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CLIMATOLOGICAL BULLETIN

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CLIMATOLOGY IN CANADA: IMPRESSIONS OVER THREE DECADES

by

Marie Sanderson*

Knowing that I have been involved with climatology in Canada for a very long time, the editor of the Climatological Bulletin has asked me to write my reflections on the Canadian climatic scene during the past thirty years. The article will be subjective, based on my imperfect memory and with help from Morley Thomas' bibliographies of Canadian climate (1961, 1973, 1979). It will not include work in Canadian climate done in the United States or in the French language, with which I am less familiar. I have chosen 1946 as the date on which to begin since it was the year after the end of the second world war and a start of a new era in climatology and it also happened to be my first year of involvement in climatology in Canada. I had just recieved my Master's degree in Geography from the University of Maryland, where I had done research under the distinguished climatologist, C.W. Thornthwaite, and had returned to Canada to work as a research climatologist at the Ontario Research Foundation in Toronto. Prior to the Maryland experience, I had completed the honours geography course at the University of Toronto under Griffith Taylor. I was a member of the third graduating class in that program, so I really do belong to the Precambrian era in Canadian climatology!

In official government circles, climatology in 1946 was the record-keeping division of the Meteorological Branch of the Department of Transport. The main offices were at 315 Bloor St. W. and the Director of the Branch was Andrew Thomson. The climatology division under Clarence Boughner was housed in a house on Admiral Road. I remember because I used to walk there from my office at the Ontario Research Foundation which was then located at 43 Queens Park Crescent. I had come to the Research Foundation burning with zeal to work in the "new" climatology enunciated by Thornthwaite as "the science dealing with the exchanges of heat and moisture at the surface of the earth".

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My research at the ORF was to work on the Thornthwaite concept of "potential evapotranspiration" - the measurement of which took me from Mount Pleasant cemetery in Toronto to Kapuskasing, Ontario to Norman Wells in the Northwest Territories. My advisors at the Foundation were Lyman Chapman and Donald Putnam who were then completing their study of the Physiography of Southern Ontario.

In this article I will discuss the climatological, as distinct from the meteorological, scene in Canada. There is often much confusion over definitions of climatology and meteorology. Although many meteorologists do climatic research I think most climatologists would agree that their research deals in some way with the surface of the earth. It is for this reason that many, although certainly not all, climatologists are geographers since the surface of the earth is their bailiwick.

Who were the Canadian climatologists and what research were they doing in the late 1940's? In the Climatology Branch, Boughner with his young assistant, Morley Thomas, were beginning to publish much needed climatic summaries for Canada. There were approximately 1000 climatic stations then and it must be remembered that all of the computations were done by hand, with no computers to speed up the process! At the University of Toronto, Grif Taylor was still lecturing in his own inimitable way on climatology, based on Köppen and with a soupcon of Huntington! However, he did interest many of his graduate students in the topic, although some who did their dissertations in climatology would not now call themselves climatologists. Bill Wonders' dissertation for his Ph.D. in 1949 was entitled "Climate of the Canadian Archipelago" and Don Kerr in 1950 wrote his Ph.D. dissertation on the "Climatology of Southern British Columbia". A classmate of mine, D.W. Kirk, wrote in Scientific Agriculture in 1951 an article entitled "Moisture Regions in the East Kootenay Lowlands of British Columbia", Don was to die tragically that same year in a plane crash in the Eastern Arctic.

As a result of the war and the new airfields built in the Arctic, there was a great interest in northern climatic research. "Exercise Musk Ox", led by Tuzo Wilson had just been completed across Canada's Northwest Territories and Pat Baird wrote about snow and ice conditions on the Musk-Ox expedition. Lewis Robinson now at the University of British Columbia had just completed his Ph.D. at Clark University on the "Canadian Eastern Arctic".

One of the first climatologists to visit me at the Ontario Research Foundation was Ken Hare from McGill, newly arrived from England. I think the meeting was suggested by C.W. Thornthwaite whom Ken had just visited in New Jersey! Largely because of Hare's interest in the North, McGill University became, and still is, a centre for Arctic climatology. His first article on Canadian climate was written, with Marjorie Montgomery as co-author on""Ice, Open Water and Winter Climate in the Eastern Arctic", in 1949. His dissertation for his Ph.D. degree at the University of Montreal also concerned the Arctic, "Climate of the Eastern Arctic", in 1950. There was a lively climate group at McGill in those days and Svenn Orvig with Baird and Montgomery, wrote about the McGill Baffin Island Expedition in 1950. Orvig has remained at McGill and has attained an international reputation as an Arctic climatologist.

Other scientists who began doing climatology in those days have made great contributions to climatology in Canada and continue to be active in the field. Rich Longley who was to do a good deal of his climatic research at the University of Alberta, was writing his first articles on climate, on the variability of the mean daily temperature of Montreal, while Don Boyd who was to work so faithfully for the Division of Building Research of the National Research Council was writing on frost in the Annapolis Valley. In 1952, George Robertson was writing on the probability of frost, beginning a long and outstanding career in agricultural climatology. Another topic appeared for the first time in 1952, that of surface temperatures of the Great Lakes and Frank Millar's article in the Journal of the Fisheries Research Board is quoted to this day. The names J.G. Potter and G.A. McKay were first heard in climatic circles in 1953, in publications dealing with snow cover for the former, and the climate of Torbay, Newfoundland for the latter for his M.Sc. degree at McGill. Certainly these two people need no introduction to Canadian climatologists. The two Dunbars, M.J. (Max) and Moira also began their research on Arctic ice distribution at this time, Moira writing about ice distribution in Canadian Arctic seas and Max on climatic change.

My first climatic research in Canada concerned the measurement of the climatic parameter introduced to the literature by Thornthwaite - potential evapotranspiration. "Three years of evapotranspiration at Toronto" described the work at Mount Pleasant cemetery. Later I was fortunate in obtaining a grant from the Arctic Institute of North America to measure potential evapotranspiration at Norman Wells in the Northwest Territories. The results of the first year were published in the Geographical Review in 1951 but the experiment at Norman Wells was carried on for several years by the Ontario Research Foundation under Lyman Chapman and was also used by Roger Brown in his permafrost work.

The Canadian Association of Geographers was formed in 1951 and the "Canadian Geographer" began publishing in that year. An early climatic article by Bob Packer of the University of Western Ontario was "Annual Periodicity of Daily Rainfall in Canada". A climatic parameter fairly new on the Canadian scene appeared in 1954 when Mateer wrote in the Canadian Journal of Agricultural Science a "Preliminary estimate of average insolation in Canada". A good many climatic articles in the 1940's and 1950's appeared in agricultural research journals.

A new tool in climatic research that appeared in the 1950's was that of statistical techniques. Boyd and Kendall were doing research on the statistics of extreme values and J.P. Bruce who is now the Assistant Deputy Minister of the Atmospheric Environment Service was researching estimates of probability maximum precipitation over Southern Ontario.

The above names and research topics in climatology in the late 1940's and early 1950's perhaps provide a fairly representative sample of the climatic scene in Canada at the time. Not many people called themselves climatologists and those who did were often considered somehow inferior to meteorologists. But events in the 1960's began to change the outlook for climatologists. C.W. Thornthwaite in 1961 gave his presidential address to the A.A.G. on "The Task Ahead", in which he called on geographers, and climatologists among them, to use more scientific and more mathematical techniques. The quantitative revolution had begun! In addition, in the 1960's, two other important things occurred which affected climatology in Canada. The Meteorological Branch installed its first computer, making possible the expert handling of the vast amount of numbers that were generated by the observing stations. The total number of climatic stations was about 2300 during the mid 1960's. Also, the universities in Canada were expanding rapidly in both number and enrolment. In Ontario alone the total number of universities with geography departments had increased to 15 by 1970. Physical geography has always had a strong emphasis in Canadian universities, perhaps because of the

British influence, so as geography departments increased so too did the number of climatology professors. Opportunities for training climatologists in Canada were few. Since Canada was not producing many climatology Ph.D.'s the climatologists were hired from Britain, from Australia and New Zealand, and elsewhere. For example, Ben Garnier came to McGill from New Zealand, via Nigeria and Indiana University, John Davies to McMaster and Tim Oke (now at British Columbia) from England. Of special interest to climatology was the establishment of a very active group of agro-climatic research scientists at the University of Guelph under Ken King who returned to his native Canada from Wisconsin.

The number of journals publishing climatic articles also increased significantly during the 1960's. In 1961 the Journal of Applied Meteorology began and many Canadians published their climatic research there. The AES begun their series called "Climatological Studies" in 1965 and the publication "McGill Climatological Bulletin" began in 1967. The Journal of the Canadian Meteorological Society "Atmosphere" began in 1963 and has published many climatic articles. In 1978 the name was changed to Atmosphere Ocean and it is noteworthy and a source of pride for geographers that Tim Oke recently served as its editor. The number of climate articles published in agricultural research journals decreased as the other climatological journals became available.

Climatologists in Canada do not have an organization of their own but in Central Canada a "non-organization" came into being in 1969. In that year, Ken Hare came to the University of Toronto as a professor of geography and with the present author, formed the "Friends of Climatology", a group of climatologists that has managed to survive! We met first at the University of Windsor and subsequently at most universities in Ontario, in Montreal and at the Atmospheric Environment Service headquarters. A most successful initiative has been the "Climatologist-in-orbit" program in which a climatologist visits all the member universities to lecture on his/her specialty.

In 1971 there was a reorganization of the meteorological services in the federal government. They then became part of the Department of the Environand were known as the Atmospheric Environment Service. They also moved into large and beautiful new headquarters at 4905 Dufferin St. in Downsview.

I would pick the date 1972 as the year in which climatology became of age in Canada. In that year the International Geographical Union met in Montreal and I was fortunate to be asked to convene the section on Climatology, Hydrology and Glaciology. The climatologists in Canada responded in a fantastic way to the plea for papers and in all, 67 climatic papers were presented at the Congress. The report of the Congress was published in the "Climatological Bulletin" of October 1972. It is of interest to note the eight themes that were discussed: urban climatology, water balance, precipitation and runoff, energy balance, energy and water balance of the Arctic and Subarctic, bioclimatology, climatic models and climatic change, and man-climate relationships.

In 1974 the first hard-cover book dealing entirely with the Climate of Canada was published. Called "Climate Canada" it was authored by the two people who have perhaps done more for climatology than anyone else in Canada - F.K. Hare, now Provost of Trinity College and Professor of Geography, University of Toronto and Morley Thomas, who is a Director General of the AES and could be truly called the "Mr. Climatology" of Canada.

In the early 1970's, it is perhaps safe to say that the themes of radiation and energy balance and urban climatology dominated the research scene in climatology, but after the world-wide series of climatic catastrophies in the early 1970's there was a new stress on climatic change. In 1979 a world conference on climatic change was held in Geneva and a new initiative on the Canadian climatic scene was taken at the AES where a Canadian Climate Centre was organized by the then chief administrator, Art Collin a McGill Ph.D. in geography. The purpose of the Climate Centre is to process and publish all climatic data for Canada, but also to do research and respond to requests on the impact of climatic variability on man's activities. The head of the CCC is Morley Thomas and Gord McKay is the head of the climatic applications division.

Perhaps partly because of the new interest in climate by world meteorologists, partly because of the Canadian Climate Centre, but mostly because they are doing excellent research, the climatologists in Canada who call themselves geographers are being recognized as worthwhile scientists on the world scene. It is perhaps fitting that this look at climatology in Canada should end with a listing of the research interests of the current players in the field. Of course, not all of the research areas of Canadian climatologists can be included but certain important themes can be mentioned.

The bibliography of Canadian climate includes over 900 entries for the period 1972-1976. This is a tremendous increase over the previous periods and indicates a great interest in the Canadian climate scene. Almost every university in Canada has one and sometimes two or three climatologists and a good deal of research is also being done by government agencies such as the AES and Agriculture Canada. The number of research areas are extremely varied as will be seen below.

The early interest of Canadian Climatologists in the Arctic has been maintained, especially at McGill, with its Centre for Northern Studies and Research and the associated McGill Subarctic Research Station at Schefferville and the Axel Heiberg Island Station. The University of Windsor has climatologists working in the Arctic and offers a summer field course in the Arctic Environment at Frobisher Bay and Igloolik. The Geography Department at McMaster has Arctic climatology and hydrology specialists and Trent University and the University of Waterloo have climatologists active in Arctic research. The AES has recently published monographs on the climate of the Beaufort Sea and the Canadian Arctic Islands.

Excellent work in theoretical radiation and energy budget climatology continues in Canada especially at the University of British Columbia, Toronto, McMaster, Queen's and McGill. Urban climatology occupies much research time at the University of British Columbia, Calgary, Windsor and Concordia. Water balance and hydrological research were important during this period because of the very successful research undertaking called IFYGL, the International Field Year on the Great Lakes, in 1972. A great deal was learned of the exchanges of heat and moisture of Lake Ontario during this research project and the interest of climatologists in the Great Lakes has continued. Another international research project on the Great Lakes called PLUARG also involved climatologists. The Pollution from Land Use Activities Reference Group of the International Joint Commission looked at atmospheric pollution to the Great Lakes and sparked an interest among climatologists in acid rain and precipitation chemistry. Water balance and hydrology research also has high priority at the University of Alberta, Lethbridge, Waterloo, York, and Memorial.

Agricultural climatology continues to be an important aspect of climatic research in Canada in every region. Special mention must be made of the excellent work done in this area at the University of Guelph and the agrometeorology division of Agriculture Canada under Wolfgang Baier.

Climatic change has interested Arctic climatologists for a long time and continues to do so. But world-wide interest in climatic change has fostered research in climatic change in southern Canada and the Atmospheric Environment Service has taken the lead in this research.

The problems of precipitation measurement, of climatic classification, of climatic mapping have been and will remain topics of research for Canadian climatologists.

However, it is probably the impact of climate and climatic change on man's activities that is the most recent and most exciting area of interest to Canadian climatologists. The effect of climate on energy use, on transportation, recreation, on building design, as well as the possibility of using climatic sources of energy such as solar and wind energy all offer exciting challenges to Canadian climatologists. There has never been a time when climatology had so much popular interest. Perhaps the 1980's will be known as the Decade of Climatology!

AN APPROACH TOWARDS FORMULATING PROCEDURES FOR DEVELOPING TOPOCLIMATIC INDICES

by

B.J. Garnier*

It is some twenty years since Warren Thornthwaite, in a characteristically forward-looking presidential address to the Association of American Geographers stressed the importance of climatology studying the interrelationships which govern the heat and moisture balance at the surface of the earth (Thornthwaite, 1961). He emphasised also the need to recognise the abundant variability of local, or topoclimates:

> "Any region is a composite of innumerable local climates; the climate of the ravine, of the south-facing slope, of the hilltop.....Both the heat and moisture vary (within these units) because of variation in the physical characteristics, position, exposure, and aspect of these diverse surfaces."

Many studies have been made, both before and since his address, which illustrate the truth of Thornthwaite's remarks. Such studies deal with the multitude of physical relationships at the topoclimatic level; they also show the importance of aspect, exposure, or slope to plant characteristics, plant productivity, soil erosion, and related matters. Studies in the latter category, moreover, commonly recognise that, in effect, where steepness of slope is not a limiting factor, the influence of site operates through heat, energy, and moisture budgets - all of them elements of climate. As a result an enormous body of fact now exists providing details of the multitudinous facets

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involved in topographic differences in local heat, energy, and moisture budgets.

Despite the large amount of data available, however, there appear to have been few, if any, attempts to organise the knowledge derived from many disparate studies into a systematic system whereby the diverse, yet important, element of topoclimate can be given quantitative expression, by reference to factors of site on the one hand and on the other hand to the elements of mesoscale climate obtained from standard observations. Some such study is badly needed. It is, after all, at the topographic scale that the larger-scale controls and elements of climate ultimately manifest themselves. They do this because of the effect of site upon them, or, looking at it the other way round, because of the reaction of site to them. In other words, there is a coupling relationship between local and larger scales which deserves fuller examination than seems at present to have been widely undertaken.

Thornthwaite recognised this to some extent in his 1961 address when he said:

> "The ultimate objective of climatology would be to use (detailed, small scale) maps of heat budget and moisture budget in building up climatic generalizations. Generalization from such local studies would greatly enhance our understanding of climates of large regions."

This is looking at the coupling relationship by building up from detail to the larger picture. The viewpoint taken in the present article is the opposite: looking at how mesoscale characteristics may manifest themselves differentially because of the influence of site. In doing so it is important to avoid implying generalised relationships which are universally applicable. What is needed is some form of rational procedure which can be employed to link the known spatial and temporal variations of a given mesoscale climate to whatever topographic conditions exist in the area over which the mesoscale climate is found at a given time period, whether of a few days or a season. In other words, an attempt is being made to suggest a rational procedure whereby the generalisations over area derived from standard observations can be made site specific.

An approach toward this objective can be made by trying to develop what may be termed a "topoclimatic index". Moreover, because of the importance of heat and moisture to topoclimatic character suggestions for such an index will concentrate on these two aspects of the matter. In essence, what is being attempted is the development of an "indexing" procedure which can be used to show how the heat and moisture regimes at sites of different slope and aspect may be related to the standard observations which are made on, and apply only to, horizontal surfaces.

A major control of topoclimatic character lies in the impact of site on incoming solar radiation. This impact is manifested directly in terms of surface heating and the environmental temperature, and indirectly through its influence on evapotranspiration and, consequently, on the moisture regimes of the different slopes. It seems reasonable, therefore, that an initial step towards a topoclimatic index should concern itself with modelling surface variations in solar radiation income.

Such modelling can be achieved for daily totals to a sufficient degree of accuracy ($\pm$ 5%) by means of expressions in the following form (Garnier and Ohmura, 1968, 1970):

$$S{\downarrow}_s = \sum_{t=1}^{t=2} I_m \cos(\vec{X} \wedge \vec{S}) \, \Delta t \qquad \text{Eq. (1)}$$

$$D{\downarrow}_s = D{\downarrow}_h \cos^2 \Theta/2 \qquad \text{Eq. (2)}$$

Addition of the two equations provides the daily solar radiation for a slope ($K{\downarrow}_s$):

$$K{\downarrow}_s = S{\downarrow}_s + D{\downarrow}_s \qquad \text{Eq. (3)}$$

In eq. (1), I_m is the flux of direct beam solar radiation on a surface normal to the sun's rays at the central point of the time interval Δt, $(\vec{X} \wedge \vec{S})$ is the angular difference between a unit co-ordinate vector ($\vec{X}$) describing the gradient and azimuth of the slope and one ($\vec{S}$) describing the position of the sun also at the centre of the time interval Δt. In theory a value of one minute for Δt can be used. Such a refinement is, however, quite unnecessary. Careful testing (Ohmura, 1969) has shown that for slopes up to 90° an accuracy equivalent to that using Δt = 1 min is obtained by using Δt = 30 mins, and that for slopes up to 50° a similar accuracy is obtained from Δt = 60 mins. The latter interval is, therefore, appropriate for most purposes. Moreover, when radiation data are prepared for time intervals of less than a day they are routinely supplied in terms of hourly totals, as for example is done by the Atmospheric Environment Service of Canada. Using Δt = 60 mins, therefore, is both accurate and practical in terms of readily available data.

Summation to achieve daily totals of direct radiation on the slope ($S{\downarrow}_s$) is from the time of sunrise (t = 1) to sunset (t = 2) on the slope, taking into account both the slope's azimuth and gradient and any local skyline influence. The latter factor can, however, normally be safely neglected in daily totals except in regions of particularly high values of relative relief or for detailed purposes such as the siting of a solar energy collector on a building or in a study in which the surface radiation flux at the beginning or end of the day is especially important.

Eq. (2), derived by Kondratyev (1965), relates incoming sky-diffuse radiation on a slope ($D{\downarrow}_s$) to that on a horizontal surface ($D{\downarrow}_h$) through the gradient (Θ) of the slope in question. This expression assumes that sky-diffuse radiation is isotropic. Such an assumption is not strictly correct for all sun altitudes and sky conditions. Nevertheless, for daily totals on a slope it is sufficiently accurate because:

(a) when totalled over daylight hours the errors tend towards cancelling each other out (Robinson, 1966); and

(b) the assumption is least accurate when skies are clear and $D{\downarrow}/K{\downarrow}$ is small, and is most accurate under overcast conditions when $D{\downarrow}/K{\downarrow}$ is large.

It is clear from Eqs. (1) and (2) that the major contrasts between solar radiation on a slope and that on the horizontal arise from the direct beam solar flux. For a slope of 37°, for example, the ratio $D{\downarrow}_s/D{\downarrow}_h$ is 0.90. By contrast, the ratio $S{\downarrow}_s/S{\downarrow}_h$ for a similar slope commonly varies between 0.0 and more than 2.0 depending on aspect, time of year, and the transmissivity of the atmosphere to solar radiation.

The latter factor is, indeed, a key to direct beam solar radiation income. The value of I_m in eq. (1) can be replaced by

$$I_m = I_r p^m$$

where I_r is extraterrestrial radiation, p is the atmospheric transmissivity, and m is the optical air mass calculated for the central point of Δt. This relationship can, therefore, be used to evaluate daily totals of direct beam solar flux ($S{\downarrow}_s$) on any slope by means of a mean atmospheric transmissivity for the day ($\bar{p}$) as detailed in Garnier and Ohmura (1968).

In theory a drawback to using $\bar{p}$ as a basis for calculating $S{\downarrow}_s$ is that it assumes no change in the hourly value of p through the day. This is obviously only the case on completely cloudless days or on days without significant change in the cloud deck. Therefore one might expect errors to arise for different slopes as hourly values of p change. Tests have shown however that in practice for daily totals little error appears to arise on slopes with an azimuth within 60° of the north/south meridian. Errors are larger on east or west-facing slopes but even here do not normally appear to be excessive (Garnier, 1980). In this connection it is relevant to draw attention to a recent study by Revfeim and Hessel (1980) concerning the asymmetry of 'bright' sunshine hours. If such asymmetry can, indeed, be shown to be sufficiently persistent on a daily basis it might provide a way to adjust the value of $\bar{p}$ through the day when used in the summations of eq. (2).

It is easy to compute an appropriate $\bar{p}$ from daily totals of the direct solar radiation flux ($S{\downarrow}_h$). Unfortunately the latter total is not too easy to find among routine observations of solar radiation. Where sky-diffuse solar radiation ($D{\downarrow}_h$) is measured along with global solar radiation ($K{\downarrow}_h$), a value of $S{\downarrow}_h$ is easily found by subtraction ($S{\downarrow}_h = K{\downarrow}_h - D{\downarrow}_h$). Few stations, however, routinely measure $D{\downarrow}_h$. In Canada, out of 54 stations recording $K{\downarrow}_h$ only four routinely provide data on $D{\downarrow}_h$.

Because of the importance of separating $S{\downarrow}_h$ from $K{\downarrow}_h$ in the calculation of solar energy on slopes a great deal of attention has been devoted to the problem (see, for example, Liu and Jordan, 1960; Ruth and Chant, 1976; Hay, 1976; Sadler, 1975). Also because solar radiation measurements are themselves not particularly widespread and, in many cases, have been undertaken for a relatively short time, records of hours of bright sunshine have been used to provide empirical relationships between extraterrestrial radiation (Q_o) and solar radiation by way of formulae in the form originally developed by Angstrom (1924):

$$K{\downarrow} = Q_o\ (a + b.n/N)$$

where n/N is the ratio of actual to possible hours of bright sunshine.

In such analyses recent work has attempted to derive both more detailed means of estimating solar radiation and also ways of using sunshine records to obtain values of $S{\downarrow}_h$ on an hourly or daily basis (Schulze, 1976; Revfeim, 1981). There seems however to have been little recognition that n/N can also be used as a direct means for estimating $\bar{p}$. Yet a little thought shows that since the sunshine recorder only records when the sun is not obscured by clouds and since $\bar{p}$ is, in fact, a value which reduces clear sky atmospheric transmissivity by a factor depending on the reduction in time of clear sky conditions, there should be a good relationship between $\bar{p}$ and n/N. This has, indeed, been found to be the case in a recent analysis of some Canadian data (Daoust et. al,, 1981). In the present context, therefore, it could well be that a satisfactory and simple way to evaluate $S{\downarrow}_h$ is to make use of the often long-term records of hours of bright sunshine which exist for many places. If this argument is accepted, it becomes relatively easy to evaluate $S{\downarrow}_h$ and, therefore, $S{\downarrow}_s$ for any slope in a realistic manner and, if necessary, on a daily basis. Such evaluation can then be used in conjunction with observed or calculated values of $K{\downarrow}_h$ to obtain appropriate values of $K{\downarrow}_s$.

The foregoing arguments have emphasised solar radiation income. It must be remembered, however, that it is, in fact, net radiation (Q*) and its partitioning between ground, sensible, and latent heat fluxes which constitutes the dominant radiative factor in the energy/heat load of a given site and the resulting environmental conditions. Investigations into the effect of aspect or site on heat or soil moisture or temperature conditions clearly recognise this, sometimes offering quantitative evaluations (Rouse and Wilson, 1969; Greenland and Owens, 1967). Thus it is important to examine surface variations in Q* along with those of solar radiation income.

This objective may be met by relating net radiation to solar radiation income. Many studies have shown that this is possible by way of an expression in the form

$$Q^* = a + b.K{\downarrow}$$

Among examples of such work and discussion of the problems involved may be cited Davies, 1967; Gay, 1971; Fritschen, 1967.

It should be noted that the expression given above has been derived from relationships between Q* and $K{\downarrow}$ as measured on horizontal surfaces. A field experiment in southern Quebec (Wilson and Garnier, 1975) has shown that such relationships hold equally well when applied to slopes. This being so, surface variations of Q* may be conveniently established by way of $K{\downarrow}_s$ and used to develop some form of topoclimatic index.

A major contribution of solar radiation to the climate of a site is through its influence on evapotranspiration. This influence is particularly relevant to variations in soil moisture from place to place. A convenient climatic approach to evaluating the latter is by means of the water balance which, in essence, matches potential evapotranspiration with precipitation.

Thus, topographic variations in potential evapotranspiration will need to be included in formulating a topoclimatic index.

While the part played by solar radiation, or, more precisely, by Q* in potential evapotranspiration is large, the role exercised by the evaporative power of atmosphere must also be considered. In particular, varied exposure to wind enters into both soil moisture and soil temperature contrasts between slopes of different aspects and exposures. Clearly, therefore, some consideration needs to be given to the relative influence of radiation and wind speed in the topographic variations of evapotranspiration.

A convenient way to estimate this is to employ Penman's widely-used combination equation (Penman, 1963). This equation separates potential evapotranspiration (Ep) essentially into two terms: a radiative term (Erad) and an aerodynamic term (Eady) by means of the expression:

$$Ep = \frac{s}{s+g} (Q^* - G) + \frac{g}{s+g} . Ea$$

$$= Erad + Eady$$

where: Q^* = net radiation expressed in mm evaporative units

s = the slope of the saturation vapour pressure curve at temperature (T)

g = the psychrometric constant (0.66 mb K^{-1})

G = heat flux into the ground

$Ea = 0.35\ (1 + 0.01u)(e_s - e_a)$

where u = wind miles run per day at a height of 2 metres

e_s = saturation vapour pressure at temperature (T) in mm Hg

e_a = actual vapour pressure in mm Hg.

The units in the foregoing are as given in Penman (1963). A modification of Ea using wind run in kilometres per day has recently been provided by Heine (1981) in a discussion of the aerodynamic term in Penman's equation.

On a daily basis, topographic variations in Erad operate mainly through surface variations in Q* (Garnier, 1972). This is because $s/(s + g)$ varies slowly with temperature and because, on a 24 hour basis, G can be held to approach zero. There is, therefore, little difficulty in estimating variations in Erad by means of variations in Q^*_s as already discussed.

Within a given area variations in wind run (u) will be the major cause of surface variations in Eady in view of the varied exposure of different sites to the prevailing wind. Despite many observations of wind speeds in exposed places, studies are hard to find which deal specifically with local (topographic) variations in wind speed from a base, or average ambient, value. Moreover, analyses of the behaviour of wind flow over hilly terrain such as those reviewed in Barry (1981) do not yet appear to have been generalised into substantive studies which would provide ways of evaluating surface variations in wind speed by reference to prevailing wind speed and direction considered in relation to surface geometry (slope, aspect, and relative relief). Until this has been achieved, therefore, it will be necessary to fall back on conclusions derived from data such as are presented in Table One.

TABLE ONE

Potential Evapotranspiration, Wellington, N.Z.

Date (1977)	Q* ly. day^{-1}	$\bar{p}$	u km day^{-1}	T ^{o}C	Ep mm	Erad/Ep	Eu/Ep	Esd/Ep
Oct. 3	294	.70	314	5.9	2.8	.89	.07	.04
Oct. 15	299	.60	410	8.9	3.4	.80	.15	.05
Oct. 30	198	.40	519	13.5	2.7	.77	.18	.05
Nov. 10	302	.50	280	14.2	4.3	.74	.16	.10
Nov. 17	379	.60	448	13.1	6.0	.64	.26	.10
Nov. 18	407	.70	311	12.4	5.6	.73	.18	.09
Dec. 27	465	.76	276	14.0	6.1	.80	.13	.07

This table shows values of potential evapotranspiration for seven days of variable wind and solar radiation in the spring and early summer of 1977 at Wellington, New Zealand. The calculations were made by means of the Penman equation. Use of this equation enables one to isolate the contribution of the radiative terms (Erad) to total Ep, and also to separate the aerodynamic term (Eady) into its two components: the contribution of wind speed (u), and that of saturation deficit (sd). The ratios Erad/Ep, Eu/Ep, and Esd/Ep in Table One show the proportion to total Ep contributed by each of the three factors: radiation, wind speed, and saturation deficit.

It can be seen that the ratio Eu/Ep is consistently under 0.20, except on November 17, despite the range of wind speeds of the days sampled. Even doubling the wind run on the windiest day (October 30) brings the ratio Eu/Ep only to 0.30. By contrast Erad/Ep normally exceeds 0.70. Thus it would appear that consistent and major topographic contrasts in wind speed are required for this factor to override the importance of Erad and its surface variations in the evaporative term.

All this is another way of saying that evaluating surface variations in Q* is likely to be the most promising route to follow in our search for an adequate way of evaluating potential evapotranspiration as part of a topoclimatic index. The aerodynamic influence can be allowed for by reference to base station data. This could provide an appropriate factor with which to multiply the first (Erad) term of the Penman equation after the manner advanced by Priestley and Taylor (1972) in their presentation of the equilibrium model of potential evapotranspiration. Alternatively a standard value of 1.26 could be used as advocated by Priestley and Taylor.

The foregoing arguments imply that a fruitful line to pursue might be to employ surface variations in solar radiation income to develop indices of two kinds:

(a) a "heating" index derived from comparing solar radiation on the slope with that observed on the horizontal ($K{\downarrow}_s/K{\downarrow}_h$) or from using a similar relationship in terms of net radiation (Q^*_s/Q^*_h);

(b) a "moisture" index developed by way of a water balance approach through matching potential evapotranspiration on different slopes with precipitation.

Such a concept requires testing in different areas where there is sufficient topographic variety and an adequate data base. Many parts of Canada lend themselves to this. The objective would be to see how well the variations revealed by a topoclimatic approach correspond with variations in soil moisture, site temperatures, or the heat budget at different locations. The testing could also be usefully undertaken in areas of intense cultivation or fruit growing and related to variations in the productivity at different sites.

At the same time it would be necessary to examine how widely the procedures could be used. If sunshine records, for example, provide an adequate basis for developing the indices contemplated at the scales required - both in terms of time and space - the way is opened for widespread use of the technique in a spatial sense and for the evaluation of 'average' conditions of topoclimates in a manner which is comparable with the climatic 'normals' currently available. If this can be achieved, it will materially increase the usefulness of available climatic data from the viewpoint of those many situations in which site, slope, aspect, and exposure play a significant role.

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FUTURE DIRECTIONS IN CARIBBEAN CLIMATOLOGICAL RESEARCH

by

Bhawan Singh*

Introduction

A fair amount of ground work in the radiation climatology of the Caribbean has been laid by several researchers, notable Garnier and Ohmura (1969; 1970), Garnier (1972) and Wilson and Garnier (1975). The thrust of these research efforts were directed to surface variations in the intensity of direct solar radiation (S) as regulated by topographic conditions, namely slope angle and orientation, (Garnier and Ohmura, 1969; 1970). As a natural extension to these basically topoclimatic studies, Garnier (1972) examined the spatial variations of surface radiative temperatures and the measurement thereof via remote sensing techniques that exploited airborne infra-red thermometry. Most recently, Wilson and Garnier (1975) suggested a technique for deriving net radiation (Q^*) for sloping surfaces from measurements of direct (S) and diffuse (D) solar radiation, of surface albedo (α) and of net radiation (Q^*) taken at a single base station. This represents a significant step in radiation and energy balance studies that incorporate topoclimatic effects in that the basic measure (Q^*) that governs the turbulent transfer of sensible (QH) and latent (QE) heat and the conduction of soil heat (QG) is calculable.

Although all of these studies have been carried out in the island of Barbados, the results are nonetheless applicable to the vast majority of the Caribbean islands in view of the homogeneity in regional climate and the physical similarity of the islands especially as regards topographic characteristics and surface cover.

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The following is the statement of a few ideas as regards possible future areas of research that are take-offs from the research already effected and as described briefly above. The discussion will be restricted essentially to micro-scale and meso-scale climatological processes.

Future Avenues

With the possibility of deriving reasonable estimates of net radiation (Q^*) as described above (Wilson and Garnier, 1975) or through predictive models as per Davies (1981), the next logical step would be to focus upon the ways in which this available energy is consumed, namely the turbulent transfer of sensible (QH) and latent (QE) heat and the conductive transfer of soil heat (QG). Of particular interest would be the latent heat component, from several points of view.

First there is the need for testing and verification of the several micrometeorological models commonly used for estimating the latent heat flux, notably the simpler and more easily applicable models such as the Priestley and Taylor (1972) and the Monteith (1965) variants of Penman's (1948) combination model, in an insular tropical environment. Furthermore these measures would provide valuable information to island governmental agencies responsible for water management for domestic and agricultural purposes, since the popular mode of estimating evaporation seems to be the class "A" pan, which leaves much to be desired. Pan estimates of evaporation average about 100 mm per month during the wet season that normally lasts from June to November and about 180 mm per month during the dry season that normally lasts from December to May for the Island of Trinidad (Records of Water Resources Agency). These results are obviously biased by cloud cover conditions as represented by total sunshine hours which is incorporated in the pan estimates. Furthermore it would seem that evaporation is lower during the wet season, when potential conditions apply at the vaporizing surface. This goes counter to the understanding that surface wetness enhances the rates of evaporation, especially for vegetation surfaces, through the interception of rainfall, which cover at least 75 percent of the island, as was demonstrated by Singh (1977), Singh and Szeicz (1979) and Singh (1981). Micrometeorological estimates of evaporation then would go a long way towards calibrating and hence updating present measurement techniques.

Research directed at the turbulent transfer of sensible heat would also be highly desirable. An island, because of its terrain elements, especially surface roughness, drastically alters the regional field of atmospheric stability and turbulent transfer. Not only is mechanical turbulence enhanced by its rougher surface but also thermal turbulence is relatively greater than for the surrounding ocean surface because, in the apportionment of the net radiation, relatively more heat energy will be directed to surface heating and the transfer of sensible heat. Islands thus act as strong sources for sensible heat and strong sinks for momentum which in return changes the overall turbulent regime and the stability of the lower atmosphere. For seasoned Caribbean travellers this influence is very evident in that even during the stable dry season, it is not uncommon to observe billowy puffs of cumulus clouds over and on the lee side of islands, this condition most likely being due to drastic changes in the vertical temperature profile and the mixing depth, as generated by the island surface. This latter condition has been known to generate light drizzly rainfall even during the dry season (personal observation). Islands in this region then seem to have similar characteristics to the "heat islands" associated with large mid-latitude cities.

The obvious step that should follow should be an attempt to relate the micro-scale processes described above to the prevailing meso-scale conditions, especially in the sense that the timing and intensity of rainfall is influenced. It is a well known fact that the greater part of rain falls at night in the Caribbean, these rainfalls being largely of the stormy variety. Is this occurrence mere coincidence, or is it related to the way in which island surfaces influence the diurnal regime of the heat balance? It would seem that the coupling or rather the decoupling of these island effects, especially insofar as turbulent characteristics and local circulation patterns are concerned, with the meso-scale synoptic conditions is responsible for generating heavy rainfalls.

Furthermore, there is an apparent strong influence of topography on the spatial variability of rainfall. The majority of the Caribbean islands are characteristically hilly. For instance in the Island of Trinidad, rainfall on the windward section of the northern range, which rises to about 900 metres, averages 175 cm whereas on the leeward and flatter Caroni Swamp rainfall only averages 25 cm (Water Resources Agency records). A case for network analysis of gauging stations is thus strongly implied.

Further yet on the subject of rainfall, is the temporal aspect. Based on rainfall, the climate of the Caribbean has been classically divided into a dry season which occurs in the first six months of the year and a wet season that occurs during the last six months of the year. An examination of the rainfall records for the Island of Trinidad for the last 30 or 50 years however does not reveal such a simple subdivision. Quite a number of years are actually characterized by two wet seasons, one lasting from May to July and another during October and November. Furthermore an examination of the mean annual rainfall trend reveals a fair amount of cyclical variation, with periods of drought oocurring periodically (Seepersad, 1977).

These temporal variations in rainfall would seem to be related to shifts in the meso-scale synoptic patterns, with periods of drought being probably related to the fewer occurrences of storm cells such as easterly waves or to reduced intensification of these waves. A link with the frequency of occurrence and the intensity of hurricanes might also be sought.

Of course there are several other research avenues, especially with respect to economic and management viewpoints. Among these one can suggest the economic impacts of such severe climatological events as hurricanes and droughts on island communities. On the other hand, from an operations research point of view, one can include such parameters as the magnitude and timing of both rainfall and evaporation in the management of water resources.

Conclusion

The start of what promises to be an innovative and interesting endeavour of research in tropical climatology has been achieved by the group of researchers at the Bellairs research station in Barbados. Aside from this research station there are others such as le Centre de Recherches Caraïbes de l'Université de Montréal located at Martinique; la station de bioclimatologie at Guadeloupe, the Caribbean Meteorological Institute with offices at several of the islands including Trinidad and Barbados and the Water Resources Agency in Trinidad. The opportunity and the facilities are then there for the advancement of several areas of tropical climatology that have lagged behind their North American and European counterparts, mainly because of economic reasons. These advances will not only enlighten us in terms of tropical processes, but also most likely in terms of some of the mid-latitude processes that seem to escape us. Of course there is always the aspect of international cooperation and the exchange of viewpoints.

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NEWS AND COMMENTS

The 1982 meeting of Friends of Climatology was held at MacMaster University on April 15 and 16. The meeting was more structured than usual in that it contained a series of formal presentations by invited speakers, followed by informal discussion and questions.

The first day, both morning and afternoon, was devoted to the carbon dioxide problem. Ken Hare (University of Toronto) led off the discussion with an overall, global view of carbon dioxide in the atmosphere reviewing facts and figures of its present extent, causes, and possible trends. This was followed by a well-argued analytical study by R.E. Dickinson (NCAR) on using mathematical models to interpret, understand, and predict the influence of CO_2 on climate. These two morning presentations were followed in the afternoon by three talks on specific interrelationships between carbon dioxide and human affairs. J.S. Kirkcaldy (Institute of Energy Studies, MacMaster) discussed the CO_2-energy link; D.W. Stewart (Land Resource Research Institute, Ottawa) examined the effect of atmospheric warming from carbon dioxide on climate in relation to agriculture; and B.W. Boville (Institute of Environmental Studies, Toronto) looked at how this warming might be dealt with by various social, economic, and policy strategies.

As with all speculation on the earth's climatic future there was plenty of room for discussion and argument. Two features of common ground, however, came through it all. The first is the importance of recognising the inevitable chain reactions arising from a significant change in the carbon dioxide content of the atmosphere. The complications and various potential directions of this chain reaction bedevil the possibility of unanimity - perhaps one could say reliability - in predicting future scenarios. The second feature is that it is clear that, in terms of human affairs, favourable and unfavourable consequences will appear differentially over the earth. Growing seasons will shorten here and lengthen there; in some parts there will be more rain in other parts there will be less rain. Here is surely a field which should be avidly taken up by geographers with their interest in spatial features, and the varying significance and expression of interrelationships between phenomena from place to place.

The second morning of the meeting was devoted to various aspects of modelling. R.E. Dickinson gave a second presentation in which he dealt with modelling the interactions between vegetation and global climate. This was followed by a talk from C. Essex (Centre for Research in Space Science, York University) in which he examined the theory and practice of modelling the relationships between climate, thermodynamics, and radiation. The morning session ended with a brief question and answer panel discussion on the topics which had been dealt with during the meeting.

The two days were not all work. There was an excellent dinner in the Faculty Club, hosted by MacMaster University, followed by an informal gathering on the evening of the first day. Also in the Faculty Club, there were buffet lunches on both days. The second of these was followed by a "business meeting" of the Friends. At this, Ben Garnier outlined plans for the future of the Climatological Bulletin after he retires from McGill next August, and Gord McKay described the activities of the Canadian Climate Program. The Friends also accepted with gratitude an invitation to hold the meeting for 1983 at Carleton University.

Altogether a delightful two days from all points of view, with the weather adding its blessing by pouring warmth and sunshine onto the attractive MacMaster campus. Congratulations and thanks to John Davies and his assistants for flawlessly organising an excellent intellectual and social occasion.

Two years ago climatology was established as a "special interest group" of the Association of American Geographers. This has resulted in greatly increased recognition of the subject at the association's annual meeting. The following notes on the AAG meeting for 1982 have been sent by Stewart Cohen (York University).

> "The 1982 AAG Annual Meeting took place on April 24-28 in San Antonio, Texas, and increased interest in research related to climatic issues was evident. A total of 13 climatology sessions were held (as opposed to 10 at the 1981 meeting), including 2 special sessions on snow and ice organized by Roger Barry of Colorado. Many other presentations were oriented towards hydroclimatology and climatic variation. There was also a session on State Climatology Programs, which consisted of presentations on programs in Kentucky, Arizona, and Louisiana. This particular session closed with a presentation by Peter J. Robinson of the U.S. National Climate Program Office, who noted that there was a lack of participation in this program by geographers. Robinson called for greater involvement, and provided information on grants available in the U.S.
>
> In addition to the 13 sessions, there were meetings on coastal and climatic hazards, plant-climate relationships, and climatic geomorphology. There was also a panel discussion on projects of the Scientific Committee on Projects of the Environment (SCOPE). Participation at this conference was so great that during the two morning periods of April 27, for example, there were 4 sessions on climatology and the meeting on plant-climate relationships.
>
> Among the highlights of the conference were special presentations given by J. Murray Mitchell of NOAA and Arthur V. Douglas of Creighton University on global climate change and climatic variability in the Southwest U.S. respectively. Both speakers had been invited by the AAG Climatology Specialty Group, chaired by Robert A. Muller of Louisiana State University. These sessions were very well attended, thereby encouraging the specialty group to continue with this format. An invitation has been extended to Stanley A. Changnon of the Illinois State Water Survey to be the featured speaker at next year's meeting in Denver.
>
> At the specialty group's annual business meeting, Richard Skaggs of Minnesota was chosen to be the new chairperson, with Stephen Justham of Ball State University continuing as secretary-treasurer. I

> gave a short report on the Climatological Bulletin, William E. Riebsame of Clark University spoke on the SCOPE project's Climate Impact Newsletter, and Athol D. Abrahams of State University of New York at Buffalo informed the group about the new editorial policy of the Annals of the AAG."

One tends to think of the W.M.O. Bulletin, published four times a year by the World Meteorological Organisation, as dealing mainly with reports, survey and progress articles, and information concerned specifically with W.M.O. and its multivarious activities through commissions, support programs, and publications. Within the past two years, the Bulletin has added to its repertoire interviews with leading figures, usually retired, in world meteorology or climatology. These make very interesting reading. The interviews are devoted mainly to the scientific work of the persons concerned, but one can also obtain interesting insights into other sides of the well-known personalities concerned.

We learn, for example, that E.H. Palmen (W.M.O. Bulletin, April 1981) was fascinated by clouds as a child and used to try his hand at weather forecasting at the tender age of seven; he also from a later, but nonetheless relatively early age, always had to smoke a cigar to get him going for work. E.K. Fedorov (W.M.O. Bulletin, October 1981) reveals himself as deeply concerned with international peace and co-operation, recognising the total interdependence of all people upon the earth's atmosphere. For some, like R.C. Sutcliffe (W.M.O. Bulletin, July 1981) getting into meteorology was almost accidental and related to the best chance he had for getting a job in the depression years after specialising in maths and physics. For Anders K. Angstrom (W.M.O. Bulletin, April 1982), on the other hand, his career and specialisation in the field was almost inevitable; he was of the third generation of a family already working with international renown in the field of theoretical and applied physics and radiation. J. Bessemoulin (W.M.O. Bulletin, January 1982) by contrast became a meteorological specialist through a short course for which he volunteered and which he passed successfully during his compulsory military training as a young man. He now lives comfortably in retirement in a converted mill (known locally as Chateau Bessemoulin) at the foot of the Pyrenees where he continues making some weather observations, but also enjoys trout fishing and making furniture.

Altogether an attractive series which one hopes W.M.O. will continue.

Robert W. Kates writes from the Center of Technology, Environment and Development, Clark University, Worcester, Massachusetts, 01610, to say that he and his associates are involved in a review of the methodology of climatic impact assessment on behalf of the Scientific Committee on Problems of the Environment of the International Council of Scientific Unions.

> "As part of our effort we are compiling a list of scientists who share our interest in climate impact research. In this regard we urge you to send in names of individuals who should be included, reprints of your latest publications, and short summaries of your current projects and interests. In return we will send out the list, prepare a newsletter, report on latest publications, and refer inquiries to appropriate individuals."

NECROLOGY

It is with profound regret that we record the death of Geza Szeicz in April, 1982. Dr. Szeicz is well known for his many contributions in the field of micrometeorology through his many publications, more particularly those in the Quarterly Journal of the Royal Meteorological Society. He came to Canada some ten years ago as a Visiting Professor to McGill University, and subsequently joined the staff of the University of Toronto. We can only deplore that cancer took his life while he still had many years of fruitful scientific work ahead of him.

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