of the files containing this data by calling 603-868-1006 outside of normal working hours. Routine or long-term data from many cooperating scientists in the Hubbard Brook Ecosystem Study will gradually be added to the Bulletin Board. Data are provided to users in exactly the same ASCII files that are produced by the scientists.

SOLAR RADIATION

Daily total solar radiation has been measured at Headquarters since 1960. Sensors have included successively a Belfort— pyranograph, a Weather Measure pyranograph, and two LiCor pyranometers. The pyranographs were calibrated occasionally against a Kipp pyranometer. Averaging the pyranograph charts by eye over 2-hour intervals provides good daily totals. For the LiCor sensors, the manufacturer's calibration has been used and hourly integrals are obtained by the data logger. Comparisons among the various sensors generally have shown differences of less than 5%.

The scatter of data by day of the year shows two problems (Fig. 2). A few data points exceed the potential insolation but are not obvious errors and have not been eliminated. Second, the midsummer maximum daily values are only 80-85% of potential, though 90% would be expected for clear days. The site horizon is elevated up to 15° in the northeast and northwest by nearby trees. These trees have been growing gradually taller, and presumably reducing daily solar radiation gradually, especially in summer. Should we cut down the trees or move the sensor? Or would that destroy any usefulness the

^{3/}The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

Table 1.--Approximate amount of raw hydrometeorological data at HBEF

	Number of Years		Days per Year	Values per Day			Number of Stations		Number of Values
Precipitation	30	х	365	x	1	x	22	***	241,000
Temperature	30	X	365	X	2	x	5	=	110,000
Streamflow	30	x	365	x	8	x	8 ,	=	701,000
HQ Weather Station	7	Х	365	х	24	х	6 <u>a</u> /	=	$\frac{368,000}{1,420,000}$

 $\frac{a}{6}$ values per hour

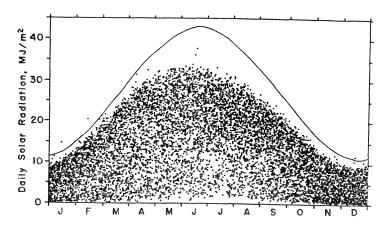


Figure 2.—Scatter plot of daily solar radiation. (MJ/m^2) at HBEF versus day of the year, for 1960-87. Curve is potential insolation for a flat horizon.

long-term record might have for detecting real change in radiation?

Missing values were estimated through the 1960's using National Weather Service data from several stations in New England. That network no longer exists. Since 1981, the pyranograph provides a backup instrument. To obtain annual totals, values for a few missing days in each year had to be guessed. How much effort should be put into estimating such missing values?

The annual radiation over 1960-87 has no long-term trend (Fig. 3), but several deviations may be instrument related. Are the 3 low years, 1967, 1968, 1969, real, or was the Belfort instrument calibration changing before its replacement? Are the low 1986, 1987 values due to the second LiCor sensor? Without considerably more effort in calibration and cross-checking of sensors, it is doubtful that such a record could detect long-term change, such as that caused by increasing haze or cloudiness.

AIR TEMPERATURE

Air temperature data begin in 1957 for HQ and Station 1, in 1961 for Station 6, and 1965

for Station 14. Which station or stations should be used to look at long-term trends? Averaging over several stations reduces the effect of any errors and the effect of geography in any one station but shortens the record. The number of stations included in an average cannot change over time or a bias will be introduced.

From an ecological viewpoint, daily maximum and minimum values contain more information than the daily mean. The average diurnal range and the normal extreme temperatures can be important to injury and survival of plants and animals. Similarly, seasonal differences are also important. The variation over years of average minimum and maximum temperatures for winter (December, January, February) and summer (June, July, August) provides a reasonably comprehensive picture in a small amount of space (Fig. 4). There is no evidence for gradual change and the year to year variations appear random. Only the sharp increase from winter 1981-82 to 1982-83, and from summer 1982 to summer 1983 suggests some abnormality such as an instrument problem. Because year-to-year variation is high, and errors are possible, evidence for climate change should not be looked for in records for a single location, even over a 30-year period.

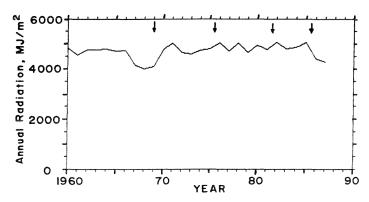


Figure 3.--Annual solar radiation (MJ/m^2) at HBEF for 1960-87. Arrows show times of sensor changes.

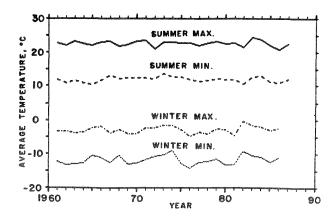


Figure 4.—Average summer (June, July, August) and winter (December, January, February) maximum and minimum daily temperatures for Stations 1, 6, and HQ at HBEF, 1961-87.

Individual Stations

The deviations of individual stations from the averages described above may be partly due to instrument calibration (Fig. 5). The hygrothermographs are currently readjusted and rotated annually in spring. In earlier times, an instrument stayed in the same location for several to many years. Standard and max-min thermometers are read weekly at each weather station, but the hygrothermograph data are not corrected to agree closely with the thermometers. In general, we have expected that errors of $\pm 1^{\circ}$ C were likely. The analysis for this paper of year-to-year variation within a station shows a range of about 2°C (Fig. 5). The sudden sharp drop in Station 1 summer maximum from 1970 to 1971 is suspicious, but is not evident in the summer minimum. The 1969 winter data for Station 1 are also suspect. For other years or

stations, abrupt changes do not occur, but gradual shifts of stations with respect to each other do occur. For instance, winter temperatures at Station 6 were about 1°C higher than Station 14 in the early record, but were about the same after the mid 1970's. Watershed 4, in which Station 6 is located, was strip clearcut in 1970-74. It is tempting to attribute some change to cutting, but such change is not obvious. We have strongly discouraged interstation comparison of temperatures, because of this lack of accuracy. Yet the general order of temperatures from highest to lowest--HQ, Station 1, Station 6. Station 14--is in the expected inverse relation to elevation. HQ and Station 14 differ by about 3°C in maximum temperature, and by 470 m in elevation, just what is expected from the lapse rate. The data may be better than we think.

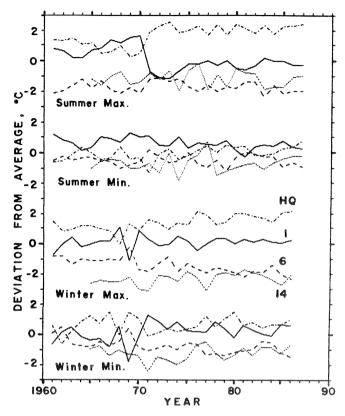


Figure 5.--Deviation by station of summer and winter maximum and minimum temperatures from the average values in Figure 4.

Persistence

Ecologists customarily use monthly or annual averages to evaluate abnormality in weather, but this ignores or discards the important information contained in the daily values. If July was 1°C above normal, does that mean that each day was 1°C above normal or that a few days were many degrees above normal? If a summer is characterized as "hot", what does that really mean in terms of distribution of temperature over time?

In work with tree rings in the Northeast, I first began looking at accumulated deviation of daily mean temperature from its normal. I was struck by the apparent persistence for months of below or above normal periods, and by the abrupt transitions from one "regime" to another. Station 1 at Hubbard Brook shows such behavior over its 31 years (Fig. 6). In such a plot, also used by Barry (1985), positive slope indicates above normal conditions and negative slope below normal.

On a year-to-year time scale, below normal temperature persisted from mid-1964 to early 1968, and from early 1980 to late 1982.

Conditions were generally above normal from early 1968 to early 1976, and from late 1982 to early 1985. A comparison with regional weather data used in our tree-ring studies shows that these persistence regimes are regional in scope.

On a month-to-month time scale, regimes occur with a persistence of several months (Fig. 7). November 1969 through April 1970 was almost uniformly below normal. The use of daily data shows that transition between these regimes can be very abrupt, and can often be pinpointed to a particular day. The intensity of the persistence regimes is not great. Regimes of about 1°C above or below normal are most common, with few extended periods reaching more than 2°C difference from normal.

Time series analysis of this data yields nothing more than a lag 1-day autocorrelation of about 0.5. The series is like taking two steps in one direction and sliding back one before deciding randomly on the next direction and step size. Persistence of the type shown here is characteristic of a random walk, or lag 1 autocorrelation. Nonetheless, it is tempting

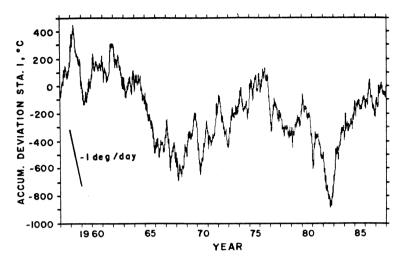


Figure 6.—Accumulated deviation of daily mean temperature for Station 1 from its normal for that day of the year, for 1957-87.

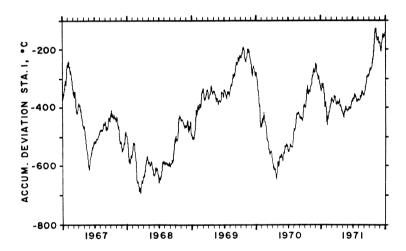


Figure 7.—Accumulated deviation of daily mean temperature for Station 1 from its normal for that day of the year, for 1967-71.

to believe that the transition from one regime to another is forced by regional or even global weather patterns, such as jet stream movement (Blackmon et al. 1977), that may be produced by El Nino Southern Oscillation episodes, or North Pacific sea surface temperature anomalies (Namias et al. 1988), which have similar persistence.

PRECIPITATION

Persistence

Persistence behavior occurs for precipitation as well as for temperature (Fig. 8).

The "normal" precipitation for a given day of the year needs to be smoothed because the actual values have large day-to-day variation. We used a cubic smoothing spline with a cutoff of 50 days. The accumulated deviation tends to go upward rapidly and in big jumps, due to individual large storms, and come downward more slowly. Because of the skewed distribution of daily precipitation, normal time series modeling cannot be done.

The 31-year record for Watershed 1 shows a single below-normal period from late 1960 through mid-1966 (the well-known northeastern drought), and above-normal conditions from early

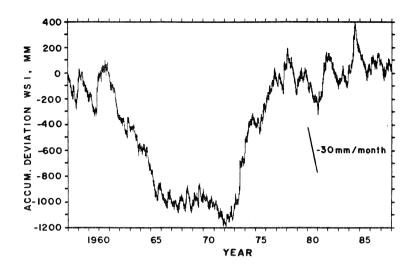


Figure 8.—Accumulated deviation of daily precipitation for Watershed 1 from its smoothed normal for that day of the year, for 1957-87.

1972 through mid-1978 (Fig. 8). The magnitude of deviation in the persistent regimes is on the order of 30 mm from normal per month, or about 30%.

Station Differences

Daily data from individual standard rain gages have not been entered onto the computer before 1965, so longer-term comparisons can only be made on a watershed basis. Both double mass comparison of one watershed with another and plotting of deviations from means show various, mostly unexplained, blips and kinks in the data. I have looked for one specific effect here. The cutting of Watershed 4 in 1970-74 altered the three rain gages in it so that they were in the open rather than in openings. Watershed 4 precipitation does seem slightly reduced in the period 1972-77, and then drifts upward (Fig. 9). The reduction is only about 2% and may be meaningless. There is a slight tendency for Watersheds 1 and 3 to drift downward while 6 and, recently, 4, drift upward. There is no obvious reason for such drift to exist. The data are dependent only on standard rain-gage catch, so no sensor or calibration error is involved. Exposure change by tree growth around the opening is possible; the openings are occasionally enlarged to compensate for ingrowth at the edges. Vegetation within the openings is cut only every several years. Should we put any more effort into examining these possible drifts and correcting for them?

ECOSYSTEM EFFECTS

Weather Variation

Weather variation has many effects on a forest ecosystem. These effects are often understood qualitatively, but are poorly quantified. We believe that drought reduces tree growth, but cannot specify how much. We know temperature affects photosynthesis and respiration, but cannot relate growing season temperature to net primary productivity. Recently I tried to relate ring widths of red spruce in New England to physiologically-based weather variables, with no success (Federer et al. 1988). Red spruce seems to be affected more by injurious winter conditions than by summer conditions (Johnson et al. 1986). But quantifying the weather conditions that cause winter conifer injury has proven elusive. Similarly, weather is known to affect outbreaks of pathogens, but quantification and modeling of the interactions are in their infancy. In general, we know that the variations in weather discussed in this paper affect the ecosystem, but we cannot say by how much.

Most effects of weather and climate variation on ecosystem processes are complex and non-linear. But many analyses of the relationships assume simple linear additive responses to monthly precipitation and mean temperature. The question of whether the available data is appropriate to the research problem is often avoided. For instance, precipitation data, or even Palmer drought

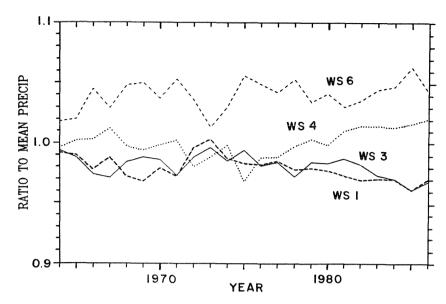


Figure 9.--Ratio of annual precipitation on each watershed to the mean of watersheds 1, 3, 4, and 6, for 1964-86.

index, are not good substitutes for soil-water deficits in terms of drought effects.

With respect to known Hubbard Brook history, the single weather event with the most impact on the ecosystem was probably the New England Hurricane of September 21, 1938. Enough trees were uprooted to induce the USDA Forest Service to carry out salvage logging in the Hubbard Brook basin. This was the only severe weather-related disturbance since the area was heavily cut prior to 1920. Hurricanes and local wind storms cause both regional and local disturbance at irregular intervals. However, treethrow mounds are common at Hubbard Brook; treethrow provides both soil mixing and seedbed for certain species.

Fire is another weather-related event with potentially severe ecosystem impact. Fires that burn surface litter are fairly common in northeastern forests in early spring. These have some effect on nutrient cycling. Only one such fire, of a few ha, has occurred in the last 30 years at Hubbard Brook. More severe crown fires are very rare, with prehistoric return periods of hundreds of years, but ecosystem impacts obviously would be severe.

Climatic Variation and Change

Climatic variation, as evidenced by persistence in the temperature and precipitation records, occurs essentially continuously at Hubbard Brook. Periods of months to years occur with temperature $1\,^{\circ}\text{C}$ above or below normal, or precipitation 30% above or below normal. Such persistence may

favor certain species of plants or animals over competing species, but demonstration and quantification of such cause and effect would be quite difficult.

The 30-year weather record at Hubbard Brook is too short to detect climatic change if climate is defined by a 30-year mean. Climatic change is very difficult to detect in any event; elaborate examination of many studies and data sets has not been able to prove the existence of a CO2-induced warming trend (Ellsaesser et al. 1986). Looking for climate change in data sets from LTER sites is futile. Nevertheless, climate change has and will affect Hubbard Brook. Hubbard Brook is at the temperate forest-boreal forest ecotone. Climatic temperature changes of a couple of degrees C may greatly change the ratio of spruce-fir to northern hardwoods and, thereby, the structure and function of the whole ecosystem. Changes in the ecosystem itself may become evident long before the weather data can prove that the climate has changed.

Chemical Climate

Although excluded from this paper, changes in the chemistry of the atmosphere may have greater effects on the ecosystem than changes in physical weather and climate. Acid precipitation, ozone and SO₂ levels, and heavy metal deposition can be considered part of weather and climate in their larger sense. Acid precipitation and related air pollution have certainly increased considerably in the northeastern United States over the past 100 years. More recently at Hubbard Brook, sulfate input in precipitation has decreased as regional sulfate emissions are reduced (Likens

et al. 1984). Lead deposition to the forest floor also has decreased recently. The ecosystem impacts of these pollutants therefore, have been partially reversed. The chemical climate at Hubbard Brook probably is changing. The impacts via acidification of soils and water and consequent ecosystem effects are receiving considerable attention at Hubbard Brook and elsewhere.

CONCLUSIONS

Climatic data collection and processing has changed almost incredibly over the past 30 years. We cannot predict what the next 30 years will bring, but need to expect more great changes.

In spite of the electronic age, mechanical weather sensors may still be more reliable than hi-tech equipment unless funds are made available for a full-time electronic technician and data analyst, backup equipment, and careful calibration.

For temperature and solar radiation, if not for precipitation, weather variation, persistence, and climatic change may be difficult to separate from error. Replication of sensors and systems can help.

Where long-term records already exist, it may be better to continue with existing instruments, methods, and exposure than to make changes that will alter long-term mean values.

There is a tradeoff between accuracy of weather data and costs. Where ecological research is the top priority, weather data should not be expected to detect climatic change.

Ecological systems may be affected more by occasional extreme events than by long-term changes in mean weather or climate.

Our knowledge of the quantitative relations between weather and ecosystem processes lags far behind our ability to collect reasonably good weather data. We should be spending much more money and time on research and maybe much less on instrumentation.

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APPLICATION OF THE Z-T EXTREME EVENT ANALYSIS

USING COWRETA STREAMFLOW AND PRECIPITATION DATA1

Lloyd W. Swift, Jr., Jack B. Waide, and David L. White2

Abstract.— A technique for drought or flood analysis, after Zelenhasič and Todorovič, promises to improve the definition of both duration and magnitude of extreme flow events for river-sized basins. The technique has been applied to a smaller basin at the Coweeta LTER Site using both streamflow data and a longer precipitation record. This report illustrates the technique and describes needed adjustments to apply the method to stream-sized basins.

Keywords: LTER, drought, duration, recurrence interval.

INTRODUCTION

Long-Term Ecological Research (LTER) sites are mandated to sponsor research in five core areas. One core area deals with natural and human-caused disturbances and their impacts on ecosystems. For most sites, common natural disturbances are driven either by short-term meteorological events such as storms and droughts or by long-term climate episodes. In either case, the researcher wants to be able to state how an apparently unique event or trend fits with past experience. In hydrology, traditional analyses of extreme value data are based upon flow magnitude and often use only the most extreme annual event (Chow 1964, Section 8I). These analyses yield little information about duration of the event and ignore other unusal but less extreme events falling within the same year. Duration is incorporated in the Palmer Drought Index, but the ability to deal with probability of return interval is not. Zelenhasić and Salvai (1987), who extend work by Todorović and Zelenhasić (1970), illustrate a method that considers the entire data record and allows statements to be made about the recurrence intervals of both the magnitude and duration of an extreme event.

Their illustration is based on a 8 800 000-ha river basin. We propose that the method can be applied to smaller basins if certain refinements in technique are made which allow for greater responsiveness of streams compared to rivers.

Our application of the Z-T method seeks to describe the southeastern drought of 1985-1988 and its significance to the Southern Appalachian Mountains and the Coweeta LTER site. Questions appropriate to the drought disturbance are: how dry was this period? how long did it last? and how does it rank with other droughts on record? In order to apply the Z-T method, we had to determine whether the technique could function with data from a smaller (approximately 1/10,000th) basin and whether the technique could be used with precipitation data. If the latter were feasible, the period of record could be doubled to over 100 years and comparison of the 1925 and 1986 droughts would be possible.

CONCEPT OF THE Z-T METHOD

For droughts, the Z-T method analyzes deficit events created by dividing a continuous streamflow record into periods of unusually low flow alternating with periods of all higher flow rates. The separation is made around a derived flow reference value, $\mathbf{Q}_{r}.$ A sequence of deficit and inter-deficit flow periods may contain intervals of normal flow that are separated by short, small deficits. Likewise, an extended low-flow sequence may contain periods when flow rates are temporarily above $\mathbf{Q}_{r}.$ These minor excursions above or below \mathbf{Q}_{r} are culled from the analysis by averaging them into the adjacent flow periods. Statistical tests for validity and serial correlation are applied to the resulting set of

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² Research Meteorologist, Coweeta Hydrologic Laboratory, Otto, NC., Principal Research Ecologist, Forest Hydrology Laboratory, Oxford, MS, and Ecologist, Southeastern Forest Experiment Station, Clemson, SC, all Forest Service, U.S. Department of Agriculture.

largest deficits and curves are fitted to the cummulative relative frequencies of the deficits and their durations. From these fits, recurrence intervals are calculated for the most extreme events.

THE Z-T PROCEDURE

Mean daily streamflow values for Coweeta Watershed 8 (WSO8) from January 1936 through December 1988 provided the data for the streamflow test of the method. Watershed 8 is a forested headwater basin of 760 ha draining into the Little Tennessee River. Mean annual precipitation of 1988 mm is evenly distributed through the year, and flow averages 1163 mm per year.

Selecting Q,

All daily flow values for Coweeta WSO8 were ranked in descending order without regard to date; \mathbf{Q}_{r} is the value occurring at the "r" percent interval. For this work, \mathbf{Q}_{r} was selected as the flow rate ranked just under 90 percent of all larger daily streamflow values. Monthly \mathbf{Q}_{90} values were also selected by ranking daily flows separately by months. \mathbf{Q}_{90} may be appropriate for slowly changing data but responsive or flashy streams may require a \mathbf{Q}_{80} or even larger reference value. The periods of consecutive days when flow was below \mathbf{Q}_{r} are the deficit events (Figure 1). The required data for the following analyses are

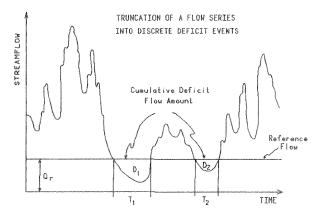


Figure 1.—Separation of a period of streamflow by Q_r into flow deficit events.

the durations of these deficits (T) and the period sums of the differences between $\mathbf{Q}_{\rm r}$ and recorded flow (D).

The seasonal cycle of streamflow suggests that low flow is relative; a level that is unusually low in the spring wet season might be a moderate level for the fall season. Using a single Q_{90} for the whole year confines most deficits to the low-flow season (see days 270-310 in Figure 2). However, an atypically low flow, such as occurred in the spring of 1985, could have significant impact upon stream ecology. To include such cases, a separate Q_{90} was calculated and applied

to each month's flow data; thereafter, deficits were identified in all seasons. Because a smooth transition between months was not possible when adjacent monthly \mathbf{Q}_{90} were quite different, a curve was fitted to the monthly \mathbf{Q}_{r} and reference values calculated for each day of the year. Figure 3

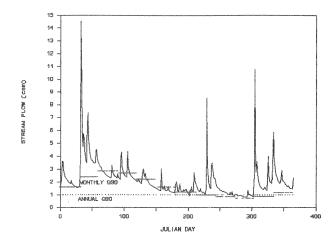


Figure 2.—Daily streamflow for Coweeta WSO8 for 1985 showing reference values for annual and monthly \mathbf{Q}_{90} .

compares the distribution of deficit periods in 1986 derived by the three types of Q_r and suggests that the extra effort needed to apply daily varying Q_r was not justified by these data.

Culling Minor Events

The chronologic series of daily streamflow was transformed by subtraction into excess flows above \mathbf{Q}_r and deficit flows below \mathbf{Q}_r . Each unbroken series of deficit days was summed, defining a deficit event with duration T and cummulative deficit (deviation from \mathbf{Q}_r) D. Similarly, excess days were summed. Low-flow periods may be

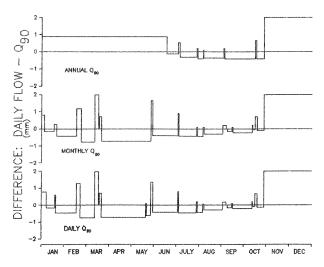


Figure 3.—Average flow for deficit and interdeficit periods in 1986 as separated by annual, monthly, and daily varying $\mathbf{Q}_{\mathbf{r}}$.